

*Machinery's Handbook 27th Edition*

A REFERENCE BOOK  
FOR THE MECHANICAL ENGINEER, DESIGNER,  
MANUFACTURING ENGINEER, DRAFTSMAN,  
TOOLMAKER, AND MACHINIST

27<sup>th</sup> Edition  
**Machinery's  
Handbook**

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## PREFACE

*Machinery's Handbook* has served as the principal reference work in metalworking, design and manufacturing facilities, and in technical schools and colleges throughout the world, for more than 90 years of continuous publication. Throughout this period, the intention of the *Handbook* editors has always been to create a comprehensive and practical tool, combining the most basic and essential aspects of sophisticated manufacturing practice. A tool to be used in much the same way that other tools are used, to make and repair products of high quality, at the lowest cost, and in the shortest time possible.

The essential basics, material that is of proven and everlasting worth, must always be included if the *Handbook* is to continue to provide for the needs of the manufacturing community. But, it remains a difficult task to select suitable material from the almost unlimited supply of data pertaining to the manufacturing and mechanical engineering fields, and to provide for the needs of design and production departments in all sizes of manufacturing plants and workshops, as well as those of job shops, the hobbyist, and students of trade and technical schools.

The editors rely to a great extent on conversations and written communications with users of the *Handbook* for guidance on topics to be introduced, revised, lengthened, shortened, or omitted. In response to such suggestions, in recent years material on logarithms, trigonometry, and sine-bar constants have been restored after numerous requests for these topics. Also at the request of users, in 1997 the first ever large-print or "desktop" edition of the *Handbook* was published, followed in 1998 by the publication of *Machinery's Handbook CD-ROM* including hundreds of additional pages of material restored from earlier editions. The large-print and CD-ROM editions have since become permanent additions to the growing family of *Machinery's Handbook* products.

Regular users of the *Handbook* will quickly discover some of the many changes embodied in the present edition. One is the combined *Mechanics and Strength of Materials* section, arising out of the two former sections of similar name; another is the *Index of Standards*, intended to assist in locating standards information. "Old style" numerals, in continuous use in the first through twenty-fifth editions, are now used only in the index for page references, and in cross reference throughout the text. The entire text of this edition, including all the tables and equations, has been reset, and a great many of the numerous figures have been redrawn. This edition contains more information than ever before, and sixty-four additional pages brings the total length of the book to 2704 pages, the longest *Handbook* ever.

The 27th edition of the *Handbook* contains significant format changes and major revisions of existing content, as well as new material on a variety of topics. The detailed tables of contents located at the beginning of each section have been expanded and fine tuned to simplify locating your topic; numerous major sections have been extensively reworked and renovated throughout, including *Mathematics*, *Mechanics and Strength of Materials*, *Properties of Materials*, *Fasteners*, *Threads and Threading*, and *Unit Conversions*. New material includes fundamentals of basic math operations, engineering economic analysis, matrix operations, disc springs, constants for metric sine-bars, additional screw thread data and information on obscure and historical threads, aerodynamic lubrication, high speed machining, grinding feeds and speeds, machining econometrics, metalworking fluids, ISO surface texture, pipe welding, geometric dimensioning and tolerancing, gearing, and EDM.

Other subjects in the *Handbook* that are new or have been revised, expanded, or updated are: analytical geometry, formulas for circular segments, construction of four-arc ellipse, geometry of rollers on a shaft, mechanisms, additional constants for measuring weight of piles, Ohm's law, binary multiples, force on inclined planes, and measurement over pins.

The large-print edition is identical to the traditional toolbox edition, but the size is increased by a comfortable 140% for easier reading, making it ideal as a desktop reference. Other than size, there are no differences between the toolbox and large-print editions.

## PREFACE

The *Machinery's Handbook 27* CD-ROM contains the complete contents of the printed edition, presented in Adobe Acrobat PDF format. This popular and well known format enables viewing and printing of pages, identical to those of the printed book, rapid searching, and the ability to magnify the view of any page. Navigation aids in the form of thousands of clickable bookmarks, page cross references, and index entries take you instantly to any page referenced.

The CD contains additional material that is not included in the toolbox or large print editions, including an extensive index of materials referenced in the Handbook, numerous useful mathematical tables, sine-bar constants for sine-bars of various lengths, material on cement and concrete, adhesives and sealants, recipes for coloring and etching metals, forge shop equipment, silent chain, worm gearing and other material on gears, and other topics.

Also new on the CD are numerous interactive math problems. Solutions are accessed from the CD by clicking an icon, located in the page margin adjacent to a covered problem, (see figure shown here). An internet connection is required to use these problems. The list of interactive math solutions currently available can be found in the *Index of Interactive Equations*, starting on page 2689. Additional interactive solutions will be added from time to time as the need becomes clear.

Those users involved in aspects of machining and grinding will be interested in the topics Machining Econometrics and Grinding Feeds and Speeds, presented in the *Machining* section. The core of all manufacturing methods start with the cutting edge and the metal removal process. Improving the control of the machining process is a major component necessary to achieve a **Lean chain** of manufacturing events. These sections describe the means that are necessary to get metal cutting processes under control and how to properly evaluate the decision making.

A major goal of the editors is to make the *Handbook* easier to use. The 27th edition of the *Handbook* continues to incorporate the timesaving thumb tabs, much requested by users in the past. The table of contents pages beginning each major section, first introduced for the 25th edition, have proven very useful to readers. Consequently, the number of contents pages has been increased to several pages each for many of the larger sections, to more thoroughly reflect the contents of these sections. In the present edition, the *Plastics* section, formerly a separate thumb tab, has been incorporated into the *Properties of Materials* section. A major task in assembling this edition has been the expansion and reorganization of the index. For the first time, most of the many Standards referenced in the *Handbook* are now included in a separate *Index Of Standards* starting on page 2677.

The editors are greatly indebted to readers who call attention to possible errors and defects in the *Handbook*, who offer suggestions concerning the omission of some matter that is considered to be of general value, or who have technical questions concerning the solution of difficult or troublesome *Handbook* problems. Such dialog is often invaluable and helps to identify topics that require additional clarification or are the source of reader confusion. Queries involving *Handbook* material usually entail an in depth review of the topic in question, and may result in the addition of new material to the *Handbook* intended to resolve or clarify the issue. The new material on the mass moment of inertia of hollow circular rings, page 248, and on the effect of temperature on the radius of thin circular rings, page 405, are good examples.

Our goal is to increase the usefulness of the *Handbook* to the greatest extent possible. All criticisms and suggestions about revisions, omissions, or inclusion of new material, and requests for assistance with manufacturing problems encountered in the shop are always welcome.

Christopher J. McCauley, Senior Editor



## ACKNOWLEDGMENTS

The editors would like to acknowledge all those who contributed ideas, suggestions, and criticisms concerning the *Handbook*.

Most importantly, we thank the readers who have contacted us with suggestions for new topics to present in this edition of the *Handbook*. We are grateful for your continuing constructive suggestions and criticisms with regard to *Handbook* topics and presentation. Your comments for this edition, as well as past and future ones are invaluable, and well appreciated.

Special thanks are also extended to current and former members of our staff, the talented engineers, recent-graduates, who performed much of the fact checking, calculations, artwork, and standards verification involved in preparing the printed and CD-ROM editions of the *Handbook*.

Many thanks to Janet Romano for her great *Handbook* cover designs. Her printing, packaging, and production expertise are irreplaceable, continuing the long tradition of *Handbook* quality and ruggedness.

Many of the American National Standards Institute (ANSI) Standards that deal with mechanical engineering, extracts from which are included in the *Handbook*, are published by the American Society of Mechanical Engineers (ASME), and we are grateful for their permission to quote extracts and to update the information contained in the standards, based on the revisions regularly carried out by the ASME.

ANSI Standards are copyrighted by the publisher. Information regarding current editions of any of these Standards can be obtained from ASME International, Three Park Avenue, New York, NY 10016, or by contacting the American National Standards Institute, West 42nd Street, New York, NY 10017, from whom current copies may be purchased. Additional information concerning Standards nomenclature and other Standards bodies that may be of interest is located on page 2079.

Several individuals in particular, contributed substantial amounts of time and information to this edition.

Mr. David Belforte, for his thorough contribution on lasers.

Manfred K. Brueckner, for his excellent presentation of formulas for circular segments, and for the material on construction of the four-arc oval.

Dr. Bertil Colding, provided extensive material on grinding speeds, feeds, depths of cut, and tool life for a wide range of materials. He also provided practical information on machining econometrics, including tool wear and tool life and machining cost relationships.

Mr. Edward Craig contributed information on welding.

Dr. Edmund Isakov, contributed material on coned disc springs as well as numerous other suggestions related to hardness scales, material properties, and other topics.

Mr. Sidney Kravitz, a frequent contributor, provided additional data on weight of piles, excellent proof reading assistance, and many useful comments and suggestions concerning many topics throughout the book.

Mr. Richard Kuzmack, for his contributions on the subject of dividing heads, and additions to the tables of dividing head indexing movements.

Mr. Robert E. Green, as editor emeritus, contributed much useful, well organized material to this edition. He also provided invaluable practical guidance to the editorial staff during the *Handbook's* compilation.

Finally, Industrial Press is extremely fortunate that Mr. Henry H. Ryffel, author and editor of *Machinery's Handbook*, continues to be deeply involved with the *Handbook*. Henry's ideas, suggestions, and vision are deeply appreciated by everyone who worked on this book.

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MATHEMATICS

↓ 0° or 180° Trigonometric and Involute Functions 179° or 359° ↓

| Min-utes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute 0°-1° | Read Up          | Min-utes |
|----------|----------|----------|-----------|-----------|----------|----------|----------------|------------------|----------|
| 0        | 0.000000 | 1.000000 | 0.000000  | Infinite  | 1.000000 | Infinite | 0.0000000      | Infinite         | 60       |
| 1        | 0.000291 | 1.000000 | 0.000291  | 3437.75   | 1.000000 | 3437.75  | 0.0000000      | 3436.176         | 59       |
| 2        | 0.000582 | 1.000000 | 0.000582  | 1718.87   | 1.000000 | 1718.87  | 0.0000000      | 1717.303         | 58       |
| 3        | 0.000873 | 1.000000 | 0.000873  | 1145.92   | 1.000000 | 1145.92  | 0.0000000      | 1144.345         | 57       |
| 4        | 0.001164 | 0.999999 | 0.001164  | 859.436   | 1.000001 | 859.437  | 0.0000000      | 857.8667         | 56       |
| 5        | 0.001454 | 0.999999 | 0.001454  | 687.549   | 1.000001 | 687.550  | 0.0000000      | 685.9795         | 55       |
| 6        | 0.001745 | 0.999998 | 0.001745  | 572.957   | 1.000002 | 572.958  | 0.0000000      | 571.3882         | 54       |
| 7        | 0.002036 | 0.999998 | 0.002036  | 491.106   | 1.000002 | 491.107  | 0.0000000      | 489.5372         | 53       |
| 8        | 0.002327 | 0.999997 | 0.002327  | 429.718   | 1.000003 | 429.719  | 0.0000000      | 428.1491         | 52       |
| 9        | 0.002618 | 0.999997 | 0.002618  | 381.971   | 1.000003 | 381.972  | 0.0000000      | 380.4028         | 51       |
| 10       | 0.002909 | 0.999996 | 0.002909  | 343.774   | 1.000004 | 343.775  | 0.0000000      | 342.2058         | 50       |
| 11       | 0.003200 | 0.999995 | 0.003200  | 312.521   | 1.000005 | 312.523  | 0.0000000      | 310.9538         | 49       |
| 12       | 0.003491 | 0.999994 | 0.003491  | 286.478   | 1.000006 | 286.479  | 0.0000000      | 284.9104         | 48       |
| 13       | 0.003782 | 0.999993 | 0.003782  | 264.441   | 1.000007 | 264.443  | 0.0000000      | 262.8738         | 47       |
| 14       | 0.004072 | 0.999992 | 0.004072  | 245.552   | 1.000008 | 245.554  | 0.0000000      | 243.9853         | 46       |
| 15       | 0.004363 | 0.999990 | 0.004363  | 229.182   | 1.000010 | 229.184  | 0.0000000      | 227.6152         | 45       |
| 16       | 0.004654 | 0.999989 | 0.004654  | 214.858   | 1.000011 | 214.860  | 0.0000000      | 213.2915         | 44       |
| 17       | 0.004945 | 0.999988 | 0.004945  | 202.219   | 1.000012 | 202.221  | 0.0000000      | 200.6529         | 43       |
| 18       | 0.005236 | 0.999986 | 0.005236  | 190.984   | 1.000014 | 190.987  | 0.0000000      | 189.4186         | 42       |
| 19       | 0.005527 | 0.999985 | 0.005527  | 180.932   | 1.000015 | 180.935  | 0.0000001      | 179.3669         | 41       |
| 20       | 0.005818 | 0.999983 | 0.005818  | 171.885   | 1.000017 | 171.888  | 0.0000001      | 170.3204         | 40       |
| 21       | 0.006109 | 0.999981 | 0.006109  | 163.700   | 1.000019 | 163.703  | 0.0000001      | 162.1355         | 39       |
| 22       | 0.006399 | 0.999980 | 0.006399  | 156.259   | 1.000020 | 156.262  | 0.0000001      | 154.6947         | 38       |
| 23       | 0.006690 | 0.999978 | 0.006691  | 149.465   | 1.000022 | 149.468  | 0.0000001      | 147.9009         | 37       |
| 24       | 0.006981 | 0.999976 | 0.006981  | 143.237   | 1.000024 | 143.241  | 0.0000001      | 141.6733         | 36       |
| 25       | 0.007272 | 0.999974 | 0.007272  | 137.507   | 1.000026 | 137.511  | 0.0000001      | 135.9429         | 35       |
| 26       | 0.007563 | 0.999971 | 0.007563  | 132.219   | 1.000029 | 132.222  | 0.0000001      | 130.6553         | 34       |
| 27       | 0.007854 | 0.999969 | 0.007854  | 127.321   | 1.000031 | 127.325  | 0.0000002      | 125.7584         | 33       |
| 28       | 0.008145 | 0.999967 | 0.008145  | 122.774   | 1.000033 | 122.778  | 0.0000002      | 121.2113         | 32       |
| 29       | 0.008436 | 0.999964 | 0.008436  | 118.540   | 1.000036 | 118.544  | 0.0000002      | 116.9778         | 31       |
| 30       | 0.008727 | 0.999962 | 0.008727  | 114.589   | 1.000038 | 114.593  | 0.0000002      | 113.0266         | 30       |
| 31       | 0.009017 | 0.999959 | 0.009018  | 110.892   | 1.000041 | 110.897  | 0.0000002      | 109.3303         | 29       |
| 32       | 0.009308 | 0.999957 | 0.009309  | 107.426   | 1.000043 | 107.431  | 0.0000003      | 105.8650         | 28       |
| 33       | 0.009599 | 0.999954 | 0.009599  | 104.171   | 1.000046 | 104.176  | 0.0000003      | 102.6097         | 27       |
| 34       | 0.009890 | 0.999951 | 0.009891  | 101.107   | 1.000049 | 101.112  | 0.0000003      | 99.54600         | 26       |
| 35       | 0.010181 | 0.999948 | 0.010181  | 98.2179   | 1.000052 | 98.2230  | 0.0000004      | 96.65733         | 25       |
| 36       | 0.010472 | 0.999945 | 0.010472  | 95.4895   | 1.000055 | 95.4947  | 0.0000004      | 93.92915         | 24       |
| 37       | 0.010763 | 0.999942 | 0.010763  | 92.9085   | 1.000058 | 92.9139  | 0.0000004      | 91.34845         | 23       |
| 38       | 0.011054 | 0.999939 | 0.011054  | 90.4633   | 1.000061 | 90.4689  | 0.0000005      | 88.90359         | 22       |
| 39       | 0.011344 | 0.999936 | 0.011345  | 88.1436   | 1.000064 | 88.1492  | 0.0000005      | 86.58412         | 21       |
| 40       | 0.011635 | 0.999932 | 0.011636  | 85.9398   | 1.000068 | 85.9456  | 0.0000005      | 84.38063         | 20       |
| 41       | 0.011926 | 0.999929 | 0.011927  | 83.8435   | 1.000071 | 83.8495  | 0.0000006      | 82.28464         | 19       |
| 42       | 0.012217 | 0.999925 | 0.012218  | 81.8470   | 1.000075 | 81.8531  | 0.0000006      | 80.28846         | 18       |
| 43       | 0.012508 | 0.999922 | 0.012509  | 79.9434   | 1.000078 | 79.9497  | 0.0000007      | 78.38514         | 17       |
| 44       | 0.012799 | 0.999918 | 0.012800  | 78.1263   | 1.000082 | 78.1327  | 0.0000007      | 76.56834         | 16       |
| 45       | 0.013090 | 0.999914 | 0.013091  | 76.3900   | 1.000086 | 76.3966  | 0.0000007      | 74.83230         | 15       |
| 46       | 0.013380 | 0.999910 | 0.013382  | 74.7292   | 1.000090 | 74.7359  | 0.0000008      | 73.17175         | 14       |
| 47       | 0.013671 | 0.999907 | 0.013673  | 73.1390   | 1.000093 | 73.1458  | 0.0000009      | 71.58187         | 13       |
| 48       | 0.013962 | 0.999903 | 0.013964  | 71.6151   | 1.000097 | 71.6221  | 0.0000009      | 70.05824         | 12       |
| 49       | 0.014253 | 0.999898 | 0.014254  | 70.1533   | 1.000102 | 70.1605  | 0.0000010      | 68.59680         | 11       |
| 50       | 0.014544 | 0.999894 | 0.014545  | 68.7501   | 1.000106 | 68.7574  | 0.0000010      | 67.19384         | 10       |
| 51       | 0.014835 | 0.999890 | 0.014836  | 67.4019   | 1.000110 | 67.4093  | 0.0000011      | 65.84589         | 9        |
| 52       | 0.015126 | 0.999886 | 0.015127  | 66.1055   | 1.000114 | 66.1130  | 0.0000012      | 64.54980         | 8        |
| 53       | 0.015416 | 0.999881 | 0.015418  | 64.8580   | 1.000119 | 64.8657  | 0.0000012      | 63.30263         | 7        |
| 54       | 0.015707 | 0.999877 | 0.015709  | 63.6567   | 1.000123 | 63.6646  | 0.0000013      | 62.10169         | 6        |
| 55       | 0.015998 | 0.999872 | 0.016000  | 62.4992   | 1.000128 | 62.5072  | 0.0000014      | 60.94436         | 5        |
| 56       | 0.016289 | 0.999867 | 0.016291  | 61.3829   | 1.000133 | 61.3911  | 0.0000014      | 59.82840         | 4        |
| 57       | 0.016580 | 0.999863 | 0.016582  | 60.3058   | 1.000137 | 60.3141  | 0.0000015      | 58.75160         | 3        |
| 58       | 0.016871 | 0.999858 | 0.016873  | 59.2659   | 1.000142 | 59.2743  | 0.0000016      | 57.71195         | 2        |
| 59       | 0.017162 | 0.999853 | 0.017164  | 58.2612   | 1.000147 | 58.2698  | 0.0000017      | 56.70754         | 1        |
| 60       | 0.017452 | 0.999848 | 0.017455  | 57.2900   | 1.000152 | 57.2987  | 0.0000018      | 55.73662         | 0        |
| Min-utes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read Down      | 89°-90° Involute | Min-utes |

↑ 90° or 270°

89° or 269° ↑

↓ 1° or 181° Trigonometric and Involute Functions 178° or 358° ↓

| Min-utes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>1°-2° | Read<br>Up | Min-utes |
|----------|----------|----------|----------|-----------|----------|----------|-------------------|------------|----------|
| 0        | 0.017452 | 0.999848 | 0.017455 | 57.2900   | 1.000152 | 57.2987  | 0.0000018         | 55.73662   | 60       |
| 1        | 0.017743 | 0.999843 | 0.017746 | 56.3506   | 1.000157 | 56.3595  | 0.0000019         | 54.79754   | 59       |
| 2        | 0.018034 | 0.999837 | 0.018037 | 55.4415   | 1.000163 | 55.4505  | 0.0000020         | 53.88876   | 58       |
| 3        | 0.018325 | 0.999832 | 0.018328 | 54.5613   | 1.000168 | 54.5705  | 0.0000021         | 53.00883   | 57       |
| 4        | 0.018616 | 0.999827 | 0.018619 | 53.7086   | 1.000173 | 53.7179  | 0.0000022         | 52.15641   | 56       |
| 5        | 0.018907 | 0.999821 | 0.018910 | 52.8821   | 1.000179 | 52.8916  | 0.0000023         | 51.33022   | 55       |
| 6        | 0.019197 | 0.999816 | 0.019201 | 52.0807   | 1.000184 | 52.0903  | 0.0000024         | 50.52907   | 54       |
| 7        | 0.019488 | 0.999810 | 0.019492 | 51.3032   | 1.000190 | 51.3129  | 0.0000025         | 49.75185   | 53       |
| 8        | 0.019779 | 0.999804 | 0.019783 | 50.5485   | 1.000196 | 50.5584  | 0.0000026         | 48.99749   | 52       |
| 9        | 0.020070 | 0.999799 | 0.020074 | 49.8157   | 1.000201 | 49.8258  | 0.0000027         | 48.26500   | 51       |
| 10       | 0.020361 | 0.999793 | 0.020365 | 49.1039   | 1.000207 | 49.1141  | 0.0000028         | 47.55345   | 50       |
| 11       | 0.020652 | 0.999787 | 0.020656 | 48.4121   | 1.000213 | 48.4224  | 0.0000029         | 46.86194   | 49       |
| 12       | 0.020942 | 0.999781 | 0.020947 | 47.7395   | 1.000219 | 47.7500  | 0.0000030         | 46.18965   | 48       |
| 13       | 0.021233 | 0.999775 | 0.021238 | 47.0853   | 1.000226 | 47.0960  | 0.0000032         | 45.53578   | 47       |
| 14       | 0.021524 | 0.999768 | 0.021529 | 46.4489   | 1.000232 | 46.4596  | 0.0000033         | 44.89959   | 46       |
| 15       | 0.021815 | 0.999762 | 0.021820 | 45.8294   | 1.000238 | 45.8403  | 0.0000035         | 44.28037   | 45       |
| 16       | 0.022106 | 0.999756 | 0.022111 | 45.2261   | 1.000244 | 45.2372  | 0.0000036         | 43.67745   | 44       |
| 17       | 0.022397 | 0.999749 | 0.022402 | 44.6386   | 1.000251 | 44.6498  | 0.0000037         | 43.09020   | 43       |
| 18       | 0.022687 | 0.999743 | 0.022693 | 44.0661   | 1.000257 | 44.0775  | 0.0000039         | 42.51801   | 42       |
| 19       | 0.022978 | 0.999736 | 0.022984 | 43.5081   | 1.000264 | 43.5196  | 0.0000040         | 41.96031   | 41       |
| 20       | 0.023269 | 0.999729 | 0.023275 | 42.9641   | 1.000271 | 42.9757  | 0.0000042         | 41.41655   | 40       |
| 21       | 0.023560 | 0.999722 | 0.023566 | 42.4335   | 1.000278 | 42.4452  | 0.0000044         | 40.88623   | 39       |
| 22       | 0.023851 | 0.999716 | 0.023857 | 41.9158   | 1.000285 | 41.9277  | 0.0000045         | 40.36885   | 38       |
| 23       | 0.024141 | 0.999709 | 0.024148 | 41.4106   | 1.000292 | 41.4227  | 0.0000047         | 39.86393   | 37       |
| 24       | 0.024432 | 0.999701 | 0.024439 | 40.9174   | 1.000299 | 40.9296  | 0.0000049         | 39.37105   | 36       |
| 25       | 0.024723 | 0.999694 | 0.024731 | 40.4358   | 1.000306 | 40.4482  | 0.0000050         | 38.88977   | 35       |
| 26       | 0.025014 | 0.999687 | 0.025022 | 39.9655   | 1.000313 | 39.9780  | 0.0000052         | 38.41968   | 34       |
| 27       | 0.025305 | 0.999680 | 0.025313 | 39.5059   | 1.000320 | 39.5185  | 0.0000054         | 37.96041   | 33       |
| 28       | 0.025595 | 0.999672 | 0.025604 | 39.0568   | 1.000328 | 39.0696  | 0.0000056         | 37.51157   | 32       |
| 29       | 0.025886 | 0.999665 | 0.025895 | 38.6177   | 1.000335 | 38.6307  | 0.0000058         | 37.07283   | 31       |
| 30       | 0.026177 | 0.999657 | 0.026186 | 38.1885   | 1.000343 | 38.2016  | 0.0000060         | 36.64384   | 30       |
| 31       | 0.026468 | 0.999650 | 0.026477 | 37.7686   | 1.000350 | 37.7818  | 0.0000062         | 36.22429   | 29       |
| 32       | 0.026759 | 0.999642 | 0.026768 | 37.3579   | 1.000358 | 37.3713  | 0.0000064         | 35.81386   | 28       |
| 33       | 0.027049 | 0.999634 | 0.027059 | 36.9560   | 1.000366 | 36.9695  | 0.0000066         | 35.41259   | 27       |
| 34       | 0.027340 | 0.999626 | 0.027350 | 36.5627   | 1.000374 | 36.5763  | 0.0000068         | 35.01921   | 26       |
| 35       | 0.027631 | 0.999618 | 0.027641 | 36.1776   | 1.000382 | 36.1914  | 0.0000070         | 34.63443   | 25       |
| 36       | 0.027922 | 0.999610 | 0.027933 | 35.8006   | 1.000390 | 35.8145  | 0.0000073         | 34.25768   | 24       |
| 37       | 0.028212 | 0.999602 | 0.028224 | 35.4313   | 1.000398 | 35.4454  | 0.0000075         | 33.88870   | 23       |
| 38       | 0.028503 | 0.999594 | 0.028515 | 35.0695   | 1.000406 | 35.0838  | 0.0000077         | 33.52726   | 22       |
| 39       | 0.028794 | 0.999585 | 0.028806 | 34.7151   | 1.000415 | 34.7295  | 0.0000080         | 33.17310   | 21       |
| 40       | 0.029085 | 0.999577 | 0.029097 | 34.3678   | 1.000423 | 34.3823  | 0.0000082         | 32.82606   | 20       |
| 41       | 0.029375 | 0.999568 | 0.029388 | 34.0273   | 1.000432 | 34.0420  | 0.0000085         | 32.48589   | 19       |
| 42       | 0.029666 | 0.999560 | 0.029679 | 33.6935   | 1.000440 | 33.7083  | 0.0000087         | 32.15238   | 18       |
| 43       | 0.029957 | 0.999551 | 0.029970 | 33.3662   | 1.000449 | 33.3812  | 0.0000090         | 31.82536   | 17       |
| 44       | 0.030248 | 0.999542 | 0.030262 | 33.0452   | 1.000458 | 33.0603  | 0.0000092         | 31.50463   | 16       |
| 45       | 0.030539 | 0.999534 | 0.030553 | 32.7303   | 1.000467 | 32.7455  | 0.0000095         | 31.19001   | 15       |
| 46       | 0.030829 | 0.999525 | 0.030844 | 32.4213   | 1.000476 | 32.4367  | 0.0000098         | 30.88133   | 14       |
| 47       | 0.031120 | 0.999516 | 0.031135 | 32.1181   | 1.000485 | 32.1337  | 0.0000101         | 30.57843   | 13       |
| 48       | 0.031411 | 0.999507 | 0.031426 | 31.8205   | 1.000494 | 31.8365  | 0.0000103         | 30.28114   | 12       |
| 49       | 0.031702 | 0.999498 | 0.031717 | 31.5284   | 1.000503 | 31.5442  | 0.0000106         | 29.98930   | 11       |
| 50       | 0.031992 | 0.999489 | 0.032009 | 31.2416   | 1.000512 | 31.2576  | 0.0000109         | 29.70278   | 10       |
| 51       | 0.032283 | 0.999479 | 0.032300 | 30.9599   | 1.000522 | 30.9761  | 0.0000112         | 29.42142   | 9        |
| 52       | 0.032574 | 0.999469 | 0.032591 | 30.6833   | 1.000531 | 30.6996  | 0.0000115         | 29.14509   | 8        |
| 53       | 0.032864 | 0.999460 | 0.032882 | 30.4116   | 1.000540 | 30.4280  | 0.0000118         | 28.87365   | 7        |
| 54       | 0.033155 | 0.999450 | 0.033173 | 30.1446   | 1.000550 | 30.1612  | 0.0000122         | 28.60698   | 6        |
| 55       | 0.033446 | 0.999441 | 0.033465 | 29.8823   | 1.000560 | 29.8990  | 0.0000125         | 28.34495   | 5        |
| 56       | 0.033737 | 0.999431 | 0.033756 | 29.6245   | 1.000570 | 29.6414  | 0.0000128         | 28.08754   | 4        |
| 57       | 0.034027 | 0.999421 | 0.034047 | 29.3711   | 1.000579 | 29.3881  | 0.0000131         | 27.83434   | 3        |
| 58       | 0.034318 | 0.999411 | 0.034338 | 29.1220   | 1.000589 | 29.1392  | 0.0000135         | 27.58553   | 2        |
| 59       | 0.034609 | 0.999401 | 0.034630 | 28.8771   | 1.000599 | 28.8944  | 0.0000138         | 27.34091   | 1        |
| 60       | 0.034899 | 0.999391 | 0.034921 | 28.6363   | 1.000610 | 28.6537  | 0.0000142         | 27.10036   | 0        |

↑ 91° or 271°

88° or 268° ↑



TRIGONOMETRY TABLES

↓ 2° or 182° Trigonometric and Involute Functions 177° or 357° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>2°-3° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|-------------------|------------|---------|
| 0       | 0.034899 | 0.999391 | 0.034921 | 28.6363   | 1.000610 | 28.6537  | 0.0000142         | 27.10036   | 60      |
| 1       | 0.035190 | 0.999381 | 0.035212 | 28.3994   | 1.000620 | 28.4170  | 0.0000145         | 26.86380   | 59      |
| 2       | 0.035481 | 0.999370 | 0.035503 | 28.1664   | 1.000630 | 28.1842  | 0.0000149         | 26.63111   | 58      |
| 3       | 0.035772 | 0.999360 | 0.035795 | 27.9372   | 1.000640 | 27.9551  | 0.0000153         | 26.40222   | 57      |
| 4       | 0.036062 | 0.999350 | 0.036086 | 27.7117   | 1.000651 | 27.7298  | 0.0000157         | 26.17701   | 56      |
| 5       | 0.036353 | 0.999339 | 0.036377 | 27.4899   | 1.000661 | 27.5080  | 0.0000160         | 25.95542   | 55      |
| 6       | 0.036644 | 0.999328 | 0.036668 | 27.2715   | 1.000672 | 27.2898  | 0.0000164         | 25.73734   | 54      |
| 7       | 0.036934 | 0.999318 | 0.036960 | 27.0566   | 1.000683 | 27.0750  | 0.0000168         | 25.52270   | 53      |
| 8       | 0.037225 | 0.999307 | 0.037251 | 26.8450   | 1.000694 | 26.8636  | 0.0000172         | 25.31142   | 52      |
| 9       | 0.037516 | 0.999296 | 0.037542 | 26.6367   | 1.000704 | 26.6555  | 0.0000176         | 25.10342   | 51      |
| 10      | 0.037806 | 0.999285 | 0.037834 | 26.4316   | 1.000715 | 26.4505  | 0.0000180         | 24.89862   | 50      |
| 11      | 0.038097 | 0.999274 | 0.038125 | 26.2296   | 1.000726 | 26.2487  | 0.0000185         | 24.69695   | 49      |
| 12      | 0.038388 | 0.999263 | 0.038416 | 26.0307   | 1.000738 | 26.0499  | 0.0000189         | 24.49834   | 48      |
| 13      | 0.038678 | 0.999252 | 0.038707 | 25.8348   | 1.000749 | 25.8542  | 0.0000193         | 24.30271   | 47      |
| 14      | 0.038969 | 0.999240 | 0.038999 | 25.6418   | 1.000760 | 25.6613  | 0.0000198         | 24.11002   | 46      |
| 15      | 0.039260 | 0.999229 | 0.039290 | 25.4517   | 1.000772 | 25.4713  | 0.0000202         | 23.92017   | 45      |
| 16      | 0.039550 | 0.999218 | 0.039581 | 25.2644   | 1.000783 | 25.2841  | 0.0000207         | 23.73313   | 44      |
| 17      | 0.039841 | 0.999206 | 0.039873 | 25.0798   | 1.000795 | 25.0997  | 0.0000211         | 23.54881   | 43      |
| 18      | 0.040132 | 0.999194 | 0.040164 | 24.8978   | 1.000806 | 24.9179  | 0.0000216         | 23.36717   | 42      |
| 19      | 0.040422 | 0.999183 | 0.040456 | 24.7185   | 1.000818 | 24.7387  | 0.0000220         | 23.18815   | 41      |
| 20      | 0.040713 | 0.999171 | 0.040747 | 24.5418   | 1.000830 | 24.5621  | 0.0000225         | 23.01169   | 40      |
| 21      | 0.041004 | 0.999159 | 0.041038 | 24.3675   | 1.000842 | 24.3880  | 0.0000230         | 22.83773   | 39      |
| 22      | 0.041294 | 0.999147 | 0.041330 | 24.1957   | 1.000854 | 24.2164  | 0.0000235         | 22.66622   | 38      |
| 23      | 0.041585 | 0.999135 | 0.041621 | 24.0263   | 1.000866 | 24.0471  | 0.0000240         | 22.49712   | 37      |
| 24      | 0.041876 | 0.999123 | 0.041912 | 23.8593   | 1.000878 | 23.8802  | 0.0000245         | 22.33037   | 36      |
| 25      | 0.042166 | 0.999111 | 0.042204 | 23.6945   | 1.000890 | 23.7156  | 0.0000250         | 22.16592   | 35      |
| 26      | 0.042457 | 0.999098 | 0.042495 | 23.5321   | 1.000903 | 23.5533  | 0.0000256         | 22.00373   | 34      |
| 27      | 0.042748 | 0.999086 | 0.042787 | 23.3718   | 1.000915 | 23.3932  | 0.0000261         | 21.84374   | 33      |
| 28      | 0.043038 | 0.999073 | 0.043078 | 23.2137   | 1.000927 | 23.2352  | 0.0000266         | 21.68592   | 32      |
| 29      | 0.043329 | 0.999061 | 0.043370 | 23.0577   | 1.000940 | 23.0794  | 0.0000272         | 21.53022   | 31      |
| 30      | 0.043619 | 0.999048 | 0.043661 | 22.9038   | 1.000953 | 22.9256  | 0.0000277         | 21.37660   | 30      |
| 31      | 0.043910 | 0.999035 | 0.043952 | 22.7519   | 1.000965 | 22.7739  | 0.0000283         | 21.22502   | 29      |
| 32      | 0.044201 | 0.999023 | 0.044244 | 22.6020   | 1.000978 | 22.6241  | 0.0000288         | 21.07543   | 28      |
| 33      | 0.044491 | 0.999010 | 0.044535 | 22.4541   | 1.000991 | 22.4764  | 0.0000294         | 20.92781   | 27      |
| 34      | 0.044782 | 0.998997 | 0.044827 | 22.3081   | 1.001004 | 22.3305  | 0.0000300         | 20.78210   | 26      |
| 35      | 0.045072 | 0.998984 | 0.045118 | 22.1640   | 1.001017 | 22.1865  | 0.0000306         | 20.63827   | 25      |
| 36      | 0.045363 | 0.998971 | 0.045410 | 22.0217   | 1.001030 | 22.0444  | 0.0000312         | 20.49629   | 24      |
| 37      | 0.045654 | 0.998957 | 0.045701 | 21.8813   | 1.001044 | 21.9041  | 0.0000318         | 20.35612   | 23      |
| 38      | 0.045944 | 0.998944 | 0.045993 | 21.7426   | 1.001057 | 21.7656  | 0.0000324         | 20.21773   | 22      |
| 39      | 0.046235 | 0.998931 | 0.046284 | 21.6056   | 1.001071 | 21.6288  | 0.0000330         | 20.08108   | 21      |
| 40      | 0.046525 | 0.998917 | 0.046576 | 21.4704   | 1.001084 | 21.4937  | 0.0000336         | 19.94615   | 20      |
| 41      | 0.046816 | 0.998904 | 0.046867 | 21.3369   | 1.001098 | 21.3603  | 0.0000343         | 19.81289   | 19      |
| 42      | 0.047106 | 0.998890 | 0.047159 | 21.2049   | 1.001111 | 21.2285  | 0.0000349         | 19.68128   | 18      |
| 43      | 0.047397 | 0.998876 | 0.047450 | 21.0747   | 1.001125 | 21.0984  | 0.0000356         | 19.55128   | 17      |
| 44      | 0.047688 | 0.998862 | 0.047742 | 20.9460   | 1.001139 | 20.9698  | 0.0000362         | 19.42288   | 16      |
| 45      | 0.047978 | 0.998848 | 0.048033 | 20.8188   | 1.001153 | 20.8428  | 0.0000369         | 19.29603   | 15      |
| 46      | 0.048269 | 0.998834 | 0.048325 | 20.6932   | 1.001167 | 20.7174  | 0.0000376         | 19.17071   | 14      |
| 47      | 0.048559 | 0.998820 | 0.048617 | 20.5691   | 1.001181 | 20.5934  | 0.0000382         | 19.04690   | 13      |
| 48      | 0.048850 | 0.998806 | 0.048908 | 20.4465   | 1.001195 | 20.4709  | 0.0000389         | 18.92456   | 12      |
| 49      | 0.049140 | 0.998792 | 0.049200 | 20.3253   | 1.001210 | 20.3499  | 0.0000396         | 18.80367   | 11      |
| 50      | 0.049431 | 0.998778 | 0.049491 | 20.2056   | 1.001224 | 20.2303  | 0.0000403         | 18.68421   | 10      |
| 51      | 0.049721 | 0.998763 | 0.049783 | 20.0872   | 1.001238 | 20.1121  | 0.0000411         | 18.56614   | 9       |
| 52      | 0.050012 | 0.998749 | 0.050075 | 19.9702   | 1.001253 | 19.9952  | 0.0000418         | 18.44946   | 8       |
| 53      | 0.050302 | 0.998734 | 0.050366 | 19.8546   | 1.001268 | 19.8798  | 0.0000425         | 18.33412   | 7       |
| 54      | 0.050593 | 0.998719 | 0.050658 | 19.7403   | 1.001282 | 19.7656  | 0.0000433         | 18.22011   | 6       |
| 55      | 0.050883 | 0.998705 | 0.050949 | 19.6273   | 1.001297 | 19.6528  | 0.0000440         | 18.10740   | 5       |
| 56      | 0.051174 | 0.998690 | 0.051241 | 19.5156   | 1.001312 | 19.5412  | 0.0000448         | 17.99598   | 4       |
| 57      | 0.051464 | 0.998675 | 0.051533 | 19.4051   | 1.001327 | 19.4309  | 0.0000455         | 17.88582   | 3       |
| 58      | 0.051755 | 0.998660 | 0.051824 | 19.2959   | 1.001342 | 19.3218  | 0.0000463         | 17.77690   | 2       |
| 59      | 0.052045 | 0.998645 | 0.052116 | 19.1879   | 1.001357 | 19.2140  | 0.0000471         | 17.66920   | 1       |
| 60      | 0.052336 | 0.998630 | 0.052408 | 19.0811   | 1.001372 | 19.1073  | 0.0000479         | 17.56270   | 0       |

↑ 92° or 272°

87° or 267° ↑

↓ 3° or 183° **Trigonometric and Involute Functions** 176° or 356° ↓

| Min-utes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>3°-4° | Read<br>Up | Min-utes |
|----------|----------|----------|----------|-----------|----------|----------|-------------------|------------|----------|
| 0        | 0.052336 | 0.998630 | 0.052408 | 19.0811   | 1.001372 | 19.1073  | 0.0000479         | 17.56270   | 60       |
| 1        | 0.052626 | 0.998614 | 0.052699 | 18.9755   | 1.001388 | 19.0019  | 0.0000487         | 17.45738   | 59       |
| 2        | 0.052917 | 0.998599 | 0.052991 | 18.8711   | 1.001403 | 18.8975  | 0.0000495         | 17.35321   | 58       |
| 3        | 0.053207 | 0.998583 | 0.053283 | 18.7678   | 1.001419 | 18.7944  | 0.0000503         | 17.25019   | 57       |
| 4        | 0.053498 | 0.998568 | 0.053575 | 18.6656   | 1.001434 | 18.6923  | 0.0000512         | 17.14829   | 56       |
| 5        | 0.053788 | 0.998552 | 0.053866 | 18.5645   | 1.001450 | 18.5914  | 0.0000520         | 17.04749   | 55       |
| 6        | 0.054079 | 0.998537 | 0.054158 | 18.4645   | 1.001465 | 18.4915  | 0.0000529         | 16.94778   | 54       |
| 7        | 0.054369 | 0.998521 | 0.054450 | 18.3655   | 1.001481 | 18.3927  | 0.0000537         | 16.84914   | 53       |
| 8        | 0.054660 | 0.998505 | 0.054742 | 18.2677   | 1.001497 | 18.2950  | 0.0000546         | 16.75155   | 52       |
| 9        | 0.054950 | 0.998489 | 0.055033 | 18.1708   | 1.001513 | 18.1983  | 0.0000555         | 16.65499   | 51       |
| 10       | 0.055241 | 0.998473 | 0.055325 | 18.0750   | 1.001529 | 18.1026  | 0.0000563         | 16.55945   | 50       |
| 11       | 0.055531 | 0.998457 | 0.055617 | 17.9802   | 1.001545 | 18.0079  | 0.0000572         | 16.46491   | 49       |
| 12       | 0.055822 | 0.998441 | 0.055909 | 17.8863   | 1.001562 | 17.9142  | 0.0000581         | 16.37136   | 48       |
| 13       | 0.056112 | 0.998424 | 0.056200 | 17.7934   | 1.001578 | 17.8215  | 0.0000591         | 16.27879   | 47       |
| 14       | 0.056402 | 0.998408 | 0.056492 | 17.7015   | 1.001594 | 17.7298  | 0.0000600         | 16.18717   | 46       |
| 15       | 0.056693 | 0.998392 | 0.056784 | 17.6106   | 1.001611 | 17.6389  | 0.0000609         | 16.09649   | 45       |
| 16       | 0.056983 | 0.998375 | 0.057076 | 17.5205   | 1.001628 | 17.5490  | 0.0000619         | 16.00673   | 44       |
| 17       | 0.057274 | 0.998359 | 0.057368 | 17.4314   | 1.001644 | 17.4600  | 0.0000628         | 15.91789   | 43       |
| 18       | 0.057564 | 0.998342 | 0.057660 | 17.3432   | 1.001661 | 17.3720  | 0.0000638         | 15.82995   | 42       |
| 19       | 0.057854 | 0.998325 | 0.057951 | 17.2558   | 1.001678 | 17.2848  | 0.0000647         | 15.74290   | 41       |
| 20       | 0.058145 | 0.998308 | 0.058243 | 17.1693   | 1.001695 | 17.1984  | 0.0000657         | 15.65672   | 40       |
| 21       | 0.058435 | 0.998291 | 0.058535 | 17.0837   | 1.001712 | 17.1130  | 0.0000667         | 15.57140   | 39       |
| 22       | 0.058726 | 0.998274 | 0.058827 | 16.9990   | 1.001729 | 17.0283  | 0.0000677         | 15.48692   | 38       |
| 23       | 0.059016 | 0.998257 | 0.059119 | 16.9150   | 1.001746 | 16.9446  | 0.0000687         | 15.40328   | 37       |
| 24       | 0.059306 | 0.998240 | 0.059411 | 16.8319   | 1.001763 | 16.8616  | 0.0000698         | 15.32046   | 36       |
| 25       | 0.059597 | 0.998223 | 0.059703 | 16.7496   | 1.001781 | 16.7794  | 0.0000708         | 15.23845   | 35       |
| 26       | 0.059887 | 0.998205 | 0.059995 | 16.6681   | 1.001798 | 16.6981  | 0.0000718         | 15.15724   | 34       |
| 27       | 0.060177 | 0.998188 | 0.060287 | 16.5874   | 1.001816 | 16.6175  | 0.0000729         | 15.07681   | 33       |
| 28       | 0.060468 | 0.998170 | 0.060579 | 16.5075   | 1.001833 | 16.5377  | 0.0000739         | 14.99716   | 32       |
| 29       | 0.060758 | 0.998153 | 0.060871 | 16.4283   | 1.001851 | 16.4587  | 0.0000750         | 14.91828   | 31       |
| 30       | 0.061049 | 0.998135 | 0.061163 | 16.3499   | 1.001869 | 16.3804  | 0.0000761         | 14.84015   | 30       |
| 31       | 0.061339 | 0.998117 | 0.061455 | 16.2722   | 1.001887 | 16.3029  | 0.0000772         | 14.76276   | 29       |
| 32       | 0.061629 | 0.998099 | 0.061747 | 16.1952   | 1.001905 | 16.2261  | 0.0000783         | 14.68610   | 28       |
| 33       | 0.061920 | 0.998081 | 0.062039 | 16.1190   | 1.001923 | 16.1500  | 0.0000794         | 14.61036   | 27       |
| 34       | 0.062210 | 0.998063 | 0.062331 | 16.0435   | 1.001941 | 16.0746  | 0.0000805         | 14.53494   | 26       |
| 35       | 0.062500 | 0.998045 | 0.062623 | 15.9687   | 1.001959 | 15.9999  | 0.0000817         | 14.46041   | 25       |
| 36       | 0.062791 | 0.998027 | 0.062915 | 15.8945   | 1.001977 | 15.9260  | 0.0000828         | 14.38658   | 24       |
| 37       | 0.063081 | 0.998008 | 0.063207 | 15.8211   | 1.001996 | 15.8527  | 0.0000840         | 14.31343   | 23       |
| 38       | 0.063371 | 0.997990 | 0.063499 | 15.7483   | 1.002014 | 15.7801  | 0.0000851         | 14.24095   | 22       |
| 39       | 0.063661 | 0.997972 | 0.063792 | 15.6762   | 1.002033 | 15.7081  | 0.0000863         | 14.16914   | 21       |
| 40       | 0.063952 | 0.997953 | 0.064083 | 15.6048   | 1.002051 | 15.6368  | 0.0000875         | 14.09798   | 20       |
| 41       | 0.064242 | 0.997934 | 0.064375 | 15.5340   | 1.002070 | 15.5661  | 0.0000887         | 14.02747   | 19       |
| 42       | 0.064532 | 0.997916 | 0.064667 | 15.4638   | 1.002089 | 15.4961  | 0.0000899         | 13.95759   | 18       |
| 43       | 0.064823 | 0.997897 | 0.064959 | 15.3943   | 1.002108 | 15.4267  | 0.0000911         | 13.88835   | 17       |
| 44       | 0.065113 | 0.997878 | 0.065251 | 15.3254   | 1.002127 | 15.3579  | 0.0000924         | 13.81972   | 16       |
| 45       | 0.065403 | 0.997859 | 0.065543 | 15.2571   | 1.002146 | 15.2898  | 0.0000936         | 13.75171   | 15       |
| 46       | 0.065693 | 0.997840 | 0.065836 | 15.1893   | 1.002165 | 15.2222  | 0.0000949         | 13.68429   | 14       |
| 47       | 0.065984 | 0.997821 | 0.066128 | 15.1222   | 1.002184 | 15.1553  | 0.0000961         | 13.61748   | 13       |
| 48       | 0.066274 | 0.997801 | 0.066420 | 15.0557   | 1.002203 | 15.0889  | 0.0000974         | 13.55125   | 12       |
| 49       | 0.066564 | 0.997782 | 0.066712 | 14.9898   | 1.002223 | 15.0231  | 0.0000987         | 13.48560   | 11       |
| 50       | 0.066854 | 0.997763 | 0.067004 | 14.9244   | 1.002242 | 14.9579  | 0.0001000         | 13.42052   | 10       |
| 51       | 0.067145 | 0.997743 | 0.067296 | 14.8596   | 1.002262 | 14.8932  | 0.0001013         | 13.35601   | 9        |
| 52       | 0.067435 | 0.997724 | 0.067589 | 14.7954   | 1.002282 | 14.8291  | 0.0001026         | 13.29206   | 8        |
| 53       | 0.067725 | 0.997704 | 0.067881 | 14.7317   | 1.002301 | 14.7656  | 0.0001040         | 13.22866   | 7        |
| 54       | 0.068015 | 0.997684 | 0.068173 | 14.6685   | 1.002321 | 14.7026  | 0.0001053         | 13.16580   | 6        |
| 55       | 0.068306 | 0.997664 | 0.068465 | 14.6059   | 1.002341 | 14.6401  | 0.0001067         | 13.10348   | 5        |
| 56       | 0.068596 | 0.997645 | 0.068758 | 14.5438   | 1.002361 | 14.5782  | 0.0001080         | 13.04169   | 4        |
| 57       | 0.068886 | 0.997625 | 0.069050 | 14.4823   | 1.002381 | 14.5168  | 0.0001094         | 12.98042   | 3        |
| 58       | 0.069176 | 0.997604 | 0.069342 | 14.4212   | 1.002401 | 14.4559  | 0.0001108         | 12.91966   | 2        |
| 59       | 0.069466 | 0.997584 | 0.069635 | 14.3607   | 1.002422 | 14.3955  | 0.0001122         | 12.85942   | 1        |
| 60       | 0.069756 | 0.997564 | 0.069927 | 14.3007   | 1.002442 | 14.3356  | 0.0001136         | 12.79968   | 0        |

↑ 93° or 273°

86° or 266° ↑

TRIGONOMETRY TABLES

↓ 4° or 184° Trigonometric and Involute Functions 175° or 355° ↓

| Min-utes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute 4°-5° | Read Up   | Min-utes |
|----------|----------|----------|----------|-----------|----------|----------|----------------|-----------|----------|
| 0        | 0.069756 | 0.997564 | 0.069927 | 14.3007   | 1.002442 | 14.3356  | 0.0001136      | 12.79968  | 60       |
| 1        | 0.070047 | 0.997544 | 0.070219 | 14.2411   | 1.002462 | 14.2762  | 0.0001151      | 12.74044  | 59       |
| 2        | 0.070337 | 0.997523 | 0.070511 | 14.1821   | 1.002483 | 14.2173  | 0.0001165      | 12.68169  | 58       |
| 3        | 0.070627 | 0.997503 | 0.070804 | 14.1235   | 1.002503 | 14.1589  | 0.0001180      | 12.62343  | 57       |
| 4        | 0.070917 | 0.997482 | 0.071096 | 14.0655   | 1.002524 | 14.1010  | 0.0001194      | 12.56564  | 56       |
| 5        | 0.071207 | 0.997462 | 0.071389 | 14.0079   | 1.002545 | 14.0435  | 0.0001209      | 12.50833  | 55       |
| 6        | 0.071497 | 0.997441 | 0.071681 | 13.9507   | 1.002566 | 13.9865  | 0.0001224      | 12.45148  | 54       |
| 7        | 0.071788 | 0.997420 | 0.071973 | 13.8940   | 1.002587 | 13.9300  | 0.0001239      | 12.39510  | 53       |
| 8        | 0.072078 | 0.997399 | 0.072266 | 13.8378   | 1.002608 | 13.8739  | 0.0001254      | 12.33917  | 52       |
| 9        | 0.072368 | 0.997378 | 0.072558 | 13.7821   | 1.002629 | 13.8183  | 0.0001269      | 12.28369  | 51       |
| 10       | 0.072658 | 0.997357 | 0.072851 | 13.7267   | 1.002650 | 13.7631  | 0.0001285      | 12.22866  | 50       |
| 11       | 0.072948 | 0.997336 | 0.073143 | 13.6719   | 1.002671 | 13.7084  | 0.0001300      | 12.17407  | 49       |
| 12       | 0.073238 | 0.997314 | 0.073435 | 13.6174   | 1.002693 | 13.6541  | 0.0001316      | 12.11992  | 48       |
| 13       | 0.073528 | 0.997293 | 0.073728 | 13.5634   | 1.002714 | 13.6002  | 0.0001332      | 12.06619  | 47       |
| 14       | 0.073818 | 0.997272 | 0.074020 | 13.5098   | 1.002736 | 13.5468  | 0.0001347      | 12.01289  | 46       |
| 15       | 0.074108 | 0.997250 | 0.074313 | 13.4566   | 1.002757 | 13.4937  | 0.0001363      | 11.96001  | 45       |
| 16       | 0.074399 | 0.997229 | 0.074607 | 13.4039   | 1.002779 | 13.4411  | 0.0001380      | 11.90754  | 44       |
| 17       | 0.074689 | 0.997207 | 0.074898 | 13.3515   | 1.002801 | 13.3889  | 0.0001396      | 11.85548  | 43       |
| 18       | 0.074979 | 0.997185 | 0.075190 | 13.2996   | 1.002823 | 13.3371  | 0.0001412      | 11.80383  | 42       |
| 19       | 0.075269 | 0.997163 | 0.075483 | 13.2480   | 1.002845 | 13.2857  | 0.0001429      | 11.75257  | 41       |
| 20       | 0.075559 | 0.997141 | 0.075775 | 13.1969   | 1.002867 | 13.2347  | 0.0001445      | 11.70172  | 40       |
| 21       | 0.075849 | 0.997119 | 0.076068 | 13.1461   | 1.002889 | 13.1841  | 0.0001462      | 11.65125  | 39       |
| 22       | 0.076139 | 0.997097 | 0.076361 | 13.0958   | 1.002911 | 13.1339  | 0.0001479      | 11.60117  | 38       |
| 23       | 0.076429 | 0.997075 | 0.076653 | 13.0458   | 1.002934 | 13.0840  | 0.0001496      | 11.55148  | 37       |
| 24       | 0.076719 | 0.997053 | 0.076946 | 12.9962   | 1.002956 | 13.0346  | 0.0001513      | 11.50216  | 36       |
| 25       | 0.077009 | 0.997030 | 0.077238 | 12.9469   | 1.002978 | 12.9855  | 0.0001530      | 11.45321  | 35       |
| 26       | 0.077299 | 0.997008 | 0.077531 | 12.8981   | 1.003001 | 12.9368  | 0.0001548      | 11.40464  | 34       |
| 27       | 0.077589 | 0.996985 | 0.077824 | 12.8496   | 1.003024 | 12.8884  | 0.0001565      | 11.35643  | 33       |
| 28       | 0.077879 | 0.996963 | 0.078116 | 12.8014   | 1.003046 | 12.8404  | 0.0001583      | 11.30858  | 32       |
| 29       | 0.078169 | 0.996940 | 0.078409 | 12.7536   | 1.003069 | 12.7928  | 0.0001601      | 11.26109  | 31       |
| 30       | 0.078459 | 0.996917 | 0.078702 | 12.7062   | 1.003092 | 12.7455  | 0.0001619      | 11.21395  | 30       |
| 31       | 0.078749 | 0.996894 | 0.078994 | 12.6591   | 1.003115 | 12.6986  | 0.0001637      | 11.16716  | 29       |
| 32       | 0.079039 | 0.996872 | 0.079287 | 12.6124   | 1.003138 | 12.6520  | 0.0001655      | 11.12072  | 28       |
| 33       | 0.079329 | 0.996848 | 0.079580 | 12.5660   | 1.003161 | 12.6057  | 0.0001674      | 11.07461  | 27       |
| 34       | 0.079619 | 0.996825 | 0.079873 | 12.5199   | 1.003185 | 12.5598  | 0.0001692      | 11.02885  | 26       |
| 35       | 0.079909 | 0.996802 | 0.080165 | 12.4742   | 1.003208 | 12.5142  | 0.0001711      | 10.98342  | 25       |
| 36       | 0.080199 | 0.996779 | 0.080458 | 12.4288   | 1.003232 | 12.4689  | 0.0001729      | 10.93832  | 24       |
| 37       | 0.080489 | 0.996756 | 0.080751 | 12.3838   | 1.003255 | 12.4241  | 0.0001748      | 10.89355  | 23       |
| 38       | 0.080779 | 0.996732 | 0.081044 | 12.3390   | 1.003279 | 12.3795  | 0.0001767      | 10.84910  | 22       |
| 39       | 0.081069 | 0.996709 | 0.081336 | 12.2946   | 1.003302 | 12.3352  | 0.0001787      | 10.80497  | 21       |
| 40       | 0.081359 | 0.996685 | 0.081629 | 12.2505   | 1.003326 | 12.2913  | 0.0001806      | 10.76116  | 20       |
| 41       | 0.081649 | 0.996661 | 0.081922 | 12.2067   | 1.003350 | 12.2476  | 0.0001825      | 10.71766  | 19       |
| 42       | 0.081939 | 0.996637 | 0.082215 | 12.1632   | 1.003374 | 12.2043  | 0.0001845      | 10.67447  | 18       |
| 43       | 0.082228 | 0.996614 | 0.082508 | 12.1201   | 1.003398 | 12.1612  | 0.0001865      | 10.63159  | 17       |
| 44       | 0.082518 | 0.996590 | 0.082801 | 12.0772   | 1.003422 | 12.1185  | 0.0001885      | 10.58901  | 16       |
| 45       | 0.082808 | 0.996566 | 0.083094 | 12.0346   | 1.003446 | 12.0761  | 0.0001905      | 10.54673  | 15       |
| 46       | 0.083098 | 0.996541 | 0.083386 | 11.9923   | 1.003471 | 12.0340  | 0.0001925      | 10.50475  | 14       |
| 47       | 0.083388 | 0.996517 | 0.083679 | 11.9504   | 1.003495 | 11.9921  | 0.0001945      | 10.46306  | 13       |
| 48       | 0.083678 | 0.996493 | 0.083972 | 11.9087   | 1.003519 | 11.9506  | 0.0001965      | 10.42166  | 12       |
| 49       | 0.083968 | 0.996468 | 0.084265 | 11.8673   | 1.003544 | 11.9093  | 0.0001986      | 10.38055  | 11       |
| 50       | 0.084258 | 0.996444 | 0.084558 | 11.8262   | 1.003569 | 11.8684  | 0.0002007      | 10.33973  | 10       |
| 51       | 0.084547 | 0.996419 | 0.084851 | 11.7853   | 1.003593 | 11.8277  | 0.0002028      | 10.29919  | 9        |
| 52       | 0.084837 | 0.996395 | 0.085144 | 11.7448   | 1.003618 | 11.7873  | 0.0002049      | 10.25892  | 8        |
| 53       | 0.085127 | 0.996370 | 0.085437 | 11.7045   | 1.003643 | 11.7471  | 0.0002070      | 10.21893  | 7        |
| 54       | 0.085417 | 0.996345 | 0.085730 | 11.6645   | 1.003668 | 11.7073  | 0.0002091      | 10.17922  | 6        |
| 55       | 0.085707 | 0.996320 | 0.086023 | 11.6248   | 1.003693 | 11.6677  | 0.0002113      | 10.13978  | 5        |
| 56       | 0.085997 | 0.996295 | 0.086316 | 11.5853   | 1.003718 | 11.6284  | 0.0002134      | 10.10060  | 4        |
| 57       | 0.086286 | 0.996270 | 0.086609 | 11.5461   | 1.003744 | 11.5893  | 0.0002156      | 10.06169  | 3        |
| 58       | 0.086576 | 0.996245 | 0.086902 | 11.5072   | 1.003769 | 11.5505  | 0.0002178      | 10.02304  | 2        |
| 59       | 0.086866 | 0.996220 | 0.087196 | 11.4685   | 1.003794 | 11.5120  | 0.0002200      | 9.9846536 | 1        |
| 60       | 0.087156 | 0.996195 | 0.087489 | 11.4301   | 1.003820 | 11.4737  | 0.0002222      | 9.9465224 | 0        |

↑ 94° or 274°

85° or 265° ↑

↓ 5° or 185° Trigonometric and Involute Functions 174° or 354° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>5°-6° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|-------------------|------------|---------|
| 0       | 0.087156 | 0.996195 | 0.087489 | 11.4301   | 1.003820 | 11.4737  | 0.0002222         | 9.9465224  | 60      |
| 1       | 0.087446 | 0.996169 | 0.087782 | 11.3919   | 1.003845 | 11.4357  | 0.0002244         | 9.9086459  | 59      |
| 2       | 0.087735 | 0.996144 | 0.088075 | 11.3540   | 1.003871 | 11.3979  | 0.0002267         | 9.8710215  | 58      |
| 3       | 0.088025 | 0.996118 | 0.088368 | 11.3163   | 1.003897 | 11.3604  | 0.0002289         | 9.8336468  | 57      |
| 4       | 0.088315 | 0.996093 | 0.088661 | 11.2789   | 1.003923 | 11.3231  | 0.0002312         | 9.7965192  | 56      |
| 5       | 0.088605 | 0.996067 | 0.088954 | 11.2417   | 1.003949 | 11.2861  | 0.0002335         | 9.7596363  | 55      |
| 6       | 0.088894 | 0.996041 | 0.089248 | 11.2048   | 1.003975 | 11.2493  | 0.0002358         | 9.7229958  | 54      |
| 7       | 0.089184 | 0.996015 | 0.089541 | 11.1681   | 1.004001 | 11.2128  | 0.0002382         | 9.6865952  | 53      |
| 8       | 0.089474 | 0.995989 | 0.089834 | 11.1316   | 1.004027 | 11.1765  | 0.0002405         | 9.6504322  | 52      |
| 9       | 0.089763 | 0.995963 | 0.090127 | 11.0954   | 1.004053 | 11.1404  | 0.0002429         | 9.6145046  | 51      |
| 10      | 0.090053 | 0.995937 | 0.090421 | 11.0594   | 1.004080 | 11.1045  | 0.0002452         | 9.5788100  | 50      |
| 11      | 0.090343 | 0.995911 | 0.090714 | 11.0237   | 1.004106 | 11.0689  | 0.0002476         | 9.5433462  | 49      |
| 12      | 0.090633 | 0.995884 | 0.091007 | 10.9882   | 1.004133 | 11.0336  | 0.0002500         | 9.5081109  | 48      |
| 13      | 0.090922 | 0.995858 | 0.091300 | 10.9529   | 1.004159 | 10.9984  | 0.0002524         | 9.4731021  | 47      |
| 14      | 0.091212 | 0.995832 | 0.091594 | 10.9178   | 1.004186 | 10.9635  | 0.0002549         | 9.4383174  | 46      |
| 15      | 0.091502 | 0.995805 | 0.091887 | 10.8829   | 1.004213 | 10.9288  | 0.0002573         | 9.4037549  | 45      |
| 16      | 0.091791 | 0.995778 | 0.092180 | 10.8483   | 1.004240 | 10.8943  | 0.0002598         | 9.3694123  | 44      |
| 17      | 0.092081 | 0.995752 | 0.092474 | 10.8139   | 1.004267 | 10.8600  | 0.0002622         | 9.3352876  | 43      |
| 18      | 0.092371 | 0.995725 | 0.092767 | 10.7797   | 1.004294 | 10.8260  | 0.0002647         | 9.3013788  | 42      |
| 19      | 0.092660 | 0.995698 | 0.093061 | 10.7457   | 1.004321 | 10.7921  | 0.0002673         | 9.2676838  | 41      |
| 20      | 0.092950 | 0.995671 | 0.093354 | 10.7119   | 1.004348 | 10.7585  | 0.0002698         | 9.2342005  | 40      |
| 21      | 0.093239 | 0.995644 | 0.093647 | 10.6783   | 1.004375 | 10.7251  | 0.0002723         | 9.2009271  | 39      |
| 22      | 0.093529 | 0.995617 | 0.093941 | 10.6450   | 1.004403 | 10.6919  | 0.0002749         | 9.1678616  | 38      |
| 23      | 0.093819 | 0.995589 | 0.094234 | 10.6118   | 1.004430 | 10.6589  | 0.0002775         | 9.1350020  | 37      |
| 24      | 0.094108 | 0.995562 | 0.094528 | 10.5789   | 1.004458 | 10.6261  | 0.0002801         | 9.1023464  | 36      |
| 25      | 0.094398 | 0.995535 | 0.094821 | 10.5462   | 1.004485 | 10.5935  | 0.0002827         | 9.0698930  | 35      |
| 26      | 0.094687 | 0.995507 | 0.095115 | 10.5136   | 1.004513 | 10.5611  | 0.0002853         | 9.0376399  | 34      |
| 27      | 0.094977 | 0.995479 | 0.095408 | 10.4813   | 1.004541 | 10.5289  | 0.0002879         | 9.0055852  | 33      |
| 28      | 0.095267 | 0.995452 | 0.095702 | 10.4491   | 1.004569 | 10.4969  | 0.0002906         | 8.9737272  | 32      |
| 29      | 0.095556 | 0.995424 | 0.095995 | 10.4172   | 1.004597 | 10.4650  | 0.0002933         | 8.9420640  | 31      |
| 30      | 0.095846 | 0.995396 | 0.096289 | 10.3854   | 1.004625 | 10.4334  | 0.0002959         | 8.9105939  | 30      |
| 31      | 0.096135 | 0.995368 | 0.096583 | 10.3538   | 1.004653 | 10.4020  | 0.0002986         | 8.8793151  | 29      |
| 32      | 0.096425 | 0.995340 | 0.096876 | 10.3224   | 1.004682 | 10.3708  | 0.0003014         | 8.8482258  | 28      |
| 33      | 0.096714 | 0.995312 | 0.097170 | 10.2913   | 1.004710 | 10.3397  | 0.0003041         | 8.8173245  | 27      |
| 34      | 0.097004 | 0.995284 | 0.097464 | 10.2602   | 1.004738 | 10.3089  | 0.0003069         | 8.7866094  | 26      |
| 35      | 0.097293 | 0.995256 | 0.097757 | 10.2294   | 1.004767 | 10.2782  | 0.0003096         | 8.7560788  | 25      |
| 36      | 0.097583 | 0.995228 | 0.098051 | 10.1988   | 1.004795 | 10.2477  | 0.0003124         | 8.7257531  | 24      |
| 37      | 0.097872 | 0.995199 | 0.098345 | 10.1683   | 1.004824 | 10.2174  | 0.0003152         | 8.6955646  | 23      |
| 38      | 0.098162 | 0.995170 | 0.098638 | 10.1381   | 1.004853 | 10.1873  | 0.0003180         | 8.6655778  | 22      |
| 39      | 0.098451 | 0.995142 | 0.098932 | 10.1080   | 1.004882 | 10.1573  | 0.0003209         | 8.6357690  | 21      |
| 40      | 0.098741 | 0.995113 | 0.099226 | 10.0780   | 1.004911 | 10.1275  | 0.0003237         | 8.6061367  | 20      |
| 41      | 0.099030 | 0.995084 | 0.099519 | 10.0483   | 1.004940 | 10.0979  | 0.0003266         | 8.5766794  | 19      |
| 42      | 0.099320 | 0.995056 | 0.099813 | 10.0187   | 1.004969 | 10.0685  | 0.0003295         | 8.5473954  | 18      |
| 43      | 0.099609 | 0.995027 | 0.100107 | 9.989305  | 1.004998 | 10.0392  | 0.0003324         | 8.5182834  | 17      |
| 44      | 0.099898 | 0.994998 | 0.100401 | 9.960072  | 1.005028 | 10.0101  | 0.0003353         | 8.4893417  | 16      |
| 45      | 0.100188 | 0.994969 | 0.100695 | 9.931009  | 1.005057 | 9.981229 | 0.0003383         | 8.4605689  | 15      |
| 46      | 0.100477 | 0.994939 | 0.100989 | 9.902113  | 1.005086 | 9.952479 | 0.0003412         | 8.4319635  | 14      |
| 47      | 0.100767 | 0.994910 | 0.101282 | 9.873382  | 1.005116 | 9.923894 | 0.0003442         | 8.4035241  | 13      |
| 48      | 0.101056 | 0.994881 | 0.101576 | 9.844817  | 1.005146 | 9.895474 | 0.0003472         | 8.3752493  | 12      |
| 49      | 0.101346 | 0.994851 | 0.101870 | 9.816414  | 1.005175 | 9.867123 | 0.0003502         | 8.3471377  | 11      |
| 50      | 0.101635 | 0.994822 | 0.102164 | 9.788173  | 1.005205 | 9.839123 | 0.0003532         | 8.3191877  | 10      |
| 51      | 0.101924 | 0.994792 | 0.102458 | 9.760093  | 1.005235 | 9.811188 | 0.0003563         | 8.2913982  | 9       |
| 52      | 0.102214 | 0.994762 | 0.102752 | 9.732171  | 1.005265 | 9.783412 | 0.0003593         | 8.2637676  | 8       |
| 53      | 0.102503 | 0.994733 | 0.103046 | 9.704407  | 1.005295 | 9.755794 | 0.0003624         | 8.2362947  | 7       |
| 54      | 0.102793 | 0.994703 | 0.103340 | 9.676800  | 1.005325 | 9.728333 | 0.0003655         | 8.2089781  | 6       |
| 55      | 0.103082 | 0.994673 | 0.103634 | 9.649347  | 1.005356 | 9.701026 | 0.0003686         | 8.1818164  | 5       |
| 56      | 0.103371 | 0.994643 | 0.103928 | 9.622049  | 1.005386 | 9.673873 | 0.0003718         | 8.1548085  | 4       |
| 57      | 0.103661 | 0.994613 | 0.104222 | 9.594902  | 1.005416 | 9.646872 | 0.0003749         | 8.1279529  | 3       |
| 58      | 0.103950 | 0.994583 | 0.104516 | 9.567907  | 1.005447 | 9.620023 | 0.0003781         | 8.1012485  | 2       |
| 59      | 0.104239 | 0.994552 | 0.104810 | 9.541061  | 1.005478 | 9.593323 | 0.0003813         | 8.0746939  | 1       |
| 60      | 0.104528 | 0.994522 | 0.105104 | 9.514364  | 1.005508 | 9.566772 | 0.0003845         | 8.0482879  | 0       |

↑ 95° or 275°

84° or 264° ↑

TRIGONOMETRY TABLES

↓ 6° or 186° Trigonometric and Involute Functions 173° or 353° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>6°-7° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|-------------------|------------|---------|
| 0       | 0.104528 | 0.994522 | 0.105104 | 9.514364  | 1.005508 | 9.566772 | 0.0003845         | 8.0482879  | 60      |
| 1       | 0.104818 | 0.994491 | 0.105398 | 9.487815  | 1.005539 | 9.540369 | 0.0003877         | 8.0220292  | 59      |
| 2       | 0.105107 | 0.994461 | 0.105692 | 9.461412  | 1.005570 | 9.514111 | 0.0003909         | 7.9959168  | 58      |
| 3       | 0.105396 | 0.994430 | 0.105987 | 9.435153  | 1.005601 | 9.487998 | 0.0003942         | 7.9699942  | 57      |
| 4       | 0.105686 | 0.994400 | 0.106281 | 9.409038  | 1.005632 | 9.462030 | 0.0003975         | 7.9441254  | 56      |
| 5       | 0.105975 | 0.994369 | 0.106575 | 9.383066  | 1.005663 | 9.436203 | 0.0004008         | 7.9184441  | 55      |
| 6       | 0.106264 | 0.994338 | 0.106869 | 9.357236  | 1.005694 | 9.410518 | 0.0004041         | 7.8929043  | 54      |
| 7       | 0.106553 | 0.994307 | 0.107163 | 9.331545  | 1.005726 | 9.384974 | 0.0004074         | 7.8675047  | 53      |
| 8       | 0.106843 | 0.994276 | 0.107458 | 9.305994  | 1.005757 | 9.359568 | 0.0004108         | 7.8422441  | 52      |
| 9       | 0.107132 | 0.994245 | 0.107752 | 9.280580  | 1.005788 | 9.334301 | 0.0004141         | 7.8171216  | 51      |
| 10      | 0.107421 | 0.994214 | 0.108046 | 9.255304  | 1.005820 | 9.309170 | 0.0004175         | 7.7921359  | 50      |
| 11      | 0.107710 | 0.994182 | 0.108340 | 9.230163  | 1.005852 | 9.284175 | 0.0004209         | 7.7672859  | 49      |
| 12      | 0.107999 | 0.994151 | 0.108635 | 9.205156  | 1.005883 | 9.259314 | 0.0004244         | 7.7425705  | 48      |
| 13      | 0.108289 | 0.994120 | 0.108929 | 9.180284  | 1.005915 | 9.234588 | 0.0004278         | 7.7179887  | 47      |
| 14      | 0.108578 | 0.994088 | 0.109223 | 9.155544  | 1.005947 | 9.209993 | 0.0004313         | 7.6935394  | 46      |
| 15      | 0.108867 | 0.994056 | 0.109518 | 9.130935  | 1.005979 | 9.185531 | 0.0004347         | 7.6692216  | 45      |
| 16      | 0.109156 | 0.994025 | 0.109812 | 9.106456  | 1.006011 | 9.161198 | 0.0004382         | 7.6450341  | 44      |
| 17      | 0.109445 | 0.993993 | 0.110107 | 9.082107  | 1.006043 | 9.136995 | 0.0004417         | 7.6209759  | 43      |
| 18      | 0.109734 | 0.993961 | 0.110401 | 9.057887  | 1.006076 | 9.112920 | 0.0004453         | 7.5970461  | 42      |
| 19      | 0.110023 | 0.993929 | 0.110695 | 9.033793  | 1.006108 | 9.088972 | 0.0004488         | 7.5732466  | 41      |
| 20      | 0.110313 | 0.993897 | 0.110990 | 9.009826  | 1.006141 | 9.065151 | 0.0004524         | 7.5495673  | 40      |
| 21      | 0.110602 | 0.993865 | 0.111284 | 8.985984  | 1.006173 | 9.041455 | 0.0004560         | 7.5260164  | 39      |
| 22      | 0.110891 | 0.993833 | 0.111579 | 8.962267  | 1.006206 | 9.017884 | 0.0004596         | 7.5025898  | 38      |
| 23      | 0.111180 | 0.993800 | 0.111873 | 8.938673  | 1.006238 | 8.994435 | 0.0004632         | 7.4792865  | 37      |
| 24      | 0.111469 | 0.993768 | 0.112168 | 8.915201  | 1.006271 | 8.971110 | 0.0004669         | 7.4561056  | 36      |
| 25      | 0.111758 | 0.993735 | 0.112463 | 8.891850  | 1.006304 | 8.947905 | 0.0004706         | 7.4330461  | 35      |
| 26      | 0.112047 | 0.993703 | 0.112757 | 8.868621  | 1.006337 | 8.924821 | 0.0004743         | 7.4101071  | 34      |
| 27      | 0.112336 | 0.993670 | 0.113052 | 8.845510  | 1.006370 | 8.901857 | 0.0004780         | 7.3872877  | 33      |
| 28      | 0.112625 | 0.993638 | 0.113346 | 8.822519  | 1.006403 | 8.879011 | 0.0004817         | 7.3645869  | 32      |
| 29      | 0.112914 | 0.993605 | 0.113641 | 8.799645  | 1.006436 | 8.856283 | 0.0004854         | 7.3420037  | 31      |
| 30      | 0.113203 | 0.993572 | 0.113936 | 8.776887  | 1.006470 | 8.833671 | 0.0004892         | 7.3195374  | 30      |
| 31      | 0.113492 | 0.993539 | 0.114230 | 8.754246  | 1.006503 | 8.811176 | 0.0004930         | 7.2971870  | 29      |
| 32      | 0.113781 | 0.993506 | 0.114525 | 8.731720  | 1.006537 | 8.788796 | 0.0004968         | 7.2749516  | 28      |
| 33      | 0.114070 | 0.993473 | 0.114820 | 8.709308  | 1.006570 | 8.766530 | 0.0005006         | 7.2528304  | 27      |
| 34      | 0.114359 | 0.993439 | 0.115114 | 8.687009  | 1.006604 | 8.744377 | 0.0005045         | 7.2308224  | 26      |
| 35      | 0.114648 | 0.993406 | 0.115409 | 8.664822  | 1.006638 | 8.722336 | 0.0005083         | 7.2089269  | 25      |
| 36      | 0.114937 | 0.993373 | 0.115704 | 8.642747  | 1.006671 | 8.700407 | 0.0005122         | 7.1871429  | 24      |
| 37      | 0.115226 | 0.993339 | 0.115999 | 8.620783  | 1.006705 | 8.678589 | 0.0005161         | 7.1654696  | 23      |
| 38      | 0.115515 | 0.993306 | 0.116294 | 8.598929  | 1.006739 | 8.656881 | 0.0005200         | 7.1439062  | 22      |
| 39      | 0.115804 | 0.993272 | 0.116588 | 8.577184  | 1.006773 | 8.635281 | 0.0005240         | 7.1224518  | 21      |
| 40      | 0.116093 | 0.993238 | 0.116883 | 8.555547  | 1.006808 | 8.613790 | 0.0005280         | 7.1011057  | 20      |
| 41      | 0.116382 | 0.993205 | 0.117178 | 8.534017  | 1.006842 | 8.592407 | 0.0005319         | 7.0798671  | 19      |
| 42      | 0.116671 | 0.993171 | 0.117473 | 8.512594  | 1.006876 | 8.571130 | 0.0005359         | 7.0587350  | 18      |
| 43      | 0.116960 | 0.993137 | 0.117768 | 8.491277  | 1.006911 | 8.549958 | 0.0005400         | 7.0377088  | 17      |
| 44      | 0.117249 | 0.993103 | 0.118063 | 8.470065  | 1.006945 | 8.528892 | 0.0005440         | 7.0167876  | 16      |
| 45      | 0.117537 | 0.993068 | 0.118358 | 8.448957  | 1.006980 | 8.507930 | 0.0005481         | 6.9959707  | 15      |
| 46      | 0.117826 | 0.993034 | 0.118653 | 8.427953  | 1.007015 | 8.487072 | 0.0005522         | 6.9752573  | 14      |
| 47      | 0.118115 | 0.993000 | 0.118948 | 8.407052  | 1.007049 | 8.466316 | 0.0005563         | 6.9546467  | 13      |
| 48      | 0.118404 | 0.992966 | 0.119243 | 8.386252  | 1.007084 | 8.445663 | 0.0005604         | 6.9341380  | 12      |
| 49      | 0.118693 | 0.992931 | 0.119538 | 8.365554  | 1.007119 | 8.425111 | 0.0005645         | 6.9137305  | 11      |
| 50      | 0.118982 | 0.992896 | 0.119833 | 8.344956  | 1.007154 | 8.404659 | 0.0005687         | 6.8934236  | 10      |
| 51      | 0.119270 | 0.992862 | 0.120128 | 8.324458  | 1.007190 | 8.384306 | 0.0005729         | 6.8732164  | 9       |
| 52      | 0.119559 | 0.992827 | 0.120423 | 8.304059  | 1.007225 | 8.364053 | 0.0005771         | 6.8531082  | 8       |
| 53      | 0.119848 | 0.992792 | 0.120718 | 8.283758  | 1.007260 | 8.343899 | 0.0005813         | 6.8330984  | 7       |
| 54      | 0.120137 | 0.992757 | 0.121013 | 8.263555  | 1.007295 | 8.323841 | 0.0005856         | 6.8131861  | 6       |
| 55      | 0.120426 | 0.992722 | 0.121308 | 8.243448  | 1.007331 | 8.303881 | 0.0005898         | 6.7933708  | 5       |
| 56      | 0.120714 | 0.992687 | 0.121604 | 8.223438  | 1.007367 | 8.284017 | 0.0005941         | 6.7736516  | 4       |
| 57      | 0.121003 | 0.992652 | 0.121899 | 8.203524  | 1.007402 | 8.264249 | 0.0005985         | 6.7540279  | 3       |
| 58      | 0.121292 | 0.992617 | 0.122194 | 8.183704  | 1.007438 | 8.244575 | 0.0006028         | 6.7344991  | 2       |
| 59      | 0.121581 | 0.992582 | 0.122489 | 8.163979  | 1.007474 | 8.224995 | 0.0006071         | 6.7150644  | 1       |
| 60      | 0.121869 | 0.992546 | 0.122785 | 8.144346  | 1.007510 | 8.205509 | 0.0006115         | 6.6957231  | 0       |

↑ 96° or 276°

83° or 263° ↑

↓ 7° or 187°      Trigonometric and Involute Functions      172° or 352° ↓

| Min-utes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>7°-8° | Read<br>Up | Min-utes |
|----------|----------|----------|----------|-----------|----------|----------|-------------------|------------|----------|
| 0        | 0.121869 | 0.992546 | 0.122785 | 8.144346  | 1.007510 | 8.205509 | 0.0006115         | 6.6957231  | 60       |
| 1        | 0.122158 | 0.992511 | 0.123080 | 8.124807  | 1.007546 | 8.186116 | 0.0006159         | 6.6764747  | 59       |
| 2        | 0.122447 | 0.992475 | 0.123375 | 8.105360  | 1.007582 | 8.166815 | 0.0006203         | 6.6573184  | 58       |
| 3        | 0.122735 | 0.992439 | 0.123670 | 8.086004  | 1.007618 | 8.147605 | 0.0006248         | 6.6382536  | 57       |
| 4        | 0.123024 | 0.992404 | 0.123966 | 8.066739  | 1.007654 | 8.128486 | 0.0006292         | 6.6192796  | 56       |
| 5        | 0.123313 | 0.992368 | 0.124261 | 8.047565  | 1.007691 | 8.109457 | 0.0006337         | 6.6003959  | 55       |
| 6        | 0.123601 | 0.992332 | 0.124557 | 8.028480  | 1.007727 | 8.090518 | 0.0006382         | 6.5816017  | 54       |
| 7        | 0.123890 | 0.992296 | 0.124852 | 8.009483  | 1.007764 | 8.071668 | 0.0006427         | 6.5628964  | 53       |
| 8        | 0.124179 | 0.992260 | 0.125147 | 7.990576  | 1.007801 | 8.052906 | 0.0006473         | 6.5442795  | 52       |
| 9        | 0.124467 | 0.992224 | 0.125443 | 7.971755  | 1.007837 | 8.034232 | 0.0006518         | 6.5257502  | 51       |
| 10       | 0.124756 | 0.992187 | 0.125738 | 7.953022  | 1.007874 | 8.015645 | 0.0006564         | 6.5073080  | 50       |
| 11       | 0.125045 | 0.992151 | 0.126034 | 7.934376  | 1.007911 | 7.997144 | 0.0006610         | 6.4889523  | 49       |
| 12       | 0.125333 | 0.992115 | 0.126329 | 7.915815  | 1.007948 | 7.978730 | 0.0006657         | 6.4706825  | 48       |
| 13       | 0.125622 | 0.992078 | 0.126625 | 7.897340  | 1.007985 | 7.960400 | 0.0006703         | 6.4524979  | 47       |
| 14       | 0.125910 | 0.992042 | 0.126920 | 7.878949  | 1.008022 | 7.942156 | 0.0006750         | 6.4343981  | 46       |
| 15       | 0.126199 | 0.992005 | 0.127216 | 7.860642  | 1.008059 | 7.923995 | 0.0006797         | 6.4163823  | 45       |
| 16       | 0.126488 | 0.991968 | 0.127512 | 7.842419  | 1.008097 | 7.905918 | 0.0006844         | 6.3984501  | 44       |
| 17       | 0.126776 | 0.991931 | 0.127807 | 7.824279  | 1.008134 | 7.887924 | 0.0006892         | 6.3806008  | 43       |
| 18       | 0.127065 | 0.991894 | 0.128103 | 7.806221  | 1.008172 | 7.870012 | 0.0006939         | 6.3628339  | 42       |
| 19       | 0.127353 | 0.991857 | 0.128399 | 7.788245  | 1.008209 | 7.852182 | 0.0006987         | 6.3451489  | 41       |
| 20       | 0.127642 | 0.991820 | 0.128694 | 7.770351  | 1.008247 | 7.834433 | 0.0007035         | 6.3275451  | 40       |
| 21       | 0.127930 | 0.991783 | 0.128990 | 7.752537  | 1.008285 | 7.816766 | 0.0007083         | 6.3100220  | 39       |
| 22       | 0.128219 | 0.991746 | 0.129286 | 7.734803  | 1.008323 | 7.799178 | 0.0007132         | 6.2925791  | 38       |
| 23       | 0.128507 | 0.991709 | 0.129582 | 7.717149  | 1.008361 | 7.781670 | 0.0007181         | 6.2752158  | 37       |
| 24       | 0.128796 | 0.991671 | 0.129877 | 7.699574  | 1.008399 | 7.764241 | 0.0007230         | 6.2579315  | 36       |
| 25       | 0.129084 | 0.991634 | 0.130173 | 7.682077  | 1.008437 | 7.746890 | 0.0007279         | 6.2407259  | 35       |
| 26       | 0.129373 | 0.991596 | 0.130469 | 7.664658  | 1.008475 | 7.729618 | 0.0007328         | 6.2235982  | 34       |
| 27       | 0.129661 | 0.991558 | 0.130765 | 7.647317  | 1.008513 | 7.712423 | 0.0007378         | 6.2065481  | 33       |
| 28       | 0.129949 | 0.991521 | 0.131061 | 7.630053  | 1.008552 | 7.695305 | 0.0007428         | 6.1895749  | 32       |
| 29       | 0.130238 | 0.991483 | 0.131357 | 7.612866  | 1.008590 | 7.678263 | 0.0007478         | 6.1726782  | 31       |
| 30       | 0.130526 | 0.991445 | 0.131652 | 7.595754  | 1.008629 | 7.661298 | 0.0007528         | 6.1558575  | 30       |
| 31       | 0.130815 | 0.991407 | 0.131948 | 7.578718  | 1.008668 | 7.644407 | 0.0007579         | 6.1391122  | 29       |
| 32       | 0.131103 | 0.991369 | 0.132244 | 7.561757  | 1.008706 | 7.627592 | 0.0007629         | 6.1224418  | 28       |
| 33       | 0.131391 | 0.991331 | 0.132540 | 7.544870  | 1.008745 | 7.610852 | 0.0007680         | 6.1058460  | 27       |
| 34       | 0.131680 | 0.991292 | 0.132836 | 7.528057  | 1.008784 | 7.594185 | 0.0007732         | 6.0893240  | 26       |
| 35       | 0.131968 | 0.991254 | 0.133132 | 7.511318  | 1.008823 | 7.577592 | 0.0007783         | 6.0728756  | 25       |
| 36       | 0.132256 | 0.991216 | 0.133428 | 7.494651  | 1.008862 | 7.561071 | 0.0007835         | 6.0565001  | 24       |
| 37       | 0.132545 | 0.991177 | 0.133725 | 7.478058  | 1.008902 | 7.544624 | 0.0007887         | 6.0401971  | 23       |
| 38       | 0.132833 | 0.991138 | 0.134021 | 7.461536  | 1.008941 | 7.528248 | 0.0007939         | 6.0239662  | 22       |
| 39       | 0.133121 | 0.991100 | 0.134317 | 7.445086  | 1.008980 | 7.511944 | 0.0007991         | 6.0078069  | 21       |
| 40       | 0.133410 | 0.991061 | 0.134613 | 7.428706  | 1.009020 | 7.495711 | 0.0008044         | 5.9917186  | 20       |
| 41       | 0.133698 | 0.991022 | 0.134909 | 7.412398  | 1.009059 | 7.479548 | 0.0008096         | 5.9757010  | 19       |
| 42       | 0.133986 | 0.990983 | 0.135205 | 7.396160  | 1.009099 | 7.463456 | 0.0008150         | 5.9597535  | 18       |
| 43       | 0.134274 | 0.990944 | 0.135502 | 7.379991  | 1.009139 | 7.447433 | 0.0008203         | 5.9438758  | 17       |
| 44       | 0.134563 | 0.990905 | 0.135798 | 7.363892  | 1.009178 | 7.431480 | 0.0008256         | 5.9280674  | 16       |
| 45       | 0.134851 | 0.990866 | 0.136094 | 7.347861  | 1.009218 | 7.415596 | 0.0008310         | 5.9123277  | 15       |
| 46       | 0.135139 | 0.990827 | 0.136390 | 7.331899  | 1.009258 | 7.399780 | 0.0008364         | 5.8966565  | 14       |
| 47       | 0.135427 | 0.990787 | 0.136687 | 7.316005  | 1.009298 | 7.384032 | 0.0008418         | 5.8810532  | 13       |
| 48       | 0.135716 | 0.990748 | 0.136983 | 7.300178  | 1.009339 | 7.368351 | 0.0008473         | 5.8655174  | 12       |
| 49       | 0.136004 | 0.990708 | 0.137279 | 7.284418  | 1.009379 | 7.352738 | 0.0008527         | 5.8500487  | 11       |
| 50       | 0.136292 | 0.990669 | 0.137576 | 7.268725  | 1.009419 | 7.337191 | 0.0008582         | 5.8346466  | 10       |
| 51       | 0.136580 | 0.990629 | 0.137872 | 7.253099  | 1.009460 | 7.321710 | 0.0008638         | 5.8193107  | 9        |
| 52       | 0.136868 | 0.990589 | 0.138169 | 7.237538  | 1.009500 | 7.306295 | 0.0008693         | 5.8040407  | 8        |
| 53       | 0.137156 | 0.990549 | 0.138465 | 7.222042  | 1.009541 | 7.290946 | 0.0008749         | 5.7888360  | 7        |
| 54       | 0.137445 | 0.990509 | 0.138761 | 7.206612  | 1.009581 | 7.275662 | 0.0008805         | 5.7736963  | 6        |
| 55       | 0.137733 | 0.990469 | 0.139058 | 7.191246  | 1.009622 | 7.260442 | 0.0008861         | 5.7586212  | 5        |
| 56       | 0.138021 | 0.990429 | 0.139354 | 7.175944  | 1.009663 | 7.245286 | 0.0008917         | 5.7436102  | 4        |
| 57       | 0.138309 | 0.990389 | 0.139651 | 7.160706  | 1.009704 | 7.230194 | 0.0008974         | 5.7286629  | 3        |
| 58       | 0.138597 | 0.990349 | 0.139948 | 7.145531  | 1.009745 | 7.215165 | 0.0009031         | 5.7137791  | 2        |
| 59       | 0.138885 | 0.990309 | 0.140244 | 7.130419  | 1.009786 | 7.200200 | 0.0009088         | 5.6989581  | 1        |
| 60       | 0.139173 | 0.990268 | 0.140541 | 7.115370  | 1.009828 | 7.185297 | 0.0009145         | 5.6841997  | 0        |

↑ 97° or 277°

82° or 262° ↑

TRIGONOMETRY TABLES

↓ 8° or 188° Trigonometric and Involute Functions 171° or 351° ↓

| Min-utes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute 8°-9° | Read Up   | Min-utes |
|----------|----------|----------|----------|-----------|----------|----------|----------------|-----------|----------|
| 0        | 0.139173 | 0.990268 | 0.140541 | 7.115370  | 1.009828 | 7.185297 | 0.0009145      | 5.6841997 | 60       |
| 1        | 0.139461 | 0.990228 | 0.140837 | 7.100383  | 1.009869 | 7.170456 | 0.0009203      | 5.6695035 | 59       |
| 2        | 0.139749 | 0.990187 | 0.141134 | 7.085457  | 1.009910 | 7.155676 | 0.0009260      | 5.6548691 | 58       |
| 3        | 0.140037 | 0.990146 | 0.141431 | 7.070593  | 1.009952 | 7.140959 | 0.0009318      | 5.6402961 | 57       |
| 4        | 0.140325 | 0.990105 | 0.141728 | 7.055790  | 1.009993 | 7.126302 | 0.0009377      | 5.6257841 | 56       |
| 5        | 0.140613 | 0.990065 | 0.142024 | 7.041048  | 1.010035 | 7.111706 | 0.0009435      | 5.6113327 | 55       |
| 6        | 0.140901 | 0.990024 | 0.142321 | 7.026366  | 1.010077 | 7.097170 | 0.0009494      | 5.5969416 | 54       |
| 7        | 0.141189 | 0.989983 | 0.142618 | 7.011744  | 1.010119 | 7.082694 | 0.0009553      | 5.5826104 | 53       |
| 8        | 0.141477 | 0.989942 | 0.142915 | 6.997182  | 1.010161 | 7.068278 | 0.0009612      | 5.5683387 | 52       |
| 9        | 0.141765 | 0.989900 | 0.143212 | 6.982678  | 1.010203 | 7.053920 | 0.0009672      | 5.5541261 | 51       |
| 10       | 0.142053 | 0.989859 | 0.143508 | 6.968234  | 1.010245 | 7.039622 | 0.0009732      | 5.5399724 | 50       |
| 11       | 0.142341 | 0.989818 | 0.143805 | 6.953847  | 1.010287 | 7.025382 | 0.0009792      | 5.5258771 | 49       |
| 12       | 0.142629 | 0.989776 | 0.144102 | 6.939519  | 1.010329 | 7.011200 | 0.0009852      | 5.5118399 | 48       |
| 13       | 0.142917 | 0.989735 | 0.144399 | 6.925249  | 1.010372 | 6.997076 | 0.0009913      | 5.4978604 | 47       |
| 14       | 0.143205 | 0.989693 | 0.144696 | 6.911036  | 1.010414 | 6.983009 | 0.0009973      | 5.4839383 | 46       |
| 15       | 0.143493 | 0.989651 | 0.144993 | 6.896880  | 1.010457 | 6.968999 | 0.0010034      | 5.4700733 | 45       |
| 16       | 0.143780 | 0.989610 | 0.145290 | 6.882781  | 1.010499 | 6.955046 | 0.0010096      | 5.4562649 | 44       |
| 17       | 0.144068 | 0.989568 | 0.145587 | 6.868738  | 1.010542 | 6.941150 | 0.0010157      | 5.4425129 | 43       |
| 18       | 0.144356 | 0.989526 | 0.145884 | 6.854751  | 1.010585 | 6.927309 | 0.0010219      | 5.4288168 | 42       |
| 19       | 0.144644 | 0.989484 | 0.146181 | 6.840820  | 1.010628 | 6.913524 | 0.0010281      | 5.4151765 | 41       |
| 20       | 0.144932 | 0.989442 | 0.146478 | 6.826944  | 1.010671 | 6.899794 | 0.0010343      | 5.4015914 | 40       |
| 21       | 0.145220 | 0.989399 | 0.146776 | 6.813123  | 1.010714 | 6.886119 | 0.0010406      | 5.3880614 | 39       |
| 22       | 0.145507 | 0.989357 | 0.147073 | 6.799357  | 1.010757 | 6.872499 | 0.0010469      | 5.3745861 | 38       |
| 23       | 0.145795 | 0.989315 | 0.147370 | 6.785645  | 1.010801 | 6.858934 | 0.0010532      | 5.3611651 | 37       |
| 24       | 0.146083 | 0.989272 | 0.147667 | 6.771987  | 1.010844 | 6.845422 | 0.0010595      | 5.3477981 | 36       |
| 25       | 0.146371 | 0.989230 | 0.147964 | 6.758383  | 1.010887 | 6.831964 | 0.0010659      | 5.3344848 | 35       |
| 26       | 0.146659 | 0.989187 | 0.148262 | 6.744832  | 1.010931 | 6.818560 | 0.0010722      | 5.3212249 | 34       |
| 27       | 0.146946 | 0.989144 | 0.148559 | 6.731334  | 1.010975 | 6.805208 | 0.0010786      | 5.3080181 | 33       |
| 28       | 0.147234 | 0.989102 | 0.148856 | 6.717889  | 1.011018 | 6.791909 | 0.0010851      | 5.2948640 | 32       |
| 29       | 0.147522 | 0.989059 | 0.149154 | 6.704497  | 1.011062 | 6.778663 | 0.0010915      | 5.2817624 | 31       |
| 30       | 0.147809 | 0.989016 | 0.149451 | 6.691156  | 1.011106 | 6.765469 | 0.0010980      | 5.2687129 | 30       |
| 31       | 0.148097 | 0.988973 | 0.149748 | 6.677868  | 1.011150 | 6.752327 | 0.0011045      | 5.2557152 | 29       |
| 32       | 0.148385 | 0.988930 | 0.150046 | 6.664631  | 1.011194 | 6.739236 | 0.0011111      | 5.2427691 | 28       |
| 33       | 0.148672 | 0.988886 | 0.150343 | 6.651445  | 1.011238 | 6.726196 | 0.0011176      | 5.2298742 | 27       |
| 34       | 0.148960 | 0.988843 | 0.150641 | 6.638310  | 1.011283 | 6.713208 | 0.0011242      | 5.2170302 | 26       |
| 35       | 0.149248 | 0.988800 | 0.150938 | 6.625226  | 1.011327 | 6.700270 | 0.0011308      | 5.2042369 | 25       |
| 36       | 0.149535 | 0.988756 | 0.151236 | 6.612192  | 1.011371 | 6.687382 | 0.0011375      | 5.1914936 | 24       |
| 37       | 0.149823 | 0.988713 | 0.151533 | 6.599208  | 1.011416 | 6.674545 | 0.0011441      | 5.1788009 | 23       |
| 38       | 0.150111 | 0.988669 | 0.151831 | 6.586274  | 1.011461 | 6.661757 | 0.0011508      | 5.1661577 | 22       |
| 39       | 0.150398 | 0.988626 | 0.152129 | 6.573389  | 1.011505 | 6.649018 | 0.0011575      | 5.1535639 | 21       |
| 40       | 0.150686 | 0.988582 | 0.152426 | 6.560554  | 1.011550 | 6.636329 | 0.0011643      | 5.1410193 | 20       |
| 41       | 0.150973 | 0.988538 | 0.152724 | 6.547767  | 1.011595 | 6.623689 | 0.0011711      | 5.1285236 | 19       |
| 42       | 0.151261 | 0.988494 | 0.153022 | 6.535029  | 1.011640 | 6.611097 | 0.0011779      | 5.1160766 | 18       |
| 43       | 0.151548 | 0.988450 | 0.153319 | 6.522340  | 1.011685 | 6.598554 | 0.0011847      | 5.1036779 | 17       |
| 44       | 0.151836 | 0.988406 | 0.153617 | 6.509698  | 1.011730 | 6.586059 | 0.0011915      | 5.0913272 | 16       |
| 45       | 0.152123 | 0.988362 | 0.153915 | 6.497104  | 1.011776 | 6.573611 | 0.0011984      | 5.0790243 | 15       |
| 46       | 0.152411 | 0.988317 | 0.154213 | 6.484558  | 1.011821 | 6.561211 | 0.0012053      | 5.0667689 | 14       |
| 47       | 0.152698 | 0.988273 | 0.154510 | 6.472059  | 1.011866 | 6.548859 | 0.0012122      | 5.0545608 | 13       |
| 48       | 0.152986 | 0.988228 | 0.154808 | 6.459607  | 1.011912 | 6.536553 | 0.0012192      | 5.0423997 | 12       |
| 49       | 0.153273 | 0.988184 | 0.155106 | 6.447202  | 1.011957 | 6.524294 | 0.0012262      | 5.0302852 | 11       |
| 50       | 0.153561 | 0.988139 | 0.155404 | 6.434843  | 1.012003 | 6.512081 | 0.0012332      | 5.0182172 | 10       |
| 51       | 0.153848 | 0.988094 | 0.155702 | 6.422530  | 1.012049 | 6.499915 | 0.0012402      | 5.0061954 | 9        |
| 52       | 0.154136 | 0.988050 | 0.156000 | 6.410263  | 1.012095 | 6.487794 | 0.0012473      | 4.9942195 | 8        |
| 53       | 0.154423 | 0.988005 | 0.156298 | 6.398042  | 1.012141 | 6.475720 | 0.0012544      | 4.9822893 | 7        |
| 54       | 0.154710 | 0.987960 | 0.156596 | 6.385866  | 1.012187 | 6.463690 | 0.0012615      | 4.9704044 | 6        |
| 55       | 0.154998 | 0.987915 | 0.156894 | 6.373736  | 1.012233 | 6.451706 | 0.0012687      | 4.9585647 | 5        |
| 56       | 0.155285 | 0.987870 | 0.157192 | 6.361650  | 1.012279 | 6.439767 | 0.0012758      | 4.9467700 | 4        |
| 57       | 0.155572 | 0.987824 | 0.157490 | 6.349609  | 1.012326 | 6.427872 | 0.0012830      | 4.9350198 | 3        |
| 58       | 0.155860 | 0.987779 | 0.157788 | 6.337613  | 1.012372 | 6.416022 | 0.0012903      | 4.9233141 | 2        |
| 59       | 0.156147 | 0.987734 | 0.158086 | 6.325660  | 1.012419 | 6.404215 | 0.0012975      | 4.9116525 | 1        |
| 60       | 0.156434 | 0.987688 | 0.158384 | 6.313752  | 1.012465 | 6.392453 | 0.0013048      | 4.9000348 | 0        |

↑ 98° or 278°

81° or 261° ↑

↓ 9° or 189°      Trigonometric and Involute Functions      170° or 350° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>9°-10° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|--------------------|------------|---------|
| 0       | 0.156434 | 0.987688 | 0.158384 | 6.313752  | 1.012465 | 6.392453 | 0.0013048          | 4.9000348  | 60      |
| 1       | 0.156722 | 0.987643 | 0.158683 | 6.301887  | 1.012512 | 6.380735 | 0.0013121          | 4.8884608  | 59      |
| 2       | 0.157009 | 0.987597 | 0.158981 | 6.290665  | 1.012559 | 6.369066 | 0.0013195          | 4.8769302  | 58      |
| 3       | 0.157296 | 0.987551 | 0.159279 | 6.278287  | 1.012605 | 6.357428 | 0.0013268          | 4.8654428  | 57      |
| 4       | 0.157584 | 0.987506 | 0.159577 | 6.266551  | 1.012652 | 6.345839 | 0.0013342          | 4.8539983  | 56      |
| 5       | 0.157871 | 0.987460 | 0.159876 | 6.254859  | 1.012699 | 6.334292 | 0.0013416          | 4.8425965  | 55      |
| 6       | 0.158158 | 0.987414 | 0.160174 | 6.243209  | 1.012747 | 6.322788 | 0.0013491          | 4.8312372  | 54      |
| 7       | 0.158445 | 0.987368 | 0.160472 | 6.231601  | 1.012794 | 6.311327 | 0.0013566          | 4.8199202  | 53      |
| 8       | 0.158732 | 0.987322 | 0.160771 | 6.220035  | 1.012841 | 6.299907 | 0.0013641          | 4.8086451  | 52      |
| 9       | 0.159020 | 0.987275 | 0.161069 | 6.208511  | 1.012889 | 6.288530 | 0.0013716          | 4.7974119  | 51      |
| 10      | 0.159307 | 0.987229 | 0.161368 | 6.197028  | 1.012936 | 6.277193 | 0.0013792          | 4.7862201  | 50      |
| 11      | 0.159594 | 0.987183 | 0.161666 | 6.185587  | 1.012984 | 6.265898 | 0.0013868          | 4.7750697  | 49      |
| 12      | 0.159881 | 0.987136 | 0.161965 | 6.174186  | 1.013031 | 6.254645 | 0.0013944          | 4.7639604  | 48      |
| 13      | 0.160168 | 0.987090 | 0.162263 | 6.162827  | 1.013079 | 6.243432 | 0.0014020          | 4.7528920  | 47      |
| 14      | 0.160455 | 0.987043 | 0.162562 | 6.151508  | 1.013127 | 6.232259 | 0.0014097          | 4.7418642  | 46      |
| 15      | 0.160743 | 0.986996 | 0.162860 | 6.140230  | 1.013175 | 6.221128 | 0.0014174          | 4.7308769  | 45      |
| 16      | 0.161030 | 0.986950 | 0.163159 | 6.128992  | 1.013223 | 6.210036 | 0.0014251          | 4.7199289  | 44      |
| 17      | 0.161317 | 0.986903 | 0.163458 | 6.117794  | 1.013271 | 6.198984 | 0.0014329          | 4.7090227  | 43      |
| 18      | 0.161604 | 0.986856 | 0.163756 | 6.106636  | 1.013319 | 6.187972 | 0.0014407          | 4.6981553  | 42      |
| 19      | 0.161891 | 0.986809 | 0.164055 | 6.095517  | 1.013368 | 6.177000 | 0.0014485          | 4.6873206  | 41      |
| 20      | 0.162178 | 0.986762 | 0.164354 | 6.084438  | 1.013416 | 6.166067 | 0.0014563          | 4.6765392  | 40      |
| 21      | 0.162465 | 0.986714 | 0.164652 | 6.073398  | 1.013465 | 6.155174 | 0.0014642          | 4.6657899  | 39      |
| 22      | 0.162752 | 0.986667 | 0.164951 | 6.062397  | 1.013513 | 6.144319 | 0.0014721          | 4.6550796  | 38      |
| 23      | 0.163039 | 0.986620 | 0.165250 | 6.051434  | 1.013562 | 6.133503 | 0.0014800          | 4.6444080  | 37      |
| 24      | 0.163326 | 0.986572 | 0.165549 | 6.040510  | 1.013611 | 6.122725 | 0.0014880          | 4.6337750  | 36      |
| 25      | 0.163613 | 0.986525 | 0.165848 | 6.029625  | 1.013659 | 6.111986 | 0.0014960          | 4.6231802  | 35      |
| 26      | 0.163900 | 0.986477 | 0.166147 | 6.018777  | 1.013708 | 6.101285 | 0.0015040          | 4.6126236  | 34      |
| 27      | 0.164187 | 0.986429 | 0.166446 | 6.007968  | 1.013757 | 6.090622 | 0.0015120          | 4.6021049  | 33      |
| 28      | 0.164474 | 0.986381 | 0.166745 | 6.007196  | 1.013806 | 6.079996 | 0.0015201          | 4.5916239  | 32      |
| 29      | 0.164761 | 0.986334 | 0.167044 | 5.996461  | 1.013856 | 6.069409 | 0.0015282          | 4.5811805  | 31      |
| 30      | 0.165048 | 0.986286 | 0.167343 | 5.975764  | 1.013905 | 6.058858 | 0.0015363          | 4.5707743  | 30      |
| 31      | 0.165334 | 0.986238 | 0.167642 | 5.965104  | 1.013954 | 6.048345 | 0.0015445          | 4.5604053  | 29      |
| 32      | 0.165621 | 0.986189 | 0.167941 | 5.954481  | 1.014004 | 6.037868 | 0.0015527          | 4.5500732  | 28      |
| 33      | 0.165908 | 0.986141 | 0.168240 | 5.943895  | 1.014054 | 6.027428 | 0.0015609          | 4.5397779  | 27      |
| 34      | 0.166195 | 0.986093 | 0.168539 | 5.933346  | 1.014103 | 6.017025 | 0.0015691          | 4.5295190  | 26      |
| 35      | 0.166482 | 0.986045 | 0.168838 | 5.922832  | 1.014153 | 6.006658 | 0.0015774          | 4.5192966  | 25      |
| 36      | 0.166769 | 0.985996 | 0.169137 | 5.912355  | 1.014203 | 5.996327 | 0.0015857          | 4.5091103  | 24      |
| 37      | 0.167056 | 0.985947 | 0.169437 | 5.901914  | 1.014253 | 5.986033 | 0.0015941          | 4.4989600  | 23      |
| 38      | 0.167342 | 0.985899 | 0.169736 | 5.891508  | 1.014303 | 5.975774 | 0.0016024          | 4.4888455  | 22      |
| 39      | 0.167629 | 0.985850 | 0.170035 | 5.881139  | 1.014353 | 5.965550 | 0.0016108          | 4.4787665  | 21      |
| 40      | 0.167916 | 0.985801 | 0.170334 | 5.870804  | 1.014403 | 5.955362 | 0.0016193          | 4.4687230  | 20      |
| 41      | 0.168203 | 0.985752 | 0.170634 | 5.860505  | 1.014453 | 5.945210 | 0.0016277          | 4.4587148  | 19      |
| 42      | 0.168489 | 0.985703 | 0.170933 | 5.850241  | 1.014504 | 5.935092 | 0.0016362          | 4.4487416  | 18      |
| 43      | 0.168776 | 0.985654 | 0.171233 | 5.840012  | 1.014554 | 5.925009 | 0.0016447          | 4.4388032  | 17      |
| 44      | 0.169063 | 0.985605 | 0.171532 | 5.829817  | 1.014605 | 5.914961 | 0.0016533          | 4.4288996  | 16      |
| 45      | 0.169350 | 0.985556 | 0.171831 | 5.819657  | 1.014656 | 5.904948 | 0.0016618          | 4.4190305  | 15      |
| 46      | 0.169636 | 0.985507 | 0.172131 | 5.809532  | 1.014706 | 5.894969 | 0.0016704          | 4.4091957  | 14      |
| 47      | 0.169923 | 0.985457 | 0.172430 | 5.799440  | 1.014757 | 5.885024 | 0.0016791          | 4.3993951  | 13      |
| 48      | 0.170209 | 0.985408 | 0.172730 | 5.789383  | 1.014808 | 5.875113 | 0.0016877          | 4.3896285  | 12      |
| 49      | 0.170496 | 0.985358 | 0.173030 | 5.779359  | 1.014859 | 5.865236 | 0.0016964          | 4.3798957  | 11      |
| 50      | 0.170783 | 0.985309 | 0.173329 | 5.769369  | 1.014910 | 5.855392 | 0.0017051          | 4.3701965  | 10      |
| 51      | 0.171069 | 0.985259 | 0.173629 | 5.759412  | 1.014962 | 5.845582 | 0.0017139          | 4.3605308  | 9       |
| 52      | 0.171356 | 0.985209 | 0.173929 | 5.749489  | 1.015013 | 5.835805 | 0.0017227          | 4.3508984  | 8       |
| 53      | 0.171643 | 0.985159 | 0.174228 | 5.739599  | 1.015064 | 5.826062 | 0.0017315          | 4.3412992  | 7       |
| 54      | 0.171929 | 0.985109 | 0.174528 | 5.729742  | 1.015116 | 5.816351 | 0.0017403          | 4.3317329  | 6       |
| 55      | 0.172216 | 0.985059 | 0.174828 | 5.719917  | 1.015167 | 5.806673 | 0.0017492          | 4.3221994  | 5       |
| 56      | 0.172502 | 0.985009 | 0.175127 | 5.710126  | 1.015219 | 5.797028 | 0.0017581          | 4.3126986  | 4       |
| 57      | 0.172789 | 0.984959 | 0.175427 | 5.700366  | 1.015271 | 5.787415 | 0.0017671          | 4.3032303  | 3       |
| 58      | 0.173075 | 0.984909 | 0.175727 | 5.690639  | 1.015323 | 5.777835 | 0.0017760          | 4.2937942  | 2       |
| 59      | 0.173362 | 0.984858 | 0.176027 | 5.680945  | 1.015375 | 5.768287 | 0.0017850          | 4.2843309  | 1       |
| 60      | 0.173648 | 0.984808 | 0.176327 | 5.671282  | 1.015427 | 5.758770 | 0.0017941          | 4.2750184  | 0       |

↑ 99° or 279°

80° or 260° ↑



TRIGONOMETRY TABLES

↓ 10° or 190° **Trigonometric and Involute Functions** 169° or 349° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>10°-11° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.173648 | 0.984808 | 0.176327 | 5.671282  | 1.015427 | 5.758770 | 0.0017941           | 4.2750184  | 60      |
| 1       | 0.173935 | 0.984757 | 0.176627 | 5.661651  | 1.015479 | 5.749286 | 0.0018031           | 4.2656783  | 59      |
| 2       | 0.174221 | 0.984707 | 0.176927 | 5.652052  | 1.015531 | 5.739833 | 0.0018122           | 4.2563699  | 58      |
| 3       | 0.174508 | 0.984656 | 0.177227 | 5.642484  | 1.015583 | 5.730412 | 0.0018213           | 4.2470930  | 57      |
| 4       | 0.174794 | 0.984605 | 0.177527 | 5.632947  | 1.015636 | 5.721022 | 0.0018305           | 4.2378475  | 56      |
| 5       | 0.175080 | 0.984554 | 0.177827 | 5.623442  | 1.015688 | 5.711664 | 0.0018397           | 4.2286332  | 55      |
| 6       | 0.175367 | 0.984503 | 0.178127 | 5.613968  | 1.015741 | 5.702336 | 0.0018489           | 4.2194499  | 54      |
| 7       | 0.175653 | 0.984452 | 0.178427 | 5.604525  | 1.015793 | 5.693039 | 0.0018581           | 4.2102975  | 53      |
| 8       | 0.175939 | 0.984401 | 0.178727 | 5.595112  | 1.015846 | 5.683773 | 0.0018674           | 4.2011758  | 52      |
| 9       | 0.176226 | 0.984350 | 0.179028 | 5.585730  | 1.015899 | 5.674538 | 0.0018767           | 4.1920848  | 51      |
| 10      | 0.176512 | 0.984298 | 0.179328 | 5.576379  | 1.015952 | 5.665333 | 0.0018860           | 4.1830241  | 50      |
| 11      | 0.176798 | 0.984247 | 0.179628 | 5.567057  | 1.016005 | 5.656158 | 0.0018954           | 4.1739938  | 49      |
| 12      | 0.177085 | 0.984196 | 0.179928 | 5.557766  | 1.016058 | 5.647014 | 0.0019048           | 4.1649936  | 48      |
| 13      | 0.177371 | 0.984144 | 0.180229 | 5.548505  | 1.016111 | 5.637899 | 0.0019142           | 4.1560234  | 47      |
| 14      | 0.177657 | 0.984092 | 0.180529 | 5.539274  | 1.016165 | 5.628815 | 0.0019237           | 4.1470830  | 46      |
| 15      | 0.177944 | 0.984041 | 0.180829 | 5.530072  | 1.016218 | 5.619760 | 0.0019332           | 4.1381724  | 45      |
| 16      | 0.178230 | 0.983989 | 0.181130 | 5.520900  | 1.016272 | 5.610735 | 0.0019427           | 4.1292913  | 44      |
| 17      | 0.178516 | 0.983937 | 0.181430 | 5.511758  | 1.016325 | 5.601739 | 0.0019523           | 4.1204396  | 43      |
| 18      | 0.178802 | 0.983885 | 0.181731 | 5.502645  | 1.016379 | 5.592772 | 0.0019619           | 4.1116172  | 42      |
| 19      | 0.179088 | 0.983833 | 0.182031 | 5.493560  | 1.016433 | 5.583834 | 0.0019715           | 4.1028239  | 41      |
| 20      | 0.179375 | 0.983781 | 0.182332 | 5.484505  | 1.016487 | 5.574926 | 0.0019812           | 4.0940596  | 40      |
| 21      | 0.179661 | 0.983729 | 0.182632 | 5.475479  | 1.016541 | 5.566046 | 0.0019909           | 4.0853241  | 39      |
| 22      | 0.179947 | 0.983676 | 0.182933 | 5.466481  | 1.016595 | 5.557195 | 0.0020006           | 4.0766173  | 38      |
| 23      | 0.180233 | 0.983624 | 0.183234 | 5.457512  | 1.016649 | 5.548373 | 0.0020103           | 4.0679392  | 37      |
| 24      | 0.180519 | 0.983571 | 0.183534 | 5.448572  | 1.016703 | 5.539579 | 0.0020201           | 4.0592894  | 36      |
| 25      | 0.180805 | 0.983519 | 0.183835 | 5.439659  | 1.016757 | 5.530806 | 0.0020299           | 4.0506680  | 35      |
| 26      | 0.181091 | 0.983466 | 0.184136 | 5.430775  | 1.016812 | 5.522075 | 0.0020398           | 4.0420747  | 34      |
| 27      | 0.181377 | 0.983414 | 0.184437 | 5.421919  | 1.016866 | 5.513366 | 0.0020496           | 4.0335094  | 33      |
| 28      | 0.181663 | 0.983361 | 0.184737 | 5.413091  | 1.016921 | 5.504684 | 0.0020596           | 4.0249720  | 32      |
| 29      | 0.181950 | 0.983308 | 0.185038 | 5.404290  | 1.016975 | 5.496030 | 0.0020695           | 4.0164624  | 31      |
| 30      | 0.182236 | 0.983255 | 0.185339 | 5.395517  | 1.017030 | 5.487404 | 0.0020795           | 4.0079804  | 30      |
| 31      | 0.182522 | 0.983202 | 0.185640 | 5.386772  | 1.017085 | 5.478806 | 0.0020895           | 3.9995259  | 29      |
| 32      | 0.182808 | 0.983149 | 0.185941 | 5.378054  | 1.017140 | 5.470234 | 0.0020995           | 3.9910988  | 28      |
| 33      | 0.183094 | 0.983096 | 0.186242 | 5.369363  | 1.017195 | 5.461690 | 0.0021096           | 3.9826989  | 27      |
| 34      | 0.183379 | 0.983042 | 0.186543 | 5.360699  | 1.017250 | 5.453173 | 0.0021197           | 3.9743261  | 26      |
| 35      | 0.183665 | 0.982989 | 0.186844 | 5.352063  | 1.017306 | 5.444683 | 0.0021298           | 3.9659803  | 25      |
| 36      | 0.183951 | 0.982935 | 0.187145 | 5.343453  | 1.017361 | 5.436220 | 0.0021400           | 3.9576713  | 24      |
| 37      | 0.184237 | 0.982882 | 0.187446 | 5.334870  | 1.017416 | 5.427784 | 0.0021502           | 3.9493691  | 23      |
| 38      | 0.184523 | 0.982828 | 0.187747 | 5.326313  | 1.017472 | 5.419374 | 0.0021605           | 3.9411034  | 22      |
| 39      | 0.184809 | 0.982774 | 0.188048 | 5.317783  | 1.017527 | 5.410990 | 0.0021707           | 3.9328643  | 21      |
| 40      | 0.185095 | 0.982721 | 0.188349 | 5.309279  | 1.017583 | 5.402633 | 0.0021810           | 3.9246514  | 20      |
| 41      | 0.185381 | 0.982667 | 0.188651 | 5.300802  | 1.017639 | 5.394303 | 0.0021914           | 3.9164648  | 19      |
| 42      | 0.185667 | 0.982613 | 0.188952 | 5.292350  | 1.017695 | 5.385998 | 0.0022017           | 3.9083054  | 18      |
| 43      | 0.185952 | 0.982559 | 0.189253 | 5.283925  | 1.017751 | 5.377719 | 0.0022121           | 3.9001698  | 17      |
| 44      | 0.186238 | 0.982505 | 0.189555 | 5.275526  | 1.017807 | 5.369466 | 0.0022226           | 3.8920612  | 16      |
| 45      | 0.186524 | 0.982450 | 0.189856 | 5.267152  | 1.017863 | 5.361239 | 0.0022330           | 3.8839783  | 15      |
| 46      | 0.186810 | 0.982396 | 0.190157 | 5.258804  | 1.017919 | 5.353038 | 0.0022435           | 3.8759210  | 14      |
| 47      | 0.187096 | 0.982342 | 0.190459 | 5.250481  | 1.017976 | 5.344862 | 0.0022541           | 3.8678892  | 13      |
| 48      | 0.187381 | 0.982287 | 0.190760 | 5.242184  | 1.018032 | 5.336711 | 0.0022646           | 3.8598828  | 12      |
| 49      | 0.187667 | 0.982233 | 0.191062 | 5.233912  | 1.018089 | 5.328586 | 0.0022752           | 3.8519017  | 11      |
| 50      | 0.187953 | 0.982178 | 0.191363 | 5.225665  | 1.018145 | 5.320486 | 0.0022859           | 3.8439457  | 10      |
| 51      | 0.188238 | 0.982123 | 0.191665 | 5.217443  | 1.018202 | 5.312411 | 0.0022965           | 3.8360147  | 9       |
| 52      | 0.188524 | 0.982069 | 0.191966 | 5.209246  | 1.018259 | 5.304361 | 0.0023073           | 3.8281087  | 8       |
| 53      | 0.188810 | 0.982014 | 0.192268 | 5.201074  | 1.018316 | 5.296335 | 0.0023180           | 3.8202275  | 7       |
| 54      | 0.189095 | 0.981959 | 0.192570 | 5.192926  | 1.018373 | 5.288333 | 0.0023288           | 3.8123709  | 6       |
| 55      | 0.189381 | 0.981904 | 0.192871 | 5.184804  | 1.018430 | 5.280359 | 0.0023396           | 3.8045390  | 5       |
| 56      | 0.189667 | 0.981849 | 0.193173 | 5.176705  | 1.018487 | 5.272407 | 0.0023504           | 3.7967315  | 4       |
| 57      | 0.189952 | 0.981793 | 0.193475 | 5.168631  | 1.018544 | 5.264480 | 0.0023613           | 3.7889483  | 3       |
| 58      | 0.190238 | 0.981738 | 0.193777 | 5.160581  | 1.018602 | 5.256577 | 0.0023722           | 3.7811894  | 2       |
| 59      | 0.190523 | 0.981683 | 0.194078 | 5.152556  | 1.018659 | 5.248698 | 0.0023831           | 3.7734547  | 1       |
| 60      | 0.190809 | 0.981627 | 0.194380 | 5.144554  | 1.018717 | 5.240843 | 0.0023941           | 3.7657439  | 0       |

↑ 100° or 280° **Trigonometric and Involute Functions** 79° or 259° ↑

TRIGONOMETRY TABLES

↓ 11° or 191° **Trigonometric and Involute Functions** 168° or 348° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>11°-12° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.190809 | 0.981627 | 0.194380 | 5.144554  | 1.018717 | 5.240843 | 0.0023941           | 3.7657439  | 60      |
| 1       | 0.191095 | 0.981572 | 0.194682 | 5.136576  | 1.018774 | 5.233012 | 0.0024051           | 3.7580571  | 59      |
| 2       | 0.191380 | 0.981516 | 0.194984 | 5.128622  | 1.018832 | 5.225205 | 0.0024161           | 3.7503940  | 58      |
| 3       | 0.191666 | 0.981460 | 0.195286 | 5.120692  | 1.018890 | 5.217422 | 0.0024272           | 3.7427547  | 57      |
| 4       | 0.191951 | 0.981405 | 0.195588 | 5.112786  | 1.018948 | 5.209662 | 0.0024383           | 3.7351390  | 56      |
| 5       | 0.192237 | 0.981349 | 0.195890 | 5.104902  | 1.019006 | 5.201925 | 0.0024495           | 3.7275467  | 55      |
| 6       | 0.192522 | 0.981293 | 0.196192 | 5.097043  | 1.019064 | 5.194212 | 0.0024607           | 3.7199778  | 54      |
| 7       | 0.192807 | 0.981237 | 0.196494 | 5.089206  | 1.019122 | 5.186523 | 0.0024719           | 3.7124322  | 53      |
| 8       | 0.193093 | 0.981180 | 0.196796 | 5.081393  | 1.019180 | 5.178856 | 0.0024831           | 3.7049098  | 52      |
| 9       | 0.193378 | 0.981124 | 0.197099 | 5.073602  | 1.019239 | 5.171213 | 0.0024944           | 3.6974104  | 51      |
| 10      | 0.193664 | 0.981068 | 0.197401 | 5.065835  | 1.019297 | 5.163592 | 0.0025057           | 3.6899340  | 50      |
| 11      | 0.193949 | 0.981012 | 0.197703 | 5.058091  | 1.019356 | 5.155995 | 0.0025171           | 3.6824804  | 49      |
| 12      | 0.194234 | 0.980955 | 0.198005 | 5.050369  | 1.019415 | 5.148420 | 0.0025285           | 3.6750496  | 48      |
| 13      | 0.194520 | 0.980899 | 0.198308 | 5.042670  | 1.019473 | 5.140868 | 0.0025399           | 3.6676144  | 47      |
| 14      | 0.194805 | 0.980842 | 0.198610 | 5.034994  | 1.019532 | 5.133338 | 0.0025513           | 3.6602558  | 46      |
| 15      | 0.195090 | 0.980785 | 0.198912 | 5.027339  | 1.019591 | 5.125831 | 0.0025628           | 3.6528927  | 45      |
| 16      | 0.195376 | 0.980728 | 0.199215 | 5.019708  | 1.019650 | 5.118346 | 0.0025744           | 3.6455519  | 44      |
| 17      | 0.195661 | 0.980672 | 0.199517 | 5.012098  | 1.019709 | 5.110884 | 0.0025859           | 3.6382334  | 43      |
| 18      | 0.195946 | 0.980615 | 0.199820 | 5.004511  | 1.019769 | 5.103443 | 0.0025975           | 3.6309370  | 42      |
| 19      | 0.196231 | 0.980558 | 0.200122 | 4.996946  | 1.019828 | 5.096025 | 0.0026091           | 3.6236627  | 41      |
| 20      | 0.196517 | 0.980500 | 0.200425 | 4.989403  | 1.019887 | 5.088628 | 0.0026208           | 3.6164103  | 40      |
| 21      | 0.196802 | 0.980443 | 0.200727 | 4.981881  | 1.019947 | 5.081254 | 0.0026325           | 3.6091798  | 39      |
| 22      | 0.197087 | 0.980386 | 0.201030 | 4.974382  | 1.020006 | 5.073901 | 0.0026443           | 3.6019711  | 38      |
| 23      | 0.197372 | 0.980329 | 0.201333 | 4.966904  | 1.020066 | 5.066570 | 0.0026560           | 3.5947840  | 37      |
| 24      | 0.197657 | 0.980271 | 0.201635 | 4.959447  | 1.020126 | 5.059261 | 0.0026678           | 3.5876186  | 36      |
| 25      | 0.197942 | 0.980214 | 0.201938 | 4.952012  | 1.020186 | 5.051973 | 0.0026797           | 3.5804746  | 35      |
| 26      | 0.198228 | 0.980156 | 0.202241 | 4.944599  | 1.020246 | 5.044706 | 0.0026916           | 3.5733520  | 34      |
| 27      | 0.198513 | 0.980098 | 0.202544 | 4.937207  | 1.020306 | 5.037461 | 0.0027035           | 3.5662507  | 33      |
| 28      | 0.198798 | 0.980041 | 0.202847 | 4.929836  | 1.020366 | 5.030237 | 0.0027154           | 3.5591705  | 32      |
| 29      | 0.199083 | 0.979983 | 0.203149 | 4.922486  | 1.020426 | 5.023034 | 0.0027274           | 3.5521115  | 31      |
| 30      | 0.199368 | 0.979925 | 0.203452 | 4.915157  | 1.020487 | 5.015852 | 0.0027394           | 3.5450736  | 30      |
| 31      | 0.199653 | 0.979867 | 0.203755 | 4.907849  | 1.020547 | 5.008691 | 0.0027515           | 3.5380565  | 29      |
| 32      | 0.199938 | 0.979809 | 0.204058 | 4.900562  | 1.020608 | 5.001551 | 0.0027636           | 3.5310603  | 28      |
| 33      | 0.200223 | 0.979750 | 0.204361 | 4.893296  | 1.020668 | 4.994431 | 0.0027757           | 3.5240848  | 27      |
| 34      | 0.200508 | 0.979692 | 0.204664 | 4.886050  | 1.020729 | 4.987332 | 0.0027879           | 3.5171300  | 26      |
| 35      | 0.200793 | 0.979634 | 0.204967 | 4.878825  | 1.020790 | 4.980254 | 0.0028001           | 3.5101958  | 25      |
| 36      | 0.201078 | 0.979575 | 0.205271 | 4.871620  | 1.020851 | 4.973196 | 0.0028123           | 3.5032820  | 24      |
| 37      | 0.201363 | 0.979517 | 0.205574 | 4.864436  | 1.020912 | 4.966159 | 0.0028246           | 3.4963886  | 23      |
| 38      | 0.201648 | 0.979458 | 0.205877 | 4.857272  | 1.020973 | 4.959142 | 0.0028369           | 3.4895156  | 22      |
| 39      | 0.201933 | 0.979399 | 0.206180 | 4.850128  | 1.021034 | 4.952145 | 0.0028493           | 3.4826627  | 21      |
| 40      | 0.202218 | 0.979341 | 0.206483 | 4.843005  | 1.021095 | 4.945169 | 0.0028616           | 3.4758300  | 20      |
| 41      | 0.202502 | 0.979282 | 0.206787 | 4.835901  | 1.021157 | 4.938212 | 0.0028741           | 3.4690173  | 19      |
| 42      | 0.202787 | 0.979223 | 0.207090 | 4.828817  | 1.021218 | 4.931275 | 0.0028865           | 3.4622245  | 18      |
| 43      | 0.203072 | 0.979164 | 0.207393 | 4.821754  | 1.021280 | 4.924359 | 0.0028990           | 3.4554517  | 17      |
| 44      | 0.203357 | 0.979105 | 0.207697 | 4.814710  | 1.021341 | 4.917462 | 0.0029115           | 3.4486986  | 16      |
| 45      | 0.203642 | 0.979045 | 0.208000 | 4.807685  | 1.021403 | 4.910584 | 0.0029241           | 3.4419653  | 15      |
| 46      | 0.203927 | 0.978986 | 0.208304 | 4.800681  | 1.021465 | 4.903727 | 0.0029367           | 3.4352515  | 14      |
| 47      | 0.204211 | 0.978927 | 0.208607 | 4.793696  | 1.021527 | 4.896889 | 0.0029494           | 3.4285573  | 13      |
| 48      | 0.204496 | 0.978867 | 0.208911 | 4.786730  | 1.021589 | 4.890070 | 0.0029620           | 3.4218825  | 12      |
| 49      | 0.204781 | 0.978808 | 0.209214 | 4.779784  | 1.021651 | 4.883271 | 0.0029747           | 3.4152272  | 11      |
| 50      | 0.205065 | 0.978748 | 0.209518 | 4.772857  | 1.021713 | 4.876491 | 0.0029875           | 3.4085911  | 10      |
| 51      | 0.205350 | 0.978689 | 0.209822 | 4.765949  | 1.021776 | 4.869730 | 0.0030003           | 3.4019742  | 9       |
| 52      | 0.205635 | 0.978629 | 0.210126 | 4.759060  | 1.021838 | 4.862988 | 0.0030131           | 3.3953764  | 8       |
| 53      | 0.205920 | 0.978569 | 0.210429 | 4.752191  | 1.021900 | 4.856266 | 0.0030260           | 3.3887977  | 7       |
| 54      | 0.206204 | 0.978509 | 0.210733 | 4.745340  | 1.021963 | 4.849562 | 0.0030389           | 3.3822379  | 6       |
| 55      | 0.206489 | 0.978449 | 0.211037 | 4.738508  | 1.022026 | 4.842877 | 0.0030518           | 3.3756971  | 5       |
| 56      | 0.206773 | 0.978389 | 0.211341 | 4.731695  | 1.022089 | 4.836211 | 0.0030648           | 3.3691750  | 4       |
| 57      | 0.207058 | 0.978329 | 0.211645 | 4.724901  | 1.022151 | 4.829564 | 0.0030778           | 3.3626717  | 3       |
| 58      | 0.207343 | 0.978268 | 0.211949 | 4.718126  | 1.022214 | 4.822936 | 0.0030908           | 3.3561870  | 2       |
| 59      | 0.207627 | 0.978208 | 0.212253 | 4.711369  | 1.022277 | 4.816326 | 0.0031039           | 3.3497209  | 1       |
| 60      | 0.207912 | 0.978148 | 0.212557 | 4.704630  | 1.022341 | 4.809734 | 0.0031171           | 3.3432733  | 0       |

↑ 101° or 281°

78° or 258° ↑

TRIGONOMETRY TABLES

↓ 12° or 192° Trigonometric and Involute Functions 167° or 347° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>12°-13° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.207912 | 0.978148 | 0.212557 | 4.704630  | 1.022341 | 4.809734 | 0.0031171           | 3.3432733  | 60      |
| 1       | 0.208196 | 0.978087 | 0.212861 | 4.697910  | 1.022404 | 4.803161 | 0.0031302           | 3.3368441  | 59      |
| 2       | 0.208481 | 0.978026 | 0.213165 | 4.691208  | 1.022467 | 4.796607 | 0.0031434           | 3.3304333  | 58      |
| 3       | 0.208765 | 0.977966 | 0.213469 | 4.684525  | 1.022531 | 4.790070 | 0.0031566           | 3.3240407  | 57      |
| 4       | 0.209050 | 0.977905 | 0.213773 | 4.677860  | 1.022594 | 4.783552 | 0.0031699           | 3.3176663  | 56      |
| 5       | 0.209334 | 0.977844 | 0.214077 | 4.671212  | 1.022658 | 4.777052 | 0.0031832           | 3.3113107  | 55      |
| 6       | 0.209619 | 0.977783 | 0.214381 | 4.664583  | 1.022722 | 4.770570 | 0.0031966           | 3.3049718  | 54      |
| 7       | 0.209903 | 0.977722 | 0.214686 | 4.657972  | 1.022785 | 4.764106 | 0.0032100           | 3.2986515  | 53      |
| 8       | 0.210187 | 0.977661 | 0.214990 | 4.651379  | 1.022849 | 4.757660 | 0.0032234           | 3.2923491  | 52      |
| 9       | 0.210472 | 0.977600 | 0.215294 | 4.644803  | 1.022913 | 4.751231 | 0.0032369           | 3.2860645  | 51      |
| 10      | 0.210756 | 0.977539 | 0.215599 | 4.638246  | 1.022977 | 4.744821 | 0.0032504           | 3.2797977  | 50      |
| 11      | 0.211040 | 0.977477 | 0.215903 | 4.631706  | 1.023042 | 4.738428 | 0.0032639           | 3.2735486  | 49      |
| 12      | 0.211325 | 0.977416 | 0.216208 | 4.625183  | 1.023106 | 4.732052 | 0.0032775           | 3.2673170  | 48      |
| 13      | 0.211609 | 0.977354 | 0.216512 | 4.618678  | 1.023170 | 4.725695 | 0.0032911           | 3.2611030  | 47      |
| 14      | 0.211893 | 0.977293 | 0.216817 | 4.612191  | 1.023235 | 4.719354 | 0.0033048           | 3.2549064  | 46      |
| 15      | 0.212178 | 0.977231 | 0.217121 | 4.605721  | 1.023299 | 4.713031 | 0.0033185           | 3.2487273  | 45      |
| 16      | 0.212462 | 0.977169 | 0.217426 | 4.599268  | 1.023364 | 4.706726 | 0.0033322           | 3.2425654  | 44      |
| 17      | 0.212746 | 0.977108 | 0.217731 | 4.592832  | 1.023429 | 4.700437 | 0.0033460           | 3.2364208  | 43      |
| 18      | 0.213030 | 0.977046 | 0.218035 | 4.586414  | 1.023494 | 4.694166 | 0.0033598           | 3.2302933  | 42      |
| 19      | 0.213315 | 0.976984 | 0.218340 | 4.580013  | 1.023559 | 4.687912 | 0.0033736           | 3.2241830  | 41      |
| 20      | 0.213599 | 0.976921 | 0.218645 | 4.573629  | 1.023624 | 4.681675 | 0.0033875           | 3.2180896  | 40      |
| 21      | 0.213883 | 0.976859 | 0.218950 | 4.567261  | 1.023689 | 4.675455 | 0.0034014           | 3.2120133  | 39      |
| 22      | 0.214167 | 0.976797 | 0.219254 | 4.560911  | 1.023754 | 4.669252 | 0.0034154           | 3.2059538  | 38      |
| 23      | 0.214451 | 0.976735 | 0.219559 | 4.554578  | 1.023819 | 4.663065 | 0.0034294           | 3.1999112  | 37      |
| 24      | 0.214735 | 0.976672 | 0.219864 | 4.548261  | 1.023885 | 4.656896 | 0.0034434           | 3.1938853  | 36      |
| 25      | 0.215019 | 0.976610 | 0.220169 | 4.541961  | 1.023950 | 4.650743 | 0.0034575           | 3.1878762  | 35      |
| 26      | 0.215303 | 0.976547 | 0.220474 | 4.535677  | 1.024016 | 4.644606 | 0.0034716           | 3.1818836  | 34      |
| 27      | 0.215588 | 0.976485 | 0.220779 | 4.529410  | 1.024082 | 4.638487 | 0.0034858           | 3.1759076  | 33      |
| 28      | 0.215872 | 0.976422 | 0.221084 | 4.523160  | 1.024148 | 4.632384 | 0.0035000           | 3.1699481  | 32      |
| 29      | 0.216156 | 0.976359 | 0.221389 | 4.516926  | 1.024214 | 4.626297 | 0.0035142           | 3.1640050  | 31      |
| 30      | 0.216440 | 0.976296 | 0.221695 | 4.510709  | 1.024280 | 4.620226 | 0.0035285           | 3.1580783  | 30      |
| 31      | 0.216724 | 0.976233 | 0.222000 | 4.504507  | 1.024346 | 4.614172 | 0.0035428           | 3.1521679  | 29      |
| 32      | 0.217008 | 0.976170 | 0.222305 | 4.498322  | 1.024412 | 4.608134 | 0.0035572           | 3.1462737  | 28      |
| 33      | 0.217292 | 0.976107 | 0.222610 | 4.492153  | 1.024478 | 4.602113 | 0.0035716           | 3.1403957  | 27      |
| 34      | 0.217575 | 0.976044 | 0.222916 | 4.486000  | 1.024544 | 4.596107 | 0.0035860           | 3.1345338  | 26      |
| 35      | 0.217859 | 0.975980 | 0.223221 | 4.479864  | 1.024611 | 4.590117 | 0.0036005           | 3.1286879  | 25      |
| 36      | 0.218143 | 0.975917 | 0.223526 | 4.473743  | 1.024678 | 4.584144 | 0.0036150           | 3.1228526  | 24      |
| 37      | 0.218427 | 0.975853 | 0.223832 | 4.467638  | 1.024744 | 4.578186 | 0.0036296           | 3.1170440  | 23      |
| 38      | 0.218711 | 0.975790 | 0.224137 | 4.461549  | 1.024811 | 4.572244 | 0.0036441           | 3.1112458  | 22      |
| 39      | 0.218995 | 0.975726 | 0.224443 | 4.455476  | 1.024878 | 4.566318 | 0.0036588           | 3.1054635  | 21      |
| 40      | 0.219279 | 0.975662 | 0.224748 | 4.449418  | 1.024945 | 4.560408 | 0.0036735           | 3.0996968  | 20      |
| 41      | 0.219562 | 0.975598 | 0.225054 | 4.443376  | 1.025012 | 4.554513 | 0.0036882           | 3.0939458  | 19      |
| 42      | 0.219846 | 0.975535 | 0.225360 | 4.437350  | 1.025079 | 4.548634 | 0.0037029           | 3.0882104  | 18      |
| 43      | 0.220130 | 0.975471 | 0.225665 | 4.431339  | 1.025146 | 4.542771 | 0.0037177           | 3.0824906  | 17      |
| 44      | 0.220414 | 0.975406 | 0.225971 | 4.425344  | 1.025214 | 4.536923 | 0.0037325           | 3.0767862  | 16      |
| 45      | 0.220697 | 0.975342 | 0.226277 | 4.419364  | 1.025281 | 4.531090 | 0.0037474           | 3.0710972  | 15      |
| 46      | 0.220981 | 0.975278 | 0.226583 | 4.413400  | 1.025349 | 4.525273 | 0.0037623           | 3.0654236  | 14      |
| 47      | 0.221265 | 0.975214 | 0.226889 | 4.407450  | 1.025416 | 4.519471 | 0.0037773           | 3.0597653  | 13      |
| 48      | 0.221548 | 0.975151 | 0.227194 | 4.401516  | 1.025484 | 4.513684 | 0.0037923           | 3.0541223  | 12      |
| 49      | 0.221832 | 0.975085 | 0.227500 | 4.395598  | 1.025552 | 4.507913 | 0.0038073           | 3.0484944  | 11      |
| 50      | 0.222116 | 0.975020 | 0.227806 | 4.389694  | 1.025620 | 4.502157 | 0.0038224           | 3.0428816  | 10      |
| 51      | 0.222399 | 0.974956 | 0.228112 | 4.383805  | 1.025688 | 4.496415 | 0.0038375           | 3.0372838  | 9       |
| 52      | 0.222683 | 0.974891 | 0.228418 | 4.377932  | 1.025756 | 4.490689 | 0.0038527           | 3.0317011  | 8       |
| 53      | 0.222967 | 0.974826 | 0.228724 | 4.372073  | 1.025824 | 4.484977 | 0.0038679           | 3.0261333  | 7       |
| 54      | 0.223250 | 0.974761 | 0.229031 | 4.366229  | 1.025892 | 4.479281 | 0.0038831           | 3.0205804  | 6       |
| 55      | 0.223534 | 0.974696 | 0.229337 | 4.360400  | 1.025961 | 4.473599 | 0.0038984           | 3.0150424  | 5       |
| 56      | 0.223817 | 0.974631 | 0.229643 | 4.354586  | 1.026029 | 4.467932 | 0.0039137           | 3.0095190  | 4       |
| 57      | 0.224101 | 0.974566 | 0.229949 | 4.348787  | 1.026098 | 4.462280 | 0.0039291           | 3.0040104  | 3       |
| 58      | 0.224384 | 0.974501 | 0.230255 | 4.343002  | 1.026166 | 4.456643 | 0.0039445           | 2.9985165  | 2       |
| 59      | 0.224668 | 0.974435 | 0.230562 | 4.337232  | 1.026235 | 4.451020 | 0.0039599           | 2.9930352  | 1       |
| 60      | 0.224951 | 0.974370 | 0.230868 | 4.331476  | 1.026304 | 4.445411 | 0.0039754           | 2.9875724  | 0       |

↑ 102° or 282° 77° or 257° ↑

↓ 13° or 193° **Trigonometric and Involute Functions** 166° or 346° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>13°-14° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.224951 | 0.974370 | 0.230868 | 4.331476  | 1.026304 | 4.445411 | 0.0039754           | 2.9875724  | 60      |
| 1       | 0.225234 | 0.974305 | 0.231175 | 4.325735  | 1.026373 | 4.439818 | 0.0039909           | 2.9821220  | 59      |
| 2       | 0.225518 | 0.974239 | 0.231481 | 4.320008  | 1.026442 | 4.434238 | 0.0040065           | 2.9766861  | 58      |
| 3       | 0.225801 | 0.974173 | 0.231788 | 4.314295  | 1.026511 | 4.428673 | 0.0040221           | 2.9712646  | 57      |
| 4       | 0.226085 | 0.974108 | 0.232094 | 4.308597  | 1.026581 | 4.423122 | 0.0040377           | 2.9658574  | 56      |
| 5       | 0.226368 | 0.974042 | 0.232401 | 4.302914  | 1.026650 | 4.417586 | 0.0040534           | 2.9604645  | 55      |
| 6       | 0.226651 | 0.973976 | 0.232707 | 4.297244  | 1.026719 | 4.412064 | 0.0040692           | 2.9550858  | 54      |
| 7       | 0.226935 | 0.973910 | 0.233014 | 4.291589  | 1.026789 | 4.406556 | 0.0040849           | 2.9497212  | 53      |
| 8       | 0.227218 | 0.973844 | 0.233321 | 4.285947  | 1.026859 | 4.401062 | 0.0041007           | 2.9443708  | 52      |
| 9       | 0.227501 | 0.973778 | 0.233627 | 4.280320  | 1.026928 | 4.395582 | 0.0041166           | 2.9390344  | 51      |
| 10      | 0.227784 | 0.973712 | 0.233934 | 4.274707  | 1.026998 | 4.390116 | 0.0041325           | 2.9337119  | 50      |
| 11      | 0.228068 | 0.973645 | 0.234241 | 4.269107  | 1.027068 | 4.384664 | 0.0041484           | 2.9284035  | 49      |
| 12      | 0.228351 | 0.973579 | 0.234548 | 4.263522  | 1.027138 | 4.379226 | 0.0041644           | 2.9231089  | 48      |
| 13      | 0.228634 | 0.973512 | 0.234855 | 4.257950  | 1.027208 | 4.373801 | 0.0041804           | 2.9178281  | 47      |
| 14      | 0.228917 | 0.973446 | 0.235162 | 4.252392  | 1.027278 | 4.368391 | 0.0041965           | 2.9125612  | 46      |
| 15      | 0.229200 | 0.973379 | 0.235469 | 4.246848  | 1.027349 | 4.362994 | 0.0042126           | 2.9073080  | 45      |
| 16      | 0.229484 | 0.973313 | 0.235776 | 4.241318  | 1.027419 | 4.357611 | 0.0042288           | 2.9020684  | 44      |
| 17      | 0.229767 | 0.973246 | 0.236083 | 4.235801  | 1.027490 | 4.352242 | 0.0042450           | 2.8968425  | 43      |
| 18      | 0.230050 | 0.973179 | 0.236390 | 4.230298  | 1.027560 | 4.346868 | 0.0042612           | 2.8916302  | 42      |
| 19      | 0.230333 | 0.973112 | 0.236697 | 4.224808  | 1.027631 | 4.341544 | 0.0042775           | 2.8864313  | 41      |
| 20      | 0.230616 | 0.973045 | 0.237004 | 4.219332  | 1.027702 | 4.336215 | 0.0042938           | 2.8812460  | 40      |
| 21      | 0.230899 | 0.972978 | 0.237312 | 4.213869  | 1.027773 | 4.330900 | 0.0043101           | 2.8760741  | 39      |
| 22      | 0.231182 | 0.972911 | 0.237619 | 4.208420  | 1.027844 | 4.325598 | 0.0043266           | 2.8709156  | 38      |
| 23      | 0.231465 | 0.972843 | 0.237926 | 4.202983  | 1.027915 | 4.320309 | 0.0043430           | 2.8657704  | 37      |
| 24      | 0.231748 | 0.972776 | 0.238234 | 4.197561  | 1.027986 | 4.315034 | 0.0043595           | 2.8606384  | 36      |
| 25      | 0.232031 | 0.972708 | 0.238541 | 4.192151  | 1.028057 | 4.309772 | 0.0043760           | 2.8555197  | 35      |
| 26      | 0.232314 | 0.972641 | 0.238848 | 4.186755  | 1.028129 | 4.304523 | 0.0043926           | 2.8504142  | 34      |
| 27      | 0.232597 | 0.972573 | 0.239156 | 4.181371  | 1.028200 | 4.299287 | 0.0044092           | 2.8453218  | 33      |
| 28      | 0.232880 | 0.972506 | 0.239464 | 4.176001  | 1.028272 | 4.294064 | 0.0044259           | 2.8402425  | 32      |
| 29      | 0.233163 | 0.972438 | 0.239771 | 4.170644  | 1.028343 | 4.288854 | 0.0044426           | 2.8351762  | 31      |
| 30      | 0.233445 | 0.972370 | 0.240079 | 4.165300  | 1.028415 | 4.283658 | 0.0044593           | 2.8301229  | 30      |
| 31      | 0.233728 | 0.972302 | 0.240386 | 4.159969  | 1.028487 | 4.278474 | 0.0044761           | 2.8250825  | 29      |
| 32      | 0.234011 | 0.972234 | 0.240694 | 4.154650  | 1.028559 | 4.273303 | 0.0044929           | 2.8200550  | 28      |
| 33      | 0.234294 | 0.972166 | 0.241002 | 4.149345  | 1.028631 | 4.268145 | 0.0045098           | 2.8150404  | 27      |
| 34      | 0.234577 | 0.972098 | 0.241310 | 4.144052  | 1.028703 | 4.263000 | 0.0045267           | 2.8100385  | 26      |
| 35      | 0.234859 | 0.972029 | 0.241618 | 4.138772  | 1.028776 | 4.257867 | 0.0045437           | 2.8050494  | 25      |
| 36      | 0.235142 | 0.971961 | 0.241925 | 4.133505  | 1.028848 | 4.252747 | 0.0045607           | 2.8000730  | 24      |
| 37      | 0.235425 | 0.971893 | 0.242233 | 4.128250  | 1.028920 | 4.247640 | 0.0045777           | 2.7951093  | 23      |
| 38      | 0.235708 | 0.971824 | 0.242541 | 4.123008  | 1.028993 | 4.242546 | 0.0045948           | 2.7901581  | 22      |
| 39      | 0.235990 | 0.971755 | 0.242849 | 4.117778  | 1.029066 | 4.237464 | 0.0046120           | 2.7852195  | 21      |
| 40      | 0.236273 | 0.971687 | 0.243157 | 4.112561  | 1.029138 | 4.232394 | 0.0046291           | 2.7802934  | 20      |
| 41      | 0.236556 | 0.971618 | 0.243466 | 4.107357  | 1.029211 | 4.227337 | 0.0046464           | 2.7753798  | 19      |
| 42      | 0.236838 | 0.971549 | 0.243774 | 4.102165  | 1.029284 | 4.222293 | 0.0046636           | 2.7704786  | 18      |
| 43      | 0.237121 | 0.971480 | 0.244082 | 4.096985  | 1.029357 | 4.217261 | 0.0046809           | 2.7655898  | 17      |
| 44      | 0.237403 | 0.971411 | 0.244390 | 4.091818  | 1.029430 | 4.212241 | 0.0046983           | 2.7607133  | 16      |
| 45      | 0.237686 | 0.971342 | 0.244698 | 4.086663  | 1.029503 | 4.207233 | 0.0047157           | 2.7558491  | 15      |
| 46      | 0.237968 | 0.971273 | 0.245007 | 4.081520  | 1.029577 | 4.202238 | 0.0047331           | 2.7509972  | 14      |
| 47      | 0.238251 | 0.971204 | 0.245315 | 4.076389  | 1.029650 | 4.197255 | 0.0047506           | 2.7461574  | 13      |
| 48      | 0.238533 | 0.971134 | 0.245624 | 4.071271  | 1.029724 | 4.192284 | 0.0047681           | 2.7413298  | 12      |
| 49      | 0.238816 | 0.971065 | 0.245932 | 4.066164  | 1.029797 | 4.187325 | 0.0047857           | 2.7365143  | 11      |
| 50      | 0.239098 | 0.970995 | 0.246241 | 4.061070  | 1.029871 | 4.182378 | 0.0048033           | 2.7317109  | 10      |
| 51      | 0.239381 | 0.970926 | 0.246549 | 4.055988  | 1.029945 | 4.177444 | 0.0048210           | 2.7269195  | 9       |
| 52      | 0.239663 | 0.970856 | 0.246858 | 4.050917  | 1.030019 | 4.172521 | 0.0048387           | 2.7221401  | 8       |
| 53      | 0.239946 | 0.970786 | 0.247166 | 4.045859  | 1.030093 | 4.167610 | 0.0048564           | 2.7173726  | 7       |
| 54      | 0.240228 | 0.970716 | 0.247475 | 4.040813  | 1.030167 | 4.162711 | 0.0048742           | 2.7126170  | 6       |
| 55      | 0.240510 | 0.970647 | 0.247784 | 4.035778  | 1.030241 | 4.157824 | 0.0048921           | 2.7078732  | 5       |
| 56      | 0.240793 | 0.970577 | 0.248092 | 4.030755  | 1.030315 | 4.152949 | 0.0049099           | 2.7031413  | 4       |
| 57      | 0.241075 | 0.970506 | 0.248401 | 4.025744  | 1.030390 | 4.148086 | 0.0049279           | 2.6984211  | 3       |
| 58      | 0.241357 | 0.970436 | 0.248710 | 4.020745  | 1.030464 | 4.143234 | 0.0049458           | 2.6937126  | 2       |
| 59      | 0.241640 | 0.970366 | 0.249019 | 4.015757  | 1.030539 | 4.138394 | 0.0049638           | 2.6890158  | 1       |
| 60      | 0.241922 | 0.970296 | 0.249328 | 4.010781  | 1.030614 | 4.133565 | 0.0049819           | 2.6843307  | 0       |

↑ 103° or 283° **Trigonometric and Involute Functions** 76° or 256° ↑

TRIGONOMETRY TABLES

↓ 14° or 194° Trigonometric and Involute Functions 165° or 345° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>14°-15° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.241922 | 0.970296 | 0.249328 | 4.010781  | 1.030614 | 4.133565 | 0.0049819           | 2.6843307  | 60      |
| 1       | 0.242204 | 0.970225 | 0.249637 | 4.005817  | 1.030688 | 4.128749 | 0.0050000           | 2.6796572  | 59      |
| 2       | 0.242486 | 0.970155 | 0.249946 | 4.000864  | 1.030763 | 4.123943 | 0.0050182           | 2.6749952  | 58      |
| 3       | 0.242769 | 0.970084 | 0.250255 | 3.995922  | 1.030838 | 4.119150 | 0.0050364           | 2.6703447  | 57      |
| 4       | 0.243051 | 0.970014 | 0.250564 | 3.990992  | 1.030913 | 4.114368 | 0.0050546           | 2.6657057  | 56      |
| 5       | 0.243333 | 0.969943 | 0.250873 | 3.986074  | 1.030989 | 4.109597 | 0.0050729           | 2.6610781  | 55      |
| 6       | 0.243615 | 0.969872 | 0.251183 | 3.981167  | 1.031064 | 4.104837 | 0.0050912           | 2.6564620  | 54      |
| 7       | 0.243897 | 0.969801 | 0.251492 | 3.976271  | 1.031139 | 4.100089 | 0.0051096           | 2.6518572  | 53      |
| 8       | 0.244179 | 0.969730 | 0.251801 | 3.971387  | 1.031215 | 4.095353 | 0.0051280           | 2.6472636  | 52      |
| 9       | 0.244461 | 0.969659 | 0.252111 | 3.966514  | 1.031290 | 4.090627 | 0.0051465           | 2.6426814  | 51      |
| 10      | 0.244743 | 0.969588 | 0.252420 | 3.961652  | 1.031366 | 4.085913 | 0.0051650           | 2.6381104  | 50      |
| 11      | 0.245025 | 0.969517 | 0.252729 | 3.956801  | 1.031442 | 4.081210 | 0.0051835           | 2.6335506  | 49      |
| 12      | 0.245307 | 0.969445 | 0.253039 | 3.951962  | 1.031518 | 4.076518 | 0.0052021           | 2.6290019  | 48      |
| 13      | 0.245589 | 0.969374 | 0.253348 | 3.947133  | 1.031594 | 4.071837 | 0.0052208           | 2.6245464  | 47      |
| 14      | 0.245871 | 0.969302 | 0.253658 | 3.942316  | 1.031670 | 4.067168 | 0.0052395           | 2.6199379  | 46      |
| 15      | 0.246153 | 0.969231 | 0.253968 | 3.937509  | 1.031746 | 4.062509 | 0.0052582           | 2.6154225  | 45      |
| 16      | 0.246435 | 0.969159 | 0.254277 | 3.932714  | 1.031822 | 4.057862 | 0.0052770           | 2.6109118  | 44      |
| 17      | 0.246717 | 0.969088 | 0.254587 | 3.927930  | 1.031899 | 4.053225 | 0.0052958           | 2.6064246  | 43      |
| 18      | 0.246999 | 0.969016 | 0.254897 | 3.923156  | 1.031975 | 4.048599 | 0.0053147           | 2.6019421  | 42      |
| 19      | 0.247281 | 0.968944 | 0.255207 | 3.918394  | 1.032052 | 4.043984 | 0.0053336           | 2.5974704  | 41      |
| 20      | 0.247563 | 0.968872 | 0.255516 | 3.913642  | 1.032128 | 4.039380 | 0.0053526           | 2.5930096  | 40      |
| 21      | 0.247845 | 0.968800 | 0.255826 | 3.908901  | 1.032205 | 4.034787 | 0.0053716           | 2.5885595  | 39      |
| 22      | 0.248126 | 0.968728 | 0.256136 | 3.904171  | 1.032282 | 4.030205 | 0.0053907           | 2.5841203  | 38      |
| 23      | 0.248408 | 0.968655 | 0.256446 | 3.899452  | 1.032359 | 4.025633 | 0.0054098           | 2.5796918  | 37      |
| 24      | 0.248690 | 0.968583 | 0.256756 | 3.894743  | 1.032436 | 4.021072 | 0.0054289           | 2.5752739  | 36      |
| 25      | 0.248972 | 0.968511 | 0.257066 | 3.890045  | 1.032513 | 4.016522 | 0.0054481           | 2.5708668  | 35      |
| 26      | 0.249253 | 0.968438 | 0.257377 | 3.885357  | 1.032590 | 4.011982 | 0.0054674           | 2.5664702  | 34      |
| 27      | 0.249535 | 0.968366 | 0.257687 | 3.880681  | 1.032668 | 4.007453 | 0.0054867           | 2.5620843  | 33      |
| 28      | 0.249817 | 0.968293 | 0.257997 | 3.876014  | 1.032745 | 4.002935 | 0.0055060           | 2.5577088  | 32      |
| 29      | 0.250098 | 0.968220 | 0.258307 | 3.871358  | 1.032823 | 3.998427 | 0.0055254           | 2.5533439  | 31      |
| 30      | 0.250380 | 0.968148 | 0.258618 | 3.866713  | 1.032900 | 3.993929 | 0.0055448           | 2.5489895  | 30      |
| 31      | 0.250662 | 0.968075 | 0.258928 | 3.862078  | 1.032978 | 3.989442 | 0.0055643           | 2.5446455  | 29      |
| 32      | 0.250943 | 0.968002 | 0.259238 | 3.857454  | 1.033056 | 3.984965 | 0.0055838           | 2.5403119  | 28      |
| 33      | 0.251225 | 0.967929 | 0.259549 | 3.852840  | 1.033134 | 3.980499 | 0.0056034           | 2.5359887  | 27      |
| 34      | 0.251506 | 0.967856 | 0.259859 | 3.848236  | 1.033212 | 3.976043 | 0.0056230           | 2.5316758  | 26      |
| 35      | 0.251788 | 0.967782 | 0.260170 | 3.843642  | 1.033290 | 3.971597 | 0.0056427           | 2.5273732  | 25      |
| 36      | 0.252069 | 0.967709 | 0.260480 | 3.839059  | 1.033368 | 3.967162 | 0.0056624           | 2.5230809  | 24      |
| 37      | 0.252351 | 0.967636 | 0.260791 | 3.834486  | 1.033447 | 3.962737 | 0.0056822           | 2.5187988  | 23      |
| 38      | 0.252632 | 0.967562 | 0.261102 | 3.829923  | 1.033525 | 3.958322 | 0.0057020           | 2.5145268  | 22      |
| 39      | 0.252914 | 0.967489 | 0.261413 | 3.825371  | 1.033604 | 3.953917 | 0.0057218           | 2.5102651  | 21      |
| 40      | 0.253195 | 0.967415 | 0.261723 | 3.820828  | 1.033682 | 3.949522 | 0.0057417           | 2.5060134  | 20      |
| 41      | 0.253477 | 0.967342 | 0.262034 | 3.816296  | 1.033761 | 3.945138 | 0.0057617           | 2.5017719  | 19      |
| 42      | 0.253758 | 0.967268 | 0.262345 | 3.811773  | 1.033840 | 3.940763 | 0.0057817           | 2.4975404  | 18      |
| 43      | 0.254039 | 0.967194 | 0.262656 | 3.807261  | 1.033919 | 3.936399 | 0.0058017           | 2.4933189  | 17      |
| 44      | 0.254321 | 0.967120 | 0.262967 | 3.802759  | 1.033998 | 3.932044 | 0.0058218           | 2.4891074  | 16      |
| 45      | 0.254602 | 0.967046 | 0.263278 | 3.798266  | 1.034077 | 3.927700 | 0.0058420           | 2.4849058  | 15      |
| 46      | 0.254883 | 0.966972 | 0.263589 | 3.793784  | 1.034156 | 3.923365 | 0.0058622           | 2.4807142  | 14      |
| 47      | 0.255165 | 0.966898 | 0.263900 | 3.789311  | 1.034236 | 3.919040 | 0.0058824           | 2.4765324  | 13      |
| 48      | 0.255446 | 0.966823 | 0.264211 | 3.784848  | 1.034315 | 3.914725 | 0.0059027           | 2.4723605  | 12      |
| 49      | 0.255727 | 0.966749 | 0.264523 | 3.780395  | 1.034395 | 3.910420 | 0.0059230           | 2.4681984  | 11      |
| 50      | 0.256008 | 0.966675 | 0.264834 | 3.775952  | 1.034474 | 3.906125 | 0.0059434           | 2.4640461  | 10      |
| 51      | 0.256289 | 0.966600 | 0.265145 | 3.771518  | 1.034554 | 3.901840 | 0.0059638           | 2.4599035  | 9       |
| 52      | 0.256571 | 0.966526 | 0.265457 | 3.767095  | 1.034634 | 3.897564 | 0.0059843           | 2.4557707  | 8       |
| 53      | 0.256852 | 0.966451 | 0.265768 | 3.762681  | 1.034714 | 3.893298 | 0.0060048           | 2.4516475  | 7       |
| 54      | 0.257133 | 0.966376 | 0.266079 | 3.758276  | 1.034794 | 3.889041 | 0.0060254           | 2.4475340  | 6       |
| 55      | 0.257414 | 0.966301 | 0.266391 | 3.753882  | 1.034874 | 3.884794 | 0.0060460           | 2.4434301  | 5       |
| 56      | 0.257695 | 0.966226 | 0.266702 | 3.749496  | 1.034954 | 3.880557 | 0.0060667           | 2.4393358  | 4       |
| 57      | 0.257976 | 0.966151 | 0.267014 | 3.745121  | 1.035035 | 3.876329 | 0.0060874           | 2.4352511  | 3       |
| 58      | 0.258257 | 0.966076 | 0.267326 | 3.740755  | 1.035115 | 3.872111 | 0.0061081           | 2.4311759  | 2       |
| 59      | 0.258538 | 0.966001 | 0.267637 | 3.736398  | 1.035196 | 3.867903 | 0.0061289           | 2.4271101  | 1       |
| 60      | 0.258819 | 0.965926 | 0.267949 | 3.732051  | 1.035276 | 3.863703 | 0.0061498           | 2.4230539  | 0       |

↑ 104° or 284° 75° or 255° ↑

↓ 15° or 195° **Trigonometric and Involute Functions** 164° or 344° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>15°-16° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.258819 | 0.965926 | 0.267949 | 3.732051  | 1.035276 | 3.863703 | 0.0061498           | 2.4230539  | 60      |
| 1       | 0.259100 | 0.965850 | 0.268261 | 3.727713  | 1.035357 | 3.859514 | 0.0061707           | 2.4190070  | 59      |
| 2       | 0.259381 | 0.965775 | 0.268573 | 3.723385  | 1.035438 | 3.855333 | 0.0061917           | 2.4149696  | 58      |
| 3       | 0.259662 | 0.965700 | 0.268885 | 3.719066  | 1.035519 | 3.851162 | 0.0062127           | 2.4109415  | 57      |
| 4       | 0.259943 | 0.965624 | 0.269197 | 3.714756  | 1.035600 | 3.847001 | 0.0062337           | 2.4069228  | 56      |
| 5       | 0.260224 | 0.965548 | 0.269509 | 3.710456  | 1.035681 | 3.842848 | 0.0062548           | 2.4029133  | 55      |
| 6       | 0.260505 | 0.965473 | 0.269821 | 3.706165  | 1.035762 | 3.838705 | 0.0062760           | 2.3989132  | 54      |
| 7       | 0.260785 | 0.965397 | 0.270133 | 3.701883  | 1.035843 | 3.834571 | 0.0062972           | 2.3949222  | 53      |
| 8       | 0.261066 | 0.965321 | 0.270445 | 3.697610  | 1.035925 | 3.830447 | 0.0063184           | 2.3909405  | 52      |
| 9       | 0.261347 | 0.965245 | 0.270757 | 3.693347  | 1.036006 | 3.826331 | 0.0063397           | 2.3869680  | 51      |
| 10      | 0.261628 | 0.965169 | 0.271069 | 3.689093  | 1.036088 | 3.822225 | 0.0063611           | 2.3830046  | 50      |
| 11      | 0.261908 | 0.965093 | 0.271382 | 3.684848  | 1.036170 | 3.818128 | 0.0063825           | 2.3790503  | 49      |
| 12      | 0.262189 | 0.965016 | 0.271694 | 3.680611  | 1.036252 | 3.814040 | 0.0064039           | 2.3751052  | 48      |
| 13      | 0.262470 | 0.964940 | 0.272006 | 3.676384  | 1.036334 | 3.809961 | 0.0064254           | 2.3711691  | 47      |
| 14      | 0.262751 | 0.964864 | 0.272319 | 3.672166  | 1.036416 | 3.805891 | 0.0064470           | 2.3672420  | 46      |
| 15      | 0.263031 | 0.964787 | 0.272631 | 3.667958  | 1.036498 | 3.801838 | 0.0064686           | 2.3633239  | 45      |
| 16      | 0.263312 | 0.964711 | 0.272944 | 3.663758  | 1.036580 | 3.797778 | 0.0064902           | 2.3594148  | 44      |
| 17      | 0.263592 | 0.964634 | 0.273256 | 3.659566  | 1.036662 | 3.793735 | 0.0065119           | 2.3555147  | 43      |
| 18      | 0.263873 | 0.964557 | 0.273569 | 3.655384  | 1.036745 | 3.789701 | 0.0065337           | 2.3516234  | 42      |
| 19      | 0.264154 | 0.964481 | 0.273882 | 3.651211  | 1.036827 | 3.785676 | 0.0065555           | 2.3477410  | 41      |
| 20      | 0.264434 | 0.964404 | 0.274194 | 3.647047  | 1.036910 | 3.781660 | 0.0065773           | 2.3438675  | 40      |
| 21      | 0.264715 | 0.964327 | 0.274507 | 3.642891  | 1.036993 | 3.777652 | 0.0065992           | 2.3400029  | 39      |
| 22      | 0.264995 | 0.964250 | 0.274820 | 3.638744  | 1.037076 | 3.773653 | 0.0066211           | 2.3361470  | 38      |
| 23      | 0.265276 | 0.964173 | 0.275133 | 3.634606  | 1.037159 | 3.769664 | 0.0066431           | 2.3322999  | 37      |
| 24      | 0.265556 | 0.964095 | 0.275446 | 3.630477  | 1.037242 | 3.765682 | 0.0066652           | 2.3284615  | 36      |
| 25      | 0.265837 | 0.964018 | 0.275759 | 3.626357  | 1.037325 | 3.761710 | 0.0066873           | 2.3246318  | 35      |
| 26      | 0.266117 | 0.963941 | 0.276072 | 3.622245  | 1.037408 | 3.757746 | 0.0067094           | 2.3208108  | 34      |
| 27      | 0.266397 | 0.963863 | 0.276385 | 3.618141  | 1.037492 | 3.753791 | 0.0067316           | 2.3169985  | 33      |
| 28      | 0.266678 | 0.963786 | 0.276698 | 3.614047  | 1.037575 | 3.749845 | 0.0067539           | 2.3131948  | 32      |
| 29      | 0.266958 | 0.963708 | 0.277011 | 3.609961  | 1.037659 | 3.745907 | 0.0067762           | 2.3093997  | 31      |
| 30      | 0.267238 | 0.963630 | 0.277325 | 3.605884  | 1.037742 | 3.741978 | 0.0067985           | 2.3056132  | 30      |
| 31      | 0.267519 | 0.963553 | 0.277638 | 3.601815  | 1.037826 | 3.738057 | 0.0068209           | 2.3018352  | 29      |
| 32      | 0.267799 | 0.963475 | 0.277951 | 3.597754  | 1.037910 | 3.734145 | 0.0068434           | 2.2980658  | 28      |
| 33      | 0.268079 | 0.963397 | 0.278265 | 3.593702  | 1.037994 | 3.730241 | 0.0068659           | 2.2943048  | 27      |
| 34      | 0.268359 | 0.963319 | 0.278578 | 3.589659  | 1.038078 | 3.726346 | 0.0068884           | 2.2905523  | 26      |
| 35      | 0.268640 | 0.963241 | 0.278891 | 3.585624  | 1.038162 | 3.722459 | 0.0069110           | 2.2868082  | 25      |
| 36      | 0.268920 | 0.963163 | 0.279205 | 3.581598  | 1.038246 | 3.718580 | 0.0069337           | 2.2830726  | 24      |
| 37      | 0.269200 | 0.963084 | 0.279519 | 3.577579  | 1.038331 | 3.714711 | 0.0069564           | 2.2793453  | 23      |
| 38      | 0.269480 | 0.963006 | 0.279832 | 3.573570  | 1.038415 | 3.710849 | 0.0069791           | 2.2756264  | 22      |
| 39      | 0.269760 | 0.962928 | 0.280146 | 3.569568  | 1.038500 | 3.706996 | 0.0070019           | 2.2719158  | 21      |
| 40      | 0.270040 | 0.962849 | 0.280460 | 3.565575  | 1.038584 | 3.703151 | 0.0070248           | 2.2682135  | 20      |
| 41      | 0.270320 | 0.962770 | 0.280773 | 3.561590  | 1.038669 | 3.699314 | 0.0070477           | 2.2645194  | 19      |
| 42      | 0.270600 | 0.962692 | 0.281087 | 3.557613  | 1.038754 | 3.695485 | 0.0070706           | 2.2608337  | 18      |
| 43      | 0.270880 | 0.962613 | 0.281401 | 3.553645  | 1.038839 | 3.691665 | 0.0070936           | 2.2571561  | 17      |
| 44      | 0.271160 | 0.962534 | 0.281715 | 3.549685  | 1.038924 | 3.687853 | 0.0071167           | 2.2534868  | 16      |
| 45      | 0.271440 | 0.962455 | 0.282029 | 3.545733  | 1.039009 | 3.684049 | 0.0071398           | 2.2498256  | 15      |
| 46      | 0.271720 | 0.962376 | 0.282343 | 3.541789  | 1.039095 | 3.680254 | 0.0071630           | 2.2461725  | 14      |
| 47      | 0.272000 | 0.962297 | 0.282657 | 3.537853  | 1.039180 | 3.676466 | 0.0071862           | 2.2425276  | 13      |
| 48      | 0.272280 | 0.962218 | 0.282971 | 3.533925  | 1.039266 | 3.672687 | 0.0072095           | 2.2388908  | 12      |
| 49      | 0.272560 | 0.962139 | 0.283286 | 3.530005  | 1.039351 | 3.668915 | 0.0072328           | 2.2352620  | 11      |
| 50      | 0.272840 | 0.962059 | 0.283600 | 3.526094  | 1.039437 | 3.665152 | 0.0072561           | 2.2316413  | 10      |
| 51      | 0.273120 | 0.961980 | 0.283914 | 3.522190  | 1.039523 | 3.661396 | 0.0072796           | 2.2280286  | 9       |
| 52      | 0.273400 | 0.961901 | 0.284229 | 3.518295  | 1.039609 | 3.657649 | 0.0073030           | 2.2244239  | 8       |
| 53      | 0.273679 | 0.961821 | 0.284543 | 3.514407  | 1.039695 | 3.653910 | 0.0073266           | 2.2208271  | 7       |
| 54      | 0.273959 | 0.961741 | 0.284857 | 3.510527  | 1.039781 | 3.650178 | 0.0073501           | 2.2172383  | 6       |
| 55      | 0.274239 | 0.961662 | 0.285172 | 3.506655  | 1.039867 | 3.646455 | 0.0073738           | 2.2136574  | 5       |
| 56      | 0.274519 | 0.961582 | 0.285487 | 3.502792  | 1.039953 | 3.642739 | 0.0073975           | 2.2100844  | 4       |
| 57      | 0.274798 | 0.961502 | 0.285801 | 3.498936  | 1.040040 | 3.639031 | 0.0074212           | 2.2065193  | 3       |
| 58      | 0.275078 | 0.961422 | 0.286116 | 3.495087  | 1.040126 | 3.635332 | 0.0074450           | 2.2029620  | 2       |
| 59      | 0.275358 | 0.961342 | 0.286431 | 3.491247  | 1.040213 | 3.631640 | 0.0074688           | 2.1994125  | 1       |
| 60      | 0.275637 | 0.961262 | 0.286745 | 3.487414  | 1.040299 | 3.627955 | 0.0074927           | 2.1958708  | 0       |

↑ 105° or 285°

74° or 254° ↑

TRIGONOMETRY TABLES

↓ 16° or 196° Trigonometric and Involute Functions 163° or 343° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>16°-17° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.275637 | 0.961262 | 0.286745 | 3.487414  | 1.040299 | 3.627955 | 0.0074927           | 2.1958708  | 60      |
| 1       | 0.275917 | 0.961181 | 0.287060 | 3.483590  | 1.040386 | 3.624279 | 0.0075166           | 2.1923369  | 59      |
| 2       | 0.276197 | 0.961101 | 0.287375 | 3.479773  | 1.040473 | 3.620610 | 0.0075406           | 2.1888107  | 58      |
| 3       | 0.276476 | 0.961021 | 0.287690 | 3.475963  | 1.040560 | 3.616949 | 0.0075647           | 2.1852922  | 57      |
| 4       | 0.276756 | 0.960940 | 0.288005 | 3.472162  | 1.040647 | 3.613296 | 0.0075888           | 2.1817815  | 56      |
| 5       | 0.277035 | 0.960860 | 0.288320 | 3.468368  | 1.040735 | 3.609650 | 0.0076130           | 2.1782784  | 55      |
| 6       | 0.277315 | 0.960779 | 0.288635 | 3.464581  | 1.040822 | 3.606012 | 0.0076372           | 2.1747830  | 54      |
| 7       | 0.277594 | 0.960698 | 0.288950 | 3.460803  | 1.040909 | 3.602382 | 0.0076614           | 2.1712951  | 53      |
| 8       | 0.277874 | 0.960618 | 0.289266 | 3.457031  | 1.040997 | 3.598759 | 0.0076857           | 2.1678149  | 52      |
| 9       | 0.278153 | 0.960537 | 0.289581 | 3.453268  | 1.041085 | 3.595144 | 0.0077101           | 2.1643423  | 51      |
| 10      | 0.278432 | 0.960456 | 0.289896 | 3.449512  | 1.041172 | 3.591536 | 0.0077345           | 2.1608772  | 50      |
| 11      | 0.278712 | 0.960375 | 0.290211 | 3.445764  | 1.041260 | 3.587936 | 0.0077590           | 2.1574196  | 49      |
| 12      | 0.278991 | 0.960294 | 0.290527 | 3.442023  | 1.041348 | 3.584344 | 0.0077835           | 2.1539696  | 48      |
| 13      | 0.279270 | 0.960212 | 0.290842 | 3.438289  | 1.041436 | 3.580759 | 0.0078081           | 2.1505270  | 47      |
| 14      | 0.279550 | 0.960131 | 0.291158 | 3.434563  | 1.041524 | 3.577181 | 0.0078327           | 2.1470919  | 46      |
| 15      | 0.279829 | 0.960050 | 0.291473 | 3.430845  | 1.041613 | 3.573611 | 0.0078574           | 2.1436643  | 45      |
| 16      | 0.280108 | 0.959968 | 0.291789 | 3.427133  | 1.041701 | 3.570048 | 0.0078822           | 2.1402440  | 44      |
| 17      | 0.280388 | 0.959887 | 0.292105 | 3.423430  | 1.041789 | 3.566493 | 0.0079069           | 2.1368311  | 43      |
| 18      | 0.280667 | 0.959805 | 0.292420 | 3.419733  | 1.041878 | 3.562945 | 0.0079318           | 2.1334256  | 42      |
| 19      | 0.280946 | 0.959724 | 0.292736 | 3.416044  | 1.041967 | 3.559404 | 0.0079567           | 2.1300275  | 41      |
| 20      | 0.281225 | 0.959642 | 0.293052 | 3.412363  | 1.042055 | 3.555871 | 0.0079817           | 2.1266367  | 40      |
| 21      | 0.281504 | 0.959560 | 0.293368 | 3.408688  | 1.042144 | 3.552345 | 0.0080067           | 2.1232532  | 39      |
| 22      | 0.281783 | 0.959478 | 0.293684 | 3.405021  | 1.042233 | 3.548826 | 0.0080317           | 2.1198769  | 38      |
| 23      | 0.282062 | 0.959396 | 0.294000 | 3.401361  | 1.042322 | 3.545315 | 0.0080568           | 2.1165079  | 37      |
| 24      | 0.282341 | 0.959314 | 0.294316 | 3.397709  | 1.042412 | 3.541811 | 0.0080820           | 2.1131462  | 36      |
| 25      | 0.282620 | 0.959232 | 0.294632 | 3.394063  | 1.042501 | 3.538314 | 0.0081072           | 2.1097917  | 35      |
| 26      | 0.282900 | 0.959150 | 0.294948 | 3.390425  | 1.042590 | 3.534824 | 0.0081325           | 2.1064443  | 34      |
| 27      | 0.283179 | 0.959067 | 0.295265 | 3.386794  | 1.042680 | 3.531341 | 0.0081578           | 2.1031041  | 33      |
| 28      | 0.283457 | 0.958985 | 0.295581 | 3.383171  | 1.042769 | 3.527866 | 0.0081832           | 2.0997711  | 32      |
| 29      | 0.283736 | 0.958902 | 0.295897 | 3.379553  | 1.042859 | 3.524398 | 0.0082087           | 2.0964452  | 31      |
| 30      | 0.284015 | 0.958820 | 0.296213 | 3.375943  | 1.042949 | 3.520937 | 0.0082342           | 2.0931264  | 30      |
| 31      | 0.284294 | 0.958737 | 0.296530 | 3.372341  | 1.043039 | 3.517482 | 0.0082597           | 2.0898147  | 29      |
| 32      | 0.284573 | 0.958654 | 0.296846 | 3.368745  | 1.043129 | 3.514035 | 0.0082853           | 2.0865101  | 28      |
| 33      | 0.284852 | 0.958572 | 0.297163 | 3.365157  | 1.043219 | 3.510595 | 0.0083110           | 2.0832124  | 27      |
| 34      | 0.285131 | 0.958489 | 0.297480 | 3.361575  | 1.043309 | 3.507162 | 0.0083367           | 2.0799219  | 26      |
| 35      | 0.285410 | 0.958406 | 0.297796 | 3.358001  | 1.043400 | 3.503737 | 0.0083625           | 2.0766383  | 25      |
| 36      | 0.285688 | 0.958323 | 0.298113 | 3.354433  | 1.043490 | 3.500318 | 0.0083883           | 2.0733616  | 24      |
| 37      | 0.285967 | 0.958239 | 0.298430 | 3.350873  | 1.043581 | 3.496906 | 0.0084142           | 2.0700920  | 23      |
| 38      | 0.286246 | 0.958156 | 0.298747 | 3.347319  | 1.043671 | 3.493500 | 0.0084401           | 2.0668292  | 22      |
| 39      | 0.286525 | 0.958073 | 0.299063 | 3.343772  | 1.043762 | 3.490102 | 0.0084661           | 2.0635734  | 21      |
| 40      | 0.286803 | 0.957990 | 0.299380 | 3.340233  | 1.043853 | 3.486711 | 0.0084921           | 2.0603245  | 20      |
| 41      | 0.287082 | 0.957906 | 0.299697 | 3.336700  | 1.043944 | 3.483327 | 0.0085182           | 2.0570824  | 19      |
| 42      | 0.287361 | 0.957822 | 0.300014 | 3.333174  | 1.044035 | 3.479949 | 0.0085444           | 2.0538472  | 18      |
| 43      | 0.287639 | 0.957739 | 0.300331 | 3.329654  | 1.044126 | 3.476578 | 0.0085706           | 2.0506189  | 17      |
| 44      | 0.287918 | 0.957655 | 0.300649 | 3.326142  | 1.044217 | 3.473215 | 0.0085969           | 2.0473973  | 16      |
| 45      | 0.288196 | 0.957571 | 0.300966 | 3.322636  | 1.044309 | 3.469858 | 0.0086232           | 2.0441825  | 15      |
| 46      | 0.288475 | 0.957487 | 0.301283 | 3.319137  | 1.044400 | 3.466507 | 0.0086496           | 2.0409746  | 14      |
| 47      | 0.288753 | 0.957404 | 0.301600 | 3.315645  | 1.044492 | 3.463164 | 0.0086760           | 2.0377733  | 13      |
| 48      | 0.289032 | 0.957319 | 0.301918 | 3.312160  | 1.044583 | 3.459827 | 0.0087025           | 2.0345788  | 12      |
| 49      | 0.289310 | 0.957235 | 0.302235 | 3.308681  | 1.044675 | 3.456497 | 0.0087290           | 2.0313910  | 11      |
| 50      | 0.289589 | 0.957151 | 0.302553 | 3.305209  | 1.044767 | 3.453173 | 0.0087556           | 2.0282099  | 10      |
| 51      | 0.289867 | 0.957067 | 0.302870 | 3.301744  | 1.044859 | 3.449857 | 0.0087823           | 2.0250354  | 9       |
| 52      | 0.290145 | 0.956983 | 0.303188 | 3.298285  | 1.044951 | 3.446547 | 0.0088090           | 2.0218676  | 8       |
| 53      | 0.290424 | 0.956898 | 0.303506 | 3.294833  | 1.045043 | 3.443243 | 0.0088358           | 2.0187064  | 7       |
| 54      | 0.290702 | 0.956814 | 0.303823 | 3.291388  | 1.045136 | 3.439947 | 0.0088626           | 2.0155519  | 6       |
| 55      | 0.290981 | 0.956729 | 0.304141 | 3.287949  | 1.045228 | 3.436656 | 0.0088895           | 2.0124039  | 5       |
| 56      | 0.291259 | 0.956644 | 0.304459 | 3.284516  | 1.045321 | 3.433373 | 0.0089164           | 2.0092625  | 4       |
| 57      | 0.291537 | 0.956560 | 0.304777 | 3.281091  | 1.045413 | 3.430096 | 0.0089434           | 2.0061277  | 3       |
| 58      | 0.291815 | 0.956475 | 0.305095 | 3.277671  | 1.045506 | 3.426825 | 0.0089704           | 2.0029994  | 2       |
| 59      | 0.292094 | 0.956390 | 0.305413 | 3.274259  | 1.045599 | 3.423561 | 0.0089975           | 1.9998776  | 1       |
| 60      | 0.292372 | 0.956305 | 0.305731 | 3.270853  | 1.045692 | 3.420304 | 0.0090247           | 1.9967623  | 0       |

↑ 106° or 286° 73° or 253° ↑

TRIGONOMETRY TABLES

↓ 17° or 197° **Trigonometric and Involute Functions** 162° or 342° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>17°-18° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.292372 | 0.956305 | 0.305731 | 3.270853  | 1.045692 | 3.420304 | 0.0090247           | 1.9967623  | 60      |
| 1       | 0.292650 | 0.956220 | 0.306049 | 3.267453  | 1.045785 | 3.417053 | 0.0090519           | 1.9936534  | 59      |
| 2       | 0.292928 | 0.956134 | 0.306367 | 3.264060  | 1.045878 | 3.413808 | 0.0090792           | 1.9905511  | 58      |
| 3       | 0.293206 | 0.956049 | 0.306685 | 3.260673  | 1.045971 | 3.410570 | 0.0091065           | 1.9874551  | 57      |
| 4       | 0.293484 | 0.955964 | 0.307003 | 3.257292  | 1.046065 | 3.407338 | 0.0091339           | 1.9843656  | 56      |
| 5       | 0.293762 | 0.955879 | 0.307322 | 3.253918  | 1.046158 | 3.404113 | 0.0091614           | 1.9812825  | 55      |
| 6       | 0.294040 | 0.955793 | 0.307640 | 3.250551  | 1.046252 | 3.400894 | 0.0091889           | 1.9782058  | 54      |
| 7       | 0.294318 | 0.955707 | 0.307959 | 3.247190  | 1.046345 | 3.397682 | 0.0092164           | 1.9751354  | 53      |
| 8       | 0.294596 | 0.955622 | 0.308277 | 3.243835  | 1.046439 | 3.394475 | 0.0092440           | 1.9720714  | 52      |
| 9       | 0.294874 | 0.955536 | 0.308596 | 3.240486  | 1.046533 | 3.391276 | 0.0092717           | 1.9690137  | 51      |
| 10      | 0.295152 | 0.955450 | 0.308914 | 3.237144  | 1.046627 | 3.388082 | 0.0092994           | 1.9659623  | 50      |
| 11      | 0.295430 | 0.955364 | 0.309233 | 3.233808  | 1.046721 | 3.384895 | 0.0093272           | 1.9629172  | 49      |
| 12      | 0.295708 | 0.955278 | 0.309552 | 3.230478  | 1.046815 | 3.381714 | 0.0093551           | 1.9598783  | 48      |
| 13      | 0.295986 | 0.955192 | 0.309870 | 3.227155  | 1.046910 | 3.378539 | 0.0093830           | 1.9568458  | 47      |
| 14      | 0.296264 | 0.955106 | 0.310189 | 3.223837  | 1.047004 | 3.375371 | 0.0094109           | 1.9538194  | 46      |
| 15      | 0.296542 | 0.955020 | 0.310508 | 3.220526  | 1.047099 | 3.372208 | 0.0094390           | 1.9507993  | 45      |
| 16      | 0.296819 | 0.954934 | 0.310827 | 3.217211  | 1.047193 | 3.369052 | 0.0094670           | 1.9477853  | 44      |
| 17      | 0.297097 | 0.954847 | 0.311146 | 3.213923  | 1.047288 | 3.365903 | 0.0094952           | 1.9447776  | 43      |
| 18      | 0.297375 | 0.954761 | 0.311465 | 3.210630  | 1.047383 | 3.362759 | 0.0095234           | 1.9417760  | 42      |
| 19      | 0.297653 | 0.954674 | 0.311784 | 3.207344  | 1.047478 | 3.359621 | 0.0095516           | 1.9387805  | 41      |
| 20      | 0.297930 | 0.954588 | 0.312104 | 3.204064  | 1.047573 | 3.356490 | 0.0095799           | 1.9357912  | 40      |
| 21      | 0.298208 | 0.954501 | 0.312423 | 3.200790  | 1.047668 | 3.353365 | 0.0096083           | 1.9328080  | 39      |
| 22      | 0.298486 | 0.954414 | 0.312742 | 3.197522  | 1.047763 | 3.350246 | 0.0096367           | 1.9298309  | 38      |
| 23      | 0.298763 | 0.954327 | 0.313062 | 3.194260  | 1.047859 | 3.347132 | 0.0096652           | 1.9268598  | 37      |
| 24      | 0.299041 | 0.954240 | 0.313381 | 3.191004  | 1.047954 | 3.344025 | 0.0096937           | 1.9238948  | 36      |
| 25      | 0.299318 | 0.954153 | 0.313700 | 3.187754  | 1.048050 | 3.340924 | 0.0097223           | 1.9209359  | 35      |
| 26      | 0.299596 | 0.954066 | 0.314020 | 3.184510  | 1.048145 | 3.337829 | 0.0097510           | 1.9179830  | 34      |
| 27      | 0.299873 | 0.953979 | 0.314340 | 3.181272  | 1.048241 | 3.334740 | 0.0097797           | 1.9150360  | 33      |
| 28      | 0.300151 | 0.953892 | 0.314659 | 3.178041  | 1.048337 | 3.331658 | 0.0098085           | 1.9120951  | 32      |
| 29      | 0.300428 | 0.953804 | 0.314979 | 3.174815  | 1.048433 | 3.328581 | 0.0098373           | 1.9091601  | 31      |
| 30      | 0.300706 | 0.953717 | 0.315299 | 3.171595  | 1.048529 | 3.325510 | 0.0098662           | 1.9062311  | 30      |
| 31      | 0.300983 | 0.953629 | 0.315619 | 3.168381  | 1.048625 | 3.322444 | 0.0098951           | 1.9033080  | 29      |
| 32      | 0.301261 | 0.953542 | 0.315939 | 3.165173  | 1.048722 | 3.319385 | 0.0099241           | 1.9003908  | 28      |
| 33      | 0.301538 | 0.953454 | 0.316258 | 3.161971  | 1.048818 | 3.316332 | 0.0099532           | 1.8974796  | 27      |
| 34      | 0.301815 | 0.953366 | 0.316578 | 3.158774  | 1.048915 | 3.313285 | 0.0099823           | 1.8945742  | 26      |
| 35      | 0.302093 | 0.953279 | 0.316899 | 3.155584  | 1.049011 | 3.310243 | 0.0100115           | 1.8916747  | 25      |
| 36      | 0.302370 | 0.953191 | 0.317219 | 3.152399  | 1.049108 | 3.307208 | 0.0100407           | 1.8887810  | 24      |
| 37      | 0.302647 | 0.953103 | 0.317539 | 3.149221  | 1.049205 | 3.304178 | 0.0100700           | 1.8858932  | 23      |
| 38      | 0.302924 | 0.953015 | 0.317859 | 3.146048  | 1.049302 | 3.301154 | 0.0100994           | 1.8830112  | 22      |
| 39      | 0.303202 | 0.952926 | 0.318179 | 3.142881  | 1.049399 | 3.298136 | 0.0101288           | 1.8801350  | 21      |
| 40      | 0.303479 | 0.952838 | 0.318500 | 3.139719  | 1.049496 | 3.295123 | 0.0101583           | 1.8772646  | 20      |
| 41      | 0.303756 | 0.952750 | 0.318820 | 3.136564  | 1.049593 | 3.292117 | 0.0101878           | 1.8743999  | 19      |
| 42      | 0.304033 | 0.952662 | 0.319141 | 3.133414  | 1.049691 | 3.289116 | 0.0102174           | 1.8715411  | 18      |
| 43      | 0.304310 | 0.952573 | 0.319461 | 3.130270  | 1.049788 | 3.286121 | 0.0102471           | 1.8686879  | 17      |
| 44      | 0.304587 | 0.952484 | 0.319782 | 3.127132  | 1.049886 | 3.283132 | 0.0102768           | 1.8658405  | 16      |
| 45      | 0.304864 | 0.952396 | 0.320103 | 3.123999  | 1.049984 | 3.280148 | 0.0103066           | 1.8629987  | 15      |
| 46      | 0.305141 | 0.952307 | 0.320423 | 3.120872  | 1.050081 | 3.277170 | 0.0103364           | 1.8601627  | 14      |
| 47      | 0.305418 | 0.952218 | 0.320744 | 3.117751  | 1.050179 | 3.274198 | 0.0103663           | 1.8573323  | 13      |
| 48      | 0.305695 | 0.952129 | 0.321065 | 3.114635  | 1.050277 | 3.271231 | 0.0103963           | 1.8545076  | 12      |
| 49      | 0.305972 | 0.952040 | 0.321386 | 3.111525  | 1.050376 | 3.268270 | 0.0104263           | 1.8516885  | 11      |
| 50      | 0.306249 | 0.951951 | 0.321707 | 3.108421  | 1.050474 | 3.265315 | 0.0104564           | 1.8488751  | 10      |
| 51      | 0.306526 | 0.951862 | 0.322028 | 3.105322  | 1.050572 | 3.262365 | 0.0104865           | 1.8460672  | 9       |
| 52      | 0.306803 | 0.951773 | 0.322349 | 3.102229  | 1.050671 | 3.259421 | 0.0105167           | 1.8432650  | 8       |
| 53      | 0.307080 | 0.951684 | 0.322670 | 3.099142  | 1.050769 | 3.256483 | 0.0105469           | 1.8404683  | 7       |
| 54      | 0.307357 | 0.951594 | 0.322991 | 3.096060  | 1.050868 | 3.253550 | 0.0105773           | 1.8376772  | 6       |
| 55      | 0.307633 | 0.951505 | 0.323312 | 3.092983  | 1.050967 | 3.250622 | 0.0106076           | 1.8348916  | 5       |
| 56      | 0.307910 | 0.951415 | 0.323634 | 3.089912  | 1.051066 | 3.247700 | 0.0106381           | 1.8321116  | 4       |
| 57      | 0.308187 | 0.951326 | 0.323955 | 3.086847  | 1.051165 | 3.244784 | 0.0106686           | 1.8293371  | 3       |
| 58      | 0.308464 | 0.951236 | 0.324277 | 3.083787  | 1.051264 | 3.241873 | 0.0106991           | 1.8265681  | 2       |
| 59      | 0.308740 | 0.951146 | 0.324598 | 3.080732  | 1.051363 | 3.238968 | 0.0107298           | 1.8238045  | 1       |
| 60      | 0.309017 | 0.951057 | 0.324920 | 3.077684  | 1.051462 | 3.236068 | 0.0107604           | 1.8210465  | 0       |

↑ 107° or 287° **Trigonometric and Involute Functions** 72° or 252° ↑



TRIGONOMETRY TABLES

↓ 18° or 198° Trigonometric and Involute Functions 161° or 341° ↓

| Minutes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute<br>18°-19° | Read<br>Up          | Minutes |
|---------|----------|----------|-----------|-----------|----------|----------|---------------------|---------------------|---------|
| 0       | 0.309017 | 0.951057 | 0.324920  | 3.077684  | 1.051462 | 3.236068 | 0.0107604           | 1.8210465           | 60      |
| 1       | 0.309294 | 0.950967 | 0.325241  | 3.074640  | 1.051562 | 3.233174 | 0.0107912           | 1.8182939           | 59      |
| 2       | 0.309570 | 0.950877 | 0.325563  | 3.071602  | 1.051661 | 3.230285 | 0.0108220           | 1.8155467           | 58      |
| 3       | 0.309847 | 0.950786 | 0.325885  | 3.068569  | 1.051761 | 3.227401 | 0.0108528           | 1.8128050           | 57      |
| 4       | 0.310123 | 0.950696 | 0.326207  | 3.065542  | 1.051861 | 3.224523 | 0.0108838           | 1.8100686           | 56      |
| 5       | 0.310400 | 0.950606 | 0.326528  | 3.062520  | 1.051960 | 3.221650 | 0.0109147           | 1.8073377           | 55      |
| 6       | 0.310676 | 0.950516 | 0.326850  | 3.059504  | 1.052060 | 3.218783 | 0.0109458           | 1.8046121           | 54      |
| 7       | 0.310953 | 0.950425 | 0.327172  | 3.056493  | 1.052161 | 3.215921 | 0.0109769           | 1.8018919           | 53      |
| 8       | 0.311229 | 0.950335 | 0.327494  | 3.053487  | 1.052261 | 3.213064 | 0.0110081           | 1.7991771           | 52      |
| 9       | 0.311506 | 0.950244 | 0.327817  | 3.050487  | 1.052361 | 3.210213 | 0.0110393           | 1.7964676           | 51      |
| 10      | 0.311782 | 0.950154 | 0.328139  | 3.047492  | 1.052461 | 3.207367 | 0.0110706           | 1.7937634           | 50      |
| 11      | 0.312059 | 0.950063 | 0.328461  | 3.044502  | 1.052562 | 3.204527 | 0.0111019           | 1.7910645           | 49      |
| 12      | 0.312335 | 0.949972 | 0.328783  | 3.041517  | 1.052663 | 3.201691 | 0.0111333           | 1.7883709           | 48      |
| 13      | 0.312611 | 0.949881 | 0.329106  | 3.038538  | 1.052763 | 3.198861 | 0.0111648           | 1.7856826           | 47      |
| 14      | 0.312888 | 0.949790 | 0.329428  | 3.035564  | 1.052864 | 3.196037 | 0.0111964           | 1.7829995           | 46      |
| 15      | 0.313164 | 0.949699 | 0.329751  | 3.032595  | 1.052965 | 3.193217 | 0.0112280           | 1.7803217           | 45      |
| 16      | 0.313440 | 0.949608 | 0.330073  | 3.029632  | 1.053066 | 3.190403 | 0.0112596           | 1.7776491           | 44      |
| 17      | 0.313716 | 0.949517 | 0.330396  | 3.026674  | 1.053167 | 3.187594 | 0.0112913           | 1.7749817           | 43      |
| 18      | 0.313992 | 0.949425 | 0.330718  | 3.023721  | 1.053269 | 3.184790 | 0.0113231           | 1.7723196           | 42      |
| 19      | 0.314269 | 0.949334 | 0.331041  | 3.020773  | 1.053370 | 3.181991 | 0.0113550           | 1.7696626           | 41      |
| 20      | 0.314545 | 0.949243 | 0.331364  | 3.017830  | 1.053471 | 3.179198 | 0.0113869           | 1.7670108           | 40      |
| 21      | 0.314821 | 0.949151 | 0.331687  | 3.014893  | 1.053573 | 3.176410 | 0.0114189           | 1.7643642           | 39      |
| 22      | 0.315097 | 0.949059 | 0.332010  | 3.011960  | 1.053675 | 3.173626 | 0.0114509           | 1.7617227           | 38      |
| 23      | 0.315373 | 0.948968 | 0.332333  | 3.009033  | 1.053777 | 3.170848 | 0.0114830           | 1.7590864           | 37      |
| 24      | 0.315649 | 0.948876 | 0.332656  | 3.006111  | 1.053878 | 3.168076 | 0.0115151           | 1.7564552           | 36      |
| 25      | 0.315925 | 0.948784 | 0.332979  | 3.003194  | 1.053981 | 3.165308 | 0.0115474           | 1.7538299           | 35      |
| 26      | 0.316201 | 0.948692 | 0.333302  | 3.000282  | 1.054083 | 3.162545 | 0.0115796           | 1.7512080           | 34      |
| 27      | 0.316477 | 0.948600 | 0.333625  | 2.997375  | 1.054185 | 3.159788 | 0.0116120           | 1.7485921           | 33      |
| 28      | 0.316753 | 0.948508 | 0.333949  | 2.994473  | 1.054287 | 3.157035 | 0.0116444           | 1.7459812           | 32      |
| 29      | 0.317029 | 0.948416 | 0.334272  | 2.991577  | 1.054390 | 3.154288 | 0.0116769           | 1.7433753           | 31      |
| 30      | 0.317305 | 0.948324 | 0.334595  | 2.988685  | 1.054492 | 3.151545 | 0.0117094           | 1.7407745           | 30      |
| 31      | 0.317580 | 0.948231 | 0.334919  | 2.985798  | 1.054595 | 3.148808 | 0.0117420           | 1.7381788           | 29      |
| 32      | 0.317856 | 0.948139 | 0.335242  | 2.982917  | 1.054698 | 3.146076 | 0.0117747           | 1.7355880           | 28      |
| 33      | 0.318132 | 0.948046 | 0.335566  | 2.980040  | 1.054801 | 3.143348 | 0.0118074           | 1.7330022           | 27      |
| 34      | 0.318408 | 0.947954 | 0.335890  | 2.977168  | 1.054904 | 3.140626 | 0.0118402           | 1.7304215           | 26      |
| 35      | 0.318684 | 0.947861 | 0.336213  | 2.974302  | 1.055007 | 3.137909 | 0.0118730           | 1.7278456           | 25      |
| 36      | 0.318959 | 0.947768 | 0.336537  | 2.971440  | 1.055110 | 3.135196 | 0.0119059           | 1.7252748           | 24      |
| 37      | 0.319235 | 0.947676 | 0.336861  | 2.968583  | 1.055213 | 3.132489 | 0.0119389           | 1.7227089           | 23      |
| 38      | 0.319511 | 0.947583 | 0.337185  | 2.965731  | 1.055317 | 3.129786 | 0.0119720           | 1.7201479           | 22      |
| 39      | 0.319786 | 0.947490 | 0.337509  | 2.962884  | 1.055420 | 3.127089 | 0.0120051           | 1.7175918           | 21      |
| 40      | 0.320062 | 0.947397 | 0.337833  | 2.960042  | 1.055524 | 3.124396 | 0.0120382           | 1.7150407           | 20      |
| 41      | 0.320337 | 0.947304 | 0.338157  | 2.957205  | 1.055628 | 3.121708 | 0.0120715           | 1.7124944           | 19      |
| 42      | 0.320613 | 0.947210 | 0.338481  | 2.954373  | 1.055732 | 3.119025 | 0.0121048           | 1.7099530           | 18      |
| 43      | 0.320889 | 0.947117 | 0.338806  | 2.951545  | 1.055836 | 3.116347 | 0.0121381           | 1.7074164           | 17      |
| 44      | 0.321164 | 0.947024 | 0.339130  | 2.948723  | 1.055940 | 3.113674 | 0.0121715           | 1.7048848           | 16      |
| 45      | 0.321439 | 0.946930 | 0.339454  | 2.945905  | 1.056044 | 3.111006 | 0.0122050           | 1.7023579           | 15      |
| 46      | 0.321715 | 0.946837 | 0.339779  | 2.943092  | 1.056148 | 3.108342 | 0.0122386           | 1.6998359           | 14      |
| 47      | 0.321990 | 0.946743 | 0.340103  | 2.940284  | 1.056253 | 3.105683 | 0.0122722           | 1.6973187           | 13      |
| 48      | 0.322266 | 0.946649 | 0.340428  | 2.937481  | 1.056357 | 3.103030 | 0.0123059           | 1.6948063           | 12      |
| 49      | 0.322541 | 0.946555 | 0.340752  | 2.934682  | 1.056462 | 3.100381 | 0.0123396           | 1.6922986           | 11      |
| 50      | 0.322816 | 0.946462 | 0.341077  | 2.931888  | 1.056567 | 3.097736 | 0.0123734           | 1.6897958           | 10      |
| 51      | 0.323092 | 0.946368 | 0.341402  | 2.929099  | 1.056672 | 3.095097 | 0.0124073           | 1.6872977           | 9       |
| 52      | 0.323367 | 0.946274 | 0.341727  | 2.926315  | 1.056777 | 3.092462 | 0.0124412           | 1.6848044           | 8       |
| 53      | 0.323642 | 0.946180 | 0.342052  | 2.923536  | 1.056882 | 3.089832 | 0.0124752           | 1.6823158           | 7       |
| 54      | 0.323917 | 0.946085 | 0.342377  | 2.920761  | 1.056987 | 3.087207 | 0.0125093           | 1.6798319           | 6       |
| 55      | 0.324193 | 0.945991 | 0.342702  | 2.917991  | 1.057092 | 3.084586 | 0.0125434           | 1.6773527           | 5       |
| 56      | 0.324468 | 0.945897 | 0.343027  | 2.915226  | 1.057198 | 3.081970 | 0.0125776           | 1.6748783           | 4       |
| 57      | 0.324743 | 0.945802 | 0.343352  | 2.912465  | 1.057303 | 3.079359 | 0.0126119           | 1.6724085           | 3       |
| 58      | 0.325018 | 0.945708 | 0.343677  | 2.909709  | 1.057409 | 3.076752 | 0.0126462           | 1.6699434           | 2       |
| 59      | 0.325293 | 0.945613 | 0.344002  | 2.906958  | 1.057515 | 3.074151 | 0.0126806           | 1.6674829           | 1       |
| 60      | 0.325568 | 0.945519 | 0.344328  | 2.904211  | 1.057621 | 3.071553 | 0.0127151           | 1.6650271           | 0       |
| Minutes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read<br>Down        | 71°-72°<br>Involute | Minutes |

↑ 108° or 288°

71° or 251° ↑

↓ 19° or 199° Trigonometric and Involute Functions 160° or 340° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>19°-20° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.325568 | 0.945519 | 0.344328 | 2.904211  | 1.057621 | 3.071553 | 0.0127151           | 1.6650271  | 60      |
| 1       | 0.325843 | 0.945424 | 0.344653 | 2.901469  | 1.057727 | 3.068961 | 0.0127496           | 1.6625759  | 59      |
| 2       | 0.326118 | 0.945329 | 0.344978 | 2.898731  | 1.057833 | 3.066373 | 0.0127842           | 1.6601294  | 58      |
| 3       | 0.326393 | 0.945234 | 0.345304 | 2.895999  | 1.057939 | 3.063790 | 0.0128188           | 1.6576875  | 57      |
| 4       | 0.326668 | 0.945139 | 0.345630 | 2.893270  | 1.058045 | 3.061211 | 0.0128535           | 1.6552502  | 56      |
| 5       | 0.326943 | 0.945044 | 0.345955 | 2.890547  | 1.058152 | 3.058637 | 0.0128883           | 1.6528174  | 55      |
| 6       | 0.327218 | 0.944949 | 0.346281 | 2.887828  | 1.058258 | 3.056068 | 0.0129232           | 1.6503893  | 54      |
| 7       | 0.327493 | 0.944854 | 0.346607 | 2.885113  | 1.058365 | 3.053503 | 0.0129581           | 1.6479657  | 53      |
| 8       | 0.327768 | 0.944758 | 0.346933 | 2.882403  | 1.058472 | 3.050942 | 0.0129931           | 1.6455466  | 52      |
| 9       | 0.328042 | 0.944663 | 0.347259 | 2.879698  | 1.058579 | 3.048386 | 0.0130281           | 1.6431321  | 51      |
| 10      | 0.328317 | 0.944568 | 0.347585 | 2.876997  | 1.058686 | 3.045835 | 0.0130632           | 1.6407221  | 50      |
| 11      | 0.328592 | 0.944472 | 0.347911 | 2.874301  | 1.058793 | 3.043288 | 0.0130984           | 1.6383167  | 49      |
| 12      | 0.328867 | 0.944376 | 0.348237 | 2.871609  | 1.058900 | 3.040746 | 0.0131336           | 1.6359157  | 48      |
| 13      | 0.329141 | 0.944281 | 0.348563 | 2.868921  | 1.059007 | 3.038208 | 0.0131689           | 1.6335193  | 47      |
| 14      | 0.329416 | 0.944185 | 0.348889 | 2.866239  | 1.059115 | 3.035675 | 0.0132043           | 1.6311273  | 46      |
| 15      | 0.329691 | 0.944089 | 0.349216 | 2.863560  | 1.059222 | 3.033146 | 0.0132398           | 1.6287398  | 45      |
| 16      | 0.329965 | 0.943993 | 0.349542 | 2.860886  | 1.059330 | 3.030622 | 0.0132753           | 1.6263567  | 44      |
| 17      | 0.330240 | 0.943897 | 0.349868 | 2.858217  | 1.059438 | 3.028102 | 0.0133108           | 1.6239781  | 43      |
| 18      | 0.330514 | 0.943801 | 0.350195 | 2.855552  | 1.059545 | 3.025587 | 0.0133465           | 1.6216040  | 42      |
| 19      | 0.330789 | 0.943705 | 0.350521 | 2.852891  | 1.059653 | 3.023076 | 0.0133822           | 1.6192342  | 41      |
| 20      | 0.331063 | 0.943609 | 0.350848 | 2.850235  | 1.059762 | 3.020569 | 0.0134180           | 1.6168689  | 40      |
| 21      | 0.331338 | 0.943512 | 0.351175 | 2.847583  | 1.059870 | 3.018067 | 0.0134538           | 1.6145080  | 39      |
| 22      | 0.331612 | 0.943416 | 0.351502 | 2.844936  | 1.059978 | 3.015569 | 0.0134897           | 1.6121514  | 38      |
| 23      | 0.331887 | 0.943319 | 0.351829 | 2.842293  | 1.060087 | 3.013076 | 0.0135257           | 1.6097993  | 37      |
| 24      | 0.332161 | 0.943223 | 0.352156 | 2.839654  | 1.060195 | 3.010587 | 0.0135617           | 1.6074515  | 36      |
| 25      | 0.332435 | 0.943126 | 0.352483 | 2.837020  | 1.060304 | 3.008102 | 0.0135978           | 1.6051083  | 35      |
| 26      | 0.332710 | 0.943029 | 0.352810 | 2.834390  | 1.060412 | 3.005622 | 0.0136340           | 1.6027689  | 34      |
| 27      | 0.332984 | 0.942932 | 0.353137 | 2.831764  | 1.060521 | 3.003146 | 0.0136702           | 1.6004342  | 33      |
| 28      | 0.333258 | 0.942836 | 0.353464 | 2.829143  | 1.060630 | 3.000675 | 0.0137065           | 1.5981037  | 32      |
| 29      | 0.333533 | 0.942739 | 0.353791 | 2.826526  | 1.060739 | 2.998207 | 0.0137429           | 1.5957776  | 31      |
| 30      | 0.333807 | 0.942644 | 0.354119 | 2.823913  | 1.060849 | 2.995744 | 0.0137794           | 1.5934558  | 30      |
| 31      | 0.334081 | 0.942548 | 0.354446 | 2.821304  | 1.060958 | 2.993286 | 0.0138159           | 1.5911382  | 29      |
| 32      | 0.334355 | 0.942452 | 0.354773 | 2.818700  | 1.061067 | 2.990831 | 0.0138525           | 1.5888250  | 28      |
| 33      | 0.334629 | 0.942356 | 0.355100 | 2.816100  | 1.061177 | 2.988381 | 0.0138891           | 1.5865107  | 27      |
| 34      | 0.334903 | 0.942259 | 0.355429 | 2.813505  | 1.061287 | 2.985935 | 0.0139258           | 1.5842112  | 26      |
| 35      | 0.335178 | 0.942163 | 0.355756 | 2.810913  | 1.061396 | 2.983494 | 0.0139626           | 1.5819107  | 25      |
| 36      | 0.335452 | 0.942067 | 0.356084 | 2.808326  | 1.061506 | 2.981056 | 0.0139994           | 1.5796145  | 24      |
| 37      | 0.335726 | 0.941970 | 0.356412 | 2.805743  | 1.061616 | 2.978623 | 0.0140364           | 1.5773224  | 23      |
| 38      | 0.336000 | 0.941874 | 0.356740 | 2.803165  | 1.061727 | 2.976194 | 0.0140734           | 1.5750346  | 22      |
| 39      | 0.336274 | 0.941778 | 0.357068 | 2.800590  | 1.061837 | 2.973769 | 0.0141104           | 1.5727510  | 21      |
| 40      | 0.336547 | 0.941682 | 0.357396 | 2.798020  | 1.061947 | 2.971349 | 0.0141475           | 1.5704716  | 20      |
| 41      | 0.336821 | 0.941586 | 0.357724 | 2.795454  | 1.062058 | 2.968933 | 0.0141847           | 1.5681963  | 19      |
| 42      | 0.337095 | 0.941491 | 0.358052 | 2.792892  | 1.062168 | 2.966521 | 0.0142220           | 1.5659252  | 18      |
| 43      | 0.337369 | 0.941395 | 0.358380 | 2.790334  | 1.062279 | 2.964113 | 0.0142593           | 1.5636583  | 17      |
| 44      | 0.337643 | 0.941299 | 0.358708 | 2.787780  | 1.062390 | 2.961709 | 0.0142967           | 1.5613955  | 16      |
| 45      | 0.337917 | 0.941203 | 0.359037 | 2.785231  | 1.062501 | 2.959309 | 0.0143342           | 1.5591369  | 15      |
| 46      | 0.338190 | 0.941107 | 0.359365 | 2.782685  | 1.062612 | 2.956914 | 0.0143717           | 1.5568824  | 14      |
| 47      | 0.338464 | 0.940979 | 0.359694 | 2.780144  | 1.062723 | 2.954522 | 0.0144093           | 1.5546320  | 13      |
| 48      | 0.338738 | 0.940881 | 0.360022 | 2.777607  | 1.062834 | 2.952135 | 0.0144470           | 1.5523857  | 12      |
| 49      | 0.339012 | 0.940782 | 0.360351 | 2.775074  | 1.062945 | 2.949752 | 0.0144847           | 1.5501435  | 11      |
| 50      | 0.339285 | 0.940684 | 0.360679 | 2.772545  | 1.063057 | 2.947372 | 0.0145225           | 1.5479054  | 10      |
| 51      | 0.339559 | 0.940585 | 0.361008 | 2.770020  | 1.063168 | 2.944997 | 0.0145604           | 1.5456714  | 9       |
| 52      | 0.339832 | 0.940486 | 0.361337 | 2.767499  | 1.063280 | 2.942627 | 0.0145983           | 1.5434415  | 8       |
| 53      | 0.340106 | 0.940387 | 0.361666 | 2.764982  | 1.063392 | 2.940260 | 0.0146363           | 1.5412156  | 7       |
| 54      | 0.340380 | 0.940288 | 0.361995 | 2.762470  | 1.063504 | 2.937897 | 0.0146744           | 1.5389937  | 6       |
| 55      | 0.340653 | 0.940189 | 0.362324 | 2.759961  | 1.063616 | 2.935538 | 0.0147126           | 1.5367759  | 5       |
| 56      | 0.340927 | 0.940090 | 0.362653 | 2.757456  | 1.063728 | 2.933183 | 0.0147508           | 1.5345621  | 4       |
| 57      | 0.341200 | 0.939991 | 0.362982 | 2.754955  | 1.063840 | 2.930833 | 0.0147891           | 1.5323523  | 3       |
| 58      | 0.341473 | 0.939891 | 0.363312 | 2.752459  | 1.063953 | 2.928486 | 0.0148275           | 1.5301465  | 2       |
| 59      | 0.341747 | 0.939792 | 0.363641 | 2.749966  | 1.064065 | 2.926143 | 0.0148659           | 1.5279447  | 1       |
| 60      | 0.342020 | 0.939693 | 0.363970 | 2.747477  | 1.064178 | 2.923804 | 0.0149044           | 1.5257469  | 0       |

↑ 109° or 289°

70° or 250° ↑

TRIGONOMETRY TABLES

↓ 20° or 200° Trigonometric and Involute Functions 159° or 339° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>20°-21° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.342020 | 0.939693 | 0.363970 | 2.747477  | 1.064178 | 2.923804 | 0.0149044           | 1.5257469  | 60      |
| 1       | 0.342293 | 0.939593 | 0.364300 | 2.744993  | 1.064290 | 2.921470 | 0.0149430           | 1.5235531  | 59      |
| 2       | 0.342567 | 0.939493 | 0.364629 | 2.742512  | 1.064403 | 2.919139 | 0.0149816           | 1.5213633  | 58      |
| 3       | 0.342840 | 0.939394 | 0.364959 | 2.740035  | 1.064516 | 2.916812 | 0.0150203           | 1.5191774  | 57      |
| 4       | 0.343113 | 0.939294 | 0.365288 | 2.737562  | 1.064629 | 2.914489 | 0.0150591           | 1.5169954  | 56      |
| 5       | 0.343387 | 0.939194 | 0.365618 | 2.735093  | 1.064743 | 2.912170 | 0.0150979           | 1.5148174  | 55      |
| 6       | 0.343660 | 0.939094 | 0.365948 | 2.732628  | 1.064856 | 2.909855 | 0.0151369           | 1.5126433  | 54      |
| 7       | 0.343933 | 0.938994 | 0.366278 | 2.730167  | 1.064969 | 2.907544 | 0.0151758           | 1.5104731  | 53      |
| 8       | 0.344206 | 0.938894 | 0.366608 | 2.727710  | 1.065083 | 2.905237 | 0.0152149           | 1.5083068  | 52      |
| 9       | 0.344479 | 0.938794 | 0.366938 | 2.725257  | 1.065196 | 2.902934 | 0.0152540           | 1.5061444  | 51      |
| 10      | 0.344752 | 0.938694 | 0.367268 | 2.722808  | 1.065310 | 2.900635 | 0.0152932           | 1.5039860  | 50      |
| 11      | 0.345025 | 0.938593 | 0.367598 | 2.720362  | 1.065424 | 2.898339 | 0.0153325           | 1.5018313  | 49      |
| 12      | 0.345298 | 0.938493 | 0.367928 | 2.717920  | 1.065538 | 2.896048 | 0.0153719           | 1.4996860  | 48      |
| 13      | 0.345571 | 0.938393 | 0.368259 | 2.715483  | 1.065652 | 2.893760 | 0.0154113           | 1.4975337  | 47      |
| 14      | 0.345844 | 0.938292 | 0.368589 | 2.713049  | 1.065766 | 2.891476 | 0.0154507           | 1.4953907  | 46      |
| 15      | 0.346117 | 0.938191 | 0.368919 | 2.710619  | 1.065881 | 2.889196 | 0.0154903           | 1.4932515  | 45      |
| 16      | 0.346390 | 0.938091 | 0.369250 | 2.708192  | 1.065995 | 2.886920 | 0.0155299           | 1.4911161  | 44      |
| 17      | 0.346663 | 0.937990 | 0.369581 | 2.705770  | 1.066110 | 2.884647 | 0.0155696           | 1.4889845  | 43      |
| 18      | 0.346936 | 0.937889 | 0.369911 | 2.703351  | 1.066224 | 2.882379 | 0.0156094           | 1.4868568  | 42      |
| 19      | 0.347208 | 0.937788 | 0.370242 | 2.700936  | 1.066339 | 2.880114 | 0.0156492           | 1.4847328  | 41      |
| 20      | 0.347481 | 0.937687 | 0.370573 | 2.698525  | 1.066454 | 2.877853 | 0.0156891           | 1.4826127  | 40      |
| 21      | 0.347754 | 0.937586 | 0.370904 | 2.696118  | 1.066569 | 2.875596 | 0.0157291           | 1.4804963  | 39      |
| 22      | 0.348027 | 0.937485 | 0.371235 | 2.693715  | 1.066684 | 2.873343 | 0.0157692           | 1.4783837  | 38      |
| 23      | 0.348299 | 0.937383 | 0.371566 | 2.691315  | 1.066799 | 2.871093 | 0.0158093           | 1.4762749  | 37      |
| 24      | 0.348572 | 0.937282 | 0.371897 | 2.688919  | 1.066915 | 2.868847 | 0.0158495           | 1.4741698  | 36      |
| 25      | 0.348845 | 0.937181 | 0.372228 | 2.686527  | 1.067030 | 2.866605 | 0.0158898           | 1.4720685  | 35      |
| 26      | 0.349117 | 0.937079 | 0.372559 | 2.684138  | 1.067146 | 2.864367 | 0.0159301           | 1.4699709  | 34      |
| 27      | 0.349390 | 0.936977 | 0.372890 | 2.681754  | 1.067262 | 2.862132 | 0.0159705           | 1.4678770  | 33      |
| 28      | 0.349662 | 0.936876 | 0.373222 | 2.679372  | 1.067377 | 2.859902 | 0.0160110           | 1.4657869  | 32      |
| 29      | 0.349935 | 0.936774 | 0.373553 | 2.676995  | 1.067493 | 2.857674 | 0.0160516           | 1.4637004  | 31      |
| 30      | 0.350207 | 0.936672 | 0.373885 | 2.674621  | 1.067609 | 2.855451 | 0.0160922           | 1.4616177  | 30      |
| 31      | 0.350480 | 0.936570 | 0.374216 | 2.672252  | 1.067726 | 2.853231 | 0.0161329           | 1.4595386  | 29      |
| 32      | 0.350752 | 0.936468 | 0.374548 | 2.669885  | 1.067842 | 2.851015 | 0.0161737           | 1.4574632  | 28      |
| 33      | 0.351025 | 0.936366 | 0.374880 | 2.667523  | 1.067958 | 2.848803 | 0.0162145           | 1.4553915  | 27      |
| 34      | 0.351297 | 0.936264 | 0.375211 | 2.665164  | 1.068075 | 2.846594 | 0.0162554           | 1.4533235  | 26      |
| 35      | 0.351569 | 0.936162 | 0.375543 | 2.662809  | 1.068191 | 2.844389 | 0.0162964           | 1.4512591  | 25      |
| 36      | 0.351842 | 0.936060 | 0.375875 | 2.660457  | 1.068308 | 2.842188 | 0.0163375           | 1.4491984  | 24      |
| 37      | 0.352114 | 0.935957 | 0.376207 | 2.658109  | 1.068425 | 2.839990 | 0.0163786           | 1.4471413  | 23      |
| 38      | 0.352386 | 0.935855 | 0.376539 | 2.655765  | 1.068542 | 2.837796 | 0.0164198           | 1.4450878  | 22      |
| 39      | 0.352658 | 0.935752 | 0.376872 | 2.653424  | 1.068659 | 2.835605 | 0.0164611           | 1.4430380  | 21      |
| 40      | 0.352931 | 0.935650 | 0.377204 | 2.651087  | 1.068776 | 2.833419 | 0.0165024           | 1.4409917  | 20      |
| 41      | 0.353203 | 0.935547 | 0.377536 | 2.648753  | 1.068894 | 2.831235 | 0.0165439           | 1.4389491  | 19      |
| 42      | 0.353475 | 0.935444 | 0.377869 | 2.646423  | 1.069011 | 2.829056 | 0.0165854           | 1.4369100  | 18      |
| 43      | 0.353747 | 0.935341 | 0.378201 | 2.644097  | 1.069129 | 2.826880 | 0.0166269           | 1.4348746  | 17      |
| 44      | 0.354019 | 0.935238 | 0.378534 | 2.641774  | 1.069246 | 2.824707 | 0.0166686           | 1.4328427  | 16      |
| 45      | 0.354291 | 0.935135 | 0.378866 | 2.639455  | 1.069364 | 2.822538 | 0.0167103           | 1.4308144  | 15      |
| 46      | 0.354563 | 0.935032 | 0.379199 | 2.637139  | 1.069482 | 2.820373 | 0.0167521           | 1.4287896  | 14      |
| 47      | 0.354835 | 0.934929 | 0.379532 | 2.634827  | 1.069600 | 2.818211 | 0.0167939           | 1.4267684  | 13      |
| 48      | 0.355107 | 0.934826 | 0.379864 | 2.632519  | 1.069718 | 2.816053 | 0.0168359           | 1.4247507  | 12      |
| 49      | 0.355379 | 0.934722 | 0.380197 | 2.630214  | 1.069836 | 2.813898 | 0.0168779           | 1.4227366  | 11      |
| 50      | 0.355651 | 0.934619 | 0.380530 | 2.627912  | 1.069955 | 2.811747 | 0.0169200           | 1.4207260  | 10      |
| 51      | 0.355923 | 0.934515 | 0.380863 | 2.625614  | 1.070073 | 2.809599 | 0.0169621           | 1.4187189  | 9       |
| 52      | 0.356194 | 0.934412 | 0.381196 | 2.623320  | 1.070192 | 2.807455 | 0.0170044           | 1.4167153  | 8       |
| 53      | 0.356466 | 0.934308 | 0.381530 | 2.621029  | 1.070311 | 2.805315 | 0.0170467           | 1.4147152  | 7       |
| 54      | 0.356738 | 0.934204 | 0.381863 | 2.618741  | 1.070429 | 2.803178 | 0.0170891           | 1.4127186  | 6       |
| 55      | 0.357010 | 0.934101 | 0.382196 | 2.616457  | 1.070548 | 2.801044 | 0.0171315           | 1.4107255  | 5       |
| 56      | 0.357281 | 0.933997 | 0.382530 | 2.614177  | 1.070668 | 2.798914 | 0.0171740           | 1.4087359  | 4       |
| 57      | 0.357553 | 0.933893 | 0.382863 | 2.611900  | 1.070787 | 2.796787 | 0.0172166           | 1.4067497  | 3       |
| 58      | 0.357825 | 0.933789 | 0.383197 | 2.609626  | 1.070906 | 2.794664 | 0.0172593           | 1.4047670  | 2       |
| 59      | 0.358096 | 0.933685 | 0.383530 | 2.607356  | 1.071025 | 2.792544 | 0.0173021           | 1.4027877  | 1       |
| 60      | 0.358368 | 0.933580 | 0.383864 | 2.605089  | 1.071145 | 2.790428 | 0.0173449           | 1.4008119  | 0       |

↑ 110° or 290°

69° or 249° ↑

↓ 21° or 201°      **Trigonometric and Involute Functions**      158° or 338° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>21°-22° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.358368 | 0.933580 | 0.383864 | 2.605089  | 1.071145 | 2.790428 | 0.0173449           | 1.4008119  | 60      |
| 1       | 0.358640 | 0.933476 | 0.384198 | 2.602826  | 1.071265 | 2.788315 | 0.0173878           | 1.3988395  | 59      |
| 2       | 0.358911 | 0.933372 | 0.384532 | 2.600566  | 1.071384 | 2.786206 | 0.0174308           | 1.3968705  | 58      |
| 3       | 0.359183 | 0.933267 | 0.384866 | 2.598309  | 1.071504 | 2.784100 | 0.0174738           | 1.3949050  | 57      |
| 4       | 0.359454 | 0.933163 | 0.385200 | 2.596056  | 1.071624 | 2.781997 | 0.0175169           | 1.3929428  | 56      |
| 5       | 0.359725 | 0.933058 | 0.385534 | 2.593807  | 1.071744 | 2.779898 | 0.0175601           | 1.3909841  | 55      |
| 6       | 0.359997 | 0.932954 | 0.385868 | 2.591561  | 1.071865 | 2.777802 | 0.0176034           | 1.3890287  | 54      |
| 7       | 0.360268 | 0.932849 | 0.386202 | 2.589318  | 1.071985 | 2.775710 | 0.0176468           | 1.3870768  | 53      |
| 8       | 0.360540 | 0.932744 | 0.386536 | 2.587078  | 1.072106 | 2.773621 | 0.0176902           | 1.3851282  | 52      |
| 9       | 0.360811 | 0.932639 | 0.386871 | 2.584842  | 1.072226 | 2.771535 | 0.0177337           | 1.3831829  | 51      |
| 10      | 0.361082 | 0.932534 | 0.387205 | 2.582609  | 1.072347 | 2.769453 | 0.0177773           | 1.3812411  | 50      |
| 11      | 0.361353 | 0.932429 | 0.387540 | 2.580380  | 1.072468 | 2.767374 | 0.0178209           | 1.3793026  | 49      |
| 12      | 0.361625 | 0.932324 | 0.387874 | 2.578154  | 1.072589 | 2.765299 | 0.0178646           | 1.3773674  | 48      |
| 13      | 0.361896 | 0.932219 | 0.388209 | 2.575931  | 1.072710 | 2.763227 | 0.0179084           | 1.3754356  | 47      |
| 14      | 0.362167 | 0.932113 | 0.388544 | 2.573712  | 1.072831 | 2.761158 | 0.0179523           | 1.3735071  | 46      |
| 15      | 0.362438 | 0.932008 | 0.388879 | 2.571496  | 1.072952 | 2.759092 | 0.0179963           | 1.3715819  | 45      |
| 16      | 0.362709 | 0.931902 | 0.389214 | 2.569283  | 1.073074 | 2.757030 | 0.0180403           | 1.3696600  | 44      |
| 17      | 0.362980 | 0.931797 | 0.389549 | 2.567074  | 1.073195 | 2.754971 | 0.0180844           | 1.3677414  | 43      |
| 18      | 0.363251 | 0.931691 | 0.389884 | 2.564867  | 1.073317 | 2.752916 | 0.0181286           | 1.3658262  | 42      |
| 19      | 0.363522 | 0.931586 | 0.390219 | 2.562665  | 1.073439 | 2.750863 | 0.0181728           | 1.3639142  | 41      |
| 20      | 0.363793 | 0.931480 | 0.390554 | 2.560465  | 1.073561 | 2.748814 | 0.0182172           | 1.3620055  | 40      |
| 21      | 0.364064 | 0.931374 | 0.390889 | 2.558269  | 1.073683 | 2.746769 | 0.0182616           | 1.3601001  | 39      |
| 22      | 0.364335 | 0.931268 | 0.391225 | 2.556076  | 1.073805 | 2.744726 | 0.0183061           | 1.3581979  | 38      |
| 23      | 0.364606 | 0.931162 | 0.391560 | 2.553886  | 1.073927 | 2.742687 | 0.0183506           | 1.3562990  | 37      |
| 24      | 0.364877 | 0.931056 | 0.391896 | 2.551699  | 1.074049 | 2.740651 | 0.0183953           | 1.3544034  | 36      |
| 25      | 0.365148 | 0.930950 | 0.392231 | 2.549516  | 1.074172 | 2.738616 | 0.0184400           | 1.3525110  | 35      |
| 26      | 0.365418 | 0.930843 | 0.392567 | 2.547336  | 1.074295 | 2.736589 | 0.0184848           | 1.3506218  | 34      |
| 27      | 0.365689 | 0.930737 | 0.392903 | 2.545159  | 1.074417 | 2.734563 | 0.0185296           | 1.3487359  | 33      |
| 28      | 0.365960 | 0.930631 | 0.393239 | 2.542985  | 1.074540 | 2.732540 | 0.0185744           | 1.3468532  | 32      |
| 29      | 0.366231 | 0.930524 | 0.393574 | 2.540815  | 1.074663 | 2.730520 | 0.0186196           | 1.3449737  | 31      |
| 30      | 0.366501 | 0.930418 | 0.393910 | 2.538648  | 1.074786 | 2.728504 | 0.0186647           | 1.3430974  | 30      |
| 31      | 0.366772 | 0.930311 | 0.394247 | 2.536484  | 1.074909 | 2.726491 | 0.0187099           | 1.3412243  | 29      |
| 32      | 0.367042 | 0.930204 | 0.394583 | 2.534323  | 1.075033 | 2.724480 | 0.0187551           | 1.3393544  | 28      |
| 33      | 0.367313 | 0.930097 | 0.394919 | 2.532165  | 1.075156 | 2.722474 | 0.0188004           | 1.3374876  | 27      |
| 34      | 0.367584 | 0.929990 | 0.395255 | 2.530011  | 1.075280 | 2.720470 | 0.0188458           | 1.3356241  | 26      |
| 35      | 0.367854 | 0.929884 | 0.395592 | 2.527860  | 1.075403 | 2.718469 | 0.0188913           | 1.3337675  | 25      |
| 36      | 0.368125 | 0.929777 | 0.395928 | 2.525712  | 1.075527 | 2.716472 | 0.0189369           | 1.3319065  | 24      |
| 37      | 0.368395 | 0.929669 | 0.396265 | 2.523567  | 1.075651 | 2.714478 | 0.0189825           | 1.3300524  | 23      |
| 38      | 0.368665 | 0.929562 | 0.396601 | 2.521425  | 1.075775 | 2.712487 | 0.0190282           | 1.3282015  | 22      |
| 39      | 0.368936 | 0.929455 | 0.396938 | 2.519286  | 1.075899 | 2.710499 | 0.0190740           | 1.3263537  | 21      |
| 40      | 0.369206 | 0.929348 | 0.397275 | 2.517151  | 1.076024 | 2.708514 | 0.0191199           | 1.3245091  | 20      |
| 41      | 0.369477 | 0.929240 | 0.397611 | 2.515018  | 1.076148 | 2.706532 | 0.0191659           | 1.3226676  | 19      |
| 42      | 0.369747 | 0.929133 | 0.397948 | 2.512889  | 1.076273 | 2.704554 | 0.0192119           | 1.3208292  | 18      |
| 43      | 0.370017 | 0.929025 | 0.398285 | 2.510763  | 1.076397 | 2.702578 | 0.0192580           | 1.3189939  | 17      |
| 44      | 0.370287 | 0.928917 | 0.398622 | 2.508640  | 1.076522 | 2.700606 | 0.0193042           | 1.3171617  | 16      |
| 45      | 0.370557 | 0.928810 | 0.398960 | 2.506520  | 1.076647 | 2.698637 | 0.0193504           | 1.3153326  | 15      |
| 46      | 0.370828 | 0.928702 | 0.399297 | 2.504403  | 1.076772 | 2.696671 | 0.0193968           | 1.3135066  | 14      |
| 47      | 0.371098 | 0.928594 | 0.399634 | 2.502289  | 1.076897 | 2.694708 | 0.0194432           | 1.3116837  | 13      |
| 48      | 0.371368 | 0.928486 | 0.399971 | 2.500177  | 1.077022 | 2.692748 | 0.0194897           | 1.3098638  | 12      |
| 49      | 0.371638 | 0.928378 | 0.400309 | 2.498071  | 1.077148 | 2.690791 | 0.0195363           | 1.3080470  | 11      |
| 50      | 0.371908 | 0.928270 | 0.400646 | 2.495966  | 1.077273 | 2.688837 | 0.0195829           | 1.3062333  | 10      |
| 51      | 0.372178 | 0.928161 | 0.400984 | 2.493865  | 1.077399 | 2.686887 | 0.0196296           | 1.3044227  | 9       |
| 52      | 0.372448 | 0.928053 | 0.401322 | 2.491766  | 1.077525 | 2.684939 | 0.0196765           | 1.3026150  | 8       |
| 53      | 0.372718 | 0.927945 | 0.401660 | 2.489671  | 1.077650 | 2.682995 | 0.0197233           | 1.3008105  | 7       |
| 54      | 0.372988 | 0.927836 | 0.401997 | 2.487578  | 1.077776 | 2.681053 | 0.0197703           | 1.2990089  | 6       |
| 55      | 0.373258 | 0.927728 | 0.402335 | 2.485489  | 1.077902 | 2.679114 | 0.0198174           | 1.2972104  | 5       |
| 56      | 0.373528 | 0.927619 | 0.402673 | 2.483402  | 1.078029 | 2.677179 | 0.0198645           | 1.2954149  | 4       |
| 57      | 0.373797 | 0.927510 | 0.403011 | 2.481319  | 1.078155 | 2.675247 | 0.0199117           | 1.2936224  | 3       |
| 58      | 0.374067 | 0.927402 | 0.403350 | 2.479239  | 1.078281 | 2.673317 | 0.0199590           | 1.2918329  | 2       |
| 59      | 0.374337 | 0.927293 | 0.403688 | 2.477161  | 1.078408 | 2.671391 | 0.0200063           | 1.2900465  | 1       |
| 60      | 0.374607 | 0.927184 | 0.404026 | 2.475087  | 1.078535 | 2.669467 | 0.0200538           | 1.2882630  | 0       |

↑ 111° or 291°

68° or 248° ↑

TRIGONOMETRY TABLES

↓ 22° or 202° **Trigonometric and Involute Functions** 157° or 337° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>22°-23° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.374607 | 0.927184 | 0.404026 | 2.475087  | 1.078535 | 2.669467 | 0.0200538           | 1.2882630  | 60      |
| 1       | 0.374876 | 0.927075 | 0.404365 | 2.473015  | 1.078662 | 2.667547 | 0.0201013           | 1.2864825  | 59      |
| 2       | 0.375146 | 0.926966 | 0.404703 | 2.470947  | 1.078788 | 2.665629 | 0.0201489           | 1.2847049  | 58      |
| 3       | 0.375416 | 0.926857 | 0.405042 | 2.468882  | 1.078916 | 2.663715 | 0.0201966           | 1.2829304  | 57      |
| 4       | 0.375685 | 0.926747 | 0.405380 | 2.466819  | 1.079043 | 2.661803 | 0.0202444           | 1.2811588  | 56      |
| 5       | 0.375955 | 0.926638 | 0.405719 | 2.464760  | 1.079170 | 2.659895 | 0.0202922           | 1.2793901  | 55      |
| 6       | 0.376224 | 0.926529 | 0.406058 | 2.462703  | 1.079297 | 2.657989 | 0.0203401           | 1.2776245  | 54      |
| 7       | 0.376494 | 0.926419 | 0.406397 | 2.460649  | 1.079425 | 2.656086 | 0.0203881           | 1.2758617  | 53      |
| 8       | 0.376763 | 0.926310 | 0.406736 | 2.458599  | 1.079553 | 2.654187 | 0.0204362           | 1.2741019  | 52      |
| 9       | 0.377033 | 0.926200 | 0.407075 | 2.456551  | 1.079680 | 2.652290 | 0.0204844           | 1.2723451  | 51      |
| 10      | 0.377302 | 0.926090 | 0.407414 | 2.454506  | 1.079808 | 2.650396 | 0.0205326           | 1.2705911  | 50      |
| 11      | 0.377571 | 0.925980 | 0.407753 | 2.452464  | 1.079936 | 2.648505 | 0.0205809           | 1.2688401  | 49      |
| 12      | 0.377841 | 0.925871 | 0.408092 | 2.450425  | 1.080065 | 2.646617 | 0.0206293           | 1.2670920  | 48      |
| 13      | 0.378110 | 0.925761 | 0.408432 | 2.448389  | 1.080193 | 2.644732 | 0.0206778           | 1.2653468  | 47      |
| 14      | 0.378379 | 0.925651 | 0.408771 | 2.446356  | 1.080321 | 2.642850 | 0.0207264           | 1.2636044  | 46      |
| 15      | 0.378649 | 0.925541 | 0.409111 | 2.444326  | 1.080450 | 2.640971 | 0.0207750           | 1.2618650  | 45      |
| 16      | 0.378918 | 0.925430 | 0.409450 | 2.442298  | 1.080578 | 2.639095 | 0.0208238           | 1.2601285  | 44      |
| 17      | 0.379187 | 0.925320 | 0.409790 | 2.440274  | 1.080707 | 2.637221 | 0.0208726           | 1.2583948  | 43      |
| 18      | 0.379456 | 0.925210 | 0.410130 | 2.438252  | 1.080836 | 2.635351 | 0.0209215           | 1.2566640  | 42      |
| 19      | 0.379725 | 0.925099 | 0.410470 | 2.436233  | 1.080965 | 2.633483 | 0.0209704           | 1.2549361  | 41      |
| 20      | 0.379994 | 0.924989 | 0.410810 | 2.434217  | 1.081094 | 2.631618 | 0.0210195           | 1.2532111  | 40      |
| 21      | 0.380263 | 0.924878 | 0.411150 | 2.432204  | 1.081223 | 2.629756 | 0.0210686           | 1.2514889  | 39      |
| 22      | 0.380532 | 0.924768 | 0.411490 | 2.430194  | 1.081353 | 2.627897 | 0.0211178           | 1.2497695  | 38      |
| 23      | 0.380801 | 0.924657 | 0.411830 | 2.428186  | 1.081482 | 2.626041 | 0.0211671           | 1.2480530  | 37      |
| 24      | 0.381070 | 0.924546 | 0.412170 | 2.426182  | 1.081612 | 2.624187 | 0.0212165           | 1.2463393  | 36      |
| 25      | 0.381339 | 0.924435 | 0.412511 | 2.424180  | 1.081742 | 2.622337 | 0.0212660           | 1.2446284  | 35      |
| 26      | 0.381608 | 0.924324 | 0.412851 | 2.422181  | 1.081872 | 2.620489 | 0.0213155           | 1.2429204  | 34      |
| 27      | 0.381877 | 0.924213 | 0.413192 | 2.420185  | 1.082002 | 2.618644 | 0.0213651           | 1.2412152  | 33      |
| 28      | 0.382146 | 0.924102 | 0.413532 | 2.418192  | 1.082132 | 2.616802 | 0.0214148           | 1.2395127  | 32      |
| 29      | 0.382415 | 0.923991 | 0.413873 | 2.416201  | 1.082262 | 2.614962 | 0.0214646           | 1.2378131  | 31      |
| 30      | 0.382684 | 0.923880 | 0.414214 | 2.414214  | 1.082392 | 2.613126 | 0.0215145           | 1.2361163  | 30      |
| 31      | 0.382952 | 0.923768 | 0.414554 | 2.412229  | 1.082523 | 2.611292 | 0.0215644           | 1.2344223  | 29      |
| 32      | 0.383221 | 0.923657 | 0.414895 | 2.410247  | 1.082653 | 2.609461 | 0.0216145           | 1.2327310  | 28      |
| 33      | 0.383490 | 0.923545 | 0.415236 | 2.408267  | 1.082784 | 2.607633 | 0.0216646           | 1.2310426  | 27      |
| 34      | 0.383758 | 0.923434 | 0.415577 | 2.406291  | 1.082915 | 2.605808 | 0.0217148           | 1.2293569  | 26      |
| 35      | 0.384027 | 0.923322 | 0.415919 | 2.404317  | 1.083046 | 2.603985 | 0.0217651           | 1.2276740  | 25      |
| 36      | 0.384295 | 0.923210 | 0.416260 | 2.402346  | 1.083177 | 2.602165 | 0.0218154           | 1.2259968  | 24      |
| 37      | 0.384564 | 0.923098 | 0.416601 | 2.400377  | 1.083308 | 2.600348 | 0.0218659           | 1.2243164  | 23      |
| 38      | 0.384832 | 0.922986 | 0.416943 | 2.398412  | 1.083439 | 2.598534 | 0.0219164           | 1.2226417  | 22      |
| 39      | 0.385101 | 0.922875 | 0.417284 | 2.396449  | 1.083571 | 2.596723 | 0.0219670           | 1.2209698  | 21      |
| 40      | 0.385369 | 0.922762 | 0.417626 | 2.394489  | 1.083703 | 2.594914 | 0.0220177           | 1.2193006  | 20      |
| 41      | 0.385638 | 0.922650 | 0.417967 | 2.392532  | 1.083834 | 2.593108 | 0.0220685           | 1.2176341  | 19      |
| 42      | 0.385906 | 0.922538 | 0.418309 | 2.390577  | 1.083966 | 2.591304 | 0.0221193           | 1.2159704  | 18      |
| 43      | 0.386174 | 0.922426 | 0.418651 | 2.388625  | 1.084098 | 2.589504 | 0.0221703           | 1.2143093  | 17      |
| 44      | 0.386443 | 0.922313 | 0.418993 | 2.386676  | 1.084230 | 2.587706 | 0.0222213           | 1.2126510  | 16      |
| 45      | 0.386711 | 0.922201 | 0.419335 | 2.384729  | 1.084362 | 2.585911 | 0.0222724           | 1.2109954  | 15      |
| 46      | 0.386979 | 0.922088 | 0.419677 | 2.382786  | 1.084495 | 2.584118 | 0.0223236           | 1.2093425  | 14      |
| 47      | 0.387247 | 0.921976 | 0.420019 | 2.380844  | 1.084627 | 2.582328 | 0.0223749           | 1.2076923  | 13      |
| 48      | 0.387516 | 0.921864 | 0.420361 | 2.378906  | 1.084760 | 2.580541 | 0.0224262           | 1.2060447  | 12      |
| 49      | 0.387784 | 0.921750 | 0.420704 | 2.376970  | 1.084892 | 2.578757 | 0.0224777           | 1.2043999  | 11      |
| 50      | 0.388052 | 0.921638 | 0.421046 | 2.375037  | 1.085025 | 2.576975 | 0.0225292           | 1.2027577  | 10      |
| 51      | 0.388320 | 0.921525 | 0.421389 | 2.373107  | 1.085158 | 2.575196 | 0.0225808           | 1.2011182  | 9       |
| 52      | 0.388588 | 0.921412 | 0.421731 | 2.371179  | 1.085291 | 2.573420 | 0.0226325           | 1.1994814  | 8       |
| 53      | 0.388856 | 0.921299 | 0.422074 | 2.369254  | 1.085424 | 2.571646 | 0.0226843           | 1.1978472  | 7       |
| 54      | 0.389124 | 0.921185 | 0.422417 | 2.367332  | 1.085558 | 2.569875 | 0.0227361           | 1.1962156  | 6       |
| 55      | 0.389392 | 0.921072 | 0.422759 | 2.365412  | 1.085691 | 2.568107 | 0.0227881           | 1.1945867  | 5       |
| 56      | 0.389660 | 0.920959 | 0.423102 | 2.363495  | 1.085825 | 2.566341 | 0.0228401           | 1.1929605  | 4       |
| 57      | 0.389928 | 0.920845 | 0.423445 | 2.361580  | 1.085959 | 2.564578 | 0.0228922           | 1.1913369  | 3       |
| 58      | 0.390196 | 0.920732 | 0.423788 | 2.359668  | 1.086092 | 2.562818 | 0.0229444           | 1.1897159  | 2       |
| 59      | 0.390463 | 0.920618 | 0.424131 | 2.357759  | 1.086226 | 2.561060 | 0.0229967           | 1.1880975  | 1       |
| 60      | 0.390731 | 0.920505 | 0.424475 | 2.355852  | 1.086360 | 2.559305 | 0.0230491           | 1.1864818  | 0       |

↑ 112° or 292°

67° or 247° ↑

↓ 23° or 203° Trigonometric and Involute Functions 156° or 336° ↓

| Minutes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute<br>23°-24° | Read<br>Up          | Minutes |
|---------|----------|----------|-----------|-----------|----------|----------|---------------------|---------------------|---------|
| 0       | 0.390731 | 0.920505 | 0.424475  | 2.355852  | 1.086360 | 2.559305 | 0.0230491           | 1.1864818           | 60      |
| 1       | 0.390999 | 0.920391 | 0.424818  | 2.353948  | 1.086495 | 2.557552 | 0.0231015           | 1.1848686           | 59      |
| 2       | 0.391267 | 0.920277 | 0.425162  | 2.352047  | 1.086629 | 2.555802 | 0.0231541           | 1.1832581           | 58      |
| 3       | 0.391534 | 0.920164 | 0.425505  | 2.350148  | 1.086763 | 2.554055 | 0.0232067           | 1.1816502           | 57      |
| 4       | 0.391802 | 0.920050 | 0.425849  | 2.348252  | 1.086898 | 2.552310 | 0.0232594           | 1.1800448           | 56      |
| 5       | 0.392070 | 0.919936 | 0.426192  | 2.346358  | 1.087033 | 2.550568 | 0.0233122           | 1.1784421           | 55      |
| 6       | 0.392337 | 0.919821 | 0.426536  | 2.344467  | 1.087167 | 2.548828 | 0.0233651           | 1.1768419           | 54      |
| 7       | 0.392605 | 0.919707 | 0.426880  | 2.342579  | 1.087302 | 2.547091 | 0.0234181           | 1.1752443           | 53      |
| 8       | 0.392872 | 0.919593 | 0.427224  | 2.340693  | 1.087437 | 2.545357 | 0.0234711           | 1.1736493           | 52      |
| 9       | 0.393140 | 0.919479 | 0.427568  | 2.338809  | 1.087573 | 2.543625 | 0.0235242           | 1.1720569           | 51      |
| 10      | 0.393407 | 0.919364 | 0.427912  | 2.336929  | 1.087708 | 2.541896 | 0.0235775           | 1.1704670           | 50      |
| 11      | 0.393675 | 0.919250 | 0.428256  | 2.335050  | 1.087843 | 2.540169 | 0.0236308           | 1.1688797           | 49      |
| 12      | 0.393942 | 0.919135 | 0.428601  | 2.333175  | 1.087979 | 2.538445 | 0.0236842           | 1.1672949           | 48      |
| 13      | 0.394209 | 0.919021 | 0.428945  | 2.331302  | 1.088115 | 2.536724 | 0.0237376           | 1.1657126           | 47      |
| 14      | 0.394477 | 0.918906 | 0.429289  | 2.329431  | 1.088251 | 2.535005 | 0.0237912           | 1.1641329           | 46      |
| 15      | 0.394744 | 0.918791 | 0.429634  | 2.327563  | 1.088387 | 2.533288 | 0.0238446           | 1.1625558           | 45      |
| 16      | 0.395011 | 0.918676 | 0.429979  | 2.325698  | 1.088523 | 2.531574 | 0.0238989           | 1.1609811           | 44      |
| 17      | 0.395278 | 0.918561 | 0.430323  | 2.323835  | 1.088659 | 2.529863 | 0.0239524           | 1.1594090           | 43      |
| 18      | 0.395546 | 0.918446 | 0.430668  | 2.321974  | 1.088795 | 2.528154 | 0.0240063           | 1.1578394           | 42      |
| 19      | 0.395813 | 0.918331 | 0.431013  | 2.320116  | 1.088932 | 2.526448 | 0.0240603           | 1.1562713           | 41      |
| 20      | 0.396080 | 0.918216 | 0.431358  | 2.318261  | 1.089068 | 2.524744 | 0.0241144           | 1.1547077           | 40      |
| 21      | 0.396347 | 0.918101 | 0.431703  | 2.316408  | 1.089205 | 2.523043 | 0.0241686           | 1.1531457           | 39      |
| 22      | 0.396614 | 0.917986 | 0.432048  | 2.314557  | 1.089342 | 2.521344 | 0.0242228           | 1.1515861           | 38      |
| 23      | 0.396881 | 0.917870 | 0.432393  | 2.312709  | 1.089479 | 2.519648 | 0.0242772           | 1.1500290           | 37      |
| 24      | 0.397148 | 0.917755 | 0.432739  | 2.310864  | 1.089616 | 2.517954 | 0.0243316           | 1.1484744           | 36      |
| 25      | 0.397415 | 0.917639 | 0.433084  | 2.309021  | 1.089753 | 2.516262 | 0.0243861           | 1.1469222           | 35      |
| 26      | 0.397682 | 0.917523 | 0.433430  | 2.307180  | 1.089890 | 2.514574 | 0.0244407           | 1.1453726           | 34      |
| 27      | 0.397949 | 0.917408 | 0.433775  | 2.305342  | 1.090028 | 2.512887 | 0.0244954           | 1.1438254           | 33      |
| 28      | 0.398215 | 0.917292 | 0.434121  | 2.303506  | 1.090166 | 2.511203 | 0.0245502           | 1.1422807           | 32      |
| 29      | 0.398482 | 0.917176 | 0.434467  | 2.301673  | 1.090303 | 2.509522 | 0.0246050           | 1.1407384           | 31      |
| 30      | 0.398749 | 0.917060 | 0.434812  | 2.299843  | 1.090441 | 2.507843 | 0.0246600           | 1.1391986           | 30      |
| 31      | 0.399016 | 0.916944 | 0.435158  | 2.298014  | 1.090579 | 2.506166 | 0.0247150           | 1.1376612           | 29      |
| 32      | 0.399283 | 0.916828 | 0.435504  | 2.296188  | 1.090717 | 2.504492 | 0.0247702           | 1.1361263           | 28      |
| 33      | 0.399549 | 0.916712 | 0.435850  | 2.294365  | 1.090855 | 2.502821 | 0.0248254           | 1.1345938           | 27      |
| 34      | 0.399816 | 0.916595 | 0.436197  | 2.292544  | 1.090994 | 2.501151 | 0.0248807           | 1.1330638           | 26      |
| 35      | 0.400082 | 0.916479 | 0.436543  | 2.290726  | 1.091132 | 2.499485 | 0.0249361           | 1.1315361           | 25      |
| 36      | 0.400349 | 0.916363 | 0.436889  | 2.288910  | 1.091271 | 2.497820 | 0.0249916           | 1.1300109           | 24      |
| 37      | 0.400616 | 0.916246 | 0.437236  | 2.287096  | 1.091410 | 2.496159 | 0.0250471           | 1.1284882           | 23      |
| 38      | 0.400882 | 0.916130 | 0.437582  | 2.285285  | 1.091549 | 2.494499 | 0.0251028           | 1.1269678           | 22      |
| 39      | 0.401149 | 0.916013 | 0.437929  | 2.283476  | 1.091688 | 2.492842 | 0.0251585           | 1.1254498           | 21      |
| 40      | 0.401415 | 0.915896 | 0.438276  | 2.281669  | 1.091827 | 2.491187 | 0.0252143           | 1.1239342           | 20      |
| 41      | 0.401681 | 0.915779 | 0.438622  | 2.279865  | 1.091966 | 2.489535 | 0.0252703           | 1.1224211           | 19      |
| 42      | 0.401948 | 0.915663 | 0.438969  | 2.278064  | 1.092105 | 2.487885 | 0.0253263           | 1.1209103           | 18      |
| 43      | 0.402214 | 0.915546 | 0.439316  | 2.276264  | 1.092245 | 2.486238 | 0.0253824           | 1.1194019           | 17      |
| 44      | 0.402480 | 0.915429 | 0.439663  | 2.274467  | 1.092384 | 2.484593 | 0.0254386           | 1.1178959           | 16      |
| 45      | 0.402747 | 0.915311 | 0.440011  | 2.272673  | 1.092524 | 2.482950 | 0.0254948           | 1.1163922           | 15      |
| 46      | 0.403013 | 0.915194 | 0.440358  | 2.270881  | 1.092664 | 2.481310 | 0.0255512           | 1.1148910           | 14      |
| 47      | 0.403279 | 0.915077 | 0.440705  | 2.269091  | 1.092804 | 2.479672 | 0.0256076           | 1.1133921           | 13      |
| 48      | 0.403545 | 0.914960 | 0.441053  | 2.267304  | 1.092944 | 2.478037 | 0.0256642           | 1.1118955           | 12      |
| 49      | 0.403811 | 0.914842 | 0.441400  | 2.265518  | 1.093085 | 2.476403 | 0.0257208           | 1.1104014           | 11      |
| 50      | 0.404078 | 0.914725 | 0.441748  | 2.263736  | 1.093225 | 2.474773 | 0.0257775           | 1.1089095           | 10      |
| 51      | 0.404344 | 0.914607 | 0.442095  | 2.261955  | 1.093366 | 2.473144 | 0.0258343           | 1.1074201           | 9       |
| 52      | 0.404610 | 0.914490 | 0.442443  | 2.260177  | 1.093506 | 2.471518 | 0.0258912           | 1.1059329           | 8       |
| 53      | 0.404876 | 0.914372 | 0.442791  | 2.258402  | 1.093647 | 2.469894 | 0.0259482           | 1.1044481           | 7       |
| 54      | 0.405142 | 0.914254 | 0.443139  | 2.256628  | 1.093788 | 2.468273 | 0.0260053           | 1.1029656           | 6       |
| 55      | 0.405408 | 0.914136 | 0.443487  | 2.254857  | 1.093929 | 2.466654 | 0.0260625           | 1.1014855           | 5       |
| 56      | 0.405673 | 0.914018 | 0.443835  | 2.253089  | 1.094070 | 2.465037 | 0.0261197           | 1.1000077           | 4       |
| 57      | 0.405939 | 0.913900 | 0.444183  | 2.251322  | 1.094212 | 2.463423 | 0.0261771           | 1.0985321           | 3       |
| 58      | 0.406205 | 0.913782 | 0.444532  | 2.249558  | 1.094353 | 2.461811 | 0.0262345           | 1.0970589           | 2       |
| 59      | 0.406471 | 0.913664 | 0.444880  | 2.247796  | 1.094495 | 2.460201 | 0.0262920           | 1.0955881           | 1       |
| 60      | 0.406737 | 0.913545 | 0.445229  | 2.246037  | 1.094636 | 2.458593 | 0.0263497           | 1.0941195           | 0       |
| Minutes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read<br>Down        | 66°-67°<br>Involute | Minutes |

↑ 113° or 293°

66° or 246° ↑

TRIGONOMETRY TABLES

↓ 24° or 204° Trigonometric and Involute Functions 155° or 335° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>24°-25° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.406737 | 0.913545 | 0.445229 | 2.246037  | 1.094636 | 2.458593 | 0.0263497           | 1.0941195  | 60      |
| 1       | 0.407002 | 0.913427 | 0.445577 | 2.244280  | 1.094778 | 2.456988 | 0.0264074           | 1.0926532  | 59      |
| 2       | 0.407268 | 0.913309 | 0.445926 | 2.242525  | 1.094920 | 2.455385 | 0.0264652           | 1.0911892  | 58      |
| 3       | 0.407534 | 0.913190 | 0.446275 | 2.240772  | 1.095062 | 2.453785 | 0.0265231           | 1.0897275  | 57      |
| 4       | 0.407799 | 0.913072 | 0.446624 | 2.239022  | 1.095204 | 2.452186 | 0.0265810           | 1.0882680  | 56      |
| 5       | 0.408065 | 0.912953 | 0.446973 | 2.237274  | 1.095347 | 2.450591 | 0.0266391           | 1.0868109  | 55      |
| 6       | 0.408330 | 0.912834 | 0.447322 | 2.235528  | 1.095489 | 2.448997 | 0.0266973           | 1.0853560  | 54      |
| 7       | 0.408596 | 0.912715 | 0.447671 | 2.233785  | 1.095632 | 2.447405 | 0.0267555           | 1.0839034  | 53      |
| 8       | 0.408861 | 0.912596 | 0.448020 | 2.232043  | 1.095775 | 2.445816 | 0.0268139           | 1.0824531  | 52      |
| 9       | 0.409127 | 0.912477 | 0.448369 | 2.230304  | 1.095917 | 2.444229 | 0.0268723           | 1.0810050  | 51      |
| 10      | 0.409392 | 0.912358 | 0.448719 | 2.228568  | 1.096060 | 2.442645 | 0.0269308           | 1.0795592  | 50      |
| 11      | 0.409658 | 0.912239 | 0.449068 | 2.226833  | 1.096204 | 2.441062 | 0.0269894           | 1.0781156  | 49      |
| 12      | 0.409923 | 0.912120 | 0.449418 | 2.225101  | 1.096347 | 2.439482 | 0.0270481           | 1.0766743  | 48      |
| 13      | 0.410188 | 0.912001 | 0.449768 | 2.223371  | 1.096490 | 2.437904 | 0.0271069           | 1.0752352  | 47      |
| 14      | 0.410454 | 0.911881 | 0.450117 | 2.221643  | 1.096634 | 2.436329 | 0.0271658           | 1.0737983  | 46      |
| 15      | 0.410719 | 0.911762 | 0.450467 | 2.219918  | 1.096777 | 2.434756 | 0.0272248           | 1.0723637  | 45      |
| 16      | 0.410984 | 0.911643 | 0.450817 | 2.218194  | 1.096921 | 2.433184 | 0.0272839           | 1.0709313  | 44      |
| 17      | 0.411249 | 0.911523 | 0.451167 | 2.216473  | 1.097065 | 2.431616 | 0.0273430           | 1.0695011  | 43      |
| 18      | 0.411514 | 0.911403 | 0.451517 | 2.214754  | 1.097209 | 2.430049 | 0.0274023           | 1.0680732  | 42      |
| 19      | 0.411779 | 0.911284 | 0.451868 | 2.213038  | 1.097353 | 2.428484 | 0.0274617           | 1.0666474  | 41      |
| 20      | 0.412045 | 0.911164 | 0.452218 | 2.211323  | 1.097498 | 2.426922 | 0.0275211           | 1.0652239  | 40      |
| 21      | 0.412310 | 0.911044 | 0.452568 | 2.209611  | 1.097642 | 2.425362 | 0.0275806           | 1.0638026  | 39      |
| 22      | 0.412575 | 0.910924 | 0.452919 | 2.207901  | 1.097787 | 2.423804 | 0.0276403           | 1.0623835  | 38      |
| 23      | 0.412840 | 0.910804 | 0.453269 | 2.206193  | 1.097931 | 2.422249 | 0.0277000           | 1.0609665  | 37      |
| 24      | 0.413104 | 0.910684 | 0.453620 | 2.204488  | 1.098076 | 2.420695 | 0.0277598           | 1.0595518  | 36      |
| 25      | 0.413369 | 0.910563 | 0.453971 | 2.202784  | 1.098221 | 2.419144 | 0.0278197           | 1.0581392  | 35      |
| 26      | 0.413634 | 0.910443 | 0.454322 | 2.201083  | 1.098366 | 2.417595 | 0.0278797           | 1.0567288  | 34      |
| 27      | 0.413899 | 0.910323 | 0.454673 | 2.199384  | 1.098511 | 2.416048 | 0.0279398           | 1.0553206  | 33      |
| 28      | 0.414164 | 0.910202 | 0.455024 | 2.197687  | 1.098657 | 2.414504 | 0.0279999           | 1.0539146  | 32      |
| 29      | 0.414429 | 0.910082 | 0.455375 | 2.195992  | 1.098802 | 2.412961 | 0.0280602           | 1.0525108  | 31      |
| 30      | 0.414693 | 0.909961 | 0.455726 | 2.194300  | 1.098948 | 2.411421 | 0.0281206           | 1.0511091  | 30      |
| 31      | 0.414958 | 0.909841 | 0.456078 | 2.192609  | 1.099094 | 2.409883 | 0.0281810           | 1.0497095  | 29      |
| 32      | 0.415223 | 0.909720 | 0.456429 | 2.190921  | 1.099239 | 2.408347 | 0.0282416           | 1.0483122  | 28      |
| 33      | 0.415487 | 0.909599 | 0.456781 | 2.189235  | 1.099386 | 2.406813 | 0.0283022           | 1.0469169  | 27      |
| 34      | 0.415752 | 0.909478 | 0.457132 | 2.187551  | 1.099532 | 2.405281 | 0.0283630           | 1.0455238  | 26      |
| 35      | 0.416016 | 0.909357 | 0.457484 | 2.185869  | 1.099678 | 2.403752 | 0.0284238           | 1.0441329  | 25      |
| 36      | 0.416281 | 0.909236 | 0.457836 | 2.184189  | 1.099824 | 2.402225 | 0.0284847           | 1.0427441  | 24      |
| 37      | 0.416545 | 0.909115 | 0.458188 | 2.182512  | 1.099971 | 2.400700 | 0.0285458           | 1.0413574  | 23      |
| 38      | 0.416810 | 0.908994 | 0.458540 | 2.180836  | 1.100118 | 2.399176 | 0.0286069           | 1.0399729  | 22      |
| 39      | 0.417074 | 0.908872 | 0.458892 | 2.179163  | 1.100264 | 2.397656 | 0.0286681           | 1.0385905  | 21      |
| 40      | 0.417338 | 0.908751 | 0.459244 | 2.177492  | 1.100411 | 2.396137 | 0.0287294           | 1.0372102  | 20      |
| 41      | 0.417603 | 0.908630 | 0.459596 | 2.175823  | 1.100558 | 2.394620 | 0.0287908           | 1.0358320  | 19      |
| 42      | 0.417867 | 0.908508 | 0.459949 | 2.174156  | 1.100706 | 2.393106 | 0.0288523           | 1.0344559  | 18      |
| 43      | 0.418131 | 0.908387 | 0.460301 | 2.172491  | 1.100853 | 2.391593 | 0.0289139           | 1.0330820  | 17      |
| 44      | 0.418396 | 0.908265 | 0.460654 | 2.170828  | 1.101000 | 2.390083 | 0.0289756           | 1.0317101  | 16      |
| 45      | 0.418660 | 0.908143 | 0.461006 | 2.169168  | 1.101148 | 2.388575 | 0.0290373           | 1.0303403  | 15      |
| 46      | 0.418924 | 0.908021 | 0.461359 | 2.167509  | 1.101296 | 2.387068 | 0.0290992           | 1.0289727  | 14      |
| 47      | 0.419188 | 0.907899 | 0.461712 | 2.165853  | 1.101444 | 2.385564 | 0.0291612           | 1.0276071  | 13      |
| 48      | 0.419452 | 0.907777 | 0.462065 | 2.164198  | 1.101592 | 2.384063 | 0.0292232           | 1.0262436  | 12      |
| 49      | 0.419716 | 0.907655 | 0.462418 | 2.162546  | 1.101740 | 2.382563 | 0.0292854           | 1.0248822  | 11      |
| 50      | 0.419980 | 0.907533 | 0.462771 | 2.160896  | 1.101888 | 2.381065 | 0.0293476           | 1.0235229  | 10      |
| 51      | 0.420244 | 0.907411 | 0.463124 | 2.159248  | 1.102036 | 2.379569 | 0.0294100           | 1.0221656  | 9       |
| 52      | 0.420508 | 0.907289 | 0.463478 | 2.157602  | 1.102185 | 2.378076 | 0.0294724           | 1.0208104  | 8       |
| 53      | 0.420772 | 0.907166 | 0.463831 | 2.155958  | 1.102334 | 2.376584 | 0.0295349           | 1.0194573  | 7       |
| 54      | 0.421036 | 0.907044 | 0.464185 | 2.154316  | 1.102482 | 2.375095 | 0.0295976           | 1.0181062  | 6       |
| 55      | 0.421300 | 0.906922 | 0.464538 | 2.152676  | 1.102631 | 2.373608 | 0.0296603           | 1.0167572  | 5       |
| 56      | 0.421563 | 0.906799 | 0.464892 | 2.151038  | 1.102780 | 2.372122 | 0.0297231           | 1.0154103  | 4       |
| 57      | 0.421827 | 0.906676 | 0.465246 | 2.149402  | 1.102930 | 2.370639 | 0.0297860           | 1.0140654  | 3       |
| 58      | 0.422091 | 0.906554 | 0.465600 | 2.147768  | 1.103079 | 2.369158 | 0.0298490           | 1.0127225  | 2       |
| 59      | 0.422355 | 0.906431 | 0.465954 | 2.146137  | 1.103228 | 2.367679 | 0.0299121           | 1.0113817  | 1       |
| 60      | 0.422618 | 0.906308 | 0.466308 | 2.144507  | 1.103378 | 2.366202 | 0.0299753           | 1.0100429  | 0       |

↑ 114° or 294° 65° or 245° ↑

↓ 25° or 205° **Trigonometric and Involute Functions** 154° or 334° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>25°-26° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.422618 | 0.906308 | 0.466308 | 2.144507  | 1.103378 | 2.366202 | 0.0299753           | 1.0100429  | 60      |
| 1       | 0.422882 | 0.906185 | 0.466662 | 2.142879  | 1.103528 | 2.364727 | 0.0300386           | 1.0087062  | 59      |
| 2       | 0.423145 | 0.906062 | 0.467016 | 2.141254  | 1.103678 | 2.363254 | 0.0301020           | 1.0073714  | 58      |
| 3       | 0.423409 | 0.905939 | 0.467371 | 2.139630  | 1.103828 | 2.361783 | 0.0301655           | 1.0060387  | 57      |
| 4       | 0.423673 | 0.905815 | 0.467725 | 2.138009  | 1.103978 | 2.360314 | 0.0302291           | 1.0047080  | 56      |
| 5       | 0.423936 | 0.905692 | 0.468080 | 2.136389  | 1.104128 | 2.358847 | 0.0302928           | 1.0033794  | 55      |
| 6       | 0.424199 | 0.905569 | 0.468434 | 2.134771  | 1.104278 | 2.357382 | 0.0303566           | 1.0020527  | 54      |
| 7       | 0.424463 | 0.905445 | 0.468789 | 2.133156  | 1.104429 | 2.355919 | 0.0304205           | 1.0007281  | 53      |
| 8       | 0.424726 | 0.905322 | 0.469144 | 2.131542  | 1.104580 | 2.354458 | 0.0304844           | 0.9994054  | 52      |
| 9       | 0.424990 | 0.905198 | 0.469499 | 2.129931  | 1.104730 | 2.352999 | 0.0305485           | 0.9980848  | 51      |
| 10      | 0.425253 | 0.905075 | 0.469854 | 2.128321  | 1.104881 | 2.351542 | 0.0306127           | 0.9967661  | 50      |
| 11      | 0.425516 | 0.904951 | 0.470209 | 2.126714  | 1.105032 | 2.350088 | 0.0306769           | 0.9954495  | 49      |
| 12      | 0.425779 | 0.904827 | 0.470564 | 2.125108  | 1.105184 | 2.348635 | 0.0307413           | 0.9941348  | 48      |
| 13      | 0.426042 | 0.904703 | 0.470920 | 2.123505  | 1.105335 | 2.347184 | 0.0308058           | 0.9928221  | 47      |
| 14      | 0.426306 | 0.904579 | 0.471275 | 2.121903  | 1.105486 | 2.345735 | 0.0308703           | 0.9915114  | 46      |
| 15      | 0.426569 | 0.904455 | 0.471631 | 2.120303  | 1.105638 | 2.344288 | 0.0309350           | 0.9902027  | 45      |
| 16      | 0.426832 | 0.904331 | 0.471986 | 2.118706  | 1.105790 | 2.342843 | 0.0309997           | 0.9888959  | 44      |
| 17      | 0.427095 | 0.904207 | 0.472342 | 2.117110  | 1.105942 | 2.341400 | 0.0310646           | 0.9875912  | 43      |
| 18      | 0.427358 | 0.904083 | 0.472698 | 2.115516  | 1.106094 | 2.339959 | 0.0311295           | 0.9862883  | 42      |
| 19      | 0.427621 | 0.903958 | 0.473054 | 2.113925  | 1.106246 | 2.338520 | 0.0311946           | 0.9849875  | 41      |
| 20      | 0.427884 | 0.903834 | 0.473410 | 2.112335  | 1.106398 | 2.337083 | 0.0312597           | 0.9836886  | 40      |
| 21      | 0.428147 | 0.903709 | 0.473766 | 2.110747  | 1.106551 | 2.335648 | 0.0313250           | 0.9823916  | 39      |
| 22      | 0.428410 | 0.903585 | 0.474122 | 2.109161  | 1.106703 | 2.334215 | 0.0313903           | 0.9810966  | 38      |
| 23      | 0.428672 | 0.903460 | 0.474478 | 2.107577  | 1.106856 | 2.332784 | 0.0314557           | 0.9798035  | 37      |
| 24      | 0.428935 | 0.903335 | 0.474835 | 2.105995  | 1.107009 | 2.331355 | 0.0315213           | 0.9785124  | 36      |
| 25      | 0.429198 | 0.903210 | 0.475191 | 2.104415  | 1.107162 | 2.329928 | 0.0315869           | 0.9772232  | 35      |
| 26      | 0.429461 | 0.903086 | 0.475548 | 2.102837  | 1.107315 | 2.328502 | 0.0316527           | 0.9759360  | 34      |
| 27      | 0.429723 | 0.902961 | 0.475905 | 2.101261  | 1.107468 | 2.327079 | 0.0317185           | 0.9746507  | 33      |
| 28      | 0.429986 | 0.902836 | 0.476262 | 2.099686  | 1.107621 | 2.325658 | 0.0317844           | 0.9733673  | 32      |
| 29      | 0.430249 | 0.902711 | 0.476619 | 2.098114  | 1.107775 | 2.324238 | 0.0318504           | 0.9720858  | 31      |
| 30      | 0.430511 | 0.902585 | 0.476976 | 2.096544  | 1.107929 | 2.322820 | 0.0319166           | 0.9708062  | 30      |
| 31      | 0.430774 | 0.902460 | 0.477333 | 2.094975  | 1.108082 | 2.321405 | 0.0319828           | 0.9695286  | 29      |
| 32      | 0.431036 | 0.902335 | 0.477690 | 2.093408  | 1.108236 | 2.319991 | 0.0320491           | 0.9682529  | 28      |
| 33      | 0.431299 | 0.902209 | 0.478047 | 2.091844  | 1.108390 | 2.318579 | 0.0321156           | 0.9669790  | 27      |
| 34      | 0.431561 | 0.902084 | 0.478405 | 2.090281  | 1.108545 | 2.317169 | 0.0321821           | 0.9657071  | 26      |
| 35      | 0.431823 | 0.901958 | 0.478762 | 2.088720  | 1.108699 | 2.315761 | 0.0322487           | 0.9644371  | 25      |
| 36      | 0.432086 | 0.901833 | 0.479120 | 2.087161  | 1.108855 | 2.314355 | 0.0323154           | 0.9631690  | 24      |
| 37      | 0.432348 | 0.901707 | 0.479477 | 2.085604  | 1.109008 | 2.312951 | 0.0323823           | 0.9619027  | 23      |
| 38      | 0.432610 | 0.901581 | 0.479835 | 2.084049  | 1.109163 | 2.311549 | 0.0324492           | 0.9606384  | 22      |
| 39      | 0.432873 | 0.901455 | 0.480193 | 2.082495  | 1.109318 | 2.310149 | 0.0325162           | 0.9593759  | 21      |
| 40      | 0.433135 | 0.901329 | 0.480551 | 2.080944  | 1.109473 | 2.308750 | 0.0325833           | 0.9581153  | 20      |
| 41      | 0.433397 | 0.901203 | 0.480909 | 2.079394  | 1.109628 | 2.307354 | 0.0326506           | 0.9568566  | 19      |
| 42      | 0.433659 | 0.901077 | 0.481267 | 2.077847  | 1.109783 | 2.305959 | 0.0327179           | 0.9555998  | 18      |
| 43      | 0.433921 | 0.900951 | 0.481626 | 2.076301  | 1.109938 | 2.304566 | 0.0327853           | 0.9543449  | 17      |
| 44      | 0.434183 | 0.900825 | 0.481984 | 2.074757  | 1.110094 | 2.303175 | 0.0328528           | 0.9530918  | 16      |
| 45      | 0.434445 | 0.900698 | 0.482343 | 2.073215  | 1.110250 | 2.301786 | 0.0329205           | 0.9518405  | 15      |
| 46      | 0.434707 | 0.900572 | 0.482701 | 2.071674  | 1.110406 | 2.300399 | 0.0329882           | 0.9505912  | 14      |
| 47      | 0.434969 | 0.900445 | 0.483060 | 2.070136  | 1.110562 | 2.299013 | 0.0330560           | 0.9493436  | 13      |
| 48      | 0.435231 | 0.900319 | 0.483419 | 2.068599  | 1.110718 | 2.297630 | 0.0331239           | 0.9480980  | 12      |
| 49      | 0.435493 | 0.900192 | 0.483778 | 2.067065  | 1.110874 | 2.296248 | 0.0331920           | 0.9468542  | 11      |
| 50      | 0.435755 | 0.900065 | 0.484137 | 2.065532  | 1.111030 | 2.294869 | 0.0332601           | 0.9456122  | 10      |
| 51      | 0.436017 | 0.899939 | 0.484496 | 2.064001  | 1.111187 | 2.293491 | 0.0333283           | 0.9443721  | 9       |
| 52      | 0.436278 | 0.899812 | 0.484855 | 2.062472  | 1.111344 | 2.292115 | 0.0333967           | 0.9431338  | 8       |
| 53      | 0.436540 | 0.899685 | 0.485214 | 2.060944  | 1.111500 | 2.290740 | 0.0334651           | 0.9418973  | 7       |
| 54      | 0.436802 | 0.899558 | 0.485574 | 2.059419  | 1.111657 | 2.289368 | 0.0335336           | 0.9406627  | 6       |
| 55      | 0.437063 | 0.899431 | 0.485933 | 2.057895  | 1.111814 | 2.287997 | 0.0336023           | 0.9394299  | 5       |
| 56      | 0.437325 | 0.899304 | 0.486293 | 2.056373  | 1.111972 | 2.286629 | 0.0336710           | 0.9381989  | 4       |
| 57      | 0.437587 | 0.899176 | 0.486653 | 2.054853  | 1.112129 | 2.285262 | 0.0337399           | 0.9369697  | 3       |
| 58      | 0.437848 | 0.899049 | 0.487013 | 2.053335  | 1.112287 | 2.283897 | 0.0338088           | 0.9357424  | 2       |
| 59      | 0.438110 | 0.898922 | 0.487373 | 2.051818  | 1.112444 | 2.282533 | 0.0338778           | 0.9345168  | 1       |
| 60      | 0.438371 | 0.898794 | 0.487733 | 2.050304  | 1.112602 | 2.281172 | 0.0339470           | 0.9332931  | 0       |

↑ 115° or 295°

64° or 244° ↑



TRIGONOMETRY TABLES

↓ 26° or 206° Trigonometric and Involute Functions 153° or 333° ↓

| Minutes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute<br>26°-27° | Read<br>Up          | Minutes |
|---------|----------|----------|-----------|-----------|----------|----------|---------------------|---------------------|---------|
| 0       | 0.438371 | 0.898794 | 0.487733  | 2.050304  | 1.112602 | 2.281172 | 0.0339470           | 0.9332931           | 60      |
| 1       | 0.438633 | 0.898666 | 0.488093  | 2.048791  | 1.112760 | 2.279812 | 0.0340162           | 0.9320712           | 59      |
| 2       | 0.438894 | 0.898539 | 0.488453  | 2.047280  | 1.112918 | 2.278455 | 0.0340856           | 0.9308511           | 58      |
| 3       | 0.439155 | 0.898411 | 0.488813  | 2.045771  | 1.113076 | 2.277099 | 0.0341550           | 0.9296328           | 57      |
| 4       | 0.439417 | 0.898283 | 0.489174  | 2.044263  | 1.113234 | 2.275744 | 0.0342246           | 0.9284162           | 56      |
| 5       | 0.439678 | 0.898156 | 0.489534  | 2.042758  | 1.113393 | 2.274392 | 0.0342942           | 0.9272015           | 55      |
| 6       | 0.439939 | 0.898028 | 0.489895  | 2.041254  | 1.113552 | 2.273040 | 0.0343640           | 0.9259886           | 54      |
| 7       | 0.440200 | 0.897900 | 0.490256  | 2.039752  | 1.113710 | 2.271693 | 0.0344339           | 0.9247774           | 53      |
| 8       | 0.440462 | 0.897771 | 0.490617  | 2.038252  | 1.113869 | 2.270346 | 0.0345038           | 0.9235680           | 52      |
| 9       | 0.440723 | 0.897643 | 0.490978  | 2.036753  | 1.114028 | 2.269001 | 0.0345739           | 0.9223604           | 51      |
| 10      | 0.440984 | 0.897515 | 0.491339  | 2.035256  | 1.114187 | 2.267657 | 0.0346441           | 0.9211546           | 50      |
| 11      | 0.441245 | 0.897387 | 0.491700  | 2.033762  | 1.114347 | 2.266315 | 0.0347144           | 0.9199506           | 49      |
| 12      | 0.441506 | 0.897258 | 0.492061  | 2.032268  | 1.114506 | 2.264976 | 0.0347847           | 0.9187483           | 48      |
| 13      | 0.441767 | 0.897130 | 0.492422  | 2.030777  | 1.114666 | 2.263638 | 0.0348552           | 0.9175478           | 47      |
| 14      | 0.442028 | 0.897001 | 0.492784  | 2.029287  | 1.114826 | 2.262301 | 0.0349258           | 0.9163490           | 46      |
| 15      | 0.442289 | 0.896873 | 0.493145  | 2.027799  | 1.114985 | 2.260967 | 0.0349965           | 0.9151520           | 45      |
| 16      | 0.442550 | 0.896744 | 0.493507  | 2.026313  | 1.115145 | 2.259634 | 0.0350673           | 0.9139568           | 44      |
| 17      | 0.442810 | 0.896615 | 0.493869  | 2.024829  | 1.115306 | 2.258303 | 0.0351382           | 0.9127633           | 43      |
| 18      | 0.443071 | 0.896486 | 0.494231  | 2.023346  | 1.115466 | 2.256974 | 0.0352092           | 0.9115715           | 42      |
| 19      | 0.443332 | 0.896358 | 0.494593  | 2.021865  | 1.115626 | 2.255646 | 0.0352803           | 0.9103815           | 41      |
| 20      | 0.443593 | 0.896229 | 0.494955  | 2.020386  | 1.115787 | 2.254320 | 0.0353515           | 0.9091932           | 40      |
| 21      | 0.443853 | 0.896099 | 0.495317  | 2.018909  | 1.115948 | 2.252996 | 0.0354228           | 0.9080067           | 39      |
| 22      | 0.444114 | 0.895970 | 0.495679  | 2.017433  | 1.116108 | 2.251674 | 0.0354942           | 0.9068219           | 38      |
| 23      | 0.444375 | 0.895841 | 0.496042  | 2.015959  | 1.116269 | 2.250354 | 0.0355658           | 0.9056389           | 37      |
| 24      | 0.444635 | 0.895712 | 0.496404  | 2.014487  | 1.116431 | 2.249035 | 0.0356374           | 0.9044575           | 36      |
| 25      | 0.444896 | 0.895582 | 0.496767  | 2.013016  | 1.116592 | 2.247718 | 0.0357091           | 0.9032779           | 35      |
| 26      | 0.445156 | 0.895453 | 0.497130  | 2.011548  | 1.116753 | 2.246402 | 0.0357810           | 0.9021000           | 34      |
| 27      | 0.445417 | 0.895323 | 0.497492  | 2.010081  | 1.116915 | 2.245089 | 0.0358529           | 0.9009239           | 33      |
| 28      | 0.445677 | 0.895194 | 0.497855  | 2.008615  | 1.117077 | 2.243777 | 0.0359249           | 0.8997494           | 32      |
| 29      | 0.445937 | 0.895064 | 0.498218  | 2.007152  | 1.117238 | 2.242467 | 0.0359971           | 0.8985767           | 31      |
| 30      | 0.446198 | 0.894934 | 0.498582  | 2.005690  | 1.117400 | 2.241158 | 0.0360694           | 0.8974056           | 30      |
| 31      | 0.446458 | 0.894805 | 0.498945  | 2.004229  | 1.117563 | 2.239852 | 0.0361417           | 0.8962363           | 29      |
| 32      | 0.446718 | 0.894675 | 0.499308  | 2.002771  | 1.117725 | 2.238547 | 0.0362142           | 0.8950687           | 28      |
| 33      | 0.446979 | 0.894545 | 0.499672  | 2.001314  | 1.117887 | 2.237243 | 0.0362868           | 0.8939027           | 27      |
| 34      | 0.447239 | 0.894415 | 0.500035  | 1.999859  | 1.118050 | 2.235942 | 0.0363594           | 0.8927385           | 26      |
| 35      | 0.447499 | 0.894284 | 0.500399  | 1.998406  | 1.118212 | 2.234642 | 0.0364322           | 0.8915760           | 25      |
| 36      | 0.447759 | 0.894154 | 0.500763  | 1.996954  | 1.118375 | 2.233344 | 0.0365051           | 0.8904151           | 24      |
| 37      | 0.448019 | 0.894024 | 0.501127  | 1.995504  | 1.118538 | 2.232047 | 0.0365781           | 0.8892559           | 23      |
| 38      | 0.448279 | 0.893894 | 0.501491  | 1.994055  | 1.118701 | 2.230753 | 0.0366512           | 0.8880985           | 22      |
| 39      | 0.448539 | 0.893763 | 0.501855  | 1.992609  | 1.118865 | 2.229459 | 0.0367244           | 0.8869426           | 21      |
| 40      | 0.448799 | 0.893633 | 0.502219  | 1.991164  | 1.119028 | 2.228168 | 0.0367977           | 0.8857885           | 20      |
| 41      | 0.449059 | 0.893502 | 0.502583  | 1.989720  | 1.119192 | 2.226878 | 0.0368712           | 0.8846361           | 19      |
| 42      | 0.449319 | 0.893371 | 0.502948  | 1.988279  | 1.119355 | 2.225590 | 0.0369447           | 0.8834853           | 18      |
| 43      | 0.449579 | 0.893241 | 0.503312  | 1.986839  | 1.119519 | 2.224304 | 0.0370183           | 0.8823361           | 17      |
| 44      | 0.449839 | 0.893110 | 0.503677  | 1.985400  | 1.119683 | 2.223019 | 0.0370921           | 0.8811887           | 16      |
| 45      | 0.450098 | 0.892979 | 0.504041  | 1.983964  | 1.119847 | 2.221736 | 0.0371659           | 0.8800429           | 15      |
| 46      | 0.450358 | 0.892848 | 0.504406  | 1.982529  | 1.120011 | 2.220455 | 0.0372399           | 0.8788988           | 14      |
| 47      | 0.450618 | 0.892717 | 0.504771  | 1.981095  | 1.120176 | 2.219175 | 0.0373139           | 0.8777563           | 13      |
| 48      | 0.450878 | 0.892586 | 0.505136  | 1.979666  | 1.120340 | 2.217897 | 0.0373881           | 0.8766154           | 12      |
| 49      | 0.451137 | 0.892455 | 0.505502  | 1.978233  | 1.120505 | 2.216621 | 0.0374624           | 0.8754762           | 11      |
| 50      | 0.451397 | 0.892323 | 0.505867  | 1.976805  | 1.120670 | 2.215346 | 0.0375368           | 0.8743387           | 10      |
| 51      | 0.451656 | 0.892192 | 0.506232  | 1.975378  | 1.120835 | 2.214073 | 0.0376113           | 0.8732028           | 9       |
| 52      | 0.451916 | 0.892061 | 0.506598  | 1.973953  | 1.121000 | 2.212802 | 0.0376859           | 0.8720685           | 8       |
| 53      | 0.452175 | 0.891929 | 0.506963  | 1.972530  | 1.121165 | 2.211532 | 0.0377606           | 0.8709359           | 7       |
| 54      | 0.452435 | 0.891798 | 0.507329  | 1.971108  | 1.121331 | 2.210264 | 0.0378354           | 0.8698049           | 6       |
| 55      | 0.452694 | 0.891666 | 0.507695  | 1.969687  | 1.121496 | 2.208997 | 0.0379103           | 0.8686756           | 5       |
| 56      | 0.452953 | 0.891534 | 0.508061  | 1.968269  | 1.121662 | 2.207732 | 0.0379853           | 0.8675478           | 4       |
| 57      | 0.453213 | 0.891402 | 0.508427  | 1.966852  | 1.121828 | 2.206469 | 0.0380605           | 0.8664217           | 3       |
| 58      | 0.453472 | 0.891270 | 0.508793  | 1.965436  | 1.121994 | 2.205208 | 0.0381357           | 0.8652972           | 2       |
| 59      | 0.453731 | 0.891139 | 0.509159  | 1.964023  | 1.122160 | 2.203948 | 0.0382111           | 0.8641743           | 1       |
| 60      | 0.453990 | 0.891007 | 0.509525  | 1.962611  | 1.122326 | 2.202689 | 0.0382866           | 0.8630531           | 0       |
| Minutes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read<br>Down        | 63°-64°<br>Involute | Minutes |

↑ 116° or 296°

63° or 243° ↑

↓ 27° or 207° **Trigonometric and Involute Functions** 152° or 332° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>27°-28° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.453990 | 0.891007 | 0.509525 | 1.962611  | 1.122326 | 2.202689 | 0.0382866           | 0.8630531  | 60      |
| 1       | 0.454250 | 0.890874 | 0.509892 | 1.961200  | 1.122493 | 2.201433 | 0.0383621           | 0.8619334  | 59      |
| 2       | 0.454509 | 0.890742 | 0.510258 | 1.959791  | 1.122659 | 2.200177 | 0.0384378           | 0.8608154  | 58      |
| 3       | 0.454768 | 0.890610 | 0.510625 | 1.958384  | 1.122826 | 2.198924 | 0.0385136           | 0.8596990  | 57      |
| 4       | 0.455027 | 0.890478 | 0.510992 | 1.956978  | 1.122993 | 2.197672 | 0.0385895           | 0.8585841  | 56      |
| 5       | 0.455286 | 0.890345 | 0.511359 | 1.955574  | 1.123160 | 2.196422 | 0.0386655           | 0.8574709  | 55      |
| 6       | 0.455545 | 0.890213 | 0.511726 | 1.954171  | 1.123327 | 2.195173 | 0.0387416           | 0.8563592  | 54      |
| 7       | 0.455804 | 0.890080 | 0.512093 | 1.952770  | 1.123494 | 2.193926 | 0.0388179           | 0.8552492  | 53      |
| 8       | 0.456063 | 0.889948 | 0.512460 | 1.951371  | 1.123662 | 2.192681 | 0.0388942           | 0.8541408  | 52      |
| 9       | 0.456322 | 0.889815 | 0.512828 | 1.949973  | 1.123829 | 2.191437 | 0.0389706           | 0.8530339  | 51      |
| 10      | 0.456580 | 0.889682 | 0.513195 | 1.948577  | 1.123997 | 2.190195 | 0.0390472           | 0.8519286  | 50      |
| 11      | 0.456839 | 0.889549 | 0.513563 | 1.947183  | 1.124165 | 2.188954 | 0.0391239           | 0.8508249  | 49      |
| 12      | 0.457098 | 0.889416 | 0.513930 | 1.945790  | 1.124333 | 2.187715 | 0.0392006           | 0.8497228  | 48      |
| 13      | 0.457357 | 0.889283 | 0.514298 | 1.944398  | 1.124501 | 2.186478 | 0.0392775           | 0.8486222  | 47      |
| 14      | 0.457615 | 0.889150 | 0.514666 | 1.943008  | 1.124669 | 2.185242 | 0.0393545           | 0.8475233  | 46      |
| 15      | 0.457874 | 0.889017 | 0.515034 | 1.941620  | 1.124838 | 2.184007 | 0.0394316           | 0.8464259  | 45      |
| 16      | 0.458133 | 0.888884 | 0.515402 | 1.940233  | 1.125006 | 2.182775 | 0.0395088           | 0.8453300  | 44      |
| 17      | 0.458391 | 0.888751 | 0.515770 | 1.938848  | 1.125175 | 2.181543 | 0.0395862           | 0.8442358  | 43      |
| 18      | 0.458650 | 0.888617 | 0.516138 | 1.937465  | 1.125344 | 2.180314 | 0.0396636           | 0.8431431  | 42      |
| 19      | 0.458908 | 0.888484 | 0.516507 | 1.936082  | 1.125513 | 2.179086 | 0.0397411           | 0.8420519  | 41      |
| 20      | 0.459166 | 0.888350 | 0.516875 | 1.934702  | 1.125682 | 2.177859 | 0.0398188           | 0.8409623  | 40      |
| 21      | 0.459425 | 0.888217 | 0.517244 | 1.933323  | 1.125851 | 2.176635 | 0.0398966           | 0.8398743  | 39      |
| 22      | 0.459683 | 0.888083 | 0.517613 | 1.931946  | 1.126021 | 2.175411 | 0.0399745           | 0.8387878  | 38      |
| 23      | 0.459942 | 0.887949 | 0.517982 | 1.930570  | 1.126191 | 2.174189 | 0.0400524           | 0.8377029  | 37      |
| 24      | 0.460200 | 0.887815 | 0.518351 | 1.929196  | 1.126360 | 2.172969 | 0.0401306           | 0.8366195  | 36      |
| 25      | 0.460458 | 0.887681 | 0.518720 | 1.927823  | 1.126530 | 2.171751 | 0.0402088           | 0.8355376  | 35      |
| 26      | 0.460716 | 0.887548 | 0.519089 | 1.926452  | 1.126700 | 2.170534 | 0.0402871           | 0.8344573  | 34      |
| 27      | 0.460974 | 0.887413 | 0.519458 | 1.925082  | 1.126870 | 2.169318 | 0.0403655           | 0.8333785  | 33      |
| 28      | 0.461232 | 0.887279 | 0.519828 | 1.923714  | 1.127041 | 2.168104 | 0.0404441           | 0.8323013  | 32      |
| 29      | 0.461491 | 0.887145 | 0.520197 | 1.922347  | 1.127211 | 2.166892 | 0.0405227           | 0.8312255  | 31      |
| 30      | 0.461749 | 0.887011 | 0.520567 | 1.920982  | 1.127382 | 2.165681 | 0.0406015           | 0.8301513  | 30      |
| 31      | 0.462007 | 0.886876 | 0.520937 | 1.919619  | 1.127553 | 2.164471 | 0.0406804           | 0.8290787  | 29      |
| 32      | 0.462265 | 0.886742 | 0.521307 | 1.918257  | 1.127724 | 2.163263 | 0.0407594           | 0.8280075  | 28      |
| 33      | 0.462523 | 0.886608 | 0.521677 | 1.916896  | 1.127895 | 2.162057 | 0.0408385           | 0.8269379  | 27      |
| 34      | 0.462780 | 0.886473 | 0.522047 | 1.915537  | 1.128066 | 2.160852 | 0.0409177           | 0.8258698  | 26      |
| 35      | 0.463038 | 0.886338 | 0.522417 | 1.914180  | 1.128237 | 2.159649 | 0.0409970           | 0.8248032  | 25      |
| 36      | 0.463296 | 0.886204 | 0.522787 | 1.912824  | 1.128409 | 2.158447 | 0.0410765           | 0.8237381  | 24      |
| 37      | 0.463554 | 0.886069 | 0.523158 | 1.911469  | 1.128581 | 2.157247 | 0.0411561           | 0.8226745  | 23      |
| 38      | 0.463812 | 0.885934 | 0.523528 | 1.910116  | 1.128752 | 2.156048 | 0.0412357           | 0.8216115  | 22      |
| 39      | 0.464069 | 0.885799 | 0.523899 | 1.908765  | 1.128924 | 2.154851 | 0.0413155           | 0.8205519  | 21      |
| 40      | 0.464327 | 0.885664 | 0.524270 | 1.907415  | 1.129096 | 2.153655 | 0.0413954           | 0.8194928  | 20      |
| 41      | 0.464584 | 0.885529 | 0.524641 | 1.906066  | 1.129269 | 2.152461 | 0.0414754           | 0.8184353  | 19      |
| 42      | 0.464842 | 0.885394 | 0.525012 | 1.904719  | 1.129441 | 2.151268 | 0.0415555           | 0.8173792  | 18      |
| 43      | 0.465100 | 0.885258 | 0.525383 | 1.903374  | 1.129614 | 2.150077 | 0.0416358           | 0.8163246  | 17      |
| 44      | 0.465357 | 0.885123 | 0.525754 | 1.902030  | 1.129786 | 2.148888 | 0.0417161           | 0.8152715  | 16      |
| 45      | 0.465615 | 0.884988 | 0.526125 | 1.900687  | 1.129959 | 2.147699 | 0.0417966           | 0.8142199  | 15      |
| 46      | 0.465872 | 0.884852 | 0.526497 | 1.899346  | 1.130132 | 2.146513 | 0.0418772           | 0.8131698  | 14      |
| 47      | 0.466129 | 0.884717 | 0.526868 | 1.898007  | 1.130305 | 2.145327 | 0.0419579           | 0.8121211  | 13      |
| 48      | 0.466387 | 0.884581 | 0.527240 | 1.896669  | 1.130479 | 2.144144 | 0.0420387           | 0.8110740  | 12      |
| 49      | 0.466644 | 0.884445 | 0.527612 | 1.895332  | 1.130652 | 2.142962 | 0.0421196           | 0.8100283  | 11      |
| 50      | 0.466901 | 0.884309 | 0.527984 | 1.893997  | 1.130826 | 2.141781 | 0.0422006           | 0.8089841  | 10      |
| 51      | 0.467158 | 0.884174 | 0.528356 | 1.892663  | 1.131000 | 2.140602 | 0.0422818           | 0.8079413  | 9       |
| 52      | 0.467416 | 0.884038 | 0.528728 | 1.891331  | 1.131173 | 2.139424 | 0.0423630           | 0.8069000  | 8       |
| 53      | 0.467673 | 0.883902 | 0.529100 | 1.890001  | 1.131348 | 2.138247 | 0.0424444           | 0.8058602  | 7       |
| 54      | 0.467930 | 0.883766 | 0.529473 | 1.888671  | 1.131522 | 2.137073 | 0.0425259           | 0.8048219  | 6       |
| 55      | 0.468187 | 0.883629 | 0.529845 | 1.887344  | 1.131696 | 2.135899 | 0.0426075           | 0.8037850  | 5       |
| 56      | 0.468444 | 0.883493 | 0.530218 | 1.886017  | 1.131871 | 2.134727 | 0.0426892           | 0.8027495  | 4       |
| 57      | 0.468701 | 0.883357 | 0.530591 | 1.884692  | 1.132045 | 2.133557 | 0.0427710           | 0.8017156  | 3       |
| 58      | 0.468958 | 0.883221 | 0.530963 | 1.883369  | 1.132220 | 2.132388 | 0.0428530           | 0.8006830  | 2       |
| 59      | 0.469215 | 0.883084 | 0.531336 | 1.882047  | 1.132395 | 2.131221 | 0.0429351           | 0.7996520  | 1       |
| 60      | 0.469472 | 0.882948 | 0.531709 | 1.880726  | 1.132570 | 2.130054 | 0.0430172           | 0.7986223  | 0       |

↑ 117° or 297° **Trigonometric and Involute Functions** 62° or 242° ↑

TRIGONOMETRY TABLES

↓ 28° or 208° **Trigonometric and Involute Functions** 151° or 331° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>28°-29° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.469472 | 0.882948 | 0.531709 | 1.880726  | 1.132570 | 2.130054 | 0.0430172           | 0.7986223  | 60      |
| 1       | 0.469728 | 0.882811 | 0.532083 | 1.879407  | 1.132745 | 2.128890 | 0.0430995           | 0.7975941  | 59      |
| 2       | 0.469985 | 0.882674 | 0.532456 | 1.878090  | 1.132921 | 2.127727 | 0.0431819           | 0.7965654  | 58      |
| 3       | 0.470242 | 0.882538 | 0.532829 | 1.876774  | 1.133096 | 2.126565 | 0.0432645           | 0.7955421  | 57      |
| 4       | 0.470499 | 0.882401 | 0.533203 | 1.875459  | 1.133272 | 2.125405 | 0.0433471           | 0.7945182  | 56      |
| 5       | 0.470755 | 0.882264 | 0.533577 | 1.874145  | 1.133448 | 2.124246 | 0.0434299           | 0.7934958  | 55      |
| 6       | 0.471012 | 0.882127 | 0.533950 | 1.872834  | 1.133624 | 2.123089 | 0.0435128           | 0.7924748  | 54      |
| 7       | 0.471268 | 0.881990 | 0.534324 | 1.871523  | 1.133800 | 2.121933 | 0.0435957           | 0.7914552  | 53      |
| 8       | 0.471525 | 0.881853 | 0.534698 | 1.870214  | 1.133976 | 2.120778 | 0.0436789           | 0.7904370  | 52      |
| 9       | 0.471782 | 0.881715 | 0.535072 | 1.868906  | 1.134153 | 2.119625 | 0.0437621           | 0.7894203  | 51      |
| 10      | 0.472038 | 0.881578 | 0.535446 | 1.867600  | 1.134329 | 2.118474 | 0.0438454           | 0.7884050  | 50      |
| 11      | 0.472294 | 0.881441 | 0.535821 | 1.866295  | 1.134506 | 2.117324 | 0.0439289           | 0.7873911  | 49      |
| 12      | 0.472551 | 0.881303 | 0.536195 | 1.864992  | 1.134683 | 2.116175 | 0.0440121           | 0.7863786  | 48      |
| 13      | 0.472807 | 0.881166 | 0.536570 | 1.863690  | 1.134860 | 2.115027 | 0.0440961           | 0.7853676  | 47      |
| 14      | 0.473063 | 0.881028 | 0.536945 | 1.862390  | 1.135037 | 2.113882 | 0.0441799           | 0.7843579  | 46      |
| 15      | 0.473320 | 0.880891 | 0.537319 | 1.861091  | 1.135215 | 2.112737 | 0.0442639           | 0.7833497  | 45      |
| 16      | 0.473576 | 0.880753 | 0.537694 | 1.859793  | 1.135392 | 2.111594 | 0.0443479           | 0.7823429  | 44      |
| 17      | 0.473832 | 0.880615 | 0.538069 | 1.858496  | 1.135570 | 2.110452 | 0.0444321           | 0.7813374  | 43      |
| 18      | 0.474088 | 0.880477 | 0.538445 | 1.857202  | 1.135748 | 2.109312 | 0.0445163           | 0.7803334  | 42      |
| 19      | 0.474344 | 0.880339 | 0.538820 | 1.855908  | 1.135926 | 2.108173 | 0.0446007           | 0.7793308  | 41      |
| 20      | 0.474600 | 0.880201 | 0.539195 | 1.854616  | 1.136104 | 2.107036 | 0.0446853           | 0.7783295  | 40      |
| 21      | 0.474856 | 0.880063 | 0.539571 | 1.853325  | 1.136282 | 2.105900 | 0.0447699           | 0.7773297  | 39      |
| 22      | 0.475112 | 0.879925 | 0.539946 | 1.852036  | 1.136460 | 2.104765 | 0.0448546           | 0.7763312  | 38      |
| 23      | 0.475368 | 0.879787 | 0.540322 | 1.850748  | 1.136639 | 2.103632 | 0.0449395           | 0.7753342  | 37      |
| 24      | 0.475624 | 0.879649 | 0.540698 | 1.849461  | 1.136818 | 2.102500 | 0.0450245           | 0.7743385  | 36      |
| 25      | 0.475880 | 0.879510 | 0.541074 | 1.848176  | 1.136997 | 2.101370 | 0.0451096           | 0.7733442  | 35      |
| 26      | 0.476136 | 0.879372 | 0.541450 | 1.846892  | 1.137176 | 2.100241 | 0.0451948           | 0.7723513  | 34      |
| 27      | 0.476392 | 0.879233 | 0.541826 | 1.845610  | 1.137355 | 2.099113 | 0.0452801           | 0.7713598  | 33      |
| 28      | 0.476647 | 0.879095 | 0.542203 | 1.844329  | 1.137534 | 2.097987 | 0.0453656           | 0.7703696  | 32      |
| 29      | 0.476903 | 0.878956 | 0.542579 | 1.843049  | 1.137714 | 2.096862 | 0.0454512           | 0.7693808  | 31      |
| 30      | 0.477159 | 0.878817 | 0.542956 | 1.841771  | 1.137893 | 2.095739 | 0.0455369           | 0.7683934  | 30      |
| 31      | 0.477414 | 0.878678 | 0.543332 | 1.840494  | 1.138073 | 2.094616 | 0.0456227           | 0.7674074  | 29      |
| 32      | 0.477670 | 0.878539 | 0.543709 | 1.839218  | 1.138253 | 2.093496 | 0.0457086           | 0.7664227  | 28      |
| 33      | 0.477925 | 0.878400 | 0.544086 | 1.837944  | 1.138433 | 2.092376 | 0.0457947           | 0.7654394  | 27      |
| 34      | 0.478181 | 0.878261 | 0.544463 | 1.836671  | 1.138613 | 2.091258 | 0.0458808           | 0.7644574  | 26      |
| 35      | 0.478436 | 0.878122 | 0.544840 | 1.835400  | 1.138794 | 2.090142 | 0.0459671           | 0.7634768  | 25      |
| 36      | 0.478692 | 0.877983 | 0.545218 | 1.834130  | 1.138974 | 2.089027 | 0.0460535           | 0.7624976  | 24      |
| 37      | 0.478947 | 0.877844 | 0.545595 | 1.832861  | 1.139155 | 2.087913 | 0.0461401           | 0.7615197  | 23      |
| 38      | 0.479203 | 0.877704 | 0.545973 | 1.831594  | 1.139336 | 2.086800 | 0.0462267           | 0.7605432  | 22      |
| 39      | 0.479458 | 0.877565 | 0.546350 | 1.830327  | 1.139517 | 2.085689 | 0.0463135           | 0.7595680  | 21      |
| 40      | 0.479713 | 0.877425 | 0.546728 | 1.829063  | 1.139698 | 2.084579 | 0.0464004           | 0.7585942  | 20      |
| 41      | 0.479968 | 0.877286 | 0.547106 | 1.827799  | 1.139879 | 2.083471 | 0.0464874           | 0.7576217  | 19      |
| 42      | 0.480223 | 0.877146 | 0.547484 | 1.826537  | 1.140061 | 2.082364 | 0.0465745           | 0.7566505  | 18      |
| 43      | 0.480479 | 0.877006 | 0.547862 | 1.825277  | 1.140242 | 2.081258 | 0.0466618           | 0.7556807  | 17      |
| 44      | 0.480734 | 0.876867 | 0.548240 | 1.824017  | 1.140424 | 2.080154 | 0.0467491           | 0.7547123  | 16      |
| 45      | 0.480989 | 0.876727 | 0.548619 | 1.822759  | 1.140606 | 2.079051 | 0.0468366           | 0.7537451  | 15      |
| 46      | 0.481244 | 0.876587 | 0.548997 | 1.821503  | 1.140788 | 2.077949 | 0.0469242           | 0.7527793  | 14      |
| 47      | 0.481499 | 0.876447 | 0.549376 | 1.820247  | 1.140971 | 2.076849 | 0.0470120           | 0.7518149  | 13      |
| 48      | 0.481754 | 0.876307 | 0.549755 | 1.818993  | 1.141153 | 2.075750 | 0.0470998           | 0.7508517  | 12      |
| 49      | 0.482009 | 0.876167 | 0.550134 | 1.817741  | 1.141336 | 2.074652 | 0.0471878           | 0.7498899  | 11      |
| 50      | 0.482263 | 0.876026 | 0.550513 | 1.816489  | 1.141518 | 2.073556 | 0.0472759           | 0.7489294  | 10      |
| 51      | 0.482518 | 0.875886 | 0.550892 | 1.815239  | 1.141701 | 2.072461 | 0.0473641           | 0.7479703  | 9       |
| 52      | 0.482773 | 0.875746 | 0.551271 | 1.813990  | 1.141884 | 2.071367 | 0.0474525           | 0.7470124  | 8       |
| 53      | 0.483028 | 0.875605 | 0.551650 | 1.812743  | 1.142067 | 2.070275 | 0.0475409           | 0.7460559  | 7       |
| 54      | 0.483282 | 0.875465 | 0.552030 | 1.811497  | 1.142251 | 2.069184 | 0.0476295           | 0.7451007  | 6       |
| 55      | 0.483537 | 0.875324 | 0.552409 | 1.810252  | 1.142434 | 2.068094 | 0.0477182           | 0.7441468  | 5       |
| 56      | 0.483792 | 0.875183 | 0.552789 | 1.809009  | 1.142618 | 2.067006 | 0.0478070           | 0.7431942  | 4       |
| 57      | 0.484046 | 0.875042 | 0.553169 | 1.807766  | 1.142802 | 2.065919 | 0.0478960           | 0.7422429  | 3       |
| 58      | 0.484301 | 0.874902 | 0.553549 | 1.806526  | 1.142986 | 2.064833 | 0.0479851           | 0.7412930  | 2       |
| 59      | 0.484555 | 0.874761 | 0.553929 | 1.805286  | 1.143170 | 2.063748 | 0.0480743           | 0.7403443  | 1       |
| 60      | 0.484810 | 0.874620 | 0.554309 | 1.804048  | 1.143354 | 2.062665 | 0.0481636           | 0.7393969  | 0       |

↑ 118° or 298°

61° or 241° ↑

↓ 29° or 209° **Trigonometric and Involute Functions** 150° or 330° ↓

| Min-utes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>29°-30° | Read<br>Up | Min-utes |
|----------|----------|----------|----------|-----------|----------|----------|---------------------|------------|----------|
| 0        | 0.484810 | 0.874620 | 0.554309 | 1.804048  | 1.143354 | 2.062665 | 0.0481636           | 0.7393969  | 60       |
| 1        | 0.485064 | 0.874479 | 0.554689 | 1.802811  | 1.143539 | 2.061584 | 0.0482530           | 0.7384508  | 59       |
| 2        | 0.485318 | 0.874338 | 0.555070 | 1.801575  | 1.143723 | 2.060510 | 0.0483426           | 0.7375061  | 58       |
| 3        | 0.485573 | 0.874196 | 0.555450 | 1.800341  | 1.143908 | 2.059424 | 0.0484323           | 0.7365626  | 57       |
| 4        | 0.485827 | 0.874055 | 0.555831 | 1.799108  | 1.144093 | 2.058346 | 0.0485221           | 0.7356204  | 56       |
| 5        | 0.486081 | 0.873914 | 0.556212 | 1.797876  | 1.144278 | 2.057269 | 0.0486120           | 0.7346795  | 55       |
| 6        | 0.486335 | 0.873772 | 0.556593 | 1.796645  | 1.144463 | 2.056194 | 0.0487020           | 0.7337399  | 54       |
| 7        | 0.486590 | 0.873631 | 0.556974 | 1.795416  | 1.144648 | 2.055120 | 0.0487922           | 0.7328016  | 53       |
| 8        | 0.486844 | 0.873489 | 0.557355 | 1.794188  | 1.144834 | 2.054048 | 0.0488825           | 0.7318645  | 52       |
| 9        | 0.487098 | 0.873347 | 0.557736 | 1.792962  | 1.145020 | 2.052976 | 0.0489730           | 0.7309288  | 51       |
| 10       | 0.487352 | 0.873206 | 0.558118 | 1.791736  | 1.145205 | 2.051906 | 0.0490635           | 0.7299943  | 50       |
| 11       | 0.487606 | 0.873064 | 0.558499 | 1.790512  | 1.145391 | 2.050837 | 0.0491542           | 0.7290611  | 49       |
| 12       | 0.487860 | 0.872922 | 0.558881 | 1.789289  | 1.145578 | 2.049770 | 0.0492450           | 0.7281291  | 48       |
| 13       | 0.488114 | 0.872780 | 0.559263 | 1.788068  | 1.145764 | 2.048704 | 0.0493359           | 0.7271985  | 47       |
| 14       | 0.488367 | 0.872638 | 0.559645 | 1.786847  | 1.145950 | 2.047639 | 0.0494269           | 0.7262691  | 46       |
| 15       | 0.488621 | 0.872496 | 0.560027 | 1.785628  | 1.146137 | 2.046575 | 0.0495181           | 0.7253410  | 45       |
| 16       | 0.488875 | 0.872354 | 0.560409 | 1.784411  | 1.146324 | 2.045513 | 0.0496094           | 0.7244141  | 44       |
| 17       | 0.489129 | 0.872212 | 0.560791 | 1.783194  | 1.146511 | 2.044451 | 0.0497008           | 0.7234885  | 43       |
| 18       | 0.489382 | 0.872070 | 0.561174 | 1.781979  | 1.146698 | 2.043392 | 0.0497924           | 0.7225642  | 42       |
| 19       | 0.489636 | 0.871927 | 0.561556 | 1.780765  | 1.146885 | 2.042333 | 0.0498840           | 0.7216411  | 41       |
| 20       | 0.489890 | 0.871784 | 0.561939 | 1.779552  | 1.147073 | 2.041276 | 0.0499758           | 0.7207193  | 40       |
| 21       | 0.490143 | 0.871642 | 0.562322 | 1.778341  | 1.147260 | 2.040220 | 0.0500677           | 0.7197987  | 39       |
| 22       | 0.490397 | 0.871499 | 0.562705 | 1.777131  | 1.147448 | 2.039165 | 0.0501598           | 0.7188794  | 38       |
| 23       | 0.490650 | 0.871357 | 0.563088 | 1.775922  | 1.147636 | 2.038111 | 0.0502519           | 0.7179614  | 37       |
| 24       | 0.490904 | 0.871214 | 0.563471 | 1.774714  | 1.147824 | 2.037059 | 0.0503442           | 0.7170446  | 36       |
| 25       | 0.491157 | 0.871071 | 0.563854 | 1.773508  | 1.148012 | 2.036008 | 0.0504367           | 0.7161290  | 35       |
| 26       | 0.491411 | 0.870928 | 0.564238 | 1.772302  | 1.148200 | 2.034958 | 0.0505292           | 0.7152147  | 34       |
| 27       | 0.491664 | 0.870785 | 0.564621 | 1.771098  | 1.148389 | 2.033910 | 0.0506219           | 0.7143016  | 33       |
| 28       | 0.491917 | 0.870642 | 0.565005 | 1.769896  | 1.148578 | 2.032863 | 0.0507147           | 0.7133898  | 32       |
| 29       | 0.492170 | 0.870499 | 0.565389 | 1.768694  | 1.148767 | 2.031817 | 0.0508076           | 0.7124792  | 31       |
| 30       | 0.492424 | 0.870356 | 0.565773 | 1.767494  | 1.148956 | 2.030772 | 0.0509006           | 0.7115698  | 30       |
| 31       | 0.492677 | 0.870212 | 0.566157 | 1.766295  | 1.149145 | 2.029729 | 0.0509938           | 0.7106617  | 29       |
| 32       | 0.492930 | 0.870069 | 0.566541 | 1.765097  | 1.149334 | 2.028686 | 0.0510871           | 0.7097548  | 28       |
| 33       | 0.493183 | 0.869926 | 0.566925 | 1.763901  | 1.149524 | 2.027645 | 0.0511806           | 0.7088491  | 27       |
| 34       | 0.493436 | 0.869782 | 0.567310 | 1.762705  | 1.149713 | 2.026606 | 0.0512741           | 0.7079447  | 26       |
| 35       | 0.493689 | 0.869639 | 0.567694 | 1.761511  | 1.149903 | 2.025567 | 0.0513678           | 0.7070415  | 25       |
| 36       | 0.493942 | 0.869495 | 0.568079 | 1.760318  | 1.150093 | 2.024530 | 0.0514616           | 0.7061395  | 24       |
| 37       | 0.494195 | 0.869351 | 0.568464 | 1.759127  | 1.150283 | 2.023494 | 0.0515555           | 0.7052387  | 23       |
| 38       | 0.494448 | 0.869207 | 0.568849 | 1.757936  | 1.150473 | 2.022459 | 0.0516496           | 0.7043392  | 22       |
| 39       | 0.494700 | 0.869064 | 0.569234 | 1.756747  | 1.150664 | 2.021425 | 0.0517438           | 0.7034408  | 21       |
| 40       | 0.494953 | 0.868920 | 0.569619 | 1.755559  | 1.150854 | 2.020393 | 0.0518381           | 0.7025437  | 20       |
| 41       | 0.495206 | 0.868776 | 0.570004 | 1.754372  | 1.151045 | 2.019362 | 0.0519326           | 0.7016478  | 19       |
| 42       | 0.495459 | 0.868632 | 0.570390 | 1.753187  | 1.151236 | 2.018332 | 0.0520271           | 0.7007531  | 18       |
| 43       | 0.495711 | 0.868487 | 0.570776 | 1.752002  | 1.151427 | 2.017303 | 0.0521218           | 0.6998596  | 17       |
| 44       | 0.495964 | 0.868343 | 0.571161 | 1.750819  | 1.151618 | 2.016276 | 0.0522167           | 0.6989673  | 16       |
| 45       | 0.496217 | 0.868199 | 0.571547 | 1.749637  | 1.151810 | 2.015249 | 0.0523116           | 0.6980762  | 15       |
| 46       | 0.496469 | 0.868054 | 0.571933 | 1.748456  | 1.152001 | 2.014224 | 0.0524067           | 0.6971864  | 14       |
| 47       | 0.496722 | 0.867910 | 0.572319 | 1.747277  | 1.152193 | 2.013200 | 0.0525019           | 0.6962977  | 13       |
| 48       | 0.496974 | 0.867765 | 0.572705 | 1.746098  | 1.152385 | 2.012178 | 0.0525973           | 0.6954102  | 12       |
| 49       | 0.497226 | 0.867621 | 0.573092 | 1.744921  | 1.152577 | 2.011156 | 0.0526928           | 0.6945239  | 11       |
| 50       | 0.497479 | 0.867476 | 0.573478 | 1.743745  | 1.152769 | 2.010136 | 0.0527884           | 0.6936389  | 10       |
| 51       | 0.497731 | 0.867331 | 0.573865 | 1.742571  | 1.152962 | 2.009117 | 0.0528841           | 0.6927550  | 9        |
| 52       | 0.497983 | 0.867187 | 0.574252 | 1.741397  | 1.153154 | 2.008099 | 0.0529799           | 0.6918723  | 8        |
| 53       | 0.498236 | 0.867042 | 0.574638 | 1.740225  | 1.153347 | 2.007083 | 0.0530759           | 0.6909907  | 7        |
| 54       | 0.498488 | 0.866897 | 0.575026 | 1.739053  | 1.153540 | 2.006067 | 0.0531721           | 0.6901104  | 6        |
| 55       | 0.498740 | 0.866752 | 0.575413 | 1.737883  | 1.153733 | 2.005053 | 0.0532683           | 0.6892313  | 5        |
| 56       | 0.498992 | 0.866607 | 0.575800 | 1.736714  | 1.153926 | 2.004040 | 0.0533647           | 0.6883533  | 4        |
| 57       | 0.499244 | 0.866461 | 0.576187 | 1.735547  | 1.154119 | 2.003028 | 0.0534612           | 0.6874765  | 3        |
| 58       | 0.499496 | 0.866316 | 0.576575 | 1.734380  | 1.154313 | 2.002018 | 0.0535578           | 0.6866009  | 2        |
| 59       | 0.499748 | 0.866171 | 0.576962 | 1.733215  | 1.154507 | 2.001008 | 0.0536546           | 0.6857265  | 1        |
| 60       | 0.500000 | 0.866025 | 0.577350 | 1.732051  | 1.154701 | 2.000000 | 0.0537515           | 0.6848533  | 0        |

↑ 119° or 299°

60° or 240° ↑

TRIGONOMETRY TABLES

↓ 30° or 210° Trigonometric and Involute Functions 149° or 329° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>30°-31° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.500000 | 0.866025 | 0.577350 | 1.732051  | 1.154701 | 2.000000 | 0.0537515           | 0.6848533  | 60      |
| 1       | 0.500252 | 0.865880 | 0.577738 | 1.730888  | 1.154895 | 1.998993 | 0.0538485           | 0.6839812  | 59      |
| 2       | 0.500504 | 0.865734 | 0.578126 | 1.729787  | 1.155089 | 1.997987 | 0.0539457           | 0.6831103  | 58      |
| 3       | 0.500756 | 0.865589 | 0.578514 | 1.728565  | 1.155283 | 1.996982 | 0.0540430           | 0.6822405  | 57      |
| 4       | 0.501007 | 0.865443 | 0.578903 | 1.727406  | 1.155478 | 1.995979 | 0.0541404           | 0.6813720  | 56      |
| 5       | 0.501259 | 0.865297 | 0.579291 | 1.726248  | 1.155672 | 1.994976 | 0.0542379           | 0.6805045  | 55      |
| 6       | 0.501511 | 0.865151 | 0.579680 | 1.725091  | 1.155867 | 1.993975 | 0.0543356           | 0.6796383  | 54      |
| 7       | 0.501762 | 0.865006 | 0.580068 | 1.723935  | 1.156062 | 1.992975 | 0.0544334           | 0.6787732  | 53      |
| 8       | 0.502014 | 0.864860 | 0.580457 | 1.722780  | 1.156257 | 1.991976 | 0.0545314           | 0.6779093  | 52      |
| 9       | 0.502266 | 0.864713 | 0.580846 | 1.721626  | 1.156452 | 1.990979 | 0.0546295           | 0.6770465  | 51      |
| 10      | 0.502517 | 0.864567 | 0.581235 | 1.720474  | 1.156648 | 1.989982 | 0.0547277           | 0.6761849  | 50      |
| 11      | 0.502769 | 0.864421 | 0.581625 | 1.719322  | 1.156844 | 1.988987 | 0.0548260           | 0.6753244  | 49      |
| 12      | 0.503020 | 0.864275 | 0.582014 | 1.718172  | 1.157039 | 1.987993 | 0.0549245           | 0.6744651  | 48      |
| 13      | 0.503271 | 0.864128 | 0.582403 | 1.717023  | 1.157235 | 1.987000 | 0.0550231           | 0.6736070  | 47      |
| 14      | 0.503523 | 0.863982 | 0.582793 | 1.715875  | 1.157432 | 1.986008 | 0.0551218           | 0.6727500  | 46      |
| 15      | 0.503774 | 0.863836 | 0.583183 | 1.714728  | 1.157628 | 1.985017 | 0.0552207           | 0.6718941  | 45      |
| 16      | 0.504025 | 0.863689 | 0.583573 | 1.713583  | 1.157824 | 1.984028 | 0.0553197           | 0.6710394  | 44      |
| 17      | 0.504276 | 0.863542 | 0.583963 | 1.712438  | 1.158021 | 1.983039 | 0.0554188           | 0.6701858  | 43      |
| 18      | 0.504528 | 0.863396 | 0.584353 | 1.711295  | 1.158218 | 1.982052 | 0.0555181           | 0.6693333  | 42      |
| 19      | 0.504779 | 0.863249 | 0.584743 | 1.710153  | 1.158415 | 1.981066 | 0.0556175           | 0.6684820  | 41      |
| 20      | 0.505030 | 0.863102 | 0.585134 | 1.709012  | 1.158612 | 1.980081 | 0.0557170           | 0.6676319  | 40      |
| 21      | 0.505281 | 0.862955 | 0.585524 | 1.707872  | 1.158809 | 1.979097 | 0.0558166           | 0.6667828  | 39      |
| 22      | 0.505532 | 0.862808 | 0.585915 | 1.706733  | 1.159007 | 1.978115 | 0.0559164           | 0.6659349  | 38      |
| 23      | 0.505783 | 0.862661 | 0.586306 | 1.705595  | 1.159204 | 1.977133 | 0.0560164           | 0.6650881  | 37      |
| 24      | 0.506034 | 0.862514 | 0.586697 | 1.704459  | 1.159402 | 1.976153 | 0.0561166           | 0.6642425  | 36      |
| 25      | 0.506285 | 0.862366 | 0.587088 | 1.703323  | 1.159600 | 1.975174 | 0.0562166           | 0.6633980  | 35      |
| 26      | 0.506535 | 0.862219 | 0.587479 | 1.702189  | 1.159798 | 1.974195 | 0.0563169           | 0.6625546  | 34      |
| 27      | 0.506786 | 0.862072 | 0.587870 | 1.701056  | 1.159996 | 1.973218 | 0.0564174           | 0.6617123  | 33      |
| 28      | 0.507037 | 0.861924 | 0.588262 | 1.699924  | 1.160195 | 1.972243 | 0.0565180           | 0.6608712  | 32      |
| 29      | 0.507288 | 0.861777 | 0.588653 | 1.698793  | 1.160393 | 1.971268 | 0.0566187           | 0.6600311  | 31      |
| 30      | 0.507538 | 0.861629 | 0.589045 | 1.697663  | 1.160592 | 1.970294 | 0.0567196           | 0.6591922  | 30      |
| 31      | 0.507789 | 0.861481 | 0.589437 | 1.696534  | 1.160791 | 1.969322 | 0.0568206           | 0.6583544  | 29      |
| 32      | 0.508040 | 0.861334 | 0.589829 | 1.695407  | 1.160990 | 1.968351 | 0.0569217           | 0.6575177  | 28      |
| 33      | 0.508290 | 0.861186 | 0.590221 | 1.694280  | 1.161189 | 1.967381 | 0.0570230           | 0.6566822  | 27      |
| 34      | 0.508541 | 0.861038 | 0.590613 | 1.693155  | 1.161389 | 1.966411 | 0.0571244           | 0.6558477  | 26      |
| 35      | 0.508791 | 0.860890 | 0.591006 | 1.692031  | 1.161588 | 1.965444 | 0.0572259           | 0.6550143  | 25      |
| 36      | 0.509041 | 0.860742 | 0.591398 | 1.690908  | 1.161789 | 1.964477 | 0.0573276           | 0.6541821  | 24      |
| 37      | 0.509292 | 0.860594 | 0.591791 | 1.689786  | 1.161988 | 1.963511 | 0.0574294           | 0.6533509  | 23      |
| 38      | 0.509542 | 0.860446 | 0.592184 | 1.688665  | 1.162188 | 1.962546 | 0.0575313           | 0.6525209  | 22      |
| 39      | 0.509792 | 0.860297 | 0.592577 | 1.687545  | 1.162389 | 1.961583 | 0.0576334           | 0.6516919  | 21      |
| 40      | 0.510043 | 0.860149 | 0.592970 | 1.686426  | 1.162589 | 1.960621 | 0.0577356           | 0.6508641  | 20      |
| 41      | 0.510293 | 0.860001 | 0.593363 | 1.685308  | 1.162790 | 1.959659 | 0.0578380           | 0.6500374  | 19      |
| 42      | 0.510543 | 0.859852 | 0.593757 | 1.684192  | 1.162990 | 1.958699 | 0.0579405           | 0.6492117  | 18      |
| 43      | 0.510793 | 0.859704 | 0.594150 | 1.683077  | 1.163191 | 1.957740 | 0.0580431           | 0.6483871  | 17      |
| 44      | 0.511043 | 0.859555 | 0.594544 | 1.681962  | 1.163393 | 1.956782 | 0.0581458           | 0.6475637  | 16      |
| 45      | 0.511293 | 0.859406 | 0.594937 | 1.680849  | 1.163594 | 1.955825 | 0.0582487           | 0.6467413  | 15      |
| 46      | 0.511543 | 0.859258 | 0.595331 | 1.679737  | 1.163795 | 1.954870 | 0.0583518           | 0.6459200  | 14      |
| 47      | 0.511793 | 0.859109 | 0.595725 | 1.678626  | 1.163997 | 1.953915 | 0.0584549           | 0.6450988  | 13      |
| 48      | 0.512043 | 0.858960 | 0.596120 | 1.677516  | 1.164199 | 1.952961 | 0.0585582           | 0.6442807  | 12      |
| 49      | 0.512293 | 0.858811 | 0.596514 | 1.676407  | 1.164401 | 1.952009 | 0.0586617           | 0.6434627  | 11      |
| 50      | 0.512543 | 0.858662 | 0.596908 | 1.675299  | 1.164603 | 1.951058 | 0.0587652           | 0.6426457  | 10      |
| 51      | 0.512792 | 0.858513 | 0.597303 | 1.674192  | 1.164805 | 1.950107 | 0.0588686           | 0.6418298  | 9       |
| 52      | 0.513042 | 0.858364 | 0.597698 | 1.673086  | 1.165008 | 1.949158 | 0.0589728           | 0.6410150  | 8       |
| 53      | 0.513292 | 0.858214 | 0.598093 | 1.671982  | 1.165210 | 1.948210 | 0.0590768           | 0.6402013  | 7       |
| 54      | 0.513541 | 0.858065 | 0.598488 | 1.670878  | 1.165413 | 1.947263 | 0.0591809           | 0.6393887  | 6       |
| 55      | 0.513791 | 0.857915 | 0.598883 | 1.669776  | 1.165616 | 1.946317 | 0.0592852           | 0.6385771  | 5       |
| 56      | 0.514040 | 0.857766 | 0.599278 | 1.668674  | 1.165819 | 1.945373 | 0.0593896           | 0.6377666  | 4       |
| 57      | 0.514290 | 0.857616 | 0.599674 | 1.667574  | 1.166022 | 1.944429 | 0.0594941           | 0.6369571  | 3       |
| 58      | 0.514539 | 0.857467 | 0.600069 | 1.666475  | 1.166226 | 1.943486 | 0.0595988           | 0.6361488  | 2       |
| 59      | 0.514789 | 0.857317 | 0.600465 | 1.665377  | 1.166430 | 1.942545 | 0.0597036           | 0.6353415  | 1       |
| 60      | 0.515038 | 0.857167 | 0.600861 | 1.664279  | 1.166633 | 1.941604 | 0.0598086           | 0.6345352  | 0       |

↑ 120° or 300°

59° or 239° ↑

↓ 31° or 211° Trigonometric and Involute Functions 148° or 328° ↓

| Min-utes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute<br>31°-32° | Read<br>Up          | Min-utes |
|----------|----------|----------|-----------|-----------|----------|----------|---------------------|---------------------|----------|
| 0        | 0.515038 | 0.857167 | 0.600861  | 1.664279  | 1.166633 | 1.941604 | 0.0598086           | 0.6345352           | 60       |
| 1        | 0.515287 | 0.857017 | 0.601257  | 1.663183  | 1.166837 | 1.940665 | 0.0599136           | 0.6337300           | 59       |
| 2        | 0.515537 | 0.856868 | 0.601653  | 1.662088  | 1.167042 | 1.939726 | 0.0600189           | 0.6329259           | 58       |
| 3        | 0.515786 | 0.856718 | 0.602049  | 1.660994  | 1.167246 | 1.938789 | 0.0601242           | 0.6321229           | 57       |
| 4        | 0.516035 | 0.856567 | 0.602445  | 1.659902  | 1.167450 | 1.937853 | 0.0602297           | 0.6313209           | 56       |
| 5        | 0.516284 | 0.856417 | 0.602842  | 1.658810  | 1.167655 | 1.936918 | 0.0603354           | 0.6305199           | 55       |
| 6        | 0.516533 | 0.856267 | 0.603239  | 1.657719  | 1.167860 | 1.935983 | 0.0604412           | 0.6297200           | 54       |
| 7        | 0.516782 | 0.856117 | 0.603635  | 1.656629  | 1.168065 | 1.935050 | 0.0605471           | 0.6289212           | 53       |
| 8        | 0.517031 | 0.855966 | 0.604032  | 1.655541  | 1.168270 | 1.934119 | 0.0606532           | 0.6281234           | 52       |
| 9        | 0.517280 | 0.855816 | 0.604429  | 1.654453  | 1.168475 | 1.933188 | 0.0607594           | 0.6273266           | 51       |
| 10       | 0.517529 | 0.855665 | 0.604827  | 1.653366  | 1.168681 | 1.932258 | 0.0608657           | 0.6265309           | 50       |
| 11       | 0.517778 | 0.855515 | 0.605224  | 1.652281  | 1.168887 | 1.931329 | 0.0609722           | 0.6257363           | 49       |
| 12       | 0.518027 | 0.855364 | 0.605622  | 1.651196  | 1.169093 | 1.930401 | 0.0610788           | 0.6249427           | 48       |
| 13       | 0.518276 | 0.855214 | 0.606019  | 1.650113  | 1.169299 | 1.929475 | 0.0611856           | 0.6241501           | 47       |
| 14       | 0.518525 | 0.855063 | 0.606417  | 1.649030  | 1.169505 | 1.928549 | 0.0612925           | 0.6233586           | 46       |
| 15       | 0.518773 | 0.854912 | 0.606815  | 1.647949  | 1.169711 | 1.927624 | 0.0613995           | 0.6225681           | 45       |
| 16       | 0.519022 | 0.854761 | 0.607213  | 1.646869  | 1.169918 | 1.926701 | 0.0615067           | 0.6217786           | 44       |
| 17       | 0.519271 | 0.854610 | 0.607611  | 1.645789  | 1.170124 | 1.925778 | 0.0616140           | 0.6209902           | 43       |
| 18       | 0.519519 | 0.854459 | 0.608010  | 1.644711  | 1.170331 | 1.924857 | 0.0617215           | 0.6202028           | 42       |
| 19       | 0.519768 | 0.854308 | 0.608408  | 1.643634  | 1.170538 | 1.923937 | 0.0618291           | 0.6194164           | 41       |
| 20       | 0.520016 | 0.854156 | 0.608807  | 1.642558  | 1.170746 | 1.923017 | 0.0619368           | 0.6186311           | 40       |
| 21       | 0.520265 | 0.854005 | 0.609205  | 1.641482  | 1.170953 | 1.922099 | 0.0620447           | 0.6178468           | 39       |
| 22       | 0.520513 | 0.853854 | 0.609604  | 1.640408  | 1.171161 | 1.921182 | 0.0621527           | 0.6170635           | 38       |
| 23       | 0.520761 | 0.853702 | 0.610003  | 1.639335  | 1.171368 | 1.920265 | 0.0622609           | 0.6162813           | 37       |
| 24       | 0.521010 | 0.853551 | 0.610403  | 1.638263  | 1.171576 | 1.919350 | 0.0623692           | 0.6155000           | 36       |
| 25       | 0.521258 | 0.853399 | 0.610802  | 1.637192  | 1.171785 | 1.918436 | 0.0624777           | 0.6147198           | 35       |
| 26       | 0.521506 | 0.853248 | 0.611201  | 1.636122  | 1.171993 | 1.917523 | 0.0625863           | 0.6139407           | 34       |
| 27       | 0.521754 | 0.853096 | 0.611601  | 1.635053  | 1.172201 | 1.916611 | 0.0626950           | 0.6131625           | 33       |
| 28       | 0.522002 | 0.852944 | 0.612001  | 1.633985  | 1.172410 | 1.915700 | 0.0628039           | 0.6123853           | 32       |
| 29       | 0.522251 | 0.852792 | 0.612401  | 1.632918  | 1.172619 | 1.914790 | 0.0629129           | 0.6116092           | 31       |
| 30       | 0.522499 | 0.852640 | 0.612801  | 1.631852  | 1.172828 | 1.913881 | 0.0630221           | 0.6108341           | 30       |
| 31       | 0.522747 | 0.852488 | 0.613201  | 1.630787  | 1.173037 | 1.912973 | 0.0631314           | 0.6100600           | 29       |
| 32       | 0.522995 | 0.852336 | 0.613601  | 1.629723  | 1.173246 | 1.912066 | 0.0632408           | 0.6092869           | 28       |
| 33       | 0.523242 | 0.852184 | 0.614002  | 1.628660  | 1.173456 | 1.911160 | 0.0633504           | 0.6085148           | 27       |
| 34       | 0.523490 | 0.852032 | 0.614402  | 1.627598  | 1.173665 | 1.910255 | 0.0634602           | 0.6077437           | 26       |
| 35       | 0.523738 | 0.851879 | 0.614803  | 1.626537  | 1.173875 | 1.909351 | 0.0635700           | 0.6069736           | 25       |
| 36       | 0.523986 | 0.851727 | 0.615204  | 1.625477  | 1.174085 | 1.908448 | 0.0636801           | 0.6062045           | 24       |
| 37       | 0.524234 | 0.851574 | 0.615605  | 1.624418  | 1.174295 | 1.907546 | 0.0637902           | 0.6054364           | 23       |
| 38       | 0.524481 | 0.851422 | 0.616006  | 1.623360  | 1.174506 | 1.906646 | 0.0639005           | 0.6046694           | 22       |
| 39       | 0.524729 | 0.851269 | 0.616408  | 1.622303  | 1.174716 | 1.905746 | 0.0640110           | 0.6039033           | 21       |
| 40       | 0.524977 | 0.851117 | 0.616809  | 1.621247  | 1.174927 | 1.904847 | 0.0641216           | 0.6031382           | 20       |
| 41       | 0.525224 | 0.850964 | 0.617211  | 1.620192  | 1.175138 | 1.903949 | 0.0642323           | 0.6023741           | 19       |
| 42       | 0.525472 | 0.850811 | 0.617613  | 1.619138  | 1.175349 | 1.903052 | 0.0643432           | 0.6016110           | 18       |
| 43       | 0.525719 | 0.850658 | 0.618015  | 1.618085  | 1.175560 | 1.902156 | 0.0644542           | 0.6008489           | 17       |
| 44       | 0.525967 | 0.850505 | 0.618417  | 1.617033  | 1.175772 | 1.901262 | 0.0645654           | 0.6000878           | 16       |
| 45       | 0.526214 | 0.850352 | 0.618819  | 1.615982  | 1.175983 | 1.900368 | 0.0646767           | 0.5993277           | 15       |
| 46       | 0.526461 | 0.850199 | 0.619221  | 1.614932  | 1.176195 | 1.899475 | 0.0647882           | 0.5985686           | 14       |
| 47       | 0.526709 | 0.850046 | 0.619624  | 1.613883  | 1.176407 | 1.898583 | 0.0648998           | 0.5978104           | 13       |
| 48       | 0.526956 | 0.849893 | 0.620026  | 1.612835  | 1.176619 | 1.897692 | 0.0650116           | 0.5970533           | 12       |
| 49       | 0.527203 | 0.849739 | 0.620429  | 1.611788  | 1.176831 | 1.896803 | 0.0651235           | 0.5962971           | 11       |
| 50       | 0.527450 | 0.849586 | 0.620832  | 1.610742  | 1.177044 | 1.895914 | 0.0652355           | 0.5955419           | 10       |
| 51       | 0.527697 | 0.849433 | 0.621235  | 1.609697  | 1.177257 | 1.895026 | 0.0653477           | 0.5947877           | 9        |
| 52       | 0.527944 | 0.849279 | 0.621638  | 1.608653  | 1.177469 | 1.894139 | 0.0654600           | 0.5940344           | 8        |
| 53       | 0.528191 | 0.849125 | 0.622042  | 1.607609  | 1.177682 | 1.893253 | 0.0655725           | 0.5932822           | 7        |
| 54       | 0.528438 | 0.848972 | 0.622445  | 1.606567  | 1.177896 | 1.892368 | 0.0656851           | 0.5925309           | 6        |
| 55       | 0.528685 | 0.848818 | 0.622849  | 1.605526  | 1.178109 | 1.891485 | 0.0657979           | 0.5917806           | 5        |
| 56       | 0.528932 | 0.848664 | 0.623253  | 1.604486  | 1.178322 | 1.890602 | 0.0659108           | 0.5910312           | 4        |
| 57       | 0.529179 | 0.848510 | 0.623657  | 1.603446  | 1.178536 | 1.889720 | 0.0660239           | 0.5902829           | 3        |
| 58       | 0.529426 | 0.848356 | 0.624061  | 1.602408  | 1.178750 | 1.888839 | 0.0661371           | 0.5895355           | 2        |
| 59       | 0.529673 | 0.848202 | 0.624465  | 1.601371  | 1.178964 | 1.887959 | 0.0662505           | 0.5887890           | 1        |
| 60       | 0.529919 | 0.848048 | 0.624869  | 1.600335  | 1.179178 | 1.887080 | 0.0663640           | 0.5880436           | 0        |
| Min-utes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read<br>Down        | 58°-59°<br>Involute | Min-utes |

↑ 121° or 301° 58° or 238° ↑

TRIGONOMETRY TABLES

↓ 32° or 212° Trigonometric and Involute Functions 147° or 327° ↓

| Minutes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute<br>32°-33° | Read<br>Up          | Minutes |
|---------|----------|----------|-----------|-----------|----------|----------|---------------------|---------------------|---------|
| 0       | 0.529919 | 0.848048 | 0.624869  | 1.600335  | 1.179178 | 1.887080 | 0.0663640           | 0.5880436           | 60      |
| 1       | 0.530166 | 0.847894 | 0.625274  | 1.599299  | 1.179393 | 1.886202 | 0.0664776           | 0.5872991           | 59      |
| 2       | 0.530413 | 0.847740 | 0.625679  | 1.598265  | 1.179607 | 1.885325 | 0.0665914           | 0.5865555           | 58      |
| 3       | 0.530659 | 0.847585 | 0.626083  | 1.597231  | 1.179822 | 1.884449 | 0.0667054           | 0.5858129           | 57      |
| 4       | 0.530906 | 0.847431 | 0.626488  | 1.596199  | 1.180037 | 1.883574 | 0.0668195           | 0.5850713           | 56      |
| 5       | 0.531152 | 0.847276 | 0.626894  | 1.595167  | 1.180252 | 1.882700 | 0.0669337           | 0.5843307           | 55      |
| 6       | 0.531399 | 0.847122 | 0.627299  | 1.594137  | 1.180468 | 1.881827 | 0.0670481           | 0.5835910           | 54      |
| 7       | 0.531645 | 0.846967 | 0.627704  | 1.593107  | 1.180683 | 1.880954 | 0.0671627           | 0.5828522           | 53      |
| 8       | 0.531891 | 0.846813 | 0.628110  | 1.592078  | 1.180899 | 1.880083 | 0.0672774           | 0.5821144           | 52      |
| 9       | 0.532138 | 0.846658 | 0.628516  | 1.591051  | 1.181115 | 1.879213 | 0.0673922           | 0.5813776           | 51      |
| 10      | 0.532384 | 0.846503 | 0.628921  | 1.590024  | 1.181331 | 1.878344 | 0.0675072           | 0.5806417           | 50      |
| 11      | 0.532630 | 0.846348 | 0.629327  | 1.588998  | 1.181547 | 1.877476 | 0.0676223           | 0.5799067           | 49      |
| 12      | 0.532876 | 0.846193 | 0.629734  | 1.587973  | 1.181763 | 1.876608 | 0.0677376           | 0.5791727           | 48      |
| 13      | 0.533122 | 0.846038 | 0.630140  | 1.586949  | 1.181980 | 1.875742 | 0.0678530           | 0.5784397           | 47      |
| 14      | 0.533368 | 0.845883 | 0.630546  | 1.585926  | 1.182197 | 1.874876 | 0.0679686           | 0.5777076           | 46      |
| 15      | 0.533615 | 0.845728 | 0.630953  | 1.584904  | 1.182414 | 1.874012 | 0.0680843           | 0.5769764           | 45      |
| 16      | 0.533861 | 0.845573 | 0.631360  | 1.583883  | 1.182631 | 1.873148 | 0.0682002           | 0.5762462           | 44      |
| 17      | 0.534106 | 0.845417 | 0.631767  | 1.582863  | 1.182848 | 1.872286 | 0.0683162           | 0.5755169           | 43      |
| 18      | 0.534352 | 0.845262 | 0.632174  | 1.581844  | 1.183065 | 1.871424 | 0.0684324           | 0.5747886           | 42      |
| 19      | 0.534598 | 0.845106 | 0.632581  | 1.580825  | 1.183283 | 1.870564 | 0.0685487           | 0.5740612           | 41      |
| 20      | 0.534844 | 0.844951 | 0.632988  | 1.579808  | 1.183501 | 1.869704 | 0.0686652           | 0.5733347           | 40      |
| 21      | 0.535090 | 0.844795 | 0.633396  | 1.578792  | 1.183719 | 1.868845 | 0.0687818           | 0.5726092           | 39      |
| 22      | 0.535335 | 0.844640 | 0.633804  | 1.577776  | 1.183937 | 1.867987 | 0.0688986           | 0.5718846           | 38      |
| 23      | 0.535581 | 0.844484 | 0.634211  | 1.576761  | 1.184155 | 1.867131 | 0.0690155           | 0.5711609           | 37      |
| 24      | 0.535827 | 0.844328 | 0.634619  | 1.575748  | 1.184374 | 1.866275 | 0.0691326           | 0.5704382           | 36      |
| 25      | 0.536072 | 0.844172 | 0.635027  | 1.574735  | 1.184593 | 1.865420 | 0.0692498           | 0.5697164           | 35      |
| 26      | 0.536318 | 0.844016 | 0.635436  | 1.573723  | 1.184812 | 1.864566 | 0.0693672           | 0.5689955           | 34      |
| 27      | 0.536563 | 0.843860 | 0.635844  | 1.572713  | 1.185031 | 1.863713 | 0.0694848           | 0.5682756           | 33      |
| 28      | 0.536809 | 0.843704 | 0.636253  | 1.571703  | 1.185250 | 1.862860 | 0.0696024           | 0.5675565           | 32      |
| 29      | 0.537054 | 0.843548 | 0.636661  | 1.570694  | 1.185469 | 1.862009 | 0.0697203           | 0.5668384           | 31      |
| 30      | 0.537300 | 0.843391 | 0.637070  | 1.569686  | 1.185689 | 1.861159 | 0.0698383           | 0.5661213           | 30      |
| 31      | 0.537545 | 0.843235 | 0.637479  | 1.568678  | 1.185909 | 1.860310 | 0.0699564           | 0.5654050           | 29      |
| 32      | 0.537790 | 0.843079 | 0.637888  | 1.567672  | 1.186129 | 1.859461 | 0.0700747           | 0.5646896           | 28      |
| 33      | 0.538035 | 0.842922 | 0.638298  | 1.566667  | 1.186349 | 1.858614 | 0.0701931           | 0.5639752           | 27      |
| 34      | 0.538281 | 0.842766 | 0.638707  | 1.565662  | 1.186569 | 1.857767 | 0.0703117           | 0.5632617           | 26      |
| 35      | 0.538526 | 0.842609 | 0.639117  | 1.564659  | 1.186790 | 1.856922 | 0.0704304           | 0.5625491           | 25      |
| 36      | 0.538771 | 0.842452 | 0.639527  | 1.563656  | 1.187011 | 1.856077 | 0.0705493           | 0.5618374           | 24      |
| 37      | 0.539016 | 0.842296 | 0.639937  | 1.562655  | 1.187232 | 1.855233 | 0.0706684           | 0.5611267           | 23      |
| 38      | 0.539261 | 0.842139 | 0.640347  | 1.561654  | 1.187453 | 1.854390 | 0.0707876           | 0.5604168           | 22      |
| 39      | 0.539506 | 0.841982 | 0.640757  | 1.560654  | 1.187674 | 1.853548 | 0.0709069           | 0.5597078           | 21      |
| 40      | 0.539751 | 0.841825 | 0.641167  | 1.559655  | 1.187895 | 1.852707 | 0.0710265           | 0.5589998           | 20      |
| 41      | 0.539996 | 0.841668 | 0.641578  | 1.558657  | 1.188117 | 1.851867 | 0.0711461           | 0.5582927           | 19      |
| 42      | 0.540240 | 0.841511 | 0.641989  | 1.557660  | 1.188339 | 1.851028 | 0.0712659           | 0.5575864           | 18      |
| 43      | 0.540485 | 0.841354 | 0.642399  | 1.556664  | 1.188561 | 1.850190 | 0.0713859           | 0.5568811           | 17      |
| 44      | 0.540730 | 0.841196 | 0.642810  | 1.555669  | 1.188783 | 1.849352 | 0.0715060           | 0.5561767           | 16      |
| 45      | 0.540974 | 0.841039 | 0.643222  | 1.554674  | 1.189005 | 1.848516 | 0.0716263           | 0.5554731           | 15      |
| 46      | 0.541219 | 0.840882 | 0.643633  | 1.553681  | 1.189228 | 1.847681 | 0.0717467           | 0.5547705           | 14      |
| 47      | 0.541464 | 0.840724 | 0.644044  | 1.552688  | 1.189451 | 1.846846 | 0.0718673           | 0.5540688           | 13      |
| 48      | 0.541708 | 0.840567 | 0.644456  | 1.551696  | 1.189674 | 1.846012 | 0.0719880           | 0.5533679           | 12      |
| 49      | 0.541953 | 0.840409 | 0.644868  | 1.550705  | 1.189897 | 1.845179 | 0.0721089           | 0.5526680           | 11      |
| 50      | 0.542197 | 0.840251 | 0.645280  | 1.549715  | 1.190120 | 1.844348 | 0.0722300           | 0.5519689           | 10      |
| 51      | 0.542442 | 0.840094 | 0.645692  | 1.548726  | 1.190344 | 1.843517 | 0.0723512           | 0.5512708           | 9       |
| 52      | 0.542686 | 0.839936 | 0.646104  | 1.547738  | 1.190567 | 1.842687 | 0.0724725           | 0.5505735           | 8       |
| 53      | 0.542930 | 0.839778 | 0.646516  | 1.546751  | 1.190791 | 1.841857 | 0.0725940           | 0.5498771           | 7       |
| 54      | 0.543174 | 0.839620 | 0.646929  | 1.545765  | 1.191015 | 1.841029 | 0.0727157           | 0.5491816           | 6       |
| 55      | 0.543419 | 0.839462 | 0.647342  | 1.544779  | 1.191239 | 1.840202 | 0.0728375           | 0.5484870           | 5       |
| 56      | 0.543663 | 0.839304 | 0.647755  | 1.543795  | 1.191464 | 1.839375 | 0.0729595           | 0.5477933           | 4       |
| 57      | 0.543907 | 0.839146 | 0.648168  | 1.542811  | 1.191688 | 1.838550 | 0.0730816           | 0.5471005           | 3       |
| 58      | 0.544151 | 0.838987 | 0.648581  | 1.541828  | 1.191913 | 1.837725 | 0.0732039           | 0.5464085           | 2       |
| 59      | 0.544395 | 0.838829 | 0.648994  | 1.540846  | 1.192138 | 1.836901 | 0.0733263           | 0.5457175           | 1       |
| 60      | 0.544639 | 0.838671 | 0.649408  | 1.539865  | 1.192363 | 1.836078 | 0.0734489           | 0.5450273           | 0       |
| Minutes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read<br>Down        | 57°-58°<br>Involute | Minutes |

↑ 122° or 302°

57° or 237° ↑

↓ 33° or 213° **Trigonometric and Involute Functions** 146° or 326° ↓

| Minutes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute<br>33°-34° | Read<br>Up          | Minutes |
|---------|----------|----------|-----------|-----------|----------|----------|---------------------|---------------------|---------|
| 0       | 0.544639 | 0.838671 | 0.649408  | 1.539865  | 1.192363 | 1.836078 | 0.0734489           | 0.5450273           | 60      |
| 1       | 0.544883 | 0.838512 | 0.649821  | 1.538885  | 1.192589 | 1.835256 | 0.0735717           | 0.5443380           | 59      |
| 2       | 0.545127 | 0.838354 | 0.650235  | 1.537905  | 1.192814 | 1.834435 | 0.0736946           | 0.5436495           | 58      |
| 3       | 0.545371 | 0.838195 | 0.650649  | 1.536927  | 1.193040 | 1.833615 | 0.0738177           | 0.5429620           | 57      |
| 4       | 0.545615 | 0.838036 | 0.651063  | 1.535949  | 1.193266 | 1.832796 | 0.0739409           | 0.5422753           | 56      |
| 5       | 0.545858 | 0.837878 | 0.651477  | 1.534973  | 1.193492 | 1.831977 | 0.0740643           | 0.5415895           | 55      |
| 6       | 0.546102 | 0.837719 | 0.651892  | 1.533997  | 1.193718 | 1.831160 | 0.0741878           | 0.5409046           | 54      |
| 7       | 0.546346 | 0.837560 | 0.652306  | 1.533022  | 1.193945 | 1.830343 | 0.0743115           | 0.5402205           | 53      |
| 8       | 0.546589 | 0.837401 | 0.652721  | 1.532048  | 1.194171 | 1.829527 | 0.0744354           | 0.5395373           | 52      |
| 9       | 0.546833 | 0.837242 | 0.653136  | 1.531075  | 1.194398 | 1.828713 | 0.0745594           | 0.5388550           | 51      |
| 10      | 0.547076 | 0.837083 | 0.653551  | 1.530102  | 1.194625 | 1.827899 | 0.0746835           | 0.5381735           | 50      |
| 11      | 0.547320 | 0.836924 | 0.653966  | 1.529131  | 1.194852 | 1.827085 | 0.0748079           | 0.5374929           | 49      |
| 12      | 0.547563 | 0.836764 | 0.654382  | 1.528160  | 1.195080 | 1.826273 | 0.0749324           | 0.5368132           | 48      |
| 13      | 0.547807 | 0.836605 | 0.654797  | 1.527190  | 1.195307 | 1.825462 | 0.0750570           | 0.5361343           | 47      |
| 14      | 0.548050 | 0.836446 | 0.655213  | 1.526222  | 1.195535 | 1.824651 | 0.0751818           | 0.5354563           | 46      |
| 15      | 0.548293 | 0.836286 | 0.655629  | 1.525253  | 1.195763 | 1.823842 | 0.0753068           | 0.5347791           | 45      |
| 16      | 0.548536 | 0.836127 | 0.656045  | 1.524286  | 1.195991 | 1.823033 | 0.0754319           | 0.5341028           | 44      |
| 17      | 0.548780 | 0.835967 | 0.656461  | 1.523320  | 1.196219 | 1.822225 | 0.0755571           | 0.5334274           | 43      |
| 18      | 0.549023 | 0.835807 | 0.656877  | 1.522355  | 1.196448 | 1.821418 | 0.0756826           | 0.5327528           | 42      |
| 19      | 0.549266 | 0.835648 | 0.657294  | 1.521390  | 1.196677 | 1.820612 | 0.0758082           | 0.5320791           | 41      |
| 20      | 0.549509 | 0.835488 | 0.657710  | 1.520426  | 1.196906 | 1.819806 | 0.0759339           | 0.5314062           | 40      |
| 21      | 0.549752 | 0.835328 | 0.658127  | 1.519463  | 1.197135 | 1.819002 | 0.0760598           | 0.5307342           | 39      |
| 22      | 0.549995 | 0.835168 | 0.658544  | 1.518501  | 1.197364 | 1.818199 | 0.0761859           | 0.5300630           | 38      |
| 23      | 0.550238 | 0.835008 | 0.658961  | 1.517540  | 1.197593 | 1.817396 | 0.0763121           | 0.5293927           | 37      |
| 24      | 0.550481 | 0.834848 | 0.659379  | 1.516580  | 1.197823 | 1.816594 | 0.0764385           | 0.5287232           | 36      |
| 25      | 0.550724 | 0.834688 | 0.659796  | 1.515620  | 1.198053 | 1.815793 | 0.0765651           | 0.5280546           | 35      |
| 26      | 0.550966 | 0.834527 | 0.660214  | 1.514661  | 1.198283 | 1.814993 | 0.0766918           | 0.5273868           | 34      |
| 27      | 0.551209 | 0.834367 | 0.660631  | 1.513704  | 1.198513 | 1.814194 | 0.0768187           | 0.5267199           | 33      |
| 28      | 0.551452 | 0.834207 | 0.661049  | 1.512747  | 1.198744 | 1.813395 | 0.0769457           | 0.5260538           | 32      |
| 29      | 0.551694 | 0.834046 | 0.661467  | 1.511790  | 1.198974 | 1.812598 | 0.0770729           | 0.5253886           | 31      |
| 30      | 0.551937 | 0.833886 | 0.661886  | 1.510835  | 1.199205 | 1.811801 | 0.0772003           | 0.5247242           | 30      |
| 31      | 0.552180 | 0.833725 | 0.662304  | 1.509881  | 1.199436 | 1.811005 | 0.0773278           | 0.5240606           | 29      |
| 32      | 0.552422 | 0.833565 | 0.662723  | 1.508927  | 1.199667 | 1.810210 | 0.0774555           | 0.5233979           | 28      |
| 33      | 0.552664 | 0.833404 | 0.663141  | 1.507974  | 1.199898 | 1.809416 | 0.0775833           | 0.5227360           | 27      |
| 34      | 0.552907 | 0.833243 | 0.663560  | 1.507022  | 1.200130 | 1.808623 | 0.0777113           | 0.5220749           | 26      |
| 35      | 0.553149 | 0.833082 | 0.663979  | 1.506071  | 1.200362 | 1.807830 | 0.0778395           | 0.5214147           | 25      |
| 36      | 0.553392 | 0.832921 | 0.664398  | 1.505121  | 1.200594 | 1.807039 | 0.0779678           | 0.5207598           | 24      |
| 37      | 0.553634 | 0.832760 | 0.664818  | 1.504172  | 1.200826 | 1.806248 | 0.0780963           | 0.5201097           | 23      |
| 38      | 0.553876 | 0.832599 | 0.665237  | 1.503223  | 1.201058 | 1.805458 | 0.0782249           | 0.5194390           | 22      |
| 39      | 0.554118 | 0.832438 | 0.665657  | 1.502275  | 1.201291 | 1.804669 | 0.0783537           | 0.5187681           | 21      |
| 40      | 0.554360 | 0.832277 | 0.666077  | 1.501328  | 1.201523 | 1.803881 | 0.0784827           | 0.5181260           | 20      |
| 41      | 0.554602 | 0.832115 | 0.666497  | 1.500382  | 1.201756 | 1.803094 | 0.0786118           | 0.5174708           | 19      |
| 42      | 0.554844 | 0.831954 | 0.666917  | 1.499437  | 1.201989 | 1.802307 | 0.0787411           | 0.5168164           | 18      |
| 43      | 0.555086 | 0.831793 | 0.667337  | 1.498492  | 1.202223 | 1.801521 | 0.0788706           | 0.5161628           | 17      |
| 44      | 0.555328 | 0.831631 | 0.667758  | 1.497549  | 1.202456 | 1.800736 | 0.0790002           | 0.5155100           | 16      |
| 45      | 0.555570 | 0.831470 | 0.668179  | 1.496606  | 1.202690 | 1.799952 | 0.0791300           | 0.5148581           | 15      |
| 46      | 0.555812 | 0.831308 | 0.668599  | 1.495664  | 1.202924 | 1.799169 | 0.0792600           | 0.5142069           | 14      |
| 47      | 0.556054 | 0.831146 | 0.669020  | 1.494723  | 1.203158 | 1.798387 | 0.0793901           | 0.5135566           | 13      |
| 48      | 0.556296 | 0.830984 | 0.669442  | 1.493782  | 1.203392 | 1.797605 | 0.0795204           | 0.5129071           | 12      |
| 49      | 0.556537 | 0.830823 | 0.669863  | 1.492843  | 1.203626 | 1.796825 | 0.0796508           | 0.5122585           | 11      |
| 50      | 0.556779 | 0.830661 | 0.670284  | 1.491904  | 1.203861 | 1.796045 | 0.0797814           | 0.5116106           | 10      |
| 51      | 0.557021 | 0.830499 | 0.670706  | 1.490966  | 1.204096 | 1.795266 | 0.0799122           | 0.5109635           | 9       |
| 52      | 0.557262 | 0.830337 | 0.671128  | 1.490029  | 1.204331 | 1.794488 | 0.0800431           | 0.5103173           | 8       |
| 53      | 0.557504 | 0.830174 | 0.671550  | 1.489092  | 1.204566 | 1.793710 | 0.0801742           | 0.5096719           | 7       |
| 54      | 0.557745 | 0.830012 | 0.671972  | 1.488157  | 1.204801 | 1.792934 | 0.0803055           | 0.5090273           | 6       |
| 55      | 0.557987 | 0.829850 | 0.672394  | 1.487222  | 1.205037 | 1.792158 | 0.0804369           | 0.5083835           | 5       |
| 56      | 0.558228 | 0.829688 | 0.672817  | 1.486288  | 1.205273 | 1.791383 | 0.0805685           | 0.5077405           | 4       |
| 57      | 0.558469 | 0.829525 | 0.673240  | 1.485355  | 1.205509 | 1.790609 | 0.0807003           | 0.5070983           | 3       |
| 58      | 0.558710 | 0.829363 | 0.673662  | 1.484423  | 1.205745 | 1.789836 | 0.0808322           | 0.5064569           | 2       |
| 59      | 0.558952 | 0.829200 | 0.674085  | 1.483492  | 1.205981 | 1.789063 | 0.0809643           | 0.5058164           | 1       |
| 60      | 0.559193 | 0.829038 | 0.674509  | 1.482561  | 1.206218 | 1.788292 | 0.0810966           | 0.5051766           | 0       |
| Minutes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read<br>Down        | 56°-57°<br>Involute | Minutes |

↑ 123° or 303°

56° or 236° ↑



TRIGONOMETRY TABLES

↓ 34° or 214° Trigonometric and Involute Functions 145° or 325° ↓

| Minutes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute<br>34°-35° | Read<br>Up          | Minutes |
|---------|----------|----------|-----------|-----------|----------|----------|---------------------|---------------------|---------|
| 0       | 0.559193 | 0.829038 | 0.674509  | 1.482561  | 1.206218 | 1.788292 | 0.0810966           | 0.5051766           | 60      |
| 1       | 0.559434 | 0.828875 | 0.674932  | 1.481631  | 1.206455 | 1.787521 | 0.0812290           | 0.5045376           | 59      |
| 2       | 0.559675 | 0.828712 | 0.675355  | 1.480702  | 1.206692 | 1.786751 | 0.0813616           | 0.5038995           | 58      |
| 3       | 0.559916 | 0.828549 | 0.675779  | 1.479774  | 1.206929 | 1.785982 | 0.0814943           | 0.5032621           | 57      |
| 4       | 0.560157 | 0.828386 | 0.676203  | 1.478846  | 1.207166 | 1.785213 | 0.0816273           | 0.5026255           | 56      |
| 5       | 0.560398 | 0.828223 | 0.676627  | 1.477920  | 1.207404 | 1.784446 | 0.0817604           | 0.5019877           | 55      |
| 6       | 0.560639 | 0.828060 | 0.677051  | 1.476994  | 1.207641 | 1.783679 | 0.0818936           | 0.5013548           | 54      |
| 7       | 0.560880 | 0.827897 | 0.677475  | 1.476069  | 1.207879 | 1.782913 | 0.0820271           | 0.5007206           | 53      |
| 8       | 0.561121 | 0.827734 | 0.677900  | 1.475144  | 1.208118 | 1.782148 | 0.0821606           | 0.5000872           | 52      |
| 9       | 0.561362 | 0.827571 | 0.678324  | 1.474221  | 1.208356 | 1.781384 | 0.0822944           | 0.4994546           | 51      |
| 10      | 0.561603 | 0.827407 | 0.678749  | 1.473298  | 1.208594 | 1.780620 | 0.0824283           | 0.4988228           | 50      |
| 11      | 0.561843 | 0.827244 | 0.679174  | 1.472376  | 1.208833 | 1.779857 | 0.0825624           | 0.4981918           | 49      |
| 12      | 0.562083 | 0.827081 | 0.679599  | 1.471455  | 1.209072 | 1.779095 | 0.0826967           | 0.4975616           | 48      |
| 13      | 0.562324 | 0.826917 | 0.680025  | 1.470535  | 1.209311 | 1.778334 | 0.0828311           | 0.4969322           | 47      |
| 14      | 0.562564 | 0.826753 | 0.680450  | 1.469615  | 1.209550 | 1.777574 | 0.0829657           | 0.4963035           | 46      |
| 15      | 0.562805 | 0.826590 | 0.680876  | 1.468697  | 1.209790 | 1.776815 | 0.0831005           | 0.4956757           | 45      |
| 16      | 0.563045 | 0.826426 | 0.681302  | 1.467779  | 1.210030 | 1.776056 | 0.0832354           | 0.4950486           | 44      |
| 17      | 0.563286 | 0.826262 | 0.681728  | 1.466862  | 1.210270 | 1.775298 | 0.0833705           | 0.4944223           | 43      |
| 18      | 0.563526 | 0.826098 | 0.682154  | 1.465945  | 1.210510 | 1.774541 | 0.0835058           | 0.4937968           | 42      |
| 19      | 0.563766 | 0.825934 | 0.682580  | 1.465030  | 1.210750 | 1.773785 | 0.0836413           | 0.4931721           | 41      |
| 20      | 0.564007 | 0.825770 | 0.683007  | 1.464115  | 1.210991 | 1.773029 | 0.0837769           | 0.4925481           | 40      |
| 21      | 0.564247 | 0.825606 | 0.683433  | 1.463201  | 1.211231 | 1.772274 | 0.0839127           | 0.4919249           | 39      |
| 22      | 0.564487 | 0.825442 | 0.683860  | 1.462287  | 1.211472 | 1.771520 | 0.0840486           | 0.4913026           | 38      |
| 23      | 0.564727 | 0.825278 | 0.684287  | 1.461375  | 1.211713 | 1.770767 | 0.0841847           | 0.4906809           | 37      |
| 24      | 0.564967 | 0.825113 | 0.684714  | 1.460463  | 1.211954 | 1.770015 | 0.0843210           | 0.4900601           | 36      |
| 25      | 0.565207 | 0.824949 | 0.685142  | 1.459552  | 1.212196 | 1.769263 | 0.0844575           | 0.4894450           | 35      |
| 26      | 0.565447 | 0.824785 | 0.685569  | 1.458642  | 1.212438 | 1.768513 | 0.0845941           | 0.4888207           | 34      |
| 27      | 0.565687 | 0.824620 | 0.685997  | 1.457733  | 1.212680 | 1.767763 | 0.0847309           | 0.4882022           | 33      |
| 28      | 0.565927 | 0.824456 | 0.686425  | 1.456824  | 1.212922 | 1.767013 | 0.0848679           | 0.4875845           | 32      |
| 29      | 0.566166 | 0.824291 | 0.686853  | 1.455916  | 1.213164 | 1.766265 | 0.0850050           | 0.4869675           | 31      |
| 30      | 0.566406 | 0.824126 | 0.687281  | 1.455009  | 1.213406 | 1.765517 | 0.0851424           | 0.4863513           | 30      |
| 31      | 0.566646 | 0.823961 | 0.687709  | 1.454103  | 1.213649 | 1.764770 | 0.0852799           | 0.4857359           | 29      |
| 32      | 0.566886 | 0.823797 | 0.688138  | 1.453197  | 1.213892 | 1.764024 | 0.0854175           | 0.4851212           | 28      |
| 33      | 0.567125 | 0.823632 | 0.688567  | 1.452292  | 1.214135 | 1.763279 | 0.0855555           | 0.4845073           | 27      |
| 34      | 0.567365 | 0.823467 | 0.688995  | 1.451388  | 1.214378 | 1.762535 | 0.0856933           | 0.4838941           | 26      |
| 35      | 0.567604 | 0.823302 | 0.689425  | 1.450485  | 1.214622 | 1.761791 | 0.0858313           | 0.4832817           | 25      |
| 36      | 0.567844 | 0.823136 | 0.689854  | 1.449583  | 1.214866 | 1.761048 | 0.0859699           | 0.4826701           | 24      |
| 37      | 0.568083 | 0.822971 | 0.690283  | 1.448681  | 1.215109 | 1.760306 | 0.0861084           | 0.4820593           | 23      |
| 38      | 0.568323 | 0.822806 | 0.690713  | 1.447780  | 1.215354 | 1.759564 | 0.0862471           | 0.4814492           | 22      |
| 39      | 0.568562 | 0.822641 | 0.691143  | 1.446880  | 1.215598 | 1.758824 | 0.0863859           | 0.4808398           | 21      |
| 40      | 0.568801 | 0.822475 | 0.691572  | 1.445980  | 1.215842 | 1.758084 | 0.0865250           | 0.4802312           | 20      |
| 41      | 0.569040 | 0.822310 | 0.692003  | 1.445081  | 1.216087 | 1.757345 | 0.0866642           | 0.4796234           | 19      |
| 42      | 0.569280 | 0.822144 | 0.692433  | 1.444183  | 1.216332 | 1.756606 | 0.0868036           | 0.4790163           | 18      |
| 43      | 0.569519 | 0.821978 | 0.692863  | 1.443286  | 1.216577 | 1.755869 | 0.0869431           | 0.4784100           | 17      |
| 44      | 0.569758 | 0.821813 | 0.693294  | 1.442390  | 1.216822 | 1.755132 | 0.0870829           | 0.4778044           | 16      |
| 45      | 0.569997 | 0.821647 | 0.693725  | 1.441494  | 1.217068 | 1.754396 | 0.0872228           | 0.4771996           | 15      |
| 46      | 0.570236 | 0.821481 | 0.694156  | 1.440599  | 1.217313 | 1.753661 | 0.0873628           | 0.4765956           | 14      |
| 47      | 0.570475 | 0.821315 | 0.694587  | 1.439705  | 1.217559 | 1.752926 | 0.0875031           | 0.4759923           | 13      |
| 48      | 0.570714 | 0.821149 | 0.695018  | 1.438811  | 1.217805 | 1.752192 | 0.0876435           | 0.4753897           | 12      |
| 49      | 0.570952 | 0.820983 | 0.695450  | 1.437919  | 1.218052 | 1.751459 | 0.0877841           | 0.4747879           | 11      |
| 50      | 0.571191 | 0.820817 | 0.695881  | 1.437027  | 1.218298 | 1.750727 | 0.0879249           | 0.4741868           | 10      |
| 51      | 0.571430 | 0.820651 | 0.696313  | 1.436136  | 1.218545 | 1.749996 | 0.0880659           | 0.4735865           | 9       |
| 52      | 0.571669 | 0.820485 | 0.696745  | 1.435245  | 1.218792 | 1.749265 | 0.0882070           | 0.4729869           | 8       |
| 53      | 0.571907 | 0.820318 | 0.697177  | 1.434355  | 1.219039 | 1.748535 | 0.0883483           | 0.4723881           | 7       |
| 54      | 0.572146 | 0.820152 | 0.697610  | 1.433466  | 1.219286 | 1.747806 | 0.0884898           | 0.4717900           | 6       |
| 55      | 0.572384 | 0.819985 | 0.698042  | 1.432578  | 1.219534 | 1.747078 | 0.0886314           | 0.4711926           | 5       |
| 56      | 0.572623 | 0.819819 | 0.698475  | 1.431691  | 1.219782 | 1.746350 | 0.0887732           | 0.4705960           | 4       |
| 57      | 0.572861 | 0.819652 | 0.698908  | 1.430804  | 1.220030 | 1.745623 | 0.0889152           | 0.4700001           | 3       |
| 58      | 0.573100 | 0.819486 | 0.699341  | 1.429918  | 1.220278 | 1.744897 | 0.0890574           | 0.4694050           | 2       |
| 59      | 0.573338 | 0.819319 | 0.699774  | 1.429033  | 1.220526 | 1.744171 | 0.0891998           | 0.4688106           | 1       |
| 60      | 0.573576 | 0.819152 | 0.700208  | 1.428148  | 1.220775 | 1.743447 | 0.0893423           | 0.4682169           | 0       |
| Minutes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read<br>Down        | 55°-56°<br>Involute | Minutes |

↑ 124° or 304°

55° or 235° ↑

↓ 35° or 215° Trigonometric and Involute Functions 144° or 324° ↓

| Minutes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute<br>35°-36° | Read<br>Up          | Minutes |
|---------|----------|----------|-----------|-----------|----------|----------|---------------------|---------------------|---------|
| 0       | 0.573576 | 0.819152 | 0.700208  | 1.428148  | 1.220775 | 1.743447 | 0.0893423           | 0.4682169           | 60      |
| 1       | 0.573815 | 0.818985 | 0.700641  | 1.427264  | 1.221023 | 1.742723 | 0.0894850           | 0.4676240           | 59      |
| 2       | 0.574053 | 0.818818 | 0.701075  | 1.426381  | 1.221272 | 1.742000 | 0.0896279           | 0.4670318           | 58      |
| 3       | 0.574291 | 0.818651 | 0.701509  | 1.425499  | 1.221521 | 1.741277 | 0.0897710           | 0.4664403           | 57      |
| 4       | 0.574529 | 0.818484 | 0.701943  | 1.424617  | 1.221771 | 1.740556 | 0.0899142           | 0.4658496           | 56      |
| 5       | 0.574767 | 0.818317 | 0.702377  | 1.423736  | 1.222020 | 1.739835 | 0.0900576           | 0.4652596           | 55      |
| 6       | 0.575005 | 0.818150 | 0.702812  | 1.422856  | 1.222270 | 1.739115 | 0.0902012           | 0.4646703           | 54      |
| 7       | 0.575243 | 0.817982 | 0.703246  | 1.421977  | 1.222520 | 1.738395 | 0.0903450           | 0.4640818           | 53      |
| 8       | 0.575481 | 0.817815 | 0.703681  | 1.421098  | 1.222770 | 1.737676 | 0.0904889           | 0.4634940           | 52      |
| 9       | 0.575719 | 0.817648 | 0.704116  | 1.420220  | 1.223021 | 1.736958 | 0.0906331           | 0.4629069           | 51      |
| 10      | 0.575957 | 0.817480 | 0.704551  | 1.419343  | 1.223271 | 1.736241 | 0.0907774           | 0.4623205           | 50      |
| 11      | 0.576195 | 0.817313 | 0.704987  | 1.418466  | 1.223522 | 1.735525 | 0.0909218           | 0.4617349           | 49      |
| 12      | 0.576432 | 0.817145 | 0.705422  | 1.417590  | 1.223773 | 1.734809 | 0.0910665           | 0.4611499           | 48      |
| 13      | 0.576670 | 0.816977 | 0.705858  | 1.416715  | 1.224024 | 1.734094 | 0.0912113           | 0.4605657           | 47      |
| 14      | 0.576908 | 0.816809 | 0.706294  | 1.415841  | 1.224276 | 1.733380 | 0.0913564           | 0.4599823           | 46      |
| 15      | 0.577145 | 0.816642 | 0.706730  | 1.414967  | 1.224527 | 1.732666 | 0.0915016           | 0.4593995           | 45      |
| 16      | 0.577383 | 0.816474 | 0.707166  | 1.414094  | 1.224779 | 1.731953 | 0.0916469           | 0.4588175           | 44      |
| 17      | 0.577620 | 0.816306 | 0.707603  | 1.413222  | 1.225031 | 1.731241 | 0.0917925           | 0.4582361           | 43      |
| 18      | 0.577858 | 0.816138 | 0.708039  | 1.412351  | 1.225284 | 1.730530 | 0.0919382           | 0.4576555           | 42      |
| 19      | 0.578095 | 0.815969 | 0.708476  | 1.411480  | 1.225536 | 1.729819 | 0.0920842           | 0.4570757           | 41      |
| 20      | 0.578332 | 0.815801 | 0.708913  | 1.410610  | 1.225789 | 1.729110 | 0.0922303           | 0.4564965           | 40      |
| 21      | 0.578570 | 0.815633 | 0.709350  | 1.409740  | 1.226042 | 1.728400 | 0.0923765           | 0.4559180           | 39      |
| 22      | 0.578807 | 0.815465 | 0.709788  | 1.408872  | 1.226295 | 1.727692 | 0.0925230           | 0.4553403           | 38      |
| 23      | 0.579044 | 0.815296 | 0.710225  | 1.408004  | 1.226548 | 1.726984 | 0.0926696           | 0.4547632           | 37      |
| 24      | 0.579281 | 0.815128 | 0.710663  | 1.407137  | 1.226801 | 1.726277 | 0.0928165           | 0.4541869           | 36      |
| 25      | 0.579518 | 0.814959 | 0.711101  | 1.406270  | 1.227055 | 1.725571 | 0.0929635           | 0.4536113           | 35      |
| 26      | 0.579755 | 0.814791 | 0.711539  | 1.405404  | 1.227309 | 1.724866 | 0.0931106           | 0.4530364           | 34      |
| 27      | 0.579992 | 0.814622 | 0.711977  | 1.404539  | 1.227563 | 1.724161 | 0.0932580           | 0.4524622           | 33      |
| 28      | 0.580229 | 0.814453 | 0.712416  | 1.403675  | 1.227818 | 1.723457 | 0.0934055           | 0.4518887           | 32      |
| 29      | 0.580466 | 0.814284 | 0.712854  | 1.402811  | 1.228072 | 1.722753 | 0.0935533           | 0.4513159           | 31      |
| 30      | 0.580703 | 0.814116 | 0.713293  | 1.401948  | 1.228327 | 1.722051 | 0.0937012           | 0.4507439           | 30      |
| 31      | 0.580940 | 0.813947 | 0.713732  | 1.401086  | 1.228582 | 1.721349 | 0.0938493           | 0.4501725           | 29      |
| 32      | 0.581176 | 0.813778 | 0.714171  | 1.400224  | 1.228837 | 1.720648 | 0.0939975           | 0.4496018           | 28      |
| 33      | 0.581413 | 0.813608 | 0.714611  | 1.399364  | 1.229092 | 1.719947 | 0.0941460           | 0.4490318           | 27      |
| 34      | 0.581650 | 0.813439 | 0.715050  | 1.398503  | 1.229348 | 1.719247 | 0.0942946           | 0.4484626           | 26      |
| 35      | 0.581886 | 0.813270 | 0.715490  | 1.397644  | 1.229604 | 1.718548 | 0.0944435           | 0.4478940           | 25      |
| 36      | 0.582123 | 0.813101 | 0.715930  | 1.396785  | 1.229860 | 1.717850 | 0.0945925           | 0.4473261           | 24      |
| 37      | 0.582359 | 0.812931 | 0.716370  | 1.395927  | 1.230116 | 1.717152 | 0.0947417           | 0.4467589           | 23      |
| 38      | 0.582596 | 0.812762 | 0.716810  | 1.395070  | 1.230373 | 1.716456 | 0.0948910           | 0.4461924           | 22      |
| 39      | 0.582832 | 0.812592 | 0.717250  | 1.394213  | 1.230629 | 1.715759 | 0.0950406           | 0.4456267           | 21      |
| 40      | 0.583069 | 0.812423 | 0.717691  | 1.393357  | 1.230886 | 1.715064 | 0.0951903           | 0.4450616           | 20      |
| 41      | 0.583305 | 0.812253 | 0.718132  | 1.392502  | 1.231143 | 1.714369 | 0.0953402           | 0.4444972           | 19      |
| 42      | 0.583541 | 0.812084 | 0.718573  | 1.391647  | 1.231400 | 1.713675 | 0.0954904           | 0.4439353           | 18      |
| 43      | 0.583777 | 0.811914 | 0.719014  | 1.390793  | 1.231658 | 1.712982 | 0.0956406           | 0.4433705           | 17      |
| 44      | 0.584014 | 0.811744 | 0.719455  | 1.389940  | 1.231916 | 1.712289 | 0.0957911           | 0.4428081           | 16      |
| 45      | 0.584250 | 0.811574 | 0.719897  | 1.389088  | 1.232174 | 1.711597 | 0.0959418           | 0.4422465           | 15      |
| 46      | 0.584486 | 0.811404 | 0.720339  | 1.388236  | 1.232432 | 1.710906 | 0.0960926           | 0.4416856           | 14      |
| 47      | 0.584722 | 0.811234 | 0.720781  | 1.387385  | 1.232690 | 1.710215 | 0.0962437           | 0.4411253           | 13      |
| 48      | 0.584958 | 0.811064 | 0.721223  | 1.386534  | 1.232949 | 1.709525 | 0.0963949           | 0.4405657           | 12      |
| 49      | 0.585194 | 0.810894 | 0.721665  | 1.385684  | 1.233207 | 1.708836 | 0.0965463           | 0.4400069           | 11      |
| 50      | 0.585429 | 0.810723 | 0.722108  | 1.384835  | 1.233466 | 1.708148 | 0.0966979           | 0.4394487           | 10      |
| 51      | 0.585665 | 0.810553 | 0.722550  | 1.383987  | 1.233726 | 1.707460 | 0.0968496           | 0.4388911           | 9       |
| 52      | 0.585901 | 0.810383 | 0.722993  | 1.383139  | 1.233985 | 1.706773 | 0.0970016           | 0.4383343           | 8       |
| 53      | 0.586137 | 0.810212 | 0.723436  | 1.382292  | 1.234245 | 1.706087 | 0.0971537           | 0.4377782           | 7       |
| 54      | 0.586372 | 0.810042 | 0.723879  | 1.381446  | 1.234504 | 1.705401 | 0.0973061           | 0.4372227           | 6       |
| 55      | 0.586608 | 0.809871 | 0.724323  | 1.380600  | 1.234764 | 1.704716 | 0.0974586           | 0.4366679           | 5       |
| 56      | 0.586844 | 0.809700 | 0.724766  | 1.379755  | 1.235025 | 1.704032 | 0.0976113           | 0.4361138           | 4       |
| 57      | 0.587079 | 0.809530 | 0.725210  | 1.378911  | 1.235285 | 1.703348 | 0.0977642           | 0.4355604           | 3       |
| 58      | 0.587314 | 0.809359 | 0.725654  | 1.378067  | 1.235546 | 1.702665 | 0.0979173           | 0.4350076           | 2       |
| 59      | 0.587550 | 0.809188 | 0.726098  | 1.377224  | 1.235807 | 1.701983 | 0.0980705           | 0.4344555           | 1       |
| 60      | 0.587785 | 0.809017 | 0.726543  | 1.376382  | 1.236068 | 1.701302 | 0.0982240           | 0.4339041           | 0       |
| Minutes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read<br>Down        | 54°-55°<br>Involute | Minutes |

↑ 125° or 305°

54° or 234° ↑

TRIGONOMETRY TABLES

↓ 36° or 216° Trigonometric and Involute Functions 143° or 323° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>36°-37° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.587785 | 0.809017 | 0.726543 | 1.376382  | 1.236068 | 1.701302 | 0.0982240           | 0.4339041  | 60      |
| 1       | 0.588021 | 0.808846 | 0.726987 | 1.375540  | 1.236329 | 1.700621 | 0.0983776           | 0.4333534  | 59      |
| 2       | 0.588256 | 0.808675 | 0.727432 | 1.374699  | 1.236591 | 1.699941 | 0.0985315           | 0.4328033  | 58      |
| 3       | 0.588491 | 0.808504 | 0.727877 | 1.373859  | 1.236853 | 1.699261 | 0.0986855           | 0.4322540  | 57      |
| 4       | 0.588726 | 0.808333 | 0.728322 | 1.373019  | 1.237115 | 1.698582 | 0.0988397           | 0.4317052  | 56      |
| 5       | 0.588961 | 0.808161 | 0.728767 | 1.372181  | 1.237377 | 1.697904 | 0.0989941           | 0.4311572  | 55      |
| 6       | 0.589196 | 0.807990 | 0.729213 | 1.371342  | 1.237639 | 1.697227 | 0.0991487           | 0.4306098  | 54      |
| 7       | 0.589431 | 0.807818 | 0.729658 | 1.370505  | 1.237902 | 1.696550 | 0.0993035           | 0.4300631  | 53      |
| 8       | 0.589666 | 0.807647 | 0.730104 | 1.369668  | 1.238165 | 1.695874 | 0.0994584           | 0.4295171  | 52      |
| 9       | 0.589901 | 0.807475 | 0.730550 | 1.368832  | 1.238428 | 1.695199 | 0.0996130           | 0.4289717  | 51      |
| 10      | 0.590136 | 0.807304 | 0.730996 | 1.367996  | 1.238691 | 1.694524 | 0.0997689           | 0.4284270  | 50      |
| 11      | 0.590371 | 0.807132 | 0.731443 | 1.367161  | 1.238955 | 1.693850 | 0.0999244           | 0.4278830  | 49      |
| 12      | 0.590606 | 0.806960 | 0.731889 | 1.366327  | 1.239218 | 1.693177 | 0.1000802           | 0.4273396  | 48      |
| 13      | 0.590840 | 0.806788 | 0.732336 | 1.365493  | 1.239482 | 1.692505 | 0.1002361           | 0.4267969  | 47      |
| 14      | 0.591075 | 0.806617 | 0.732783 | 1.364660  | 1.239746 | 1.691833 | 0.1003922           | 0.4262548  | 46      |
| 15      | 0.591310 | 0.806445 | 0.733230 | 1.363828  | 1.240011 | 1.691161 | 0.1005485           | 0.4257134  | 45      |
| 16      | 0.591544 | 0.806273 | 0.733678 | 1.362996  | 1.240275 | 1.690491 | 0.1007050           | 0.4251727  | 44      |
| 17      | 0.591779 | 0.806100 | 0.734125 | 1.362165  | 1.240540 | 1.689821 | 0.1008616           | 0.4246326  | 43      |
| 18      | 0.592013 | 0.805928 | 0.734573 | 1.361335  | 1.240805 | 1.689152 | 0.1010185           | 0.4240932  | 42      |
| 19      | 0.592248 | 0.805756 | 0.735021 | 1.360505  | 1.241070 | 1.688483 | 0.1011756           | 0.4235545  | 41      |
| 20      | 0.592482 | 0.805584 | 0.735469 | 1.359676  | 1.241336 | 1.687815 | 0.1013328           | 0.4230164  | 40      |
| 21      | 0.592716 | 0.805411 | 0.735917 | 1.358848  | 1.241602 | 1.687148 | 0.1014903           | 0.4224789  | 39      |
| 22      | 0.592951 | 0.805239 | 0.736366 | 1.358020  | 1.241867 | 1.686481 | 0.1016479           | 0.4219421  | 38      |
| 23      | 0.593185 | 0.805066 | 0.736815 | 1.357193  | 1.242134 | 1.685815 | 0.1018057           | 0.4214060  | 37      |
| 24      | 0.593419 | 0.804894 | 0.737264 | 1.356367  | 1.242400 | 1.685150 | 0.1019637           | 0.4208705  | 36      |
| 25      | 0.593653 | 0.804721 | 0.737713 | 1.355541  | 1.242666 | 1.684486 | 0.1021219           | 0.4203357  | 35      |
| 26      | 0.593887 | 0.804548 | 0.738162 | 1.354716  | 1.242933 | 1.683822 | 0.1022804           | 0.4198015  | 34      |
| 27      | 0.594121 | 0.804376 | 0.738611 | 1.353892  | 1.243200 | 1.683159 | 0.1024389           | 0.4192680  | 33      |
| 28      | 0.594355 | 0.804203 | 0.739061 | 1.353068  | 1.243467 | 1.682496 | 0.1025977           | 0.4187351  | 32      |
| 29      | 0.594589 | 0.804030 | 0.739511 | 1.352245  | 1.243735 | 1.681834 | 0.1027567           | 0.4182029  | 31      |
| 30      | 0.594823 | 0.803857 | 0.739961 | 1.351422  | 1.244003 | 1.681173 | 0.1029159           | 0.4176713  | 30      |
| 31      | 0.595057 | 0.803684 | 0.740411 | 1.350601  | 1.244270 | 1.680512 | 0.1030753           | 0.4171403  | 29      |
| 32      | 0.595290 | 0.803511 | 0.740862 | 1.349779  | 1.244539 | 1.679853 | 0.1032348           | 0.4166101  | 28      |
| 33      | 0.595524 | 0.803337 | 0.741312 | 1.348959  | 1.244807 | 1.679193 | 0.1033946           | 0.4160804  | 27      |
| 34      | 0.595758 | 0.803164 | 0.741763 | 1.348139  | 1.245075 | 1.678535 | 0.1035545           | 0.4155514  | 26      |
| 35      | 0.595991 | 0.802991 | 0.742214 | 1.347320  | 1.245344 | 1.677877 | 0.1037147           | 0.4150230  | 25      |
| 36      | 0.596225 | 0.802817 | 0.742666 | 1.346501  | 1.245613 | 1.677220 | 0.1038750           | 0.4144965  | 24      |
| 37      | 0.596458 | 0.802644 | 0.743117 | 1.345683  | 1.245882 | 1.676563 | 0.1040356           | 0.4139682  | 23      |
| 38      | 0.596692 | 0.802470 | 0.743569 | 1.344866  | 1.246152 | 1.675907 | 0.1041963           | 0.4134418  | 22      |
| 39      | 0.596925 | 0.802297 | 0.744020 | 1.344049  | 1.246421 | 1.675252 | 0.1043572           | 0.4129160  | 21      |
| 40      | 0.597159 | 0.802123 | 0.744472 | 1.343233  | 1.246691 | 1.674597 | 0.1045184           | 0.4123908  | 20      |
| 41      | 0.597392 | 0.801949 | 0.744925 | 1.342418  | 1.246961 | 1.673943 | 0.1046797           | 0.4118663  | 19      |
| 42      | 0.597625 | 0.801776 | 0.745377 | 1.341603  | 1.247232 | 1.673290 | 0.1048412           | 0.4113424  | 18      |
| 43      | 0.597858 | 0.801602 | 0.745830 | 1.340789  | 1.247502 | 1.672637 | 0.1050029           | 0.4108192  | 17      |
| 44      | 0.598091 | 0.801428 | 0.746282 | 1.339975  | 1.247773 | 1.671985 | 0.1051648           | 0.4102966  | 16      |
| 45      | 0.598325 | 0.801254 | 0.746735 | 1.339162  | 1.248044 | 1.671334 | 0.1053269           | 0.4097746  | 15      |
| 46      | 0.598558 | 0.801080 | 0.747189 | 1.338350  | 1.248315 | 1.670683 | 0.1054892           | 0.4092532  | 14      |
| 47      | 0.598791 | 0.800906 | 0.747642 | 1.337539  | 1.248587 | 1.670033 | 0.1056517           | 0.4087325  | 13      |
| 48      | 0.599024 | 0.800731 | 0.748096 | 1.336728  | 1.248858 | 1.669383 | 0.1058144           | 0.4082124  | 12      |
| 49      | 0.599256 | 0.800557 | 0.748549 | 1.335917  | 1.249130 | 1.668735 | 0.1059773           | 0.4076930  | 11      |
| 50      | 0.599489 | 0.800383 | 0.749003 | 1.335108  | 1.249402 | 1.668086 | 0.1061404           | 0.4071741  | 10      |
| 51      | 0.599722 | 0.800208 | 0.749458 | 1.334298  | 1.249675 | 1.667439 | 0.1063037           | 0.4066559  | 9       |
| 52      | 0.599955 | 0.800034 | 0.749912 | 1.333490  | 1.249947 | 1.666792 | 0.1064672           | 0.4061384  | 8       |
| 53      | 0.600188 | 0.799859 | 0.750366 | 1.332682  | 1.250220 | 1.666146 | 0.1066309           | 0.4056214  | 7       |
| 54      | 0.600420 | 0.799685 | 0.750821 | 1.331875  | 1.250493 | 1.665500 | 0.1067947           | 0.4051051  | 6       |
| 55      | 0.600653 | 0.799510 | 0.751276 | 1.331068  | 1.250766 | 1.664855 | 0.1069588           | 0.4045894  | 5       |
| 56      | 0.600885 | 0.799335 | 0.751731 | 1.330262  | 1.251040 | 1.664211 | 0.1071231           | 0.4040744  | 4       |
| 57      | 0.601118 | 0.799160 | 0.752187 | 1.329457  | 1.251313 | 1.663567 | 0.1072876           | 0.4035599  | 3       |
| 58      | 0.601350 | 0.798985 | 0.752642 | 1.328652  | 1.251587 | 1.662924 | 0.1074523           | 0.4030461  | 2       |
| 59      | 0.601583 | 0.798811 | 0.753098 | 1.327848  | 1.251861 | 1.662282 | 0.1076171           | 0.4025329  | 1       |
| 60      | 0.601815 | 0.798636 | 0.753554 | 1.327045  | 1.252136 | 1.661640 | 0.1077822           | 0.4020203  | 0       |

↑ 126° or 306°

53° or 233° ↑

↓ 37° or 217° **Trigonometric and Involute Functions** 142° or 322° ↓

| Minutes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute<br>37°-38° | Read<br>Up          | Minutes |
|---------|----------|----------|-----------|-----------|----------|----------|---------------------|---------------------|---------|
| 0       | 0.601815 | 0.798636 | 0.753554  | 1.327045  | 1.252136 | 1.661640 | 0.1077822           | 0.4020203           | 60      |
| 1       | 0.602047 | 0.798460 | 0.754010  | 1.326242  | 1.252410 | 1.660999 | 0.1079475           | 0.4015084           | 59      |
| 2       | 0.602280 | 0.798285 | 0.754467  | 1.325440  | 1.252685 | 1.660359 | 0.1081130           | 0.4009970           | 58      |
| 3       | 0.602512 | 0.798110 | 0.754923  | 1.324638  | 1.252960 | 1.659719 | 0.1082787           | 0.4004863           | 57      |
| 4       | 0.602744 | 0.797935 | 0.755380  | 1.323837  | 1.253235 | 1.659080 | 0.1084445           | 0.3999762           | 56      |
| 5       | 0.602976 | 0.797759 | 0.755837  | 1.323037  | 1.253511 | 1.658441 | 0.1086106           | 0.3994667           | 55      |
| 6       | 0.603208 | 0.797584 | 0.756294  | 1.322237  | 1.253787 | 1.657803 | 0.1087769           | 0.3989578           | 54      |
| 7       | 0.603440 | 0.797408 | 0.756751  | 1.321438  | 1.254062 | 1.657166 | 0.1089434           | 0.3984496           | 53      |
| 8       | 0.603672 | 0.797233 | 0.757209  | 1.320639  | 1.254339 | 1.656529 | 0.1091101           | 0.3979419           | 52      |
| 9       | 0.603904 | 0.797057 | 0.757667  | 1.319841  | 1.254615 | 1.655893 | 0.1092770           | 0.3974349           | 51      |
| 10      | 0.604136 | 0.796882 | 0.758125  | 1.319044  | 1.254892 | 1.655258 | 0.1094440           | 0.3969285           | 50      |
| 11      | 0.604367 | 0.796706 | 0.758583  | 1.318247  | 1.255169 | 1.654623 | 0.1096113           | 0.3964227           | 49      |
| 12      | 0.604599 | 0.796530 | 0.759041  | 1.317451  | 1.255446 | 1.653989 | 0.1097788           | 0.3959175           | 48      |
| 13      | 0.604831 | 0.796354 | 0.759500  | 1.316656  | 1.255723 | 1.653355 | 0.1099465           | 0.3954129           | 47      |
| 14      | 0.605062 | 0.796178 | 0.759959  | 1.315861  | 1.256000 | 1.652722 | 0.1101144           | 0.3949089           | 46      |
| 15      | 0.605294 | 0.796002 | 0.760418  | 1.315067  | 1.256278 | 1.652090 | 0.1102825           | 0.3944056           | 45      |
| 16      | 0.605526 | 0.795826 | 0.760877  | 1.314273  | 1.256556 | 1.651458 | 0.1104508           | 0.3939028           | 44      |
| 17      | 0.605757 | 0.795650 | 0.761336  | 1.313480  | 1.256834 | 1.650827 | 0.1106193           | 0.3934007           | 43      |
| 18      | 0.605988 | 0.795473 | 0.761796  | 1.312688  | 1.257113 | 1.650197 | 0.1107880           | 0.3928991           | 42      |
| 19      | 0.606220 | 0.795297 | 0.762256  | 1.311896  | 1.257392 | 1.649567 | 0.1109570           | 0.3923962           | 41      |
| 20      | 0.606451 | 0.795121 | 0.762716  | 1.311105  | 1.257671 | 1.648938 | 0.1111261           | 0.3918978           | 40      |
| 21      | 0.606682 | 0.794944 | 0.763176  | 1.310314  | 1.257950 | 1.648309 | 0.1112954           | 0.3913981           | 39      |
| 22      | 0.606914 | 0.794768 | 0.763636  | 1.309524  | 1.258229 | 1.647681 | 0.1114649           | 0.3908990           | 38      |
| 23      | 0.607145 | 0.794591 | 0.764097  | 1.308735  | 1.258509 | 1.647054 | 0.1116347           | 0.3904004           | 37      |
| 24      | 0.607376 | 0.794415 | 0.764558  | 1.307946  | 1.258789 | 1.646427 | 0.1118046           | 0.3899025           | 36      |
| 25      | 0.607607 | 0.794238 | 0.765019  | 1.307157  | 1.259069 | 1.645801 | 0.1119747           | 0.3894052           | 35      |
| 26      | 0.607838 | 0.794061 | 0.765480  | 1.306370  | 1.259349 | 1.645175 | 0.1121451           | 0.3889085           | 34      |
| 27      | 0.608069 | 0.793884 | 0.765941  | 1.305583  | 1.259629 | 1.644551 | 0.1123156           | 0.3884123           | 33      |
| 28      | 0.608300 | 0.793707 | 0.766403  | 1.304796  | 1.259910 | 1.643926 | 0.1124864           | 0.3879168           | 32      |
| 29      | 0.608531 | 0.793530 | 0.766865  | 1.304011  | 1.260191 | 1.643303 | 0.1126573           | 0.3874219           | 31      |
| 30      | 0.608761 | 0.793353 | 0.767327  | 1.303225  | 1.260472 | 1.642680 | 0.1128285           | 0.3869275           | 30      |
| 31      | 0.608992 | 0.793176 | 0.767789  | 1.302441  | 1.260754 | 1.642057 | 0.1129999           | 0.3864338           | 29      |
| 32      | 0.609223 | 0.792999 | 0.768252  | 1.301657  | 1.261036 | 1.641435 | 0.1131715           | 0.3859406           | 28      |
| 33      | 0.609454 | 0.792822 | 0.768714  | 1.300873  | 1.261317 | 1.640814 | 0.1133433           | 0.3854481           | 27      |
| 34      | 0.609684 | 0.792644 | 0.769177  | 1.300090  | 1.261600 | 1.640194 | 0.1135153           | 0.3849561           | 26      |
| 35      | 0.609915 | 0.792467 | 0.769640  | 1.299308  | 1.261882 | 1.639574 | 0.1136875           | 0.3844647           | 25      |
| 36      | 0.610145 | 0.792290 | 0.770104  | 1.298526  | 1.262165 | 1.638954 | 0.1138599           | 0.3839739           | 24      |
| 37      | 0.610376 | 0.792112 | 0.770567  | 1.297745  | 1.262448 | 1.638335 | 0.1140325           | 0.3834837           | 23      |
| 38      | 0.610606 | 0.791935 | 0.771031  | 1.296965  | 1.262731 | 1.637717 | 0.1142053           | 0.3829941           | 22      |
| 39      | 0.610836 | 0.791757 | 0.771495  | 1.296185  | 1.263014 | 1.637100 | 0.1143784           | 0.3825045           | 21      |
| 40      | 0.611067 | 0.791579 | 0.771959  | 1.295406  | 1.263298 | 1.636483 | 0.1145516           | 0.3820167           | 20      |
| 41      | 0.611297 | 0.791401 | 0.772423  | 1.294627  | 1.263581 | 1.635866 | 0.1147250           | 0.3815289           | 19      |
| 42      | 0.611527 | 0.791224 | 0.772888  | 1.293849  | 1.263865 | 1.635251 | 0.1148987           | 0.3810416           | 18      |
| 43      | 0.611757 | 0.791046 | 0.773353  | 1.293071  | 1.264150 | 1.634636 | 0.1150726           | 0.3805549           | 17      |
| 44      | 0.611987 | 0.790868 | 0.773818  | 1.292294  | 1.264434 | 1.634021 | 0.1152466           | 0.3800689           | 16      |
| 45      | 0.612217 | 0.790690 | 0.774283  | 1.291518  | 1.264719 | 1.633407 | 0.1154209           | 0.3795834           | 15      |
| 46      | 0.612447 | 0.790511 | 0.774748  | 1.290742  | 1.265004 | 1.632794 | 0.1155954           | 0.3790984           | 14      |
| 47      | 0.612677 | 0.790333 | 0.775214  | 1.289967  | 1.265289 | 1.632181 | 0.1157701           | 0.3786141           | 13      |
| 48      | 0.612907 | 0.790155 | 0.775680  | 1.289192  | 1.265574 | 1.631569 | 0.1159451           | 0.3781304           | 12      |
| 49      | 0.613137 | 0.789977 | 0.776146  | 1.288418  | 1.265860 | 1.630957 | 0.1161202           | 0.3776472           | 11      |
| 50      | 0.613367 | 0.789798 | 0.776612  | 1.287645  | 1.266146 | 1.630346 | 0.1162955           | 0.3771646           | 10      |
| 51      | 0.613596 | 0.789620 | 0.777078  | 1.286872  | 1.266432 | 1.629736 | 0.1164711           | 0.3766826           | 9       |
| 52      | 0.613826 | 0.789441 | 0.777545  | 1.286099  | 1.266719 | 1.629126 | 0.1166468           | 0.3762012           | 8       |
| 53      | 0.614056 | 0.789263 | 0.778012  | 1.285328  | 1.267005 | 1.628517 | 0.1168228           | 0.3757203           | 7       |
| 54      | 0.614285 | 0.789084 | 0.778479  | 1.284557  | 1.267292 | 1.627908 | 0.1169990           | 0.3752400           | 6       |
| 55      | 0.614515 | 0.788905 | 0.778946  | 1.283786  | 1.267579 | 1.627300 | 0.1171754           | 0.3747603           | 5       |
| 56      | 0.614744 | 0.788727 | 0.779414  | 1.283016  | 1.267866 | 1.626693 | 0.1173520           | 0.3742812           | 4       |
| 57      | 0.614974 | 0.788548 | 0.779881  | 1.282247  | 1.268154 | 1.626086 | 0.1175288           | 0.3738026           | 3       |
| 58      | 0.615203 | 0.788369 | 0.780349  | 1.281478  | 1.268442 | 1.625480 | 0.1177058           | 0.3733247           | 2       |
| 59      | 0.615433 | 0.788190 | 0.780817  | 1.280709  | 1.268730 | 1.624874 | 0.1178831           | 0.3728473           | 1       |
| 60      | 0.615661 | 0.788011 | 0.781286  | 1.279942  | 1.269018 | 1.624269 | 0.1180605           | 0.3723704           | 0       |
| Minutes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read<br>Down        | 52°-53°<br>Involute | Minutes |

↑ 127° or 307°

52° or 332° ↑

TRIGONOMETRY TABLES

↓ 38° or 218° Trigonometric and Involute Functions 141° or 321° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>38°-39° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.615661 | 0.788011 | 0.781286 | 1.279942  | 1.269018 | 1.624269 | 0.1180605           | 0.3723704  | 60      |
| 1       | 0.615891 | 0.787832 | 0.781754 | 1.279174  | 1.269307 | 1.623665 | 0.1182382           | 0.3718942  | 59      |
| 2       | 0.616120 | 0.787652 | 0.782223 | 1.278408  | 1.269596 | 1.623061 | 0.1184161           | 0.3714185  | 58      |
| 3       | 0.616349 | 0.787473 | 0.782692 | 1.277642  | 1.269885 | 1.622458 | 0.1185942           | 0.3709433  | 57      |
| 4       | 0.616578 | 0.787294 | 0.783161 | 1.276876  | 1.270174 | 1.621855 | 0.1187725           | 0.3704688  | 56      |
| 5       | 0.616807 | 0.787114 | 0.783631 | 1.276112  | 1.270463 | 1.621253 | 0.1189510           | 0.3699948  | 55      |
| 6       | 0.617036 | 0.786935 | 0.784100 | 1.275347  | 1.270753 | 1.620651 | 0.1191297           | 0.3695214  | 54      |
| 7       | 0.617265 | 0.786756 | 0.784570 | 1.274584  | 1.271043 | 1.620050 | 0.1193087           | 0.3690485  | 53      |
| 8       | 0.617494 | 0.786576 | 0.785040 | 1.273820  | 1.271333 | 1.619450 | 0.1194878           | 0.3685763  | 52      |
| 9       | 0.617722 | 0.786396 | 0.785510 | 1.273058  | 1.271624 | 1.618850 | 0.1196672           | 0.3681045  | 51      |
| 10      | 0.617951 | 0.786217 | 0.785981 | 1.272296  | 1.271914 | 1.618251 | 0.1198468           | 0.3676334  | 50      |
| 11      | 0.618180 | 0.786037 | 0.786451 | 1.271534  | 1.272205 | 1.617652 | 0.1200266           | 0.3671628  | 49      |
| 12      | 0.618408 | 0.785857 | 0.786922 | 1.270773  | 1.272496 | 1.617054 | 0.1202066           | 0.3666928  | 48      |
| 13      | 0.618637 | 0.785677 | 0.787394 | 1.270013  | 1.272788 | 1.616457 | 0.1203869           | 0.3662233  | 47      |
| 14      | 0.618865 | 0.785497 | 0.787865 | 1.269253  | 1.273079 | 1.615860 | 0.1205673           | 0.3657544  | 46      |
| 15      | 0.619094 | 0.785317 | 0.788336 | 1.268494  | 1.273371 | 1.615264 | 0.1207480           | 0.3652861  | 45      |
| 16      | 0.619322 | 0.785137 | 0.788808 | 1.267735  | 1.273663 | 1.614668 | 0.1209289           | 0.3648183  | 44      |
| 17      | 0.619551 | 0.784957 | 0.789280 | 1.266977  | 1.273956 | 1.614073 | 0.1211100           | 0.3643511  | 43      |
| 18      | 0.619779 | 0.784776 | 0.789752 | 1.266220  | 1.274248 | 1.613478 | 0.1212913           | 0.3638844  | 42      |
| 19      | 0.620007 | 0.784596 | 0.790225 | 1.265463  | 1.274541 | 1.612884 | 0.1214728           | 0.3634183  | 41      |
| 20      | 0.620235 | 0.784416 | 0.790697 | 1.264706  | 1.274834 | 1.612291 | 0.1216546           | 0.3629527  | 40      |
| 21      | 0.620464 | 0.784235 | 0.791170 | 1.263950  | 1.275128 | 1.611698 | 0.1218366           | 0.3624878  | 39      |
| 22      | 0.620692 | 0.784055 | 0.791643 | 1.263195  | 1.275421 | 1.611106 | 0.1220186           | 0.3620233  | 38      |
| 23      | 0.620920 | 0.783874 | 0.792117 | 1.262440  | 1.275715 | 1.610514 | 0.1222012           | 0.3615594  | 37      |
| 24      | 0.621148 | 0.783693 | 0.792590 | 1.261686  | 1.276009 | 1.609923 | 0.1223838           | 0.3610961  | 36      |
| 25      | 0.621376 | 0.783513 | 0.793064 | 1.260932  | 1.276303 | 1.609332 | 0.1225666           | 0.3606333  | 35      |
| 26      | 0.621604 | 0.783332 | 0.793538 | 1.260179  | 1.276598 | 1.608742 | 0.1227497           | 0.3601711  | 34      |
| 27      | 0.621831 | 0.783151 | 0.794012 | 1.259427  | 1.276893 | 1.608153 | 0.1229330           | 0.3597094  | 33      |
| 28      | 0.622059 | 0.782970 | 0.794486 | 1.258675  | 1.277188 | 1.607564 | 0.1231165           | 0.3592483  | 32      |
| 29      | 0.622287 | 0.782789 | 0.794961 | 1.257923  | 1.277483 | 1.606976 | 0.1233002           | 0.3587878  | 31      |
| 30      | 0.622515 | 0.782608 | 0.795436 | 1.257172  | 1.277779 | 1.606388 | 0.1234842           | 0.3583277  | 30      |
| 31      | 0.622742 | 0.782427 | 0.795911 | 1.256422  | 1.278074 | 1.605801 | 0.1236683           | 0.3578683  | 29      |
| 32      | 0.622970 | 0.782246 | 0.796386 | 1.255672  | 1.278370 | 1.605214 | 0.1238527           | 0.3574093  | 28      |
| 33      | 0.623197 | 0.782065 | 0.796862 | 1.254923  | 1.278667 | 1.604628 | 0.1240373           | 0.3569510  | 27      |
| 34      | 0.623425 | 0.781883 | 0.797337 | 1.254174  | 1.278963 | 1.604043 | 0.1242221           | 0.3564931  | 26      |
| 35      | 0.623652 | 0.781702 | 0.797813 | 1.253426  | 1.279260 | 1.603458 | 0.1244072           | 0.3560359  | 25      |
| 36      | 0.623880 | 0.781520 | 0.798290 | 1.252678  | 1.279557 | 1.602873 | 0.1245924           | 0.3555791  | 24      |
| 37      | 0.624107 | 0.781339 | 0.798766 | 1.251931  | 1.279854 | 1.602290 | 0.1247779           | 0.3551229  | 23      |
| 38      | 0.624334 | 0.781157 | 0.799242 | 1.251185  | 1.280152 | 1.601706 | 0.1249636           | 0.3546673  | 22      |
| 39      | 0.624561 | 0.780976 | 0.799719 | 1.250439  | 1.280450 | 1.601124 | 0.1251495           | 0.3542122  | 21      |
| 40      | 0.624789 | 0.780794 | 0.800196 | 1.249693  | 1.280748 | 1.600542 | 0.1253357           | 0.3537576  | 20      |
| 41      | 0.625016 | 0.780612 | 0.800674 | 1.248948  | 1.281046 | 1.599960 | 0.1255221           | 0.3533036  | 19      |
| 42      | 0.625243 | 0.780430 | 0.801151 | 1.248204  | 1.281344 | 1.599379 | 0.1257087           | 0.3528501  | 18      |
| 43      | 0.625470 | 0.780248 | 0.801629 | 1.247460  | 1.281643 | 1.598799 | 0.1258955           | 0.3523972  | 17      |
| 44      | 0.625697 | 0.780067 | 0.802107 | 1.246717  | 1.281942 | 1.598219 | 0.1260825           | 0.3519448  | 16      |
| 45      | 0.625923 | 0.779884 | 0.802585 | 1.245974  | 1.282241 | 1.597639 | 0.1262698           | 0.3514929  | 15      |
| 46      | 0.626150 | 0.779702 | 0.803063 | 1.245232  | 1.282541 | 1.597061 | 0.1264573           | 0.3510416  | 14      |
| 47      | 0.626377 | 0.779520 | 0.803542 | 1.244490  | 1.282840 | 1.596482 | 0.1266450           | 0.3505908  | 13      |
| 48      | 0.626604 | 0.779338 | 0.804021 | 1.243749  | 1.283140 | 1.595905 | 0.1268329           | 0.3501406  | 12      |
| 49      | 0.626830 | 0.779156 | 0.804500 | 1.243009  | 1.283441 | 1.595328 | 0.1270210           | 0.3496909  | 11      |
| 50      | 0.627057 | 0.778973 | 0.804979 | 1.242268  | 1.283741 | 1.594751 | 0.1272094           | 0.3492417  | 10      |
| 51      | 0.627284 | 0.778791 | 0.805458 | 1.241529  | 1.284042 | 1.594175 | 0.1273980           | 0.3487931  | 9       |
| 52      | 0.627510 | 0.778608 | 0.805938 | 1.240790  | 1.284343 | 1.593600 | 0.1275869           | 0.3483450  | 8       |
| 53      | 0.627737 | 0.778426 | 0.806418 | 1.240052  | 1.284644 | 1.593025 | 0.1277759           | 0.3478974  | 7       |
| 54      | 0.627963 | 0.778243 | 0.806898 | 1.239314  | 1.284945 | 1.592450 | 0.1279652           | 0.3474503  | 6       |
| 55      | 0.628189 | 0.778060 | 0.807379 | 1.238576  | 1.285247 | 1.591877 | 0.1281547           | 0.3470038  | 5       |
| 56      | 0.628416 | 0.777878 | 0.807859 | 1.237839  | 1.285549 | 1.591303 | 0.1283444           | 0.3465579  | 4       |
| 57      | 0.628642 | 0.777695 | 0.808340 | 1.237103  | 1.285851 | 1.590731 | 0.1285344           | 0.3461124  | 3       |
| 58      | 0.628868 | 0.777512 | 0.808821 | 1.236367  | 1.286154 | 1.590158 | 0.1287246           | 0.3456675  | 2       |
| 59      | 0.629094 | 0.777329 | 0.809303 | 1.235632  | 1.286457 | 1.589587 | 0.1289150           | 0.3452231  | 1       |
| 60      | 0.629320 | 0.777146 | 0.809784 | 1.234897  | 1.286760 | 1.589016 | 0.1291056           | 0.3447792  | 0       |

↑ 128° or 308°

51° or 231° ↑

↓ 39° or 219°      Trigonometric and Involute Functions      140° or 320° ↓

| Minutes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>39°-40° | Read<br>Up | Minutes |
|---------|----------|----------|----------|-----------|----------|----------|---------------------|------------|---------|
| 0       | 0.629320 | 0.777146 | 0.809784 | 1.234897  | 1.286760 | 1.589016 | 0.1291056           | 0.3447792  | 60      |
| 1       | 0.629546 | 0.776963 | 0.810266 | 1.234163  | 1.287063 | 1.588445 | 0.1292965           | 0.3443359  | 59      |
| 2       | 0.629772 | 0.776780 | 0.810748 | 1.233429  | 1.287366 | 1.587875 | 0.1294876           | 0.3438931  | 58      |
| 3       | 0.629998 | 0.776596 | 0.811230 | 1.232696  | 1.287670 | 1.587306 | 0.1296789           | 0.3434508  | 57      |
| 4       | 0.630224 | 0.776413 | 0.811712 | 1.231963  | 1.287974 | 1.586737 | 0.1298704           | 0.3430091  | 56      |
| 5       | 0.630450 | 0.776230 | 0.812195 | 1.231231  | 1.288278 | 1.586169 | 0.1300622           | 0.3425678  | 55      |
| 6       | 0.630676 | 0.776046 | 0.812678 | 1.230500  | 1.288583 | 1.585601 | 0.1302542           | 0.3421271  | 54      |
| 7       | 0.630902 | 0.775863 | 0.813161 | 1.229769  | 1.288887 | 1.585033 | 0.1304464           | 0.3416870  | 53      |
| 8       | 0.631127 | 0.775679 | 0.813644 | 1.229038  | 1.289192 | 1.584467 | 0.1306389           | 0.3412473  | 52      |
| 9       | 0.631353 | 0.775496 | 0.814128 | 1.228308  | 1.289498 | 1.583900 | 0.1308316           | 0.3408082  | 51      |
| 10      | 0.631578 | 0.775312 | 0.814612 | 1.227579  | 1.289803 | 1.583335 | 0.1310245           | 0.3403695  | 50      |
| 11      | 0.631804 | 0.775128 | 0.815096 | 1.226850  | 1.290109 | 1.582770 | 0.1312177           | 0.3399315  | 49      |
| 12      | 0.632029 | 0.774944 | 0.815580 | 1.226121  | 1.290415 | 1.582205 | 0.1314110           | 0.3394939  | 48      |
| 13      | 0.632255 | 0.774761 | 0.816065 | 1.225393  | 1.290721 | 1.581641 | 0.1316046           | 0.3390568  | 47      |
| 14      | 0.632480 | 0.774577 | 0.816549 | 1.224666  | 1.291028 | 1.581078 | 0.1317985           | 0.3386203  | 46      |
| 15      | 0.632705 | 0.774393 | 0.817034 | 1.223939  | 1.291335 | 1.580515 | 0.1319925           | 0.3381843  | 45      |
| 16      | 0.632931 | 0.774209 | 0.817519 | 1.223212  | 1.291642 | 1.579952 | 0.1321868           | 0.3377488  | 44      |
| 17      | 0.633156 | 0.774024 | 0.818005 | 1.222487  | 1.291949 | 1.579390 | 0.1323814           | 0.3373138  | 43      |
| 18      | 0.633381 | 0.773840 | 0.818491 | 1.221761  | 1.292256 | 1.578829 | 0.1325761           | 0.3368793  | 42      |
| 19      | 0.633606 | 0.773656 | 0.818976 | 1.221036  | 1.292564 | 1.578268 | 0.1327711           | 0.3364454  | 41      |
| 20      | 0.633831 | 0.773472 | 0.819463 | 1.220312  | 1.292872 | 1.577708 | 0.1329663           | 0.3360119  | 40      |
| 21      | 0.634056 | 0.773287 | 0.819949 | 1.219588  | 1.293181 | 1.577148 | 0.1331618           | 0.3355790  | 39      |
| 22      | 0.634281 | 0.773103 | 0.820435 | 1.218865  | 1.293489 | 1.576589 | 0.1333575           | 0.3351466  | 38      |
| 23      | 0.634506 | 0.772918 | 0.820922 | 1.218142  | 1.293798 | 1.576030 | 0.1335534           | 0.3347147  | 37      |
| 24      | 0.634731 | 0.772734 | 0.821409 | 1.217420  | 1.294107 | 1.575472 | 0.1337495           | 0.3342833  | 36      |
| 25      | 0.634955 | 0.772549 | 0.821897 | 1.216698  | 1.294416 | 1.574914 | 0.1339459           | 0.3338525  | 35      |
| 26      | 0.635180 | 0.772364 | 0.822384 | 1.215977  | 1.294726 | 1.574357 | 0.1341425           | 0.3334221  | 34      |
| 27      | 0.635405 | 0.772179 | 0.822872 | 1.215256  | 1.295036 | 1.573800 | 0.1343394           | 0.3329922  | 33      |
| 28      | 0.635629 | 0.771995 | 0.823360 | 1.214536  | 1.295346 | 1.573244 | 0.1345366           | 0.3325629  | 32      |
| 29      | 0.635854 | 0.771810 | 0.823848 | 1.213816  | 1.295656 | 1.572689 | 0.1347338           | 0.3321341  | 31      |
| 30      | 0.636078 | 0.771625 | 0.824336 | 1.213097  | 1.295967 | 1.572134 | 0.1349313           | 0.3317057  | 30      |
| 31      | 0.636303 | 0.771440 | 0.824825 | 1.212378  | 1.296278 | 1.571579 | 0.1351291           | 0.3312779  | 29      |
| 32      | 0.636527 | 0.771254 | 0.825314 | 1.211660  | 1.296589 | 1.571025 | 0.1353271           | 0.3308506  | 28      |
| 33      | 0.636751 | 0.771069 | 0.825803 | 1.210942  | 1.296900 | 1.570472 | 0.1355254           | 0.3304238  | 27      |
| 34      | 0.636976 | 0.770884 | 0.826292 | 1.210225  | 1.297212 | 1.569919 | 0.1357239           | 0.3299975  | 26      |
| 35      | 0.637200 | 0.770699 | 0.826782 | 1.209509  | 1.297524 | 1.569366 | 0.1359226           | 0.3295717  | 25      |
| 36      | 0.637424 | 0.770513 | 0.827272 | 1.208792  | 1.297836 | 1.568815 | 0.1361216           | 0.3291464  | 24      |
| 37      | 0.637648 | 0.770328 | 0.827762 | 1.208077  | 1.298149 | 1.568263 | 0.1363208           | 0.3287216  | 23      |
| 38      | 0.637872 | 0.770142 | 0.828252 | 1.207362  | 1.298461 | 1.567712 | 0.1365202           | 0.3282973  | 22      |
| 39      | 0.638096 | 0.769957 | 0.828743 | 1.206647  | 1.298774 | 1.567162 | 0.1367199           | 0.3278736  | 21      |
| 40      | 0.638320 | 0.769771 | 0.829234 | 1.205933  | 1.299088 | 1.566612 | 0.1369198           | 0.3274503  | 20      |
| 41      | 0.638544 | 0.769585 | 0.829725 | 1.205219  | 1.299401 | 1.566063 | 0.1371199           | 0.3270275  | 19      |
| 42      | 0.638768 | 0.769400 | 0.830216 | 1.204506  | 1.299715 | 1.565514 | 0.1373203           | 0.3266052  | 18      |
| 43      | 0.638992 | 0.769214 | 0.830707 | 1.203793  | 1.300029 | 1.564966 | 0.1375209           | 0.3261834  | 17      |
| 44      | 0.639215 | 0.769028 | 0.831199 | 1.203081  | 1.300343 | 1.564418 | 0.1377218           | 0.3257621  | 16      |
| 45      | 0.639439 | 0.768842 | 0.831691 | 1.202369  | 1.300658 | 1.563871 | 0.1379228           | 0.3253414  | 15      |
| 46      | 0.639663 | 0.768656 | 0.832183 | 1.201658  | 1.300972 | 1.563324 | 0.1381242           | 0.3249211  | 14      |
| 47      | 0.639886 | 0.768470 | 0.832676 | 1.200947  | 1.301287 | 1.562778 | 0.1383257           | 0.3245013  | 13      |
| 48      | 0.640110 | 0.768284 | 0.833169 | 1.200237  | 1.301603 | 1.562232 | 0.1385275           | 0.3240820  | 12      |
| 49      | 0.640333 | 0.768097 | 0.833662 | 1.199528  | 1.301918 | 1.561687 | 0.1387296           | 0.3236632  | 11      |
| 50      | 0.640557 | 0.767911 | 0.834155 | 1.198818  | 1.302234 | 1.561142 | 0.1389319           | 0.3232449  | 10      |
| 51      | 0.640780 | 0.767725 | 0.834648 | 1.198110  | 1.302550 | 1.560598 | 0.1391344           | 0.3228271  | 9       |
| 52      | 0.641003 | 0.767538 | 0.835142 | 1.197402  | 1.302867 | 1.560055 | 0.1393372           | 0.3224098  | 8       |
| 53      | 0.641226 | 0.767352 | 0.835636 | 1.196694  | 1.303183 | 1.559511 | 0.1395404           | 0.3219930  | 7       |
| 54      | 0.641450 | 0.767165 | 0.836130 | 1.195987  | 1.303500 | 1.558969 | 0.1397434           | 0.3215766  | 6       |
| 55      | 0.641673 | 0.766979 | 0.836624 | 1.195280  | 1.303817 | 1.558427 | 0.1399469           | 0.3211608  | 5       |
| 56      | 0.641896 | 0.766792 | 0.837119 | 1.194574  | 1.304135 | 1.557885 | 0.1401506           | 0.3207454  | 4       |
| 57      | 0.642119 | 0.766605 | 0.837614 | 1.193868  | 1.304453 | 1.557344 | 0.1403546           | 0.3203306  | 3       |
| 58      | 0.642342 | 0.766418 | 0.838109 | 1.193163  | 1.304771 | 1.556803 | 0.1405588           | 0.3199162  | 2       |
| 59      | 0.642565 | 0.766231 | 0.838604 | 1.192458  | 1.305089 | 1.556263 | 0.1407632           | 0.3195024  | 1       |
| 60      | 0.642788 | 0.766044 | 0.839100 | 1.191754  | 1.305407 | 1.555724 | 0.1409679           | 0.3190890  | 0       |

↑ 129° or 309°

50° or 230° ↑

TRIGONOMETRY TABLES

↓ 40° or 220° **Trigonometric and Involute Functions** 139° or 319° ↓

| Minutes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute<br>40°-41° | Read<br>Up          | Minutes |
|---------|----------|----------|-----------|-----------|----------|----------|---------------------|---------------------|---------|
| 0       | 0.642788 | 0.766044 | 0.839100  | 1.191754  | 1.305407 | 1.555724 | 0.1409679           | 0.3190890           | 60      |
| 1       | 0.643010 | 0.765887 | 0.839595  | 1.191050  | 1.305726 | 1.555185 | 0.1411729           | 0.3186761           | 59      |
| 2       | 0.643233 | 0.765670 | 0.840092  | 1.190347  | 1.306045 | 1.554646 | 0.1413780           | 0.3182637           | 58      |
| 3       | 0.643456 | 0.765483 | 0.840588  | 1.189644  | 1.306364 | 1.554108 | 0.1415835           | 0.3178517           | 57      |
| 4       | 0.643679 | 0.765296 | 0.841084  | 1.188941  | 1.306684 | 1.553571 | 0.1417891           | 0.3174403           | 56      |
| 5       | 0.643901 | 0.765109 | 0.841581  | 1.188240  | 1.307004 | 1.553034 | 0.1419950           | 0.3170293           | 55      |
| 6       | 0.644124 | 0.764921 | 0.842078  | 1.187538  | 1.307324 | 1.552497 | 0.1422012           | 0.3166189           | 54      |
| 7       | 0.644346 | 0.764734 | 0.842575  | 1.186837  | 1.307644 | 1.551961 | 0.1424076           | 0.3162089           | 53      |
| 8       | 0.644569 | 0.764547 | 0.843073  | 1.186137  | 1.307965 | 1.551425 | 0.1426142           | 0.3157994           | 52      |
| 9       | 0.644791 | 0.764359 | 0.843571  | 1.185437  | 1.308286 | 1.550890 | 0.1428211           | 0.3153904           | 51      |
| 10      | 0.645013 | 0.764171 | 0.844069  | 1.184738  | 1.308607 | 1.550356 | 0.1430282           | 0.3149819           | 50      |
| 11      | 0.645235 | 0.763984 | 0.844567  | 1.184039  | 1.308928 | 1.549822 | 0.1432355           | 0.3145738           | 49      |
| 12      | 0.645458 | 0.763796 | 0.845066  | 1.183340  | 1.309250 | 1.549288 | 0.1434432           | 0.3141662           | 48      |
| 13      | 0.645680 | 0.763608 | 0.845564  | 1.182642  | 1.309572 | 1.548755 | 0.1436510           | 0.3137591           | 47      |
| 14      | 0.645902 | 0.763420 | 0.846063  | 1.181945  | 1.309894 | 1.548223 | 0.1438591           | 0.3133525           | 46      |
| 15      | 0.646124 | 0.763232 | 0.846562  | 1.181248  | 1.310217 | 1.547691 | 0.1440675           | 0.3129464           | 45      |
| 16      | 0.646346 | 0.763044 | 0.847062  | 1.180551  | 1.310540 | 1.547159 | 0.1442761           | 0.3125408           | 44      |
| 17      | 0.646568 | 0.762856 | 0.847562  | 1.179855  | 1.310863 | 1.546628 | 0.1444849           | 0.3121356           | 43      |
| 18      | 0.646790 | 0.762668 | 0.848062  | 1.179160  | 1.311186 | 1.546097 | 0.1446940           | 0.3117309           | 42      |
| 19      | 0.647012 | 0.762480 | 0.848562  | 1.178464  | 1.311510 | 1.545567 | 0.1449033           | 0.3113267           | 41      |
| 20      | 0.647233 | 0.762292 | 0.849062  | 1.177770  | 1.311833 | 1.545038 | 0.1451129           | 0.3109229           | 40      |
| 21      | 0.647455 | 0.762104 | 0.849563  | 1.177076  | 1.312158 | 1.544509 | 0.1453227           | 0.3105197           | 39      |
| 22      | 0.647677 | 0.761915 | 0.850064  | 1.176382  | 1.312482 | 1.543980 | 0.1455328           | 0.3101169           | 38      |
| 23      | 0.647898 | 0.761727 | 0.850565  | 1.175689  | 1.312807 | 1.543452 | 0.1457431           | 0.3097146           | 37      |
| 24      | 0.648120 | 0.761538 | 0.851067  | 1.174996  | 1.313132 | 1.542924 | 0.1459537           | 0.3093127           | 36      |
| 25      | 0.648341 | 0.761350 | 0.851568  | 1.174304  | 1.313457 | 1.542397 | 0.1461645           | 0.3089113           | 35      |
| 26      | 0.648563 | 0.761161 | 0.852070  | 1.173612  | 1.313782 | 1.541871 | 0.1463756           | 0.3085105           | 34      |
| 27      | 0.648784 | 0.760972 | 0.852573  | 1.172921  | 1.314108 | 1.541345 | 0.1465869           | 0.3081100           | 33      |
| 28      | 0.649006 | 0.760784 | 0.853075  | 1.172230  | 1.314434 | 1.540819 | 0.1467985           | 0.3077101           | 32      |
| 29      | 0.649227 | 0.760595 | 0.853578  | 1.171539  | 1.314760 | 1.540294 | 0.1470103           | 0.3073106           | 31      |
| 30      | 0.649448 | 0.760406 | 0.854081  | 1.170850  | 1.315087 | 1.539769 | 0.1472223           | 0.3069116           | 30      |
| 31      | 0.649669 | 0.760217 | 0.854584  | 1.170160  | 1.315414 | 1.539245 | 0.1474347           | 0.3065130           | 29      |
| 32      | 0.649890 | 0.760028 | 0.855087  | 1.169471  | 1.315741 | 1.538721 | 0.1476472           | 0.3061150           | 28      |
| 33      | 0.650111 | 0.759839 | 0.855591  | 1.168783  | 1.316068 | 1.538198 | 0.1478600           | 0.3057174           | 27      |
| 34      | 0.650332 | 0.759650 | 0.856095  | 1.168095  | 1.316396 | 1.537675 | 0.1480731           | 0.3053202           | 26      |
| 35      | 0.650553 | 0.759461 | 0.856599  | 1.167407  | 1.316724 | 1.537153 | 0.1482864           | 0.3049234           | 25      |
| 36      | 0.650774 | 0.759271 | 0.857104  | 1.166720  | 1.317052 | 1.536631 | 0.1485000           | 0.3045276           | 24      |
| 37      | 0.650995 | 0.759082 | 0.857608  | 1.166033  | 1.317381 | 1.536110 | 0.1487138           | 0.3041316           | 23      |
| 38      | 0.651216 | 0.758893 | 0.858113  | 1.165347  | 1.317710 | 1.535589 | 0.1489279           | 0.3037364           | 22      |
| 39      | 0.651437 | 0.758703 | 0.858619  | 1.164662  | 1.318039 | 1.535069 | 0.1491422           | 0.3033416           | 21      |
| 40      | 0.651657 | 0.758514 | 0.859124  | 1.163976  | 1.318368 | 1.534549 | 0.1493568           | 0.3029472           | 20      |
| 41      | 0.651878 | 0.758324 | 0.859630  | 1.163292  | 1.318698 | 1.534030 | 0.1495716           | 0.3025533           | 19      |
| 42      | 0.652098 | 0.758134 | 0.860136  | 1.162607  | 1.319027 | 1.533511 | 0.1497867           | 0.3021599           | 18      |
| 43      | 0.652319 | 0.757945 | 0.860642  | 1.161923  | 1.319358 | 1.532993 | 0.1500020           | 0.3017670           | 17      |
| 44      | 0.652539 | 0.757755 | 0.861148  | 1.161240  | 1.319688 | 1.532475 | 0.1502176           | 0.3013745           | 16      |
| 45      | 0.652760 | 0.757565 | 0.861655  | 1.160557  | 1.320019 | 1.531957 | 0.1504335           | 0.3009825           | 15      |
| 46      | 0.652980 | 0.757375 | 0.862162  | 1.159875  | 1.320350 | 1.531440 | 0.1506496           | 0.3005909           | 14      |
| 47      | 0.653200 | 0.757185 | 0.862669  | 1.159193  | 1.320681 | 1.530924 | 0.1508659           | 0.3001998           | 13      |
| 48      | 0.653421 | 0.756995 | 0.863177  | 1.158511  | 1.321013 | 1.530408 | 0.1510825           | 0.2998092           | 12      |
| 49      | 0.653641 | 0.756805 | 0.863685  | 1.157830  | 1.321344 | 1.529892 | 0.1512994           | 0.2994190           | 11      |
| 50      | 0.653861 | 0.756615 | 0.864193  | 1.157149  | 1.321677 | 1.529377 | 0.1515165           | 0.2990292           | 10      |
| 51      | 0.654081 | 0.756425 | 0.864701  | 1.156469  | 1.322009 | 1.528863 | 0.1517339           | 0.2986400           | 9       |
| 52      | 0.654301 | 0.756234 | 0.865209  | 1.155790  | 1.322342 | 1.528349 | 0.1519515           | 0.2982512           | 8       |
| 53      | 0.654521 | 0.756044 | 0.865718  | 1.155110  | 1.322675 | 1.527835 | 0.1521694           | 0.2978628           | 7       |
| 54      | 0.654741 | 0.755853 | 0.866227  | 1.154432  | 1.323008 | 1.527322 | 0.1523875           | 0.2974749           | 6       |
| 55      | 0.654961 | 0.755663 | 0.866736  | 1.153753  | 1.323341 | 1.526809 | 0.1526059           | 0.2970875           | 5       |
| 56      | 0.655180 | 0.755472 | 0.867246  | 1.153075  | 1.323675 | 1.526297 | 0.1528246           | 0.2967005           | 4       |
| 57      | 0.655400 | 0.755282 | 0.867756  | 1.152398  | 1.324009 | 1.525785 | 0.1530435           | 0.2963140           | 3       |
| 58      | 0.655620 | 0.755091 | 0.868266  | 1.151721  | 1.324343 | 1.525274 | 0.1532626           | 0.2959279           | 2       |
| 59      | 0.655839 | 0.754900 | 0.868776  | 1.151044  | 1.324678 | 1.524763 | 0.1534821           | 0.2955422           | 1       |
| 60      | 0.656059 | 0.754710 | 0.869287  | 1.150368  | 1.325013 | 1.524253 | 0.1537017           | 0.2951571           | 0       |
| Minutes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read<br>Down        | 49°-50°<br>Involute | Minutes |

↑ 130° or 310° **49° or 229°** ↑

↓ 41° or 221° Trigonometric and Involute Functions 138° or 318° ↓

| Min-utes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>41°-42° | Read<br>Up | Min-utes |
|----------|----------|----------|----------|-----------|----------|----------|---------------------|------------|----------|
| 0        | 0.656059 | 0.754710 | 0.869287 | 1.150368  | 1.325013 | 1.524253 | 0.1537017           | 0.2951571  | 60       |
| 1        | 0.656279 | 0.754519 | 0.869798 | 1.149693  | 1.325348 | 1.523743 | 0.1539217           | 0.2947724  | 59       |
| 2        | 0.656488 | 0.754328 | 0.870309 | 1.149018  | 1.325684 | 1.523234 | 0.1541419           | 0.2943881  | 58       |
| 3        | 0.656717 | 0.754137 | 0.870820 | 1.148343  | 1.326019 | 1.522725 | 0.1543623           | 0.2940043  | 57       |
| 4        | 0.656937 | 0.753946 | 0.871332 | 1.147669  | 1.326355 | 1.522217 | 0.1545831           | 0.2936209  | 56       |
| 5        | 0.657156 | 0.753755 | 0.871843 | 1.146995  | 1.326692 | 1.521709 | 0.1548040           | 0.2932380  | 55       |
| 6        | 0.657375 | 0.753563 | 0.872356 | 1.146322  | 1.327028 | 1.521201 | 0.1550253           | 0.2928555  | 54       |
| 7        | 0.657594 | 0.753372 | 0.872868 | 1.145649  | 1.327365 | 1.520694 | 0.1552468           | 0.2924735  | 53       |
| 8        | 0.657814 | 0.753181 | 0.873381 | 1.144976  | 1.327702 | 1.520188 | 0.1554685           | 0.2920919  | 52       |
| 9        | 0.658033 | 0.752989 | 0.873894 | 1.144304  | 1.328040 | 1.519682 | 0.1556908           | 0.2917108  | 51       |
| 10       | 0.658252 | 0.752798 | 0.874407 | 1.143633  | 1.328378 | 1.519176 | 0.1559126           | 0.2913301  | 50       |
| 11       | 0.658471 | 0.752606 | 0.874920 | 1.142961  | 1.328716 | 1.518671 | 0.1561354           | 0.2909499  | 49       |
| 12       | 0.658689 | 0.752415 | 0.875434 | 1.142291  | 1.329054 | 1.518166 | 0.1563582           | 0.2905701  | 48       |
| 13       | 0.658908 | 0.752223 | 0.875948 | 1.141621  | 1.329393 | 1.517662 | 0.1565812           | 0.2901908  | 47       |
| 14       | 0.659127 | 0.752032 | 0.876462 | 1.140951  | 1.329731 | 1.517158 | 0.1568046           | 0.2898119  | 46       |
| 15       | 0.659346 | 0.751840 | 0.876976 | 1.140281  | 1.330071 | 1.516655 | 0.1570281           | 0.2894334  | 45       |
| 16       | 0.659564 | 0.751648 | 0.877491 | 1.139613  | 1.330410 | 1.516152 | 0.1572520           | 0.2890554  | 44       |
| 17       | 0.659783 | 0.751456 | 0.878006 | 1.138944  | 1.330750 | 1.515650 | 0.1574761           | 0.2886779  | 43       |
| 18       | 0.660002 | 0.751264 | 0.878521 | 1.138276  | 1.331090 | 1.515148 | 0.1577005           | 0.2883008  | 42       |
| 19       | 0.660220 | 0.751072 | 0.879037 | 1.137609  | 1.331430 | 1.514646 | 0.1579251           | 0.2879241  | 41       |
| 20       | 0.660439 | 0.750880 | 0.879553 | 1.136941  | 1.331771 | 1.514145 | 0.1581500           | 0.2875479  | 40       |
| 21       | 0.660657 | 0.750688 | 0.880069 | 1.136275  | 1.332112 | 1.513645 | 0.1583752           | 0.2871721  | 39       |
| 22       | 0.660875 | 0.750496 | 0.880585 | 1.135609  | 1.332453 | 1.513145 | 0.1586006           | 0.2867967  | 38       |
| 23       | 0.661094 | 0.750303 | 0.881102 | 1.134943  | 1.332794 | 1.512645 | 0.1588263           | 0.2864218  | 37       |
| 24       | 0.661312 | 0.750111 | 0.881619 | 1.134277  | 1.333136 | 1.512146 | 0.1590523           | 0.2860473  | 36       |
| 25       | 0.661530 | 0.749919 | 0.882136 | 1.133612  | 1.333478 | 1.511647 | 0.1592785           | 0.2856733  | 35       |
| 26       | 0.661748 | 0.749726 | 0.882653 | 1.132948  | 1.333820 | 1.511149 | 0.1595050           | 0.2852997  | 34       |
| 27       | 0.661966 | 0.749534 | 0.883171 | 1.132284  | 1.334163 | 1.510651 | 0.1597318           | 0.2849265  | 33       |
| 28       | 0.662184 | 0.749341 | 0.883689 | 1.131620  | 1.334506 | 1.510154 | 0.1599588           | 0.2845538  | 32       |
| 29       | 0.662402 | 0.749148 | 0.884207 | 1.130957  | 1.334849 | 1.509657 | 0.1601861           | 0.2841815  | 31       |
| 30       | 0.662620 | 0.748956 | 0.884725 | 1.130294  | 1.335192 | 1.509160 | 0.1604136           | 0.2838097  | 30       |
| 31       | 0.662838 | 0.748763 | 0.885244 | 1.129632  | 1.335536 | 1.508665 | 0.1606414           | 0.2834383  | 29       |
| 32       | 0.663056 | 0.748570 | 0.885763 | 1.128970  | 1.335880 | 1.508169 | 0.1608695           | 0.2830673  | 28       |
| 33       | 0.663273 | 0.748377 | 0.886282 | 1.128309  | 1.336225 | 1.507674 | 0.1610979           | 0.2826968  | 27       |
| 34       | 0.663491 | 0.748184 | 0.886802 | 1.127648  | 1.336569 | 1.507179 | 0.1613265           | 0.2823267  | 26       |
| 35       | 0.663709 | 0.747991 | 0.887321 | 1.126987  | 1.336914 | 1.506685 | 0.1615554           | 0.2819570  | 25       |
| 36       | 0.663926 | 0.747798 | 0.887842 | 1.126327  | 1.337259 | 1.506191 | 0.1617846           | 0.2815874  | 24       |
| 37       | 0.664144 | 0.747605 | 0.888362 | 1.125667  | 1.337605 | 1.505698 | 0.1620140           | 0.2812189  | 23       |
| 38       | 0.664361 | 0.747412 | 0.888882 | 1.125008  | 1.337951 | 1.505205 | 0.1622437           | 0.2808506  | 22       |
| 39       | 0.664579 | 0.747218 | 0.889403 | 1.124349  | 1.338297 | 1.504713 | 0.1624737           | 0.2804826  | 21       |
| 40       | 0.664796 | 0.747025 | 0.889924 | 1.123691  | 1.338643 | 1.504221 | 0.1627039           | 0.2801151  | 20       |
| 41       | 0.665013 | 0.746832 | 0.890446 | 1.123033  | 1.338990 | 1.503730 | 0.1629344           | 0.2797480  | 19       |
| 42       | 0.665230 | 0.746638 | 0.890967 | 1.122375  | 1.339337 | 1.503239 | 0.1631652           | 0.2793814  | 18       |
| 43       | 0.665448 | 0.746445 | 0.891489 | 1.121718  | 1.339684 | 1.502748 | 0.1633963           | 0.2790151  | 17       |
| 44       | 0.665665 | 0.746251 | 0.892012 | 1.121062  | 1.340032 | 1.502258 | 0.1636276           | 0.2786493  | 16       |
| 45       | 0.665882 | 0.746057 | 0.892534 | 1.120405  | 1.340379 | 1.501768 | 0.1638592           | 0.2782840  | 15       |
| 46       | 0.666099 | 0.745864 | 0.893057 | 1.119750  | 1.340728 | 1.501279 | 0.1640910           | 0.2779190  | 14       |
| 47       | 0.666316 | 0.745670 | 0.893580 | 1.119094  | 1.341076 | 1.500790 | 0.1643232           | 0.2775545  | 13       |
| 48       | 0.666532 | 0.745476 | 0.894103 | 1.118439  | 1.341425 | 1.500302 | 0.1645556           | 0.2771904  | 12       |
| 49       | 0.666749 | 0.745282 | 0.894627 | 1.117785  | 1.341774 | 1.499814 | 0.1647882           | 0.2768268  | 11       |
| 50       | 0.666966 | 0.745088 | 0.895151 | 1.117130  | 1.342123 | 1.499327 | 0.1650212           | 0.2764635  | 10       |
| 51       | 0.667183 | 0.744894 | 0.895675 | 1.116477  | 1.342473 | 1.498840 | 0.1652544           | 0.2761007  | 9        |
| 52       | 0.667399 | 0.744700 | 0.896199 | 1.115823  | 1.342823 | 1.498353 | 0.1654879           | 0.2757383  | 8        |
| 53       | 0.667616 | 0.744506 | 0.896724 | 1.115171  | 1.343173 | 1.497867 | 0.1657217           | 0.2753764  | 7        |
| 54       | 0.667833 | 0.744312 | 0.897249 | 1.114518  | 1.343523 | 1.497381 | 0.1659557           | 0.2750148  | 6        |
| 55       | 0.668049 | 0.744117 | 0.897774 | 1.113866  | 1.343874 | 1.496896 | 0.1661900           | 0.2746537  | 5        |
| 56       | 0.668265 | 0.743923 | 0.898299 | 1.113215  | 1.344225 | 1.496411 | 0.1664246           | 0.2742930  | 4        |
| 57       | 0.668482 | 0.743728 | 0.898825 | 1.112563  | 1.344577 | 1.495927 | 0.1666595           | 0.2739328  | 3        |
| 58       | 0.668698 | 0.743534 | 0.899351 | 1.111913  | 1.344928 | 1.495443 | 0.1668946           | 0.2735729  | 2        |
| 59       | 0.668914 | 0.743339 | 0.899877 | 1.111262  | 1.345280 | 1.494960 | 0.1671301           | 0.2732135  | 1        |
| 60       | 0.669131 | 0.743145 | 0.900404 | 1.110613  | 1.345633 | 1.494477 | 0.1673658           | 0.2728545  | 0        |

↑ 131° or 311° 48° or 228° ↑



TRIGONOMETRY TABLES

↓ 42° or 222° Trigonometric and Involute Functions 137° or 317° ↓

| Minutes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute<br>42°-43° | Read<br>Up          | Minutes |
|---------|----------|----------|-----------|-----------|----------|----------|---------------------|---------------------|---------|
| 0       | 0.669131 | 0.743145 | 0.900404  | 1.110613  | 1.345633 | 1.494477 | 0.1673658           | 0.2728545           | 60      |
| 1       | 0.669347 | 0.742950 | 0.900931  | 1.110963  | 1.345985 | 1.493994 | 0.1676017           | 0.2724959           | 59      |
| 2       | 0.669563 | 0.742755 | 0.901458  | 1.1109314 | 1.346338 | 1.493512 | 0.1678380           | 0.2721377           | 58      |
| 3       | 0.669779 | 0.742561 | 0.901985  | 1.108665  | 1.346691 | 1.493030 | 0.1680745           | 0.2717800           | 57      |
| 4       | 0.669995 | 0.742366 | 0.902513  | 1.108017  | 1.347045 | 1.492549 | 0.1683113           | 0.2714226           | 56      |
| 5       | 0.670211 | 0.742171 | 0.903041  | 1.107369  | 1.347399 | 1.492068 | 0.1685484           | 0.2710657           | 55      |
| 6       | 0.670427 | 0.741976 | 0.903569  | 1.106722  | 1.347753 | 1.491588 | 0.1687857           | 0.2707092           | 54      |
| 7       | 0.670642 | 0.741781 | 0.904098  | 1.106075  | 1.348107 | 1.491108 | 0.1690234           | 0.2703531           | 53      |
| 8       | 0.670858 | 0.741586 | 0.904627  | 1.105428  | 1.348462 | 1.490628 | 0.1692613           | 0.2699975           | 52      |
| 9       | 0.671074 | 0.741391 | 0.905156  | 1.104782  | 1.348817 | 1.490149 | 0.1694994           | 0.2696422           | 51      |
| 10      | 0.671289 | 0.741195 | 0.905685  | 1.104137  | 1.349172 | 1.489670 | 0.1697379           | 0.2692874           | 50      |
| 11      | 0.671505 | 0.741000 | 0.906215  | 1.103491  | 1.349528 | 1.489192 | 0.1699767           | 0.2689330           | 49      |
| 12      | 0.671721 | 0.740805 | 0.906745  | 1.102846  | 1.349884 | 1.488714 | 0.1702157           | 0.2685790           | 48      |
| 13      | 0.671936 | 0.740609 | 0.907275  | 1.102202  | 1.350240 | 1.488237 | 0.1704550           | 0.2682254           | 47      |
| 14      | 0.672151 | 0.740414 | 0.907805  | 1.101558  | 1.350596 | 1.487760 | 0.1706946           | 0.2678722           | 46      |
| 15      | 0.672367 | 0.740218 | 0.908336  | 1.100914  | 1.350953 | 1.487283 | 0.1709344           | 0.2675194           | 45      |
| 16      | 0.672582 | 0.740023 | 0.908867  | 1.100271  | 1.351310 | 1.486807 | 0.1711746           | 0.2671671           | 44      |
| 17      | 0.672797 | 0.739827 | 0.909398  | 1.099628  | 1.351668 | 1.486332 | 0.1714150           | 0.2668151           | 43      |
| 18      | 0.673013 | 0.739631 | 0.909930  | 1.098986  | 1.352025 | 1.485856 | 0.1716557           | 0.2664636           | 42      |
| 19      | 0.673228 | 0.739435 | 0.910462  | 1.098344  | 1.352383 | 1.485382 | 0.1718967           | 0.2661125           | 41      |
| 20      | 0.673443 | 0.739239 | 0.910994  | 1.097702  | 1.352742 | 1.484907 | 0.1721380           | 0.2657618           | 40      |
| 21      | 0.673658 | 0.739043 | 0.911526  | 1.097061  | 1.353100 | 1.484433 | 0.1723795           | 0.2654115           | 39      |
| 22      | 0.673873 | 0.738848 | 0.912059  | 1.096420  | 1.353459 | 1.483960 | 0.1726214           | 0.2650616           | 38      |
| 23      | 0.674088 | 0.738651 | 0.912592  | 1.095780  | 1.353818 | 1.483487 | 0.1728635           | 0.2647121           | 37      |
| 24      | 0.674302 | 0.738455 | 0.913125  | 1.095140  | 1.354178 | 1.483014 | 0.1731059           | 0.2643630           | 36      |
| 25      | 0.674517 | 0.738259 | 0.913659  | 1.094500  | 1.354538 | 1.482542 | 0.1733486           | 0.2640143           | 35      |
| 26      | 0.674732 | 0.738063 | 0.914193  | 1.093861  | 1.354898 | 1.482070 | 0.1735915           | 0.2636661           | 34      |
| 27      | 0.674947 | 0.737867 | 0.914727  | 1.093222  | 1.355258 | 1.481599 | 0.1738348           | 0.2633182           | 33      |
| 28      | 0.675161 | 0.737670 | 0.915261  | 1.092584  | 1.355619 | 1.481128 | 0.1740783           | 0.2629708           | 32      |
| 29      | 0.675376 | 0.737474 | 0.915796  | 1.091946  | 1.355980 | 1.480657 | 0.1743221           | 0.2626237           | 31      |
| 30      | 0.675590 | 0.737277 | 0.916331  | 1.091309  | 1.356342 | 1.480187 | 0.1745662           | 0.2622771           | 30      |
| 31      | 0.675805 | 0.737081 | 0.916866  | 1.090671  | 1.356703 | 1.479718 | 0.1748106           | 0.2619309           | 29      |
| 32      | 0.676019 | 0.736884 | 0.917402  | 1.090035  | 1.357065 | 1.479248 | 0.1750553           | 0.2615850           | 28      |
| 33      | 0.676233 | 0.736687 | 0.917938  | 1.089398  | 1.357428 | 1.478779 | 0.1753003           | 0.2612396           | 27      |
| 34      | 0.676448 | 0.736491 | 0.918474  | 1.088762  | 1.357790 | 1.478311 | 0.1755455           | 0.2608946           | 26      |
| 35      | 0.676662 | 0.736294 | 0.919010  | 1.088127  | 1.358153 | 1.477843 | 0.1757911           | 0.2605500           | 25      |
| 36      | 0.676876 | 0.736097 | 0.919547  | 1.087492  | 1.358516 | 1.477376 | 0.1760369           | 0.2602058           | 24      |
| 37      | 0.677090 | 0.735900 | 0.920084  | 1.086857  | 1.358880 | 1.476908 | 0.1762830           | 0.2598619           | 23      |
| 38      | 0.677304 | 0.735703 | 0.920621  | 1.086223  | 1.359244 | 1.476442 | 0.1765294           | 0.2595185           | 22      |
| 39      | 0.677518 | 0.735506 | 0.921159  | 1.085589  | 1.359608 | 1.475975 | 0.1767761           | 0.2591755           | 21      |
| 40      | 0.677732 | 0.735309 | 0.921697  | 1.084955  | 1.359972 | 1.475509 | 0.1770230           | 0.2588329           | 20      |
| 41      | 0.677946 | 0.735112 | 0.922235  | 1.084322  | 1.360337 | 1.475044 | 0.1772703           | 0.2584907           | 19      |
| 42      | 0.678160 | 0.734915 | 0.922773  | 1.083690  | 1.360702 | 1.474579 | 0.1775179           | 0.2581489           | 18      |
| 43      | 0.678373 | 0.734717 | 0.923312  | 1.083057  | 1.361068 | 1.474114 | 0.1777657           | 0.2578075           | 17      |
| 44      | 0.678587 | 0.734520 | 0.923851  | 1.082425  | 1.361433 | 1.473650 | 0.1780138           | 0.2574665           | 16      |
| 45      | 0.678801 | 0.734323 | 0.924390  | 1.081794  | 1.361799 | 1.473186 | 0.1782622           | 0.2571258           | 15      |
| 46      | 0.679014 | 0.734125 | 0.924930  | 1.081163  | 1.362166 | 1.472723 | 0.1785109           | 0.2567856           | 14      |
| 47      | 0.679228 | 0.733927 | 0.925470  | 1.080532  | 1.362532 | 1.472260 | 0.1787599           | 0.2564458           | 13      |
| 48      | 0.679441 | 0.733730 | 0.926010  | 1.079902  | 1.362899 | 1.471797 | 0.1790092           | 0.2561064           | 12      |
| 49      | 0.679655 | 0.733532 | 0.926551  | 1.079272  | 1.363267 | 1.471335 | 0.1792588           | 0.2557673           | 11      |
| 50      | 0.679868 | 0.733334 | 0.927091  | 1.078642  | 1.363634 | 1.470874 | 0.1795087           | 0.2554287           | 10      |
| 51      | 0.680081 | 0.733137 | 0.927632  | 1.078013  | 1.364002 | 1.470412 | 0.1797589           | 0.2550904           | 9       |
| 52      | 0.680295 | 0.732939 | 0.928174  | 1.077384  | 1.364370 | 1.469951 | 0.1800093           | 0.2547526           | 8       |
| 53      | 0.680508 | 0.732741 | 0.928715  | 1.076756  | 1.364739 | 1.469491 | 0.1802601           | 0.2544151           | 7       |
| 54      | 0.680721 | 0.732543 | 0.929257  | 1.076128  | 1.365108 | 1.469031 | 0.1805111           | 0.2540781           | 6       |
| 55      | 0.680934 | 0.732345 | 0.929800  | 1.075501  | 1.365477 | 1.468571 | 0.1807624           | 0.2537414           | 5       |
| 56      | 0.681147 | 0.732147 | 0.930342  | 1.074873  | 1.365846 | 1.468112 | 0.1810141           | 0.2534051           | 4       |
| 57      | 0.681360 | 0.731949 | 0.930885  | 1.074247  | 1.366216 | 1.467653 | 0.1812660           | 0.2530693           | 3       |
| 58      | 0.681573 | 0.731750 | 0.931428  | 1.073620  | 1.366586 | 1.467195 | 0.1815182           | 0.2527338           | 2       |
| 59      | 0.681786 | 0.731552 | 0.931971  | 1.072994  | 1.366957 | 1.466737 | 0.1817707           | 0.2523987           | 1       |
| 60      | 0.681998 | 0.731354 | 0.932515  | 1.072369  | 1.367327 | 1.466279 | 0.1820235           | 0.2520640           | 0       |
| Minutes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read<br>Down        | 47°-48°<br>Involute | Minutes |

↑ 132° or 312°

47° or 227° ↑

↓ 43° or 223° Trigonometric and Involute Functions 136° or 316° ↓

| Min-utes | Sine     | Cosine   | Tangent  | Cotangent | Secant   | Cosecant | Involute<br>43°-44° | Read<br>Up | Min-utes |
|----------|----------|----------|----------|-----------|----------|----------|---------------------|------------|----------|
| 0        | 0.681998 | 0.731354 | 0.932515 | 1.072369  | 1.367327 | 1.466279 | 0.1820235           | 0.2520640  | 60       |
| 1        | 0.682211 | 0.731155 | 0.933059 | 1.071744  | 1.367699 | 1.465822 | 0.1822766           | 0.2517296  | 59       |
| 2        | 0.682424 | 0.730957 | 0.933603 | 1.071119  | 1.368070 | 1.465365 | 0.1825300           | 0.2513957  | 58       |
| 3        | 0.682636 | 0.730758 | 0.934148 | 1.070494  | 1.368442 | 1.464909 | 0.1827837           | 0.2510622  | 57       |
| 4        | 0.682849 | 0.730560 | 0.934693 | 1.069870  | 1.368814 | 1.464453 | 0.1830377           | 0.2507290  | 56       |
| 5        | 0.683061 | 0.730361 | 0.935238 | 1.069247  | 1.369186 | 1.463997 | 0.1832920           | 0.2503963  | 55       |
| 6        | 0.683274 | 0.730162 | 0.935783 | 1.068623  | 1.369559 | 1.463542 | 0.1835465           | 0.2500639  | 54       |
| 7        | 0.683486 | 0.729963 | 0.936329 | 1.068000  | 1.369932 | 1.463087 | 0.1838014           | 0.2497319  | 53       |
| 8        | 0.683698 | 0.729765 | 0.936875 | 1.067378  | 1.370305 | 1.462633 | 0.1840566           | 0.2494003  | 52       |
| 9        | 0.683911 | 0.729566 | 0.937422 | 1.066756  | 1.370678 | 1.462179 | 0.1843121           | 0.2490691  | 51       |
| 10       | 0.684123 | 0.729367 | 0.937968 | 1.066134  | 1.371052 | 1.461726 | 0.1845678           | 0.2487383  | 50       |
| 11       | 0.684335 | 0.729168 | 0.938515 | 1.065513  | 1.371427 | 1.461273 | 0.1848239           | 0.2484078  | 49       |
| 12       | 0.684547 | 0.728969 | 0.939063 | 1.064892  | 1.371801 | 1.460820 | 0.1850803           | 0.2480778  | 48       |
| 13       | 0.684759 | 0.728769 | 0.939610 | 1.064271  | 1.372176 | 1.460368 | 0.1853369           | 0.2477481  | 47       |
| 14       | 0.684971 | 0.728570 | 0.940158 | 1.063651  | 1.372551 | 1.459916 | 0.1855939           | 0.2474188  | 46       |
| 15       | 0.685183 | 0.728371 | 0.940706 | 1.063031  | 1.372927 | 1.459464 | 0.1858512           | 0.2470895  | 45       |
| 16       | 0.685395 | 0.728172 | 0.941255 | 1.062412  | 1.373303 | 1.459013 | 0.1861087           | 0.2467614  | 44       |
| 17       | 0.685607 | 0.727972 | 0.941803 | 1.061793  | 1.373679 | 1.458562 | 0.1863666           | 0.2464332  | 43       |
| 18       | 0.685818 | 0.727773 | 0.942352 | 1.061174  | 1.374055 | 1.458112 | 0.1866248           | 0.2461055  | 42       |
| 19       | 0.686030 | 0.727573 | 0.942902 | 1.060556  | 1.374432 | 1.457662 | 0.1868832           | 0.2457801  | 41       |
| 20       | 0.686242 | 0.727374 | 0.943451 | 1.059938  | 1.374809 | 1.457213 | 0.1871420           | 0.2454511  | 40       |
| 21       | 0.686453 | 0.727174 | 0.944001 | 1.059321  | 1.375187 | 1.456764 | 0.1874011           | 0.2451245  | 39       |
| 22       | 0.686665 | 0.726974 | 0.944552 | 1.058703  | 1.375564 | 1.456315 | 0.1876604           | 0.2447982  | 38       |
| 23       | 0.686876 | 0.726775 | 0.945102 | 1.058087  | 1.375943 | 1.455867 | 0.1879201           | 0.2444724  | 37       |
| 24       | 0.687088 | 0.726575 | 0.945653 | 1.057470  | 1.376321 | 1.455419 | 0.1881801           | 0.2441469  | 36       |
| 25       | 0.687299 | 0.726375 | 0.946204 | 1.056854  | 1.376700 | 1.454971 | 0.1884404           | 0.2438218  | 35       |
| 26       | 0.687510 | 0.726175 | 0.946756 | 1.056239  | 1.377079 | 1.454524 | 0.1887010           | 0.2434971  | 34       |
| 27       | 0.687721 | 0.725975 | 0.947307 | 1.055624  | 1.377458 | 1.454077 | 0.1889619           | 0.2431728  | 33       |
| 28       | 0.687932 | 0.725775 | 0.947859 | 1.055009  | 1.377838 | 1.453631 | 0.1892230           | 0.2428488  | 32       |
| 29       | 0.688144 | 0.725575 | 0.948412 | 1.054394  | 1.378218 | 1.453185 | 0.1894845           | 0.2425252  | 31       |
| 30       | 0.688355 | 0.725374 | 0.948965 | 1.053780  | 1.378598 | 1.452740 | 0.1897463           | 0.2422020  | 30       |
| 31       | 0.688566 | 0.725174 | 0.949518 | 1.053166  | 1.378979 | 1.452295 | 0.1900084           | 0.2418792  | 29       |
| 32       | 0.688776 | 0.724974 | 0.950071 | 1.052553  | 1.379360 | 1.451850 | 0.1902709           | 0.2415567  | 28       |
| 33       | 0.688987 | 0.724773 | 0.950624 | 1.051940  | 1.379742 | 1.451406 | 0.1905336           | 0.2412347  | 27       |
| 34       | 0.689198 | 0.724573 | 0.951178 | 1.051328  | 1.380123 | 1.450962 | 0.1907966           | 0.2409130  | 26       |
| 35       | 0.689409 | 0.724372 | 0.951733 | 1.050715  | 1.380505 | 1.450518 | 0.1910599           | 0.2405916  | 25       |
| 36       | 0.689620 | 0.724172 | 0.952287 | 1.050103  | 1.380888 | 1.450075 | 0.1913236           | 0.2402707  | 24       |
| 37       | 0.689830 | 0.723971 | 0.952842 | 1.049492  | 1.381270 | 1.449632 | 0.1915875           | 0.2399501  | 23       |
| 38       | 0.690041 | 0.723771 | 0.953397 | 1.048881  | 1.381653 | 1.449190 | 0.1918518           | 0.2396299  | 22       |
| 39       | 0.690251 | 0.723570 | 0.953953 | 1.048270  | 1.382037 | 1.448748 | 0.1921163           | 0.2393103  | 21       |
| 40       | 0.690462 | 0.723369 | 0.954508 | 1.047660  | 1.382420 | 1.448306 | 0.1923812           | 0.2389906  | 20       |
| 41       | 0.690672 | 0.723168 | 0.955064 | 1.047050  | 1.382804 | 1.447865 | 0.1926464           | 0.2386715  | 19       |
| 42       | 0.690882 | 0.722967 | 0.955621 | 1.046440  | 1.383189 | 1.447424 | 0.1929119           | 0.2383528  | 18       |
| 43       | 0.691093 | 0.722766 | 0.956177 | 1.045831  | 1.383573 | 1.446984 | 0.1931777           | 0.2380344  | 17       |
| 44       | 0.691303 | 0.722565 | 0.956734 | 1.045222  | 1.383958 | 1.446544 | 0.1934438           | 0.2377165  | 16       |
| 45       | 0.691513 | 0.722364 | 0.957292 | 1.044614  | 1.384344 | 1.446104 | 0.1937102           | 0.2373988  | 15       |
| 46       | 0.691723 | 0.722163 | 0.957849 | 1.044006  | 1.384729 | 1.445665 | 0.1939769           | 0.2370816  | 14       |
| 47       | 0.691933 | 0.721962 | 0.958407 | 1.043398  | 1.385115 | 1.445226 | 0.1942440           | 0.2367647  | 13       |
| 48       | 0.692143 | 0.721760 | 0.958966 | 1.042790  | 1.385502 | 1.444788 | 0.1945113           | 0.2364482  | 12       |
| 49       | 0.692353 | 0.721559 | 0.959524 | 1.042183  | 1.385888 | 1.444350 | 0.1947790           | 0.2361321  | 11       |
| 50       | 0.692563 | 0.721357 | 0.960083 | 1.041577  | 1.386275 | 1.443912 | 0.1950469           | 0.2358163  | 10       |
| 51       | 0.692773 | 0.721156 | 0.960642 | 1.040970  | 1.386663 | 1.443475 | 0.1953152           | 0.2355010  | 9        |
| 52       | 0.692983 | 0.720954 | 0.961202 | 1.040364  | 1.387050 | 1.443038 | 0.1955838           | 0.2351859  | 8        |
| 53       | 0.693192 | 0.720753 | 0.961761 | 1.039759  | 1.387438 | 1.442601 | 0.1958527           | 0.2348713  | 7        |
| 54       | 0.693402 | 0.720551 | 0.962322 | 1.039154  | 1.387827 | 1.442165 | 0.1961220           | 0.2345570  | 6        |
| 55       | 0.693611 | 0.720349 | 0.962882 | 1.038549  | 1.388215 | 1.441729 | 0.1963915           | 0.2342430  | 5        |
| 56       | 0.693821 | 0.720148 | 0.963443 | 1.037944  | 1.388604 | 1.441294 | 0.1966613           | 0.2339295  | 4        |
| 57       | 0.694030 | 0.719946 | 0.964004 | 1.037340  | 1.388994 | 1.440859 | 0.1969315           | 0.2336163  | 3        |
| 58       | 0.694240 | 0.719744 | 0.964565 | 1.036737  | 1.389383 | 1.440425 | 0.1972020           | 0.2333034  | 2        |
| 59       | 0.694449 | 0.719542 | 0.965127 | 1.036133  | 1.389773 | 1.439990 | 0.1974728           | 0.2329910  | 1        |
| 60       | 0.694658 | 0.719340 | 0.965689 | 1.035530  | 1.390164 | 1.439557 | 0.1977439           | 0.2326789  | 0        |

↑ 133° or 313°

46° or 226° ↑

TRIGONOMETRY TABLES

↓ 44° or 224° Trigonometric and Involute Functions 135° or 315° ↓

| Min-utes | Sine     | Cosine   | Tangent   | Cotangent | Secant   | Cosecant | Involute<br>44°-45° | Read<br>Up          | Min-utes |
|----------|----------|----------|-----------|-----------|----------|----------|---------------------|---------------------|----------|
| 0        | 0.694658 | 0.719340 | 0.965689  | 1.035530  | 1.390164 | 1.439557 | 0.1977439           | 0.2326789           | 60       |
| 1        | 0.694868 | 0.719138 | 0.966251  | 1.034928  | 1.390554 | 1.439123 | 0.1980153           | 0.2323671           | 59       |
| 2        | 0.695077 | 0.718936 | 0.966814  | 1.034325  | 1.390945 | 1.438690 | 0.1982871           | 0.2320557           | 58       |
| 3        | 0.695286 | 0.718733 | 0.967377  | 1.033724  | 1.391337 | 1.438257 | 0.1985591           | 0.2317447           | 57       |
| 4        | 0.695495 | 0.718531 | 0.967940  | 1.033122  | 1.391728 | 1.437825 | 0.1988315           | 0.2314341           | 56       |
| 5        | 0.695704 | 0.718329 | 0.968504  | 1.032521  | 1.392120 | 1.437393 | 0.1991042           | 0.2311238           | 55       |
| 6        | 0.695913 | 0.718126 | 0.969067  | 1.031920  | 1.392513 | 1.436962 | 0.1993772           | 0.2308138           | 54       |
| 7        | 0.696122 | 0.717924 | 0.969632  | 1.031319  | 1.392905 | 1.436531 | 0.1996505           | 0.2305042           | 53       |
| 8        | 0.696330 | 0.717721 | 0.970196  | 1.030719  | 1.393298 | 1.436100 | 0.1999242           | 0.2301950           | 52       |
| 9        | 0.696539 | 0.717519 | 0.970761  | 1.030120  | 1.393692 | 1.435669 | 0.2001982           | 0.2298862           | 51       |
| 10       | 0.696748 | 0.717316 | 0.971326  | 1.029520  | 1.394086 | 1.435239 | 0.2004724           | 0.2295777           | 50       |
| 11       | 0.696957 | 0.717113 | 0.971892  | 1.028921  | 1.394480 | 1.434810 | 0.2007471           | 0.2292695           | 49       |
| 12       | 0.697165 | 0.716911 | 0.972458  | 1.028323  | 1.394874 | 1.434380 | 0.2010220           | 0.2289618           | 48       |
| 13       | 0.697374 | 0.716708 | 0.973024  | 1.027724  | 1.395269 | 1.433952 | 0.2012972           | 0.2286543           | 47       |
| 14       | 0.697582 | 0.716505 | 0.973590  | 1.027126  | 1.395664 | 1.433523 | 0.2015728           | 0.2283473           | 46       |
| 15       | 0.697790 | 0.716302 | 0.974157  | 1.026529  | 1.396059 | 1.433095 | 0.2018487           | 0.2280406           | 45       |
| 16       | 0.697999 | 0.716099 | 0.974724  | 1.025931  | 1.396455 | 1.432667 | 0.2021249           | 0.2277342           | 44       |
| 17       | 0.698207 | 0.715896 | 0.975291  | 1.025335  | 1.396851 | 1.432240 | 0.2024014           | 0.2274282           | 43       |
| 18       | 0.698415 | 0.715693 | 0.975859  | 1.024738  | 1.397248 | 1.431813 | 0.2026783           | 0.2271226           | 42       |
| 19       | 0.698623 | 0.715490 | 0.976427  | 1.024142  | 1.397644 | 1.431386 | 0.2029554           | 0.2268173           | 41       |
| 20       | 0.698832 | 0.715286 | 0.976996  | 1.023546  | 1.398042 | 1.430960 | 0.2032329           | 0.2265124           | 40       |
| 21       | 0.699040 | 0.715083 | 0.977564  | 1.022951  | 1.398439 | 1.430534 | 0.2035108           | 0.2262078           | 39       |
| 22       | 0.699248 | 0.714880 | 0.978133  | 1.022356  | 1.398837 | 1.430109 | 0.2037889           | 0.2259036           | 38       |
| 23       | 0.699455 | 0.714676 | 0.978703  | 1.021761  | 1.399235 | 1.429684 | 0.2040674           | 0.2255997           | 37       |
| 24       | 0.699663 | 0.714473 | 0.979272  | 1.021166  | 1.399634 | 1.429259 | 0.2043462           | 0.2252962           | 36       |
| 25       | 0.699871 | 0.714269 | 0.979842  | 1.020572  | 1.400033 | 1.428834 | 0.2046253           | 0.2249931           | 35       |
| 26       | 0.700079 | 0.714066 | 0.980413  | 1.019979  | 1.400432 | 1.428410 | 0.2049047           | 0.2246903           | 34       |
| 27       | 0.700287 | 0.713862 | 0.980983  | 1.019385  | 1.400831 | 1.427987 | 0.2051845           | 0.2243878           | 33       |
| 28       | 0.700494 | 0.713658 | 0.981554  | 1.018792  | 1.401231 | 1.427564 | 0.2054646           | 0.2240857           | 32       |
| 29       | 0.700702 | 0.713454 | 0.982126  | 1.018200  | 1.401631 | 1.427141 | 0.2057450           | 0.2237840           | 31       |
| 30       | 0.700909 | 0.713250 | 0.982697  | 1.017607  | 1.402032 | 1.426718 | 0.2060257           | 0.2234826           | 30       |
| 31       | 0.701117 | 0.713047 | 0.983269  | 1.017015  | 1.402433 | 1.426296 | 0.2063068           | 0.2231815           | 29       |
| 32       | 0.701324 | 0.712843 | 0.983842  | 1.016424  | 1.402834 | 1.425874 | 0.2065882           | 0.2228808           | 28       |
| 33       | 0.701531 | 0.712639 | 0.984414  | 1.015833  | 1.403236 | 1.425453 | 0.2068699           | 0.2225805           | 27       |
| 34       | 0.701739 | 0.712434 | 0.984987  | 1.015242  | 1.403638 | 1.425032 | 0.2071520           | 0.2222805           | 26       |
| 35       | 0.701946 | 0.712230 | 0.985560  | 1.014651  | 1.404040 | 1.424611 | 0.2074344           | 0.2219808           | 25       |
| 36       | 0.702153 | 0.712026 | 0.986134  | 1.014061  | 1.404443 | 1.424191 | 0.2077171           | 0.2216815           | 24       |
| 37       | 0.702360 | 0.711822 | 0.986708  | 1.013471  | 1.404846 | 1.423771 | 0.2080001           | 0.2213826           | 23       |
| 38       | 0.702567 | 0.711617 | 0.987282  | 1.012882  | 1.405249 | 1.423351 | 0.2082835           | 0.2210840           | 22       |
| 39       | 0.702774 | 0.711413 | 0.987857  | 1.012293  | 1.405653 | 1.422932 | 0.2085672           | 0.2207857           | 21       |
| 40       | 0.702981 | 0.711209 | 0.988432  | 1.011704  | 1.406057 | 1.422513 | 0.2088512           | 0.2204878           | 20       |
| 41       | 0.703188 | 0.711004 | 0.989007  | 1.011115  | 1.406462 | 1.422095 | 0.2091356           | 0.2201903           | 19       |
| 42       | 0.703395 | 0.710799 | 0.989582  | 1.010527  | 1.406867 | 1.421677 | 0.2094203           | 0.2198930           | 18       |
| 43       | 0.703601 | 0.710595 | 0.990158  | 1.009939  | 1.407272 | 1.421259 | 0.2097053           | 0.2195962           | 17       |
| 44       | 0.703808 | 0.710390 | 0.990735  | 1.009352  | 1.407677 | 1.420842 | 0.2099907           | 0.2192996           | 16       |
| 45       | 0.704015 | 0.710185 | 0.991311  | 1.008765  | 1.408083 | 1.420425 | 0.2102764           | 0.2190035           | 15       |
| 46       | 0.704221 | 0.709981 | 0.991888  | 1.008178  | 1.408489 | 1.420008 | 0.2105624           | 0.2187076           | 14       |
| 47       | 0.704428 | 0.709776 | 0.992465  | 1.007592  | 1.408896 | 1.419592 | 0.2108487           | 0.2184121           | 13       |
| 48       | 0.704634 | 0.709571 | 0.993043  | 1.007006  | 1.409303 | 1.419176 | 0.2111354           | 0.2181170           | 12       |
| 49       | 0.704841 | 0.709366 | 0.993621  | 1.006420  | 1.409710 | 1.418761 | 0.2114225           | 0.2178222           | 11       |
| 50       | 0.705047 | 0.709161 | 0.994199  | 1.005835  | 1.410118 | 1.418345 | 0.2117098           | 0.2175277           | 10       |
| 51       | 0.705253 | 0.708956 | 0.994778  | 1.005250  | 1.410526 | 1.417931 | 0.2119975           | 0.2172336           | 9        |
| 52       | 0.705459 | 0.708750 | 0.995357  | 1.004665  | 1.410934 | 1.417516 | 0.2122855           | 0.2169398           | 8        |
| 53       | 0.705665 | 0.708545 | 0.995936  | 1.004081  | 1.411343 | 1.417102 | 0.2125739           | 0.2166464           | 7        |
| 54       | 0.705872 | 0.708340 | 0.996515  | 1.003497  | 1.411752 | 1.416688 | 0.2128626           | 0.2163533           | 6        |
| 55       | 0.706078 | 0.708134 | 0.997095  | 1.002913  | 1.412161 | 1.416275 | 0.2131516           | 0.2160605           | 5        |
| 56       | 0.706284 | 0.707929 | 0.997676  | 1.002330  | 1.412571 | 1.415862 | 0.2134410           | 0.2157681           | 4        |
| 57       | 0.706489 | 0.707724 | 0.998256  | 1.001747  | 1.412981 | 1.415449 | 0.2137307           | 0.2154760           | 3        |
| 58       | 0.706695 | 0.707518 | 0.998837  | 1.001164  | 1.413392 | 1.415037 | 0.2140207           | 0.2151843           | 2        |
| 59       | 0.706901 | 0.707312 | 0.999418  | 1.000582  | 1.413802 | 1.414625 | 0.2143111           | 0.2148929           | 1        |
| 60       | 0.707107 | 0.707107 | 1.000000  | 1.000000  | 1.414214 | 1.414214 | 0.2146018           | 0.2146018           | 0        |
| Min-utes | Cosine   | Sine     | Cotangent | Tangent   | Cosecant | Secant   | Read<br>Down        | 45°-46°<br>Involute | Min-utes |

↑ 134° or 314°

45° or 225° ↑

## Constants for 2.5-inch Sine-Bar

## Constants for Setting a 2.5-inch Sine-Bar for 0° to 7°

| Min. | 0°       | 1°       | 2°       | 3°       | 4°       | 5°       | 6°       | 7°       |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 0.000000 | 0.043631 | 0.087249 | 0.130840 | 0.174391 | 0.217889 | 0.261321 | 0.304673 |
| 1    | 0.000727 | 0.044358 | 0.087976 | 0.131566 | 0.175117 | 0.218614 | 0.262044 | 0.305395 |
| 2    | 0.001454 | 0.045085 | 0.088702 | 0.132292 | 0.175842 | 0.219338 | 0.262768 | 0.306117 |
| 3    | 0.002182 | 0.045812 | 0.089429 | 0.133019 | 0.176567 | 0.220063 | 0.263491 | 0.306839 |
| 4    | 0.002909 | 0.046539 | 0.090156 | 0.133745 | 0.177293 | 0.220787 | 0.264214 | 0.307560 |
| 5    | 0.003636 | 0.047267 | 0.090883 | 0.134471 | 0.178018 | 0.221511 | 0.264937 | 0.308282 |
| 6    | 0.004363 | 0.047994 | 0.091609 | 0.135197 | 0.178744 | 0.222236 | 0.265660 | 0.309004 |
| 7    | 0.005091 | 0.048721 | 0.092336 | 0.135923 | 0.179469 | 0.222960 | 0.266383 | 0.309725 |
| 8    | 0.005818 | 0.049448 | 0.093063 | 0.136649 | 0.180194 | 0.223684 | 0.267106 | 0.310447 |
| 9    | 0.006545 | 0.050175 | 0.093789 | 0.137375 | 0.180920 | 0.224409 | 0.267829 | 0.311169 |
| 10   | 0.007272 | 0.050902 | 0.094516 | 0.138102 | 0.181645 | 0.225133 | 0.268552 | 0.311890 |
| 11   | 0.007999 | 0.051629 | 0.095243 | 0.138828 | 0.182370 | 0.225857 | 0.269275 | 0.312612 |
| 12   | 0.008727 | 0.052356 | 0.095970 | 0.139554 | 0.183095 | 0.226581 | 0.269998 | 0.313333 |
| 13   | 0.009454 | 0.053083 | 0.096696 | 0.140280 | 0.183821 | 0.227306 | 0.270721 | 0.314055 |
| 14   | 0.010181 | 0.053810 | 0.097423 | 0.141006 | 0.184546 | 0.228030 | 0.271444 | 0.314776 |
| 15   | 0.010908 | 0.054537 | 0.098150 | 0.141732 | 0.185271 | 0.228754 | 0.272167 | 0.315497 |
| 16   | 0.011635 | 0.055264 | 0.098876 | 0.142458 | 0.185996 | 0.229478 | 0.272890 | 0.316219 |
| 17   | 0.012363 | 0.055991 | 0.099603 | 0.143184 | 0.186722 | 0.230202 | 0.273613 | 0.316940 |
| 18   | 0.013090 | 0.056718 | 0.100329 | 0.143910 | 0.187447 | 0.230926 | 0.274336 | 0.317662 |
| 19   | 0.013817 | 0.057445 | 0.101056 | 0.144636 | 0.188172 | 0.231651 | 0.275059 | 0.318383 |
| 20   | 0.014544 | 0.058172 | 0.101783 | 0.145362 | 0.188897 | 0.232375 | 0.275781 | 0.319104 |
| 21   | 0.015272 | 0.058899 | 0.102509 | 0.146088 | 0.189622 | 0.233099 | 0.276504 | 0.319825 |
| 22   | 0.015999 | 0.059626 | 0.103236 | 0.146814 | 0.190347 | 0.233823 | 0.277227 | 0.320547 |
| 23   | 0.016726 | 0.060353 | 0.103963 | 0.147540 | 0.191072 | 0.234547 | 0.277950 | 0.321268 |
| 24   | 0.017453 | 0.061080 | 0.104689 | 0.148266 | 0.191798 | 0.235271 | 0.278672 | 0.321989 |
| 25   | 0.018180 | 0.061807 | 0.105416 | 0.148992 | 0.192523 | 0.235995 | 0.279395 | 0.322710 |
| 26   | 0.018908 | 0.062534 | 0.106142 | 0.149718 | 0.193248 | 0.236719 | 0.280118 | 0.323431 |
| 27   | 0.019635 | 0.063261 | 0.106869 | 0.150444 | 0.193973 | 0.237443 | 0.280840 | 0.324152 |
| 28   | 0.020362 | 0.063988 | 0.107595 | 0.151170 | 0.194698 | 0.238167 | 0.281563 | 0.324873 |
| 29   | 0.021089 | 0.064715 | 0.108322 | 0.151895 | 0.195423 | 0.238890 | 0.282285 | 0.325594 |
| 30   | 0.021816 | 0.065442 | 0.109048 | 0.152621 | 0.196148 | 0.239614 | 0.283008 | 0.326315 |
| 31   | 0.022544 | 0.066169 | 0.109775 | 0.153347 | 0.196873 | 0.240338 | 0.283731 | 0.327036 |
| 32   | 0.023271 | 0.066896 | 0.110502 | 0.154073 | 0.197598 | 0.241062 | 0.284453 | 0.327757 |
| 33   | 0.023998 | 0.067623 | 0.111228 | 0.154799 | 0.198323 | 0.241786 | 0.285176 | 0.328478 |
| 34   | 0.024725 | 0.068350 | 0.111955 | 0.155525 | 0.199048 | 0.242510 | 0.285898 | 0.329199 |
| 35   | 0.025452 | 0.069077 | 0.112681 | 0.156251 | 0.199772 | 0.243234 | 0.286620 | 0.329920 |
| 36   | 0.026179 | 0.069804 | 0.113407 | 0.156976 | 0.200497 | 0.243957 | 0.287343 | 0.330641 |
| 37   | 0.026907 | 0.070531 | 0.114134 | 0.157702 | 0.201222 | 0.244681 | 0.288065 | 0.331362 |
| 38   | 0.027634 | 0.071258 | 0.114860 | 0.158428 | 0.201947 | 0.245405 | 0.288788 | 0.332083 |
| 39   | 0.028361 | 0.071985 | 0.115587 | 0.159154 | 0.202672 | 0.246128 | 0.289510 | 0.332803 |
| 40   | 0.029088 | 0.072712 | 0.116313 | 0.159879 | 0.203397 | 0.246852 | 0.290232 | 0.333524 |
| 41   | 0.029815 | 0.073439 | 0.117040 | 0.160605 | 0.204122 | 0.247576 | 0.290955 | 0.334245 |
| 42   | 0.030543 | 0.074166 | 0.117766 | 0.161331 | 0.204846 | 0.248299 | 0.291677 | 0.334965 |
| 43   | 0.031270 | 0.074893 | 0.118493 | 0.162056 | 0.205571 | 0.249023 | 0.292399 | 0.335686 |
| 44   | 0.031997 | 0.075619 | 0.119219 | 0.162782 | 0.206296 | 0.249747 | 0.293121 | 0.336407 |
| 45   | 0.032724 | 0.076346 | 0.119945 | 0.163508 | 0.207021 | 0.250470 | 0.293844 | 0.337127 |
| 46   | 0.033451 | 0.077073 | 0.120672 | 0.164233 | 0.207745 | 0.251194 | 0.294566 | 0.337848 |
| 47   | 0.034178 | 0.077800 | 0.121398 | 0.164959 | 0.208470 | 0.251917 | 0.295288 | 0.338568 |
| 48   | 0.034905 | 0.078527 | 0.122124 | 0.165685 | 0.209195 | 0.252641 | 0.296010 | 0.339289 |
| 49   | 0.035633 | 0.079254 | 0.122851 | 0.166410 | 0.209919 | 0.253364 | 0.296732 | 0.340009 |
| 50   | 0.036360 | 0.079981 | 0.123577 | 0.167136 | 0.210644 | 0.254088 | 0.297454 | 0.340730 |
| 51   | 0.037087 | 0.080707 | 0.124303 | 0.167862 | 0.211369 | 0.254811 | 0.298176 | 0.341450 |
| 52   | 0.037814 | 0.081434 | 0.125030 | 0.168587 | 0.212093 | 0.255535 | 0.298898 | 0.342171 |
| 53   | 0.038541 | 0.082161 | 0.125756 | 0.169313 | 0.212818 | 0.256258 | 0.299620 | 0.342891 |
| 54   | 0.039268 | 0.082888 | 0.126482 | 0.170038 | 0.213542 | 0.256981 | 0.300342 | 0.343611 |
| 55   | 0.039995 | 0.083615 | 0.127209 | 0.170764 | 0.214267 | 0.257705 | 0.301064 | 0.344332 |
| 56   | 0.040723 | 0.084342 | 0.127935 | 0.171489 | 0.214991 | 0.258428 | 0.301786 | 0.345052 |
| 57   | 0.041450 | 0.085068 | 0.128661 | 0.172215 | 0.215716 | 0.259151 | 0.302508 | 0.345772 |
| 58   | 0.042177 | 0.085795 | 0.129387 | 0.172940 | 0.216440 | 0.259875 | 0.303230 | 0.346492 |
| 59   | 0.042904 | 0.086522 | 0.130114 | 0.173666 | 0.217165 | 0.260598 | 0.303952 | 0.347213 |
| 60   | 0.043631 | 0.087249 | 0.130840 | 0.174391 | 0.217889 | 0.261321 | 0.304673 | 0.347933 |

## SINE BAR CONSTANTS

## Constants for Setting a 2.5-inch Sine-Bar for 8° to 15°

| Min. | 8°       | 9°       | 10°      | 11°      | 12°      | 13°      | 14°      | 15°      |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 0.347933 | 0.391086 | 0.434120 | 0.477022 | 0.519779 | 0.562378 | 0.604805 | 0.647048 |
| 1    | 0.348653 | 0.391804 | 0.434837 | 0.477736 | 0.520491 | 0.563086 | 0.605510 | 0.647750 |
| 2    | 0.349373 | 0.392523 | 0.435553 | 0.478450 | 0.521202 | 0.563795 | 0.606216 | 0.648452 |
| 3    | 0.350093 | 0.393241 | 0.436269 | 0.479164 | 0.521913 | 0.564503 | 0.606921 | 0.649155 |
| 4    | 0.350813 | 0.393959 | 0.436985 | 0.479878 | 0.522624 | 0.565212 | 0.607627 | 0.649857 |
| 5    | 0.351533 | 0.394677 | 0.437701 | 0.480591 | 0.523335 | 0.565920 | 0.608332 | 0.650559 |
| 6    | 0.352253 | 0.395395 | 0.438417 | 0.481305 | 0.524046 | 0.566628 | 0.609038 | 0.651261 |
| 7    | 0.352973 | 0.396113 | 0.439133 | 0.482019 | 0.524757 | 0.567337 | 0.609743 | 0.651963 |
| 8    | 0.353693 | 0.396831 | 0.439849 | 0.482732 | 0.525468 | 0.568045 | 0.610448 | 0.652665 |
| 9    | 0.354413 | 0.397549 | 0.440564 | 0.483446 | 0.526179 | 0.568753 | 0.611153 | 0.653367 |
| 10   | 0.355133 | 0.398267 | 0.441280 | 0.484159 | 0.526890 | 0.569461 | 0.611858 | 0.654069 |
| 11   | 0.355853 | 0.398985 | 0.441996 | 0.484872 | 0.527601 | 0.570169 | 0.612563 | 0.654771 |
| 12   | 0.356572 | 0.399703 | 0.442712 | 0.485586 | 0.528312 | 0.570877 | 0.613268 | 0.655473 |
| 13   | 0.357292 | 0.400421 | 0.443428 | 0.486299 | 0.529023 | 0.571585 | 0.613973 | 0.656175 |
| 14   | 0.358012 | 0.401139 | 0.444143 | 0.487013 | 0.529734 | 0.572293 | 0.614678 | 0.656876 |
| 15   | 0.358732 | 0.401856 | 0.444859 | 0.487726 | 0.530444 | 0.573001 | 0.615383 | 0.657578 |
| 16   | 0.359451 | 0.402574 | 0.445574 | 0.488439 | 0.531155 | 0.573709 | 0.616088 | 0.658280 |
| 17   | 0.360171 | 0.403292 | 0.446290 | 0.489152 | 0.531865 | 0.574417 | 0.616793 | 0.658981 |
| 18   | 0.360891 | 0.404010 | 0.447006 | 0.489865 | 0.532576 | 0.575124 | 0.617498 | 0.659683 |
| 19   | 0.361610 | 0.404727 | 0.447721 | 0.490578 | 0.533287 | 0.575832 | 0.618202 | 0.660384 |
| 20   | 0.362330 | 0.405445 | 0.448436 | 0.491292 | 0.533997 | 0.576540 | 0.618907 | 0.661085 |
| 21   | 0.363049 | 0.406162 | 0.449152 | 0.492005 | 0.534707 | 0.577247 | 0.619611 | 0.661787 |
| 22   | 0.363769 | 0.406880 | 0.449867 | 0.492718 | 0.535418 | 0.577955 | 0.620316 | 0.662488 |
| 23   | 0.364488 | 0.407597 | 0.450583 | 0.493430 | 0.536128 | 0.578662 | 0.621020 | 0.663189 |
| 24   | 0.365208 | 0.408315 | 0.451298 | 0.494143 | 0.536838 | 0.579370 | 0.621725 | 0.663890 |
| 25   | 0.365927 | 0.409032 | 0.452013 | 0.494856 | 0.537549 | 0.580077 | 0.622429 | 0.664591 |
| 26   | 0.366646 | 0.409750 | 0.452728 | 0.495569 | 0.538259 | 0.580784 | 0.623133 | 0.665292 |
| 27   | 0.367366 | 0.410467 | 0.453444 | 0.496282 | 0.538969 | 0.581492 | 0.623838 | 0.665993 |
| 28   | 0.368085 | 0.411184 | 0.454159 | 0.496994 | 0.539679 | 0.582199 | 0.624542 | 0.666694 |
| 29   | 0.368804 | 0.411902 | 0.454874 | 0.497707 | 0.540389 | 0.582906 | 0.625246 | 0.667395 |
| 30   | 0.369524 | 0.412619 | 0.455589 | 0.498420 | 0.541099 | 0.583613 | 0.625950 | 0.668096 |
| 31   | 0.370243 | 0.413336 | 0.456304 | 0.499132 | 0.541809 | 0.584321 | 0.626654 | 0.668797 |
| 32   | 0.370962 | 0.414053 | 0.457019 | 0.499845 | 0.542519 | 0.585028 | 0.627358 | 0.669497 |
| 33   | 0.371681 | 0.414771 | 0.457734 | 0.500558 | 0.543229 | 0.585735 | 0.628062 | 0.670198 |
| 34   | 0.372400 | 0.415488 | 0.458449 | 0.501270 | 0.543939 | 0.586442 | 0.628766 | 0.670899 |
| 35   | 0.373119 | 0.416205 | 0.459164 | 0.501982 | 0.544648 | 0.587148 | 0.629470 | 0.671599 |
| 36   | 0.373838 | 0.416922 | 0.459878 | 0.502695 | 0.545358 | 0.587855 | 0.630173 | 0.672300 |
| 37   | 0.374557 | 0.417639 | 0.460593 | 0.503407 | 0.546068 | 0.588562 | 0.630877 | 0.673000 |
| 38   | 0.375276 | 0.418356 | 0.461308 | 0.504119 | 0.546777 | 0.589269 | 0.631581 | 0.673700 |
| 39   | 0.375995 | 0.419073 | 0.462023 | 0.504832 | 0.547487 | 0.589976 | 0.632284 | 0.674401 |
| 40   | 0.376714 | 0.419790 | 0.462737 | 0.505544 | 0.548197 | 0.590682 | 0.632988 | 0.675101 |
| 41   | 0.377433 | 0.420507 | 0.463452 | 0.506256 | 0.548906 | 0.591389 | 0.633691 | 0.675801 |
| 42   | 0.378152 | 0.421223 | 0.464167 | 0.506968 | 0.549616 | 0.592095 | 0.634395 | 0.676501 |
| 43   | 0.378871 | 0.421940 | 0.464881 | 0.507680 | 0.550325 | 0.592802 | 0.635098 | 0.677201 |
| 44   | 0.379590 | 0.422657 | 0.465596 | 0.508392 | 0.551034 | 0.593508 | 0.635802 | 0.677901 |
| 45   | 0.380308 | 0.423374 | 0.466310 | 0.509104 | 0.551744 | 0.594215 | 0.636505 | 0.678601 |
| 46   | 0.381027 | 0.424090 | 0.467025 | 0.509816 | 0.552453 | 0.594921 | 0.637208 | 0.679301 |
| 47   | 0.381746 | 0.424807 | 0.467739 | 0.510528 | 0.553162 | 0.595627 | 0.637911 | 0.680001 |
| 48   | 0.382465 | 0.425524 | 0.468453 | 0.511240 | 0.553871 | 0.596334 | 0.638614 | 0.680701 |
| 49   | 0.383183 | 0.426240 | 0.469168 | 0.511952 | 0.554580 | 0.597040 | 0.639317 | 0.681400 |
| 50   | 0.383902 | 0.426957 | 0.469882 | 0.512664 | 0.555289 | 0.597746 | 0.640020 | 0.682100 |
| 51   | 0.384620 | 0.427673 | 0.470596 | 0.513376 | 0.555999 | 0.598452 | 0.640723 | 0.682800 |
| 52   | 0.385339 | 0.428390 | 0.471310 | 0.514087 | 0.556708 | 0.599158 | 0.641426 | 0.683499 |
| 53   | 0.386057 | 0.429106 | 0.472025 | 0.514799 | 0.557416 | 0.599864 | 0.642129 | 0.684199 |
| 54   | 0.386776 | 0.429823 | 0.472739 | 0.515510 | 0.558125 | 0.600570 | 0.642832 | 0.684898 |
| 55   | 0.387494 | 0.430539 | 0.473453 | 0.516222 | 0.558834 | 0.601276 | 0.643535 | 0.685597 |
| 56   | 0.388213 | 0.431255 | 0.474167 | 0.516934 | 0.559543 | 0.601982 | 0.644237 | 0.686297 |
| 57   | 0.388931 | 0.431972 | 0.474881 | 0.517645 | 0.560252 | 0.602688 | 0.644940 | 0.686996 |
| 58   | 0.389650 | 0.432688 | 0.475595 | 0.518357 | 0.560960 | 0.603393 | 0.645643 | 0.687695 |
| 59   | 0.390368 | 0.433404 | 0.476309 | 0.519068 | 0.561669 | 0.604099 | 0.646345 | 0.688394 |
| 60   | 0.391086 | 0.434120 | 0.477022 | 0.519779 | 0.562378 | 0.604805 | 0.647048 | 0.689093 |

## Constants for Setting a 2.5-inch Sine-Bar for 16° to 23°

| Min. | 16°      | 17°      | 18°      | 19°      | 20°      | 21°      | 22°      | 23°      |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 0.689093 | 0.730929 | 0.772543 | 0.813920 | 0.855050 | 0.895920 | 0.936517 | 0.976828 |
| 1    | 0.689792 | 0.731625 | 0.773234 | 0.814608 | 0.855734 | 0.896599 | 0.937191 | 0.977497 |
| 2    | 0.690491 | 0.732320 | 0.773926 | 0.815295 | 0.856417 | 0.897278 | 0.937865 | 0.978166 |
| 3    | 0.691190 | 0.733015 | 0.774617 | 0.815983 | 0.857100 | 0.897956 | 0.938539 | 0.978836 |
| 4    | 0.691889 | 0.733711 | 0.775309 | 0.816670 | 0.857783 | 0.898635 | 0.939213 | 0.979505 |
| 5    | 0.692588 | 0.734406 | 0.776000 | 0.817358 | 0.858466 | 0.899314 | 0.939887 | 0.980174 |
| 6    | 0.693287 | 0.735101 | 0.776691 | 0.818045 | 0.859149 | 0.899992 | 0.940561 | 0.980843 |
| 7    | 0.693985 | 0.735796 | 0.777382 | 0.818732 | 0.859832 | 0.900670 | 0.941234 | 0.981512 |
| 8    | 0.694684 | 0.736491 | 0.778073 | 0.819419 | 0.860515 | 0.901349 | 0.941908 | 0.982180 |
| 9    | 0.695382 | 0.737186 | 0.778764 | 0.820106 | 0.861198 | 0.902027 | 0.942582 | 0.982849 |
| 10   | 0.696081 | 0.737881 | 0.779455 | 0.820793 | 0.861880 | 0.902705 | 0.943255 | 0.983518 |
| 11   | 0.696779 | 0.738575 | 0.780146 | 0.821480 | 0.862563 | 0.903383 | 0.943929 | 0.984186 |
| 12   | 0.697478 | 0.739270 | 0.780837 | 0.822167 | 0.863246 | 0.904061 | 0.944602 | 0.984855 |
| 13   | 0.698176 | 0.739965 | 0.781528 | 0.822853 | 0.863928 | 0.904739 | 0.945275 | 0.985523 |
| 14   | 0.698874 | 0.740659 | 0.782219 | 0.823540 | 0.864610 | 0.905417 | 0.945948 | 0.986191 |
| 15   | 0.699573 | 0.741354 | 0.782910 | 0.824227 | 0.865293 | 0.906095 | 0.946622 | 0.986860 |
| 16   | 0.700271 | 0.742048 | 0.783600 | 0.824913 | 0.865975 | 0.906773 | 0.947295 | 0.987528 |
| 17   | 0.700969 | 0.742743 | 0.784291 | 0.825600 | 0.866657 | 0.907450 | 0.947968 | 0.988196 |
| 18   | 0.701667 | 0.743437 | 0.784981 | 0.826286 | 0.867339 | 0.908128 | 0.948640 | 0.988864 |
| 19   | 0.702365 | 0.744132 | 0.785672 | 0.826972 | 0.868021 | 0.908806 | 0.949313 | 0.989532 |
| 20   | 0.703063 | 0.744826 | 0.786362 | 0.827659 | 0.868703 | 0.909483 | 0.949986 | 0.990199 |
| 21   | 0.703761 | 0.745520 | 0.787052 | 0.828345 | 0.869385 | 0.910160 | 0.950659 | 0.990867 |
| 22   | 0.704458 | 0.746214 | 0.787742 | 0.829031 | 0.870067 | 0.910838 | 0.951331 | 0.991535 |
| 23   | 0.705156 | 0.746908 | 0.788433 | 0.829717 | 0.870748 | 0.911515 | 0.952004 | 0.992202 |
| 24   | 0.705854 | 0.747602 | 0.789123 | 0.830403 | 0.871430 | 0.912192 | 0.952676 | 0.992870 |
| 25   | 0.706551 | 0.748296 | 0.789813 | 0.831089 | 0.872112 | 0.912869 | 0.953348 | 0.993537 |
| 26   | 0.707249 | 0.748990 | 0.790503 | 0.831775 | 0.872793 | 0.913546 | 0.954020 | 0.994204 |
| 27   | 0.707946 | 0.749684 | 0.791192 | 0.832460 | 0.873475 | 0.914223 | 0.954693 | 0.994872 |
| 28   | 0.708644 | 0.750377 | 0.791882 | 0.833146 | 0.874156 | 0.914900 | 0.955365 | 0.995539 |
| 29   | 0.709341 | 0.751071 | 0.792572 | 0.833832 | 0.874837 | 0.915576 | 0.956037 | 0.996206 |
| 30   | 0.710038 | 0.751765 | 0.793262 | 0.834517 | 0.875519 | 0.916253 | 0.956709 | 0.996873 |
| 31   | 0.710736 | 0.752458 | 0.793951 | 0.835203 | 0.876200 | 0.916930 | 0.957380 | 0.997540 |
| 32   | 0.711433 | 0.753151 | 0.794641 | 0.835888 | 0.876881 | 0.917606 | 0.958052 | 0.998206 |
| 33   | 0.712130 | 0.753845 | 0.795330 | 0.836573 | 0.877562 | 0.918283 | 0.958724 | 0.998873 |
| 34   | 0.712827 | 0.754538 | 0.796020 | 0.837259 | 0.878243 | 0.918959 | 0.959395 | 0.999540 |
| 35   | 0.713524 | 0.755232 | 0.796709 | 0.837944 | 0.878923 | 0.919635 | 0.960067 | 1.000206 |
| 36   | 0.714221 | 0.755925 | 0.797398 | 0.838629 | 0.879604 | 0.920311 | 0.960738 | 1.000873 |
| 37   | 0.714918 | 0.756618 | 0.798087 | 0.839314 | 0.880285 | 0.920988 | 0.961410 | 1.001539 |
| 38   | 0.715615 | 0.757311 | 0.798777 | 0.839999 | 0.880965 | 0.921664 | 0.962081 | 1.002205 |
| 39   | 0.716311 | 0.758004 | 0.799466 | 0.840684 | 0.881646 | 0.922339 | 0.962752 | 1.002871 |
| 40   | 0.717008 | 0.758697 | 0.800155 | 0.841369 | 0.882326 | 0.923015 | 0.963423 | 1.003538 |
| 41   | 0.717705 | 0.759390 | 0.800844 | 0.842053 | 0.883007 | 0.923691 | 0.964094 | 1.004204 |
| 42   | 0.718401 | 0.760083 | 0.801533 | 0.842738 | 0.883687 | 0.924367 | 0.964765 | 1.004869 |
| 43   | 0.719098 | 0.760775 | 0.802221 | 0.843423 | 0.884367 | 0.925043 | 0.965436 | 1.005535 |
| 44   | 0.719794 | 0.761468 | 0.802910 | 0.844107 | 0.885048 | 0.925718 | 0.966107 | 1.006201 |
| 45   | 0.720491 | 0.762161 | 0.803599 | 0.844792 | 0.885728 | 0.926394 | 0.966777 | 1.006867 |
| 46   | 0.721187 | 0.762853 | 0.804287 | 0.845476 | 0.886408 | 0.927069 | 0.967448 | 1.007532 |
| 47   | 0.721883 | 0.763546 | 0.804976 | 0.846161 | 0.887088 | 0.927744 | 0.968119 | 1.008198 |
| 48   | 0.722579 | 0.764238 | 0.805664 | 0.846845 | 0.887767 | 0.928420 | 0.968789 | 1.008863 |
| 49   | 0.723276 | 0.764931 | 0.806353 | 0.847529 | 0.888447 | 0.929095 | 0.969459 | 1.009529 |
| 50   | 0.723972 | 0.765623 | 0.807041 | 0.848213 | 0.889127 | 0.929770 | 0.970130 | 1.010194 |
| 51   | 0.724668 | 0.766315 | 0.807729 | 0.848897 | 0.889807 | 0.930445 | 0.970800 | 1.010859 |
| 52   | 0.725364 | 0.767007 | 0.808417 | 0.849581 | 0.890486 | 0.931120 | 0.971470 | 1.011524 |
| 53   | 0.726060 | 0.767699 | 0.809106 | 0.850265 | 0.891166 | 0.931795 | 0.972140 | 1.012189 |
| 54   | 0.726755 | 0.768392 | 0.809794 | 0.850949 | 0.891845 | 0.932469 | 0.972810 | 1.012854 |
| 55   | 0.727451 | 0.769083 | 0.810482 | 0.851633 | 0.892524 | 0.933144 | 0.973480 | 1.013519 |
| 56   | 0.728147 | 0.769775 | 0.811169 | 0.852316 | 0.893204 | 0.933819 | 0.974150 | 1.014184 |
| 57   | 0.728843 | 0.770467 | 0.811857 | 0.853000 | 0.893883 | 0.934493 | 0.974819 | 1.014848 |
| 58   | 0.729538 | 0.771159 | 0.812545 | 0.853684 | 0.894562 | 0.935168 | 0.975489 | 1.015513 |
| 59   | 0.730234 | 0.771851 | 0.813233 | 0.854367 | 0.895241 | 0.935842 | 0.976158 | 1.016177 |
| 60   | 0.730929 | 0.772543 | 0.813920 | 0.855050 | 0.895920 | 0.936517 | 0.976828 | 1.016842 |

## SINE BAR CONSTANTS

## Constants for Setting a 2.5-inch Sine-Bar for 24° to 31°

| Min. | 24°      | 25°      | 26°      | 27°      | 28°      | 29°      | 30°      | 31°      |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 1.016842 | 1.056546 | 1.095928 | 1.134976 | 1.173679 | 1.212024 | 1.250000 | 1.287595 |
| 1    | 1.017506 | 1.057205 | 1.096581 | 1.135624 | 1.174321 | 1.212660 | 1.250630 | 1.288218 |
| 2    | 1.018170 | 1.057864 | 1.097235 | 1.136272 | 1.174963 | 1.213296 | 1.251259 | 1.288842 |
| 3    | 1.018834 | 1.058522 | 1.097888 | 1.136920 | 1.175605 | 1.213932 | 1.251889 | 1.289465 |
| 4    | 1.019498 | 1.059181 | 1.098542 | 1.137567 | 1.176247 | 1.214567 | 1.252518 | 1.290088 |
| 5    | 1.020162 | 1.059840 | 1.099195 | 1.138215 | 1.176888 | 1.215203 | 1.253148 | 1.290711 |
| 6    | 1.020826 | 1.060499 | 1.099848 | 1.138862 | 1.177530 | 1.215839 | 1.253777 | 1.291333 |
| 7    | 1.021490 | 1.061157 | 1.100501 | 1.139510 | 1.178171 | 1.216474 | 1.254406 | 1.291956 |
| 8    | 1.022154 | 1.061816 | 1.101154 | 1.140157 | 1.178813 | 1.217109 | 1.255035 | 1.292579 |
| 9    | 1.022817 | 1.062474 | 1.101807 | 1.140804 | 1.179454 | 1.217744 | 1.255664 | 1.293201 |
| 10   | 1.023481 | 1.063132 | 1.102459 | 1.141451 | 1.180095 | 1.218379 | 1.256293 | 1.293823 |
| 11   | 1.024144 | 1.063790 | 1.103112 | 1.142098 | 1.180736 | 1.219014 | 1.256921 | 1.294445 |
| 12   | 1.024808 | 1.064448 | 1.103765 | 1.142745 | 1.181377 | 1.219649 | 1.257550 | 1.295068 |
| 13   | 1.025471 | 1.065106 | 1.104417 | 1.143392 | 1.182018 | 1.220284 | 1.258178 | 1.295690 |
| 14   | 1.026134 | 1.065764 | 1.105070 | 1.144038 | 1.182659 | 1.220919 | 1.258807 | 1.296311 |
| 15   | 1.026797 | 1.066422 | 1.105722 | 1.144685 | 1.183299 | 1.221553 | 1.259435 | 1.296933 |
| 16   | 1.027460 | 1.067080 | 1.106374 | 1.145331 | 1.183940 | 1.222188 | 1.260063 | 1.297555 |
| 17   | 1.028123 | 1.067737 | 1.107026 | 1.145978 | 1.184580 | 1.222822 | 1.260691 | 1.298176 |
| 18   | 1.028786 | 1.068395 | 1.107678 | 1.146624 | 1.185220 | 1.223456 | 1.261319 | 1.298798 |
| 19   | 1.029449 | 1.069052 | 1.108330 | 1.147270 | 1.185861 | 1.224090 | 1.261947 | 1.299419 |
| 20   | 1.030111 | 1.069709 | 1.108982 | 1.147916 | 1.186501 | 1.224724 | 1.262575 | 1.300040 |
| 21   | 1.030774 | 1.070367 | 1.109633 | 1.148562 | 1.187141 | 1.225358 | 1.263202 | 1.300661 |
| 22   | 1.031436 | 1.071024 | 1.110285 | 1.149208 | 1.187781 | 1.225992 | 1.263830 | 1.301282 |
| 23   | 1.032099 | 1.071681 | 1.110937 | 1.149854 | 1.188421 | 1.226626 | 1.264457 | 1.301903 |
| 24   | 1.032761 | 1.072338 | 1.111588 | 1.150499 | 1.189061 | 1.227259 | 1.265084 | 1.302524 |
| 25   | 1.033423 | 1.072995 | 1.112239 | 1.151145 | 1.189700 | 1.227893 | 1.265712 | 1.303145 |
| 26   | 1.034085 | 1.073652 | 1.112890 | 1.151790 | 1.190340 | 1.228526 | 1.266339 | 1.303765 |
| 27   | 1.034748 | 1.074308 | 1.113542 | 1.152436 | 1.190979 | 1.229160 | 1.266966 | 1.304386 |
| 28   | 1.035409 | 1.074965 | 1.114193 | 1.153081 | 1.191619 | 1.229793 | 1.267593 | 1.305006 |
| 29   | 1.036071 | 1.075621 | 1.114844 | 1.153726 | 1.192258 | 1.230426 | 1.268219 | 1.305626 |
| 30   | 1.036733 | 1.076278 | 1.115495 | 1.154372 | 1.192897 | 1.231059 | 1.268846 | 1.306246 |
| 31   | 1.037395 | 1.076934 | 1.116145 | 1.155017 | 1.193536 | 1.231692 | 1.269472 | 1.306866 |
| 32   | 1.038056 | 1.077590 | 1.116796 | 1.155661 | 1.194175 | 1.232325 | 1.270099 | 1.307486 |
| 33   | 1.038718 | 1.078246 | 1.117447 | 1.156306 | 1.194814 | 1.232957 | 1.270725 | 1.308106 |
| 34   | 1.039379 | 1.078903 | 1.118097 | 1.156951 | 1.195453 | 1.233590 | 1.271351 | 1.308726 |
| 35   | 1.040041 | 1.079558 | 1.118747 | 1.157596 | 1.196091 | 1.234222 | 1.271978 | 1.309346 |
| 36   | 1.040702 | 1.080214 | 1.119398 | 1.158240 | 1.196730 | 1.234855 | 1.272604 | 1.309965 |
| 37   | 1.041363 | 1.080870 | 1.120048 | 1.158885 | 1.197368 | 1.235487 | 1.273229 | 1.310584 |
| 38   | 1.042024 | 1.081526 | 1.120698 | 1.159529 | 1.198006 | 1.236119 | 1.273855 | 1.311203 |
| 39   | 1.042685 | 1.082181 | 1.121348 | 1.160173 | 1.198645 | 1.236751 | 1.274481 | 1.311822 |
| 40   | 1.043346 | 1.082837 | 1.121998 | 1.160817 | 1.199283 | 1.237383 | 1.275106 | 1.312441 |
| 41   | 1.044007 | 1.083492 | 1.122648 | 1.161461 | 1.199921 | 1.238015 | 1.275732 | 1.313060 |
| 42   | 1.044668 | 1.084148 | 1.123298 | 1.162105 | 1.200559 | 1.238647 | 1.276357 | 1.313679 |
| 43   | 1.045328 | 1.084803 | 1.123947 | 1.162749 | 1.201197 | 1.239278 | 1.276983 | 1.314298 |
| 44   | 1.045989 | 1.085458 | 1.124597 | 1.163393 | 1.201834 | 1.239910 | 1.277608 | 1.314916 |
| 45   | 1.046649 | 1.086113 | 1.125246 | 1.164036 | 1.202472 | 1.240541 | 1.278233 | 1.315535 |
| 46   | 1.047310 | 1.086768 | 1.125896 | 1.164680 | 1.203110 | 1.241173 | 1.278858 | 1.316153 |
| 47   | 1.047970 | 1.087423 | 1.126545 | 1.165323 | 1.203747 | 1.241804 | 1.279482 | 1.316771 |
| 48   | 1.048630 | 1.088078 | 1.127194 | 1.165967 | 1.204384 | 1.242435 | 1.280107 | 1.317389 |
| 49   | 1.049290 | 1.088732 | 1.127843 | 1.166610 | 1.205022 | 1.243066 | 1.280732 | 1.318008 |
| 50   | 1.049950 | 1.089387 | 1.128492 | 1.167253 | 1.205659 | 1.243697 | 1.281356 | 1.318625 |
| 51   | 1.050610 | 1.090042 | 1.129141 | 1.167896 | 1.206296 | 1.244328 | 1.281981 | 1.319243 |
| 52   | 1.051270 | 1.090696 | 1.129790 | 1.168539 | 1.206932 | 1.244958 | 1.282605 | 1.319861 |
| 53   | 1.051930 | 1.091350 | 1.130438 | 1.169182 | 1.207569 | 1.245589 | 1.283229 | 1.320478 |
| 54   | 1.052590 | 1.092005 | 1.131087 | 1.169825 | 1.208206 | 1.246219 | 1.283853 | 1.321096 |
| 55   | 1.053249 | 1.092659 | 1.131735 | 1.170467 | 1.208843 | 1.246850 | 1.284477 | 1.321713 |
| 56   | 1.053909 | 1.093313 | 1.132384 | 1.171110 | 1.209479 | 1.247480 | 1.285101 | 1.322330 |
| 57   | 1.054568 | 1.093967 | 1.133032 | 1.171752 | 1.210116 | 1.248110 | 1.285725 | 1.322948 |
| 58   | 1.055227 | 1.094620 | 1.133680 | 1.172395 | 1.210752 | 1.248740 | 1.286348 | 1.323565 |
| 59   | 1.055887 | 1.095274 | 1.134328 | 1.173037 | 1.211388 | 1.249370 | 1.286972 | 1.324181 |
| 60   | 1.056546 | 1.095928 | 1.134976 | 1.173679 | 1.212024 | 1.250000 | 1.287595 | 1.324798 |

## Constants for Setting a 2.5-inch Sine-Bar for 32° to 39°

| Min. | 32°      | 33°      | 34°      | 35°      | 36°      | 37°      | 38°      | 39°      |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 1.324798 | 1.361598 | 1.397982 | 1.433941 | 1.469463 | 1.504538 | 1.539154 | 1.573301 |
| 1    | 1.325415 | 1.362207 | 1.398585 | 1.434537 | 1.470051 | 1.505118 | 1.539727 | 1.573866 |
| 2    | 1.326031 | 1.362817 | 1.399188 | 1.435132 | 1.470640 | 1.505699 | 1.540300 | 1.574431 |
| 3    | 1.326648 | 1.363427 | 1.399790 | 1.435728 | 1.471228 | 1.506279 | 1.540872 | 1.574996 |
| 4    | 1.327264 | 1.364036 | 1.400393 | 1.436323 | 1.471815 | 1.506860 | 1.541445 | 1.575561 |
| 5    | 1.327880 | 1.364646 | 1.400995 | 1.436918 | 1.472403 | 1.507440 | 1.542017 | 1.576125 |
| 6    | 1.328496 | 1.365255 | 1.401597 | 1.437513 | 1.472991 | 1.508020 | 1.542590 | 1.576689 |
| 7    | 1.329112 | 1.365864 | 1.402200 | 1.438108 | 1.473578 | 1.508600 | 1.543162 | 1.577254 |
| 8    | 1.329728 | 1.366473 | 1.402802 | 1.438703 | 1.474166 | 1.509180 | 1.543734 | 1.577818 |
| 9    | 1.330344 | 1.367082 | 1.403404 | 1.439298 | 1.474753 | 1.509760 | 1.544306 | 1.578382 |
| 10   | 1.330960 | 1.367691 | 1.404005 | 1.439892 | 1.475340 | 1.510339 | 1.544878 | 1.578946 |
| 11   | 1.331575 | 1.368300 | 1.404607 | 1.440487 | 1.475927 | 1.510918 | 1.545449 | 1.579510 |
| 12   | 1.332191 | 1.368908 | 1.405208 | 1.441081 | 1.476514 | 1.511498 | 1.546021 | 1.580073 |
| 13   | 1.332806 | 1.369517 | 1.405810 | 1.441675 | 1.477101 | 1.512077 | 1.546592 | 1.580637 |
| 14   | 1.333421 | 1.370125 | 1.406411 | 1.442269 | 1.477688 | 1.512656 | 1.547164 | 1.581200 |
| 15   | 1.334036 | 1.370733 | 1.407012 | 1.442863 | 1.478274 | 1.513235 | 1.547735 | 1.581763 |
| 16   | 1.334651 | 1.371341 | 1.407613 | 1.443457 | 1.478860 | 1.513814 | 1.548306 | 1.582326 |
| 17   | 1.335266 | 1.371949 | 1.408214 | 1.444051 | 1.479447 | 1.514392 | 1.548877 | 1.582889 |
| 18   | 1.335881 | 1.372557 | 1.408815 | 1.444644 | 1.480033 | 1.514971 | 1.549448 | 1.583452 |
| 19   | 1.336496 | 1.373165 | 1.409416 | 1.445238 | 1.480619 | 1.515549 | 1.550018 | 1.584015 |
| 20   | 1.337110 | 1.373772 | 1.410016 | 1.445831 | 1.481205 | 1.516128 | 1.550589 | 1.584577 |
| 21   | 1.337724 | 1.374380 | 1.410617 | 1.446424 | 1.481791 | 1.516706 | 1.551159 | 1.585140 |
| 22   | 1.338339 | 1.374987 | 1.411217 | 1.447017 | 1.482376 | 1.517284 | 1.551729 | 1.585702 |
| 23   | 1.338953 | 1.375595 | 1.411818 | 1.447610 | 1.482962 | 1.517862 | 1.552300 | 1.586264 |
| 24   | 1.339567 | 1.376202 | 1.412418 | 1.448203 | 1.483547 | 1.518440 | 1.552870 | 1.586826 |
| 25   | 1.340181 | 1.376809 | 1.413018 | 1.448796 | 1.484133 | 1.519017 | 1.553439 | 1.587388 |
| 26   | 1.340795 | 1.377416 | 1.413617 | 1.449388 | 1.484718 | 1.519595 | 1.554009 | 1.587950 |
| 27   | 1.341409 | 1.378023 | 1.414217 | 1.449981 | 1.485303 | 1.520172 | 1.554579 | 1.588512 |
| 28   | 1.342022 | 1.378629 | 1.414817 | 1.450573 | 1.485888 | 1.520749 | 1.555148 | 1.589073 |
| 29   | 1.342636 | 1.379236 | 1.415416 | 1.451165 | 1.486472 | 1.521327 | 1.555717 | 1.589634 |
| 30   | 1.343249 | 1.379843 | 1.416016 | 1.451757 | 1.487057 | 1.521904 | 1.556287 | 1.590196 |
| 31   | 1.343862 | 1.380449 | 1.416615 | 1.452349 | 1.487641 | 1.522480 | 1.556856 | 1.590757 |
| 32   | 1.344476 | 1.381055 | 1.417214 | 1.452941 | 1.488226 | 1.523057 | 1.557425 | 1.591318 |
| 33   | 1.345088 | 1.381661 | 1.417813 | 1.453533 | 1.488810 | 1.523634 | 1.557993 | 1.591878 |
| 34   | 1.345701 | 1.382267 | 1.418412 | 1.454125 | 1.489394 | 1.524210 | 1.558562 | 1.592439 |
| 35   | 1.346314 | 1.382873 | 1.419011 | 1.454716 | 1.489978 | 1.524787 | 1.559131 | 1.593000 |
| 36   | 1.346927 | 1.383479 | 1.419609 | 1.455307 | 1.490562 | 1.525363 | 1.559699 | 1.593560 |
| 37   | 1.347540 | 1.384084 | 1.420208 | 1.455899 | 1.491146 | 1.525939 | 1.560267 | 1.594120 |
| 38   | 1.348152 | 1.384690 | 1.420806 | 1.456490 | 1.491730 | 1.526515 | 1.560835 | 1.594680 |
| 39   | 1.348765 | 1.385296 | 1.421405 | 1.457081 | 1.492313 | 1.527091 | 1.561404 | 1.595240 |
| 40   | 1.349377 | 1.385901 | 1.422003 | 1.457672 | 1.492897 | 1.527667 | 1.561971 | 1.595800 |
| 41   | 1.349989 | 1.386506 | 1.422601 | 1.458262 | 1.493480 | 1.528242 | 1.562539 | 1.596360 |
| 42   | 1.350601 | 1.387111 | 1.423199 | 1.458853 | 1.494063 | 1.528818 | 1.563107 | 1.596920 |
| 43   | 1.351213 | 1.387716 | 1.423797 | 1.459444 | 1.494646 | 1.529393 | 1.563674 | 1.597479 |
| 44   | 1.351825 | 1.388321 | 1.424394 | 1.460034 | 1.495229 | 1.529968 | 1.564242 | 1.598038 |
| 45   | 1.352436 | 1.388926 | 1.424992 | 1.460624 | 1.495812 | 1.530543 | 1.564809 | 1.598598 |
| 46   | 1.353048 | 1.389530 | 1.425589 | 1.461214 | 1.496394 | 1.531118 | 1.565376 | 1.599157 |
| 47   | 1.353659 | 1.390135 | 1.426187 | 1.461804 | 1.496977 | 1.531693 | 1.565943 | 1.599715 |
| 48   | 1.354271 | 1.390739 | 1.426784 | 1.462394 | 1.497559 | 1.532268 | 1.566509 | 1.600274 |
| 49   | 1.354882 | 1.391343 | 1.427381 | 1.462984 | 1.498141 | 1.532842 | 1.567076 | 1.600833 |
| 50   | 1.355493 | 1.391947 | 1.427978 | 1.463574 | 1.498723 | 1.533417 | 1.567643 | 1.601391 |
| 51   | 1.356104 | 1.392551 | 1.428575 | 1.464163 | 1.499305 | 1.533991 | 1.568209 | 1.601950 |
| 52   | 1.356715 | 1.393155 | 1.429172 | 1.464752 | 1.499887 | 1.534565 | 1.568775 | 1.602508 |
| 53   | 1.357326 | 1.393759 | 1.429768 | 1.465342 | 1.500469 | 1.535139 | 1.569342 | 1.603066 |
| 54   | 1.357936 | 1.394363 | 1.430365 | 1.465931 | 1.501051 | 1.535713 | 1.569908 | 1.603624 |
| 55   | 1.358547 | 1.394966 | 1.430961 | 1.466520 | 1.501632 | 1.536287 | 1.570474 | 1.604182 |
| 56   | 1.359157 | 1.395570 | 1.431557 | 1.467109 | 1.502213 | 1.536860 | 1.571039 | 1.604740 |
| 57   | 1.359767 | 1.396173 | 1.432153 | 1.467698 | 1.502795 | 1.537434 | 1.571605 | 1.605297 |
| 58   | 1.360378 | 1.396776 | 1.432750 | 1.468286 | 1.503376 | 1.538007 | 1.572170 | 1.605855 |
| 59   | 1.360988 | 1.397379 | 1.433345 | 1.468875 | 1.503957 | 1.538581 | 1.572736 | 1.606412 |
| 60   | 1.361598 | 1.397982 | 1.433941 | 1.469463 | 1.504538 | 1.539154 | 1.573301 | 1.606969 |



## SINE BAR CONSTANTS

## Constants for Setting a 2.5-inch Sine-Bar for 40° to 47°

| Min. | 40°      | 41°      | 42°      | 43°      | 44°      | 45°      | 46°      | 47°      |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 1.606969 | 1.640148 | 1.672827 | 1.704996 | 1.736646 | 1.767767 | 1.798349 | 1.828384 |
| 1    | 1.607526 | 1.640696 | 1.673367 | 1.705528 | 1.737169 | 1.768281 | 1.798855 | 1.828880 |
| 2    | 1.608083 | 1.641245 | 1.673907 | 1.706059 | 1.737692 | 1.768795 | 1.799360 | 1.829376 |
| 3    | 1.608640 | 1.641793 | 1.674447 | 1.706591 | 1.738215 | 1.769309 | 1.799864 | 1.829871 |
| 4    | 1.609196 | 1.642342 | 1.674987 | 1.707122 | 1.738737 | 1.769823 | 1.800369 | 1.830367 |
| 5    | 1.609753 | 1.642890 | 1.675527 | 1.707653 | 1.739260 | 1.770336 | 1.800873 | 1.830862 |
| 6    | 1.610309 | 1.643438 | 1.676067 | 1.708184 | 1.739782 | 1.770850 | 1.801378 | 1.831357 |
| 7    | 1.610865 | 1.643986 | 1.676606 | 1.708715 | 1.740304 | 1.771363 | 1.801882 | 1.831852 |
| 8    | 1.611421 | 1.644534 | 1.677145 | 1.709246 | 1.740826 | 1.771876 | 1.802386 | 1.832347 |
| 9    | 1.611977 | 1.645082 | 1.677685 | 1.709777 | 1.741348 | 1.772389 | 1.802890 | 1.832842 |
| 10   | 1.612533 | 1.645629 | 1.678224 | 1.710307 | 1.741870 | 1.772902 | 1.803394 | 1.833336 |
| 11   | 1.613089 | 1.646176 | 1.678763 | 1.710838 | 1.742391 | 1.773414 | 1.803897 | 1.833831 |
| 12   | 1.613644 | 1.646724 | 1.679302 | 1.711368 | 1.742913 | 1.773927 | 1.804401 | 1.834325 |
| 13   | 1.614200 | 1.647271 | 1.679840 | 1.711898 | 1.743434 | 1.774439 | 1.804904 | 1.834819 |
| 14   | 1.614755 | 1.647818 | 1.680379 | 1.712428 | 1.743955 | 1.774951 | 1.805407 | 1.835313 |
| 15   | 1.615310 | 1.648365 | 1.680917 | 1.712958 | 1.744476 | 1.775463 | 1.805910 | 1.835806 |
| 16   | 1.615865 | 1.648911 | 1.681455 | 1.713487 | 1.744997 | 1.775975 | 1.806413 | 1.836300 |
| 17   | 1.616420 | 1.649458 | 1.681993 | 1.714017 | 1.745518 | 1.776487 | 1.806915 | 1.836793 |
| 18   | 1.616974 | 1.650004 | 1.682531 | 1.714546 | 1.746038 | 1.776999 | 1.807418 | 1.837286 |
| 19   | 1.617529 | 1.650550 | 1.683069 | 1.715075 | 1.746559 | 1.777510 | 1.807920 | 1.837780 |
| 20   | 1.618083 | 1.651097 | 1.683607 | 1.715604 | 1.747079 | 1.778021 | 1.808422 | 1.838273 |
| 21   | 1.618638 | 1.651643 | 1.684144 | 1.716133 | 1.747599 | 1.778533 | 1.808924 | 1.838765 |
| 22   | 1.619192 | 1.652188 | 1.684682 | 1.716662 | 1.748119 | 1.779044 | 1.809426 | 1.839258 |
| 23   | 1.619746 | 1.652734 | 1.685219 | 1.717190 | 1.748639 | 1.779554 | 1.809928 | 1.839751 |
| 24   | 1.620300 | 1.653280 | 1.685756 | 1.717719 | 1.749158 | 1.780065 | 1.810430 | 1.840243 |
| 25   | 1.620854 | 1.653825 | 1.686293 | 1.718247 | 1.749678 | 1.780576 | 1.810931 | 1.840735 |
| 26   | 1.621407 | 1.654370 | 1.686830 | 1.718775 | 1.750197 | 1.781086 | 1.811432 | 1.841227 |
| 27   | 1.621961 | 1.654916 | 1.687366 | 1.719303 | 1.750716 | 1.781596 | 1.811934 | 1.841719 |
| 28   | 1.622514 | 1.655461 | 1.687903 | 1.719831 | 1.751235 | 1.782106 | 1.812435 | 1.842211 |
| 29   | 1.623067 | 1.656005 | 1.688439 | 1.720359 | 1.751754 | 1.782616 | 1.812935 | 1.842702 |
| 30   | 1.623620 | 1.656550 | 1.688976 | 1.720886 | 1.752273 | 1.783126 | 1.813436 | 1.843193 |
| 31   | 1.624173 | 1.657095 | 1.689512 | 1.721414 | 1.752792 | 1.783636 | 1.813936 | 1.843685 |
| 32   | 1.624726 | 1.657639 | 1.690048 | 1.721941 | 1.753310 | 1.784145 | 1.814437 | 1.844176 |
| 33   | 1.625278 | 1.658183 | 1.690583 | 1.722468 | 1.753829 | 1.784655 | 1.814937 | 1.844667 |
| 34   | 1.625831 | 1.658728 | 1.691119 | 1.722995 | 1.754347 | 1.785164 | 1.815437 | 1.845157 |
| 35   | 1.626383 | 1.659272 | 1.691655 | 1.723522 | 1.754865 | 1.785673 | 1.815937 | 1.845648 |
| 36   | 1.626935 | 1.659816 | 1.692190 | 1.724049 | 1.755383 | 1.786182 | 1.816437 | 1.846138 |
| 37   | 1.627488 | 1.660359 | 1.692725 | 1.724575 | 1.755900 | 1.786690 | 1.816936 | 1.846629 |
| 38   | 1.628040 | 1.660903 | 1.693260 | 1.725102 | 1.756418 | 1.787199 | 1.817436 | 1.847119 |
| 39   | 1.628592 | 1.661446 | 1.693795 | 1.725628 | 1.756935 | 1.787708 | 1.817935 | 1.847609 |
| 40   | 1.629143 | 1.661990 | 1.694330 | 1.726154 | 1.757453 | 1.788216 | 1.818434 | 1.848099 |
| 41   | 1.629695 | 1.662533 | 1.694865 | 1.726680 | 1.757970 | 1.788724 | 1.818933 | 1.848588 |
| 42   | 1.630246 | 1.663076 | 1.695399 | 1.727206 | 1.758487 | 1.789232 | 1.819432 | 1.849078 |
| 43   | 1.630797 | 1.663619 | 1.695934 | 1.727732 | 1.759004 | 1.789740 | 1.819931 | 1.849567 |
| 44   | 1.631348 | 1.664162 | 1.696468 | 1.728257 | 1.759520 | 1.790247 | 1.820429 | 1.850056 |
| 45   | 1.631899 | 1.664704 | 1.697002 | 1.728783 | 1.760037 | 1.790755 | 1.820928 | 1.850545 |
| 46   | 1.632450 | 1.665247 | 1.697536 | 1.729308 | 1.760553 | 1.791262 | 1.821426 | 1.851034 |
| 47   | 1.633001 | 1.665789 | 1.698070 | 1.729833 | 1.761069 | 1.791770 | 1.821924 | 1.851523 |
| 48   | 1.633551 | 1.666331 | 1.698603 | 1.730358 | 1.761586 | 1.792277 | 1.822422 | 1.852012 |
| 49   | 1.634102 | 1.666873 | 1.699137 | 1.730883 | 1.762102 | 1.792783 | 1.822919 | 1.852500 |
| 50   | 1.634652 | 1.667415 | 1.699670 | 1.731407 | 1.762617 | 1.793290 | 1.823417 | 1.852988 |
| 51   | 1.635202 | 1.667957 | 1.700203 | 1.731932 | 1.763133 | 1.793797 | 1.823914 | 1.853476 |
| 52   | 1.635752 | 1.668499 | 1.700736 | 1.732456 | 1.763648 | 1.794303 | 1.824412 | 1.853964 |
| 53   | 1.636302 | 1.669040 | 1.701270 | 1.732981 | 1.764164 | 1.794810 | 1.824909 | 1.854452 |
| 54   | 1.636852 | 1.669582 | 1.701802 | 1.733505 | 1.764679 | 1.795316 | 1.825406 | 1.854940 |
| 55   | 1.637402 | 1.670123 | 1.702335 | 1.734029 | 1.765194 | 1.795822 | 1.825903 | 1.855427 |
| 56   | 1.637951 | 1.670664 | 1.702867 | 1.734552 | 1.765709 | 1.796328 | 1.826399 | 1.855914 |
| 57   | 1.638500 | 1.671205 | 1.703400 | 1.735076 | 1.766224 | 1.796833 | 1.826896 | 1.856402 |
| 58   | 1.639050 | 1.671745 | 1.703932 | 1.735599 | 1.766738 | 1.797339 | 1.827392 | 1.856889 |
| 59   | 1.639599 | 1.672286 | 1.704464 | 1.736123 | 1.767253 | 1.797844 | 1.827888 | 1.857375 |
| 60   | 1.640148 | 1.672827 | 1.704996 | 1.736646 | 1.767767 | 1.798349 | 1.828384 | 1.857862 |

## Constants for Setting a 2.5-inch Sine-Bar for 48° to 55°

| Min. | 48°      | 49°      | 50°      | 51°      | 52°      | 53°      | 54°      | 55°      |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 1.857862 | 1.886774 | 1.915111 | 1.942865 | 1.970027 | 1.996589 | 2.022542 | 2.047880 |
| 1    | 1.858349 | 1.887251 | 1.915578 | 1.943323 | 1.970475 | 1.997026 | 2.022970 | 2.048297 |
| 2    | 1.858835 | 1.887728 | 1.916046 | 1.943780 | 1.970922 | 1.997464 | 2.023397 | 2.048714 |
| 3    | 1.859321 | 1.888205 | 1.916513 | 1.944237 | 1.971369 | 1.997901 | 2.023824 | 2.049131 |
| 4    | 1.859807 | 1.888681 | 1.916980 | 1.944694 | 1.971816 | 1.998338 | 2.024251 | 2.049547 |
| 5    | 1.860293 | 1.889157 | 1.917446 | 1.945151 | 1.972263 | 1.998775 | 2.024678 | 2.049963 |
| 6    | 1.860779 | 1.889634 | 1.917913 | 1.945608 | 1.972710 | 1.999212 | 2.025104 | 2.050380 |
| 7    | 1.861264 | 1.890110 | 1.918379 | 1.946064 | 1.973157 | 1.999648 | 2.025530 | 2.050796 |
| 8    | 1.861750 | 1.890586 | 1.918846 | 1.946521 | 1.973603 | 2.000085 | 2.025957 | 2.051212 |
| 9    | 1.862235 | 1.891061 | 1.919312 | 1.946977 | 1.974050 | 2.000521 | 2.026383 | 2.051627 |
| 10   | 1.862720 | 1.891537 | 1.919778 | 1.947433 | 1.974496 | 2.000957 | 2.026809 | 2.052043 |
| 11   | 1.863205 | 1.892012 | 1.920243 | 1.947889 | 1.974942 | 2.001393 | 2.027234 | 2.052458 |
| 12   | 1.863690 | 1.892488 | 1.920709 | 1.948345 | 1.975388 | 2.001828 | 2.027660 | 2.052873 |
| 13   | 1.864175 | 1.892963 | 1.921174 | 1.948801 | 1.975833 | 2.002264 | 2.028085 | 2.053288 |
| 14   | 1.864659 | 1.893438 | 1.921640 | 1.949256 | 1.976279 | 2.002699 | 2.028510 | 2.053703 |
| 15   | 1.865143 | 1.893913 | 1.922105 | 1.949711 | 1.976724 | 2.003134 | 2.028935 | 2.054117 |
| 16   | 1.865628 | 1.894387 | 1.922570 | 1.950166 | 1.977169 | 2.003570 | 2.029360 | 2.054532 |
| 17   | 1.866112 | 1.894862 | 1.923034 | 1.950621 | 1.977614 | 2.004004 | 2.029784 | 2.054946 |
| 18   | 1.866596 | 1.895336 | 1.923499 | 1.951076 | 1.978059 | 2.004439 | 2.030209 | 2.055360 |
| 19   | 1.867079 | 1.895810 | 1.923963 | 1.951531 | 1.978503 | 2.004874 | 2.030633 | 2.055774 |
| 20   | 1.867563 | 1.896284 | 1.924428 | 1.951985 | 1.978948 | 2.005308 | 2.031057 | 2.056188 |
| 21   | 1.868046 | 1.896758 | 1.924892 | 1.952439 | 1.979392 | 2.005742 | 2.031481 | 2.056601 |
| 22   | 1.868529 | 1.897231 | 1.925356 | 1.952893 | 1.979836 | 2.006176 | 2.031905 | 2.057015 |
| 23   | 1.869012 | 1.897705 | 1.925820 | 1.953347 | 1.980280 | 2.006610 | 2.032329 | 2.057428 |
| 24   | 1.869495 | 1.898178 | 1.926283 | 1.953801 | 1.980724 | 2.007044 | 2.032752 | 2.057841 |
| 25   | 1.869978 | 1.898651 | 1.926747 | 1.954255 | 1.981168 | 2.007477 | 2.033175 | 2.058254 |
| 26   | 1.870461 | 1.899125 | 1.927210 | 1.954708 | 1.981611 | 2.007910 | 2.033598 | 2.058666 |
| 27   | 1.870943 | 1.899597 | 1.927673 | 1.955162 | 1.982055 | 2.008344 | 2.034021 | 2.059079 |
| 28   | 1.871425 | 1.900070 | 1.928136 | 1.955615 | 1.982498 | 2.008777 | 2.034444 | 2.059491 |
| 29   | 1.871907 | 1.900543 | 1.928599 | 1.956068 | 1.982941 | 2.009210 | 2.034867 | 2.059904 |
| 30   | 1.872389 | 1.901015 | 1.929062 | 1.956520 | 1.983383 | 2.009642 | 2.035289 | 2.060316 |
| 31   | 1.872871 | 1.901487 | 1.929524 | 1.956973 | 1.983826 | 2.010075 | 2.035711 | 2.060727 |
| 32   | 1.873353 | 1.901959 | 1.929986 | 1.957425 | 1.984268 | 2.010507 | 2.036133 | 2.061139 |
| 33   | 1.873834 | 1.902431 | 1.930448 | 1.957878 | 1.984711 | 2.010939 | 2.036555 | 2.061550 |
| 34   | 1.874316 | 1.902903 | 1.930910 | 1.958330 | 1.985153 | 2.011371 | 2.036977 | 2.061962 |
| 35   | 1.874797 | 1.903374 | 1.931372 | 1.958782 | 1.985595 | 2.011803 | 2.037398 | 2.062373 |
| 36   | 1.875278 | 1.903846 | 1.931834 | 1.959234 | 1.986037 | 2.012234 | 2.037819 | 2.062784 |
| 37   | 1.875759 | 1.904317 | 1.932295 | 1.959685 | 1.986478 | 2.012666 | 2.038241 | 2.063195 |
| 38   | 1.876239 | 1.904788 | 1.932757 | 1.960137 | 1.986920 | 2.013097 | 2.038662 | 2.063605 |
| 39   | 1.876720 | 1.905259 | 1.933218 | 1.960588 | 1.987361 | 2.013528 | 2.039083 | 2.064016 |
| 40   | 1.877200 | 1.905730 | 1.933679 | 1.961039 | 1.987802 | 2.013959 | 2.039503 | 2.064426 |
| 41   | 1.877680 | 1.906200 | 1.934140 | 1.961490 | 1.988243 | 2.014390 | 2.039924 | 2.064836 |
| 42   | 1.878160 | 1.906671 | 1.934601 | 1.961941 | 1.988684 | 2.014821 | 2.040344 | 2.065246 |
| 43   | 1.878640 | 1.907141 | 1.935061 | 1.962392 | 1.989124 | 2.015251 | 2.040764 | 2.065655 |
| 44   | 1.879120 | 1.907611 | 1.935521 | 1.962842 | 1.989565 | 2.015682 | 2.041184 | 2.066065 |
| 45   | 1.879600 | 1.908081 | 1.935982 | 1.963292 | 1.990005 | 2.016112 | 2.041604 | 2.066474 |
| 46   | 1.880079 | 1.908551 | 1.936442 | 1.963742 | 1.990445 | 2.016541 | 2.042024 | 2.066884 |
| 47   | 1.880558 | 1.909021 | 1.936902 | 1.964193 | 1.990885 | 2.016971 | 2.042443 | 2.067293 |
| 48   | 1.881037 | 1.909490 | 1.937361 | 1.964642 | 1.991325 | 2.017401 | 2.042862 | 2.067701 |
| 49   | 1.881516 | 1.909959 | 1.937821 | 1.965092 | 1.991764 | 2.017830 | 2.043281 | 2.068110 |
| 50   | 1.881995 | 1.910429 | 1.938280 | 1.965541 | 1.992204 | 2.018260 | 2.043700 | 2.068519 |
| 51   | 1.882474 | 1.910897 | 1.938739 | 1.965991 | 1.992643 | 2.018688 | 2.044119 | 2.068927 |
| 52   | 1.882952 | 1.911366 | 1.939198 | 1.966440 | 1.993082 | 2.019117 | 2.044538 | 2.069335 |
| 53   | 1.883430 | 1.911835 | 1.939657 | 1.966889 | 1.993521 | 2.019546 | 2.044956 | 2.069743 |
| 54   | 1.883909 | 1.912304 | 1.940116 | 1.967338 | 1.993960 | 2.019975 | 2.045374 | 2.070151 |
| 55   | 1.884387 | 1.912772 | 1.940575 | 1.967786 | 1.994398 | 2.020403 | 2.045792 | 2.070559 |
| 56   | 1.884864 | 1.913240 | 1.941033 | 1.968235 | 1.994837 | 2.020831 | 2.046210 | 2.070966 |
| 57   | 1.885342 | 1.913708 | 1.941491 | 1.968683 | 1.995275 | 2.021259 | 2.046628 | 2.071373 |
| 58   | 1.885819 | 1.914176 | 1.941949 | 1.969131 | 1.995713 | 2.021687 | 2.047045 | 2.071780 |
| 59   | 1.886297 | 1.914644 | 1.942407 | 1.969579 | 1.996151 | 2.022115 | 2.047463 | 2.072187 |
| 60   | 1.886774 | 1.915111 | 1.942865 | 1.970027 | 1.996589 | 2.022542 | 2.047880 | 2.072594 |

## SINE BAR CONSTANTS

## Constants for 3-inch Sine-Bar

## Constants for Setting a 3-inch Sine-Bar for 0° to 7°

| Min. | 0°       | 1°       | 2°       | 3°       | 4°       | 5°       | 6°       | 7°       |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 0.000000 | 0.052357 | 0.104698 | 0.157008 | 0.209269 | 0.261467 | 0.313585 | 0.365608 |
| 1    | 0.000873 | 0.053230 | 0.105571 | 0.157879 | 0.210140 | 0.262337 | 0.314453 | 0.366474 |
| 2    | 0.001745 | 0.054102 | 0.106443 | 0.158751 | 0.211010 | 0.263206 | 0.315321 | 0.367340 |
| 3    | 0.002618 | 0.054975 | 0.107315 | 0.159622 | 0.211881 | 0.264075 | 0.316189 | 0.368206 |
| 4    | 0.003491 | 0.055847 | 0.108187 | 0.160494 | 0.212751 | 0.264944 | 0.317057 | 0.369072 |
| 5    | 0.004363 | 0.056720 | 0.109059 | 0.161365 | 0.213622 | 0.265814 | 0.317924 | 0.369938 |
| 6    | 0.005236 | 0.057592 | 0.109931 | 0.162236 | 0.214492 | 0.266683 | 0.318792 | 0.370804 |
| 7    | 0.006109 | 0.058465 | 0.110803 | 0.163108 | 0.215363 | 0.267552 | 0.319660 | 0.371670 |
| 8    | 0.006981 | 0.059337 | 0.111675 | 0.163979 | 0.216233 | 0.268421 | 0.320528 | 0.372536 |
| 9    | 0.007854 | 0.060210 | 0.112547 | 0.164851 | 0.217104 | 0.269290 | 0.321395 | 0.373402 |
| 10   | 0.008727 | 0.061082 | 0.113419 | 0.165722 | 0.217974 | 0.270160 | 0.322263 | 0.374268 |
| 11   | 0.009599 | 0.061955 | 0.114291 | 0.166593 | 0.218844 | 0.271029 | 0.323131 | 0.375134 |
| 12   | 0.010472 | 0.062827 | 0.115163 | 0.167465 | 0.219715 | 0.271898 | 0.323998 | 0.376000 |
| 13   | 0.011345 | 0.063700 | 0.116035 | 0.168336 | 0.220585 | 0.272767 | 0.324866 | 0.376865 |
| 14   | 0.012217 | 0.064572 | 0.116907 | 0.169207 | 0.221455 | 0.273636 | 0.325733 | 0.377731 |
| 15   | 0.013090 | 0.065445 | 0.117779 | 0.170078 | 0.222325 | 0.274505 | 0.326601 | 0.378597 |
| 16   | 0.013963 | 0.066317 | 0.118651 | 0.170950 | 0.223196 | 0.275374 | 0.327468 | 0.379463 |
| 17   | 0.014835 | 0.067190 | 0.119523 | 0.171821 | 0.224066 | 0.276243 | 0.328336 | 0.380328 |
| 18   | 0.015708 | 0.068062 | 0.120395 | 0.172692 | 0.224936 | 0.277112 | 0.329203 | 0.381194 |
| 19   | 0.016581 | 0.068934 | 0.121267 | 0.173563 | 0.225806 | 0.277981 | 0.330070 | 0.382059 |
| 20   | 0.017453 | 0.069807 | 0.122139 | 0.174434 | 0.226677 | 0.278850 | 0.330938 | 0.382925 |
| 21   | 0.018326 | 0.070679 | 0.123011 | 0.175306 | 0.227547 | 0.279718 | 0.331805 | 0.383790 |
| 22   | 0.019198 | 0.071552 | 0.123883 | 0.176177 | 0.228417 | 0.280587 | 0.332672 | 0.384656 |
| 23   | 0.020071 | 0.072424 | 0.124755 | 0.177048 | 0.229287 | 0.281456 | 0.333540 | 0.385521 |
| 24   | 0.020944 | 0.073297 | 0.125627 | 0.177919 | 0.230157 | 0.282325 | 0.334407 | 0.386387 |
| 25   | 0.021816 | 0.074169 | 0.126499 | 0.178790 | 0.231027 | 0.283194 | 0.335274 | 0.387252 |
| 26   | 0.022689 | 0.075041 | 0.127371 | 0.179661 | 0.231897 | 0.284062 | 0.336141 | 0.388118 |
| 27   | 0.023562 | 0.075914 | 0.128243 | 0.180532 | 0.232767 | 0.284931 | 0.337008 | 0.388983 |
| 28   | 0.024434 | 0.076786 | 0.129114 | 0.181404 | 0.233637 | 0.285800 | 0.337875 | 0.389848 |
| 29   | 0.025307 | 0.077658 | 0.129986 | 0.182275 | 0.234507 | 0.286669 | 0.338743 | 0.390713 |
| 30   | 0.026180 | 0.078531 | 0.130858 | 0.183146 | 0.235377 | 0.287537 | 0.339610 | 0.391579 |
| 31   | 0.027052 | 0.079403 | 0.131730 | 0.184017 | 0.236247 | 0.288406 | 0.340477 | 0.392444 |
| 32   | 0.027925 | 0.080276 | 0.132602 | 0.184888 | 0.237117 | 0.289275 | 0.341344 | 0.393309 |
| 33   | 0.028797 | 0.081148 | 0.133474 | 0.185759 | 0.237987 | 0.290143 | 0.342211 | 0.394174 |
| 34   | 0.029670 | 0.082020 | 0.134345 | 0.186630 | 0.238857 | 0.291012 | 0.343078 | 0.395039 |
| 35   | 0.030543 | 0.082893 | 0.135217 | 0.187501 | 0.239727 | 0.291880 | 0.343945 | 0.395904 |
| 36   | 0.031415 | 0.083765 | 0.136089 | 0.188372 | 0.240597 | 0.292749 | 0.344811 | 0.396769 |
| 37   | 0.032288 | 0.084637 | 0.136961 | 0.189242 | 0.241467 | 0.293617 | 0.345678 | 0.397634 |
| 38   | 0.033161 | 0.085510 | 0.137832 | 0.190113 | 0.242336 | 0.294486 | 0.346545 | 0.398499 |
| 39   | 0.034033 | 0.086382 | 0.138704 | 0.190984 | 0.243206 | 0.295354 | 0.347412 | 0.399364 |
| 40   | 0.034906 | 0.087254 | 0.139576 | 0.191855 | 0.244076 | 0.296223 | 0.348279 | 0.400229 |
| 41   | 0.035778 | 0.088126 | 0.140448 | 0.192726 | 0.244946 | 0.297091 | 0.349146 | 0.401094 |
| 42   | 0.036651 | 0.088999 | 0.141319 | 0.193597 | 0.245816 | 0.297959 | 0.350012 | 0.401959 |
| 43   | 0.037524 | 0.089871 | 0.142191 | 0.194468 | 0.246685 | 0.298828 | 0.350879 | 0.402823 |
| 44   | 0.038396 | 0.090743 | 0.143063 | 0.195339 | 0.247555 | 0.299696 | 0.351746 | 0.403688 |
| 45   | 0.039269 | 0.091616 | 0.143934 | 0.196209 | 0.248425 | 0.300564 | 0.352612 | 0.404553 |
| 46   | 0.040141 | 0.092488 | 0.144806 | 0.197080 | 0.249294 | 0.301432 | 0.353479 | 0.405418 |
| 47   | 0.041014 | 0.093360 | 0.145678 | 0.197951 | 0.250164 | 0.302301 | 0.354345 | 0.406282 |
| 48   | 0.041887 | 0.094232 | 0.146549 | 0.198822 | 0.251034 | 0.303169 | 0.355212 | 0.407147 |
| 49   | 0.042759 | 0.095105 | 0.147421 | 0.199692 | 0.251903 | 0.304037 | 0.356078 | 0.408011 |
| 50   | 0.043632 | 0.095977 | 0.148293 | 0.200563 | 0.252773 | 0.304905 | 0.356945 | 0.408876 |
| 51   | 0.044504 | 0.096849 | 0.149164 | 0.201434 | 0.253642 | 0.305773 | 0.357811 | 0.409740 |
| 52   | 0.045377 | 0.097721 | 0.150036 | 0.202305 | 0.254512 | 0.306641 | 0.358678 | 0.410605 |
| 53   | 0.046249 | 0.098593 | 0.150907 | 0.203175 | 0.255381 | 0.307510 | 0.359544 | 0.411469 |
| 54   | 0.047122 | 0.099466 | 0.151779 | 0.204046 | 0.256251 | 0.308378 | 0.360411 | 0.412334 |
| 55   | 0.047995 | 0.100338 | 0.152650 | 0.204917 | 0.257120 | 0.309246 | 0.361277 | 0.413198 |
| 56   | 0.048867 | 0.101210 | 0.153522 | 0.205787 | 0.257990 | 0.310114 | 0.362143 | 0.414062 |
| 57   | 0.049740 | 0.102082 | 0.154393 | 0.206658 | 0.258859 | 0.310982 | 0.363009 | 0.414927 |
| 58   | 0.050612 | 0.102954 | 0.155265 | 0.207528 | 0.259728 | 0.311850 | 0.363876 | 0.415791 |
| 59   | 0.051485 | 0.103826 | 0.156136 | 0.208399 | 0.260598 | 0.312717 | 0.364742 | 0.416655 |
| 60   | 0.052357 | 0.104698 | 0.157008 | 0.209269 | 0.261467 | 0.313585 | 0.365608 | 0.417519 |

## Constants for Setting a 3-inch Sine-Bar for 8° to 15°

| Min. | 8°       | 9°       | 10°      | 11°      | 12°      | 13°      | 14°      | 15°      |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 0.417519 | 0.469303 | 0.520945 | 0.572427 | 0.623735 | 0.674853 | 0.725766 | 0.776457 |
| 1    | 0.418383 | 0.470165 | 0.521804 | 0.573284 | 0.624589 | 0.675703 | 0.726612 | 0.777300 |
| 2    | 0.419248 | 0.471027 | 0.522663 | 0.574140 | 0.625442 | 0.676554 | 0.727459 | 0.778143 |
| 3    | 0.420112 | 0.471889 | 0.523523 | 0.574997 | 0.626296 | 0.677404 | 0.728306 | 0.778986 |
| 4    | 0.420976 | 0.472751 | 0.524382 | 0.575853 | 0.627149 | 0.678254 | 0.729152 | 0.779828 |
| 5    | 0.421840 | 0.473612 | 0.525241 | 0.576710 | 0.628002 | 0.679104 | 0.729999 | 0.780671 |
| 6    | 0.422704 | 0.474474 | 0.526100 | 0.577566 | 0.628856 | 0.679954 | 0.730845 | 0.781514 |
| 7    | 0.423568 | 0.475336 | 0.526959 | 0.578422 | 0.629709 | 0.680804 | 0.731691 | 0.782356 |
| 8    | 0.424432 | 0.476197 | 0.527818 | 0.579278 | 0.630562 | 0.681654 | 0.732538 | 0.783198 |
| 9    | 0.425295 | 0.477059 | 0.528677 | 0.580135 | 0.631415 | 0.682504 | 0.733384 | 0.784041 |
| 10   | 0.426159 | 0.477921 | 0.529536 | 0.580991 | 0.632268 | 0.683353 | 0.734230 | 0.784883 |
| 11   | 0.427023 | 0.478782 | 0.530395 | 0.581847 | 0.633121 | 0.684203 | 0.735076 | 0.785725 |
| 12   | 0.427887 | 0.479644 | 0.531254 | 0.582703 | 0.633974 | 0.685053 | 0.735922 | 0.786568 |
| 13   | 0.428751 | 0.480505 | 0.532113 | 0.583559 | 0.634827 | 0.685902 | 0.736768 | 0.787410 |
| 14   | 0.429614 | 0.481366 | 0.532972 | 0.584415 | 0.635680 | 0.686752 | 0.737614 | 0.788252 |
| 15   | 0.430478 | 0.482228 | 0.533831 | 0.585271 | 0.636533 | 0.687601 | 0.738460 | 0.789094 |
| 16   | 0.431341 | 0.483089 | 0.534689 | 0.586127 | 0.637386 | 0.688451 | 0.739306 | 0.789936 |
| 17   | 0.432205 | 0.483950 | 0.535548 | 0.586983 | 0.638239 | 0.689300 | 0.740151 | 0.790777 |
| 18   | 0.433069 | 0.484811 | 0.536407 | 0.587838 | 0.639091 | 0.690149 | 0.740997 | 0.791619 |
| 19   | 0.433932 | 0.485673 | 0.537265 | 0.588694 | 0.639944 | 0.690998 | 0.741843 | 0.792461 |
| 20   | 0.434796 | 0.486534 | 0.538124 | 0.589550 | 0.640796 | 0.691848 | 0.742688 | 0.793302 |
| 21   | 0.435659 | 0.487395 | 0.538982 | 0.590405 | 0.641649 | 0.692697 | 0.743534 | 0.794144 |
| 22   | 0.436522 | 0.488256 | 0.539841 | 0.591261 | 0.642501 | 0.693546 | 0.744379 | 0.794986 |
| 23   | 0.437386 | 0.489117 | 0.540699 | 0.592117 | 0.643354 | 0.694395 | 0.745224 | 0.795827 |
| 24   | 0.438249 | 0.489978 | 0.541557 | 0.592972 | 0.644206 | 0.695244 | 0.746070 | 0.796668 |
| 25   | 0.439112 | 0.490839 | 0.542416 | 0.593827 | 0.645058 | 0.696093 | 0.746915 | 0.797510 |
| 26   | 0.439976 | 0.491700 | 0.543274 | 0.594683 | 0.645911 | 0.696941 | 0.747760 | 0.798351 |
| 27   | 0.440839 | 0.492561 | 0.544132 | 0.595538 | 0.646763 | 0.697790 | 0.748605 | 0.799192 |
| 28   | 0.441702 | 0.493421 | 0.544990 | 0.596393 | 0.647615 | 0.698639 | 0.749450 | 0.800033 |
| 29   | 0.442565 | 0.494282 | 0.545849 | 0.597249 | 0.648467 | 0.699488 | 0.750295 | 0.800874 |
| 30   | 0.443428 | 0.495143 | 0.546707 | 0.598104 | 0.649319 | 0.700336 | 0.751140 | 0.801715 |
| 31   | 0.444291 | 0.496004 | 0.547565 | 0.598959 | 0.650171 | 0.701185 | 0.751985 | 0.802556 |
| 32   | 0.445154 | 0.496864 | 0.548423 | 0.599814 | 0.651023 | 0.702033 | 0.752830 | 0.803397 |
| 33   | 0.446017 | 0.497725 | 0.549281 | 0.600669 | 0.651875 | 0.702882 | 0.753674 | 0.804238 |
| 34   | 0.446880 | 0.498585 | 0.550138 | 0.601524 | 0.652726 | 0.703730 | 0.754519 | 0.805078 |
| 35   | 0.447743 | 0.499446 | 0.550996 | 0.602379 | 0.653578 | 0.704578 | 0.755364 | 0.805919 |
| 36   | 0.448606 | 0.500306 | 0.551854 | 0.603234 | 0.654430 | 0.705426 | 0.756208 | 0.806759 |
| 37   | 0.449469 | 0.501167 | 0.552712 | 0.604089 | 0.655281 | 0.706275 | 0.757053 | 0.807600 |
| 38   | 0.450332 | 0.502027 | 0.553569 | 0.604943 | 0.656133 | 0.707123 | 0.757897 | 0.808440 |
| 39   | 0.451194 | 0.502887 | 0.554427 | 0.605798 | 0.656984 | 0.707971 | 0.758741 | 0.809281 |
| 40   | 0.452057 | 0.503748 | 0.555285 | 0.606653 | 0.657836 | 0.708819 | 0.759586 | 0.810121 |
| 41   | 0.452920 | 0.504608 | 0.556142 | 0.607507 | 0.658687 | 0.709667 | 0.760430 | 0.810961 |
| 42   | 0.453782 | 0.505468 | 0.557000 | 0.608362 | 0.659539 | 0.710514 | 0.761274 | 0.811801 |
| 43   | 0.454645 | 0.506328 | 0.557857 | 0.609216 | 0.660390 | 0.711362 | 0.762118 | 0.812641 |
| 44   | 0.455508 | 0.507188 | 0.558715 | 0.610071 | 0.661241 | 0.712210 | 0.762962 | 0.813481 |
| 45   | 0.456370 | 0.508049 | 0.559572 | 0.610925 | 0.662092 | 0.713058 | 0.763806 | 0.814321 |
| 46   | 0.457233 | 0.508909 | 0.560429 | 0.611780 | 0.662943 | 0.713905 | 0.764650 | 0.815161 |
| 47   | 0.458095 | 0.509769 | 0.561287 | 0.612634 | 0.663795 | 0.714753 | 0.765494 | 0.816001 |
| 48   | 0.458958 | 0.510629 | 0.562144 | 0.613488 | 0.664645 | 0.715600 | 0.766337 | 0.816841 |
| 49   | 0.459820 | 0.511488 | 0.563001 | 0.614342 | 0.665496 | 0.716448 | 0.767181 | 0.817680 |
| 50   | 0.460682 | 0.512348 | 0.563858 | 0.615197 | 0.666347 | 0.717295 | 0.768025 | 0.818520 |
| 51   | 0.461545 | 0.513208 | 0.564715 | 0.616051 | 0.667198 | 0.718143 | 0.768868 | 0.819360 |
| 52   | 0.462407 | 0.514068 | 0.565572 | 0.616905 | 0.668049 | 0.718990 | 0.769712 | 0.820199 |
| 53   | 0.463269 | 0.514928 | 0.566429 | 0.617759 | 0.668900 | 0.719837 | 0.770555 | 0.821038 |
| 54   | 0.464131 | 0.515787 | 0.567286 | 0.618613 | 0.669750 | 0.720684 | 0.771398 | 0.821878 |
| 55   | 0.464993 | 0.516647 | 0.568143 | 0.619466 | 0.670601 | 0.721531 | 0.772242 | 0.822717 |
| 56   | 0.465855 | 0.517507 | 0.569000 | 0.620320 | 0.671452 | 0.722378 | 0.773085 | 0.823556 |
| 57   | 0.466717 | 0.518366 | 0.569857 | 0.621174 | 0.672302 | 0.723225 | 0.773928 | 0.824395 |
| 58   | 0.467579 | 0.519226 | 0.570714 | 0.622028 | 0.673152 | 0.724072 | 0.774771 | 0.825234 |
| 59   | 0.468441 | 0.520085 | 0.571570 | 0.622881 | 0.674003 | 0.724919 | 0.775614 | 0.826073 |
| 60   | 0.469303 | 0.520945 | 0.572427 | 0.623735 | 0.674853 | 0.725766 | 0.776457 | 0.826912 |

## Constants for Setting a 3-inch Sine-Bar for 16° to 23°

| Min. | 16°      | 17°      | 18°      | 19°      | 20°      | 21°      | 22°      | 23°      |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 0.826912 | 0.877115 | 0.927051 | 0.976704 | 1.026060 | 1.075104 | 1.123820 | 1.172193 |
| 1    | 0.827751 | 0.877950 | 0.927881 | 0.977530 | 1.026880 | 1.075919 | 1.124629 | 1.172997 |
| 2    | 0.828590 | 0.878784 | 0.928711 | 0.978355 | 1.027700 | 1.076733 | 1.125438 | 1.173800 |
| 3    | 0.829428 | 0.879618 | 0.929540 | 0.979179 | 1.028520 | 1.077548 | 1.126247 | 1.174603 |
| 4    | 0.830267 | 0.880453 | 0.930370 | 0.980004 | 1.029340 | 1.078362 | 1.127056 | 1.175406 |
| 5    | 0.831106 | 0.881287 | 0.931200 | 0.980829 | 1.030160 | 1.079176 | 1.127864 | 1.176209 |
| 6    | 0.831944 | 0.882121 | 0.932029 | 0.981654 | 1.030979 | 1.079991 | 1.128673 | 1.177011 |
| 7    | 0.832782 | 0.882955 | 0.932859 | 0.982478 | 1.031799 | 1.080805 | 1.129481 | 1.177814 |
| 8    | 0.833621 | 0.883789 | 0.933688 | 0.983303 | 1.032618 | 1.081619 | 1.130290 | 1.178617 |
| 9    | 0.834459 | 0.884623 | 0.934517 | 0.984127 | 1.033437 | 1.082433 | 1.131098 | 1.179419 |
| 10   | 0.835297 | 0.885457 | 0.935347 | 0.984951 | 1.034256 | 1.083246 | 1.131906 | 1.180221 |
| 11   | 0.836135 | 0.886290 | 0.936176 | 0.985776 | 1.035076 | 1.084060 | 1.132714 | 1.181024 |
| 12   | 0.836973 | 0.887124 | 0.937005 | 0.986600 | 1.035895 | 1.084874 | 1.133522 | 1.181826 |
| 13   | 0.837811 | 0.887958 | 0.937834 | 0.987424 | 1.036714 | 1.085687 | 1.134330 | 1.182628 |
| 14   | 0.838649 | 0.888791 | 0.938663 | 0.988248 | 1.037532 | 1.086501 | 1.135138 | 1.183430 |
| 15   | 0.839487 | 0.889625 | 0.939491 | 0.989072 | 1.038351 | 1.087314 | 1.135946 | 1.184232 |
| 16   | 0.840325 | 0.890458 | 0.940320 | 0.989896 | 1.039170 | 1.088127 | 1.136754 | 1.185033 |
| 17   | 0.841163 | 0.891291 | 0.941149 | 0.990719 | 1.039988 | 1.088941 | 1.137561 | 1.185835 |
| 18   | 0.842000 | 0.892125 | 0.941977 | 0.991543 | 1.040807 | 1.089754 | 1.138368 | 1.186636 |
| 19   | 0.842838 | 0.892958 | 0.942806 | 0.992367 | 1.041625 | 1.090567 | 1.139176 | 1.187438 |
| 20   | 0.843675 | 0.893791 | 0.943634 | 0.993190 | 1.042444 | 1.091380 | 1.139983 | 1.188239 |
| 21   | 0.844513 | 0.894624 | 0.944463 | 0.994014 | 1.043262 | 1.092193 | 1.140790 | 1.189041 |
| 22   | 0.845350 | 0.895457 | 0.945291 | 0.994837 | 1.044080 | 1.093005 | 1.141597 | 1.189842 |
| 23   | 0.846187 | 0.896290 | 0.946119 | 0.995660 | 1.044898 | 1.093818 | 1.142404 | 1.190643 |
| 24   | 0.847024 | 0.897122 | 0.946947 | 0.996483 | 1.045716 | 1.094630 | 1.143211 | 1.191444 |
| 25   | 0.847861 | 0.897955 | 0.947775 | 0.997306 | 1.046534 | 1.095443 | 1.144018 | 1.192245 |
| 26   | 0.848698 | 0.898788 | 0.948603 | 0.998129 | 1.047352 | 1.096255 | 1.144825 | 1.193045 |
| 27   | 0.849536 | 0.899620 | 0.949431 | 0.998952 | 1.048170 | 1.097067 | 1.145631 | 1.193846 |
| 28   | 0.850372 | 0.900453 | 0.950259 | 0.999775 | 1.048987 | 1.097880 | 1.146438 | 1.194646 |
| 29   | 0.851209 | 0.901285 | 0.951086 | 1.000598 | 1.049805 | 1.098692 | 1.147244 | 1.195447 |
| 30   | 0.852046 | 0.902117 | 0.951914 | 1.001421 | 1.050622 | 1.099504 | 1.148050 | 1.196247 |
| 31   | 0.852883 | 0.902950 | 0.952742 | 1.002243 | 1.051440 | 1.100316 | 1.148857 | 1.197047 |
| 32   | 0.853719 | 0.903782 | 0.953569 | 1.003066 | 1.052257 | 1.101127 | 1.149663 | 1.197848 |
| 33   | 0.854556 | 0.904614 | 0.954396 | 1.003888 | 1.053074 | 1.101939 | 1.150469 | 1.198648 |
| 34   | 0.855392 | 0.905446 | 0.955224 | 1.004710 | 1.053891 | 1.102751 | 1.151275 | 1.199448 |
| 35   | 0.856229 | 0.906278 | 0.956051 | 1.005533 | 1.054708 | 1.103562 | 1.152080 | 1.200247 |
| 36   | 0.857065 | 0.907110 | 0.956878 | 1.006355 | 1.055525 | 1.104374 | 1.152886 | 1.201047 |
| 37   | 0.857901 | 0.907941 | 0.957705 | 1.007177 | 1.056342 | 1.105185 | 1.153692 | 1.201847 |
| 38   | 0.858738 | 0.908773 | 0.958532 | 1.007999 | 1.057158 | 1.105996 | 1.154497 | 1.202646 |
| 39   | 0.859574 | 0.909605 | 0.959359 | 1.008821 | 1.057975 | 1.106807 | 1.155303 | 1.203446 |
| 40   | 0.860410 | 0.910436 | 0.960186 | 1.009642 | 1.058792 | 1.107618 | 1.156108 | 1.204245 |
| 41   | 0.861246 | 0.911268 | 0.961012 | 1.010464 | 1.059608 | 1.108429 | 1.156913 | 1.205044 |
| 42   | 0.862082 | 0.912099 | 0.961839 | 1.011286 | 1.060425 | 1.109240 | 1.157718 | 1.205843 |
| 43   | 0.862917 | 0.912931 | 0.962666 | 1.012107 | 1.061241 | 1.110051 | 1.158523 | 1.206642 |
| 44   | 0.863753 | 0.913762 | 0.963492 | 1.012929 | 1.062057 | 1.110862 | 1.159328 | 1.207441 |
| 45   | 0.864589 | 0.914593 | 0.964318 | 1.013750 | 1.062873 | 1.111672 | 1.160133 | 1.208240 |
| 46   | 0.865424 | 0.915424 | 0.965145 | 1.014571 | 1.063689 | 1.112483 | 1.160938 | 1.209039 |
| 47   | 0.866260 | 0.916255 | 0.965971 | 1.015393 | 1.064505 | 1.113293 | 1.161742 | 1.209837 |
| 48   | 0.867095 | 0.917086 | 0.966797 | 1.016214 | 1.065321 | 1.114104 | 1.162547 | 1.210636 |
| 49   | 0.867931 | 0.917917 | 0.967623 | 1.017035 | 1.066137 | 1.114914 | 1.163351 | 1.211434 |
| 50   | 0.868766 | 0.918748 | 0.968449 | 1.017856 | 1.066952 | 1.115724 | 1.164156 | 1.212233 |
| 51   | 0.869601 | 0.919578 | 0.969275 | 1.018677 | 1.067768 | 1.116534 | 1.164960 | 1.213031 |
| 52   | 0.870436 | 0.920409 | 0.970101 | 1.019497 | 1.068583 | 1.117344 | 1.165764 | 1.213829 |
| 53   | 0.871272 | 0.921239 | 0.970927 | 1.020318 | 1.069399 | 1.118154 | 1.166568 | 1.214627 |
| 54   | 0.872107 | 0.922070 | 0.971752 | 1.021139 | 1.070214 | 1.118963 | 1.167372 | 1.215425 |
| 55   | 0.872941 | 0.922900 | 0.972578 | 1.021959 | 1.071029 | 1.119773 | 1.168176 | 1.216223 |
| 56   | 0.873776 | 0.923731 | 0.973403 | 1.022780 | 1.071844 | 1.120583 | 1.168979 | 1.217020 |
| 57   | 0.874611 | 0.924561 | 0.974229 | 1.023600 | 1.072659 | 1.121392 | 1.169783 | 1.217818 |
| 58   | 0.875446 | 0.925391 | 0.975054 | 1.024420 | 1.073474 | 1.122201 | 1.170587 | 1.218615 |
| 59   | 0.876281 | 0.926221 | 0.975879 | 1.025240 | 1.074289 | 1.123011 | 1.171390 | 1.219413 |
| 60   | 0.877115 | 0.927051 | 0.976704 | 1.026060 | 1.075104 | 1.123820 | 1.172193 | 1.220210 |

## Constants for Setting a 3-inch Sine-Bar for 24° to 31°

| Min. | 24°      | 25°      | 26°      | 27°      | 28°      | 29°      | 30°      | 31°      |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 1.220210 | 1.267855 | 1.315113 | 1.361971 | 1.408415 | 1.454429 | 1.500000 | 1.545114 |
| 1    | 1.221007 | 1.268646 | 1.315898 | 1.362749 | 1.409185 | 1.455192 | 1.500756 | 1.545862 |
| 2    | 1.221804 | 1.269436 | 1.316682 | 1.363526 | 1.409956 | 1.455955 | 1.501511 | 1.546610 |
| 3    | 1.222601 | 1.270227 | 1.317466 | 1.364304 | 1.410726 | 1.456718 | 1.502267 | 1.547358 |
| 4    | 1.223398 | 1.271018 | 1.318250 | 1.365081 | 1.411496 | 1.457481 | 1.503022 | 1.548105 |
| 5    | 1.224195 | 1.271808 | 1.319034 | 1.365858 | 1.412266 | 1.458244 | 1.503777 | 1.548853 |
| 6    | 1.224991 | 1.272598 | 1.319818 | 1.366635 | 1.413036 | 1.459006 | 1.504532 | 1.549600 |
| 7    | 1.225788 | 1.273389 | 1.320601 | 1.367412 | 1.413805 | 1.459769 | 1.505287 | 1.550347 |
| 8    | 1.226584 | 1.274179 | 1.321385 | 1.368188 | 1.414575 | 1.460531 | 1.506042 | 1.551094 |
| 9    | 1.227381 | 1.274969 | 1.322168 | 1.368965 | 1.415344 | 1.461293 | 1.506797 | 1.551841 |
| 10   | 1.228177 | 1.275758 | 1.322951 | 1.369741 | 1.416114 | 1.462055 | 1.507551 | 1.552588 |
| 11   | 1.228973 | 1.276548 | 1.323735 | 1.370518 | 1.416883 | 1.462817 | 1.508306 | 1.553334 |
| 12   | 1.229769 | 1.277338 | 1.324518 | 1.371294 | 1.417652 | 1.463579 | 1.509060 | 1.554081 |
| 13   | 1.230565 | 1.278127 | 1.325301 | 1.372070 | 1.418421 | 1.464341 | 1.509814 | 1.554827 |
| 14   | 1.231361 | 1.278917 | 1.326083 | 1.372846 | 1.419190 | 1.465102 | 1.510568 | 1.555574 |
| 15   | 1.232157 | 1.279706 | 1.326866 | 1.373622 | 1.419959 | 1.465864 | 1.511322 | 1.556320 |
| 16   | 1.232952 | 1.280496 | 1.327649 | 1.374398 | 1.420728 | 1.466625 | 1.512076 | 1.557066 |
| 17   | 1.233748 | 1.281285 | 1.328431 | 1.375173 | 1.421496 | 1.467386 | 1.512829 | 1.557812 |
| 18   | 1.234543 | 1.282074 | 1.329214 | 1.375949 | 1.422265 | 1.468147 | 1.513583 | 1.558557 |
| 19   | 1.235338 | 1.282863 | 1.329996 | 1.376724 | 1.423033 | 1.468908 | 1.514336 | 1.559303 |
| 20   | 1.236134 | 1.283651 | 1.330778 | 1.377499 | 1.423801 | 1.469669 | 1.515090 | 1.560048 |
| 21   | 1.236929 | 1.284440 | 1.331560 | 1.378275 | 1.424569 | 1.470430 | 1.515843 | 1.560794 |
| 22   | 1.237724 | 1.285229 | 1.332342 | 1.379050 | 1.425337 | 1.471190 | 1.516596 | 1.561539 |
| 23   | 1.238519 | 1.286017 | 1.333124 | 1.379825 | 1.426105 | 1.471951 | 1.517349 | 1.562284 |
| 24   | 1.239313 | 1.286805 | 1.333906 | 1.380599 | 1.426873 | 1.472711 | 1.518101 | 1.563029 |
| 25   | 1.240108 | 1.287594 | 1.334687 | 1.381374 | 1.427640 | 1.473472 | 1.518854 | 1.563774 |
| 26   | 1.240903 | 1.288382 | 1.335469 | 1.382149 | 1.428408 | 1.474232 | 1.519606 | 1.564518 |
| 27   | 1.241697 | 1.289170 | 1.336250 | 1.382923 | 1.429175 | 1.474992 | 1.520359 | 1.565263 |
| 28   | 1.242491 | 1.289958 | 1.337031 | 1.383698 | 1.429942 | 1.475751 | 1.521111 | 1.566007 |
| 29   | 1.243286 | 1.290746 | 1.337812 | 1.384472 | 1.430709 | 1.476511 | 1.521863 | 1.566752 |
| 30   | 1.244080 | 1.291533 | 1.338593 | 1.385246 | 1.431476 | 1.477271 | 1.522615 | 1.567496 |
| 31   | 1.244874 | 1.292321 | 1.339374 | 1.386020 | 1.432243 | 1.478030 | 1.523367 | 1.568240 |
| 32   | 1.245668 | 1.293108 | 1.340155 | 1.386794 | 1.433010 | 1.478789 | 1.524119 | 1.568984 |
| 33   | 1.246462 | 1.293896 | 1.340936 | 1.387568 | 1.433776 | 1.479549 | 1.524870 | 1.569727 |
| 34   | 1.247255 | 1.294683 | 1.341717 | 1.388341 | 1.434543 | 1.480308 | 1.525622 | 1.570471 |
| 35   | 1.248049 | 1.295470 | 1.342497 | 1.389115 | 1.435309 | 1.481067 | 1.526373 | 1.571214 |
| 36   | 1.248842 | 1.296257 | 1.343277 | 1.389888 | 1.436076 | 1.481826 | 1.527124 | 1.571958 |
| 37   | 1.249636 | 1.297044 | 1.344058 | 1.390661 | 1.436842 | 1.482584 | 1.527875 | 1.572701 |
| 38   | 1.250429 | 1.297831 | 1.344838 | 1.391435 | 1.437608 | 1.483343 | 1.528626 | 1.573444 |
| 39   | 1.251222 | 1.298618 | 1.345618 | 1.392208 | 1.438374 | 1.484101 | 1.529377 | 1.574187 |
| 40   | 1.252015 | 1.299404 | 1.346398 | 1.392981 | 1.439139 | 1.484860 | 1.530128 | 1.574930 |
| 41   | 1.252808 | 1.300191 | 1.347177 | 1.393753 | 1.439905 | 1.485618 | 1.530878 | 1.575672 |
| 42   | 1.253601 | 1.300977 | 1.347957 | 1.394526 | 1.440671 | 1.486376 | 1.531629 | 1.576415 |
| 43   | 1.254394 | 1.301764 | 1.348737 | 1.395299 | 1.441436 | 1.487134 | 1.532379 | 1.577157 |
| 44   | 1.255187 | 1.302550 | 1.349516 | 1.396071 | 1.442201 | 1.487892 | 1.533129 | 1.577900 |
| 45   | 1.255979 | 1.303336 | 1.350295 | 1.396844 | 1.442966 | 1.488650 | 1.533879 | 1.578642 |
| 46   | 1.256772 | 1.304122 | 1.351075 | 1.397616 | 1.443731 | 1.489407 | 1.534629 | 1.579384 |
| 47   | 1.257564 | 1.304908 | 1.351854 | 1.398388 | 1.444496 | 1.490165 | 1.535379 | 1.580126 |
| 48   | 1.258356 | 1.305693 | 1.352633 | 1.399160 | 1.445261 | 1.490922 | 1.536129 | 1.580867 |
| 49   | 1.259148 | 1.306479 | 1.353412 | 1.399932 | 1.446026 | 1.491679 | 1.536878 | 1.581609 |
| 50   | 1.259941 | 1.307264 | 1.354190 | 1.400704 | 1.446790 | 1.492436 | 1.537628 | 1.582350 |
| 51   | 1.260732 | 1.308050 | 1.354969 | 1.401475 | 1.447555 | 1.493193 | 1.538377 | 1.583092 |
| 52   | 1.261524 | 1.308835 | 1.355747 | 1.402247 | 1.448319 | 1.493950 | 1.539126 | 1.583833 |
| 53   | 1.262316 | 1.309620 | 1.356526 | 1.403018 | 1.449083 | 1.494707 | 1.539875 | 1.584574 |
| 54   | 1.263107 | 1.310405 | 1.357304 | 1.403790 | 1.449847 | 1.495463 | 1.540624 | 1.585315 |
| 55   | 1.263899 | 1.311190 | 1.358082 | 1.404561 | 1.450611 | 1.496220 | 1.541373 | 1.586056 |
| 56   | 1.264690 | 1.311975 | 1.358860 | 1.405332 | 1.451375 | 1.496976 | 1.542121 | 1.586797 |
| 57   | 1.265482 | 1.312760 | 1.359638 | 1.406103 | 1.452139 | 1.497732 | 1.542870 | 1.587537 |
| 58   | 1.266273 | 1.313545 | 1.360416 | 1.406873 | 1.452902 | 1.498488 | 1.543618 | 1.588277 |
| 59   | 1.267064 | 1.314329 | 1.361194 | 1.407644 | 1.453666 | 1.499244 | 1.544366 | 1.589018 |
| 60   | 1.267855 | 1.315113 | 1.361971 | 1.408415 | 1.454429 | 1.500000 | 1.545114 | 1.589758 |

## SINE BAR CONSTANTS

## Constants for Setting a 3-inch Sine-Bar for 32° to 39°

| Min. | 32°      | 33°      | 34°      | 35°      | 36°      | 37°      | 38°      | 39°      |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 1.589758 | 1.633917 | 1.677579 | 1.720729 | 1.763356 | 1.805445 | 1.846985 | 1.887961 |
| 1    | 1.590498 | 1.634649 | 1.678302 | 1.721444 | 1.764062 | 1.806142 | 1.847672 | 1.888639 |
| 2    | 1.591238 | 1.635381 | 1.679025 | 1.722159 | 1.764768 | 1.806839 | 1.848359 | 1.889317 |
| 3    | 1.591977 | 1.636112 | 1.679749 | 1.722873 | 1.765473 | 1.807535 | 1.849047 | 1.889995 |
| 4    | 1.592717 | 1.636844 | 1.680471 | 1.723588 | 1.766179 | 1.808232 | 1.849734 | 1.890673 |
| 5    | 1.593456 | 1.637575 | 1.681194 | 1.724302 | 1.766884 | 1.808928 | 1.850421 | 1.891350 |
| 6    | 1.594196 | 1.638306 | 1.681917 | 1.725016 | 1.767589 | 1.809624 | 1.851108 | 1.892027 |
| 7    | 1.594935 | 1.639037 | 1.682639 | 1.725730 | 1.768294 | 1.810320 | 1.851794 | 1.892704 |
| 8    | 1.595674 | 1.639768 | 1.683362 | 1.726444 | 1.768999 | 1.811016 | 1.852481 | 1.893382 |
| 9    | 1.596413 | 1.640499 | 1.684084 | 1.727157 | 1.769704 | 1.811711 | 1.853167 | 1.894058 |
| 10   | 1.597152 | 1.641229 | 1.684806 | 1.727871 | 1.770408 | 1.812407 | 1.853853 | 1.894735 |
| 11   | 1.597890 | 1.641959 | 1.685528 | 1.728584 | 1.771113 | 1.813102 | 1.854539 | 1.895412 |
| 12   | 1.598629 | 1.642690 | 1.686250 | 1.729297 | 1.771817 | 1.813797 | 1.855225 | 1.896088 |
| 13   | 1.599367 | 1.643420 | 1.686972 | 1.730010 | 1.772521 | 1.814492 | 1.855911 | 1.896764 |
| 14   | 1.600106 | 1.644150 | 1.687693 | 1.730723 | 1.773225 | 1.815187 | 1.856596 | 1.897440 |
| 15   | 1.600844 | 1.644880 | 1.688415 | 1.731436 | 1.773929 | 1.815882 | 1.857282 | 1.898116 |
| 16   | 1.601582 | 1.645609 | 1.689136 | 1.732148 | 1.774633 | 1.816577 | 1.857967 | 1.898792 |
| 17   | 1.602319 | 1.646339 | 1.689857 | 1.732861 | 1.775336 | 1.817271 | 1.858652 | 1.899467 |
| 18   | 1.603057 | 1.647069 | 1.690578 | 1.733573 | 1.776040 | 1.817965 | 1.859337 | 1.900143 |
| 19   | 1.603795 | 1.647798 | 1.691299 | 1.734285 | 1.776743 | 1.818659 | 1.860022 | 1.900818 |
| 20   | 1.604532 | 1.648527 | 1.692020 | 1.734997 | 1.777446 | 1.819353 | 1.860706 | 1.901493 |
| 21   | 1.605269 | 1.649256 | 1.692740 | 1.735709 | 1.778149 | 1.820047 | 1.861391 | 1.902168 |
| 22   | 1.606007 | 1.649985 | 1.693461 | 1.736421 | 1.778852 | 1.820741 | 1.862075 | 1.902843 |
| 23   | 1.606744 | 1.650714 | 1.694181 | 1.737132 | 1.779554 | 1.821434 | 1.862759 | 1.903517 |
| 24   | 1.607481 | 1.651442 | 1.694901 | 1.737844 | 1.780257 | 1.822128 | 1.863443 | 1.904192 |
| 25   | 1.608217 | 1.652171 | 1.695621 | 1.738555 | 1.780959 | 1.822821 | 1.864127 | 1.904866 |
| 26   | 1.608954 | 1.652899 | 1.696341 | 1.739266 | 1.781661 | 1.823514 | 1.864811 | 1.905540 |
| 27   | 1.609690 | 1.653627 | 1.697061 | 1.739977 | 1.782363 | 1.824207 | 1.865494 | 1.906214 |
| 28   | 1.610427 | 1.654355 | 1.697780 | 1.740688 | 1.783065 | 1.824899 | 1.866178 | 1.906888 |
| 29   | 1.611163 | 1.655083 | 1.698500 | 1.741398 | 1.783767 | 1.825592 | 1.866861 | 1.907561 |
| 30   | 1.611899 | 1.655811 | 1.699219 | 1.742109 | 1.784468 | 1.826284 | 1.867544 | 1.908235 |
| 31   | 1.612635 | 1.656539 | 1.699938 | 1.742819 | 1.785170 | 1.826977 | 1.868227 | 1.908908 |
| 32   | 1.613371 | 1.657266 | 1.700657 | 1.743529 | 1.785871 | 1.827669 | 1.868909 | 1.909581 |
| 33   | 1.614106 | 1.657993 | 1.701376 | 1.744240 | 1.786572 | 1.828361 | 1.869592 | 1.910254 |
| 34   | 1.614842 | 1.658721 | 1.702094 | 1.744949 | 1.787273 | 1.829052 | 1.870274 | 1.910927 |
| 35   | 1.615577 | 1.659448 | 1.702813 | 1.745659 | 1.787974 | 1.829744 | 1.870957 | 1.911600 |
| 36   | 1.616312 | 1.660175 | 1.703531 | 1.746369 | 1.788675 | 1.830436 | 1.871639 | 1.912272 |
| 37   | 1.617047 | 1.660901 | 1.704250 | 1.747078 | 1.789375 | 1.831127 | 1.872321 | 1.912944 |
| 38   | 1.617783 | 1.661628 | 1.704968 | 1.747788 | 1.790076 | 1.831818 | 1.873003 | 1.913617 |
| 39   | 1.618517 | 1.662355 | 1.705686 | 1.748497 | 1.790776 | 1.832509 | 1.873684 | 1.914289 |
| 40   | 1.619252 | 1.663081 | 1.706403 | 1.749206 | 1.791476 | 1.833200 | 1.874366 | 1.914960 |
| 41   | 1.619987 | 1.663807 | 1.707121 | 1.749915 | 1.792176 | 1.833891 | 1.875047 | 1.915632 |
| 42   | 1.620721 | 1.664533 | 1.707839 | 1.750624 | 1.792876 | 1.834581 | 1.875728 | 1.916304 |
| 43   | 1.621455 | 1.665259 | 1.708556 | 1.751332 | 1.793575 | 1.835272 | 1.876409 | 1.916975 |
| 44   | 1.622189 | 1.665985 | 1.709273 | 1.752041 | 1.794275 | 1.835962 | 1.877090 | 1.917646 |
| 45   | 1.622923 | 1.666711 | 1.709990 | 1.752749 | 1.794974 | 1.836652 | 1.877770 | 1.918317 |
| 46   | 1.623657 | 1.667436 | 1.710707 | 1.753457 | 1.795673 | 1.837342 | 1.878451 | 1.918988 |
| 47   | 1.624391 | 1.668162 | 1.711424 | 1.754165 | 1.796372 | 1.838032 | 1.879131 | 1.919659 |
| 48   | 1.625125 | 1.668887 | 1.712141 | 1.754873 | 1.797071 | 1.838721 | 1.879811 | 1.920329 |
| 49   | 1.625858 | 1.669612 | 1.712857 | 1.755581 | 1.797770 | 1.839411 | 1.880491 | 1.921000 |
| 50   | 1.626591 | 1.670337 | 1.713574 | 1.756288 | 1.798468 | 1.840100 | 1.881171 | 1.921670 |
| 51   | 1.627325 | 1.671062 | 1.714290 | 1.756996 | 1.799166 | 1.840789 | 1.881851 | 1.922340 |
| 52   | 1.628058 | 1.671786 | 1.715006 | 1.757703 | 1.799865 | 1.841478 | 1.882531 | 1.923010 |
| 53   | 1.628791 | 1.672511 | 1.715722 | 1.758410 | 1.800563 | 1.842167 | 1.883210 | 1.923679 |
| 54   | 1.629524 | 1.673235 | 1.716438 | 1.759117 | 1.801261 | 1.842856 | 1.883889 | 1.924349 |
| 55   | 1.630256 | 1.673960 | 1.717153 | 1.759824 | 1.801959 | 1.843544 | 1.884568 | 1.925018 |
| 56   | 1.630989 | 1.674684 | 1.717869 | 1.760531 | 1.802656 | 1.844233 | 1.885247 | 1.925688 |
| 57   | 1.631721 | 1.675408 | 1.718584 | 1.761237 | 1.803354 | 1.844921 | 1.885926 | 1.926357 |
| 58   | 1.632453 | 1.676131 | 1.719299 | 1.761944 | 1.804051 | 1.845609 | 1.886605 | 1.927026 |
| 59   | 1.633185 | 1.676855 | 1.720014 | 1.762650 | 1.804748 | 1.846297 | 1.887283 | 1.927694 |
| 60   | 1.633917 | 1.677579 | 1.720729 | 1.763356 | 1.805445 | 1.846985 | 1.887961 | 1.928363 |

## Constants for Setting a 3-inch Sine-Bar for 40° to 47°

| Min. | 40°      | 41°      | 42°      | 43°      | 44°      | 45°      | 46°      | 47°      |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 1.928363 | 1.968177 | 2.007392 | 2.045995 | 2.083975 | 2.121320 | 2.158020 | 2.194061 |
| 1    | 1.929031 | 1.968836 | 2.008040 | 2.046633 | 2.084603 | 2.121937 | 2.158626 | 2.194656 |
| 2    | 1.929700 | 1.969494 | 2.008688 | 2.047271 | 2.085230 | 2.122554 | 2.159231 | 2.195251 |
| 3    | 1.930368 | 1.970152 | 2.009337 | 2.047909 | 2.085858 | 2.123171 | 2.159837 | 2.195846 |
| 4    | 1.931036 | 1.970810 | 2.009984 | 2.048547 | 2.086485 | 2.123787 | 2.160443 | 2.196440 |
| 5    | 1.931703 | 1.971468 | 2.010632 | 2.049184 | 2.087112 | 2.124403 | 2.161048 | 2.197035 |
| 6    | 1.932371 | 1.972126 | 2.011280 | 2.049821 | 2.087738 | 2.125020 | 2.161653 | 2.197629 |
| 7    | 1.933038 | 1.972783 | 2.011927 | 2.050458 | 2.088365 | 2.125635 | 2.162258 | 2.198223 |
| 8    | 1.933706 | 1.973441 | 2.012575 | 2.051095 | 2.088991 | 2.126251 | 2.162863 | 2.198817 |
| 9    | 1.934373 | 1.974098 | 2.013222 | 2.051732 | 2.089618 | 2.126867 | 2.163468 | 2.199410 |
| 10   | 1.935040 | 1.974755 | 2.013869 | 2.052369 | 2.090244 | 2.127482 | 2.164072 | 2.200003 |
| 11   | 1.935706 | 1.975412 | 2.014515 | 2.053005 | 2.090870 | 2.128097 | 2.164677 | 2.200597 |
| 12   | 1.936373 | 1.976068 | 2.015162 | 2.053641 | 2.091495 | 2.128712 | 2.165281 | 2.201190 |
| 13   | 1.937040 | 1.976725 | 2.015808 | 2.054277 | 2.092121 | 2.129327 | 2.165885 | 2.201782 |
| 14   | 1.937706 | 1.977381 | 2.016454 | 2.054913 | 2.092746 | 2.129942 | 2.166488 | 2.202375 |
| 15   | 1.938372 | 1.978037 | 2.017101 | 2.055549 | 2.093371 | 2.130556 | 2.167092 | 2.202968 |
| 16   | 1.939038 | 1.978693 | 2.017746 | 2.056185 | 2.093997 | 2.131171 | 2.167695 | 2.203560 |
| 17   | 1.939704 | 1.979349 | 2.018392 | 2.056820 | 2.094621 | 2.131784 | 2.168298 | 2.204152 |
| 18   | 1.940369 | 1.980005 | 2.019037 | 2.057455 | 2.095246 | 2.132398 | 2.168901 | 2.204744 |
| 19   | 1.941035 | 1.980661 | 2.019683 | 2.058090 | 2.095870 | 2.133012 | 2.169504 | 2.205336 |
| 20   | 1.941700 | 1.981316 | 2.020328 | 2.058725 | 2.096495 | 2.133626 | 2.170107 | 2.205927 |
| 21   | 1.942365 | 1.981971 | 2.020973 | 2.059360 | 2.097119 | 2.134239 | 2.170709 | 2.206518 |
| 22   | 1.943030 | 1.982626 | 2.021618 | 2.059994 | 2.097743 | 2.134852 | 2.171312 | 2.207109 |
| 23   | 1.943695 | 1.983281 | 2.022263 | 2.060628 | 2.098366 | 2.135465 | 2.171914 | 2.207700 |
| 24   | 1.944360 | 1.983936 | 2.022907 | 2.061263 | 2.098990 | 2.136078 | 2.172516 | 2.208291 |
| 25   | 1.945024 | 1.984590 | 2.023552 | 2.061897 | 2.099613 | 2.136691 | 2.173117 | 2.208882 |
| 26   | 1.945689 | 1.985245 | 2.024196 | 2.062530 | 2.100237 | 2.137303 | 2.173719 | 2.209472 |
| 27   | 1.946353 | 1.985899 | 2.024840 | 2.063164 | 2.100860 | 2.137916 | 2.174320 | 2.210063 |
| 28   | 1.947017 | 1.986553 | 2.025484 | 2.063797 | 2.101483 | 2.138528 | 2.174922 | 2.210653 |
| 29   | 1.947681 | 1.987207 | 2.026127 | 2.064431 | 2.102105 | 2.139140 | 2.175522 | 2.211242 |
| 30   | 1.948344 | 1.987860 | 2.026771 | 2.065064 | 2.102728 | 2.139751 | 2.176123 | 2.211832 |
| 31   | 1.949008 | 1.988514 | 2.027414 | 2.065697 | 2.103350 | 2.140363 | 2.176724 | 2.212421 |
| 32   | 1.949671 | 1.989167 | 2.028057 | 2.066329 | 2.103972 | 2.140974 | 2.177324 | 2.213011 |
| 33   | 1.950334 | 1.989820 | 2.028700 | 2.066962 | 2.104594 | 2.141586 | 2.177924 | 2.213600 |
| 34   | 1.950997 | 1.990473 | 2.029343 | 2.067594 | 2.105216 | 2.142197 | 2.178524 | 2.214189 |
| 35   | 1.951660 | 1.991126 | 2.029985 | 2.068227 | 2.105838 | 2.142807 | 2.179124 | 2.214777 |
| 36   | 1.952323 | 1.991779 | 2.030628 | 2.068859 | 2.106459 | 2.143418 | 2.179724 | 2.215366 |
| 37   | 1.952985 | 1.992431 | 2.031270 | 2.069490 | 2.107080 | 2.144028 | 2.180324 | 2.215954 |
| 38   | 1.953648 | 1.993084 | 2.031912 | 2.070122 | 2.107702 | 2.144639 | 2.180923 | 2.216543 |
| 39   | 1.954310 | 1.993736 | 2.032554 | 2.070754 | 2.108323 | 2.145249 | 2.181522 | 2.217131 |
| 40   | 1.954972 | 1.994388 | 2.033196 | 2.071385 | 2.108943 | 2.145859 | 2.182121 | 2.217718 |
| 41   | 1.955634 | 1.995039 | 2.033838 | 2.072016 | 2.109564 | 2.146469 | 2.182720 | 2.218306 |
| 42   | 1.956295 | 1.995691 | 2.034479 | 2.072647 | 2.110184 | 2.147078 | 2.183318 | 2.218893 |
| 43   | 1.956957 | 1.996343 | 2.035120 | 2.073278 | 2.110804 | 2.147688 | 2.183917 | 2.219481 |
| 44   | 1.957618 | 1.996994 | 2.035761 | 2.073909 | 2.111424 | 2.148297 | 2.184515 | 2.220068 |
| 45   | 1.958279 | 1.997645 | 2.036402 | 2.074539 | 2.112044 | 2.148906 | 2.185113 | 2.220654 |
| 46   | 1.958940 | 1.998296 | 2.037043 | 2.075170 | 2.112664 | 2.149515 | 2.185711 | 2.221241 |
| 47   | 1.959601 | 1.998947 | 2.037683 | 2.075800 | 2.113283 | 2.150123 | 2.186308 | 2.221828 |
| 48   | 1.960262 | 1.999597 | 2.038324 | 2.076430 | 2.113903 | 2.150732 | 2.186906 | 2.222414 |
| 49   | 1.960922 | 2.000248 | 2.038964 | 2.077059 | 2.114522 | 2.151340 | 2.187503 | 2.223000 |
| 50   | 1.961583 | 2.000898 | 2.039604 | 2.077689 | 2.115141 | 2.151948 | 2.188100 | 2.223586 |
| 51   | 1.962243 | 2.001548 | 2.040244 | 2.078318 | 2.115759 | 2.152556 | 2.188697 | 2.224171 |
| 52   | 1.962903 | 2.002198 | 2.040884 | 2.078948 | 2.116378 | 2.153164 | 2.189294 | 2.224757 |
| 53   | 1.963563 | 2.002848 | 2.041523 | 2.079577 | 2.116997 | 2.153772 | 2.189891 | 2.225343 |
| 54   | 1.964223 | 2.003498 | 2.042163 | 2.080206 | 2.117615 | 2.154379 | 2.190487 | 2.225928 |
| 55   | 1.964882 | 2.004147 | 2.042802 | 2.080834 | 2.118233 | 2.154986 | 2.191083 | 2.226513 |
| 56   | 1.965541 | 2.004797 | 2.043441 | 2.081463 | 2.118851 | 2.155593 | 2.191679 | 2.227097 |
| 57   | 1.966201 | 2.005445 | 2.044080 | 2.082091 | 2.119468 | 2.156200 | 2.192275 | 2.227682 |
| 58   | 1.966860 | 2.006094 | 2.044718 | 2.082719 | 2.120086 | 2.156807 | 2.192870 | 2.228266 |
| 59   | 1.967518 | 2.006743 | 2.045357 | 2.083347 | 2.120703 | 2.157413 | 2.193466 | 2.228851 |
| 60   | 1.968177 | 2.007392 | 2.045995 | 2.083975 | 2.121320 | 2.158020 | 2.194061 | 2.229434 |



## SINE BAR CONSTANTS

## Constants for Setting a 3-inch Sine-Bar for 48° to 55°

| Min. | 48°      | 49°      | 50°      | 51°      | 52°      | 53°      | 54°      | 55°      |
|------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0    | 2.229434 | 2.264129 | 2.298133 | 2.331438 | 2.364032 | 2.395907 | 2.427051 | 2.457456 |
| 1    | 2.230018 | 2.264701 | 2.298694 | 2.331987 | 2.364569 | 2.396432 | 2.427564 | 2.457957 |
| 2    | 2.230602 | 2.265273 | 2.299255 | 2.332536 | 2.365106 | 2.396956 | 2.428077 | 2.458457 |
| 3    | 2.231185 | 2.265846 | 2.299815 | 2.333085 | 2.365643 | 2.397481 | 2.428589 | 2.458957 |
| 4    | 2.231769 | 2.266417 | 2.300375 | 2.333633 | 2.366180 | 2.398006 | 2.429101 | 2.459457 |
| 5    | 2.232352 | 2.266989 | 2.300936 | 2.334181 | 2.366716 | 2.398530 | 2.429613 | 2.459956 |
| 6    | 2.232935 | 2.267560 | 2.301496 | 2.334729 | 2.367252 | 2.399054 | 2.430125 | 2.460456 |
| 7    | 2.233517 | 2.268132 | 2.302055 | 2.335277 | 2.367788 | 2.399578 | 2.430636 | 2.460955 |
| 8    | 2.234100 | 2.268703 | 2.302615 | 2.335825 | 2.368324 | 2.400102 | 2.431148 | 2.461454 |
| 9    | 2.234682 | 2.269274 | 2.303174 | 2.336373 | 2.368860 | 2.400625 | 2.431659 | 2.461953 |
| 10   | 2.235264 | 2.269845 | 2.303733 | 2.336920 | 2.369395 | 2.401148 | 2.432170 | 2.462451 |
| 11   | 2.235846 | 2.270415 | 2.304292 | 2.337467 | 2.369930 | 2.401671 | 2.432681 | 2.462950 |
| 12   | 2.236428 | 2.270985 | 2.304851 | 2.338014 | 2.370465 | 2.402194 | 2.433192 | 2.463448 |
| 13   | 2.237010 | 2.271555 | 2.305409 | 2.338561 | 2.371000 | 2.402717 | 2.433702 | 2.463946 |
| 14   | 2.237591 | 2.272125 | 2.305967 | 2.339107 | 2.371534 | 2.403239 | 2.434212 | 2.464443 |
| 15   | 2.238172 | 2.272695 | 2.306525 | 2.339653 | 2.372069 | 2.403761 | 2.434722 | 2.464941 |
| 16   | 2.238753 | 2.273265 | 2.307083 | 2.340200 | 2.372603 | 2.404284 | 2.435232 | 2.465438 |
| 17   | 2.239334 | 2.273834 | 2.307641 | 2.340745 | 2.373137 | 2.404805 | 2.435741 | 2.465935 |
| 18   | 2.239915 | 2.274403 | 2.308199 | 2.341291 | 2.373671 | 2.405327 | 2.436251 | 2.466432 |
| 19   | 2.240495 | 2.274972 | 2.308756 | 2.341837 | 2.374204 | 2.405848 | 2.436760 | 2.466929 |
| 20   | 2.241075 | 2.275541 | 2.309313 | 2.342382 | 2.374738 | 2.406370 | 2.437269 | 2.467425 |
| 21   | 2.241655 | 2.276109 | 2.309870 | 2.342927 | 2.375271 | 2.406891 | 2.437777 | 2.467921 |
| 22   | 2.242235 | 2.276678 | 2.310427 | 2.343472 | 2.375804 | 2.407411 | 2.438286 | 2.468418 |
| 23   | 2.242815 | 2.277246 | 2.310983 | 2.344017 | 2.376337 | 2.407932 | 2.438794 | 2.468914 |
| 24   | 2.243394 | 2.277814 | 2.311540 | 2.344562 | 2.376869 | 2.408453 | 2.439302 | 2.469409 |
| 25   | 2.243974 | 2.278382 | 2.312096 | 2.345106 | 2.377401 | 2.408973 | 2.439810 | 2.469905 |
| 26   | 2.244553 | 2.278949 | 2.312652 | 2.345650 | 2.377934 | 2.409493 | 2.440318 | 2.470400 |
| 27   | 2.245132 | 2.279517 | 2.313208 | 2.346194 | 2.378465 | 2.410012 | 2.440825 | 2.470895 |
| 28   | 2.245710 | 2.280084 | 2.313763 | 2.346738 | 2.378997 | 2.410532 | 2.441333 | 2.471390 |
| 29   | 2.246289 | 2.280651 | 2.314319 | 2.347281 | 2.379529 | 2.411052 | 2.441840 | 2.471884 |
| 30   | 2.246867 | 2.281218 | 2.314874 | 2.347825 | 2.380060 | 2.411571 | 2.442347 | 2.472379 |
| 31   | 2.247445 | 2.281785 | 2.315429 | 2.348368 | 2.380591 | 2.412090 | 2.442853 | 2.472873 |
| 32   | 2.248023 | 2.282351 | 2.315984 | 2.348911 | 2.381122 | 2.412608 | 2.443360 | 2.473367 |
| 33   | 2.248601 | 2.282917 | 2.316538 | 2.349453 | 2.381653 | 2.413127 | 2.443866 | 2.473861 |
| 34   | 2.249179 | 2.283483 | 2.317092 | 2.349996 | 2.382183 | 2.413645 | 2.444372 | 2.474354 |
| 35   | 2.249756 | 2.284049 | 2.317647 | 2.350538 | 2.382714 | 2.414161 | 2.444878 | 2.474847 |
| 36   | 2.250333 | 2.284615 | 2.318201 | 2.351080 | 2.383244 | 2.414681 | 2.445383 | 2.475341 |
| 37   | 2.250910 | 2.285180 | 2.318754 | 2.351622 | 2.383774 | 2.415199 | 2.445889 | 2.475833 |
| 38   | 2.251487 | 2.285746 | 2.319308 | 2.352164 | 2.384304 | 2.415717 | 2.446394 | 2.476326 |
| 39   | 2.252064 | 2.286311 | 2.319862 | 2.352706 | 2.384833 | 2.416234 | 2.446899 | 2.476819 |
| 40   | 2.252640 | 2.286876 | 2.320415 | 2.353247 | 2.385362 | 2.416751 | 2.447404 | 2.477311 |
| 41   | 2.253217 | 2.287441 | 2.320968 | 2.353788 | 2.385892 | 2.417268 | 2.447908 | 2.477803 |
| 42   | 2.253793 | 2.288005 | 2.321521 | 2.354329 | 2.386420 | 2.417785 | 2.448413 | 2.478295 |
| 43   | 2.254368 | 2.288569 | 2.322073 | 2.354870 | 2.386949 | 2.418301 | 2.448917 | 2.478787 |
| 44   | 2.254944 | 2.289134 | 2.322626 | 2.355411 | 2.387478 | 2.418818 | 2.449421 | 2.479278 |
| 45   | 2.255519 | 2.289697 | 2.323178 | 2.355951 | 2.388006 | 2.419334 | 2.449925 | 2.479769 |
| 46   | 2.256095 | 2.290261 | 2.323730 | 2.356491 | 2.388534 | 2.419850 | 2.450428 | 2.480260 |
| 47   | 2.256670 | 2.290825 | 2.324282 | 2.357031 | 2.389062 | 2.420366 | 2.450932 | 2.480751 |
| 48   | 2.257245 | 2.291388 | 2.324833 | 2.357571 | 2.389590 | 2.420881 | 2.451435 | 2.481242 |
| 49   | 2.257819 | 2.291951 | 2.325385 | 2.358110 | 2.390117 | 2.421396 | 2.451938 | 2.481732 |
| 50   | 2.258394 | 2.292514 | 2.325936 | 2.358650 | 2.390645 | 2.421911 | 2.452440 | 2.482222 |
| 51   | 2.258968 | 2.293077 | 2.326487 | 2.359189 | 2.391172 | 2.422426 | 2.452943 | 2.482712 |
| 52   | 2.259542 | 2.293640 | 2.327038 | 2.359728 | 2.391699 | 2.422941 | 2.453445 | 2.483202 |
| 53   | 2.260117 | 2.294202 | 2.327589 | 2.360267 | 2.392226 | 2.423455 | 2.453947 | 2.483692 |
| 54   | 2.260690 | 2.294764 | 2.328139 | 2.360805 | 2.392752 | 2.423970 | 2.454449 | 2.484181 |
| 55   | 2.261264 | 2.295326 | 2.328690 | 2.361344 | 2.393278 | 2.424484 | 2.454951 | 2.484670 |
| 56   | 2.261837 | 2.295888 | 2.329240 | 2.361882 | 2.393804 | 2.424998 | 2.455452 | 2.485159 |
| 57   | 2.262410 | 2.296450 | 2.329789 | 2.362420 | 2.394330 | 2.425511 | 2.455954 | 2.485648 |
| 58   | 2.262983 | 2.297011 | 2.330339 | 2.362957 | 2.394856 | 2.426025 | 2.456455 | 2.486136 |
| 59   | 2.263556 | 2.297572 | 2.330889 | 2.363495 | 2.395381 | 2.426538 | 2.456955 | 2.486625 |
| 60   | 2.264129 | 2.298133 | 2.331438 | 2.364032 | 2.395907 | 2.427051 | 2.457456 | 2.487113 |

## SINE BAR CONSTANTS

## Constants for 5-inch Sine-Bar

## Constants for Setting a 5-inch Sine-Bar for 1° to 7°

| Min. | 0°      | 1°      | 2°      | 3°      | 4°      | 5°      | 6°      | 7°      |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 0.00000 | 0.08726 | 0.17450 | 0.26168 | 0.34878 | 0.43578 | 0.52264 | 0.60935 |
| 1    | 0.00145 | 0.08872 | 0.17595 | 0.26313 | 0.35023 | 0.43723 | 0.52409 | 0.61079 |
| 2    | 0.00291 | 0.09017 | 0.17740 | 0.26458 | 0.35168 | 0.43868 | 0.52554 | 0.61223 |
| 3    | 0.00436 | 0.09162 | 0.17886 | 0.26604 | 0.35313 | 0.44013 | 0.52698 | 0.61368 |
| 4    | 0.00582 | 0.09308 | 0.18031 | 0.26749 | 0.35459 | 0.44157 | 0.52843 | 0.61512 |
| 5    | 0.00727 | 0.09453 | 0.18177 | 0.26894 | 0.35604 | 0.44302 | 0.52987 | 0.61656 |
| 6    | 0.00873 | 0.09599 | 0.18322 | 0.27039 | 0.35749 | 0.44447 | 0.53132 | 0.61801 |
| 7    | 0.01018 | 0.09744 | 0.18467 | 0.27185 | 0.35894 | 0.44592 | 0.53277 | 0.61945 |
| 8    | 0.01164 | 0.09890 | 0.18613 | 0.27330 | 0.36039 | 0.44737 | 0.53421 | 0.62089 |
| 9    | 0.01309 | 0.10035 | 0.18758 | 0.27475 | 0.36184 | 0.44882 | 0.53566 | 0.62234 |
| 10   | 0.01454 | 0.10180 | 0.18903 | 0.27620 | 0.36329 | 0.45027 | 0.53710 | 0.62378 |
| 11   | 0.01600 | 0.10326 | 0.19049 | 0.27766 | 0.36474 | 0.45171 | 0.53855 | 0.62522 |
| 12   | 0.01745 | 0.10471 | 0.19194 | 0.27911 | 0.36619 | 0.45316 | 0.54000 | 0.62667 |
| 13   | 0.01891 | 0.10617 | 0.19339 | 0.28056 | 0.36764 | 0.45461 | 0.54144 | 0.62811 |
| 14   | 0.02036 | 0.10762 | 0.19485 | 0.28201 | 0.36909 | 0.45606 | 0.54289 | 0.62955 |
| 15   | 0.02182 | 0.10907 | 0.19630 | 0.28346 | 0.37054 | 0.45751 | 0.54433 | 0.63099 |
| 16   | 0.02327 | 0.11053 | 0.19775 | 0.28492 | 0.37199 | 0.45896 | 0.54578 | 0.63244 |
| 17   | 0.02473 | 0.11198 | 0.19921 | 0.28637 | 0.37344 | 0.46040 | 0.54723 | 0.63388 |
| 18   | 0.02618 | 0.11344 | 0.20066 | 0.28782 | 0.37489 | 0.46185 | 0.54867 | 0.63532 |
| 19   | 0.02763 | 0.11489 | 0.20211 | 0.28927 | 0.37634 | 0.46330 | 0.55012 | 0.63677 |
| 20   | 0.02909 | 0.11634 | 0.20357 | 0.29072 | 0.37779 | 0.46475 | 0.55156 | 0.63821 |
| 21   | 0.03054 | 0.11780 | 0.20502 | 0.29218 | 0.37924 | 0.46620 | 0.55301 | 0.63965 |
| 22   | 0.03200 | 0.11925 | 0.20647 | 0.29363 | 0.38069 | 0.46765 | 0.55445 | 0.64109 |
| 23   | 0.03345 | 0.12071 | 0.20793 | 0.29508 | 0.38214 | 0.46909 | 0.55590 | 0.64254 |
| 24   | 0.03491 | 0.12216 | 0.20938 | 0.29653 | 0.38360 | 0.47054 | 0.55734 | 0.64398 |
| 25   | 0.03636 | 0.12361 | 0.21083 | 0.29798 | 0.38505 | 0.47199 | 0.55879 | 0.64542 |
| 26   | 0.03782 | 0.12507 | 0.21228 | 0.29944 | 0.38650 | 0.47344 | 0.56024 | 0.64686 |
| 27   | 0.03927 | 0.12652 | 0.21374 | 0.30089 | 0.38795 | 0.47489 | 0.56168 | 0.64830 |
| 28   | 0.04072 | 0.12798 | 0.21519 | 0.30234 | 0.38940 | 0.47633 | 0.56313 | 0.64975 |
| 29   | 0.04218 | 0.12943 | 0.21664 | 0.30379 | 0.39085 | 0.47778 | 0.56457 | 0.65119 |
| 30   | 0.04363 | 0.13088 | 0.21810 | 0.30524 | 0.39230 | 0.47923 | 0.56602 | 0.65263 |
| 31   | 0.04509 | 0.13234 | 0.21955 | 0.30669 | 0.39375 | 0.48068 | 0.56746 | 0.65407 |
| 32   | 0.04654 | 0.13379 | 0.22100 | 0.30815 | 0.39520 | 0.48212 | 0.56891 | 0.65551 |
| 33   | 0.04800 | 0.13525 | 0.22246 | 0.30960 | 0.39665 | 0.48357 | 0.57035 | 0.65696 |
| 34   | 0.04945 | 0.13670 | 0.22391 | 0.31105 | 0.39810 | 0.48502 | 0.57180 | 0.65840 |
| 35   | 0.05090 | 0.13815 | 0.22536 | 0.31250 | 0.39954 | 0.48647 | 0.57324 | 0.65984 |
| 36   | 0.05236 | 0.13961 | 0.22681 | 0.31395 | 0.40099 | 0.48791 | 0.57469 | 0.66128 |
| 37   | 0.05381 | 0.14106 | 0.22827 | 0.31540 | 0.40244 | 0.48936 | 0.57613 | 0.66272 |
| 38   | 0.05527 | 0.14252 | 0.22972 | 0.31686 | 0.40389 | 0.49081 | 0.57758 | 0.66417 |
| 39   | 0.05672 | 0.14397 | 0.23117 | 0.31831 | 0.40534 | 0.49226 | 0.57902 | 0.66561 |
| 40   | 0.05818 | 0.14542 | 0.23263 | 0.31976 | 0.40679 | 0.49370 | 0.58046 | 0.66705 |
| 41   | 0.05963 | 0.14688 | 0.23408 | 0.32121 | 0.40824 | 0.49515 | 0.58191 | 0.66849 |
| 42   | 0.06109 | 0.14833 | 0.23553 | 0.32266 | 0.40969 | 0.49660 | 0.58335 | 0.66993 |
| 43   | 0.06254 | 0.14979 | 0.23699 | 0.32411 | 0.41114 | 0.49805 | 0.58480 | 0.67137 |
| 44   | 0.06399 | 0.15124 | 0.23844 | 0.32556 | 0.41259 | 0.49949 | 0.58624 | 0.67281 |
| 45   | 0.06545 | 0.15269 | 0.23989 | 0.32702 | 0.41404 | 0.50094 | 0.58769 | 0.67425 |
| 46   | 0.06690 | 0.15415 | 0.24134 | 0.32847 | 0.41549 | 0.50239 | 0.58913 | 0.67570 |
| 47   | 0.06836 | 0.15560 | 0.24280 | 0.32992 | 0.41694 | 0.50383 | 0.59058 | 0.67714 |
| 48   | 0.06981 | 0.15705 | 0.24425 | 0.33137 | 0.41839 | 0.50528 | 0.59202 | 0.67858 |
| 49   | 0.07127 | 0.15851 | 0.24570 | 0.33282 | 0.41984 | 0.50673 | 0.59346 | 0.68002 |
| 50   | 0.07272 | 0.15996 | 0.24715 | 0.33427 | 0.42129 | 0.50818 | 0.59491 | 0.68146 |
| 51   | 0.07417 | 0.16141 | 0.24861 | 0.33572 | 0.42274 | 0.50962 | 0.59635 | 0.68290 |
| 52   | 0.07563 | 0.16287 | 0.25006 | 0.33717 | 0.42419 | 0.51107 | 0.59780 | 0.68434 |
| 53   | 0.07708 | 0.16432 | 0.25151 | 0.33863 | 0.42564 | 0.51252 | 0.59924 | 0.68578 |
| 54   | 0.07854 | 0.16578 | 0.25296 | 0.34008 | 0.42708 | 0.51396 | 0.60068 | 0.68722 |
| 55   | 0.07999 | 0.16723 | 0.25442 | 0.34153 | 0.42853 | 0.51541 | 0.60213 | 0.68866 |
| 56   | 0.08145 | 0.16868 | 0.25587 | 0.34298 | 0.42998 | 0.51686 | 0.60357 | 0.69010 |
| 57   | 0.08290 | 0.17014 | 0.25732 | 0.34443 | 0.43143 | 0.51830 | 0.60502 | 0.69154 |
| 58   | 0.08435 | 0.17159 | 0.25877 | 0.34588 | 0.43288 | 0.51975 | 0.60646 | 0.69298 |
| 59   | 0.08581 | 0.17304 | 0.26023 | 0.34733 | 0.43433 | 0.52120 | 0.60790 | 0.69443 |
| 60   | 0.08726 | 0.17450 | 0.26168 | 0.34878 | 0.43578 | 0.52264 | 0.60935 | 0.69587 |

## SINE BAR CONSTANTS

## Constants for Setting a 5-inch Sine-Bar for 8° to 15°

| Min. | 8°      | 9°      | 10°     | 11°     | 12°     | 13°     | 14°     | 15°     |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 0.69587 | 0.78217 | 0.86824 | 0.95404 | 1.03956 | 1.12476 | 1.20961 | 1.29410 |
| 1    | 0.69731 | 0.78361 | 0.86967 | 0.95547 | 1.04098 | 1.12617 | 1.21102 | 1.29550 |
| 2    | 0.69875 | 0.78505 | 0.87111 | 0.95690 | 1.04240 | 1.12759 | 1.21243 | 1.29690 |
| 3    | 0.70019 | 0.78648 | 0.87254 | 0.95833 | 1.04383 | 1.12901 | 1.21384 | 1.29831 |
| 4    | 0.70163 | 0.78792 | 0.87397 | 0.95976 | 1.04525 | 1.13042 | 1.21525 | 1.29971 |
| 5    | 0.70307 | 0.78935 | 0.87540 | 0.96118 | 1.04667 | 1.13184 | 1.21666 | 1.30112 |
| 6    | 0.70451 | 0.79079 | 0.87683 | 0.96261 | 1.04809 | 1.13326 | 1.21808 | 1.30252 |
| 7    | 0.70595 | 0.79223 | 0.87827 | 0.96404 | 1.04951 | 1.13467 | 1.21949 | 1.30393 |
| 8    | 0.70739 | 0.79366 | 0.87970 | 0.96546 | 1.05094 | 1.13609 | 1.22090 | 1.30533 |
| 9    | 0.70883 | 0.79510 | 0.88113 | 0.96689 | 1.05236 | 1.13751 | 1.22231 | 1.30673 |
| 10   | 0.71027 | 0.79653 | 0.88256 | 0.96832 | 1.05378 | 1.13892 | 1.22372 | 1.30814 |
| 11   | 0.71171 | 0.79797 | 0.88399 | 0.96974 | 1.05520 | 1.14034 | 1.22513 | 1.30954 |
| 12   | 0.71314 | 0.79941 | 0.88542 | 0.97117 | 1.05662 | 1.14175 | 1.22654 | 1.31095 |
| 13   | 0.71458 | 0.80084 | 0.88686 | 0.97260 | 1.05805 | 1.14317 | 1.22795 | 1.31235 |
| 14   | 0.71602 | 0.80228 | 0.88829 | 0.97403 | 1.05947 | 1.14459 | 1.22936 | 1.31375 |
| 15   | 0.71746 | 0.80371 | 0.88972 | 0.97545 | 1.06089 | 1.14600 | 1.23077 | 1.31516 |
| 16   | 0.71890 | 0.80515 | 0.89115 | 0.97688 | 1.06231 | 1.14742 | 1.23218 | 1.31656 |
| 17   | 0.72034 | 0.80658 | 0.89258 | 0.97830 | 1.06373 | 1.14883 | 1.23359 | 1.31796 |
| 18   | 0.72178 | 0.80802 | 0.89401 | 0.97973 | 1.06515 | 1.15025 | 1.23500 | 1.31937 |
| 19   | 0.72322 | 0.80945 | 0.89544 | 0.98116 | 1.06657 | 1.15166 | 1.23640 | 1.32077 |
| 20   | 0.72466 | 0.81089 | 0.89687 | 0.98258 | 1.06799 | 1.15308 | 1.23781 | 1.32217 |
| 21   | 0.72610 | 0.81232 | 0.89830 | 0.98401 | 1.06941 | 1.15449 | 1.23922 | 1.32357 |
| 22   | 0.72754 | 0.81376 | 0.89973 | 0.98544 | 1.07084 | 1.15591 | 1.24063 | 1.32498 |
| 23   | 0.72898 | 0.81519 | 0.90117 | 0.98686 | 1.07226 | 1.15732 | 1.24204 | 1.32638 |
| 24   | 0.73042 | 0.81663 | 0.90260 | 0.98829 | 1.07368 | 1.15874 | 1.24345 | 1.32778 |
| 25   | 0.73185 | 0.81806 | 0.90403 | 0.98971 | 1.07510 | 1.16015 | 1.24486 | 1.32918 |
| 26   | 0.73329 | 0.81950 | 0.90546 | 0.99114 | 1.07652 | 1.16157 | 1.24627 | 1.33058 |
| 27   | 0.73473 | 0.82093 | 0.90689 | 0.99256 | 1.07794 | 1.16298 | 1.24768 | 1.33199 |
| 28   | 0.73617 | 0.82237 | 0.90832 | 0.99399 | 1.07936 | 1.16440 | 1.24908 | 1.33339 |
| 29   | 0.73761 | 0.82380 | 0.90975 | 0.99541 | 1.08078 | 1.16581 | 1.25049 | 1.33479 |
| 30   | 0.73905 | 0.82524 | 0.91118 | 0.99684 | 1.08220 | 1.16723 | 1.25190 | 1.33619 |
| 31   | 0.74049 | 0.82667 | 0.91261 | 0.99826 | 1.08362 | 1.16864 | 1.25331 | 1.33759 |
| 32   | 0.74192 | 0.82811 | 0.91404 | 0.99969 | 1.08504 | 1.17006 | 1.25472 | 1.33899 |
| 33   | 0.74336 | 0.82954 | 0.91547 | 1.00112 | 1.08646 | 1.17147 | 1.25612 | 1.34040 |
| 34   | 0.74480 | 0.83098 | 0.91690 | 1.00254 | 1.08788 | 1.17288 | 1.25753 | 1.34180 |
| 35   | 0.74624 | 0.83241 | 0.91833 | 1.00396 | 1.08930 | 1.17430 | 1.25894 | 1.34320 |
| 36   | 0.74768 | 0.83384 | 0.91976 | 1.00539 | 1.09072 | 1.17571 | 1.26035 | 1.34460 |
| 37   | 0.74911 | 0.83528 | 0.92119 | 1.00681 | 1.09214 | 1.17712 | 1.26175 | 1.34600 |
| 38   | 0.75055 | 0.83671 | 0.92262 | 1.00824 | 1.09355 | 1.17854 | 1.26316 | 1.34740 |
| 39   | 0.75199 | 0.83815 | 0.92405 | 1.00966 | 1.09497 | 1.17995 | 1.26457 | 1.34880 |
| 40   | 0.75343 | 0.83958 | 0.92547 | 1.01109 | 1.09639 | 1.18136 | 1.26598 | 1.35020 |
| 41   | 0.75487 | 0.84101 | 0.92690 | 1.01251 | 1.09781 | 1.18278 | 1.26738 | 1.35160 |
| 42   | 0.75630 | 0.84245 | 0.92833 | 1.01394 | 1.09923 | 1.18419 | 1.26879 | 1.35300 |
| 43   | 0.75774 | 0.84388 | 0.92976 | 1.01536 | 1.10065 | 1.18560 | 1.27020 | 1.35440 |
| 44   | 0.75918 | 0.84531 | 0.93119 | 1.01678 | 1.10207 | 1.18702 | 1.27160 | 1.35580 |
| 45   | 0.76062 | 0.84675 | 0.93262 | 1.01821 | 1.10349 | 1.18843 | 1.27301 | 1.35720 |
| 46   | 0.76205 | 0.84818 | 0.93405 | 1.01963 | 1.10491 | 1.18984 | 1.27442 | 1.35860 |
| 47   | 0.76349 | 0.84961 | 0.93548 | 1.02106 | 1.10632 | 1.19125 | 1.27582 | 1.36000 |
| 48   | 0.76493 | 0.85105 | 0.93691 | 1.02248 | 1.10774 | 1.19267 | 1.27723 | 1.36140 |
| 49   | 0.76637 | 0.85248 | 0.93834 | 1.02390 | 1.10916 | 1.19408 | 1.27863 | 1.36280 |
| 50   | 0.76780 | 0.85391 | 0.93976 | 1.02533 | 1.11058 | 1.19549 | 1.28004 | 1.36420 |
| 51   | 0.76924 | 0.85535 | 0.94119 | 1.02675 | 1.11200 | 1.19690 | 1.28145 | 1.36560 |
| 52   | 0.77068 | 0.85678 | 0.94262 | 1.02817 | 1.11342 | 1.19832 | 1.28285 | 1.36700 |
| 53   | 0.77211 | 0.85821 | 0.94405 | 1.02960 | 1.11483 | 1.19973 | 1.28426 | 1.36840 |
| 54   | 0.77355 | 0.85965 | 0.94548 | 1.03102 | 1.11625 | 1.20114 | 1.28566 | 1.36980 |
| 55   | 0.77499 | 0.86108 | 0.94691 | 1.03244 | 1.11767 | 1.20255 | 1.28707 | 1.37119 |
| 56   | 0.77643 | 0.86251 | 0.94833 | 1.03387 | 1.11909 | 1.20396 | 1.28847 | 1.37259 |
| 57   | 0.77786 | 0.86394 | 0.94976 | 1.03529 | 1.12050 | 1.20538 | 1.28988 | 1.37399 |
| 58   | 0.77930 | 0.86538 | 0.95119 | 1.03671 | 1.12192 | 1.20679 | 1.29129 | 1.37539 |
| 59   | 0.78074 | 0.86681 | 0.95262 | 1.03814 | 1.12334 | 1.20820 | 1.29269 | 1.37679 |
| 60   | 0.78217 | 0.86824 | 0.95404 | 1.03956 | 1.12476 | 1.20961 | 1.29410 | 1.37819 |

## Constants for Setting a 5-inch Sine-Bar for 16° to 23°

| Min. | 16°     | 17°     | 18°     | 19°     | 20°     | 21°     | 22°     | 23°     |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 1.37819 | 1.46186 | 1.54509 | 1.62784 | 1.71010 | 1.79184 | 1.87303 | 1.95366 |
| 1    | 1.37958 | 1.46325 | 1.54647 | 1.62922 | 1.71147 | 1.79320 | 1.87438 | 1.95499 |
| 2    | 1.38098 | 1.46464 | 1.54785 | 1.63059 | 1.71283 | 1.79456 | 1.87573 | 1.95633 |
| 3    | 1.38238 | 1.46603 | 1.54923 | 1.63197 | 1.71420 | 1.79591 | 1.87708 | 1.95767 |
| 4    | 1.38378 | 1.46742 | 1.55062 | 1.63334 | 1.71557 | 1.79727 | 1.87843 | 1.95901 |
| 5    | 1.38518 | 1.46881 | 1.55200 | 1.63472 | 1.71693 | 1.79863 | 1.87977 | 1.96035 |
| 6    | 1.38657 | 1.47020 | 1.55338 | 1.63609 | 1.71830 | 1.79998 | 1.88112 | 1.96169 |
| 7    | 1.38797 | 1.47159 | 1.55476 | 1.63746 | 1.71966 | 1.80134 | 1.88247 | 1.96302 |
| 8    | 1.38937 | 1.47298 | 1.55615 | 1.63884 | 1.72103 | 1.80270 | 1.88382 | 1.96436 |
| 9    | 1.39076 | 1.47437 | 1.55753 | 1.64021 | 1.72240 | 1.80405 | 1.88516 | 1.96570 |
| 10   | 1.39216 | 1.47576 | 1.55891 | 1.64159 | 1.72376 | 1.80541 | 1.88651 | 1.96704 |
| 11   | 1.39356 | 1.47715 | 1.56029 | 1.64296 | 1.72513 | 1.80677 | 1.88786 | 1.96837 |
| 12   | 1.39496 | 1.47854 | 1.56167 | 1.64433 | 1.72649 | 1.80812 | 1.88920 | 1.96971 |
| 13   | 1.39635 | 1.47993 | 1.56306 | 1.64571 | 1.72786 | 1.80948 | 1.89055 | 1.97105 |
| 14   | 1.39775 | 1.48132 | 1.56444 | 1.64708 | 1.72922 | 1.81083 | 1.89190 | 1.97238 |
| 15   | 1.39915 | 1.48271 | 1.56582 | 1.64845 | 1.73059 | 1.81219 | 1.89324 | 1.97372 |
| 16   | 1.40054 | 1.48410 | 1.56720 | 1.64983 | 1.73195 | 1.81355 | 1.89459 | 1.97506 |
| 17   | 1.40194 | 1.48549 | 1.56858 | 1.65120 | 1.73331 | 1.81490 | 1.89594 | 1.97639 |
| 18   | 1.40333 | 1.48687 | 1.56996 | 1.65257 | 1.73468 | 1.81626 | 1.89728 | 1.97773 |
| 19   | 1.40473 | 1.48826 | 1.57134 | 1.65394 | 1.73604 | 1.81761 | 1.89863 | 1.97906 |
| 20   | 1.40613 | 1.48965 | 1.57272 | 1.65532 | 1.73741 | 1.81897 | 1.89997 | 1.98040 |
| 21   | 1.40752 | 1.49104 | 1.57410 | 1.65669 | 1.73877 | 1.82032 | 1.90132 | 1.98173 |
| 22   | 1.40892 | 1.49243 | 1.57548 | 1.65806 | 1.74013 | 1.82168 | 1.90266 | 1.98307 |
| 23   | 1.41031 | 1.49382 | 1.57687 | 1.65943 | 1.74150 | 1.82303 | 1.90401 | 1.98440 |
| 24   | 1.41171 | 1.49520 | 1.57825 | 1.66081 | 1.74286 | 1.82438 | 1.90535 | 1.98574 |
| 25   | 1.41310 | 1.49659 | 1.57963 | 1.66218 | 1.74422 | 1.82574 | 1.90670 | 1.98707 |
| 26   | 1.41450 | 1.49798 | 1.58101 | 1.66355 | 1.74559 | 1.82709 | 1.90804 | 1.98841 |
| 27   | 1.41589 | 1.49937 | 1.58238 | 1.66492 | 1.74695 | 1.82845 | 1.90939 | 1.98974 |
| 28   | 1.41729 | 1.50075 | 1.58376 | 1.66629 | 1.74831 | 1.82980 | 1.91073 | 1.99108 |
| 29   | 1.41868 | 1.50214 | 1.58514 | 1.66766 | 1.74967 | 1.83115 | 1.91207 | 1.99241 |
| 30   | 1.42008 | 1.50353 | 1.58652 | 1.66903 | 1.75104 | 1.83251 | 1.91342 | 1.99375 |
| 31   | 1.42147 | 1.50492 | 1.58790 | 1.67041 | 1.75240 | 1.83386 | 1.91476 | 1.99508 |
| 32   | 1.42287 | 1.50630 | 1.58928 | 1.67178 | 1.75376 | 1.83521 | 1.91610 | 1.99641 |
| 33   | 1.42426 | 1.50769 | 1.59066 | 1.67315 | 1.75512 | 1.83657 | 1.91745 | 1.99775 |
| 34   | 1.42565 | 1.50908 | 1.59204 | 1.67452 | 1.75649 | 1.83792 | 1.91879 | 1.99908 |
| 35   | 1.42705 | 1.51046 | 1.59342 | 1.67589 | 1.75785 | 1.83927 | 1.92013 | 2.00041 |
| 36   | 1.42844 | 1.51185 | 1.59480 | 1.67726 | 1.75921 | 1.84062 | 1.92148 | 2.00175 |
| 37   | 1.42984 | 1.51324 | 1.59617 | 1.67863 | 1.76057 | 1.84198 | 1.92282 | 2.00308 |
| 38   | 1.43123 | 1.51462 | 1.59755 | 1.68000 | 1.76193 | 1.84333 | 1.92416 | 2.00441 |
| 39   | 1.43262 | 1.51601 | 1.59893 | 1.68137 | 1.76329 | 1.84468 | 1.92550 | 2.00574 |
| 40   | 1.43402 | 1.51739 | 1.60031 | 1.68274 | 1.76465 | 1.84603 | 1.92685 | 2.00708 |
| 41   | 1.43541 | 1.51878 | 1.60169 | 1.68411 | 1.76601 | 1.84738 | 1.92819 | 2.00841 |
| 42   | 1.43680 | 1.52017 | 1.60307 | 1.68548 | 1.76737 | 1.84873 | 1.92953 | 2.00974 |
| 43   | 1.43820 | 1.52155 | 1.60444 | 1.68685 | 1.76873 | 1.85009 | 1.93087 | 2.01107 |
| 44   | 1.43959 | 1.52294 | 1.60582 | 1.68821 | 1.77010 | 1.85144 | 1.93221 | 2.01240 |
| 45   | 1.44098 | 1.52432 | 1.60720 | 1.68958 | 1.77146 | 1.85279 | 1.93355 | 2.01373 |
| 46   | 1.44237 | 1.52571 | 1.60857 | 1.69095 | 1.77282 | 1.85414 | 1.93490 | 2.01506 |
| 47   | 1.44377 | 1.52709 | 1.60995 | 1.69232 | 1.77418 | 1.85549 | 1.93624 | 2.01640 |
| 48   | 1.44516 | 1.52848 | 1.61133 | 1.69369 | 1.77553 | 1.85684 | 1.93758 | 2.01773 |
| 49   | 1.44655 | 1.52986 | 1.61271 | 1.69506 | 1.77689 | 1.85819 | 1.93892 | 2.01906 |
| 50   | 1.44794 | 1.53125 | 1.61408 | 1.69643 | 1.77825 | 1.85954 | 1.94026 | 2.02039 |
| 51   | 1.44934 | 1.53263 | 1.61546 | 1.69779 | 1.77961 | 1.86089 | 1.94160 | 2.02172 |
| 52   | 1.45073 | 1.53401 | 1.61683 | 1.69916 | 1.78097 | 1.86224 | 1.94294 | 2.02305 |
| 53   | 1.45212 | 1.53540 | 1.61821 | 1.70053 | 1.78233 | 1.86359 | 1.94428 | 2.02438 |
| 54   | 1.45351 | 1.53678 | 1.61959 | 1.70190 | 1.78369 | 1.86494 | 1.94562 | 2.02571 |
| 55   | 1.45490 | 1.53817 | 1.62096 | 1.70327 | 1.78505 | 1.86629 | 1.94696 | 2.02704 |
| 56   | 1.45629 | 1.53955 | 1.62234 | 1.70463 | 1.78641 | 1.86764 | 1.94830 | 2.02837 |
| 57   | 1.45769 | 1.54093 | 1.62371 | 1.70600 | 1.78777 | 1.86899 | 1.94964 | 2.02970 |
| 58   | 1.45908 | 1.54232 | 1.62509 | 1.70737 | 1.78912 | 1.87034 | 1.95098 | 2.03103 |
| 59   | 1.46047 | 1.54370 | 1.62647 | 1.70873 | 1.79048 | 1.87168 | 1.95232 | 2.03235 |
| 60   | 1.46186 | 1.54509 | 1.62784 | 1.71010 | 1.79184 | 1.87303 | 1.95366 | 2.03368 |

## SINE BAR CONSTANTS

## Constants for Setting a 5-inch Sine-Bar for 24° to 31°

| Min. | 24°     | 25°     | 26°     | 27°     | 28°     | 29°     | 30°     | 31°     |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 2.03368 | 2.11309 | 2.19186 | 2.26995 | 2.34736 | 2.42405 | 2.50000 | 2.57519 |
| 1    | 2.03501 | 2.11441 | 2.19316 | 2.27125 | 2.34864 | 2.42532 | 2.50126 | 2.57644 |
| 2    | 2.03634 | 2.11573 | 2.19447 | 2.27254 | 2.34993 | 2.42659 | 2.50252 | 2.57768 |
| 3    | 2.03767 | 2.11704 | 2.19578 | 2.27384 | 2.35121 | 2.42786 | 2.50378 | 2.57893 |
| 4    | 2.03900 | 2.11836 | 2.19708 | 2.27513 | 2.35249 | 2.42913 | 2.50504 | 2.58018 |
| 5    | 2.04032 | 2.11968 | 2.19839 | 2.27643 | 2.35378 | 2.43041 | 2.50630 | 2.58142 |
| 6    | 2.04165 | 2.12100 | 2.19970 | 2.27772 | 2.35506 | 2.43168 | 2.50755 | 2.58267 |
| 7    | 2.04298 | 2.12231 | 2.20100 | 2.27902 | 2.35634 | 2.43295 | 2.50881 | 2.58391 |
| 8    | 2.04431 | 2.12363 | 2.20231 | 2.28031 | 2.35763 | 2.43422 | 2.51007 | 2.58516 |
| 9    | 2.04563 | 2.12495 | 2.20361 | 2.28161 | 2.35891 | 2.43549 | 2.51133 | 2.58640 |
| 10   | 2.04696 | 2.12626 | 2.20492 | 2.28290 | 2.36019 | 2.43676 | 2.51259 | 2.58765 |
| 11   | 2.04829 | 2.12758 | 2.20622 | 2.28420 | 2.36147 | 2.43803 | 2.51384 | 2.58889 |
| 12   | 2.04962 | 2.12890 | 2.20753 | 2.28549 | 2.36275 | 2.43930 | 2.51510 | 2.59014 |
| 13   | 2.05094 | 2.13021 | 2.20883 | 2.28678 | 2.36404 | 2.44057 | 2.51636 | 2.59138 |
| 14   | 2.05227 | 2.13153 | 2.21014 | 2.28808 | 2.36532 | 2.44184 | 2.51761 | 2.59262 |
| 15   | 2.05359 | 2.13284 | 2.21144 | 2.28937 | 2.36660 | 2.44311 | 2.51887 | 2.59387 |
| 16   | 2.05492 | 2.13416 | 2.21275 | 2.29066 | 2.36788 | 2.44438 | 2.52013 | 2.59511 |
| 17   | 2.05625 | 2.13547 | 2.21405 | 2.29196 | 2.36916 | 2.44564 | 2.52138 | 2.59635 |
| 18   | 2.05757 | 2.13679 | 2.21536 | 2.29325 | 2.37044 | 2.44691 | 2.52264 | 2.59760 |
| 19   | 2.05890 | 2.13810 | 2.21666 | 2.29454 | 2.37172 | 2.44818 | 2.52389 | 2.59884 |
| 20   | 2.06022 | 2.13942 | 2.21796 | 2.29583 | 2.37300 | 2.44945 | 2.52515 | 2.60008 |
| 21   | 2.06155 | 2.14073 | 2.21927 | 2.29712 | 2.37428 | 2.45072 | 2.52640 | 2.60132 |
| 22   | 2.06287 | 2.14205 | 2.22057 | 2.29842 | 2.37556 | 2.45198 | 2.52766 | 2.60256 |
| 23   | 2.06420 | 2.14336 | 2.22187 | 2.29971 | 2.37684 | 2.45325 | 2.52891 | 2.60381 |
| 24   | 2.06552 | 2.14468 | 2.22318 | 2.30100 | 2.37812 | 2.45452 | 2.53017 | 2.60505 |
| 25   | 2.06685 | 2.14599 | 2.22448 | 2.30229 | 2.37940 | 2.45579 | 2.53142 | 2.60629 |
| 26   | 2.06817 | 2.14730 | 2.22578 | 2.30358 | 2.38068 | 2.45705 | 2.53268 | 2.60753 |
| 27   | 2.06950 | 2.14862 | 2.22708 | 2.30487 | 2.38196 | 2.45832 | 2.53393 | 2.60877 |
| 28   | 2.07082 | 2.14993 | 2.22839 | 2.30616 | 2.38324 | 2.45959 | 2.53519 | 2.61001 |
| 29   | 2.07214 | 2.15124 | 2.22969 | 2.30745 | 2.38452 | 2.46085 | 2.53644 | 2.61125 |
| 30   | 2.07347 | 2.15256 | 2.23099 | 2.30874 | 2.38579 | 2.46212 | 2.53769 | 2.61249 |
| 31   | 2.07479 | 2.15387 | 2.23229 | 2.31003 | 2.38707 | 2.46338 | 2.53894 | 2.61373 |
| 32   | 2.07611 | 2.15518 | 2.23359 | 2.31132 | 2.38835 | 2.46465 | 2.54020 | 2.61497 |
| 33   | 2.07744 | 2.15649 | 2.23489 | 2.31261 | 2.38963 | 2.46591 | 2.54145 | 2.61621 |
| 34   | 2.07876 | 2.15781 | 2.23619 | 2.31390 | 2.39091 | 2.46718 | 2.54270 | 2.61745 |
| 35   | 2.08008 | 2.15912 | 2.23749 | 2.31519 | 2.39218 | 2.46844 | 2.54396 | 2.61869 |
| 36   | 2.08140 | 2.16043 | 2.23880 | 2.31648 | 2.39346 | 2.46971 | 2.54521 | 2.61993 |
| 37   | 2.08273 | 2.16174 | 2.24010 | 2.31777 | 2.39474 | 2.47097 | 2.54646 | 2.62117 |
| 38   | 2.08405 | 2.16305 | 2.24140 | 2.31906 | 2.39601 | 2.47224 | 2.54771 | 2.62241 |
| 39   | 2.08537 | 2.16436 | 2.24270 | 2.32035 | 2.39729 | 2.47350 | 2.54896 | 2.62364 |
| 40   | 2.08669 | 2.16567 | 2.24400 | 2.32163 | 2.39857 | 2.47477 | 2.55021 | 2.62488 |
| 41   | 2.08801 | 2.16698 | 2.24530 | 2.32292 | 2.39984 | 2.47603 | 2.55146 | 2.62612 |
| 42   | 2.08934 | 2.16830 | 2.24660 | 2.32421 | 2.40112 | 2.47729 | 2.55271 | 2.62736 |
| 43   | 2.09066 | 2.16961 | 2.24789 | 2.32550 | 2.40239 | 2.47856 | 2.55397 | 2.62860 |
| 44   | 2.09198 | 2.17092 | 2.24919 | 2.32679 | 2.40367 | 2.47982 | 2.55522 | 2.62983 |
| 45   | 2.09330 | 2.17223 | 2.25049 | 2.32807 | 2.40494 | 2.48108 | 2.55647 | 2.63107 |
| 46   | 2.09462 | 2.17354 | 2.25179 | 2.32936 | 2.40622 | 2.48235 | 2.55772 | 2.63231 |
| 47   | 2.09594 | 2.17485 | 2.25309 | 2.33065 | 2.40749 | 2.48361 | 2.55896 | 2.63354 |
| 48   | 2.09726 | 2.17616 | 2.25439 | 2.33193 | 2.40877 | 2.48487 | 2.56021 | 2.63478 |
| 49   | 2.09858 | 2.17746 | 2.25569 | 2.33322 | 2.41004 | 2.48613 | 2.56146 | 2.63602 |
| 50   | 2.09990 | 2.17877 | 2.25698 | 2.33451 | 2.41132 | 2.48739 | 2.56271 | 2.63725 |
| 51   | 2.10122 | 2.18008 | 2.25828 | 2.33579 | 2.41259 | 2.48866 | 2.56396 | 2.63849 |
| 52   | 2.10254 | 2.18139 | 2.25958 | 2.33708 | 2.41386 | 2.48992 | 2.56521 | 2.63972 |
| 53   | 2.10386 | 2.18270 | 2.26088 | 2.33836 | 2.41514 | 2.49118 | 2.56646 | 2.64096 |
| 54   | 2.10518 | 2.18401 | 2.26217 | 2.33965 | 2.41641 | 2.49244 | 2.56771 | 2.64219 |
| 55   | 2.10650 | 2.18532 | 2.26347 | 2.34093 | 2.41769 | 2.49370 | 2.56895 | 2.64343 |
| 56   | 2.10782 | 2.18663 | 2.26477 | 2.34222 | 2.41896 | 2.49496 | 2.57020 | 2.64466 |
| 57   | 2.10914 | 2.18793 | 2.26606 | 2.34350 | 2.42023 | 2.49622 | 2.57145 | 2.64590 |
| 58   | 2.11045 | 2.18924 | 2.26736 | 2.34479 | 2.42150 | 2.49748 | 2.57270 | 2.64713 |
| 59   | 2.11177 | 2.19055 | 2.26866 | 2.34607 | 2.42278 | 2.49874 | 2.57394 | 2.64836 |
| 60   | 2.11309 | 2.19186 | 2.26995 | 2.34736 | 2.42405 | 2.50000 | 2.57519 | 2.64960 |

## Constants for Setting a 5-inch Sine-Bar for 32° to 39°

| Min. | 32°     | 33°     | 34°     | 35°     | 36°     | 37°     | 38°     | 39°     |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 2.64960 | 2.72320 | 2.79596 | 2.86788 | 2.93893 | 3.00908 | 3.07831 | 3.14660 |
| 1    | 2.65083 | 2.72441 | 2.79717 | 2.86907 | 2.94010 | 3.01024 | 3.07945 | 3.14773 |
| 2    | 2.65206 | 2.72563 | 2.79838 | 2.87026 | 2.94128 | 3.01140 | 3.08060 | 3.14886 |
| 3    | 2.65330 | 2.72685 | 2.79958 | 2.87146 | 2.94246 | 3.01256 | 3.08174 | 3.14999 |
| 4    | 2.65453 | 2.72807 | 2.80079 | 2.87265 | 2.94363 | 3.01372 | 3.08289 | 3.15112 |
| 5    | 2.65576 | 2.72929 | 2.80199 | 2.87384 | 2.94481 | 3.01488 | 3.08403 | 3.15225 |
| 6    | 2.65699 | 2.73051 | 2.80319 | 2.87503 | 2.94598 | 3.01604 | 3.08518 | 3.15338 |
| 7    | 2.65822 | 2.73173 | 2.80440 | 2.87622 | 2.94716 | 3.01720 | 3.08632 | 3.15451 |
| 8    | 2.65946 | 2.73295 | 2.80560 | 2.87741 | 2.94833 | 3.01836 | 3.08747 | 3.15564 |
| 9    | 2.66069 | 2.73416 | 2.80681 | 2.87860 | 2.94951 | 3.01952 | 3.08861 | 3.15676 |
| 10   | 2.66192 | 2.73538 | 2.80801 | 2.87978 | 2.95068 | 3.02068 | 3.08976 | 3.15789 |
| 11   | 2.66315 | 2.73660 | 2.80921 | 2.88097 | 2.95185 | 3.02184 | 3.09090 | 3.15902 |
| 12   | 2.66438 | 2.73782 | 2.81042 | 2.88216 | 2.95303 | 3.02300 | 3.09204 | 3.16015 |
| 13   | 2.66561 | 2.73903 | 2.81162 | 2.88335 | 2.95420 | 3.02415 | 3.09318 | 3.16127 |
| 14   | 2.66684 | 2.74025 | 2.81282 | 2.88454 | 2.95538 | 3.02531 | 3.09433 | 3.16240 |
| 15   | 2.66807 | 2.74147 | 2.81402 | 2.88573 | 2.95655 | 3.02647 | 3.09547 | 3.16353 |
| 16   | 2.66930 | 2.74268 | 2.81523 | 2.88691 | 2.95772 | 3.02763 | 3.09661 | 3.16465 |
| 17   | 2.67053 | 2.74390 | 2.81643 | 2.88810 | 2.95889 | 3.02878 | 3.09775 | 3.16578 |
| 18   | 2.67176 | 2.74511 | 2.81763 | 2.88929 | 2.96007 | 3.02994 | 3.09890 | 3.16690 |
| 19   | 2.67299 | 2.74633 | 2.81883 | 2.89048 | 2.96124 | 3.03110 | 3.10004 | 3.16803 |
| 20   | 2.67422 | 2.74754 | 2.82003 | 2.89166 | 2.96241 | 3.03226 | 3.10118 | 3.16915 |
| 21   | 2.67545 | 2.74876 | 2.82123 | 2.89285 | 2.96358 | 3.03341 | 3.10232 | 3.17028 |
| 22   | 2.67668 | 2.74997 | 2.82243 | 2.89403 | 2.96475 | 3.03457 | 3.10346 | 3.17140 |
| 23   | 2.67791 | 2.75119 | 2.82364 | 2.89522 | 2.96592 | 3.03572 | 3.10460 | 3.17253 |
| 24   | 2.67913 | 2.75240 | 2.82484 | 2.89641 | 2.96709 | 3.03688 | 3.10574 | 3.17365 |
| 25   | 2.68036 | 2.75362 | 2.82604 | 2.89759 | 2.96827 | 3.03803 | 3.10688 | 3.17478 |
| 26   | 2.68159 | 2.75483 | 2.82723 | 2.89878 | 2.96944 | 3.03919 | 3.10802 | 3.17590 |
| 27   | 2.68282 | 2.75605 | 2.82843 | 2.89996 | 2.97061 | 3.04034 | 3.10916 | 3.17702 |
| 28   | 2.68404 | 2.75726 | 2.82963 | 2.90115 | 2.97178 | 3.04150 | 3.11030 | 3.17815 |
| 29   | 2.68527 | 2.75847 | 2.83083 | 2.90233 | 2.97294 | 3.04265 | 3.11143 | 3.17927 |
| 30   | 2.68650 | 2.75969 | 2.83203 | 2.90351 | 2.97411 | 3.04381 | 3.11257 | 3.18039 |
| 31   | 2.68772 | 2.76090 | 2.83323 | 2.90470 | 2.97528 | 3.04496 | 3.11371 | 3.18151 |
| 32   | 2.68895 | 2.76211 | 2.83443 | 2.90588 | 2.97645 | 3.04611 | 3.11485 | 3.18264 |
| 33   | 2.69018 | 2.76332 | 2.83563 | 2.90707 | 2.97762 | 3.04727 | 3.11599 | 3.18376 |
| 34   | 2.69140 | 2.76453 | 2.83682 | 2.90825 | 2.97879 | 3.04842 | 3.11712 | 3.18488 |
| 35   | 2.69263 | 2.76575 | 2.83802 | 2.90943 | 2.97996 | 3.04957 | 3.11826 | 3.18600 |
| 36   | 2.69385 | 2.76696 | 2.83922 | 2.91061 | 2.98112 | 3.05073 | 3.11940 | 3.18712 |
| 37   | 2.69508 | 2.76817 | 2.84042 | 2.91180 | 2.98229 | 3.05188 | 3.12053 | 3.18824 |
| 38   | 2.69630 | 2.76938 | 2.84161 | 2.91298 | 2.98346 | 3.05303 | 3.12167 | 3.18936 |
| 39   | 2.69753 | 2.77059 | 2.84281 | 2.91416 | 2.98463 | 3.05418 | 3.12281 | 3.19048 |
| 40   | 2.69875 | 2.77180 | 2.84401 | 2.91534 | 2.98579 | 3.05533 | 3.12394 | 3.19160 |
| 41   | 2.69998 | 2.77301 | 2.84520 | 2.91652 | 2.98696 | 3.05648 | 3.12508 | 3.19272 |
| 42   | 2.70120 | 2.77422 | 2.84640 | 2.91771 | 2.98813 | 3.05764 | 3.12621 | 3.19384 |
| 43   | 2.70243 | 2.77543 | 2.84759 | 2.91889 | 2.98929 | 3.05879 | 3.12735 | 3.19496 |
| 44   | 2.70365 | 2.77664 | 2.84879 | 2.92007 | 2.99046 | 3.05994 | 3.12848 | 3.19608 |
| 45   | 2.70487 | 2.77785 | 2.84998 | 2.92125 | 2.99162 | 3.06109 | 3.12962 | 3.19720 |
| 46   | 2.70610 | 2.77906 | 2.85118 | 2.92243 | 2.99279 | 3.06224 | 3.13075 | 3.19831 |
| 47   | 2.70732 | 2.78027 | 2.85237 | 2.92361 | 2.99395 | 3.06339 | 3.13189 | 3.19943 |
| 48   | 2.70854 | 2.78148 | 2.85357 | 2.92479 | 2.99512 | 3.06454 | 3.13302 | 3.20055 |
| 49   | 2.70976 | 2.78269 | 2.85476 | 2.92597 | 2.99628 | 3.06568 | 3.13415 | 3.20167 |
| 50   | 2.71099 | 2.78389 | 2.85596 | 2.92715 | 2.99745 | 3.06683 | 3.13529 | 3.20278 |
| 51   | 2.71221 | 2.78510 | 2.85715 | 2.92833 | 2.99861 | 3.06798 | 3.13642 | 3.20390 |
| 52   | 2.71343 | 2.78631 | 2.85834 | 2.92950 | 2.99977 | 3.06913 | 3.13755 | 3.20502 |
| 53   | 2.71465 | 2.78752 | 2.85954 | 2.93068 | 3.00094 | 3.07028 | 3.13868 | 3.20613 |
| 54   | 2.71587 | 2.78873 | 2.86073 | 2.93186 | 3.00210 | 3.07143 | 3.13982 | 3.20725 |
| 55   | 2.71709 | 2.78993 | 2.86192 | 2.93304 | 3.00326 | 3.07257 | 3.14095 | 3.20836 |
| 56   | 2.71831 | 2.79114 | 2.86311 | 2.93422 | 3.00443 | 3.07372 | 3.14208 | 3.20948 |
| 57   | 2.71953 | 2.79235 | 2.86431 | 2.93540 | 3.00559 | 3.07487 | 3.14321 | 3.21059 |
| 58   | 2.72076 | 2.79355 | 2.86550 | 2.93657 | 3.00675 | 3.07601 | 3.14434 | 3.21171 |
| 59   | 2.72198 | 2.79476 | 2.86669 | 2.93775 | 3.00791 | 3.07716 | 3.14547 | 3.21282 |
| 60   | 2.72320 | 2.79596 | 2.86788 | 2.93893 | 3.00908 | 3.07831 | 3.14660 | 3.21394 |

## SINE BAR CONSTANTS

## Constants for Setting a 5-inch Sine-Bar for 40° to 47°

| Min. | 40°     | 41°     | 42°     | 43°     | 44°     | 45°     | 46°     | 47°     |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 3.21394 | 3.28030 | 3.34565 | 3.40999 | 3.47329 | 3.53553 | 3.59670 | 3.65677 |
| 1    | 3.21505 | 3.28139 | 3.34673 | 3.41106 | 3.47434 | 3.53656 | 3.59771 | 3.65776 |
| 2    | 3.21617 | 3.28249 | 3.34781 | 3.41212 | 3.47538 | 3.53759 | 3.59872 | 3.65875 |
| 3    | 3.21728 | 3.28359 | 3.34889 | 3.41318 | 3.47643 | 3.53862 | 3.59973 | 3.65974 |
| 4    | 3.21839 | 3.28468 | 3.34997 | 3.41424 | 3.47747 | 3.53965 | 3.60074 | 3.66073 |
| 5    | 3.21951 | 3.28578 | 3.35105 | 3.41531 | 3.47852 | 3.54067 | 3.60175 | 3.66172 |
| 6    | 3.22062 | 3.28688 | 3.35213 | 3.41637 | 3.47956 | 3.54170 | 3.60276 | 3.66271 |
| 7    | 3.22173 | 3.28797 | 3.35321 | 3.41743 | 3.48061 | 3.54273 | 3.60376 | 3.66370 |
| 8    | 3.22284 | 3.28907 | 3.35429 | 3.41849 | 3.48165 | 3.54375 | 3.60477 | 3.66469 |
| 9    | 3.22395 | 3.29016 | 3.35537 | 3.41955 | 3.48270 | 3.54478 | 3.60578 | 3.66568 |
| 10   | 3.22507 | 3.29126 | 3.35645 | 3.42061 | 3.48374 | 3.54580 | 3.60679 | 3.66667 |
| 11   | 3.22618 | 3.29235 | 3.35753 | 3.42168 | 3.48478 | 3.54683 | 3.60779 | 3.66766 |
| 12   | 3.22729 | 3.29345 | 3.35860 | 3.42274 | 3.48583 | 3.54785 | 3.60880 | 3.66865 |
| 13   | 3.22840 | 3.29454 | 3.35968 | 3.42380 | 3.48687 | 3.54888 | 3.60981 | 3.66964 |
| 14   | 3.22951 | 3.29564 | 3.36076 | 3.42486 | 3.48791 | 3.54990 | 3.61081 | 3.67063 |
| 15   | 3.23062 | 3.29673 | 3.36183 | 3.42592 | 3.48895 | 3.55093 | 3.61182 | 3.67161 |
| 16   | 3.23173 | 3.29782 | 3.36291 | 3.42697 | 3.48999 | 3.55195 | 3.61283 | 3.67260 |
| 17   | 3.23284 | 3.29892 | 3.36399 | 3.42803 | 3.49104 | 3.55297 | 3.61383 | 3.67359 |
| 18   | 3.23395 | 3.30001 | 3.36506 | 3.42909 | 3.49208 | 3.55400 | 3.61484 | 3.67457 |
| 19   | 3.23506 | 3.30110 | 3.36614 | 3.43015 | 3.49312 | 3.55502 | 3.61584 | 3.67556 |
| 20   | 3.23617 | 3.30219 | 3.36721 | 3.43121 | 3.49416 | 3.55604 | 3.61684 | 3.67655 |
| 21   | 3.23728 | 3.30329 | 3.36829 | 3.43227 | 3.49520 | 3.55707 | 3.61785 | 3.67753 |
| 22   | 3.23838 | 3.30438 | 3.36936 | 3.43332 | 3.49624 | 3.55809 | 3.61885 | 3.67852 |
| 23   | 3.23949 | 3.30547 | 3.37044 | 3.43438 | 3.49728 | 3.55911 | 3.61986 | 3.67950 |
| 24   | 3.24060 | 3.30656 | 3.37151 | 3.43544 | 3.49832 | 3.56013 | 3.62086 | 3.68049 |
| 25   | 3.24171 | 3.30765 | 3.37259 | 3.43649 | 3.49936 | 3.56115 | 3.62186 | 3.68147 |
| 26   | 3.24281 | 3.30874 | 3.37366 | 3.43755 | 3.50039 | 3.56217 | 3.62286 | 3.68245 |
| 27   | 3.24392 | 3.30983 | 3.37473 | 3.43861 | 3.50143 | 3.56319 | 3.62387 | 3.68344 |
| 28   | 3.24503 | 3.31092 | 3.37581 | 3.43966 | 3.50247 | 3.56421 | 3.62487 | 3.68442 |
| 29   | 3.24613 | 3.31201 | 3.37688 | 3.44072 | 3.50351 | 3.56523 | 3.62587 | 3.68540 |
| 30   | 3.24724 | 3.31310 | 3.37795 | 3.44177 | 3.50455 | 3.56625 | 3.62687 | 3.68639 |
| 31   | 3.24835 | 3.31419 | 3.37902 | 3.44283 | 3.50558 | 3.56727 | 3.62787 | 3.68737 |
| 32   | 3.24945 | 3.31528 | 3.38010 | 3.44388 | 3.50662 | 3.56829 | 3.62887 | 3.68835 |
| 33   | 3.25056 | 3.31637 | 3.38117 | 3.44494 | 3.50766 | 3.56931 | 3.62987 | 3.68933 |
| 34   | 3.25166 | 3.31746 | 3.38224 | 3.44599 | 3.50869 | 3.57033 | 3.63087 | 3.69031 |
| 35   | 3.25277 | 3.31854 | 3.38331 | 3.44704 | 3.50973 | 3.57135 | 3.63187 | 3.69130 |
| 36   | 3.25387 | 3.31963 | 3.38438 | 3.44810 | 3.51077 | 3.57236 | 3.63287 | 3.69228 |
| 37   | 3.25498 | 3.32072 | 3.38545 | 3.44915 | 3.51180 | 3.57338 | 3.63387 | 3.69326 |
| 38   | 3.25608 | 3.32181 | 3.38652 | 3.45020 | 3.51284 | 3.57440 | 3.63487 | 3.69424 |
| 39   | 3.25718 | 3.32289 | 3.38759 | 3.45126 | 3.51387 | 3.57542 | 3.63587 | 3.69522 |
| 40   | 3.25829 | 3.32398 | 3.38866 | 3.45231 | 3.51491 | 3.57643 | 3.63687 | 3.69620 |
| 41   | 3.25939 | 3.32507 | 3.38973 | 3.45336 | 3.51594 | 3.57745 | 3.63787 | 3.69718 |
| 42   | 3.26049 | 3.32615 | 3.39080 | 3.45441 | 3.51697 | 3.57846 | 3.63886 | 3.69816 |
| 43   | 3.26159 | 3.32724 | 3.39187 | 3.45546 | 3.51801 | 3.57948 | 3.63986 | 3.69913 |
| 44   | 3.26270 | 3.32832 | 3.39294 | 3.45651 | 3.51904 | 3.58049 | 3.64086 | 3.70011 |
| 45   | 3.26380 | 3.32941 | 3.39400 | 3.45757 | 3.52007 | 3.58151 | 3.64186 | 3.70109 |
| 46   | 3.26490 | 3.33049 | 3.39507 | 3.45862 | 3.52111 | 3.58252 | 3.64285 | 3.70207 |
| 47   | 3.26600 | 3.33158 | 3.39614 | 3.45967 | 3.52214 | 3.58354 | 3.64385 | 3.70305 |
| 48   | 3.26710 | 3.33266 | 3.39721 | 3.46072 | 3.52317 | 3.58455 | 3.64484 | 3.70402 |
| 49   | 3.26820 | 3.33375 | 3.39827 | 3.46177 | 3.52420 | 3.58557 | 3.64584 | 3.70500 |
| 50   | 3.26930 | 3.33483 | 3.39934 | 3.46281 | 3.52523 | 3.58658 | 3.64683 | 3.70598 |
| 51   | 3.27040 | 3.33591 | 3.40041 | 3.46386 | 3.52627 | 3.58759 | 3.64783 | 3.70695 |
| 52   | 3.27150 | 3.33700 | 3.40147 | 3.46491 | 3.52730 | 3.58861 | 3.64882 | 3.70793 |
| 53   | 3.27260 | 3.33808 | 3.40254 | 3.46596 | 3.52833 | 3.58962 | 3.64982 | 3.70890 |
| 54   | 3.27370 | 3.33916 | 3.40360 | 3.46701 | 3.52936 | 3.59063 | 3.65081 | 3.70988 |
| 55   | 3.27480 | 3.34025 | 3.40467 | 3.46806 | 3.53039 | 3.59164 | 3.65181 | 3.71085 |
| 56   | 3.27590 | 3.34133 | 3.40573 | 3.46910 | 3.53142 | 3.59266 | 3.65280 | 3.71183 |
| 57   | 3.27700 | 3.34241 | 3.40680 | 3.47015 | 3.53245 | 3.59367 | 3.65379 | 3.71280 |
| 58   | 3.27810 | 3.34349 | 3.40786 | 3.47120 | 3.53348 | 3.59468 | 3.65478 | 3.71378 |
| 59   | 3.27920 | 3.34457 | 3.40893 | 3.47225 | 3.53451 | 3.59569 | 3.65578 | 3.71475 |
| 60   | 3.28030 | 3.34565 | 3.40999 | 3.47329 | 3.53553 | 3.59670 | 3.65677 | 3.71572 |

## SINE BAR CONSTANTS

## Constants for Setting a 5-inch Sine-Bar for 48° to 55°

| Min. | 48°     | 49°     | 50°     | 51°     | 52°     | 53°     | 54°     | 55°     |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 3.71572 | 3.77355 | 3.83022 | 3.88573 | 3.94005 | 3.99318 | 4.04508 | 4.09576 |
| 1    | 3.71670 | 3.77450 | 3.83116 | 3.88665 | 3.94095 | 3.99405 | 4.04594 | 4.09659 |
| 2    | 3.71767 | 3.77546 | 3.83209 | 3.88756 | 3.94184 | 3.99493 | 4.04679 | 4.09743 |
| 3    | 3.71864 | 3.77641 | 3.83303 | 3.88847 | 3.94274 | 3.99580 | 4.04765 | 4.09826 |
| 4    | 3.71961 | 3.77736 | 3.83396 | 3.88939 | 3.94363 | 3.99668 | 4.04850 | 4.09909 |
| 5    | 3.72059 | 3.77831 | 3.83489 | 3.89030 | 3.94453 | 3.99755 | 4.04936 | 4.09993 |
| 6    | 3.72156 | 3.77927 | 3.83583 | 3.89122 | 3.94542 | 3.99842 | 4.05021 | 4.10076 |
| 7    | 3.72253 | 3.78022 | 3.83676 | 3.89213 | 3.94631 | 3.99930 | 4.05106 | 4.10159 |
| 8    | 3.72350 | 3.78117 | 3.83769 | 3.89304 | 3.94721 | 4.00017 | 4.05191 | 4.10242 |
| 9    | 3.72447 | 3.78212 | 3.83862 | 3.89395 | 3.94810 | 4.00104 | 4.05277 | 4.10325 |
| 10   | 3.72544 | 3.78307 | 3.83956 | 3.89487 | 3.94899 | 4.00191 | 4.05362 | 4.10409 |
| 11   | 3.72641 | 3.78402 | 3.84049 | 3.89578 | 3.94988 | 4.00279 | 4.05447 | 4.10492 |
| 12   | 3.72738 | 3.78498 | 3.84142 | 3.89669 | 3.95078 | 4.00366 | 4.05532 | 4.10575 |
| 13   | 3.72835 | 3.78593 | 3.84235 | 3.89760 | 3.95167 | 4.00453 | 4.05617 | 4.10658 |
| 14   | 3.72932 | 3.78688 | 3.84328 | 3.89851 | 3.95256 | 4.00540 | 4.05702 | 4.10741 |
| 15   | 3.73029 | 3.78783 | 3.84421 | 3.89942 | 3.95345 | 4.00627 | 4.05787 | 4.10823 |
| 16   | 3.73126 | 3.78877 | 3.84514 | 3.90033 | 3.95434 | 4.00714 | 4.05872 | 4.10906 |
| 17   | 3.73222 | 3.78972 | 3.84607 | 3.90124 | 3.95523 | 4.00801 | 4.05957 | 4.10989 |
| 18   | 3.73319 | 3.79067 | 3.84700 | 3.90215 | 3.95612 | 4.00888 | 4.06042 | 4.11072 |
| 19   | 3.73416 | 3.79162 | 3.84793 | 3.90306 | 3.95701 | 4.00975 | 4.06127 | 4.11155 |
| 20   | 3.73513 | 3.79257 | 3.84886 | 3.90397 | 3.95790 | 4.01062 | 4.06211 | 4.11238 |
| 21   | 3.73609 | 3.79352 | 3.84978 | 3.90488 | 3.95878 | 4.01148 | 4.06296 | 4.11320 |
| 22   | 3.73706 | 3.79446 | 3.85071 | 3.90579 | 3.95967 | 4.01235 | 4.06381 | 4.11403 |
| 23   | 3.73802 | 3.79541 | 3.85164 | 3.90669 | 3.96056 | 4.01322 | 4.06466 | 4.11486 |
| 24   | 3.73899 | 3.79636 | 3.85257 | 3.90760 | 3.96145 | 4.01409 | 4.06550 | 4.11568 |
| 25   | 3.73996 | 3.79730 | 3.85349 | 3.90851 | 3.96234 | 4.01495 | 4.06635 | 4.11651 |
| 26   | 3.74092 | 3.79825 | 3.85442 | 3.90942 | 3.96322 | 4.01582 | 4.06720 | 4.11733 |
| 27   | 3.74189 | 3.79919 | 3.85535 | 3.91032 | 3.96411 | 4.01669 | 4.06804 | 4.11816 |
| 28   | 3.74285 | 3.80014 | 3.85627 | 3.91123 | 3.96500 | 4.01755 | 4.06889 | 4.11898 |
| 29   | 3.74381 | 3.80109 | 3.85720 | 3.91214 | 3.96588 | 4.01842 | 4.06973 | 4.11981 |
| 30   | 3.74478 | 3.80203 | 3.85812 | 3.91304 | 3.96677 | 4.01928 | 4.07058 | 4.12063 |
| 31   | 3.74574 | 3.80297 | 3.85905 | 3.91395 | 3.96765 | 4.02015 | 4.07142 | 4.12145 |
| 32   | 3.74671 | 3.80392 | 3.85997 | 3.91485 | 3.96854 | 4.02101 | 4.07227 | 4.12228 |
| 33   | 3.74767 | 3.80486 | 3.86090 | 3.91576 | 3.96942 | 4.02188 | 4.07311 | 4.12310 |
| 34   | 3.74863 | 3.80581 | 3.86182 | 3.91666 | 3.97031 | 4.02274 | 4.07395 | 4.12392 |
| 35   | 3.74959 | 3.80675 | 3.86274 | 3.91756 | 3.97119 | 4.02361 | 4.07480 | 4.12475 |
| 36   | 3.75056 | 3.80769 | 3.86367 | 3.91847 | 3.97207 | 4.02447 | 4.07564 | 4.12557 |
| 37   | 3.75152 | 3.80863 | 3.86459 | 3.91937 | 3.97296 | 4.02533 | 4.07648 | 4.12639 |
| 38   | 3.75248 | 3.80958 | 3.86551 | 3.92027 | 3.97384 | 4.02619 | 4.07732 | 4.12721 |
| 39   | 3.75344 | 3.81052 | 3.86644 | 3.92118 | 3.97472 | 4.02706 | 4.07817 | 4.12803 |
| 40   | 3.75440 | 3.81146 | 3.86736 | 3.92208 | 3.97560 | 4.02792 | 4.07901 | 4.12885 |
| 41   | 3.75536 | 3.81240 | 3.86828 | 3.92298 | 3.97649 | 4.02878 | 4.07985 | 4.12967 |
| 42   | 3.75632 | 3.81334 | 3.86920 | 3.92388 | 3.97737 | 4.02964 | 4.08069 | 4.13049 |
| 43   | 3.75728 | 3.81428 | 3.87012 | 3.92478 | 3.97825 | 4.03050 | 4.08153 | 4.13131 |
| 44   | 3.75824 | 3.81522 | 3.87104 | 3.92568 | 3.97913 | 4.03136 | 4.08237 | 4.13213 |
| 45   | 3.75920 | 3.81616 | 3.87196 | 3.92658 | 3.98001 | 4.03222 | 4.08321 | 4.13295 |
| 46   | 3.76016 | 3.81710 | 3.87288 | 3.92748 | 3.98089 | 4.03308 | 4.08405 | 4.13377 |
| 47   | 3.76112 | 3.81804 | 3.87380 | 3.92839 | 3.98177 | 4.03394 | 4.08489 | 4.13459 |
| 48   | 3.76207 | 3.81898 | 3.87472 | 3.92928 | 3.98265 | 4.03480 | 4.08572 | 4.13540 |
| 49   | 3.76303 | 3.81992 | 3.87564 | 3.93018 | 3.98353 | 4.03566 | 4.08656 | 4.13622 |
| 50   | 3.76399 | 3.82086 | 3.87656 | 3.93108 | 3.98441 | 4.03652 | 4.08740 | 4.13704 |
| 51   | 3.76495 | 3.82179 | 3.87748 | 3.93198 | 3.98529 | 4.03738 | 4.08824 | 4.13785 |
| 52   | 3.76590 | 3.82273 | 3.87840 | 3.93288 | 3.98616 | 4.03823 | 4.08908 | 4.13867 |
| 53   | 3.76686 | 3.82367 | 3.87931 | 3.93378 | 3.98704 | 4.03909 | 4.08991 | 4.13949 |
| 54   | 3.76782 | 3.82461 | 3.88023 | 3.93468 | 3.98792 | 4.03995 | 4.09075 | 4.14030 |
| 55   | 3.76877 | 3.82554 | 3.88115 | 3.93557 | 3.98880 | 4.04081 | 4.09158 | 4.14112 |
| 56   | 3.76973 | 3.82648 | 3.88207 | 3.93647 | 3.98967 | 4.04166 | 4.09242 | 4.14193 |
| 57   | 3.77068 | 3.82742 | 3.88298 | 3.93737 | 3.99055 | 4.04252 | 4.09326 | 4.14275 |
| 58   | 3.77164 | 3.82835 | 3.88390 | 3.93826 | 3.99143 | 4.04337 | 4.09409 | 4.14356 |
| 59   | 3.77259 | 3.82929 | 3.88481 | 3.93916 | 3.99230 | 4.04423 | 4.09493 | 4.14437 |
| 60   | 3.77355 | 3.83022 | 3.88573 | 3.94005 | 3.99318 | 4.04508 | 4.09576 | 4.14519 |



## SINE BAR CONSTANTS

## Constants for 10-inch Sine-Bar

## Constants for Setting a 10-inch Sine-Bar for 0° to 7°

| Min. | 0°       | 1°      | 2°      | 3°      | 4°      | 5°      | 6°      | 7°       |
|------|----------|---------|---------|---------|---------|---------|---------|----------|
| 0    | 0.000000 | 0.17452 | 0.34899 | 0.52336 | 0.69756 | 0.87156 | 1.04528 | 1.218693 |
| 1    | 0.002909 | 0.17743 | 0.35190 | 0.52626 | 0.70047 | 0.87446 | 1.04818 | 1.221581 |
| 2    | 0.005818 | 0.18034 | 0.35481 | 0.52917 | 0.70337 | 0.87735 | 1.05107 | 1.224468 |
| 3    | 0.008727 | 0.18325 | 0.35772 | 0.53207 | 0.70627 | 0.88025 | 1.05396 | 1.227355 |
| 4    | 0.011636 | 0.18616 | 0.36062 | 0.53498 | 0.70917 | 0.88315 | 1.05686 | 1.230241 |
| 5    | 0.014544 | 0.18907 | 0.36353 | 0.53788 | 0.71207 | 0.88605 | 1.05975 | 1.233128 |
| 6    | 0.017453 | 0.19197 | 0.36644 | 0.54079 | 0.71497 | 0.88894 | 1.06264 | 1.236015 |
| 7    | 0.020362 | 0.19488 | 0.36934 | 0.54369 | 0.71788 | 0.89184 | 1.06553 | 1.238901 |
| 8    | 0.023271 | 0.19779 | 0.37225 | 0.54660 | 0.72078 | 0.89474 | 1.06843 | 1.241788 |
| 9    | 0.026180 | 0.20070 | 0.37516 | 0.54950 | 0.72368 | 0.89763 | 1.07132 | 1.244674 |
| 10   | 0.029089 | 0.20361 | 0.37806 | 0.55241 | 0.72658 | 0.90053 | 1.07421 | 1.247560 |
| 11   | 0.031998 | 0.20652 | 0.38097 | 0.55531 | 0.72948 | 0.90343 | 1.07710 | 1.250446 |
| 12   | 0.034907 | 0.20942 | 0.38388 | 0.55822 | 0.73238 | 0.90633 | 1.07999 | 1.253332 |
| 13   | 0.037815 | 0.21233 | 0.38678 | 0.56112 | 0.73528 | 0.90922 | 1.08289 | 1.256218 |
| 14   | 0.040724 | 0.21524 | 0.38969 | 0.56402 | 0.73818 | 0.91212 | 1.08578 | 1.259104 |
| 15   | 0.043633 | 0.21815 | 0.39260 | 0.56693 | 0.74108 | 0.91502 | 1.08867 | 1.261990 |
| 16   | 0.046542 | 0.22106 | 0.39550 | 0.56983 | 0.74399 | 0.91791 | 1.09156 | 1.264875 |
| 17   | 0.049451 | 0.22397 | 0.39841 | 0.57274 | 0.74689 | 0.92081 | 1.09445 | 1.267761 |
| 18   | 0.052360 | 0.22687 | 0.40132 | 0.57564 | 0.74979 | 0.92371 | 1.09734 | 1.270646 |
| 19   | 0.055268 | 0.22978 | 0.40422 | 0.57854 | 0.75269 | 0.92660 | 1.10023 | 1.273531 |
| 20   | 0.058177 | 0.23269 | 0.40713 | 0.58145 | 0.75559 | 0.92950 | 1.10313 | 1.276417 |
| 21   | 0.061086 | 0.23560 | 0.41004 | 0.58435 | 0.75849 | 0.93239 | 1.10602 | 1.279302 |
| 22   | 0.063995 | 0.23851 | 0.41294 | 0.58726 | 0.76139 | 0.93529 | 1.10891 | 1.282187 |
| 23   | 0.066904 | 0.24141 | 0.41585 | 0.59016 | 0.76429 | 0.93819 | 1.11180 | 1.285071 |
| 24   | 0.069813 | 0.24432 | 0.41876 | 0.59306 | 0.76719 | 0.94108 | 1.11469 | 1.287956 |
| 25   | 0.072721 | 0.24723 | 0.42166 | 0.59597 | 0.77009 | 0.94398 | 1.11758 | 1.290841 |
| 26   | 0.075630 | 0.25014 | 0.42457 | 0.59887 | 0.77299 | 0.94687 | 1.12047 | 1.293725 |
| 27   | 0.078539 | 0.25305 | 0.42748 | 0.60177 | 0.77589 | 0.94977 | 1.12336 | 1.296609 |
| 28   | 0.081448 | 0.25595 | 0.43038 | 0.60468 | 0.77879 | 0.95267 | 1.12625 | 1.299494 |
| 29   | 0.084357 | 0.25886 | 0.43329 | 0.60758 | 0.78169 | 0.95556 | 1.12914 | 1.302378 |
| 30   | 0.087265 | 0.26177 | 0.43619 | 0.61049 | 0.78459 | 0.95846 | 1.13203 | 1.305262 |
| 31   | 0.090174 | 0.26468 | 0.43910 | 0.61339 | 0.78749 | 0.96135 | 1.13492 | 1.308146 |
| 32   | 0.093083 | 0.26759 | 0.44201 | 0.61629 | 0.79039 | 0.96425 | 1.13781 | 1.311030 |
| 33   | 0.095992 | 0.27049 | 0.44491 | 0.61920 | 0.79329 | 0.96714 | 1.14070 | 1.313913 |
| 34   | 0.098900 | 0.27340 | 0.44782 | 0.62210 | 0.79619 | 0.97004 | 1.14359 | 1.316797 |
| 35   | 0.101809 | 0.27631 | 0.45072 | 0.62500 | 0.79909 | 0.97293 | 1.14648 | 1.319681 |
| 36   | 0.104718 | 0.27922 | 0.45363 | 0.62791 | 0.80199 | 0.97583 | 1.14937 | 1.322564 |
| 37   | 0.107627 | 0.28212 | 0.45654 | 0.63081 | 0.80489 | 0.97872 | 1.15226 | 1.325447 |
| 38   | 0.110535 | 0.28503 | 0.45944 | 0.63371 | 0.80779 | 0.98162 | 1.15515 | 1.328330 |
| 39   | 0.113444 | 0.28794 | 0.46235 | 0.63661 | 0.81069 | 0.98451 | 1.15804 | 1.331213 |
| 40   | 0.116353 | 0.29085 | 0.46525 | 0.63952 | 0.81359 | 0.98741 | 1.16093 | 1.334096 |
| 41   | 0.119261 | 0.29375 | 0.46816 | 0.64242 | 0.81649 | 0.99030 | 1.16382 | 1.336979 |
| 42   | 0.122170 | 0.29666 | 0.47106 | 0.64532 | 0.81939 | 0.99320 | 1.16671 | 1.339862 |
| 43   | 0.125079 | 0.29957 | 0.47397 | 0.64823 | 0.82228 | 0.99609 | 1.16960 | 1.342744 |
| 44   | 0.127987 | 0.30248 | 0.47688 | 0.65113 | 0.82518 | 0.99899 | 1.17249 | 1.345627 |
| 45   | 0.130896 | 0.30539 | 0.47978 | 0.65403 | 0.82808 | 1.00188 | 1.17537 | 1.348509 |
| 46   | 0.133805 | 0.30829 | 0.48269 | 0.65693 | 0.83098 | 1.00477 | 1.17826 | 1.351392 |
| 47   | 0.136713 | 0.31120 | 0.48559 | 0.65984 | 0.83388 | 1.00767 | 1.18115 | 1.354274 |
| 48   | 0.139622 | 0.31411 | 0.48850 | 0.66274 | 0.83678 | 1.01056 | 1.18404 | 1.357156 |
| 49   | 0.142530 | 0.31702 | 0.49140 | 0.66564 | 0.83968 | 1.01346 | 1.18693 | 1.360038 |
| 50   | 0.145439 | 0.31992 | 0.49431 | 0.66854 | 0.84258 | 1.01635 | 1.18982 | 1.362919 |
| 51   | 0.148348 | 0.32283 | 0.49721 | 0.67145 | 0.84547 | 1.01924 | 1.19270 | 1.365801 |
| 52   | 0.151256 | 0.32574 | 0.50012 | 0.67435 | 0.84837 | 1.02214 | 1.19559 | 1.368683 |
| 53   | 0.154165 | 0.32864 | 0.50302 | 0.67725 | 0.85127 | 1.02503 | 1.19848 | 1.371564 |
| 54   | 0.157073 | 0.33155 | 0.50593 | 0.68015 | 0.85417 | 1.02793 | 1.20137 | 1.374446 |
| 55   | 0.159982 | 0.33446 | 0.50883 | 0.68306 | 0.85707 | 1.03082 | 1.20426 | 1.377327 |
| 56   | 0.162890 | 0.33737 | 0.51174 | 0.68596 | 0.85997 | 1.03371 | 1.20714 | 1.380208 |
| 57   | 0.165799 | 0.34027 | 0.51464 | 0.68886 | 0.86286 | 1.03661 | 1.21003 | 1.383089 |
| 58   | 0.168707 | 0.34318 | 0.51755 | 0.69176 | 0.86576 | 1.03950 | 1.21292 | 1.385970 |
| 59   | 0.171616 | 0.34609 | 0.52045 | 0.69466 | 0.86866 | 1.04239 | 1.21581 | 1.388850 |
| 60   | 0.174524 | 0.34899 | 0.52336 | 0.69756 | 0.87156 | 1.04528 | 1.21869 | 1.391731 |

## Constants for Setting a 10-inch Sine-Bar for 8° to 15°

| Min. | 8°       | 9°      | 10°     | 11°     | 12°     | 13°     | 14°     | 15°      |
|------|----------|---------|---------|---------|---------|---------|---------|----------|
| 0    | 1.391731 | 1.56434 | 1.73648 | 1.90809 | 2.07912 | 2.24951 | 2.41922 | 2.588191 |
| 1    | 1.394611 | 1.56722 | 1.73935 | 1.91095 | 2.08196 | 2.25234 | 2.42204 | 2.591000 |
| 2    | 1.397492 | 1.57009 | 1.74221 | 1.91380 | 2.08481 | 2.25518 | 2.42486 | 2.593810 |
| 3    | 1.400372 | 1.57296 | 1.74508 | 1.91666 | 2.08765 | 2.25801 | 2.42769 | 2.596619 |
| 4    | 1.403252 | 1.57584 | 1.74794 | 1.91951 | 2.09050 | 2.26085 | 2.43051 | 2.599428 |
| 5    | 1.406132 | 1.57871 | 1.75080 | 1.92237 | 2.09334 | 2.26368 | 2.43333 | 2.602237 |
| 6    | 1.409012 | 1.58158 | 1.75367 | 1.92522 | 2.09619 | 2.26651 | 2.43615 | 2.605045 |
| 7    | 1.411892 | 1.58445 | 1.75653 | 1.92807 | 2.09903 | 2.26935 | 2.43897 | 2.607853 |
| 8    | 1.414772 | 1.58732 | 1.75939 | 1.93093 | 2.10187 | 2.27218 | 2.44179 | 2.610662 |
| 9    | 1.417651 | 1.59020 | 1.76226 | 1.93378 | 2.10472 | 2.27501 | 2.44461 | 2.613469 |
| 10   | 1.420531 | 1.59307 | 1.76512 | 1.93664 | 2.10756 | 2.27784 | 2.44743 | 2.616277 |
| 11   | 1.423410 | 1.59594 | 1.76798 | 1.93949 | 2.11040 | 2.28068 | 2.45025 | 2.619085 |
| 12   | 1.426289 | 1.59881 | 1.77085 | 1.94234 | 2.11325 | 2.28351 | 2.45307 | 2.621892 |
| 13   | 1.429168 | 1.60168 | 1.77371 | 1.94520 | 2.11609 | 2.28634 | 2.45589 | 2.624699 |
| 14   | 1.432047 | 1.60455 | 1.77657 | 1.94805 | 2.11893 | 2.28917 | 2.45871 | 2.627506 |
| 15   | 1.434926 | 1.60743 | 1.77944 | 1.95090 | 2.12178 | 2.29200 | 2.46153 | 2.630312 |
| 16   | 1.437805 | 1.61030 | 1.78230 | 1.95376 | 2.12462 | 2.29484 | 2.46435 | 2.633119 |
| 17   | 1.440684 | 1.61317 | 1.78516 | 1.95661 | 2.12746 | 2.29767 | 2.46717 | 2.635925 |
| 18   | 1.443562 | 1.61604 | 1.78802 | 1.95946 | 2.13030 | 2.30050 | 2.46999 | 2.638731 |
| 19   | 1.446440 | 1.61891 | 1.79088 | 1.96231 | 2.13315 | 2.30333 | 2.47281 | 2.641536 |
| 20   | 1.449319 | 1.62178 | 1.79375 | 1.96517 | 2.13599 | 2.30616 | 2.47563 | 2.644342 |
| 21   | 1.452197 | 1.62465 | 1.79661 | 1.96802 | 2.13883 | 2.30899 | 2.47845 | 2.647147 |
| 22   | 1.455075 | 1.62752 | 1.79947 | 1.97087 | 2.14167 | 2.31182 | 2.48126 | 2.649952 |
| 23   | 1.457953 | 1.63039 | 1.80233 | 1.97372 | 2.14451 | 2.31465 | 2.48408 | 2.652757 |
| 24   | 1.460830 | 1.63326 | 1.80519 | 1.97657 | 2.14735 | 2.31748 | 2.48690 | 2.655561 |
| 25   | 1.463708 | 1.63613 | 1.80805 | 1.97942 | 2.15019 | 2.32031 | 2.48972 | 2.658366 |
| 26   | 1.466585 | 1.63900 | 1.81091 | 1.98228 | 2.15303 | 2.32314 | 2.49253 | 2.661170 |
| 27   | 1.469463 | 1.64187 | 1.81377 | 1.98513 | 2.15588 | 2.32597 | 2.49535 | 2.663974 |
| 28   | 1.472340 | 1.64474 | 1.81663 | 1.98798 | 2.15872 | 2.32880 | 2.49817 | 2.666777 |
| 29   | 1.475217 | 1.64761 | 1.81950 | 1.99083 | 2.16156 | 2.33163 | 2.50098 | 2.669581 |
| 30   | 1.478094 | 1.65048 | 1.82236 | 1.99368 | 2.16440 | 2.33445 | 2.50380 | 2.672384 |
| 31   | 1.480971 | 1.65334 | 1.82522 | 1.99653 | 2.16724 | 2.33728 | 2.50662 | 2.675187 |
| 32   | 1.483848 | 1.65621 | 1.82808 | 1.99938 | 2.17008 | 2.34011 | 2.50943 | 2.677990 |
| 33   | 1.486724 | 1.65908 | 1.83094 | 2.00223 | 2.17292 | 2.34294 | 2.51225 | 2.680792 |
| 34   | 1.489601 | 1.66195 | 1.83379 | 2.00508 | 2.17575 | 2.34577 | 2.51506 | 2.683594 |
| 35   | 1.492477 | 1.66482 | 1.83665 | 2.00793 | 2.17859 | 2.34859 | 2.51788 | 2.686396 |
| 36   | 1.495354 | 1.66769 | 1.83951 | 2.01078 | 2.18143 | 2.35142 | 2.52069 | 2.689198 |
| 37   | 1.498230 | 1.67056 | 1.84237 | 2.01363 | 2.18427 | 2.35425 | 2.52351 | 2.692000 |
| 38   | 1.501106 | 1.67342 | 1.84523 | 2.01648 | 2.18711 | 2.35708 | 2.52632 | 2.694801 |
| 39   | 1.503981 | 1.67629 | 1.84809 | 2.01933 | 2.18995 | 2.35990 | 2.52914 | 2.697602 |
| 40   | 1.506857 | 1.67916 | 1.85095 | 2.02218 | 2.19279 | 2.36273 | 2.53195 | 2.700403 |
| 41   | 1.509733 | 1.68203 | 1.85381 | 2.02502 | 2.19562 | 2.36556 | 2.53477 | 2.703204 |
| 42   | 1.512608 | 1.68489 | 1.85667 | 2.02787 | 2.19846 | 2.36838 | 2.53758 | 2.706005 |
| 43   | 1.515483 | 1.68776 | 1.85952 | 2.03072 | 2.20130 | 2.37121 | 2.54039 | 2.708805 |
| 44   | 1.518359 | 1.69063 | 1.86238 | 2.03357 | 2.20414 | 2.37403 | 2.54321 | 2.711605 |
| 45   | 1.521234 | 1.69350 | 1.86524 | 2.03642 | 2.20697 | 2.37686 | 2.54602 | 2.714405 |
| 46   | 1.524109 | 1.69636 | 1.86810 | 2.03927 | 2.20981 | 2.37968 | 2.54883 | 2.717204 |
| 47   | 1.526984 | 1.69923 | 1.87096 | 2.04211 | 2.21265 | 2.38251 | 2.55165 | 2.720004 |
| 48   | 1.529858 | 1.70210 | 1.87381 | 2.04496 | 2.21549 | 2.38533 | 2.55446 | 2.722803 |
| 49   | 1.532733 | 1.70496 | 1.87667 | 2.04781 | 2.21832 | 2.38816 | 2.55727 | 2.725601 |
| 50   | 1.535607 | 1.70783 | 1.87953 | 2.05065 | 2.22116 | 2.39098 | 2.56008 | 2.728400 |
| 51   | 1.538482 | 1.71069 | 1.88238 | 2.05350 | 2.22399 | 2.39381 | 2.56289 | 2.731199 |
| 52   | 1.541356 | 1.71356 | 1.88524 | 2.05635 | 2.22683 | 2.39663 | 2.56571 | 2.733997 |
| 53   | 1.544230 | 1.71643 | 1.88810 | 2.05920 | 2.22967 | 2.39946 | 2.56852 | 2.736794 |
| 54   | 1.547104 | 1.71929 | 1.89095 | 2.06204 | 2.23250 | 2.40228 | 2.57133 | 2.739592 |
| 55   | 1.549978 | 1.72216 | 1.89381 | 2.06489 | 2.23534 | 2.40510 | 2.57414 | 2.742390 |
| 56   | 1.552851 | 1.72502 | 1.89667 | 2.06773 | 2.23817 | 2.40793 | 2.57695 | 2.745187 |
| 57   | 1.555725 | 1.72789 | 1.89952 | 2.07058 | 2.24101 | 2.41075 | 2.57976 | 2.747984 |
| 58   | 1.558598 | 1.73075 | 1.90238 | 2.07343 | 2.24384 | 2.41357 | 2.58257 | 2.750781 |
| 59   | 1.561472 | 1.73362 | 1.90523 | 2.07627 | 2.24668 | 2.41640 | 2.58538 | 2.753577 |
| 60   | 1.564345 | 1.73648 | 1.90809 | 2.07912 | 2.24951 | 2.41922 | 2.58819 | 2.756374 |

## SINE BAR CONSTANTS

## Constants for Setting a 10-inch Sine-Bar for 16° to 23°

| Min. | 16°      | 17°     | 18°     | 19°     | 20°     | 21°     | 22°     | 23°      |
|------|----------|---------|---------|---------|---------|---------|---------|----------|
| 0    | 2.756374 | 2.92372 | 3.09017 | 3.25568 | 3.42020 | 3.58368 | 3.74607 | 3.907311 |
| 1    | 2.759170 | 2.92650 | 3.09294 | 3.25843 | 3.42293 | 3.58640 | 3.74876 | 3.909989 |
| 2    | 2.761966 | 2.92928 | 3.09570 | 3.26118 | 3.42567 | 3.58911 | 3.75146 | 3.912666 |
| 3    | 2.764761 | 2.93206 | 3.09847 | 3.26393 | 3.42840 | 3.59183 | 3.75416 | 3.915343 |
| 4    | 2.767557 | 2.93484 | 3.10123 | 3.26668 | 3.43113 | 3.59454 | 3.75685 | 3.918020 |
| 5    | 2.770352 | 2.93762 | 3.10400 | 3.26943 | 3.43387 | 3.59725 | 3.75955 | 3.920696 |
| 6    | 2.773147 | 2.94040 | 3.10676 | 3.27218 | 3.43660 | 3.59997 | 3.76224 | 3.923371 |
| 7    | 2.775941 | 2.94318 | 3.10953 | 3.27493 | 3.43933 | 3.60268 | 3.76494 | 3.926047 |
| 8    | 2.778736 | 2.94596 | 3.11229 | 3.27768 | 3.44206 | 3.60540 | 3.76763 | 3.928722 |
| 9    | 2.781530 | 2.94874 | 3.11506 | 3.28042 | 3.44479 | 3.60811 | 3.77033 | 3.931397 |
| 10   | 2.784324 | 2.95152 | 3.11782 | 3.28317 | 3.44752 | 3.61082 | 3.77302 | 3.934071 |
| 11   | 2.787117 | 2.95430 | 3.12059 | 3.28592 | 3.45025 | 3.61353 | 3.77571 | 3.936745 |
| 12   | 2.789911 | 2.95708 | 3.12335 | 3.28867 | 3.45298 | 3.61625 | 3.77841 | 3.939419 |
| 13   | 2.792705 | 2.95986 | 3.12611 | 3.29141 | 3.45571 | 3.61896 | 3.78110 | 3.942093 |
| 14   | 2.795497 | 2.96264 | 3.12888 | 3.29416 | 3.45844 | 3.62167 | 3.78379 | 3.944766 |
| 15   | 2.798290 | 2.96542 | 3.13164 | 3.29691 | 3.46117 | 3.62438 | 3.78649 | 3.947439 |
| 16   | 2.801083 | 2.96819 | 3.13440 | 3.29965 | 3.46390 | 3.62709 | 3.78918 | 3.950111 |
| 17   | 2.803875 | 2.97097 | 3.13716 | 3.30240 | 3.46663 | 3.62980 | 3.79187 | 3.952783 |
| 18   | 2.806667 | 2.97375 | 3.13992 | 3.30514 | 3.46936 | 3.63251 | 3.79456 | 3.955455 |
| 19   | 2.809459 | 2.97653 | 3.14269 | 3.30789 | 3.47208 | 3.63522 | 3.79725 | 3.958127 |
| 20   | 2.812251 | 2.97930 | 3.14545 | 3.31063 | 3.47481 | 3.63793 | 3.79994 | 3.960798 |
| 21   | 2.815042 | 2.98208 | 3.14821 | 3.31338 | 3.47754 | 3.64064 | 3.80263 | 3.963469 |
| 22   | 2.817833 | 2.98486 | 3.15097 | 3.31612 | 3.48027 | 3.64335 | 3.80532 | 3.966139 |
| 23   | 2.820624 | 2.98763 | 3.15373 | 3.31887 | 3.48299 | 3.64606 | 3.80801 | 3.968809 |
| 24   | 2.823415 | 2.99041 | 3.15649 | 3.32161 | 3.48572 | 3.64877 | 3.81070 | 3.971479 |
| 25   | 2.826205 | 2.99318 | 3.15925 | 3.32435 | 3.48845 | 3.65148 | 3.81339 | 3.974148 |
| 26   | 2.828995 | 2.99596 | 3.16201 | 3.32710 | 3.49117 | 3.65418 | 3.81608 | 3.976817 |
| 27   | 2.831785 | 2.99873 | 3.16477 | 3.32984 | 3.49390 | 3.65689 | 3.81877 | 3.979486 |
| 28   | 2.834575 | 3.00151 | 3.16753 | 3.33258 | 3.49662 | 3.65960 | 3.82146 | 3.982155 |
| 29   | 2.837364 | 3.00428 | 3.17029 | 3.33533 | 3.49935 | 3.66231 | 3.82415 | 3.984823 |
| 30   | 2.840153 | 3.00706 | 3.17305 | 3.33807 | 3.50207 | 3.66501 | 3.82683 | 3.987491 |
| 31   | 2.842942 | 3.00983 | 3.17581 | 3.34081 | 3.50480 | 3.66772 | 3.82952 | 3.990158 |
| 32   | 2.845731 | 3.01261 | 3.17856 | 3.34355 | 3.50752 | 3.67042 | 3.83221 | 3.992825 |
| 33   | 2.848520 | 3.01538 | 3.18132 | 3.34629 | 3.51025 | 3.67313 | 3.83490 | 3.995492 |
| 34   | 2.851308 | 3.01815 | 3.18408 | 3.34903 | 3.51297 | 3.67584 | 3.83758 | 3.998159 |
| 35   | 2.854096 | 3.02093 | 3.18684 | 3.35178 | 3.51569 | 3.67854 | 3.84027 | 4.000825 |
| 36   | 2.856884 | 3.02370 | 3.18959 | 3.35452 | 3.51842 | 3.68125 | 3.84295 | 4.003490 |
| 37   | 2.859671 | 3.02647 | 3.19235 | 3.35726 | 3.52114 | 3.68395 | 3.84564 | 4.006156 |
| 38   | 2.862458 | 3.02924 | 3.19511 | 3.36000 | 3.52386 | 3.68665 | 3.84832 | 4.008821 |
| 39   | 2.865246 | 3.03202 | 3.19786 | 3.36274 | 3.52658 | 3.68936 | 3.85101 | 4.011486 |
| 40   | 2.868032 | 3.03479 | 3.20062 | 3.36547 | 3.52931 | 3.69206 | 3.85369 | 4.014150 |
| 41   | 2.870819 | 3.03756 | 3.20337 | 3.36821 | 3.53203 | 3.69476 | 3.85638 | 4.016814 |
| 42   | 2.873605 | 3.04033 | 3.20613 | 3.37095 | 3.53475 | 3.69747 | 3.85906 | 4.019478 |
| 43   | 2.876391 | 3.04310 | 3.20889 | 3.37369 | 3.53747 | 3.70017 | 3.86174 | 4.022141 |
| 44   | 2.879177 | 3.04587 | 3.21164 | 3.37643 | 3.54019 | 3.70287 | 3.86443 | 4.024804 |
| 45   | 2.881963 | 3.04864 | 3.21439 | 3.37917 | 3.54291 | 3.70557 | 3.86711 | 4.027467 |
| 46   | 2.884748 | 3.05141 | 3.21715 | 3.38190 | 3.54563 | 3.70828 | 3.86979 | 4.030129 |
| 47   | 2.887533 | 3.05418 | 3.21990 | 3.38464 | 3.54835 | 3.71098 | 3.87247 | 4.032791 |
| 48   | 2.890318 | 3.05695 | 3.22266 | 3.38738 | 3.55107 | 3.71368 | 3.87516 | 4.035453 |
| 49   | 2.893103 | 3.05972 | 3.22541 | 3.39012 | 3.55379 | 3.71638 | 3.87784 | 4.038115 |
| 50   | 2.895887 | 3.06249 | 3.22816 | 3.39285 | 3.55651 | 3.71908 | 3.88052 | 4.040775 |
| 51   | 2.898671 | 3.06526 | 3.23092 | 3.39559 | 3.55923 | 3.72178 | 3.88320 | 4.043436 |
| 52   | 2.901455 | 3.06803 | 3.23367 | 3.39832 | 3.56194 | 3.72448 | 3.88588 | 4.046096 |
| 53   | 2.904239 | 3.07080 | 3.23642 | 3.40106 | 3.56466 | 3.72718 | 3.88856 | 4.048756 |
| 54   | 2.907022 | 3.07357 | 3.23917 | 3.40380 | 3.56738 | 3.72988 | 3.89124 | 4.051416 |
| 55   | 2.909805 | 3.07633 | 3.24193 | 3.40653 | 3.57010 | 3.73258 | 3.89392 | 4.054075 |
| 56   | 2.912588 | 3.07910 | 3.24468 | 3.40927 | 3.57281 | 3.73528 | 3.89660 | 4.056734 |
| 57   | 2.915371 | 3.08187 | 3.24743 | 3.41200 | 3.57553 | 3.73797 | 3.89928 | 4.059393 |
| 58   | 2.918153 | 3.08464 | 3.25018 | 3.41473 | 3.57825 | 3.74067 | 3.90196 | 4.062051 |
| 59   | 2.920935 | 3.08740 | 3.25293 | 3.41747 | 3.58096 | 3.74337 | 3.90463 | 4.064709 |
| 60   | 2.923717 | 3.09017 | 3.25568 | 3.42020 | 3.58368 | 3.74607 | 3.90731 | 4.067367 |

## SINE BAR CONSTANTS

## Constants for Setting a 10-inch Sine-Bar for 24° to 31°

| Min. | 24°      | 25°     | 26°     | 27°     | 28°     | 29°     | 30°     | 31°      |
|------|----------|---------|---------|---------|---------|---------|---------|----------|
| 0    | 4.067367 | 4.22618 | 4.38371 | 4.53991 | 4.69472 | 4.84810 | 5.00000 | 5.150381 |
| 1    | 4.070024 | 4.22882 | 4.38633 | 4.54250 | 4.69728 | 4.85064 | 5.00252 | 5.152874 |
| 2    | 4.072680 | 4.23145 | 4.38894 | 4.54509 | 4.69985 | 4.85318 | 5.00504 | 5.155367 |
| 3    | 4.075337 | 4.23409 | 4.39155 | 4.54768 | 4.70242 | 4.85573 | 5.00756 | 5.157859 |
| 4    | 4.077993 | 4.23673 | 4.39417 | 4.55027 | 4.70499 | 4.85827 | 5.01007 | 5.160351 |
| 5    | 4.080649 | 4.23936 | 4.39678 | 4.55286 | 4.70755 | 4.86081 | 5.01259 | 5.162843 |
| 6    | 4.083305 | 4.24199 | 4.39939 | 4.55545 | 4.71012 | 4.86335 | 5.01511 | 5.165333 |
| 7    | 4.085960 | 4.24463 | 4.40200 | 4.55804 | 4.71268 | 4.86590 | 5.01762 | 5.167824 |
| 8    | 4.088614 | 4.24726 | 4.40462 | 4.56063 | 4.71525 | 4.86844 | 5.02014 | 5.170314 |
| 9    | 4.091269 | 4.24990 | 4.40723 | 4.56322 | 4.71781 | 4.87098 | 5.02266 | 5.172804 |
| 10   | 4.093923 | 4.25253 | 4.40984 | 4.56580 | 4.72038 | 4.87352 | 5.02517 | 5.175293 |
| 11   | 4.096577 | 4.25516 | 4.41245 | 4.56839 | 4.72294 | 4.87606 | 5.02769 | 5.177782 |
| 12   | 4.099231 | 4.25779 | 4.41506 | 4.57098 | 4.72551 | 4.87860 | 5.03020 | 5.180270 |
| 13   | 4.101883 | 4.26043 | 4.41767 | 4.57357 | 4.72807 | 4.88114 | 5.03271 | 5.182758 |
| 14   | 4.104536 | 4.26306 | 4.42028 | 4.57615 | 4.73063 | 4.88367 | 5.03523 | 5.185246 |
| 15   | 4.107189 | 4.26569 | 4.42289 | 4.57874 | 4.73320 | 4.88621 | 5.03774 | 5.187733 |
| 16   | 4.109840 | 4.26832 | 4.42550 | 4.58133 | 4.73576 | 4.88875 | 5.04025 | 5.190219 |
| 17   | 4.112492 | 4.27095 | 4.42810 | 4.58391 | 4.73832 | 4.89129 | 5.04276 | 5.192706 |
| 18   | 4.115144 | 4.27358 | 4.43071 | 4.58650 | 4.74088 | 4.89382 | 5.04528 | 5.195191 |
| 19   | 4.117795 | 4.27621 | 4.43332 | 4.58908 | 4.74344 | 4.89636 | 5.04779 | 5.197677 |
| 20   | 4.120445 | 4.27884 | 4.43593 | 4.59166 | 4.74600 | 4.89890 | 5.05030 | 5.200161 |
| 21   | 4.123096 | 4.28147 | 4.43853 | 4.59425 | 4.74856 | 4.90143 | 5.05281 | 5.202646 |
| 22   | 4.125746 | 4.28410 | 4.44114 | 4.59683 | 4.75112 | 4.90397 | 5.05532 | 5.205130 |
| 23   | 4.128395 | 4.28672 | 4.44375 | 4.59942 | 4.75368 | 4.90650 | 5.05783 | 5.207613 |
| 24   | 4.131044 | 4.28935 | 4.44635 | 4.60200 | 4.75624 | 4.90904 | 5.06034 | 5.210096 |
| 25   | 4.133693 | 4.29198 | 4.44896 | 4.60458 | 4.75880 | 4.91157 | 5.06285 | 5.212579 |
| 26   | 4.136342 | 4.29461 | 4.45156 | 4.60716 | 4.76136 | 4.91411 | 5.06535 | 5.215061 |
| 27   | 4.138990 | 4.29723 | 4.45417 | 4.60974 | 4.76392 | 4.91664 | 5.06786 | 5.217543 |
| 28   | 4.141638 | 4.29986 | 4.45677 | 4.61233 | 4.76647 | 4.91917 | 5.07037 | 5.220025 |
| 29   | 4.144285 | 4.30249 | 4.45937 | 4.61491 | 4.76903 | 4.92170 | 5.07288 | 5.222506 |
| 30   | 4.146933 | 4.30511 | 4.46198 | 4.61749 | 4.77159 | 4.92424 | 5.07538 | 5.224986 |
| 31   | 4.149580 | 4.30774 | 4.46458 | 4.62007 | 4.77414 | 4.92677 | 5.07789 | 5.227466 |
| 32   | 4.152225 | 4.31036 | 4.46718 | 4.62265 | 4.77670 | 4.92930 | 5.08040 | 5.229945 |
| 33   | 4.154872 | 4.31299 | 4.46979 | 4.62523 | 4.77925 | 4.93183 | 5.08290 | 5.232424 |
| 34   | 4.157518 | 4.31561 | 4.47239 | 4.62780 | 4.78181 | 4.93436 | 5.08541 | 5.234903 |
| 35   | 4.160163 | 4.31823 | 4.47499 | 4.63038 | 4.78436 | 4.93689 | 5.08791 | 5.237381 |
| 36   | 4.162808 | 4.32086 | 4.47759 | 4.63296 | 4.78692 | 4.93942 | 5.09041 | 5.239859 |
| 37   | 4.165453 | 4.32348 | 4.48019 | 4.63554 | 4.78947 | 4.94195 | 5.09292 | 5.242337 |
| 38   | 4.168097 | 4.32610 | 4.48279 | 4.63812 | 4.79203 | 4.94448 | 5.09542 | 5.244813 |
| 39   | 4.170741 | 4.32873 | 4.48539 | 4.64069 | 4.79458 | 4.94700 | 5.09792 | 5.247290 |
| 40   | 4.173385 | 4.33135 | 4.48799 | 4.64327 | 4.79713 | 4.94953 | 5.10043 | 5.249766 |
| 41   | 4.176028 | 4.33397 | 4.49059 | 4.64584 | 4.79968 | 4.95206 | 5.10293 | 5.252242 |
| 42   | 4.178671 | 4.33659 | 4.49319 | 4.64842 | 4.80224 | 4.95459 | 5.10543 | 5.254717 |
| 43   | 4.181314 | 4.33921 | 4.49579 | 4.65100 | 4.80479 | 4.95711 | 5.10793 | 5.257191 |
| 44   | 4.183956 | 4.34183 | 4.49839 | 4.65357 | 4.80734 | 4.95964 | 5.11043 | 5.259665 |
| 45   | 4.186597 | 4.34445 | 4.50098 | 4.65615 | 4.80989 | 4.96217 | 5.11293 | 5.262139 |
| 46   | 4.189239 | 4.34707 | 4.50358 | 4.65872 | 4.81244 | 4.96469 | 5.11543 | 5.264613 |
| 47   | 4.191880 | 4.34969 | 4.50618 | 4.66129 | 4.81499 | 4.96722 | 5.11793 | 5.267086 |
| 48   | 4.194521 | 4.35231 | 4.50878 | 4.66387 | 4.81754 | 4.96974 | 5.12043 | 5.269558 |
| 49   | 4.197162 | 4.35493 | 4.51137 | 4.66644 | 4.82009 | 4.97226 | 5.12293 | 5.272030 |
| 50   | 4.199801 | 4.35755 | 4.51397 | 4.66901 | 4.82263 | 4.97479 | 5.12543 | 5.274502 |
| 51   | 4.202441 | 4.36017 | 4.51656 | 4.67158 | 4.82518 | 4.97731 | 5.12792 | 5.276973 |
| 52   | 4.205080 | 4.36278 | 4.51916 | 4.67416 | 4.82773 | 4.97983 | 5.13042 | 5.279443 |
| 53   | 4.207719 | 4.36540 | 4.52175 | 4.67673 | 4.83028 | 4.98236 | 5.13292 | 5.281914 |
| 54   | 4.210358 | 4.36802 | 4.52435 | 4.67930 | 4.83282 | 4.98488 | 5.13541 | 5.284383 |
| 55   | 4.212996 | 4.37063 | 4.52694 | 4.68187 | 4.83537 | 4.98740 | 5.13791 | 5.286853 |
| 56   | 4.215634 | 4.37325 | 4.52953 | 4.68444 | 4.83792 | 4.98992 | 5.14040 | 5.289321 |
| 57   | 4.218272 | 4.37587 | 4.53213 | 4.68701 | 4.84046 | 4.99244 | 5.14290 | 5.291790 |
| 58   | 4.220910 | 4.37848 | 4.53472 | 4.68958 | 4.84301 | 4.99496 | 5.14539 | 5.294258 |
| 59   | 4.223546 | 4.38110 | 4.53731 | 4.69215 | 4.84555 | 4.99748 | 5.14789 | 5.296726 |
| 60   | 4.226183 | 4.38371 | 4.53991 | 4.69472 | 4.84810 | 5.00000 | 5.15038 | 5.299193 |

## SINE BAR CONSTANTS

## Constants for Setting a 10-inch Sine-Bar for 32° to 39°

| Min. | 32°      | 33°     | 34°     | 35°     | 36°     | 37°     | 38°     | 39°      |
|------|----------|---------|---------|---------|---------|---------|---------|----------|
| 0    | 5.299193 | 5.44639 | 5.59193 | 5.73576 | 5.87785 | 6.01815 | 6.15661 | 6.293204 |
| 1    | 5.301660 | 5.44883 | 5.59434 | 5.73815 | 5.88021 | 6.02047 | 6.15891 | 6.295465 |
| 2    | 5.304125 | 5.45127 | 5.59675 | 5.74053 | 5.88256 | 6.02280 | 6.16120 | 6.297724 |
| 3    | 5.306591 | 5.45371 | 5.59916 | 5.74291 | 5.88491 | 6.02512 | 6.16349 | 6.299984 |
| 4    | 5.309057 | 5.45614 | 5.60157 | 5.74529 | 5.88726 | 6.02744 | 6.16578 | 6.302242 |
| 5    | 5.311522 | 5.45858 | 5.60398 | 5.74767 | 5.88961 | 6.02976 | 6.16807 | 6.304501 |
| 6    | 5.313986 | 5.46102 | 5.60639 | 5.75005 | 5.89196 | 6.03208 | 6.17036 | 6.306758 |
| 7    | 5.316450 | 5.46346 | 5.60880 | 5.75243 | 5.89431 | 6.03440 | 6.17265 | 6.309015 |
| 8    | 5.318913 | 5.46589 | 5.61121 | 5.75481 | 5.89666 | 6.03672 | 6.17494 | 6.311272 |
| 9    | 5.321377 | 5.46833 | 5.61361 | 5.75719 | 5.89901 | 6.03904 | 6.17722 | 6.313529 |
| 10   | 5.323839 | 5.47076 | 5.61602 | 5.75957 | 5.90136 | 6.04136 | 6.17951 | 6.315784 |
| 11   | 5.326302 | 5.47320 | 5.61843 | 5.76195 | 5.90371 | 6.04367 | 6.18180 | 6.318039 |
| 12   | 5.328763 | 5.47563 | 5.62083 | 5.76432 | 5.90606 | 6.04599 | 6.18408 | 6.320293 |
| 13   | 5.331224 | 5.47807 | 5.62324 | 5.76670 | 5.90840 | 6.04831 | 6.18637 | 6.322547 |
| 14   | 5.333685 | 5.48050 | 5.62564 | 5.76908 | 5.91075 | 6.05062 | 6.18865 | 6.324800 |
| 15   | 5.336145 | 5.48293 | 5.62805 | 5.77145 | 5.91310 | 6.05294 | 6.19094 | 6.327054 |
| 16   | 5.338605 | 5.48536 | 5.63045 | 5.77383 | 5.91544 | 6.05526 | 6.19322 | 6.329306 |
| 17   | 5.341064 | 5.48780 | 5.63286 | 5.77620 | 5.91779 | 6.05757 | 6.19551 | 6.331558 |
| 18   | 5.343524 | 5.49023 | 5.63526 | 5.77858 | 5.92013 | 6.05988 | 6.19779 | 6.333809 |
| 19   | 5.345982 | 5.49266 | 5.63766 | 5.78095 | 5.92248 | 6.06220 | 6.20007 | 6.336060 |
| 20   | 5.348440 | 5.49509 | 5.64007 | 5.78332 | 5.92482 | 6.06451 | 6.20235 | 6.338310 |
| 21   | 5.350898 | 5.49752 | 5.64247 | 5.78570 | 5.92716 | 6.06682 | 6.20464 | 6.340559 |
| 22   | 5.353355 | 5.49995 | 5.64487 | 5.78807 | 5.92950 | 6.06914 | 6.20692 | 6.342808 |
| 23   | 5.355812 | 5.50238 | 5.64727 | 5.79044 | 5.93185 | 6.07145 | 6.20920 | 6.345057 |
| 24   | 5.358268 | 5.50481 | 5.64967 | 5.79281 | 5.93419 | 6.07376 | 6.21148 | 6.347305 |
| 25   | 5.360724 | 5.50724 | 5.65207 | 5.79518 | 5.93653 | 6.07607 | 6.21376 | 6.349553 |
| 26   | 5.363179 | 5.50966 | 5.65447 | 5.79755 | 5.93887 | 6.07838 | 6.21604 | 6.351800 |
| 27   | 5.365634 | 5.51209 | 5.65687 | 5.79992 | 5.94121 | 6.08069 | 6.21831 | 6.354046 |
| 28   | 5.368089 | 5.51452 | 5.65927 | 5.80229 | 5.94355 | 6.08300 | 6.22059 | 6.356292 |
| 29   | 5.370543 | 5.51694 | 5.66166 | 5.80466 | 5.94589 | 6.08531 | 6.22287 | 6.358538 |
| 30   | 5.372996 | 5.51937 | 5.66406 | 5.80703 | 5.94823 | 6.08761 | 6.22515 | 6.360782 |
| 31   | 5.375449 | 5.52180 | 5.66646 | 5.80940 | 5.95057 | 6.08992 | 6.22742 | 6.363027 |
| 32   | 5.377902 | 5.52422 | 5.66886 | 5.81177 | 5.95290 | 6.09223 | 6.22970 | 6.365270 |
| 33   | 5.380354 | 5.52664 | 5.67125 | 5.81413 | 5.95524 | 6.09454 | 6.23197 | 6.367514 |
| 34   | 5.382806 | 5.52907 | 5.67365 | 5.81650 | 5.95758 | 6.09684 | 6.23425 | 6.369756 |
| 35   | 5.385257 | 5.53149 | 5.67604 | 5.81886 | 5.95991 | 6.09915 | 6.23652 | 6.371998 |
| 36   | 5.387708 | 5.53392 | 5.67844 | 5.82123 | 5.96225 | 6.10145 | 6.23880 | 6.374240 |
| 37   | 5.390158 | 5.53634 | 5.68083 | 5.82359 | 5.96458 | 6.10376 | 6.24107 | 6.376481 |
| 38   | 5.392609 | 5.53876 | 5.68323 | 5.82596 | 5.96692 | 6.10606 | 6.24334 | 6.378722 |
| 39   | 5.395058 | 5.54118 | 5.68562 | 5.82832 | 5.96925 | 6.10836 | 6.24561 | 6.380962 |
| 40   | 5.397507 | 5.54360 | 5.68801 | 5.83069 | 5.97159 | 6.11067 | 6.24789 | 6.383201 |
| 41   | 5.399955 | 5.54602 | 5.69040 | 5.83305 | 5.97392 | 6.11297 | 6.25016 | 6.385440 |
| 42   | 5.402403 | 5.54844 | 5.69280 | 5.83541 | 5.97625 | 6.11527 | 6.25243 | 6.387679 |
| 43   | 5.404851 | 5.55086 | 5.69519 | 5.83777 | 5.97858 | 6.11757 | 6.25470 | 6.389916 |
| 44   | 5.407298 | 5.55328 | 5.69758 | 5.84014 | 5.98092 | 6.11987 | 6.25697 | 6.392153 |
| 45   | 5.409745 | 5.55570 | 5.69997 | 5.84250 | 5.98325 | 6.12217 | 6.25923 | 6.394390 |
| 46   | 5.412191 | 5.55812 | 5.70236 | 5.84486 | 5.98558 | 6.12447 | 6.26150 | 6.396626 |
| 47   | 5.414637 | 5.56054 | 5.70475 | 5.84722 | 5.98791 | 6.12677 | 6.26377 | 6.398862 |
| 48   | 5.417082 | 5.56296 | 5.70714 | 5.84958 | 5.99024 | 6.12907 | 6.26604 | 6.401097 |
| 49   | 5.419527 | 5.56537 | 5.70952 | 5.85194 | 5.99257 | 6.13137 | 6.26830 | 6.403332 |
| 50   | 5.421971 | 5.56779 | 5.71191 | 5.85429 | 5.99489 | 6.13367 | 6.27057 | 6.405566 |
| 51   | 5.424415 | 5.57021 | 5.71430 | 5.85665 | 5.99722 | 6.13596 | 6.27284 | 6.407799 |
| 52   | 5.426859 | 5.57262 | 5.71669 | 5.85901 | 5.99955 | 6.13826 | 6.27510 | 6.410032 |
| 53   | 5.429302 | 5.57504 | 5.71907 | 5.86137 | 6.00188 | 6.14056 | 6.27737 | 6.412265 |
| 54   | 5.431745 | 5.57745 | 5.72146 | 5.86372 | 6.00420 | 6.14285 | 6.27963 | 6.414497 |
| 55   | 5.434187 | 5.57987 | 5.72384 | 5.86608 | 6.00653 | 6.14515 | 6.28189 | 6.416728 |
| 56   | 5.436628 | 5.58228 | 5.72623 | 5.86844 | 6.00885 | 6.14744 | 6.28416 | 6.418959 |
| 57   | 5.439070 | 5.58469 | 5.72861 | 5.87079 | 6.01118 | 6.14974 | 6.28642 | 6.421189 |
| 58   | 5.441511 | 5.58711 | 5.73100 | 5.87315 | 6.01350 | 6.15203 | 6.28868 | 6.423419 |
| 59   | 5.443951 | 5.58952 | 5.73338 | 5.87550 | 6.01583 | 6.15432 | 6.29094 | 6.425648 |
| 60   | 5.446391 | 5.59193 | 5.73576 | 5.87785 | 6.01815 | 6.15661 | 6.29320 | 6.427876 |

## Constants for Setting a 10-inch Sine-Bar for 40° to 47°

| Min. | 40°      | 41°     | 42°     | 43°     | 44°     | 45°     | 46°     | 47°      |
|------|----------|---------|---------|---------|---------|---------|---------|----------|
| 0    | 6.427876 | 6.56059 | 6.69131 | 6.81998 | 6.94658 | 7.07107 | 7.19340 | 7.313537 |
| 1    | 6.430104 | 6.56279 | 6.69347 | 6.82211 | 6.94868 | 7.07312 | 7.19542 | 7.315521 |
| 2    | 6.432332 | 6.56498 | 6.69563 | 6.82424 | 6.95077 | 7.07518 | 7.19744 | 7.317503 |
| 3    | 6.434559 | 6.56717 | 6.69779 | 6.82636 | 6.95286 | 7.07724 | 7.19946 | 7.319486 |
| 4    | 6.436785 | 6.56937 | 6.69995 | 6.82849 | 6.95495 | 7.07929 | 7.20148 | 7.321467 |
| 5    | 6.439011 | 6.57156 | 6.70211 | 6.83061 | 6.95704 | 7.08134 | 7.20349 | 7.323449 |
| 6    | 6.441236 | 6.57375 | 6.70427 | 6.83274 | 6.95913 | 7.08340 | 7.20551 | 7.325429 |
| 7    | 6.443461 | 6.57594 | 6.70642 | 6.83486 | 6.96122 | 7.08545 | 7.20753 | 7.327409 |
| 8    | 6.445686 | 6.57814 | 6.70858 | 6.83698 | 6.96330 | 7.08750 | 7.20954 | 7.329389 |
| 9    | 6.447909 | 6.58033 | 6.71074 | 6.83911 | 6.96539 | 7.08956 | 7.21156 | 7.331367 |
| 10   | 6.450132 | 6.58252 | 6.71290 | 6.84123 | 6.96748 | 7.09161 | 7.21357 | 7.333345 |
| 11   | 6.452355 | 6.58471 | 6.71505 | 6.84335 | 6.96957 | 7.09366 | 7.21559 | 7.335322 |
| 12   | 6.454577 | 6.58689 | 6.71721 | 6.84547 | 6.97165 | 7.09571 | 7.21760 | 7.337299 |
| 13   | 6.456799 | 6.58908 | 6.71936 | 6.84759 | 6.97374 | 7.09776 | 7.21962 | 7.339275 |
| 14   | 6.459020 | 6.59127 | 6.72151 | 6.84971 | 6.97582 | 7.09981 | 7.22163 | 7.341250 |
| 15   | 6.461240 | 6.59346 | 6.72367 | 6.85183 | 6.97790 | 7.10185 | 7.22364 | 7.343225 |
| 16   | 6.463460 | 6.59564 | 6.72582 | 6.85395 | 6.97999 | 7.10390 | 7.22565 | 7.345200 |
| 17   | 6.465679 | 6.59783 | 6.72797 | 6.85607 | 6.98207 | 7.10595 | 7.22766 | 7.347173 |
| 18   | 6.467898 | 6.60002 | 6.73012 | 6.85818 | 6.98415 | 7.10800 | 7.22967 | 7.349146 |
| 19   | 6.470116 | 6.60220 | 6.73228 | 6.86030 | 6.98623 | 7.11004 | 7.23168 | 7.351119 |
| 20   | 6.472334 | 6.60439 | 6.73443 | 6.86242 | 6.98832 | 7.11209 | 7.23369 | 7.353090 |
| 21   | 6.474551 | 6.60657 | 6.73658 | 6.86453 | 6.99040 | 7.11413 | 7.23570 | 7.355061 |
| 22   | 6.476768 | 6.60875 | 6.73873 | 6.86665 | 6.99248 | 7.11617 | 7.23771 | 7.357032 |
| 23   | 6.478984 | 6.61094 | 6.74088 | 6.86876 | 6.99455 | 7.11822 | 7.23971 | 7.359002 |
| 24   | 6.481199 | 6.61312 | 6.74302 | 6.87088 | 6.99663 | 7.12026 | 7.24172 | 7.360971 |
| 25   | 6.483414 | 6.61530 | 6.74517 | 6.87299 | 6.99871 | 7.12230 | 7.24372 | 7.362940 |
| 26   | 6.485629 | 6.61748 | 6.74732 | 6.87510 | 7.00079 | 7.12434 | 7.24573 | 7.364908 |
| 27   | 6.487843 | 6.61966 | 6.74947 | 6.87721 | 7.00287 | 7.12639 | 7.24773 | 7.366875 |
| 28   | 6.490056 | 6.62184 | 6.75161 | 6.87932 | 7.00494 | 7.12843 | 7.24974 | 7.368842 |
| 29   | 6.492269 | 6.62402 | 6.75376 | 6.88144 | 7.00702 | 7.13047 | 7.25174 | 7.370808 |
| 30   | 6.494481 | 6.62620 | 6.75590 | 6.88355 | 7.00909 | 7.13250 | 7.25374 | 7.372774 |
| 31   | 6.496692 | 6.62838 | 6.75805 | 6.88566 | 7.01117 | 7.13454 | 7.25575 | 7.374738 |
| 32   | 6.498903 | 6.63056 | 6.76019 | 6.88776 | 7.01324 | 7.13658 | 7.25775 | 7.376703 |
| 33   | 6.501114 | 6.63273 | 6.76233 | 6.88987 | 7.01531 | 7.13862 | 7.25975 | 7.378666 |
| 34   | 6.503324 | 6.63491 | 6.76448 | 6.89198 | 7.01739 | 7.14066 | 7.26175 | 7.380629 |
| 35   | 6.505533 | 6.63709 | 6.76662 | 6.89409 | 7.01946 | 7.14269 | 7.26375 | 7.382592 |
| 36   | 6.507742 | 6.63926 | 6.76876 | 6.89620 | 7.02153 | 7.14473 | 7.26575 | 7.384553 |
| 37   | 6.509951 | 6.64144 | 6.77090 | 6.89830 | 7.02360 | 7.14676 | 7.26775 | 7.386515 |
| 38   | 6.512159 | 6.64361 | 6.77304 | 6.90041 | 7.02567 | 7.14880 | 7.26974 | 7.388475 |
| 39   | 6.514366 | 6.64579 | 6.77518 | 6.90251 | 7.02774 | 7.15083 | 7.27174 | 7.390435 |
| 40   | 6.516572 | 6.64796 | 6.77732 | 6.90462 | 7.02981 | 7.15286 | 7.27374 | 7.392395 |
| 41   | 6.518779 | 6.65013 | 6.77946 | 6.90672 | 7.03188 | 7.15490 | 7.27573 | 7.394353 |
| 42   | 6.520984 | 6.65230 | 6.78160 | 6.90882 | 7.03395 | 7.15693 | 7.27773 | 7.396311 |
| 43   | 6.523189 | 6.65448 | 6.78373 | 6.91093 | 7.03601 | 7.15896 | 7.27972 | 7.398269 |
| 44   | 6.525394 | 6.65665 | 6.78587 | 6.91303 | 7.03808 | 7.16099 | 7.28172 | 7.400225 |
| 45   | 6.527598 | 6.65882 | 6.78801 | 6.91513 | 7.04015 | 7.16302 | 7.28371 | 7.402182 |
| 46   | 6.529801 | 6.66099 | 6.79014 | 6.91723 | 7.04221 | 7.16505 | 7.28570 | 7.404137 |
| 47   | 6.532004 | 6.66316 | 6.79228 | 6.91933 | 7.04428 | 7.16708 | 7.28769 | 7.406092 |
| 48   | 6.534206 | 6.66532 | 6.79441 | 6.92143 | 7.04634 | 7.16911 | 7.28969 | 7.408046 |
| 49   | 6.536408 | 6.66749 | 6.79655 | 6.92353 | 7.04841 | 7.17113 | 7.29168 | 7.410000 |
| 50   | 6.538609 | 6.66966 | 6.79868 | 6.92563 | 7.05047 | 7.17316 | 7.29367 | 7.411952 |
| 51   | 6.540810 | 6.67183 | 6.80081 | 6.92773 | 7.05253 | 7.17519 | 7.29566 | 7.413905 |
| 52   | 6.543010 | 6.67399 | 6.80295 | 6.92982 | 7.05459 | 7.17721 | 7.29765 | 7.415857 |
| 53   | 6.545209 | 6.67616 | 6.80508 | 6.93192 | 7.05666 | 7.17924 | 7.29964 | 7.417808 |
| 54   | 6.547409 | 6.67833 | 6.80721 | 6.93402 | 7.05872 | 7.18126 | 7.30162 | 7.419759 |
| 55   | 6.549607 | 6.68049 | 6.80934 | 6.93611 | 7.06078 | 7.18329 | 7.30361 | 7.421709 |
| 56   | 6.551805 | 6.68265 | 6.81147 | 6.93821 | 7.06284 | 7.18531 | 7.30560 | 7.423658 |
| 57   | 6.554002 | 6.68482 | 6.81360 | 6.94030 | 7.06489 | 7.18733 | 7.30758 | 7.425606 |
| 58   | 6.556199 | 6.68698 | 6.81573 | 6.94240 | 7.06695 | 7.18936 | 7.30957 | 7.427554 |
| 59   | 6.558395 | 6.68914 | 6.81786 | 6.94449 | 7.06901 | 7.19138 | 7.31155 | 7.429502 |
| 60   | 6.560590 | 6.69131 | 6.81998 | 6.94658 | 7.07107 | 7.19340 | 7.31354 | 7.431448 |

## SINE BAR CONSTANTS

## Constants for Setting a 10-inch Sine-Bar for 48° to 55°

| Min. | 48°      | 49°     | 50°     | 51°     | 52°     | 53°     | 54°     | 55°      |
|------|----------|---------|---------|---------|---------|---------|---------|----------|
| 0    | 7.431448 | 7.54710 | 7.66044 | 7.77146 | 7.88011 | 7.98636 | 8.09017 | 8.191521 |
| 1    | 7.433394 | 7.54900 | 7.66231 | 7.77329 | 7.88190 | 7.98811 | 8.09188 | 8.193189 |
| 2    | 7.435340 | 7.55091 | 7.66418 | 7.77512 | 7.88369 | 7.98986 | 8.09359 | 8.194856 |
| 3    | 7.437285 | 7.55282 | 7.66605 | 7.77695 | 7.88548 | 7.99160 | 8.09530 | 8.196523 |
| 4    | 7.439229 | 7.55472 | 7.66792 | 7.77878 | 7.88727 | 7.99335 | 8.09700 | 8.198189 |
| 5    | 7.441173 | 7.55663 | 7.66979 | 7.78060 | 7.88905 | 7.99510 | 8.09871 | 8.199854 |
| 6    | 7.443115 | 7.55853 | 7.67165 | 7.78243 | 7.89084 | 7.99685 | 8.10042 | 8.201519 |
| 7    | 7.445058 | 7.56044 | 7.67352 | 7.78426 | 7.89263 | 7.99859 | 8.10212 | 8.203182 |
| 8    | 7.447000 | 7.56234 | 7.67538 | 7.78608 | 7.89441 | 8.00034 | 8.10383 | 8.204846 |
| 9    | 7.448941 | 7.56425 | 7.67725 | 7.78791 | 7.89620 | 8.00208 | 8.10553 | 8.206509 |
| 10   | 7.450881 | 7.56615 | 7.67911 | 7.78973 | 7.89798 | 8.00383 | 8.10723 | 8.208171 |
| 11   | 7.452821 | 7.56805 | 7.68097 | 7.79156 | 7.89977 | 8.00557 | 8.10894 | 8.209832 |
| 12   | 7.454760 | 7.56995 | 7.68284 | 7.79338 | 7.90155 | 8.00731 | 8.11064 | 8.211493 |
| 13   | 7.456699 | 7.57185 | 7.68470 | 7.79520 | 7.90333 | 8.00906 | 8.11234 | 8.213152 |
| 14   | 7.458637 | 7.57375 | 7.68656 | 7.79702 | 7.90511 | 8.01080 | 8.11404 | 8.214811 |
| 15   | 7.460574 | 7.57565 | 7.68842 | 7.79884 | 7.90690 | 8.01254 | 8.11574 | 8.216470 |
| 16   | 7.462511 | 7.57755 | 7.69028 | 7.80067 | 7.90868 | 8.01428 | 8.11744 | 8.218127 |
| 17   | 7.464447 | 7.57945 | 7.69214 | 7.80248 | 7.91046 | 8.01602 | 8.11914 | 8.219784 |
| 18   | 7.466382 | 7.58134 | 7.69400 | 7.80430 | 7.91224 | 8.01776 | 8.12084 | 8.221440 |
| 19   | 7.468317 | 7.58324 | 7.69585 | 7.80612 | 7.91401 | 8.01950 | 8.12253 | 8.223096 |
| 20   | 7.470251 | 7.58514 | 7.69771 | 7.80794 | 7.91579 | 8.02123 | 8.12423 | 8.224751 |
| 21   | 7.472184 | 7.58703 | 7.69957 | 7.80976 | 7.91757 | 8.02297 | 8.12592 | 8.226405 |
| 22   | 7.474117 | 7.58893 | 7.70142 | 7.81157 | 7.91935 | 8.02470 | 8.12762 | 8.228059 |
| 23   | 7.476050 | 7.59082 | 7.70328 | 7.81339 | 7.92112 | 8.02644 | 8.12931 | 8.229712 |
| 24   | 7.477981 | 7.59271 | 7.70513 | 7.81521 | 7.92290 | 8.02818 | 8.13101 | 8.231364 |
| 25   | 7.479912 | 7.59461 | 7.70699 | 7.81702 | 7.92467 | 8.02991 | 8.13270 | 8.233015 |
| 26   | 7.481843 | 7.59650 | 7.70884 | 7.81883 | 7.92645 | 8.03164 | 8.13439 | 8.234666 |
| 27   | 7.483772 | 7.59839 | 7.71069 | 7.82065 | 7.92822 | 8.03337 | 8.13608 | 8.236316 |
| 28   | 7.485701 | 7.60028 | 7.71254 | 7.82246 | 7.92999 | 8.03511 | 8.13778 | 8.237966 |
| 29   | 7.487629 | 7.60217 | 7.71440 | 7.82427 | 7.93176 | 8.03684 | 8.13947 | 8.239614 |
| 30   | 7.489557 | 7.60406 | 7.71625 | 7.82608 | 7.93353 | 8.03857 | 8.14116 | 8.241262 |
| 31   | 7.491485 | 7.60595 | 7.71810 | 7.82789 | 7.93530 | 8.04030 | 8.14284 | 8.242909 |
| 32   | 7.493411 | 7.60784 | 7.71994 | 7.82970 | 7.93707 | 8.04203 | 8.14453 | 8.244555 |
| 33   | 7.495337 | 7.60972 | 7.72179 | 7.83151 | 7.93884 | 8.04376 | 8.14622 | 8.246202 |
| 34   | 7.497262 | 7.61161 | 7.72364 | 7.83332 | 7.94061 | 8.04548 | 8.14791 | 8.247847 |
| 35   | 7.499187 | 7.61350 | 7.72549 | 7.83513 | 7.94238 | 8.04721 | 8.14959 | 8.249492 |
| 36   | 7.501111 | 7.61538 | 7.72734 | 7.83693 | 7.94415 | 8.04894 | 8.15128 | 8.251135 |
| 37   | 7.503034 | 7.61727 | 7.72918 | 7.83874 | 7.94591 | 8.05066 | 8.15296 | 8.252778 |
| 38   | 7.504957 | 7.61915 | 7.73103 | 7.84055 | 7.94768 | 8.05239 | 8.15465 | 8.254421 |
| 39   | 7.506879 | 7.62104 | 7.73287 | 7.84235 | 7.94944 | 8.05411 | 8.15633 | 8.256063 |
| 40   | 7.508801 | 7.62292 | 7.73472 | 7.84416 | 7.95121 | 8.05584 | 8.15801 | 8.257704 |
| 41   | 7.510721 | 7.62480 | 7.73656 | 7.84596 | 7.95297 | 8.05756 | 8.15969 | 8.259343 |
| 42   | 7.512641 | 7.62668 | 7.73840 | 7.84776 | 7.95474 | 8.05928 | 8.16138 | 8.260983 |
| 43   | 7.514561 | 7.62856 | 7.74024 | 7.84957 | 7.95650 | 8.06100 | 8.16306 | 8.262622 |
| 44   | 7.516480 | 7.63045 | 7.74209 | 7.85137 | 7.95826 | 8.06273 | 8.16474 | 8.264260 |
| 45   | 7.518398 | 7.63232 | 7.74393 | 7.85317 | 7.96002 | 8.06445 | 8.16642 | 8.265898 |
| 46   | 7.520316 | 7.63420 | 7.74577 | 7.85497 | 7.96178 | 8.06617 | 8.16809 | 8.267534 |
| 47   | 7.522233 | 7.63608 | 7.74761 | 7.85677 | 7.96354 | 8.06788 | 8.16977 | 8.269171 |
| 48   | 7.524149 | 7.63796 | 7.74944 | 7.85857 | 7.96530 | 8.06960 | 8.17145 | 8.270805 |
| 49   | 7.526065 | 7.63984 | 7.75128 | 7.86037 | 7.96706 | 8.07132 | 8.17313 | 8.272441 |
| 50   | 7.527980 | 7.64171 | 7.75312 | 7.86217 | 7.96882 | 8.07304 | 8.17480 | 8.274075 |
| 51   | 7.529894 | 7.64359 | 7.75496 | 7.86396 | 7.97057 | 8.07475 | 8.17648 | 8.275707 |
| 52   | 7.531808 | 7.64547 | 7.75679 | 7.86576 | 7.97233 | 8.07647 | 8.17815 | 8.277340 |
| 53   | 7.533722 | 7.64734 | 7.75863 | 7.86756 | 7.97408 | 8.07819 | 8.17982 | 8.278973 |
| 54   | 7.535634 | 7.64921 | 7.76046 | 7.86935 | 7.97584 | 8.07990 | 8.18150 | 8.280603 |
| 55   | 7.537546 | 7.65109 | 7.76230 | 7.87115 | 7.97759 | 8.08161 | 8.18317 | 8.282234 |
| 56   | 7.539457 | 7.65296 | 7.76413 | 7.87294 | 7.97935 | 8.08333 | 8.18484 | 8.283864 |
| 57   | 7.541368 | 7.65483 | 7.76596 | 7.87473 | 7.98110 | 8.08504 | 8.18651 | 8.285493 |
| 58   | 7.543278 | 7.65670 | 7.76780 | 7.87652 | 7.98285 | 8.08675 | 8.18818 | 8.287121 |
| 59   | 7.545187 | 7.65857 | 7.76963 | 7.87832 | 7.98460 | 8.08846 | 8.18985 | 8.288749 |
| 60   | 7.547096 | 7.66044 | 7.77146 | 7.88011 | 7.98636 | 8.09017 | 8.19152 | 8.290376 |

## SINE BAR CONSTANTS

## Constants for 75-mm Sine-Bar

## Constants for Setting a 75-mm Sine-Bar for 0° to 7°

| Min. | 0°       | 1°       | 2°       | 3°       | 4°       | 5°       | 6°       | 7°        |
|------|----------|----------|----------|----------|----------|----------|----------|-----------|
| 0    | 0.000000 | 1.308931 | 2.617462 | 3.925197 | 5.231736 | 6.536681 | 7.839635 | 9.140201  |
| 1    | 0.021817 | 1.330744 | 2.639266 | 3.946983 | 5.253499 | 6.558414 | 7.861332 | 9.161855  |
| 2    | 0.043633 | 1.352557 | 2.661068 | 3.968770 | 5.275262 | 6.580147 | 7.883028 | 9.183507  |
| 3    | 0.065450 | 1.374370 | 2.682871 | 3.990556 | 5.297024 | 6.601880 | 7.904724 | 9.205160  |
| 4    | 0.087266 | 1.396183 | 2.704674 | 4.012341 | 5.318786 | 6.623611 | 7.926418 | 9.226810  |
| 5    | 0.109083 | 1.417996 | 2.726476 | 4.034126 | 5.340548 | 6.645342 | 7.948112 | 9.248462  |
| 6    | 0.130900 | 1.439808 | 2.748278 | 4.055911 | 5.362309 | 6.667072 | 7.969805 | 9.270111  |
| 7    | 0.152716 | 1.461621 | 2.770080 | 4.077695 | 5.384069 | 6.688803 | 7.991498 | 9.291760  |
| 8    | 0.174533 | 1.483433 | 2.791882 | 4.099480 | 5.405829 | 6.710532 | 8.013190 | 9.313408  |
| 9    | 0.196349 | 1.505245 | 2.813683 | 4.121264 | 5.427589 | 6.732261 | 8.034882 | 9.335055  |
| 10   | 0.218166 | 1.527058 | 2.835484 | 4.143047 | 5.449348 | 6.753989 | 8.056572 | 9.356702  |
| 11   | 0.239982 | 1.548870 | 2.857285 | 4.164830 | 5.471107 | 6.775717 | 8.078262 | 9.378348  |
| 12   | 0.261799 | 1.570682 | 2.879086 | 4.186613 | 5.492865 | 6.797443 | 8.099952 | 9.399993  |
| 13   | 0.283615 | 1.592493 | 2.900886 | 4.208395 | 5.514623 | 6.819170 | 8.121640 | 9.421637  |
| 14   | 0.305432 | 1.614305 | 2.922686 | 4.230177 | 5.536380 | 6.840896 | 8.143329 | 9.443280  |
| 15   | 0.327248 | 1.636116 | 2.944486 | 4.251959 | 5.558137 | 6.862622 | 8.165016 | 9.464923  |
| 16   | 0.349065 | 1.657928 | 2.966286 | 4.273740 | 5.579894 | 6.884346 | 8.186703 | 9.486565  |
| 17   | 0.370881 | 1.679739 | 2.988085 | 4.295521 | 5.601649 | 6.906071 | 8.208388 | 9.508205  |
| 18   | 0.392697 | 1.701550 | 3.009884 | 4.317302 | 5.623405 | 6.927794 | 8.230074 | 9.529846  |
| 19   | 0.414514 | 1.723361 | 3.031683 | 4.339082 | 5.645160 | 6.949517 | 8.251758 | 9.551485  |
| 20   | 0.436330 | 1.745172 | 3.053482 | 4.360862 | 5.666914 | 6.971240 | 8.273442 | 9.573124  |
| 21   | 0.458146 | 1.766982 | 3.075280 | 4.382642 | 5.688668 | 6.992965 | 8.295125 | 9.594762  |
| 22   | 0.479962 | 1.788793 | 3.097079 | 4.404421 | 5.710422 | 7.014683 | 8.316808 | 9.616399  |
| 23   | 0.501778 | 1.810603 | 3.118877 | 4.426200 | 5.732174 | 7.036404 | 8.338489 | 9.638035  |
| 24   | 0.523595 | 1.832413 | 3.140674 | 4.447978 | 5.753927 | 7.058124 | 8.360170 | 9.659670  |
| 25   | 0.545411 | 1.854223 | 3.162472 | 4.469756 | 5.775679 | 7.079843 | 8.381850 | 9.681304  |
| 26   | 0.567227 | 1.876033 | 3.184269 | 4.491534 | 5.797431 | 7.101562 | 8.403530 | 9.702938  |
| 27   | 0.589043 | 1.897843 | 3.206065 | 4.513311 | 5.819182 | 7.123280 | 8.425209 | 9.724571  |
| 28   | 0.610859 | 1.919653 | 3.227862 | 4.535088 | 5.840933 | 7.144998 | 8.446887 | 9.746203  |
| 29   | 0.632674 | 1.941462 | 3.249658 | 4.556864 | 5.862682 | 7.166715 | 8.468564 | 9.767834  |
| 30   | 0.654490 | 1.963271 | 3.271454 | 4.578640 | 5.884432 | 7.188432 | 8.490241 | 9.789465  |
| 31   | 0.676306 | 1.985080 | 3.293250 | 4.600416 | 5.906182 | 7.210148 | 8.511917 | 9.811094  |
| 32   | 0.698122 | 2.006889 | 3.315045 | 4.622191 | 5.927930 | 7.231863 | 8.533592 | 9.832723  |
| 33   | 0.719937 | 2.028698 | 3.336840 | 4.643967 | 5.949678 | 7.253578 | 8.555267 | 9.854351  |
| 34   | 0.741753 | 2.050506 | 3.358635 | 4.665741 | 5.971426 | 7.275291 | 8.576941 | 9.875978  |
| 35   | 0.763568 | 2.072315 | 3.380430 | 4.687515 | 5.993173 | 7.297005 | 8.598615 | 9.897604  |
| 36   | 0.785384 | 2.094123 | 3.402224 | 4.709289 | 6.014919 | 7.318717 | 8.620286 | 9.919230  |
| 37   | 0.807199 | 2.115931 | 3.424018 | 4.731062 | 6.036666 | 7.340430 | 8.641958 | 9.940854  |
| 38   | 0.829015 | 2.137739 | 3.445812 | 4.752836 | 6.058411 | 7.362141 | 8.663629 | 9.962478  |
| 39   | 0.850830 | 2.159546 | 3.467606 | 4.774608 | 6.080156 | 7.383852 | 8.685300 | 9.984100  |
| 40   | 0.872645 | 2.181354 | 3.489399 | 4.796380 | 6.101901 | 7.405562 | 8.706968 | 10.005722 |
| 41   | 0.894460 | 2.203161 | 3.511191 | 4.818152 | 6.123645 | 7.427272 | 8.728638 | 10.027344 |
| 42   | 0.916275 | 2.224968 | 3.532984 | 4.839923 | 6.145388 | 7.448981 | 8.750305 | 10.048964 |
| 43   | 0.938090 | 2.246775 | 3.554776 | 4.861694 | 6.167131 | 7.470690 | 8.771973 | 10.070583 |
| 44   | 0.959905 | 2.268582 | 3.576568 | 4.883465 | 6.188873 | 7.492397 | 8.793639 | 10.092202 |
| 45   | 0.981720 | 2.290389 | 3.598360 | 4.905235 | 6.210616 | 7.514105 | 8.815305 | 10.113820 |
| 46   | 1.003534 | 2.312195 | 3.620151 | 4.927004 | 6.232358 | 7.535811 | 8.836970 | 10.135437 |
| 47   | 1.025349 | 2.334001 | 3.641942 | 4.948774 | 6.254098 | 7.557517 | 8.858634 | 10.157053 |
| 48   | 1.047164 | 2.355807 | 3.663733 | 4.970542 | 6.275839 | 7.579223 | 8.880298 | 10.178668 |
| 49   | 1.068978 | 2.377613 | 3.685523 | 4.992311 | 6.297578 | 7.600927 | 8.901960 | 10.200282 |
| 50   | 1.090792 | 2.399418 | 3.707313 | 5.014079 | 6.319318 | 7.622631 | 8.923623 | 10.221896 |
| 51   | 1.112607 | 2.421224 | 3.729103 | 5.035847 | 6.341056 | 7.644334 | 8.945284 | 10.243508 |
| 52   | 1.134421 | 2.443029 | 3.750892 | 5.057614 | 6.362795 | 7.666037 | 8.966945 | 10.265121 |
| 53   | 1.156235 | 2.464834 | 3.772682 | 5.079381 | 6.384532 | 7.687739 | 8.988604 | 10.286731 |
| 54   | 1.178049 | 2.486638 | 3.794471 | 5.101147 | 6.406270 | 7.709441 | 9.010263 | 10.308341 |
| 55   | 1.199863 | 2.508443 | 3.816259 | 5.122913 | 6.428006 | 7.731141 | 9.031921 | 10.329950 |
| 56   | 1.221676 | 2.530247 | 3.838048 | 5.144678 | 6.449742 | 7.752841 | 9.053579 | 10.351559 |
| 57   | 1.243490 | 2.552051 | 3.859835 | 5.166443 | 6.471478 | 7.774540 | 9.075235 | 10.373166 |
| 58   | 1.265304 | 2.573855 | 3.881623 | 5.188208 | 6.493213 | 7.796239 | 9.096891 | 10.394773 |
| 59   | 1.287117 | 2.595659 | 3.903410 | 5.209972 | 6.514947 | 7.817937 | 9.118546 | 10.416378 |
| 60   | 1.308931 | 2.617462 | 3.925197 | 5.231736 | 6.536681 | 7.839635 | 9.140201 | 10.437983 |



## SINE BAR CONSTANTS

## Constants for Setting a 75-mm Sine-Bar for 8° to 15°

| Min. | 8°        | 9°        | 10°       | 11°       | 12°       | 13°       | 14°       | 15°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 10.437983 | 11.732585 | 13.023614 | 14.310675 | 15.593377 | 16.871330 | 18.144142 | 19.411428 |
| 1    | 10.459586 | 11.754132 | 13.045098 | 14.332089 | 15.614717 | 16.892586 | 18.165310 | 19.432501 |
| 2    | 10.481191 | 11.775680 | 13.066583 | 14.353505 | 15.636055 | 16.913841 | 18.186748 | 19.453573 |
| 3    | 10.502792 | 11.797225 | 13.088064 | 14.374917 | 15.657392 | 16.935095 | 18.207642 | 19.474642 |
| 4    | 10.524393 | 11.818769 | 13.109546 | 14.396328 | 15.678726 | 16.956348 | 18.228804 | 19.495708 |
| 5    | 10.545993 | 11.840312 | 13.131025 | 14.417738 | 15.700060 | 16.977598 | 18.249966 | 19.516773 |
| 6    | 10.567594 | 11.861856 | 13.152505 | 14.439148 | 15.721394 | 16.998850 | 18.271128 | 19.537840 |
| 7    | 10.589191 | 11.883397 | 13.173983 | 14.460556 | 15.742724 | 17.020098 | 18.292286 | 19.558901 |
| 8    | 10.610788 | 11.904937 | 13.195459 | 14.481962 | 15.764053 | 17.041344 | 18.313442 | 19.579962 |
| 9    | 10.632385 | 11.926476 | 13.216935 | 14.503367 | 15.785382 | 17.062588 | 18.334597 | 19.601021 |
| 10   | 10.653982 | 11.948016 | 13.238410 | 14.524773 | 15.806710 | 17.083834 | 18.355751 | 19.622080 |
| 11   | 10.675576 | 11.969553 | 13.259884 | 14.546175 | 15.828035 | 17.105076 | 18.376904 | 19.643135 |
| 12   | 10.697170 | 11.991089 | 13.281356 | 14.567576 | 15.849360 | 17.126316 | 18.398054 | 19.664188 |
| 13   | 10.718762 | 12.012625 | 13.302827 | 14.588977 | 15.870683 | 17.147554 | 18.419203 | 19.685242 |
| 14   | 10.740356 | 12.034160 | 13.324298 | 14.610377 | 15.892006 | 17.168793 | 18.440351 | 19.706293 |
| 15   | 10.761947 | 12.055693 | 13.345766 | 14.631775 | 15.913326 | 17.190029 | 18.461498 | 19.727341 |
| 16   | 10.783537 | 12.077225 | 13.367234 | 14.653171 | 15.934645 | 17.211264 | 18.482641 | 19.748388 |
| 17   | 10.805127 | 12.098757 | 13.388701 | 14.674567 | 15.955963 | 17.232500 | 18.503786 | 19.769436 |
| 18   | 10.826715 | 12.120287 | 13.410167 | 14.695961 | 15.977280 | 17.253731 | 18.524927 | 19.790480 |
| 19   | 10.848303 | 12.141816 | 13.431631 | 14.717354 | 15.998594 | 17.274961 | 18.546066 | 19.811522 |
| 20   | 10.869889 | 12.163344 | 13.453094 | 14.738746 | 16.019909 | 17.296190 | 18.567204 | 19.832561 |
| 21   | 10.891476 | 12.184873 | 13.474557 | 14.760138 | 16.041222 | 17.317419 | 18.588343 | 19.853601 |
| 22   | 10.913060 | 12.206398 | 13.496017 | 14.781527 | 16.062532 | 17.338646 | 18.609476 | 19.874640 |
| 23   | 10.934645 | 12.227923 | 13.517477 | 14.802914 | 16.083841 | 17.359869 | 18.630610 | 19.895676 |
| 24   | 10.956227 | 12.249447 | 13.538936 | 14.824301 | 16.105150 | 17.381092 | 18.651741 | 19.916708 |
| 25   | 10.977810 | 12.270971 | 13.560394 | 14.845687 | 16.126457 | 17.402315 | 18.672873 | 19.937742 |
| 26   | 10.999391 | 12.292493 | 13.581850 | 14.867071 | 16.147762 | 17.423536 | 18.694002 | 19.958773 |
| 27   | 11.020970 | 12.314013 | 13.603306 | 14.888453 | 16.169067 | 17.444754 | 18.715128 | 19.979801 |
| 28   | 11.042550 | 12.335533 | 13.624760 | 14.909835 | 16.190369 | 17.465971 | 18.736254 | 20.000828 |
| 29   | 11.064129 | 12.357053 | 13.646214 | 14.931216 | 16.211672 | 17.487188 | 18.757380 | 20.021854 |
| 30   | 11.085706 | 12.378571 | 13.667665 | 14.952596 | 16.232971 | 17.508402 | 18.778502 | 20.042879 |
| 31   | 11.107283 | 12.400087 | 13.689116 | 14.973973 | 16.254271 | 17.529615 | 18.799622 | 20.063900 |
| 32   | 11.128859 | 12.421604 | 13.710566 | 14.995351 | 16.275568 | 17.550829 | 18.820742 | 20.084923 |
| 33   | 11.150434 | 12.443118 | 13.732014 | 15.016726 | 16.296864 | 17.572039 | 18.841860 | 20.105940 |
| 34   | 11.172007 | 12.464632 | 13.753461 | 15.038100 | 16.318159 | 17.593246 | 18.862974 | 20.126957 |
| 35   | 11.193579 | 12.486144 | 13.774906 | 15.059472 | 16.339451 | 17.614452 | 18.884089 | 20.147972 |
| 36   | 11.215152 | 12.507657 | 13.796352 | 15.080845 | 16.360744 | 17.635660 | 18.905203 | 20.168987 |
| 37   | 11.236722 | 12.529167 | 13.817796 | 15.102215 | 16.382034 | 17.656864 | 18.926313 | 20.189999 |
| 38   | 11.258291 | 12.550676 | 13.839238 | 15.123584 | 16.403322 | 17.678066 | 18.947424 | 20.211010 |
| 39   | 11.279860 | 12.572185 | 13.860679 | 15.144951 | 16.424610 | 17.699266 | 18.968531 | 20.232018 |
| 40   | 11.301429 | 12.593693 | 13.882120 | 15.166319 | 16.445898 | 17.720467 | 18.989639 | 20.253025 |
| 41   | 11.322996 | 12.615199 | 13.903559 | 15.187684 | 16.467182 | 17.741665 | 19.010742 | 20.274031 |
| 42   | 11.344562 | 12.636703 | 13.924996 | 15.209047 | 16.488466 | 17.762861 | 19.031847 | 20.295034 |
| 43   | 11.366126 | 12.658208 | 13.946433 | 15.230410 | 16.509747 | 17.784056 | 19.052948 | 20.316034 |
| 44   | 11.387691 | 12.679711 | 13.967869 | 15.251772 | 16.531029 | 17.805250 | 19.074049 | 20.337036 |
| 45   | 11.409254 | 12.701213 | 13.989303 | 15.273131 | 16.552307 | 17.826443 | 19.095146 | 20.358034 |
| 46   | 11.430816 | 12.722713 | 14.010736 | 15.294490 | 16.573586 | 17.847633 | 19.116243 | 20.379030 |
| 47   | 11.452378 | 12.744215 | 14.032168 | 15.315848 | 16.594864 | 17.868822 | 19.137339 | 20.400026 |
| 48   | 11.473938 | 12.765713 | 14.053599 | 15.337205 | 16.616138 | 17.890011 | 19.158432 | 20.421019 |
| 49   | 11.495498 | 12.787210 | 14.075028 | 15.358560 | 16.637411 | 17.911196 | 19.179523 | 20.442011 |
| 50   | 11.517056 | 12.808706 | 14.096457 | 15.379912 | 16.658684 | 17.932381 | 19.200615 | 20.462999 |
| 51   | 11.538613 | 12.830203 | 14.117885 | 15.401266 | 16.679955 | 17.953564 | 19.221704 | 20.483990 |
| 52   | 11.560169 | 12.851697 | 14.139310 | 15.422616 | 16.701225 | 17.974745 | 19.242790 | 20.504974 |
| 53   | 11.581725 | 12.873191 | 14.160735 | 15.443966 | 16.722492 | 17.995926 | 19.263876 | 20.525959 |
| 54   | 11.603279 | 12.894682 | 14.182158 | 15.465314 | 16.743759 | 18.017103 | 19.284960 | 20.546942 |
| 55   | 11.624833 | 12.916175 | 14.203582 | 15.486662 | 16.765024 | 18.038280 | 19.306042 | 20.567923 |
| 56   | 11.646385 | 12.937664 | 14.225002 | 15.508007 | 16.786289 | 18.059456 | 19.327124 | 20.588902 |
| 57   | 11.667936 | 12.959153 | 14.246422 | 15.529351 | 16.807550 | 18.080629 | 19.348202 | 20.609880 |
| 58   | 11.689487 | 12.980640 | 14.267840 | 15.550694 | 16.828812 | 18.101803 | 19.369278 | 20.630856 |
| 59   | 11.711037 | 13.002129 | 14.289259 | 15.572037 | 16.850071 | 18.122974 | 19.390356 | 20.651831 |
| 60   | 11.732585 | 13.023614 | 14.310675 | 15.593377 | 16.871330 | 18.144142 | 19.411428 | 20.672802 |

## SINE BAR CONSTANTS

## Constants for Setting a 75-mm Sine-Bar for 16° to 23°

| Min. | 16°       | 17°       | 18°       | 19°       | 20°       | 21°       | 22°       | 23°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 20.672802 | 21.927879 | 23.176275 | 24.417612 | 25.651512 | 26.877598 | 28.095495 | 29.304836 |
| 1    | 20.693773 | 21.948740 | 23.197023 | 24.438238 | 25.672010 | 26.897963 | 28.115723 | 29.324917 |
| 2    | 20.714741 | 21.969601 | 23.217768 | 24.458864 | 25.692509 | 26.918327 | 28.135946 | 29.344994 |
| 3    | 20.735708 | 21.990459 | 23.238512 | 24.479486 | 25.713003 | 26.938688 | 28.156168 | 29.365070 |
| 4    | 20.756676 | 22.011318 | 23.259256 | 24.500109 | 25.733500 | 26.959049 | 28.176390 | 29.385145 |
| 5    | 20.777639 | 22.032173 | 23.279995 | 24.520727 | 25.753990 | 26.979406 | 28.196606 | 29.405216 |
| 6    | 20.798599 | 22.053026 | 23.300734 | 24.541344 | 25.774479 | 26.999762 | 28.216822 | 29.425285 |
| 7    | 20.819559 | 22.073877 | 23.321468 | 24.561958 | 25.794964 | 27.020115 | 28.237034 | 29.445351 |
| 8    | 20.840517 | 22.094725 | 23.342203 | 24.582569 | 25.815449 | 27.040464 | 28.257242 | 29.465414 |
| 9    | 20.861473 | 22.115572 | 23.362934 | 24.603180 | 25.835932 | 27.060812 | 28.277451 | 29.485476 |
| 10   | 20.882429 | 22.136417 | 23.383665 | 24.623789 | 25.856411 | 27.081158 | 28.297655 | 29.505533 |
| 11   | 20.903381 | 22.157261 | 23.404392 | 24.644394 | 25.876888 | 27.101501 | 28.317858 | 29.525589 |
| 12   | 20.924334 | 22.178104 | 23.425121 | 24.665001 | 25.897367 | 27.121845 | 28.338060 | 29.545645 |
| 13   | 20.945284 | 22.198944 | 23.445845 | 24.685602 | 25.917839 | 27.142183 | 28.358259 | 29.565697 |
| 14   | 20.966230 | 22.219782 | 23.466566 | 24.706202 | 25.938311 | 27.162519 | 28.378454 | 29.585745 |
| 15   | 20.987177 | 22.240620 | 23.487286 | 24.726799 | 25.958780 | 27.182854 | 28.398647 | 29.605789 |
| 16   | 21.008120 | 22.261454 | 23.508003 | 24.747395 | 25.979246 | 27.203186 | 28.418839 | 29.625834 |
| 17   | 21.029062 | 22.282286 | 23.528721 | 24.767988 | 25.999712 | 27.223515 | 28.439026 | 29.645874 |
| 18   | 21.050003 | 22.303116 | 23.549435 | 24.788580 | 26.020174 | 27.243841 | 28.459211 | 29.665913 |
| 19   | 21.070944 | 22.323946 | 23.570148 | 24.809170 | 26.040636 | 27.264170 | 28.479397 | 29.685951 |
| 20   | 21.091881 | 22.344772 | 23.590858 | 24.829758 | 26.061094 | 27.284492 | 28.499578 | 29.705984 |
| 21   | 21.112816 | 22.365597 | 23.611567 | 24.850344 | 26.081551 | 27.304811 | 28.519756 | 29.726015 |
| 22   | 21.133749 | 22.386419 | 23.632273 | 24.870926 | 26.102003 | 27.325130 | 28.539934 | 29.746042 |
| 23   | 21.154680 | 22.407240 | 23.652975 | 24.891506 | 26.122456 | 27.345446 | 28.560106 | 29.766069 |
| 24   | 21.175610 | 22.428059 | 23.673677 | 24.912085 | 26.142904 | 27.365759 | 28.580278 | 29.786093 |
| 25   | 21.196537 | 22.448877 | 23.694378 | 24.932661 | 26.163351 | 27.386070 | 28.600447 | 29.806112 |
| 26   | 21.217463 | 22.469692 | 23.715076 | 24.953236 | 26.183796 | 27.406380 | 28.620613 | 29.826132 |
| 27   | 21.238390 | 22.490507 | 23.735775 | 24.973810 | 26.204241 | 27.426687 | 28.640779 | 29.846149 |
| 28   | 21.259312 | 22.511318 | 23.756468 | 24.994381 | 26.224680 | 27.446991 | 28.660942 | 29.866161 |
| 29   | 21.280233 | 22.532127 | 23.777161 | 25.014950 | 26.245119 | 27.467293 | 28.681101 | 29.886173 |
| 30   | 21.301151 | 22.552935 | 23.797850 | 25.035515 | 26.265554 | 27.487593 | 28.701258 | 29.906181 |
| 31   | 21.322069 | 22.573742 | 23.818539 | 25.056080 | 26.285988 | 27.507891 | 28.721413 | 29.926186 |
| 32   | 21.342983 | 22.594545 | 23.839224 | 25.076641 | 26.306419 | 27.528185 | 28.741564 | 29.946190 |
| 33   | 21.363897 | 22.615347 | 23.859907 | 25.097200 | 26.326849 | 27.548477 | 28.761715 | 29.966190 |
| 34   | 21.384811 | 22.636148 | 23.880592 | 25.117760 | 26.347279 | 27.568769 | 28.781864 | 29.986191 |
| 35   | 21.405720 | 22.656946 | 23.901272 | 25.138315 | 26.367702 | 27.589058 | 28.802008 | 30.006186 |
| 36   | 21.426628 | 22.677742 | 23.921949 | 25.158869 | 26.388124 | 27.609343 | 28.822151 | 30.026178 |
| 37   | 21.447535 | 22.698538 | 23.942625 | 25.179420 | 26.408545 | 27.629625 | 28.842291 | 30.046169 |
| 38   | 21.468439 | 22.719330 | 23.963299 | 25.199968 | 26.428963 | 27.649906 | 28.862427 | 30.066156 |
| 39   | 21.489342 | 22.740120 | 23.983971 | 25.220516 | 26.449379 | 27.670185 | 28.882563 | 30.086142 |
| 40   | 21.510242 | 22.760908 | 24.004641 | 25.241060 | 26.469791 | 27.690460 | 28.902695 | 30.106125 |
| 41   | 21.531141 | 22.781694 | 24.025309 | 25.261602 | 26.490204 | 27.710735 | 28.922825 | 30.126104 |
| 42   | 21.552040 | 22.802481 | 24.045977 | 25.282146 | 26.510614 | 27.731009 | 28.942955 | 30.146086 |
| 43   | 21.572935 | 22.823263 | 24.066639 | 25.302685 | 26.531021 | 27.751278 | 28.963079 | 30.166059 |
| 44   | 21.593828 | 22.844044 | 24.087301 | 25.323221 | 26.551426 | 27.771544 | 28.983202 | 30.186033 |
| 45   | 21.614721 | 22.864822 | 24.107960 | 25.343754 | 26.571829 | 27.791809 | 29.003323 | 30.206003 |
| 46   | 21.635611 | 22.885599 | 24.128618 | 25.364286 | 26.592228 | 27.812071 | 29.023441 | 30.225969 |
| 47   | 21.656498 | 22.906374 | 24.149273 | 25.384815 | 26.612627 | 27.832331 | 29.043556 | 30.245935 |
| 48   | 21.677385 | 22.927147 | 24.169928 | 25.405344 | 26.633022 | 27.852587 | 29.063669 | 30.265898 |
| 49   | 21.698271 | 22.947922 | 24.190580 | 25.425871 | 26.653418 | 27.872845 | 29.083782 | 30.285860 |
| 50   | 21.719154 | 22.968689 | 24.211229 | 25.446394 | 26.673809 | 27.893097 | 29.103889 | 30.305817 |
| 51   | 21.740034 | 22.989456 | 24.231876 | 25.466915 | 26.694197 | 27.913347 | 29.123995 | 30.325771 |
| 52   | 21.760912 | 23.010221 | 24.252522 | 25.487434 | 26.714584 | 27.933596 | 29.144098 | 30.345722 |
| 53   | 21.781790 | 23.030985 | 24.273165 | 25.507952 | 26.734968 | 27.953840 | 29.164198 | 30.365673 |
| 54   | 21.802664 | 23.051746 | 24.293806 | 25.528467 | 26.755350 | 27.974085 | 29.184296 | 30.385620 |
| 55   | 21.823538 | 23.072506 | 24.314445 | 25.548979 | 26.775730 | 27.994326 | 29.204391 | 30.405563 |
| 56   | 21.844410 | 23.093264 | 24.335083 | 25.569489 | 26.796108 | 28.014563 | 29.224485 | 30.425505 |
| 57   | 21.865280 | 23.114021 | 24.355721 | 25.590000 | 26.816484 | 28.034801 | 29.244577 | 30.445446 |
| 58   | 21.886148 | 23.134775 | 24.376352 | 25.610506 | 26.836859 | 28.055035 | 29.264666 | 30.465384 |
| 59   | 21.907015 | 23.155525 | 24.396984 | 25.631010 | 26.857229 | 28.075266 | 29.284752 | 30.485317 |
| 60   | 21.927879 | 23.176275 | 24.417612 | 25.651512 | 26.877598 | 28.095495 | 29.304836 | 30.505249 |

## SINE BAR CONSTANTS

## Constants for Setting a 75-mm Sine-Bar for 24° to 31°

| Min. | 24°       | 25°       | 26°       | 27°       | 28°       | 29°       | 30°       | 31°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 30.505249 | 31.696371 | 32.877838 | 34.049290 | 35.210369 | 36.360722 | 37.500000 | 38.627857 |
| 1    | 30.525177 | 31.716141 | 32.897446 | 34.068726 | 35.229630 | 36.379803 | 37.518894 | 38.646557 |
| 2    | 30.545105 | 31.735910 | 32.917049 | 34.088158 | 35.248886 | 36.398880 | 37.537781 | 38.665249 |
| 3    | 30.565027 | 31.755674 | 32.936649 | 34.107590 | 35.268143 | 36.417950 | 37.556667 | 38.683941 |
| 4    | 30.584951 | 31.775440 | 32.956249 | 34.127022 | 35.287395 | 36.437023 | 37.575550 | 38.702633 |
| 5    | 30.604870 | 31.795200 | 32.975845 | 34.146446 | 35.306644 | 36.456089 | 37.594429 | 38.721317 |
| 6    | 30.624786 | 31.814959 | 32.995438 | 34.165871 | 35.325893 | 36.475155 | 37.613308 | 38.740002 |
| 7    | 30.644699 | 31.834713 | 33.015030 | 34.185287 | 35.345135 | 36.494217 | 37.632179 | 38.758678 |
| 8    | 30.664610 | 31.854465 | 33.034618 | 34.204704 | 35.364376 | 36.513275 | 37.651051 | 38.777355 |
| 9    | 30.684519 | 31.874214 | 33.054203 | 34.224121 | 35.383614 | 36.532330 | 37.669914 | 38.796208 |
| 10   | 30.704424 | 31.893961 | 33.073784 | 34.243530 | 35.402847 | 36.551380 | 37.688778 | 38.814697 |
| 11   | 30.724327 | 31.913706 | 33.093361 | 34.262939 | 35.422077 | 36.570427 | 37.707638 | 38.833363 |
| 12   | 30.744228 | 31.933449 | 33.112942 | 34.282345 | 35.441311 | 36.589478 | 37.726498 | 38.852028 |
| 13   | 30.764128 | 31.953188 | 33.132515 | 34.301750 | 35.460533 | 36.608521 | 37.745350 | 38.870686 |
| 14   | 30.784021 | 31.972923 | 33.152084 | 34.321148 | 35.479755 | 36.627560 | 37.764202 | 38.889343 |
| 15   | 30.803915 | 31.992657 | 33.171654 | 34.340546 | 35.498978 | 36.646595 | 37.783051 | 38.907997 |
| 16   | 30.823805 | 32.012386 | 33.191219 | 34.359940 | 35.518192 | 36.665627 | 37.801895 | 38.926643 |
| 17   | 30.843693 | 32.032116 | 33.210781 | 34.379330 | 35.537407 | 36.684658 | 37.820736 | 38.945290 |
| 18   | 30.863577 | 32.051838 | 33.230339 | 34.398716 | 35.556614 | 36.703686 | 37.839573 | 38.963932 |
| 19   | 30.883461 | 32.071564 | 33.249897 | 34.418102 | 35.575825 | 36.722710 | 37.858410 | 38.982574 |
| 20   | 30.903341 | 32.091286 | 33.269451 | 34.437485 | 35.595028 | 36.741730 | 37.877239 | 39.001213 |
| 21   | 30.923218 | 32.111000 | 33.289001 | 34.456863 | 35.614231 | 36.760750 | 37.896069 | 39.019844 |
| 22   | 30.943092 | 32.130714 | 33.308552 | 34.476242 | 35.633430 | 36.779762 | 37.914894 | 39.038475 |
| 23   | 30.962963 | 32.150425 | 33.328094 | 34.495613 | 35.652622 | 36.798775 | 37.933716 | 39.057098 |
| 24   | 30.982832 | 32.170135 | 33.347637 | 34.514984 | 35.671818 | 36.817783 | 37.952534 | 39.075722 |
| 25   | 31.002699 | 32.189842 | 33.367180 | 34.534351 | 35.691006 | 36.836788 | 37.971348 | 39.094341 |
| 26   | 31.022562 | 32.209545 | 33.386715 | 34.553715 | 35.710190 | 36.855789 | 37.990162 | 39.112961 |
| 27   | 31.042427 | 32.229248 | 33.406250 | 34.573078 | 35.729378 | 36.874790 | 38.008972 | 39.131573 |
| 28   | 31.062284 | 32.248947 | 33.425781 | 34.592438 | 35.748558 | 36.893787 | 38.027775 | 39.150185 |
| 29   | 31.082140 | 32.268642 | 33.445313 | 34.611794 | 35.767735 | 36.912777 | 38.046577 | 39.168789 |
| 30   | 31.101994 | 32.288334 | 33.464836 | 34.631145 | 35.786907 | 36.931767 | 38.065376 | 39.187393 |
| 31   | 31.121845 | 32.308022 | 33.484360 | 34.650497 | 35.806080 | 36.950756 | 38.084175 | 39.205994 |
| 32   | 31.141693 | 32.327709 | 33.503880 | 34.669842 | 35.825249 | 36.969738 | 38.102966 | 39.224590 |
| 33   | 31.161537 | 32.347393 | 33.523396 | 34.689186 | 35.844414 | 36.988716 | 38.121758 | 39.243183 |
| 34   | 31.181383 | 32.367077 | 33.542912 | 34.708530 | 35.863575 | 37.007698 | 38.140545 | 39.261776 |
| 35   | 31.201223 | 32.386757 | 33.562424 | 34.727867 | 35.882736 | 37.026672 | 38.159328 | 39.280361 |
| 36   | 31.221060 | 32.406433 | 33.581932 | 34.747204 | 35.901890 | 37.045643 | 38.178108 | 39.298943 |
| 37   | 31.240896 | 32.426105 | 33.601440 | 34.766537 | 35.921043 | 37.064610 | 38.196884 | 39.317524 |
| 38   | 31.260727 | 32.445778 | 33.620941 | 34.785866 | 35.940193 | 37.083572 | 38.215656 | 39.336102 |
| 39   | 31.280558 | 32.465443 | 33.640442 | 34.805191 | 35.959339 | 37.102535 | 38.234428 | 39.354675 |
| 40   | 31.300385 | 32.485107 | 33.659939 | 34.824516 | 35.978485 | 37.121494 | 38.253193 | 39.373245 |
| 41   | 31.320208 | 32.504772 | 33.679432 | 34.843834 | 35.997623 | 37.140450 | 38.271957 | 39.391811 |
| 42   | 31.340033 | 32.524433 | 33.698925 | 34.863155 | 36.016766 | 37.159401 | 38.290722 | 39.410378 |
| 43   | 31.359852 | 32.544090 | 33.718414 | 34.882469 | 36.035900 | 37.178352 | 38.309479 | 39.428936 |
| 44   | 31.379667 | 32.563744 | 33.737900 | 34.901783 | 36.055031 | 37.197296 | 38.328232 | 39.447491 |
| 45   | 31.399481 | 32.583397 | 33.757385 | 34.921089 | 36.074158 | 37.216240 | 38.346981 | 39.466045 |
| 46   | 31.419292 | 32.603043 | 33.776863 | 34.940395 | 36.093285 | 37.235180 | 38.365730 | 39.484596 |
| 47   | 31.439100 | 32.622688 | 33.796341 | 34.959698 | 36.112408 | 37.254116 | 38.384476 | 39.503143 |
| 48   | 31.458906 | 32.642334 | 33.815815 | 34.978996 | 36.131527 | 37.273048 | 38.403214 | 39.521687 |
| 49   | 31.478712 | 32.661976 | 33.835289 | 34.998299 | 36.150642 | 37.291981 | 38.421955 | 39.540226 |
| 50   | 31.498512 | 32.681614 | 33.854759 | 35.017590 | 36.169758 | 37.310905 | 38.440689 | 39.558762 |
| 51   | 31.518309 | 32.701248 | 33.874222 | 35.036880 | 36.188866 | 37.329830 | 38.459419 | 39.577297 |
| 52   | 31.538105 | 32.720879 | 33.893688 | 35.056171 | 36.207973 | 37.348751 | 38.478149 | 39.595825 |
| 53   | 31.557898 | 32.740509 | 33.913147 | 35.075455 | 36.227077 | 37.367668 | 38.496872 | 39.614353 |
| 54   | 31.577686 | 32.760136 | 33.932602 | 35.094738 | 36.246178 | 37.386581 | 38.515594 | 39.632877 |
| 55   | 31.597473 | 32.779758 | 33.952057 | 35.114014 | 36.265278 | 37.405491 | 38.534313 | 39.651394 |
| 56   | 31.617258 | 32.799377 | 33.971508 | 35.133293 | 36.284370 | 37.424400 | 38.553028 | 39.669910 |
| 57   | 31.637041 | 32.819000 | 33.990959 | 35.152565 | 36.303467 | 37.443306 | 38.571743 | 39.688427 |
| 58   | 31.656820 | 32.838615 | 34.010406 | 35.171837 | 36.322556 | 37.462208 | 38.590450 | 39.706936 |
| 59   | 31.676598 | 32.858227 | 34.029850 | 35.191105 | 36.341640 | 37.481106 | 38.609154 | 39.725441 |
| 60   | 31.696371 | 32.877838 | 34.049290 | 35.210369 | 36.360722 | 37.500000 | 38.627857 | 39.743946 |

## Constants for Setting a 75-mm Sine-Bar for 32° to 39°

| Min. | 32°       | 33°       | 34°       | 35°       | 36°       | 37°       | 38°       | 39°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 39.743946 | 40.847927 | 41.939468 | 43.018234 | 44.083897 | 45.136127 | 46.174610 | 47.199032 |
| 1    | 39.762444 | 40.866222 | 41.957554 | 43.036102 | 44.101543 | 45.153549 | 46.191803 | 47.215984 |
| 2    | 39.780941 | 40.884514 | 41.975636 | 43.053967 | 44.119186 | 45.170967 | 46.208988 | 47.232933 |
| 3    | 39.799435 | 40.902802 | 41.993713 | 43.071831 | 44.136826 | 45.188381 | 46.226170 | 47.249874 |
| 4    | 39.817924 | 40.921089 | 42.011787 | 43.089687 | 44.154465 | 45.205791 | 46.243347 | 47.266815 |
| 5    | 39.836411 | 40.939369 | 42.029858 | 43.107544 | 44.172096 | 45.223198 | 46.260521 | 47.283752 |
| 6    | 39.854893 | 40.957645 | 42.047924 | 43.125393 | 44.189728 | 45.240597 | 46.277691 | 47.300686 |
| 7    | 39.873371 | 40.975922 | 42.065987 | 43.143242 | 44.207352 | 45.257996 | 46.294857 | 47.317612 |
| 8    | 39.891853 | 40.994194 | 42.084053 | 43.161087 | 44.224976 | 45.275394 | 46.312023 | 47.334541 |
| 9    | 39.910324 | 41.012463 | 42.102108 | 43.178928 | 44.242596 | 45.292786 | 46.329182 | 47.351463 |
| 10   | 39.928795 | 41.030727 | 42.120159 | 43.196766 | 44.260208 | 45.310173 | 46.346336 | 47.368378 |
| 11   | 39.947262 | 41.048988 | 42.138210 | 43.214596 | 44.277821 | 45.327557 | 46.363483 | 47.385292 |
| 12   | 39.965721 | 41.067245 | 42.156254 | 43.232426 | 44.295425 | 45.344936 | 46.380630 | 47.402199 |
| 13   | 39.984180 | 41.085499 | 42.174297 | 43.250252 | 44.313030 | 45.362312 | 46.397774 | 47.419106 |
| 14   | 40.002636 | 41.103748 | 42.192337 | 43.268074 | 44.330627 | 45.379681 | 46.414913 | 47.436005 |
| 15   | 40.021091 | 41.121994 | 42.210369 | 43.285889 | 44.348225 | 45.397049 | 46.432049 | 47.452900 |
| 16   | 40.039539 | 41.140236 | 42.228401 | 43.303703 | 44.365818 | 45.414413 | 46.449177 | 47.469791 |
| 17   | 40.057983 | 41.158474 | 42.246429 | 43.321514 | 44.383404 | 45.431774 | 46.466305 | 47.486683 |
| 18   | 40.076427 | 41.176712 | 42.264454 | 43.339321 | 44.400990 | 45.449131 | 46.483429 | 47.503567 |
| 19   | 40.094864 | 41.194942 | 42.282475 | 43.357124 | 44.418568 | 45.466484 | 46.500546 | 47.520447 |
| 20   | 40.113300 | 41.213173 | 42.300491 | 43.374924 | 44.436146 | 45.483829 | 46.517662 | 47.537323 |
| 21   | 40.131733 | 41.231400 | 42.318504 | 43.392719 | 44.453720 | 45.501175 | 46.534771 | 47.554195 |
| 22   | 40.150162 | 41.249622 | 42.336514 | 43.410515 | 44.471287 | 45.518517 | 46.551880 | 47.571064 |
| 23   | 40.168591 | 41.267841 | 42.354527 | 43.428307 | 44.488857 | 45.535858 | 46.568989 | 47.587933 |
| 24   | 40.187012 | 41.286057 | 42.372528 | 43.446091 | 44.506420 | 45.553192 | 46.586086 | 47.604790 |
| 25   | 40.205429 | 41.304268 | 42.390526 | 43.463871 | 44.523975 | 45.570518 | 46.603180 | 47.621647 |
| 26   | 40.223846 | 41.322479 | 42.408524 | 43.481647 | 44.541531 | 45.587845 | 46.620274 | 47.638500 |
| 27   | 40.242256 | 41.340683 | 42.426514 | 43.499424 | 44.559082 | 45.605167 | 46.637360 | 47.655346 |
| 28   | 40.260666 | 41.358883 | 42.444504 | 43.517193 | 44.576630 | 45.622486 | 46.654446 | 47.672192 |
| 29   | 40.279072 | 41.377079 | 42.462486 | 43.534962 | 44.594170 | 45.639797 | 46.671524 | 47.689034 |
| 30   | 40.297470 | 41.395275 | 42.480469 | 43.552723 | 44.611710 | 45.657108 | 46.688599 | 47.705868 |
| 31   | 40.315868 | 41.413464 | 42.498447 | 43.570480 | 44.629246 | 45.674416 | 46.705669 | 47.722698 |
| 32   | 40.334263 | 41.431652 | 42.516418 | 43.588238 | 44.646778 | 45.691715 | 46.722736 | 47.739529 |
| 33   | 40.352654 | 41.449837 | 42.534389 | 43.605988 | 44.664303 | 45.709015 | 46.739803 | 47.756351 |
| 34   | 40.371044 | 41.468018 | 42.552357 | 43.623737 | 44.681828 | 45.726311 | 46.756863 | 47.773170 |
| 35   | 40.389427 | 41.486191 | 42.570320 | 43.641483 | 44.699348 | 45.743599 | 46.773918 | 47.789976 |
| 36   | 40.407806 | 41.504364 | 42.588280 | 43.659222 | 44.716866 | 45.760887 | 46.790970 | 47.806797 |
| 37   | 40.426186 | 41.522533 | 42.606236 | 43.676960 | 44.734379 | 45.778172 | 46.808018 | 47.823608 |
| 38   | 40.444565 | 41.540707 | 42.624191 | 43.694698 | 44.751892 | 45.795452 | 46.825066 | 47.840412 |
| 39   | 40.462936 | 41.558868 | 42.642143 | 43.712425 | 44.769394 | 45.812729 | 46.842106 | 47.857212 |
| 40   | 40.481300 | 41.577026 | 42.660088 | 43.730152 | 44.786896 | 45.829998 | 46.859142 | 47.874008 |
| 41   | 40.499664 | 41.595181 | 42.678028 | 43.747875 | 44.804394 | 45.847267 | 46.876175 | 47.890800 |
| 42   | 40.518024 | 41.613335 | 42.695965 | 43.765594 | 44.821888 | 45.864529 | 46.893200 | 47.907589 |
| 43   | 40.536385 | 41.631481 | 42.713902 | 43.783306 | 44.839378 | 45.881790 | 46.910225 | 47.924370 |
| 44   | 40.554737 | 41.649628 | 42.731831 | 43.801018 | 44.856865 | 45.899044 | 46.927246 | 47.941151 |
| 45   | 40.573086 | 41.667770 | 42.749760 | 43.818726 | 44.874348 | 45.916298 | 46.944260 | 47.957928 |
| 46   | 40.591434 | 41.685905 | 42.767681 | 43.836430 | 44.891823 | 45.933544 | 46.961273 | 47.974697 |
| 47   | 40.609776 | 41.704041 | 42.785603 | 43.854130 | 44.909298 | 45.950790 | 46.978283 | 47.991467 |
| 48   | 40.628117 | 41.722172 | 42.803516 | 43.871826 | 44.926769 | 45.968029 | 46.995285 | 48.008228 |
| 49   | 40.646454 | 41.740299 | 42.821430 | 43.889519 | 44.944237 | 45.985264 | 47.012287 | 48.024986 |
| 50   | 40.664783 | 41.758423 | 42.839340 | 43.907207 | 44.961700 | 46.002499 | 47.029282 | 48.041740 |
| 51   | 40.683113 | 41.776543 | 42.857246 | 43.924892 | 44.979160 | 46.019726 | 47.046276 | 48.058495 |
| 52   | 40.701439 | 41.794659 | 42.875145 | 43.942574 | 44.996616 | 46.036953 | 47.063263 | 48.075241 |
| 53   | 40.719769 | 41.812775 | 42.893047 | 43.960255 | 45.014072 | 46.054176 | 47.080250 | 48.091988 |
| 54   | 40.738087 | 41.830887 | 42.910942 | 43.977928 | 45.031521 | 46.071392 | 47.097233 | 48.108727 |
| 55   | 40.756401 | 41.848991 | 42.928833 | 43.995598 | 45.048965 | 46.088604 | 47.114208 | 48.125462 |
| 56   | 40.774715 | 41.867096 | 42.946720 | 44.013268 | 45.066402 | 46.105816 | 47.131180 | 48.142189 |
| 57   | 40.793022 | 41.885193 | 42.964603 | 44.030930 | 45.083839 | 46.123020 | 47.148148 | 48.158916 |
| 58   | 40.811329 | 41.903290 | 42.982483 | 44.048588 | 45.101273 | 46.140221 | 47.165115 | 48.175640 |
| 59   | 40.829632 | 41.921379 | 43.000362 | 44.066242 | 45.118702 | 46.157417 | 47.182076 | 48.192356 |
| 60   | 40.847927 | 41.939468 | 43.018234 | 44.083897 | 45.136127 | 46.174610 | 47.199032 | 48.209072 |

## SINE BAR CONSTANTS

## Constants for Setting a 75-mm Sine-Bar for 40° to 47°

| Min. | 40°       | 41°       | 42°       | 43°       | 44°       | 45°       | 46°       | 47°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 48.209072 | 49.204430 | 50.184795 | 51.149879 | 52.099380 | 53.033009 | 53.950485 | 54.851528 |
| 1    | 48.225780 | 49.220890 | 50.201008 | 51.165833 | 52.115070 | 53.048435 | 53.965637 | 54.866405 |
| 2    | 48.242489 | 49.237350 | 50.217213 | 51.181782 | 52.130756 | 53.063854 | 53.980785 | 54.881275 |
| 3    | 48.259190 | 49.253803 | 50.233414 | 51.197723 | 52.146439 | 53.079269 | 53.995930 | 54.896145 |
| 4    | 48.275887 | 49.270256 | 50.249615 | 51.213665 | 52.162117 | 53.094681 | 54.011070 | 54.911007 |
| 5    | 48.292583 | 49.286701 | 50.265808 | 51.229603 | 52.177792 | 53.110085 | 54.026203 | 54.925865 |
| 6    | 48.309273 | 49.303143 | 50.281998 | 51.245533 | 52.193459 | 53.125488 | 54.041332 | 54.940716 |
| 7    | 48.325958 | 49.319580 | 50.298180 | 51.261459 | 52.209126 | 53.140884 | 54.056458 | 54.955566 |
| 8    | 48.342644 | 49.336018 | 50.314365 | 51.277386 | 52.224789 | 53.156281 | 54.071583 | 54.970413 |
| 9    | 48.359322 | 49.352448 | 50.330544 | 51.293304 | 52.240444 | 53.171669 | 54.086697 | 54.985252 |
| 10   | 48.375996 | 49.368874 | 50.346714 | 51.309219 | 52.256096 | 53.187054 | 54.101810 | 55.000088 |
| 11   | 48.392662 | 49.385296 | 50.362881 | 51.325130 | 52.271744 | 53.202431 | 54.116917 | 55.014915 |
| 12   | 48.409328 | 49.401711 | 50.379047 | 51.341034 | 52.287384 | 53.217808 | 54.132019 | 55.029743 |
| 13   | 48.425991 | 49.418125 | 50.395206 | 51.356937 | 52.303024 | 53.233177 | 54.147118 | 55.044563 |
| 14   | 48.442646 | 49.434532 | 50.411362 | 51.372833 | 52.318657 | 53.248543 | 54.162209 | 55.059380 |
| 15   | 48.459301 | 49.450935 | 50.427513 | 51.388725 | 52.334286 | 53.263905 | 54.177299 | 55.074188 |
| 16   | 48.475948 | 49.467339 | 50.443657 | 51.404613 | 52.349911 | 53.279263 | 54.192383 | 55.088997 |
| 17   | 48.492592 | 49.483734 | 50.459801 | 51.420498 | 52.365532 | 53.294613 | 54.207462 | 55.103798 |
| 18   | 48.509235 | 49.500126 | 50.475941 | 51.436378 | 52.381145 | 53.309959 | 54.222538 | 55.118595 |
| 19   | 48.525871 | 49.516514 | 50.492073 | 51.452251 | 52.396759 | 53.325306 | 54.237606 | 55.133389 |
| 20   | 48.542503 | 49.532898 | 50.508202 | 51.468124 | 52.412365 | 53.340641 | 54.252674 | 55.148174 |
| 21   | 48.559132 | 49.549274 | 50.524326 | 51.483990 | 52.427967 | 53.355976 | 54.267735 | 55.162960 |
| 22   | 48.575756 | 49.565651 | 50.540447 | 51.499851 | 52.443565 | 53.371307 | 54.282791 | 55.177738 |
| 23   | 48.592381 | 49.582027 | 50.556568 | 51.515713 | 52.459164 | 53.386635 | 54.297844 | 55.192516 |
| 24   | 48.608994 | 49.598392 | 50.572681 | 51.531567 | 52.474754 | 53.401955 | 54.312893 | 55.207283 |
| 25   | 48.625607 | 49.614754 | 50.588791 | 51.547417 | 52.490337 | 53.417271 | 54.327934 | 55.222050 |
| 26   | 48.642216 | 49.631115 | 50.604893 | 51.563259 | 52.505920 | 53.432583 | 54.342972 | 55.236809 |
| 27   | 48.658817 | 49.647469 | 50.620995 | 51.579102 | 52.521496 | 53.447891 | 54.358006 | 55.251564 |
| 28   | 48.675419 | 49.663818 | 50.637089 | 51.594936 | 52.537067 | 53.463192 | 54.373035 | 55.266315 |
| 29   | 48.692013 | 49.680164 | 50.653179 | 51.610767 | 52.552631 | 53.478493 | 54.388058 | 55.281059 |
| 30   | 48.708603 | 49.696507 | 50.669266 | 51.626595 | 52.568195 | 53.493786 | 54.403080 | 55.295803 |
| 31   | 48.725193 | 49.712841 | 50.685349 | 51.642418 | 52.583755 | 53.509075 | 54.418095 | 55.310539 |
| 32   | 48.741776 | 49.729176 | 50.701427 | 51.658234 | 52.599308 | 53.524357 | 54.433105 | 55.325272 |
| 33   | 48.758354 | 49.745502 | 50.717503 | 51.674049 | 52.614857 | 53.539639 | 54.448109 | 55.339996 |
| 34   | 48.774929 | 49.761829 | 50.733570 | 51.689857 | 52.630402 | 53.554913 | 54.463112 | 55.354721 |
| 35   | 48.791500 | 49.778149 | 50.749638 | 51.705666 | 52.645943 | 53.570183 | 54.478107 | 55.369438 |
| 36   | 48.808067 | 49.794464 | 50.765697 | 51.721466 | 52.661480 | 53.585449 | 54.493099 | 55.384151 |
| 37   | 48.824627 | 49.810776 | 50.781754 | 51.737263 | 52.677010 | 53.600712 | 54.508087 | 55.398857 |
| 38   | 48.841190 | 49.827087 | 50.797810 | 51.753059 | 52.692539 | 53.615974 | 54.523075 | 55.413567 |
| 39   | 48.857746 | 49.843391 | 50.813858 | 51.768845 | 52.708065 | 53.631226 | 54.538052 | 55.428265 |
| 40   | 48.874294 | 49.859692 | 50.829903 | 51.784630 | 52.723583 | 53.646473 | 54.553024 | 55.442959 |
| 41   | 48.890839 | 49.875988 | 50.845943 | 51.800407 | 52.739094 | 53.661716 | 54.567993 | 55.457649 |
| 42   | 48.907383 | 49.892277 | 50.861977 | 51.816181 | 52.754604 | 53.676956 | 54.582958 | 55.472336 |
| 43   | 48.923920 | 49.908566 | 50.878010 | 51.831951 | 52.770111 | 53.692192 | 54.597919 | 55.487015 |
| 44   | 48.940453 | 49.924847 | 50.894035 | 51.847717 | 52.785610 | 53.707420 | 54.612873 | 55.501690 |
| 45   | 48.956982 | 49.941128 | 50.910057 | 51.863480 | 52.801105 | 53.722649 | 54.627823 | 55.516361 |
| 46   | 48.973507 | 49.957401 | 50.926075 | 51.879238 | 52.816597 | 53.737869 | 54.642769 | 55.531029 |
| 47   | 48.990028 | 49.973671 | 50.942089 | 51.894989 | 52.832085 | 53.753086 | 54.657711 | 55.545689 |
| 48   | 49.006546 | 49.989937 | 50.958099 | 51.910740 | 52.847565 | 53.768295 | 54.672649 | 55.560345 |
| 49   | 49.023060 | 50.006199 | 50.974102 | 51.926483 | 52.863045 | 53.783504 | 54.687580 | 55.574997 |
| 50   | 49.039566 | 50.022453 | 50.990105 | 51.942223 | 52.878517 | 53.798706 | 54.702507 | 55.589645 |
| 51   | 49.056072 | 50.038708 | 51.006100 | 51.957958 | 52.893986 | 53.813904 | 54.717430 | 55.604286 |
| 52   | 49.072571 | 50.054955 | 51.022091 | 51.973686 | 52.909451 | 53.829098 | 54.732349 | 55.618927 |
| 53   | 49.089073 | 50.071205 | 51.038086 | 51.989418 | 52.924915 | 53.844292 | 54.747265 | 55.633560 |
| 54   | 49.105564 | 50.087444 | 51.054070 | 52.005138 | 52.940369 | 53.859474 | 54.762173 | 55.648190 |
| 55   | 49.122051 | 50.103680 | 51.070045 | 52.020859 | 52.955822 | 53.874657 | 54.777077 | 55.662815 |
| 56   | 49.138535 | 50.119911 | 51.086021 | 52.036572 | 52.971268 | 53.889832 | 54.791977 | 55.677433 |
| 57   | 49.155014 | 50.136139 | 51.101994 | 52.052280 | 52.986710 | 53.905003 | 54.806873 | 55.692047 |
| 58   | 49.171490 | 50.152363 | 51.117958 | 52.067982 | 53.002148 | 53.920166 | 54.821762 | 55.706657 |
| 59   | 49.187962 | 50.168583 | 51.133919 | 52.083683 | 53.017582 | 53.935329 | 54.836647 | 55.721264 |
| 60   | 49.204430 | 50.184795 | 51.149879 | 52.099380 | 53.033009 | 53.950485 | 54.851528 | 55.735863 |

## Constants for Setting a 75-mm Sine-Bar for 48° to 55°

| Min. | 48°       | 49°       | 50°       | 51°       | 52°       | 53°       | 54°       | 55°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 55.735863 | 56.603218 | 57.453335 | 58.285950 | 59.100807 | 59.897663 | 60.676277 | 61.436405 |
| 1    | 55.750458 | 56.617531 | 57.467354 | 58.299675 | 59.114235 | 59.910789 | 60.689098 | 61.448914 |
| 2    | 55.765049 | 56.631836 | 57.481373 | 58.313396 | 59.127659 | 59.923912 | 60.701912 | 61.461422 |
| 3    | 55.779636 | 56.646137 | 57.495380 | 58.327114 | 59.141079 | 59.937031 | 60.714722 | 61.473923 |
| 4    | 55.794216 | 56.660431 | 57.509388 | 58.340828 | 59.154495 | 59.950142 | 60.727528 | 61.486416 |
| 5    | 55.808792 | 56.674725 | 57.523388 | 58.354534 | 59.167904 | 59.963249 | 60.740330 | 61.498905 |
| 6    | 55.823364 | 56.689011 | 57.537388 | 58.368237 | 59.181305 | 59.976349 | 60.753124 | 61.511391 |
| 7    | 55.837933 | 56.703293 | 57.551376 | 58.381935 | 59.194706 | 59.989445 | 60.765911 | 61.523869 |
| 8    | 55.852497 | 56.717571 | 57.565369 | 58.395630 | 59.208103 | 60.002541 | 60.778702 | 61.536346 |
| 9    | 55.867058 | 56.731842 | 57.579350 | 58.409317 | 59.221493 | 60.015625 | 60.791481 | 61.548817 |
| 10   | 55.881611 | 56.746113 | 57.593327 | 58.423000 | 59.234875 | 60.028706 | 60.804256 | 61.561279 |
| 11   | 55.896156 | 56.760372 | 57.607300 | 58.436676 | 59.248253 | 60.041782 | 60.817024 | 61.573738 |
| 12   | 55.910702 | 56.774632 | 57.621265 | 58.450348 | 59.261627 | 60.054855 | 60.829788 | 61.586193 |
| 13   | 55.925240 | 56.788883 | 57.635227 | 58.464016 | 59.274998 | 60.067921 | 60.842548 | 61.598640 |
| 14   | 55.939774 | 56.803131 | 57.649185 | 58.477680 | 59.288361 | 60.080982 | 60.855301 | 61.611084 |
| 15   | 55.954304 | 56.817375 | 57.663139 | 58.491337 | 59.301720 | 60.094036 | 60.868050 | 61.623520 |
| 16   | 55.968830 | 56.831612 | 57.677086 | 58.504990 | 59.315071 | 60.107086 | 60.880795 | 61.635956 |
| 17   | 55.983349 | 56.845848 | 57.691029 | 58.518639 | 59.328423 | 60.120132 | 60.893532 | 61.648380 |
| 18   | 55.997864 | 56.860077 | 57.704967 | 58.532280 | 59.341766 | 60.133175 | 60.906265 | 61.660805 |
| 19   | 56.012375 | 56.874298 | 57.718899 | 58.545918 | 59.355103 | 60.146210 | 60.918995 | 61.673222 |
| 20   | 56.026882 | 56.888519 | 57.732830 | 58.559551 | 59.368439 | 60.159241 | 60.931717 | 61.685631 |
| 21   | 56.041382 | 56.902733 | 57.746754 | 58.573181 | 59.381767 | 60.172264 | 60.944435 | 61.698040 |
| 22   | 56.055878 | 56.916943 | 57.760670 | 58.586803 | 59.395092 | 60.185284 | 60.957146 | 61.710422 |
| 23   | 56.070374 | 56.931152 | 57.774586 | 58.600426 | 59.408413 | 60.198303 | 60.969856 | 61.722839 |
| 24   | 56.084858 | 56.945351 | 57.788494 | 58.614037 | 59.421726 | 60.211311 | 60.982559 | 61.735229 |
| 25   | 56.099342 | 56.959545 | 57.802399 | 58.627647 | 59.435036 | 60.224319 | 60.995258 | 61.747616 |
| 26   | 56.113819 | 56.973736 | 57.816299 | 58.641251 | 59.448338 | 60.237316 | 61.007590 | 61.759995 |
| 27   | 56.128292 | 56.987923 | 57.830193 | 58.654846 | 59.461636 | 60.250313 | 61.020634 | 61.772369 |
| 28   | 56.142757 | 57.002102 | 57.844082 | 58.668442 | 59.474930 | 60.263302 | 61.033318 | 61.784740 |
| 29   | 56.157223 | 57.016277 | 57.857967 | 58.682030 | 59.488216 | 60.276287 | 61.045994 | 61.797108 |
| 30   | 56.171680 | 57.030449 | 57.871845 | 58.695614 | 59.501503 | 60.289265 | 61.058666 | 61.809464 |
| 31   | 56.186134 | 57.044613 | 57.885719 | 58.709190 | 59.514782 | 60.302238 | 61.071331 | 61.821819 |
| 32   | 56.200584 | 57.058777 | 57.899590 | 58.722763 | 59.528053 | 60.315208 | 61.083992 | 61.834167 |
| 33   | 56.215027 | 57.072933 | 57.913452 | 58.736332 | 59.541321 | 60.328175 | 61.096649 | 61.846512 |
| 34   | 56.229465 | 57.087086 | 57.927315 | 58.749897 | 59.554585 | 60.341133 | 61.109299 | 61.858852 |
| 35   | 56.243900 | 57.101231 | 57.941170 | 58.763454 | 59.567844 | 60.354088 | 61.121944 | 61.871185 |
| 36   | 56.258331 | 57.115372 | 57.955017 | 58.777008 | 59.581097 | 60.367035 | 61.134586 | 61.883511 |
| 37   | 56.272755 | 57.129509 | 57.968864 | 58.790558 | 59.594345 | 60.379978 | 61.147221 | 61.895836 |
| 38   | 56.287178 | 57.143646 | 57.982708 | 58.804104 | 59.607590 | 60.392921 | 61.159851 | 61.908157 |
| 39   | 56.301594 | 57.157772 | 57.996540 | 58.817642 | 59.620831 | 60.405853 | 61.172478 | 61.920467 |
| 40   | 56.316006 | 57.171894 | 58.010372 | 58.831177 | 59.634064 | 60.418781 | 61.185097 | 61.932774 |
| 41   | 56.330410 | 57.186012 | 58.024197 | 58.844707 | 59.647289 | 60.431705 | 61.197712 | 61.945076 |
| 42   | 56.344810 | 57.200127 | 58.038017 | 58.858231 | 59.660511 | 60.444622 | 61.210320 | 61.957375 |
| 43   | 56.359207 | 57.214233 | 58.051834 | 58.871750 | 59.673729 | 60.457535 | 61.222923 | 61.969666 |
| 44   | 56.373600 | 57.228336 | 58.065643 | 58.885262 | 59.686943 | 60.470444 | 61.235523 | 61.981953 |
| 45   | 56.387985 | 57.242435 | 58.079449 | 58.898769 | 59.700150 | 60.483345 | 61.248119 | 61.994232 |
| 46   | 56.402370 | 57.256531 | 58.093250 | 58.912273 | 59.713352 | 60.496243 | 61.260708 | 62.006508 |
| 47   | 56.416744 | 57.270618 | 58.107048 | 58.925774 | 59.726551 | 60.509136 | 61.273289 | 62.018780 |
| 48   | 56.431118 | 57.284702 | 58.120838 | 58.939266 | 59.739746 | 60.522022 | 61.285870 | 62.031044 |
| 49   | 56.445488 | 57.298782 | 58.134624 | 58.952755 | 59.752934 | 60.534904 | 61.298443 | 62.043304 |
| 50   | 56.459850 | 57.312855 | 58.148403 | 58.966240 | 59.766113 | 60.547783 | 61.311008 | 62.055557 |
| 51   | 56.474209 | 57.326927 | 58.162182 | 58.979721 | 59.779293 | 60.560654 | 61.323570 | 62.067806 |
| 52   | 56.488560 | 57.340988 | 58.175953 | 58.993195 | 59.792465 | 60.573521 | 61.336128 | 62.080051 |
| 53   | 56.502914 | 57.355053 | 58.189720 | 59.006664 | 59.805634 | 60.586388 | 61.348682 | 62.092293 |
| 54   | 56.517258 | 57.369106 | 58.203484 | 59.020130 | 59.818798 | 60.599243 | 61.361233 | 62.104527 |
| 55   | 56.531597 | 57.383156 | 58.217239 | 59.033588 | 59.831955 | 60.612095 | 61.373772 | 62.116756 |
| 56   | 56.545929 | 57.397202 | 58.230991 | 59.047043 | 59.845108 | 60.624943 | 61.386311 | 62.128979 |
| 57   | 56.560261 | 57.411243 | 58.244740 | 59.060490 | 59.858253 | 60.637783 | 61.398842 | 62.141197 |
| 58   | 56.574585 | 57.425278 | 58.258480 | 59.073936 | 59.871395 | 60.650620 | 61.411369 | 62.153408 |
| 59   | 56.588905 | 57.439308 | 58.272217 | 59.087376 | 59.884533 | 60.663448 | 61.423889 | 62.165615 |
| 60   | 56.603218 | 57.453335 | 58.285950 | 59.100807 | 59.897663 | 60.676277 | 61.436405 | 62.177818 |

## SINE BAR CONSTANTS

## Constants for 125-mm Sine-Bar

## Constants for Setting a 125-mm Sine-Bar for 0° to 7°

| Min. | 0°       | 1°       | 2°       | 3°       | 4°        | 5°        | 6°        | 7°        |
|------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|
| 0    | 0.000000 | 2.181551 | 4.362437 | 6.541995 | 8.719560  | 10.894468 | 13.066058 | 15.233668 |
| 1    | 0.036361 | 2.217906 | 4.398776 | 6.578306 | 8.755832  | 10.930691 | 13.102220 | 15.269758 |
| 2    | 0.072722 | 2.254261 | 4.435114 | 6.614616 | 8.792103  | 10.966911 | 13.138380 | 15.305845 |
| 3    | 0.109083 | 2.290616 | 4.471452 | 6.650926 | 8.828374  | 11.003133 | 13.174540 | 15.341933 |
| 4    | 0.145444 | 2.326972 | 4.507790 | 6.687235 | 8.864643  | 11.039351 | 13.210696 | 15.378017 |
| 5    | 0.181805 | 2.363326 | 4.544127 | 6.723544 | 8.900913  | 11.075570 | 13.246854 | 15.414103 |
| 6    | 0.218166 | 2.399680 | 4.580463 | 6.759851 | 8.937181  | 11.111787 | 13.283010 | 15.450185 |
| 7    | 0.254527 | 2.436035 | 4.616800 | 6.796159 | 8.973449  | 11.148005 | 13.319164 | 15.486267 |
| 8    | 0.290888 | 2.472389 | 4.653136 | 6.832467 | 9.009715  | 11.184219 | 13.355317 | 15.522346 |
| 9    | 0.327249 | 2.508742 | 4.689472 | 6.868773 | 9.045981  | 11.220434 | 13.391470 | 15.558426 |
| 10   | 0.363610 | 2.545096 | 4.725807 | 6.905079 | 9.082246  | 11.256648 | 13.427621 | 15.594503 |
| 11   | 0.399971 | 2.581449 | 4.762142 | 6.941384 | 9.118511  | 11.292861 | 13.463771 | 15.630580 |
| 12   | 0.436331 | 2.617803 | 4.798476 | 6.977688 | 9.154775  | 11.329072 | 13.499920 | 15.666655 |
| 13   | 0.472692 | 2.654155 | 4.834810 | 7.013992 | 9.191038  | 11.365284 | 13.536068 | 15.702728 |
| 14   | 0.509053 | 2.690508 | 4.871144 | 7.050296 | 9.227300  | 11.401493 | 13.572214 | 15.738800 |
| 15   | 0.545414 | 2.726861 | 4.907477 | 7.086599 | 9.263561  | 11.437702 | 13.608359 | 15.774872 |
| 16   | 0.581774 | 2.763213 | 4.943810 | 7.122901 | 9.299823  | 11.473911 | 13.644505 | 15.810942 |
| 17   | 0.618135 | 2.799565 | 4.980142 | 7.159203 | 9.336082  | 11.510118 | 13.680647 | 15.847010 |
| 18   | 0.654496 | 2.835917 | 5.016474 | 7.195503 | 9.372341  | 11.546324 | 13.716789 | 15.883077 |
| 19   | 0.690856 | 2.872268 | 5.052805 | 7.231804 | 9.408599  | 11.582529 | 13.752930 | 15.919142 |
| 20   | 0.727216 | 2.908620 | 5.089137 | 7.268104 | 9.444858  | 11.618733 | 13.789070 | 15.955207 |
| 21   | 0.763577 | 2.944971 | 5.125467 | 7.304403 | 9.481113  | 11.654936 | 13.825208 | 15.991269 |
| 22   | 0.799937 | 2.981322 | 5.161798 | 7.340702 | 9.517369  | 11.691138 | 13.861346 | 16.027330 |
| 23   | 0.836297 | 3.017672 | 5.198128 | 7.377000 | 9.553624  | 11.727339 | 13.897482 | 16.063391 |
| 24   | 0.872658 | 3.054022 | 5.234457 | 7.413297 | 9.589879  | 11.763539 | 13.933618 | 16.099451 |
| 25   | 0.909018 | 3.090372 | 5.270786 | 7.449594 | 9.626132  | 11.799738 | 13.969750 | 16.135508 |
| 26   | 0.945378 | 3.126722 | 5.307115 | 7.485890 | 9.662385  | 11.835937 | 14.005883 | 16.171564 |
| 27   | 0.981738 | 3.163072 | 5.343442 | 7.522185 | 9.698636  | 11.872133 | 14.042014 | 16.207619 |
| 28   | 1.018098 | 3.199421 | 5.379770 | 7.558480 | 9.734888  | 11.908330 | 14.078145 | 16.243671 |
| 29   | 1.054457 | 3.235770 | 5.416097 | 7.594774 | 9.771137  | 11.944525 | 14.114274 | 16.279724 |
| 30   | 1.090817 | 3.272119 | 5.452424 | 7.631068 | 9.807387  | 11.980720 | 14.150402 | 16.315775 |
| 31   | 1.127177 | 3.308467 | 5.488750 | 7.667360 | 9.843637  | 12.016913 | 14.186529 | 16.351824 |
| 32   | 1.163536 | 3.344815 | 5.525075 | 7.703653 | 9.879884  | 12.053104 | 14.222654 | 16.387871 |
| 33   | 1.199896 | 3.381163 | 5.561400 | 7.739944 | 9.916131  | 12.089296 | 14.258779 | 16.423918 |
| 34   | 1.236255 | 3.417511 | 5.597725 | 7.776235 | 9.952376  | 12.125485 | 14.294902 | 16.459963 |
| 35   | 1.272614 | 3.453858 | 5.634050 | 7.812525 | 9.988622  | 12.161675 | 14.331024 | 16.496008 |
| 36   | 1.308973 | 3.490205 | 5.670373 | 7.848815 | 10.024865 | 12.197863 | 14.367144 | 16.532049 |
| 37   | 1.345332 | 3.526552 | 5.706697 | 7.885104 | 10.061110 | 12.234050 | 14.403264 | 16.568090 |
| 38   | 1.381691 | 3.562898 | 5.743020 | 7.921392 | 10.097352 | 12.270235 | 14.439382 | 16.604130 |
| 39   | 1.418050 | 3.599244 | 5.779343 | 7.957680 | 10.133594 | 12.306421 | 14.475499 | 16.640167 |
| 40   | 1.454408 | 3.635590 | 5.815664 | 7.993967 | 10.169834 | 12.342604 | 14.511615 | 16.676205 |
| 41   | 1.490767 | 3.671935 | 5.851986 | 8.030253 | 10.206075 | 12.378787 | 14.547729 | 16.712240 |
| 42   | 1.527125 | 3.708281 | 5.888307 | 8.066539 | 10.242313 | 12.414968 | 14.583842 | 16.748274 |
| 43   | 1.563483 | 3.744626 | 5.924627 | 8.102823 | 10.278552 | 12.451150 | 14.619955 | 16.784306 |
| 44   | 1.599842 | 3.780970 | 5.960947 | 8.139108 | 10.314789 | 12.487329 | 14.656065 | 16.820337 |
| 45   | 1.636199 | 3.817314 | 5.997266 | 8.175391 | 10.351027 | 12.523508 | 14.692175 | 16.856367 |
| 46   | 1.672557 | 3.853658 | 6.033585 | 8.211674 | 10.387262 | 12.559686 | 14.728284 | 16.892395 |
| 47   | 1.708915 | 3.890002 | 6.069903 | 8.247956 | 10.423496 | 12.595862 | 14.764391 | 16.928421 |
| 48   | 1.745273 | 3.926345 | 6.106221 | 8.284238 | 10.459731 | 12.632038 | 14.800497 | 16.964447 |
| 49   | 1.781630 | 3.962688 | 6.142539 | 8.320518 | 10.495964 | 12.668212 | 14.836601 | 17.000471 |
| 50   | 1.817987 | 3.999031 | 6.178855 | 8.356798 | 10.532196 | 12.704386 | 14.872705 | 17.036493 |
| 51   | 1.854344 | 4.035373 | 6.215172 | 8.393078 | 10.568427 | 12.740557 | 14.908807 | 17.072514 |
| 52   | 1.890701 | 4.071715 | 6.251487 | 8.429357 | 10.604658 | 12.776729 | 14.944907 | 17.108534 |
| 53   | 1.927058 | 4.108056 | 6.287803 | 8.465634 | 10.640887 | 12.812899 | 14.981007 | 17.144552 |
| 54   | 1.963415 | 4.144397 | 6.324118 | 8.501912 | 10.677115 | 12.849068 | 15.017105 | 17.180569 |
| 55   | 1.999771 | 4.180738 | 6.360432 | 8.538188 | 10.713343 | 12.885235 | 15.053202 | 17.216583 |
| 56   | 2.036128 | 4.217079 | 6.396746 | 8.574464 | 10.749570 | 12.921402 | 15.089298 | 17.252598 |
| 57   | 2.072484 | 4.253419 | 6.433059 | 8.610739 | 10.785795 | 12.957567 | 15.125392 | 17.288610 |
| 58   | 2.108840 | 4.289759 | 6.469371 | 8.647013 | 10.822021 | 12.993732 | 15.161486 | 17.324621 |
| 59   | 2.145195 | 4.326098 | 6.505683 | 8.683287 | 10.858245 | 13.029896 | 15.197577 | 17.360630 |
| 60   | 2.181551 | 4.362437 | 6.541995 | 8.719560 | 10.894468 | 13.066058 | 15.233668 | 17.396639 |

## SINE BAR CONSTANTS

## Constants for Setting a 125-mm Sine-Bar for 8° to 15°

| Min. | 8°        | 9°        | 10°       | 11°       | 12°       | 13°       | 14°       | 15°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 17.396639 | 19.554308 | 21.706022 | 23.851126 | 25.988962 | 28.118883 | 30.240238 | 32.352383 |
| 1    | 17.432644 | 19.590221 | 21.741831 | 23.886816 | 26.024527 | 28.154310 | 30.275517 | 32.387501 |
| 2    | 17.468651 | 19.626133 | 21.777637 | 23.922508 | 26.060091 | 28.189737 | 30.310795 | 32.422623 |
| 3    | 17.504654 | 19.662043 | 21.813440 | 23.958195 | 26.095652 | 28.225159 | 30.346069 | 32.457737 |
| 4    | 17.540655 | 19.697948 | 21.849243 | 23.993881 | 26.131210 | 28.260580 | 30.381340 | 32.492847 |
| 5    | 17.576654 | 19.733854 | 21.885042 | 24.029564 | 26.166765 | 28.295998 | 30.416611 | 32.527958 |
| 6    | 17.612656 | 19.769760 | 21.920843 | 24.065247 | 26.202322 | 28.331415 | 30.451878 | 32.563065 |
| 7    | 17.648653 | 19.805662 | 21.956638 | 24.100927 | 26.237873 | 28.366829 | 30.487143 | 32.598167 |
| 8    | 17.684649 | 19.841562 | 21.992432 | 24.136604 | 26.273422 | 28.402239 | 30.522404 | 32.633270 |
| 9    | 17.720642 | 19.877460 | 22.028225 | 24.172279 | 26.308969 | 28.437647 | 30.557661 | 32.668369 |
| 10   | 17.756636 | 19.913361 | 22.064018 | 24.207954 | 26.344517 | 28.473055 | 30.592920 | 32.703465 |
| 11   | 17.792627 | 19.949255 | 22.099806 | 24.243626 | 26.380060 | 28.508459 | 30.628174 | 32.738560 |
| 12   | 17.828617 | 19.985149 | 22.135593 | 24.279295 | 26.415600 | 28.543859 | 30.663424 | 32.773647 |
| 13   | 17.864605 | 20.021040 | 22.171377 | 24.314960 | 26.451138 | 28.579258 | 30.698671 | 32.808735 |
| 14   | 17.900593 | 20.056932 | 22.207163 | 24.350628 | 26.486675 | 28.614656 | 30.733919 | 32.843822 |
| 15   | 17.936579 | 20.092821 | 22.242945 | 24.386292 | 26.522209 | 28.650049 | 30.769163 | 32.878902 |
| 16   | 17.972561 | 20.128708 | 22.278723 | 24.421951 | 26.557741 | 28.685440 | 30.804403 | 32.913982 |
| 17   | 18.008545 | 20.164595 | 22.314503 | 24.457613 | 26.593273 | 28.720833 | 30.839643 | 32.949059 |
| 18   | 18.044525 | 20.200480 | 22.350279 | 24.493269 | 26.628799 | 28.756218 | 30.874878 | 32.984131 |
| 19   | 18.080505 | 20.236361 | 22.386051 | 24.528923 | 26.664324 | 28.791603 | 30.910110 | 33.019203 |
| 20   | 18.116482 | 20.272240 | 22.421824 | 24.564577 | 26.699846 | 28.826984 | 30.945341 | 33.054272 |
| 21   | 18.152460 | 20.308121 | 22.457596 | 24.600229 | 26.735369 | 28.862366 | 30.980570 | 33.089336 |
| 22   | 18.188435 | 20.343998 | 22.493362 | 24.635878 | 26.770887 | 28.897741 | 31.015795 | 33.124401 |
| 23   | 18.224407 | 20.379871 | 22.529129 | 24.671524 | 26.806402 | 28.933117 | 31.051016 | 33.159458 |
| 24   | 18.260378 | 20.415745 | 22.564894 | 24.707167 | 26.841915 | 28.968489 | 31.086235 | 33.194515 |
| 25   | 18.296350 | 20.451618 | 22.600657 | 24.742811 | 26.877428 | 29.003859 | 31.121454 | 33.229568 |
| 26   | 18.332317 | 20.487488 | 22.636417 | 24.778452 | 26.912937 | 29.039227 | 31.156670 | 33.264622 |
| 27   | 18.368284 | 20.523355 | 22.672176 | 24.814098 | 26.948444 | 29.074591 | 31.191881 | 33.299667 |
| 28   | 18.404249 | 20.559221 | 22.707932 | 24.849726 | 26.983950 | 29.109953 | 31.227089 | 33.334713 |
| 29   | 18.440214 | 20.595089 | 22.743689 | 24.885361 | 27.019453 | 29.145313 | 31.262299 | 33.369759 |
| 30   | 18.476177 | 20.630951 | 22.779442 | 24.920992 | 27.054953 | 29.180672 | 31.297501 | 33.404797 |
| 31   | 18.512136 | 20.666813 | 22.815191 | 24.956621 | 27.090450 | 29.216026 | 31.332703 | 33.439835 |
| 32   | 18.548098 | 20.702673 | 22.850943 | 24.992250 | 27.125948 | 29.251381 | 31.367903 | 33.474869 |
| 33   | 18.584055 | 20.738531 | 22.886690 | 25.027876 | 27.161440 | 29.286730 | 31.403099 | 33.509903 |
| 34   | 18.620010 | 20.774387 | 22.922434 | 25.063499 | 27.196930 | 29.322077 | 31.438292 | 33.544930 |
| 35   | 18.655964 | 20.810240 | 22.958178 | 25.099121 | 27.232418 | 29.357422 | 31.473482 | 33.579956 |
| 36   | 18.691919 | 20.846094 | 22.993919 | 25.134741 | 27.267906 | 29.392765 | 31.508671 | 33.614979 |
| 37   | 18.727871 | 20.881945 | 23.029659 | 25.170359 | 27.303391 | 29.428106 | 31.543856 | 33.649998 |
| 38   | 18.763819 | 20.917793 | 23.065397 | 25.205973 | 27.338871 | 29.463442 | 31.579039 | 33.685017 |
| 39   | 18.799767 | 20.953640 | 23.101131 | 25.241585 | 27.374352 | 29.498777 | 31.614218 | 33.720028 |
| 40   | 18.835714 | 20.989489 | 23.136868 | 25.277199 | 27.409830 | 29.534111 | 31.649397 | 33.755043 |
| 41   | 18.871660 | 21.025331 | 23.172598 | 25.312807 | 27.445303 | 29.569441 | 31.684572 | 33.790051 |
| 42   | 18.907602 | 21.061172 | 23.208326 | 25.348412 | 27.480776 | 29.604769 | 31.719744 | 33.825058 |
| 43   | 18.943544 | 21.097012 | 23.244055 | 25.384016 | 27.516245 | 29.640093 | 31.754913 | 33.860058 |
| 44   | 18.979486 | 21.132853 | 23.279781 | 25.419621 | 27.551716 | 29.675417 | 31.790081 | 33.895061 |
| 45   | 19.015425 | 21.168688 | 23.315506 | 25.455219 | 27.587179 | 29.710737 | 31.825245 | 33.930058 |
| 46   | 19.051361 | 21.204523 | 23.351227 | 25.490816 | 27.622643 | 29.746054 | 31.860405 | 33.965050 |
| 47   | 19.087297 | 21.240358 | 23.386948 | 25.526415 | 27.658106 | 29.781372 | 31.895565 | 34.000046 |
| 48   | 19.123230 | 21.276188 | 23.422665 | 25.562008 | 27.693563 | 29.816683 | 31.930721 | 34.035030 |
| 49   | 19.159163 | 21.312017 | 23.458382 | 25.597599 | 27.729019 | 29.851994 | 31.965874 | 34.070019 |
| 50   | 19.195091 | 21.347845 | 23.494095 | 25.633188 | 27.764473 | 29.887300 | 32.001022 | 34.105000 |
| 51   | 19.231022 | 21.383673 | 23.529808 | 25.668776 | 27.799925 | 29.922607 | 32.036175 | 34.139988 |
| 52   | 19.266949 | 21.419497 | 23.565517 | 25.704361 | 27.835375 | 29.957909 | 32.071320 | 34.174957 |
| 53   | 19.302874 | 21.455317 | 23.601225 | 25.739943 | 27.870821 | 29.993208 | 32.106461 | 34.209930 |
| 54   | 19.338799 | 21.491137 | 23.636930 | 25.775522 | 27.906265 | 30.028505 | 32.141598 | 34.244904 |
| 55   | 19.374722 | 21.526957 | 23.672636 | 25.811104 | 27.941708 | 30.063803 | 32.176739 | 34.279873 |
| 56   | 19.410643 | 21.562775 | 23.708338 | 25.846680 | 27.977148 | 30.099094 | 32.211872 | 34.314838 |
| 57   | 19.446560 | 21.598589 | 23.744038 | 25.882252 | 28.012585 | 30.134382 | 32.247002 | 34.349800 |
| 58   | 19.482477 | 21.634401 | 23.779734 | 25.917824 | 28.048019 | 30.169670 | 32.282131 | 34.384758 |
| 59   | 19.518394 | 21.670214 | 23.815432 | 25.953396 | 28.083452 | 30.204956 | 32.317257 | 34.419716 |
| 60   | 19.554308 | 21.706022 | 23.851126 | 25.988962 | 28.118883 | 30.240238 | 32.352383 | 34.454670 |



## Constants for Setting a 125-mm Sine-Bar for 16° to 23°

| Min. | 16°       | 17°       | 18°       | 19°       | 20°       | 21°       | 22°       | 23°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 34.454670 | 36.546463 | 38.627125 | 40.696022 | 42.752518 | 44.795994 | 46.825825 | 48.841393 |
| 1    | 34.489620 | 36.581234 | 38.661705 | 40.730396 | 42.786686 | 44.829937 | 46.859535 | 48.874859 |
| 2    | 34.524567 | 36.616001 | 38.696281 | 40.764774 | 42.820847 | 44.863876 | 46.893242 | 48.908325 |
| 3    | 34.559513 | 36.650764 | 38.730854 | 40.799145 | 42.855007 | 44.897816 | 46.926945 | 48.941874 |
| 4    | 34.594460 | 36.685532 | 38.765427 | 40.833515 | 42.889164 | 44.931751 | 46.960648 | 48.975243 |
| 5    | 34.629398 | 36.720287 | 38.799992 | 40.867878 | 42.923317 | 44.965679 | 46.994343 | 49.008694 |
| 6    | 34.664333 | 36.755043 | 38.834557 | 40.902241 | 42.957462 | 44.999603 | 47.028034 | 49.042141 |
| 7    | 34.699265 | 36.789795 | 38.869114 | 40.936596 | 42.991608 | 45.033524 | 47.061722 | 49.075584 |
| 8    | 34.734196 | 36.824543 | 38.903671 | 40.970951 | 43.025749 | 45.067440 | 47.095406 | 49.109024 |
| 9    | 34.769123 | 36.859287 | 38.938225 | 41.005299 | 43.059887 | 45.101353 | 47.129086 | 49.142460 |
| 10   | 34.804047 | 36.894032 | 38.972775 | 41.039646 | 43.094017 | 45.135262 | 47.162758 | 49.175888 |
| 11   | 34.838970 | 36.928768 | 39.007320 | 41.073990 | 43.128147 | 45.169170 | 47.196430 | 49.209316 |
| 12   | 34.873890 | 36.963509 | 39.041866 | 41.108334 | 43.162277 | 45.203075 | 47.230103 | 49.242741 |
| 13   | 34.908806 | 36.998241 | 39.076408 | 41.142670 | 43.196400 | 45.236973 | 47.263763 | 49.276161 |
| 14   | 34.943718 | 37.032970 | 39.110943 | 41.177002 | 43.230518 | 45.270866 | 47.297424 | 49.309574 |
| 15   | 34.978626 | 37.067699 | 39.145477 | 41.211330 | 43.264633 | 45.304756 | 47.331078 | 49.342983 |
| 16   | 35.013535 | 37.102421 | 39.180008 | 41.245659 | 43.298744 | 45.338642 | 47.364731 | 49.376389 |
| 17   | 35.048439 | 37.137142 | 39.214535 | 41.279980 | 43.332851 | 45.372524 | 47.398376 | 49.409790 |
| 18   | 35.083340 | 37.171860 | 39.249058 | 41.314297 | 43.366955 | 45.406403 | 47.432018 | 49.443188 |
| 19   | 35.118240 | 37.206577 | 39.283581 | 41.348618 | 43.401062 | 45.440281 | 47.465664 | 49.476585 |
| 20   | 35.153133 | 37.241287 | 39.318096 | 41.382931 | 43.435158 | 45.474152 | 47.499298 | 49.509972 |
| 21   | 35.188026 | 37.275993 | 39.352612 | 41.417236 | 43.469250 | 45.508018 | 47.532928 | 49.543358 |
| 22   | 35.222916 | 37.310699 | 39.387119 | 41.451542 | 43.503338 | 45.541885 | 47.566555 | 49.576740 |
| 23   | 35.257801 | 37.345402 | 39.421627 | 41.485844 | 43.537426 | 45.575745 | 47.600178 | 49.610115 |
| 24   | 35.292683 | 37.380100 | 39.456131 | 41.520142 | 43.571507 | 45.609600 | 47.633797 | 49.643486 |
| 25   | 35.327560 | 37.414795 | 39.490631 | 41.554436 | 43.605583 | 45.643452 | 47.667412 | 49.676853 |
| 26   | 35.362438 | 37.449486 | 39.525127 | 41.588726 | 43.639660 | 45.677299 | 47.701023 | 49.710220 |
| 27   | 35.397316 | 37.484180 | 39.559624 | 41.623016 | 43.673733 | 45.711147 | 47.734634 | 49.743580 |
| 28   | 35.432186 | 37.518864 | 39.594112 | 41.657303 | 43.707802 | 45.744987 | 47.768238 | 49.776936 |
| 29   | 35.467056 | 37.553547 | 39.628601 | 41.691582 | 43.741863 | 45.778824 | 47.801834 | 49.810287 |
| 30   | 35.501919 | 37.588226 | 39.663082 | 41.725857 | 43.775925 | 45.812656 | 47.835430 | 49.843636 |
| 31   | 35.536781 | 37.622902 | 39.697563 | 41.760132 | 43.809978 | 45.846481 | 47.869022 | 49.876976 |
| 32   | 35.571640 | 37.657574 | 39.732040 | 41.794403 | 43.844032 | 45.880306 | 47.902607 | 49.910316 |
| 33   | 35.606495 | 37.692245 | 39.766514 | 41.828667 | 43.878082 | 45.914127 | 47.936192 | 49.943649 |
| 34   | 35.641350 | 37.726913 | 39.800987 | 41.862934 | 43.912128 | 45.947948 | 47.969772 | 49.976982 |
| 35   | 35.676201 | 37.761578 | 39.835453 | 41.897194 | 43.946171 | 45.981762 | 48.003345 | 50.010311 |
| 36   | 35.711048 | 37.796238 | 39.869915 | 41.931450 | 43.980209 | 46.015572 | 48.036919 | 50.043633 |
| 37   | 35.745892 | 37.830894 | 39.904377 | 41.965698 | 44.014240 | 46.049377 | 48.070484 | 50.076950 |
| 38   | 35.780731 | 37.865547 | 39.938831 | 41.999947 | 44.048271 | 46.083176 | 48.104046 | 50.110260 |
| 39   | 35.815571 | 37.900200 | 39.973286 | 42.034195 | 44.082298 | 46.116974 | 48.137604 | 50.143570 |
| 40   | 35.850403 | 37.934845 | 40.007732 | 42.068436 | 44.116322 | 46.150768 | 48.171158 | 50.176876 |
| 41   | 35.885235 | 37.969490 | 40.042179 | 42.102673 | 44.150341 | 46.184559 | 48.204708 | 50.210175 |
| 42   | 35.920067 | 38.004135 | 40.076626 | 42.136909 | 44.184357 | 46.218346 | 48.238258 | 50.243473 |
| 43   | 35.954891 | 38.038773 | 40.111065 | 42.171139 | 44.218369 | 46.252129 | 48.271801 | 50.276768 |
| 44   | 35.989716 | 38.073406 | 40.145500 | 42.205368 | 44.252377 | 46.285908 | 48.305336 | 50.310055 |
| 45   | 36.024536 | 38.108040 | 40.179935 | 42.239590 | 44.286381 | 46.319679 | 48.338871 | 50.343338 |
| 46   | 36.059349 | 38.142666 | 40.214363 | 42.273811 | 44.320381 | 46.353451 | 48.372402 | 50.376617 |
| 47   | 36.094162 | 38.177292 | 40.248791 | 42.308025 | 44.354378 | 46.387218 | 48.405926 | 50.409893 |
| 48   | 36.128975 | 38.211914 | 40.283211 | 42.342239 | 44.388371 | 46.420979 | 48.439449 | 50.443161 |
| 49   | 36.163784 | 38.246536 | 40.317635 | 42.376453 | 44.422363 | 46.454742 | 48.472969 | 50.476433 |
| 50   | 36.198589 | 38.281151 | 40.352051 | 42.410660 | 44.456348 | 46.488495 | 48.506481 | 50.509693 |
| 51   | 36.233391 | 38.315762 | 40.386463 | 42.444859 | 44.490330 | 46.522247 | 48.539993 | 50.542950 |
| 52   | 36.268188 | 38.350368 | 40.420872 | 42.479057 | 44.524307 | 46.555992 | 48.573498 | 50.576206 |
| 53   | 36.302982 | 38.384975 | 40.455276 | 42.513252 | 44.558281 | 46.589733 | 48.606998 | 50.609455 |
| 54   | 36.337776 | 38.419579 | 40.489677 | 42.547443 | 44.592251 | 46.623474 | 48.640495 | 50.642700 |
| 55   | 36.372562 | 38.454178 | 40.524075 | 42.581631 | 44.626217 | 46.657207 | 48.673988 | 50.675938 |
| 56   | 36.407349 | 38.488773 | 40.558472 | 42.615814 | 44.660179 | 46.690937 | 48.707474 | 50.709175 |
| 57   | 36.442135 | 38.523369 | 40.592865 | 42.650002 | 44.694141 | 46.724670 | 48.740963 | 50.742413 |
| 58   | 36.476913 | 38.557957 | 40.627254 | 42.684177 | 44.728096 | 46.758392 | 48.774445 | 50.775639 |
| 59   | 36.511692 | 38.592545 | 40.661640 | 42.718349 | 44.762047 | 46.792110 | 48.807919 | 50.808861 |
| 60   | 36.546463 | 38.627125 | 40.696022 | 42.752518 | 44.795994 | 46.825825 | 48.841393 | 50.842083 |

## SINE BAR CONSTANTS

## Constants for Setting a 125-mm Sine-Bar for 20° to 31°

| Min. | 24°       | 25°       | 26°       | 27°       | 28°       | 29°       | 30°       | 31°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 50.842083 | 52.827286 | 54.796394 | 56.748814 | 58.683949 | 60.601204 | 62.500000 | 64.379761 |
| 1    | 50.875298 | 52.860237 | 54.829075 | 56.781208 | 58.716049 | 60.633003 | 62.531487 | 64.410927 |
| 2    | 50.908508 | 52.893181 | 54.861748 | 56.813599 | 58.748146 | 60.664799 | 62.562969 | 64.442085 |
| 3    | 50.941711 | 52.926125 | 54.894417 | 56.845985 | 58.780239 | 60.696587 | 62.594444 | 64.473236 |
| 4    | 50.974918 | 52.959068 | 54.927082 | 56.878368 | 58.812328 | 60.728374 | 62.625919 | 64.504387 |
| 5    | 51.008118 | 52.992001 | 54.959743 | 56.910744 | 58.844410 | 60.760151 | 62.657383 | 64.535530 |
| 6    | 51.041309 | 53.024929 | 54.992397 | 56.943115 | 58.876488 | 60.791924 | 62.688843 | 64.566666 |
| 7    | 51.074497 | 53.057854 | 55.025047 | 56.975483 | 58.908558 | 60.823692 | 62.720299 | 64.597801 |
| 8    | 51.107681 | 53.090775 | 55.057693 | 57.007843 | 58.940628 | 60.855457 | 62.751747 | 64.628929 |
| 9    | 51.140865 | 53.123692 | 55.090336 | 57.040199 | 58.972687 | 60.887215 | 62.783192 | 64.660049 |
| 10   | 51.174038 | 53.156601 | 55.122971 | 57.072552 | 59.004745 | 60.918466 | 62.814632 | 64.691162 |
| 11   | 51.207211 | 53.189507 | 55.155605 | 57.104897 | 59.036797 | 60.950714 | 62.846066 | 64.722275 |
| 12   | 51.240383 | 53.222416 | 55.188236 | 57.137245 | 59.068848 | 60.982460 | 62.877495 | 64.753380 |
| 13   | 51.273544 | 53.255314 | 55.220856 | 57.169582 | 59.100891 | 61.014198 | 62.908920 | 64.784477 |
| 14   | 51.306705 | 53.288204 | 55.253475 | 57.201912 | 59.132927 | 61.045929 | 62.940338 | 64.815575 |
| 15   | 51.339859 | 53.321095 | 55.286087 | 57.234241 | 59.164959 | 61.077656 | 62.971748 | 64.846657 |
| 16   | 51.373009 | 53.353977 | 55.318695 | 57.266563 | 59.196987 | 61.109379 | 63.003155 | 64.877739 |
| 17   | 51.406155 | 53.386856 | 55.351299 | 57.298882 | 59.229008 | 61.141094 | 63.034557 | 64.908821 |
| 18   | 51.439293 | 53.419731 | 55.383900 | 57.331196 | 59.261024 | 61.172806 | 63.065952 | 64.939888 |
| 19   | 51.472435 | 53.452606 | 55.416496 | 57.363506 | 59.293041 | 61.204517 | 63.097347 | 64.970955 |
| 20   | 51.505569 | 53.485474 | 55.449085 | 57.395809 | 59.325050 | 61.236217 | 63.128735 | 65.002022 |
| 21   | 51.538696 | 53.518333 | 55.481670 | 57.428108 | 59.357052 | 61.267914 | 63.160114 | 65.033073 |
| 22   | 51.571819 | 53.551193 | 55.514252 | 57.460400 | 59.389050 | 61.299603 | 63.191486 | 65.064125 |
| 23   | 51.604939 | 53.584045 | 55.546825 | 57.492691 | 59.421040 | 61.331291 | 63.222858 | 65.095169 |
| 24   | 51.638054 | 53.616894 | 55.579399 | 57.524975 | 59.453026 | 61.362968 | 63.254223 | 65.126205 |
| 25   | 51.671165 | 53.649734 | 55.611965 | 57.557251 | 59.485008 | 61.394646 | 63.285580 | 65.157234 |
| 26   | 51.704273 | 53.682575 | 55.644527 | 57.589527 | 59.516987 | 61.426315 | 63.316933 | 65.188263 |
| 27   | 51.737377 | 53.715412 | 55.677086 | 57.621799 | 59.548962 | 61.457985 | 63.348286 | 65.219292 |
| 28   | 51.770473 | 53.748241 | 55.709637 | 57.654064 | 59.580929 | 61.489643 | 63.379627 | 65.250305 |
| 29   | 51.803566 | 53.781067 | 55.742184 | 57.686325 | 59.612888 | 61.521297 | 63.410965 | 65.281319 |
| 30   | 51.836658 | 53.813889 | 55.774727 | 57.718578 | 59.644848 | 61.552948 | 63.442295 | 65.312325 |
| 31   | 51.869740 | 53.846706 | 55.807266 | 57.750828 | 59.676800 | 61.584591 | 63.473625 | 65.343323 |
| 32   | 51.902821 | 53.879517 | 55.839798 | 57.783073 | 59.708744 | 61.616230 | 63.504944 | 65.374313 |
| 33   | 51.935898 | 53.912323 | 55.872326 | 57.815311 | 59.740688 | 61.647861 | 63.536259 | 65.405304 |
| 34   | 51.968971 | 53.945129 | 55.904854 | 57.847549 | 59.772625 | 61.679493 | 63.567574 | 65.436295 |
| 35   | 52.002037 | 53.977928 | 55.937374 | 57.879780 | 59.804558 | 61.711117 | 63.598881 | 65.467270 |
| 36   | 52.035103 | 54.010719 | 55.969887 | 57.912006 | 59.836483 | 61.742737 | 63.630180 | 65.498238 |
| 37   | 52.068161 | 54.043510 | 56.002399 | 57.944225 | 59.868404 | 61.774349 | 63.661472 | 65.529205 |
| 38   | 52.101212 | 54.076294 | 56.034901 | 57.976444 | 59.900322 | 61.805954 | 63.692764 | 65.560165 |
| 39   | 52.134262 | 54.109074 | 56.067402 | 58.008652 | 59.932232 | 61.837559 | 63.724045 | 65.591125 |
| 40   | 52.167309 | 54.141850 | 56.099899 | 58.040859 | 59.964138 | 61.869156 | 63.755325 | 65.622070 |
| 41   | 52.200348 | 54.174618 | 56.132389 | 58.073059 | 59.996040 | 61.900745 | 63.786598 | 65.653015 |
| 42   | 52.233387 | 54.207390 | 56.164879 | 58.105259 | 60.027939 | 61.932335 | 63.817867 | 65.683960 |
| 43   | 52.266418 | 54.240150 | 56.197357 | 58.137451 | 60.059830 | 61.963917 | 63.849129 | 65.714890 |
| 44   | 52.299446 | 54.272907 | 56.229836 | 58.169636 | 60.091717 | 61.995495 | 63.880386 | 65.745819 |
| 45   | 52.332470 | 54.305660 | 56.262306 | 58.201817 | 60.123596 | 62.027065 | 63.911636 | 65.776741 |
| 46   | 52.365486 | 54.338406 | 56.294773 | 58.233994 | 60.155472 | 62.058632 | 63.942883 | 65.807655 |
| 47   | 52.398502 | 54.371147 | 56.327236 | 58.266163 | 60.187344 | 62.090191 | 63.974125 | 65.838570 |
| 48   | 52.431511 | 54.403889 | 56.359692 | 58.298328 | 60.219208 | 62.121746 | 64.005356 | 65.869474 |
| 49   | 52.464520 | 54.436626 | 56.392147 | 58.330494 | 60.251072 | 62.153297 | 64.036591 | 65.900375 |
| 50   | 52.497520 | 54.469353 | 56.424595 | 58.362652 | 60.282928 | 62.184845 | 64.067818 | 65.931274 |
| 51   | 52.530514 | 54.502079 | 56.457039 | 58.394802 | 60.314777 | 62.216381 | 64.099037 | 65.962158 |
| 52   | 52.563507 | 54.534798 | 56.489479 | 58.426949 | 60.346622 | 62.247917 | 64.130249 | 65.993042 |
| 53   | 52.596493 | 54.567513 | 56.521912 | 58.459091 | 60.378464 | 62.279446 | 64.161453 | 66.023918 |
| 54   | 52.629478 | 54.600224 | 56.554340 | 58.491226 | 60.410297 | 62.310966 | 64.192657 | 66.054794 |
| 55   | 52.662457 | 54.632931 | 56.586761 | 58.523357 | 60.442127 | 62.342487 | 64.223854 | 66.085655 |
| 56   | 52.695431 | 54.665630 | 56.619183 | 58.555485 | 60.473953 | 62.374001 | 64.255043 | 66.116516 |
| 57   | 52.728401 | 54.698334 | 56.651600 | 58.587612 | 60.505775 | 62.405510 | 64.286232 | 66.147377 |
| 58   | 52.761368 | 54.731026 | 56.684010 | 58.619728 | 60.537590 | 62.437012 | 64.317413 | 66.178230 |
| 59   | 52.794327 | 54.763710 | 56.716415 | 58.651840 | 60.569401 | 62.468510 | 64.348595 | 66.209068 |
| 60   | 52.827286 | 54.796394 | 56.748814 | 58.683949 | 60.601204 | 62.500000 | 64.379761 | 66.239906 |

## Constants for Setting a 125-mm Sine-Bar for 32° to 39°

| Min. | 32°       | 33°       | 34°       | 35°       | 36°       | 37°       | 38°       | 39°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 66.239906 | 68.079880 | 69.899117 | 71.697060 | 73.473160 | 75.226883 | 76.957687 | 78.665054 |
| 1    | 66.270744 | 68.110374 | 69.929253 | 71.726837 | 73.502571 | 75.255913 | 76.986336 | 78.693306 |
| 2    | 66.301567 | 68.140862 | 69.959389 | 71.756615 | 73.531975 | 75.284943 | 77.014977 | 78.721550 |
| 3    | 66.332390 | 68.171341 | 69.989517 | 71.786385 | 73.561378 | 75.313965 | 77.043617 | 78.749794 |
| 4    | 66.363205 | 68.201813 | 70.019646 | 71.816147 | 73.590775 | 75.342987 | 77.072243 | 78.778030 |
| 5    | 66.394020 | 68.232285 | 70.049759 | 71.845901 | 73.620163 | 75.371994 | 77.100868 | 78.806252 |
| 6    | 66.424820 | 68.262741 | 70.079872 | 71.875656 | 73.649544 | 75.401001 | 77.129486 | 78.834473 |
| 7    | 66.455620 | 68.293198 | 70.109978 | 71.905403 | 73.678917 | 75.429993 | 77.158096 | 78.862686 |
| 8    | 66.486420 | 68.323662 | 70.140083 | 71.935150 | 73.708298 | 75.458992 | 77.186707 | 78.890900 |
| 9    | 66.517212 | 68.354103 | 70.170181 | 71.964882 | 73.737656 | 75.487976 | 77.215302 | 78.919106 |
| 10   | 66.547989 | 68.384544 | 70.200264 | 71.994606 | 73.767014 | 75.516953 | 77.243889 | 78.947296 |
| 11   | 66.578766 | 68.414978 | 70.230347 | 72.024330 | 73.796364 | 75.545929 | 77.272476 | 78.975487 |
| 12   | 66.609535 | 68.445404 | 70.260422 | 72.054039 | 73.825714 | 75.574890 | 77.301056 | 79.003670 |
| 13   | 66.640305 | 68.475830 | 70.290497 | 72.083748 | 73.855049 | 75.603851 | 77.329620 | 79.031837 |
| 14   | 66.671059 | 68.506248 | 70.320557 | 72.113457 | 73.884384 | 75.632805 | 77.358185 | 79.060005 |
| 15   | 66.701813 | 68.536652 | 70.350616 | 72.143150 | 73.913712 | 75.661751 | 77.386749 | 79.088165 |
| 16   | 66.732567 | 68.567062 | 70.380669 | 72.172844 | 73.943024 | 75.690689 | 77.415298 | 79.116325 |
| 17   | 66.763306 | 68.597458 | 70.410713 | 72.202522 | 73.972343 | 75.719620 | 77.443840 | 79.144470 |
| 18   | 66.794044 | 68.627853 | 70.440758 | 72.232201 | 74.001648 | 75.748550 | 77.472382 | 79.172607 |
| 19   | 66.824776 | 68.658241 | 70.470787 | 72.261879 | 74.030945 | 75.777473 | 77.500908 | 79.200745 |
| 20   | 66.855499 | 68.688622 | 70.500816 | 72.291542 | 74.060242 | 75.806389 | 77.529434 | 79.228874 |
| 21   | 66.886223 | 68.718994 | 70.530838 | 72.321205 | 74.089531 | 75.835297 | 77.557953 | 79.256989 |
| 22   | 66.916939 | 68.749367 | 70.560860 | 72.350853 | 74.118813 | 75.864197 | 77.586464 | 79.285103 |
| 23   | 66.947647 | 68.779739 | 70.590874 | 72.380508 | 74.148094 | 75.893097 | 77.614975 | 79.313217 |
| 24   | 66.978355 | 68.810097 | 70.620880 | 72.410149 | 74.177368 | 75.921982 | 77.643478 | 79.341316 |
| 25   | 67.009048 | 68.840446 | 70.650879 | 72.439789 | 74.206627 | 75.950867 | 77.671967 | 79.369415 |
| 26   | 67.039742 | 68.870796 | 70.680870 | 72.469414 | 74.235886 | 75.979744 | 77.700455 | 79.397499 |
| 27   | 67.070427 | 68.901138 | 70.710861 | 72.499039 | 74.265137 | 76.008614 | 77.728935 | 79.425583 |
| 28   | 67.101112 | 68.931473 | 70.740837 | 72.528656 | 74.294380 | 76.037476 | 77.757408 | 79.453651 |
| 29   | 67.131783 | 68.961800 | 70.770813 | 72.558266 | 74.323616 | 76.066330 | 77.785873 | 79.481720 |
| 30   | 67.162453 | 68.992126 | 70.800781 | 72.587868 | 74.352852 | 76.095177 | 77.814331 | 79.509781 |
| 31   | 67.193115 | 69.022446 | 70.830742 | 72.617470 | 74.382072 | 76.124023 | 77.842781 | 79.537834 |
| 32   | 67.223770 | 69.052757 | 70.860703 | 72.647064 | 74.411293 | 76.152863 | 77.871231 | 79.565880 |
| 33   | 67.254425 | 69.083061 | 70.890648 | 72.676651 | 74.440506 | 76.181694 | 77.899673 | 79.593918 |
| 34   | 67.285072 | 69.113358 | 70.920593 | 72.706230 | 74.469711 | 76.210518 | 77.928101 | 79.621956 |
| 35   | 67.315712 | 69.143654 | 70.950531 | 72.735802 | 74.498917 | 76.239334 | 77.956528 | 79.649979 |
| 36   | 67.346344 | 69.173943 | 70.980469 | 72.765373 | 74.528107 | 76.268143 | 77.984947 | 79.678001 |
| 37   | 67.376976 | 69.204224 | 71.010391 | 72.794930 | 74.557297 | 76.296951 | 78.013359 | 79.706009 |
| 38   | 67.407608 | 69.234512 | 71.040321 | 72.824493 | 74.586487 | 76.325752 | 78.041779 | 79.734024 |
| 39   | 67.438225 | 69.264778 | 71.070236 | 72.854042 | 74.615662 | 76.354546 | 78.070175 | 79.762024 |
| 40   | 67.468834 | 69.295044 | 71.100143 | 72.883583 | 74.644829 | 76.383331 | 78.098572 | 79.790016 |
| 41   | 67.499443 | 69.325302 | 71.130051 | 72.913124 | 74.673988 | 76.412109 | 78.126953 | 79.818001 |
| 42   | 67.530045 | 69.355560 | 71.159943 | 72.942657 | 74.703148 | 76.440880 | 78.155334 | 79.845978 |
| 43   | 67.560638 | 69.385803 | 71.189835 | 72.972176 | 74.732300 | 76.469650 | 78.183708 | 79.873955 |
| 44   | 67.591225 | 69.416046 | 71.219719 | 73.001701 | 74.761436 | 76.498405 | 78.212074 | 79.901917 |
| 45   | 67.621811 | 69.446281 | 71.249596 | 73.031212 | 74.790573 | 76.527161 | 78.240433 | 79.929878 |
| 46   | 67.652390 | 69.476509 | 71.279472 | 73.060715 | 74.819710 | 76.555908 | 78.268791 | 79.957832 |
| 47   | 67.682961 | 69.506737 | 71.309334 | 73.090218 | 74.848831 | 76.584648 | 78.297134 | 79.985771 |
| 48   | 67.713524 | 69.536949 | 71.339195 | 73.119713 | 74.877953 | 76.613380 | 78.325478 | 80.013710 |
| 49   | 67.744087 | 69.567162 | 71.369049 | 73.149200 | 74.907059 | 76.642113 | 78.353813 | 80.041641 |
| 50   | 67.774643 | 69.597374 | 71.398895 | 73.178680 | 74.936165 | 76.670830 | 78.382141 | 80.069572 |
| 51   | 67.805191 | 69.627571 | 71.428741 | 73.208153 | 74.965263 | 76.699547 | 78.410461 | 80.097488 |
| 52   | 67.835732 | 69.657768 | 71.458580 | 73.237625 | 74.994362 | 76.728249 | 78.438774 | 80.125397 |
| 53   | 67.866280 | 69.687958 | 71.488411 | 73.267090 | 75.023453 | 76.756958 | 78.467087 | 80.153313 |
| 54   | 67.896812 | 69.718140 | 71.518242 | 73.296547 | 75.052536 | 76.785652 | 78.495384 | 80.181206 |
| 55   | 67.927338 | 69.748322 | 71.548058 | 73.325996 | 75.081604 | 76.814346 | 78.523682 | 80.209099 |
| 56   | 67.957855 | 69.778488 | 71.577866 | 73.355446 | 75.110672 | 76.843025 | 78.551971 | 80.236984 |
| 57   | 67.988373 | 69.808655 | 71.607674 | 73.384880 | 75.139732 | 76.871696 | 78.580246 | 80.264862 |
| 58   | 68.018883 | 69.838814 | 71.637474 | 73.414314 | 75.168793 | 76.900368 | 78.608521 | 80.292732 |
| 59   | 68.049385 | 69.868965 | 71.667267 | 73.443741 | 75.197838 | 76.929031 | 78.636787 | 80.320595 |
| 60   | 68.079880 | 69.899117 | 71.697060 | 73.473160 | 75.226883 | 76.957687 | 78.665054 | 80.348450 |

## SINE BAR CONSTANTS

## Constants for Setting a 125-mm Sine-Bar for 40° to 47°

| Min. | 40°       | 41°       | 42°       | 43°       | 44°       | 45°       | 46°       | 47°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 80.348450 | 82.007378 | 83.641327 | 85.249794 | 86.832298 | 88.388351 | 89.917480 | 91.419212 |
| 1    | 80.376305 | 82.034821 | 83.668343 | 85.276382 | 86.858452 | 88.414055 | 89.942734 | 91.444008 |
| 2    | 80.404144 | 82.062248 | 83.695358 | 85.302971 | 86.884598 | 88.439758 | 89.969779 | 91.468796 |
| 3    | 80.431984 | 82.089676 | 83.722359 | 85.329544 | 86.910728 | 88.464544 | 89.993217 | 91.493576 |
| 4    | 80.459816 | 82.117088 | 83.749359 | 85.356110 | 86.936859 | 88.491135 | 90.018448 | 91.518341 |
| 5    | 80.487640 | 82.144501 | 83.776344 | 85.382668 | 86.962982 | 88.516808 | 90.043671 | 91.543106 |
| 6    | 80.515450 | 82.171906 | 83.803329 | 85.409218 | 86.989098 | 88.542480 | 90.068886 | 91.567863 |
| 7    | 80.543266 | 82.199303 | 83.830299 | 85.435768 | 87.015205 | 88.568138 | 90.094101 | 91.592613 |
| 8    | 80.571068 | 82.226700 | 83.857277 | 85.462311 | 87.041313 | 88.593803 | 90.119301 | 91.617355 |
| 9    | 80.598869 | 82.254082 | 83.884239 | 85.488838 | 87.067406 | 88.619446 | 90.144501 | 91.642090 |
| 10   | 80.626656 | 82.281456 | 83.911194 | 85.515366 | 87.093491 | 88.645088 | 90.169685 | 91.666809 |
| 11   | 80.654442 | 82.308823 | 83.938141 | 85.541885 | 87.119568 | 88.670723 | 90.194862 | 91.691528 |
| 12   | 80.682213 | 82.336189 | 83.965080 | 85.568390 | 87.145638 | 88.696342 | 90.220032 | 91.716240 |
| 13   | 80.709984 | 82.363541 | 83.992012 | 85.594894 | 87.171707 | 88.721962 | 90.245193 | 91.740936 |
| 14   | 80.737747 | 82.390884 | 84.018936 | 85.621391 | 87.197762 | 88.747574 | 90.270348 | 91.765633 |
| 15   | 80.765503 | 82.418228 | 84.045853 | 85.647873 | 87.223808 | 88.773170 | 90.295494 | 91.790314 |
| 16   | 80.793251 | 82.445564 | 84.072762 | 85.674355 | 87.249847 | 88.798767 | 90.320641 | 91.814995 |
| 17   | 80.820992 | 82.472893 | 84.099670 | 85.700829 | 87.275887 | 88.824356 | 90.345772 | 91.839661 |
| 18   | 80.848724 | 82.500206 | 84.126564 | 85.727295 | 87.301910 | 88.849937 | 90.370895 | 91.864326 |
| 19   | 80.876450 | 82.527519 | 84.153458 | 85.753754 | 87.327934 | 88.875504 | 90.396011 | 91.888977 |
| 20   | 80.904175 | 82.554825 | 84.180336 | 85.780205 | 87.353943 | 88.901070 | 90.421120 | 91.913628 |
| 21   | 80.931885 | 82.582130 | 84.207214 | 85.806648 | 87.379944 | 88.926628 | 90.446220 | 91.938263 |
| 22   | 80.959595 | 82.609421 | 84.234077 | 85.833084 | 87.405945 | 88.952179 | 90.471313 | 91.962898 |
| 23   | 80.987297 | 82.636711 | 84.260948 | 85.859520 | 87.431938 | 88.977722 | 90.496407 | 91.987526 |
| 24   | 81.014992 | 82.663986 | 84.287804 | 85.885941 | 87.457924 | 89.003258 | 90.521484 | 92.012138 |
| 25   | 81.042679 | 82.691261 | 84.314651 | 85.912361 | 87.483894 | 89.028786 | 90.546555 | 92.036751 |
| 26   | 81.070358 | 82.718521 | 84.341492 | 85.938766 | 87.509865 | 89.054306 | 90.571625 | 92.061348 |
| 27   | 81.098030 | 82.745781 | 84.368324 | 85.965164 | 87.535828 | 89.079819 | 90.596680 | 92.085938 |
| 28   | 81.125694 | 82.773026 | 84.395149 | 85.991562 | 87.561775 | 89.105324 | 90.621727 | 92.110527 |
| 29   | 81.153358 | 82.800270 | 84.421967 | 86.017944 | 87.587723 | 89.130821 | 90.646767 | 92.135101 |
| 30   | 81.181007 | 82.827507 | 84.448776 | 86.044327 | 87.613663 | 89.156311 | 90.671799 | 92.159668 |
| 31   | 81.208656 | 82.854736 | 84.475578 | 86.070694 | 87.639587 | 89.181793 | 90.696823 | 92.184227 |
| 32   | 81.236290 | 82.881958 | 84.502380 | 86.097061 | 87.665512 | 89.207260 | 90.721840 | 92.208786 |
| 33   | 81.263924 | 82.909172 | 84.529167 | 86.123413 | 87.691429 | 89.232727 | 90.746849 | 92.233330 |
| 34   | 81.291550 | 82.936378 | 84.555954 | 86.149765 | 87.717339 | 89.258186 | 90.771851 | 92.257866 |
| 35   | 81.319168 | 82.963585 | 84.582726 | 86.176109 | 87.743240 | 89.283638 | 90.796844 | 92.282394 |
| 36   | 81.346779 | 82.990776 | 84.609497 | 86.202446 | 87.769135 | 89.309082 | 90.821831 | 92.306915 |
| 37   | 81.374382 | 83.017960 | 84.636253 | 86.228767 | 87.795013 | 89.334518 | 90.846809 | 92.331429 |
| 38   | 81.401985 | 83.045151 | 84.663017 | 86.255096 | 87.820900 | 89.359955 | 90.871788 | 92.355942 |
| 39   | 81.429573 | 83.072319 | 84.689766 | 86.281410 | 87.846771 | 89.385376 | 90.896751 | 92.380440 |
| 40   | 81.457161 | 83.099487 | 84.716507 | 86.307716 | 87.872635 | 89.410789 | 90.921707 | 92.404930 |
| 41   | 81.484734 | 83.126648 | 84.743233 | 86.334015 | 87.898491 | 89.436195 | 90.946655 | 92.429413 |
| 42   | 81.512306 | 83.153801 | 84.769958 | 86.360306 | 87.924339 | 89.461594 | 90.971596 | 92.453888 |
| 43   | 81.539864 | 83.180939 | 84.796677 | 86.386589 | 87.950180 | 89.486984 | 90.996529 | 92.478355 |
| 44   | 81.567421 | 83.208076 | 84.823395 | 86.412865 | 87.976013 | 89.512367 | 91.021454 | 92.502815 |
| 45   | 81.594971 | 83.235207 | 84.850098 | 86.439133 | 88.001839 | 89.537743 | 91.046371 | 92.527267 |
| 46   | 81.622513 | 83.262337 | 84.876793 | 86.465393 | 88.027664 | 89.563110 | 91.071281 | 92.551712 |
| 47   | 81.650047 | 83.289452 | 84.903481 | 86.491653 | 88.053474 | 89.588470 | 91.096184 | 92.576149 |
| 48   | 81.677574 | 83.316559 | 84.930161 | 86.517899 | 88.079277 | 89.613823 | 91.121078 | 92.600578 |
| 49   | 81.705101 | 83.343658 | 84.956841 | 86.544136 | 88.105072 | 89.639175 | 91.145966 | 92.624992 |
| 50   | 81.732613 | 83.370758 | 84.983505 | 86.570374 | 88.130859 | 89.664513 | 91.170845 | 92.649406 |
| 51   | 81.760117 | 83.397842 | 85.010170 | 86.596596 | 88.156647 | 89.689842 | 91.195717 | 92.673813 |
| 52   | 81.787621 | 83.424927 | 85.036819 | 86.622810 | 88.182419 | 89.715164 | 91.220581 | 92.698212 |
| 53   | 81.815117 | 83.452003 | 85.063477 | 86.649033 | 88.208191 | 89.740486 | 91.245438 | 92.722603 |
| 54   | 81.842606 | 83.479073 | 85.090111 | 86.675232 | 88.233948 | 89.765793 | 91.270287 | 92.746986 |
| 55   | 81.870087 | 83.506134 | 85.116745 | 86.701431 | 88.259705 | 89.791092 | 91.295128 | 92.771355 |
| 56   | 81.897560 | 83.533188 | 85.143372 | 86.727615 | 88.285446 | 89.816383 | 91.319962 | 92.795723 |
| 57   | 81.925026 | 83.560234 | 85.169991 | 86.753799 | 88.311180 | 89.841667 | 91.344788 | 92.820084 |
| 58   | 81.952484 | 83.587273 | 85.196594 | 86.779976 | 88.336914 | 89.866943 | 91.369606 | 92.844429 |
| 59   | 81.979935 | 83.614304 | 85.223198 | 86.806137 | 88.362633 | 89.892212 | 91.394417 | 92.868774 |
| 60   | 82.007378 | 83.641327 | 85.249794 | 86.832298 | 88.388351 | 89.917480 | 91.419212 | 92.893105 |

## SINE BAR CONSTANTS

## Constants for Setting a 125-mm Sine-Bar for 48° to 55°

| Min. | 48°       | 49°       | 50°       | 51°       | 52°       | 53°        | 54°        | 55°        |
|------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|
| 0    | 92.893105 | 94.338699 | 95.755554 | 97.143250 | 98.501343 | 99.829437  | 101.127129 | 102.394005 |
| 1    | 92.917435 | 94.362549 | 95.778923 | 97.166122 | 98.523727 | 99.851318  | 101.148491 | 102.414856 |
| 2    | 92.941750 | 94.386391 | 95.802284 | 97.188995 | 98.546104 | 99.873192  | 101.169853 | 102.435699 |
| 3    | 92.966057 | 94.410225 | 95.825638 | 97.211861 | 98.568466 | 99.895050  | 101.191208 | 102.456535 |
| 4    | 92.990364 | 94.434052 | 95.848984 | 97.234711 | 98.590820 | 99.916901  | 101.212547 | 102.477364 |
| 5    | 93.014656 | 94.457870 | 95.872314 | 97.257553 | 98.613174 | 99.938744  | 101.233879 | 102.498177 |
| 6    | 93.038940 | 94.481682 | 95.895645 | 97.280396 | 98.635513 | 99.960579  | 101.255203 | 102.518982 |
| 7    | 93.063225 | 94.505486 | 95.918961 | 97.303223 | 98.657845 | 99.982407  | 101.276520 | 102.539787 |
| 8    | 93.087502 | 94.529289 | 95.942276 | 97.326050 | 98.680168 | 100.004234 | 101.297836 | 102.560577 |
| 9    | 93.111763 | 94.553070 | 95.965584 | 97.348862 | 98.702484 | 100.026047 | 101.319130 | 102.581360 |
| 10   | 93.136017 | 94.576851 | 95.988876 | 97.371666 | 98.724792 | 100.047844 | 101.340424 | 102.602135 |
| 11   | 93.160263 | 94.600624 | 96.012161 | 97.394463 | 98.747093 | 100.069641 | 101.361710 | 102.622902 |
| 12   | 93.184502 | 94.624382 | 96.035446 | 97.417252 | 98.769379 | 100.091423 | 101.382980 | 102.643654 |
| 13   | 93.208733 | 94.648140 | 96.058716 | 97.440025 | 98.791664 | 100.113197 | 101.404243 | 102.664398 |
| 14   | 93.232956 | 94.671883 | 96.081978 | 97.462799 | 98.813934 | 100.134972 | 101.425499 | 102.685143 |
| 15   | 93.257172 | 94.695625 | 96.105232 | 97.485565 | 98.836197 | 100.156731 | 101.446747 | 102.705872 |
| 16   | 93.281380 | 94.719353 | 96.128479 | 97.508316 | 98.858452 | 100.178482 | 101.467987 | 102.726593 |
| 17   | 93.305580 | 94.743080 | 96.151718 | 97.531067 | 98.880699 | 100.200226 | 101.489220 | 102.747299 |
| 18   | 93.329773 | 94.766792 | 96.174942 | 97.553802 | 98.902939 | 100.221954 | 101.510445 | 102.768005 |
| 19   | 93.353958 | 94.790497 | 96.198166 | 97.576530 | 98.925171 | 100.243683 | 101.531654 | 102.788704 |
| 20   | 93.378136 | 94.814201 | 96.221382 | 97.599251 | 98.947395 | 100.265396 | 101.552864 | 102.809387 |
| 21   | 93.402306 | 94.837891 | 96.244583 | 97.621964 | 98.969612 | 100.287109 | 101.574059 | 102.830063 |
| 22   | 93.426460 | 94.861572 | 96.267784 | 97.644669 | 98.991814 | 100.308807 | 101.595245 | 102.850731 |
| 23   | 93.450623 | 94.885254 | 96.290977 | 97.667374 | 99.014023 | 100.330505 | 101.616432 | 102.871399 |
| 24   | 93.474762 | 94.908920 | 96.314163 | 97.690063 | 99.036209 | 100.352188 | 101.637596 | 102.892052 |
| 25   | 93.498901 | 94.932579 | 96.337334 | 97.712746 | 99.058388 | 100.373863 | 101.658760 | 102.912689 |
| 26   | 93.523033 | 94.956230 | 96.360497 | 97.735413 | 99.080566 | 100.395531 | 101.679916 | 102.933327 |
| 27   | 93.547150 | 94.979866 | 96.383652 | 97.758080 | 99.102730 | 100.417191 | 101.701057 | 102.953949 |
| 28   | 93.571266 | 95.003502 | 96.406799 | 97.780739 | 99.124886 | 100.438835 | 101.722198 | 102.974571 |
| 29   | 93.595367 | 95.027130 | 96.429939 | 97.803383 | 99.147034 | 100.460480 | 101.743324 | 102.995178 |
| 30   | 93.619469 | 95.050751 | 96.453072 | 97.826019 | 99.169167 | 100.482109 | 101.764442 | 103.015778 |
| 31   | 93.643555 | 95.074356 | 96.476196 | 97.848656 | 99.191299 | 100.503731 | 101.785553 | 103.036369 |
| 32   | 93.667641 | 95.097961 | 96.499313 | 97.871277 | 99.213425 | 100.525345 | 101.806656 | 103.056946 |
| 33   | 93.691711 | 95.121552 | 96.522423 | 97.893890 | 99.235535 | 100.546959 | 101.827744 | 103.077522 |
| 34   | 93.715775 | 95.145142 | 96.545525 | 97.916496 | 99.257645 | 100.568550 | 101.848831 | 103.098083 |
| 35   | 93.739838 | 95.168716 | 96.568611 | 97.939095 | 99.279739 | 100.590141 | 101.869904 | 103.118637 |
| 36   | 93.763885 | 95.192291 | 96.591698 | 97.961685 | 99.301826 | 100.611725 | 101.890976 | 103.139191 |
| 37   | 93.787926 | 95.215851 | 96.614769 | 97.984261 | 99.323906 | 100.633301 | 101.912033 | 103.159729 |
| 38   | 93.811966 | 95.239410 | 96.637840 | 98.006844 | 99.345985 | 100.654869 | 101.933090 | 103.180260 |
| 39   | 93.835991 | 95.262955 | 96.660904 | 98.029404 | 99.368050 | 100.676422 | 101.954132 | 103.200783 |
| 40   | 93.860008 | 95.286491 | 96.683952 | 98.051964 | 99.390106 | 100.697968 | 101.975159 | 103.221291 |
| 41   | 93.884018 | 95.310020 | 96.706993 | 98.074509 | 99.412148 | 100.719505 | 101.996185 | 103.241798 |
| 42   | 93.908020 | 95.333542 | 96.730026 | 98.097046 | 99.434189 | 100.741035 | 102.017204 | 103.262291 |
| 43   | 93.932014 | 95.357056 | 96.753052 | 98.119583 | 99.456215 | 100.762558 | 102.038208 | 103.282776 |
| 44   | 93.956001 | 95.380562 | 96.776070 | 98.142105 | 99.478241 | 100.784073 | 102.059204 | 103.303253 |
| 45   | 93.979980 | 95.404060 | 96.799080 | 98.164619 | 99.500252 | 100.805580 | 102.080193 | 103.323723 |
| 46   | 94.003944 | 95.427551 | 96.822083 | 98.187126 | 99.522255 | 100.827072 | 102.101181 | 103.344177 |
| 47   | 94.027908 | 95.451035 | 96.845078 | 98.209625 | 99.544250 | 100.848564 | 102.122147 | 103.364632 |
| 48   | 94.051865 | 95.474503 | 96.868065 | 98.232109 | 99.566238 | 100.870041 | 102.143112 | 103.385071 |
| 49   | 94.075813 | 95.497971 | 96.891037 | 98.254593 | 99.588219 | 100.891510 | 102.164070 | 103.405502 |
| 50   | 94.099747 | 95.521423 | 96.914009 | 98.277069 | 99.610191 | 100.912971 | 102.185013 | 103.425934 |
| 51   | 94.123680 | 95.544876 | 96.936966 | 98.299530 | 99.632156 | 100.934425 | 102.205956 | 103.446342 |
| 52   | 94.147598 | 95.568314 | 96.959923 | 98.321991 | 99.654106 | 100.955872 | 102.226883 | 103.466751 |
| 53   | 94.171524 | 95.591751 | 96.982872 | 98.344444 | 99.676056 | 100.977310 | 102.247810 | 103.487160 |
| 54   | 94.195427 | 95.615181 | 97.005806 | 98.366882 | 99.697998 | 100.998741 | 102.268715 | 103.507545 |
| 55   | 94.219330 | 95.638596 | 97.028732 | 98.389313 | 99.719925 | 101.020157 | 102.289619 | 103.527924 |
| 56   | 94.243217 | 95.662003 | 97.051651 | 98.411736 | 99.741844 | 101.041573 | 102.310516 | 103.548302 |
| 57   | 94.267097 | 95.685402 | 97.074562 | 98.434151 | 99.763756 | 101.062973 | 102.331406 | 103.568665 |
| 58   | 94.290977 | 95.708794 | 97.097466 | 98.456558 | 99.785660 | 101.084366 | 102.352280 | 103.589102 |
| 59   | 94.314842 | 95.732178 | 97.120361 | 98.478958 | 99.807556 | 101.105751 | 102.373146 | 103.609360 |
| 60   | 94.338699 | 95.755554 | 97.143250 | 98.501343 | 99.829437 | 101.127129 | 102.394005 | 103.629700 |

## Squares of Numbers

## Squares of Numbers from 1 to 999

|    | 0      | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      |
|----|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 0  | 0      | 1      | 4      | 9      | 16     | 25     | 36     | 49     | 64     | 81     |
| 1  | 100    | 121    | 144    | 169    | 196    | 225    | 256    | 289    | 324    | 361    |
| 2  | 400    | 441    | 484    | 529    | 576    | 625    | 676    | 729    | 784    | 841    |
| 3  | 900    | 961    | 1024   | 1089   | 1156   | 1225   | 1296   | 1369   | 1444   | 1521   |
| 4  | 1600   | 1681   | 1764   | 1849   | 1936   | 2025   | 2116   | 2209   | 2304   | 2401   |
| 5  | 2500   | 2601   | 2704   | 2809   | 2916   | 3025   | 3136   | 3249   | 3364   | 3481   |
| 6  | 3600   | 3721   | 3844   | 3969   | 4096   | 4225   | 4356   | 4489   | 4624   | 4761   |
| 7  | 4900   | 5041   | 5184   | 5329   | 5476   | 5625   | 5776   | 5929   | 6084   | 6241   |
| 8  | 6400   | 6561   | 6724   | 6889   | 7056   | 7225   | 7396   | 7569   | 7744   | 7921   |
| 9  | 8100   | 8281   | 8464   | 8649   | 8836   | 9025   | 9216   | 9409   | 9604   | 9801   |
| 10 | 10000  | 10201  | 10404  | 10609  | 10816  | 11025  | 11236  | 11449  | 11664  | 11881  |
| 11 | 12100  | 12321  | 12544  | 12769  | 12996  | 13225  | 13456  | 13689  | 13924  | 14161  |
| 12 | 14400  | 14641  | 14884  | 15129  | 15376  | 15625  | 15876  | 16129  | 16384  | 16641  |
| 13 | 16900  | 17161  | 17424  | 17689  | 17956  | 18225  | 18496  | 18769  | 19044  | 19321  |
| 14 | 19600  | 19881  | 20164  | 20449  | 20736  | 21025  | 21316  | 21609  | 21904  | 22201  |
| 15 | 22500  | 22801  | 23104  | 23409  | 23716  | 24025  | 24336  | 24649  | 24964  | 25281  |
| 16 | 25600  | 25921  | 26244  | 26569  | 26896  | 27225  | 27556  | 27889  | 28224  | 28561  |
| 17 | 28900  | 29241  | 29584  | 29929  | 30276  | 30625  | 30976  | 31329  | 31684  | 32041  |
| 18 | 32400  | 32761  | 33124  | 33489  | 33856  | 34225  | 34596  | 34969  | 35344  | 35721  |
| 19 | 36100  | 36481  | 36864  | 37249  | 37636  | 38025  | 38416  | 38809  | 39204  | 39601  |
| 20 | 40000  | 40401  | 40804  | 41209  | 41616  | 42025  | 42436  | 42849  | 43264  | 43681  |
| 21 | 44100  | 44521  | 44944  | 45369  | 45796  | 46225  | 46656  | 47089  | 47524  | 47961  |
| 22 | 48400  | 48841  | 49284  | 49729  | 50176  | 50625  | 51076  | 51529  | 51984  | 52441  |
| 23 | 52900  | 53361  | 53824  | 54289  | 54756  | 55225  | 55696  | 56169  | 56644  | 57121  |
| 24 | 57600  | 58081  | 58564  | 59049  | 59536  | 60025  | 60516  | 61009  | 61504  | 62001  |
| 25 | 62500  | 63001  | 63504  | 64009  | 64516  | 65025  | 65536  | 66049  | 66564  | 67081  |
| 26 | 67600  | 68121  | 68644  | 69169  | 69696  | 70225  | 70756  | 71289  | 71824  | 72361  |
| 27 | 72900  | 73441  | 73984  | 74529  | 75076  | 75625  | 76176  | 76729  | 77284  | 77841  |
| 28 | 78400  | 78961  | 79524  | 80089  | 80656  | 81225  | 81796  | 82369  | 82944  | 83521  |
| 29 | 84100  | 84681  | 85264  | 85849  | 86436  | 87025  | 87616  | 88209  | 88804  | 89401  |
| 30 | 90000  | 90601  | 91204  | 91809  | 92416  | 93025  | 93636  | 94249  | 94864  | 95481  |
| 31 | 96100  | 96721  | 97344  | 97969  | 98596  | 99225  | 99856  | 100489 | 101124 | 101761 |
| 32 | 102400 | 103041 | 103684 | 104329 | 104976 | 105625 | 106276 | 106929 | 107584 | 108241 |
| 33 | 108900 | 109561 | 110224 | 110889 | 111556 | 112225 | 112896 | 113569 | 114244 | 114921 |
| 34 | 115600 | 116281 | 116964 | 117649 | 118336 | 119025 | 119716 | 120409 | 121104 | 121801 |
| 35 | 122500 | 123201 | 123904 | 124609 | 125316 | 126025 | 126736 | 127449 | 128164 | 128881 |
| 36 | 129600 | 130321 | 131044 | 131769 | 132496 | 133225 | 133956 | 134689 | 135424 | 136161 |
| 37 | 136900 | 137641 | 138384 | 139129 | 139876 | 140625 | 141376 | 142129 | 142884 | 143641 |
| 38 | 144400 | 145161 | 145924 | 146689 | 147456 | 148225 | 148996 | 149769 | 150544 | 151321 |
| 39 | 152100 | 152881 | 153664 | 154449 | 155236 | 156025 | 156816 | 157609 | 158404 | 159201 |
| 40 | 160000 | 160801 | 161604 | 162409 | 163216 | 164025 | 164836 | 165649 | 166464 | 167281 |
| 41 | 168100 | 168921 | 169744 | 170569 | 171396 | 172225 | 173056 | 173889 | 174724 | 175561 |
| 42 | 176400 | 177241 | 178084 | 178929 | 179776 | 180625 | 181476 | 182329 | 183184 | 184041 |
| 43 | 184900 | 185761 | 186624 | 187489 | 188356 | 189225 | 190096 | 190969 | 191844 | 192721 |
| 44 | 193600 | 194481 | 195364 | 196249 | 197136 | 198025 | 198916 | 199809 | 200704 | 201601 |
| 45 | 202500 | 203401 | 204304 | 205209 | 206116 | 207025 | 207936 | 208849 | 209764 | 210681 |
| 46 | 211600 | 212521 | 213444 | 214369 | 215296 | 216225 | 217156 | 218089 | 219024 | 219961 |
| 47 | 220900 | 221841 | 222784 | 223729 | 224676 | 225625 | 226576 | 227529 | 228484 | 229441 |
| 48 | 230400 | 231361 | 232324 | 233289 | 234256 | 235225 | 236196 | 237169 | 238144 | 239121 |
| 49 | 240100 | 241081 | 242064 | 243049 | 244036 | 245025 | 246016 | 247009 | 248004 | 249001 |
| 50 | 250000 | 251001 | 252004 | 253009 | 254016 | 255025 | 256036 | 257049 | 258064 | 259081 |

## SQUARES OF NUMBERS

## Squares of Numbers from 1 to 999

|    | 0      | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      |
|----|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 51 | 260100 | 261121 | 262144 | 263169 | 264196 | 265225 | 266256 | 267289 | 268324 | 269361 |
| 52 | 270400 | 271441 | 272484 | 273529 | 274576 | 275625 | 276676 | 277729 | 278784 | 279841 |
| 53 | 280900 | 281961 | 283024 | 284089 | 285156 | 286225 | 287296 | 288369 | 289444 | 290521 |
| 54 | 291600 | 292681 | 293764 | 294849 | 295936 | 297025 | 298116 | 299209 | 300304 | 301401 |
| 55 | 302500 | 303601 | 304704 | 305809 | 306916 | 308025 | 309136 | 310249 | 311364 | 312481 |
| 56 | 313600 | 314721 | 315844 | 316969 | 318096 | 319225 | 320356 | 321489 | 322624 | 323761 |
| 57 | 324900 | 326041 | 327184 | 328329 | 329476 | 330625 | 331776 | 332929 | 334084 | 335241 |
| 58 | 336400 | 337561 | 338724 | 339889 | 341056 | 342225 | 343396 | 344569 | 345744 | 346921 |
| 59 | 348100 | 349281 | 350464 | 351649 | 352836 | 354025 | 355216 | 356409 | 357604 | 358801 |
| 60 | 360000 | 361201 | 362404 | 363609 | 364816 | 366025 | 367236 | 368449 | 369664 | 370881 |
| 61 | 372100 | 373321 | 374544 | 375769 | 376996 | 378225 | 379456 | 380689 | 381924 | 383161 |
| 62 | 384400 | 385641 | 386884 | 388129 | 389376 | 390625 | 391876 | 393129 | 394384 | 395641 |
| 63 | 396900 | 398161 | 399424 | 400689 | 401956 | 403225 | 404496 | 405769 | 407044 | 408321 |
| 64 | 409600 | 410881 | 412164 | 413449 | 414736 | 416025 | 417316 | 418609 | 419904 | 421201 |
| 65 | 422500 | 423801 | 425104 | 426409 | 427716 | 429025 | 430336 | 431649 | 432964 | 434281 |
| 66 | 435600 | 436921 | 438244 | 439569 | 440896 | 442225 | 443556 | 444889 | 446224 | 447561 |
| 67 | 448900 | 450241 | 451584 | 452929 | 454276 | 455625 | 456976 | 458329 | 459684 | 461041 |
| 68 | 462400 | 463761 | 465124 | 466489 | 467856 | 469225 | 470596 | 471969 | 473344 | 474721 |
| 69 | 476100 | 477481 | 478864 | 480249 | 481636 | 483025 | 484416 | 485809 | 487204 | 488601 |
| 70 | 490000 | 491401 | 492804 | 494209 | 495616 | 497025 | 498436 | 499849 | 501264 | 502681 |
| 71 | 504100 | 505521 | 506944 | 508369 | 509796 | 511225 | 512656 | 514089 | 515524 | 516961 |
| 72 | 518400 | 519841 | 521284 | 522729 | 524176 | 525625 | 527076 | 528529 | 529984 | 531441 |
| 73 | 532900 | 534361 | 535824 | 537289 | 538756 | 540225 | 541696 | 543169 | 544644 | 546121 |
| 74 | 547600 | 549081 | 550564 | 552049 | 553536 | 555025 | 556516 | 558009 | 559504 | 561001 |
| 75 | 562500 | 564001 | 565504 | 567009 | 568516 | 570025 | 571536 | 573049 | 574564 | 576081 |
| 76 | 577600 | 579121 | 580644 | 582169 | 583696 | 585225 | 586756 | 588289 | 589824 | 591361 |
| 77 | 592900 | 594441 | 595984 | 597529 | 599076 | 600625 | 602176 | 603729 | 605284 | 606841 |
| 78 | 608400 | 609961 | 611524 | 613089 | 614656 | 616225 | 617796 | 619369 | 620944 | 622521 |
| 79 | 624100 | 625681 | 627264 | 628849 | 630436 | 632025 | 633616 | 635209 | 636804 | 638401 |
| 80 | 640000 | 641601 | 643204 | 644809 | 646416 | 648025 | 649636 | 651249 | 652864 | 654481 |
| 81 | 656100 | 657721 | 659344 | 660969 | 662596 | 664225 | 665856 | 667489 | 669124 | 670761 |
| 82 | 672400 | 674041 | 675684 | 677329 | 678976 | 680625 | 682276 | 683929 | 685584 | 687241 |
| 83 | 688900 | 690561 | 692224 | 693889 | 695556 | 697225 | 698896 | 700569 | 702244 | 703921 |
| 84 | 705600 | 707281 | 708964 | 710649 | 712336 | 714025 | 715716 | 717409 | 719104 | 720801 |
| 85 | 722500 | 724201 | 725904 | 727609 | 729316 | 731025 | 732736 | 734449 | 736164 | 737881 |
| 86 | 739600 | 741321 | 743044 | 744769 | 746496 | 748225 | 749956 | 751689 | 753424 | 755161 |
| 87 | 756900 | 758641 | 760384 | 762129 | 763876 | 765625 | 767376 | 769129 | 770884 | 772641 |
| 88 | 774400 | 776161 | 777924 | 779689 | 781456 | 783225 | 784996 | 786769 | 788544 | 790321 |
| 89 | 792100 | 793881 | 795664 | 797449 | 799236 | 801025 | 802816 | 804609 | 806404 | 808201 |
| 90 | 810000 | 811801 | 813604 | 815409 | 817216 | 819025 | 820836 | 822649 | 824464 | 826281 |
| 91 | 828100 | 829921 | 831744 | 833569 | 835396 | 837225 | 839056 | 840889 | 842724 | 844561 |
| 92 | 846400 | 848241 | 850084 | 851929 | 853776 | 855625 | 857476 | 859329 | 861184 | 863041 |
| 93 | 864900 | 866761 | 868624 | 870489 | 872356 | 874225 | 876096 | 877969 | 879844 | 881721 |
| 94 | 883600 | 885481 | 887364 | 889249 | 891136 | 893025 | 894916 | 896809 | 898704 | 900601 |
| 95 | 902500 | 904401 | 906304 | 908209 | 910116 | 912025 | 913936 | 915849 | 917764 | 919681 |
| 96 | 921600 | 923521 | 925444 | 927369 | 929296 | 931225 | 933156 | 935089 | 937024 | 938961 |
| 97 | 940900 | 942841 | 944784 | 946729 | 948676 | 950625 | 952576 | 954529 | 956484 | 958441 |
| 98 | 960400 | 962361 | 964324 | 966289 | 968256 | 970225 | 972196 | 974169 | 976144 | 978121 |
| 99 | 980100 | 982081 | 984064 | 986049 | 988036 | 990025 | 992016 | 994009 | 996004 | 998001 |

To find the square of a given whole number, divide the number by 10 and find the row in the first column that contains the whole number portion of the result. The selected row contains the square of given number under the column corresponding to the last digit in the number.

*Example:* The square of 673, found in row labeled 67, under column labeled 3, is given as 452,929.

Squares of Mixed Numbers from  $\frac{1}{64}$  to 6, by 64ths

| No.             | 0       | 1       | 2       | 3        | 4        | 5        |
|-----------------|---------|---------|---------|----------|----------|----------|
| $\frac{1}{64}$  | 0.00024 | 1.03149 | 4.06274 | 9.09399  | 16.12524 | 25.15649 |
| $\frac{2}{64}$  | 0.00098 | 1.06348 | 4.12598 | 9.18848  | 16.25098 | 25.31348 |
| $\frac{3}{64}$  | 0.00220 | 1.09595 | 4.18970 | 9.28345  | 16.37720 | 25.47095 |
| $\frac{4}{64}$  | 0.00391 | 1.12891 | 4.25391 | 9.37891  | 16.50391 | 25.62891 |
| $\frac{5}{64}$  | 0.00610 | 1.16235 | 4.31860 | 9.47485  | 16.63110 | 25.78735 |
| $\frac{6}{64}$  | 0.00879 | 1.19629 | 4.38379 | 9.57129  | 16.75879 | 25.94629 |
| $\frac{7}{64}$  | 0.01196 | 1.23071 | 4.44946 | 9.66821  | 16.88696 | 26.10571 |
| $\frac{8}{64}$  | 0.01563 | 1.26563 | 4.51563 | 9.76563  | 17.01563 | 26.26563 |
| $\frac{9}{64}$  | 0.01978 | 1.30103 | 4.58228 | 9.86353  | 17.14478 | 26.42603 |
| $\frac{10}{64}$ | 0.02441 | 1.33691 | 4.64941 | 9.96191  | 17.27441 | 26.58691 |
| $\frac{11}{64}$ | 0.02954 | 1.37329 | 4.71704 | 10.06079 | 17.40454 | 26.74829 |
| $\frac{12}{64}$ | 0.03516 | 1.41016 | 4.78516 | 10.16016 | 17.53516 | 26.91016 |
| $\frac{13}{64}$ | 0.04126 | 1.44751 | 4.85376 | 10.26001 | 17.66626 | 27.07251 |
| $\frac{14}{64}$ | 0.04785 | 1.48535 | 4.92285 | 10.36035 | 17.79785 | 27.23535 |
| $\frac{15}{64}$ | 0.05493 | 1.52368 | 4.99243 | 10.46118 | 17.92993 | 27.39868 |
| $\frac{1}{4}$   | 0.06250 | 1.56250 | 5.06250 | 10.56250 | 18.06250 | 27.56250 |
| $\frac{17}{64}$ | 0.07056 | 1.60181 | 5.13306 | 10.66431 | 18.19556 | 27.72681 |
| $\frac{18}{64}$ | 0.07910 | 1.64160 | 5.20410 | 10.76660 | 18.32910 | 27.89160 |
| $\frac{19}{64}$ | 0.08813 | 1.68188 | 5.27563 | 10.86938 | 18.46313 | 28.05688 |
| $\frac{20}{64}$ | 0.09766 | 1.72266 | 5.34766 | 10.97266 | 18.59766 | 28.22266 |
| $\frac{21}{64}$ | 0.10767 | 1.76392 | 5.42017 | 11.07642 | 18.73267 | 28.38892 |
| $\frac{1}{32}$  | 0.11816 | 1.80566 | 5.49316 | 11.18066 | 18.86816 | 28.55566 |
| $\frac{23}{64}$ | 0.12915 | 1.84790 | 5.56665 | 11.28540 | 19.00415 | 28.72290 |
| $\frac{3}{8}$   | 0.14063 | 1.89063 | 5.64063 | 11.39063 | 19.14063 | 28.89063 |
| $\frac{25}{64}$ | 0.15259 | 1.93384 | 5.71509 | 11.49634 | 19.27759 | 29.05884 |
| $\frac{1}{16}$  | 0.16504 | 1.97754 | 5.79004 | 11.60254 | 19.41504 | 29.22754 |
| $\frac{27}{64}$ | 0.17798 | 2.02173 | 5.86548 | 11.70923 | 19.55298 | 29.39673 |
| $\frac{7}{16}$  | 0.19141 | 2.06641 | 5.94141 | 11.81641 | 19.69141 | 29.56641 |
| $\frac{29}{64}$ | 0.20532 | 2.11157 | 6.01782 | 11.92407 | 19.83032 | 29.73657 |
| $\frac{1}{8}$   | 0.21973 | 2.15723 | 6.09473 | 12.03223 | 19.96973 | 29.90723 |
| $\frac{31}{64}$ | 0.23462 | 2.20337 | 6.17212 | 12.14087 | 20.10962 | 30.07837 |
| $\frac{1}{2}$   | 0.25000 | 2.25000 | 6.25000 | 12.25000 | 20.25000 | 30.25000 |
| $\frac{33}{64}$ | 0.26587 | 2.29712 | 6.32837 | 12.35962 | 20.39087 | 30.42212 |
| $\frac{1}{32}$  | 0.28223 | 2.34473 | 6.40723 | 12.46973 | 20.53223 | 30.59473 |
| $\frac{35}{64}$ | 0.29907 | 2.39282 | 6.48657 | 12.58032 | 20.67407 | 30.76782 |
| $\frac{9}{16}$  | 0.31641 | 2.44141 | 6.56641 | 12.69141 | 20.81641 | 30.94141 |
| $\frac{37}{64}$ | 0.33423 | 2.49048 | 6.64673 | 12.80298 | 20.95923 | 31.11548 |
| $\frac{19}{32}$ | 0.35254 | 2.54004 | 6.72754 | 12.91504 | 21.10254 | 31.29004 |
| $\frac{39}{64}$ | 0.37134 | 2.59009 | 6.80884 | 13.02759 | 21.24634 | 31.46509 |
| $\frac{3}{8}$   | 0.39063 | 2.64063 | 6.89063 | 13.14063 | 21.39063 | 31.64063 |
| $\frac{41}{64}$ | 0.41040 | 2.69165 | 6.97290 | 13.25415 | 21.53540 | 31.81665 |
| $\frac{21}{32}$ | 0.43066 | 2.74316 | 7.05566 | 13.36816 | 21.68066 | 31.99316 |
| $\frac{43}{64}$ | 0.45142 | 2.79517 | 7.13892 | 13.48267 | 21.82642 | 32.17017 |
| $\frac{11}{16}$ | 0.47266 | 2.84766 | 7.22266 | 13.59766 | 21.97266 | 32.34766 |
| $\frac{45}{64}$ | 0.49438 | 2.90063 | 7.30688 | 13.71313 | 22.11938 | 32.52563 |
| $\frac{23}{32}$ | 0.51660 | 2.95410 | 7.39160 | 13.82910 | 22.26660 | 32.70410 |
| $\frac{47}{64}$ | 0.53931 | 3.00806 | 7.47681 | 13.94556 | 22.41431 | 32.88306 |
| $\frac{3}{4}$   | 0.56250 | 3.06250 | 7.56250 | 14.06250 | 22.56250 | 33.06250 |
| $\frac{49}{64}$ | 0.58618 | 3.11743 | 7.64868 | 14.17993 | 22.71118 | 33.24243 |
| $\frac{25}{32}$ | 0.61035 | 3.17285 | 7.73535 | 14.29785 | 22.86035 | 33.42285 |
| $\frac{51}{64}$ | 0.63501 | 3.22876 | 7.82251 | 14.41626 | 23.01001 | 33.60376 |
| $\frac{13}{16}$ | 0.66016 | 3.28516 | 7.91016 | 14.53516 | 23.16016 | 33.78516 |
| $\frac{53}{64}$ | 0.68579 | 3.34204 | 7.99829 | 14.65454 | 23.31079 | 33.96704 |
| $\frac{27}{32}$ | 0.71191 | 3.39941 | 8.08691 | 14.77441 | 23.46191 | 34.14941 |
| $\frac{55}{64}$ | 0.73853 | 3.45728 | 8.17603 | 14.89478 | 23.61353 | 34.33228 |
| $\frac{7}{8}$   | 0.76563 | 3.51563 | 8.26563 | 15.01563 | 23.76563 | 34.51563 |
| $\frac{57}{64}$ | 0.79321 | 3.57446 | 8.35571 | 15.13696 | 23.91821 | 34.69946 |
| $\frac{29}{32}$ | 0.82129 | 3.63379 | 8.44629 | 15.25879 | 24.07129 | 34.88379 |
| $\frac{59}{64}$ | 0.84985 | 3.69360 | 8.53735 | 15.38110 | 24.22485 | 35.06860 |
| $\frac{15}{16}$ | 0.87891 | 3.75391 | 8.62891 | 15.50391 | 24.37891 | 35.25391 |
| $\frac{61}{64}$ | 0.90845 | 3.81470 | 8.72095 | 15.62720 | 24.53345 | 35.43970 |
| $\frac{31}{32}$ | 0.93848 | 3.87598 | 8.81348 | 15.75098 | 24.68848 | 35.62598 |
| $\frac{63}{64}$ | 0.96899 | 3.93774 | 8.90649 | 15.87524 | 24.84399 | 35.81274 |
| 1               | 1.00000 | 4.00000 | 9.00000 | 16.00000 | 25.00000 | 36.00000 |



Squares of Mixed Numbers from  $6\frac{1}{64}$  to 12, by 64ths

| No.             | 6        | 7        | 8        | 9         | 10        | 11        |
|-----------------|----------|----------|----------|-----------|-----------|-----------|
| $\frac{1}{64}$  | 36.18774 | 49.21899 | 64.25024 | 81.28149  | 100.31274 | 121.34399 |
| $\frac{2}{64}$  | 36.37598 | 49.43848 | 64.50098 | 81.56348  | 100.62598 | 121.68848 |
| $\frac{3}{64}$  | 36.56470 | 49.65845 | 64.75220 | 81.84595  | 100.93970 | 122.03345 |
| $\frac{4}{64}$  | 36.75391 | 49.87891 | 65.00391 | 82.12891  | 101.25391 | 122.37891 |
| $\frac{5}{64}$  | 36.94360 | 50.09985 | 65.25610 | 82.41235  | 101.56860 | 122.72485 |
| $\frac{6}{64}$  | 37.13379 | 50.32129 | 65.50879 | 82.69629  | 101.88379 | 123.07129 |
| $\frac{7}{64}$  | 37.32446 | 50.54321 | 65.76196 | 82.98071  | 102.19946 | 123.41821 |
| $\frac{8}{64}$  | 37.51563 | 50.76563 | 66.01563 | 83.26563  | 102.51563 | 123.76563 |
| $\frac{9}{64}$  | 37.70728 | 50.98853 | 66.26978 | 83.55103  | 102.83228 | 124.11353 |
| $\frac{10}{64}$ | 37.89941 | 51.21191 | 66.52441 | 83.83691  | 103.14941 | 124.46191 |
| $\frac{11}{64}$ | 38.09204 | 51.43579 | 66.77954 | 84.12329  | 103.46704 | 124.81079 |
| $\frac{12}{64}$ | 38.28516 | 51.66016 | 67.03516 | 84.41016  | 103.78516 | 125.16016 |
| $\frac{13}{64}$ | 38.47876 | 51.88501 | 67.29126 | 84.69751  | 104.10376 | 125.51001 |
| $\frac{14}{64}$ | 38.67285 | 52.11035 | 67.54785 | 84.98535  | 104.42285 | 125.86035 |
| $\frac{15}{64}$ | 38.86743 | 52.33618 | 67.80493 | 85.27368  | 104.74243 | 126.21118 |
| $\frac{16}{64}$ | 39.06250 | 52.56250 | 68.06250 | 85.56250  | 105.06250 | 126.56250 |
| $\frac{17}{64}$ | 39.25806 | 52.78931 | 68.32056 | 85.85181  | 105.38306 | 126.91431 |
| $\frac{18}{64}$ | 39.45410 | 53.01660 | 68.57910 | 86.14160  | 105.70410 | 127.26660 |
| $\frac{19}{64}$ | 39.65063 | 53.24438 | 68.83813 | 86.43188  | 106.02563 | 127.61938 |
| $\frac{20}{64}$ | 39.84766 | 53.47266 | 69.09766 | 86.72266  | 106.34766 | 127.97266 |
| $\frac{21}{64}$ | 40.04517 | 53.70142 | 69.35767 | 87.01392  | 106.67017 | 128.32642 |
| $\frac{22}{64}$ | 40.24316 | 53.93066 | 69.61816 | 87.30566  | 106.99316 | 128.68066 |
| $\frac{23}{64}$ | 40.44165 | 54.16040 | 69.87915 | 87.59790  | 107.31665 | 129.03540 |
| $\frac{24}{64}$ | 40.64063 | 54.39063 | 70.14063 | 87.89063  | 107.64063 | 129.39063 |
| $\frac{25}{64}$ | 40.84009 | 54.62134 | 70.40259 | 88.18384  | 107.96509 | 129.74634 |
| $\frac{26}{64}$ | 41.04004 | 54.85254 | 70.66504 | 88.47754  | 108.29004 | 130.10254 |
| $\frac{27}{64}$ | 41.24048 | 55.08423 | 70.92798 | 88.77173  | 108.61548 | 130.45923 |
| $\frac{28}{64}$ | 41.44141 | 55.31641 | 71.19141 | 89.06641  | 108.94141 | 130.81641 |
| $\frac{29}{64}$ | 41.64282 | 55.54907 | 71.45532 | 89.36157  | 109.26782 | 131.17407 |
| $\frac{30}{64}$ | 41.84473 | 55.78223 | 71.71973 | 89.65723  | 109.59473 | 131.53223 |
| $\frac{31}{64}$ | 42.04712 | 56.01587 | 71.98462 | 89.95337  | 109.92212 | 131.89087 |
| $\frac{32}{64}$ | 42.25000 | 56.25000 | 72.25000 | 90.25000  | 110.25000 | 132.25000 |
| $\frac{33}{64}$ | 42.45337 | 56.48462 | 72.51587 | 90.54712  | 110.57837 | 132.60962 |
| $\frac{34}{64}$ | 42.65723 | 56.71973 | 72.78223 | 90.84473  | 110.90723 | 132.96973 |
| $\frac{35}{64}$ | 42.86157 | 56.95532 | 73.04907 | 91.14282  | 111.23657 | 133.33032 |
| $\frac{36}{64}$ | 43.06641 | 57.19141 | 73.31641 | 91.44141  | 111.56641 | 133.69141 |
| $\frac{37}{64}$ | 43.27173 | 57.42798 | 73.58423 | 91.74048  | 111.89673 | 134.05298 |
| $\frac{38}{64}$ | 43.47754 | 57.66504 | 73.85254 | 92.04004  | 112.22754 | 134.41504 |
| $\frac{39}{64}$ | 43.68384 | 57.90259 | 74.12134 | 92.34009  | 112.55884 | 134.77759 |
| $\frac{40}{64}$ | 43.89063 | 58.14063 | 74.39063 | 92.64063  | 112.89063 | 135.14063 |
| $\frac{41}{64}$ | 44.09790 | 58.37915 | 74.66040 | 92.94165  | 113.22290 | 135.50415 |
| $\frac{42}{64}$ | 44.30566 | 58.61816 | 74.93066 | 93.24316  | 113.55566 | 135.86816 |
| $\frac{43}{64}$ | 44.51392 | 58.85767 | 75.20142 | 93.54517  | 113.88892 | 136.23267 |
| $\frac{44}{64}$ | 44.72266 | 59.09766 | 75.47266 | 93.84766  | 114.22266 | 136.59766 |
| $\frac{45}{64}$ | 44.93188 | 59.33813 | 75.74438 | 94.15063  | 114.55688 | 136.96313 |
| $\frac{46}{64}$ | 45.14160 | 59.57910 | 76.01660 | 94.45410  | 114.89160 | 137.32910 |
| $\frac{47}{64}$ | 45.35181 | 59.82056 | 76.28931 | 94.75806  | 115.22681 | 137.69586 |
| $\frac{48}{64}$ | 45.56250 | 60.06250 | 76.56250 | 95.06250  | 115.56250 | 138.06250 |
| $\frac{49}{64}$ | 45.77368 | 60.30493 | 76.83618 | 95.36743  | 115.89868 | 138.42993 |
| $\frac{50}{64}$ | 45.98535 | 60.54785 | 77.11035 | 95.67285  | 116.23535 | 138.79785 |
| $\frac{51}{64}$ | 46.19751 | 60.79126 | 77.38501 | 95.97876  | 116.57251 | 139.16626 |
| $\frac{52}{64}$ | 46.41016 | 61.03516 | 77.66016 | 96.28516  | 116.91016 | 139.53516 |
| $\frac{53}{64}$ | 46.62329 | 61.27954 | 77.93579 | 96.59204  | 117.24829 | 139.90454 |
| $\frac{54}{64}$ | 46.83691 | 61.52441 | 78.21191 | 96.89941  | 117.58691 | 140.27441 |
| $\frac{55}{64}$ | 47.05103 | 61.76978 | 78.48853 | 97.20728  | 117.92603 | 140.64478 |
| $\frac{56}{64}$ | 47.26563 | 62.01563 | 78.76563 | 97.51563  | 118.26563 | 141.01563 |
| $\frac{57}{64}$ | 47.48071 | 62.26196 | 79.04321 | 97.82446  | 118.60571 | 141.38696 |
| $\frac{58}{64}$ | 47.69629 | 62.50879 | 79.32129 | 98.13379  | 118.94629 | 141.75879 |
| $\frac{59}{64}$ | 47.91235 | 62.75610 | 79.59985 | 98.44360  | 119.28735 | 142.13110 |
| $\frac{60}{64}$ | 48.12891 | 63.00391 | 79.87891 | 98.75391  | 119.62891 | 142.50391 |
| $\frac{61}{64}$ | 48.34595 | 63.25220 | 80.15845 | 99.06470  | 119.97095 | 142.87720 |
| $\frac{62}{64}$ | 48.56348 | 63.50098 | 80.43848 | 99.37598  | 120.31348 | 143.25098 |
| $\frac{63}{64}$ | 48.78149 | 63.75024 | 80.71899 | 99.68774  | 120.65649 | 143.62524 |
| 1               | 49.00000 | 64.00000 | 81.00000 | 100.00000 | 121.00000 | 144.00000 |

## Squares and Cubes of Fractions

Squares and Cubes of Numbers from  $\frac{1}{32}$  to  $6\frac{15}{16}$ 

| No.              | Square  | Cube    | No.              | Square   | Cube     | No.              | Square   | Cube      |
|------------------|---------|---------|------------------|----------|----------|------------------|----------|-----------|
| $\frac{1}{32}$   | 0.00098 | 0.00003 | $1\frac{17}{32}$ | 2.34473  | 3.59036  | 4                | 16.00000 | 64.00000  |
| $\frac{1}{16}$   | 0.00391 | 0.00024 | $1\frac{9}{16}$  | 2.44141  | 3.81470  | $4\frac{1}{16}$  | 16.50391 | 67.04712  |
| $\frac{3}{32}$   | 0.00879 | 0.00082 | $1\frac{19}{32}$ | 2.54004  | 4.04819  | $4\frac{1}{8}$   | 17.01563 | 70.18945  |
| $\frac{1}{8}$    | 0.01563 | 0.00195 | $1\frac{5}{8}$   | 2.64063  | 4.29102  | $4\frac{3}{16}$  | 17.53516 | 73.42847  |
| $\frac{3}{32}$   | 0.02441 | 0.00381 | $1\frac{27}{32}$ | 2.74316  | 4.54337  | $4\frac{1}{4}$   | 18.06250 | 76.76563  |
| $\frac{3}{16}$   | 0.03516 | 0.00659 | $1\frac{11}{16}$ | 2.84766  | 4.80542  | $4\frac{5}{16}$  | 18.59766 | 80.20239  |
| $\frac{7}{32}$   | 0.04785 | 0.01047 | $1\frac{23}{32}$ | 2.95410  | 5.07736  | $4\frac{3}{8}$   | 19.14063 | 83.74023  |
| $\frac{1}{4}$    | 0.06250 | 0.01563 | $1\frac{3}{4}$   | 3.06250  | 5.35938  | $4\frac{7}{16}$  | 19.69141 | 87.38062  |
| $\frac{9}{32}$   | 0.07910 | 0.02225 | $1\frac{29}{32}$ | 3.17285  | 5.65164  | $4\frac{1}{2}$   | 20.25000 | 91.12500  |
| $\frac{5}{16}$   | 0.09766 | 0.03052 | $1\frac{13}{16}$ | 3.28516  | 5.95435  | $4\frac{9}{16}$  | 20.81641 | 94.97485  |
| $\frac{11}{32}$  | 0.11816 | 0.04062 | $1\frac{27}{32}$ | 3.39941  | 6.26767  | $4\frac{5}{8}$   | 21.39063 | 98.93164  |
| $\frac{3}{8}$    | 0.14063 | 0.05273 | $1\frac{7}{8}$   | 3.51563  | 6.59180  | $4\frac{11}{16}$ | 21.97266 | 102.99683 |
| $\frac{13}{32}$  | 0.16504 | 0.06705 | $1\frac{29}{32}$ | 3.63379  | 6.92691  | $4\frac{3}{4}$   | 22.56250 | 107.17188 |
| $\frac{7}{16}$   | 0.19141 | 0.08374 | $1\frac{15}{16}$ | 3.75391  | 7.27319  | $4\frac{13}{16}$ | 23.16016 | 111.45825 |
| $\frac{15}{32}$  | 0.21973 | 0.10300 | $1\frac{31}{32}$ | 3.87598  | 7.63083  | $4\frac{7}{8}$   | 23.76563 | 115.85742 |
| $\frac{1}{2}$    | 0.25000 | 0.12500 | 2                | 4.00000  | 8.00000  | $4\frac{15}{16}$ | 24.37891 | 120.37085 |
| $\frac{17}{32}$  | 0.28223 | 0.14993 | $2\frac{1}{32}$  | 4.12598  | 8.38089  | 5                | 25.00000 | 125.00000 |
| $\frac{9}{16}$   | 0.31641 | 0.17798 | $2\frac{1}{16}$  | 4.25391  | 8.77368  | $5\frac{1}{16}$  | 25.62891 | 129.74634 |
| $\frac{19}{32}$  | 0.35254 | 0.20932 | $2\frac{1}{8}$   | 4.51563  | 9.59570  | $5\frac{1}{8}$   | 26.26563 | 134.61133 |
| $\frac{5}{8}$    | 0.39063 | 0.24414 | $2\frac{3}{16}$  | 4.78516  | 10.46753 | $5\frac{3}{16}$  | 26.91016 | 139.59644 |
| $\frac{21}{32}$  | 0.43066 | 0.28262 | $2\frac{1}{4}$   | 5.06250  | 11.39063 | $5\frac{1}{4}$   | 27.56250 | 144.70313 |
| $\frac{11}{16}$  | 0.47266 | 0.32495 | $2\frac{3}{16}$  | 5.34766  | 12.36646 | $5\frac{5}{16}$  | 28.22266 | 149.93286 |
| $\frac{23}{32}$  | 0.51660 | 0.37131 | $2\frac{5}{8}$   | 5.64063  | 13.39648 | $5\frac{3}{8}$   | 28.89063 | 155.28711 |
| $\frac{3}{4}$    | 0.56250 | 0.42188 | $2\frac{7}{16}$  | 5.94141  | 14.48218 | $5\frac{7}{16}$  | 29.56641 | 160.76733 |
| $\frac{25}{32}$  | 0.61035 | 0.47684 | $2\frac{1}{2}$   | 6.25000  | 15.62500 | $5\frac{1}{2}$   | 30.25000 | 166.37500 |
| $\frac{13}{16}$  | 0.66016 | 0.53638 | $2\frac{9}{16}$  | 6.56641  | 16.82642 | $5\frac{9}{16}$  | 30.94141 | 172.11157 |
| $\frac{27}{32}$  | 0.71191 | 0.60068 | $2\frac{3}{8}$   | 6.89063  | 18.08789 | $5\frac{5}{8}$   | 31.64063 | 177.97852 |
| $\frac{7}{8}$    | 0.76563 | 0.66992 | $2\frac{11}{16}$ | 7.22266  | 19.41089 | $5\frac{11}{16}$ | 32.34766 | 183.97729 |
| $\frac{29}{32}$  | 0.82129 | 0.74429 | $2\frac{3}{4}$   | 7.56250  | 20.79688 | $5\frac{3}{4}$   | 33.06250 | 190.10938 |
| $\frac{15}{16}$  | 0.87891 | 0.82397 | $2\frac{13}{16}$ | 7.91016  | 22.24731 | $5\frac{13}{16}$ | 33.78516 | 196.37622 |
| $\frac{31}{32}$  | 0.93848 | 0.90915 | $2\frac{5}{8}$   | 8.26563  | 23.76367 | $5\frac{7}{8}$   | 34.51563 | 202.77930 |
| 1                | 1.00000 | 1.00000 | $2\frac{15}{16}$ | 8.62891  | 25.34741 | $5\frac{15}{16}$ | 35.25391 | 209.32007 |
| $1\frac{1}{32}$  | 1.06348 | 1.09671 | 3                | 9.00000  | 27.00000 | 6                | 36.00000 | 216.00000 |
| $1\frac{1}{16}$  | 1.12891 | 1.19946 | $3\frac{1}{16}$  | 9.37891  | 28.72290 | $6\frac{1}{16}$  | 36.75391 | 222.82056 |
| $1\frac{3}{32}$  | 1.19629 | 1.30844 | $3\frac{1}{8}$   | 9.76563  | 30.51758 | $6\frac{1}{8}$   | 37.51563 | 229.78320 |
| $1\frac{1}{8}$   | 1.26563 | 1.42383 | $3\frac{3}{16}$  | 10.16016 | 32.38550 | $6\frac{3}{16}$  | 38.28516 | 236.88940 |
| $1\frac{3}{32}$  | 1.33691 | 1.54581 | $3\frac{1}{4}$   | 10.56250 | 34.32813 | $6\frac{1}{4}$   | 39.06250 | 244.14063 |
| $1\frac{5}{16}$  | 1.41016 | 1.67456 | $3\frac{5}{16}$  | 10.97266 | 36.34692 | $6\frac{5}{16}$  | 39.84766 | 251.53833 |
| $1\frac{7}{32}$  | 1.48535 | 1.81027 | $3\frac{3}{8}$   | 11.39063 | 38.44336 | $6\frac{3}{8}$   | 40.64063 | 259.08398 |
| $1\frac{1}{4}$   | 1.56250 | 1.95313 | $3\frac{7}{16}$  | 11.81641 | 40.61890 | $6\frac{7}{16}$  | 41.44141 | 266.77905 |
| $1\frac{9}{32}$  | 1.64160 | 2.10330 | $3\frac{1}{2}$   | 12.25000 | 42.87500 | $6\frac{1}{2}$   | 42.25000 | 274.62500 |
| $1\frac{5}{16}$  | 1.72266 | 2.26099 | $3\frac{9}{16}$  | 12.69141 | 45.21313 | $6\frac{9}{16}$  | 43.06641 | 282.62329 |
| $1\frac{11}{32}$ | 1.80566 | 2.42636 | $3\frac{5}{8}$   | 13.14063 | 47.63477 | $6\frac{5}{8}$   | 43.89063 | 290.77539 |
| $1\frac{3}{8}$   | 1.89063 | 2.59961 | $3\frac{11}{16}$ | 13.59766 | 50.14136 | $6\frac{11}{16}$ | 44.72266 | 299.08276 |
| $1\frac{13}{32}$ | 1.97754 | 2.78091 | $3\frac{3}{4}$   | 14.06250 | 52.73438 | $6\frac{3}{4}$   | 45.56250 | 307.54688 |
| $1\frac{7}{16}$  | 2.06641 | 2.97046 | $3\frac{13}{16}$ | 14.53516 | 55.41528 | $6\frac{13}{16}$ | 46.41016 | 316.16919 |
| $1\frac{15}{32}$ | 2.15723 | 3.16843 | $3\frac{7}{8}$   | 15.01563 | 58.18555 | $6\frac{7}{8}$   | 47.26563 | 324.95117 |
| $1\frac{1}{2}$   | 2.25000 | 3.37500 | $3\frac{15}{16}$ | 15.50391 | 61.04663 | $6\frac{15}{16}$ | 48.12891 | 333.89429 |

## SQUARES AND CUBES OF NUMBERS

Squares and Cubes of Numbers from 7 to  $21\frac{7}{8}$ 

| No.             | Square   | Cube      | No.           | Square    | Cube       | No.           | Square    | Cube        |
|-----------------|----------|-----------|---------------|-----------|------------|---------------|-----------|-------------|
| 7               | 49.00000 | 343.00000 | 10            | 100.00000 | 1000.00000 | 16            | 256.00000 | 4096.00000  |
| $\frac{1}{16}$  | 49.87891 | 352.26978 | $\frac{1}{8}$ | 102.51563 | 1037.97070 | $\frac{1}{8}$ | 260.01563 | 4192.75195  |
| $\frac{1}{8}$   | 50.76563 | 361.70508 | $\frac{1}{4}$ | 105.06250 | 1076.89063 | $\frac{1}{4}$ | 264.06250 | 4291.01563  |
| $\frac{3}{16}$  | 51.66016 | 371.30737 | $\frac{3}{8}$ | 107.64063 | 1116.77148 | $\frac{3}{8}$ | 268.14063 | 4390.80273  |
| $\frac{1}{4}$   | 52.56250 | 381.07813 | $\frac{1}{2}$ | 110.25000 | 1157.62500 | $\frac{1}{2}$ | 272.25000 | 4492.12500  |
| $\frac{5}{16}$  | 53.47266 | 391.01880 | $\frac{5}{8}$ | 112.89063 | 1199.46289 | $\frac{5}{8}$ | 276.39063 | 4594.99414  |
| $\frac{3}{8}$   | 54.39063 | 401.13086 | $\frac{3}{4}$ | 115.56250 | 1242.29688 | $\frac{3}{4}$ | 280.56250 | 4699.42188  |
| $\frac{7}{16}$  | 55.31641 | 411.41577 | $\frac{7}{8}$ | 118.26563 | 1286.13867 | $\frac{7}{8}$ | 284.76563 | 4805.41992  |
| $\frac{1}{2}$   | 56.25000 | 421.87500 | 11            | 121.00000 | 1331.00000 | 17            | 289.00000 | 4913.00000  |
| $\frac{9}{16}$  | 57.19141 | 432.51001 | $\frac{1}{8}$ | 123.76563 | 1376.89258 | $\frac{1}{8}$ | 293.26563 | 5022.17383  |
| $\frac{5}{8}$   | 58.14063 | 443.32227 | $\frac{1}{4}$ | 126.56250 | 1423.82813 | $\frac{1}{4}$ | 297.56250 | 5132.95313  |
| $\frac{11}{16}$ | 59.09766 | 454.31323 | $\frac{3}{8}$ | 129.39063 | 1471.81836 | $\frac{3}{8}$ | 301.89063 | 5245.34961  |
| $\frac{3}{4}$   | 60.06250 | 465.48438 | $\frac{1}{2}$ | 132.25000 | 1520.87500 | $\frac{1}{2}$ | 306.25000 | 5359.37500  |
| $\frac{13}{16}$ | 61.03516 | 476.83716 | $\frac{5}{8}$ | 135.14063 | 1571.00977 | $\frac{5}{8}$ | 310.64063 | 5475.04102  |
| $\frac{7}{8}$   | 62.01563 | 488.37305 | $\frac{3}{4}$ | 138.06250 | 1622.23438 | $\frac{3}{4}$ | 315.06250 | 5592.35938  |
| $\frac{15}{16}$ | 63.00391 | 500.09351 | $\frac{7}{8}$ | 141.01563 | 1674.56055 | $\frac{7}{8}$ | 319.51563 | 5711.34180  |
| 8               | 64.00000 | 512.00000 | 12            | 144.00000 | 1728.00000 | 18            | 324.00000 | 5832.00000  |
| $\frac{1}{16}$  | 65.00391 | 524.09399 | $\frac{1}{8}$ | 147.01563 | 1782.56445 | $\frac{1}{8}$ | 328.51563 | 5954.34570  |
| $\frac{1}{8}$   | 66.01563 | 536.37695 | $\frac{1}{4}$ | 150.06250 | 1838.26563 | $\frac{1}{4}$ | 333.06250 | 6078.39063  |
| $\frac{3}{16}$  | 67.03516 | 548.85034 | $\frac{3}{8}$ | 153.14063 | 1895.11523 | $\frac{3}{8}$ | 337.64063 | 6204.14648  |
| $\frac{1}{4}$   | 68.06250 | 561.51563 | $\frac{1}{2}$ | 156.25000 | 1953.12500 | $\frac{1}{2}$ | 342.25000 | 6331.62500  |
| $\frac{5}{16}$  | 69.09766 | 574.37427 | $\frac{5}{8}$ | 159.39063 | 2012.30664 | $\frac{5}{8}$ | 346.89063 | 6460.83789  |
| $\frac{3}{8}$   | 70.14063 | 587.42773 | $\frac{3}{4}$ | 162.56250 | 2072.67188 | $\frac{3}{4}$ | 351.56250 | 6591.79688  |
| $\frac{7}{16}$  | 71.19141 | 600.67749 | $\frac{7}{8}$ | 165.76563 | 2134.23242 | $\frac{7}{8}$ | 356.26563 | 6724.51367  |
| $\frac{1}{2}$   | 72.25000 | 614.12500 | 13            | 169.00000 | 2197.00000 | 19            | 361.00000 | 6859.00000  |
| $\frac{9}{16}$  | 73.31641 | 627.77173 | $\frac{1}{8}$ | 172.26563 | 2260.98633 | $\frac{1}{8}$ | 365.76563 | 6995.26758  |
| $\frac{5}{8}$   | 74.39063 | 641.61914 | $\frac{1}{4}$ | 175.56250 | 2326.20313 | $\frac{1}{4}$ | 370.56250 | 7133.32813  |
| $\frac{11}{16}$ | 75.47266 | 655.66870 | $\frac{3}{8}$ | 178.89063 | 2392.66211 | $\frac{3}{8}$ | 375.39063 | 7273.19336  |
| $\frac{3}{4}$   | 76.56250 | 669.92188 | $\frac{1}{2}$ | 182.25000 | 2460.37500 | $\frac{1}{2}$ | 380.25000 | 7414.87500  |
| $\frac{13}{16}$ | 77.66016 | 684.38013 | $\frac{5}{8}$ | 185.64063 | 2529.35352 | $\frac{5}{8}$ | 385.14063 | 7558.38477  |
| $\frac{7}{8}$   | 78.76563 | 699.04492 | $\frac{3}{4}$ | 189.06250 | 2599.60938 | $\frac{3}{4}$ | 390.06250 | 7703.73438  |
| $\frac{15}{16}$ | 79.87891 | 713.91772 | $\frac{7}{8}$ | 192.51563 | 2671.15430 | $\frac{7}{8}$ | 395.01563 | 7850.93555  |
| 9               | 81.00000 | 729.00000 | 14            | 196.00000 | 2744.00000 | 20            | 400.00000 | 8000.00000  |
| $\frac{1}{16}$  | 82.12891 | 744.29321 | $\frac{1}{8}$ | 199.51563 | 2818.15820 | $\frac{1}{8}$ | 405.01563 | 8150.93945  |
| $\frac{1}{8}$   | 83.26563 | 759.79883 | $\frac{1}{4}$ | 203.06250 | 2893.64063 | $\frac{1}{4}$ | 410.06250 | 8303.76563  |
| $\frac{3}{16}$  | 84.41016 | 775.51831 | $\frac{3}{8}$ | 206.64063 | 2970.45898 | $\frac{3}{8}$ | 415.14063 | 8458.49023  |
| $\frac{1}{4}$   | 85.56250 | 791.45313 | $\frac{1}{2}$ | 210.25000 | 3048.62500 | $\frac{1}{2}$ | 420.25000 | 8615.12500  |
| $\frac{5}{16}$  | 86.72266 | 807.60474 | $\frac{5}{8}$ | 213.89063 | 3128.15039 | $\frac{5}{8}$ | 425.39063 | 8773.68164  |
| $\frac{3}{8}$   | 87.89063 | 823.97461 | $\frac{3}{4}$ | 217.56250 | 3209.04688 | $\frac{3}{4}$ | 430.56250 | 8934.17188  |
| $\frac{7}{16}$  | 89.06641 | 840.56421 | $\frac{7}{8}$ | 221.26563 | 3291.32617 | $\frac{7}{8}$ | 435.76563 | 9096.60742  |
| $\frac{1}{2}$   | 90.25000 | 857.37500 | 15            | 225.00000 | 3375.00000 | 21            | 441.00000 | 9261.00000  |
| $\frac{9}{16}$  | 91.44141 | 874.40845 | $\frac{1}{8}$ | 228.76563 | 3460.08008 | $\frac{1}{8}$ | 446.26563 | 9427.36133  |
| $\frac{5}{8}$   | 92.64063 | 891.66602 | $\frac{1}{4}$ | 232.56250 | 3546.57813 | $\frac{1}{4}$ | 451.56250 | 9595.70313  |
| $\frac{11}{16}$ | 93.84766 | 909.14917 | $\frac{3}{8}$ | 236.39063 | 3634.50586 | $\frac{3}{8}$ | 456.89063 | 9766.03711  |
| $\frac{3}{4}$   | 95.06250 | 926.85938 | $\frac{1}{2}$ | 240.25000 | 3723.87500 | $\frac{1}{2}$ | 462.25000 | 9938.37500  |
| $\frac{13}{16}$ | 96.28516 | 944.79810 | $\frac{5}{8}$ | 244.14063 | 3814.69727 | $\frac{5}{8}$ | 467.64063 | 10112.72852 |
| $\frac{7}{8}$   | 97.51563 | 962.96680 | $\frac{3}{4}$ | 248.06250 | 3906.98438 | $\frac{3}{4}$ | 473.06250 | 10289.10938 |
| $\frac{15}{16}$ | 98.75391 | 981.36694 | $\frac{7}{8}$ | 252.01563 | 4000.74805 | $\frac{7}{8}$ | 478.51563 | 10467.52930 |

Squares and Cubes of Numbers from 22 to 39  $\frac{7}{8}$ 

| No.           | Square    | Cube        | No.           | Square     | Cube        | No.           | Square     | Cube        |
|---------------|-----------|-------------|---------------|------------|-------------|---------------|------------|-------------|
| 22            | 484.00000 | 10648.00000 | 28            | 784.00000  | 21952.00000 | 34            | 1156.00000 | 39304.00000 |
| $\frac{1}{8}$ | 489.51563 | 10830.53320 | $\frac{1}{8}$ | 791.01563  | 22247.31445 | $\frac{1}{8}$ | 1164.51563 | 39739.09570 |
| $\frac{1}{4}$ | 500.62500 | 11015.14063 | $\frac{1}{4}$ | 798.06250  | 22545.26563 | $\frac{1}{4}$ | 1173.06250 | 40177.39063 |
| $\frac{3}{8}$ | 506.44063 | 11201.83398 | $\frac{3}{8}$ | 805.14063  | 22845.86523 | $\frac{3}{8}$ | 1181.64063 | 40618.89648 |
| $\frac{1}{2}$ | 506.25000 | 11390.62500 | $\frac{1}{2}$ | 812.25000  | 23149.12500 | $\frac{1}{2}$ | 1190.25000 | 41063.62500 |
| $\frac{5}{8}$ | 511.89063 | 11581.52539 | $\frac{5}{8}$ | 819.39063  | 23455.05664 | $\frac{5}{8}$ | 1198.89063 | 41511.58789 |
| $\frac{3}{4}$ | 517.56250 | 11774.54688 | $\frac{3}{4}$ | 826.56250  | 23763.67188 | $\frac{3}{4}$ | 1207.56250 | 41962.79688 |
| $\frac{7}{8}$ | 523.26563 | 11969.70117 | $\frac{7}{8}$ | 833.76563  | 24074.98242 | $\frac{7}{8}$ | 1216.26563 | 42417.26367 |
| 23            | 529.00000 | 12167.00000 | 29            | 841.00000  | 24389.00000 | 35            | 1225.00000 | 42875.00000 |
| $\frac{1}{8}$ | 534.76563 | 12366.45508 | $\frac{1}{8}$ | 848.26563  | 24705.73633 | $\frac{1}{8}$ | 1233.76563 | 43336.01758 |
| $\frac{1}{4}$ | 540.56250 | 12568.07813 | $\frac{1}{4}$ | 855.56250  | 25025.20313 | $\frac{1}{4}$ | 1242.56250 | 43800.32813 |
| $\frac{3}{8}$ | 546.39063 | 12771.88086 | $\frac{3}{8}$ | 862.89063  | 25347.41211 | $\frac{3}{8}$ | 1251.39063 | 44267.94336 |
| $\frac{1}{2}$ | 552.25000 | 12977.87500 | $\frac{1}{2}$ | 870.25000  | 25672.37500 | $\frac{1}{2}$ | 1260.25000 | 44738.87500 |
| $\frac{5}{8}$ | 558.14063 | 13186.07227 | $\frac{5}{8}$ | 877.64063  | 26000.10352 | $\frac{5}{8}$ | 1269.14063 | 45213.13477 |
| $\frac{3}{4}$ | 564.06250 | 13396.48438 | $\frac{3}{4}$ | 885.06250  | 26330.60938 | $\frac{3}{4}$ | 1278.06250 | 45690.73438 |
| $\frac{7}{8}$ | 570.01563 | 13609.12305 | $\frac{7}{8}$ | 892.51563  | 26663.90430 | $\frac{7}{8}$ | 1287.01563 | 46171.68555 |
| 24            | 576.00000 | 13824.00000 | 30            | 900.00000  | 27000.00000 | 36            | 1296.00000 | 46656.00000 |
| $\frac{1}{8}$ | 582.01563 | 14041.12695 | $\frac{1}{8}$ | 907.51563  | 27338.90820 | $\frac{1}{8}$ | 1305.01563 | 47143.68945 |
| $\frac{1}{4}$ | 588.06250 | 14260.51563 | $\frac{1}{4}$ | 915.06250  | 27680.64063 | $\frac{1}{4}$ | 1314.06250 | 47634.76563 |
| $\frac{3}{8}$ | 594.14063 | 14482.17773 | $\frac{3}{8}$ | 922.64063  | 28025.20898 | $\frac{3}{8}$ | 1323.14063 | 48129.24023 |
| $\frac{1}{2}$ | 600.25000 | 14706.12500 | $\frac{1}{2}$ | 930.25000  | 28372.62500 | $\frac{1}{2}$ | 1332.25000 | 48627.12500 |
| $\frac{5}{8}$ | 606.39063 | 14932.36914 | $\frac{5}{8}$ | 937.89063  | 28722.90039 | $\frac{5}{8}$ | 1341.39063 | 49128.43164 |
| $\frac{3}{4}$ | 612.56250 | 15160.92188 | $\frac{3}{4}$ | 945.56250  | 29076.04688 | $\frac{3}{4}$ | 1350.56250 | 49633.17188 |
| $\frac{7}{8}$ | 618.76563 | 15391.79492 | $\frac{7}{8}$ | 953.26563  | 29432.07617 | $\frac{7}{8}$ | 1359.76563 | 50141.35742 |
| 25            | 625.00000 | 15625.00000 | 31            | 961.00000  | 29791.00000 | 37            | 1369.00000 | 50653.00000 |
| $\frac{1}{8}$ | 631.26563 | 15860.54883 | $\frac{1}{8}$ | 968.76563  | 30152.83008 | $\frac{1}{8}$ | 1378.26563 | 51168.11133 |
| $\frac{1}{4}$ | 637.56250 | 16098.45313 | $\frac{1}{4}$ | 976.56250  | 30517.57813 | $\frac{1}{4}$ | 1387.56250 | 51686.70313 |
| $\frac{3}{8}$ | 643.89063 | 16338.72461 | $\frac{3}{8}$ | 984.39063  | 30885.25586 | $\frac{3}{8}$ | 1396.89063 | 52208.78711 |
| $\frac{1}{2}$ | 650.25000 | 16581.37500 | $\frac{1}{2}$ | 992.25000  | 31255.87500 | $\frac{1}{2}$ | 1406.25000 | 52734.37500 |
| $\frac{5}{8}$ | 656.64063 | 16826.41602 | $\frac{5}{8}$ | 1000.14063 | 31629.44727 | $\frac{5}{8}$ | 1415.64063 | 53263.47852 |
| $\frac{3}{4}$ | 663.06250 | 17073.85938 | $\frac{3}{4}$ | 1008.06250 | 32005.98438 | $\frac{3}{4}$ | 1425.06250 | 53796.10938 |
| $\frac{7}{8}$ | 669.51563 | 17323.71680 | $\frac{7}{8}$ | 1016.01563 | 32385.49805 | $\frac{7}{8}$ | 1434.51563 | 54332.27930 |
| 26            | 676.00000 | 17576.00000 | 32            | 1024.00000 | 32768.00000 | 38            | 1444.00000 | 54872.00000 |
| $\frac{1}{8}$ | 682.51563 | 17830.72070 | $\frac{1}{8}$ | 1032.01563 | 33153.50195 | $\frac{1}{8}$ | 1453.51563 | 55415.28320 |
| $\frac{1}{4}$ | 689.06250 | 18087.89063 | $\frac{1}{4}$ | 1040.06250 | 33542.01563 | $\frac{1}{4}$ | 1463.06250 | 55962.14063 |
| $\frac{3}{8}$ | 695.64063 | 18347.52148 | $\frac{3}{8}$ | 1048.14063 | 33933.55273 | $\frac{3}{8}$ | 1472.64063 | 56512.58398 |
| $\frac{1}{2}$ | 702.25000 | 18609.62500 | $\frac{1}{2}$ | 1056.25000 | 34328.12500 | $\frac{1}{2}$ | 1482.25000 | 57066.62500 |
| $\frac{5}{8}$ | 708.89063 | 18874.21289 | $\frac{5}{8}$ | 1064.39063 | 34725.74414 | $\frac{5}{8}$ | 1491.89063 | 57624.27539 |
| $\frac{3}{4}$ | 715.56250 | 19141.29688 | $\frac{3}{4}$ | 1072.56250 | 35126.42188 | $\frac{3}{4}$ | 1501.56250 | 58185.54688 |
| $\frac{7}{8}$ | 722.26563 | 19410.88867 | $\frac{7}{8}$ | 1080.76563 | 35530.16992 | $\frac{7}{8}$ | 1511.26563 | 58750.45117 |
| 27            | 729.00000 | 19683.00000 | 33            | 1089.00000 | 35937.00000 | 39            | 1521.00000 | 59319.00000 |
| $\frac{1}{8}$ | 735.76563 | 19957.64258 | $\frac{1}{8}$ | 1097.26563 | 36346.92383 | $\frac{1}{8}$ | 1530.76563 | 59891.20508 |
| $\frac{1}{4}$ | 742.56250 | 20234.82813 | $\frac{1}{4}$ | 1105.56250 | 36759.95313 | $\frac{1}{4}$ | 1540.56250 | 60467.07813 |
| $\frac{3}{8}$ | 749.39063 | 20514.56836 | $\frac{3}{8}$ | 1113.89063 | 37176.09961 | $\frac{3}{8}$ | 1550.39063 | 61046.63086 |
| $\frac{1}{2}$ | 756.25000 | 20796.87500 | $\frac{1}{2}$ | 1122.25000 | 37595.37500 | $\frac{1}{2}$ | 1560.25000 | 61629.87500 |
| $\frac{5}{8}$ | 763.14063 | 21081.75977 | $\frac{5}{8}$ | 1130.64063 | 38017.79102 | $\frac{5}{8}$ | 1570.14063 | 62216.82227 |
| $\frac{3}{4}$ | 770.06250 | 21369.23438 | $\frac{3}{4}$ | 1139.06250 | 38443.35938 | $\frac{3}{4}$ | 1580.06250 | 62807.48438 |
| $\frac{7}{8}$ | 777.01563 | 21659.31055 | $\frac{7}{8}$ | 1147.51563 | 38872.09180 | $\frac{7}{8}$ | 1590.01563 | 63401.87305 |

Squares and Cubes of Numbers from 40 to 57  $\frac{7}{8}$ 

| No.           | Square     | Cube        | No.           | Square     | Cube         | No.           | Square     | Cube         |
|---------------|------------|-------------|---------------|------------|--------------|---------------|------------|--------------|
| 40            | 1600.00000 | 64000.00000 | 46            | 2116.00000 | 97336.00000  | 52            | 2704.00000 | 140608.00000 |
| $\frac{1}{8}$ | 1610.01563 | 64601.87695 | $\frac{1}{8}$ | 2127.51563 | 98131.65820  | $\frac{1}{8}$ | 2717.01563 | 141624.43945 |
| $\frac{1}{4}$ | 1620.06250 | 65207.51563 | $\frac{1}{4}$ | 2139.06250 | 98931.64063  | $\frac{1}{4}$ | 2730.06250 | 142645.76563 |
| $\frac{3}{8}$ | 1630.14063 | 65816.92773 | $\frac{3}{8}$ | 2150.64063 | 99735.95898  | $\frac{3}{8}$ | 2743.14063 | 143671.99023 |
| $\frac{1}{2}$ | 1640.25000 | 66430.12500 | $\frac{1}{2}$ | 2162.25000 | 100544.62500 | $\frac{1}{2}$ | 2756.25000 | 144703.12500 |
| $\frac{5}{8}$ | 1650.39063 | 67047.11914 | $\frac{5}{8}$ | 2173.89063 | 101357.65039 | $\frac{5}{8}$ | 2769.39063 | 145739.18164 |
| $\frac{3}{4}$ | 1660.56250 | 67667.92188 | $\frac{3}{4}$ | 2185.56250 | 102175.04688 | $\frac{3}{4}$ | 2782.56250 | 146780.17188 |
| $\frac{7}{8}$ | 1670.76563 | 68292.54492 | $\frac{7}{8}$ | 2197.26563 | 102996.82617 | $\frac{7}{8}$ | 2795.76563 | 147826.10742 |
| 41            | 1681.00000 | 68921.00000 | 47            | 2209.00000 | 103823.00000 | 53            | 2809.00000 | 148877.00000 |
| $\frac{1}{8}$ | 1691.26563 | 69553.29883 | $\frac{1}{8}$ | 2220.76563 | 104653.58008 | $\frac{1}{8}$ | 2822.26563 | 149932.86133 |
| $\frac{1}{4}$ | 1701.56250 | 70189.45313 | $\frac{1}{4}$ | 2232.56250 | 105488.57813 | $\frac{1}{4}$ | 2835.56250 | 150993.70313 |
| $\frac{3}{8}$ | 1711.89063 | 70829.47461 | $\frac{3}{8}$ | 2244.39063 | 106328.00586 | $\frac{3}{8}$ | 2848.89063 | 152059.53711 |
| $\frac{1}{2}$ | 1722.25000 | 71473.37500 | $\frac{1}{2}$ | 2256.25000 | 107171.87500 | $\frac{1}{2}$ | 2862.25000 | 153130.37500 |
| $\frac{5}{8}$ | 1732.64063 | 72121.16602 | $\frac{5}{8}$ | 2268.14063 | 108020.19727 | $\frac{5}{8}$ | 2875.64063 | 154206.22852 |
| $\frac{3}{4}$ | 1743.06250 | 72772.85938 | $\frac{3}{4}$ | 2280.06250 | 108872.98438 | $\frac{3}{4}$ | 2889.06250 | 155287.10938 |
| $\frac{7}{8}$ | 1753.51563 | 73428.46680 | $\frac{7}{8}$ | 2292.01563 | 109730.24805 | $\frac{7}{8}$ | 2902.51563 | 156373.02930 |
| 42            | 1764.00000 | 74088.00000 | 48            | 2304.00000 | 110592.00000 | 54            | 2916.00000 | 157464.00000 |
| $\frac{1}{8}$ | 1774.51563 | 74751.47070 | $\frac{1}{8}$ | 2316.01563 | 111458.25195 | $\frac{1}{8}$ | 2929.51563 | 158560.03320 |
| $\frac{1}{4}$ | 1785.06250 | 75418.89063 | $\frac{1}{4}$ | 2328.06250 | 112329.01563 | $\frac{1}{4}$ | 2943.06250 | 159661.14063 |
| $\frac{3}{8}$ | 1795.64063 | 76090.27148 | $\frac{3}{8}$ | 2340.14063 | 113204.30273 | $\frac{3}{8}$ | 2956.64063 | 160767.33398 |
| $\frac{1}{2}$ | 1806.25000 | 76765.62500 | $\frac{1}{2}$ | 2352.25000 | 114084.12500 | $\frac{1}{2}$ | 2970.25000 | 161878.62500 |
| $\frac{5}{8}$ | 1816.89063 | 77444.96289 | $\frac{5}{8}$ | 2364.39063 | 114968.49414 | $\frac{5}{8}$ | 2983.89063 | 162995.02539 |
| $\frac{3}{4}$ | 1827.56250 | 78128.29688 | $\frac{3}{4}$ | 2376.56250 | 115857.42188 | $\frac{3}{4}$ | 2997.56250 | 164116.54688 |
| $\frac{7}{8}$ | 1838.26563 | 78815.63867 | $\frac{7}{8}$ | 2388.76563 | 116750.91992 | $\frac{7}{8}$ | 3011.26563 | 165243.20117 |
| 43            | 1849.00000 | 79507.00000 | 49            | 2401.00000 | 117649.00000 | 55            | 3025.00000 | 166375.00000 |
| $\frac{1}{8}$ | 1859.76563 | 80202.39258 | $\frac{1}{8}$ | 2413.26563 | 118551.67383 | $\frac{1}{8}$ | 3038.76563 | 167511.95508 |
| $\frac{1}{4}$ | 1870.56250 | 80901.82813 | $\frac{1}{4}$ | 2425.56250 | 119458.95313 | $\frac{1}{4}$ | 3052.56250 | 168654.07813 |
| $\frac{3}{8}$ | 1881.39063 | 81605.31836 | $\frac{3}{8}$ | 2437.89063 | 120370.84961 | $\frac{3}{8}$ | 3066.39063 | 169801.38086 |
| $\frac{1}{2}$ | 1892.25000 | 82312.87500 | $\frac{1}{2}$ | 2450.25000 | 121287.37500 | $\frac{1}{2}$ | 3080.25000 | 170953.87500 |
| $\frac{5}{8}$ | 1903.14063 | 83024.50977 | $\frac{5}{8}$ | 2462.64063 | 122208.54102 | $\frac{5}{8}$ | 3094.14063 | 172111.57227 |
| $\frac{3}{4}$ | 1914.06250 | 83740.23438 | $\frac{3}{4}$ | 2475.06250 | 123134.35938 | $\frac{3}{4}$ | 3108.06250 | 173274.48438 |
| $\frac{7}{8}$ | 1925.01563 | 84460.06055 | $\frac{7}{8}$ | 2487.51563 | 124064.84180 | $\frac{7}{8}$ | 3122.01563 | 174442.62305 |
| 44            | 1936.00000 | 85184.00000 | 50            | 2500.00000 | 125000.00000 | 56            | 3136.00000 | 175616.00000 |
| $\frac{1}{8}$ | 1947.01563 | 85912.06445 | $\frac{1}{8}$ | 2512.51563 | 125939.84570 | $\frac{1}{8}$ | 3150.01563 | 176794.62695 |
| $\frac{1}{4}$ | 1958.06250 | 86644.26563 | $\frac{1}{4}$ | 2525.06250 | 126884.39063 | $\frac{1}{4}$ | 3164.06250 | 177978.51563 |
| $\frac{3}{8}$ | 1969.14063 | 87380.61523 | $\frac{3}{8}$ | 2537.64063 | 127833.64648 | $\frac{3}{8}$ | 3178.14063 | 179167.67773 |
| $\frac{1}{2}$ | 1980.25000 | 88121.12500 | $\frac{1}{2}$ | 2550.25000 | 128787.62500 | $\frac{1}{2}$ | 3192.25000 | 180362.12500 |
| $\frac{5}{8}$ | 1991.39063 | 88865.80664 | $\frac{5}{8}$ | 2562.89063 | 129746.33789 | $\frac{5}{8}$ | 3206.39063 | 181561.86914 |
| $\frac{3}{4}$ | 2002.56250 | 89614.67188 | $\frac{3}{4}$ | 2575.56250 | 130709.79688 | $\frac{3}{4}$ | 3220.56250 | 182766.92188 |
| $\frac{7}{8}$ | 2013.76563 | 90367.73242 | $\frac{7}{8}$ | 2588.26563 | 131678.01367 | $\frac{7}{8}$ | 3234.76563 | 183977.29492 |
| 45            | 2025.00000 | 91125.00000 | 51            | 2601.00000 | 132651.00000 | 57            | 3249.00000 | 185193.00000 |
| $\frac{1}{8}$ | 2036.26563 | 91886.48633 | $\frac{1}{8}$ | 2613.76563 | 133628.76758 | $\frac{1}{8}$ | 3263.26563 | 186414.04883 |
| $\frac{1}{4}$ | 2047.56250 | 92652.20313 | $\frac{1}{4}$ | 2626.56250 | 134611.32813 | $\frac{1}{4}$ | 3277.56250 | 187640.45313 |
| $\frac{3}{8}$ | 2058.89063 | 93422.16211 | $\frac{3}{8}$ | 2639.39063 | 135598.69336 | $\frac{3}{8}$ | 3291.89063 | 188872.22461 |
| $\frac{1}{2}$ | 2070.25000 | 94196.37500 | $\frac{1}{2}$ | 2652.25000 | 136590.87500 | $\frac{1}{2}$ | 3306.25000 | 190109.37500 |
| $\frac{5}{8}$ | 2081.64063 | 94974.85352 | $\frac{5}{8}$ | 2665.14063 | 137587.88477 | $\frac{5}{8}$ | 3320.64063 | 191351.91602 |
| $\frac{3}{4}$ | 2093.06250 | 95757.60938 | $\frac{3}{4}$ | 2678.06250 | 138589.73438 | $\frac{3}{4}$ | 3335.06250 | 192599.85938 |
| $\frac{7}{8}$ | 2104.51563 | 96544.65430 | $\frac{7}{8}$ | 2691.01563 | 139596.43555 | $\frac{7}{8}$ | 3349.51563 | 193853.21680 |

Squares and Cubes of Numbers from 58 to 75 $\frac{7}{8}$ 

| No.           | Square     | Cube         | No.           | Square     | Cube         | No.           | Square     | Cube         |
|---------------|------------|--------------|---------------|------------|--------------|---------------|------------|--------------|
| 58            | 3364.00000 | 195112.00000 | 64            | 4096.00000 | 262144.00000 | 70            | 4900.00000 | 343000.00000 |
| $\frac{1}{8}$ | 3378.51563 | 196376.22070 | $\frac{1}{8}$ | 4112.01563 | 263683.00195 | $\frac{1}{8}$ | 4917.51563 | 344840.78320 |
| $\frac{1}{4}$ | 3393.06250 | 197645.89063 | $\frac{1}{4}$ | 4128.06250 | 265228.01563 | $\frac{1}{4}$ | 4935.06250 | 346688.14063 |
| $\frac{3}{8}$ | 3407.64063 | 198921.02148 | $\frac{3}{8}$ | 4144.14063 | 266779.05273 | $\frac{3}{8}$ | 4952.64063 | 348542.08398 |
| $\frac{1}{2}$ | 3422.25000 | 200201.62500 | $\frac{1}{2}$ | 4160.25000 | 268336.12500 | $\frac{1}{2}$ | 4970.25000 | 350402.62500 |
| $\frac{5}{8}$ | 3436.89063 | 201487.71289 | $\frac{5}{8}$ | 4176.39063 | 269899.24414 | $\frac{5}{8}$ | 4987.89063 | 352269.77539 |
| $\frac{3}{4}$ | 3451.56250 | 202779.29688 | $\frac{3}{4}$ | 4192.56250 | 271468.42188 | $\frac{3}{4}$ | 5005.56250 | 354143.54688 |
| $\frac{7}{8}$ | 3466.26563 | 204076.38867 | $\frac{7}{8}$ | 4208.76563 | 273043.66992 | $\frac{7}{8}$ | 5023.26563 | 356023.95117 |
| 59            | 3481.00000 | 205379.00000 | 65            | 4225.00000 | 274625.00000 | 71            | 5041.00000 | 357911.00000 |
| $\frac{1}{8}$ | 3495.76563 | 206687.14258 | $\frac{1}{8}$ | 4241.26563 | 276212.42383 | $\frac{1}{8}$ | 5058.76563 | 359804.70508 |
| $\frac{1}{4}$ | 3510.56250 | 208000.82813 | $\frac{1}{4}$ | 4257.56250 | 277805.95313 | $\frac{1}{4}$ | 5076.56250 | 361705.07813 |
| $\frac{3}{8}$ | 3525.39063 | 209320.06836 | $\frac{3}{8}$ | 4273.89063 | 279405.59961 | $\frac{3}{8}$ | 5094.39063 | 363612.13086 |
| $\frac{1}{2}$ | 3540.25000 | 210644.87500 | $\frac{1}{2}$ | 4290.25000 | 281011.37500 | $\frac{1}{2}$ | 5112.25000 | 365525.87500 |
| $\frac{5}{8}$ | 3555.14063 | 211975.25977 | $\frac{5}{8}$ | 4306.64063 | 282623.29102 | $\frac{5}{8}$ | 5130.14063 | 367446.32227 |
| $\frac{3}{4}$ | 3570.06250 | 213311.23438 | $\frac{3}{4}$ | 4323.06250 | 284241.35938 | $\frac{3}{4}$ | 5148.06250 | 369373.48438 |
| $\frac{7}{8}$ | 3585.01563 | 214652.81055 | $\frac{7}{8}$ | 4339.51563 | 285865.59180 | $\frac{7}{8}$ | 5166.01563 | 371307.37305 |
| 60            | 3600.00000 | 216000.00000 | 66            | 4356.00000 | 287496.00000 | 72            | 5184.00000 | 373248.00000 |
| $\frac{1}{8}$ | 3615.01563 | 217352.81445 | $\frac{1}{8}$ | 4372.51563 | 289132.59570 | $\frac{1}{8}$ | 5202.01563 | 375199.57695 |
| $\frac{1}{4}$ | 3630.06250 | 218711.26563 | $\frac{1}{4}$ | 4389.06250 | 290775.39063 | $\frac{1}{4}$ | 5220.06250 | 377149.51563 |
| $\frac{3}{8}$ | 3645.14063 | 220075.36523 | $\frac{3}{8}$ | 4405.64063 | 292424.39648 | $\frac{3}{8}$ | 5238.14063 | 379110.42773 |
| $\frac{1}{2}$ | 3660.25000 | 221445.12500 | $\frac{1}{2}$ | 4422.25000 | 294079.62500 | $\frac{1}{2}$ | 5256.25000 | 381078.12500 |
| $\frac{5}{8}$ | 3675.39063 | 222820.55664 | $\frac{5}{8}$ | 4438.89063 | 295741.08789 | $\frac{5}{8}$ | 5274.39063 | 383052.61914 |
| $\frac{3}{4}$ | 3690.56250 | 224201.67188 | $\frac{3}{4}$ | 4455.56250 | 297408.79688 | $\frac{3}{4}$ | 5292.56250 | 385033.92188 |
| $\frac{7}{8}$ | 3705.76563 | 225588.48242 | $\frac{7}{8}$ | 4472.26563 | 299082.76367 | $\frac{7}{8}$ | 5310.76563 | 387022.04492 |
| 61            | 3721.00000 | 226981.00000 | 67            | 4489.00000 | 300763.00000 | 73            | 5329.00000 | 389017.00000 |
| $\frac{1}{8}$ | 3736.26563 | 228379.23633 | $\frac{1}{8}$ | 4505.76563 | 302449.51758 | $\frac{1}{8}$ | 5347.26563 | 391018.79883 |
| $\frac{1}{4}$ | 3751.56250 | 229783.20313 | $\frac{1}{4}$ | 4522.56250 | 304142.32813 | $\frac{1}{4}$ | 5365.56250 | 393027.45313 |
| $\frac{3}{8}$ | 3766.89063 | 231192.91211 | $\frac{3}{8}$ | 4539.39063 | 305841.44336 | $\frac{3}{8}$ | 5383.89063 | 395042.97461 |
| $\frac{1}{2}$ | 3782.25000 | 232608.37500 | $\frac{1}{2}$ | 4556.25000 | 307546.87500 | $\frac{1}{2}$ | 5402.25000 | 397065.37500 |
| $\frac{5}{8}$ | 3797.64063 | 234029.60352 | $\frac{5}{8}$ | 4573.14063 | 309258.63477 | $\frac{5}{8}$ | 5420.64063 | 399094.66602 |
| $\frac{3}{4}$ | 3813.06250 | 235456.60938 | $\frac{3}{4}$ | 4590.06250 | 310976.73438 | $\frac{3}{4}$ | 5439.06250 | 401130.85938 |
| $\frac{7}{8}$ | 3828.51563 | 236889.40430 | $\frac{7}{8}$ | 4607.01563 | 312701.18555 | $\frac{7}{8}$ | 5457.51563 | 403173.96680 |
| 62            | 3844.00000 | 238328.00000 | 68            | 4624.00000 | 314432.00000 | 74            | 5476.00000 | 405224.00000 |
| $\frac{1}{8}$ | 3859.51563 | 239772.40820 | $\frac{1}{8}$ | 4641.01563 | 316169.18945 | $\frac{1}{8}$ | 5494.51563 | 407280.97070 |
| $\frac{1}{4}$ | 3875.06250 | 241222.64063 | $\frac{1}{4}$ | 4658.06250 | 317912.76563 | $\frac{1}{4}$ | 5513.06250 | 409344.89063 |
| $\frac{3}{8}$ | 3890.64063 | 242678.70898 | $\frac{3}{8}$ | 4675.14063 | 319662.74023 | $\frac{3}{8}$ | 5531.64063 | 411415.77148 |
| $\frac{1}{2}$ | 3906.25000 | 244140.62500 | $\frac{1}{2}$ | 4692.25000 | 321419.12500 | $\frac{1}{2}$ | 5550.25000 | 413493.62500 |
| $\frac{5}{8}$ | 3921.89063 | 245608.40039 | $\frac{5}{8}$ | 4709.39063 | 323181.93164 | $\frac{5}{8}$ | 5568.89063 | 415578.46289 |
| $\frac{3}{4}$ | 3937.56250 | 247082.04688 | $\frac{3}{4}$ | 4726.56250 | 324951.17188 | $\frac{3}{4}$ | 5587.56250 | 417670.29688 |
| $\frac{7}{8}$ | 3953.26563 | 248561.57617 | $\frac{7}{8}$ | 4743.76563 | 326726.85742 | $\frac{7}{8}$ | 5606.26563 | 419769.13867 |
| 63            | 3969.00000 | 250047.00000 | 69            | 4761.00000 | 328509.00000 | 75            | 5625.00000 | 421875.00000 |
| $\frac{1}{8}$ | 3984.76563 | 251538.33008 | $\frac{1}{8}$ | 4778.26563 | 330297.61133 | $\frac{1}{8}$ | 5643.76563 | 423987.89258 |
| $\frac{1}{4}$ | 4000.56250 | 253035.57813 | $\frac{1}{4}$ | 4795.56250 | 332092.70313 | $\frac{1}{4}$ | 5662.56250 | 426107.82813 |
| $\frac{3}{8}$ | 4016.39063 | 254538.75586 | $\frac{3}{8}$ | 4812.89063 | 333894.28711 | $\frac{3}{8}$ | 5681.39063 | 428234.81836 |
| $\frac{1}{2}$ | 4032.25000 | 256047.87500 | $\frac{1}{2}$ | 4830.25000 | 335702.37500 | $\frac{1}{2}$ | 5700.25000 | 430368.87500 |
| $\frac{5}{8}$ | 4048.14063 | 257562.94727 | $\frac{5}{8}$ | 4847.64063 | 337516.97852 | $\frac{5}{8}$ | 5719.14063 | 432510.00977 |
| $\frac{3}{4}$ | 4064.06250 | 259083.98438 | $\frac{3}{4}$ | 4865.06250 | 339338.10938 | $\frac{3}{4}$ | 5738.06250 | 434658.23438 |
| $\frac{7}{8}$ | 4080.01563 | 260610.99805 | $\frac{7}{8}$ | 4882.51563 | 341165.77930 | $\frac{7}{8}$ | 5757.01563 | 436813.56055 |

## SQUARES AND CUBES OF NUMBERS

Squares and Cubes of Numbers from 76 to 93 $\frac{7}{8}$ 

| No.           | Square     | Cube         | No.           | Square     | Cube         | No.           | Square     | Cube         |
|---------------|------------|--------------|---------------|------------|--------------|---------------|------------|--------------|
| 76            | 5776.00000 | 438976.00000 | 82            | 6724.00000 | 551368.00000 | 88            | 7744.00000 | 681472.00000 |
| $\frac{1}{8}$ | 5795.01563 | 441145.56445 | $\frac{1}{8}$ | 6744.51563 | 553893.34570 | $\frac{1}{8}$ | 7766.01563 | 684380.12695 |
| $\frac{1}{4}$ | 5814.06250 | 443322.26563 | $\frac{1}{4}$ | 6765.06250 | 556426.39063 | $\frac{1}{4}$ | 7788.06250 | 687296.51563 |
| $\frac{3}{8}$ | 5833.14063 | 445506.11523 | $\frac{3}{8}$ | 6785.64063 | 558967.14648 | $\frac{3}{8}$ | 7810.14063 | 690221.17773 |
| $\frac{1}{2}$ | 5852.25000 | 447697.12500 | $\frac{1}{2}$ | 6806.25000 | 561515.62500 | $\frac{1}{2}$ | 7832.25000 | 693154.12500 |
| $\frac{5}{8}$ | 5871.39063 | 449895.30664 | $\frac{5}{8}$ | 6826.89063 | 564071.83789 | $\frac{5}{8}$ | 7854.39063 | 696095.36914 |
| $\frac{3}{4}$ | 5890.56250 | 452100.67188 | $\frac{3}{4}$ | 6847.56250 | 566635.79688 | $\frac{3}{4}$ | 7876.56250 | 699044.92188 |
| $\frac{7}{8}$ | 5909.76563 | 454313.23242 | $\frac{7}{8}$ | 6868.26563 | 569207.51367 | $\frac{7}{8}$ | 7898.76563 | 702002.79492 |
| 77            | 5929.00000 | 456533.00000 | 83            | 6889.00000 | 571787.00000 | 89            | 7921.00000 | 704969.00000 |
| $\frac{1}{8}$ | 5948.26563 | 458759.98633 | $\frac{1}{8}$ | 6909.76563 | 574374.26758 | $\frac{1}{8}$ | 7943.26563 | 707943.54883 |
| $\frac{1}{4}$ | 5967.56250 | 460994.20313 | $\frac{1}{4}$ | 6930.56250 | 576969.32813 | $\frac{1}{4}$ | 7965.56250 | 710926.45313 |
| $\frac{3}{8}$ | 5986.89063 | 463235.66211 | $\frac{3}{8}$ | 6951.39063 | 579572.19336 | $\frac{3}{8}$ | 7987.89063 | 713917.72461 |
| $\frac{1}{2}$ | 6006.25000 | 465484.37500 | $\frac{1}{2}$ | 6972.25000 | 582182.87500 | $\frac{1}{2}$ | 8010.25000 | 716917.37500 |
| $\frac{5}{8}$ | 6025.64063 | 467740.35352 | $\frac{5}{8}$ | 6993.14063 | 584801.38477 | $\frac{5}{8}$ | 8032.64063 | 719925.41602 |
| $\frac{3}{4}$ | 6045.06250 | 470003.60938 | $\frac{3}{4}$ | 7014.06250 | 587427.73438 | $\frac{3}{4}$ | 8055.06250 | 722941.85938 |
| $\frac{7}{8}$ | 6064.51563 | 472274.15430 | $\frac{7}{8}$ | 7035.01563 | 590061.93555 | $\frac{7}{8}$ | 8077.51563 | 725966.71680 |
| 78            | 6084.00000 | 474552.00000 | 84            | 7056.00000 | 592704.00000 | 90            | 8100.00000 | 729000.00000 |
| $\frac{1}{8}$ | 6103.51563 | 476837.15820 | $\frac{1}{8}$ | 7077.01563 | 595353.93945 | $\frac{1}{8}$ | 8122.51563 | 732041.72070 |
| $\frac{1}{4}$ | 6123.06250 | 479129.64063 | $\frac{1}{4}$ | 7098.06250 | 598011.76563 | $\frac{1}{4}$ | 8145.06250 | 735091.89063 |
| $\frac{3}{8}$ | 6142.64063 | 481429.45898 | $\frac{3}{8}$ | 7119.14063 | 600677.49023 | $\frac{3}{8}$ | 8167.64063 | 738150.52148 |
| $\frac{1}{2}$ | 6162.25000 | 483736.62500 | $\frac{1}{2}$ | 7140.25000 | 603351.12500 | $\frac{1}{2}$ | 8190.25000 | 741217.62500 |
| $\frac{5}{8}$ | 6181.89063 | 486051.15039 | $\frac{5}{8}$ | 7161.39063 | 606032.68164 | $\frac{5}{8}$ | 8212.89063 | 744293.21289 |
| $\frac{3}{4}$ | 6201.56250 | 488373.04688 | $\frac{3}{4}$ | 7182.56250 | 608722.17188 | $\frac{3}{4}$ | 8235.56250 | 747377.29688 |
| $\frac{7}{8}$ | 6221.26563 | 490702.32617 | $\frac{7}{8}$ | 7203.76563 | 611419.60742 | $\frac{7}{8}$ | 8258.26563 | 750469.88867 |
| 79            | 6241.00000 | 493039.00000 | 85            | 7225.00000 | 614125.00000 | 91            | 8281.00000 | 753571.00000 |
| $\frac{1}{8}$ | 6260.76563 | 495383.08008 | $\frac{1}{8}$ | 7246.26563 | 616838.36133 | $\frac{1}{8}$ | 8303.76563 | 756680.64258 |
| $\frac{1}{4}$ | 6280.56250 | 497734.57813 | $\frac{1}{4}$ | 7267.56250 | 619559.70313 | $\frac{1}{4}$ | 8326.56250 | 759798.82813 |
| $\frac{3}{8}$ | 6300.39063 | 500093.50586 | $\frac{3}{8}$ | 7288.89063 | 622289.03711 | $\frac{3}{8}$ | 8349.39063 | 762925.56836 |
| $\frac{1}{2}$ | 6320.25000 | 502459.87500 | $\frac{1}{2}$ | 7310.25000 | 625026.37500 | $\frac{1}{2}$ | 8372.25000 | 766060.87500 |
| $\frac{5}{8}$ | 6340.14063 | 504833.69727 | $\frac{5}{8}$ | 7331.64063 | 627771.72852 | $\frac{5}{8}$ | 8395.14063 | 769204.75977 |
| $\frac{3}{4}$ | 6360.06250 | 507214.98438 | $\frac{3}{4}$ | 7353.06250 | 630525.10938 | $\frac{3}{4}$ | 8418.06250 | 772357.23438 |
| $\frac{7}{8}$ | 6380.01563 | 509603.74805 | $\frac{7}{8}$ | 7374.51563 | 633286.52930 | $\frac{7}{8}$ | 8441.01563 | 775518.31055 |
| 80            | 6400.00000 | 512000.00000 | 86            | 7396.00000 | 636056.00000 | 92            | 8464.00000 | 778688.00000 |
| $\frac{1}{8}$ | 6420.01563 | 514403.75195 | $\frac{1}{8}$ | 7417.51563 | 638833.53320 | $\frac{1}{8}$ | 8487.01563 | 781866.31445 |
| $\frac{1}{4}$ | 6440.06250 | 516815.01563 | $\frac{1}{4}$ | 7439.06250 | 641619.14063 | $\frac{1}{4}$ | 8510.06250 | 785053.26563 |
| $\frac{3}{8}$ | 6460.14063 | 519233.80273 | $\frac{3}{8}$ | 7460.64063 | 644412.83398 | $\frac{3}{8}$ | 8533.14063 | 788248.86523 |
| $\frac{1}{2}$ | 6480.25000 | 521660.12500 | $\frac{1}{2}$ | 7482.25000 | 647214.62500 | $\frac{1}{2}$ | 8556.25000 | 791453.12500 |
| $\frac{5}{8}$ | 6500.39063 | 524093.99414 | $\frac{5}{8}$ | 7503.89063 | 650024.52539 | $\frac{5}{8}$ | 8579.39063 | 794666.05664 |
| $\frac{3}{4}$ | 6520.56250 | 526535.42188 | $\frac{3}{4}$ | 7525.56250 | 652842.54688 | $\frac{3}{4}$ | 8602.56250 | 797887.67188 |
| $\frac{7}{8}$ | 6540.76563 | 528984.41992 | $\frac{7}{8}$ | 7547.26563 | 655668.70117 | $\frac{7}{8}$ | 8625.76563 | 801117.98242 |
| 81            | 6561.00000 | 531441.00000 | 87            | 7569.00000 | 658503.00000 | 93            | 8649.00000 | 804357.00000 |
| $\frac{1}{8}$ | 6581.26563 | 533905.17383 | $\frac{1}{8}$ | 7590.76563 | 661345.45508 | $\frac{1}{8}$ | 8672.26563 | 807604.73633 |
| $\frac{1}{4}$ | 6601.56250 | 536376.95313 | $\frac{1}{4}$ | 7612.56250 | 664196.07813 | $\frac{1}{4}$ | 8695.56250 | 810861.20313 |
| $\frac{3}{8}$ | 6621.89063 | 538856.34961 | $\frac{3}{8}$ | 7634.39063 | 667054.88086 | $\frac{3}{8}$ | 8718.89063 | 814126.41211 |
| $\frac{1}{2}$ | 6642.25000 | 541343.37500 | $\frac{1}{2}$ | 7656.25000 | 669921.87500 | $\frac{1}{2}$ | 8742.25000 | 817400.37500 |
| $\frac{5}{8}$ | 6662.64063 | 543838.04102 | $\frac{5}{8}$ | 7678.14063 | 672797.07227 | $\frac{5}{8}$ | 8765.64063 | 820683.10352 |
| $\frac{3}{4}$ | 6683.06250 | 546340.35938 | $\frac{3}{4}$ | 7700.06250 | 675680.48438 | $\frac{3}{4}$ | 8789.06250 | 823974.60938 |
| $\frac{7}{8}$ | 6703.51563 | 548850.34180 | $\frac{7}{8}$ | 7722.01563 | 678572.12305 | $\frac{7}{8}$ | 8812.51563 | 827274.90430 |

## Squares and Cubes of Numbers from 94 to 100

| No.           | Square     | Cube         | No.           | Square     | Cube         | No.           | Square     | Cube         |
|---------------|------------|--------------|---------------|------------|--------------|---------------|------------|--------------|
| 94            | 8836.00000 | 830584.00000 | 96            | 9216.00000 | 884736.00000 | 98            | 9604.00000 | 941192.00000 |
| $\frac{1}{8}$ | 8859.51563 | 833901.90820 | $\frac{1}{8}$ | 9240.01563 | 888196.50195 | $\frac{1}{8}$ | 9628.51563 | 944798.09570 |
| $\frac{1}{4}$ | 8883.06250 | 837228.64063 | $\frac{1}{4}$ | 9264.06250 | 891666.01563 | $\frac{1}{4}$ | 9653.06250 | 948413.39063 |
| $\frac{3}{8}$ | 8906.64063 | 840564.20898 | $\frac{3}{8}$ | 9288.14063 | 895144.55273 | $\frac{3}{8}$ | 9677.64063 | 952037.89648 |
| $\frac{1}{2}$ | 8930.25000 | 843908.62500 | $\frac{1}{2}$ | 9312.25000 | 898632.12500 | $\frac{1}{2}$ | 9702.25000 | 955671.62500 |
| $\frac{5}{8}$ | 8953.89063 | 847261.90039 | $\frac{5}{8}$ | 9336.39063 | 902128.74414 | $\frac{5}{8}$ | 9726.89063 | 959314.58789 |
| $\frac{3}{4}$ | 8977.56250 | 850624.04688 | $\frac{3}{4}$ | 9360.56250 | 905634.42188 | $\frac{3}{4}$ | 9751.56250 | 962966.79688 |
| $\frac{7}{8}$ | 9001.26563 | 853995.07617 | $\frac{7}{8}$ | 9384.76563 | 909149.16992 | $\frac{7}{8}$ | 9776.26563 | 966628.26367 |
| 95            | 9025.00000 | 857375.00000 | 97            | 9409.00000 | 912673.00000 | 99            | 9801.00000 | 970299.00000 |
| $\frac{1}{8}$ | 9048.76563 | 860763.83008 | $\frac{1}{8}$ | 9433.26563 | 916205.92383 | $\frac{1}{8}$ | 9825.76563 | 973979.01758 |
| $\frac{1}{4}$ | 9072.56250 | 864161.57813 | $\frac{1}{4}$ | 9457.56250 | 919747.95313 | $\frac{1}{4}$ | 9850.56250 | 977668.32813 |
| $\frac{3}{8}$ | 9096.39063 | 867568.25586 | $\frac{3}{8}$ | 9481.89063 | 923299.09961 | $\frac{3}{8}$ | 9875.39063 | 981366.94336 |
| $\frac{1}{2}$ | 9120.25000 | 870983.87500 | $\frac{1}{2}$ | 9506.25000 | 926859.37500 | $\frac{1}{2}$ | 9900.25000 | 985074.87500 |
| $\frac{5}{8}$ | 9144.14063 | 874408.44727 | $\frac{5}{8}$ | 9530.64063 | 930428.79102 | $\frac{5}{8}$ | 9925.14063 | 988792.13477 |
| $\frac{3}{4}$ | 9168.06250 | 877841.98438 | $\frac{3}{4}$ | 9555.06250 | 934007.35938 | $\frac{3}{4}$ | 9950.06250 | 992518.73438 |
| $\frac{7}{8}$ | 9192.01563 | 881284.49805 | $\frac{7}{8}$ | 9579.51563 | 937595.09180 | $\frac{7}{8}$ | 9975.01563 | 996254.68555 |
|               |            |              |               |            |              | 100           | 10,000.00  | 1,000,000    |

Fractions of Pi ( $\pi$ )Table of Fractions of  $\pi = 3.14159265$ 

| a  | $\pi/a$ | a  | $\pi/a$ | a  | $\pi/a$ | a  | $\pi/a$ | a   | $\pi/a$ |
|----|---------|----|---------|----|---------|----|---------|-----|---------|
| 1  | 3.14159 | 21 | 0.14960 | 41 | 0.07662 | 61 | 0.05150 | 81  | 0.03879 |
| 2  | 1.57080 | 22 | 0.14280 | 42 | 0.07480 | 62 | 0.05067 | 82  | 0.03831 |
| 3  | 1.04720 | 23 | 0.13659 | 43 | 0.07306 | 63 | 0.04987 | 83  | 0.03785 |
| 4  | 0.78540 | 24 | 0.13090 | 44 | 0.07140 | 64 | 0.04909 | 84  | 0.03740 |
| 5  | 0.62832 | 25 | 0.12566 | 45 | 0.06981 | 65 | 0.04833 | 85  | 0.03696 |
| 6  | 0.52360 | 26 | 0.12083 | 46 | 0.06830 | 66 | 0.04760 | 86  | 0.03653 |
| 7  | 0.44880 | 27 | 0.11636 | 47 | 0.06684 | 67 | 0.04689 | 87  | 0.03611 |
| 8  | 0.39270 | 28 | 0.11220 | 48 | 0.06545 | 68 | 0.04620 | 88  | 0.03570 |
| 9  | 0.34907 | 29 | 0.10833 | 49 | 0.06411 | 69 | 0.04553 | 89  | 0.03530 |
| 10 | 0.31416 | 30 | 0.10472 | 50 | 0.06283 | 70 | 0.04488 | 90  | 0.03491 |
| 11 | 0.28560 | 31 | 0.10134 | 51 | 0.06160 | 71 | 0.04425 | 91  | 0.03452 |
| 12 | 0.26180 | 32 | 0.09817 | 52 | 0.06042 | 72 | 0.04363 | 92  | 0.03415 |
| 13 | 0.24166 | 33 | 0.09520 | 53 | 0.05928 | 73 | 0.04304 | 93  | 0.03378 |
| 14 | 0.22440 | 34 | 0.09240 | 54 | 0.05818 | 74 | 0.04245 | 94  | 0.03342 |
| 15 | 0.20944 | 35 | 0.08976 | 55 | 0.05712 | 75 | 0.04189 | 95  | 0.03307 |
| 16 | 0.19635 | 36 | 0.08727 | 56 | 0.05610 | 76 | 0.04134 | 96  | 0.03272 |
| 17 | 0.18480 | 37 | 0.08491 | 57 | 0.05512 | 77 | 0.04080 | 97  | 0.03239 |
| 18 | 0.17453 | 38 | 0.08267 | 58 | 0.05417 | 78 | 0.04028 | 98  | 0.03206 |
| 19 | 0.16535 | 39 | 0.08055 | 59 | 0.05325 | 79 | 0.03977 | 99  | 0.03173 |
| 20 | 0.15708 | 40 | 0.07854 | 60 | 0.05236 | 80 | 0.03927 | 100 | 0.03142 |



## Powers, Roots, and Reciprocals

## Powers, Roots, and Reciprocals From 1 to 50

| No. | Square | Cube   | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|--------|----------|-----------|------------|-----|
| 1   | 1      | 1      | 1.00000  | 1.00000   | 1.0000000  | 1   |
| 2   | 4      | 8      | 1.41421  | 1.25992   | 0.5000000  | 2   |
| 3   | 9      | 27     | 1.73205  | 1.44225   | 0.3333333  | 3   |
| 4   | 16     | 64     | 2.00000  | 1.58740   | 0.2500000  | 4   |
| 5   | 25     | 125    | 2.23607  | 1.70998   | 0.2000000  | 5   |
| 6   | 36     | 216    | 2.44949  | 1.81712   | 0.1666667  | 6   |
| 7   | 49     | 343    | 2.64575  | 1.91293   | 0.1428571  | 7   |
| 8   | 64     | 512    | 2.82843  | 2.00000   | 0.1250000  | 8   |
| 9   | 81     | 729    | 3.00000  | 2.08008   | 0.1111111  | 9   |
| 10  | 100    | 1000   | 3.16228  | 2.15443   | 0.1000000  | 10  |
| 11  | 121    | 1331   | 3.31662  | 2.22398   | 0.0909091  | 11  |
| 12  | 144    | 1728   | 3.46410  | 2.28943   | 0.0833333  | 12  |
| 13  | 169    | 2197   | 3.60555  | 2.35133   | 0.0769231  | 13  |
| 14  | 196    | 2744   | 3.74166  | 2.41014   | 0.0714286  | 14  |
| 15  | 225    | 3375   | 3.87298  | 2.46621   | 0.0666667  | 15  |
| 16  | 256    | 4096   | 4.00000  | 2.51984   | 0.0625000  | 16  |
| 17  | 289    | 4913   | 4.12311  | 2.57128   | 0.0588235  | 17  |
| 18  | 324    | 5832   | 4.24264  | 2.62074   | 0.0555556  | 18  |
| 19  | 361    | 6859   | 4.35890  | 2.66840   | 0.0526316  | 19  |
| 20  | 400    | 8000   | 4.47214  | 2.71442   | 0.0500000  | 20  |
| 21  | 441    | 9261   | 4.58258  | 2.75892   | 0.0476190  | 21  |
| 22  | 484    | 10648  | 4.69042  | 2.80204   | 0.0454545  | 22  |
| 23  | 529    | 12167  | 4.79583  | 2.84387   | 0.0434783  | 23  |
| 24  | 576    | 13824  | 4.89898  | 2.88450   | 0.0416667  | 24  |
| 25  | 625    | 15625  | 5.00000  | 2.92402   | 0.0400000  | 25  |
| 26  | 676    | 17576  | 5.09902  | 2.96250   | 0.0384615  | 26  |
| 27  | 729    | 19683  | 5.19615  | 3.00000   | 0.0370370  | 27  |
| 28  | 784    | 21952  | 5.29150  | 3.03659   | 0.0357143  | 28  |
| 29  | 841    | 24389  | 5.38516  | 3.07232   | 0.0344828  | 29  |
| 30  | 900    | 27000  | 5.47723  | 3.10723   | 0.0333333  | 30  |
| 31  | 961    | 29791  | 5.56776  | 3.14138   | 0.0322581  | 31  |
| 32  | 1024   | 32768  | 5.65685  | 3.17480   | 0.0312500  | 32  |
| 33  | 1089   | 35937  | 5.74456  | 3.20753   | 0.0303030  | 33  |
| 34  | 1156   | 39304  | 5.83095  | 3.23961   | 0.0294118  | 34  |
| 35  | 1225   | 42875  | 5.91608  | 3.27107   | 0.0285714  | 35  |
| 36  | 1296   | 46656  | 6.00000  | 3.30193   | 0.0277778  | 36  |
| 37  | 1369   | 50653  | 6.08276  | 3.33222   | 0.0270270  | 37  |
| 38  | 1444   | 54872  | 6.16441  | 3.36198   | 0.0263158  | 38  |
| 39  | 1521   | 59319  | 6.24500  | 3.39121   | 0.0256410  | 39  |
| 40  | 1600   | 64000  | 6.32456  | 3.41995   | 0.0250000  | 40  |
| 41  | 1681   | 68921  | 6.40312  | 3.44822   | 0.0243902  | 41  |
| 42  | 1764   | 74088  | 6.48074  | 3.47603   | 0.0238095  | 42  |
| 43  | 1849   | 79507  | 6.55744  | 3.50340   | 0.0232558  | 43  |
| 44  | 1936   | 85184  | 6.63325  | 3.53035   | 0.0227273  | 44  |
| 45  | 2025   | 91125  | 6.70820  | 3.55689   | 0.0222222  | 45  |
| 46  | 2116   | 97336  | 6.78233  | 3.58305   | 0.0217391  | 46  |
| 47  | 2209   | 103823 | 6.85565  | 3.60883   | 0.0212766  | 47  |
| 48  | 2304   | 110592 | 6.92820  | 3.63424   | 0.0208333  | 48  |
| 49  | 2401   | 117649 | 7.00000  | 3.65931   | 0.0204082  | 49  |
| 50  | 2500   | 125000 | 7.07107  | 3.68403   | 0.0200000  | 50  |

**Powers, Roots, and Reciprocals From 51 to 100**

| No. | Square | Cube    | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|---------|----------|-----------|------------|-----|
| 51  | 2601   | 132651  | 7.14143  | 3.70843   | 0.0196078  | 51  |
| 52  | 2704   | 140608  | 7.21110  | 3.73251   | 0.0192308  | 52  |
| 53  | 2809   | 148877  | 7.28011  | 3.75629   | 0.0188679  | 53  |
| 54  | 2916   | 157464  | 7.34847  | 3.77976   | 0.0185185  | 54  |
| 55  | 3025   | 166375  | 7.41620  | 3.80295   | 0.0181818  | 55  |
| 56  | 3136   | 175616  | 7.48331  | 3.82586   | 0.0178571  | 56  |
| 57  | 3249   | 185193  | 7.54983  | 3.84850   | 0.0175439  | 57  |
| 58  | 3364   | 195112  | 7.61577  | 3.87088   | 0.0172414  | 58  |
| 59  | 3481   | 205379  | 7.68115  | 3.89300   | 0.0169492  | 59  |
| 60  | 3600   | 216000  | 7.74597  | 3.91487   | 0.0166667  | 60  |
| 61  | 3721   | 226981  | 7.81025  | 3.93650   | 0.0163934  | 61  |
| 62  | 3844   | 238328  | 7.87401  | 3.95789   | 0.0161290  | 62  |
| 63  | 3969   | 250047  | 7.93725  | 3.97906   | 0.0158730  | 63  |
| 64  | 4096   | 262144  | 8.00000  | 4.00000   | 0.0156250  | 64  |
| 65  | 4225   | 274625  | 8.06226  | 4.02073   | 0.0153846  | 65  |
| 66  | 4356   | 287496  | 8.12404  | 4.04124   | 0.0151515  | 66  |
| 67  | 4489   | 300763  | 8.18535  | 4.06155   | 0.0149254  | 67  |
| 68  | 4624   | 314432  | 8.24621  | 4.08166   | 0.0147059  | 68  |
| 69  | 4761   | 328509  | 8.30662  | 4.10157   | 0.0144928  | 69  |
| 70  | 4900   | 343000  | 8.36660  | 4.12129   | 0.0142857  | 70  |
| 71  | 5041   | 357911  | 8.42615  | 4.14082   | 0.0140845  | 71  |
| 72  | 5184   | 373248  | 8.48528  | 4.16017   | 0.0138889  | 72  |
| 73  | 5329   | 389017  | 8.54400  | 4.17934   | 0.0136986  | 73  |
| 74  | 5476   | 405224  | 8.60233  | 4.19834   | 0.0135135  | 74  |
| 75  | 5625   | 421875  | 8.66025  | 4.21716   | 0.0133333  | 75  |
| 76  | 5776   | 438976  | 8.71780  | 4.23582   | 0.0131579  | 76  |
| 77  | 5929   | 456533  | 8.77496  | 4.25432   | 0.0129870  | 77  |
| 78  | 6084   | 474552  | 8.83176  | 4.27266   | 0.0128205  | 78  |
| 79  | 6241   | 493039  | 8.88819  | 4.29084   | 0.0126582  | 79  |
| 80  | 6400   | 512000  | 8.94427  | 4.30887   | 0.0125000  | 80  |
| 81  | 6561   | 531441  | 9.00000  | 4.32675   | 0.0123457  | 81  |
| 82  | 6724   | 551368  | 9.05539  | 4.34448   | 0.0121951  | 82  |
| 83  | 6889   | 571787  | 9.11043  | 4.36207   | 0.0120482  | 83  |
| 84  | 7056   | 592704  | 9.16515  | 4.37952   | 0.0119048  | 84  |
| 85  | 7225   | 614125  | 9.21954  | 4.39683   | 0.0117647  | 85  |
| 86  | 7396   | 636056  | 9.27362  | 4.41400   | 0.0116279  | 86  |
| 87  | 7569   | 658503  | 9.32738  | 4.43105   | 0.0114943  | 87  |
| 88  | 7744   | 681472  | 9.38083  | 4.44796   | 0.0113636  | 88  |
| 89  | 7921   | 704969  | 9.43398  | 4.46475   | 0.0112360  | 89  |
| 90  | 8100   | 729000  | 9.48683  | 4.48140   | 0.0111111  | 90  |
| 91  | 8281   | 753571  | 9.53939  | 4.49794   | 0.0109890  | 91  |
| 92  | 8464   | 778688  | 9.59166  | 4.51436   | 0.0108696  | 92  |
| 93  | 8649   | 804357  | 9.64365  | 4.53065   | 0.0107527  | 93  |
| 94  | 8836   | 830584  | 9.69536  | 4.54684   | 0.0106383  | 94  |
| 95  | 9025   | 857375  | 9.74679  | 4.56290   | 0.0105263  | 95  |
| 96  | 9216   | 884736  | 9.79796  | 4.57886   | 0.0104167  | 96  |
| 97  | 9409   | 912673  | 9.84886  | 4.59470   | 0.0103093  | 97  |
| 98  | 9604   | 941192  | 9.89949  | 4.61044   | 0.0102041  | 98  |
| 99  | 9801   | 970299  | 9.94987  | 4.62607   | 0.0101010  | 99  |
| 100 | 10000  | 1000000 | 10.00000 | 4.64159   | 0.0100000  | 100 |

**Powers, Roots, and Reciprocals From 101 to 150**

| No. | Square | Cube    | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|---------|----------|-----------|------------|-----|
| 101 | 10201  | 1030301 | 10.04988 | 4.65701   | 0.0099010  | 101 |
| 102 | 10404  | 1061208 | 10.09950 | 4.67233   | 0.0098039  | 102 |
| 103 | 10609  | 1092727 | 10.14889 | 4.68755   | 0.0097087  | 103 |
| 104 | 10816  | 1124864 | 10.19804 | 4.70267   | 0.0096154  | 104 |
| 105 | 11025  | 1157625 | 10.24695 | 4.71769   | 0.0095238  | 105 |
| 106 | 11236  | 1191016 | 10.29563 | 4.73262   | 0.0094340  | 106 |
| 107 | 11449  | 1225043 | 10.34408 | 4.74746   | 0.0093458  | 107 |
| 108 | 11664  | 1259712 | 10.39230 | 4.76220   | 0.0092593  | 108 |
| 109 | 11881  | 1295029 | 10.44031 | 4.77686   | 0.0091743  | 109 |
| 110 | 12100  | 1331000 | 10.48809 | 4.79142   | 0.0090909  | 110 |
| 111 | 12321  | 1367631 | 10.53565 | 4.80590   | 0.0090090  | 111 |
| 112 | 12544  | 1404928 | 10.58301 | 4.82028   | 0.0089286  | 112 |
| 113 | 12769  | 1442897 | 10.63015 | 4.83459   | 0.0088496  | 113 |
| 114 | 12996  | 1481544 | 10.67708 | 4.84881   | 0.0087719  | 114 |
| 115 | 13225  | 1520875 | 10.72381 | 4.86294   | 0.0086957  | 115 |
| 116 | 13456  | 1560896 | 10.77033 | 4.87700   | 0.0086207  | 116 |
| 117 | 13689  | 1601613 | 10.81665 | 4.89097   | 0.0085470  | 117 |
| 118 | 13924  | 1643032 | 10.86278 | 4.90487   | 0.0084746  | 118 |
| 119 | 14161  | 1685159 | 10.90871 | 4.91868   | 0.0084034  | 119 |
| 120 | 14400  | 1728000 | 10.95445 | 4.93242   | 0.0083333  | 120 |
| 121 | 14641  | 1771561 | 11.00000 | 4.94609   | 0.0082645  | 121 |
| 122 | 14884  | 1815848 | 11.04536 | 4.95968   | 0.0081967  | 122 |
| 123 | 15129  | 1860867 | 11.09054 | 4.97319   | 0.0081301  | 123 |
| 124 | 15376  | 1906624 | 11.13553 | 4.98663   | 0.0080645  | 124 |
| 125 | 15625  | 1953125 | 11.18034 | 5.00000   | 0.0080000  | 125 |
| 126 | 15876  | 2000376 | 11.22497 | 5.01330   | 0.0079365  | 126 |
| 127 | 16129  | 2048383 | 11.26943 | 5.02653   | 0.0078740  | 127 |
| 128 | 16384  | 2097152 | 11.31371 | 5.03968   | 0.0078125  | 128 |
| 129 | 16641  | 2146689 | 11.35782 | 5.05277   | 0.0077519  | 129 |
| 130 | 16900  | 2197000 | 11.40175 | 5.06580   | 0.0076923  | 130 |
| 131 | 17161  | 2248091 | 11.44552 | 5.07875   | 0.0076336  | 131 |
| 132 | 17424  | 2299968 | 11.48913 | 5.09164   | 0.0075758  | 132 |
| 133 | 17689  | 2352637 | 11.53256 | 5.10447   | 0.0075188  | 133 |
| 134 | 17956  | 2406104 | 11.57584 | 5.11723   | 0.0074627  | 134 |
| 135 | 18225  | 2460375 | 11.61895 | 5.12993   | 0.0074074  | 135 |
| 136 | 18496  | 2515456 | 11.66190 | 5.14256   | 0.0073529  | 136 |
| 137 | 18769  | 2571353 | 11.70470 | 5.15514   | 0.0072993  | 137 |
| 138 | 19044  | 2628072 | 11.74734 | 5.16765   | 0.0072464  | 138 |
| 139 | 19321  | 2685619 | 11.78983 | 5.18010   | 0.0071942  | 139 |
| 140 | 19600  | 2744000 | 11.83216 | 5.19249   | 0.0071429  | 140 |
| 141 | 19881  | 2803221 | 11.87434 | 5.20483   | 0.0070922  | 141 |
| 142 | 20164  | 2863288 | 11.91638 | 5.21710   | 0.0070423  | 142 |
| 143 | 20449  | 2924207 | 11.95826 | 5.22932   | 0.0069930  | 143 |
| 144 | 20736  | 2985984 | 12.00000 | 5.24148   | 0.0069444  | 144 |
| 145 | 21025  | 3048625 | 12.04159 | 5.25359   | 0.0068966  | 145 |
| 146 | 21316  | 3112136 | 12.08305 | 5.26564   | 0.0068493  | 146 |
| 147 | 21609  | 3176523 | 12.12436 | 5.27763   | 0.0068027  | 147 |
| 148 | 21904  | 3241792 | 12.16553 | 5.28957   | 0.0067568  | 148 |
| 149 | 22201  | 3307949 | 12.20656 | 5.30146   | 0.0067114  | 149 |
| 150 | 22500  | 3375000 | 12.24745 | 5.31329   | 0.0066667  | 150 |

**Powers, Roots, and Reciprocals From 151 to 200**

| No. | Square | Cube    | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|---------|----------|-----------|------------|-----|
| 151 | 22801  | 3442951 | 12.28821 | 5.32507   | 0.0066225  | 151 |
| 152 | 23104  | 3511808 | 12.32883 | 5.33680   | 0.0065789  | 152 |
| 153 | 23409  | 3581577 | 12.36932 | 5.34848   | 0.0065359  | 153 |
| 154 | 23716  | 3652264 | 12.40967 | 5.36011   | 0.0064935  | 154 |
| 155 | 24025  | 3723875 | 12.44990 | 5.37169   | 0.0064516  | 155 |
| 156 | 24336  | 3796416 | 12.49000 | 5.38321   | 0.0064103  | 156 |
| 157 | 24649  | 3869893 | 12.52996 | 5.39469   | 0.0063694  | 157 |
| 158 | 24964  | 3944312 | 12.56981 | 5.40612   | 0.0063291  | 158 |
| 159 | 25281  | 4019679 | 12.60952 | 5.41750   | 0.0062893  | 159 |
| 160 | 25600  | 4096000 | 12.64911 | 5.42884   | 0.0062500  | 160 |
| 161 | 25921  | 4173281 | 12.68858 | 5.44012   | 0.0062112  | 161 |
| 162 | 26244  | 4251528 | 12.72792 | 5.45136   | 0.0061728  | 162 |
| 163 | 26569  | 4330747 | 12.76715 | 5.46256   | 0.0061350  | 163 |
| 164 | 26896  | 4410944 | 12.80625 | 5.47370   | 0.0060976  | 164 |
| 165 | 27225  | 4492125 | 12.84523 | 5.48481   | 0.0060606  | 165 |
| 166 | 27556  | 4574296 | 12.88410 | 5.49586   | 0.0060241  | 166 |
| 167 | 27889  | 4657463 | 12.92285 | 5.50688   | 0.0059880  | 167 |
| 168 | 28224  | 4741632 | 12.96148 | 5.51785   | 0.0059524  | 168 |
| 169 | 28561  | 4826809 | 13.00000 | 5.52877   | 0.0059172  | 169 |
| 170 | 28900  | 4913000 | 13.03840 | 5.53966   | 0.0058824  | 170 |
| 171 | 29241  | 5000211 | 13.07670 | 5.55050   | 0.0058480  | 171 |
| 172 | 29584  | 5088448 | 13.11488 | 5.56130   | 0.0058140  | 172 |
| 173 | 29929  | 5177717 | 13.15295 | 5.57205   | 0.0057803  | 173 |
| 174 | 30276  | 5268024 | 13.19091 | 5.58277   | 0.0057471  | 174 |
| 175 | 30625  | 5359375 | 13.22876 | 5.59344   | 0.0057143  | 175 |
| 176 | 30976  | 5451776 | 13.26650 | 5.60408   | 0.0056818  | 176 |
| 177 | 31329  | 5545233 | 13.30413 | 5.61467   | 0.0056497  | 177 |
| 178 | 31684  | 5639752 | 13.34166 | 5.62523   | 0.0056180  | 178 |
| 179 | 32041  | 5735339 | 13.37909 | 5.63574   | 0.0055866  | 179 |
| 180 | 32400  | 5832000 | 13.41641 | 5.64622   | 0.0055556  | 180 |
| 181 | 32761  | 5929741 | 13.45362 | 5.65665   | 0.0055249  | 181 |
| 182 | 33124  | 6028568 | 13.49074 | 5.66705   | 0.0054945  | 182 |
| 183 | 33489  | 6128487 | 13.52775 | 5.67741   | 0.0054645  | 183 |
| 184 | 33856  | 6229504 | 13.56466 | 5.68773   | 0.0054348  | 184 |
| 185 | 34225  | 6331625 | 13.60147 | 5.69802   | 0.0054054  | 185 |
| 186 | 34596  | 6434856 | 13.63818 | 5.70827   | 0.0053763  | 186 |
| 187 | 34969  | 6539203 | 13.67479 | 5.71848   | 0.0053476  | 187 |
| 188 | 35344  | 6644672 | 13.71131 | 5.72865   | 0.0053191  | 188 |
| 189 | 35721  | 6751269 | 13.74773 | 5.73879   | 0.0052910  | 189 |
| 190 | 36100  | 6859000 | 13.78405 | 5.74890   | 0.0052632  | 190 |
| 191 | 36481  | 6967871 | 13.82027 | 5.75897   | 0.0052356  | 191 |
| 192 | 36864  | 7077888 | 13.85641 | 5.76900   | 0.0052083  | 192 |
| 193 | 37249  | 7189057 | 13.89244 | 5.77900   | 0.0051813  | 193 |
| 194 | 37636  | 7301384 | 13.92839 | 5.78896   | 0.0051546  | 194 |
| 195 | 38025  | 7414875 | 13.96424 | 5.79889   | 0.0051282  | 195 |
| 196 | 38416  | 7529536 | 14.00000 | 5.80879   | 0.0051020  | 196 |
| 197 | 38809  | 7645373 | 14.03567 | 5.81865   | 0.0050761  | 197 |
| 198 | 39204  | 7762392 | 14.07125 | 5.82848   | 0.0050505  | 198 |
| 199 | 39601  | 7880599 | 14.10674 | 5.83827   | 0.0050251  | 199 |
| 200 | 40000  | 8000000 | 14.14214 | 5.84804   | 0.0050000  | 200 |

## Powers, Roots, and Reciprocals From 201 to 250

| No. | Square | Cube     | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|----------|----------|-----------|------------|-----|
| 201 | 40401  | 8120601  | 14.17745 | 5.85777   | 0.0049751  | 201 |
| 202 | 40804  | 8242408  | 14.21267 | 5.86746   | 0.0049505  | 202 |
| 203 | 41209  | 8365427  | 14.24781 | 5.87713   | 0.0049261  | 203 |
| 204 | 41616  | 8489664  | 14.28286 | 5.88677   | 0.0049020  | 204 |
| 205 | 42025  | 8615125  | 14.31782 | 5.89637   | 0.0048780  | 205 |
| 206 | 42436  | 8741816  | 14.35270 | 5.90594   | 0.0048544  | 206 |
| 207 | 42849  | 8869743  | 14.38749 | 5.91548   | 0.0048309  | 207 |
| 208 | 43264  | 8998912  | 14.42221 | 5.92499   | 0.0048077  | 208 |
| 209 | 43681  | 9129329  | 14.45683 | 5.93447   | 0.0047847  | 209 |
| 210 | 44100  | 9261000  | 14.49138 | 5.94392   | 0.0047619  | 210 |
| 211 | 44521  | 9393931  | 14.52584 | 5.95334   | 0.0047393  | 211 |
| 212 | 44944  | 9528128  | 14.56022 | 5.96273   | 0.0047170  | 212 |
| 213 | 45369  | 9663597  | 14.59452 | 5.97209   | 0.0046948  | 213 |
| 214 | 45796  | 9800344  | 14.62874 | 5.98142   | 0.0046729  | 214 |
| 215 | 46225  | 9938375  | 14.66288 | 5.99073   | 0.0046512  | 215 |
| 216 | 46656  | 10077696 | 14.69694 | 6.00000   | 0.0046296  | 216 |
| 217 | 47089  | 10218313 | 14.73092 | 6.00925   | 0.0046083  | 217 |
| 218 | 47524  | 10360232 | 14.76482 | 6.01846   | 0.0045872  | 218 |
| 219 | 47961  | 10503459 | 14.79865 | 6.02765   | 0.0045662  | 219 |
| 220 | 48400  | 10648000 | 14.83240 | 6.03681   | 0.0045455  | 220 |
| 221 | 48841  | 10793861 | 14.86607 | 6.04594   | 0.0045249  | 221 |
| 222 | 49284  | 10941048 | 14.89966 | 6.05505   | 0.0045045  | 222 |
| 223 | 49729  | 11089567 | 14.93318 | 6.06413   | 0.0044843  | 223 |
| 224 | 50176  | 11239424 | 14.96663 | 6.07318   | 0.0044643  | 224 |
| 225 | 50625  | 11390625 | 15.00000 | 6.08220   | 0.0044444  | 225 |
| 226 | 51076  | 11543176 | 15.03330 | 6.09120   | 0.0044248  | 226 |
| 227 | 51529  | 11697083 | 15.06652 | 6.10017   | 0.0044053  | 227 |
| 228 | 51984  | 11852352 | 15.09967 | 6.10911   | 0.0043860  | 228 |
| 229 | 52441  | 12008989 | 15.13275 | 6.11803   | 0.0043668  | 229 |
| 230 | 52900  | 12167000 | 15.16575 | 6.12693   | 0.0043478  | 230 |
| 231 | 53361  | 12326391 | 15.19868 | 6.13579   | 0.0043290  | 231 |
| 232 | 53824  | 12487168 | 15.23155 | 6.14463   | 0.0043103  | 232 |
| 233 | 54289  | 12649337 | 15.26434 | 6.15345   | 0.0042918  | 233 |
| 234 | 54756  | 12812904 | 15.29706 | 6.16224   | 0.0042735  | 234 |
| 235 | 55225  | 12977875 | 15.32971 | 6.17101   | 0.0042553  | 235 |
| 236 | 55696  | 13144256 | 15.36229 | 6.17975   | 0.0042373  | 236 |
| 237 | 56169  | 13312053 | 15.39480 | 6.18846   | 0.0042194  | 237 |
| 238 | 56644  | 13481272 | 15.42725 | 6.19715   | 0.0042017  | 238 |
| 239 | 57121  | 13651919 | 15.45962 | 6.20582   | 0.0041841  | 239 |
| 240 | 57600  | 13824000 | 15.49193 | 6.21447   | 0.0041667  | 240 |
| 241 | 58081  | 13997521 | 15.52417 | 6.22308   | 0.0041494  | 241 |
| 242 | 58564  | 14172488 | 15.55635 | 6.23168   | 0.0041322  | 242 |
| 243 | 59049  | 14348907 | 15.58846 | 6.24025   | 0.0041152  | 243 |
| 244 | 59536  | 14526784 | 15.62050 | 6.24880   | 0.0040984  | 244 |
| 245 | 60025  | 14706125 | 15.65248 | 6.25732   | 0.0040816  | 245 |
| 246 | 60516  | 14886936 | 15.68439 | 6.26583   | 0.0040650  | 246 |
| 247 | 61009  | 15069223 | 15.71623 | 6.27431   | 0.0040486  | 247 |
| 248 | 61504  | 15252992 | 15.74802 | 6.28276   | 0.0040323  | 248 |
| 249 | 62001  | 15438249 | 15.77973 | 6.29119   | 0.0040161  | 249 |
| 250 | 62500  | 15625000 | 15.81139 | 6.29961   | 0.0040000  | 250 |

**Powers, Roots, and Reciprocals From 251 to 300**

| No. | Square | Cube     | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|----------|----------|-----------|------------|-----|
| 251 | 63001  | 15813251 | 15.84298 | 6.30799   | 0.0039841  | 251 |
| 252 | 63504  | 16003008 | 15.87451 | 6.31636   | 0.0039683  | 252 |
| 253 | 64009  | 16194277 | 15.90597 | 6.32470   | 0.0039526  | 253 |
| 254 | 64516  | 16387064 | 15.93738 | 6.33303   | 0.0039370  | 254 |
| 255 | 65025  | 16581375 | 15.96872 | 6.34133   | 0.0039216  | 255 |
| 256 | 65536  | 16777216 | 16.00000 | 6.34960   | 0.0039063  | 256 |
| 257 | 66049  | 16974593 | 16.03122 | 6.35786   | 0.0038911  | 257 |
| 258 | 66564  | 17173512 | 16.06238 | 6.36610   | 0.0038760  | 258 |
| 259 | 67081  | 17373979 | 16.09348 | 6.37431   | 0.0038610  | 259 |
| 260 | 67600  | 17576000 | 16.12452 | 6.38250   | 0.0038462  | 260 |
| 261 | 68121  | 17779581 | 16.15549 | 6.39068   | 0.0038314  | 261 |
| 262 | 68644  | 17984728 | 16.18641 | 6.39883   | 0.0038168  | 262 |
| 263 | 69169  | 18191447 | 16.21727 | 6.40696   | 0.0038023  | 263 |
| 264 | 69696  | 18399744 | 16.24808 | 6.41507   | 0.0037879  | 264 |
| 265 | 70225  | 18609625 | 16.27882 | 6.42316   | 0.0037736  | 265 |
| 266 | 70756  | 18821096 | 16.30951 | 6.43123   | 0.0037594  | 266 |
| 267 | 71289  | 19034163 | 16.34013 | 6.43928   | 0.0037453  | 267 |
| 268 | 71824  | 19248832 | 16.37071 | 6.44731   | 0.0037313  | 268 |
| 269 | 72361  | 19465109 | 16.40122 | 6.45531   | 0.0037175  | 269 |
| 270 | 72900  | 19683000 | 16.43168 | 6.46330   | 0.0037037  | 270 |
| 271 | 73441  | 19902511 | 16.46208 | 6.47127   | 0.0036900  | 271 |
| 272 | 73984  | 20123648 | 16.49242 | 6.47922   | 0.0036765  | 272 |
| 273 | 74529  | 20346417 | 16.52271 | 6.48715   | 0.0036630  | 273 |
| 274 | 75076  | 20570824 | 16.55295 | 6.49507   | 0.0036496  | 274 |
| 275 | 75625  | 20796875 | 16.58312 | 6.50296   | 0.0036364  | 275 |
| 276 | 76176  | 21024576 | 16.61325 | 6.51083   | 0.0036232  | 276 |
| 277 | 76729  | 21253933 | 16.64332 | 6.51868   | 0.0036101  | 277 |
| 278 | 77284  | 21484952 | 16.67333 | 6.52652   | 0.0035971  | 278 |
| 279 | 77841  | 21717639 | 16.70329 | 6.53434   | 0.0035842  | 279 |
| 280 | 78400  | 21952000 | 16.73320 | 6.54213   | 0.0035714  | 280 |
| 281 | 78961  | 22188041 | 16.76305 | 6.54991   | 0.0035587  | 281 |
| 282 | 79524  | 22425768 | 16.79286 | 6.55767   | 0.0035461  | 282 |
| 283 | 80089  | 22665187 | 16.82260 | 6.56541   | 0.0035336  | 283 |
| 284 | 80656  | 22906304 | 16.85230 | 6.57314   | 0.0035211  | 284 |
| 285 | 81225  | 23149125 | 16.88194 | 6.58084   | 0.0035088  | 285 |
| 286 | 81796  | 23393656 | 16.91153 | 6.58853   | 0.0034965  | 286 |
| 287 | 82369  | 23639903 | 16.94107 | 6.59620   | 0.0034843  | 287 |
| 288 | 82944  | 23887872 | 16.97056 | 6.60385   | 0.0034722  | 288 |
| 289 | 83521  | 24137569 | 17.00000 | 6.61149   | 0.0034602  | 289 |
| 290 | 84100  | 24389000 | 17.02939 | 6.61911   | 0.0034483  | 290 |
| 291 | 84681  | 24642171 | 17.05872 | 6.62671   | 0.0034364  | 291 |
| 292 | 85264  | 24897088 | 17.08801 | 6.63429   | 0.0034247  | 292 |
| 293 | 85849  | 25153757 | 17.11724 | 6.64185   | 0.0034130  | 293 |
| 294 | 86436  | 25412184 | 17.14643 | 6.64940   | 0.0034014  | 294 |
| 295 | 87025  | 25672375 | 17.17556 | 6.65693   | 0.0033898  | 295 |
| 296 | 87616  | 25934336 | 17.20465 | 6.66444   | 0.0033784  | 296 |
| 297 | 88209  | 26198073 | 17.23369 | 6.67194   | 0.0033670  | 297 |
| 298 | 88804  | 26463592 | 17.26268 | 6.67942   | 0.0033557  | 298 |
| 299 | 89401  | 26730899 | 17.29162 | 6.68688   | 0.0033445  | 299 |
| 300 | 90000  | 27000000 | 17.32051 | 6.69433   | 0.0033333  | 300 |

## Powers, Roots, and Reciprocals From 301 to 350

| No. | Square | Cube     | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|----------|----------|-----------|------------|-----|
| 301 | 90601  | 27270901 | 17.34935 | 6.70176   | 0.0033223  | 301 |
| 302 | 91204  | 27543608 | 17.37815 | 6.70917   | 0.0033113  | 302 |
| 303 | 91809  | 27818127 | 17.40690 | 6.71657   | 0.0033003  | 303 |
| 304 | 92416  | 28094464 | 17.43560 | 6.72395   | 0.0032895  | 304 |
| 305 | 93025  | 28372625 | 17.46425 | 6.73132   | 0.0032787  | 305 |
| 306 | 93636  | 28652616 | 17.49286 | 6.73866   | 0.0032680  | 306 |
| 307 | 94249  | 28934443 | 17.52142 | 6.74600   | 0.0032573  | 307 |
| 308 | 94864  | 29218112 | 17.54993 | 6.75331   | 0.0032468  | 308 |
| 309 | 95481  | 29503629 | 17.57840 | 6.76061   | 0.0032362  | 309 |
| 310 | 96100  | 29791000 | 17.60682 | 6.76790   | 0.0032258  | 310 |
| 311 | 96721  | 30080231 | 17.63519 | 6.77517   | 0.0032154  | 311 |
| 312 | 97344  | 30371328 | 17.66352 | 6.78242   | 0.0032051  | 312 |
| 313 | 97969  | 30664297 | 17.69181 | 6.78966   | 0.0031949  | 313 |
| 314 | 98596  | 30959144 | 17.72005 | 6.79688   | 0.0031847  | 314 |
| 315 | 99225  | 31255875 | 17.74824 | 6.80409   | 0.0031746  | 315 |
| 316 | 99856  | 31554496 | 17.77639 | 6.81128   | 0.0031646  | 316 |
| 317 | 100489 | 31855013 | 17.80449 | 6.81846   | 0.0031546  | 317 |
| 318 | 101124 | 32157432 | 17.83255 | 6.82562   | 0.0031447  | 318 |
| 319 | 101761 | 32461759 | 17.86057 | 6.83277   | 0.0031348  | 319 |
| 320 | 102400 | 32768000 | 17.88854 | 6.83990   | 0.0031250  | 320 |
| 321 | 103041 | 33076161 | 17.91647 | 6.84702   | 0.0031153  | 321 |
| 322 | 103684 | 33386248 | 17.94436 | 6.85412   | 0.0031056  | 322 |
| 323 | 104329 | 33698267 | 17.97220 | 6.86121   | 0.0030960  | 323 |
| 324 | 104976 | 34012224 | 18.00000 | 6.86829   | 0.0030864  | 324 |
| 325 | 105625 | 34328125 | 18.02776 | 6.87534   | 0.0030769  | 325 |
| 326 | 106276 | 34645976 | 18.05547 | 6.88239   | 0.0030675  | 326 |
| 327 | 106929 | 34965783 | 18.08314 | 6.88942   | 0.0030581  | 327 |
| 328 | 107584 | 35287552 | 18.11077 | 6.89643   | 0.0030488  | 328 |
| 329 | 108241 | 35611289 | 18.13836 | 6.90344   | 0.0030395  | 329 |
| 330 | 108900 | 35937000 | 18.16590 | 6.91042   | 0.0030303  | 330 |
| 331 | 109561 | 36264691 | 18.19341 | 6.91740   | 0.0030211  | 331 |
| 332 | 110224 | 36594368 | 18.22087 | 6.92436   | 0.0030120  | 332 |
| 333 | 110889 | 36926037 | 18.24829 | 6.93130   | 0.0030030  | 333 |
| 334 | 111556 | 37259704 | 18.27567 | 6.93823   | 0.0029940  | 334 |
| 335 | 112225 | 37595375 | 18.30301 | 6.94515   | 0.0029851  | 335 |
| 336 | 112896 | 37933056 | 18.33030 | 6.95205   | 0.0029762  | 336 |
| 337 | 113569 | 38272753 | 18.35756 | 6.95894   | 0.0029674  | 337 |
| 338 | 114244 | 38614472 | 18.38478 | 6.96582   | 0.0029586  | 338 |
| 339 | 114921 | 38958219 | 18.41195 | 6.97268   | 0.0029499  | 339 |
| 340 | 115600 | 39304000 | 18.43909 | 6.97953   | 0.0029412  | 340 |
| 341 | 116281 | 39651821 | 18.46619 | 6.98637   | 0.0029326  | 341 |
| 342 | 116964 | 40001688 | 18.49324 | 6.99319   | 0.0029240  | 342 |
| 343 | 117649 | 40353607 | 18.52026 | 7.00000   | 0.0029155  | 343 |
| 344 | 118336 | 40707584 | 18.54724 | 7.00680   | 0.0029070  | 344 |
| 345 | 119025 | 41063625 | 18.57418 | 7.01358   | 0.0028986  | 345 |
| 346 | 119716 | 41421736 | 18.60108 | 7.02035   | 0.0028902  | 346 |
| 347 | 120409 | 41781923 | 18.62794 | 7.02711   | 0.0028818  | 347 |
| 348 | 121104 | 42144192 | 18.65476 | 7.03385   | 0.0028736  | 348 |
| 349 | 121801 | 42508549 | 18.68154 | 7.04058   | 0.0028653  | 349 |
| 350 | 122500 | 42875000 | 18.70829 | 7.04730   | 0.0028571  | 350 |

**Powers, Roots, and Reciprocals From 351 to 400**

| No. | Square | Cube     | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|----------|----------|-----------|------------|-----|
| 351 | 123201 | 43243551 | 18.73499 | 7.05400   | 0.0028490  | 351 |
| 352 | 123904 | 43614208 | 18.76166 | 7.06070   | 0.0028409  | 352 |
| 353 | 124609 | 43986977 | 18.78829 | 7.06738   | 0.0028329  | 353 |
| 354 | 125316 | 44361864 | 18.81489 | 7.07404   | 0.0028249  | 354 |
| 355 | 126025 | 44738875 | 18.84144 | 7.08070   | 0.0028169  | 355 |
| 356 | 126736 | 45118016 | 18.86796 | 7.08734   | 0.0028090  | 356 |
| 357 | 127449 | 45499293 | 18.89444 | 7.09397   | 0.0028011  | 357 |
| 358 | 128164 | 45882712 | 18.92089 | 7.10059   | 0.0027933  | 358 |
| 359 | 128881 | 46268279 | 18.94730 | 7.10719   | 0.0027855  | 359 |
| 360 | 129600 | 46656000 | 18.97367 | 7.11379   | 0.0027778  | 360 |
| 361 | 130321 | 47045881 | 19.00000 | 7.12037   | 0.0027701  | 361 |
| 362 | 131044 | 47437928 | 19.02630 | 7.12694   | 0.0027624  | 362 |
| 363 | 131769 | 47832147 | 19.05256 | 7.13349   | 0.0027548  | 363 |
| 364 | 132496 | 48228544 | 19.07878 | 7.14004   | 0.0027473  | 364 |
| 365 | 133225 | 48627125 | 19.10497 | 7.14657   | 0.0027397  | 365 |
| 366 | 133956 | 49027896 | 19.13113 | 7.15309   | 0.0027322  | 366 |
| 367 | 134689 | 49430863 | 19.15724 | 7.15960   | 0.0027248  | 367 |
| 368 | 135424 | 49836032 | 19.18333 | 7.16610   | 0.0027174  | 368 |
| 369 | 136161 | 50243409 | 19.20937 | 7.17258   | 0.0027100  | 369 |
| 370 | 136900 | 50653000 | 19.23538 | 7.17905   | 0.0027027  | 370 |
| 371 | 137641 | 51064811 | 19.26136 | 7.18552   | 0.0026954  | 371 |
| 372 | 138384 | 51478848 | 19.28730 | 7.19197   | 0.0026882  | 372 |
| 373 | 139129 | 51895117 | 19.31321 | 7.19840   | 0.0026810  | 373 |
| 374 | 139876 | 52313624 | 19.33908 | 7.20483   | 0.0026738  | 374 |
| 375 | 140625 | 52734375 | 19.36492 | 7.21125   | 0.0026667  | 375 |
| 376 | 141376 | 53157376 | 19.39072 | 7.21765   | 0.0026596  | 376 |
| 377 | 142129 | 53582633 | 19.41649 | 7.22405   | 0.0026525  | 377 |
| 378 | 142884 | 54010152 | 19.44222 | 7.23043   | 0.0026455  | 378 |
| 379 | 143641 | 54439939 | 19.46792 | 7.23680   | 0.0026385  | 379 |
| 380 | 144400 | 54872000 | 19.49359 | 7.24316   | 0.0026316  | 380 |
| 381 | 145161 | 55306341 | 19.51922 | 7.24950   | 0.0026247  | 381 |
| 382 | 145924 | 55742968 | 19.54482 | 7.25584   | 0.0026178  | 382 |
| 383 | 146689 | 56181887 | 19.57039 | 7.26217   | 0.0026110  | 383 |
| 384 | 147456 | 56623104 | 19.59592 | 7.26848   | 0.0026042  | 384 |
| 385 | 148225 | 57066625 | 19.62142 | 7.27479   | 0.0025974  | 385 |
| 386 | 148996 | 57512456 | 19.64688 | 7.28108   | 0.0025907  | 386 |
| 387 | 149769 | 57960603 | 19.67232 | 7.28736   | 0.0025840  | 387 |
| 388 | 150544 | 58411072 | 19.69772 | 7.29363   | 0.0025773  | 388 |
| 389 | 151321 | 58863869 | 19.72308 | 7.29989   | 0.0025707  | 389 |
| 390 | 152100 | 59319000 | 19.74842 | 7.30614   | 0.0025641  | 390 |
| 391 | 152881 | 59776471 | 19.77372 | 7.31238   | 0.0025575  | 391 |
| 392 | 153664 | 60236288 | 19.79899 | 7.31861   | 0.0025510  | 392 |
| 393 | 154449 | 60698457 | 19.82423 | 7.32483   | 0.0025445  | 393 |
| 394 | 155236 | 61162984 | 19.84943 | 7.33104   | 0.0025381  | 394 |
| 395 | 156025 | 61629875 | 19.87461 | 7.33723   | 0.0025316  | 395 |
| 396 | 156816 | 62099136 | 19.89975 | 7.34342   | 0.0025253  | 396 |
| 397 | 157609 | 62570773 | 19.92486 | 7.34960   | 0.0025189  | 397 |
| 398 | 158404 | 63044792 | 19.94994 | 7.35576   | 0.0025126  | 398 |
| 399 | 159201 | 63521199 | 19.97498 | 7.36192   | 0.0025063  | 399 |
| 400 | 160000 | 64000000 | 20.00000 | 7.36806   | 0.0025000  | 400 |



## Powers, Roots, and Reciprocals From 401 to 450

| No. | Square | Cube     | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|----------|----------|-----------|------------|-----|
| 401 | 160801 | 64481201 | 20.02498 | 7.37420   | 0.0024938  | 401 |
| 402 | 161604 | 64964808 | 20.04994 | 7.38032   | 0.0024876  | 402 |
| 403 | 162409 | 65450827 | 20.07486 | 7.38644   | 0.0024814  | 403 |
| 404 | 163216 | 65939264 | 20.09975 | 7.39254   | 0.0024752  | 404 |
| 405 | 164025 | 66430125 | 20.12461 | 7.39864   | 0.0024691  | 405 |
| 406 | 164836 | 66923416 | 20.14944 | 7.40472   | 0.0024631  | 406 |
| 407 | 165649 | 67419143 | 20.17424 | 7.41080   | 0.0024570  | 407 |
| 408 | 166464 | 67917312 | 20.19901 | 7.41686   | 0.0024510  | 408 |
| 409 | 167281 | 68417929 | 20.22375 | 7.42291   | 0.0024450  | 409 |
| 410 | 168100 | 68921000 | 20.24846 | 7.42896   | 0.0024390  | 410 |
| 411 | 168921 | 69426531 | 20.27313 | 7.43499   | 0.0024331  | 411 |
| 412 | 169744 | 69934528 | 20.29778 | 7.44102   | 0.0024272  | 412 |
| 413 | 170569 | 70444997 | 20.32240 | 7.44703   | 0.0024213  | 413 |
| 414 | 171396 | 70957944 | 20.34699 | 7.45304   | 0.0024155  | 414 |
| 415 | 172225 | 71473375 | 20.37155 | 7.45904   | 0.0024096  | 415 |
| 416 | 173056 | 71991296 | 20.39608 | 7.46502   | 0.0024038  | 416 |
| 417 | 173889 | 72511713 | 20.42058 | 7.47100   | 0.0023981  | 417 |
| 418 | 174724 | 73034632 | 20.44505 | 7.47697   | 0.0023923  | 418 |
| 419 | 175561 | 73560059 | 20.46949 | 7.48292   | 0.0023866  | 419 |
| 420 | 176400 | 74088000 | 20.49390 | 7.48887   | 0.0023810  | 420 |
| 421 | 177241 | 74618461 | 20.51828 | 7.49481   | 0.0023753  | 421 |
| 422 | 178084 | 75151448 | 20.54264 | 7.50074   | 0.0023697  | 422 |
| 423 | 178929 | 75686967 | 20.56696 | 7.50666   | 0.0023641  | 423 |
| 424 | 179776 | 76225024 | 20.59126 | 7.51257   | 0.0023585  | 424 |
| 425 | 180625 | 76765625 | 20.61553 | 7.51847   | 0.0023529  | 425 |
| 426 | 181476 | 77308776 | 20.63977 | 7.52437   | 0.0023474  | 426 |
| 427 | 182329 | 77854483 | 20.66398 | 7.53025   | 0.0023419  | 427 |
| 428 | 183184 | 78402752 | 20.68816 | 7.53612   | 0.0023364  | 428 |
| 429 | 184041 | 78953589 | 20.71232 | 7.54199   | 0.0023310  | 429 |
| 430 | 184900 | 79507000 | 20.73644 | 7.54784   | 0.0023256  | 430 |
| 431 | 185761 | 80062991 | 20.76054 | 7.55369   | 0.0023202  | 431 |
| 432 | 186624 | 80621568 | 20.78461 | 7.55953   | 0.0023148  | 432 |
| 433 | 187489 | 81182737 | 20.80865 | 7.56535   | 0.0023095  | 433 |
| 434 | 188356 | 81746504 | 20.83267 | 7.57117   | 0.0023041  | 434 |
| 435 | 189225 | 82312875 | 20.85665 | 7.57698   | 0.0022989  | 435 |
| 436 | 190096 | 82881856 | 20.88061 | 7.58279   | 0.0022936  | 436 |
| 437 | 190969 | 83453453 | 20.90454 | 7.58858   | 0.0022883  | 437 |
| 438 | 191844 | 84027672 | 20.92845 | 7.59436   | 0.0022831  | 438 |
| 439 | 192721 | 84604519 | 20.95233 | 7.60014   | 0.0022779  | 439 |
| 440 | 193600 | 85184000 | 20.97618 | 7.60590   | 0.0022727  | 440 |
| 441 | 194481 | 85766121 | 21.00000 | 7.61166   | 0.0022676  | 441 |
| 442 | 195364 | 86350888 | 21.02380 | 7.61741   | 0.0022624  | 442 |
| 443 | 196249 | 86938307 | 21.04757 | 7.62315   | 0.0022573  | 443 |
| 444 | 197136 | 87528384 | 21.07131 | 7.62888   | 0.0022523  | 444 |
| 445 | 198025 | 88121125 | 21.09502 | 7.63461   | 0.0022472  | 445 |
| 446 | 198916 | 88716536 | 21.11871 | 7.64032   | 0.0022422  | 446 |
| 447 | 199809 | 89314623 | 21.14237 | 7.64603   | 0.0022371  | 447 |
| 448 | 200704 | 89915392 | 21.16601 | 7.65172   | 0.0022321  | 448 |
| 449 | 201601 | 90518849 | 21.18962 | 7.65741   | 0.0022272  | 449 |
| 450 | 202500 | 91125000 | 21.21320 | 7.66309   | 0.0022222  | 450 |

**Powers, Roots, and Reciprocals From 451 to 500**

| No. | Square | Cube      | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|-----------|----------|-----------|------------|-----|
| 451 | 203401 | 91733851  | 21.23676 | 7.66877   | 0.0022173  | 451 |
| 452 | 204304 | 92345408  | 21.26029 | 7.67443   | 0.0022124  | 452 |
| 453 | 205209 | 92959677  | 21.28380 | 7.68009   | 0.0022075  | 453 |
| 454 | 206116 | 93576664  | 21.30728 | 7.68573   | 0.0022026  | 454 |
| 455 | 207025 | 94196375  | 21.33073 | 7.69137   | 0.0021978  | 455 |
| 456 | 207936 | 94818816  | 21.35416 | 7.69700   | 0.0021930  | 456 |
| 457 | 208849 | 95443993  | 21.37756 | 7.70262   | 0.0021882  | 457 |
| 458 | 209764 | 96071912  | 21.40093 | 7.70824   | 0.0021834  | 458 |
| 459 | 210681 | 96702579  | 21.42429 | 7.71384   | 0.0021786  | 459 |
| 460 | 211600 | 97336000  | 21.44761 | 7.71944   | 0.0021739  | 460 |
| 461 | 212521 | 97972181  | 21.47091 | 7.72503   | 0.0021692  | 461 |
| 462 | 213444 | 98611128  | 21.49419 | 7.73061   | 0.0021645  | 462 |
| 463 | 214369 | 99252847  | 21.51743 | 7.73619   | 0.0021598  | 463 |
| 464 | 215296 | 99897344  | 21.54066 | 7.74175   | 0.0021552  | 464 |
| 465 | 216225 | 100544625 | 21.56386 | 7.74731   | 0.0021505  | 465 |
| 466 | 217156 | 101194696 | 21.58703 | 7.75286   | 0.0021459  | 466 |
| 467 | 218089 | 101847563 | 21.61018 | 7.75840   | 0.0021413  | 467 |
| 468 | 219024 | 102503232 | 21.63331 | 7.76394   | 0.0021368  | 468 |
| 469 | 219961 | 103161709 | 21.65641 | 7.76946   | 0.0021322  | 469 |
| 470 | 220900 | 103823000 | 21.67948 | 7.77498   | 0.0021277  | 470 |
| 471 | 221841 | 104487111 | 21.70253 | 7.78049   | 0.0021231  | 471 |
| 472 | 222784 | 105154048 | 21.72556 | 7.78599   | 0.0021186  | 472 |
| 473 | 223729 | 105823817 | 21.74856 | 7.79149   | 0.0021142  | 473 |
| 474 | 224676 | 106496424 | 21.77154 | 7.79697   | 0.0021097  | 474 |
| 475 | 225625 | 107171875 | 21.79449 | 7.80245   | 0.0021053  | 475 |
| 476 | 226576 | 107850176 | 21.81742 | 7.80793   | 0.0021008  | 476 |
| 477 | 227529 | 108531333 | 21.84033 | 7.81339   | 0.0020964  | 477 |
| 478 | 228484 | 109215352 | 21.86321 | 7.81885   | 0.0020921  | 478 |
| 479 | 229441 | 109902239 | 21.88607 | 7.82429   | 0.0020877  | 479 |
| 480 | 230400 | 110592000 | 21.90890 | 7.82974   | 0.0020833  | 480 |
| 481 | 231361 | 111284641 | 21.93171 | 7.83517   | 0.0020790  | 481 |
| 482 | 232324 | 111980168 | 21.95450 | 7.84059   | 0.0020747  | 482 |
| 483 | 233289 | 112678587 | 21.97726 | 7.84601   | 0.0020704  | 483 |
| 484 | 234256 | 113379904 | 22.00000 | 7.85142   | 0.0020661  | 484 |
| 485 | 235225 | 114084125 | 22.02272 | 7.85683   | 0.0020619  | 485 |
| 486 | 236196 | 114791256 | 22.04541 | 7.86222   | 0.0020576  | 486 |
| 487 | 237169 | 115501303 | 22.06808 | 7.86761   | 0.0020534  | 487 |
| 488 | 238144 | 116214272 | 22.09072 | 7.87299   | 0.0020492  | 488 |
| 489 | 239121 | 116930169 | 22.11334 | 7.87837   | 0.0020450  | 489 |
| 490 | 240100 | 117649000 | 22.13594 | 7.88374   | 0.0020408  | 490 |
| 491 | 241081 | 118370771 | 22.15852 | 7.88909   | 0.0020367  | 491 |
| 492 | 242064 | 119095488 | 22.18107 | 7.89445   | 0.0020325  | 492 |
| 493 | 243049 | 119823157 | 22.20360 | 7.89979   | 0.0020284  | 493 |
| 494 | 244036 | 120553784 | 22.22611 | 7.90513   | 0.0020243  | 494 |
| 495 | 245025 | 121287375 | 22.24860 | 7.91046   | 0.0020202  | 495 |
| 496 | 246016 | 122023936 | 22.27106 | 7.91578   | 0.0020161  | 496 |
| 497 | 247009 | 122763473 | 22.29350 | 7.92110   | 0.0020121  | 497 |
| 498 | 248004 | 123505992 | 22.31591 | 7.92641   | 0.0020080  | 498 |
| 499 | 249001 | 124251499 | 22.33831 | 7.93171   | 0.0020040  | 499 |
| 500 | 250000 | 125000000 | 22.36068 | 7.93701   | 0.0020000  | 500 |

## Powers, Roots, and Reciprocals From 501 to 550

| No. | Square | Cube      | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|-----------|----------|-----------|------------|-----|
| 501 | 251001 | 125751501 | 22.38303 | 7.94229   | 0.0019960  | 501 |
| 502 | 252004 | 126506008 | 22.40536 | 7.94757   | 0.0019920  | 502 |
| 503 | 253009 | 127263527 | 22.42766 | 7.95285   | 0.0019881  | 503 |
| 504 | 254016 | 128024064 | 22.44994 | 7.95811   | 0.0019841  | 504 |
| 505 | 255025 | 128787625 | 22.47221 | 7.96337   | 0.0019802  | 505 |
| 506 | 256036 | 129554216 | 22.49444 | 7.96863   | 0.0019763  | 506 |
| 507 | 257049 | 130323843 | 22.51666 | 7.97387   | 0.0019724  | 507 |
| 508 | 258064 | 131096512 | 22.53886 | 7.97911   | 0.0019685  | 508 |
| 509 | 259081 | 131872229 | 22.56103 | 7.98434   | 0.0019646  | 509 |
| 510 | 260100 | 132651000 | 22.58318 | 7.98957   | 0.0019608  | 510 |
| 511 | 261121 | 133432831 | 22.60531 | 7.99479   | 0.0019569  | 511 |
| 512 | 262144 | 134217728 | 22.62742 | 8.00000   | 0.0019531  | 512 |
| 513 | 263169 | 135005697 | 22.64950 | 8.00520   | 0.0019493  | 513 |
| 514 | 264196 | 135796744 | 22.67157 | 8.01040   | 0.0019455  | 514 |
| 515 | 265225 | 136590875 | 22.69361 | 8.01559   | 0.0019417  | 515 |
| 516 | 266256 | 137388096 | 22.71563 | 8.02078   | 0.0019380  | 516 |
| 517 | 267289 | 138188413 | 22.73763 | 8.02596   | 0.0019342  | 517 |
| 518 | 268324 | 138991832 | 22.75961 | 8.03113   | 0.0019305  | 518 |
| 519 | 269361 | 139798359 | 22.78157 | 8.03629   | 0.0019268  | 519 |
| 520 | 270400 | 140608000 | 22.80351 | 8.04145   | 0.0019231  | 520 |
| 521 | 271441 | 141420761 | 22.82542 | 8.04660   | 0.0019194  | 521 |
| 522 | 272484 | 142236648 | 22.84732 | 8.05175   | 0.0019157  | 522 |
| 523 | 273529 | 143055667 | 22.86919 | 8.05689   | 0.0019120  | 523 |
| 524 | 274576 | 143877824 | 22.89105 | 8.06202   | 0.0019084  | 524 |
| 525 | 275625 | 144703125 | 22.91288 | 8.06714   | 0.0019048  | 525 |
| 526 | 276676 | 145531576 | 22.93469 | 8.07226   | 0.0019011  | 526 |
| 527 | 277729 | 146363183 | 22.95648 | 8.07737   | 0.0018975  | 527 |
| 528 | 278784 | 147197952 | 22.97825 | 8.08248   | 0.0018939  | 528 |
| 529 | 279841 | 148035889 | 23.00000 | 8.08758   | 0.0018904  | 529 |
| 530 | 280900 | 148877000 | 23.02173 | 8.09267   | 0.0018868  | 530 |
| 531 | 281961 | 149721291 | 23.04344 | 8.09776   | 0.0018832  | 531 |
| 532 | 283024 | 150568768 | 23.06513 | 8.10284   | 0.0018797  | 532 |
| 533 | 284089 | 151419437 | 23.08679 | 8.10791   | 0.0018762  | 533 |
| 534 | 285156 | 152273304 | 23.10844 | 8.11298   | 0.0018727  | 534 |
| 535 | 286225 | 153130375 | 23.13007 | 8.11804   | 0.0018692  | 535 |
| 536 | 287296 | 153990656 | 23.15167 | 8.12310   | 0.0018657  | 536 |
| 537 | 288369 | 154854153 | 23.17326 | 8.12814   | 0.0018622  | 537 |
| 538 | 289444 | 155720872 | 23.19483 | 8.13319   | 0.0018587  | 538 |
| 539 | 290521 | 156590819 | 23.21637 | 8.13822   | 0.0018553  | 539 |
| 540 | 291600 | 157464000 | 23.23790 | 8.14325   | 0.0018519  | 540 |
| 541 | 292681 | 158340421 | 23.25941 | 8.14828   | 0.0018484  | 541 |
| 542 | 293764 | 159220088 | 23.28089 | 8.15329   | 0.0018450  | 542 |
| 543 | 294849 | 160103007 | 23.30236 | 8.15831   | 0.0018416  | 543 |
| 544 | 295936 | 160989184 | 23.32381 | 8.16331   | 0.0018382  | 544 |
| 545 | 297025 | 161878625 | 23.34524 | 8.16831   | 0.0018349  | 545 |
| 546 | 298116 | 162771336 | 23.36664 | 8.17330   | 0.0018315  | 546 |
| 547 | 299209 | 163667323 | 23.38803 | 8.17829   | 0.0018282  | 547 |
| 548 | 300304 | 164566592 | 23.40940 | 8.18327   | 0.0018248  | 548 |
| 549 | 301401 | 165469149 | 23.43075 | 8.18824   | 0.0018215  | 549 |
| 550 | 302500 | 166375000 | 23.45208 | 8.19321   | 0.0018182  | 550 |

## Powers, Roots, and Reciprocals From 551 to 600

| No. | Square | Cube      | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|-----------|----------|-----------|------------|-----|
| 551 | 303601 | 167284151 | 23.47339 | 8.19818   | 0.0018149  | 551 |
| 552 | 304704 | 168196608 | 23.49468 | 8.20313   | 0.0018116  | 552 |
| 553 | 305809 | 169112377 | 23.51595 | 8.20808   | 0.0018083  | 553 |
| 554 | 306916 | 170031464 | 23.53720 | 8.21303   | 0.0018051  | 554 |
| 555 | 308025 | 170953875 | 23.55844 | 8.21797   | 0.0018018  | 555 |
| 556 | 309136 | 171879616 | 23.57965 | 8.22290   | 0.0017986  | 556 |
| 557 | 310249 | 172808693 | 23.60085 | 8.22783   | 0.0017953  | 557 |
| 558 | 311364 | 173741112 | 23.62202 | 8.23275   | 0.0017921  | 558 |
| 559 | 312481 | 174676879 | 23.64318 | 8.23766   | 0.0017889  | 559 |
| 560 | 313600 | 175616000 | 23.66432 | 8.24257   | 0.0017857  | 560 |
| 561 | 314721 | 176558481 | 23.68544 | 8.24747   | 0.0017825  | 561 |
| 562 | 315844 | 177504328 | 23.70654 | 8.25237   | 0.0017794  | 562 |
| 563 | 316969 | 178453547 | 23.72762 | 8.25726   | 0.0017762  | 563 |
| 564 | 318096 | 179406144 | 23.74868 | 8.26215   | 0.0017730  | 564 |
| 565 | 319225 | 180362125 | 23.76973 | 8.26703   | 0.0017699  | 565 |
| 566 | 320356 | 181321496 | 23.79075 | 8.27190   | 0.0017668  | 566 |
| 567 | 321489 | 182284263 | 23.81176 | 8.27677   | 0.0017637  | 567 |
| 568 | 322624 | 183250432 | 23.83275 | 8.28164   | 0.0017606  | 568 |
| 569 | 323761 | 184220009 | 23.85372 | 8.28649   | 0.0017575  | 569 |
| 570 | 324900 | 185193000 | 23.87467 | 8.29134   | 0.0017544  | 570 |
| 571 | 326041 | 186169411 | 23.89561 | 8.29619   | 0.0017513  | 571 |
| 572 | 327184 | 187149248 | 23.91652 | 8.30103   | 0.0017483  | 572 |
| 573 | 328329 | 188132517 | 23.93742 | 8.30587   | 0.0017452  | 573 |
| 574 | 329476 | 189119224 | 23.95830 | 8.31069   | 0.0017422  | 574 |
| 575 | 330625 | 190109375 | 23.97916 | 8.31552   | 0.0017391  | 575 |
| 576 | 331776 | 191102976 | 24.00000 | 8.32034   | 0.0017361  | 576 |
| 577 | 332929 | 192100033 | 24.02082 | 8.32515   | 0.0017331  | 577 |
| 578 | 334084 | 193100552 | 24.04163 | 8.32995   | 0.0017301  | 578 |
| 579 | 335241 | 194104539 | 24.06242 | 8.33476   | 0.0017271  | 579 |
| 580 | 336400 | 195112000 | 24.08319 | 8.33955   | 0.0017241  | 580 |
| 581 | 337561 | 196122941 | 24.10394 | 8.34434   | 0.0017212  | 581 |
| 582 | 338724 | 197137368 | 24.12468 | 8.34913   | 0.0017182  | 582 |
| 583 | 339889 | 198155287 | 24.14539 | 8.35390   | 0.0017153  | 583 |
| 584 | 341056 | 199176704 | 24.16609 | 8.35868   | 0.0017123  | 584 |
| 585 | 342225 | 200201625 | 24.18677 | 8.36345   | 0.0017094  | 585 |
| 586 | 343396 | 201230056 | 24.20744 | 8.36821   | 0.0017065  | 586 |
| 587 | 344569 | 202262003 | 24.22808 | 8.37297   | 0.0017036  | 587 |
| 588 | 345744 | 203297472 | 24.24871 | 8.37772   | 0.0017007  | 588 |
| 589 | 346921 | 204336469 | 24.26932 | 8.38247   | 0.0016978  | 589 |
| 590 | 348100 | 205379000 | 24.28992 | 8.38721   | 0.0016949  | 590 |
| 591 | 349281 | 206425071 | 24.31049 | 8.39194   | 0.0016920  | 591 |
| 592 | 350464 | 207474688 | 24.33105 | 8.39667   | 0.0016892  | 592 |
| 593 | 351649 | 208527857 | 24.35159 | 8.40140   | 0.0016863  | 593 |
| 594 | 352836 | 209584584 | 24.37212 | 8.40612   | 0.0016835  | 594 |
| 595 | 354025 | 210644875 | 24.39262 | 8.41083   | 0.0016807  | 595 |
| 596 | 355216 | 211708736 | 24.41311 | 8.41554   | 0.0016779  | 596 |
| 597 | 356409 | 212776173 | 24.43358 | 8.42025   | 0.0016750  | 597 |
| 598 | 357604 | 213847192 | 24.45404 | 8.42494   | 0.0016722  | 598 |
| 599 | 358801 | 214921799 | 24.47448 | 8.42964   | 0.0016694  | 599 |
| 600 | 360000 | 216000000 | 24.49490 | 8.43433   | 0.0016667  | 600 |

**Powers, Roots, and Reciprocals From 601 to 650**

| No. | Square | Cube      | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|-----------|----------|-----------|------------|-----|
| 601 | 361201 | 217081801 | 24.51530 | 8.43901   | 0.0016639  | 601 |
| 602 | 362404 | 218167208 | 24.53569 | 8.44369   | 0.0016611  | 602 |
| 603 | 363609 | 219256227 | 24.55606 | 8.44836   | 0.0016584  | 603 |
| 604 | 364816 | 220348864 | 24.57641 | 8.45303   | 0.0016556  | 604 |
| 605 | 366025 | 221445125 | 24.59675 | 8.45769   | 0.0016529  | 605 |
| 606 | 367236 | 222545016 | 24.61707 | 8.46235   | 0.0016502  | 606 |
| 607 | 368449 | 223648543 | 24.63737 | 8.46700   | 0.0016474  | 607 |
| 608 | 369664 | 224755712 | 24.65766 | 8.47165   | 0.0016447  | 608 |
| 609 | 370881 | 225866529 | 24.67793 | 8.47629   | 0.0016420  | 609 |
| 610 | 372100 | 226981000 | 24.69818 | 8.48093   | 0.0016393  | 610 |
| 611 | 373321 | 228099131 | 24.71841 | 8.48556   | 0.0016367  | 611 |
| 612 | 374544 | 229220928 | 24.73863 | 8.49018   | 0.0016340  | 612 |
| 613 | 375769 | 230346397 | 24.75884 | 8.49481   | 0.0016313  | 613 |
| 614 | 376996 | 231475544 | 24.77902 | 8.49942   | 0.0016287  | 614 |
| 615 | 378225 | 232608375 | 24.79919 | 8.50403   | 0.0016260  | 615 |
| 616 | 379456 | 233744896 | 24.81935 | 8.50864   | 0.0016234  | 616 |
| 617 | 380689 | 234885113 | 24.83948 | 8.51324   | 0.0016207  | 617 |
| 618 | 381924 | 236029032 | 24.85961 | 8.51784   | 0.0016181  | 618 |
| 619 | 383161 | 237176659 | 24.87971 | 8.52243   | 0.0016155  | 619 |
| 620 | 384400 | 238328000 | 24.89980 | 8.52702   | 0.0016129  | 620 |
| 621 | 385641 | 239483061 | 24.91987 | 8.53160   | 0.0016103  | 621 |
| 622 | 386884 | 240641848 | 24.93993 | 8.53618   | 0.0016077  | 622 |
| 623 | 388129 | 241804367 | 24.95997 | 8.54075   | 0.0016051  | 623 |
| 624 | 389376 | 242970624 | 24.97999 | 8.54532   | 0.0016026  | 624 |
| 625 | 390625 | 244140625 | 25.00000 | 8.54988   | 0.0016000  | 625 |
| 626 | 391876 | 245314376 | 25.01999 | 8.55444   | 0.0015974  | 626 |
| 627 | 393129 | 246491883 | 25.03997 | 8.55899   | 0.0015949  | 627 |
| 628 | 394384 | 247673152 | 25.05993 | 8.56354   | 0.0015924  | 628 |
| 629 | 395641 | 248858189 | 25.07987 | 8.56808   | 0.0015898  | 629 |
| 630 | 396900 | 250047000 | 25.09980 | 8.57262   | 0.0015873  | 630 |
| 631 | 398161 | 251239591 | 25.11971 | 8.57715   | 0.0015848  | 631 |
| 632 | 399424 | 252435968 | 25.13961 | 8.58168   | 0.0015823  | 632 |
| 633 | 400689 | 253636137 | 25.15949 | 8.58620   | 0.0015798  | 633 |
| 634 | 401956 | 254840104 | 25.17936 | 8.59072   | 0.0015773  | 634 |
| 635 | 403225 | 256047875 | 25.19921 | 8.59524   | 0.0015748  | 635 |
| 636 | 404496 | 257259456 | 25.21904 | 8.59975   | 0.0015723  | 636 |
| 637 | 405769 | 258474853 | 25.23886 | 8.60425   | 0.0015699  | 637 |
| 638 | 407044 | 259694072 | 25.25866 | 8.60875   | 0.0015674  | 638 |
| 639 | 408321 | 260917119 | 25.27845 | 8.61325   | 0.0015649  | 639 |
| 640 | 409600 | 262144000 | 25.29822 | 8.61774   | 0.0015625  | 640 |
| 641 | 410881 | 263374721 | 25.31798 | 8.62222   | 0.0015601  | 641 |
| 642 | 412164 | 264609288 | 25.33772 | 8.62671   | 0.0015576  | 642 |
| 643 | 413449 | 265847707 | 25.35744 | 8.63118   | 0.0015552  | 643 |
| 644 | 414736 | 267089984 | 25.37716 | 8.63566   | 0.0015528  | 644 |
| 645 | 416025 | 268336125 | 25.39685 | 8.64012   | 0.0015504  | 645 |
| 646 | 417316 | 269586136 | 25.41653 | 8.64459   | 0.0015480  | 646 |
| 647 | 418609 | 270840023 | 25.43619 | 8.64904   | 0.0015456  | 647 |
| 648 | 419904 | 272097792 | 25.45584 | 8.65350   | 0.0015432  | 648 |
| 649 | 421201 | 273359449 | 25.47548 | 8.65795   | 0.0015408  | 649 |
| 650 | 422500 | 274625000 | 25.49510 | 8.66239   | 0.0015385  | 650 |

**Powers, Roots, and Reciprocals From 651 to 700**

| No. | Square | Cube      | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|-----------|----------|-----------|------------|-----|
| 651 | 423801 | 275894451 | 25.51470 | 8.66683   | 0.0015361  | 651 |
| 652 | 425104 | 277167808 | 25.53429 | 8.67127   | 0.0015337  | 652 |
| 653 | 426409 | 278445077 | 25.55386 | 8.67570   | 0.0015314  | 653 |
| 654 | 427716 | 279726264 | 25.57342 | 8.68012   | 0.0015291  | 654 |
| 655 | 429025 | 281011375 | 25.59297 | 8.68455   | 0.0015267  | 655 |
| 656 | 430336 | 282300416 | 25.61250 | 8.68896   | 0.0015244  | 656 |
| 657 | 431649 | 283593393 | 25.63201 | 8.69338   | 0.0015221  | 657 |
| 658 | 432964 | 284890312 | 25.65151 | 8.69778   | 0.0015198  | 658 |
| 659 | 434281 | 286191179 | 25.67100 | 8.70219   | 0.0015175  | 659 |
| 660 | 435600 | 287496000 | 25.69047 | 8.70659   | 0.0015152  | 660 |
| 661 | 436921 | 288804781 | 25.70992 | 8.71098   | 0.0015129  | 661 |
| 662 | 438244 | 290117528 | 25.72936 | 8.71537   | 0.0015106  | 662 |
| 663 | 439569 | 291434247 | 25.74879 | 8.71976   | 0.0015083  | 663 |
| 664 | 440896 | 292754944 | 25.76820 | 8.72414   | 0.0015060  | 664 |
| 665 | 442225 | 294079625 | 25.78759 | 8.72852   | 0.0015038  | 665 |
| 666 | 443556 | 295408296 | 25.80698 | 8.73289   | 0.0015015  | 666 |
| 667 | 444889 | 296740963 | 25.82634 | 8.73726   | 0.0014993  | 667 |
| 668 | 446224 | 298077632 | 25.84570 | 8.74162   | 0.0014970  | 668 |
| 669 | 447561 | 299418309 | 25.86503 | 8.74598   | 0.0014948  | 669 |
| 670 | 448900 | 300763000 | 25.88436 | 8.75034   | 0.0014925  | 670 |
| 671 | 450241 | 302111711 | 25.90367 | 8.75469   | 0.0014903  | 671 |
| 672 | 451584 | 303464448 | 25.92296 | 8.75904   | 0.0014881  | 672 |
| 673 | 452929 | 304821217 | 25.94224 | 8.76338   | 0.0014859  | 673 |
| 674 | 454276 | 306182024 | 25.96151 | 8.76772   | 0.0014837  | 674 |
| 675 | 455625 | 307546875 | 25.98076 | 8.77205   | 0.0014815  | 675 |
| 676 | 456976 | 308915776 | 26.00000 | 8.77638   | 0.0014793  | 676 |
| 677 | 458329 | 310288733 | 26.01922 | 8.78071   | 0.0014771  | 677 |
| 678 | 459684 | 311665752 | 26.03843 | 8.78503   | 0.0014749  | 678 |
| 679 | 461041 | 313046839 | 26.05763 | 8.78935   | 0.0014728  | 679 |
| 680 | 462400 | 314432000 | 26.07681 | 8.79366   | 0.0014706  | 680 |
| 681 | 463761 | 315821241 | 26.09598 | 8.79797   | 0.0014684  | 681 |
| 682 | 465124 | 317214568 | 26.11513 | 8.80227   | 0.0014663  | 682 |
| 683 | 466489 | 318611987 | 26.13427 | 8.80657   | 0.0014641  | 683 |
| 684 | 467856 | 320013504 | 26.15339 | 8.81087   | 0.0014620  | 684 |
| 685 | 469225 | 321419125 | 26.17250 | 8.81516   | 0.0014599  | 685 |
| 686 | 470596 | 322828856 | 26.19160 | 8.81945   | 0.0014577  | 686 |
| 687 | 471969 | 324242703 | 26.21068 | 8.82373   | 0.0014556  | 687 |
| 688 | 473344 | 325660672 | 26.22975 | 8.82801   | 0.0014535  | 688 |
| 689 | 474721 | 327082769 | 26.24881 | 8.83228   | 0.0014514  | 689 |
| 690 | 476100 | 328509000 | 26.26785 | 8.83656   | 0.0014493  | 690 |
| 691 | 477481 | 329939371 | 26.28688 | 8.84082   | 0.0014472  | 691 |
| 692 | 478864 | 331373888 | 26.30589 | 8.84509   | 0.0014451  | 692 |
| 693 | 480249 | 332812557 | 26.32489 | 8.84934   | 0.0014430  | 693 |
| 694 | 481636 | 334255384 | 26.34388 | 8.85360   | 0.0014409  | 694 |
| 695 | 483025 | 335702375 | 26.36285 | 8.85785   | 0.0014388  | 695 |
| 696 | 484416 | 337153536 | 26.38181 | 8.86210   | 0.0014368  | 696 |
| 697 | 485809 | 338608873 | 26.40076 | 8.86634   | 0.0014347  | 697 |
| 698 | 487204 | 340068392 | 26.41969 | 8.87058   | 0.0014327  | 698 |
| 699 | 488601 | 341532099 | 26.43861 | 8.87481   | 0.0014306  | 699 |
| 700 | 490000 | 343000000 | 26.45751 | 8.87904   | 0.0014286  | 700 |

## Powers, Roots, and Reciprocals From 701 to 750

| No. | Square | Cube      | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|-----------|----------|-----------|------------|-----|
| 701 | 491401 | 344472101 | 26.47640 | 8.88327   | 0.0014265  | 701 |
| 702 | 492804 | 345948408 | 26.49528 | 8.88749   | 0.0014245  | 702 |
| 703 | 494209 | 347428927 | 26.51415 | 8.89171   | 0.0014225  | 703 |
| 704 | 495616 | 348913664 | 26.53300 | 8.89592   | 0.0014205  | 704 |
| 705 | 497025 | 350402625 | 26.55184 | 8.90013   | 0.0014184  | 705 |
| 706 | 498436 | 351895816 | 26.57066 | 8.90434   | 0.0014164  | 706 |
| 707 | 499849 | 353393243 | 26.58947 | 8.90854   | 0.0014144  | 707 |
| 708 | 501264 | 354894912 | 26.60827 | 8.91274   | 0.0014124  | 708 |
| 709 | 502681 | 356400829 | 26.62705 | 8.91693   | 0.0014104  | 709 |
| 710 | 504100 | 357911000 | 26.64583 | 8.92112   | 0.0014085  | 710 |
| 711 | 505521 | 359425431 | 26.66458 | 8.92531   | 0.0014065  | 711 |
| 712 | 506944 | 360944128 | 26.68333 | 8.92949   | 0.0014045  | 712 |
| 713 | 508369 | 362467097 | 26.70206 | 8.93367   | 0.0014025  | 713 |
| 714 | 509796 | 363994344 | 26.72078 | 8.93784   | 0.0014006  | 714 |
| 715 | 511225 | 365525875 | 26.73948 | 8.94201   | 0.0013986  | 715 |
| 716 | 512656 | 367061696 | 26.75818 | 8.94618   | 0.0013966  | 716 |
| 717 | 514089 | 368601813 | 26.77686 | 8.95034   | 0.0013947  | 717 |
| 718 | 515524 | 370146232 | 26.79552 | 8.95450   | 0.0013928  | 718 |
| 719 | 516961 | 371694959 | 26.81418 | 8.95866   | 0.0013908  | 719 |
| 720 | 518400 | 373248000 | 26.83282 | 8.96281   | 0.0013889  | 720 |
| 721 | 519841 | 374805361 | 26.85144 | 8.96696   | 0.0013870  | 721 |
| 722 | 521284 | 376367048 | 26.87006 | 8.97110   | 0.0013850  | 722 |
| 723 | 522729 | 377933067 | 26.88866 | 8.97524   | 0.0013831  | 723 |
| 724 | 524176 | 379503424 | 26.90725 | 8.97938   | 0.0013812  | 724 |
| 725 | 525625 | 381078125 | 26.92582 | 8.98351   | 0.0013793  | 725 |
| 726 | 527076 | 382657176 | 26.94439 | 8.98764   | 0.0013774  | 726 |
| 727 | 528529 | 384240583 | 26.96294 | 8.99176   | 0.0013755  | 727 |
| 728 | 529984 | 385828352 | 26.98148 | 8.99588   | 0.0013736  | 728 |
| 729 | 531441 | 387420489 | 27.00000 | 9.00000   | 0.0013717  | 729 |
| 730 | 532900 | 389017000 | 27.01851 | 9.00411   | 0.0013699  | 730 |
| 731 | 534361 | 390617891 | 27.03701 | 9.00822   | 0.0013680  | 731 |
| 732 | 535824 | 392223168 | 27.05550 | 9.01233   | 0.0013661  | 732 |
| 733 | 537289 | 393832837 | 27.07397 | 9.01643   | 0.0013643  | 733 |
| 734 | 538756 | 395446904 | 27.09243 | 9.02053   | 0.0013624  | 734 |
| 735 | 540225 | 397065375 | 27.11088 | 9.02462   | 0.0013605  | 735 |
| 736 | 541696 | 398688256 | 27.12932 | 9.02871   | 0.0013587  | 736 |
| 737 | 543169 | 400315553 | 27.14774 | 9.03280   | 0.0013569  | 737 |
| 738 | 544644 | 401947272 | 27.16616 | 9.03689   | 0.0013550  | 738 |
| 739 | 546121 | 403583419 | 27.18455 | 9.04097   | 0.0013532  | 739 |
| 740 | 547600 | 405224000 | 27.20294 | 9.04504   | 0.0013514  | 740 |
| 741 | 549081 | 406869021 | 27.22132 | 9.04911   | 0.0013495  | 741 |
| 742 | 550564 | 408518488 | 27.23968 | 9.05318   | 0.0013477  | 742 |
| 743 | 552049 | 410172407 | 27.25803 | 9.05725   | 0.0013459  | 743 |
| 744 | 553536 | 411830784 | 27.27636 | 9.06131   | 0.0013441  | 744 |
| 745 | 555025 | 413493625 | 27.29469 | 9.06537   | 0.0013423  | 745 |
| 746 | 556516 | 415160936 | 27.31300 | 9.06942   | 0.0013405  | 746 |
| 747 | 558009 | 416832723 | 27.33130 | 9.07347   | 0.0013387  | 747 |
| 748 | 559504 | 418508992 | 27.34959 | 9.07752   | 0.0013369  | 748 |
| 749 | 561001 | 420189749 | 27.36786 | 9.08156   | 0.0013351  | 749 |
| 750 | 562500 | 421875000 | 27.38613 | 9.08560   | 0.0013333  | 750 |

**Powers, Roots, and Reciprocals From 751 to 800**

| No. | Square | Cube      | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|-----------|----------|-----------|------------|-----|
| 751 | 564001 | 423564751 | 27.40438 | 9.08964   | 0.0013316  | 751 |
| 752 | 565504 | 425259008 | 27.42262 | 9.09367   | 0.0013298  | 752 |
| 753 | 567009 | 426957777 | 27.44085 | 9.09770   | 0.0013280  | 753 |
| 754 | 568516 | 428661064 | 27.45906 | 9.10173   | 0.0013263  | 754 |
| 755 | 570025 | 430368875 | 27.47726 | 9.10575   | 0.0013245  | 755 |
| 756 | 571536 | 432081216 | 27.49545 | 9.10977   | 0.0013228  | 756 |
| 757 | 573049 | 433798093 | 27.51363 | 9.11378   | 0.0013210  | 757 |
| 758 | 574564 | 435519512 | 27.53180 | 9.11779   | 0.0013193  | 758 |
| 759 | 576081 | 437245479 | 27.54995 | 9.12180   | 0.0013175  | 759 |
| 760 | 577600 | 438976000 | 27.56810 | 9.12581   | 0.0013158  | 760 |
| 761 | 579121 | 440711081 | 27.58623 | 9.12981   | 0.0013141  | 761 |
| 762 | 580644 | 442450728 | 27.60435 | 9.13380   | 0.0013123  | 762 |
| 763 | 582169 | 444194947 | 27.62245 | 9.13780   | 0.0013106  | 763 |
| 764 | 583696 | 445943744 | 27.64055 | 9.14179   | 0.0013089  | 764 |
| 765 | 585225 | 447697125 | 27.65863 | 9.14577   | 0.0013072  | 765 |
| 766 | 586756 | 449455096 | 27.67671 | 9.14976   | 0.0013055  | 766 |
| 767 | 588289 | 451217663 | 27.69476 | 9.15374   | 0.0013038  | 767 |
| 768 | 589824 | 452984832 | 27.71281 | 9.15771   | 0.0013021  | 768 |
| 769 | 591361 | 454756609 | 27.73085 | 9.16169   | 0.0013004  | 769 |
| 770 | 592900 | 456533000 | 27.74887 | 9.16566   | 0.0012987  | 770 |
| 771 | 594441 | 458314011 | 27.76689 | 9.16962   | 0.0012970  | 771 |
| 772 | 595984 | 460099648 | 27.78489 | 9.17359   | 0.0012953  | 772 |
| 773 | 597529 | 461889917 | 27.80288 | 9.17754   | 0.0012937  | 773 |
| 774 | 599076 | 463684824 | 27.82086 | 9.18150   | 0.0012920  | 774 |
| 775 | 600625 | 465484375 | 27.83882 | 9.18545   | 0.0012903  | 775 |
| 776 | 602176 | 467288576 | 27.85678 | 9.18940   | 0.0012887  | 776 |
| 777 | 603729 | 469097433 | 27.87472 | 9.19335   | 0.0012870  | 777 |
| 778 | 605284 | 470910952 | 27.89265 | 9.19729   | 0.0012853  | 778 |
| 779 | 606841 | 472729139 | 27.91057 | 9.20123   | 0.0012837  | 779 |
| 780 | 608400 | 474552000 | 27.92848 | 9.20516   | 0.0012821  | 780 |
| 781 | 609961 | 476379541 | 27.94638 | 9.20910   | 0.0012804  | 781 |
| 782 | 611524 | 478211768 | 27.96426 | 9.21303   | 0.0012788  | 782 |
| 783 | 613089 | 480048687 | 27.98214 | 9.21695   | 0.0012771  | 783 |
| 784 | 614656 | 481890304 | 28.00000 | 9.22087   | 0.0012755  | 784 |
| 785 | 616225 | 483736625 | 28.01785 | 9.22479   | 0.0012739  | 785 |
| 786 | 617796 | 485587656 | 28.03569 | 9.22871   | 0.0012723  | 786 |
| 787 | 619369 | 487443403 | 28.05352 | 9.23262   | 0.0012706  | 787 |
| 788 | 620944 | 489303872 | 28.07134 | 9.23653   | 0.0012690  | 788 |
| 789 | 622521 | 491169069 | 28.08914 | 9.24043   | 0.0012674  | 789 |
| 790 | 624100 | 493039000 | 28.10694 | 9.24434   | 0.0012658  | 790 |
| 791 | 625681 | 494913671 | 28.12472 | 9.24823   | 0.0012642  | 791 |
| 792 | 627264 | 496793088 | 28.14249 | 9.25213   | 0.0012626  | 792 |
| 793 | 628849 | 498677257 | 28.16026 | 9.25602   | 0.0012610  | 793 |
| 794 | 630436 | 500566184 | 28.17801 | 9.25991   | 0.0012594  | 794 |
| 795 | 632025 | 502459875 | 28.19574 | 9.26380   | 0.0012579  | 795 |
| 796 | 633616 | 504358336 | 28.21347 | 9.26768   | 0.0012563  | 796 |
| 797 | 635209 | 506261573 | 28.23119 | 9.27156   | 0.0012547  | 797 |
| 798 | 636804 | 508169592 | 28.24889 | 9.27544   | 0.0012531  | 798 |
| 799 | 638401 | 510082399 | 28.26659 | 9.27931   | 0.0012516  | 799 |
| 800 | 640000 | 512000000 | 28.28427 | 9.28318   | 0.0012500  | 800 |



## Powers, Roots, and Reciprocals From 801 to 850

| No. | Square | Cube      | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|-----------|----------|-----------|------------|-----|
| 801 | 641601 | 513922401 | 28.30194 | 9.28704   | 0.0012484  | 801 |
| 802 | 643204 | 515849608 | 28.31960 | 9.29091   | 0.0012469  | 802 |
| 803 | 644809 | 517781627 | 28.33725 | 9.29477   | 0.0012453  | 803 |
| 804 | 646416 | 519718464 | 28.35489 | 9.29862   | 0.0012438  | 804 |
| 805 | 648025 | 521660125 | 28.37252 | 9.30248   | 0.0012422  | 805 |
| 806 | 649636 | 523606616 | 28.39014 | 9.30633   | 0.0012407  | 806 |
| 807 | 651249 | 525557943 | 28.40775 | 9.31018   | 0.0012392  | 807 |
| 808 | 652864 | 527514112 | 28.42534 | 9.31402   | 0.0012376  | 808 |
| 809 | 654481 | 529475129 | 28.44293 | 9.31786   | 0.0012361  | 809 |
| 810 | 656100 | 531441000 | 28.46050 | 9.32170   | 0.0012346  | 810 |
| 811 | 657721 | 533411731 | 28.47806 | 9.32553   | 0.0012330  | 811 |
| 812 | 659344 | 535387328 | 28.49561 | 9.32936   | 0.0012315  | 812 |
| 813 | 660969 | 537367797 | 28.51315 | 9.33319   | 0.0012300  | 813 |
| 814 | 662596 | 539353144 | 28.53069 | 9.33702   | 0.0012285  | 814 |
| 815 | 664225 | 541343375 | 28.54820 | 9.34084   | 0.0012270  | 815 |
| 816 | 665856 | 543338496 | 28.56571 | 9.34466   | 0.0012255  | 816 |
| 817 | 667489 | 545338513 | 28.58321 | 9.34847   | 0.0012240  | 817 |
| 818 | 669124 | 547343432 | 28.60070 | 9.35229   | 0.0012225  | 818 |
| 819 | 670761 | 549353259 | 28.61818 | 9.35610   | 0.0012210  | 819 |
| 820 | 672400 | 551368000 | 28.63564 | 9.35990   | 0.0012195  | 820 |
| 821 | 674041 | 553387661 | 28.65310 | 9.36370   | 0.0012180  | 821 |
| 822 | 675684 | 555412248 | 28.67054 | 9.36751   | 0.0012165  | 822 |
| 823 | 677329 | 557441767 | 28.68798 | 9.37130   | 0.0012151  | 823 |
| 824 | 678976 | 559476224 | 28.70540 | 9.37510   | 0.0012136  | 824 |
| 825 | 680625 | 561515625 | 28.72281 | 9.37889   | 0.0012121  | 825 |
| 826 | 682276 | 563559976 | 28.74022 | 9.38268   | 0.0012107  | 826 |
| 827 | 683929 | 565609283 | 28.75761 | 9.38646   | 0.0012092  | 827 |
| 828 | 685584 | 567663552 | 28.77499 | 9.39024   | 0.0012077  | 828 |
| 829 | 687241 | 569722789 | 28.79236 | 9.39402   | 0.0012063  | 829 |
| 830 | 688900 | 571787000 | 28.80972 | 9.39780   | 0.0012048  | 830 |
| 831 | 690561 | 573856191 | 28.82707 | 9.40157   | 0.0012034  | 831 |
| 832 | 692224 | 575930368 | 28.84441 | 9.40534   | 0.0012019  | 832 |
| 833 | 693889 | 578009537 | 28.86174 | 9.40911   | 0.0012005  | 833 |
| 834 | 695556 | 580093704 | 28.87906 | 9.41287   | 0.0011990  | 834 |
| 835 | 697225 | 582182875 | 28.89637 | 9.41663   | 0.0011976  | 835 |
| 836 | 698896 | 584277056 | 28.91366 | 9.42039   | 0.0011962  | 836 |
| 837 | 700569 | 586376253 | 28.93095 | 9.42414   | 0.0011947  | 837 |
| 838 | 702244 | 588480472 | 28.94823 | 9.42789   | 0.0011933  | 838 |
| 839 | 703921 | 590589719 | 28.96550 | 9.43164   | 0.0011919  | 839 |
| 840 | 705600 | 592704000 | 28.98275 | 9.43539   | 0.0011905  | 840 |
| 841 | 707281 | 594823321 | 29.00000 | 9.43913   | 0.0011891  | 841 |
| 842 | 708964 | 596947688 | 29.01724 | 9.44287   | 0.0011876  | 842 |
| 843 | 710649 | 599077107 | 29.03446 | 9.44661   | 0.0011862  | 843 |
| 844 | 712336 | 601211584 | 29.05168 | 9.45034   | 0.0011848  | 844 |
| 845 | 714025 | 603351125 | 29.06888 | 9.45407   | 0.0011834  | 845 |
| 846 | 715716 | 605495736 | 29.08608 | 9.45780   | 0.0011820  | 846 |
| 847 | 717409 | 607645423 | 29.10326 | 9.46152   | 0.0011806  | 847 |
| 848 | 719104 | 609800192 | 29.12044 | 9.46525   | 0.0011792  | 848 |
| 849 | 720801 | 611960049 | 29.13760 | 9.46897   | 0.0011779  | 849 |
| 850 | 722500 | 614125000 | 29.15476 | 9.47268   | 0.0011765  | 850 |

**Powers, Roots, and Reciprocals From 851 to 900**

| No. | Square | Cube      | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|-----------|----------|-----------|------------|-----|
| 851 | 724201 | 616295051 | 29.17190 | 9.47640   | 0.0011751  | 851 |
| 852 | 725904 | 618470208 | 29.18904 | 9.48011   | 0.0011737  | 852 |
| 853 | 727609 | 620650477 | 29.20616 | 9.48381   | 0.0011723  | 853 |
| 854 | 729316 | 622835864 | 29.22328 | 9.48752   | 0.0011710  | 854 |
| 855 | 731025 | 625026375 | 29.24038 | 9.49122   | 0.0011696  | 855 |
| 856 | 732736 | 627222016 | 29.25748 | 9.49492   | 0.0011682  | 856 |
| 857 | 734449 | 629422793 | 29.27456 | 9.49861   | 0.0011669  | 857 |
| 858 | 736164 | 631628712 | 29.29164 | 9.50231   | 0.0011655  | 858 |
| 859 | 737881 | 633839779 | 29.30870 | 9.50600   | 0.0011641  | 859 |
| 860 | 739600 | 636056000 | 29.32576 | 9.50969   | 0.0011628  | 860 |
| 861 | 741321 | 638277381 | 29.34280 | 9.51337   | 0.0011614  | 861 |
| 862 | 743044 | 640503928 | 29.35984 | 9.51705   | 0.0011601  | 862 |
| 863 | 744769 | 642735647 | 29.37686 | 9.52073   | 0.0011587  | 863 |
| 864 | 746496 | 644972544 | 29.39388 | 9.52441   | 0.0011574  | 864 |
| 865 | 748225 | 647214625 | 29.41088 | 9.52808   | 0.0011561  | 865 |
| 866 | 749956 | 649461896 | 29.42788 | 9.53175   | 0.0011547  | 866 |
| 867 | 751689 | 651714363 | 29.44486 | 9.53542   | 0.0011534  | 867 |
| 868 | 753424 | 653972032 | 29.46184 | 9.53908   | 0.0011521  | 868 |
| 869 | 755161 | 656234909 | 29.47881 | 9.54274   | 0.0011507  | 869 |
| 870 | 756900 | 658503000 | 29.49576 | 9.54640   | 0.0011494  | 870 |
| 871 | 758641 | 660776311 | 29.51271 | 9.55006   | 0.0011481  | 871 |
| 872 | 760384 | 663054848 | 29.52965 | 9.55371   | 0.0011468  | 872 |
| 873 | 762129 | 665338617 | 29.54657 | 9.55736   | 0.0011455  | 873 |
| 874 | 763876 | 667627624 | 29.56349 | 9.56101   | 0.0011442  | 874 |
| 875 | 765625 | 669921875 | 29.58040 | 9.56466   | 0.0011429  | 875 |
| 876 | 767376 | 672221376 | 29.59730 | 9.56830   | 0.0011416  | 876 |
| 877 | 769129 | 674526133 | 29.61419 | 9.57194   | 0.0011403  | 877 |
| 878 | 770884 | 676836152 | 29.63106 | 9.57557   | 0.0011390  | 878 |
| 879 | 772641 | 679151439 | 29.64793 | 9.57921   | 0.0011377  | 879 |
| 880 | 774400 | 681472000 | 29.66479 | 9.58284   | 0.0011364  | 880 |
| 881 | 776161 | 683797841 | 29.68164 | 9.58647   | 0.0011351  | 881 |
| 882 | 777924 | 686128968 | 29.69848 | 9.59009   | 0.0011338  | 882 |
| 883 | 779689 | 688465387 | 29.71532 | 9.59372   | 0.0011325  | 883 |
| 884 | 781456 | 690807104 | 29.73214 | 9.59734   | 0.0011312  | 884 |
| 885 | 783225 | 693154125 | 29.74895 | 9.60095   | 0.0011299  | 885 |
| 886 | 784996 | 695506456 | 29.76575 | 9.60457   | 0.0011287  | 886 |
| 887 | 786769 | 697864103 | 29.78255 | 9.60818   | 0.0011274  | 887 |
| 888 | 788544 | 700227072 | 29.79933 | 9.61179   | 0.0011261  | 888 |
| 889 | 790321 | 702595369 | 29.81610 | 9.61540   | 0.0011249  | 889 |
| 890 | 792100 | 704969000 | 29.83287 | 9.61900   | 0.0011236  | 890 |
| 891 | 793881 | 707347971 | 29.84962 | 9.62260   | 0.0011223  | 891 |
| 892 | 795664 | 709732288 | 29.86637 | 9.62620   | 0.0011211  | 892 |
| 893 | 797449 | 712121957 | 29.88311 | 9.62980   | 0.0011198  | 893 |
| 894 | 799236 | 714516984 | 29.89983 | 9.63339   | 0.0011186  | 894 |
| 895 | 801025 | 716917375 | 29.91655 | 9.63698   | 0.0011173  | 895 |
| 896 | 802816 | 719323136 | 29.93326 | 9.64057   | 0.0011161  | 896 |
| 897 | 804609 | 721734273 | 29.94996 | 9.64415   | 0.0011148  | 897 |
| 898 | 806404 | 724150792 | 29.96665 | 9.64774   | 0.0011136  | 898 |
| 899 | 808201 | 726572699 | 29.98333 | 9.65132   | 0.0011123  | 899 |
| 900 | 810000 | 729000000 | 30.00000 | 9.65489   | 0.0011111  | 900 |

## Powers, Roots, and Reciprocals From 901 to 950

| No. | Square | Cube      | Sq. Root | Cube Root | Reciprocal | No. |
|-----|--------|-----------|----------|-----------|------------|-----|
| 901 | 811801 | 731432701 | 30.01666 | 9.65847   | 0.0011099  | 901 |
| 902 | 813604 | 733870808 | 30.03331 | 9.66204   | 0.0011086  | 902 |
| 903 | 815409 | 736314327 | 30.04996 | 9.66561   | 0.0011074  | 903 |
| 904 | 817216 | 738763264 | 30.06659 | 9.66918   | 0.0011062  | 904 |
| 905 | 819025 | 741217625 | 30.08322 | 9.67274   | 0.0011050  | 905 |
| 906 | 820836 | 743677416 | 30.09983 | 9.67630   | 0.0011038  | 906 |
| 907 | 822649 | 746142643 | 30.11644 | 9.67986   | 0.0011025  | 907 |
| 908 | 824464 | 748613312 | 30.13304 | 9.68342   | 0.0011013  | 908 |
| 909 | 826281 | 751089429 | 30.14963 | 9.68697   | 0.0011001  | 909 |
| 910 | 828100 | 753571000 | 30.16621 | 9.69052   | 0.0010989  | 910 |
| 911 | 829921 | 756058031 | 30.18278 | 9.69407   | 0.0010977  | 911 |
| 912 | 831744 | 758550528 | 30.19934 | 9.69762   | 0.0010965  | 912 |
| 913 | 833569 | 761048497 | 30.21589 | 9.70116   | 0.0010953  | 913 |
| 914 | 835396 | 763551944 | 30.23243 | 9.70470   | 0.0010941  | 914 |
| 915 | 837225 | 766060875 | 30.24897 | 9.70824   | 0.0010929  | 915 |
| 916 | 839056 | 768575296 | 30.26549 | 9.71177   | 0.0010917  | 916 |
| 917 | 840889 | 771095213 | 30.28201 | 9.71531   | 0.0010905  | 917 |
| 918 | 842724 | 773620632 | 30.29851 | 9.71884   | 0.0010893  | 918 |
| 919 | 844561 | 776151559 | 30.31501 | 9.72236   | 0.0010881  | 919 |
| 920 | 846400 | 778688000 | 30.33150 | 9.72589   | 0.0010870  | 920 |
| 921 | 848241 | 781229961 | 30.34798 | 9.72941   | 0.0010858  | 921 |
| 922 | 850084 | 783777448 | 30.36445 | 9.73293   | 0.0010846  | 922 |
| 923 | 851929 | 786330467 | 30.38092 | 9.73645   | 0.0010834  | 923 |
| 924 | 853776 | 788889024 | 30.39737 | 9.73996   | 0.0010823  | 924 |
| 925 | 855625 | 791453125 | 30.41381 | 9.74348   | 0.0010811  | 925 |
| 926 | 857476 | 794022776 | 30.43025 | 9.74699   | 0.0010799  | 926 |
| 927 | 859329 | 796597983 | 30.44667 | 9.75049   | 0.0010787  | 927 |
| 928 | 861184 | 799178752 | 30.46309 | 9.75400   | 0.0010776  | 928 |
| 929 | 863041 | 801765089 | 30.47950 | 9.75750   | 0.0010764  | 929 |
| 930 | 864900 | 804357000 | 30.49590 | 9.76100   | 0.0010753  | 930 |
| 931 | 866761 | 806954491 | 30.51229 | 9.76450   | 0.0010741  | 931 |
| 932 | 868624 | 809557568 | 30.52868 | 9.76799   | 0.0010730  | 932 |
| 933 | 870489 | 812166237 | 30.54505 | 9.77148   | 0.0010718  | 933 |
| 934 | 872356 | 814780504 | 30.56141 | 9.77497   | 0.0010707  | 934 |
| 935 | 874225 | 817400375 | 30.57777 | 9.77846   | 0.0010695  | 935 |
| 936 | 876096 | 820025856 | 30.59412 | 9.78195   | 0.0010684  | 936 |
| 937 | 877969 | 822656953 | 30.61046 | 9.78543   | 0.0010672  | 937 |
| 938 | 879844 | 825293672 | 30.62679 | 9.78891   | 0.0010661  | 938 |
| 939 | 881721 | 827936019 | 30.64311 | 9.79239   | 0.0010650  | 939 |
| 940 | 883600 | 830584000 | 30.65942 | 9.79586   | 0.0010638  | 940 |
| 941 | 885481 | 833237621 | 30.67572 | 9.79933   | 0.0010627  | 941 |
| 942 | 887364 | 835896888 | 30.69202 | 9.80280   | 0.0010616  | 942 |
| 943 | 889249 | 838561807 | 30.70831 | 9.80627   | 0.0010604  | 943 |
| 944 | 891136 | 841232384 | 30.72458 | 9.80974   | 0.0010593  | 944 |
| 945 | 893025 | 843908625 | 30.74085 | 9.81320   | 0.0010582  | 945 |
| 946 | 894916 | 846590536 | 30.75711 | 9.81666   | 0.0010571  | 946 |
| 947 | 896809 | 849278123 | 30.77337 | 9.82012   | 0.0010560  | 947 |
| 948 | 898704 | 851971392 | 30.78961 | 9.82357   | 0.0010549  | 948 |
| 949 | 900601 | 854670349 | 30.80584 | 9.82703   | 0.0010537  | 949 |
| 950 | 902500 | 857375000 | 30.82207 | 9.83048   | 0.0010526  | 950 |

**Powers, Roots, and Reciprocals From 951 to 1000**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 951  | 904401  | 860085351  | 30.83829 | 9.83392   | 0.0010515  | 951  |
| 952  | 906304  | 862801408  | 30.85450 | 9.83737   | 0.0010504  | 952  |
| 953  | 908209  | 865523177  | 30.87070 | 9.84081   | 0.0010493  | 953  |
| 954  | 910116  | 868250664  | 30.88689 | 9.84425   | 0.0010482  | 954  |
| 955  | 912025  | 870983875  | 30.90307 | 9.84769   | 0.0010471  | 955  |
| 956  | 913936  | 873722816  | 30.91925 | 9.85113   | 0.0010460  | 956  |
| 957  | 915849  | 876467493  | 30.93542 | 9.85456   | 0.0010449  | 957  |
| 958  | 917764  | 879217912  | 30.95158 | 9.85799   | 0.0010438  | 958  |
| 959  | 919681  | 881974079  | 30.96773 | 9.86142   | 0.0010428  | 959  |
| 960  | 921600  | 884736000  | 30.98387 | 9.86485   | 0.0010417  | 960  |
| 961  | 923521  | 887503681  | 31.00000 | 9.86827   | 0.0010406  | 961  |
| 962  | 925444  | 890277128  | 31.01612 | 9.87169   | 0.0010395  | 962  |
| 963  | 927369  | 893056347  | 31.03224 | 9.87511   | 0.0010384  | 963  |
| 964  | 929296  | 895841344  | 31.04835 | 9.87853   | 0.0010373  | 964  |
| 965  | 931225  | 898632125  | 31.06445 | 9.88195   | 0.0010363  | 965  |
| 966  | 933156  | 901428696  | 31.08054 | 9.88536   | 0.0010352  | 966  |
| 967  | 935089  | 904231063  | 31.09662 | 9.88877   | 0.0010341  | 967  |
| 968  | 937024  | 907039232  | 31.11270 | 9.89217   | 0.0010331  | 968  |
| 969  | 938961  | 909853209  | 31.12876 | 9.89558   | 0.0010320  | 969  |
| 970  | 940900  | 912673000  | 31.14482 | 9.89898   | 0.0010309  | 970  |
| 971  | 942841  | 915498611  | 31.16087 | 9.90238   | 0.0010299  | 971  |
| 972  | 944784  | 918330048  | 31.17691 | 9.90578   | 0.0010288  | 972  |
| 973  | 946729  | 921167317  | 31.19295 | 9.90918   | 0.0010277  | 973  |
| 974  | 948676  | 924010424  | 31.20897 | 9.91257   | 0.0010267  | 974  |
| 975  | 950625  | 926859375  | 31.22499 | 9.91596   | 0.0010256  | 975  |
| 976  | 952576  | 929714176  | 31.24100 | 9.91935   | 0.0010246  | 976  |
| 977  | 954529  | 932574833  | 31.25700 | 9.92274   | 0.0010235  | 977  |
| 978  | 956484  | 935441352  | 31.27299 | 9.92612   | 0.0010225  | 978  |
| 979  | 958441  | 938313739  | 31.28898 | 9.92950   | 0.0010215  | 979  |
| 980  | 960400  | 941192000  | 31.30495 | 9.93288   | 0.0010204  | 980  |
| 981  | 962361  | 944076141  | 31.32092 | 9.93626   | 0.0010194  | 981  |
| 982  | 964324  | 946966168  | 31.33688 | 9.93964   | 0.0010183  | 982  |
| 983  | 966289  | 949862087  | 31.35283 | 9.94301   | 0.0010173  | 983  |
| 984  | 968256  | 952763904  | 31.36877 | 9.94638   | 0.0010163  | 984  |
| 985  | 970225  | 955671625  | 31.38471 | 9.94975   | 0.0010152  | 985  |
| 986  | 972196  | 958585256  | 31.40064 | 9.95311   | 0.0010142  | 986  |
| 987  | 974169  | 961504803  | 31.41656 | 9.95648   | 0.0010132  | 987  |
| 988  | 976144  | 964430272  | 31.43247 | 9.95984   | 0.0010121  | 988  |
| 989  | 978121  | 967361669  | 31.44837 | 9.96320   | 0.0010111  | 989  |
| 990  | 980100  | 970299000  | 31.46427 | 9.96655   | 0.0010101  | 990  |
| 991  | 982081  | 973242271  | 31.48015 | 9.96991   | 0.0010091  | 991  |
| 992  | 984064  | 976191488  | 31.49603 | 9.97326   | 0.0010081  | 992  |
| 993  | 986049  | 979146657  | 31.51190 | 9.97661   | 0.0010070  | 993  |
| 994  | 988036  | 982107784  | 31.52777 | 9.97996   | 0.0010060  | 994  |
| 995  | 990025  | 985074875  | 31.54362 | 9.98331   | 0.0010050  | 995  |
| 996  | 992016  | 988047936  | 31.55947 | 9.98665   | 0.0010040  | 996  |
| 997  | 994009  | 991026973  | 31.57531 | 9.98999   | 0.0010030  | 997  |
| 998  | 996004  | 994011992  | 31.59114 | 9.99333   | 0.0010020  | 998  |
| 999  | 998001  | 997002999  | 31.60696 | 9.99667   | 0.0010010  | 999  |
| 1000 | 1000000 | 1000000000 | 31.62278 | 10.00000  | 0.0010000  | 1000 |

**Powers, Roots, and Reciprocals From 1001 to 1050**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1001 | 1002001 | 1003003001 | 31.63858 | 10.00333  | 0.0009990  | 1001 |
| 1002 | 1004004 | 1006012008 | 31.65438 | 10.00666  | 0.0009980  | 1002 |
| 1003 | 1006009 | 1009027027 | 31.67018 | 10.00999  | 0.0009970  | 1003 |
| 1004 | 1008016 | 1012048064 | 31.68596 | 10.01332  | 0.0009960  | 1004 |
| 1005 | 1010025 | 1015075125 | 31.70173 | 10.01664  | 0.0009950  | 1005 |
| 1006 | 1012036 | 1018108216 | 31.71750 | 10.01996  | 0.0009940  | 1006 |
| 1007 | 1014049 | 1021147343 | 31.73326 | 10.02328  | 0.0009930  | 1007 |
| 1008 | 1016064 | 1024192512 | 31.74902 | 10.02660  | 0.0009921  | 1008 |
| 1009 | 1018081 | 1027243729 | 31.76476 | 10.02991  | 0.0009911  | 1009 |
| 1010 | 1020100 | 1030301000 | 31.78050 | 10.03322  | 0.0009901  | 1010 |
| 1011 | 1022121 | 1033364331 | 31.79623 | 10.03653  | 0.0009891  | 1011 |
| 1012 | 1024144 | 1036433728 | 31.81195 | 10.03984  | 0.0009881  | 1012 |
| 1013 | 1026169 | 1039509197 | 31.82766 | 10.04315  | 0.0009872  | 1013 |
| 1014 | 1028196 | 1042590744 | 31.84337 | 10.04645  | 0.0009862  | 1014 |
| 1015 | 1030225 | 1045678375 | 31.85906 | 10.04975  | 0.0009852  | 1015 |
| 1016 | 1032256 | 1048772096 | 31.87475 | 10.05305  | 0.0009843  | 1016 |
| 1017 | 1034289 | 1051871913 | 31.89044 | 10.05635  | 0.0009833  | 1017 |
| 1018 | 1036324 | 1054977832 | 31.90611 | 10.05964  | 0.0009823  | 1018 |
| 1019 | 1038361 | 1058089859 | 31.92178 | 10.06294  | 0.0009814  | 1019 |
| 1020 | 1040400 | 1061208000 | 31.93744 | 10.06623  | 0.0009804  | 1020 |
| 1021 | 1042441 | 1064332261 | 31.95309 | 10.06952  | 0.0009794  | 1021 |
| 1022 | 1044484 | 1067462648 | 31.96873 | 10.07280  | 0.0009785  | 1022 |
| 1023 | 1046529 | 1070599167 | 31.98437 | 10.07609  | 0.0009775  | 1023 |
| 1024 | 1048576 | 1073741824 | 32.00000 | 10.07937  | 0.0009766  | 1024 |
| 1025 | 1050625 | 1076890625 | 32.01562 | 10.08265  | 0.0009756  | 1025 |
| 1026 | 1052676 | 1080045576 | 32.03123 | 10.08593  | 0.0009747  | 1026 |
| 1027 | 1054729 | 1083206683 | 32.04684 | 10.08920  | 0.0009737  | 1027 |
| 1028 | 1056784 | 1086373952 | 32.06244 | 10.09248  | 0.0009728  | 1028 |
| 1029 | 1058841 | 1089547389 | 32.07803 | 10.09575  | 0.0009718  | 1029 |
| 1030 | 1060900 | 1092727000 | 32.09361 | 10.09902  | 0.0009709  | 1030 |
| 1031 | 1062961 | 1095912791 | 32.10919 | 10.10228  | 0.0009699  | 1031 |
| 1032 | 1065024 | 1099104768 | 32.12476 | 10.10555  | 0.0009690  | 1032 |
| 1033 | 1067089 | 1102302937 | 32.14032 | 10.10881  | 0.0009681  | 1033 |
| 1034 | 1069156 | 1105507304 | 32.15587 | 10.11207  | 0.0009671  | 1034 |
| 1035 | 1071225 | 1108717875 | 32.17142 | 10.11533  | 0.0009662  | 1035 |
| 1036 | 1073296 | 1111934656 | 32.18695 | 10.11859  | 0.0009653  | 1036 |
| 1037 | 1075369 | 1115157653 | 32.20248 | 10.12184  | 0.0009643  | 1037 |
| 1038 | 1077444 | 1118386872 | 32.21801 | 10.12510  | 0.0009634  | 1038 |
| 1039 | 1079521 | 1121622319 | 32.23352 | 10.12835  | 0.0009625  | 1039 |
| 1040 | 1081600 | 1124864000 | 32.24903 | 10.13159  | 0.0009615  | 1040 |
| 1041 | 1083681 | 1128111921 | 32.26453 | 10.13484  | 0.0009606  | 1041 |
| 1042 | 1085764 | 1131366088 | 32.28002 | 10.13808  | 0.0009597  | 1042 |
| 1043 | 1087849 | 1134626507 | 32.29551 | 10.14133  | 0.0009588  | 1043 |
| 1044 | 1089936 | 1137893184 | 32.31099 | 10.14457  | 0.0009579  | 1044 |
| 1045 | 1092025 | 1141166125 | 32.32646 | 10.14780  | 0.0009569  | 1045 |
| 1046 | 1094116 | 1144445336 | 32.34192 | 10.15104  | 0.0009560  | 1046 |
| 1047 | 1096209 | 1147730823 | 32.35738 | 10.15427  | 0.0009551  | 1047 |
| 1048 | 1098304 | 1151022592 | 32.37283 | 10.15751  | 0.0009542  | 1048 |
| 1049 | 1100401 | 1154320649 | 32.38827 | 10.16074  | 0.0009533  | 1049 |
| 1050 | 1102500 | 1157625000 | 32.40370 | 10.16396  | 0.0009524  | 1050 |

**Powers, Roots, and Reciprocals From 1051 to 1100**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1051 | 1104601 | 1160935651 | 32.41913 | 10.16719  | 0.0009515  | 1051 |
| 1052 | 1106704 | 1164252608 | 32.43455 | 10.17041  | 0.0009506  | 1052 |
| 1053 | 1108809 | 1167575877 | 32.44996 | 10.17363  | 0.0009497  | 1053 |
| 1054 | 1110916 | 1170905464 | 32.46537 | 10.17685  | 0.0009488  | 1054 |
| 1055 | 1113025 | 1174241375 | 32.48076 | 10.18007  | 0.0009479  | 1055 |
| 1056 | 1115136 | 1177583616 | 32.49615 | 10.18329  | 0.0009470  | 1056 |
| 1057 | 1117249 | 1180932193 | 32.51154 | 10.18650  | 0.0009461  | 1057 |
| 1058 | 1119364 | 1184287112 | 32.52691 | 10.18971  | 0.0009452  | 1058 |
| 1059 | 1121481 | 1187648379 | 32.54228 | 10.19292  | 0.0009443  | 1059 |
| 1060 | 1123600 | 1191016000 | 32.55764 | 10.19613  | 0.0009434  | 1060 |
| 1061 | 1125721 | 1194389981 | 32.57299 | 10.19933  | 0.0009425  | 1061 |
| 1062 | 1127844 | 1197770328 | 32.58834 | 10.20254  | 0.0009416  | 1062 |
| 1063 | 1129969 | 1201157047 | 32.60368 | 10.20574  | 0.0009407  | 1063 |
| 1064 | 1132096 | 1204550144 | 32.61901 | 10.20894  | 0.0009398  | 1064 |
| 1065 | 1134225 | 1207949625 | 32.63434 | 10.21213  | 0.0009390  | 1065 |
| 1066 | 1136356 | 1211355496 | 32.64966 | 10.21533  | 0.0009381  | 1066 |
| 1067 | 1138489 | 1214767763 | 32.66497 | 10.21852  | 0.0009372  | 1067 |
| 1068 | 1140624 | 1218186432 | 32.68027 | 10.22171  | 0.0009363  | 1068 |
| 1069 | 1142761 | 1221611509 | 32.69557 | 10.22490  | 0.0009355  | 1069 |
| 1070 | 1144900 | 1225043000 | 32.71085 | 10.22809  | 0.0009346  | 1070 |
| 1071 | 1147041 | 1228480911 | 32.72614 | 10.23128  | 0.0009337  | 1071 |
| 1072 | 1149184 | 1231925248 | 32.74141 | 10.23446  | 0.0009328  | 1072 |
| 1073 | 1151329 | 1235376017 | 32.75668 | 10.23764  | 0.0009320  | 1073 |
| 1074 | 1153476 | 1238833224 | 32.77194 | 10.24082  | 0.0009311  | 1074 |
| 1075 | 1155625 | 1242296875 | 32.78719 | 10.24400  | 0.0009302  | 1075 |
| 1076 | 1157776 | 1245766976 | 32.80244 | 10.24717  | 0.0009294  | 1076 |
| 1077 | 1159929 | 1249243533 | 32.81768 | 10.25035  | 0.0009285  | 1077 |
| 1078 | 1162084 | 1252726552 | 32.83291 | 10.25352  | 0.0009276  | 1078 |
| 1079 | 1164241 | 1256216039 | 32.84814 | 10.25669  | 0.0009268  | 1079 |
| 1080 | 1166400 | 1259712000 | 32.86335 | 10.25986  | 0.0009259  | 1080 |
| 1081 | 1168561 | 1263214441 | 32.87856 | 10.26302  | 0.0009251  | 1081 |
| 1082 | 1170724 | 1266723368 | 32.89377 | 10.26619  | 0.0009242  | 1082 |
| 1083 | 1172889 | 1270238787 | 32.90897 | 10.26935  | 0.0009234  | 1083 |
| 1084 | 1175056 | 1273760704 | 32.92416 | 10.27251  | 0.0009225  | 1084 |
| 1085 | 1177225 | 1277289125 | 32.93934 | 10.27566  | 0.0009217  | 1085 |
| 1086 | 1179396 | 1280824056 | 32.95451 | 10.27882  | 0.0009208  | 1086 |
| 1087 | 1181569 | 1284365503 | 32.96968 | 10.28197  | 0.0009200  | 1087 |
| 1088 | 1183744 | 1287913472 | 32.98485 | 10.28513  | 0.0009191  | 1088 |
| 1089 | 1185921 | 1291467969 | 33.00000 | 10.28828  | 0.0009183  | 1089 |
| 1090 | 1188100 | 1295029000 | 33.01515 | 10.29142  | 0.0009174  | 1090 |
| 1091 | 1190281 | 1298596571 | 33.03029 | 10.29457  | 0.0009166  | 1091 |
| 1092 | 1192464 | 1302170688 | 33.04542 | 10.29772  | 0.0009158  | 1092 |
| 1093 | 1194649 | 1305751357 | 33.06055 | 10.30086  | 0.0009149  | 1093 |
| 1094 | 1196836 | 1309338584 | 33.07567 | 10.30400  | 0.0009141  | 1094 |
| 1095 | 1199025 | 1312932375 | 33.09078 | 10.30714  | 0.0009132  | 1095 |
| 1096 | 1201216 | 1316532736 | 33.10589 | 10.31027  | 0.0009124  | 1096 |
| 1097 | 1203409 | 1320139673 | 33.12099 | 10.31341  | 0.0009116  | 1097 |
| 1098 | 1205604 | 1323753192 | 33.13608 | 10.31654  | 0.0009107  | 1098 |
| 1099 | 1207801 | 1327373299 | 33.15117 | 10.31967  | 0.0009099  | 1099 |
| 1100 | 1210000 | 1331000000 | 33.16625 | 10.32280  | 0.0009091  | 1100 |

**Powers, Roots, and Reciprocals From 1101 to 1150**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1101 | 1212201 | 1334633301 | 33.18132 | 10.32593  | 0.0009083  | 1101 |
| 1102 | 1214404 | 1338273208 | 33.19639 | 10.32905  | 0.0009074  | 1102 |
| 1103 | 1216609 | 1341919727 | 33.21144 | 10.33218  | 0.0009066  | 1103 |
| 1104 | 1218816 | 1345572864 | 33.22650 | 10.33530  | 0.0009058  | 1104 |
| 1105 | 1221025 | 1349232625 | 33.24154 | 10.33842  | 0.0009050  | 1105 |
| 1106 | 1223236 | 1352899016 | 33.25658 | 10.34154  | 0.0009042  | 1106 |
| 1107 | 1225449 | 1356572043 | 33.27161 | 10.34465  | 0.0009033  | 1107 |
| 1108 | 1227664 | 1360251712 | 33.28663 | 10.34777  | 0.0009025  | 1108 |
| 1109 | 1229881 | 1363938029 | 33.30165 | 10.35088  | 0.0009017  | 1109 |
| 1110 | 1232100 | 1367631000 | 33.31666 | 10.35399  | 0.0009009  | 1110 |
| 1111 | 1234321 | 1371330631 | 33.33167 | 10.35710  | 0.0009001  | 1111 |
| 1112 | 1236544 | 1375036928 | 33.34666 | 10.36020  | 0.0008993  | 1112 |
| 1113 | 1238769 | 1378749897 | 33.36165 | 10.36331  | 0.0008985  | 1113 |
| 1114 | 1240996 | 1382469544 | 33.37664 | 10.36641  | 0.0008977  | 1114 |
| 1115 | 1243225 | 1386195875 | 33.39162 | 10.36951  | 0.0008969  | 1115 |
| 1116 | 1245456 | 1389928896 | 33.40659 | 10.37261  | 0.0008961  | 1116 |
| 1117 | 1247689 | 1393668613 | 33.42155 | 10.37571  | 0.0008953  | 1117 |
| 1118 | 1249924 | 1397415032 | 33.43651 | 10.37880  | 0.0008945  | 1118 |
| 1119 | 1252161 | 1401168159 | 33.45146 | 10.38190  | 0.0008937  | 1119 |
| 1120 | 1254400 | 1404928000 | 33.46640 | 10.38499  | 0.0008929  | 1120 |
| 1121 | 1256641 | 1408694561 | 33.48134 | 10.38808  | 0.0008921  | 1121 |
| 1122 | 1258884 | 1412467848 | 33.49627 | 10.39117  | 0.0008913  | 1122 |
| 1123 | 1261129 | 1416247867 | 33.51119 | 10.39425  | 0.0008905  | 1123 |
| 1124 | 1263376 | 1420034624 | 33.52611 | 10.39734  | 0.0008897  | 1124 |
| 1125 | 1265625 | 1423828125 | 33.54102 | 10.40042  | 0.0008889  | 1125 |
| 1126 | 1267876 | 1427628376 | 33.55592 | 10.40350  | 0.0008881  | 1126 |
| 1127 | 1270129 | 1431435383 | 33.57082 | 10.40658  | 0.0008873  | 1127 |
| 1128 | 1272384 | 1435249152 | 33.58571 | 10.40966  | 0.0008865  | 1128 |
| 1129 | 1274641 | 1439069689 | 33.60060 | 10.41273  | 0.0008857  | 1129 |
| 1130 | 1276900 | 1442897000 | 33.61547 | 10.41580  | 0.0008850  | 1130 |
| 1131 | 1279161 | 1446731091 | 33.63034 | 10.41888  | 0.0008842  | 1131 |
| 1132 | 1281424 | 1450571968 | 33.64521 | 10.42195  | 0.0008834  | 1132 |
| 1133 | 1283689 | 1454419637 | 33.66007 | 10.42501  | 0.0008826  | 1133 |
| 1134 | 1285956 | 1458274104 | 33.67492 | 10.42808  | 0.0008818  | 1134 |
| 1135 | 1288225 | 1462135375 | 33.68976 | 10.43114  | 0.0008811  | 1135 |
| 1136 | 1290496 | 1466003456 | 33.70460 | 10.43421  | 0.0008803  | 1136 |
| 1137 | 1292769 | 1469878353 | 33.71943 | 10.43727  | 0.0008795  | 1137 |
| 1138 | 1295044 | 1473760072 | 33.73426 | 10.44033  | 0.0008787  | 1138 |
| 1139 | 1297321 | 1477648619 | 33.74907 | 10.44338  | 0.0008780  | 1139 |
| 1140 | 1299600 | 1481544000 | 33.76389 | 10.44644  | 0.0008772  | 1140 |
| 1141 | 1301881 | 1485446221 | 33.77869 | 10.44949  | 0.0008764  | 1141 |
| 1142 | 1304164 | 1489355288 | 33.79349 | 10.45254  | 0.0008757  | 1142 |
| 1143 | 1306449 | 1493271207 | 33.80828 | 10.45559  | 0.0008749  | 1143 |
| 1144 | 1308736 | 1497193984 | 33.82307 | 10.45864  | 0.0008741  | 1144 |
| 1145 | 1311025 | 1501123625 | 33.83785 | 10.46169  | 0.0008734  | 1145 |
| 1146 | 1313316 | 1505060136 | 33.85262 | 10.46473  | 0.0008726  | 1146 |
| 1147 | 1315609 | 1509003523 | 33.86739 | 10.46778  | 0.0008718  | 1147 |
| 1148 | 1317904 | 1512953792 | 33.88215 | 10.47082  | 0.0008711  | 1148 |
| 1149 | 1320201 | 1516910949 | 33.89690 | 10.47386  | 0.0008703  | 1149 |
| 1150 | 1322500 | 1520875000 | 33.91165 | 10.47690  | 0.0008696  | 1150 |

**Powers, Roots, and Reciprocals From 1151 to 1200**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1151 | 1324801 | 1524845951 | 33.92639 | 10.47993  | 0.0008688  | 1151 |
| 1152 | 1327104 | 1528823808 | 33.94113 | 10.48297  | 0.0008681  | 1152 |
| 1153 | 1329409 | 1532808577 | 33.95585 | 10.48600  | 0.0008673  | 1153 |
| 1154 | 1331716 | 1536800264 | 33.97058 | 10.48903  | 0.0008666  | 1154 |
| 1155 | 1334025 | 1540798875 | 33.98529 | 10.49206  | 0.0008658  | 1155 |
| 1156 | 1336336 | 1544804416 | 34.00000 | 10.49508  | 0.0008651  | 1156 |
| 1157 | 1338649 | 1548816893 | 34.01470 | 10.49811  | 0.0008643  | 1157 |
| 1158 | 1340964 | 1552836312 | 34.02940 | 10.50113  | 0.0008636  | 1158 |
| 1159 | 1343281 | 1556862679 | 34.04409 | 10.50416  | 0.0008628  | 1159 |
| 1160 | 1345600 | 1560896000 | 34.05877 | 10.50718  | 0.0008621  | 1160 |
| 1161 | 1347921 | 1564936281 | 34.07345 | 10.51019  | 0.0008613  | 1161 |
| 1162 | 1350244 | 1568983528 | 34.08812 | 10.51321  | 0.0008606  | 1162 |
| 1163 | 1352569 | 1573037747 | 34.10279 | 10.51623  | 0.0008598  | 1163 |
| 1164 | 1354896 | 1577098944 | 34.11744 | 10.51924  | 0.0008591  | 1164 |
| 1165 | 1357225 | 1581167125 | 34.13210 | 10.52225  | 0.0008584  | 1165 |
| 1166 | 1359556 | 1585242296 | 34.14674 | 10.52526  | 0.0008576  | 1166 |
| 1167 | 1361889 | 1589324463 | 34.16138 | 10.52827  | 0.0008569  | 1167 |
| 1168 | 1364224 | 1593413632 | 34.17601 | 10.53127  | 0.0008562  | 1168 |
| 1169 | 1366561 | 1597509809 | 34.19064 | 10.53428  | 0.0008554  | 1169 |
| 1170 | 1368900 | 1601613000 | 34.20526 | 10.53728  | 0.0008547  | 1170 |
| 1171 | 1371241 | 1605723211 | 34.21988 | 10.54028  | 0.0008540  | 1171 |
| 1172 | 1373584 | 1609840448 | 34.23449 | 10.54328  | 0.0008532  | 1172 |
| 1173 | 1375929 | 1613964717 | 34.24909 | 10.54628  | 0.0008525  | 1173 |
| 1174 | 1378276 | 1618096024 | 34.26368 | 10.54928  | 0.0008518  | 1174 |
| 1175 | 1380625 | 1622234375 | 34.27827 | 10.55227  | 0.0008511  | 1175 |
| 1176 | 1382976 | 1626379776 | 34.29286 | 10.55526  | 0.0008503  | 1176 |
| 1177 | 1385329 | 1630532233 | 34.30743 | 10.55826  | 0.0008496  | 1177 |
| 1178 | 1387684 | 1634691752 | 34.32200 | 10.56124  | 0.0008489  | 1178 |
| 1179 | 1390041 | 1638858339 | 34.33657 | 10.56423  | 0.0008482  | 1179 |
| 1180 | 1392400 | 1643032000 | 34.35113 | 10.56722  | 0.0008475  | 1180 |
| 1181 | 1394761 | 1647212741 | 34.36568 | 10.57020  | 0.0008467  | 1181 |
| 1182 | 1397124 | 1651400568 | 34.38023 | 10.57318  | 0.0008460  | 1182 |
| 1183 | 1399489 | 1655595487 | 34.39477 | 10.57617  | 0.0008453  | 1183 |
| 1184 | 1401856 | 1659797504 | 34.40930 | 10.57914  | 0.0008446  | 1184 |
| 1185 | 1404225 | 1664006625 | 34.42383 | 10.58212  | 0.0008439  | 1185 |
| 1186 | 1406596 | 1668222856 | 34.43835 | 10.58510  | 0.0008432  | 1186 |
| 1187 | 1408969 | 1672446203 | 34.45287 | 10.58807  | 0.0008425  | 1187 |
| 1188 | 1411344 | 1676676672 | 34.46738 | 10.59105  | 0.0008418  | 1188 |
| 1189 | 1413721 | 1680914269 | 34.48188 | 10.59402  | 0.0008410  | 1189 |
| 1190 | 1416100 | 1685159000 | 34.49638 | 10.59699  | 0.0008403  | 1190 |
| 1191 | 1418481 | 1689410871 | 34.51087 | 10.59995  | 0.0008396  | 1191 |
| 1192 | 1420864 | 1693669888 | 34.52535 | 10.60292  | 0.0008389  | 1192 |
| 1193 | 1423249 | 1697936057 | 34.53983 | 10.60588  | 0.0008382  | 1193 |
| 1194 | 1425636 | 1702209384 | 34.55431 | 10.60885  | 0.0008375  | 1194 |
| 1195 | 1428025 | 1706489875 | 34.56877 | 10.61181  | 0.0008368  | 1195 |
| 1196 | 1430416 | 1710777536 | 34.58323 | 10.61477  | 0.0008361  | 1196 |
| 1197 | 1432809 | 1715072373 | 34.59769 | 10.61772  | 0.0008354  | 1197 |
| 1198 | 1435204 | 1719374392 | 34.61214 | 10.62068  | 0.0008347  | 1198 |
| 1199 | 1437601 | 1723683599 | 34.62658 | 10.62363  | 0.0008340  | 1199 |
| 1200 | 1440000 | 1728000000 | 34.64102 | 10.62659  | 0.0008333  | 1200 |



## Powers, Roots, and Reciprocals From 1201 to 1250

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1201 | 1442401 | 1732323601 | 34.65545 | 10.62954  | 0.0008326  | 1201 |
| 1202 | 1444804 | 1736654408 | 34.66987 | 10.63249  | 0.0008319  | 1202 |
| 1203 | 1447209 | 1740992427 | 34.68429 | 10.63543  | 0.0008313  | 1203 |
| 1204 | 1449616 | 1745337664 | 34.69870 | 10.63838  | 0.0008306  | 1204 |
| 1205 | 1452025 | 1749690125 | 34.71311 | 10.64132  | 0.0008299  | 1205 |
| 1206 | 1454436 | 1754049816 | 34.72751 | 10.64427  | 0.0008292  | 1206 |
| 1207 | 1456849 | 1758416743 | 34.74191 | 10.64721  | 0.0008285  | 1207 |
| 1208 | 1459264 | 1762790912 | 34.75629 | 10.65015  | 0.0008278  | 1208 |
| 1209 | 1461681 | 1767172329 | 34.77068 | 10.65309  | 0.0008271  | 1209 |
| 1210 | 1464100 | 1771561000 | 34.78505 | 10.65602  | 0.0008264  | 1210 |
| 1211 | 1466521 | 1775956931 | 34.79943 | 10.65896  | 0.0008258  | 1211 |
| 1212 | 1468944 | 1780360128 | 34.81379 | 10.66189  | 0.0008251  | 1212 |
| 1213 | 1471369 | 1784770597 | 34.82815 | 10.66482  | 0.0008244  | 1213 |
| 1214 | 1473796 | 1789188344 | 34.84250 | 10.66775  | 0.0008237  | 1214 |
| 1215 | 1476225 | 1793613375 | 34.85685 | 10.67068  | 0.0008230  | 1215 |
| 1216 | 1478656 | 1798045696 | 34.87119 | 10.67361  | 0.0008224  | 1216 |
| 1217 | 1481089 | 1802485313 | 34.88553 | 10.67653  | 0.0008217  | 1217 |
| 1218 | 1483524 | 1806932232 | 34.89986 | 10.67946  | 0.0008210  | 1218 |
| 1219 | 1485961 | 1811386459 | 34.91418 | 10.68238  | 0.0008203  | 1219 |
| 1220 | 1488400 | 1815848000 | 34.92850 | 10.68530  | 0.0008197  | 1220 |
| 1221 | 1490841 | 1820316861 | 34.94281 | 10.68822  | 0.0008190  | 1221 |
| 1222 | 1493284 | 1824793048 | 34.95712 | 10.69113  | 0.0008183  | 1222 |
| 1223 | 1495729 | 1829276567 | 34.97142 | 10.69405  | 0.0008177  | 1223 |
| 1224 | 1498176 | 1833767424 | 34.98571 | 10.69696  | 0.0008170  | 1224 |
| 1225 | 1500625 | 1838265625 | 35.00000 | 10.69987  | 0.0008163  | 1225 |
| 1226 | 1503076 | 1842771176 | 35.01428 | 10.70279  | 0.0008157  | 1226 |
| 1227 | 1505529 | 1847284083 | 35.02856 | 10.70569  | 0.0008150  | 1227 |
| 1228 | 1507984 | 1851804352 | 35.04283 | 10.70860  | 0.0008143  | 1228 |
| 1229 | 1510441 | 1856331989 | 35.05710 | 10.71151  | 0.0008137  | 1229 |
| 1230 | 1512900 | 1860867000 | 35.07136 | 10.71441  | 0.0008130  | 1230 |
| 1231 | 1515361 | 1865409391 | 35.08561 | 10.71732  | 0.0008123  | 1231 |
| 1232 | 1517824 | 1869959168 | 35.09986 | 10.72022  | 0.0008117  | 1232 |
| 1233 | 1520289 | 1874516337 | 35.11410 | 10.72312  | 0.0008110  | 1233 |
| 1234 | 1522756 | 1879080904 | 35.12834 | 10.72601  | 0.0008104  | 1234 |
| 1235 | 1525225 | 1883652875 | 35.14257 | 10.72891  | 0.0008097  | 1235 |
| 1236 | 1527696 | 1888232256 | 35.15679 | 10.73181  | 0.0008091  | 1236 |
| 1237 | 1530169 | 1892819053 | 35.17101 | 10.73470  | 0.0008084  | 1237 |
| 1238 | 1532644 | 1897413272 | 35.18522 | 10.73759  | 0.0008078  | 1238 |
| 1239 | 1535121 | 1902014919 | 35.19943 | 10.74048  | 0.0008071  | 1239 |
| 1240 | 1537600 | 1906624000 | 35.21363 | 10.74337  | 0.0008065  | 1240 |
| 1241 | 1540081 | 1911240521 | 35.22783 | 10.74626  | 0.0008058  | 1241 |
| 1242 | 1542564 | 1915864488 | 35.24202 | 10.74914  | 0.0008052  | 1242 |
| 1243 | 1545049 | 1920495907 | 35.25621 | 10.75203  | 0.0008045  | 1243 |
| 1244 | 1547536 | 1925134784 | 35.27038 | 10.75491  | 0.0008039  | 1244 |
| 1245 | 1550025 | 1929781125 | 35.28456 | 10.75779  | 0.0008032  | 1245 |
| 1246 | 1552516 | 1934434936 | 35.29873 | 10.76067  | 0.0008026  | 1246 |
| 1247 | 1555009 | 1939096223 | 35.31289 | 10.76355  | 0.0008019  | 1247 |
| 1248 | 1557504 | 1943764992 | 35.32704 | 10.76643  | 0.0008013  | 1248 |
| 1249 | 1560001 | 1948441249 | 35.34119 | 10.76930  | 0.0008006  | 1249 |
| 1250 | 1562500 | 1953125000 | 35.35534 | 10.77217  | 0.0008000  | 1250 |

**Powers, Roots, and Reciprocals From 1251 to 1300**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1251 | 1565001 | 1957816251 | 35.36948 | 10.77505  | 0.0007994  | 1251 |
| 1252 | 1567504 | 1962515008 | 35.38361 | 10.77792  | 0.0007987  | 1252 |
| 1253 | 1570009 | 1967221277 | 35.39774 | 10.78078  | 0.0007981  | 1253 |
| 1254 | 1572516 | 1971935064 | 35.41186 | 10.78365  | 0.0007974  | 1254 |
| 1255 | 1575025 | 1976656375 | 35.42598 | 10.78652  | 0.0007968  | 1255 |
| 1256 | 1577536 | 1981385216 | 35.44009 | 10.78938  | 0.0007962  | 1256 |
| 1257 | 1580049 | 1986121593 | 35.45420 | 10.79224  | 0.0007955  | 1257 |
| 1258 | 1582564 | 1990865512 | 35.46830 | 10.79511  | 0.0007949  | 1258 |
| 1259 | 1585081 | 1995616979 | 35.48239 | 10.79796  | 0.0007943  | 1259 |
| 1260 | 1587600 | 2000376000 | 35.49648 | 10.80082  | 0.0007937  | 1260 |
| 1261 | 1590121 | 2005142581 | 35.51056 | 10.80368  | 0.0007930  | 1261 |
| 1262 | 1592644 | 2009916728 | 35.52464 | 10.80653  | 0.0007924  | 1262 |
| 1263 | 1595169 | 2014698447 | 35.53871 | 10.80939  | 0.0007918  | 1263 |
| 1264 | 1597696 | 2019487744 | 35.55278 | 10.81224  | 0.0007911  | 1264 |
| 1265 | 1600225 | 2024284625 | 35.56684 | 10.81509  | 0.0007905  | 1265 |
| 1266 | 1602756 | 2029089096 | 35.58089 | 10.81794  | 0.0007899  | 1266 |
| 1267 | 1605289 | 2033901163 | 35.59494 | 10.82079  | 0.0007893  | 1267 |
| 1268 | 1607824 | 2038720832 | 35.60899 | 10.82363  | 0.0007886  | 1268 |
| 1269 | 1610361 | 2043548109 | 35.62303 | 10.82648  | 0.0007880  | 1269 |
| 1270 | 1612900 | 2048383000 | 35.63706 | 10.82932  | 0.0007874  | 1270 |
| 1271 | 1615441 | 2053225511 | 35.65109 | 10.83216  | 0.0007868  | 1271 |
| 1272 | 1617984 | 2058075648 | 35.66511 | 10.83500  | 0.0007862  | 1272 |
| 1273 | 1620529 | 2062933417 | 35.67913 | 10.83784  | 0.0007855  | 1273 |
| 1274 | 1623076 | 2067798824 | 35.69314 | 10.84068  | 0.0007849  | 1274 |
| 1275 | 1625625 | 2072671875 | 35.70714 | 10.84351  | 0.0007843  | 1275 |
| 1276 | 1628176 | 2077552576 | 35.72114 | 10.84635  | 0.0007837  | 1276 |
| 1277 | 1630729 | 2082440933 | 35.73514 | 10.84918  | 0.0007831  | 1277 |
| 1278 | 1633284 | 2087336952 | 35.74913 | 10.85201  | 0.0007825  | 1278 |
| 1279 | 1635841 | 2092240639 | 35.76311 | 10.85484  | 0.0007819  | 1279 |
| 1280 | 1638400 | 2097152000 | 35.77709 | 10.85767  | 0.0007813  | 1280 |
| 1281 | 1640961 | 2102071041 | 35.79106 | 10.86050  | 0.0007806  | 1281 |
| 1282 | 1643524 | 2106997768 | 35.80503 | 10.86332  | 0.0007800  | 1282 |
| 1283 | 1646089 | 2111932187 | 35.81899 | 10.86615  | 0.0007794  | 1283 |
| 1284 | 1648656 | 2116874304 | 35.83295 | 10.86897  | 0.0007788  | 1284 |
| 1285 | 1651225 | 2121824125 | 35.84690 | 10.87179  | 0.0007782  | 1285 |
| 1286 | 1653796 | 2126781656 | 35.86084 | 10.87461  | 0.0007776  | 1286 |
| 1287 | 1656369 | 2131746903 | 35.87478 | 10.87743  | 0.0007770  | 1287 |
| 1288 | 1658944 | 2136719872 | 35.88872 | 10.88024  | 0.0007764  | 1288 |
| 1289 | 1661521 | 2141700569 | 35.90265 | 10.88306  | 0.0007758  | 1289 |
| 1290 | 1664100 | 2146689000 | 35.91657 | 10.88587  | 0.0007752  | 1290 |
| 1291 | 1666681 | 2151685171 | 35.93049 | 10.88868  | 0.0007746  | 1291 |
| 1292 | 1669264 | 2156689088 | 35.94440 | 10.89150  | 0.0007740  | 1292 |
| 1293 | 1671849 | 2161700757 | 35.95831 | 10.89430  | 0.0007734  | 1293 |
| 1294 | 1674436 | 2166720184 | 35.97221 | 10.89711  | 0.0007728  | 1294 |
| 1295 | 1677025 | 2171747375 | 35.98611 | 10.89992  | 0.0007722  | 1295 |
| 1296 | 1679616 | 2176782336 | 36.00000 | 10.90272  | 0.0007716  | 1296 |
| 1297 | 1682209 | 2181825073 | 36.01389 | 10.90553  | 0.0007710  | 1297 |
| 1298 | 1684804 | 2186875592 | 36.02777 | 10.90833  | 0.0007704  | 1298 |
| 1299 | 1687401 | 2191933899 | 36.04164 | 10.91113  | 0.0007698  | 1299 |
| 1300 | 1690000 | 2197000000 | 36.05551 | 10.91393  | 0.0007692  | 1300 |

**Powers, Roots, and Reciprocals From 1301 to 1350**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1301 | 1692601 | 2202073901 | 36.06938 | 10.91673  | 0.0007686  | 1301 |
| 1302 | 1695204 | 2207155608 | 36.08324 | 10.91952  | 0.0007680  | 1302 |
| 1303 | 1697809 | 2212245127 | 36.09709 | 10.92232  | 0.0007675  | 1303 |
| 1304 | 1700416 | 2217342464 | 36.11094 | 10.92511  | 0.0007669  | 1304 |
| 1305 | 1703025 | 2222447625 | 36.12478 | 10.92790  | 0.0007663  | 1305 |
| 1306 | 1705636 | 2227560616 | 36.13862 | 10.93069  | 0.0007657  | 1306 |
| 1307 | 1708249 | 2232681443 | 36.15245 | 10.93348  | 0.0007651  | 1307 |
| 1308 | 1710864 | 2237810112 | 36.16628 | 10.93627  | 0.0007645  | 1308 |
| 1309 | 1713481 | 2242946629 | 36.18011 | 10.93906  | 0.0007639  | 1309 |
| 1310 | 1716100 | 2248091000 | 36.19392 | 10.94184  | 0.0007634  | 1310 |
| 1311 | 1718721 | 2253243231 | 36.20773 | 10.94463  | 0.0007628  | 1311 |
| 1312 | 1721344 | 2258403328 | 36.22154 | 10.94741  | 0.0007622  | 1312 |
| 1313 | 1723969 | 2263571297 | 36.23534 | 10.95019  | 0.0007616  | 1313 |
| 1314 | 1726596 | 2268747144 | 36.24914 | 10.95297  | 0.0007610  | 1314 |
| 1315 | 1729225 | 2273930875 | 36.26293 | 10.95575  | 0.0007605  | 1315 |
| 1316 | 1731856 | 2279122496 | 36.27671 | 10.95852  | 0.0007599  | 1316 |
| 1317 | 1734489 | 2284322013 | 36.29049 | 10.96130  | 0.0007593  | 1317 |
| 1318 | 1737124 | 2289529432 | 36.30427 | 10.96407  | 0.0007587  | 1318 |
| 1319 | 1739761 | 2294744759 | 36.31804 | 10.96684  | 0.0007582  | 1319 |
| 1320 | 1742400 | 2299968000 | 36.33180 | 10.96961  | 0.0007576  | 1320 |
| 1321 | 1745041 | 2305199161 | 36.34556 | 10.97238  | 0.0007570  | 1321 |
| 1322 | 1747684 | 2310438248 | 36.35932 | 10.97515  | 0.0007564  | 1322 |
| 1323 | 1750329 | 2315685267 | 36.37307 | 10.97792  | 0.0007559  | 1323 |
| 1324 | 1752976 | 2320940224 | 36.38681 | 10.98068  | 0.0007553  | 1324 |
| 1325 | 1755625 | 2326203125 | 36.40055 | 10.98345  | 0.0007547  | 1325 |
| 1326 | 1758276 | 2331473976 | 36.41428 | 10.98621  | 0.0007541  | 1326 |
| 1327 | 1760929 | 2336752783 | 36.42801 | 10.98897  | 0.0007536  | 1327 |
| 1328 | 1763584 | 2342039552 | 36.44173 | 10.99173  | 0.0007530  | 1328 |
| 1329 | 1766241 | 2347334289 | 36.45545 | 10.99449  | 0.0007524  | 1329 |
| 1330 | 1768900 | 2352637000 | 36.46917 | 10.99724  | 0.0007519  | 1330 |
| 1331 | 1771561 | 2357947691 | 36.48287 | 11.00000  | 0.0007513  | 1331 |
| 1332 | 1774224 | 2363266368 | 36.49658 | 11.00275  | 0.0007508  | 1332 |
| 1333 | 1776889 | 2368593037 | 36.51027 | 11.00551  | 0.0007502  | 1333 |
| 1334 | 1779556 | 2373927704 | 36.52396 | 11.00826  | 0.0007496  | 1334 |
| 1335 | 1782225 | 2379270375 | 36.53765 | 11.01101  | 0.0007491  | 1335 |
| 1336 | 1784896 | 2384621056 | 36.55133 | 11.01376  | 0.0007485  | 1336 |
| 1337 | 1787569 | 2389979753 | 36.56501 | 11.01650  | 0.0007479  | 1337 |
| 1338 | 1790244 | 2395346472 | 36.57868 | 11.01925  | 0.0007474  | 1338 |
| 1339 | 1792921 | 2400721219 | 36.59235 | 11.02199  | 0.0007468  | 1339 |
| 1340 | 1795600 | 2406104000 | 36.60601 | 11.02474  | 0.0007463  | 1340 |
| 1341 | 1798281 | 2411494821 | 36.61967 | 11.02748  | 0.0007457  | 1341 |
| 1342 | 1800964 | 2416893688 | 36.63332 | 11.03022  | 0.0007452  | 1342 |
| 1343 | 1803649 | 2422300607 | 36.64696 | 11.03296  | 0.0007446  | 1343 |
| 1344 | 1806336 | 2427715584 | 36.66061 | 11.03570  | 0.0007440  | 1344 |
| 1345 | 1809025 | 2433138625 | 36.67424 | 11.03843  | 0.0007435  | 1345 |
| 1346 | 1811716 | 2438569736 | 36.68787 | 11.04117  | 0.0007429  | 1346 |
| 1347 | 1814409 | 2444008923 | 36.70150 | 11.04390  | 0.0007424  | 1347 |
| 1348 | 1817104 | 2449456192 | 36.71512 | 11.04663  | 0.0007418  | 1348 |
| 1349 | 1819801 | 2454911549 | 36.72874 | 11.04936  | 0.0007413  | 1349 |
| 1350 | 1822500 | 2460375000 | 36.74235 | 11.05209  | 0.0007407  | 1350 |

**Powers, Roots, and Reciprocals From 1351 to 1400**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1351 | 1825201 | 2465846551 | 36.75595 | 11.05482  | 0.0007402  | 1351 |
| 1352 | 1827904 | 2471326208 | 36.76955 | 11.05755  | 0.0007396  | 1352 |
| 1353 | 1830609 | 2476813977 | 36.78315 | 11.06028  | 0.0007391  | 1353 |
| 1354 | 1833316 | 2482309864 | 36.79674 | 11.06300  | 0.0007386  | 1354 |
| 1355 | 1836025 | 2487813875 | 36.81032 | 11.06572  | 0.0007380  | 1355 |
| 1356 | 1838736 | 2493326016 | 36.82391 | 11.06844  | 0.0007375  | 1356 |
| 1357 | 1841449 | 2498846293 | 36.83748 | 11.07116  | 0.0007369  | 1357 |
| 1358 | 1844164 | 2504374712 | 36.85105 | 11.07388  | 0.0007364  | 1358 |
| 1359 | 1846881 | 2509911279 | 36.86462 | 11.07660  | 0.0007358  | 1359 |
| 1360 | 1849600 | 2515456000 | 36.87818 | 11.07932  | 0.0007353  | 1360 |
| 1361 | 1852321 | 2521008881 | 36.89173 | 11.08203  | 0.0007348  | 1361 |
| 1362 | 1855044 | 2526569928 | 36.90528 | 11.08474  | 0.0007342  | 1362 |
| 1363 | 1857769 | 2532139147 | 36.91883 | 11.08746  | 0.0007337  | 1363 |
| 1364 | 1860496 | 2537716544 | 36.93237 | 11.09017  | 0.0007331  | 1364 |
| 1365 | 1863225 | 2543302125 | 36.94591 | 11.09288  | 0.0007326  | 1365 |
| 1366 | 1865956 | 2548895896 | 36.95944 | 11.09559  | 0.0007321  | 1366 |
| 1367 | 1868689 | 2554497863 | 36.97296 | 11.09829  | 0.0007315  | 1367 |
| 1368 | 1871424 | 2560108032 | 36.98648 | 11.10100  | 0.0007310  | 1368 |
| 1369 | 1874161 | 2565726409 | 37.00000 | 11.10370  | 0.0007305  | 1369 |
| 1370 | 1876900 | 2571353000 | 37.01351 | 11.10641  | 0.0007299  | 1370 |
| 1371 | 1879641 | 2576987811 | 37.02702 | 11.10911  | 0.0007294  | 1371 |
| 1372 | 1882384 | 2582630848 | 37.04052 | 11.11181  | 0.0007289  | 1372 |
| 1373 | 1885129 | 2588282117 | 37.05401 | 11.11451  | 0.0007283  | 1373 |
| 1374 | 1887876 | 2593941624 | 37.06751 | 11.11720  | 0.0007278  | 1374 |
| 1375 | 1890625 | 2599609375 | 37.08099 | 11.11990  | 0.0007273  | 1375 |
| 1376 | 1893376 | 2605285376 | 37.09447 | 11.12260  | 0.0007267  | 1376 |
| 1377 | 1896129 | 2610969633 | 37.10795 | 11.12529  | 0.0007262  | 1377 |
| 1378 | 1898884 | 2616662152 | 37.12142 | 11.12798  | 0.0007257  | 1378 |
| 1379 | 1901641 | 2622362939 | 37.13489 | 11.13067  | 0.0007252  | 1379 |
| 1380 | 1904400 | 2628072000 | 37.14835 | 11.13336  | 0.0007246  | 1380 |
| 1381 | 1907161 | 2633789341 | 37.16181 | 11.13605  | 0.0007241  | 1381 |
| 1382 | 1909924 | 2639514968 | 37.17526 | 11.13874  | 0.0007236  | 1382 |
| 1383 | 1912689 | 2645248887 | 37.18871 | 11.14142  | 0.0007231  | 1383 |
| 1384 | 1915456 | 2650991104 | 37.20215 | 11.14411  | 0.0007225  | 1384 |
| 1385 | 1918225 | 2656741625 | 37.21559 | 11.14679  | 0.0007220  | 1385 |
| 1386 | 1920996 | 2662500456 | 37.22902 | 11.14947  | 0.0007215  | 1386 |
| 1387 | 1923769 | 2668267603 | 37.24245 | 11.15216  | 0.0007210  | 1387 |
| 1388 | 1926544 | 2674043072 | 37.25587 | 11.15484  | 0.0007205  | 1388 |
| 1389 | 1929321 | 2679826869 | 37.26929 | 11.15751  | 0.0007199  | 1389 |
| 1390 | 1932100 | 2685619000 | 37.28270 | 11.16019  | 0.0007194  | 1390 |
| 1391 | 1934881 | 2691419471 | 37.29611 | 11.16287  | 0.0007189  | 1391 |
| 1392 | 1937664 | 2697228288 | 37.30952 | 11.16554  | 0.0007184  | 1392 |
| 1393 | 1940449 | 2703045457 | 37.32292 | 11.16821  | 0.0007179  | 1393 |
| 1394 | 1943236 | 2708870984 | 37.33631 | 11.17089  | 0.0007174  | 1394 |
| 1395 | 1946025 | 2714704875 | 37.34970 | 11.17356  | 0.0007168  | 1395 |
| 1396 | 1948816 | 2720547136 | 37.36308 | 11.17623  | 0.0007163  | 1396 |
| 1397 | 1951609 | 2726397773 | 37.37646 | 11.17889  | 0.0007158  | 1397 |
| 1398 | 1954404 | 2732256792 | 37.38984 | 11.18156  | 0.0007153  | 1398 |
| 1399 | 1957201 | 2738124199 | 37.40321 | 11.18423  | 0.0007148  | 1399 |
| 1400 | 1960000 | 2744000000 | 37.41657 | 11.18689  | 0.0007143  | 1400 |

**Powers, Roots, and Reciprocals From 1401 to 1450**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1401 | 1962801 | 2749884201 | 37.42993 | 11.18955  | 0.0007138  | 1401 |
| 1402 | 1965604 | 2755776808 | 37.44329 | 11.19221  | 0.0007133  | 1402 |
| 1403 | 1968409 | 2761677827 | 37.45664 | 11.19487  | 0.0007128  | 1403 |
| 1404 | 1971216 | 2767587264 | 37.46999 | 11.19753  | 0.0007123  | 1404 |
| 1405 | 1974025 | 2773505125 | 37.48333 | 11.20019  | 0.0007117  | 1405 |
| 1406 | 1976836 | 2779431416 | 37.49667 | 11.20285  | 0.0007112  | 1406 |
| 1407 | 1979649 | 2785366143 | 37.51000 | 11.20550  | 0.0007107  | 1407 |
| 1408 | 1982464 | 2791309312 | 37.52333 | 11.20816  | 0.0007102  | 1408 |
| 1409 | 1985281 | 2797260929 | 37.53665 | 11.21081  | 0.0007097  | 1409 |
| 1410 | 1988100 | 2803221000 | 37.54997 | 11.21346  | 0.0007092  | 1410 |
| 1411 | 1990921 | 2809189531 | 37.56328 | 11.21611  | 0.0007087  | 1411 |
| 1412 | 1993744 | 2815166528 | 37.57659 | 11.21876  | 0.0007082  | 1412 |
| 1413 | 1996569 | 2821151997 | 37.58989 | 11.22141  | 0.0007077  | 1413 |
| 1414 | 1999396 | 2827145944 | 37.60319 | 11.22406  | 0.0007072  | 1414 |
| 1415 | 2002225 | 2833148375 | 37.61649 | 11.22670  | 0.0007067  | 1415 |
| 1416 | 2005056 | 2839159296 | 37.62978 | 11.22934  | 0.0007062  | 1416 |
| 1417 | 2007889 | 2845178713 | 37.64306 | 11.23199  | 0.0007057  | 1417 |
| 1418 | 2010724 | 2851206632 | 37.65634 | 11.23463  | 0.0007052  | 1418 |
| 1419 | 2013561 | 2857243059 | 37.66962 | 11.23727  | 0.0007047  | 1419 |
| 1420 | 2016400 | 2863288000 | 37.68289 | 11.23991  | 0.0007042  | 1420 |
| 1421 | 2019241 | 2869341461 | 37.69615 | 11.24255  | 0.0007037  | 1421 |
| 1422 | 2022084 | 2875403448 | 37.70942 | 11.24518  | 0.0007032  | 1422 |
| 1423 | 2024929 | 2881473967 | 37.72267 | 11.24782  | 0.0007027  | 1423 |
| 1424 | 2027776 | 2887553024 | 37.73592 | 11.25045  | 0.0007022  | 1424 |
| 1425 | 2030625 | 2893640625 | 37.74917 | 11.25309  | 0.0007018  | 1425 |
| 1426 | 2033476 | 2899736776 | 37.76242 | 11.25572  | 0.0007013  | 1426 |
| 1427 | 2036329 | 2905841483 | 37.77565 | 11.25835  | 0.0007008  | 1427 |
| 1428 | 2039184 | 2911954752 | 37.78889 | 11.26098  | 0.0007003  | 1428 |
| 1429 | 2042041 | 2918076589 | 37.80212 | 11.26360  | 0.0006998  | 1429 |
| 1430 | 2044900 | 2924207000 | 37.81534 | 11.26623  | 0.0006993  | 1430 |
| 1431 | 2047761 | 2930345991 | 37.82856 | 11.26886  | 0.0006988  | 1431 |
| 1432 | 2050624 | 2936493568 | 37.84178 | 11.27148  | 0.0006983  | 1432 |
| 1433 | 2053489 | 2942649737 | 37.85499 | 11.27410  | 0.0006978  | 1433 |
| 1434 | 2056356 | 2948814504 | 37.86819 | 11.27673  | 0.0006974  | 1434 |
| 1435 | 2059225 | 2954987875 | 37.88139 | 11.27935  | 0.0006969  | 1435 |
| 1436 | 2062096 | 2961169856 | 37.89459 | 11.28197  | 0.0006964  | 1436 |
| 1437 | 2064969 | 2967360453 | 37.90778 | 11.28458  | 0.0006959  | 1437 |
| 1438 | 2067844 | 2973559672 | 37.92097 | 11.28720  | 0.0006954  | 1438 |
| 1439 | 2070721 | 2979767519 | 37.93415 | 11.28982  | 0.0006949  | 1439 |
| 1440 | 2073600 | 2985984000 | 37.94733 | 11.29243  | 0.0006944  | 1440 |
| 1441 | 2076481 | 2992209121 | 37.96051 | 11.29505  | 0.0006940  | 1441 |
| 1442 | 2079364 | 2998442888 | 37.97368 | 11.29766  | 0.0006935  | 1442 |
| 1443 | 2082249 | 3004685307 | 37.98684 | 11.30027  | 0.0006930  | 1443 |
| 1444 | 2085136 | 3010936384 | 38.00000 | 11.30288  | 0.0006925  | 1444 |
| 1445 | 2088025 | 3017196125 | 38.01316 | 11.30549  | 0.0006920  | 1445 |
| 1446 | 2090916 | 3023464536 | 38.02631 | 11.30809  | 0.0006916  | 1446 |
| 1447 | 2093809 | 3029741623 | 38.03945 | 11.31070  | 0.0006911  | 1447 |
| 1448 | 2096704 | 3036027392 | 38.05260 | 11.31331  | 0.0006906  | 1448 |
| 1449 | 2099601 | 3042321849 | 38.06573 | 11.31591  | 0.0006901  | 1449 |
| 1450 | 2102500 | 3048625000 | 38.07887 | 11.31851  | 0.0006897  | 1450 |

## Powers, Roots, and Reciprocals From 1451 to 1500

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1451 | 2105401 | 3054936851 | 38.09199 | 11.32111  | 0.0006892  | 1451 |
| 1452 | 2108304 | 3061257408 | 38.10512 | 11.32371  | 0.0006887  | 1452 |
| 1453 | 2111209 | 3067586677 | 38.11824 | 11.32631  | 0.0006882  | 1453 |
| 1454 | 2114116 | 3073924664 | 38.13135 | 11.32891  | 0.0006878  | 1454 |
| 1455 | 2117025 | 3080271375 | 38.14446 | 11.33151  | 0.0006873  | 1455 |
| 1456 | 2119936 | 3086626816 | 38.15757 | 11.33410  | 0.0006868  | 1456 |
| 1457 | 2122849 | 3092990993 | 38.17067 | 11.33670  | 0.0006863  | 1457 |
| 1458 | 2125764 | 3099363912 | 38.18377 | 11.33929  | 0.0006859  | 1458 |
| 1459 | 2128681 | 3105745579 | 38.19686 | 11.34188  | 0.0006854  | 1459 |
| 1460 | 2131600 | 3112136000 | 38.20995 | 11.34447  | 0.0006849  | 1460 |
| 1461 | 2134521 | 3118535181 | 38.22303 | 11.34706  | 0.0006845  | 1461 |
| 1462 | 2137444 | 3124943128 | 38.23611 | 11.34965  | 0.0006840  | 1462 |
| 1463 | 2140369 | 3131359847 | 38.24918 | 11.35224  | 0.0006835  | 1463 |
| 1464 | 2143296 | 3137785344 | 38.26225 | 11.35482  | 0.0006831  | 1464 |
| 1465 | 2146225 | 3144219625 | 38.27532 | 11.35741  | 0.0006826  | 1465 |
| 1466 | 2149156 | 3150662696 | 38.28838 | 11.35999  | 0.0006821  | 1466 |
| 1467 | 2152089 | 3157114563 | 38.30144 | 11.36257  | 0.0006817  | 1467 |
| 1468 | 2155024 | 3163575232 | 38.31449 | 11.36515  | 0.0006812  | 1468 |
| 1469 | 2157961 | 3170044709 | 38.32754 | 11.36773  | 0.0006807  | 1469 |
| 1470 | 2160900 | 3176523000 | 38.34058 | 11.37031  | 0.0006803  | 1470 |
| 1471 | 2163841 | 3183010111 | 38.35362 | 11.37289  | 0.0006798  | 1471 |
| 1472 | 2166784 | 3189506048 | 38.36665 | 11.37547  | 0.0006793  | 1472 |
| 1473 | 2169729 | 3196010817 | 38.37968 | 11.37804  | 0.0006789  | 1473 |
| 1474 | 2172676 | 3202524424 | 38.39271 | 11.38062  | 0.0006784  | 1474 |
| 1475 | 2175625 | 3209046875 | 38.40573 | 11.38319  | 0.0006780  | 1475 |
| 1476 | 2178576 | 3215578176 | 38.41875 | 11.38576  | 0.0006775  | 1476 |
| 1477 | 2181529 | 3222118333 | 38.43176 | 11.38833  | 0.0006770  | 1477 |
| 1478 | 2184484 | 3228667352 | 38.44477 | 11.39090  | 0.0006766  | 1478 |
| 1479 | 2187441 | 3235225239 | 38.45777 | 11.39347  | 0.0006761  | 1479 |
| 1480 | 2190400 | 3241792000 | 38.47077 | 11.39604  | 0.0006757  | 1480 |
| 1481 | 2193361 | 3248367641 | 38.48376 | 11.39860  | 0.0006752  | 1481 |
| 1482 | 2196324 | 3254952168 | 38.49675 | 11.40117  | 0.0006748  | 1482 |
| 1483 | 2199289 | 3261545587 | 38.50974 | 11.40373  | 0.0006743  | 1483 |
| 1484 | 2202256 | 3268147904 | 38.52272 | 11.40630  | 0.0006739  | 1484 |
| 1485 | 2205225 | 3274759125 | 38.53570 | 11.40886  | 0.0006734  | 1485 |
| 1486 | 2208196 | 3281379256 | 38.54867 | 11.41142  | 0.0006729  | 1486 |
| 1487 | 2211169 | 3288008303 | 38.56164 | 11.41398  | 0.0006725  | 1487 |
| 1488 | 2214144 | 3294646272 | 38.57460 | 11.41653  | 0.0006720  | 1488 |
| 1489 | 2217121 | 3301293169 | 38.58756 | 11.41909  | 0.0006716  | 1489 |
| 1490 | 2220100 | 3307949000 | 38.60052 | 11.42165  | 0.0006711  | 1490 |
| 1491 | 2223081 | 3314613771 | 38.61347 | 11.42420  | 0.0006707  | 1491 |
| 1492 | 2226064 | 3321287488 | 38.62642 | 11.42676  | 0.0006702  | 1492 |
| 1493 | 2229049 | 3327970157 | 38.63936 | 11.42931  | 0.0006698  | 1493 |
| 1494 | 2232036 | 3334661784 | 38.65230 | 11.43186  | 0.0006693  | 1494 |
| 1495 | 2235025 | 3341362375 | 38.66523 | 11.43441  | 0.0006689  | 1495 |
| 1496 | 2238016 | 3348071936 | 38.67816 | 11.43696  | 0.0006684  | 1496 |
| 1497 | 2241009 | 3354790473 | 38.69108 | 11.43951  | 0.0006680  | 1497 |
| 1498 | 2244004 | 3361517992 | 38.70400 | 11.44205  | 0.0006676  | 1498 |
| 1499 | 2247001 | 3368254499 | 38.71692 | 11.44460  | 0.0006671  | 1499 |
| 1500 | 2250000 | 3375000000 | 38.72983 | 11.44714  | 0.0006667  | 1500 |

**Powers, Roots, and Reciprocals From 1501 to 1550**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1501 | 2253001 | 3381754501 | 38.74274 | 11.44969  | 0.0006662  | 1501 |
| 1502 | 2256004 | 3388518008 | 38.75564 | 11.45223  | 0.0006658  | 1502 |
| 1503 | 2259009 | 3395290527 | 38.76854 | 11.45477  | 0.0006653  | 1503 |
| 1504 | 2262016 | 3402072064 | 38.78144 | 11.45731  | 0.0006649  | 1504 |
| 1505 | 2265025 | 3408862625 | 38.79433 | 11.45985  | 0.0006645  | 1505 |
| 1506 | 2268036 | 3415662216 | 38.80722 | 11.46238  | 0.0006640  | 1506 |
| 1507 | 2271049 | 3422470843 | 38.82010 | 11.46492  | 0.0006636  | 1507 |
| 1508 | 2274064 | 3429288512 | 38.83298 | 11.46746  | 0.0006631  | 1508 |
| 1509 | 2277081 | 3436115229 | 38.84585 | 11.46999  | 0.0006627  | 1509 |
| 1510 | 2280100 | 3442951000 | 38.85872 | 11.47252  | 0.0006623  | 1510 |
| 1511 | 2283121 | 3449795831 | 38.87158 | 11.47506  | 0.0006618  | 1511 |
| 1512 | 2286144 | 3456649728 | 38.88444 | 11.47759  | 0.0006614  | 1512 |
| 1513 | 2289169 | 3463512697 | 38.89730 | 11.48012  | 0.0006609  | 1513 |
| 1514 | 2292196 | 3470384744 | 38.91015 | 11.48265  | 0.0006605  | 1514 |
| 1515 | 2295225 | 3477265875 | 38.92300 | 11.48517  | 0.0006601  | 1515 |
| 1516 | 2298256 | 3484156096 | 38.93584 | 11.48770  | 0.0006596  | 1516 |
| 1517 | 2301289 | 3491055413 | 38.94868 | 11.49022  | 0.0006592  | 1517 |
| 1518 | 2304324 | 3497963832 | 38.96152 | 11.49275  | 0.0006588  | 1518 |
| 1519 | 2307361 | 3504881359 | 38.97435 | 11.49527  | 0.0006583  | 1519 |
| 1520 | 2310400 | 3511808000 | 38.98718 | 11.49779  | 0.0006579  | 1520 |
| 1521 | 2313441 | 3518743761 | 39.00000 | 11.50032  | 0.0006575  | 1521 |
| 1522 | 2316484 | 3525688648 | 39.01282 | 11.50283  | 0.0006570  | 1522 |
| 1523 | 2319529 | 3532642667 | 39.02563 | 11.50535  | 0.0006566  | 1523 |
| 1524 | 2322576 | 3539605824 | 39.03844 | 11.50787  | 0.0006562  | 1524 |
| 1525 | 2325625 | 3546578125 | 39.05125 | 11.51039  | 0.0006557  | 1525 |
| 1526 | 2328676 | 3553559576 | 39.06405 | 11.51290  | 0.0006553  | 1526 |
| 1527 | 2331729 | 3560550183 | 39.07685 | 11.51542  | 0.0006549  | 1527 |
| 1528 | 2334784 | 3567549952 | 39.08964 | 11.51793  | 0.0006545  | 1528 |
| 1529 | 2337841 | 3574558889 | 39.10243 | 11.52044  | 0.0006540  | 1529 |
| 1530 | 2340900 | 3581577000 | 39.11521 | 11.52295  | 0.0006536  | 1530 |
| 1531 | 2343961 | 3588604291 | 39.12800 | 11.52546  | 0.0006532  | 1531 |
| 1532 | 2347024 | 3595640768 | 39.14077 | 11.52797  | 0.0006527  | 1532 |
| 1533 | 2350089 | 3602686437 | 39.15354 | 11.53048  | 0.0006523  | 1533 |
| 1534 | 2353156 | 3609741304 | 39.16631 | 11.53299  | 0.0006519  | 1534 |
| 1535 | 2356225 | 3616805375 | 39.17908 | 11.53549  | 0.0006515  | 1535 |
| 1536 | 2359296 | 3623878656 | 39.19184 | 11.53800  | 0.0006510  | 1536 |
| 1537 | 2362369 | 3630961153 | 39.20459 | 11.54050  | 0.0006506  | 1537 |
| 1538 | 2365444 | 3638052872 | 39.21734 | 11.54300  | 0.0006502  | 1538 |
| 1539 | 2368521 | 3645153819 | 39.23009 | 11.54550  | 0.0006498  | 1539 |
| 1540 | 2371600 | 3652264000 | 39.24283 | 11.54800  | 0.0006494  | 1540 |
| 1541 | 2374681 | 3659383421 | 39.25557 | 11.55050  | 0.0006489  | 1541 |
| 1542 | 2377764 | 3666512088 | 39.26831 | 11.55300  | 0.0006485  | 1542 |
| 1543 | 2380849 | 3673650007 | 39.28104 | 11.55550  | 0.0006481  | 1543 |
| 1544 | 2383936 | 3680797184 | 39.29377 | 11.55799  | 0.0006477  | 1544 |
| 1545 | 2387025 | 3687953625 | 39.30649 | 11.56049  | 0.0006472  | 1545 |
| 1546 | 2390116 | 3695119336 | 39.31921 | 11.56298  | 0.0006468  | 1546 |
| 1547 | 2393209 | 3702294323 | 39.33192 | 11.56547  | 0.0006464  | 1547 |
| 1548 | 2396304 | 3709478592 | 39.34463 | 11.56797  | 0.0006460  | 1548 |
| 1549 | 2399401 | 3716672149 | 39.35734 | 11.57046  | 0.0006456  | 1549 |
| 1550 | 2402500 | 3723875000 | 39.37004 | 11.57295  | 0.0006452  | 1550 |

**Powers, Roots, and Reciprocals From 1551 to 1600**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1551 | 2405601 | 3731087151 | 39.38274 | 11.57543  | 0.0006447  | 1551 |
| 1552 | 2408704 | 3738308608 | 39.39543 | 11.57792  | 0.0006443  | 1552 |
| 1553 | 2411809 | 3745539377 | 39.40812 | 11.58041  | 0.0006439  | 1553 |
| 1554 | 2414916 | 3752779464 | 39.42081 | 11.58289  | 0.0006435  | 1554 |
| 1555 | 2418025 | 3760028875 | 39.43349 | 11.58538  | 0.0006431  | 1555 |
| 1556 | 2421136 | 3767287616 | 39.44617 | 11.58786  | 0.0006427  | 1556 |
| 1557 | 2424249 | 3774555693 | 39.45884 | 11.59034  | 0.0006423  | 1557 |
| 1558 | 2427364 | 3781833112 | 39.47151 | 11.59282  | 0.0006418  | 1558 |
| 1559 | 2430481 | 3789119879 | 39.48417 | 11.59530  | 0.0006414  | 1559 |
| 1560 | 2433600 | 3796416000 | 39.49684 | 11.59778  | 0.0006410  | 1560 |
| 1561 | 2436721 | 3803721481 | 39.50949 | 11.60026  | 0.0006406  | 1561 |
| 1562 | 2439844 | 3811036328 | 39.52215 | 11.60273  | 0.0006402  | 1562 |
| 1563 | 2442969 | 3818360547 | 39.53479 | 11.60521  | 0.0006398  | 1563 |
| 1564 | 2446096 | 3825694144 | 39.54744 | 11.60768  | 0.0006394  | 1564 |
| 1565 | 2449225 | 3833037125 | 39.56008 | 11.61016  | 0.0006390  | 1565 |
| 1566 | 2452356 | 3840389496 | 39.57272 | 11.61263  | 0.0006386  | 1566 |
| 1567 | 2455489 | 3847751263 | 39.58535 | 11.61510  | 0.0006382  | 1567 |
| 1568 | 2458624 | 3855122432 | 39.59798 | 11.61757  | 0.0006378  | 1568 |
| 1569 | 2461761 | 3862503009 | 39.61060 | 11.62004  | 0.0006373  | 1569 |
| 1570 | 2464900 | 3869893000 | 39.62323 | 11.62251  | 0.0006369  | 1570 |
| 1571 | 2468041 | 3877292411 | 39.63584 | 11.62498  | 0.0006365  | 1571 |
| 1572 | 2471184 | 3884701248 | 39.64846 | 11.62744  | 0.0006361  | 1572 |
| 1573 | 2474329 | 3892119517 | 39.66106 | 11.62991  | 0.0006357  | 1573 |
| 1574 | 2477476 | 3899547224 | 39.67367 | 11.63237  | 0.0006353  | 1574 |
| 1575 | 2480625 | 3906984375 | 39.68627 | 11.63483  | 0.0006349  | 1575 |
| 1576 | 2483776 | 3914430976 | 39.69887 | 11.63730  | 0.0006345  | 1576 |
| 1577 | 2486929 | 3921887033 | 39.71146 | 11.63976  | 0.0006341  | 1577 |
| 1578 | 2490084 | 3929352552 | 39.72405 | 11.64222  | 0.0006337  | 1578 |
| 1579 | 2493241 | 3936827539 | 39.73663 | 11.64468  | 0.0006333  | 1579 |
| 1580 | 2496400 | 3944312000 | 39.74921 | 11.64713  | 0.0006329  | 1580 |
| 1581 | 2499561 | 3951805941 | 39.76179 | 11.64959  | 0.0006325  | 1581 |
| 1582 | 2502724 | 3959309368 | 39.77436 | 11.65205  | 0.0006321  | 1582 |
| 1583 | 2505889 | 3966822287 | 39.78693 | 11.65450  | 0.0006317  | 1583 |
| 1584 | 2509056 | 3974344704 | 39.79950 | 11.65695  | 0.0006313  | 1584 |
| 1585 | 2512225 | 3981876625 | 39.81206 | 11.65941  | 0.0006309  | 1585 |
| 1586 | 2515396 | 3989418056 | 39.82462 | 11.66186  | 0.0006305  | 1586 |
| 1587 | 2518569 | 3996969003 | 39.83717 | 11.66431  | 0.0006301  | 1587 |
| 1588 | 2521744 | 4004529472 | 39.84972 | 11.66676  | 0.0006297  | 1588 |
| 1589 | 2524921 | 4012099469 | 39.86226 | 11.66921  | 0.0006293  | 1589 |
| 1590 | 2528100 | 4019679000 | 39.87480 | 11.67165  | 0.0006289  | 1590 |
| 1591 | 2531281 | 4027268071 | 39.88734 | 11.67410  | 0.0006285  | 1591 |
| 1592 | 2534464 | 4034866688 | 39.89987 | 11.67654  | 0.0006281  | 1592 |
| 1593 | 2537649 | 4042474857 | 39.91240 | 11.67899  | 0.0006277  | 1593 |
| 1594 | 2540836 | 4050092584 | 39.92493 | 11.68143  | 0.0006274  | 1594 |
| 1595 | 2544025 | 4057719875 | 39.93745 | 11.68387  | 0.0006270  | 1595 |
| 1596 | 2547216 | 4065356736 | 39.94997 | 11.68632  | 0.0006266  | 1596 |
| 1597 | 2550409 | 4073003173 | 39.96248 | 11.68876  | 0.0006262  | 1597 |
| 1598 | 2553604 | 4080659192 | 39.97499 | 11.69120  | 0.0006258  | 1598 |
| 1599 | 2556801 | 4088324799 | 39.98750 | 11.69363  | 0.0006254  | 1599 |
| 1600 | 2560000 | 4096000000 | 40.00000 | 11.69607  | 0.0006250  | 1600 |



**Powers, Roots, and Reciprocals From 1601 to 1650**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1601 | 2563201 | 4103684801 | 40.01250 | 11.69851  | 0.0006246  | 1601 |
| 1602 | 2566404 | 4111379208 | 40.02499 | 11.70094  | 0.0006242  | 1602 |
| 1603 | 2569609 | 4119083227 | 40.03748 | 11.70338  | 0.0006238  | 1603 |
| 1604 | 2572816 | 4126796864 | 40.04997 | 11.70581  | 0.0006234  | 1604 |
| 1605 | 2576025 | 4134520125 | 40.06245 | 11.70824  | 0.0006231  | 1605 |
| 1606 | 2579236 | 4142253016 | 40.07493 | 11.71067  | 0.0006227  | 1606 |
| 1607 | 2582449 | 4149995543 | 40.08740 | 11.71310  | 0.0006223  | 1607 |
| 1608 | 2585664 | 4157747712 | 40.09988 | 11.71553  | 0.0006219  | 1608 |
| 1609 | 2588881 | 4165509529 | 40.11234 | 11.71796  | 0.0006215  | 1609 |
| 1610 | 2592100 | 4173281000 | 40.12481 | 11.72039  | 0.0006211  | 1610 |
| 1611 | 2595321 | 4181062131 | 40.13726 | 11.72281  | 0.0006207  | 1611 |
| 1612 | 2598544 | 4188852928 | 40.14972 | 11.72524  | 0.0006203  | 1612 |
| 1613 | 2601769 | 4196653397 | 40.16217 | 11.72766  | 0.0006200  | 1613 |
| 1614 | 2604996 | 4204463544 | 40.17462 | 11.73009  | 0.0006196  | 1614 |
| 1615 | 2608225 | 4212283375 | 40.18706 | 11.73251  | 0.0006192  | 1615 |
| 1616 | 2611456 | 4220112896 | 40.19950 | 11.73493  | 0.0006188  | 1616 |
| 1617 | 2614689 | 4227952113 | 40.21194 | 11.73735  | 0.0006184  | 1617 |
| 1618 | 2617924 | 4235801032 | 40.22437 | 11.73977  | 0.0006180  | 1618 |
| 1619 | 2621161 | 4243659659 | 40.23680 | 11.74219  | 0.0006177  | 1619 |
| 1620 | 2624400 | 4251528000 | 40.24922 | 11.74460  | 0.0006173  | 1620 |
| 1621 | 2627641 | 4259406061 | 40.26164 | 11.74702  | 0.0006169  | 1621 |
| 1622 | 2630884 | 4267293848 | 40.27406 | 11.74943  | 0.0006165  | 1622 |
| 1623 | 2634129 | 4275191367 | 40.28647 | 11.75185  | 0.0006161  | 1623 |
| 1624 | 2637376 | 4283098624 | 40.29888 | 11.75426  | 0.0006158  | 1624 |
| 1625 | 2640625 | 4291015625 | 40.31129 | 11.75667  | 0.0006154  | 1625 |
| 1626 | 2643876 | 4298942376 | 40.32369 | 11.75908  | 0.0006150  | 1626 |
| 1627 | 2647129 | 4306878883 | 40.33609 | 11.76149  | 0.0006146  | 1627 |
| 1628 | 2650384 | 4314825152 | 40.34848 | 11.76390  | 0.0006143  | 1628 |
| 1629 | 2653641 | 4322781189 | 40.36087 | 11.76631  | 0.0006139  | 1629 |
| 1630 | 2656900 | 4330747000 | 40.37326 | 11.76872  | 0.0006135  | 1630 |
| 1631 | 2660161 | 4338722591 | 40.38564 | 11.77113  | 0.0006131  | 1631 |
| 1632 | 2663424 | 4346707968 | 40.39802 | 11.77353  | 0.0006127  | 1632 |
| 1633 | 2666689 | 4354703137 | 40.41039 | 11.77593  | 0.0006124  | 1633 |
| 1634 | 2669956 | 4362708104 | 40.42277 | 11.77834  | 0.0006120  | 1634 |
| 1635 | 2673225 | 4370722875 | 40.43513 | 11.78074  | 0.0006116  | 1635 |
| 1636 | 2676496 | 4378747456 | 40.44750 | 11.78314  | 0.0006112  | 1636 |
| 1637 | 2679769 | 4386781853 | 40.45986 | 11.78554  | 0.0006109  | 1637 |
| 1638 | 2683044 | 4394826072 | 40.47221 | 11.78794  | 0.0006105  | 1638 |
| 1639 | 2686321 | 4402880119 | 40.48456 | 11.79034  | 0.0006101  | 1639 |
| 1640 | 2689600 | 4410944000 | 40.49691 | 11.79274  | 0.0006098  | 1640 |
| 1641 | 2692881 | 4419017721 | 40.50926 | 11.79513  | 0.0006094  | 1641 |
| 1642 | 2696164 | 4427101288 | 40.52160 | 11.79753  | 0.0006090  | 1642 |
| 1643 | 2699449 | 4435194707 | 40.53394 | 11.79992  | 0.0006086  | 1643 |
| 1644 | 2702736 | 4443297984 | 40.54627 | 11.80232  | 0.0006083  | 1644 |
| 1645 | 2706025 | 4451411125 | 40.55860 | 11.80471  | 0.0006079  | 1645 |
| 1646 | 2709316 | 4459534136 | 40.57093 | 11.80710  | 0.0006075  | 1646 |
| 1647 | 2712609 | 4467667023 | 40.58325 | 11.80949  | 0.0006072  | 1647 |
| 1648 | 2715904 | 4475809792 | 40.59557 | 11.81188  | 0.0006068  | 1648 |
| 1649 | 2719201 | 4483962449 | 40.60788 | 11.81427  | 0.0006064  | 1649 |
| 1650 | 2722500 | 4492125000 | 40.62019 | 11.81666  | 0.0006061  | 1650 |

## Powers, Roots, and Reciprocals From 1651 to 1700

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1651 | 2725801 | 4500297451 | 40.63250 | 11.81904  | 0.0006057  | 1651 |
| 1652 | 2729104 | 4508479808 | 40.64480 | 11.82143  | 0.0006053  | 1652 |
| 1653 | 2732409 | 4516672077 | 40.65710 | 11.82381  | 0.0006050  | 1653 |
| 1654 | 2735716 | 4524874264 | 40.66940 | 11.82620  | 0.0006046  | 1654 |
| 1655 | 2739025 | 4533086375 | 40.68169 | 11.82858  | 0.0006042  | 1655 |
| 1656 | 2742336 | 4541308416 | 40.69398 | 11.83096  | 0.0006039  | 1656 |
| 1657 | 2745649 | 4549540393 | 40.70626 | 11.83334  | 0.0006035  | 1657 |
| 1658 | 2748964 | 4557782312 | 40.71855 | 11.83572  | 0.0006031  | 1658 |
| 1659 | 2752281 | 4566034179 | 40.73082 | 11.83810  | 0.0006028  | 1659 |
| 1660 | 2755600 | 4574296000 | 40.74310 | 11.84048  | 0.0006024  | 1660 |
| 1661 | 2758921 | 4582567781 | 40.75537 | 11.84286  | 0.0006020  | 1661 |
| 1662 | 2762244 | 4590849528 | 40.76763 | 11.84523  | 0.0006017  | 1662 |
| 1663 | 2765569 | 4599141247 | 40.77990 | 11.84761  | 0.0006013  | 1663 |
| 1664 | 2768896 | 4607442944 | 40.79216 | 11.84998  | 0.0006010  | 1664 |
| 1665 | 2772225 | 4615754625 | 40.80441 | 11.85236  | 0.0006006  | 1665 |
| 1666 | 2775556 | 4624076296 | 40.81666 | 11.85473  | 0.0006002  | 1666 |
| 1667 | 2778889 | 4632407963 | 40.82891 | 11.85710  | 0.0005999  | 1667 |
| 1668 | 2782224 | 4640749632 | 40.84116 | 11.85947  | 0.0005995  | 1668 |
| 1669 | 2785561 | 4649101309 | 40.85340 | 11.86184  | 0.0005992  | 1669 |
| 1670 | 2788900 | 4657463000 | 40.86563 | 11.86421  | 0.0005988  | 1670 |
| 1671 | 2792241 | 4665834711 | 40.87787 | 11.86658  | 0.0005984  | 1671 |
| 1672 | 2795584 | 4674216448 | 40.89010 | 11.86894  | 0.0005981  | 1672 |
| 1673 | 2798929 | 4682608217 | 40.90232 | 11.87131  | 0.0005977  | 1673 |
| 1674 | 2802276 | 4691010024 | 40.91455 | 11.87367  | 0.0005974  | 1674 |
| 1675 | 2805625 | 4699421875 | 40.92676 | 11.87604  | 0.0005970  | 1675 |
| 1676 | 2808976 | 4707843776 | 40.93898 | 11.87840  | 0.0005967  | 1676 |
| 1677 | 2812329 | 4716275733 | 40.95119 | 11.88076  | 0.0005963  | 1677 |
| 1678 | 2815684 | 4724717752 | 40.96340 | 11.88312  | 0.0005959  | 1678 |
| 1679 | 2819041 | 4733169839 | 40.97560 | 11.88548  | 0.0005956  | 1679 |
| 1680 | 2822400 | 4741632000 | 40.98780 | 11.88784  | 0.0005952  | 1680 |
| 1681 | 2825761 | 4750104241 | 41.00000 | 11.89020  | 0.0005949  | 1681 |
| 1682 | 2829124 | 4758586568 | 41.01219 | 11.89256  | 0.0005945  | 1682 |
| 1683 | 2832489 | 4767078987 | 41.02438 | 11.89492  | 0.0005942  | 1683 |
| 1684 | 2835856 | 4775581504 | 41.03657 | 11.89727  | 0.0005938  | 1684 |
| 1685 | 2839225 | 4784094125 | 41.04875 | 11.89963  | 0.0005935  | 1685 |
| 1686 | 2842596 | 4792608856 | 41.06093 | 11.90198  | 0.0005931  | 1686 |
| 1687 | 2845969 | 4801149703 | 41.07311 | 11.90433  | 0.0005928  | 1687 |
| 1688 | 2849344 | 4809692672 | 41.08528 | 11.90668  | 0.0005924  | 1688 |
| 1689 | 2852721 | 4818245769 | 41.09745 | 11.90903  | 0.0005921  | 1689 |
| 1690 | 2856100 | 4826809000 | 41.10961 | 11.91138  | 0.0005917  | 1690 |
| 1691 | 2859481 | 4835382371 | 41.12177 | 11.91373  | 0.0005914  | 1691 |
| 1692 | 2862864 | 4843965888 | 41.13393 | 11.91608  | 0.0005910  | 1692 |
| 1693 | 2866249 | 4852559557 | 41.14608 | 11.91843  | 0.0005907  | 1693 |
| 1694 | 2869636 | 4861163384 | 41.15823 | 11.92077  | 0.0005903  | 1694 |
| 1695 | 2873025 | 4869777375 | 41.17038 | 11.92312  | 0.0005900  | 1695 |
| 1696 | 2876416 | 4878401536 | 41.18252 | 11.92546  | 0.0005896  | 1696 |
| 1697 | 2879809 | 4887035873 | 41.19466 | 11.92781  | 0.0005893  | 1697 |
| 1698 | 2883204 | 4895680392 | 41.20680 | 11.93015  | 0.0005889  | 1698 |
| 1699 | 2886601 | 4904335099 | 41.21893 | 11.93249  | 0.0005886  | 1699 |
| 1700 | 2890000 | 4913000000 | 41.23106 | 11.93483  | 0.0005882  | 1700 |

**Powers, Roots, and Reciprocals From 1701 to 1750**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1701 | 2893401 | 4921675101 | 41.24318 | 11.93717  | 0.0005879  | 1701 |
| 1702 | 2896804 | 4930360408 | 41.25530 | 11.93951  | 0.0005875  | 1702 |
| 1703 | 2900209 | 4939055927 | 41.26742 | 11.94185  | 0.0005872  | 1703 |
| 1704 | 2903616 | 4947761664 | 41.27953 | 11.94419  | 0.0005869  | 1704 |
| 1705 | 2907025 | 4956477625 | 41.29165 | 11.94652  | 0.0005865  | 1705 |
| 1706 | 2910436 | 4965203816 | 41.30375 | 11.94886  | 0.0005862  | 1706 |
| 1707 | 2913849 | 4973940243 | 41.31586 | 11.95119  | 0.0005858  | 1707 |
| 1708 | 2917264 | 4982686912 | 41.32796 | 11.95352  | 0.0005855  | 1708 |
| 1709 | 2920681 | 4991443829 | 41.34005 | 11.95586  | 0.0005851  | 1709 |
| 1710 | 2924100 | 5000211000 | 41.35215 | 11.95819  | 0.0005848  | 1710 |
| 1711 | 2927521 | 5008988431 | 41.36424 | 11.96052  | 0.0005845  | 1711 |
| 1712 | 2930944 | 5017776128 | 41.37632 | 11.96285  | 0.0005841  | 1712 |
| 1713 | 2934369 | 5026574097 | 41.38840 | 11.96518  | 0.0005838  | 1713 |
| 1714 | 2937796 | 5035382344 | 41.40048 | 11.96750  | 0.0005834  | 1714 |
| 1715 | 2941225 | 5044200875 | 41.41256 | 11.96983  | 0.0005831  | 1715 |
| 1716 | 2944656 | 5053029696 | 41.42463 | 11.97216  | 0.0005828  | 1716 |
| 1717 | 2948089 | 5061868813 | 41.43670 | 11.97448  | 0.0005824  | 1717 |
| 1718 | 2951524 | 5070718232 | 41.44876 | 11.97681  | 0.0005821  | 1718 |
| 1719 | 2954961 | 5079577959 | 41.46082 | 11.97913  | 0.0005817  | 1719 |
| 1720 | 2958400 | 5088448000 | 41.47288 | 11.98145  | 0.0005814  | 1720 |
| 1721 | 2961841 | 5097328361 | 41.48494 | 11.98377  | 0.0005811  | 1721 |
| 1722 | 2965284 | 5106219048 | 41.49699 | 11.98610  | 0.0005807  | 1722 |
| 1723 | 2968729 | 5115120067 | 41.50904 | 11.98841  | 0.0005804  | 1723 |
| 1724 | 2972176 | 5124031424 | 41.52108 | 11.99073  | 0.0005800  | 1724 |
| 1725 | 2975625 | 5132953125 | 41.53312 | 11.99305  | 0.0005797  | 1725 |
| 1726 | 2979076 | 5141885176 | 41.54516 | 11.99537  | 0.0005794  | 1726 |
| 1727 | 2982529 | 5150827583 | 41.55719 | 11.99768  | 0.0005790  | 1727 |
| 1728 | 2985984 | 5159780352 | 41.56922 | 12.00000  | 0.0005787  | 1728 |
| 1729 | 2989441 | 5168743489 | 41.58125 | 12.00231  | 0.0005784  | 1729 |
| 1730 | 2992900 | 5177717000 | 41.59327 | 12.00463  | 0.0005780  | 1730 |
| 1731 | 2996361 | 5186700891 | 41.60529 | 12.00694  | 0.0005777  | 1731 |
| 1732 | 2999824 | 5195695168 | 41.61730 | 12.00925  | 0.0005774  | 1732 |
| 1733 | 3003289 | 5204699837 | 41.62932 | 12.01156  | 0.0005770  | 1733 |
| 1734 | 3006756 | 5213714904 | 41.64133 | 12.01387  | 0.0005767  | 1734 |
| 1735 | 3010225 | 5222740375 | 41.65333 | 12.01618  | 0.0005764  | 1735 |
| 1736 | 3013696 | 5231776256 | 41.66533 | 12.01849  | 0.0005760  | 1736 |
| 1737 | 3017169 | 5240822553 | 41.67733 | 12.02080  | 0.0005757  | 1737 |
| 1738 | 3020644 | 5249879272 | 41.68933 | 12.02310  | 0.0005754  | 1738 |
| 1739 | 3024121 | 5258946419 | 41.70132 | 12.02541  | 0.0005750  | 1739 |
| 1740 | 3027600 | 5268024000 | 41.71331 | 12.02771  | 0.0005747  | 1740 |
| 1741 | 3031081 | 5277112021 | 41.72529 | 12.03002  | 0.0005744  | 1741 |
| 1742 | 3034564 | 5286210488 | 41.73727 | 12.03232  | 0.0005741  | 1742 |
| 1743 | 3038049 | 5295319407 | 41.74925 | 12.03462  | 0.0005737  | 1743 |
| 1744 | 3041536 | 5304438784 | 41.76123 | 12.03692  | 0.0005734  | 1744 |
| 1745 | 3045025 | 5313568625 | 41.77320 | 12.03922  | 0.0005731  | 1745 |
| 1746 | 3048516 | 5322708936 | 41.78516 | 12.04152  | 0.0005727  | 1746 |
| 1747 | 3052009 | 5331859723 | 41.79713 | 12.04382  | 0.0005724  | 1747 |
| 1748 | 3055504 | 5341020992 | 41.80909 | 12.04612  | 0.0005721  | 1748 |
| 1749 | 3059001 | 5350192749 | 41.82105 | 12.04842  | 0.0005718  | 1749 |
| 1750 | 3062500 | 5359375000 | 41.83300 | 12.05071  | 0.0005714  | 1750 |

**Powers, Roots, and Reciprocals From 1751 to 1800**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1751 | 3066001 | 5368567751 | 41.84495 | 12.05301  | 0.0005711  | 1751 |
| 1752 | 3069504 | 5377771008 | 41.85690 | 12.05530  | 0.0005708  | 1752 |
| 1753 | 3073009 | 5386984777 | 41.86884 | 12.05759  | 0.0005705  | 1753 |
| 1754 | 3076516 | 5396209064 | 41.88078 | 12.05989  | 0.0005701  | 1754 |
| 1755 | 3080025 | 5405443875 | 41.89272 | 12.06218  | 0.0005698  | 1755 |
| 1756 | 3083536 | 5414689216 | 41.90465 | 12.06447  | 0.0005695  | 1756 |
| 1757 | 3087049 | 5423945093 | 41.91658 | 12.06676  | 0.0005692  | 1757 |
| 1758 | 3090564 | 5433211512 | 41.92851 | 12.06905  | 0.0005688  | 1758 |
| 1759 | 3094081 | 5442488479 | 41.94043 | 12.07133  | 0.0005685  | 1759 |
| 1760 | 3097600 | 5451776000 | 41.95235 | 12.07362  | 0.0005682  | 1760 |
| 1761 | 3101121 | 5461074081 | 41.96427 | 12.07591  | 0.0005679  | 1761 |
| 1762 | 3104644 | 5470382728 | 41.97618 | 12.07819  | 0.0005675  | 1762 |
| 1763 | 3108169 | 5479701947 | 41.98809 | 12.08048  | 0.0005672  | 1763 |
| 1764 | 3111696 | 5489031744 | 42.00000 | 12.08276  | 0.0005669  | 1764 |
| 1765 | 3115225 | 5498372125 | 42.01190 | 12.08504  | 0.0005666  | 1765 |
| 1766 | 3118756 | 5507723096 | 42.02380 | 12.08733  | 0.0005663  | 1766 |
| 1767 | 3122289 | 5517084663 | 42.03570 | 12.08961  | 0.0005659  | 1767 |
| 1768 | 3125824 | 5526456832 | 42.04759 | 12.09189  | 0.0005656  | 1768 |
| 1769 | 3129361 | 5535839609 | 42.05948 | 12.09417  | 0.0005653  | 1769 |
| 1770 | 3132900 | 5545233000 | 42.07137 | 12.09645  | 0.0005650  | 1770 |
| 1771 | 3136441 | 5554637011 | 42.08325 | 12.09872  | 0.0005647  | 1771 |
| 1772 | 3139984 | 5564051648 | 42.09513 | 12.10100  | 0.0005643  | 1772 |
| 1773 | 3143529 | 5573476917 | 42.10701 | 12.10328  | 0.0005640  | 1773 |
| 1774 | 3147076 | 5582912824 | 42.11888 | 12.10555  | 0.0005637  | 1774 |
| 1775 | 3150625 | 5592359375 | 42.13075 | 12.10782  | 0.0005634  | 1775 |
| 1776 | 3154176 | 5601816576 | 42.14262 | 12.11010  | 0.0005631  | 1776 |
| 1777 | 3157729 | 5611284433 | 42.15448 | 12.11237  | 0.0005627  | 1777 |
| 1778 | 3161284 | 5620762952 | 42.16634 | 12.11464  | 0.0005624  | 1778 |
| 1779 | 3164841 | 5630252139 | 42.17819 | 12.11691  | 0.0005621  | 1779 |
| 1780 | 3168400 | 5639752000 | 42.19005 | 12.11918  | 0.0005618  | 1780 |
| 1781 | 3171961 | 5649262541 | 42.20190 | 12.12145  | 0.0005615  | 1781 |
| 1782 | 3175524 | 5658783768 | 42.21374 | 12.12372  | 0.0005612  | 1782 |
| 1783 | 3179089 | 5668315687 | 42.22558 | 12.12599  | 0.0005609  | 1783 |
| 1784 | 3182656 | 5677858304 | 42.23742 | 12.12825  | 0.0005605  | 1784 |
| 1785 | 3186225 | 5687411625 | 42.24926 | 12.13052  | 0.0005602  | 1785 |
| 1786 | 3189796 | 5696975656 | 42.26109 | 12.13278  | 0.0005599  | 1786 |
| 1787 | 3193369 | 5706550403 | 42.27292 | 12.13505  | 0.0005596  | 1787 |
| 1788 | 3196944 | 5716135872 | 42.28475 | 12.13731  | 0.0005593  | 1788 |
| 1789 | 3200521 | 5725732069 | 42.29657 | 12.13957  | 0.0005590  | 1789 |
| 1790 | 3204100 | 5735339000 | 42.30839 | 12.14184  | 0.0005587  | 1790 |
| 1791 | 3207681 | 5744956671 | 42.32021 | 12.14410  | 0.0005583  | 1791 |
| 1792 | 3211264 | 5754585088 | 42.33202 | 12.14636  | 0.0005580  | 1792 |
| 1793 | 3214849 | 5764224257 | 42.34383 | 12.14861  | 0.0005577  | 1793 |
| 1794 | 3218436 | 5773874184 | 42.35564 | 12.15087  | 0.0005574  | 1794 |
| 1795 | 3222025 | 5783534875 | 42.36744 | 12.15313  | 0.0005571  | 1795 |
| 1796 | 3225616 | 5793206336 | 42.37924 | 12.15539  | 0.0005568  | 1796 |
| 1797 | 3229209 | 5802888573 | 42.39104 | 12.15764  | 0.0005565  | 1797 |
| 1798 | 3232804 | 5812581592 | 42.40283 | 12.15990  | 0.0005562  | 1798 |
| 1799 | 3236401 | 5822285399 | 42.41462 | 12.16215  | 0.0005559  | 1799 |
| 1800 | 3240000 | 5832000000 | 42.42641 | 12.16440  | 0.0005556  | 1800 |

**Powers, Roots, and Reciprocals From 1801 to 1850**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1801 | 3243601 | 5841725401 | 42.43819 | 12.16666  | 0.0005552  | 1801 |
| 1802 | 3247204 | 5851461608 | 42.44997 | 12.16891  | 0.0005549  | 1802 |
| 1803 | 3250809 | 5861208627 | 42.46175 | 12.17116  | 0.0005546  | 1803 |
| 1804 | 3254416 | 5870966464 | 42.47352 | 12.17341  | 0.0005543  | 1804 |
| 1805 | 3258025 | 5880735125 | 42.48529 | 12.17566  | 0.0005540  | 1805 |
| 1806 | 3261636 | 5890514616 | 42.49706 | 12.17791  | 0.0005537  | 1806 |
| 1807 | 3265249 | 5900304943 | 42.50882 | 12.18015  | 0.0005534  | 1807 |
| 1808 | 3268864 | 5910106112 | 42.52058 | 12.18240  | 0.0005531  | 1808 |
| 1809 | 3272481 | 5919918129 | 42.53234 | 12.18464  | 0.0005528  | 1809 |
| 1810 | 3276100 | 5929741000 | 42.54409 | 12.18689  | 0.0005525  | 1810 |
| 1811 | 3279721 | 5939574731 | 42.55585 | 12.18913  | 0.0005522  | 1811 |
| 1812 | 3283344 | 5949419328 | 42.56759 | 12.19138  | 0.0005519  | 1812 |
| 1813 | 3286969 | 5959274797 | 42.57934 | 12.19362  | 0.0005516  | 1813 |
| 1814 | 3290596 | 5969141144 | 42.59108 | 12.19586  | 0.0005513  | 1814 |
| 1815 | 3294225 | 5979018375 | 42.60282 | 12.19810  | 0.0005510  | 1815 |
| 1816 | 3297856 | 5988906496 | 42.61455 | 12.20034  | 0.0005507  | 1816 |
| 1817 | 3301489 | 5998805513 | 42.62628 | 12.20258  | 0.0005504  | 1817 |
| 1818 | 3305124 | 6008715432 | 42.63801 | 12.20482  | 0.0005501  | 1818 |
| 1819 | 3308761 | 6018636259 | 42.64974 | 12.20705  | 0.0005498  | 1819 |
| 1820 | 3312400 | 6028568000 | 42.66146 | 12.20929  | 0.0005495  | 1820 |
| 1821 | 3316041 | 6038510661 | 42.67318 | 12.21153  | 0.0005491  | 1821 |
| 1822 | 3319684 | 6048464248 | 42.68489 | 12.21376  | 0.0005488  | 1822 |
| 1823 | 3323329 | 6058428767 | 42.69660 | 12.21600  | 0.0005485  | 1823 |
| 1824 | 3326976 | 6068404224 | 42.70831 | 12.21823  | 0.0005482  | 1824 |
| 1825 | 3330625 | 6078390625 | 42.72002 | 12.22046  | 0.0005479  | 1825 |
| 1826 | 3334276 | 6088387976 | 42.73172 | 12.22269  | 0.0005476  | 1826 |
| 1827 | 3337929 | 6098396283 | 42.74342 | 12.22492  | 0.0005473  | 1827 |
| 1828 | 3341584 | 6108415552 | 42.75512 | 12.22715  | 0.0005470  | 1828 |
| 1829 | 3345241 | 6118445789 | 42.76681 | 12.22938  | 0.0005467  | 1829 |
| 1830 | 3348900 | 6128487000 | 42.77850 | 12.23161  | 0.0005464  | 1830 |
| 1831 | 3352561 | 6138539191 | 42.79019 | 12.23384  | 0.0005461  | 1831 |
| 1832 | 3356224 | 6148602368 | 42.80187 | 12.23607  | 0.0005459  | 1832 |
| 1833 | 3359889 | 6158676537 | 42.81355 | 12.23829  | 0.0005456  | 1833 |
| 1834 | 3363556 | 6168761704 | 42.82523 | 12.24052  | 0.0005453  | 1834 |
| 1835 | 3367225 | 6178857875 | 42.83690 | 12.24274  | 0.0005450  | 1835 |
| 1836 | 3370896 | 6188965056 | 42.84857 | 12.24497  | 0.0005447  | 1836 |
| 1837 | 3374569 | 6199083253 | 42.86024 | 12.24719  | 0.0005444  | 1837 |
| 1838 | 3378244 | 6209212472 | 42.87190 | 12.24941  | 0.0005441  | 1838 |
| 1839 | 3381921 | 6219352719 | 42.88356 | 12.25163  | 0.0005438  | 1839 |
| 1840 | 3385600 | 6229504000 | 42.89522 | 12.25385  | 0.0005435  | 1840 |
| 1841 | 3389281 | 6239666321 | 42.90688 | 12.25607  | 0.0005432  | 1841 |
| 1842 | 3392964 | 6249839688 | 42.91853 | 12.25829  | 0.0005429  | 1842 |
| 1843 | 3396649 | 6260024107 | 42.93018 | 12.26051  | 0.0005426  | 1843 |
| 1844 | 3400336 | 6270219584 | 42.94182 | 12.26272  | 0.0005423  | 1844 |
| 1845 | 3404025 | 6280426125 | 42.95346 | 12.26494  | 0.0005420  | 1845 |
| 1846 | 3407716 | 6290643736 | 42.96510 | 12.26716  | 0.0005417  | 1846 |
| 1847 | 3411409 | 6300872423 | 42.97674 | 12.26937  | 0.0005414  | 1847 |
| 1848 | 3415104 | 6311112192 | 42.98837 | 12.27158  | 0.0005411  | 1848 |
| 1849 | 3418801 | 6321363049 | 43.00000 | 12.27380  | 0.0005408  | 1849 |
| 1850 | 3422500 | 6331625000 | 43.01163 | 12.27601  | 0.0005405  | 1850 |

## Powers, Roots, and Reciprocals From 1851 to 1900

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1851 | 3426201 | 6341898051 | 43.02325 | 12.27822  | 0.0005402  | 1851 |
| 1852 | 3429904 | 6352182208 | 43.03487 | 12.28043  | 0.0005400  | 1852 |
| 1853 | 3433609 | 6362477477 | 43.04649 | 12.28264  | 0.0005397  | 1853 |
| 1854 | 3437316 | 6372783864 | 43.05810 | 12.28485  | 0.0005394  | 1854 |
| 1855 | 3441025 | 6383101375 | 43.06971 | 12.28706  | 0.0005391  | 1855 |
| 1856 | 3444736 | 6393430016 | 43.08132 | 12.28927  | 0.0005388  | 1856 |
| 1857 | 3448449 | 6403769793 | 43.09292 | 12.29147  | 0.0005385  | 1857 |
| 1858 | 3452164 | 6414120712 | 43.10452 | 12.29368  | 0.0005382  | 1858 |
| 1859 | 3455881 | 6424482779 | 43.11612 | 12.29589  | 0.0005379  | 1859 |
| 1860 | 3459600 | 6434856000 | 43.12772 | 12.29809  | 0.0005376  | 1860 |
| 1861 | 3463321 | 6445240381 | 43.13931 | 12.30029  | 0.0005373  | 1861 |
| 1862 | 3467044 | 6455635928 | 43.15090 | 12.30250  | 0.0005371  | 1862 |
| 1863 | 3470769 | 6466042647 | 43.16248 | 12.30470  | 0.0005368  | 1863 |
| 1864 | 3474496 | 6476460544 | 43.17407 | 12.30690  | 0.0005365  | 1864 |
| 1865 | 3478225 | 6486889625 | 43.18565 | 12.30910  | 0.0005362  | 1865 |
| 1866 | 3481956 | 6497329896 | 43.19722 | 12.31130  | 0.0005359  | 1866 |
| 1867 | 3485689 | 6507781363 | 43.20880 | 12.31350  | 0.0005356  | 1867 |
| 1868 | 3489424 | 6518244032 | 43.22037 | 12.31570  | 0.0005353  | 1868 |
| 1869 | 3493161 | 6528717909 | 43.23193 | 12.31789  | 0.0005350  | 1869 |
| 1870 | 3496900 | 6539203000 | 43.24350 | 12.32009  | 0.0005348  | 1870 |
| 1871 | 3500641 | 6549699311 | 43.25506 | 12.32229  | 0.0005345  | 1871 |
| 1872 | 3504384 | 6560206848 | 43.26662 | 12.32448  | 0.0005342  | 1872 |
| 1873 | 3508129 | 6570725617 | 43.27817 | 12.32667  | 0.0005339  | 1873 |
| 1874 | 3511876 | 6581255624 | 43.28972 | 12.32887  | 0.0005336  | 1874 |
| 1875 | 3515625 | 6591796875 | 43.30127 | 12.33106  | 0.0005333  | 1875 |
| 1876 | 3519376 | 6602349376 | 43.31282 | 12.33325  | 0.0005330  | 1876 |
| 1877 | 3523129 | 6612913133 | 43.32436 | 12.33544  | 0.0005328  | 1877 |
| 1878 | 3526884 | 6623488152 | 43.33590 | 12.33763  | 0.0005325  | 1878 |
| 1879 | 3530641 | 6634074439 | 43.34743 | 12.33982  | 0.0005322  | 1879 |
| 1880 | 3534400 | 6644672000 | 43.35897 | 12.34201  | 0.0005319  | 1880 |
| 1881 | 3538161 | 6655280841 | 43.37050 | 12.34420  | 0.0005316  | 1881 |
| 1882 | 3541924 | 6665900968 | 43.38202 | 12.34639  | 0.0005313  | 1882 |
| 1883 | 3545689 | 6676532387 | 43.39355 | 12.34857  | 0.0005311  | 1883 |
| 1884 | 3549456 | 6687175104 | 43.40507 | 12.35076  | 0.0005308  | 1884 |
| 1885 | 3553225 | 6697829125 | 43.41659 | 12.35294  | 0.0005305  | 1885 |
| 1886 | 3556996 | 6708494456 | 43.42810 | 12.35513  | 0.0005302  | 1886 |
| 1887 | 3560769 | 6719171103 | 43.43961 | 12.35731  | 0.0005299  | 1887 |
| 1888 | 3564544 | 6729859072 | 43.45112 | 12.35949  | 0.0005297  | 1888 |
| 1889 | 3568321 | 6740558369 | 43.46263 | 12.36167  | 0.0005294  | 1889 |
| 1890 | 3572100 | 6751269000 | 43.47413 | 12.36386  | 0.0005291  | 1890 |
| 1891 | 3575881 | 6761990971 | 43.48563 | 12.36604  | 0.0005288  | 1891 |
| 1892 | 3579664 | 6772724288 | 43.49713 | 12.36822  | 0.0005285  | 1892 |
| 1893 | 3583449 | 6783468957 | 43.50862 | 12.37039  | 0.0005283  | 1893 |
| 1894 | 3587236 | 6794224984 | 43.52011 | 12.37257  | 0.0005280  | 1894 |
| 1895 | 3591025 | 6804992375 | 43.53160 | 12.37475  | 0.0005277  | 1895 |
| 1896 | 3594816 | 6815771136 | 43.54308 | 12.37693  | 0.0005274  | 1896 |
| 1897 | 3598609 | 6826561273 | 43.55456 | 12.37910  | 0.0005271  | 1897 |
| 1898 | 3602404 | 6837362792 | 43.56604 | 12.38128  | 0.0005269  | 1898 |
| 1899 | 3606201 | 6848175699 | 43.57752 | 12.38345  | 0.0005266  | 1899 |
| 1900 | 3610000 | 6859000000 | 43.58899 | 12.38562  | 0.0005263  | 1900 |

## Powers, Roots, and Reciprocals From 1901 to 1950

| No.  | Square  | Cube        | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|-------------|----------|-----------|------------|------|
| 1901 | 3613801 | 6869835701  | 43.60046 | 12.38780  | 0.0005260  | 1901 |
| 1902 | 3617604 | 6880682808  | 43.61192 | 12.38997  | 0.0005258  | 1902 |
| 1903 | 3621409 | 6891541327  | 43.62339 | 12.39214  | 0.0005255  | 1903 |
| 1904 | 3625216 | 6902411264  | 43.63485 | 12.39431  | 0.0005252  | 1904 |
| 1905 | 3629025 | 6913292625  | 43.64631 | 12.39648  | 0.0005249  | 1905 |
| 1906 | 3632836 | 6924185416  | 43.65776 | 12.39865  | 0.0005247  | 1906 |
| 1907 | 3636649 | 6935089643  | 43.66921 | 12.40082  | 0.0005244  | 1907 |
| 1908 | 3640464 | 6946005312  | 43.68066 | 12.40298  | 0.0005241  | 1908 |
| 1909 | 3644281 | 6956932429  | 43.69210 | 12.40515  | 0.0005238  | 1909 |
| 1910 | 3648100 | 6967871000  | 43.70355 | 12.40731  | 0.0005236  | 1910 |
| 1911 | 3651921 | 6978821031  | 43.71499 | 12.40948  | 0.0005233  | 1911 |
| 1912 | 3655744 | 6989782528  | 43.72642 | 12.41164  | 0.0005230  | 1912 |
| 1913 | 3659569 | 7000755497  | 43.73786 | 12.41381  | 0.0005227  | 1913 |
| 1914 | 3663396 | 7011739944  | 43.74929 | 12.41597  | 0.0005225  | 1914 |
| 1915 | 3667225 | 7022735875  | 43.76071 | 12.41813  | 0.0005222  | 1915 |
| 1916 | 3671056 | 7033743296  | 43.77214 | 12.42029  | 0.0005219  | 1916 |
| 1917 | 3674889 | 7044762213  | 43.78356 | 12.42245  | 0.0005216  | 1917 |
| 1918 | 3678724 | 7055792632  | 43.79498 | 12.42461  | 0.0005214  | 1918 |
| 1919 | 3682561 | 7066834559  | 43.80639 | 12.42677  | 0.0005211  | 1919 |
| 1920 | 3686400 | 7077888000  | 43.81780 | 12.42893  | 0.0005208  | 1920 |
| 1921 | 3690241 | 7088952961  | 43.82921 | 12.43109  | 0.0005206  | 1921 |
| 1922 | 3694084 | 7100029448  | 43.84062 | 12.43324  | 0.0005203  | 1922 |
| 1923 | 3697929 | 7111117467  | 43.85202 | 12.43540  | 0.0005200  | 1923 |
| 1924 | 3701776 | 7122217024  | 43.86342 | 12.43756  | 0.0005198  | 1924 |
| 1925 | 3705625 | 7133328125  | 43.87482 | 12.43971  | 0.0005195  | 1925 |
| 1926 | 3709476 | 71444450776 | 43.88622 | 12.44186  | 0.0005192  | 1926 |
| 1927 | 3713329 | 7155584983  | 43.89761 | 12.44402  | 0.0005189  | 1927 |
| 1928 | 3717184 | 7166730752  | 43.90900 | 12.44617  | 0.0005187  | 1928 |
| 1929 | 3721041 | 7177888089  | 43.92038 | 12.44832  | 0.0005184  | 1929 |
| 1930 | 3724900 | 7189057000  | 43.93177 | 12.45047  | 0.0005181  | 1930 |
| 1931 | 3728761 | 7200237491  | 43.94315 | 12.45262  | 0.0005179  | 1931 |
| 1932 | 3732624 | 7211429568  | 43.95452 | 12.45477  | 0.0005176  | 1932 |
| 1933 | 3736489 | 7222633237  | 43.96590 | 12.45692  | 0.0005173  | 1933 |
| 1934 | 3740356 | 7233848504  | 43.97727 | 12.45907  | 0.0005171  | 1934 |
| 1935 | 3744225 | 7245075375  | 43.98863 | 12.46121  | 0.0005168  | 1935 |
| 1936 | 3748096 | 7256313856  | 44.00000 | 12.46336  | 0.0005165  | 1936 |
| 1937 | 3751969 | 7267563953  | 44.01136 | 12.46550  | 0.0005163  | 1937 |
| 1938 | 3755844 | 7278825672  | 44.02272 | 12.46765  | 0.0005160  | 1938 |
| 1939 | 3759721 | 7290099019  | 44.03408 | 12.46979  | 0.0005157  | 1939 |
| 1940 | 3763600 | 7301384000  | 44.04543 | 12.47194  | 0.0005155  | 1940 |
| 1941 | 3767481 | 7312680621  | 44.05678 | 12.47408  | 0.0005152  | 1941 |
| 1942 | 3771364 | 7323988888  | 44.06813 | 12.47622  | 0.0005149  | 1942 |
| 1943 | 3775249 | 7335308807  | 44.07947 | 12.47836  | 0.0005147  | 1943 |
| 1944 | 3779136 | 7346640384  | 44.09082 | 12.48050  | 0.0005144  | 1944 |
| 1945 | 3783025 | 7357983625  | 44.10215 | 12.48264  | 0.0005141  | 1945 |
| 1946 | 3786916 | 7369338536  | 44.11349 | 12.48478  | 0.0005139  | 1946 |
| 1947 | 3790809 | 7380705123  | 44.12482 | 12.48692  | 0.0005136  | 1947 |
| 1948 | 3794704 | 7392083392  | 44.13615 | 12.48906  | 0.0005133  | 1948 |
| 1949 | 3798601 | 7403473349  | 44.14748 | 12.49119  | 0.0005131  | 1949 |
| 1950 | 3802500 | 7414875000  | 44.15880 | 12.49333  | 0.0005128  | 1950 |

**Powers, Roots, and Reciprocals From 1951 to 2000**

| No.  | Square  | Cube       | Sq. Root | Cube Root | Reciprocal | No.  |
|------|---------|------------|----------|-----------|------------|------|
| 1951 | 3806401 | 7426288351 | 44.17013 | 12.49547  | 0.0005126  | 1951 |
| 1952 | 3810304 | 7437713408 | 44.18144 | 12.49760  | 0.0005123  | 1952 |
| 1953 | 3814209 | 7449150177 | 44.19276 | 12.49973  | 0.0005120  | 1953 |
| 1954 | 3818116 | 7460598664 | 44.20407 | 12.50187  | 0.0005118  | 1954 |
| 1955 | 3822025 | 7472058875 | 44.21538 | 12.50400  | 0.0005115  | 1955 |
| 1956 | 3825936 | 7483530816 | 44.22669 | 12.50613  | 0.0005112  | 1956 |
| 1957 | 3829849 | 7495014493 | 44.23799 | 12.50826  | 0.0005110  | 1957 |
| 1958 | 3833764 | 7506509912 | 44.24929 | 12.51039  | 0.0005107  | 1958 |
| 1959 | 3837681 | 7518017079 | 44.26059 | 12.51252  | 0.0005105  | 1959 |
| 1960 | 3841600 | 7529536000 | 44.27189 | 12.51465  | 0.0005102  | 1960 |
| 1961 | 3845521 | 7541066681 | 44.28318 | 12.51678  | 0.0005099  | 1961 |
| 1962 | 3849444 | 7552609128 | 44.29447 | 12.51890  | 0.0005097  | 1962 |
| 1963 | 3853369 | 7564163347 | 44.30576 | 12.52103  | 0.0005094  | 1963 |
| 1964 | 3857296 | 7575729344 | 44.31704 | 12.52316  | 0.0005092  | 1964 |
| 1965 | 3861225 | 7587307125 | 44.32832 | 12.52528  | 0.0005089  | 1965 |
| 1966 | 3865156 | 7598896696 | 44.33960 | 12.52741  | 0.0005086  | 1966 |
| 1967 | 3869089 | 7610498063 | 44.35087 | 12.52953  | 0.0005084  | 1967 |
| 1968 | 3873024 | 7622111232 | 44.36215 | 12.53165  | 0.0005081  | 1968 |
| 1969 | 3876961 | 7633736209 | 44.37342 | 12.53378  | 0.0005079  | 1969 |
| 1970 | 3880900 | 7645373000 | 44.38468 | 12.53590  | 0.0005076  | 1970 |
| 1971 | 3884841 | 7657021611 | 44.39595 | 12.53802  | 0.0005074  | 1971 |
| 1972 | 3888784 | 7668682048 | 44.40721 | 12.54014  | 0.0005071  | 1972 |
| 1973 | 3892729 | 7680354317 | 44.41846 | 12.54226  | 0.0005068  | 1973 |
| 1974 | 3896676 | 7692038424 | 44.42972 | 12.54438  | 0.0005066  | 1974 |
| 1975 | 3900625 | 7703734375 | 44.44097 | 12.54649  | 0.0005063  | 1975 |
| 1976 | 3904576 | 7715442176 | 44.45222 | 12.54861  | 0.0005061  | 1976 |
| 1977 | 3908529 | 7727161833 | 44.46347 | 12.55073  | 0.0005058  | 1977 |
| 1978 | 3912484 | 7738893352 | 44.47471 | 12.55284  | 0.0005056  | 1978 |
| 1979 | 3916441 | 7750636739 | 44.48595 | 12.55496  | 0.0005053  | 1979 |
| 1980 | 3920400 | 7762392000 | 44.49719 | 12.55707  | 0.0005051  | 1980 |
| 1981 | 3924361 | 7774159141 | 44.50843 | 12.55919  | 0.0005048  | 1981 |
| 1982 | 3928324 | 7785938168 | 44.51966 | 12.56130  | 0.0005045  | 1982 |
| 1983 | 3932289 | 7797729087 | 44.53089 | 12.56341  | 0.0005043  | 1983 |
| 1984 | 3936256 | 7809531904 | 44.54211 | 12.56552  | 0.0005040  | 1984 |
| 1985 | 3940225 | 7821346625 | 44.55334 | 12.56763  | 0.0005038  | 1985 |
| 1986 | 3944196 | 7833173256 | 44.56456 | 12.56974  | 0.0005035  | 1986 |
| 1987 | 3948169 | 7845011803 | 44.57578 | 12.57185  | 0.0005033  | 1987 |
| 1988 | 3952144 | 7856862272 | 44.58699 | 12.57396  | 0.0005030  | 1988 |
| 1989 | 3956121 | 7868724669 | 44.59821 | 12.57607  | 0.0005028  | 1989 |
| 1990 | 3960100 | 7880599000 | 44.60942 | 12.57818  | 0.0005025  | 1990 |
| 1991 | 3964081 | 7892485271 | 44.62062 | 12.58028  | 0.0005023  | 1991 |
| 1992 | 3968064 | 7904383488 | 44.63183 | 12.58239  | 0.0005020  | 1992 |
| 1993 | 3972049 | 7916293657 | 44.64303 | 12.58449  | 0.0005018  | 1993 |
| 1994 | 3976036 | 7928215784 | 44.65423 | 12.58660  | 0.0005015  | 1994 |
| 1995 | 3980025 | 7940149875 | 44.66542 | 12.58870  | 0.0005013  | 1995 |
| 1996 | 3984016 | 7952095936 | 44.67662 | 12.59081  | 0.0005010  | 1996 |
| 1997 | 3988009 | 7964053973 | 44.68781 | 12.59291  | 0.0005008  | 1997 |
| 1998 | 3992004 | 7976023992 | 44.69899 | 12.59501  | 0.0005005  | 1998 |
| 1999 | 3996001 | 7988005999 | 44.71018 | 12.59711  | 0.0005003  | 1999 |
| 2000 | 4000000 | 8000000000 | 44.72136 | 12.59921  | 0.0005000  | 2000 |



## MULTIPLICATION OF FRACTIONS

## Multiplication Tables for Fractions

## Multiplication Table for Common Fractions and Whole Numbers From 1 to 9

|                 | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      |
|-----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| $\frac{1}{64}$  | 0.0156 | 0.0313 | 0.0469 | 0.0625 | 0.0781 | 0.0938 | 0.1094 | 0.1250 | 0.1406 |
| $\frac{1}{32}$  | 0.0313 | 0.0625 | 0.0938 | 0.1250 | 0.1563 | 0.1875 | 0.2188 | 0.2500 | 0.2813 |
| $\frac{3}{64}$  | 0.0469 | 0.0938 | 0.1406 | 0.1875 | 0.2344 | 0.2813 | 0.3281 | 0.3750 | 0.4219 |
| $\frac{1}{16}$  | 0.0625 | 0.1250 | 0.1875 | 0.2500 | 0.3125 | 0.3750 | 0.4375 | 0.5000 | 0.5625 |
| $\frac{5}{64}$  | 0.0781 | 0.1563 | 0.2344 | 0.3125 | 0.3906 | 0.4688 | 0.5469 | 0.6250 | 0.7031 |
| $\frac{3}{32}$  | 0.0938 | 0.1875 | 0.2813 | 0.3750 | 0.4688 | 0.5625 | 0.6563 | 0.7500 | 0.8438 |
| $\frac{7}{64}$  | 0.1094 | 0.2188 | 0.3281 | 0.4375 | 0.5469 | 0.6563 | 0.7656 | 0.8750 | 0.9844 |
| $\frac{1}{8}$   | 0.1250 | 0.2500 | 0.3750 | 0.5000 | 0.6250 | 0.7500 | 0.8750 | 1.0000 | 1.1250 |
| $\frac{9}{64}$  | 0.1406 | 0.2813 | 0.4219 | 0.5625 | 0.7031 | 0.8438 | 0.9844 | 1.1250 | 1.2656 |
| $\frac{5}{32}$  | 0.1563 | 0.3125 | 0.4688 | 0.6250 | 0.7813 | 0.9375 | 1.0938 | 1.2500 | 1.4063 |
| $\frac{11}{64}$ | 0.1719 | 0.3438 | 0.5156 | 0.6875 | 0.8594 | 1.0313 | 1.2031 | 1.3750 | 1.5469 |
| $\frac{3}{16}$  | 0.1875 | 0.3750 | 0.5625 | 0.7500 | 0.9375 | 1.1250 | 1.3125 | 1.5000 | 1.6875 |
| $\frac{13}{64}$ | 0.2031 | 0.4063 | 0.6094 | 0.8125 | 1.0156 | 1.2188 | 1.4219 | 1.6250 | 1.8281 |
| $\frac{7}{32}$  | 0.2188 | 0.4375 | 0.6563 | 0.8750 | 1.0938 | 1.3125 | 1.5313 | 1.7500 | 1.9688 |
| $\frac{15}{64}$ | 0.2344 | 0.4688 | 0.7031 | 0.9375 | 1.1719 | 1.4063 | 1.6406 | 1.8750 | 2.1094 |
| $\frac{1}{4}$   | 0.2500 | 0.5000 | 0.7500 | 1.0000 | 1.2500 | 1.5000 | 1.7500 | 2.0000 | 2.2500 |
| $\frac{17}{64}$ | 0.2656 | 0.5313 | 0.7969 | 1.0625 | 1.3281 | 1.5938 | 1.8594 | 2.1250 | 2.3906 |
| $\frac{9}{32}$  | 0.2813 | 0.5625 | 0.8438 | 1.1250 | 1.4063 | 1.6875 | 1.9688 | 2.2500 | 2.5313 |
| $\frac{19}{64}$ | 0.2969 | 0.5938 | 0.8906 | 1.1875 | 1.4844 | 1.7813 | 2.0781 | 2.3750 | 2.6719 |
| $\frac{5}{16}$  | 0.3125 | 0.6250 | 0.9375 | 1.2500 | 1.5625 | 1.8750 | 2.1875 | 2.5000 | 2.8125 |
| $\frac{21}{64}$ | 0.3281 | 0.6563 | 0.9844 | 1.3125 | 1.6406 | 1.9688 | 2.2969 | 2.6250 | 2.9531 |
| $\frac{11}{32}$ | 0.3438 | 0.6875 | 1.0313 | 1.3750 | 1.7188 | 2.0625 | 2.4063 | 2.7500 | 3.0938 |
| $\frac{23}{64}$ | 0.3594 | 0.7188 | 1.0781 | 1.4375 | 1.7969 | 2.1563 | 2.5156 | 2.8750 | 3.2344 |
| $\frac{3}{8}$   | 0.3750 | 0.7500 | 1.1250 | 1.5000 | 1.8750 | 2.2500 | 2.6250 | 3.0000 | 3.3750 |
| $\frac{25}{64}$ | 0.3906 | 0.7813 | 1.1719 | 1.5625 | 1.9531 | 2.3438 | 2.7344 | 3.1250 | 3.5156 |
| $\frac{13}{32}$ | 0.4063 | 0.8125 | 1.2188 | 1.6250 | 2.0313 | 2.4375 | 2.8438 | 3.2500 | 3.6563 |
| $\frac{27}{64}$ | 0.4219 | 0.8438 | 1.2656 | 1.6875 | 2.1094 | 2.5313 | 2.9531 | 3.3750 | 3.7969 |
| $\frac{7}{16}$  | 0.4375 | 0.8750 | 1.3125 | 1.7500 | 2.1875 | 2.6250 | 3.0625 | 3.5000 | 3.9375 |
| $\frac{29}{64}$ | 0.4531 | 0.9063 | 1.3594 | 1.8125 | 2.2656 | 2.7188 | 3.1719 | 3.6250 | 4.0781 |
| $\frac{15}{32}$ | 0.4688 | 0.9375 | 1.4063 | 1.8750 | 2.3438 | 2.8125 | 3.2813 | 3.7500 | 4.2188 |
| $\frac{31}{64}$ | 0.4844 | 0.9688 | 1.4531 | 1.9375 | 2.4219 | 2.9063 | 3.3906 | 3.8750 | 4.3594 |
| $\frac{1}{2}$   | 0.5000 | 1.0000 | 1.5000 | 2.0000 | 2.5000 | 3.0000 | 3.5000 | 4.0000 | 4.5000 |
| $\frac{33}{64}$ | 0.5156 | 1.0313 | 1.5469 | 2.0625 | 2.5781 | 3.0938 | 3.6094 | 4.1250 | 4.6406 |
| $\frac{17}{32}$ | 0.5313 | 1.0625 | 1.5938 | 2.1250 | 2.6563 | 3.1875 | 3.7188 | 4.2500 | 4.7813 |
| $\frac{35}{64}$ | 0.5469 | 1.0938 | 1.6406 | 2.1875 | 2.7344 | 3.2813 | 3.8281 | 4.3750 | 4.9219 |
| $\frac{9}{16}$  | 0.5625 | 1.1250 | 1.6875 | 2.2500 | 2.8125 | 3.3750 | 3.9375 | 4.5000 | 5.0625 |
| $\frac{37}{64}$ | 0.5781 | 1.1563 | 1.7344 | 2.3125 | 2.8906 | 3.4688 | 4.0469 | 4.6250 | 5.2031 |
| $\frac{19}{32}$ | 0.5938 | 1.1875 | 1.7813 | 2.3750 | 2.9688 | 3.5625 | 4.1563 | 4.7500 | 5.3438 |
| $\frac{39}{64}$ | 0.6094 | 1.2188 | 1.8281 | 2.4375 | 3.0469 | 3.6563 | 4.2656 | 4.8750 | 5.4844 |
| $\frac{5}{8}$   | 0.6250 | 1.2500 | 1.8750 | 2.5000 | 3.1250 | 3.7500 | 4.3750 | 5.0000 | 5.6250 |
| $\frac{41}{64}$ | 0.6406 | 1.2813 | 1.9219 | 2.5625 | 3.2031 | 3.8438 | 4.4844 | 5.1250 | 5.7656 |
| $\frac{21}{32}$ | 0.6563 | 1.3125 | 1.9688 | 2.6250 | 3.2813 | 3.9375 | 4.5938 | 5.2500 | 5.9063 |
| $\frac{43}{64}$ | 0.6719 | 1.3438 | 2.0156 | 2.6875 | 3.3594 | 4.0313 | 4.7031 | 5.3750 | 6.0469 |
| $\frac{11}{16}$ | 0.6875 | 1.3750 | 2.0625 | 2.7500 | 3.4375 | 4.1250 | 4.8125 | 5.5000 | 6.1875 |
| $\frac{45}{64}$ | 0.7031 | 1.4063 | 2.1094 | 2.8125 | 3.5156 | 4.2188 | 4.9219 | 5.6250 | 6.3281 |
| $\frac{23}{32}$ | 0.7188 | 1.4375 | 2.1563 | 2.8750 | 3.5938 | 4.3125 | 5.0313 | 5.7500 | 6.4688 |
| $\frac{47}{64}$ | 0.7344 | 1.4688 | 2.2031 | 2.9375 | 3.6719 | 4.4063 | 5.1406 | 5.8750 | 6.6094 |
| $\frac{3}{4}$   | 0.7500 | 1.5000 | 2.2500 | 3.0000 | 3.7500 | 4.5000 | 5.2500 | 6.0000 | 6.7500 |
| $\frac{49}{64}$ | 0.7656 | 1.5313 | 2.2969 | 3.0625 | 3.8281 | 4.5938 | 5.3594 | 6.1250 | 6.8906 |
| $\frac{25}{32}$ | 0.7813 | 1.5625 | 2.3438 | 3.1250 | 3.9063 | 4.6875 | 5.4688 | 6.2500 | 7.0313 |
| $\frac{51}{64}$ | 0.7969 | 1.5938 | 2.3906 | 3.1875 | 3.9844 | 4.7813 | 5.5781 | 6.3750 | 7.1719 |
| $\frac{13}{16}$ | 0.8125 | 1.6250 | 2.4375 | 3.2500 | 4.0625 | 4.8750 | 5.6875 | 6.5000 | 7.3125 |
| $\frac{53}{64}$ | 0.8281 | 1.6563 | 2.4844 | 3.3125 | 4.1406 | 4.9688 | 5.7969 | 6.6250 | 7.4531 |
| $\frac{27}{32}$ | 0.8438 | 1.6875 | 2.5313 | 3.3750 | 4.2188 | 5.0625 | 5.9063 | 6.7500 | 7.5938 |
| $\frac{55}{64}$ | 0.8594 | 1.7188 | 2.5781 | 3.4375 | 4.2969 | 5.1563 | 6.0156 | 6.8750 | 7.7344 |
| $\frac{7}{8}$   | 0.8750 | 1.7500 | 2.6250 | 3.5000 | 4.3750 | 5.2500 | 6.1250 | 7.0000 | 7.8750 |
| $\frac{57}{64}$ | 0.8906 | 1.7813 | 2.6719 | 3.5625 | 4.4531 | 5.3438 | 6.2344 | 7.1250 | 8.0156 |
| $\frac{29}{32}$ | 0.9063 | 1.8125 | 2.7188 | 3.6250 | 4.5313 | 5.4375 | 6.3438 | 7.2500 | 8.1563 |
| $\frac{59}{64}$ | 0.9219 | 1.8438 | 2.7656 | 3.6875 | 4.6094 | 5.5313 | 6.4531 | 7.3750 | 8.2969 |
| $\frac{15}{16}$ | 0.9375 | 1.8750 | 2.8125 | 3.7500 | 4.6875 | 5.6250 | 6.5625 | 7.5000 | 8.4375 |
| $\frac{61}{64}$ | 0.9531 | 1.9063 | 2.8594 | 3.8125 | 4.7656 | 5.7188 | 6.6719 | 7.6250 | 8.5781 |
| $\frac{31}{32}$ | 0.9688 | 1.9375 | 2.9063 | 3.8750 | 4.8438 | 5.8125 | 6.7813 | 7.7500 | 8.7188 |
| $\frac{63}{64}$ | 0.9844 | 1.9688 | 2.9531 | 3.9375 | 4.9219 | 5.9063 | 6.8906 | 7.8750 | 8.8594 |

Multiplication Table for Common Fractions From  $\frac{1}{32}$  to  $\frac{1}{2}$ 

|                 | $\frac{1}{32}$ | $\frac{1}{16}$ | $\frac{3}{32}$ | $\frac{1}{8}$ | $\frac{5}{32}$ | $\frac{3}{16}$ | $\frac{7}{32}$ | $\frac{1}{4}$ | $\frac{9}{32}$ | $\frac{5}{16}$ | $\frac{11}{32}$ | $\frac{3}{8}$ | $\frac{13}{32}$ | $\frac{7}{16}$ | $\frac{15}{32}$ | $\frac{1}{2}$ |
|-----------------|----------------|----------------|----------------|---------------|----------------|----------------|----------------|---------------|----------------|----------------|-----------------|---------------|-----------------|----------------|-----------------|---------------|
| $\frac{1}{32}$  | 0.0098         | 0.0195         | 0.00293        | 0.00391       | 0.00488        | 0.00586        | 0.00684        | 0.00781       | 0.00879        | 0.00977        | 0.01074         | 0.01172       | 0.01270         | 0.01367        | 0.01465         | 0.01563       |
| $\frac{1}{16}$  | 0.00195        | 0.00391        | 0.00586        | 0.00781       | 0.00977        | 0.01172        | 0.01367        | 0.01563       | 0.01758        | 0.01953        | 0.02148         | 0.02344       | 0.02539         | 0.02734        | 0.02930         | 0.03125       |
| $\frac{3}{32}$  | 0.00293        | 0.00586        | 0.00879        | 0.01172       | 0.01465        | 0.01758        | 0.02051        | 0.02344       | 0.02637        | 0.02930        | 0.03223         | 0.03516       | 0.03809         | 0.04102        | 0.04395         | 0.04688       |
| $\frac{1}{8}$   | 0.00391        | 0.00781        | 0.01172        | 0.01563       | 0.01953        | 0.02344        | 0.02734        | 0.03125       | 0.03516        | 0.03906        | 0.04297         | 0.04688       | 0.05078         | 0.05469        | 0.05859         | 0.06250       |
| $\frac{5}{32}$  | 0.00488        | 0.00977        | 0.01465        | 0.01953       | 0.02441        | 0.02930        | 0.03418        | 0.03906       | 0.04395        | 0.04883        | 0.05371         | 0.05859       | 0.06348         | 0.06836        | 0.07324         | 0.07813       |
| $\frac{3}{16}$  | 0.00586        | 0.01172        | 0.01758        | 0.02344       | 0.02930        | 0.03516        | 0.04102        | 0.04688       | 0.05273        | 0.05859        | 0.06445         | 0.07031       | 0.07617         | 0.08203        | 0.08789         | 0.09375       |
| $\frac{7}{32}$  | 0.00684        | 0.01367        | 0.02051        | 0.02734       | 0.03418        | 0.04102        | 0.04785        | 0.05469       | 0.06152        | 0.06836        | 0.07520         | 0.08203       | 0.08887         | 0.09570        | 0.10254         | 0.10938       |
| $\frac{1}{4}$   | 0.00781        | 0.01563        | 0.02344        | 0.03125       | 0.03906        | 0.04688        | 0.05469        | 0.06250       | 0.07031        | 0.07813        | 0.08594         | 0.09375       | 0.10156         | 0.10938        | 0.11719         | 0.12500       |
| $\frac{9}{32}$  | 0.00879        | 0.01758        | 0.02637        | 0.03516       | 0.04395        | 0.05273        | 0.06152        | 0.07031       | 0.07910        | 0.08789        | 0.09668         | 0.10547       | 0.11426         | 0.12305        | 0.13184         | 0.14063       |
| $\frac{5}{16}$  | 0.00977        | 0.01953        | 0.02930        | 0.03906       | 0.04883        | 0.05859        | 0.06836        | 0.07813       | 0.08789        | 0.09766        | 0.10742         | 0.11719       | 0.12695         | 0.13672        | 0.14648         | 0.15625       |
| $\frac{11}{32}$ | 0.01074        | 0.02148        | 0.03223        | 0.04297       | 0.05371        | 0.06445        | 0.07520        | 0.08594       | 0.09668        | 0.10742        | 0.11816         | 0.12891       | 0.13965         | 0.15039        | 0.16113         | 0.17188       |
| $\frac{3}{8}$   | 0.01172        | 0.02344        | 0.03516        | 0.04688       | 0.05859        | 0.07031        | 0.08203        | 0.09375       | 0.10547        | 0.11719        | 0.12891         | 0.14063       | 0.15234         | 0.16406        | 0.17578         | 0.18750       |
| $\frac{13}{32}$ | 0.01270        | 0.02539        | 0.03809        | 0.05078       | 0.06348        | 0.07617        | 0.08887        | 0.10156       | 0.11426        | 0.12695        | 0.13965         | 0.15234       | 0.16504         | 0.17773        | 0.19043         | 0.20313       |
| $\frac{7}{16}$  | 0.01367        | 0.02734        | 0.04102        | 0.05469       | 0.06836        | 0.08203        | 0.09570        | 0.10938       | 0.12305        | 0.13672        | 0.15039         | 0.16406       | 0.17773         | 0.19141        | 0.20508         | 0.21875       |
| $\frac{9}{16}$  | 0.01465        | 0.02930        | 0.04395        | 0.05859       | 0.07324        | 0.08789        | 0.10254        | 0.11719       | 0.13184        | 0.14648        | 0.16113         | 0.17578       | 0.19043         | 0.20508        | 0.21973         | 0.23438       |
| $\frac{1}{2}$   | 0.01563        | 0.03125        | 0.04688        | 0.06250       | 0.07813        | 0.09375        | 0.10938        | 0.12500       | 0.14063        | 0.15625        | 0.17188         | 0.18750       | 0.20313         | 0.21875        | 0.23438         | 0.25000       |
| $\frac{17}{32}$ | 0.01660        | 0.03320        | 0.04980        | 0.06641       | 0.08301        | 0.09961        | 0.11621        | 0.13281       | 0.14941        | 0.16602        | 0.18262         | 0.19922       | 0.21582         | 0.23242        | 0.24902         | 0.26563       |
| $\frac{19}{32}$ | 0.01758        | 0.03516        | 0.05273        | 0.07031       | 0.08789        | 0.10547        | 0.12305        | 0.14063       | 0.15820        | 0.17578        | 0.19336         | 0.21094       | 0.22852         | 0.24609        | 0.26367         | 0.28125       |
| $\frac{5}{8}$   | 0.01855        | 0.03711        | 0.05566        | 0.07422       | 0.09277        | 0.11133        | 0.12988        | 0.14844       | 0.16699        | 0.18555        | 0.20410         | 0.22266       | 0.24121         | 0.25977        | 0.27832         | 0.29688       |
| $\frac{3}{4}$   | 0.01953        | 0.03906        | 0.05859        | 0.07813       | 0.09766        | 0.11719        | 0.13672        | 0.15625       | 0.17578        | 0.19531        | 0.21484         | 0.23438       | 0.25391         | 0.27344        | 0.29297         | 0.31250       |
| $\frac{21}{32}$ | 0.02051        | 0.04102        | 0.06152        | 0.08203       | 0.10254        | 0.12305        | 0.14355        | 0.16406       | 0.18457        | 0.20508        | 0.22559         | 0.24609       | 0.26660         | 0.28711        | 0.30762         | 0.32813       |
| $\frac{11}{16}$ | 0.02148        | 0.04297        | 0.06445        | 0.08594       | 0.10742        | 0.12891        | 0.15039        | 0.17188       | 0.19336        | 0.21484        | 0.23633         | 0.25781       | 0.27930         | 0.30078        | 0.32227         | 0.34375       |
| $\frac{23}{32}$ | 0.02246        | 0.04492        | 0.06738        | 0.08984       | 0.11230        | 0.13477        | 0.15723        | 0.17969       | 0.20215        | 0.22461        | 0.24707         | 0.26953       | 0.29199         | 0.31445        | 0.33691         | 0.35938       |
| $\frac{5}{4}$   | 0.02344        | 0.04688        | 0.07031        | 0.09375       | 0.11719        | 0.14063        | 0.16406        | 0.18750       | 0.21094        | 0.23438        | 0.25781         | 0.28125       | 0.30469         | 0.32813        | 0.35156         | 0.37500       |
| $\frac{25}{32}$ | 0.02441        | 0.04883        | 0.07324        | 0.09766       | 0.12207        | 0.14648        | 0.17090        | 0.19531       | 0.21973        | 0.24414        | 0.26855         | 0.29297       | 0.31738         | 0.34180        | 0.36621         | 0.39063       |
| $\frac{13}{16}$ | 0.02539        | 0.05078        | 0.07617        | 0.10156       | 0.12695        | 0.15234        | 0.17773        | 0.20313       | 0.22852        | 0.25391        | 0.27930         | 0.30469       | 0.33008         | 0.35547        | 0.38086         | 0.40625       |
| $\frac{27}{32}$ | 0.02637        | 0.05273        | 0.07910        | 0.10547       | 0.13184        | 0.15820        | 0.18457        | 0.21094       | 0.23730        | 0.26367        | 0.29004         | 0.31641       | 0.34277         | 0.36914        | 0.39551         | 0.42188       |
| $\frac{7}{8}$   | 0.02734        | 0.05469        | 0.08203        | 0.10938       | 0.13672        | 0.16406        | 0.19141        | 0.21875       | 0.24609        | 0.27344        | 0.30078         | 0.32813       | 0.35547         | 0.38281        | 0.41016         | 0.43750       |
| $\frac{29}{32}$ | 0.02832        | 0.05664        | 0.08496        | 0.11328       | 0.14160        | 0.16992        | 0.19824        | 0.22656       | 0.25488        | 0.28320        | 0.31152         | 0.33984       | 0.36816         | 0.39648        | 0.42480         | 0.45313       |
| $\frac{15}{16}$ | 0.02930        | 0.05859        | 0.08789        | 0.11719       | 0.14648        | 0.17578        | 0.20508        | 0.23438       | 0.26367        | 0.29297        | 0.32227         | 0.35156       | 0.38086         | 0.41016        | 0.43945         | 0.46875       |
| $\frac{31}{32}$ | 0.03027        | 0.06055        | 0.09082        | 0.12109       | 0.15137        | 0.18164        | 0.21191        | 0.24219       | 0.27246        | 0.30273        | 0.33301         | 0.36328       | 0.39355         | 0.42383        | 0.45410         | 0.48438       |
| 1               | 0.03125        | 0.06250        | 0.09375        | 0.12500       | 0.15625        | 0.18750        | 0.21875        | 0.25000       | 0.28125        | 0.31250        | 0.34375         | 0.37500       | 0.40625         | 0.43750        | 0.46875         | 0.50000       |

Multiplication Table for Common Fractions From  $\frac{17}{32}$  to 1

|                 | $\frac{17}{32}$ | $\frac{9}{16}$ | $\frac{19}{32}$ | $\frac{5}{8}$ | $\frac{21}{32}$ | $\frac{11}{16}$ | $\frac{23}{32}$ | $\frac{3}{4}$ | $\frac{25}{32}$ | $\frac{13}{16}$ | $\frac{27}{32}$ | $\frac{7}{8}$ | $\frac{29}{32}$ | $\frac{15}{16}$ | $\frac{31}{32}$ | 1       |
|-----------------|-----------------|----------------|-----------------|---------------|-----------------|-----------------|-----------------|---------------|-----------------|-----------------|-----------------|---------------|-----------------|-----------------|-----------------|---------|
| $\frac{1}{32}$  | 0.01660         | 0.01758        | 0.01855         | 0.01953       | 0.02051         | 0.02148         | 0.02246         | 0.02344       | 0.02441         | 0.02539         | 0.02637         | 0.02734       | 0.02832         | 0.02930         | 0.03027         | 0.03125 |
| $\frac{1}{16}$  | 0.03320         | 0.03516        | 0.03711         | 0.03906       | 0.04102         | 0.04297         | 0.04492         | 0.04688       | 0.04883         | 0.05078         | 0.05273         | 0.05469       | 0.05664         | 0.05859         | 0.06055         | 0.06250 |
| $\frac{3}{32}$  | 0.04980         | 0.05273        | 0.05566         | 0.05859       | 0.06152         | 0.06445         | 0.06738         | 0.07031       | 0.07324         | 0.07617         | 0.07910         | 0.08203       | 0.08496         | 0.08789         | 0.09082         | 0.09375 |
| $\frac{1}{8}$   | 0.06641         | 0.07031        | 0.07422         | 0.07813       | 0.08203         | 0.08594         | 0.08984         | 0.09375       | 0.09766         | 0.10156         | 0.10547         | 0.10938       | 0.11328         | 0.11719         | 0.12109         | 0.12500 |
| $\frac{5}{32}$  | 0.08301         | 0.08789        | 0.09277         | 0.09766       | 0.10254         | 0.10742         | 0.11230         | 0.11719       | 0.12207         | 0.12695         | 0.13184         | 0.13672       | 0.14160         | 0.14648         | 0.15137         | 0.15625 |
| $\frac{3}{16}$  | 0.09961         | 0.10547        | 0.11133         | 0.11719       | 0.12305         | 0.12891         | 0.13477         | 0.14063       | 0.14648         | 0.15234         | 0.15820         | 0.16406       | 0.16992         | 0.17578         | 0.18164         | 0.18750 |
| $\frac{7}{32}$  | 0.11621         | 0.12305        | 0.12988         | 0.13672       | 0.14355         | 0.15039         | 0.15723         | 0.16406       | 0.17090         | 0.17773         | 0.18457         | 0.19141       | 0.19824         | 0.20508         | 0.21191         | 0.21875 |
| $\frac{1}{4}$   | 0.13281         | 0.14063        | 0.14844         | 0.15625       | 0.16406         | 0.17188         | 0.17969         | 0.18750       | 0.19531         | 0.20313         | 0.21094         | 0.21875       | 0.22656         | 0.23438         | 0.24219         | 0.25000 |
| $\frac{9}{32}$  | 0.14941         | 0.15820        | 0.16699         | 0.17578       | 0.18457         | 0.19336         | 0.20215         | 0.21094       | 0.21973         | 0.22852         | 0.23730         | 0.24609       | 0.25488         | 0.26367         | 0.27246         | 0.28125 |
| $\frac{5}{16}$  | 0.16602         | 0.17578        | 0.18555         | 0.19531       | 0.20508         | 0.21484         | 0.22461         | 0.23438       | 0.24414         | 0.25391         | 0.26367         | 0.27344       | 0.28320         | 0.29297         | 0.30273         | 0.31250 |
| $\frac{11}{32}$ | 0.18262         | 0.19336        | 0.20410         | 0.21484       | 0.22559         | 0.23633         | 0.24707         | 0.25781       | 0.26855         | 0.27930         | 0.29004         | 0.30078       | 0.31152         | 0.32227         | 0.33301         | 0.34375 |
| $\frac{3}{8}$   | 0.19922         | 0.21094        | 0.22266         | 0.23438       | 0.24609         | 0.25781         | 0.26953         | 0.28125       | 0.29297         | 0.30469         | 0.31641         | 0.32813       | 0.33984         | 0.35156         | 0.36328         | 0.37500 |
| $\frac{13}{32}$ | 0.21582         | 0.22852        | 0.24121         | 0.25391       | 0.26660         | 0.27930         | 0.29199         | 0.30469       | 0.31738         | 0.33008         | 0.34277         | 0.35547       | 0.36816         | 0.38086         | 0.39355         | 0.40625 |
| $\frac{7}{16}$  | 0.23242         | 0.24609        | 0.25977         | 0.27344       | 0.28711         | 0.30078         | 0.31445         | 0.32813       | 0.34180         | 0.35547         | 0.36914         | 0.38281       | 0.39648         | 0.41016         | 0.42383         | 0.43750 |
| $\frac{15}{32}$ | 0.24902         | 0.26367        | 0.27832         | 0.29297       | 0.30762         | 0.32227         | 0.33691         | 0.35156       | 0.36621         | 0.38086         | 0.39551         | 0.41016       | 0.42480         | 0.43945         | 0.45410         | 0.46875 |
| $\frac{1}{2}$   | 0.26563         | 0.28125        | 0.29688         | 0.31250       | 0.32813         | 0.34375         | 0.35938         | 0.37500       | 0.39063         | 0.40625         | 0.42188         | 0.43750       | 0.45313         | 0.46875         | 0.48438         | 0.50000 |
| $\frac{17}{32}$ | 0.28223         | 0.29883        | 0.31543         | 0.33203       | 0.34863         | 0.36523         | 0.38184         | 0.39844       | 0.41504         | 0.43164         | 0.44824         | 0.46484       | 0.48145         | 0.49805         | 0.51465         | 0.53125 |
| $\frac{9}{16}$  | 0.29883         | 0.31641        | 0.33398         | 0.35156       | 0.36914         | 0.38672         | 0.40430         | 0.42188       | 0.43945         | 0.45703         | 0.47461         | 0.49219       | 0.50977         | 0.52734         | 0.54492         | 0.56250 |
| $\frac{19}{32}$ | 0.31543         | 0.33398        | 0.35254         | 0.37109       | 0.38965         | 0.40820         | 0.42676         | 0.44531       | 0.46387         | 0.48242         | 0.50098         | 0.51953       | 0.53809         | 0.55664         | 0.57520         | 0.59375 |
| $\frac{5}{8}$   | 0.33203         | 0.35156        | 0.37109         | 0.39063       | 0.41016         | 0.42969         | 0.44922         | 0.46875       | 0.48828         | 0.50781         | 0.52734         | 0.54688       | 0.56641         | 0.58594         | 0.60547         | 0.62500 |
| $\frac{21}{32}$ | 0.34863         | 0.36914        | 0.38965         | 0.41016       | 0.43066         | 0.45117         | 0.47168         | 0.49219       | 0.51270         | 0.53320         | 0.55371         | 0.57422       | 0.59473         | 0.61523         | 0.63574         | 0.65625 |
| $\frac{11}{16}$ | 0.36523         | 0.38672        | 0.40820         | 0.42969       | 0.45117         | 0.47266         | 0.49414         | 0.51563       | 0.53711         | 0.55859         | 0.58008         | 0.60156       | 0.62305         | 0.64453         | 0.66602         | 0.68750 |
| $\frac{23}{32}$ | 0.38184         | 0.40430        | 0.42676         | 0.44922       | 0.47168         | 0.49414         | 0.51660         | 0.53906       | 0.56152         | 0.58398         | 0.60645         | 0.62891       | 0.65137         | 0.67383         | 0.69629         | 0.71875 |
| $\frac{3}{4}$   | 0.39844         | 0.42188        | 0.44531         | 0.46875       | 0.49219         | 0.51563         | 0.53906         | 0.56250       | 0.58594         | 0.60938         | 0.63281         | 0.65625       | 0.67969         | 0.70313         | 0.72656         | 0.75000 |
| $\frac{25}{32}$ | 0.41504         | 0.43945        | 0.46387         | 0.48828       | 0.51270         | 0.53711         | 0.56152         | 0.58594       | 0.61035         | 0.63477         | 0.65918         | 0.68359       | 0.70801         | 0.73242         | 0.75684         | 0.78125 |
| $\frac{13}{16}$ | 0.43164         | 0.45703        | 0.48242         | 0.50781       | 0.53320         | 0.55859         | 0.58398         | 0.60938       | 0.63477         | 0.66016         | 0.68555         | 0.71094       | 0.73633         | 0.76172         | 0.78711         | 0.81250 |
| $\frac{27}{32}$ | 0.44824         | 0.47461        | 0.50098         | 0.52734       | 0.55371         | 0.58008         | 0.60645         | 0.63281       | 0.65918         | 0.68555         | 0.71191         | 0.73828       | 0.76465         | 0.79102         | 0.81738         | 0.84375 |
| $\frac{7}{8}$   | 0.46484         | 0.49219        | 0.51953         | 0.54688       | 0.57422         | 0.60156         | 0.62891         | 0.65625       | 0.68359         | 0.71094         | 0.73828         | 0.76563       | 0.79297         | 0.82031         | 0.84766         | 0.87500 |
| $\frac{29}{32}$ | 0.48145         | 0.50977        | 0.53809         | 0.56641       | 0.59473         | 0.62305         | 0.65137         | 0.67969       | 0.70801         | 0.73633         | 0.76465         | 0.79297       | 0.82129         | 0.84961         | 0.87793         | 0.90625 |
| $\frac{15}{16}$ | 0.49805         | 0.52734        | 0.55664         | 0.58594       | 0.61523         | 0.64453         | 0.67383         | 0.70313       | 0.73242         | 0.76172         | 0.79102         | 0.82031       | 0.84961         | 0.87891         | 0.90820         | 0.93750 |
| $\frac{31}{32}$ | 0.51465         | 0.54492        | 0.57520         | 0.60547       | 0.63574         | 0.66602         | 0.69629         | 0.72656       | 0.75684         | 0.78711         | 0.81738         | 0.84766       | 0.87793         | 0.90820         | 0.93848         | 0.96875 |
| 1               | 0.53125         | 0.56250        | 0.59375         | 0.62500       | 0.65625         | 0.68750         | 0.71875         | 0.75000       | 0.78125         | 0.81250         | 0.84375         | 0.87500       | 0.90625         | 0.93750         | 0.96875         | 1.00000 |

## Area and Volume of Spheres\*

Surface Area and Volume of Spheres From  $\frac{1}{64}$  to  $14\frac{3}{4}$ 

| <i>d</i> = diameter |         |          | Surface = $\pi d^2$ |         |        | Volume = $\pi d^3 \div 6$ |         |        |
|---------------------|---------|----------|---------------------|---------|--------|---------------------------|---------|--------|
| Dia.                | Surface | Volume   | Dia.                | Surface | Volume | Dia.                      | Surface | Volume |
| $\frac{1}{64}$      | 0.00077 | 0.000002 | 2                   | 12.566  | 4.1888 | $6\frac{1}{2}$            | 132.73  | 143.79 |
| $\frac{1}{32}$      | 0.00307 | 0.00002  | $2\frac{1}{16}$     | 13.364  | 4.5939 | $6\frac{5}{8}$            | 137.89  | 152.25 |
| $\frac{1}{16}$      | 0.01227 | 0.00013  | $2\frac{1}{8}$      | 14.186  | 5.0243 | $6\frac{3}{4}$            | 143.14  | 161.03 |
| $\frac{3}{32}$      | 0.02761 | 0.00043  | $2\frac{3}{16}$     | 15.033  | 5.4808 | $6\frac{7}{8}$            | 148.49  | 170.14 |
| $\frac{1}{8}$       | 0.04909 | 0.00102  | $2\frac{1}{4}$      | 15.904  | 5.9641 | 7                         | 153.94  | 179.59 |
| $\frac{3}{32}$      | 0.07670 | 0.00200  | $2\frac{3}{16}$     | 16.800  | 6.4751 | $7\frac{1}{8}$            | 159.48  | 189.39 |
| $\frac{3}{16}$      | 0.11045 | 0.00345  | $2\frac{3}{8}$      | 17.721  | 7.0144 | $7\frac{1}{4}$            | 165.13  | 199.53 |
| $\frac{7}{32}$      | 0.15033 | 0.00548  | $2\frac{1}{2}$      | 18.665  | 7.5829 | $7\frac{3}{8}$            | 170.87  | 210.03 |
| $\frac{1}{4}$       | 0.19635 | 0.00818  | $2\frac{1}{2}$      | 19.635  | 8.1812 | $7\frac{1}{2}$            | 176.71  | 220.89 |
| $\frac{9}{32}$      | 0.24850 | 0.01165  | $2\frac{9}{16}$     | 20.629  | 8.8103 | $7\frac{5}{8}$            | 182.65  | 232.12 |
| $\frac{5}{16}$      | 0.30680 | 0.01598  | $2\frac{5}{8}$      | 21.648  | 9.4708 | $7\frac{3}{4}$            | 188.69  | 243.73 |
| $\frac{1}{2}$       | 0.37122 | 0.02127  | $2\frac{1}{2}$      | 22.691  | 10.164 | $7\frac{7}{8}$            | 194.83  | 255.71 |
| $\frac{3}{8}$       | 0.44179 | 0.02761  | $2\frac{3}{4}$      | 23.758  | 10.889 | 8                         | 201.06  | 268.08 |
| $\frac{13}{32}$     | 0.51849 | 0.03511  | $2\frac{13}{16}$    | 24.850  | 11.649 | $8\frac{1}{8}$            | 207.39  | 280.85 |
| $\frac{7}{16}$      | 0.60132 | 0.04385  | $2\frac{7}{8}$      | 25.967  | 12.443 | $8\frac{1}{4}$            | 213.82  | 294.01 |
| $\frac{15}{32}$     | 0.69029 | 0.05393  | $2\frac{15}{16}$    | 27.109  | 13.272 | $8\frac{3}{8}$            | 220.35  | 307.58 |
| $\frac{1}{2}$       | 0.78540 | 0.06545  | 3                   | 28.274  | 14.137 | $8\frac{1}{2}$            | 226.98  | 321.56 |
| $\frac{17}{32}$     | 0.88664 | 0.07850  | $3\frac{1}{16}$     | 29.465  | 15.039 | $8\frac{5}{8}$            | 233.71  | 335.95 |
| $\frac{9}{16}$      | 0.99402 | 0.09319  | $3\frac{1}{8}$      | 30.680  | 15.979 | $8\frac{3}{4}$            | 240.53  | 350.77 |
| $\frac{19}{32}$     | 1.1075  | 0.10960  | $3\frac{3}{16}$     | 31.919  | 16.957 | $8\frac{7}{8}$            | 247.45  | 366.02 |
| $\frac{5}{8}$       | 1.2272  | 0.12783  | $3\frac{1}{4}$      | 33.183  | 17.974 | 9                         | 254.47  | 381.70 |
| $\frac{21}{32}$     | 1.3530  | 0.14798  | $3\frac{5}{16}$     | 34.472  | 19.031 | $9\frac{1}{8}$            | 261.59  | 397.83 |
| $\frac{11}{16}$     | 1.4849  | 0.17014  | $3\frac{3}{8}$      | 35.785  | 20.129 | $9\frac{1}{4}$            | 268.80  | 414.40 |
| $\frac{23}{32}$     | 1.6230  | 0.19442  | $3\frac{7}{16}$     | 37.122  | 21.268 | $9\frac{3}{8}$            | 276.12  | 431.43 |
| $\frac{3}{4}$       | 1.7671  | 0.22089  | $3\frac{1}{2}$      | 38.485  | 22.449 | $9\frac{1}{2}$            | 283.53  | 448.92 |
| $\frac{25}{32}$     | 1.9175  | 0.24967  | $3\frac{5}{8}$      | 41.282  | 24.942 | $9\frac{5}{8}$            | 291.04  | 466.88 |
| $\frac{13}{16}$     | 2.0739  | 0.28085  | $3\frac{3}{4}$      | 44.179  | 27.612 | $9\frac{3}{4}$            | 298.65  | 485.30 |
| $\frac{27}{32}$     | 2.2365  | 0.31451  | $3\frac{7}{8}$      | 47.173  | 30.466 | $9\frac{7}{8}$            | 306.35  | 504.21 |
| $\frac{7}{8}$       | 2.4053  | 0.35077  | 4                   | 50.265  | 33.510 | 10                        | 314.16  | 523.60 |
| $\frac{29}{32}$     | 2.5802  | 0.38971  | $4\frac{1}{8}$      | 53.456  | 36.751 | $10\frac{1}{4}$           | 330.06  | 563.86 |
| $\frac{15}{16}$     | 2.7612  | 0.43143  | $4\frac{1}{4}$      | 56.745  | 40.194 | $10\frac{1}{2}$           | 346.36  | 606.13 |
| $\frac{31}{32}$     | 2.9483  | 0.47603  | $4\frac{3}{8}$      | 60.132  | 43.846 | $10\frac{3}{4}$           | 363.05  | 650.47 |
| 1                   | 3.1416  | 0.52360  | $4\frac{1}{2}$      | 63.617  | 47.713 | 11                        | 380.13  | 696.91 |
| $1\frac{1}{16}$     | 3.5466  | 0.62804  | $4\frac{3}{4}$      | 67.201  | 51.800 | $11\frac{1}{4}$           | 397.61  | 745.51 |
| $1\frac{1}{8}$      | 3.9761  | 0.74551  | $4\frac{3}{4}$      | 70.882  | 56.115 | $11\frac{1}{2}$           | 415.48  | 796.33 |
| $1\frac{3}{16}$     | 4.4301  | 0.87680  | $4\frac{7}{8}$      | 74.662  | 60.663 | $11\frac{3}{4}$           | 433.74  | 849.40 |
| $1\frac{1}{4}$      | 4.9087  | 1.0227   | 5                   | 78.540  | 65.450 | 12                        | 452.39  | 904.78 |
| $1\frac{5}{16}$     | 5.4119  | 1.1838   | $5\frac{1}{8}$      | 82.516  | 70.482 | $12\frac{1}{4}$           | 471.44  | 962.51 |
| $1\frac{3}{8}$      | 5.9396  | 1.3612   | $5\frac{1}{4}$      | 86.590  | 75.766 | $12\frac{1}{2}$           | 490.87  | 1022.7 |
| $1\frac{7}{16}$     | 6.4918  | 1.5553   | $5\frac{3}{8}$      | 90.763  | 81.308 | $12\frac{3}{4}$           | 510.71  | 1085.2 |
| $1\frac{1}{2}$      | 7.0686  | 1.7671   | $5\frac{1}{2}$      | 95.033  | 87.114 | 13                        | 530.93  | 1150.3 |
| $1\frac{9}{16}$     | 7.6699  | 1.9974   | $5\frac{5}{8}$      | 99.402  | 93.189 | $13\frac{1}{4}$           | 551.55  | 1218.0 |
| $1\frac{5}{8}$      | 8.2958  | 2.2468   | $5\frac{3}{4}$      | 103.87  | 99.541 | $13\frac{1}{2}$           | 572.56  | 1288.2 |
| $1\frac{11}{16}$    | 8.9462  | 2.5161   | $5\frac{7}{8}$      | 108.43  | 106.17 | $13\frac{3}{4}$           | 593.96  | 1361.2 |
| $1\frac{3}{4}$      | 9.6211  | 2.8062   | 6                   | 113.10  | 113.10 | 14                        | 615.75  | 1436.8 |
| $1\frac{13}{16}$    | 10.321  | 3.1177   | $6\frac{1}{8}$      | 117.86  | 120.31 | $14\frac{1}{4}$           | 637.94  | 1515.1 |
| $1\frac{7}{8}$      | 11.045  | 3.4515   | $6\frac{1}{4}$      | 122.72  | 127.83 | $14\frac{1}{2}$           | 660.52  | 1596.3 |
| $1\frac{15}{16}$    | 11.793  | 3.8082   | $6\frac{3}{8}$      | 127.68  | 135.66 | $14\frac{3}{4}$           | 683.49  | 1680.3 |

\*The figures given in the table can be used for English and Metric (SI) units.

## Surface Area and Volume of Spheres From 15 to 75½

| Dia. | Surface | Volume | Dia. | Surface | Volume | Dia. | Surface | Volume  |
|------|---------|--------|------|---------|--------|------|---------|---------|
| 15   | 706.86  | 1767.1 | 27½  | 2375.8  | 10,889 | 51   | 8171.3  | 69,456  |
| 15¼  | 730.62  | 1857.0 | 27¾  | 2419.2  | 11,189 | 51½  | 8332.3  | 71,519  |
| 15½  | 754.77  | 1949.8 | 28   | 2463.0  | 11,494 | 52   | 8494.9  | 73,622  |
| 15¾  | 779.31  | 2045.7 | 28¼  | 2507.2  | 11,805 | 52½  | 8659.0  | 75,766  |
| 16   | 804.25  | 2144.7 | 28½  | 2551.8  | 12,121 | 53   | 8824.7  | 77,952  |
| 16¼  | 829.58  | 2246.8 | 28¾  | 2596.7  | 12,443 | 53½  | 8992.0  | 80,179  |
| 16½  | 855.30  | 2352.1 | 29   | 2642.1  | 12,770 | 54   | 9160.9  | 82,448  |
| 16¾  | 881.41  | 2460.6 | 29½  | 2734.0  | 13,442 | 54½  | 9331.3  | 84,759  |
| 17   | 907.92  | 2572.4 | 30   | 2827.4  | 14,137 | 55   | 9503.3  | 87,114  |
| 17¼  | 934.82  | 2687.6 | 30½  | 2922.5  | 14,856 | 55½  | 9676.9  | 89,511  |
| 17½  | 962.11  | 2806.2 | 31   | 3019.1  | 15,599 | 56   | 9852.0  | 91,952  |
| 17¾  | 989.80  | 2928.2 | 31½  | 3117.2  | 16,366 | 56½  | 10,029  | 94,437  |
| 18   | 1017.9  | 3053.6 | 32   | 3217.0  | 17,157 | 57   | 10,207  | 96,967  |
| 18¼  | 1046.3  | 3182.6 | 32½  | 3318.3  | 17,974 | 57½  | 10,387  | 99,541  |
| 18½  | 1075.2  | 3315.2 | 33   | 3421.2  | 18,817 | 58   | 10,568  | 102,160 |
| 18¾  | 1104.5  | 3451.5 | 33½  | 3525.7  | 19,685 | 58½  | 10,751  | 104,825 |
| 19   | 1134.1  | 3591.4 | 34   | 3631.7  | 20,580 | 59   | 10,936  | 107,536 |
| 19¼  | 1164.2  | 3735.0 | 34½  | 3739.3  | 21,501 | 59½  | 11,122  | 110,293 |
| 19½  | 1194.6  | 3882.4 | 35   | 3848.5  | 22,449 | 60   | 11,310  | 113,097 |
| 19¾  | 1225.4  | 4033.7 | 35½  | 3959.2  | 23,425 | 60½  | 11,499  | 115,948 |
| 20   | 1256.6  | 4188.8 | 36   | 4071.5  | 24,429 | 61   | 11,690  | 118,847 |
| 20¼  | 1288.2  | 4347.8 | 36½  | 4185.4  | 25,461 | 61½  | 11,882  | 121,793 |
| 20½  | 1320.3  | 4510.9 | 37   | 4300.8  | 26,522 | 62   | 12,076  | 124,788 |
| 20¾  | 1352.7  | 4677.9 | 37½  | 4417.9  | 27,612 | 62½  | 12,272  | 127,832 |
| 21   | 1385.4  | 4849.0 | 38   | 4536.5  | 28,731 | 63   | 12,469  | 130,924 |
| 21¼  | 1418.6  | 5024.3 | 38½  | 4656.6  | 29,880 | 63½  | 12,668  | 134,066 |
| 21½  | 1452.2  | 5203.7 | 39   | 4778.4  | 31,059 | 64   | 12,868  | 137,258 |
| 21¾  | 1486.2  | 5387.4 | 39½  | 4901.7  | 32,269 | 64½  | 13,070  | 140,500 |
| 22   | 1520.5  | 5575.3 | 40   | 5026.5  | 33,510 | 65   | 13,273  | 143,793 |
| 22¼  | 1555.3  | 5767.5 | 40½  | 5153.0  | 34,783 | 65½  | 13,478  | 147,137 |
| 22½  | 1590.4  | 5964.1 | 41   | 5281.0  | 36,087 | 66   | 13,685  | 150,533 |
| 22¾  | 1626.0  | 6165.1 | 41½  | 5410.6  | 37,423 | 66½  | 13,893  | 153,980 |
| 23   | 1661.9  | 6370.6 | 42   | 5541.8  | 38,792 | 67   | 14,103  | 157,479 |
| 23¼  | 1698.2  | 6580.6 | 42½  | 5674.5  | 40,194 | 67½  | 14,314  | 161,031 |
| 23½  | 1734.9  | 6795.2 | 43   | 5808.8  | 41,630 | 68   | 14,527  | 164,636 |
| 23¾  | 1772.1  | 7014.4 | 43½  | 5944.7  | 43,099 | 68½  | 14,741  | 168,295 |
| 24   | 1809.6  | 7238.2 | 44   | 6082.1  | 44,602 | 69   | 14,957  | 172,007 |
| 24¼  | 1847.5  | 7466.8 | 44½  | 6221.1  | 46,140 | 69½  | 15,175  | 175,773 |
| 24½  | 1885.7  | 7700.1 | 45   | 6361.7  | 47,713 | 70   | 15,394  | 179,594 |
| 24¾  | 1924.4  | 7938.2 | 45½  | 6503.9  | 49,321 | 70½  | 15,615  | 183,470 |
| 25   | 1963.5  | 8181.2 | 46   | 6647.6  | 50,965 | 71   | 15,837  | 187,402 |
| 25¼  | 2003.0  | 8429.1 | 46½  | 6792.9  | 52,645 | 71½  | 16,061  | 191,389 |
| 25½  | 2042.8  | 8682.0 | 47   | 6939.8  | 54,362 | 72   | 16,286  | 195,432 |
| 25¾  | 2083.1  | 8939.9 | 47½  | 7088.2  | 56,115 | 72½  | 16,513  | 199,532 |
| 26   | 2123.7  | 9202.8 | 48   | 7238.2  | 57,906 | 73   | 16,742  | 203,689 |
| 26¼  | 2164.8  | 9470.8 | 48½  | 7389.8  | 59,734 | 73½  | 16,972  | 207,903 |
| 26½  | 2206.2  | 9744.0 | 49   | 7543.0  | 61,601 | 74   | 17,203  | 212,175 |
| 26¾  | 2248.0  | 10,022 | 49½  | 7697.7  | 63,506 | 74½  | 17,437  | 216,505 |
| 27   | 2290.2  | 10,306 | 50   | 7854.0  | 65,450 | 75   | 17,671  | 220,893 |
| 27¼  | 2332.8  | 10,595 | 50½  | 8011.8  | 67,433 | 75½  | 17,908  | 225,341 |

## Surface Area and Volume of Spheres From 76 to 200

| Dia. | Surface | Volume  | Dia. | Surface | Volume    | Dia. | Surface | Volume    |
|------|---------|---------|------|---------|-----------|------|---------|-----------|
| 76   | 18,146  | 229,847 | 101  | 32,047  | 539,464   | 151  | 71,631  | 1,802,725 |
| 76½  | 18,385  | 234,414 | 102  | 32,685  | 555,647   | 152  | 72,583  | 1,838,778 |
| 77   | 18,627  | 239,040 | 103  | 33,329  | 572,151   | 153  | 73,542  | 1,875,309 |
| 77½  | 18,869  | 243,727 | 104  | 33,979  | 588,977   | 154  | 74,506  | 1,912,321 |
| 78   | 19,113  | 248,475 | 105  | 34,636  | 606,131   | 155  | 75,477  | 1,949,816 |
| 78½  | 19,359  | 253,284 | 106  | 35,299  | 623,615   | 156  | 76,454  | 1,987,799 |
| 79   | 19,607  | 258,155 | 107  | 35,968  | 641,431   | 157  | 77,437  | 2,026,271 |
| 79½  | 19,856  | 263,087 | 108  | 36,644  | 659,584   | 158  | 78,427  | 2,065,237 |
| 80   | 20,106  | 268,083 | 109  | 37,325  | 678,076   | 159  | 79,423  | 2,104,699 |
| 80½  | 20,358  | 273,141 | 110  | 38,013  | 696,910   | 160  | 80,425  | 2,144,661 |
| 81   | 20,612  | 278,262 | 111  | 38,708  | 716,090   | 161  | 81,433  | 2,185,125 |
| 81½  | 20,867  | 283,447 | 112  | 39,408  | 735,619   | 162  | 82,448  | 2,226,095 |
| 82   | 21,124  | 288,696 | 113  | 40,115  | 755,499   | 163  | 83,469  | 2,267,574 |
| 82½  | 21,382  | 294,009 | 114  | 40,828  | 775,735   | 164  | 84,496  | 2,309,565 |
| 83   | 21,642  | 299,387 | 115  | 41,548  | 796,328   | 165  | 85,530  | 2,352,071 |
| 83½  | 21,904  | 304,830 | 116  | 42,273  | 817,283   | 166  | 86,570  | 2,395,096 |
| 84   | 22,167  | 310,339 | 117  | 43,005  | 838,603   | 167  | 87,616  | 2,438,642 |
| 84½  | 22,432  | 315,914 | 118  | 43,744  | 860,290   | 168  | 88,668  | 2,482,713 |
| 85   | 22,698  | 321,555 | 119  | 44,488  | 882,347   | 169  | 89,727  | 2,527,311 |
| 85½  | 22,966  | 327,263 | 120  | 45,239  | 904,779   | 170  | 90,792  | 2,572,441 |
| 86   | 23,235  | 333,038 | 121  | 45,996  | 927,587   | 171  | 91,863  | 2,618,104 |
| 86½  | 23,506  | 338,881 | 122  | 46,759  | 950,776   | 172  | 92,941  | 2,664,305 |
| 87   | 23,779  | 344,791 | 123  | 47,529  | 974,348   | 173  | 94,025  | 2,711,046 |
| 87½  | 24,053  | 350,770 | 124  | 48,305  | 998,306   | 174  | 95,115  | 2,758,331 |
| 88   | 24,328  | 356,818 | 125  | 49,087  | 1,022,654 | 175  | 96,211  | 2,806,162 |
| 88½  | 24,606  | 362,935 | 126  | 49,876  | 1,047,394 | 176  | 97,314  | 2,854,543 |
| 89   | 24,885  | 369,121 | 127  | 50,671  | 1,072,531 | 177  | 98,423  | 2,903,477 |
| 89½  | 25,165  | 375,377 | 128  | 51,472  | 1,098,066 | 178  | 99,538  | 2,952,967 |
| 90   | 25,447  | 381,704 | 129  | 52,279  | 1,124,004 | 179  | 100,660 | 3,003,016 |
| 90½  | 25,730  | 388,101 | 130  | 53,093  | 1,150,347 | 180  | 101,788 | 3,053,628 |
| 91   | 26,016  | 394,569 | 131  | 53,913  | 1,177,098 | 181  | 102,922 | 3,104,805 |
| 91½  | 26,302  | 401,109 | 132  | 54,739  | 1,204,260 | 182  | 104,062 | 3,156,551 |
| 92   | 26,590  | 407,720 | 133  | 55,572  | 1,231,838 | 183  | 105,209 | 3,208,868 |
| 92½  | 26,880  | 414,404 | 134  | 56,410  | 1,259,833 | 184  | 106,362 | 3,261,761 |
| 93   | 27,172  | 421,160 | 135  | 57,256  | 1,288,249 | 185  | 107,521 | 3,315,231 |
| 93½  | 27,465  | 427,990 | 136  | 58,107  | 1,317,090 | 186  | 108,687 | 3,369,283 |
| 94   | 27,759  | 434,893 | 137  | 58,965  | 1,346,357 | 187  | 109,858 | 3,423,919 |
| 94½  | 28,055  | 441,870 | 138  | 59,828  | 1,376,055 | 188  | 111,036 | 3,479,142 |
| 95   | 28,353  | 448,921 | 139  | 60,699  | 1,406,187 | 189  | 112,221 | 3,534,956 |
| 95½  | 28,652  | 456,046 | 140  | 61,575  | 1,436,755 | 190  | 113,411 | 3,591,364 |
| 96   | 28,953  | 463,247 | 141  | 62,458  | 1,467,763 | 191  | 114,608 | 3,648,369 |
| 96½  | 29,255  | 470,523 | 142  | 63,347  | 1,499,214 | 192  | 115,812 | 3,705,973 |
| 97   | 29,559  | 477,874 | 143  | 64,242  | 1,531,111 | 193  | 117,021 | 3,764,181 |
| 97½  | 29,865  | 485,302 | 144  | 65,144  | 1,563,458 | 194  | 118,237 | 3,822,996 |
| 98   | 30,172  | 492,807 | 145  | 66,052  | 1,596,256 | 195  | 119,459 | 3,882,419 |
| 98½  | 30,481  | 500,388 | 146  | 66,966  | 1,629,511 | 196  | 120,687 | 3,942,456 |
| 99   | 30,791  | 508,047 | 147  | 67,887  | 1,663,224 | 197  | 121,922 | 4,003,108 |
| 99½  | 31,103  | 515,784 | 148  | 68,813  | 1,697,398 | 198  | 123,163 | 4,064,379 |
| 100  | 31,416  | 523,599 | 149  | 69,746  | 1,732,038 | 199  | 124,410 | 4,126,272 |
| 100½ | 31,731  | 531,492 | 150  | 70,686  | 1,767,146 | 200  | 125,664 | 4,188,790 |

Circumference and Area of Circles

Circumferences and Areas of Circles From  $\frac{1}{64}$  to  $9\frac{7}{8}$

| Diameter         | Circumference | Area   | Diameter         | Circumference | Area    | Diameter         | Circumference | Area   |
|------------------|---------------|--------|------------------|---------------|---------|------------------|---------------|--------|
| $\frac{1}{64}$   | 0.0491        | 0.0002 | 2                | 6.2832        | 3.1416  | 5                | 15.7080       | 19.635 |
| $\frac{1}{32}$   | 0.0982        | 0.0008 | $2\frac{1}{16}$  | 6.4795        | 3.3410  | $5\frac{1}{16}$  | 15.9043       | 20.129 |
| $\frac{1}{16}$   | 0.1963        | 0.0031 | $2\frac{1}{8}$   | 6.6759        | 3.5466  | $5\frac{1}{8}$   | 16.1007       | 20.629 |
| $\frac{3}{32}$   | 0.2945        | 0.0069 | $2\frac{3}{16}$  | 6.8722        | 3.7583  | $5\frac{3}{16}$  | 16.2970       | 21.135 |
| $\frac{1}{8}$    | 0.3927        | 0.0123 | $2\frac{1}{4}$   | 7.0686        | 3.9761  | $5\frac{1}{4}$   | 16.4934       | 21.648 |
| $\frac{5}{32}$   | 0.4909        | 0.0192 | $2\frac{5}{16}$  | 7.2649        | 4.2000  | $5\frac{5}{16}$  | 16.6897       | 22.166 |
| $\frac{3}{16}$   | 0.5890        | 0.0276 | $2\frac{3}{8}$   | 7.4613        | 4.4301  | $5\frac{3}{8}$   | 16.8861       | 22.691 |
| $\frac{7}{32}$   | 0.6872        | 0.0376 | $2\frac{7}{16}$  | 7.6576        | 4.6664  | $5\frac{7}{16}$  | 17.0824       | 23.221 |
| $\frac{1}{4}$    | 0.7854        | 0.0491 | $2\frac{1}{2}$   | 7.8540        | 4.9087  | $5\frac{1}{2}$   | 17.2788       | 23.758 |
| $\frac{9}{32}$   | 0.8836        | 0.0621 | $2\frac{9}{16}$  | 8.0503        | 5.1572  | $5\frac{9}{16}$  | 17.4751       | 24.301 |
| $\frac{5}{16}$   | 0.9817        | 0.0767 | $2\frac{5}{8}$   | 8.2467        | 5.4119  | $5\frac{5}{8}$   | 17.6715       | 24.850 |
| $\frac{11}{32}$  | 1.0799        | 0.0928 | $2\frac{11}{16}$ | 8.4430        | 5.6727  | $5\frac{11}{16}$ | 17.8678       | 25.406 |
| $\frac{3}{8}$    | 1.1781        | 0.1104 | $2\frac{3}{4}$   | 8.6394        | 5.9396  | $5\frac{3}{4}$   | 18.0642       | 25.967 |
| $\frac{13}{32}$  | 1.2763        | 0.1296 | $2\frac{13}{16}$ | 8.8357        | 6.2126  | $5\frac{13}{16}$ | 18.2605       | 26.535 |
| $\frac{7}{16}$   | 1.3744        | 0.1503 | $2\frac{7}{8}$   | 9.0321        | 6.4918  | $5\frac{7}{8}$   | 18.4569       | 27.109 |
| $\frac{15}{32}$  | 1.4726        | 0.1726 | $2\frac{15}{16}$ | 9.2284        | 6.7771  | $5\frac{15}{16}$ | 18.6532       | 27.688 |
| $\frac{1}{2}$    | 1.5708        | 0.1963 | 3                | 9.4248        | 7.0686  | 6                | 18.8496       | 28.274 |
| $\frac{17}{32}$  | 1.6690        | 0.2217 | $3\frac{1}{16}$  | 9.6211        | 7.3662  | $6\frac{1}{8}$   | 19.2423       | 29.465 |
| $\frac{9}{16}$   | 1.7671        | 0.2485 | $3\frac{1}{8}$   | 9.8175        | 7.6699  | $6\frac{1}{4}$   | 19.6350       | 30.680 |
| $\frac{19}{32}$  | 1.8653        | 0.2769 | $3\frac{3}{16}$  | 10.0138       | 7.9798  | $6\frac{3}{8}$   | 20.0277       | 31.919 |
| $\frac{5}{8}$    | 1.9635        | 0.3068 | $3\frac{1}{4}$   | 10.2102       | 8.2958  | $6\frac{1}{2}$   | 20.4204       | 33.183 |
| $\frac{21}{32}$  | 2.0617        | 0.3382 | $3\frac{5}{16}$  | 10.4065       | 8.6179  | $6\frac{5}{8}$   | 20.8131       | 34.472 |
| $\frac{11}{16}$  | 2.1598        | 0.3712 | $3\frac{3}{8}$   | 10.6029       | 8.9462  | $6\frac{3}{4}$   | 21.2058       | 35.785 |
| $\frac{23}{32}$  | 2.2580        | 0.4057 | $3\frac{7}{16}$  | 10.7992       | 9.2806  | $6\frac{7}{8}$   | 21.5984       | 37.122 |
| $\frac{3}{4}$    | 2.3562        | 0.4418 | $3\frac{1}{2}$   | 10.9956       | 9.6211  | 7                | 21.9911       | 38.485 |
| $\frac{25}{32}$  | 2.4544        | 0.4794 | $3\frac{9}{16}$  | 11.1919       | 9.9678  | $7\frac{1}{8}$   | 22.3838       | 39.871 |
| $\frac{13}{16}$  | 2.5525        | 0.5185 | $3\frac{5}{8}$   | 11.388        | 10.3206 | $7\frac{1}{4}$   | 22.7765       | 41.282 |
| $\frac{27}{32}$  | 2.6507        | 0.5591 | $3\frac{11}{16}$ | 11.585        | 10.6796 | $7\frac{3}{8}$   | 23.1692       | 42.718 |
| $\frac{7}{8}$    | 2.7489        | 0.6013 | $3\frac{3}{4}$   | 11.781        | 11.0447 | $7\frac{1}{2}$   | 23.5619       | 44.179 |
| $\frac{29}{32}$  | 2.8471        | 0.6450 | $3\frac{13}{16}$ | 11.977        | 11.4159 | $7\frac{5}{8}$   | 23.9546       | 45.664 |
| $\frac{15}{16}$  | 2.9452        | 0.6903 | $3\frac{7}{8}$   | 12.174        | 11.7932 | $7\frac{3}{4}$   | 24.3473       | 47.173 |
| $\frac{31}{32}$  | 3.0434        | 0.7371 | $3\frac{15}{16}$ | 12.370        | 12.1767 | $7\frac{7}{8}$   | 24.7400       | 48.707 |
| 1                | 3.1416        | 0.7854 | 4                | 12.566        | 12.5664 | 8                | 25.1327       | 50.265 |
| $1\frac{1}{16}$  | 3.3379        | 0.8866 | $4\frac{1}{16}$  | 12.763        | 12.9621 | $8\frac{1}{8}$   | 25.5254       | 51.849 |
| $1\frac{1}{8}$   | 3.5343        | 0.9940 | $4\frac{1}{8}$   | 12.959        | 13.3640 | $8\frac{1}{4}$   | 25.9181       | 53.456 |
| $1\frac{1}{4}$   | 3.7306        | 1.1075 | $4\frac{3}{16}$  | 13.155        | 13.7721 | $8\frac{3}{8}$   | 26.3108       | 55.088 |
| $1\frac{1}{2}$   | 3.9270        | 1.2272 | $4\frac{1}{4}$   | 13.352        | 14.1863 | $8\frac{1}{2}$   | 26.7035       | 56.745 |
| $1\frac{5}{16}$  | 4.1233        | 1.3530 | $4\frac{5}{16}$  | 13.548        | 14.6066 | $8\frac{5}{8}$   | 27.0962       | 58.426 |
| $1\frac{3}{8}$   | 4.3197        | 1.4849 | $4\frac{3}{8}$   | 13.744        | 15.0330 | $8\frac{3}{4}$   | 27.4889       | 60.132 |
| $1\frac{7}{16}$  | 4.5160        | 1.6230 | $4\frac{7}{16}$  | 13.941        | 15.4656 | $8\frac{7}{8}$   | 27.8816       | 61.862 |
| $1\frac{1}{2}$   | 4.7124        | 1.7671 | $4\frac{1}{2}$   | 14.137        | 15.9043 | 9                | 28.2743       | 63.617 |
| $1\frac{9}{16}$  | 4.9087        | 1.9175 | $4\frac{9}{16}$  | 14.334        | 16.3492 | $9\frac{1}{8}$   | 28.6670       | 65.397 |
| $1\frac{5}{8}$   | 5.1051        | 2.0739 | $4\frac{5}{8}$   | 14.530        | 16.8002 | $9\frac{1}{4}$   | 29.0597       | 67.201 |
| $1\frac{11}{16}$ | 5.3014        | 2.2365 | $4\frac{11}{16}$ | 14.726        | 17.2573 | $9\frac{3}{8}$   | 29.4524       | 69.029 |
| $1\frac{3}{4}$   | 5.4978        | 2.4053 | $4\frac{3}{4}$   | 14.923        | 17.7205 | $9\frac{1}{2}$   | 29.8451       | 70.882 |
| $1\frac{13}{16}$ | 5.6941        | 2.5802 | $4\frac{13}{16}$ | 15.119        | 18.1899 | $9\frac{5}{8}$   | 30.2378       | 72.760 |
| $1\frac{7}{8}$   | 5.8905        | 2.7612 | $4\frac{7}{8}$   | 15.315        | 18.6655 | $9\frac{3}{4}$   | 30.6305       | 74.662 |
| $1\frac{15}{16}$ | 6.0868        | 2.9483 | $4\frac{15}{16}$ | 15.512        | 19.1471 | $9\frac{7}{8}$   | 31.0232       | 76.589 |

Circumferences and Areas of Circles From 10 to 27 $\frac{7}{8}$ 

| Diameter      | Circumference | Area      | Diameter      | Circumference | Area      | Diameter      | Circumference | Area      |
|---------------|---------------|-----------|---------------|---------------|-----------|---------------|---------------|-----------|
| 10            | 31.41593      | 78.53983  | 16            | 50.26549      | 201.06195 | 22            | 69.11505      | 380.13275 |
| $\frac{1}{8}$ | 31.80863      | 80.51559  | $\frac{1}{8}$ | 50.65819      | 204.21582 | $\frac{1}{8}$ | 69.50775      | 384.46472 |
| $\frac{1}{4}$ | 32.20133      | 82.51590  | $\frac{1}{4}$ | 51.05089      | 207.39423 | $\frac{1}{4}$ | 69.90044      | 388.82122 |
| $\frac{3}{8}$ | 32.59403      | 84.54076  | $\frac{3}{8}$ | 51.44359      | 210.59718 | $\frac{3}{8}$ | 70.29314      | 393.20227 |
| $\frac{1}{2}$ | 32.98673      | 86.59016  | $\frac{1}{2}$ | 51.83628      | 213.82467 | $\frac{1}{2}$ | 70.68584      | 397.60786 |
| $\frac{5}{8}$ | 33.37943      | 88.66410  | $\frac{5}{8}$ | 52.22898      | 217.07671 | $\frac{5}{8}$ | 71.07854      | 402.03800 |
| $\frac{3}{4}$ | 33.77212      | 90.76259  | $\frac{3}{4}$ | 52.62168      | 220.35330 | $\frac{3}{4}$ | 71.47124      | 406.49268 |
| $\frac{7}{8}$ | 34.16482      | 92.88561  | $\frac{7}{8}$ | 53.01438      | 223.65442 | $\frac{7}{8}$ | 71.86394      | 410.97191 |
| 11            | 34.55752      | 95.03319  | 17            | 53.40708      | 226.98009 | 23            | 72.25664      | 415.47567 |
| $\frac{1}{8}$ | 34.95022      | 97.20531  | $\frac{1}{8}$ | 53.79978      | 230.33031 | $\frac{1}{8}$ | 72.64934      | 420.00399 |
| $\frac{1}{4}$ | 35.34292      | 99.40197  | $\frac{1}{4}$ | 54.19248      | 233.70507 | $\frac{1}{4}$ | 73.04204      | 424.55684 |
| $\frac{3}{8}$ | 35.73562      | 101.62317 | $\frac{3}{8}$ | 54.58518      | 237.10437 | $\frac{3}{8}$ | 73.43474      | 429.13424 |
| $\frac{1}{2}$ | 36.12832      | 103.86892 | $\frac{1}{2}$ | 54.97788      | 240.52821 | $\frac{1}{2}$ | 73.82744      | 433.73618 |
| $\frac{5}{8}$ | 36.52102      | 106.13921 | $\frac{5}{8}$ | 55.37058      | 243.97660 | $\frac{5}{8}$ | 74.22013      | 438.36267 |
| $\frac{3}{4}$ | 36.91372      | 108.43405 | $\frac{3}{4}$ | 55.76328      | 247.44954 | $\frac{3}{4}$ | 74.61283      | 443.01370 |
| $\frac{7}{8}$ | 37.30642      | 110.75343 | $\frac{7}{8}$ | 56.15597      | 250.94701 | $\frac{7}{8}$ | 75.00553      | 447.68927 |
| 12            | 37.69912      | 113.09735 | 18            | 56.54867      | 254.46903 | 24            | 75.39823      | 452.38939 |
| $\frac{1}{8}$ | 38.09182      | 115.46581 | $\frac{1}{8}$ | 56.94137      | 258.01560 | $\frac{1}{8}$ | 75.79093      | 457.11405 |
| $\frac{1}{4}$ | 38.48451      | 117.85882 | $\frac{1}{4}$ | 57.33407      | 261.58670 | $\frac{1}{4}$ | 76.18363      | 461.86326 |
| $\frac{3}{8}$ | 38.87721      | 120.27638 | $\frac{3}{8}$ | 57.72677      | 265.18236 | $\frac{3}{8}$ | 76.57633      | 466.63701 |
| $\frac{1}{2}$ | 39.26991      | 122.71848 | $\frac{1}{2}$ | 58.11947      | 268.80255 | $\frac{1}{2}$ | 76.96903      | 471.43530 |
| $\frac{5}{8}$ | 39.66261      | 125.18512 | $\frac{5}{8}$ | 58.51217      | 272.44729 | $\frac{5}{8}$ | 77.36173      | 476.25814 |
| $\frac{3}{4}$ | 40.05531      | 127.67630 | $\frac{3}{4}$ | 58.90487      | 276.11657 | $\frac{3}{4}$ | 77.75443      | 481.10552 |
| $\frac{7}{8}$ | 40.44801      | 130.19203 | $\frac{7}{8}$ | 59.29757      | 279.81040 | $\frac{7}{8}$ | 78.14713      | 485.97744 |
| 13            | 40.84071      | 132.73230 | 19            | 59.69027      | 283.52877 | 25            | 78.53983      | 490.87391 |
| $\frac{1}{8}$ | 41.23341      | 135.29712 | $\frac{1}{8}$ | 60.08297      | 287.27168 | $\frac{1}{8}$ | 78.93252      | 495.79492 |
| $\frac{1}{4}$ | 41.62611      | 137.88648 | $\frac{1}{4}$ | 60.47567      | 291.03914 | $\frac{1}{4}$ | 79.32522      | 500.74047 |
| $\frac{3}{8}$ | 42.01881      | 140.50038 | $\frac{3}{8}$ | 60.86836      | 294.83114 | $\frac{3}{8}$ | 79.71792      | 505.71057 |
| $\frac{1}{2}$ | 42.41151      | 143.13883 | $\frac{1}{2}$ | 61.26106      | 298.64768 | $\frac{1}{2}$ | 80.11062      | 510.70521 |
| $\frac{5}{8}$ | 42.80420      | 145.80182 | $\frac{5}{8}$ | 61.65376      | 302.48877 | $\frac{5}{8}$ | 80.50332      | 515.72440 |
| $\frac{3}{4}$ | 43.19690      | 148.48936 | $\frac{3}{4}$ | 62.04646      | 306.35440 | $\frac{3}{4}$ | 80.89602      | 520.76813 |
| $\frac{7}{8}$ | 43.58960      | 151.20143 | $\frac{7}{8}$ | 62.43916      | 310.24458 | $\frac{7}{8}$ | 81.28872      | 525.83640 |
| 14            | 43.98230      | 153.93806 | 20            | 62.83186      | 314.15930 | 26            | 81.68142      | 530.92922 |
| $\frac{1}{8}$ | 44.37500      | 156.69922 | $\frac{1}{8}$ | 63.22456      | 318.09856 | $\frac{1}{8}$ | 82.07412      | 536.04658 |
| $\frac{1}{4}$ | 44.76770      | 159.48493 | $\frac{1}{4}$ | 63.61726      | 322.06237 | $\frac{1}{4}$ | 82.46682      | 541.18848 |
| $\frac{3}{8}$ | 45.16040      | 162.29519 | $\frac{3}{8}$ | 64.00996      | 326.05072 | $\frac{3}{8}$ | 82.85952      | 546.35493 |
| $\frac{1}{2}$ | 45.55310      | 165.12998 | $\frac{1}{2}$ | 64.40266      | 330.06361 | $\frac{1}{2}$ | 83.25222      | 551.54592 |
| $\frac{5}{8}$ | 45.94580      | 167.98932 | $\frac{5}{8}$ | 64.79536      | 334.10105 | $\frac{5}{8}$ | 83.64491      | 556.76146 |
| $\frac{3}{4}$ | 46.33850      | 170.87321 | $\frac{3}{4}$ | 65.18805      | 338.16303 | $\frac{3}{4}$ | 84.03761      | 562.00154 |
| $\frac{7}{8}$ | 46.73120      | 173.78163 | $\frac{7}{8}$ | 65.58075      | 342.24956 | $\frac{7}{8}$ | 84.43031      | 567.26616 |
| 15            | 47.12390      | 176.71461 | 21            | 65.97345      | 346.36063 | 27            | 84.82301      | 572.55532 |
| $\frac{1}{8}$ | 47.51659      | 179.67212 | $\frac{1}{8}$ | 66.36615      | 350.49624 | $\frac{1}{8}$ | 85.21571      | 577.86903 |
| $\frac{1}{4}$ | 47.90929      | 182.65418 | $\frac{1}{4}$ | 66.75885      | 354.65640 | $\frac{1}{4}$ | 85.60841      | 583.20729 |
| $\frac{3}{8}$ | 48.30199      | 185.66078 | $\frac{3}{8}$ | 67.15155      | 358.84110 | $\frac{3}{8}$ | 86.00111      | 588.57009 |
| $\frac{1}{2}$ | 48.69469      | 188.69193 | $\frac{1}{2}$ | 67.54425      | 363.05034 | $\frac{1}{2}$ | 86.39381      | 593.95743 |
| $\frac{5}{8}$ | 49.08739      | 191.74762 | $\frac{5}{8}$ | 67.93695      | 367.28413 | $\frac{5}{8}$ | 86.78651      | 599.36931 |
| $\frac{3}{4}$ | 49.48009      | 194.82785 | $\frac{3}{4}$ | 68.32965      | 371.54246 | $\frac{3}{4}$ | 87.17921      | 604.80574 |
| $\frac{7}{8}$ | 49.87279      | 197.93263 | $\frac{7}{8}$ | 68.72235      | 375.82533 | $\frac{7}{8}$ | 87.57190      | 610.26671 |
| 16            | 50.26549      | 201.06195 | 22            | 69.11505      | 380.13275 | 28            | 87.96460      | 615.75223 |



Circumferences and Areas of Circles From 28 to 45 $\frac{7}{8}$ 

| Diameter      | Circumference | Area      | Diameter      | Circumference | Area       | Diameter      | Circumference | Area       |
|---------------|---------------|-----------|---------------|---------------|------------|---------------|---------------|------------|
| 28            | 87.96460      | 615.75223 | 34            | 106.81416     | 907.92038  | 40            | 125.66372     | 1256.63720 |
| $\frac{1}{8}$ | 88.35730      | 621.26229 | $\frac{1}{8}$ | 107.20686     | 914.60853  | $\frac{1}{8}$ | 126.05642     | 1264.50345 |
| $\frac{1}{4}$ | 88.75000      | 626.79689 | $\frac{1}{4}$ | 107.59956     | 921.32123  | $\frac{1}{4}$ | 126.44912     | 1272.39425 |
| $\frac{3}{8}$ | 89.14270      | 632.35604 | $\frac{3}{8}$ | 107.99226     | 928.05848  | $\frac{3}{8}$ | 126.84182     | 1280.30959 |
| $\frac{1}{2}$ | 89.53540      | 637.93973 | $\frac{1}{2}$ | 108.38496     | 934.82027  | $\frac{1}{2}$ | 127.23452     | 1288.24948 |
| $\frac{5}{8}$ | 89.92810      | 643.54796 | $\frac{5}{8}$ | 108.77766     | 941.60660  | $\frac{5}{8}$ | 127.62722     | 1296.21391 |
| $\frac{3}{4}$ | 90.32080      | 649.18074 | $\frac{3}{4}$ | 109.17036     | 948.41747  | $\frac{3}{4}$ | 128.01991     | 1304.20288 |
| $\frac{7}{8}$ | 90.71350      | 654.83806 | $\frac{7}{8}$ | 109.56306     | 955.25289  | $\frac{7}{8}$ | 128.41261     | 1312.21640 |
| 29            | 91.10620      | 660.51993 | 35            | 109.95576     | 962.11286  | 41            | 128.80531     | 1320.25446 |
| $\frac{1}{8}$ | 91.49890      | 666.22634 | $\frac{1}{8}$ | 110.34845     | 968.99736  | $\frac{1}{8}$ | 129.19801     | 1328.31706 |
| $\frac{1}{4}$ | 91.89160      | 671.95729 | $\frac{1}{4}$ | 110.74115     | 975.90641  | $\frac{1}{4}$ | 129.59071     | 1336.40421 |
| $\frac{3}{8}$ | 92.28429      | 677.71279 | $\frac{3}{8}$ | 111.13385     | 982.84001  | $\frac{3}{8}$ | 129.98341     | 1344.51590 |
| $\frac{1}{2}$ | 92.67699      | 683.49283 | $\frac{1}{2}$ | 111.52655     | 989.79814  | $\frac{1}{2}$ | 130.37611     | 1352.65214 |
| $\frac{5}{8}$ | 93.06969      | 689.29741 | $\frac{5}{8}$ | 111.91925     | 996.78083  | $\frac{5}{8}$ | 130.76881     | 1360.81291 |
| $\frac{3}{4}$ | 93.46239      | 695.12654 | $\frac{3}{4}$ | 112.31195     | 1003.78805 | $\frac{3}{4}$ | 131.16151     | 1368.99824 |
| $\frac{7}{8}$ | 93.85509      | 700.98021 | $\frac{7}{8}$ | 112.70465     | 1010.81982 | $\frac{7}{8}$ | 131.55421     | 1377.20810 |
| 30            | 94.24779      | 706.85843 | 36            | 113.09735     | 1017.87613 | 42            | 131.94691     | 1385.44251 |
| $\frac{1}{8}$ | 94.64049      | 712.76118 | $\frac{1}{8}$ | 113.49005     | 1024.95699 | $\frac{1}{8}$ | 132.33961     | 1393.70147 |
| $\frac{1}{4}$ | 95.03319      | 718.68849 | $\frac{1}{4}$ | 113.88275     | 1032.06239 | $\frac{1}{4}$ | 132.73230     | 1401.98496 |
| $\frac{3}{8}$ | 95.42589      | 724.64033 | $\frac{3}{8}$ | 114.27545     | 1039.19233 | $\frac{3}{8}$ | 133.12500     | 1410.29300 |
| $\frac{1}{2}$ | 95.81859      | 730.61672 | $\frac{1}{2}$ | 114.66814     | 1046.34682 | $\frac{1}{2}$ | 133.51770     | 1418.62559 |
| $\frac{5}{8}$ | 96.21129      | 736.61766 | $\frac{5}{8}$ | 115.06084     | 1053.52585 | $\frac{5}{8}$ | 133.91040     | 1426.98272 |
| $\frac{3}{4}$ | 96.60398      | 742.64313 | $\frac{3}{4}$ | 115.45354     | 1060.72942 | $\frac{3}{4}$ | 134.30310     | 1435.36439 |
| $\frac{7}{8}$ | 96.99668      | 748.69315 | $\frac{7}{8}$ | 115.84624     | 1067.95754 | $\frac{7}{8}$ | 134.69580     | 1443.77060 |
| 31            | 97.38938      | 754.76772 | 37            | 116.23894     | 1075.21020 | 43            | 135.08850     | 1452.20136 |
| $\frac{1}{8}$ | 97.78208      | 760.86683 | $\frac{1}{8}$ | 116.63164     | 1082.48741 | $\frac{1}{8}$ | 135.48120     | 1460.65667 |
| $\frac{1}{4}$ | 98.17478      | 766.99048 | $\frac{1}{4}$ | 117.02434     | 1089.78916 | $\frac{1}{4}$ | 135.87390     | 1469.13651 |
| $\frac{3}{8}$ | 98.56748      | 773.13867 | $\frac{3}{8}$ | 117.41704     | 1097.11545 | $\frac{3}{8}$ | 136.26660     | 1477.64090 |
| $\frac{1}{2}$ | 98.96018      | 779.31141 | $\frac{1}{2}$ | 117.80974     | 1104.46629 | $\frac{1}{2}$ | 136.65930     | 1486.16984 |
| $\frac{5}{8}$ | 99.35288      | 785.50870 | $\frac{5}{8}$ | 118.20244     | 1111.84167 | $\frac{5}{8}$ | 137.05199     | 1494.72332 |
| $\frac{3}{4}$ | 99.74558      | 791.73052 | $\frac{3}{4}$ | 118.59514     | 1119.24159 | $\frac{3}{4}$ | 137.44469     | 1503.30134 |
| $\frac{7}{8}$ | 100.13828     | 797.97689 | $\frac{7}{8}$ | 118.98783     | 1126.66606 | $\frac{7}{8}$ | 137.83739     | 1511.90390 |
| 32            | 100.53098     | 804.24781 | 38            | 119.38053     | 1134.11507 | 44            | 138.23009     | 1520.53101 |
| $\frac{1}{8}$ | 100.92368     | 810.54327 | $\frac{1}{8}$ | 119.77323     | 1141.58863 | $\frac{1}{8}$ | 138.62279     | 1529.18266 |
| $\frac{1}{4}$ | 101.31637     | 816.86327 | $\frac{1}{4}$ | 120.16593     | 1149.08673 | $\frac{1}{4}$ | 139.01549     | 1537.85886 |
| $\frac{3}{8}$ | 101.70907     | 823.20781 | $\frac{3}{8}$ | 120.55863     | 1156.60937 | $\frac{3}{8}$ | 139.40819     | 1546.55960 |
| $\frac{1}{2}$ | 102.10177     | 829.57690 | $\frac{1}{2}$ | 120.95133     | 1164.15656 | $\frac{1}{2}$ | 139.80089     | 1555.28488 |
| $\frac{5}{8}$ | 102.49447     | 835.97053 | $\frac{5}{8}$ | 121.34403     | 1171.72829 | $\frac{5}{8}$ | 140.19359     | 1564.03471 |
| $\frac{3}{4}$ | 102.88717     | 842.38871 | $\frac{3}{4}$ | 121.73673     | 1179.32456 | $\frac{3}{4}$ | 140.58629     | 1572.80908 |
| $\frac{7}{8}$ | 103.27987     | 848.83143 | $\frac{7}{8}$ | 122.12943     | 1186.94538 | $\frac{7}{8}$ | 140.97899     | 1581.60800 |
| 33            | 103.67257     | 855.29869 | 39            | 122.52213     | 1194.59074 | 45            | 141.37169     | 1590.43146 |
| $\frac{1}{8}$ | 104.06527     | 861.79050 | $\frac{1}{8}$ | 122.91483     | 1202.26064 | $\frac{1}{8}$ | 141.76438     | 1599.27946 |
| $\frac{1}{4}$ | 104.45797     | 868.30685 | $\frac{1}{4}$ | 123.30753     | 1209.95509 | $\frac{1}{4}$ | 142.15708     | 1608.15200 |
| $\frac{3}{8}$ | 104.85067     | 874.84775 | $\frac{3}{8}$ | 123.70022     | 1217.67408 | $\frac{3}{8}$ | 142.54978     | 1617.04909 |
| $\frac{1}{2}$ | 105.24337     | 881.41319 | $\frac{1}{2}$ | 124.09292     | 1225.41762 | $\frac{1}{2}$ | 142.94248     | 1625.97073 |
| $\frac{5}{8}$ | 105.63606     | 888.00317 | $\frac{5}{8}$ | 124.48562     | 1233.18570 | $\frac{5}{8}$ | 143.33518     | 1634.91690 |
| $\frac{3}{4}$ | 106.02876     | 894.61769 | $\frac{3}{4}$ | 124.87832     | 1240.97832 | $\frac{3}{4}$ | 143.72788     | 1643.88762 |
| $\frac{7}{8}$ | 106.42146     | 901.25676 | $\frac{7}{8}$ | 125.27102     | 1248.79549 | $\frac{7}{8}$ | 144.12058     | 1652.88289 |
| 34            | 106.81416     | 907.92038 | 40            | 125.66372     | 1256.63720 | 46            | 144.51328     | 1661.90270 |

Circumferences and Areas of Circles From 46 to 63 $\frac{7}{8}$ 

| Diameter      | Circumference | Area       | Diameter      | Circumference | Area       | Diameter      | Circumference | Area       |
|---------------|---------------|------------|---------------|---------------|------------|---------------|---------------|------------|
| 46            | 144.51328     | 1661.90270 | 52            | 163.36284     | 2123.71687 | 58            | 182.21239     | 2642.07971 |
| $\frac{1}{8}$ | 144.90598     | 1670.94705 | $\frac{1}{8}$ | 163.75554     | 2133.93932 | $\frac{1}{8}$ | 182.60509     | 2653.48026 |
| $\frac{1}{4}$ | 145.29868     | 1680.01594 | $\frac{1}{4}$ | 164.14823     | 2144.18631 | $\frac{1}{4}$ | 182.99779     | 2664.90535 |
| $\frac{3}{8}$ | 145.69138     | 1689.10938 | $\frac{3}{8}$ | 164.54093     | 2154.45785 | $\frac{3}{8}$ | 183.39049     | 2676.35498 |
| $\frac{1}{2}$ | 146.08407     | 1698.22737 | $\frac{1}{2}$ | 164.93363     | 2164.75393 | $\frac{1}{2}$ | 183.78319     | 2687.82916 |
| $\frac{5}{8}$ | 146.47677     | 1707.36989 | $\frac{5}{8}$ | 165.32633     | 2175.07455 | $\frac{5}{8}$ | 184.17589     | 2699.32788 |
| $\frac{3}{4}$ | 146.86947     | 1716.53696 | $\frac{3}{4}$ | 165.71903     | 2185.41972 | $\frac{3}{4}$ | 184.56859     | 2710.85115 |
| $\frac{7}{8}$ | 147.26217     | 1725.72858 | $\frac{7}{8}$ | 166.11173     | 2195.78943 | $\frac{7}{8}$ | 184.96129     | 2722.39896 |
| 47            | 147.65487     | 1734.94473 | 53            | 166.50443     | 2206.18368 | 59            | 185.35399     | 2733.97131 |
| $\frac{1}{8}$ | 148.04757     | 1744.18544 | $\frac{1}{8}$ | 166.89713     | 2216.60248 | $\frac{1}{8}$ | 185.74669     | 2745.56820 |
| $\frac{1}{4}$ | 148.44027     | 1753.45068 | $\frac{1}{4}$ | 167.28983     | 2227.04583 | $\frac{1}{4}$ | 186.13939     | 2757.18964 |
| $\frac{3}{8}$ | 148.83297     | 1762.74047 | $\frac{3}{8}$ | 167.68253     | 2237.51371 | $\frac{3}{8}$ | 186.53208     | 2768.83563 |
| $\frac{1}{2}$ | 149.22567     | 1772.05480 | $\frac{1}{2}$ | 168.07523     | 2248.00614 | $\frac{1}{2}$ | 186.92478     | 2780.50615 |
| $\frac{5}{8}$ | 149.61837     | 1781.39368 | $\frac{5}{8}$ | 168.46792     | 2258.52311 | $\frac{5}{8}$ | 187.31748     | 2792.20123 |
| $\frac{3}{4}$ | 150.01107     | 1790.75710 | $\frac{3}{4}$ | 168.86062     | 2269.06463 | $\frac{3}{4}$ | 187.71018     | 2803.92084 |
| $\frac{7}{8}$ | 150.40376     | 1800.14506 | $\frac{7}{8}$ | 169.25332     | 2279.63069 | $\frac{7}{8}$ | 188.10288     | 2815.66500 |
| 48            | 150.79646     | 1809.55757 | 54            | 169.64602     | 2290.22130 | 60            | 188.49558     | 2827.43370 |
| $\frac{1}{8}$ | 151.18916     | 1818.99462 | $\frac{1}{8}$ | 170.03872     | 2300.83645 | $\frac{1}{8}$ | 188.88828     | 2839.22695 |
| $\frac{1}{4}$ | 151.58186     | 1828.45621 | $\frac{1}{4}$ | 170.43142     | 2311.47614 | $\frac{1}{4}$ | 189.28098     | 2851.04473 |
| $\frac{3}{8}$ | 151.97456     | 1837.94235 | $\frac{3}{8}$ | 170.82412     | 2322.14037 | $\frac{3}{8}$ | 189.67368     | 2862.88707 |
| $\frac{1}{2}$ | 152.36726     | 1847.45303 | $\frac{1}{2}$ | 171.21682     | 2332.82915 | $\frac{1}{2}$ | 190.06638     | 2874.75394 |
| $\frac{5}{8}$ | 152.75996     | 1856.98826 | $\frac{5}{8}$ | 171.60952     | 2343.54248 | $\frac{5}{8}$ | 190.45908     | 2886.64536 |
| $\frac{3}{4}$ | 153.15266     | 1866.54803 | $\frac{3}{4}$ | 172.00222     | 2354.28034 | $\frac{3}{4}$ | 190.85177     | 2898.56133 |
| $\frac{7}{8}$ | 153.54536     | 1876.13234 | $\frac{7}{8}$ | 172.39492     | 2365.04275 | $\frac{7}{8}$ | 191.24447     | 2910.50184 |
| 49            | 153.93806     | 1885.74120 | 55            | 172.78762     | 2375.82971 | 61            | 191.63717     | 2922.46689 |
| $\frac{1}{8}$ | 154.33076     | 1895.37460 | $\frac{1}{8}$ | 173.18031     | 2386.64120 | $\frac{1}{8}$ | 192.02987     | 2934.45648 |
| $\frac{1}{4}$ | 154.72346     | 1905.03254 | $\frac{1}{4}$ | 173.57301     | 2397.47725 | $\frac{1}{4}$ | 192.42257     | 2946.47062 |
| $\frac{3}{8}$ | 155.11615     | 1914.71503 | $\frac{3}{8}$ | 173.96571     | 2408.33783 | $\frac{3}{8}$ | 192.81527     | 2958.50930 |
| $\frac{1}{2}$ | 155.50885     | 1924.42206 | $\frac{1}{2}$ | 174.35841     | 2419.22296 | $\frac{1}{2}$ | 193.20797     | 2970.57253 |
| $\frac{5}{8}$ | 155.90155     | 1934.15364 | $\frac{5}{8}$ | 174.75111     | 2430.13263 | $\frac{5}{8}$ | 193.60067     | 2982.66030 |
| $\frac{3}{4}$ | 156.29425     | 1943.90976 | $\frac{3}{4}$ | 175.14381     | 2441.06685 | $\frac{3}{4}$ | 193.99337     | 2994.77261 |
| $\frac{7}{8}$ | 156.68695     | 1953.69042 | $\frac{7}{8}$ | 175.53651     | 2452.02561 | $\frac{7}{8}$ | 194.38607     | 3006.90947 |
| 50            | 157.07965     | 1963.49563 | 56            | 175.92921     | 2463.00891 | 62            | 194.77877     | 3019.07087 |
| $\frac{1}{8}$ | 157.47235     | 1973.32537 | $\frac{1}{8}$ | 176.32191     | 2474.01676 | $\frac{1}{8}$ | 195.17147     | 3031.25682 |
| $\frac{1}{4}$ | 157.86505     | 1983.17967 | $\frac{1}{4}$ | 176.71461     | 2485.04915 | $\frac{1}{4}$ | 195.56416     | 3043.46731 |
| $\frac{3}{8}$ | 158.25775     | 1993.05851 | $\frac{3}{8}$ | 177.10731     | 2496.10609 | $\frac{3}{8}$ | 195.95686     | 3055.70234 |
| $\frac{1}{2}$ | 158.65045     | 2002.96189 | $\frac{1}{2}$ | 177.50001     | 2507.18756 | $\frac{1}{2}$ | 196.34956     | 3067.96191 |
| $\frac{5}{8}$ | 159.04315     | 2012.88981 | $\frac{5}{8}$ | 177.89270     | 2518.29359 | $\frac{5}{8}$ | 196.74226     | 3080.24603 |
| $\frac{3}{4}$ | 159.43584     | 2022.84228 | $\frac{3}{4}$ | 178.28540     | 2529.42415 | $\frac{3}{4}$ | 197.13496     | 3092.55470 |
| $\frac{7}{8}$ | 159.82854     | 2032.81929 | $\frac{7}{8}$ | 178.67810     | 2540.57926 | $\frac{7}{8}$ | 197.52766     | 3104.88790 |
| 51            | 160.22124     | 2042.82085 | 57            | 179.07080     | 2551.75891 | 63            | 197.92036     | 3117.24565 |
| $\frac{1}{8}$ | 160.61394     | 2052.84695 | $\frac{1}{8}$ | 179.46350     | 2562.96311 | $\frac{1}{8}$ | 198.31306     | 3129.62795 |
| $\frac{1}{4}$ | 161.00664     | 2062.89759 | $\frac{1}{4}$ | 179.85620     | 2574.19185 | $\frac{1}{4}$ | 198.70576     | 3142.03479 |
| $\frac{3}{8}$ | 161.39934     | 2072.97278 | $\frac{3}{8}$ | 180.24890     | 2585.44514 | $\frac{3}{8}$ | 199.09846     | 3154.46617 |
| $\frac{1}{2}$ | 161.79204     | 2083.07251 | $\frac{1}{2}$ | 180.64160     | 2596.72296 | $\frac{1}{2}$ | 199.49116     | 3166.92209 |
| $\frac{5}{8}$ | 162.18474     | 2093.19678 | $\frac{5}{8}$ | 181.03430     | 2608.02534 | $\frac{5}{8}$ | 199.88385     | 3179.40256 |
| $\frac{3}{4}$ | 162.57744     | 2103.34560 | $\frac{3}{4}$ | 181.42700     | 2619.35225 | $\frac{3}{4}$ | 200.27655     | 3191.90758 |
| $\frac{7}{8}$ | 162.97014     | 2113.51896 | $\frac{7}{8}$ | 181.81969     | 2630.70371 | $\frac{7}{8}$ | 200.66925     | 3204.43713 |
| 52            | 163.36284     | 2123.71687 | 58            | 182.21239     | 2642.07971 | 64            | 201.06195     | 3216.99123 |

Circumferences and Areas of Circles From 64 to 81 $\frac{7}{8}$ 

| Diameter      | Circumference | Area       | Diameter      | Circumference | Area       | Diameter      | Circumference | Area       |
|---------------|---------------|------------|---------------|---------------|------------|---------------|---------------|------------|
| 64            | 201.06195     | 3216.99123 | 70            | 219.91151     | 3848.45143 | 76            | 238.76107     | 4536.46029 |
| $\frac{1}{8}$ | 201.45465     | 3229.56988 | $\frac{1}{8}$ | 220.30421     | 3862.20817 | $\frac{1}{8}$ | 239.15377     | 4551.39513 |
| $\frac{1}{4}$ | 201.84735     | 3242.17306 | $\frac{1}{4}$ | 220.69691     | 3875.98945 | $\frac{1}{4}$ | 239.54647     | 4566.35451 |
| $\frac{3}{8}$ | 202.24005     | 3254.80079 | $\frac{3}{8}$ | 221.08961     | 3889.79528 | $\frac{3}{8}$ | 239.93917     | 4581.33844 |
| $\frac{1}{2}$ | 202.63275     | 3267.45307 | $\frac{1}{2}$ | 221.48231     | 3903.62565 | $\frac{1}{2}$ | 240.33186     | 4596.34691 |
| $\frac{5}{8}$ | 203.02545     | 3280.12989 | $\frac{5}{8}$ | 221.87501     | 3917.48057 | $\frac{5}{8}$ | 240.72456     | 4611.37992 |
| $\frac{3}{4}$ | 203.41815     | 3292.83125 | $\frac{3}{4}$ | 222.26770     | 3931.36003 | $\frac{3}{4}$ | 241.11726     | 4626.43748 |
| $\frac{7}{8}$ | 203.81085     | 3305.55716 | $\frac{7}{8}$ | 222.66040     | 3945.26403 | $\frac{7}{8}$ | 241.50996     | 4641.51958 |
| 65            | 204.20355     | 3318.30761 | 71            | 223.05310     | 3959.19258 | 77            | 241.90266     | 4656.62622 |
| $\frac{1}{8}$ | 204.59624     | 3331.08260 | $\frac{1}{8}$ | 223.44580     | 3973.14567 | $\frac{1}{8}$ | 242.29536     | 4671.75741 |
| $\frac{1}{4}$ | 204.98894     | 3343.88214 | $\frac{1}{4}$ | 223.83850     | 3987.12330 | $\frac{1}{4}$ | 242.68806     | 4686.91314 |
| $\frac{3}{8}$ | 205.38164     | 3356.70622 | $\frac{3}{8}$ | 224.23120     | 4001.12548 | $\frac{3}{8}$ | 243.08076     | 4702.09342 |
| $\frac{1}{2}$ | 205.77434     | 3369.55484 | $\frac{1}{2}$ | 224.62390     | 4015.15220 | $\frac{1}{2}$ | 243.47346     | 4717.29824 |
| $\frac{5}{8}$ | 206.16704     | 3382.42801 | $\frac{5}{8}$ | 225.01660     | 4029.20347 | $\frac{5}{8}$ | 243.86616     | 4732.52760 |
| $\frac{3}{4}$ | 206.55974     | 3395.32572 | $\frac{3}{4}$ | 225.40930     | 4043.27928 | $\frac{3}{4}$ | 244.25886     | 4747.78151 |
| $\frac{7}{8}$ | 206.95244     | 3408.24798 | $\frac{7}{8}$ | 225.80200     | 4057.37963 | $\frac{7}{8}$ | 244.65155     | 4763.05996 |
| 66            | 207.34514     | 3421.19478 | 72            | 226.19470     | 4071.50453 | 78            | 245.04425     | 4778.36295 |
| $\frac{1}{8}$ | 207.73784     | 3434.16624 | $\frac{1}{8}$ | 226.58740     | 4085.65397 | $\frac{1}{8}$ | 245.43695     | 4793.69049 |
| $\frac{1}{4}$ | 208.13054     | 3447.16201 | $\frac{1}{4}$ | 226.98009     | 4099.82795 | $\frac{1}{4}$ | 245.82965     | 4809.04257 |
| $\frac{3}{8}$ | 208.52324     | 3460.18244 | $\frac{3}{8}$ | 227.37279     | 4114.02648 | $\frac{3}{8}$ | 246.22235     | 4824.41920 |
| $\frac{1}{2}$ | 208.91593     | 3473.22741 | $\frac{1}{2}$ | 227.76549     | 4128.24955 | $\frac{1}{2}$ | 246.61505     | 4839.82037 |
| $\frac{5}{8}$ | 209.30863     | 3486.29693 | $\frac{5}{8}$ | 228.15819     | 4142.49717 | $\frac{5}{8}$ | 247.00775     | 4855.24608 |
| $\frac{3}{4}$ | 209.70133     | 3499.39099 | $\frac{3}{4}$ | 228.55089     | 4156.76933 | $\frac{3}{4}$ | 247.40045     | 4870.69633 |
| $\frac{7}{8}$ | 210.09403     | 3512.50960 | $\frac{7}{8}$ | 228.94359     | 4171.06603 | $\frac{7}{8}$ | 247.79315     | 4886.17113 |
| 67            | 210.48673     | 3525.65274 | 73            | 229.33629     | 4185.38727 | 79            | 248.18585     | 4901.67048 |
| $\frac{1}{8}$ | 210.87943     | 3538.82044 | $\frac{1}{8}$ | 229.72899     | 4199.73306 | $\frac{1}{8}$ | 248.57855     | 4917.19437 |
| $\frac{1}{4}$ | 211.27213     | 3552.01267 | $\frac{1}{4}$ | 230.12169     | 4214.10340 | $\frac{1}{4}$ | 248.97125     | 4932.74280 |
| $\frac{3}{8}$ | 211.66483     | 3565.22945 | $\frac{3}{8}$ | 230.51439     | 4228.49828 | $\frac{3}{8}$ | 249.36394     | 4948.31577 |
| $\frac{1}{2}$ | 212.05753     | 3578.47078 | $\frac{1}{2}$ | 230.90709     | 4242.91770 | $\frac{1}{2}$ | 249.75664     | 4963.91329 |
| $\frac{5}{8}$ | 212.45023     | 3591.73664 | $\frac{5}{8}$ | 231.29978     | 4257.36166 | $\frac{5}{8}$ | 250.14934     | 4979.53535 |
| $\frac{3}{4}$ | 212.84293     | 3605.02705 | $\frac{3}{4}$ | 231.69248     | 4271.83017 | $\frac{3}{4}$ | 250.54204     | 4995.18196 |
| $\frac{7}{8}$ | 213.23562     | 3618.34201 | $\frac{7}{8}$ | 232.08518     | 4286.32322 | $\frac{7}{8}$ | 250.93474     | 5010.85311 |
| 68            | 213.62832     | 3631.68151 | 74            | 232.47788     | 4300.84082 | 80            | 251.32744     | 5026.54880 |
| $\frac{1}{8}$ | 214.02102     | 3645.04555 | $\frac{1}{8}$ | 232.87058     | 4315.38296 | $\frac{1}{8}$ | 251.72014     | 5042.26904 |
| $\frac{1}{4}$ | 214.41372     | 3658.43414 | $\frac{1}{4}$ | 233.26328     | 4329.94964 | $\frac{1}{4}$ | 252.11284     | 5058.01382 |
| $\frac{3}{8}$ | 214.80642     | 3671.84727 | $\frac{3}{8}$ | 233.65598     | 4344.54087 | $\frac{3}{8}$ | 252.50554     | 5073.78314 |
| $\frac{1}{2}$ | 215.19912     | 3685.28494 | $\frac{1}{2}$ | 234.04868     | 4359.15664 | $\frac{1}{2}$ | 252.89824     | 5089.57701 |
| $\frac{5}{8}$ | 215.59182     | 3698.74716 | $\frac{5}{8}$ | 234.44138     | 4373.79695 | $\frac{5}{8}$ | 253.29094     | 5105.39542 |
| $\frac{3}{4}$ | 215.98452     | 3712.23392 | $\frac{3}{4}$ | 234.83408     | 4388.46181 | $\frac{3}{4}$ | 253.68363     | 5121.23838 |
| $\frac{7}{8}$ | 216.37722     | 3725.74522 | $\frac{7}{8}$ | 235.22678     | 4403.15121 | $\frac{7}{8}$ | 254.07633     | 5137.10588 |
| 69            | 216.76992     | 3739.28107 | 75            | 235.61948     | 4417.86516 | 81            | 254.46903     | 5152.99792 |
| $\frac{1}{8}$ | 217.16262     | 3752.84146 | $\frac{1}{8}$ | 236.01217     | 4432.60365 | $\frac{1}{8}$ | 254.86173     | 5168.91450 |
| $\frac{1}{4}$ | 217.55532     | 3766.42640 | $\frac{1}{4}$ | 236.40487     | 4447.36668 | $\frac{1}{4}$ | 255.25443     | 5184.85563 |
| $\frac{3}{8}$ | 217.94801     | 3780.03587 | $\frac{3}{8}$ | 236.79757     | 4462.15425 | $\frac{3}{8}$ | 255.64713     | 5200.82131 |
| $\frac{1}{2}$ | 218.34071     | 3793.66990 | $\frac{1}{2}$ | 237.19027     | 4476.96637 | $\frac{1}{2}$ | 256.03983     | 5216.81153 |
| $\frac{5}{8}$ | 218.73341     | 3807.32846 | $\frac{5}{8}$ | 237.58297     | 4491.80304 | $\frac{5}{8}$ | 256.43253     | 5232.82629 |
| $\frac{3}{4}$ | 219.12611     | 3821.01157 | $\frac{3}{4}$ | 237.97567     | 4506.66425 | $\frac{3}{4}$ | 256.82523     | 5248.86559 |
| $\frac{7}{8}$ | 219.51881     | 3834.71923 | $\frac{7}{8}$ | 238.36837     | 4521.55000 | $\frac{7}{8}$ | 257.21793     | 5264.92944 |
| 70            | 219.91151     | 3848.45143 | 76            | 238.76107     | 4536.46029 | 82            | 257.61063     | 5281.01783 |

Circumferences and Areas of Circles From 82 to 99 $\frac{7}{8}$ 

| Diameter      | Circumference | Area       | Diameter      | Circumference | Area       | Diameter      | Circumference | Area       |
|---------------|---------------|------------|---------------|---------------|------------|---------------|---------------|------------|
| 82            | 257.61063     | 5281.01783 | 88            | 276.46018     | 6082.12405 | 94            | 295.30974     | 6939.77894 |
| $\frac{1}{8}$ | 258.00333     | 5297.13077 | $\frac{1}{8}$ | 276.85288     | 6099.41508 | $\frac{1}{8}$ | 295.70244     | 6958.24807 |
| $\frac{1}{4}$ | 258.39602     | 5313.26825 | $\frac{1}{4}$ | 277.24558     | 6116.73066 | $\frac{1}{4}$ | 296.09514     | 6976.74174 |
| $\frac{3}{8}$ | 258.78872     | 5329.43027 | $\frac{3}{8}$ | 277.63828     | 6134.07078 | $\frac{3}{8}$ | 296.48784     | 6995.25996 |
| $\frac{1}{2}$ | 259.18142     | 5345.61684 | $\frac{1}{2}$ | 278.03098     | 6151.43544 | $\frac{1}{2}$ | 296.88054     | 7013.80272 |
| $\frac{5}{8}$ | 259.57412     | 5361.82795 | $\frac{5}{8}$ | 278.42368     | 6168.82465 | $\frac{5}{8}$ | 297.27324     | 7032.37003 |
| $\frac{3}{4}$ | 259.96682     | 5378.06360 | $\frac{3}{4}$ | 278.81638     | 6186.23840 | $\frac{3}{4}$ | 297.66594     | 7050.96188 |
| $\frac{7}{8}$ | 260.35952     | 5394.32380 | $\frac{7}{8}$ | 279.20908     | 6203.67670 | $\frac{7}{8}$ | 298.05864     | 7069.57827 |
| 83            | 260.75222     | 5410.60854 | 89            | 279.60178     | 6221.13954 | 95            | 298.45134     | 7088.21921 |
| $\frac{1}{8}$ | 261.14492     | 5426.91783 | $\frac{1}{8}$ | 279.99448     | 6238.62692 | $\frac{1}{8}$ | 298.84403     | 7106.88469 |
| $\frac{1}{4}$ | 261.53762     | 5443.25166 | $\frac{1}{4}$ | 280.38718     | 6256.13885 | $\frac{1}{4}$ | 299.23673     | 7125.57471 |
| $\frac{3}{8}$ | 261.93032     | 5459.61003 | $\frac{3}{8}$ | 280.77987     | 6273.67532 | $\frac{3}{8}$ | 299.62943     | 7144.28928 |
| $\frac{1}{2}$ | 262.32302     | 5475.99295 | $\frac{1}{2}$ | 281.17257     | 6291.23633 | $\frac{1}{2}$ | 300.02213     | 7163.02839 |
| $\frac{5}{8}$ | 262.71571     | 5492.40041 | $\frac{5}{8}$ | 281.56527     | 6308.82189 | $\frac{5}{8}$ | 300.41483     | 7181.79204 |
| $\frac{3}{4}$ | 263.10841     | 5508.83241 | $\frac{3}{4}$ | 281.95797     | 6326.43199 | $\frac{3}{4}$ | 300.80753     | 7200.58024 |
| $\frac{7}{8}$ | 263.50111     | 5525.28896 | $\frac{7}{8}$ | 282.35067     | 6344.06664 | $\frac{7}{8}$ | 301.20023     | 7219.39299 |
| 84            | 263.89381     | 5541.77005 | 90            | 282.74337     | 6361.72583 | 96            | 301.59293     | 7238.23027 |
| $\frac{1}{8}$ | 264.28651     | 5558.27569 | $\frac{1}{8}$ | 283.13607     | 6379.40956 | $\frac{1}{8}$ | 301.98563     | 7257.09210 |
| $\frac{1}{4}$ | 264.67921     | 5574.80587 | $\frac{1}{4}$ | 283.52877     | 6397.11783 | $\frac{1}{4}$ | 302.37833     | 7275.97848 |
| $\frac{3}{8}$ | 265.07191     | 5591.36059 | $\frac{3}{8}$ | 283.92147     | 6414.85065 | $\frac{3}{8}$ | 302.77103     | 7294.88939 |
| $\frac{1}{2}$ | 265.46461     | 5607.93985 | $\frac{1}{2}$ | 284.31417     | 6432.60802 | $\frac{1}{2}$ | 303.16372     | 7313.82485 |
| $\frac{5}{8}$ | 265.85731     | 5624.54366 | $\frac{5}{8}$ | 284.70687     | 6450.38992 | $\frac{5}{8}$ | 303.55642     | 7332.78486 |
| $\frac{3}{4}$ | 266.25001     | 5641.17202 | $\frac{3}{4}$ | 285.09956     | 6468.19638 | $\frac{3}{4}$ | 303.94912     | 7351.76941 |
| $\frac{7}{8}$ | 266.64271     | 5657.82492 | $\frac{7}{8}$ | 285.49226     | 6486.02737 | $\frac{7}{8}$ | 304.34182     | 7370.77850 |
| 85            | 267.03541     | 5674.50236 | 91            | 285.88496     | 6503.88291 | 97            | 304.73452     | 7389.81213 |
| $\frac{1}{8}$ | 267.42810     | 5691.20434 | $\frac{1}{8}$ | 286.27766     | 6521.76299 | $\frac{1}{8}$ | 305.12722     | 7408.87031 |
| $\frac{1}{4}$ | 267.82080     | 5707.93087 | $\frac{1}{4}$ | 286.67036     | 6539.66762 | $\frac{1}{4}$ | 305.51992     | 7427.95304 |
| $\frac{3}{8}$ | 268.21350     | 5724.68194 | $\frac{3}{8}$ | 287.06306     | 6557.59679 | $\frac{3}{8}$ | 305.91262     | 7447.06030 |
| $\frac{1}{2}$ | 268.60620     | 5741.45756 | $\frac{1}{2}$ | 287.45576     | 6575.55050 | $\frac{1}{2}$ | 306.30532     | 7466.19211 |
| $\frac{5}{8}$ | 268.99890     | 5758.25772 | $\frac{5}{8}$ | 287.84846     | 6593.52876 | $\frac{5}{8}$ | 306.69802     | 7485.34847 |
| $\frac{3}{4}$ | 269.39160     | 5775.08242 | $\frac{3}{4}$ | 288.24116     | 6611.53156 | $\frac{3}{4}$ | 307.09072     | 7504.52937 |
| $\frac{7}{8}$ | 269.78430     | 5791.93167 | $\frac{7}{8}$ | 288.63386     | 6629.55890 | $\frac{7}{8}$ | 307.48341     | 7523.73481 |
| 86            | 270.17700     | 5808.80546 | 92            | 289.02656     | 6647.61079 | 98            | 307.87611     | 7542.96479 |
| $\frac{1}{8}$ | 270.56970     | 5825.70379 | $\frac{1}{8}$ | 289.41926     | 6665.68722 | $\frac{1}{8}$ | 308.26881     | 7562.21932 |
| $\frac{1}{4}$ | 270.96240     | 5842.62667 | $\frac{1}{4}$ | 289.81195     | 6683.78819 | $\frac{1}{4}$ | 308.66151     | 7581.49839 |
| $\frac{3}{8}$ | 271.35510     | 5859.57409 | $\frac{3}{8}$ | 290.20465     | 6701.91371 | $\frac{3}{8}$ | 309.05421     | 7600.80201 |
| $\frac{1}{2}$ | 271.74779     | 5876.54606 | $\frac{1}{2}$ | 290.59735     | 6720.06378 | $\frac{1}{2}$ | 309.44691     | 7620.13017 |
| $\frac{5}{8}$ | 272.14049     | 5893.54257 | $\frac{5}{8}$ | 290.99005     | 6738.23838 | $\frac{5}{8}$ | 309.83961     | 7639.48287 |
| $\frac{3}{4}$ | 272.53319     | 5910.56362 | $\frac{3}{4}$ | 291.38275     | 6756.43753 | $\frac{3}{4}$ | 310.23231     | 7658.86012 |
| $\frac{7}{8}$ | 272.92589     | 5927.60921 | $\frac{7}{8}$ | 291.77545     | 6774.66123 | $\frac{7}{8}$ | 310.62501     | 7678.26191 |
| 87            | 273.31859     | 5944.67935 | 93            | 292.16815     | 6792.90946 | 99            | 311.01771     | 7697.68825 |
| $\frac{1}{8}$ | 273.71129     | 5961.77404 | $\frac{1}{8}$ | 292.56085     | 6811.18225 | $\frac{1}{8}$ | 311.41041     | 7717.13913 |
| $\frac{1}{4}$ | 274.10399     | 5978.89327 | $\frac{1}{4}$ | 292.95355     | 6829.47957 | $\frac{1}{4}$ | 311.80311     | 7736.61455 |
| $\frac{3}{8}$ | 274.49669     | 5996.03704 | $\frac{3}{8}$ | 293.34625     | 6847.80144 | $\frac{3}{8}$ | 312.19580     | 7756.11451 |
| $\frac{1}{2}$ | 274.88939     | 6013.20535 | $\frac{1}{2}$ | 293.73895     | 6866.14785 | $\frac{1}{2}$ | 312.58850     | 7775.63902 |
| $\frac{5}{8}$ | 275.28209     | 6030.39821 | $\frac{5}{8}$ | 294.13164     | 6884.51881 | $\frac{5}{8}$ | 312.98120     | 7795.18808 |
| $\frac{3}{4}$ | 275.67479     | 6047.61561 | $\frac{3}{4}$ | 294.52434     | 6902.91431 | $\frac{3}{4}$ | 313.37390     | 7814.76167 |
| $\frac{7}{8}$ | 276.06748     | 6064.85756 | $\frac{7}{8}$ | 294.91704     | 6921.33435 | $\frac{7}{8}$ | 313.76660     | 7834.35982 |
| 88            | 276.46018     | 6082.12405 | 94            | 295.30974     | 6939.77894 | 100           | 314.15930     | 7853.98250 |

## Circumferences and Areas of Circles From 100 to 249

| Diameter | Circumference | Area        | Diameter | Circumference | Area        | Diameter | Circumference | Area        |
|----------|---------------|-------------|----------|---------------|-------------|----------|---------------|-------------|
| 100      | 314.15930     | 7853.98250  | 150      | 471.23895     | 17671.46063 | 200      | 628.31860     | 31415.93000 |
| 101      | 317.30089     | 8011.84755  | 151      | 474.38054     | 17907.86550 | 201      | 631.46019     | 31730.87470 |
| 102      | 320.44249     | 8171.28339  | 152      | 477.52214     | 18145.84117 | 202      | 634.60179     | 32047.39019 |
| 103      | 323.58408     | 8332.29003  | 153      | 480.66373     | 18385.38763 | 203      | 637.74338     | 32365.47648 |
| 104      | 326.72567     | 8494.86747  | 154      | 483.80532     | 18626.50490 | 204      | 640.88497     | 32685.13357 |
| 105      | 329.86727     | 8659.01571  | 155      | 486.94692     | 18869.19296 | 205      | 644.02657     | 33006.36146 |
| 106      | 333.00886     | 8824.73474  | 156      | 490.08851     | 19113.45181 | 206      | 647.16816     | 33329.16014 |
| 107      | 336.15045     | 8992.02456  | 157      | 493.23010     | 19359.28146 | 207      | 650.30975     | 33653.52961 |
| 108      | 339.29204     | 9160.88519  | 158      | 496.37169     | 19606.68191 | 208      | 653.45134     | 33979.46989 |
| 109      | 342.43364     | 9331.31661  | 159      | 499.51329     | 19855.65316 | 209      | 656.59294     | 34306.98096 |
| 110      | 345.57523     | 9503.31883  | 160      | 502.65488     | 20106.19520 | 210      | 659.73453     | 34636.06283 |
| 111      | 348.71682     | 9676.89184  | 161      | 505.79647     | 20358.30804 | 211      | 662.87612     | 34966.71549 |
| 112      | 351.85842     | 9852.03565  | 162      | 508.93807     | 20611.99167 | 212      | 666.01772     | 35298.93895 |
| 113      | 355.00001     | 10028.75025 | 163      | 512.07966     | 20867.24610 | 213      | 669.15931     | 35632.73320 |
| 114      | 358.14160     | 10207.03566 | 164      | 515.22125     | 21124.07133 | 214      | 672.30090     | 35968.09826 |
| 115      | 361.28320     | 10386.89186 | 165      | 518.36285     | 21382.46736 | 215      | 675.44250     | 36305.03411 |
| 116      | 364.42479     | 10568.31885 | 166      | 521.50444     | 21642.43418 | 216      | 678.58409     | 36643.54075 |
| 117      | 367.56638     | 10751.31664 | 167      | 524.64603     | 21903.97179 | 217      | 681.72568     | 36983.61819 |
| 118      | 370.70797     | 10935.88523 | 168      | 527.78762     | 22167.08021 | 218      | 684.86727     | 37325.26643 |
| 119      | 373.84957     | 11122.02462 | 169      | 530.92922     | 22431.75942 | 219      | 688.00887     | 37668.48547 |
| 120      | 376.99116     | 11309.73480 | 170      | 534.07081     | 22698.00943 | 220      | 691.15046     | 38013.27530 |
| 121      | 380.13275     | 11499.01578 | 171      | 537.21240     | 22965.83023 | 221      | 694.29205     | 38359.63593 |
| 122      | 383.27435     | 11689.86755 | 172      | 540.35400     | 23235.22183 | 222      | 697.43365     | 38707.56735 |
| 123      | 386.41594     | 11882.29012 | 173      | 543.49559     | 23506.18422 | 223      | 700.57524     | 39057.06957 |
| 124      | 389.55753     | 12076.28349 | 174      | 546.63718     | 23778.71742 | 224      | 703.71683     | 39408.14259 |
| 125      | 392.69913     | 12271.84766 | 175      | 549.77878     | 24052.82141 | 225      | 706.85843     | 39760.78641 |
| 126      | 395.84072     | 12468.98262 | 176      | 552.92037     | 24328.49619 | 226      | 710.00002     | 40115.00102 |
| 127      | 398.98231     | 12667.68837 | 177      | 556.06196     | 24605.74177 | 227      | 713.14161     | 40470.78642 |
| 128      | 402.12390     | 12867.96493 | 178      | 559.20355     | 24884.55815 | 228      | 716.28320     | 40828.14263 |
| 129      | 405.26550     | 13069.81228 | 179      | 562.34515     | 25164.94533 | 229      | 719.42480     | 41187.06963 |
| 130      | 408.40709     | 13273.23043 | 180      | 565.48674     | 25446.90330 | 230      | 722.56639     | 41547.56743 |
| 131      | 411.54868     | 13478.21937 | 181      | 568.62833     | 25730.43207 | 231      | 725.70798     | 41909.63602 |
| 132      | 414.69028     | 13684.77911 | 182      | 571.76993     | 26015.53163 | 232      | 728.84958     | 42273.27541 |
| 133      | 417.83187     | 13892.90964 | 183      | 574.91152     | 26302.20199 | 233      | 731.99117     | 42638.48559 |
| 134      | 420.97346     | 14102.61098 | 184      | 578.05311     | 26590.44315 | 234      | 735.13276     | 43005.26658 |
| 135      | 424.11506     | 14313.88311 | 185      | 581.19471     | 26880.25511 | 235      | 738.27436     | 43373.61836 |
| 136      | 427.25665     | 14526.72603 | 186      | 584.33630     | 27171.63786 | 236      | 741.41595     | 43743.54093 |
| 137      | 430.39824     | 14741.13975 | 187      | 587.47789     | 27464.59140 | 237      | 744.55754     | 44115.03430 |
| 138      | 433.53983     | 14957.12427 | 188      | 590.61948     | 27759.11575 | 238      | 747.69913     | 44488.09847 |
| 139      | 436.68143     | 15174.67959 | 189      | 593.76108     | 28055.21089 | 239      | 750.84073     | 44862.73344 |
| 140      | 439.82302     | 15393.80570 | 190      | 596.90267     | 28352.87683 | 240      | 753.98232     | 45238.93920 |
| 141      | 442.96461     | 15614.50261 | 191      | 600.04426     | 28652.11356 | 241      | 757.12391     | 45616.71576 |
| 142      | 446.10621     | 15836.77031 | 192      | 603.18586     | 28952.92109 | 242      | 760.26551     | 45996.06311 |
| 143      | 449.24780     | 16060.60881 | 193      | 606.32745     | 29255.29941 | 243      | 763.40710     | 46376.98126 |
| 144      | 452.38939     | 16286.01811 | 194      | 609.46904     | 29559.24854 | 244      | 766.54869     | 46759.47021 |
| 145      | 455.53099     | 16512.99821 | 195      | 612.61064     | 29864.76846 | 245      | 769.69029     | 47143.52996 |
| 146      | 458.67258     | 16741.54910 | 196      | 615.75223     | 30171.85917 | 246      | 772.83188     | 47529.16050 |
| 147      | 461.81417     | 16971.67078 | 197      | 618.89382     | 30480.52068 | 247      | 775.97347     | 47916.36183 |
| 148      | 464.95576     | 17203.36327 | 198      | 622.03541     | 30790.75299 | 248      | 779.11506     | 48305.13397 |
| 149      | 468.09736     | 17436.62655 | 199      | 625.17701     | 31102.55610 | 249      | 782.25666     | 48695.47690 |

## Circumferences and Areas of Circles From 250 to 399

| Diameter | Circumference | Area        | Diameter | Circumference | Area        | Diameter | Circumference | Area         |
|----------|---------------|-------------|----------|---------------|-------------|----------|---------------|--------------|
| 250      | 785.39825     | 49087.39063 | 300      | 942.47790     | 70685.84250 | 350      | 1099.55755    | 96211.28563  |
| 251      | 788.53984     | 49480.87515 | 301      | 945.61949     | 71157.86685 | 351      | 1102.69914    | 96761.84980  |
| 252      | 791.68144     | 49875.93047 | 302      | 948.76109     | 71631.46199 | 352      | 1105.84074    | 97313.98477  |
| 253      | 794.82303     | 50272.55658 | 303      | 951.90268     | 72106.62793 | 353      | 1108.98233    | 97867.69053  |
| 254      | 797.96462     | 50670.75350 | 304      | 955.04427     | 72583.36467 | 354      | 1112.12392    | 98422.96710  |
| 255      | 801.10622     | 51070.52121 | 305      | 958.18587     | 73061.67221 | 355      | 1115.26552    | 98979.81446  |
| 256      | 804.24781     | 51471.85971 | 306      | 961.32746     | 73541.55054 | 356      | 1118.40711    | 99538.23261  |
| 257      | 807.38940     | 51874.76901 | 307      | 964.46905     | 74022.99966 | 357      | 1121.54870    | 100098.22156 |
| 258      | 810.53099     | 52279.24911 | 308      | 967.61064     | 74506.01959 | 358      | 1124.69029    | 100659.78131 |
| 259      | 813.67259     | 52685.30001 | 309      | 970.75224     | 74990.61031 | 359      | 1127.83189    | 101222.91186 |
| 260      | 816.81418     | 53092.92170 | 310      | 973.89383     | 75476.77183 | 360      | 1130.97348    | 101787.61320 |
| 261      | 819.95577     | 53502.11419 | 311      | 977.03542     | 75964.50414 | 361      | 1134.11507    | 102353.88534 |
| 262      | 823.09737     | 53912.87747 | 312      | 980.17702     | 76453.80725 | 362      | 1137.25667    | 102921.72827 |
| 263      | 826.23896     | 54325.21155 | 313      | 983.31861     | 76944.68115 | 363      | 1140.39826    | 103491.14200 |
| 264      | 829.38055     | 54739.11643 | 314      | 986.46020     | 77437.12586 | 364      | 1143.53985    | 104062.12653 |
| 265      | 832.52215     | 55154.59211 | 315      | 989.60180     | 77931.14136 | 365      | 1146.68145    | 104634.68186 |
| 266      | 835.66374     | 55571.63858 | 316      | 992.74339     | 78426.72765 | 366      | 1149.82304    | 105208.80798 |
| 267      | 838.80533     | 55990.25584 | 317      | 995.88498     | 78923.88474 | 367      | 1152.96463    | 105784.50489 |
| 268      | 841.94692     | 56410.44391 | 318      | 999.02657     | 79422.61263 | 368      | 1156.10622    | 106361.77261 |
| 269      | 845.08852     | 56832.20277 | 319      | 1002.16817    | 79922.91132 | 369      | 1159.24782    | 106940.61112 |
| 270      | 848.23011     | 57255.53243 | 320      | 1005.30976    | 80424.78080 | 370      | 1162.38941    | 107521.02043 |
| 271      | 851.37170     | 57680.43288 | 321      | 1008.45135    | 80928.22108 | 371      | 1165.53100    | 108103.00053 |
| 272      | 854.51330     | 58106.90413 | 322      | 1011.59295    | 81433.23215 | 372      | 1168.67260    | 108686.55143 |
| 273      | 857.65489     | 58534.94617 | 323      | 1014.73454    | 81939.81402 | 373      | 1171.81419    | 109271.67312 |
| 274      | 860.79648     | 58964.55902 | 324      | 1017.87613    | 82447.96669 | 374      | 1174.95578    | 109858.36562 |
| 275      | 863.93808     | 59395.74266 | 325      | 1021.01773    | 82957.69016 | 375      | 1178.09738    | 110446.62891 |
| 276      | 867.07967     | 59828.49709 | 326      | 1024.15932    | 83468.98442 | 376      | 1181.23897    | 111036.46299 |
| 277      | 870.22126     | 60262.82232 | 327      | 1027.30091    | 83981.84947 | 377      | 1184.38056    | 111627.86787 |
| 278      | 873.36285     | 60698.71835 | 328      | 1030.44250    | 84496.28533 | 378      | 1187.52215    | 112220.84355 |
| 279      | 876.50445     | 61136.18518 | 329      | 1033.58410    | 85012.29198 | 379      | 1190.66375    | 112815.39003 |
| 280      | 879.64604     | 61575.22280 | 330      | 1036.72569    | 85529.86943 | 380      | 1193.80534    | 113411.50730 |
| 281      | 882.78763     | 62015.83122 | 331      | 1039.86728    | 86049.01767 | 381      | 1196.94693    | 114009.19537 |
| 282      | 885.92923     | 62458.01043 | 332      | 1043.00888    | 86569.73671 | 382      | 1200.08853    | 114608.45423 |
| 283      | 889.07082     | 62901.76044 | 333      | 1046.15047    | 87092.02654 | 383      | 1203.23012    | 115209.28389 |
| 284      | 892.21241     | 63347.08125 | 334      | 1049.29206    | 87615.88718 | 384      | 1206.37171    | 115811.68435 |
| 285      | 895.35401     | 63793.97286 | 335      | 1052.43366    | 88141.31861 | 385      | 1209.51331    | 116415.65561 |
| 286      | 898.49560     | 64242.43526 | 336      | 1055.57525    | 88668.32083 | 386      | 1212.65490    | 117021.19766 |
| 287      | 901.63719     | 64692.46845 | 337      | 1058.71684    | 89196.89385 | 387      | 1215.79649    | 117628.31050 |
| 288      | 904.77878     | 65144.07245 | 338      | 1061.85843    | 89727.03767 | 388      | 1218.93808    | 118236.99415 |
| 289      | 907.92038     | 65597.24724 | 339      | 1065.00003    | 90258.75229 | 389      | 1222.07968    | 118847.24859 |
| 290      | 911.06197     | 66051.99283 | 340      | 1068.14162    | 90792.03770 | 390      | 1225.22127    | 119459.07383 |
| 291      | 914.20356     | 66508.30921 | 341      | 1071.28321    | 91326.89391 | 391      | 1228.36286    | 120072.46986 |
| 292      | 917.34516     | 66966.19639 | 342      | 1074.42481    | 91863.32091 | 392      | 1231.50446    | 120687.43669 |
| 293      | 920.48675     | 67425.65436 | 343      | 1077.56640    | 92401.31871 | 393      | 1234.64605    | 121303.97431 |
| 294      | 923.62834     | 67886.68314 | 344      | 1080.70799    | 92940.88731 | 394      | 1237.78764    | 121922.08274 |
| 295      | 926.76994     | 68349.28271 | 345      | 1083.84959    | 93482.02671 | 395      | 1240.92924    | 122541.76196 |
| 296      | 929.91153     | 68813.45307 | 346      | 1086.99118    | 94024.73690 | 396      | 1244.07083    | 123163.01197 |
| 297      | 933.05312     | 69279.19423 | 347      | 1090.13277    | 94569.01788 | 397      | 1247.21242    | 123785.83278 |
| 298      | 936.19471     | 69746.50619 | 348      | 1093.27436    | 95114.86967 | 398      | 1250.35401    | 124410.22439 |
| 299      | 939.33631     | 70215.38895 | 349      | 1096.41596    | 95662.29225 | 399      | 1253.49561    | 125036.18680 |

## Circumferences and Areas of Circles From 400 to 549

| Dia-<br>meter | Circum-<br>ference | Area         | Dia-<br>meter | Circum-<br>ference | Area         | Dia-<br>meter | Circum-<br>ference | Area         |
|---------------|--------------------|--------------|---------------|--------------------|--------------|---------------|--------------------|--------------|
| 400           | 1256.63720         | 125663.72000 | 450           | 1413.71685         | 159043.14563 | 500           | 1570.79650         | 196349.56250 |
| 401           | 1259.77879         | 126292.82400 | 451           | 1416.85844         | 159750.78945 | 501           | 1573.93809         | 197135.74615 |
| 402           | 1262.92039         | 126923.49879 | 452           | 1420.00004         | 160460.00407 | 502           | 1577.07969         | 197923.50059 |
| 403           | 1266.06198         | 127555.74438 | 453           | 1423.14163         | 161170.78948 | 503           | 1580.22128         | 198712.82583 |
| 404           | 1269.20357         | 128189.56077 | 454           | 1426.28322         | 161883.14570 | 504           | 1583.36287         | 199503.72187 |
| 405           | 1272.34517         | 128824.94796 | 455           | 1429.42482         | 162597.07271 | 505           | 1586.50447         | 200296.18871 |
| 406           | 1275.48676         | 129461.90594 | 456           | 1432.56641         | 163312.57051 | 506           | 1589.64606         | 201090.22634 |
| 407           | 1278.62835         | 130100.43471 | 457           | 1435.70800         | 164029.63911 | 507           | 1592.78765         | 201885.83476 |
| 408           | 1281.76994         | 130740.53429 | 458           | 1438.84959         | 164748.27851 | 508           | 1595.92924         | 202683.01399 |
| 409           | 1284.91154         | 131382.20466 | 459           | 1441.99119         | 165468.48871 | 509           | 1599.07084         | 203481.76401 |
| 410           | 1288.05313         | 132025.44583 | 460           | 1445.13278         | 166190.26970 | 510           | 1602.21243         | 204282.08483 |
| 411           | 1291.19472         | 132670.25779 | 461           | 1448.27437         | 166913.62149 | 511           | 1605.35402         | 205083.97644 |
| 412           | 1294.33632         | 133316.64055 | 462           | 1451.41597         | 167638.54407 | 512           | 1608.49562         | 205887.43885 |
| 413           | 1297.47791         | 133964.59410 | 463           | 1454.55756         | 168365.03745 | 513           | 1611.63721         | 206692.47205 |
| 414           | 1300.61950         | 134614.11846 | 464           | 1457.69915         | 169093.10163 | 514           | 1614.77880         | 207499.07606 |
| 415           | 1303.76110         | 135265.21361 | 465           | 1460.84075         | 169822.73661 | 515           | 1617.92040         | 208307.25086 |
| 416           | 1306.90269         | 135917.87955 | 466           | 1463.98234         | 170553.94238 | 516           | 1621.06199         | 209116.99645 |
| 417           | 1310.04428         | 136572.11629 | 467           | 1467.12393         | 171286.71894 | 517           | 1624.20358         | 209928.31284 |
| 418           | 1313.18587         | 137227.92383 | 468           | 1470.26552         | 172021.06631 | 518           | 1627.34517         | 210741.20003 |
| 419           | 1316.32747         | 137885.30217 | 469           | 1473.40712         | 172756.98447 | 519           | 1630.48677         | 211555.65802 |
| 420           | 1319.46906         | 138544.25130 | 470           | 1476.54871         | 173494.47343 | 520           | 1633.62836         | 212371.68680 |
| 421           | 1322.61065         | 139204.77123 | 471           | 1479.69030         | 174233.53318 | 521           | 1636.76995         | 213189.28638 |
| 422           | 1325.75225         | 139866.86195 | 472           | 1482.83190         | 174974.16373 | 522           | 1639.91155         | 214008.45675 |
| 423           | 1328.89384         | 140530.52347 | 473           | 1485.97349         | 175716.36507 | 523           | 1643.05314         | 214829.19792 |
| 424           | 1332.03543         | 141195.75579 | 474           | 1489.11508         | 176460.13322 | 524           | 1646.19473         | 215651.50989 |
| 425           | 1335.17703         | 141862.55891 | 475           | 1492.25668         | 177205.48016 | 525           | 1649.33633         | 216475.39266 |
| 426           | 1338.31862         | 142530.93282 | 476           | 1495.39827         | 177952.39389 | 526           | 1652.47792         | 217300.84622 |
| 427           | 1341.46021         | 143200.87752 | 477           | 1498.53986         | 178700.87842 | 527           | 1655.61951         | 218127.87057 |
| 428           | 1344.60180         | 143872.39303 | 478           | 1501.68145         | 179450.93375 | 528           | 1658.76110         | 218956.46573 |
| 429           | 1347.74340         | 144545.47933 | 479           | 1504.82305         | 180202.55988 | 529           | 1661.90270         | 219786.63168 |
| 430           | 1350.88499         | 145220.13643 | 480           | 1507.96464         | 180955.75680 | 530           | 1665.04429         | 220618.36843 |
| 431           | 1354.02658         | 145896.36432 | 481           | 1511.10623         | 181710.52452 | 531           | 1668.18588         | 221451.67597 |
| 432           | 1357.16818         | 146574.16301 | 482           | 1514.24783         | 182466.86303 | 532           | 1671.32748         | 222286.55431 |
| 433           | 1360.30977         | 147253.53249 | 483           | 1517.38942         | 183224.77234 | 533           | 1674.46907         | 223123.00344 |
| 434           | 1363.45136         | 147934.47278 | 484           | 1520.53101         | 183984.25245 | 534           | 1677.61066         | 223961.02338 |
| 435           | 1366.59296         | 148616.98386 | 485           | 1523.67261         | 184745.30336 | 535           | 1680.75226         | 224800.61411 |
| 436           | 1369.73455         | 149301.06573 | 486           | 1526.81420         | 185507.92506 | 536           | 1683.89385         | 225641.77563 |
| 437           | 1372.87614         | 149986.71840 | 487           | 1529.95579         | 186272.11755 | 537           | 1687.03544         | 226484.50795 |
| 438           | 1376.01773         | 150673.94187 | 488           | 1533.09738         | 187037.88085 | 538           | 1690.17703         | 227328.81107 |
| 439           | 1379.15933         | 151362.73614 | 489           | 1536.23898         | 187805.21494 | 539           | 1693.31863         | 228174.68499 |
| 440           | 1382.30092         | 152053.10120 | 490           | 1539.38057         | 188574.11983 | 540           | 1696.46022         | 229022.12970 |
| 441           | 1385.44251         | 152745.03706 | 491           | 1542.52216         | 189344.59551 | 541           | 1699.60181         | 229871.14521 |
| 442           | 1388.58411         | 153438.54371 | 492           | 1545.66376         | 190116.64199 | 542           | 1702.74341         | 230721.73151 |
| 443           | 1391.72570         | 154133.62116 | 493           | 1548.80535         | 190890.25926 | 543           | 1705.88500         | 231573.88861 |
| 444           | 1394.86729         | 154830.26941 | 494           | 1551.94694         | 191665.44734 | 544           | 1709.02659         | 232427.61651 |
| 445           | 1398.00889         | 155528.48846 | 495           | 1555.08854         | 192442.20621 | 545           | 1712.16819         | 233282.91521 |
| 446           | 1401.15048         | 156228.27830 | 496           | 1558.23013         | 193220.53587 | 546           | 1715.30978         | 234139.78470 |
| 447           | 1404.29207         | 156929.63893 | 497           | 1561.37172         | 194000.43633 | 547           | 1718.45137         | 234998.22498 |
| 448           | 1407.43366         | 157632.57037 | 498           | 1564.51331         | 194781.90759 | 548           | 1721.59296         | 235858.23607 |
| 449           | 1410.57526         | 158337.07260 | 499           | 1567.65491         | 195564.94965 | 549           | 1724.73456         | 236719.81795 |

## Circumferences and Areas of Circles From 550 to 699

| Dia-<br>meter | Circum-<br>ference | Area         | Dia-<br>meter | Circum-<br>ference | Area         | Dia-<br>meter | Circum-<br>ference | Area         |
|---------------|--------------------|--------------|---------------|--------------------|--------------|---------------|--------------------|--------------|
| 550           | 1727.87615         | 237582.97063 | 600           | 1884.95580         | 282743.37000 | 650           | 2042.03545         | 331830.76063 |
| 551           | 1731.01774         | 238447.69410 | 601           | 1888.09739         | 283686.63330 | 651           | 2045.17704         | 332852.56375 |
| 552           | 1734.15934         | 239313.98837 | 602           | 1891.23899         | 284631.46739 | 652           | 2048.31864         | 333875.93767 |
| 553           | 1737.30093         | 240181.85343 | 603           | 1894.38058         | 285577.87228 | 653           | 2051.46023         | 334900.88238 |
| 554           | 1740.44252         | 241051.28930 | 604           | 1897.52217         | 286525.84797 | 654           | 2054.60182         | 335927.39790 |
| 555           | 1743.58412         | 241922.29596 | 605           | 1900.66377         | 287475.39446 | 655           | 2057.74342         | 336955.84821 |
| 556           | 1746.72571         | 242794.87341 | 606           | 1903.80536         | 288426.51174 | 656           | 2060.88501         | 337985.14131 |
| 557           | 1749.86730         | 243669.02166 | 607           | 1906.94695         | 289379.19981 | 657           | 2064.02660         | 339016.36921 |
| 558           | 1753.00889         | 244544.74071 | 608           | 1910.08854         | 290333.45869 | 658           | 2067.16819         | 340049.16791 |
| 559           | 1756.15049         | 245422.03056 | 609           | 1913.23014         | 291289.28836 | 659           | 2070.30979         | 341083.53741 |
| 560           | 1759.29208         | 246300.89120 | 610           | 1916.37173         | 292246.68883 | 660           | 2073.45138         | 342119.47770 |
| 561           | 1762.43367         | 247181.32264 | 611           | 1919.51332         | 293205.66009 | 661           | 2076.59297         | 343156.98879 |
| 562           | 1765.57527         | 248063.32487 | 612           | 1922.65492         | 294166.20215 | 662           | 2079.73457         | 344196.07067 |
| 563           | 1768.71686         | 248946.89790 | 613           | 1925.79651         | 295128.31500 | 663           | 2082.87616         | 345236.72335 |
| 564           | 1771.85845         | 249832.04173 | 614           | 1928.93810         | 296091.99866 | 664           | 2086.01775         | 346278.94683 |
| 565           | 1775.00005         | 250718.75636 | 615           | 1932.07970         | 297057.25311 | 665           | 2089.15935         | 347322.74111 |
| 566           | 1778.14164         | 251607.04178 | 616           | 1935.22129         | 298024.07835 | 666           | 2092.30094         | 348368.10618 |
| 567           | 1781.28323         | 252496.89799 | 617           | 1938.36288         | 298992.47439 | 667           | 2095.44253         | 349415.04204 |
| 568           | 1784.42482         | 253388.32501 | 618           | 1941.50447         | 299962.44123 | 668           | 2098.58412         | 350463.54871 |
| 569           | 1787.56642         | 254281.32282 | 619           | 1944.64607         | 300933.97887 | 669           | 2101.72572         | 351513.62617 |
| 570           | 1790.70801         | 255175.89143 | 620           | 1947.78766         | 301907.08730 | 670           | 2104.86731         | 352565.27443 |
| 571           | 1793.84960         | 256072.03083 | 621           | 1950.92925         | 302881.76653 | 671           | 2108.00890         | 353618.49348 |
| 572           | 1796.99120         | 256969.74103 | 622           | 1954.07085         | 303858.01655 | 672           | 2111.15050         | 354673.28333 |
| 573           | 1800.13279         | 257869.02202 | 623           | 1957.21244         | 304835.83737 | 673           | 2114.29209         | 355729.64397 |
| 574           | 1803.27438         | 258769.87382 | 624           | 1960.35403         | 305815.22899 | 674           | 2117.43368         | 356787.57542 |
| 575           | 1806.41598         | 259672.29641 | 625           | 1963.49563         | 306796.19141 | 675           | 2120.57528         | 357847.07766 |
| 576           | 1809.55757         | 260576.28979 | 626           | 1966.63722         | 307778.72462 | 676           | 2123.71687         | 358908.15069 |
| 577           | 1812.69916         | 261481.85397 | 627           | 1969.77881         | 308762.82862 | 677           | 2126.85846         | 359970.79452 |
| 578           | 1815.84075         | 262388.98895 | 628           | 1972.92040         | 309748.50343 | 678           | 2130.00005         | 361035.00915 |
| 579           | 1818.98235         | 263297.69473 | 629           | 1976.06200         | 310735.74903 | 679           | 2133.14165         | 362100.79458 |
| 580           | 1822.12394         | 264207.97130 | 630           | 1979.20359         | 311724.56543 | 680           | 2136.28324         | 363168.15080 |
| 581           | 1825.26553         | 265119.81867 | 631           | 1982.34518         | 312714.95262 | 681           | 2139.42483         | 364237.07782 |
| 582           | 1828.40713         | 266033.23683 | 632           | 1985.48678         | 313706.91061 | 682           | 2142.56643         | 365307.57563 |
| 583           | 1831.54872         | 266948.22579 | 633           | 1988.62837         | 314700.43939 | 683           | 2145.70802         | 366379.64424 |
| 584           | 1834.69031         | 267864.78555 | 634           | 1991.76996         | 315695.53898 | 684           | 2148.84961         | 367453.28365 |
| 585           | 1837.83191         | 268782.91611 | 635           | 1994.91156         | 316692.20936 | 685           | 2151.99121         | 368528.49386 |
| 586           | 1840.97350         | 269702.61746 | 636           | 1998.05315         | 317690.45053 | 686           | 2155.13280         | 369605.27486 |
| 587           | 1844.11509         | 270623.88960 | 637           | 2001.19474         | 318690.26250 | 687           | 2158.27439         | 370683.62665 |
| 588           | 1847.25668         | 271546.73255 | 638           | 2004.33633         | 319691.64527 | 688           | 2161.41598         | 371763.54925 |
| 589           | 1850.39828         | 272471.14629 | 639           | 2007.47793         | 320694.59884 | 689           | 2164.55758         | 372845.04264 |
| 590           | 1853.53987         | 273397.13083 | 640           | 2010.61952         | 321699.12320 | 690           | 2167.69917         | 373928.10683 |
| 591           | 1856.68146         | 274324.68616 | 641           | 2013.76111         | 322705.21836 | 691           | 2170.84076         | 375012.74181 |
| 592           | 1859.82306         | 275253.81229 | 642           | 2016.90271         | 323712.88431 | 692           | 2173.98236         | 376098.94759 |
| 593           | 1862.96465         | 276184.50921 | 643           | 2020.04430         | 324722.12106 | 693           | 2177.12395         | 377186.72416 |
| 594           | 1866.10624         | 277116.77694 | 644           | 2023.18589         | 325732.92861 | 694           | 2180.26554         | 378276.07154 |
| 595           | 1869.24784         | 278050.61546 | 645           | 2026.32749         | 326745.30696 | 695           | 2183.40714         | 379366.98971 |
| 596           | 1872.38943         | 278986.02477 | 646           | 2029.46908         | 327759.25610 | 696           | 2186.54873         | 380459.47867 |
| 597           | 1875.53102         | 279923.00488 | 647           | 2032.61067         | 328774.77603 | 697           | 2189.69032         | 381553.53843 |
| 598           | 1878.67261         | 280861.55579 | 648           | 2035.75226         | 329791.86677 | 698           | 2192.83191         | 382649.16899 |
| 599           | 1881.81421         | 281801.67750 | 649           | 2038.89386         | 330810.52830 | 699           | 2195.97351         | 383746.37035 |



## Circumferences and Areas of Circles From 700 to 849

| Dia-<br>meter | Circum-<br>ference | Area         | Dia-<br>meter | Circum-<br>ference | Area         | Dia-<br>meter | Circum-<br>ference | Area         |
|---------------|--------------------|--------------|---------------|--------------------|--------------|---------------|--------------------|--------------|
| 700           | 2199.11510         | 384845.14250 | 750           | 2356.19475         | 441786.51563 | 800           | 2513.27440         | 502654.88000 |
| 701           | 2202.25669         | 385945.48545 | 751           | 2359.33634         | 442965.39840 | 801           | 2516.41599         | 503912.30260 |
| 702           | 2205.39829         | 387047.39919 | 752           | 2362.47794         | 444145.85197 | 802           | 2519.55759         | 505171.29599 |
| 703           | 2208.53988         | 388150.88373 | 753           | 2365.61953         | 445327.87633 | 803           | 2522.69918         | 506431.86018 |
| 704           | 2211.68147         | 389255.93907 | 754           | 2368.76112         | 446511.47150 | 804           | 2525.84077         | 507693.99517 |
| 705           | 2214.82307         | 390362.56521 | 755           | 2371.90272         | 447696.63746 | 805           | 2528.98237         | 508957.70096 |
| 706           | 2217.96466         | 391470.76214 | 756           | 2375.04431         | 448883.37421 | 806           | 2532.12396         | 510222.97754 |
| 707           | 2221.10625         | 392580.52986 | 757           | 2378.18590         | 450071.68176 | 807           | 2535.26555         | 511489.82491 |
| 708           | 2224.24784         | 393691.86839 | 758           | 2381.32749         | 451261.56011 | 808           | 2538.40714         | 512758.24309 |
| 709           | 2227.38944         | 394804.77771 | 759           | 2384.46909         | 452453.00926 | 809           | 2541.54874         | 514028.23206 |
| 710           | 2230.53103         | 395919.25783 | 760           | 2387.61068         | 453646.02920 | 810           | 2544.69033         | 515299.79183 |
| 711           | 2233.67262         | 397035.30874 | 761           | 2390.75227         | 454840.61994 | 811           | 2547.83192         | 516572.92239 |
| 712           | 2236.81422         | 398152.93045 | 762           | 2393.89387         | 456036.78147 | 812           | 2550.97352         | 517847.62375 |
| 713           | 2239.95581         | 399272.12295 | 763           | 2397.03546         | 457234.51380 | 813           | 2554.11511         | 519123.89590 |
| 714           | 2243.09740         | 400392.88626 | 764           | 2400.17705         | 458433.81693 | 814           | 2557.25670         | 520401.73886 |
| 715           | 2246.23900         | 401515.22036 | 765           | 2403.31865         | 459634.69086 | 815           | 2560.39830         | 521681.15261 |
| 716           | 2249.38059         | 402639.12525 | 766           | 2406.46024         | 460837.13558 | 816           | 2563.53989         | 522962.13715 |
| 717           | 2252.52218         | 403764.60094 | 767           | 2409.60183         | 462041.15109 | 817           | 2566.68148         | 524244.69249 |
| 718           | 2255.66377         | 404891.64743 | 768           | 2412.74342         | 463246.73741 | 818           | 2569.82307         | 525528.81863 |
| 719           | 2258.80537         | 406020.26472 | 769           | 2415.88502         | 464453.89452 | 819           | 2572.96467         | 526814.51557 |
| 720           | 2261.94696         | 407150.45280 | 770           | 2419.02661         | 465662.62243 | 820           | 2576.10626         | 528101.78330 |
| 721           | 2265.08855         | 408282.21168 | 771           | 2422.16820         | 466872.92113 | 821           | 2579.24785         | 529390.62183 |
| 722           | 2268.23015         | 409415.54135 | 772           | 2425.30980         | 468084.79063 | 822           | 2582.38945         | 530681.03115 |
| 723           | 2271.37174         | 410550.44182 | 773           | 2428.45139         | 469298.23092 | 823           | 2585.53104         | 531973.01127 |
| 724           | 2274.51333         | 411686.91309 | 774           | 2431.59298         | 470513.24202 | 824           | 2588.67263         | 533266.56219 |
| 725           | 2277.65493         | 412824.95516 | 775           | 2434.73458         | 471729.82391 | 825           | 2591.81423         | 534561.68391 |
| 726           | 2280.79652         | 413964.56802 | 776           | 2437.87617         | 472947.97659 | 826           | 2594.95582         | 535858.37642 |
| 727           | 2283.93811         | 415105.75167 | 777           | 2441.01776         | 474167.70007 | 827           | 2598.09741         | 537156.63972 |
| 728           | 2287.07970         | 416248.50613 | 778           | 2444.15935         | 475388.99435 | 828           | 2601.23900         | 538456.47383 |
| 729           | 2290.22130         | 417392.83138 | 779           | 2447.30095         | 476611.85943 | 829           | 2604.38060         | 539757.87873 |
| 730           | 2293.36289         | 418538.72743 | 780           | 2450.44254         | 477836.29530 | 830           | 2607.52219         | 541060.85443 |
| 731           | 2296.50448         | 419686.19427 | 781           | 2453.58413         | 479062.30197 | 831           | 2610.66378         | 542365.40092 |
| 732           | 2299.64608         | 420835.23191 | 782           | 2456.72573         | 480289.87943 | 832           | 2613.80538         | 543671.51821 |
| 733           | 2302.78767         | 421985.84034 | 783           | 2459.86732         | 481519.02769 | 833           | 2616.94697         | 544979.20629 |
| 734           | 2305.92926         | 423138.01958 | 784           | 2463.00891         | 482749.74675 | 834           | 2620.08856         | 546288.46518 |
| 735           | 2309.07086         | 424291.76961 | 785           | 2466.15051         | 483982.03661 | 835           | 2623.23016         | 547599.29486 |
| 736           | 2312.21245         | 425447.09043 | 786           | 2469.29210         | 485215.89726 | 836           | 2626.37175         | 548911.69533 |
| 737           | 2315.35404         | 426603.98205 | 787           | 2472.43369         | 486451.32870 | 837           | 2629.51334         | 550225.66660 |
| 738           | 2318.49563         | 427762.44447 | 788           | 2475.57528         | 487688.33095 | 838           | 2632.65493         | 551541.20867 |
| 739           | 2321.63723         | 428922.47769 | 789           | 2478.71688         | 488926.90399 | 839           | 2635.79653         | 552858.32154 |
| 740           | 2324.77882         | 430084.08170 | 790           | 2481.85847         | 490167.04783 | 840           | 2638.93812         | 554177.00520 |
| 741           | 2327.92041         | 431247.25651 | 791           | 2485.00006         | 491408.76246 | 841           | 2642.07971         | 555497.25966 |
| 742           | 2331.06201         | 432412.00211 | 792           | 2488.14166         | 492652.04789 | 842           | 2645.22131         | 556819.08491 |
| 743           | 2334.20360         | 433578.31851 | 793           | 2491.28325         | 493896.90411 | 843           | 2648.36290         | 558142.48096 |
| 744           | 2337.34519         | 434746.20571 | 794           | 2494.42484         | 495143.33114 | 844           | 2651.50449         | 559467.44781 |
| 745           | 2340.48679         | 435915.66371 | 795           | 2497.56644         | 496391.32896 | 845           | 2654.64609         | 560793.98546 |
| 746           | 2343.62838         | 437086.69250 | 796           | 2500.70803         | 497640.89757 | 846           | 2657.78768         | 562122.09390 |
| 747           | 2346.76997         | 438259.29208 | 797           | 2503.84962         | 498892.03698 | 847           | 2660.92927         | 563451.77313 |
| 748           | 2349.91156         | 439433.46247 | 798           | 2506.99121         | 500144.74719 | 848           | 2664.07086         | 564783.02317 |
| 749           | 2353.05316         | 440609.20365 | 799           | 2510.13281         | 501399.02820 | 849           | 2667.21246         | 566115.84400 |

## Circumferences and Areas of Circles From 850-999

| Diameter | Circumference | Area         | Diameter | Circumference | Area         | Diameter | Circumference | Area         |
|----------|---------------|--------------|----------|---------------|--------------|----------|---------------|--------------|
| 850      | 2670.35405    | 567450.23563 | 900      | 2827.43370    | 636172.58250 | 950      | 2984.51335    | 708821.92063 |
| 851      | 2673.49564    | 568786.19805 | 901      | 2830.57529    | 637587.08475 | 951      | 2987.65494    | 710314.96270 |
| 852      | 2676.63724    | 570123.73127 | 902      | 2833.71689    | 639003.15779 | 952      | 2990.79654    | 711809.57557 |
| 853      | 2679.77883    | 571462.83528 | 903      | 2836.85848    | 640420.80163 | 953      | 2993.93813    | 713305.75923 |
| 854      | 2682.92042    | 572803.51010 | 904      | 2840.00007    | 641840.01627 | 954      | 2997.07972    | 714803.51370 |
| 855      | 2686.06202    | 574145.75571 | 905      | 2843.14167    | 643260.80171 | 955      | 3000.22132    | 716302.83896 |
| 856      | 2689.20361    | 575489.57211 | 906      | 2846.28326    | 644683.15794 | 956      | 3003.36291    | 717803.73501 |
| 857      | 2692.34520    | 576834.95931 | 907      | 2849.42485    | 646107.08496 | 957      | 3006.50450    | 719306.20186 |
| 858      | 2695.48679    | 578181.91731 | 908      | 2852.56644    | 647532.58279 | 958      | 3009.64609    | 720810.23951 |
| 859      | 2698.62839    | 579530.44611 | 909      | 2855.70804    | 648959.65141 | 959      | 3012.78769    | 722315.84796 |
| 860      | 2701.76998    | 580880.54570 | 910      | 2858.84963    | 650388.29083 | 960      | 3015.92928    | 723823.02720 |
| 861      | 2704.91157    | 582232.21609 | 911      | 2861.99122    | 651818.50104 | 961      | 3019.07087    | 725331.77724 |
| 862      | 2708.05317    | 583585.45727 | 912      | 2865.13282    | 653250.28205 | 962      | 3022.21247    | 726842.09807 |
| 863      | 2711.19476    | 584940.26925 | 913      | 2868.27441    | 654683.63385 | 963      | 3025.35406    | 728353.98970 |
| 864      | 2714.33635    | 586296.65203 | 914      | 2871.41600    | 656118.55646 | 964      | 3028.49565    | 729867.45213 |
| 865      | 2717.47795    | 587654.60561 | 915      | 2874.55760    | 657555.04986 | 965      | 3031.63725    | 731382.48536 |
| 866      | 2720.61954    | 589014.12998 | 916      | 2877.69919    | 658993.11405 | 966      | 3034.77884    | 732899.08938 |
| 867      | 2723.76113    | 590375.22514 | 917      | 2880.84078    | 660432.74904 | 967      | 3037.92043    | 734417.26419 |
| 868      | 2726.90272    | 591737.89111 | 918      | 2883.98237    | 661873.95483 | 968      | 3041.06202    | 735937.00981 |
| 869      | 2730.04432    | 593102.12787 | 919      | 2887.12397    | 663316.73142 | 969      | 3044.20362    | 737458.32622 |
| 870      | 2733.18591    | 594467.93543 | 920      | 2890.26556    | 664761.07880 | 970      | 3047.34521    | 738981.21343 |
| 871      | 2736.32750    | 595835.31378 | 921      | 2893.40715    | 666206.99698 | 971      | 3050.48680    | 740505.67143 |
| 872      | 2739.46910    | 597204.26293 | 922      | 2896.54875    | 667654.48595 | 972      | 3053.62840    | 742031.70023 |
| 873      | 2742.61069    | 598574.78287 | 923      | 2899.69034    | 669103.54572 | 973      | 3056.76999    | 743559.29982 |
| 874      | 2745.75228    | 599946.87362 | 924      | 2902.83193    | 670554.17629 | 974      | 3059.91158    | 745088.47022 |
| 875      | 2748.89388    | 601320.53516 | 925      | 2905.97353    | 672006.37766 | 975      | 3063.05318    | 746619.21141 |
| 876      | 2752.03547    | 602695.76749 | 926      | 2909.11512    | 673460.14982 | 976      | 3066.19477    | 748151.52339 |
| 877      | 2755.17706    | 604072.57062 | 927      | 2912.25671    | 674915.49277 | 977      | 3069.33636    | 749685.40617 |
| 878      | 2758.31865    | 605450.94455 | 928      | 2915.39830    | 676372.40653 | 978      | 3072.47795    | 751220.85975 |
| 879      | 2761.46025    | 606830.88928 | 929      | 2918.53990    | 677830.89108 | 979      | 3075.61955    | 752757.88413 |
| 880      | 2764.60184    | 608212.40480 | 930      | 2921.68149    | 679290.94643 | 980      | 3078.76114    | 754296.47930 |
| 881      | 2767.74343    | 609595.49112 | 931      | 2924.82308    | 680752.57257 | 981      | 3081.90273    | 755836.64527 |
| 882      | 2770.88503    | 610980.14823 | 932      | 2927.96468    | 682215.76951 | 982      | 3085.04433    | 757378.38203 |
| 883      | 2774.02662    | 612366.37614 | 933      | 2931.10627    | 683680.53724 | 983      | 3088.18592    | 758921.68959 |
| 884      | 2777.16821    | 613754.17485 | 934      | 2934.24786    | 685146.87578 | 984      | 3091.32751    | 760466.56795 |
| 885      | 2780.30981    | 615143.54436 | 935      | 2937.38946    | 686614.78511 | 985      | 3094.46911    | 762013.01711 |
| 886      | 2783.45140    | 616534.48466 | 936      | 2940.53105    | 688084.26523 | 986      | 3097.61070    | 763561.03706 |
| 887      | 2786.59299    | 617926.99575 | 937      | 2943.67264    | 689555.31615 | 987      | 3100.75229    | 765110.62780 |
| 888      | 2789.73458    | 619321.07765 | 938      | 2946.81423    | 691027.93787 | 988      | 3103.89388    | 766661.78935 |
| 889      | 2792.87618    | 620716.73034 | 939      | 2949.95583    | 692502.13039 | 989      | 3107.03548    | 768214.52169 |
| 890      | 2796.01777    | 622113.95383 | 940      | 2953.09742    | 693977.89370 | 990      | 3110.17707    | 769768.82483 |
| 891      | 2799.15936    | 623512.74811 | 941      | 2956.23901    | 695455.22781 | 991      | 3113.31866    | 771324.69876 |
| 892      | 2802.30096    | 624913.11319 | 942      | 2959.38061    | 696934.13271 | 992      | 3116.46026    | 772882.14349 |
| 893      | 2805.44255    | 626315.04906 | 943      | 2962.52220    | 698414.60841 | 993      | 3119.60185    | 774441.15901 |
| 894      | 2808.58414    | 627718.55574 | 944      | 2965.66379    | 699896.65491 | 994      | 3122.74344    | 776001.74534 |
| 895      | 2811.72574    | 629123.63321 | 945      | 2968.80539    | 701380.27221 | 995      | 3125.88504    | 777563.90246 |
| 896      | 2814.86733    | 630530.28147 | 946      | 2971.94698    | 702865.46030 | 996      | 3129.02663    | 779127.63037 |
| 897      | 2818.00892    | 631938.50053 | 947      | 2975.08857    | 704352.21918 | 997      | 3132.16822    | 780692.92908 |
| 898      | 2821.15051    | 633348.29039 | 948      | 2978.23016    | 705840.54887 | 998      | 3135.30981    | 782259.79859 |
| 899      | 2824.29211    | 634759.65105 | 949      | 2981.37176    | 707330.44935 | 999      | 3138.45141    | 783828.23890 |

**Table of Decimal Equivalents, Squares, Cubes, Square Roots,  
Cube Roots, and Logarithms of Fractions from  $\frac{1}{64}$  to 1, by 64ths**

| Fraction        | Decimal  | Log      | Square  | Log      | Cube    | Log      | Sq. Root | Log      | Cube Root | Log      |
|-----------------|----------|----------|---------|----------|---------|----------|----------|----------|-----------|----------|
| $\frac{1}{64}$  | 0.015625 | -1.80618 | 0.00024 | -3.61236 | 0.00000 | -5.41854 | 0.12500  | -0.90309 | 0.25000   | -0.60206 |
| $\frac{1}{32}$  | 0.031250 | -1.50515 | 0.00098 | -3.01030 | 0.00003 | -4.51545 | 0.17678  | -0.75257 | 0.31498   | -0.50172 |
| $\frac{3}{64}$  | 0.046875 | -1.32906 | 0.00220 | -2.65812 | 0.00010 | -3.98718 | 0.21651  | -0.66453 | 0.36056   | -0.44302 |
| $\frac{1}{16}$  | 0.062500 | -1.20412 | 0.00391 | -2.40824 | 0.00024 | -3.61236 | 0.25000  | -0.60206 | 0.39685   | -0.40137 |
| $\frac{5}{64}$  | 0.078125 | -1.10721 | 0.00610 | -2.21442 | 0.00048 | -3.32163 | 0.27951  | -0.55361 | 0.42749   | -0.36907 |
| $\frac{3}{32}$  | 0.093750 | -1.02803 | 0.00879 | -2.05606 | 0.00082 | -3.08409 | 0.30619  | -0.51402 | 0.45428   | -0.34268 |
| $\frac{7}{64}$  | 0.109375 | -0.96108 | 0.01196 | -1.92216 | 0.00131 | -2.88325 | 0.33072  | -0.48054 | 0.47823   | -0.32036 |
| $\frac{1}{8}$   | 0.125000 | -0.90309 | 0.01563 | -1.80618 | 0.00195 | -2.70927 | 0.35355  | -0.45155 | 0.50000   | -0.30103 |
| $\frac{9}{64}$  | 0.140625 | -0.85194 | 0.01978 | -1.70388 | 0.00278 | -2.55581 | 0.37500  | -0.42597 | 0.52002   | -0.28398 |
| $\frac{5}{32}$  | 0.156250 | -0.80618 | 0.02441 | -1.61236 | 0.00381 | -2.41854 | 0.39529  | -0.40309 | 0.53861   | -0.26873 |
| $\frac{11}{64}$ | 0.171875 | -0.76479 | 0.02954 | -1.52958 | 0.00508 | -2.29436 | 0.41458  | -0.38239 | 0.55600   | -0.25493 |
| $\frac{3}{16}$  | 0.187500 | -0.72700 | 0.03516 | -1.45400 | 0.00659 | -2.18100 | 0.43301  | -0.36350 | 0.57236   | -0.24233 |
| $\frac{13}{64}$ | 0.203125 | -0.69224 | 0.04126 | -1.38447 | 0.00838 | -2.07671 | 0.45069  | -0.34612 | 0.58783   | -0.23075 |
| $\frac{7}{32}$  | 0.218750 | -0.66005 | 0.04785 | -1.32010 | 0.01047 | -1.98016 | 0.46771  | -0.33003 | 0.60254   | -0.22002 |
| $\frac{15}{64}$ | 0.234375 | -0.63009 | 0.05493 | -1.26018 | 0.01287 | -1.89027 | 0.48412  | -0.31504 | 0.61655   | -0.21003 |
| $\frac{1}{4}$   | 0.250000 | -0.60206 | 0.06250 | -1.20412 | 0.01563 | -1.80618 | 0.50000  | -0.30103 | 0.62996   | -0.20069 |
| $\frac{17}{64}$ | 0.265625 | -0.57573 | 0.07056 | -1.15146 | 0.01874 | -1.72719 | 0.51539  | -0.28787 | 0.64282   | -0.19191 |
| $\frac{9}{32}$  | 0.281250 | -0.55091 | 0.07910 | -1.10182 | 0.02225 | -1.65272 | 0.53033  | -0.27545 | 0.65519   | -0.18364 |
| $\frac{19}{64}$ | 0.296875 | -0.52743 | 0.08813 | -1.05485 | 0.02617 | -1.58228 | 0.54486  | -0.26371 | 0.66710   | -0.17581 |
| $\frac{5}{16}$  | 0.312500 | -0.50515 | 0.09766 | -1.01030 | 0.03052 | -1.51545 | 0.55902  | -0.25258 | 0.67860   | -0.16838 |
| $\frac{21}{64}$ | 0.328125 | -0.48396 | 0.10767 | -0.96792 | 0.03533 | -1.45188 | 0.57282  | -0.24198 | 0.68973   | -0.16132 |
| $\frac{11}{32}$ | 0.343750 | -0.46376 | 0.11816 | -0.92752 | 0.04062 | -1.39127 | 0.58630  | -0.23188 | 0.70051   | -0.15459 |
| $\frac{23}{64}$ | 0.359375 | -0.44445 | 0.12915 | -0.88890 | 0.04641 | -1.33336 | 0.59948  | -0.22223 | 0.71097   | -0.14815 |
| $\frac{3}{8}$   | 0.375000 | -0.42597 | 0.14063 | -0.85194 | 0.05273 | -1.27791 | 0.61237  | -0.21299 | 0.72113   | -0.14199 |
| $\frac{25}{64}$ | 0.390625 | -0.40824 | 0.15259 | -0.81648 | 0.05960 | -1.22472 | 0.62500  | -0.20412 | 0.73100   | -0.13608 |
| $\frac{13}{32}$ | 0.406250 | -0.39121 | 0.16504 | -0.78241 | 0.06705 | -1.17362 | 0.63738  | -0.19560 | 0.74062   | -0.13040 |
| $\frac{27}{64}$ | 0.421875 | -0.37482 | 0.17798 | -0.74963 | 0.07508 | -1.12445 | 0.64952  | -0.18741 | 0.75000   | -0.12494 |
| $\frac{7}{16}$  | 0.437500 | -0.35902 | 0.19141 | -0.71804 | 0.08374 | -1.07707 | 0.66144  | -0.17951 | 0.75915   | -0.11967 |
| $\frac{29}{64}$ | 0.453125 | -0.34378 | 0.20532 | -0.68756 | 0.09304 | -1.03135 | 0.67315  | -0.17189 | 0.76808   | -0.11459 |
| $\frac{15}{32}$ | 0.468750 | -0.32906 | 0.21973 | -0.65812 | 0.10300 | -0.98718 | 0.68465  | -0.16453 | 0.77681   | -0.10969 |
| $\frac{31}{64}$ | 0.484375 | -0.31482 | 0.23462 | -0.62964 | 0.11364 | -0.94446 | 0.69597  | -0.15741 | 0.78535   | -0.10494 |
| $\frac{1}{2}$   | 0.500000 | -0.30103 | 0.25000 | -0.60206 | 0.12500 | -0.90309 | 0.70711  | -0.15052 | 0.79370   | -0.10034 |
| $\frac{33}{64}$ | 0.515625 | -0.28767 | 0.26587 | -0.57533 | 0.13709 | -0.86300 | 0.71807  | -0.14383 | 0.80188   | -0.09589 |
| $\frac{17}{32}$ | 0.531250 | -0.27470 | 0.28223 | -0.54940 | 0.14993 | -0.82410 | 0.72887  | -0.13735 | 0.80990   | -0.09157 |
| $\frac{35}{64}$ | 0.546875 | -0.26211 | 0.29907 | -0.52422 | 0.16356 | -0.78634 | 0.73951  | -0.13106 | 0.81777   | -0.08737 |
| $\frac{9}{16}$  | 0.562500 | -0.24988 | 0.31641 | -0.49976 | 0.17798 | -0.74963 | 0.75000  | -0.12494 | 0.82548   | -0.08329 |
| $\frac{37}{64}$ | 0.578125 | -0.23798 | 0.33423 | -0.47596 | 0.19323 | -0.71394 | 0.76035  | -0.11899 | 0.83306   | -0.07933 |
| $\frac{19}{32}$ | 0.593750 | -0.22640 | 0.35254 | -0.45279 | 0.20932 | -0.67919 | 0.77055  | -0.11320 | 0.84049   | -0.07547 |
| $\frac{41}{64}$ | 0.609375 | -0.21512 | 0.37134 | -0.43023 | 0.22628 | -0.64535 | 0.78063  | -0.10756 | 0.84780   | -0.07171 |
| $\frac{5}{8}$   | 0.625000 | -0.20412 | 0.39063 | -0.40824 | 0.24414 | -0.61236 | 0.79057  | -0.10206 | 0.85499   | -0.06804 |
| $\frac{43}{64}$ | 0.640625 | -0.19340 | 0.41040 | -0.38679 | 0.26291 | -0.58019 | 0.80039  | -0.09670 | 0.86205   | -0.06447 |
| $\frac{21}{32}$ | 0.656250 | -0.18293 | 0.43066 | -0.36586 | 0.28262 | -0.54879 | 0.81009  | -0.09147 | 0.86901   | -0.06098 |
| $\frac{45}{64}$ | 0.671875 | -0.17271 | 0.45142 | -0.34542 | 0.30330 | -0.51814 | 0.81968  | -0.08636 | 0.87585   | -0.05757 |
| $\frac{11}{16}$ | 0.687500 | -0.16273 | 0.47266 | -0.32546 | 0.32495 | -0.48818 | 0.82916  | -0.08136 | 0.88259   | -0.05424 |
| $\frac{47}{64}$ | 0.703125 | -0.15297 | 0.49438 | -0.30594 | 0.34761 | -0.45890 | 0.83853  | -0.07648 | 0.88922   | -0.05099 |
| $\frac{23}{32}$ | 0.718750 | -0.14342 | 0.51660 | -0.28684 | 0.37131 | -0.43027 | 0.84779  | -0.07171 | 0.89576   | -0.04781 |
| $\frac{49}{64}$ | 0.734375 | -0.13408 | 0.53931 | -0.26816 | 0.39605 | -0.40225 | 0.85696  | -0.06704 | 0.90221   | -0.04469 |
| $\frac{3}{4}$   | 0.750000 | -0.12494 | 0.56250 | -0.24988 | 0.42188 | -0.37482 | 0.86603  | -0.06247 | 0.90856   | -0.04165 |
| $\frac{51}{64}$ | 0.765625 | -0.11598 | 0.58618 | -0.23197 | 0.44880 | -0.34795 | 0.87500  | -0.05799 | 0.91483   | -0.03866 |
| $\frac{25}{32}$ | 0.781250 | -0.10721 | 0.61035 | -0.21442 | 0.47684 | -0.32163 | 0.88388  | -0.05361 | 0.92101   | -0.03574 |
| $\frac{53}{64}$ | 0.796875 | -0.09861 | 0.63501 | -0.19722 | 0.50602 | -0.29583 | 0.89268  | -0.04931 | 0.92711   | -0.03287 |
| $\frac{13}{16}$ | 0.812500 | -0.09018 | 0.66016 | -0.18035 | 0.53638 | -0.27053 | 0.90139  | -0.04509 | 0.93313   | -0.03006 |
| $\frac{55}{64}$ | 0.828125 | -0.08190 | 0.68579 | -0.16381 | 0.56792 | -0.24571 | 0.91001  | -0.04095 | 0.93907   | -0.02730 |
| $\frac{27}{32}$ | 0.843750 | -0.07379 | 0.71191 | -0.14757 | 0.60068 | -0.22136 | 0.91856  | -0.03689 | 0.94494   | -0.02460 |
| $\frac{57}{64}$ | 0.859375 | -0.06582 | 0.73853 | -0.13164 | 0.63467 | -0.19745 | 0.92703  | -0.03291 | 0.95074   | -0.02194 |
| $\frac{31}{16}$ | 0.875000 | -0.05799 | 0.76563 | -0.11598 | 0.66992 | -0.17398 | 0.93541  | -0.02900 | 0.95647   | -0.01933 |
| $\frac{59}{64}$ | 0.890625 | -0.05031 | 0.79321 | -0.10061 | 0.70646 | -0.15092 | 0.94373  | -0.02515 | 0.96213   | -0.01677 |
| $\frac{33}{16}$ | 0.906250 | -0.04275 | 0.82129 | -0.08550 | 0.74429 | -0.12826 | 0.95197  | -0.02138 | 0.96772   | -0.01425 |
| $\frac{61}{64}$ | 0.921875 | -0.03533 | 0.84985 | -0.07066 | 0.78346 | -0.10598 | 0.96014  | -0.01766 | 0.97325   | -0.01178 |
| $\frac{15}{8}$  | 0.937500 | -0.02803 | 0.87891 | -0.05606 | 0.82397 | -0.08409 | 0.96825  | -0.01401 | 0.97872   | -0.00934 |
| $\frac{63}{64}$ | 0.953125 | -0.02085 | 0.90845 | -0.04170 | 0.86586 | -0.06255 | 0.97628  | -0.01043 | 0.98412   | -0.00695 |
| $\frac{35}{16}$ | 0.968750 | -0.01379 | 0.93848 | -0.02758 | 0.90915 | -0.04137 | 0.98425  | -0.00689 | 0.98947   | -0.00460 |
| $\frac{65}{64}$ | 0.984375 | -0.00684 | 0.96899 | -0.01368 | 0.95385 | -0.02052 | 0.99216  | -0.00342 | 0.99476   | -0.00228 |
| 1               | 1.000000 | 0.00000  | 1.00000 | 0.00000  | 1.00000 | 0.00000  | 1.00000  | 0.00000  | 1.00000   | 0.00000  |

**CEMENT, CONCRETE, LUTES, ADHESIVES, AND SEALANTS****Cement**

The cements used in concrete construction are classified as:

- 1) Portland cements.
- 2) Natural cements.
- 3) Pozzuolanic, pozzuolan, or slag cements.

These different classes are all hydraulic cements as they will set or harden under water. When the powdered cement is mixed with water to a plastic condition, the cement sets or solidifies as the result of chemical action. After the preliminary hardening or initial set, the cement slowly increases in strength, the increase extending over months or years.

**Portland Cement.**— Portland and natural cements are the kinds most commonly used. Portland cement should be used for all structures which must withstand stresses and for masonry that is either under water or heavily exposed to water or the weather. According to the specifications of the American Society for Testing Materials, the specific gravity of Portland cement must be not less than 8:1. If the tested cement is below this requirement. A second test should be made on a sample ignited at a low red heat. The ignited cement should not lose more than four per cent of its weight. A satisfactory Portland cement must not develop initial set in less than 30 minutes; it must not develop hard set in less than 1 hour; but the time required for developing hard set must not exceed 10 hours. The minimum requirements for tensile strength in pounds, for briquettes one square inch in cross-section, should be as follows:

For cement 24 hours old in moist air, 175 pounds.

For cement 7 days old, one day in moist air and six days in water, 500 pounds.

For cement 28 days old, one day in moist air and 27 days in water, 600 pounds.

For one part of cement and three parts of standard Ottawa sand, 7 days old, one day in moist air and six days in water, 200 pounds.

For one part of cement and three parts of standard Ottawa sand, 28 days old, one day in moist air and 27 days in water, 275 pounds.

The cements must under no circumstances show a decrease in strength during the time periods specified.

**Natural Cement.**— Natural cement is used in mortar for ordinary brick work and stone masonry, street sub-pavements, as a backing or filling for massive concrete or stone masonry, and for similar purposes. Natural cement does not develop its strength as quickly and is not as uniform in composition as Portland cement. It should not be used for columns, beams, floors or any structural members which must withstand considerable stress. Natural cement is also unsuitable for work that is exposed to water. Foundations which are subjected to moderate compressive stresses may be made of natural cement, which is also satisfactory for massive masonry where weight rather than strength is the essential feature.

The American Society for Testing Materials gives the following specifications for natural cement: An initial set must not develop in less than 10 minutes, and the hard set must not develop in less than 30 minutes, but must develop in less than three hours. The minimum requirements for tensile strength in pounds, for briquettes one inch in cross-section, are as follows:

For natural cement 24 hours old in moist air, 75 pounds.

For natural cement 7 days old, one day in moist air and six days in water, 150 pounds.

For natural cement 28 days old, one day in moist air and 27 days in water, 250 pounds.

For one part of cement and three parts of standard Ottawa sand, 7 days old, one day in moist air and six days in water, 50 pounds.

For one part of cement and three parts of standard Ottawa sand, 28 days old, one day in moist air and 27 days in water, 125 pounds.

**Pozzolan or Slag Cement.**—This cement is adapted for structures which are constantly exposed to fresh or salt water and for drains, sewers, foundation work underground, etc. It is not suitable where masonry is exposed to dry air for long periods. Pozzolan cement sets slowly but its strength increases considerably with age. While this cement is relatively cheap, it is not as strong, uniform, or reliable as Portland and natural cements, and is not used extensively.

### Concrete

**Concrete.**—The principal ingredients of concrete are the matrix or mortar and the “coarse aggregate.” The matrix consists of cement and sand mixed with water, and the coarse aggregate is usually broken stone or gravel. What is known as *rubble concrete* or cyclopean masonry contains large stones which are used for reducing the cost of massive dams and walls. These rubble stones may vary from a few per cent to over one-half the volume. When concrete without much strength but light in weight is required, cinders may be used. This cinder concrete is porous and is used for light floor construction or fire-proofing.

**Concrete Mixtures.**—In the mixing of concrete, it is desirable to use as little cement as is consistent with the required strength, because the cement is much more expensive than the other ingredients. The proportioning of the ingredients is usually by volume and mixtures are generally designated by giving the amount of each ingredient in a fixed order, as 1 : 2 : 5, the first figure indicating the amount of cement by volume, the second the amount of sand, and the third the amount of broken stone or gravel.

For ordinary machine foundations, retaining walls, bridge abutments, and piers exposed to the air, a 1 : 2½ : 5 concrete is satisfactory; and for ordinary foundations, heavy walls, etc., a lean mixture of 1 : 3 : 6 may be used. For reinforced floors, beams, columns, and arches, as well as for machine foundations which are subjected to vibration, a 1 : 2 : 4 concrete is generally used. This composition is also employed when concrete is used under water. For water tanks and similar structures subjected to considerable pressure and required to be water-tight, mixtures rich in cement and composed of either 1 : 1 : 2 or 1 : 1½ : 3 concrete are used. Portland cement should preferably be used in concrete construction.

**Sand, Gravel, and Stone for Concrete.**—The sand used must be free from dust, loam, vegetable, or other organic matter; it should pass, when dry, through a screen with holes of ¼-inch mesh. The gravel should consist of clean pebbles free from foreign matter and should be of such coarseness that it will not pass through a screen of ¼-inch mesh. Gravel containing loam or clay should be washed by a hose before mixing. The broken stone should be of a hard and durable kind, such as granite or limestone. This stone should pass through a 2½-inch screen.

**Amount of Water for Mixing Concrete.**—The amount of water required to combine chemically with cement is about 16 per cent by weight, but in mixing concrete a greater amount than this must be used, because of losses and the difficulty of uniformly distributing the water. In hot weather more water is required than in cool weather because of the loss due to evaporation. The same applies when absorbent sand is used, or when the concrete is not rammed tightly. An excess of water is not desirable, because this excess will flow away and carry some of the cement with it. The water must be free from oils, acids, and impurities that would prevent a proper chemical combination with the cement. It is important to mix the ingredients thoroughly. Lime cement, sand and stone should be mixed while dry, preferably using a machine. Enough water should then be added to produce a mixture which will flow readily and fill different parts of the form.

**Reinforced Concrete.**—Concrete reinforced with steel is widely used, especially where the concrete must resist tensile as well as compressive stresses. This reinforcement may be in the form of round bars twisted square bars, corrugated bars, expanded metal, steel mesh, or wire fabric. The proportions for reinforced concrete structures are usually 1 : 2 : 4, or 1

barrel of portland cement, 2 barrels of sand, and 4 barrels of broken stone or gravel. The lateral spacing between reinforcement bars should not be less than three times the bar diameter from center to center, with a clear space between the bars of at least one inch. The distance from the side of a beam to the center of the nearest bar should be not less than two diameters.

**Strength of Concrete.**—The strength varies greatly depending upon the quality and proportions of the ingredients and the care in mixing and depositing in the forms. The compressive strength of concrete which, after having been mixed and laid, has set 28 days, varies from 1000 to 3300 pounds per square inch, according to the mixture used. If made in the proportion 1 : 3 : 6, using soft limestone and sandstone a compressive strength of only 1000 pounds per square inch may be expected, whereas a mixture of 1 : 1 : 2, made with soft limestone and sandstone, will show a strength of 2200 pounds per square inch. A mixture of 1 : 3 : 6, made from granite or trap rock, will have a compressive strength of 1400 pounds per square inch, while a mixture of 1 : 1 : 2, made from granite or trap rock, will have a strength of 3300 pounds per square inch. Other mixtures will have values between those given. The richer in cement in proportion to sand, gravel, and stone, the stronger will be the concrete. The strongest concretes are also obtained by using granite or trap rock. A medium strength is obtained by using gravel, hard limestone, or hard sandstone, whereas the least strength is obtained by using soft limestone or sandstone. Concrete may also be mixed with cinders, but, in this case, very inferior strength is obtained; the richest mixtures will only give a strength of about 800 pounds per square inch.

**Durability of Concrete in Sea Water.**—Experiments have been made to determine the durability of different mixtures of concrete when exposed to sea water. It has been found that the mixtures that give the best results are those that are richest in cement. Mixtures of 1 : 1 : 2, for example, will give much better results than mixtures of 1 : 3 : 6. Also, very wet mixtures seem to give better results than those that are comparatively dry when deposited. It has also been found that, in order to insure the permanence of Portland cement concrete in sea water, the cement must contain as little lime and alumina as possible and must also be free from sulfates, and the proportion of sand and stones in the concrete must be such that the structure is practically non-porous. Natural cement should never be used for concrete exposed to sea water.

**Waterproofing Concrete.**—Several formulas for making concrete waterproof have been successfully used but some of them are too expensive for general application. One of the simplest, cheapest, and most effective is that developed by the U.S. Geological Survey. A heavy residual mineral oil of 0.93 specific gravity, mixed with Portland cement, makes it waterproof and does not weaken when the concrete consists of, say, cement, 1 part, sand, 3 parts, and oil, not more than 10 per cent, by weight, of the cement. Concrete mixed with oil requires about fifty per cent longer time to set hard, and the compressive strength is slightly decreased but not seriously. The bond or grip of oil concrete on steel is much decreased when plain bars are used, but formed bars, wire mesh, or expanded metal act as effectively in it as in ordinary concrete.

**Resistance to Acids and Oils.**—Concrete of a good quality, that has thoroughly hardened, resists the action of acids and mineral oils as well as other building materials, but vegetable oils containing fatty acids produce injurious effects by combining with the lime in the cement and causing disintegration of the concrete.

### Lutes and Cements

Luting and cementing materials for various purposes in the laboratory and shops may be classified as follows: water- and steam-proof; oil-proof; acid-proof; proof to hydrocarbon gases; chlorine-proof; elastic; general purposes; marine glue; gaskets; machinists; leather (belting); crucible; iron; and stone.

**Water-proof Compositions.**—The asphalt fluid coatings for reservoir wall, concrete foundations, brick, wood, etc., are often of use to engineers. Asphalt only partly dissolves in petroleum naphtha, but when heated in a steam-jacketed kettle and not thinned out too much, a mixture of the two may be obtained in which the part of the asphalt not dissolved is held in suspension. Asphalt is entirely soluble in benzol or toluol, which are about the cheapest solvents for all the constituents of asphalt. Tar and pitch are sometimes used in this connection, but tar contains water, light oils and free carbon, and does not wear as well as good refined asphalt; pitch also contains free carbon, which is sometimes objectionable when it is thinned out with a solvent. Asphalt alone is somewhat pervious to water, but it can be improved in this respect by adding about one-fourth its weight of paraffin; it is also well to add a little boiled linseed oil. For thicker compositions, where body is required, asbestos, stone powder, cement, etc., may be added as fillers. Lutes of linseed oil thickened with clay, asbestos, red or white lead, etc., are waterproof if made thick enough. These are much used for steam joints. Flaxseed meal made into a paste with water is often serviceable, the oil contained serving as a binder as the water evaporates.

**Oil-proof Cements.**—The well-known “hektograph composition” is the most useful lute for small leaks, etc. It consists of the following ingredients: Good glue or gelatin, 2 parts; glycerin, 1 part; water, 7 parts. This preparation is applied warm and stiffens quickly on cooling. Another very useful composition is a stiff paste of molasses and flour. Another preparation, impervious to oil vapors, is the “flaxseed poultice,” mentioned in the preceding paragraph, which is proof to oil vapors. One of the strongest cements, and one which is really oil-proof, waterproof and acid-proof, is a stiff paste of glycerin and litharge. These form a chemical combination which sets in a few minutes. If a little water is added, it sets more slowly, which is often an advantage. This cement is mixed when required for use. A mixture of plaster-of-paris and water is useful, and it is sometimes advantageous to mix straw or hair with it. A solution of silicate of soda made into a stiff paste with carbonate of lime gets hard in six to eight hours.

**Acid-proof Cements.**—The asphalt compositions already mentioned, compositions of melted sulphur with fillers of stone powder, cement, sand, etc., may be used, and also the following, which withstands hydrochloric acid vapors: rosin, 1 part; sulphur, 1 part; fireclay, 2 parts. The lute composed of boiled linseed oil and fireclay acts well with most acid vapors. The composition of glycerin and litharge previously referred to is useful in this connection, especially when made up according to the following formula: Litharge, 80 pounds; red lead, 8 pounds; “flock” asbestos, 10 pounds. It should be fed into a mixer, a little at a time, with small quantities of boiled oil (about six quarts of oil being used). Sockets in 3-inch pipes carrying nitric acid, calked with this preparation, showed no leaks in nine months.

A particularly useful cement for withstanding acid vapors, which is tough and elastic, is composed of crude rubber, cut fine, 1 part; linseed oil, boiled, 4 parts; fireclay, 6 parts. The rubber is dissolved in carbon disulphide to the consistency of molasses and is then mixed with the oil. Other acid-proof cements are as follows: “Black putty” made by carefully mixing equal portions of china-clay, gas-tar and linseed oil. The china-clay must be well dried by placing it over a boiler or by other means. Barytes cement is composed of pure, finely ground sulfate of barium, and is made into a putty with a solution of silicate of soda. This sets very hard when moderately heated, and is then proof against acids. The gravity of the silicate of soda should be between 1.2 and 1.4, 24 degrees to 42 degrees Baume. If too thin, it does not hold; and when thicker than 1.4, it expands and breaks.

**Gasket Compositions.**—Almost any cementing substance may be used with rings of asbestos, etc., for gaskets, but some are especially adapted for the purpose. Asphalt, tar, petroleum residuum and soft or hard pitch are recommended. Silicate of soda is much used, and is sometimes advantageously mixed with casein, fine sand, clay, carbonate of lime, caustic lime, magnesia, oxides of heavy metals, such as lead, zinc, iron and powdered

barytes. A few mixtures that might be selected are: Silicate of soda and asbestos; silicate of soda, asbestos and slaked lime; silicate of soda and fine sand; silicate of soda and fireclay.

**Machinists Cements.**—These are also known as red and white leads. The red lead is often diluted with an equal bulk of silica or other inert substance to make it less powdery. The best way to do this is to add rubber or gutta-percha to the oil as follows: Linseed oil, 6 parts, by weight; rubber or gutta-percha, 1 part by weight. The rubber or gutta-percha is dissolved in sufficient carbon disulphide to give it the consistency of molasses, mixed with the oil, and left exposed to the air for about twenty-four hours. The red lead is then mixed to a putty. Oxide of iron makes a less brittle cement than red lead.

**Leather Cements.**—a) Equal parts of good hide glue and American isinglass, softened in water for ten hours and then boiled with pure tannin until the whole mass is sticky. The surface of the joint should be roughened and the cement applied hot.

b) 1 pound of finely shredded gutta-percha digested over a water-bath with 10 pounds of benzol, until dissolved, and 12 pounds of linseed oil varnish stirred in.

c) 7  $\frac{1}{2}$  pounds of finely shredded india-rubber is completely dissolved in 10 pounds of carbon disulphide by treating while hot; 1 pound of shellac and 1 pound of turpentine are added, and the hot solution heated until the two latter ingredients are also dissolved.

d) another leather cement is as follows: gutta-percha, 8 ounces; pitch, 1 ounce; shellac, 1 ounce; sweet oil, 1 ounce. These are melted together.

e) still another is as follows: fish glue is soaked in water twenty-four hours, allowed to drain for a like period, boiled well, and a previously melted mixture of 2 ounces of rosin and  $\frac{1}{2}$  ounce of boiled oil is added to every two pounds of glue solution.

**Iron and Stone Cements.**—When finely divided iron, such as filings or cast iron borings that have been powdered, is mixed with an oxidizing agent, such as manganese dioxide, or a substance electro-negative to iron, such as sulphur, in a good conducting solution like salt or sal-ammoniac, galvanic action sets in very rapidly and the iron swells, by forming iron oxide, and cements the mass together. It is best diluted with Portland cement, the proportions being as follows: iron filings, 40 parts; manganese dioxide or flowers of sulphur, 10 parts; sal-ammoniac, 1 part; Portland cement, 23 to 40 parts; water to form a paste. A hard stone-like composition is made as follows: zinc oxide, 2 parts; zinc chloride, 1 part; water to make a paste. Magnesium oxide and chloride may also be used in like proportions. When used in considerable quantity, this cement is mixed with powdered stone, for reasons of economy, the proportions depending upon the character of the work.

**Cement Proof to Hydrocarbon Gases.**—Compositions of plaster and cement, the former setting more quickly, are used; also compositions of casein, such as finely powdered casein, 2 parts; fresh slaked lime, 50 parts; fine sand, 50 parts. Water is added, when used, to form a thick mass. Various mixtures of silicate of soda are employed in which the thick silicate is absorbed in some inert material such as clay, sand or asbestos.

**Cements Proof to Chlorine.**—The best and only reliable compositions are a few made with Portland cement, and the following is used for electrolytic and chemical plants: powdered glass, 1 part; Portland cement, 1 part; silicate of soda, 1 part; a small amount of powdered slate. This lute withstands acids and alkalies, as well as the influences of chlorine. Linseed oil made into a paste with fireclay serves for a time.

**Elastic Cements.**—The various cements containing rubber are elastic, if the rubber is in a predominating amount; many containing boiled linseed oil and the hektograph composition already mentioned are quite elastic. The rubber and linseed-oil cement, given in *Acid-proof Cements* on page 2906, is very tough and useful for nearly all purposes except when oil vapors are to be confined. The most useful single rubber lute is probably the so-called Hart's india-rubber cement. Equal parts of raw linseed oil and pure masticated rubber are digested together by heating, and this mixture is made into a stiff putty with fine "paper stock" asbestos. It is more convenient, however, to dissolve the rubber first in carbon disulphide, and, after mixing the oil with it, to let the solvent evaporate spontaneously.



**General Purposes.**—Plaster-of-paris, especially when mixed with straw, flush trimmings, hair, broken stone, etc., and used according to temperature strain and other conditions, is one of the most useful preparations for general purposes. A putty of flour and molasses is a good composition to keep in a works ready for quick application when needed. It serves, for a time, almost any purpose at moderate temperatures. Casein compositions have great strength. the white of an egg made into a paste with slaked lime is strong and efficient, but must be used promptly on account of its quick setting qualities.

**Marine Glue.**—This can be purchased almost as cheaply as made. It consists of crude rubber, 1 part; shellac, 2 parts; pitch, 3 parts. The rubber must first be dissolved in carbon disulphide or turpentine before mixing with the heated combination of the other two ingredients.

**Acid-proof Lining.**—A lining for protecting tanks from the influence of acids is made from a mixture consisting of 75 parts (by weight), of pitch; 9 parts plaster-of-paris; 9 parts ochre; 15 parts beeswax; and 3 parts litharge. The tanks are covered on the inside with a thick coat of this mixture.

**Cements for Pipe Joints.**—A strong cement which is oil-proof, waterproof, and acid-proof, consists of a stiff paste of glycerin and litharge. These form a chemical combination which sets in a few minutes. If a little water is added, it sets more slowly, which is often an advantage. This cement is mixed when required for use.

*Mixture for Threaded Pipe Joints:* A good material to apply to pipe threads before making up the joints, in order to obtain a tight joint that will resist the action of gases or liquids, is made of red lead mixed with pure boiled linseed oil. This mixture has been widely used and is very satisfactory. It should have a heavy fluid-like consistency, and if applied to a clean, well-cut thread will give an excellent joint.

*Shellac for Pipe Connections:* Shellac has proved to be a very satisfactory substitute for lead in sealing air and gas pipe connections. It is applied with a brush to the joints and hardens very rapidly, and being brittle, the pipes can be readily disconnected.

*Graphic, Litharge, Chalk Cement:* A good cement for use in making steam pipe joints is made in the following manner: Grind and wash in clean cold water 15 parts of chalk and 50 parts of graphite; mix the two together thoroughly and allow to dry. When dry regrind to a fine powder, to which add 20 parts of ground litharge and mix to a stiff paste with 15 parts of boiled linseed oil. The preparation may be set aside for future use, as it will remain plastic for a long time if placed in a cool place. It is applied to the joint packing as any ordinary cement.

*White and Red Lead Mixture:* Mix in ordinary white lead, enough powdered red lead to make a paste the consistency of putty. Spread this mixture on the joint, and when it hardens, the joint will be water tight. This mixture was used on stand-pipe flanges after testing all kinds of rubber gaskets without success. The mixture hardened and made a tight joint, never leaking afterward.

### Adhesives

**Adhesives Bonding.**—By strict definition, an adhesive is any substance that fastens or bonds materials to be joined (adherends) by means of surface attachment. However, besides bonding a joint, an adhesive may serve as a seal against attack by or passage of foreign materials. When an adhesive performs both bonding and sealing functions, it is usually called an adhesive sealant.

Where the design of an assembly permits, bonding with adhesives can replace bolting, welding, and riveting. When considering other fastening methods for thin cross-sections, the joint loads might be of such an unacceptable concentration that adhesives bonding may provide the only viable alternative. Properly designed adhesive joints can minimize or eliminate irregularities and breaks in the contour of an assembly. Adhesives can also serve

as dielectric insulation. An adhesive with dielectric properties can act as a barrier against galvanic corrosion when two dissimilar metals such as aluminum and magnesium are joined together. Conversely, adhesive products are available which also conduct electricity.

An adhesive can be classified as structural or non-structural. Agreement is not universal on the exact separation between both classifications. But, in a general way, an adhesive can be considered structural when it is capable of supporting heavy loads; non-structural when it cannot. Most adhesives are found in liquid, paste, or granular form, though film and fabric-backed tape varieties are available. Adhesive formulations are applied by brush, roller, trowel, or spatula. If application surfaces are particularly large or if high rates of production are required, power-fed flow guns, brushes, or sprays can be used.

The hot-melt adhesives are relatively new to the assembly field. In general, they permit fastening speeds that are much greater than water- or solvent-based adhesives. Supplied in solid form, the hot-melts liquefy when heated. After application, they cool quickly, solidifying and forming the adhesive bond. They have been used successfully for a wide variety of adherends, and can greatly reduce the need for clamping and lengths of time for curing storage.

If an adhesive bonding agent is to give the best results, time restrictions recommended by the manufacturer, such as shelf life and working life must be observed. The shelf life is considered as the period of time an adhesive can be stored after its manufacture. Working or "pot" life is the span of time between the mixing or making ready of an adhesive, on the job, and when it is no longer usable.

The actual performance of an adhesive-bonded joint depends on a wide range of factors, many of them quite complex. They include: the size and nature of the applied loads; environmental conditions such as moisture or contact with other fluids or vapors; the nature of prior surface treatment of adherends; temperatures, pressures and curing times in the bonding process.

A great number of adhesives, under various brand names, may be available for a particular bonding task. However, there can be substantial differences in the cost of purchase and difficulties in application. Therefore, it is always best to check with manufacturers' information before making a proper choice. Also, testing under conditions approximating those required of the assembly in service will help assure that joints meet expected performance.

Though not meant to be all-inclusive, the information which follows correlates classes of adherends and some successful adhesive compositions from the many that can be readily purchased.

*Bonding Metal:* Epoxy resin adhesives perform well in bonding metallic adherends. One type of epoxy formulation is a two-part adhesive which can be applied at room temperature. It takes, however, seven days at room temperature for full curing, achieving shear strengths as high as 2500 psi (17.2 MPa). Curing times for this adhesive can be greatly accelerated by elevating the bonding temperature. For example, curing takes only one hour at 160°F (71°C).

A structural adhesive-filler is available for metals which is composed of aluminum powder and epoxy resin. It is made ready by adding a catalyst to the base components, and can be used to repair structural defects. At a temperature of 140°F (60°C) it cures in approximately one hour. Depending on service temperatures and design of the joint, this adhesive-filler is capable of withstanding flexural stresses above 10,000 psi (69 MPa), tension above 5,000 psi (34 MPa), and compression over 30,000 psi (207 MPa).

Many non-structural adhesives for metal-to-metal bonding are also suitable for fastening combinations of types of materials. Polysulfide, neoprene, or rubber-based adhesives are used to bond metal foils. Ethylene cellulose cements, available in a selection of colors, are used to plug machined recesses in metal surfaces, such as with screw insets. They harden within 24 hours. Other, stronger adhesive fillers are available for the non-structural patch-

ing of defects in metallic parts. One variety, used for iron and steel castings, is a cement that combines powdered iron with water-activated binding agents. The consistency of the prepared mix is such that it can be applied with a trowel and sets within 24 hours at room temperature. The filler comes in types that can be applied to both dry and wet castings, and is able to resist the quick changes of temperature during quenching operations.

Polyester cement can replace lead and other fillers for dents and openings in sheet metal. One type, used successfully on truck and auto bodies, is a two-part cement consisting of a paste resin that can be combined with a paste or powder extender. It is brushed or trowelled on, and is ready for finishing operations in one hour.

Adhesives can be used for both structural and non-structural applications which combine metals with non-metals. Structural polyester-based adhesives can bond reinforced plastic laminates to metal surfaces. One type has produced joints, between glass reinforced epoxy and stainless steel, that have tensile strengths of over 3000 psi (21 MPa). Elevated temperature service is not recommended for this adhesive. However, it is easily brushed on and bonds under slight pressure at room temperature, requiring several days for curing. The curing process accelerates when heat is added in a controlled environment, but there results a moderate reduction in tensile strength.

Low-density epoxy adhesives are successful in structurally adhering light plastics, such as polyurethane foam, to various metals. Applied by brush or spatula, the bonds cure within 24 hours at room temperatures.

Metals can be bonded structurally to wood with a liquid adhesive made up of neoprene and synthetic resin. For the best surface coverage, the adhesive should be applied in a minimum of two coats. The joints formed are capable of reaching shear stresses of 125 psi, and can gain an additional 25 percent in shear strength with the passage of time. This adhesive also serves as a strong, general purpose bonding agent for other adherend combinations, including fabrics and ceramics.

For bonding strengths in shear over 500 psi (3.4 MPa) and at service temperatures slightly above 160°F (71°C), one- and two-part powder and jelly forms of metal-to-wood types are available.

Besides epoxy formulations, there are general purpose rubber, cellulose, and vinyl adhesives suitable for the non-structural bonding of metals to other adherends, which include glass and leather. These adhesives, however, are not limited only to applications in which one of the adherends is metal. The vinyl and cellulose types have similar bonding properties, however the vinyls are less flammable and are weaker in resistance to moisture than the comparable cellulose. Rubber-based adhesives, in turn, have good resistance to moisture and lubricating oil. They can form non-structural bonds between metal and rubber.

One manufacturer has produced an acrylic-based adhesive that is highly suitable for rapidly bonding metal with other adherends at room temperature. For some applications it can be used as a structural adhesive, in the absence of moisture and high temperature. It cures within 24 hours and can be purchased in small bottles with dispenser tips.

A two-part epoxy adhesive is commercially available for non-structural bonding of joints or for patchwork in which one of the adherends is metal. Supplied in small tubes, it performs well even when temperatures vary between -50° to 200°F (-46° to 93°C). However, it is not recommended for use on assemblies that may experience heavy vibrations.

*Bonding Plastic:* Depending on the type of resin compound used in its manufacture, a plastic material can be classified as one of two types: a thermoplastic or a thermoset.

Thermoplastic materials have the capability of being repeatedly softened by heat and hardened by cooling. Common thermoplastics are nylon, polyethylene, acetal, polycarbonate, polyvinyl chloride, cellulose nitrate and cellulose acetate. Also, solvents can easily dissolve a number of thermoplastic materials. Because of these physical and chemical characteristics of thermoplastics, heat or solvent welding may in many instances offer a better bonding alternative than adhesives.

Thermoplastics commonly require temperatures between 200° and 400°F (93° and 204°C) for successful heat welding. However, if the maximum temperature limit for a particular thermoplastic formulation is exceeded, the plastic material will experience permanent damage. Heat can be applied directly to thermoplastic adherends, as in hot-air welding. More sophisticated joining techniques employ processes in which the heat generated for fusing thermoplastics is activated by electrical, sonic, or frictional means.

In the solvent welding of thermoplastics, solvent is applied to the adherend surfaces with the bond forming as the solvent dries. Some common solvents for thermoplastics are: a solution of phenol and formic acid for nylon; methylene chloride for polycarbonate; and methyl alcohol for the cellulose.

Many adhesive bonding agents for thermoplastics are “dope” cements. Dope or solvent cements combine solvent with a base material that is the same thermoplastic as the adherend. One type is used successfully on polyvinyl chloride water (PVC) pipe. This liquid adhesive, with a polyvinyl chloride base, is applied in at least two coats. The pipe joint, however, must be closed in less than a minute after the adhesive is applied. Resulting joint bonds can resist hydrostatic pressures over 400 psi (28 MPa), for limited periods, and also have good resistance to impact.

Previously mentioned general purpose adhesives, such as the cellulose, vinyls, rubber cements, and epoxies are also used successfully on thermoplastics.

Thermoset plastics lack the fusibility and solubility of the thermoplastics and are usually joined by adhesive bonding. The phenolics, epoxies, and alkyds are common thermoset plastics. Epoxy-based adhesives can join most thermoset materials, as can neoprene, nitrile rubber, and polyester-based cements. Again, these adhesives are of a general purpose nature, and can bond both thermoplastics and thermosets to other materials which include ceramics, fabric, wood, and metal.

**Bonding Rubber:** Adhesives are available commercially which can bond natural, butyl, nitrile, neoprene, and silicone rubbers. Natural and synthetic rubber cements will provide flexible joints; some types resist lubricating and other oils. Certain general purpose adhesives, such as the acrylics or epoxies, can bond rubber to almost anything else, though joints will be rigid. Depending on the choice of adhesive as well as adherend types, the bonds can carry loadings that vary from weak non-structural to mild structural in description. One type of natural rubber with a benzene-naphtha solvent can resist shear stresses to 1252.5 psi (83 kPa).

**Bonding Wood:** Animal glues, available in liquid and powder form, are familiar types of wood-to-wood adhesives, commonly used in building laminated assemblies. Both forms, however, require heavy bonding pressures for joints capable of resisting substantial loadings. Also, animal glues are very sensitive to variations in temperature and moisture.

Casein types of adhesive offer moderate resistance to moisture and high temperature, but also require heavy bonding pressures, as much as 200 psi, for strong joints. Urea resin adhesives also offer moderate weather resistance, but are good for bonding wood to laminated plastics as well as to other wooden adherends. For outdoor service, under severe weather conditions, phenol-resorcinol adhesives are recommended.

Vinyl-acetate emulsions are excellent for bonding wood to other materials that have especially non-porous surfaces, such as metal and certain plastic laminates. These adhesives, too, tend to be sensitive to temperature and moisture, but are recommended for wooden pattern making.

Rubber, acrylic, and epoxy general-purpose adhesives also perform well with wood and other adherend combinations. Specific rubber-based formulations resist attack by oil.

**Fabric and Paper Bonding:** The general purpose adhesives, which include the rubber cements and epoxies previously mentioned, are capable of bonding fabrics together and fabrics with other adherend materials. A butadiene-acrylonitrile adhesive, suitable also for fastening metals, glass, plastic, and rubber, forms joints in fabric that are highly resistant to

oil and which maintain bonding strength at temperatures up to 160°F (70°C). This adhesive, however, requires a long curing period, the first few hours of which are at an elevated temperature.

Commonly, when coated fabric materials must be joined, the base material forming the suitable adhesive is of the same type as that protecting the fabric. For example, a polyvinyl chloride-based adhesive is acceptable for vinyl-coated fabrics; and neoprene-based cements for neoprene-coated materials.

Rubber cements, gum mucilages, wheat pastes, and wood rosin adhesive can join paper as well as fabric assemblies. Solvent-based rosins can be used on glass and wood also. Rosin adhesives can also be treated as hot-melt adhesives for rapid curing. Generally, the rosins are water resistant, but usually weak against attack by organic solvents.

### Sealants

**Sealants.**—Normally, the primary role of a sealant composition is the prevention of leakage or access by dust, fluid, and other materials in assembly structures. Nevertheless, many products are currently being manufactured that are capable of performing additional functions. For example, though a sealant is normally not an adhesive, there exists a family of adhesive sealants which in varying degrees can bond structural joints as well. Besides resisting chemical attack, some sealant surface coatings can protect against physical wear. Sealants can also dampen noise and vibration, or restrict the flow of heat or electricity. Many sealant products are available in decorative tints that can help improve the appearance of an assembly.

Most sealants tend to be limited by the operating temperatures and pressures under which they are capable of sustained performance. Also, before a suitable choice of sealant formulation is made, other properties have to be examined; these include: strength of the sealant; its degree of rigidity; ease of repair; curing characteristics; and even shelf and working life.

Dozens of manufacturers supply hundreds of sealant compounds, a number of which may fill the requirements for a particular application. The following information, however, lists common uses for sealants, along with types of compositions that have been employed successfully within each category.

*Gasket Materials:* Silicone rubber gasket compositions are supplied in tubes in a semi-liquid form ready for manual application. They can also be obtained in larger containers for power-fed applications. Suppliers offer a silicone rubber-based composition that can replace preformed paper, cork, and rubber gaskets for many manufacturing operations. This composition has performed successfully in sealing water pumps, engine filter housings, and oil pans. It can also seal gear housings and other joints that require a flexible gasket material that besides resisting shock can sustain large temperature changes. Silicone rubber compositions can withstand temperatures that vary from -100°F to 450°F (-73°C to 232°C).

Gasket tapes, ropes, and strips can also be readily purchased to fit many assembly applications. One type of sealant tape combines a pressure-sensitive adhesive with a strip of silicone-rubber sponge. This tape has good cushioning properties for vibration damping and can stick to metal, plastic, ceramic, and glass combinations.

TFE-based gasketing strips are also available. This non-stick gasketing material can perform at pressures up to 200 psi (1.4 MPa) and temperatures to 250°F (120°C). Because of the TFE base, the strip does not adhere to or gum joint surfaces.

*Sealing Pipe Joints:* Phenolic-based sealants can seal threaded joints on high-pressure steam lines. One type, that is available in liquid or paste form, resists pressure up to 1200 psi (8.3 MPa) and temperatures to 950°F (510°C). This compound is brushed on and the joint closed and tightened to a torque of 135 in.-lb. (15.3 N m). The connection is then subjected to a 24-hour cure with superheated steam.

The joining and sealing of plastic pipe is covered under the previous adhesives bonding section.

Sulfur-based compounds, though lacking the durability of caulking lead, can be used on bell and spigot sewer pipe. Available in a formulation that can resist temperatures up to 200°F (93°C), one sulfur-based sealant is applied as a hot-melt and allowed to flow into the bell and spigot connection. It quickly solidifies at room temperature, and can develop a joint tensile strength over 300 psi (2.1 MPa).

There are asphalt, coal-tar and plastic-based compositions that can be used on both cast-iron and ceramic bell and spigot pipe. Portland cement mortars also seal ceramic piping.

**SURFACE TREATMENTS FOR METALS****Coloring Metals**

**General Requirements in the Coloring of Metal Surfaces.**—Copper is more susceptible to coloring processes and materials than any of the other metals, and hence the alloys containing large percentages of copper are readily given various shades of yellow, brown, red, blue, purple, and black. Alloys with smaller percentages of copper (or none at all) can be given various colors, but not as easily as if copper were the principal ingredient, and the higher the copper content, the more readily can the alloy be colored. The shades, and even the colors, can be altered by varying the density of the solution, its temperature and the length of time the object is immersed. They can also be altered by finishing the work in different ways. If a cotton buff is used, one shade will be produced; a scratch brush will produce another, etc. Thus to color work the same shade as that of a former lot, all the data in connection with these operations must be preserved so they can be repeated with exactness.

**Cleaning Metals for Coloring.**—Metal surfaces to be colored chemically must first be thoroughly cleaned. To remove grease from small parts, dip in benzine, ether or some other solvent for the grease. Boil large pieces in a solution of one part caustic soda and ten parts water. For zinc, tin or britannia metal, do not use caustic soda, but a bath composed of one part carbonate of soda or potash and ten parts water. After boiling, wash in clean water. Do not touch the clean surfaces with the fingers, but handle the objects by the use of tongs or wires.

**Pickling Solutions or Dips for Coloring.**—The grease removal should be followed by chemical cleansing, which principally serves the purpose of removing the greenish or brownish films which form on copper, brass, bronze, etc. The composition of the bath or mixture for pickling varies for different metals. For copper and its alloys, a mixture of 100 parts concentrated sulphuric acid (66 degrees Baume and 75 parts nitric acid (40 degrees Baume is sometimes used. If the metal is to be given a luster instead of a mat or dull finish, add about 1 part common salt to 100 parts of the pickling solution, by weight. A better dip for a mat surface consists of 90 parts nitric acid (36 degrees Baume 45 parts concentrated sulphuric acid, 1 part salt, and from 1 to 5 parts of sulphate of zinc, by weight. The composition of copper-zinc alloys will produce different color tones in the same dip and will affect the results of chemical coloring. After pickling, washing in water is necessary.

Another good method of removing these films is to soak the work in a pickle composed of spent aquafortis until a black scale is formed, and then dip it for a few minutes into a solution of 64 parts water, 64 parts commercial sulphuric acid, 32 parts aquafortis, and 1 part hydrochloric acid. After that the work should be thoroughly rinsed several times with distilled water.

**Coloring Brass.**—Polished brass pieces can be given various shades from golden yellow to orange by immersing them for a certain length of time in a solution composed of 5 parts, by weight, of caustic soda, 50 parts water and 10 parts copper carbonate. When the desired shade is reached, the work must be well washed with water and dried in sawdust. Golden yellow may be produced as follows: Dissolve 100 grains lead acetate in 1 pint of water and add a solution of sodium hydrate until the precipitate which first forms is re-dissolved; then add 300 grains red potassium ferro-cyanide. With the solution at ordinary temperatures, the work will assume a golden yellow, but heating the solution darkens the color, until at 125 degrees F. it has changed to a brown.

**To Produce a Rich Gold Color.**—Brass can be given a rich gold color by boiling it in a solution composed of 2 parts, by weight, of saltpeter, 1 part common salt, 1 part alum, 24 parts water and 1 part hydrochloric acid. Another method is to apply a mixture of 3 parts alum, 6 parts saltpeter, 3 parts sulphate of zinc, and 3 parts common salt. After applying

this mixture the work is heated over a hot plate until it becomes black, after which it is washed with water, rubbed with vinegar, and again washed and dried.

**White Colors or Coatings.**—The white color or coating that is given to such brass articles as pins, hooks and eyes, buttons, etc., can be produced by dipping them in a solution made as follows: Dissolve 2 ounces fine-grain silver in nitric acid, then add 1 gallon distilled water, and put this into a strong solution of sodium chloride. The silver will precipitate in the form of chloride, and must be washed until all traces of the acid are removed. Testing the last rinse water with litmus paper will show when the acid has disappeared; then mix this chloride of silver with an equal amount of potassium bitartrate (cream of tartar), and add enough water to give it the consistency of cream. The work is then immersed in this solution and stirred around until properly coated, after which it is rinsed in hot water and dried in sawdust.

**Silvering.**—A solution for silvering, that is applicable to such work as gage or clock dials, etc., can be made by grinding together in a mortar 1 ounce of very dry chloride of silver, 2 ounces cream of tartar, and 3 ounces common salt, then add enough water to obtain the desired consistency and rub it onto the work with a soft cloth. This will give brass or bronze surfaces a dead-white thin silver coating, but it will tarnish and wear if not given a coat of lacquer. The ordinary silver lacquers that can be applied cold are the best. Before adding the water, the mixture, as it leaves the mortar, can be kept a long time if put in very dark colored bottles, but if left in the light it will decompose.

**To Give Brass a Green Tint.**—One solution that will produce the Verde antique, or rust green, is composed of 3 ounces crystallized chloride of iron, 1 pound ammonium chloride, 8 ounces verdigris, 10 ounces common salt, 4 ounces potassium bitartrate and 1 gallon of water. If the objects to be colored are large, the solution can be put on with a brush. Several applications may be required to give the desired depth of color. Small work should be immersed and the length of time it remains in the solution will govern the intensity of the color. After immersion, stippling the surface with a soft round brush, dampened with the solution, will give it the variegated appearance of the naturally aged brass or bronze.

**Blackening Brass.**—There are many different processes and solutions for blackening brass. Trioxide of arsenic, white arsenic or arsenious acid are different names for the chemical that is most commonly used. It is the cheapest chemical for producing black on brass, copper, nickel, German silver, etc., but has a tendency to fade, especially if not properly applied, although a coat of lacquer will preserve it a long time. A good black can be produced by immersing the work in a solution composed of 2 ounces white arsenic, 5 ounces cyanide of potassium, and 1 gallon of water. This should be boiled in an enamel or agate vessel, and used hot. Another cheap solution is composed of 8 ounces of sugar of lead, 8 ounces hyposulphite of soda and 1 gallon of water. This must also be used hot and the work afterwards lacquered to prevent fading. When immersed, the brass first turns yellow, then blue and then black, the latter being a deposit of sulphide of lead.

**Preservation of Color.**—After a part has been given the desired color, it is usually washed in water and then dried with clean sawdust. The colored surfaces of alloys are commonly protected and preserved by coating with a colorless lacquer, such as japan lacquer. Small parts are coated by dipping, and large ones by rubbing the lacquer on. The lacquer is hard after drying, and insoluble in most fluids; hence, it can be washed without injury.

**Niter Process of Bluing Steel.**—The niter process of bluing iron and steel is as follows: The niter or nitrate of potash (often called saltpeter) is melted in an iron pot and heated to about 600 degrees F. The parts to be blued are cleaned and polished and then immersed in the molten niter until a uniform color of the desired shade has been obtained. This requires only a few seconds. The articles are then removed and allowed to cool, after which the adhering niter is washed off in water. Parts which will not warp may be immersed immediately after removing from the niter bath. After cleaning, dry in sawdust, and then apply some suitable oil, such as linseed, to prevent rusting. To secure uniform coloring, a pyrom-



eter should be used to gage the temperature of the niter, because a higher heat than 600 degrees F. will produce a dark color, whereas a lower heat will give a lighter shade.

**Bluing Steel by Heat-treatment.**—Polished steel parts can be given a blue color by heating in hot sand, wood ashes, or pulverized charcoal. Place the substance in an iron receptacle and stir constantly, while heating, in order to heat uniformly. Heat just hot enough to char a pine stick. The parts to be blued must be absolutely free from grease. They are placed in the heated substance until the desired color is obtained. Further coloring is then checked by immersing in oil. Small parts are sometimes heated by a Bunsen burner or by laying upon a heated plate. For a light blue color, heat in sand or wood ashes, and for a dark blue, use pulverized charcoal. The quality of the color depends largely upon the fineness of the finish. Still another method of coloring by heat is to immerse the parts in a molten bath of potassium nitrate and sodium nitrate. The coloring is then checked by plunging the work into boiling water.

**Blue-black Finish.**—To obtain a blue-black finish on small steel parts, use a mixture of 16 parts, by weight, of saltpeter and 2 parts of black oxide of manganese. This mixture is heated to a temperature of 750 degrees F. and the objects are immersed in it. The oxide of manganese is deposited on the work and must, therefore, be frequently replenished in the mixture.

**Black Finish.**—To obtain a black rust-protecting finish on hardened parts, temper, after hardening, in "heavy" cylinder oil; then immediately place the part with the oil on it in an oven having a temperature of from 300 to 350 degrees F. Remove the work in from to 8 minutes, when the black finish is baked onto it.

**Gun Metal Finish.**—Several different chemical solutions have been used successfully for giving steel a gun metal finish or black color. Among these are the following:

- 1) Bismuth chloride, one part; copper chloride, one part; mercury chloride, two parts; hydrochloric acid, six parts; and water, fifty parts.
- 2) Ferric chloride, one part; alcohol, eight parts; and water, eight parts.
- 3) Copper sulphate, two parts; hydrochloric acid, three parts; nitric acid, seven parts; and perchloride of iron, eighty-eight parts.

Other solutions have been prepared from nitric ether, nitric acid, copper sulphate, iron chloride, alcohol and water and from nitric acid, copper sulphate, iron chloride and water. The method of applying these and finishing the work is practically the same in all cases.

The surface is given a very thin coating with a soft brush or sponge that has been well squeezed, and is then allowed to dry. The work is then put in a closed retort to which steam is admitted and maintained at a temperature of about 100 degrees F., until the parts are covered with a slight rust. They are then boiled in clean water for about fifteen minutes and allowed to dry. A coating of black oxide will cover the surface, and this is scratch brushed. After brushing, the surface will show a grayish black. By repeating the sponging, steaming and brushing operations several times, a shiny black lasting surface will be obtained. For the best finishes, these operations are repeated as many as eight times.

Another process employs a solution of mercury chloride and ammonium chloride which is applied to the work three times and dried each time. A solution of copper sulphate, ferric chloride, nitric acid, alcohol and water is then applied three times and dried as before. A third solution of ferrous chloride, nitric acid and water is applied three times, and the work is boiled in clean water and dried each time. Finally, a solution of potassium chloride is applied and the work boiled and dried three times. The work is then scratch brushed and given a thin coating of oil. Ordnance for the French Government is treated in this way. The above methods are applicable to hardened and tempered steels, as a temperature of 100 degrees F. does not affect the hardness of the steel. For steels that will stand 600 degrees temperature without losing the desired hardness, better and much cheaper methods have been devised.

The American Gas Furnace Co. has developed a process employing a furnace with a revolving retort. The work is charged in this, together with well-burnt bone. A chemical solution that gasifies when it enters the furnace is then injected into this retort while the work is heated to the proper temperature. This solution has been named "Carbonia." The color does not form a coating on the outside, as with the other processes, but a thin layer of the metal itself is turned to the proper color. By varying the temperature of the furnace, the time the work is in it, and the chemical, different colors can be produced from light straw to brown, blue, purple and black, or gun metal finish. Rough or sand-blasted surfaces will have a frosted appearance, while smooth polished surfaces will have a shiny brilliant appearance.

**Browning Iron and Steel.**—A good brown color can be obtained as follows: Coat the steel with ammonia and dry it in a warm place; then coat it with muriatic or nitric acid and dry it in a warm place; then place the steel in a solution of tannin or gallic acid and again dry it. The color can be deepened by placing the work near the fire, but it should be withdrawn the minute the desired shade is reached or it will turn black.

**To Produce a Bronze Color.**—A bronze-like color can be produced by exposing iron or steel parts to the vapors of heated aquaregia, dipping them in melted petroleum jelly, and then heating them until it begins to decompose, when it is wiped off with a soft cloth. Another method of producing this bronze-brown color is to slightly heat the work, evenly cover the surfaces with a paste of antimony chloride (known as "bronzing salt"), and let the object stand until the desired color is obtained. The paste can be made more active by adding a little nitric acid.

**To Produce a Gray Color.**—A gray color on steel can be obtained by immersing the work in a heated solution of ten grains of antimony chloride, ten grains of gallic acid, 400 grains of ferric chloride and five fluid ounces of water. The first color to appear is pale blue, and this passes through the darker blues to the purple, and, finally, to the gray. If immersed long enough, the metal will assume the gray color, but any of the intermediate colors may be produced. When used cold, this is also one of the bronzing solutions.

**Mottled Coloring.**—Mottled colors on steel can be produced by heating the objects to a good cherry-red for several minutes in cyanide of potassium, then pouring the cyanide off, and placing the receptacle containing the work back on the tire for five minutes. The contents are then quickly dumped into clean water. To heighten the colors, boil afterward in water and oil.

**Coppering Solution.**—A coppering solution for coating finished surfaces in order that lay-out lines may be more easily seen, is composed of the following ingredients: To 4 ounces of distilled water (or rain water) add all the copper sulphate (blue vitriol) it will dissolve; then add 10 drops of sulphuric acid. Test by applying to a piece of steel, and, if necessary, add four or five drops of acid. The surface to be coppered should be polished and free from grease. Apply the solution with clean waste, and, if a bright copper coating is not obtained, add a few more drops of the solution; then scour the surface with fine emery cloth, and apply rapidly a small quantity of fresh solution.

**White Coatings for Laying Out Lines.**—Powdered chalk or whiting mixed with alcohol is commonly used for coating finished metal surfaces preparatory to laying out lines for machining operations. Alcohol is preferable to water, because it will dry quicker and does not tend to rust the surface. This mixture can be applied with a brush and is more convenient than a coppering solution for general work. For many purposes, the surface can be coated satisfactorily by simply rubbing dry chalk over it.

**To Produce Gray Colors.**—A solution of 1 ounce of arsenic chloride in 1 pint of water will produce a gray color on brass, but if the work is left in this solution too long it will become black. The brass objects are left in the bath until they have assumed the correct shade, and are then washed in clean warm water, dried in sawdust and finally in warm air.

**Blue and Violet Shades.**—To give brass a blue color, dissolve 1 ounce of antimony chloride in 20 ounces of water, and add 3 ounces hydrochloric acid; then warm the work and immerse it in this solution, until the desired blue is obtained. After that wash in clean water and dry in sawdust. A permanent and beautiful blue-black can be obtained by using just enough water to dissolve 2 ounces copper sulphate and then adding enough ammonia to neutralize and make it slightly alkaline. The work must be heated before immersion.

**To Give Brass a Green Tint.**—One solution that will produce the Verde antique, or rust green, is composed of 3 ounces crystallized chloride of iron, 1 pound ammonium chloride, 8 ounces verdigris, 10 ounces common salt, 4 ounces potassium bitartrate and 1 gallon of water. If the objects to be colored are large, the solution can be put on with a brush. Several applications may be required to give the desired depth of color. Small work should be immersed and the length of time it remains in the solution will govern the intensity of the color. After immersion, stippling the surface with a soft round brush, dampened with the solution, will give it the variegated appearance of the naturally aged brass or bronze.

### Etching And Etching Fluids

**Etching Fluids for Different Metals.**—A common method of etching names or simple designs upon steel is to apply a thin, even coating of beeswax or some similar substance which will resist acid; then mark the required lines or letters in the wax with a sharp-pointed scribe, thus exposing the steel (where the wax has been removed by the scribe point) to the action of an acid, which is finally applied. To apply a very thin coating of beeswax, place the latter in a silk cloth, warm the piece to be etched, and rub the pad over it. Regular coach varnish is also used instead of wax, as a "resist."

An etching fluid ordinarily used for carbon steel consists of nitric acid, 1 part; water, 4 parts. It may be necessary to vary the amount of water, as the exact proportion depends upon the carbon in the steel and whether it is hard or soft. For hard steel, use nitric acid, 2 parts; acetic acid, 1 part. For high-speed steel, nickel or brass, use nitro-hydrochloric acid (nitric, 1 part; hydrochloric, 4 parts). For high-speed steel it is sometimes better to add a little more nitric acid. For etching bronze, use nitric acid, 100 parts; muriatic acid, parts. For brass, nitric acid, 16 parts; water, 160 parts; dissolve 6 parts potassium chlorate in 100 parts of water; then mix the two solutions and apply.

A fluid which may be used either for producing a frosted effect or for deep etching (depending upon the time it is allowed to act) is composed of 1 ounce sulphate of copper (blue vitriol);  $\frac{1}{4}$  ounce alum;  $\frac{1}{2}$  teaspoonful of salt; 1 gill of vinegar, and 20 drops of nitric acid. For aluminum, use a solution composed of alcohol, 4 ounces; acetic acid, 6 ounces; antimony chloride, 4 ounces; water, 40 ounces.

The National Twist Drill Co. employs the following method for etching on cutters and other tools: The steel is brushed with asphaltum varnish which is allowed to stand until it thickens and hardens to the right degree; then the desired inscription is pressed through the asphaltum with a rubber stamp and the etching fluid (nitrohydrochloric acid or *aquaregia*) is applied with a medicine dropper. Practice and experience are required to judge just when the varnish has dried to the right consistency. A similar method, which has been successfully used for etching names on cutlery, is to coat the surface with gum guaiacum varnish. A rubber stamp having the name or design is then coated with a thin layer of potash solution. When this stamp is applied to the work, the varnish is "cut" by the potash wherever the coated stamp comes into contact with it; the surface is then brushed lightly with water to remove the loosened varnish and expose the lettering or design, which is then etched by applying dilute nitric acid. The rubber-stamp method is a very cheap and rapid process. One method of applying the potash is to press the stamp against a pad soaked with the solution. The action of etching fluids on steels varies somewhat according to the composition, high-carbon and alloy steels being acted upon more slowly than low-carbon steel or wrought iron.

**Etching Brass Nameplates.**—Etched brass nameplates having a black background are now often used in preference to cast plates, as they are less expensive. The etched plate is produced by coating a flat and polished sheet of brass with a thin layer of bichromated albumen, and exposing it to the light for a few minutes under a glass negative upon which are a number of the desired nameplate designs. (In order to prepare the bichromated albumen, mix together 10 parts of the white of egg with 30 parts of water. A second mixture is then made consisting of 2 parts of potassium bichromate and 58 parts of water. The first mixture composed of the white of egg and water, and the second mixture containing potassium bichromate and water, are next mixed together in a dark room. The bichromated albumen thus obtained should be kept and used in the dark.) When the brass plate is developed, this removes the albumen not exposed to the light (or that which has been protected by the black portions of the negative), and leaves the brass free to be etched. The etching solution will not attack the parts protected by the albumen or “resist.”

The etching is done by a solution of perchlorate of iron, or by making the plate the anode in an acid-copper solution. When the plate has been etched to the required depth, it is washed. If the etched surface is tarnished, as it usually is after drying, a solution made of 2 parts of water and 1 part of muriatic acid should be spread over the surface to remove the stains and leave it clean and uniform. The plate should then be rinsed, but not dried. Then, without removing the resist, it is treated in some manner to produce a black background. When this has been done, the resist is removed and the sheet is cut up to form the individual nameplates, which are then lacquered.

**Producing a Black Background.**—The use of a black nickel deposit is the best method of producing a black background on etched brass name-plates. This solution does not affect any of the various kinds of resist used, and a large number of plates can be treated in a tank at one time. The black nickel bath is composed of water, 1 gallon; double-nickel salts, 8 ounces; ammonium sulpho-cyanate, 2 ounces; zinc sulphate, 1 ounce. This solution is used cold, with a weak current of about 1 volt. With a greater voltage, the deposit will be streaked and gray. As soon as the deposit is black, remove the plates, rinse, dry and cut to the desired size; then lacquer immediately in order to prevent the brownish discoloration which will otherwise form on the surface of the deposit. This solution can be used for brass, copper, bronze, etc.

**Etching Ornamental Designs in Metal.**—When metal plates having an ornamental design are required in small quantities, the etching process is sometimes used. The photographic method which is employed for nearly all intricate designs is as follows: The design is first drawn on white paper to any convenient scale, in black and white. A photographic negative is then made, or this may be procured from photo engravers who make a specialty of such work. The blacks and whites must be, respectively, opaque and transparent. This negative is used to print the design on the work to be etched, the metal, in order to take the design, being coated with a sensitized emulsion of bi-chromated albumen which has the property of remaining insoluble in water after exposure to the light. The portions corresponding to the opaque parts of the negative thus wash out in warm water, leaving the metal bare. Just prior to washing, however, the surface is coated with special lithographic ink, by means of a roller. The design is now on the metal, surrounded by a resist of a bi-chromated albumen base covered with a sticky ink. This resist is further reinforced by sprinkling the surface with dragon's blood. The latter is melted by heating and adheres to the resist, but forms a powder on the unprotected surface which can readily be blown off. This resist is effective, provided the etching is not done too deeply. For brass and copper, a strong solution of perchloride of iron is generally preferred as an etching fluid, as this does not attack the resist like strong acids, although its action is comparatively slow. Nitric acid may be used with proper resists. While etching is usually employed for cutting into the surface of the metal, the same process can be used for perforating the design in the plate.

Various acid-resisting materials are used for covering the surfaces of steel rules, etc., prior to marking off the lines on a graduating machine. When the graduation lines are fine

and very closely spaced, as on machinists' scales which are divided into hundredths or sixty-fourths, it is very important to use a thin resist that will cling to the metal and prevent any under-cutting of the acid; the resist should also enable fine lines to be drawn without tearing or crumbling as the tool passes through it. One resist that has been extensively used is composed of about 50 per cent of asphaltum, 25 per cent of beeswax, and, in addition, a small percentage of Burgundy pitch, black pitch, and turpentine. A thin covering of this resisting material is applied to the clean polished surface to be graduated and, after it is dry, the work is ready for the graduating machine. For some classes of work, paraffin is used for protecting the surface surrounding the graduation lines which are to be etched. The method of application consists in melting the paraffin and raising its temperature high enough so that it will flow freely; then the work is held at a slight angle and the paraffin is poured on its upper surface. The melted paraffin forms a thin protective coating.

**MANUFACTURING****Welding with Thermit**

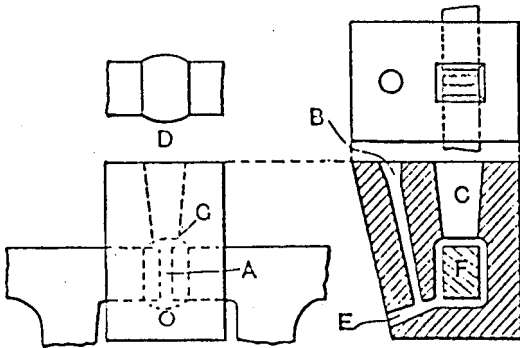
**Thermit Process.**—This process of welding metals is effected by pouring superheated thermit steel around the parts to be united. Thermit is a mixture of finely divided aluminum and iron oxide. This mixture is placed in a crucible and the steel is produced by igniting the thermit in one spot by means of a special powder, which generates the intense heat necessary to start the chemical reaction. When the reaction is once started it continues throughout the entire mass, the oxygen of the iron being taken up by the aluminum (which has a strong affinity for it), producing aluminum oxide (or slag) and superheated thermit steel. ordinarily, the reaction requires from 35 seconds to one minute, depending upon the amount of thermit used. As soon as it ceases, the steel sinks to the bottom of the crucible and is tapped into a mold surrounding the parts to be welded. As the temperature of the steel is about 5400 degrees F., it fuses and amalgamates with the broken sections, thus forming a homogeneous weld.

It is necessary to pre-heat the sections to be welded before pouring, to prevent chilling the steel. The principal steps of the welding operation are, to clean the sections to be welded, remove enough metal at the fracture to provide for a free flow of thermit steel, align the broken members and surround them with a mold to retain the steel, pre-heat by means of a gasoline torch to prevent chilling the steel, ignite the thermit and tap the molten steel into the mold. This process is especially applicable to the welding of large sections. It has been extensively used for welding locomotive frames, broken motor casings, rudder- and stern-posts of ships, crankshafts, spokes of driving wheels, connecting rods, and heavy repair work in general. One of the great advantages of the thermit process is that broken parts can usually be welded in place. For example, locomotive frames are welded by simply removing parts that would interfere with the application of a suitable mold. Thermit is also used for pipe welding, rail welding, and in foundry practice, to prevent the "piping" of ingots.

**Preparation of Part to be Welded.**—The first step in the operation of thermit welding is to clean the fractured parts and cut away enough metal to insure an unobstructed flow of the molten thermit. The oxy-acetylene or oxy-hydrogen cutting torch is very efficient for this operation. The amount that should be cut away depends upon the size of the work. Assuming that a locomotive frame is to be welded, the space should be about  $\frac{3}{4}$  inch wide for a small frame, and 1 inch wide for a large frame. The frame sections are then jacked apart about  $\frac{1}{4}$  inch to allow for contraction of the weld when cooling; trammel marks are scribed on each side of the fracture to show the normal length. If the weld is to be made on one member of a double-bar frame, the other parallel member should be heated with a torch to equalize the expansion in both sections and prevent unequal strains.

**Mold for Thermit Welding.**—The mold surrounding the fractured part should be so arranged that the molten thermit will run through a gate to the lowest part of the mold and rise through and around the parts to be welded into a large riser. The accompanying illustration shows a mold applied to a locomotive frame that is broken between the pedestals at *A*. The thermit steel is poured through gate *B*, and rises into space *C* after passing around and between the ends of frame *F*. The mold must allow for a reinforcing band or collar of thermit steel to be cast around the ends to be welded. Space *G*, for forming this collar, and the opening between the frame ends, must be filled before ramming up the mold. Yellow wax is ordinarily used for this purpose. The shape of this band or collar should be as indicated by the view of the completed weld at *D*. The thickest part is directly over the fracture and the band overlaps the edges of the fracture at least one inch.

## WELDING WITH THERMIT



For a frame of average size, the collars are made about 4 inches wide and 1 inch thick at the center, the thickness being increased for comparatively large sections. An opening is also made at *E* for pre-heating the ends to be welded.

Patterns for the riser, pouring and heating gates can be made of wood. The riser *C* should be quite large because the steel that first enters the mold is chilled somewhat by coming into contact with the metal, even when pre-heated. This chilling effect is overcome by using enough thermit steel to force the chilled portion up into the riser and replacing it by metal which has practically the full temperature received during reaction. The mold must be made of a refractory material, owing to the intense heat. The best material is made of one part fire sand, one part fire-clay and one part ground firebrick, thoroughly mixed while dry and moistened just enough to pack well. If these ingredients cannot be obtained, one part fire-clay and one part clean, dry sand may be used. When the mold and box are filled and tamped, the wooden runner and riser patterns are withdrawn. The mold is then ready for the pre-heating and drying operation which causes the wax matrix to melt and run out.

**Thermit Required for Welding.**—The quantity of thermit required for making a weld can be determined from the cubic contents of the weld. Calculate the cubic contents of the weld and its reinforcement in cubic inches; double this amount to allow for filling the gate and riser, and multiply by 0.56 to get the number of pounds of thermit required. When wax is used for filling, the weight of the thermit can be determined as follows: Weigh the wax supply before and after filling the fracture. The difference in weight (in pounds, or the quantity used, multiplied by 32 will give the weight of thermit in pounds.

**Thermit Additions.**—When a quantity of more than 10 pounds of thermit is to be used, add 10 per cent of steel punchings (not over  $\frac{1}{2}$  inch in diameter) or steel scrap, free from grease, into the thermit powder. If the thermit exceeds 50 pounds, 15 per cent of small mild steel rivets may be mixed with it. One per cent (by weight) of pure manganese and 1 per cent of nickel - thermit should be added to increase the strength of the thermit steel.

**Pre-heating — Making a Weld.**—The ends to be welded should be red hot at the moment the thermit steel is tapped into the mold. This pre-heating is done, preferably, by a gasoline, compressed-air torch, and, as previously mentioned, it melts the wax matrix used for filling the fracture to form the pattern for the reinforcing band. When the ends have been heated red, quickly remove the torch and plug the pre-heating hole *E* with a dry sand core, backing it up with a few shovelfuls of sand, well packed. The end of the cone-shaped crucible should be directly over the pouring gate and not more than 4 inches above it. To start the reaction, place one-half teaspoonful of ignition powder on top of the thermit and ignite with a storm match. It is important that sufficient time be allowed for the completion of the thermit reaction and for fusion of the steel punchings which have been

mixed within the thermit. Within charges containing from 30 to 50 pounds of thermit, the crucible should not be tapped in less than 35 seconds; with charges containing from 50 to 75 pounds, 40 seconds; 75 to 100 pounds, 50 seconds to one minute.

When welding a frame broken as shown in the illustration previously referred to, the screw jack used for forcing the pedestals apart should be turned back somewhat to release the pressure gradually as the weld cools. After pouring, the mold should remain in place as long as possible (preferably 10 or 12 hours) to anneal the steel in the weld, and, in any case, it should not be disturbed for at least two hours after pouring.

When welding a broken spoke in a driving wheel, or a similar part, it is necessary to pre-heat the adjacent spokes in order to prevent undue strains due to expansion and contraction. If a section of a spoke is broken out, it can be cast in, but if the space is over 6 inches long, it is better to insert a piece of steel and make a weld at each end. Owing to the high temperature 5400 degrees F.) and the violent ebullition of thermit during reaction, the crucible must be lined with a very refractory material. The crucibles used for this purpose have a sheet-iron shell and are lined with magnesia.

**Filling Shrinkage Holes and Surface Flaws.**—The filling of surface flaws in castings and forgings usually requires from 2 to 10 pounds of thermit. To make a weld of this kind, place an open mold around the part to be filled, large enough to overlap it about  $\frac{1}{2}$  inch. Clean the hole thoroughly and heat to a red heat by means of a strong blow-torch. Use eighteen ounces of thermit for each cubic inch of space to be filled, but do not use less than two pounds for any one weld. Place a small amount of thermit in the crucible which, in this case, is of a small size for hand use. Ignite the thermit with ignition powder and as soon as it begins to burn, add the remainder, feeding it fast enough to keep the combustion going. When the reaction is completed, quickly pour the slag (which is about three-fourths of the total liquid) into dry sand; then pour the steel into the open mold and sprinkle loose thermit on top to prolong the reaction, as the casting, even when pre-heated, will have a chilling effect on the steel.

**Composition of Thermit Steel.**—An average analysis of thermit steel is as follows: carbon, 0.05 to 0.10 per cent; manganese, 0.08 to 0.10 per cent; silicon, 0.09 to 0.20 per cent; sulphur, 0.03 to 0.04 per cent; phosphorus, 0.04 to 0.05 per cent; aluminum, 0.07 to 0.18 per cent. The tensile strength is about 65,000 pounds per square inch.

**High- and Low-pressure Torches.**—The difference between high- and low-pressure welding and cutting torches, according to the generally accepted meaning of the term, is in the pressure of the acetylene. The first oxy-acetylene torches developed by Fouche were of the high-pressure type, using acetylene dissolved in acetone. Later, he developed a low-pressure torch, working on the injector principle, acetylene being drawn into the carburetor chamber where it mixed with the oxygen. The high pressures originally employed in the first torches could not be safely employed with the acetylene produced in generators, because the safe pressure of acetylene in volume should never exceed from 15 to 20 pounds per square inch, and the pressure is limited to 25 pounds per square inch by the Underwriters' Association in the United States: hence, the medium pressure which is in general use was developed. The proportion of oxygen to acetylene varies somewhat in the different torches. Usually from 1.04 to 1.12 times more oxygen is consumed than acetylene.












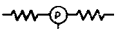



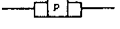


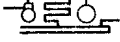

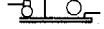





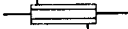

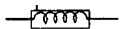

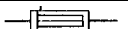








Welders and cutters should be provided with goggles or spectacles fitted with approved colored lenses that protect the eye from destructive light rays, flying sparks and globules of molten metal.













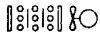





## SYMBOLS FOR DRAFTING

## Symbols For Drafting

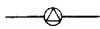

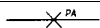
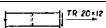
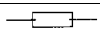
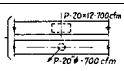
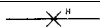
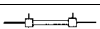
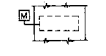



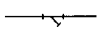
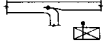

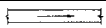
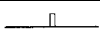
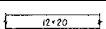

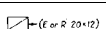
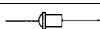
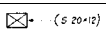
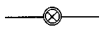
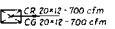
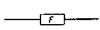
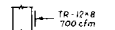

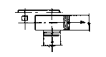
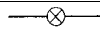
Table 58. Standard Graphical Symbols for Air Conditioning

|  |   |   |   |
|--|---|---|---|
| Capillary tube   |    | Filter line   |    |
| Compressor   |    | Filter and strainer, line   |    |
| Compressor, rotary<br>(Enclosed crankcase,<br>belted)                        |    | Float, high side  |    |
| Compressor, reciprocating<br>(open crankcase, belted)                        |    | Float, low side   |    |
| Compressor, reciprocating<br>(open crankcase, direct-<br>drive)              |    | Gage  |    |
| Motor compressor, reciprocating<br>(direct connected,<br>enclosed crankcase) |    | Pressurestat  |    |
| Motor compressor, rotary<br>(direct connected,<br>enclosed crankcase)        |    | Pressure switch   |    |
| Motor compressor, reciprocating<br>(sealed crankcase)                        |    | Pressure switch (with high<br>pressure cut-out)   |    |
| Motor compressor, rotary<br>(sealed crankcase)                               |    | Receiver, horizontal  |    |
| Condensing Unit<br>(air cooled)  |    | Receiver, vertical  |    |
| Condensing Unit<br>(water-cooled)  |    | Scale trap  |    |
| Condenser air cooled<br>(finned, forced air)                                 |  | Spray pond  |  |
| Condenser air cooled<br>(finned, static)                                     |  | Thermal bulb  |  |
| Condenser water cooled<br>(concentric tube in a tube)                        |  | Thermostat (remote bulb)  |  |
| Condenser water cooled<br>(shell and coil)                                   |  | Valve, expansion, automatic   |  |
| Condenser water cooled<br>(shell and tube)                                   |  | Valve, expansion, hand  |  |
| Condenser evaporative  |  | Valve, expansion,<br>thermostatic   |  |
|  |   | Valve, compressor suction<br>pressure limiting (throt-<br>tling type, compressor<br>side) |  |
| Cooling unit, finned (natural<br>convection)                                 |  | Valve, constant pressure,<br>suction  |  |
| Cooling unit<br>(forced convection)  |  | Valve, evaporator pressure<br>regulating (snap action)                                    |  |

**Table 58. (Continued) Standard Graphical Symbols for Air Conditioning**

|  |   |  |   |
|--|---|--|---|
| Cooling unit, immersion                          |  | Valve, evaporator pressure regulating (thermostatic throttling type)     |  |
| Cooling tower                                    |  | Valve, evaporator pressure regulating (throttling type, evaporator side) |  |
| Dryer  |  | Valve, magnetic stop   |  |
| Evaporator, circular (Ceiling type, finned)      |  | Valve, snap action   |  |
| Evaporator, manifolded (Bare tube, gravity air)  |  | Valve, suction vapor regulating  |  |
| Evaporator, manifolded (finned, forced air)      |  | Valve suction  |  |
| Evaporator, manifolded (finned, gravity air)     |  | Valve water  |  |
| Evaporator, plate coils (headered or manifolded) |  | Vibration absorber, line   |  |

**Table 59. Standard Graphical Symbols for Heating and Ventilation**

|  |   |  |   |
|--|---|--|---|
| Air eliminator   |    | Access door                            |    |
| Anchor   |    | Adjustable blank off                   |    |
| Expansion joint  |    | Adjustable plaque                      |    |
| Hanger or support  |    |  |   |
| Heat exchanger   |    | Automatic damper                       |   |
| Heat transfer surface (plan, indicate type, such as convector) |   |  |   |
| Pump (Indicate type, such as vacuum)                           |  | Canvas connection                      |  |
| Strainer   |  | Deflecting damper                      |  |
| Tank (designate type)  |  | Direction of flow                      |  |
| Thermometer  |  | Duct (first figure is side shown)      |  |
| Thermostat   |  | Duct section (exhaust or return)       |  |
| Trap, boiler return  |  | Duct section (supply)                  |  |
| Trap, blast thermostatic                                       |  | Exhaust inlet, ceiling (indicate type) |  |
| Trap, float  |  | Exhaust inlet, wall (indicate type)    |  |
| Trap, float and thermostatic                                   |  | Fan and motor (with belt guard)        |  |
| Trap, thermostatic   |  |  |   |

**Table 59. (Continued) Standard Graphical Symbols for Heating and Ventilation**

|   |  |   |  |
|---|--|---|--|
| Unit heater<br>(centrifugal fan type- plan) |  | Inclined drop<br>(with respect to air flow) |  |
| Unit heater<br>(propeller fan type- plan)   |  | Inclined rise<br>(with respect to air flow) |  |
| Unit ventilator, plan                       |  | Intake louvers                              |  |
| Valve, check                                |  |   |  |
| Valve, diaphragm                            |  | Louber opening                              |  |
| Valve, gate                                 |  | Supply outlet, ceiling<br>(Indicate type)   |  |
| Valve, glove                                |  | Supply outlet, wall<br>(Indicate type)      |  |
| Valve, lock and shield                      |  |   |  |
| Valve, motor operated                       |  | Vanes                                       |  |
| Valve, pressure reducing                    |  |   |  |
| Valve relief (either pressure<br>or vacuum) |  | Volume damper                               |  |
| Vent point                                  |  |   |  |

**Table 60. Standard Graphical Symbols for Valves**

| Name of Valve                     | Flanged | Screwed | Bell & Spigot | Welded | Soldered |
|-----------------------------------|---------|---------|---------------|--------|----------|
| Angle valve, check                |         |         |               |        |          |
| Angle valve, gate (elevation)     |         |         |               |        |          |
| Angle valve, gate (plan)          |         |         |               |        |          |
| Angle valve, globe (elevation)    |         |         |               |        |          |
| Angle valve, globe (plan)         |         |         |               |        |          |
| Automatic by-pass valve           |         |         |               |        |          |
| Automatic governor operated valve |         |         |               |        |          |
| Automatic reducing valve          |         |         |               |        |          |
| Check valve, straight way         |         |         |               |        |          |
| Cock                              |         |         |               |        |          |
| Diaphragm valve                   |         |         |               |        |          |

**Table 60. (Continued) Standard Graphical Symbols for Valves**

| Name of Valve                      | Flanged | Screwed | Bell & Spigot | Welded | Soldered |
|------------------------------------|---------|---------|---------------|--------|----------|
| Float valve                        |         |         |               |        |          |
| Gate valve also used as Stop valve |         |         |               |        |          |
| Gate valve motor operated          |         |         |               |        |          |
| Globe valve                        |         |         |               |        |          |
| Globe valve motor operated         |         |         |               |        |          |
| Hose valve, angle                  |         |         |               |        |          |
| Hose valve, gate                   |         |         |               |        |          |
| Hose valve, glove                  |         |         |               |        |          |
| Lockshield valve                   |         |         |               |        |          |
| Quick opening valve                |         |         |               |        |          |
| Safety valve                       |         |         |               |        |          |

**Table 61. Standard Graphical Symbols for Piping**

| Air Conditioning                        |  |   |  |
|---|--|---|--|
| Brine return                            |  | Brine supply                              |  |
| Chilled or hot water flow (circulating) |  | Chilled or hot water return (circulating) |  |
| Condenser water flow                    |  | Condenser water return                    |  |
| Drain                                   |  | Humidification line                       |  |
| Make-up water                           |  | Refrigerant discharge                     |  |
| Refrigerant liquid                      |  | Refrigerant liquid                        |  |
| Heating                                 |  |   |  |
| Air relief line                         |  | Boiler blow-off                           |  |
| Compressed air                          |  | Condensate discharge                      |  |
| Feed water pump discharge               |  | Fuel-oil flow                             |  |
| Fuel-oil return                         |  | Fuel-oil tank vent                        |  |
| High pressure return                    |  | High pressure steam                       |  |
| Hot water heating return                |  | Hot water heating supply                  |  |
| Low pressure return                     |  | Low pressure steam                        |  |
| Make-up water                           |  | Medium pressure return                    |  |
| Medium pressure steam                   |  |   |  |

























**Table 61. (Continued) Standard Graphical Symbols for Piping**

| Plumbing                                |  |   |  |
|---|--|---|--|
| Acid waste                              |  | Cold water                              |  |
| Compressed air                          |  | Drinking water flow                     |  |
| Drinking water return                   |  | Fire line                               |  |
| Gas                                     |  |   |  |
| Hot water                               |  | Hot water return                        |  |
| Soil, waste, or leader<br>(above grade) |  | Soil, waste, or leader<br>(below grade) |  |
| Vacuum cleaning                         |  | Vent                                    |  |
| Pneumatic Tubes                         |  |   |  |
| Tube runs                               |  |   |  |
| Sprinklers                              |  |   |  |
| Branch and head                         |  | Drain                                   |  |
| Main supplies                           |  |   |  |

**Table 62. Standard Graphical Symbols for Pipe Fittings**

| Name of Fitting      | Flanged | Screwed | Bell & Spigot | Welded | Soldered |
|----------------------|---------|---------|---------------|--------|----------|
| Bushing              |         |         |               |        |          |
| Cap                  |         |         |               |        |          |
| Cross, reducing      |         |         |               |        |          |
| Cross, straight size |         |         |               |        |          |
| Cross                |         |         |               |        |          |
| Elbow, 45-degree     |         |         |               |        |          |
| Elbow, 90-degree     |         |         |               |        |          |
| Elbow, turned down   |         |         |               |        |          |
| Elbow, turned up     |         |         |               |        |          |
| Elbow, base          |         |         |               |        |          |

**Table 62. (Continued) Standard Graphical Symbols for Pipe Fittings**

| Name of Fitting                     | Flanged   | Screwed   | Bell & Spigot   | Welded  | Soldered  |
|-------------------------------------|---|---|---|---|---|
| Elbow, double branch                |  |  |   |   |   |
| Elbow, long branch                  |  |  |   |   |   |
| Elbow, reducing                     |  |  |   |   |  |
| Elbow, side outlet<br>(outlet down) |  |  |  |   |   |
| Elbow, side outlet<br>(outlet up)   |  |  |  |   |   |
| Elbow, street                       |   |  |   |   |   |
| Joint, connecting pipe              |  |  |  |  |  |
| Joint, expansion                    |  |  |  |  |  |

**FORGE SHOP EQUIPMENT****Hammer and Anvil**

**Blacksmiths' Anvils.**—The quality of an anvil can generally be judged by its ring, a good anvil giving out a clear, sharp sound when struck with a hammer. If soft or defective, the sound will be dull. A good anvil so mounted that it gives out a full volume of sound is easier to work upon than one having a dead ring. Anvils ordinarily vary in weight from 150 to 300 pounds. A mistake is often made in selecting anvils that are too light for the service required. A 300-pound anvil is suitable for almost any kind of machine blacksmithing, and, if of this weight or heavier, it will not move around while in use or need to be strapped to its block. The square hole in the face of an anvil for receiving the cutting and forming tools is called the "hardie hole," and the small round hole near it is called the "pritchel hole." Anvils are usually made with a wrought-iron body to which is welded a hardened steel face.

**Setting the Anvil.**—The height of an anvil should be such that when standing beside if the knuckles of the hands will just reach the top surface or face. A solid oak block set endwise in the ground is often used as a foundation, but a cast-iron mounting block is preferable as it can easily be moved. The casting should have a fairly broad base, and a pocket at the top for receiving the anvil; a flat block of wood is provided to act as a cushion. An anvil should not be strapped rigidly to its foundation, as this checks the vibration which tends to keep the face free from scales, and renders a high-grade wrought-iron anvil little better than one made of cast iron. When a wooden block is used under the anvil, it is necessary to drive in a few spikes to keep the anvil in place, but these should be so placed that they do not bear directly upon or bind against the corners.

**Steam Hammer Rating.**—The capacity of a steam hammer or its rating is the weight of the ram and its attached parts, such as the piston and rod. The steam pressure behind the piston is not considered as far as the rating is concerned. For example, a 1000-pound hammer has reciprocating parts of that weight. The steam pressures for operating hammers usually vary from 75 to 100 pounds per square inch.

**Capacity of Steam Hammers.**—Capacity of a steam hammer or the proper size to use for working iron and steel of a given cross-sectional area can be determined approximately by the following rule: Multiply the area of the largest cross-section to be worked by 80, if of steel, or 60, if of iron, and the product will be the required rating of the hammer in pounds. For example, the capacity of a hammer for working steel billets 5 inches square would be determined as follows:  $5 \times 5 = 25$ ; and  $25 \times 80 = 2000$ , which is the rating of the hammer in pounds. A hammer rated according to this rule is an economical size to use, although it can, of course, be employed for heavier work.

**Power for Operating Steam Hammers.**—The boiler horsepower for operating a steam hammer depends upon the service required and the number of hammers in use. Ordinarily, the boiler capacity can be less where there are a number of hammers, because all of the hammers are rarely, if ever, used at the same time; consequently, there is a reserve power; but with a single hammer, especially when in constant service, the boiler capacity should be proportionately greater. For average conditions, the boiler horsepower can be determined approximately by the following rule: Divide the rated capacity of the hammer in pounds by 100, and the quotient will be the boiler horsepower required for continuous operation. For example, if the hammer is rated at 2000 pounds, the boiler horsepower would equal  $2000 \div 100 = 20$  H.P. This rule is also applicable in cases where the hammer is not used continually, by estimating the amount of idle time and making suitable allowance, but the boiler capacity must not be reduced to such an extent that there is a decided diminution in the pressure during the working period.

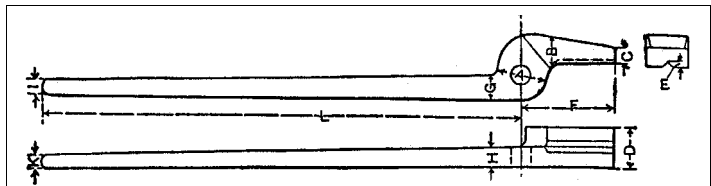
For foundations for steam hammers, see section on "Machinery and Hammer Foundations."

**Board Drop-hammers.**—This type of hammer is generally considered superior to the steam hammer for producing drop-forgings of small and medium size. When the work is heavy and requires a great deal of "breaking down" or drawing, or even when the forgings are light, but have thin sections that cool quickly, thus requiring sharp, rapid blows, the steam hammer will usually give better results than aboard drop. The capacity of most of the board drop-hammers in use varies from 800 to 1500 pounds; the steam hammers found in drop forging plants usually range from 2000 to 5000 pounds capacity, for handling average work. It does not seem practicable to build board drops larger than 3000 pounds falling weight, and where the forgings are heavy enough to require a capacity over 1500 or 2000 pounds, steam hammers are usually preferred. The latter type is also preferred in some forge shops for all classes of work. It is generally conceded that the cost of operation and repairs is greater for steam hammers, but the latter has a greater output for a given capacity.

The power required for operating board drop-hammers varies considerably with the nature of the work. Very little power is required at the point of "pick up," if the work is practically "die to die;" but when the work is soft and there is no rebound, a great deal more power is required, as the rolls have to pick up a "dead load" from rest and there is little kinetic energy in the driving pulleys. When there is a good rebound, with the knock-off properly timed, the board will be moving upward with considerable velocity when engaged by the rolls, and much less power is required. Seasoned maple boards have proved superior to any other kind for board drop-hammers. Paper fiber has been tried with fair results, but at present the cost of this material is too high.

For foundations for drop-hammers, see section on "Machinery and Hammer Foundations."

**Table 63. Dimensions of Flat-jawed Tongs**



| Capacity, Inches | A     | B     | C    | D     | E    | F     | G      | H     | I     | K    | L  | Rivet |
|------------------|-------|-------|------|-------|------|-------|--------|-------|-------|------|----|-------|
| 0 - 1/8          | 5/8   | 3/8   | 1/4  | 5/8   | 1/16 | 2 1/8 | 1/2    | 5/16  | 5/16  | 1/4  | 14 | 1/4   |
| 3/16 - 5/16      | 3/4   | 7/16  | 5/16 | 5/8   | 1/16 | 2 1/4 | 9/16   | 5/16  | 5/16  | 1/4  | 15 | 1/4   |
| 3/8 - 7/16       | 7/8   | 1/2   | 5/16 | 3/4   | 1/16 | 2 1/2 | 5/8    | 3/8   | 3/8   | 5/16 | 16 | 5/16  |
| 1/2 - 5/8        | 1     | 9/16  | 3/8  | 7/8   | 3/32 | 2 3/4 | 11/16  | 7/16  | 3/8   | 5/16 | 18 | 3/8   |
| 3/4 - 7/8        | 1 1/8 | 5/8   | 3/8  | 1     | 5/32 | 3     | 3/4    | 1/2   | 7/16  | 3/8  | 20 | 7/16  |
| 1 - 1 1/8        | 1 1/4 | 11/16 | 7/16 | 1 1/8 | 3/16 | 3 1/4 | 13/16  | 9/16  | 1/2   | 7/16 | 22 | 1/2   |
| 1 1/4 - 1 3/8    | 1 3/8 | 3/4   | 1/2  | 1 1/8 | 1/4  | 3 1/2 | 7/8    | 9/16  | 1/2   | 7/16 | 24 | 9/16  |
| 1 1/2 - 1 5/8    | 1 1/2 | 3/4   | 1/2  | 1 1/4 | 3/8  | 3 3/4 | 1      | 5/8   | 5/8   | 1/2  | 26 | 5/8   |
| 1 3/4 - 1 7/8    | 1 5/8 | 13/16 | 9/16 | 1 3/8 | 7/16 | 4     | 1 1/16 | 11/16 | 5/8   | 1/2  | 28 | 5/8   |
| 2                | 1 3/4 | 7/8   | 5/8  | 1 1/2 | 7/16 | 4 1/4 | 1 1/8  | 1 1/8 | 11/16 | 1/2  | 30 | 11/16 |



Table 64. Dimensions of Goose-neck Tong

| Capacity, Inches              | A              | B               | C               | D               | E              | F              | G              | H               | I              | L  | Rivet          |
|-------------------------------|----------------|-----------------|-----------------|-----------------|----------------|----------------|----------------|-----------------|----------------|----|----------------|
| $\frac{1}{4} - \frac{5}{16}$  | $\frac{5}{8}$  | $\frac{1}{2}$   | $\frac{7}{16}$  | $\frac{5}{16}$  | $\frac{1}{8}$  | 1              | $\frac{1}{2}$  | $\frac{5}{16}$  | $\frac{1}{4}$  | 14 | $\frac{1}{4}$  |
| $\frac{3}{8} - \frac{7}{16}$  | $\frac{3}{4}$  | $\frac{9}{16}$  | $\frac{1}{2}$   | $\frac{5}{16}$  | $\frac{3}{16}$ | $1\frac{1}{8}$ | $\frac{9}{16}$ | $\frac{5}{16}$  | $\frac{1}{4}$  | 16 | $\frac{5}{16}$ |
| $\frac{1}{2} - \frac{5}{8}$   | $\frac{7}{8}$  | $\frac{5}{8}$   | $\frac{9}{16}$  | $\frac{3}{8}$   | $\frac{1}{4}$  | $1\frac{1}{4}$ | $\frac{5}{8}$  | $\frac{3}{8}$   | $\frac{5}{16}$ | 18 | $\frac{3}{8}$  |
| $\frac{3}{4} - \frac{7}{8}$   | 1              | $\frac{3}{4}$   | $\frac{5}{8}$   | $\frac{7}{16}$  | $\frac{3}{8}$  | $1\frac{1}{2}$ | $\frac{3}{4}$  | $\frac{3}{8}$   | $\frac{5}{16}$ | 20 | $\frac{7}{16}$ |
| $1 - 1\frac{1}{8}$            | $1\frac{1}{8}$ | $\frac{7}{8}$   | $1\frac{1}{16}$ | $\frac{1}{2}$   | $\frac{1}{2}$  | $1\frac{3}{4}$ | $\frac{7}{8}$  | $\frac{3}{8}$   | $\frac{5}{16}$ | 20 | $\frac{1}{2}$  |
| $1\frac{1}{4} - 1\frac{3}{8}$ | $1\frac{1}{4}$ | 1               | $\frac{3}{4}$   | $\frac{9}{16}$  | $\frac{5}{8}$  | 2              | 1              | $\frac{7}{16}$  | $\frac{3}{8}$  | 22 | $\frac{1}{2}$  |
| $1\frac{1}{2} - 1\frac{3}{4}$ | $1\frac{3}{8}$ | $\frac{3}{4}$   | $\frac{1}{2}$   | $1\frac{1}{8}$  | $\frac{3}{4}$  | $2\frac{1}{8}$ | $1\frac{1}{8}$ | $\frac{1}{2}$   | $\frac{3}{8}$  | 24 | $\frac{9}{16}$ |
| $1\frac{7}{8} - 2\frac{1}{8}$ | $1\frac{3}{8}$ | $1\frac{3}{16}$ | $1\frac{5}{16}$ | $1\frac{1}{16}$ | 1              | $2\frac{1}{4}$ | $1\frac{1}{4}$ | $\frac{1}{2}$   | $\frac{3}{8}$  | 26 | $\frac{5}{8}$  |
| $2\frac{1}{4} - 2\frac{1}{2}$ | $1\frac{1}{2}$ | $1\frac{1}{4}$  | 1               | $\frac{3}{4}$   | $1\frac{1}{8}$ | $2\frac{1}{2}$ | $1\frac{1}{2}$ | $\frac{9}{16}$  | $\frac{7}{16}$ | 28 | $\frac{5}{8}$  |
| $2\frac{5}{8} - 2\frac{7}{8}$ | $1\frac{1}{2}$ | $1\frac{5}{16}$ | $1\frac{1}{16}$ | $\frac{3}{4}$   | $1\frac{1}{4}$ | $2\frac{3}{4}$ | $1\frac{3}{4}$ | $\frac{9}{16}$  | $\frac{7}{16}$ | 30 | $\frac{3}{4}$  |
| $3 - 3\frac{1}{4}$            | $1\frac{5}{8}$ | $1\frac{3}{8}$  | $1\frac{1}{8}$  | $\frac{3}{4}$   | $1\frac{1}{2}$ | 3              | 2              | $\frac{5}{8}$   | $\frac{1}{2}$  | 32 | $\frac{3}{4}$  |
| $3\frac{1}{2} - 3\frac{3}{4}$ | $1\frac{3}{4}$ | $1\frac{1}{2}$  | $1\frac{1}{4}$  | $\frac{3}{4}$   | $1\frac{3}{4}$ | $3\frac{1}{4}$ | $2\frac{1}{4}$ | $\frac{5}{8}$   | $\frac{1}{2}$  | 34 | $\frac{3}{4}$  |
| $4 - 4\frac{1}{4}$            | 2              | $1\frac{5}{8}$  | $1\frac{5}{16}$ | $1\frac{3}{16}$ | 2              | $3\frac{1}{4}$ | $2\frac{1}{2}$ | $1\frac{1}{16}$ | $\frac{9}{16}$ | 36 | $\frac{3}{4}$  |
| $4\frac{1}{2} - 4\frac{3}{4}$ | $2\frac{1}{8}$ | $1\frac{5}{8}$  | $1\frac{5}{16}$ | $1\frac{3}{16}$ | $2\frac{1}{8}$ | $3\frac{1}{4}$ | $2\frac{3}{4}$ | $1\frac{1}{16}$ | $\frac{9}{16}$ | 38 | $\frac{3}{4}$  |
| 5                             | $2\frac{1}{4}$ | $1\frac{3}{4}$  | $1\frac{3}{8}$  | $\frac{7}{8}$   | $2\frac{1}{4}$ | $3\frac{1}{2}$ | $3\frac{1}{4}$ | $\frac{3}{4}$   | $\frac{5}{8}$  | 40 | $\frac{7}{8}$  |

**Forging Presses.**—The power of forging presses for the average line of work is approximately as follows: For mild steel at a fair heat, a pressure of from 3 to 5 tons per square inch on the faces of the tools is generally sufficient, but when swages or dies are used, it may be necessary to double these pressures. For the very hardest steels, the pressure required may be as high as 10 or even 15 tons per square inch, but this is an exceptional case. For small forgings, including such parts as can be made from 8-inch square blooms or 12- by 6-inch flats, a press of 300 tons is sufficient, and for larger forgings, such as those used for heavy marine shafts and cranks, a 3000-ton press is generally considered sufficient and can readily handle a 60-inch ingot. The table above indicates, in a general way, the capacity of presses for handling ingots of various diameters.

Table 65. Capacity of Forging Presses

| Capacity of Press, Tons | Maximum Diam. of Ingots, Inches | Capacity of Press, Tons | Maximum Diam. of Ingots, Inches |
|-------------------------|---------------------------------|-------------------------|---------------------------------|
| 300                     | 10                              | 1500                    | 36                              |
| 500                     | 14                              | 2000                    | 48                              |
| 800                     | 20                              | 3000                    | 60                              |
| 1200                    | 27                              | 4000                    | 72                              |

A press of comparatively small capacity may, with suitable appliances, handle work that is really too heavy for it, but at some sacrifice of speed; for economical operation, there should be ample power. As is generally known, the forging press is superior to the steam hammer for comparatively large forgings, because the hammer tends to spread the surface metal without acting upon the center of the ingot to the required degree. With a press, the forging action goes right to the center of the ingot, as evidenced by the bulging that takes place at the sides, and if there is a cavity in the ingot, forging under the press closes it, whereas a hammer, by spreading the surface metal, may tend to enlarge it. As forgings diminish in size, the difference in favor of the press is less marked. Owing to the recent increase in the operating speed of forging presses, however, they now compete with power hammers in the forging of comparatively light work, and the range of presses has been greatly extended.

**Air Pressures and Pipe Sizes for Forges.**—Blacksmiths' forges require air pressures varying from  $1\frac{1}{2}$  to 6 ounces per square inch. Small forges with the blower close to them are adequately supplied with  $1\frac{1}{2}$  ounce pressure. If the blower is some distance away and a long discharge pipe with many bends leads to the forge, even though the latter be small, it may be necessary to carry 3 ounces pressure or more, to overcome the friction in the air ducts. Large forges usually require from 3 to 6 ounces pressure. The table, "Air Pressures and Pipe Sizes for Forges," gives the diameters of discharge mains for various tuyere sizes and numbers of forges.

**Table 66. Air Pressures and Pipe Sizes for Forges**

| Diam.<br>Forge Tuy-<br>ere, Inches | Number of Forges Supplied by Blower       |                |                |                |                |                |                |    |    |    |
|------------------------------------|---|----------------|----------------|----------------|----------------|----------------|----------------|----|----|----|
|                                    | 1   | 2              | 3              | 4              | 5              | 6              | 7              | 8  | 9  | 10 |
|                                    | Diameter Discharge Main at Blower, Inches |                |                |                |                |                |                |    |    |    |
| $\frac{3}{4}$                      | $1\frac{1}{2}$                            | $1\frac{1}{2}$ | 2              | 2              | $2\frac{1}{2}$ | $2\frac{1}{2}$ | 3              | 3  | 3  | 3  |
| 1                                  | $1\frac{1}{2}$                            | 2              | $2\frac{1}{2}$ | 3              | 3              | $3\frac{1}{2}$ | $3\frac{1}{2}$ | 4  | 4  | 4  |
| $1\frac{1}{4}$                     | 2   | $2\frac{1}{2}$ | 3              | $3\frac{1}{2}$ | 4              | 4              | $4\frac{1}{2}$ | 5  | 5  | 5  |
| $1\frac{1}{2}$                     | 2   | 3              | $3\frac{1}{2}$ | 4              | $4\frac{1}{2}$ | 5              | 6              | 6  | 6  | 6  |
| $1\frac{3}{4}$                     | $2\frac{1}{2}$                            | $3\frac{1}{2}$ | 4              | $4\frac{1}{2}$ | 5              | 6              | 6              | 7  | 7  | 7  |
| 2                                  | 3   | 4              | $4\frac{1}{2}$ | 5              | 6              | 7              | 7              | 8  | 8  | 8  |
| $2\frac{1}{4}$                     | 3   | 4              | 5              | 6              | 7              | 7              | 8              | 9  | 9  | 9  |
| $2\frac{1}{2}$                     | $3\frac{1}{2}$                            | 5              | 6              | 7              | 8              | 8              | 9              | 9  | 10 | 10 |
| $2\frac{3}{4}$                     | 4   | 5              | 6              | 7              | 8              | 9              | 10             | 10 | 11 | 11 |
| 3                                  | 4   | 6              | 7              | 8              | 9              | 10             | 11             | 11 | 12 | 12 |
| $3\frac{1}{2}$                     | $4\frac{1}{2}$                            | 7              | 8              | 9              | 10             | 11             | 12             | 13 | 14 | 14 |
| 4                                  | 6   | 8              | 9              | 11             | 12             | 13             | 14             | 15 | 16 | 17 |

American Blower Co.

**The Cold Swaging Process.**—Cold swaging is a method of reducing or forming steel or other material while cold, by drawing to a point or reducing the diameter, as may be required. This is performed by a machine that causes the work to be struck a large number of successive blows by a pair of dies shaped to give the required form. This process is principally applied to the reduction of wires, rods and tubes, and is the only method by which rolled or plated stock can be reduced without destroying the plating or coating. For this reason, it is largely employed for jewelers' work. It is also extensively used for pointing rods or tubes which are to be drawn. The process is used in the manufacture of needles, bicycle spokes, button hooks, crochet needles, etc.

**Forging Machines.**—Some forging machines are intended especially for bolt and rivet heading, and others for more general work. The form or shape into which a part is forged is governed by dies of the required shape and also by a heading tool or plunger which bends or upsets the heated bar of metal and forces it into the die impression. The die may have a single impression, or two or three impressions may be required in order to forge the part by successive operations.

**Dies for Bolt and Rivet Forging Machines.**—Bolt and rivet dies used in forging machines are, as a rule, made from steel containing from 0.60 to 0.80 per cent carbon and are hardened and drawn. The heading tool, which must be tougher than the dies, is generally made from steel containing from 0.40 to 0.50 per cent carbon, and is drawn considerably more than the forming dies.

**Dies and Tools Used in Hot-pressed Center-feed Nut Machines.**—The dies used in hot-pressed center-feed nut machines are usually made from chilled iron castings, the dies being ground to size. It is claimed that dies made from this material will last fully eight times as long as those made from ordinary carbon steel, but as it is somewhat difficult to obtain the proper amount of chill, many manufacturers use a good grade of open-hearth crucible steel instead. A crucible steel which is found to give good results contains from 0.90 to 1.10 per cent carbon. In many cases, vanadium alloy steel is used for dies for nut forging machines. The composition of vanadium steel for dies varies. Two grades of vanadium tool steel are recommended for forging machine dies by the American Vanadium Co., of Pittsburgh, Pa. One is composed of carbon, 0.50 per cent; chromium, from 0.80 to 1.10 per cent; manganese, from 0.40 to 0.60 per cent; vanadium, not less than 0.16 per cent; silicon, not more than 0.20 per cent. The heat-treatment recommended for this steel is as follows: Heat to 1550 degrees F. and quench in oil; then reheat to from 1425 to 1450 degrees F., and quench in water, submerging the face of the die only.

The second kind of vanadium tool steel recommended has the following analysis: Carbon, from 0.65 to 0.75 per cent; manganese, from 0.40 to 0.60 per cent; vanadium, not less than 0.16 per cent; silicon, not more than 0.20 per cent. The heat-treatment for this steel should be as follows: Heat to 1525 degrees F. and quench in water, with only the face of the die submerged. Ordinary carbon tool steel dies should be drawn to a light straw color.

**Bulldozer Dies.**—Many of the tools or dies used on bulldozers are made of cast iron, in order to reduce the cost, and those parts of the dies which are subjected to wear are faced with hardened steel plates which may readily be replaced, if necessary. Whenever hot punching or cutting is done, high-speed self-hardening steel should be used for the working members of the tool.

**Helve Hammers.**—Power hammers of the helve type are adapted especially for relatively light forging operations, particularly when a rapid succession of blows is required. Ordinary helve hammers are usually built in sizes ranging from 15 to 200 pounds, this rating being based upon the weight of the hammer head. Some "upright helve" hammers are made in sizes up to 500 pounds.

**Vertical Power Hammers.**—Vertical power hammers of the crank- and pneumatically-operated types are used for general forging operations, especially on the lighter classes of work. Power hammers of the vertical type usually range in size from 25 pounds up to 500 pounds.

**Efficiency of Forging Hammers.**—The Heim method for determining the efficiency of forging hammers is based on the results of numerous tests conducted by allowing an ordinary drop-hammer to fall a predetermined distance upon a pure lead cylinder, the height of which is 1.5 times its diameter. The diameters of the cylinders which have been adopted for use in testing various sizes of hammers (with regard to their falling weight) are given in [Table 67](#). The following formula gives the number of foot-pounds of work done by one blow of the hammer:

$$\text{Work} = 36.75D^3 [8.85A + 13.12(A^2 + A^4)] \text{ foot-pounds}$$

Where  $D$  = Diameter of the lead cylinder;

$$A = (H - H_1) \div H$$

$H$  = Original height of the cylinder

$H_1$  = height of the cylinder after being struck by the hammer.

If the expression inside the brackets in the formula is designated by  $B$ , the formula may be expressed in the following form:

$$\text{Work} = 36.75D^3 B$$

After the lead cylinder has been struck by the hammer, the value of  $A$  is calculated and the number of foot-pounds of work developed by the hammer is then obtained by taking the value of  $B$  from Table 68 and substituting in the formula.

*Example:* Suppose a 100-kilogram (220-pound) hammer striking 180 blows per minute is allowed to strike a lead cylinder, the original dimensions of which are 50 millimeters (1.97 inch) in diameter by 75 millimeters (2.95 inches) high. After the blow has been struck, the resulting height of the cylinder is 48 millimeters (1.90 inch). From the preceding formula:

$$A = \frac{2.95 - 1.90}{2.95} = 0.35$$

$B = 4.9$ , from Table 68

Substituting the values of  $D$  and  $B$  in the formula for the work done by one blow of the hammer:

$$36.75 \times 1.97^3 \times 4.9 = 1376 \text{ foot-pounds} = \text{work done by one blow.}$$

$$\frac{1376 \times 180}{60} = 4128 \text{ foot-pounds} = \text{work done by one blow.}$$

The maximum power required to drive the hammer is 10.3 horsepower. As one horsepower is equivalent to 550 foot-pounds of work per second, the amount of power consumed by the hammer per second is:  $10.3 \times 550 = 5665$  foot-pounds. The efficiency of the is found to be:

$$\text{Efficiency} = \frac{\text{useful work}}{\text{power supplied}} = \frac{4128}{5665} = 72 \text{ percent.}$$

The Heim formula and method of testing may be applied to all types of hammers, but, when used on steam hammers, the test must be made while the hammer is running continuously and not when set to deliver a single blow.

**Table 67. Dimensions of Lead Plugs Used for Testing Various Sizes of Hammers**

| Falling Weight of Hammer |           | Diameter of Lead Cylinder <sup>a</sup> |             | Falling Weight of Hammer |           | Diameter of Lead Cylinder |             |
|--------------------------|-----------|--|-------------|--------------------------|-----------|---------------------------|-------------|
| Pounds                   | Kilograms | Inches                                 | Millimeters | Pounds                   | Kilograms | Inches                    | Millimeters |
| 66                       | 30        | 1.18                                   | 30          | 330                      | 150       | 2.36                      | 60          |
| 110                      | 50        | 1.38                                   | 35          | 506                      | 230       | 2.76                      | 70          |
| 165                      | 75        | 1.57                                   | 40          | 770                      | 350       | 3.15                      | 80          |
| 220                      | 100       | 1.97                                   | 50          | 1100                     | 500       | 3.54                      | 90          |

<sup>a</sup> Height equals  $1.5 \times$  diameter.

**Table 68. Values of Factors Used in Calculating Power of Hammers**

|   |      |      |      |      |      |      |      |      |      |       |       |
|---|------|------|------|------|------|------|------|------|------|-------|-------|
| A | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.35 | 0.40 | 0.45 | 0.50 | 0.55  | 0.60  |
| B | 1.01 | 1.63 | 2.31 | 3.08 | 3.94 | 4.90 | 5.97 | 7.17 | 8.52 | 10.03 | 11.73 |

### Machinery and Hammer Foundations

The materials commonly used are concrete, stone, brick, and wood in conjunction with concrete for machines subjected to considerable vertical shock. The principal characteristics of these materials are briefly as follows: Concrete is an ideal foundation material, as it becomes practically one solid piece and is much cheaper than a masonry foundation. Stone, in addition to being strong and durable, has great vibrations absorbing power, but is quite costly. Brick is not so durable as stone, but is cheaper and available everywhere. In building a foundation, provision should be made for the foundation bolts, when these are necessary. Sometimes the bolts are set permanently in the foundation, or they may be placed in pipes and have pockets at the lower ends, thus permitting adjustment or removal, if necessary. The bolts are usually located in the proper position by making a wooden templet in which holes are bored to coincide with the holes in the machine base. The inclination of the sides of a foundation should vary from  $1\frac{1}{2}$  to 3 inches per foot from the vertical. The foundation pit should be excavated below the frost line of the locality.

**Concrete Foundations.**—The timber used for making the forms in which concrete foundations are molded should be about 1 inch thick, dressed on the inner side to give a smooth surface. The form should be braced externally about every  $2\frac{1}{2}$  feet, and internally about every foot in height. As the form is being filled, the inside braces can be removed. If pocket molds are used for the lower ends of the bolts, they should be soaked in water two or three hours before using, to prevent their swelling and sticking in the concrete. Do not use concrete that has been mixed over twenty minutes. Ram with hammers weighing about 1 pound per square inch of face area, the ramming being continued until water just shows at the surface.

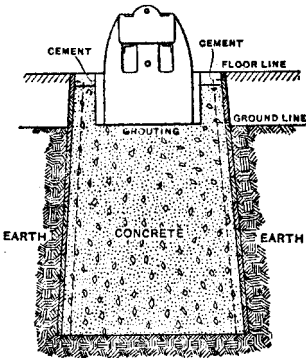


Fig. 1.

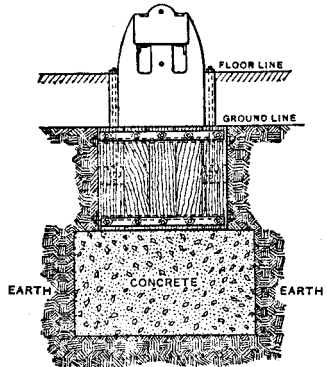


Fig. 2.

Put down the concrete in layers about 6 inches thick and work it onto the form with a shovel, to obtain a smooth, even surface. The foundation may be partly filled with stones about the size of a man's head, placed approximately one foot apart and not less than one foot from the foundation surfaces. These stones should be wet before laying. If the work is stopped at night before completion, make grooves in the surface and when starting the next

day, sprinkle and dust over with dry cement. As soon as the concrete has set, remove the form, as it is much easier to patch when the cement is somewhat "green." Foundations are sometimes "slushed" instead of being rammed. In this case, the concrete is mixed just wet enough so that it cannot be piled up. It is then dumped into the molds and worked in them to prevent air bubbles. The first method gives a more homogeneous structure as there is no chance for the broken stones to settle. When the machine is in position, the space around the foundation bolts may be filled with liquid cement, lead or melted sulphur.

**Drop Hammer Foundations.**—The following drop-hammer foundations are recommended by the E. W. Bliss Company:

*Concrete Foundation:* Excavate a hole from 10 to 14 feet deep and from 8 to 12 feet square; build up a block of concrete with tapering sides, as shown in Fig. 63, having a top about 6 to 12 inches wider, all around, than the base of the anvil. Place the anvil in position and wedge it level; then run a thin mixture of concrete the anvil and allow it to set. Next move the wedges and build up a wall of concrete from 4 to 6 inches thick around the anvil. (See Fig. 1 and Fig. 2) This will make the use of bolts unnecessary and the anvil will set solid and will not be likely to shift. Solid concrete makes an excellent foundation that does not deteriorate, as is the case with timber when subjected to dampness from the earth or atmospheric moisture. Another advantage is that it is almost impervious to sparks or hot pieces of metal.

*Timber Concrete Foundations:* Excavate a hole somewhat larger than the anvil or base of the hammer. At the bottom lay a bed of concrete from 1 to 2 feet thick, as shown in Fig. 2. On this concrete bed place, endwise, Georgia pine timbers 12 by 12 inches by 6 to 8 feet long. These should be securely strapped together by steel bands on the outside fastened with through bolts. The timber base should preferably be a little larger than the anvil. To preserve the timbers coat them with oil of tar or creosote. The tops of the timbers should be dazed off evenly to obtain a level surface for the anvil. Another method of making a foundation of this kind, for small and medium sized hammers, is to put the timbers upon a foot or more of gravel rammed down on a hard-pan bottom. When the timbers, which are also placed endwise and bolted, are in position, the space around the sides is filled with gravel tightly rammed.

**Foundation for Steam Hammer.**—To secure the greatest efficiency from steam power hammers, the foundations on which they are mounted must be solid concrete resting upon hard-pan has given better results than the combination of heavy wooden beams and concrete often used. When making solid concrete foundations, there should be several inches of cement placed over the concrete, and a cushion of wood, at least 3 inches tuck, between the cement and base of the anvil, to give the necessary resiliency and prevent the concrete from being pulverized by the impact of the blows. In the front and rear of the hammer there should be openings down to the level of the anvil base, so that it can be leveled or adjusted by wedging and grouting with cement, in case it should sag or get out of alignment with the upper parts of the hammer. These openings can be covered with hatches set level with the floor.

### Machine and Forge Shop Floor Materials

Machine shop floors are commonly made of wood or concrete. Probably there is no floor for the machine shop as good as one made of selected hard maple, properly laid and supported, as it wears smoothly and evenly. Concrete, however, has its advantages, the most important of which is its fire-resisting qualities. There are few objections to a wooden floor, and from the standpoint of health it is generally considered superior to concrete. Where there is much heat, or large quantities of moisture or chemicals in bulk, wooden floors should not be used. In certain classes of store-rooms, or where there is a likelihood of considerable moisture, as in wash rooms, concrete floors are considered superior to wood.

**Concrete and Wooden Floors.**—The following information on shop floors and their materials is abstracted from a paper by Mr. L. C. Wason read before the American Society of Mechanical Engineers. While the factor of cost is to be considered first, very often the maintenance and adaptability for the particular Service required is of first importance. The initial cost of a granolithic floor surface is at no disadvantage compared with a wooden floor, as the cost of such a surface laid in the best manner is about equal to the cost of seven-eighths maple flooring. In addition, the granolithic surface is fire-proof and will not decay or disintegrate as the result of moisture, which is one of the weak points of the wooden floor. On the other hand, a wooden floor is more easily repaired than a granolithic surface. In making a comparison between wooden and granolithic floors, it is also necessary to consider the workmanship. With a maple top floor, the wearing quality depends comparatively little on the skill of the one who lays the floor, but with a granolithic finish, the work must be done care fully and intelligently. Among the objections to the granolithic surface, one of the most prominent is the bad effect of a concrete floor upon the health and comfort of the workmen. This is not due to the hardness of the floor, but rather to its heat conductivity. When a workman stands for hours on a concrete floor, the heat of the body is conducted to the floor quite rapidly, which tends to disarrange the circulation and cause physical ailments, such as rheumatism, etc. For men working steadily at machines, and usually in one position, this objectionable feature can be overcome by the use of insulating foot-boards or wooden gratings upon which to stand.

The dust produced by the wear of some granolithic surfaces has proved harmful to delicate machinery, whereas a wooden floor does not of itself produce a dust capable of any appreciable abrasive action. It is possible, however, by gluing battleship linoleum to concrete floors, to obtain many of the advantages of a wooden surface. Linoleum is also an effective insulation against the loss of bodily heat.

High resistance to wear and practically complete dustlessness can be secured in a granolithic surface if properly made. To secure a durable and practically dustless floor, proceed as follows: Do not use sand, as sand grains are quickly broken by abrasion and form dust. The granolithic finish should contain the highest possible proportion of tough stone aggregate. Use stone suitable for macadam road, and of a size that will pass through a half-inch round mesh screen, but use nothing smaller than that passed by a 20-mesh screen. Mix the concrete dry, and of a consistency for making blocks, so that considerable tamping will be required to bring enough water to the surface for troweling. Finally, do the troweling before the mortar sets. Prolonged troweling of a wet mixture brings to the top the "laitance" of the concrete, which is the part incapable of a true set. A top layer of laitance is therefore porous and wears down quickly. Even the fine particles of good cement should not be brought to the surface, as they form a layer which is weakly bonded to the rest of the concrete and wears away rapidly, appearing in the air as dust.

**To Prevent Dust on Concrete Floors.**—The Aberthaw Construction Co. of Boston, contracting engineers specializing in concrete, recommends the following method of curing a dusty concrete floor: Have the surface entirely dry; then paint it with a mixture of boiled linseed oil thinned with gasoline. Apply several coats, until the oil shows glossy on the top. The theory of this is that the linseed oil, having been boiled, has lost most of its volatile components and is practically permanent. The gasoline thins this down enough so that it will strike into the pores. A little experimenting will show the proper proportions. The thinner it is, the more coats will be required and the deeper it will strike in. A floor that is causing serious trouble from dust can often be cured with very little trouble and expense in this way.

**Floors for Forge Shops.**—There is considerable difference in opinion as to the best material for blacksmith shop flooring. Wood is too inflammable, bricks crack and break from the heat, cement or concrete has the same objectionable features, and asphalt is out of the question. Perhaps nothing is superior to or cheaper than dirt mixed with ashes. If kept moist by sprinkling at least once a day, it is more comfortable to stand upon than the other mate-

rials mentioned. It is easily repaired and leveled in case holes are worn in it, and is not affected by dropping heavy or hot pieces upon it. The space between the walls and forges, however, may be covered with concrete to facilitate the handle of such appliances as portable surface-plates and vises.

### Drop-Forging Dies

**Steel for Drop-forging Dies.**—Practically all drop-forging dies are made of high-grade open-hearth steel. A 60-point carbon steel is mostly used, although steel as low as 40-point and as high as 85-point carbon is employed in some cases. A special hardening treatment is required for the low-carbon steel, which more than offsets the saving in price, and, except in special cases, there is no advantage in using high-carbon steels, owing to the expense. The average 60-point carbon steel die, if properly hardened, should last for from 15,000 to 40,000 forgings, and sometimes as many as 70,000 forgings can be made from one set of dies. When making dies for large forgings, it is often thought advisable to use 80-point carbon steel, and not harden the dies. This obviates the danger from “checking” or cracking in hardening, and the un-hardened steel is hard enough to resist the tendency to stretch. A steel that is quite high in carbon should always be used for dies that are intended for making forgings from tool steel or any other hard steel.

**Allowance for Shrinkage.**—When making dies for small cold-trimmed steel forgings, the proper allowance for shrinkage is  $\frac{3}{16}$  inch to the foot, or 0.015 inch to the inch. Such forgings are finished at a bright red heat and the rate of shrinkage is considerable. When making dies for hot-trimmed steel forgings of medium and large sizes, the shrinkage allowance is  $\frac{1}{8}$  inch to the foot, or 0.010 inch to the inch. Hot-trimmed forgings receive the finishing blow while comparatively cold, and shrink a smaller amount than the cold-trimmed forgings. The foregoing allowances are used for all dimensions of the die impression, such as depth, width or length. The shrinkage allowance for dies to be used in forging bronze or copper is practically the same as that for steel.

**Draft Allowance.**—The amount of draft in a drop-forging die varies from 3 to 10 degrees. If the die is for a thin forging of uniform section, 3 degrees is ample, but if the forging is deep and has narrow ribs which are apt to stick, at least 7 degrees is necessary. If a die is used for forging a piece that is ring-shaped or has an annular part, the central plug that forms the interior of the ring should have a draft of 10 degrees, because, as the forging cools while being worked, it tends to shrink around the plug and if the draft is insufficient, it will stick in the die. With the foregoing exception, most drop-forging dies have a 7-degree draft. For convenience in laying out, it is well to remember that a 7-degree taper is approximately equal to a  $\frac{1}{8}$ -inch taper to the inch, and a 10-degree taper,  $\frac{3}{16}$  inch to the inch.

**Locating Impression in the Die.**—When laying out a drop-forging die, the impression should be located so that the heaviest end of the forging will be at the front of the die-block. This makes the forging easier to handle and also permits the use of a fairly large sprue. There should be at least  $1\frac{1}{2}$  inch left all around between the impression and the outside edge of the block. This also holds true for any part of the die, such as the edger, anvil or forming impression. If the forging has a hub or other projection that extends some distance from the main part on one side, the upper or top die should contain this deeper impression.

**Obtaining Weight of Forging from Lead Proof.**—After the upper and lower dies have been completed, shrinkage allowances and the general finish of the impressions are ordinarily tested by taking a “lead proof,” and by weighing the lead, an approximate idea of the weight of the finished forging can be obtained. Roughly speaking, the finished forging will weigh two-thirds as much as the lead proof. The shrinkage of lead is practically the same as that of steel, so that the finished forging will also measure about the same as the one made of lead. In case of dies for eye-bolts and similar work, this rule must be disregarded, because the plugs that form the central opening will prevent the lead from shrinking natu-



rally. When taking the lead proof, the die impressions are dusted with powdered chalk, and after the dies are clamped together, the molten lead is poured.

**Amount of Flash for Drop-forging Dies.**—Theoretically, there should be just enough forging metal in a die to fill the impression, and no more, but this is, of course, not practicable, as there is always some stock that must be disposed of after the impression is filled. To take care of this excess metal, dies are relieved all around the impression by milling a flat shallow recess about  $\frac{1}{64}$  inch deep and  $\frac{5}{8}$  inch wide. These dimensions are for dies of average size; in comparatively large dies this recess or “flash” would be a little deeper and wider. Both the upper and lower dies are flashed in this way. In addition, the upper die is “back-flashed,” which means that there is a deeper recess, sometimes called the “gutter,” milled around the impression at a distance of  $\frac{1}{4}$  inch from the impression at every point. This back-flash is  $\frac{3}{64}$  inch deep and acts as a relief for the excess metal after it has been squeezed from the flash proper. Only the finishing impression is provided with a flash and back-flash.

**The Break-down of Drop-forging Dies.**—The width of section used as a break-down (also known as the edger or side cut) should be enough wider than the forging to give plenty of room for the work of forging. A forging 1 inch thick should have a break-down  $1\frac{1}{2}$  inch wide, and about the same proportions should be followed for forgings of other widths. The break-down should have a section corresponding with the gate and sprue of the die impression, but it should be made slightly longer, so that the forging will not be stretched when struck in the impression.

**Hardening Drop-forging Dies.**—Dies to be carburized should always be packed for hardening in cast-iron or sheet-iron boxes containing a mixture of fresh bone and charcoal. The ordinary mixture is half bone and half charcoal. More bone gives greater hardness and more charcoal, less hardness, for a given heat; hence, the proportions should be varied according to requirements. The die should be packed face down on a one- or two-inch layer of this mixture and be settled so that the impression is filled. Sometimes the face is coated, before packing, with a thick paste of linseed oil and powdered bone-black, to protect the delicate edges from oxidation when in contact with the air. Fill the space between the sides of the die and the box with the bone and charcoal mixture, and cover over with a thick layer of wet clay paste to prevent the charcoal from burning out. Dies made of steel having less than 60-point carbon content should always be carburized. Open-hearth steel dies containing 60-point carbon or over can be hardened without carburizing.

**Heating the Die.**—An oil or gas furnace is recommended for heating, although a coal or coke-fired muffle furnace, capable of maintaining a temperature of at least 1600 degrees F., may be used, provided the temperature can be held constant. A temperature indicating device is necessary. The die should be put into the furnace as soon as the latter is lighted. If the correct quenching temperature for the steel is, say, 1500 degrees F., the furnace should be checked when the pyrometer indicates 1400 degrees, the die being allowed to “soak” at that heat for three or four hours. Then the heat should be slowly raised to 1500 degrees and held at that point one or two hours longer, according to the size of the die. Five hours is the minimum total time for heating, and seven or eight hours is much safer. A 60-point carbon die should be quenched between 1425 and 1450 degrees F.

**Cooling the Heated Die.**—When cooling, the face of the die should receive a sufficient flow of cold water to cause it to harden to the greatest possible depth. The back of the die should, at the same time, be cooled to make the shrinkage of the face and back equal, and to prevent warping. A good form of cooling tank is one having a large supply pipe extending up through the bottom for cooling the die face, and a smaller pipe above the tank to cool the back. Unless a jet of water under pressure is applied to the face of the die, the sunken parts of the impression will not harden equally with the face. Dies should not be cooled in a tank of still water, because steam forms in the die cavity which prevents the water from enter-

ing, thus causing the formation of soft spots. To overcome this, the water must be forced into the impression by pressure sufficient to overcome the resistance of the steam thus formed. Oil should not be used for hardening hammer dies, as its cooling action is not great enough to produce a sufficient depth of hardening. Hammer dies which are simply surface hardened will not withstand the heavy blows received in service. To secure a greater hardening effect, brine of about 40 per cent solution is used by some die-makers.

**Tempering Dies.**—Dies should be tempered and drawn as soon as they are cool enough to remove from the tank. The dies should be heated in an oil bath, and quenched in water or cool oil. Any high-grade cylinder oil of high flash-point is suitable. Low-grade oils smoke unpleasantly and will not stand high temperatures. The drawing temperature of die steels is about 450 degrees F., for average conditions. The corners of the die and the cut-off should be drawn to a purple color with the aid of a blow torch.

**Dies for Bronze and Copper Forgings.**—Dies for producing drop-forgings from bronze or copper differ from those used for steel or iron forgings principally in the matter of finish. Owing to the softness of copper and bronze, the metal is driven into very minute impressions in the surface of the dies; hence, these surfaces must be perfectly free from scratches, in order to insure a smooth finish on the work. Even though these metals are soft, the hammering necessary when forging is very hard on the dies, and to prevent them from dishing or spreading, tool steel is ordinarily used, unless the forgings are extra large and heavy. The shrinkage, draft and finish allowances on this class of drop-forging dies are practically the same as on dies for steel and iron.

**Trimming Dies for Drop-forgings.**—Hot-trimming dies are made of a special grade of steel known as hot-trimming die-stock. The objection to use ordinary tool steel for hot-trimming dies is that the edges of a hardened die check badly after the die has been used for a short time, and this checking is followed by a breaking away of the steel around the edges, thus rendering the die unfit for use. This special steel requires no hardening, and after the die is in use, the edges toughen and give better service than the best hardened tool steel. The usual form of punch for hot-trimming dies merely supports the forging while it is being pushed through. If the forging has a broad, flat top face, the punch need only be a little more than a flat piece that covers the forging and acts as a pusher. Such punches are commonly made of cast iron. Cold-trimming dies are made from good tool steel of from 1.00 to 1.25 per cent carbon, and hardened and drawn to a dark straw color. The punches for cold trimmers are also made of tool steel and are hardened and drawn to a very dark straw color. These punches are hardened to prevent them from upsetting at the edges. As with hot-trimming punches, the punch should fit the die loosely, but it should support the forging at every point while it is being pushed through the die. There are two instances in which trimming punches should fit the dies as closely as the average punching die for sheet metal work; first, when trimming forgings on which the fin comes at the corner of the forging; second, forgings that are formed all in one die, the other die being flat. In these two cases, unless the dies fit very well, there will be burrs at the trimmed edges.

**Standard Tolerances for Forgings.**—The tolerances adopted by the Drop Forging Association in 1937 (see accompanying [Tables 69](#) through [73](#)) apply to forgings under 100 pounds each. Forging tolerances may either be "special" or "regular." *Special tolerances* are those which are particularly noted in the specifications and may state any or all tolerances in any way as required. Special tolerances apply only to the particular dimensions noted. In all cases where special tolerances are not specified, regular tolerances apply.

**Table 69. Standard Tolerances for Forgings Adopted, 1937,  
by Drop Forging Association for Forgings under 100 Pounds Each**

| Thickness Tolerances, Inch <sup>a</sup> |            |      |       |      |                                 |            |      |       |      |
|---|------------|------|-------|------|---------------------------------|------------|------|-------|------|
| Net Weights,<br>Pounds, up to –         | Commercial |      | Close |      | Net Weights,<br>Pounds, up to – | Commercial |      | Close |      |
|   | –          | +    | –     | +    |                                 | –          | +    | –     | +    |
| .2                                      | .008       | .024 | .004  | .012 | 20                              | .026       | .078 | .013  | .039 |
| .4                                      | .009       | .027 | .005  | .015 | 30                              | .030       | .090 | .015  | .045 |
| .6                                      | .010       | .030 | .005  | .015 | 40                              | .034       | .102 | .017  | .051 |
| .8                                      | .011       | .033 | .006  | .018 | 50                              | .038       | .114 | .019  | .057 |
| 1                                       | .012       | .036 | .006  | .018 | 60                              | .042       | .126 | .021  | .063 |
| 2                                       | .015       | .045 | .008  | .024 | 70                              | .046       | .138 | .023  | .069 |
| 3                                       | .017       | .051 | .009  | .027 | 80                              | .050       | .150 | .025  | .075 |
| 4                                       | .018       | .054 | .009  | .027 | 90                              | .054       | .162 | .027  | .081 |
| 5                                       | .019       | .057 | .010  | .030 | 100                             | .058       | .174 | .029  | .087 |
| 10                                      | .022       | .066 | .011  | .033 |                                 |            |      |       |      |

<sup>a</sup> Thickness tolerances apply to the over-all thickness. For drop-hammer forgings, they apply to the thickness in a direction perpendicular to the main or fundamental parting plane of the die. For upset forgings, they apply to the thickness in the direction parallel to the travel of the ram, but only to such dimensions as are enclosed by the actually formed by the die.

**Table 70. Standard Tolerances for Forgings Adopted, 1937,  
by Drop Forging Association for Forgings under 100 Pounds Each**

| Shrinkage                           |                           | Plus            |                            | Die Wear                  |                 | Mismatching                        |                 |       |
|-------------------------------------|---------------------------|-----------------|----------------------------|---------------------------|-----------------|------------------------------------|-----------------|-------|
| Lengths or<br>widths up to<br>– in. | Com-<br>mercial<br>+ or – | Close +<br>or – | Net wt.<br>up to –<br>lbs. | Com-<br>mercial<br>+ or – | Close +<br>or – | Net Weights,<br>Pounds, up<br>to – | Com-<br>mercial | Close |
| 1                                   | .003                      | .002            | 1                          | .032                      | .016            | 1                                  | .015            | .010  |
| 2                                   | .006                      | .003            | 3                          | .035                      | .018            | 7                                  | .018            | .012  |
| 3                                   | .009                      | .005            | 5                          | .038                      | .019            | 13                                 | .021            | .014  |
| 4                                   | .012                      | .006            | 7                          | .041                      | .021            | 19                                 | .024            | .016  |
| 5                                   | .015                      | .008            | 9                          | .044                      | .022            | 25                                 | .027            | .018  |
| 6                                   | .018                      | .009            | 11                         | .047                      | .024            | 31                                 | .030            | .020  |

For each additional inch under shrinkage, add 0.003 to the commercial tolerance and 0.0015 to the close tolerance. For example, if length or width is 12 inches, the commercial tolerance is plus or minus 0.036 and the close tolerance plus or minus 0.018.

For each additional 2 pounds under die wear, add 0.003 to the commercial tolerance and 0.0015 to the close tolerance. Thus, if the net weight is 21 pounds, the die wear commercial tolerance is 0.062 plus or minus, and the close tolerance 0.031 plus or minus.

For each additional 6 pounds under mismatching, add 0.003 to the commercial tolerance and 0.002 to the close tolerance. Thus, if the net weight is 37 pounds, the mismatching commercial tolerance is 0.033 and the close tolerance 0.022.

**Table 71. Standard Tolerances for Forgings Adopted, 1937, by Drop Forging Association for Forgings under 100 Pounds Each**

| Draft angle tolerances — the permissible variations from the standard or nominal draft angle |                       |                   |              |                       |                       |                   |              |
|--|-----------------------|-------------------|--------------|-----------------------|-----------------------|-------------------|--------------|
| Drop-Hammer Forgings   |                       |                   |              | Upset Forgings        |                       |                   |              |
| Location of Surface  | Nominal Angle Degrees | Commercial Limits | Close Limits | Location of Surface   | Nominal Angle Degrees | Commercial Limits | Close Limits |
| Outside  | 7                     | 0-10              | 0-8          | Outside               | 3                     | 0-5               | 0-4          |
| Holes and Depressions  | 10<br>7               | 0-13<br>...       | ...<br>0-8   | Holes and Depressions | 5                     | 0-8               | 0-7          |

**Table 72. Standard Tolerances for Forgings Adopted, 1937, by Drop Forging Association for Forgings under 100 Pounds Each**

| Quantity Tolerances       |                       |                   |                           |                       |                     |
|---------------------------|-----------------------|-------------------|---------------------------|-----------------------|---------------------|
| Number of Pieces on Order | Permissible Variation |                   | Number of Pieces on Order | Permissible Variation |                     |
|                           | Over-run, Pieces      | Under-run, Pieces |                           | Over-run, Per cent    | Under-run, Per cent |
| 1 - 2                     | 1                     | 0                 | 100 - 199                 | 10                    | 5.0                 |
| 3 - 5                     | 2                     | 1                 | 200 - 299                 | 9                     | 4.5                 |
| 6 - 19                    | 3                     | 1                 | 300 - 599                 | 8                     | 4.0                 |
| 20 - 29                   | 4                     | 2                 | 600 - 1,249               | 7                     | 3.5                 |
| 30 - 39                   | 5                     | 2                 | 1,250 - 2,999             | 6                     | 3.0                 |
| 40 - 49                   | 6                     | 3                 | 3,000 - 9,999             | 5                     | 2.5                 |
| 50 - 59                   | 7                     | 3                 | 10,000 - 39,999           | 4                     | 2.0                 |
| 60 - 69                   | 8                     | 4                 | 40,000 - 299,999          | 3                     | 1.5                 |
| 70 - 79                   | 9                     | 4                 | 300,000 up                | 2                     | 1.0                 |
| 80 - 99                   | 10                    | 5                 |                           |                       |                     |

These quantity tolerances represent the permissible over-run or under-run allowed for each release or part shipment of an order. Any shipping quantity within the limits of over-run or under-run shall be considered as completing the order.

**Table 73. Standard Tolerances for Forgings Adopted, 1937, by Drop Forging Association for Forgings under 100 Pounds Each**

| Maximum Radii of Fillets and Corners, Inch |                |                |                              |                |                |
|--|----------------|----------------|------------------------------|----------------|----------------|
| Net Weights, Pounds, up to —               | Commercial     | Close          | Net Weights, Pounds, up to — | Commercial     | Close          |
| .3   | $\frac{3}{32}$ | $\frac{3}{64}$ | 10                           | $\frac{3}{16}$ | $\frac{3}{32}$ |
| 1  | $\frac{1}{8}$  | $\frac{1}{16}$ | 30                           | $\frac{7}{32}$ | $\frac{7}{64}$ |
| 3  | $\frac{5}{32}$ | $\frac{5}{64}$ | 100                          | $\frac{1}{4}$  | $\frac{1}{8}$  |

*Regular tolerances:* are divided into two divisions — “Commercial Standard” and “Close Standard.” “Commercial Standard” tolerances are for general forging practice, but when extra close work is desired involving additional expense and care in the production of forgings, “Close Standard” may be specified. When no standard is specified, “Commercial Standard” shall apply.

Regular tolerances are applicable to 1) thickness; 2) width, including shrinkage and die wear, mismatching, and trimmed size; 3) draft angle; 4) quantity in shipment; and 5) fillets and corners.

*Thickness Tolerances:* Thickness tolerances shall apply to the overall thickness of a forging. (See [Table 69](#).)

*Width and Length Tolerances:* Width and length tolerances shall be alike and shall apply to the width or length of a forging. When applied to drop hammer forgings, they shall apply to the width or length in a direction parallel to the main or fundamental parting plane of the die, but only to such dimensions as are enclosed by and actually formed by the die. When applied to upset forgings, they shall apply to the width or length in a direction perpendicular to the direction of travel of the ramp.

Width and length tolerances consist of the three subdivisions following: a) Shrinkage and die wear tolerance; b) mismatching tolerance; and c) trimmed size tolerance.

### Welding Methods

**Classes of Welds.**—Welds are classified according to the way the ends are formed prior to making the weld. The different welds ordinarily made in hand forging practice are the scarf weld, butt weld, lap weld, cleft or split weld and jump weld. These welds are shown by the accompanying illustration. It will be seen that the surfaces, in most instances, are rounded or crowned. This is done so that when the heated ends are brought together they will unite first in the center. Any slag or dirt which may have adhered to the heated surfaces will then be forced out as the welding proceeds from the center outward. When making a lap weld, the hammering should begin at the center in order to work all the slag out, as the faces in this case are not rounded.

**Welding Heat.**—When two pieces of wrought iron or mild steel are heated until they become soft and plastic and will stick together when one is pressed or hammered against the other, they have reached what is commonly known as a welding heat. The quality of the weld depends largely upon the welding heat. If the ends to be heated are not hot enough, they will not stick together; inversely, if the work remains in the fire too long, it becomes overheated and burned, which greatly injures the metal. Iron which has been overheated has a rough, spongy appearance and is brittle. The danger of burning is increased when the air blast is too strong and the fire is oxidizing. It is important to heat the work slowly to secure a uniform temperature throughout the ends to be heated. With rapid heating, the outside may be raised to the welding temperature, while the interior is much below it; consequently, the weld will be defective.

**Fire for Welding.**—When heated iron comes into contact with the air it absorbs oxygen, thus forming a scale or oxide of iron on the surface, which prevents the formation of a good weld. A fire for heating parts to be welded should have a fairly thick bed between the tuyere and the work, so that the oxygen in the air blast will be consumed before it reaches the parts being heated. When there is only a thin bed of fuel beneath the work, or if too strong a blast is used, the excess of oxygen will pass through and oxidize the iron. The hotter the iron, the greater the formation of scale. The surface being heated can be given an additional protection by covering it with some substance that will exclude the air. (See "Fluxes for Welding.") Ordinarily, the air blast for a forge fire should have a pressure varying from 3 to 6 ounces per square inch. (See "Air Pressures and Pipe Sizes for Forges.")

**Fluxes for Welding.**—When iron is being heated preparatory to welding, the heated surfaces are oxidized to some extent or covered with oxide of iron, which forms a black scale when the hot iron comes into contact with the air. If this scale is not removed, it will cause a defective weld. Wrought iron can be heated to a high enough temperature to melt this oxide so that the latter is forced out from between the surfaces by the hammer blows; but when welding machine steel, and especially tool steel, a temperature high enough to melt the oxide would burn the steel, and it is necessary to use what is called a flux. This is a substance, such as sand or borax, having a melting temperature below the welding temperature of the work, and it is sprinkled upon the heated ends when they have reached about a yellow heat. The flux serves two purposes: It melts and covers the heated surfaces, thus protecting them from oxidation, and, when molten, aids in dissolving any oxide that may have formed, the oxide melting at a lower temperature when combined with the flux. Wrought

iron can be welded in a clean, well-kept fire without using a flux of any kind, except when the material is very thin. The fluxes commonly used are fine clean sand and borax. When borax is used, it will give better results if burned. This can be done by heating it in a crucible until reduced to the liquid state. It should then be poured onto a flat surface to form a sheet; when cold, it can easily be broken up and pulverized. The borax powder can be used plain or it can be mixed with an equal quantity of fine clean sand and about 25 per cent iron (not steel) filings. For tool steel, a flux made of one part sal-ammoniac and twelve parts borax is recommended. When pieces are put together previous to welding, as in split welds, or when taking a second heat (usually termed a "wash"), a flux that will flow easily should be used. There are many welding compounds on the market, some of which are suited for one class of welding and some for another.

**Fuels for Forge.**—Coke, coal, charcoal, oil and gas are used as fuels for heating iron and steel preparatory to forging or welding. For general work, a coke fire is the best, although bituminous coal is extensively used. With anthracite coal, it is difficult to get a hot enough fire, especially on a small forge. Coke or bituminous coal should be low in sulphur, because sulphur makes the iron "hot short" or brittle while hot. Sulphur, lead, bronze or brass must not be in the fuel or fire to be used for heating iron or steel. A weld may be spoiled by throwing brass filings into a fire before heating the work.

**Machine Welding.**—There are three common types of welds that can be made satisfactorily in a forging machine, simple examples of which are shown in the accompanying illustration.

*Lap-welding:* This is one of the most successful methods that can be used in joining pieces together in a forging machine, whenever requirements will permit. There are several applications of this type of welding: Two pieces can be joined together (as shown in the illustration) or several pieces can be welded together in one block. Machine lap-welding is also employed for enlarging the diameter of a bar, this being accomplished by welding a U-shaped piece of rectangular stock to the end, and then upsetting the mass into the shape desired. An end plunger is used to upset the bar after the latter is securely held between the opposing faces of the gripping dies.

*Pin-welding:* In order to make a pin weld, the end of the bar is reduced and inserted in a hole in the part to which it is to be joined (see illustration). The reduced end is usually made from one-quarter to one-half the diameter of the original bar. The U-shaped piece, or other part which is to be joined to it, is generally made thicker where the weld is made, in order to strengthen the weld. The welding operation is effected by a plunger in the ram of the machine, which upsets the "pin" and at the same time forms the joint.

*Butt-welding:* This method of machine welding is not as common as the other two methods referred to, but is satisfactory when properly applied. To make a butt weld, it is not necessary to prepare the stock beforehand, although the pieces should have practically the desired shape. The weld is effected by a plunger having a pointed end which is forced through the forward member to be joined, thus closely pressing together the material and insuring a solid weld (see illustration).

This method of welding is not considered as practicable as pin-welding, but when properly handled, it is satisfactory for many classes of work. Wrought iron is welded in a forging machine without using any flux but the parts to be joined must be clean and free from scale. As a rule, compressed air is used to remove the scale formed by oxidization. A small jet of air is directed against the work just before the machine is operated. For welding steel having a comparatively high carbon content, it is necessary to use a flux to make a satisfactory weld. (See "Fluxes for Welding.")

## Hydraulic Press

**Rules and Formulas for Hydraulic Press Calculations.**—To find the total pressure of a hydraulic press when the diameter of the ram in inches and the water pressure (gage pressure) in pounds per square inch are given, multiply the area of the cross-section of the ram by the pressure per square inch, and divide by 2000. The result is the capacity of the hydraulic press in tons. The same result may be obtained as follows: Multiply the square of the diameter of the ram by the pressure per square inch, and multiply this product by 0.00039. The result is the total pressure of the press in tons.

The pressure per square inch on the material under pressure in the press can be determined when the total pressure of the press and the area of the material under pressure are known. Multiply the total pressure of the press in tons by 2000, and divide the product by the area of the material to be pressed. The quotient is the pressure in pounds per square inch on the surface of the material.

Table 74. Capacity of Hydraulic Presses

| Diam. of Ram, Inches | Area of Ram, Sq. Ins. | Pressure in Pounds per Square Inch on End of Ram |      |      |      |      |      |      |      |      |      |      |
|----------------------|-----------------------|--|------|------|------|------|------|------|------|------|------|------|
|                      |                       | 2000   | 2100 | 2200 | 2300 | 2400 | 2500 | 2600 | 2700 | 2800 | 2900 | 3000 |
|                      |                       | Capacity of Hydraulic Press in Tons              |      |      |      |      |      |      |      |      |      |      |
| 1                    | 0.785                 | 0.8  | 0.8  | 0.9  | 0.9  | 0.9  | 1.0  | 1.0  | 1.1  | 1.1  | 1.1  | 1.2  |
| 2                    | 3.142                 | 3.1  | 3.3  | 3.5  | 3.6  | 3.8  | 3.9  | 4.1  | 4.2  | 4.4  | 4.5  | 4.7  |
| 3                    | 7.069                 | 7.0  | 7.4  | 7.8  | 8.1  | 8.5  | 8.8  | 9.2  | 9.5  | 9.9  | 10.2 | 10.6 |
| 4                    | 12.566                | 12.5   | 13   | 14.0 | 14.5 | 15.0 | 15.5 | 16.0 | 17.0 | 17.5 | 18.0 | 19   |
| 5                    | 19.635                | 20   | 21   | 21.5 | 22.5 | 23.5 | 24.5 | 25.5 | 26.5 | 27.5 | 28.5 | 29   |
| 6                    | 28.274                | 28   | 30   | 31   | 33   | 34   | 35   | 37   | 38   | 40   | 41   | 42   |
| 7                    | 38.484                | 38   | 40   | 42   | 44   | 46   | 48   | 50   | 52   | 54   | 56   | 58   |
| 8                    | 50.265                | 50   | 53   | 55   | 58   | 60   | 63   | 65   | 68   | 70   | 73   | 75   |
| 9                    | 63.617                | 63   | 67   | 70   | 73   | 76   | 80   | 83   | 86   | 89   | 92   | 95   |
| 10                   | 78.540                | 78   | 82   | 86   | 90   | 94   | 98   | 102  | 106  | 110  | 114  | 118  |
| 11                   | 95.033                | 95   | 100  | 105  | 109  | 114  | 119  | 124  | 128  | 133  | 138  | 143  |
| 12                   | 113.097               | 113  | 119  | 124  | 130  | 136  | 141  | 147  | 153  | 158  | 164  | 170  |
| 13                   | 132.732               | 132  | 139  | 146  | 153  | 159  | 166  | 172  | 179  | 186  | 193  | 199  |
| 14                   | 153.938               | 154  | 162  | 169  | 177  | 185  | 192  | 200  | 208  | 216  | 223  | 231  |
| 15                   | 176.715               | 177  | 185  | 194  | 203  | 212  | 221  | 230  | 239  | 247  | 256  | 265  |
| 16                   | 201.062               | 201  | 211  | 221  | 231  | 241  | 251  | 261  | 271  | 281  | 292  | 302  |
| 17                   | 226.980               | 227  | 238  | 250  | 261  | 272  | 284  | 295  | 306  | 318  | 329  | 340  |
| 18                   | 254.469               | 254  | 267  | 280  | 293  | 305  | 318  | 331  | 344  | 356  | 369  | 382  |
| 19                   | 283.529               | 284  | 298  | 312  | 326  | 340  | 354  | 369  | 383  | 397  | 411  | 425  |
| 20                   | 314.160               | 314  | 330  | 346  | 361  | 377  | 393  | 408  | 424  | 440  | 456  | 471  |
| 21                   | 346.361               | 346  | 364  | 381  | 398  | 416  | 433  | 450  | 468  | 485  | 502  | 520  |
| 22                   | 380.133               | 380  | 399  | 418  | 437  | 456  | 475  | 494  | 513  | 532  | 551  | 570  |
| 23                   | 415.476               | 415  | 436  | 457  | 478  | 499  | 519  | 540  | 561  | 582  | 602  | 623  |
| 24                   | 452.390               | 452  | 475  | 498  | 520  | 543  | 565  | 588  | 611  | 633  | 656  | 679  |
| 25                   | 490.875               | 491  | 515  | 540  | 565  | 589  | 614  | 638  | 663  | 687  | 712  | 736  |
| 26                   | 530.930               | 531  | 557  | 584  | 612  | 637  | 664  | 690  | 717  | 743  | 770  | 796  |
| 27                   | 572.556               | 573  | 601  | 630  | 658  | 687  | 716  | 744  | 773  | 802  | 830  | 859  |
| 28                   | 615.753               | 616  | 647  | 677  | 708  | 739  | 770  | 800  | 831  | 862  | 893  | 924  |
| 29                   | 660.521               | 661  | 694  | 727  | 760  | 793  | 826  | 859  | 892  | 925  | 958  | 991  |
| 30                   | 706.860               | 707  | 742  | 778  | 813  | 848  | 884  | 919  | 954  | 990  | 1025 | 1060 |

**Table 75. Capacity of Hydraulic Presses**

| Diam.<br>of<br>Ram,<br>Inches | Area of<br>Ram,<br>Sq. Ins. | Pressure in Pounds per Square Inch on End of Ram |      |      |      |      |      |      |      |      |      |
|-------------------------------|-----------------------------|--|------|------|------|------|------|------|------|------|------|
|                               |                             | 3100   | 3200 | 3300 | 3400 | 3500 | 3600 | 3700 | 3800 | 3900 | 4000 |
|                               |                             | Capacity of Hydraulic Press in Tons              |      |      |      |      |      |      |      |      |      |
| 1                             | 0.785                       | 1.2  | 1.3  | 1.3  | 1.3  | 1.4  | 1.4  | 1.4  | 1.5  | 1.5  | 1.6  |
| 2                             | 3.142                       | 4.9  | 5.0  | 5.2  | 5.3  | 5.5  | 5.7  | 5.8  | 6.0  | 6.1  | 6.3  |
| 3                             | 7.069                       | 10.9   | 11.3 | 11.7 | 12.0 | 12.4 | 12.7 | 13.1 | 13.4 | 13.8 | 14.1 |
| 4                             | 12.566                      | 19.5   | 20   | 20.5 | 21   | 22   | 22.5 | 23   | 24   | 24.5 | 25   |
| 5                             | 19.635                      | 30   | 31   | 32   | 33   | 34   | 35   | 36   | 37   | 38   | 39   |
| 6                             | 28.274                      | 44   | 45   | 47   | 48   | 49   | 51   | 52   | 54   | 55   | 56   |
| 7                             | 38.484                      | 60   | 62   | 64   | 66   | 67   | 69   | 71   | 73   | 75   | 77   |
| 8                             | 50.265                      | 78   | 80   | 83   | 85   | 88   | 90   | 93   | 95   | 98   | 100  |
| 9                             | 63.617                      | 99   | 102  | 105  | 108  | 111  | 115  | 118  | 121  | 124  | 127  |
| 10                            | 78.540                      | 122  | 126  | 130  | 134  | 137  | 141  | 145  | 149  | 153  | 157  |
| 11                            | 95.033                      | 147  | 152  | 157  | 162  | 166  | 171  | 176  | 181  | 185  | 190  |
| 12                            | 113.097                     | 175  | 181  | 187  | 192  | 198  | 204  | 209  | 215  | 221  | 226  |
| 13                            | 132.732                     | 206  | 212  | 219  | 226  | 232  | 238  | 245  | 252  | 259  | 265  |
| 14                            | 153.938                     | 239  | 246  | 254  | 262  | 269  | 277  | 285  | 293  | 300  | 308  |
| 15                            | 176.715                     | 274  | 283  | 292  | 300  | 309  | 318  | 327  | 336  | 345  | 353  |
| 16                            | 201.062                     | 312  | 322  | 332  | 342  | 352  | 362  | 372  | 382  | 392  | 402  |
| 17                            | 226.980                     | 352  | 363  | 375  | 386  | 397  | 409  | 420  | 431  | 443  | 454  |
| 18                            | 254.469                     | 394  | 407  | 420  | 433  | 445  | 458  | 471  | 483  | 496  | 509  |
| 19                            | 283.529                     | 439  | 454  | 468  | 482  | 496  | 510  | 525  | 539  | 553  | 567  |
| 20                            | 314.160                     | 487  | 503  | 518  | 534  | 550  | 566  | 581  | 597  | 613  | 628  |
| 21                            | 346.361                     | 537  | 554  | 571  | 589  | 606  | 623  | 641  | 658  | 675  | 693  |
| 22                            | 380.133                     | 589  | 608  | 627  | 646  | 665  | 684  | 703  | 722  | 741  | 760  |
| 23                            | 415.476                     | 644  | 665  | 686  | 706  | 727  | 748  | 769  | 789  | 810  | 831  |
| 24                            | 452.390                     | 701  | 724  | 746  | 769  | 792  | 814  | 837  | 860  | 882  | 905  |
| 25                            | 490.875                     | 761  | 785  | 810  | 834  | 859  | 884  | 908  | 933  | 957  | 982  |
| 26                            | 530.930                     | 823  | 850  | 876  | 903  | 929  | 956  | 982  | 1009 | 1035 | 1062 |
| 27                            | 572.556                     | 887  | 916  | 945  | 973  | 1002 | 1031 | 1059 | 1088 | 1116 | 1145 |
| 28                            | 615.753                     | 954  | 985  | 1016 | 1047 | 1078 | 1108 | 1139 | 1170 | 1201 | 1232 |
| 29                            | 660.521                     | 1024   | 1057 | 1090 | 1123 | 1156 | 1189 | 1222 | 1255 | 1288 | 1321 |
| 30                            | 706.860                     | 1096   | 1131 | 1166 | 1202 | 1237 | 1272 | 1308 | 1343 | 1378 | 1414 |

When a certain pressure per square inch on the material under pressure is required, the gage pressure of the press necessary to obtain this pressure may be calculated as follows: Multiply the area of the surface under pressure by the pressure per square inch desired on the material. Divide this product by 0.7854 times the square of the diameter of the ram. The quotient will be the desired gage pressure.

Expressing these rules as formulas, let  $D$  = diameter of ram in inches;  $P$  = water pressure in pounds per square inch (gage pressure);  $C$  = total pressure or capacity of press in tons;  $A$  = area of material to be pressed, in square inches;  $P_a$  = pressure in pounds per square inch on material under pressure; then:

$$C = 0.00039D^2 \times P \quad P_a = \frac{2000C}{A} \quad P = \frac{A \times P_a}{0.7854D^2}$$

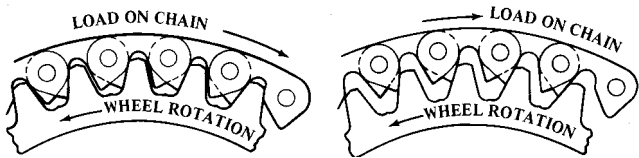


## SILENT OR INVERTED TOOTH CHAIN

Silent or inverted tooth chain consists of a series of toothed links alternately assembled either with pins or with a combination of joint components in such a way that the joints articulate between adjoining pitches. Side Guide chain has guide links which straddle the sprocket sides to control the chain laterally. Center Guide chain has guide links that run within a circumferential groove or grooves for lateral control.

### Characteristics of Silent Chain Drives

The silent or "inverted-tooth" driving chain has the following characteristics: The chain passes over the face of the wheel like a belt and the wheel teeth do not project through it; the chain engages the wheel by means of teeth extending across the full width of the under side, with the exception of those chains having a central guide link; the chain teeth and wheel teeth are of such a shape that as the chain pitch increases through wear at the joints, the chain shifts outward upon the teeth, thus engaging the wheel on a pitch circle of increasing diameter; the result of this action is that the pitch of the wheel teeth increases at the same rate as the chain pitch. The accompanying illustration shows an unworn chain to the left, and a worn chain to the right, which has moved outward as the result of wear. Another distinguishing feature of the silent chain is that the power is transmitted by and to all the teeth in the arc of contact, irrespective of the increasing pitch due to elongation. The links have no sliding action either on or off the teeth, which results in a smooth and practically noiseless action, the chain being originally designed for the transmission of power at higher speeds than are suitable for roller chains. The efficiency of the silent chain itself may be as high as 99 per cent, and for the complete drive, from 96 to 97 percent, under favorable conditions; from 94 to 96 per cent can be secured with well-designed drives under average conditions.



The life and upkeep of silent chains depend largely upon the design of the entire drive, including the provision for adjustment. If there is much slack, the whipping of the chain will greatly increase the wear, and means of adjustment may double the life of the chain. A slight amount of play is necessary for satisfactory operation. The minimum amount of sag should be about  $\frac{1}{8}$  inch. Although the silent chain shifts outward from the teeth and adjusts itself for an increase of pitch, it cannot take up the increased pitch in that portion of the chain between the wheels; therefore, the wheel must lag to the extent of the increased pitch in the straight portion of the chain.

**Standard Silent Chain Designation.**—The standard chain number or designation for  $\frac{3}{8}$ -inch pitch or larger consists of:

1) a two letter symbol SC; 2) one or two numerical digits indicating the pitch in eighths of an inch; and 3) two or three numerical digits indicating the chain width in quarter-inches.

Thus, SC302 designates a silent chain of  $\frac{3}{8}$ -inch pitch and  $\frac{1}{2}$ -inch width, while SC1012 designates a silent chain of  $1\frac{1}{4}$ -inch pitch and 3-inch width.

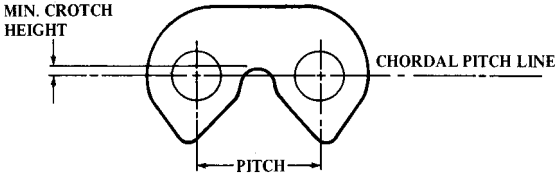
The standard chain number or designation for  $\frac{3}{16}$ -inch pitch consists of:

a) a two letter symbol SC; b) a zero followed by a numerical digit indicating pitch in sixteenths of an inch; and c) two numerical digits indicating the chain width in thirty-seconds of an inch. Thus, SC0309 designates a silent chain of  $\frac{3}{16}$ -inch pitch and  $\frac{9}{32}$ -inch width.

**Silent Chain Links.**—The joint components and link contours vary with each manufacturer's design. As shown in [Table 1](#) minimum crotch height and pitch have been standardized for interchangeability. Chain link designations for  $\frac{3}{8}$ -inch and larger pitch are given in [Table 1](#)

**Table 1. American National Standard Silent Chain Links\***

| Chain Number                      | Chain Pitch |       | Stamp      | Crotch Height, Min. |       |
|-----------------------------------|-------------|-------|------------|---------------------|-------|
|                                   | inch        | mm    |            | inch                | mm    |
| SC3 (Width in $\frac{1}{4}$ in.)  | 0.375       | 9.52  | SC3 or 3   | 0.0232              | 0.589 |
| SC4 (Width in $\frac{1}{4}$ in.)  | 0.500       | 12.70 | SC4 or 4   | 0.0310              | 0.787 |
| SC5 (Width in $\frac{1}{4}$ in.)  | 0.625       | 15.88 | SC5 or 5   | 0.0388              | 0.985 |
| SC6 (Width in $\frac{1}{4}$ in.)  | 0.750       | 19.05 | SC6 or 6   | 0.0465              | 1.181 |
| SC8 (Width in $\frac{1}{4}$ in.)  | 1.000       | 25.40 | SC8 or 8   | 0.0620              | 1.574 |
| SC10 (Width in $\frac{1}{4}$ in.) | 1.250       | 31.76 | SC10 or 10 | 0.0775              | 1.968 |
| SC12 (Width in $\frac{1}{4}$ in.) | 1.500       | 38.10 | SC12 or 12 | 0.0930              | 2.302 |
| SC16 (Width in $\frac{1}{4}$ in.) | 2.000       | 50.80 | SC16 or 16 | 0.1240              | 3.149 |



Min. Crotch Height =  $0.062 \times \text{Chain Pitch}$ .

Link contour may vary but must engage standard sprocket tooth so that joint centers lie on pitch diameter of sprockets.

**Silent Chain Sprocket Diameters.**—The important sprocket diameters are:

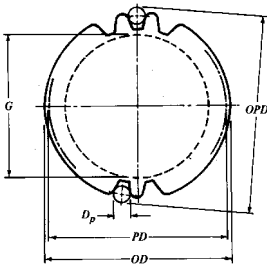
- 1) outside diameter; 2) pitch diameter; 3) maximum guide groove diameter; and
- 4) over-pin diameter.

These are shown in the diagram in [Table 2](#) and the symbols and formulas for each are also given in this table. [Table 3a](#) gives values of outside diameters for sprockets with rounded teeth and with square teeth, pitch diameters, and over-pin diameters for chains of 1-inch pitch and sprockets of various tooth numbers. Values for chains of other pitches ( $\frac{3}{8}$  inch and larger) are found by multiplying the values shown by the pitch. [Table 3b](#) gives this information for  $\frac{3}{16}$ -in. pitch chains. Note that the over-pin diameter is measured over gage pins having a diameter  $D_p = 0.625P$  in. for  $\frac{3}{8}$ -in. and larger pitch and  $D_p = 0.667P$  in. for  $\frac{3}{16}$ -in. pitch chains. Over-pin diameter tolerances are given in [Table 4a](#) and [4b](#).

**Silent Chain Sprocket Profiles and Chain Widths.**—Sprocket tooth face profiles for side guide chain, center guide chain and double guide chain are shown in [Table 4c](#) and [4d](#) together with important dimensions for chains of various pitches and widths. Maximum over-all width  $M$  of the three types of chain are also given in this table for various pitches and widths. It should be noted that the sprocket tooth width  $W$  for the side guide chain is given in [Table 5](#) for one-half-inch wide chains of  $\frac{3}{8}$ -inch and  $\frac{1}{2}$ -inch pitches. No values of  $W$  for other chain sizes are specified in American National Standard B29.2M-1982 (1987).

\* For  $\frac{3}{8}$ -inch and larger pitch chains.

**Table 2. ANSI Silent Chain Sprocket Diameters (ANSI B29.2M-1982, R1987)**



- $P$  = Chain Pitch
- $PD$  = Pitch Diameter
- $OD$  = Outside Diameter
- $D_p$  = Gage Pin Diameter
- $N$  = Number of Teeth
- $E$  = Diameter to center of Topping Curve
- $OPD$  = Over Pin Diameter
- $G$  = Max. Guide Groove Diameter

$$PD = \frac{P}{\sin \frac{180^\circ}{N}}$$

$D_p = 0.625P$ , for  $\frac{3}{8}$  in. and larger pitch chain  
 [=  $0.667P$  for  $\frac{3}{16}$  in. pitch chain ]

$$OPD \text{ (For Even No. of Teeth)} = PD - 0.125P \csc \left( 30 - \frac{180^\circ}{N} \right) + 0.625P$$

$$\left[ = PD - 0.160P \csc \left( 30 - \frac{180^\circ}{N} \right) + 0.667P \right]$$

$$OPD \text{ (For Odd No. of Teeth)} = \cos \frac{90^\circ}{N} \left[ PD - 0.125P \csc \left( 30 - \frac{180^\circ}{N} \right) \right] + 0.625P$$

$$\left[ = \cos \frac{90^\circ}{N} \left[ PD - 0.160P \csc \left( 30 - \frac{180^\circ}{N} \right) \right] + 0.625P \right]$$

$$OD \text{ (For Round Teeth)} = P \left( \cot \frac{180^\circ}{N} + 0.08 \right)$$

$$\left[ OD \text{ (For Nominal Round Teeth)} = P \left( \cot \frac{180^\circ}{N} - 0.032 \right) \right]$$

$$OD \text{ (For Square Teeth)} = 2\sqrt{X^2 + L^2} - 2XL \cos \alpha$$

Where

$$X = Y \cos \alpha - \sqrt{(0.15P)^2 - (Y \sin \alpha)^2}$$

$$Y = P(0.500 - 0.375 \sec \alpha) \cot \alpha + 0.11P$$

$$L = Y + \frac{E}{2} \text{ (See Table 8A for E);}$$

$$\alpha = \left( 30 - \frac{360^\circ}{N} \right)^\circ$$

$$G(\text{max.}) = P \left( \cot \frac{180^\circ}{N} - 1.16 \right)$$

$$\left[ G(\text{max.}) = P \left( \cot \frac{180^\circ}{N} - 1.20 \right) \right]$$

Tolerance = +0, -0.030 in. (0.76 mm)

[Tolerance = +0, -0.015 in. (0.38 mm)]<sup>a</sup>

<sup>a</sup> All inside [ ] bracket applies to  $\frac{3}{16}$ -inch pitch main. All other equations apply to  $\frac{3}{8}$ -inch and larger pitch chains.

**Table 3a. American National Standard Silent Chain  
Sprocket Diameters ANSI B29.2M-1982, R1987**

| These diameters apply only to chain of 1-inch pitch.<br>For any other pitch ( $\frac{3}{8}$ -inch and larger) multiply the values given below by the pitch. |                |                            |                           |                                |           |                |                  |              |                   |
|---|----------------|----------------------------|---------------------------|--------------------------------|-----------|----------------|------------------|--------------|-------------------|
| No. Teeth   | Pitch Diameter | Outside Diameter           |                           | Over Pin Diameter <sup>a</sup> | No. Teeth | Pitch Diameter | Outside Diameter |              | Over Pin Diameter |
|   |                | Rounded Teeth <sup>b</sup> | Square Teeth <sup>c</sup> |                                |           |                | Rounded Teeth    | Square Teeth |                   |
| 17  | 5.442          | 5.430                      | 5.302                     | 5.669                          | 56        | 17.835         | 17.887           | 17.835       | 18.182            |
| 18  | 5.759          | 5.751                      | 5.627                     | 6.018                          | 57        | 18.153         | 18.205           | 18.154       | 18.494            |
| 19  | 6.076          | 6.073                      | 5.951                     | 6.324                          | 58        | 18.471         | 18.524           | 18.473       | 18.820            |
| 20  | 6.392          | 6.394                      | 6.275                     | 6.669                          | 59        | 18.789         | 18.843           | 18.793       | 19.132            |
| 21  | 6.710          | 6.715                      | 6.599                     | 6.975                          | 60        | 19.107         | 19.161           | 19.112       | 19.457            |
| 22  | 7.027          | 7.035                      | 6.923                     | 7.315                          | 61        | 19.425         | 19.480           | 19.431       | 19.769            |
| 23  | 7.344          | 7.356                      | 7.247                     | 7.621                          | 62        | 19.744         | 19.798           | 19.750       | 20.094            |
| 24  | 7.661          | 7.676                      | 7.570                     | 7.960                          | 63        | 20.062         | 20.117           | 20.070       | 20.407            |
| 25  | 7.979          | 7.996                      | 7.894                     | 8.266                          | 64        | 20.380         | 20.435           | 20.389       | 20.731            |
| 26  | 8.296          | 8.316                      | 8.217                     | 8.602                          | 65        | 20.698         | 20.754           | 20.708       | 21.044            |
| 27  | 8.614          | 8.636                      | 8.539                     | 8.909                          | 66        | 21.016         | 21.073           | 21.027       | 21.369            |
| 28  | 8.931          | 8.955                      | 8.862                     | 9.244                          | 67        | 21.335         | 21.391           | 21.346       | 21.681            |
| 29  | 9.249          | 9.275                      | 9.184                     | 9.551                          | 68        | 21.653         | 21.710           | 21.665       | 22.006            |
| 30  | 9.567          | 9.594                      | 9.506                     | 9.884                          | 69        | 21.971         | 22.028           | 21.984       | 22.319            |
| 31  | 9.885          | 9.914                      | 9.828                     | 10.192                         | 70        | 22.289         | 22.347           | 22.303       | 22.643            |
| 32  | 10.202         | 10.233                     | 10.150                    | 10.524                         | 71        | 22.607         | 22.665           | 22.622       | 22.956            |
| 33  | 10.520         | 10.552                     | 10.471                    | 10.833                         | 72        | 22.926         | 22.984           | 22.941       | 23.280            |
| 34  | 10.838         | 10.872                     | 10.793                    | 11.164                         | 73        | 23.244         | 23.302           | 23.260       | 23.593            |
| 35  | 11.156         | 11.191                     | 11.114                    | 11.473                         | 74        | 23.562         | 23.621           | 23.579       | 23.917            |
| 36  | 11.474         | 11.510                     | 11.435                    | 11.803                         | 75        | 23.880         | 23.939           | 23.898       | 24.230            |
| 37  | 11.792         | 11.829                     | 11.756                    | 12.112                         | 76        | 24.198         | 24.258           | 24.217       | 24.554            |
| 38  | 12.110         | 12.148                     | 12.076                    | 12.442                         | 77        | 24.517         | 24.576           | 24.535       | 24.867            |
| 39  | 12.428         | 12.467                     | 12.397                    | 12.751                         | 78        | 24.835         | 24.895           | 24.854       | 25.191            |
| 40  | 12.745         | 12.786                     | 12.717                    | 13.080                         | 79        | 25.153         | 25.213           | 25.173       | 25.504            |
| 41  | 13.063         | 13.105                     | 13.038                    | 13.390                         | 80        | 25.471         | 25.532           | 25.492       | 25.828            |
| 42  | 13.381         | 13.424                     | 13.358                    | 13.718                         | 81        | 25.790         | 25.850           | 25.811       | 26.142            |
| 43  | 13.700         | 13.743                     | 13.678                    | 14.028                         | 82        | 26.108         | 26.169           | 26.129       | 26.465            |
| 44  | 14.018         | 14.062                     | 13.998                    | 14.356                         | 83        | 26.426         | 26.487           | 26.448       | 26.779            |
| 45  | 14.336         | 14.381                     | 14.319                    | 14.667                         | 84        | 26.744         | 26.806           | 26.767       | 27.102            |
| 46  | 14.654         | 14.699                     | 14.638                    | 14.994                         | 85        | 27.063         | 27.124           | 27.086       | 27.416            |
| 47  | 14.972         | 15.018                     | 14.958                    | 15.305                         | 86        | 27.381         | 27.442           | 27.405       | 27.739            |
| 48  | 15.290         | 15.337                     | 15.278                    | 15.632                         | 87        | 27.699         | 27.761           | 27.723       | 28.053            |
| 49  | 15.608         | 15.656                     | 15.598                    | 15.943                         | 88        | 28.017         | 28.079           | 28.042       | 28.376            |
| 50  | 15.926         | 15.975                     | 15.918                    | 16.270                         | 89        | 28.335         | 28.398           | 28.361       | 28.690            |
| 51  | 16.244         | 16.293                     | 16.237                    | 16.581                         | 90        | 28.654         | 28.716           | 28.679       | 29.012            |
| 52  | 16.562         | 16.612                     | 16.557                    | 16.907                         | 91        | 28.972         | 29.035           | 28.998       | 29.327            |
| 53  | 16.880         | 16.931                     | 16.876                    | 17.219                         | 92        | 29.290         | 29.353           | 29.317       | 29.649            |
| 54  | 17.198         | 17.249                     | 17.196                    | 17.545                         | 93        | 29.608         | 29.672           | 29.635       | 29.964            |
| 55  | 17.517         | 17.568                     | 17.515                    | 17.857                         | 94        | 29.927         | 29.990           | 29.954       | 30.286            |
| 56  | 17.835         | 17.887                     | 17.835                    | 18.182                         | 95        | 30.245         | 30.308           | 30.273       | 30.600            |

## SILENT OF INVERTED TOOTH CHAIN

**Table 3a. (Continued) American National Standard Silent Chain Sprocket Diameters ANSI B29.2M-1982, R1987**

| These diameters apply only to chain of 1-inch pitch.<br>For any other pitch ( $\frac{3}{8}$ -inch and larger) multiply the values given below by the pitch. |                |                            |                           |                                |           |                |                  |              |                   |
|---|----------------|----------------------------|---------------------------|--------------------------------|-----------|----------------|------------------|--------------|-------------------|
| No. Teeth   | Pitch Diameter | Outside Diameter           |                           | Over Pin Diameter <sup>a</sup> | No. Teeth | Pitch Diameter | Outside Diameter |              | Over Pin Diameter |
|   |                | Rounded Teeth <sup>b</sup> | Square Teeth <sup>c</sup> |                                |           |                | Rounded Teeth    | Square Teeth |                   |
| 96  | 30.563         | 30.627                     | 30.591                    | 30.923                         | 125       | 39.793         | 39.860           | 39.830       | 40.153            |
| 97  | 30.881         | 30.945                     | 30.910                    | 31.237                         | 126       | 40.111         | 40.179           | 40.148       | 40.475            |
| 98  | 31.200         | 31.264                     | 31.229                    | 31.560                         | 127       | 40.429         | 40.497           | 40.467       | 40.790            |
| 99  | 31.518         | 31.582                     | 31.547                    | 31.874                         | 128       | 40.748         | 40.815           | 40.785       | 41.112            |
| 100   | 31.836         | 31.901                     | 31.866                    | 32.197                         | 129       | 41.066         | 41.134           | 41.104       | 41.427            |
| 103   | 32.791         | 32.856                     | 32.822                    | 33.148                         | 130       | 41.384         | 41.452           | 41.422       | 41.748            |
| 104   | 33.109         | 33.174                     | 33.140                    | 33.470                         | 131       | 41.703         | 41.771           | 41.741       | 42.064            |
| 105   | 33.428         | 33.493                     | 33.459                    | 33.785                         | 132       | 42.021         | 42.089           | 42.059       | 42.385            |
| 106   | 33.746         | 33.811                     | 33.778                    | 34.107                         | 133       | 42.339         | 42.407           | 42.378       | 42.700            |
| 107   | 34.064         | 34.129                     | 34.096                    | 34.422                         | 134       | 42.657         | 42.726           | 42.696       | 43.022            |
| 108   | 34.382         | 34.448                     | 34.415                    | 34.744                         | 135       | 42.976         | 43.044           | 43.015       | 43.337            |
| 109   | 34.701         | 34.766                     | 34.733                    | 35.059                         | 136       | 43.294         | 43.362           | 43.333       | 43.658            |
| 110   | 35.019         | 35.085                     | 35.052                    | 35.381                         | 137       | 43.612         | 43.681           | 43.652       | 43.974            |
| 111   | 35.337         | 35.403                     | 35.371                    | 35.696                         | 138       | 43.931         | 43.999           | 43.970       | 44.295            |
| 112   | 35.655         | 35.721                     | 35.689                    | 36.017                         | 139       | 44.249         | 44.318           | 44.289       | 44.611            |
| 113   | 35.974         | 36.040                     | 36.008                    | 36.332                         | 140       | 44.567         | 44.636           | 44.607       | 44.932            |
| 114   | 36.292         | 36.358                     | 36.326                    | 36.654                         | 141       | 44.885         | 44.954           | 44.926       | 45.248            |
| 115   | 36.610         | 36.677                     | 36.645                    | 36.969                         | 142       | 45.204         | 45.273           | 45.244       | 45.569            |
| 116   | 36.928         | 36.995                     | 36.963                    | 37.291                         | 143       | 45.522         | 45.591           | 45.563       | 45.884            |
| 117   | 37.247         | 37.313                     | 37.282                    | 37.606                         | 144       | 45.840         | 45.909           | 45.881       | 46.205            |
| 118   | 37.565         | 37.632                     | 37.600                    | 37.928                         | 145       | 46.159         | 46.228           | 46.199       | 46.521            |
| 119   | 37.883         | 37.950                     | 37.919                    | 38.243                         | 146       | 46.477         | 46.546           | 46.518       | 46.842            |
| 120   | 38.202         | 38.268                     | 38.237                    | 38.565                         | 147       | 46.795         | 46.864           | 46.836       | 47.158            |
| 121   | 38.520         | 38.587                     | 38.556                    | 38.880                         | 148       | 47.113         | 47.183           | 47.155       | 47.479            |
| 122   | 38.838         | 38.905                     | 38.874                    | 39.201                         | 149       | 47.432         | 47.501           | 47.473       | 47.795            |
| 123   | 39.156         | 39.224                     | 39.193                    | 39.517                         | 150       | 47.750         | 47.820           | 47.792       | 48.115            |
| 124   | 39.475         | 39.542                     | 39.511                    | 39.838                         | ...       | ...            | ...              | ...          | ...               |

<sup>a</sup> For tolerances on over-pin diameters, see table 4.<sup>b</sup> Blank diameters are 0.020 inch larger and maximum guide groove diameters G are 1.240 inches smaller than these outside diameters.<sup>c</sup> These diameters are maximum; tolerance is +0, -0.50× pitch, inches.Tolerance for maximum eccentricity (total indicator reading) of pitch diameter with respect to bore is  $0.001 \times PD$ , but not less than 0.006 nor more than 0.032 inch.

**Table 3b. American National Standard Silent Chain Sprocket Diameters for  $\frac{3}{16}$ -in. Pitch Chain ANSI B29.2M-1982, R1987**

| No. Teeth | Pitch Diameter | Outside Diameter           |                           | Over Pin Diameter <sup>a</sup> | No. Teeth | Pitch Diameter | Outside Diameter           |                           | Over Pin Diameter <sup>a</sup> |
|-----------|----------------|----------------------------|---------------------------|--------------------------------|-----------|----------------|----------------------------|---------------------------|--------------------------------|
|           |                | Rounded Teeth <sup>b</sup> | Square Teeth <sup>c</sup> |                                |           |                | Rounded Teeth <sup>b</sup> | Square Teeth <sup>c</sup> |                                |
| 11        | 0.666          | 0.633                      | 0.691                     | 0.414                          | 53        | 3.165          | 3.153                      | 3.232                     | 2.934                          |
| 12        | 0.724          | 0.694                      | 0.762                     | 0.475                          | 54        | 3.225          | 3.213                      | 3.293                     | 2.994                          |
| 13        | 0.783          | 0.755                      | 0.820                     | 0.536                          | 55        | 3.284          | 3.273                      | 3.351                     | 3.054                          |
| 14        | 0.843          | 0.815                      | 0.888                     | 0.596                          | 56        | 3.344          | 3.333                      | 3.412                     | 3.114                          |
| 15        | 0.902          | 0.876                      | 0.946                     | 0.657                          | 57        | 3.404          | 3.392                      | 3.471                     | 3.173                          |
| 16        | 0.961          | 0.937                      | 1.012                     | 0.718                          | 58        | 3.463          | 3.452                      | 3.532                     | 3.233                          |
| 17        | 1.020          | 0.997                      | 1.069                     | 0.778                          | 59        | 3.523          | 3.512                      | 3.590                     | 3.293                          |
| 18        | 1.080          | 1.057                      | 1.134                     | 0.838                          | 60        | 3.583          | 3.572                      | 3.651                     | 3.353                          |
| 19        | 1.139          | 1.118                      | 1.191                     | 0.899                          | 61        | 3.642          | 3.631                      | 3.710                     | 3.412                          |
| 20        | 1.199          | 1.178                      | 1.255                     | 0.959                          | 62        | 3.702          | 3.691                      | 3.771                     | 3.472                          |
| 21        | 1.258          | 1.238                      | 1.312                     | 1.019                          | 63        | 3.762          | 3.751                      | 3.829                     | 3.532                          |
| 22        | 1.318          | 1.298                      | 1.376                     | 1.079                          | 64        | 3.821          | 3.811                      | 3.890                     | 3.592                          |
| 23        | 1.377          | 1.358                      | 1.433                     | 1.139                          | 65        | 3.881          | 3.870                      | 3.949                     | 3.651                          |
| 24        | 1.436          | 1.418                      | 1.497                     | 1.199                          | 66        | 3.941          | 3.930                      | 4.009                     | 3.711                          |
| 25        | 1.496          | 1.478                      | 1.554                     | 1.259                          | 67        | 4.000          | 3.990                      | 4.068                     | 3.771                          |
| 26        | 1.556          | 1.538                      | 1.617                     | 1.319                          | 68        | 4.060          | 4.050                      | 4.129                     | 3.831                          |
| 27        | 1.615          | 1.598                      | 1.674                     | 1.379                          | 69        | 4.120          | 4.109                      | 4.188                     | 3.890                          |
| 28        | 1.675          | 1.658                      | 1.737                     | 1.439                          | 70        | 4.179          | 4.169                      | 4.248                     | 3.950                          |
| 29        | 1.734          | 1.718                      | 1.795                     | 1.499                          | 71        | 4.239          | 4.229                      | 4.307                     | 4.010                          |
| 30        | 1.794          | 1.778                      | 1.857                     | 1.559                          | 72        | 4.299          | 4.288                      | 4.368                     | 4.069                          |
| 31        | 1.853          | 1.838                      | 1.915                     | 1.619                          | 73        | 4.358          | 4.348                      | 4.426                     | 4.129                          |
| 32        | 1.913          | 1.898                      | 1.977                     | 1.679                          | 74        | 4.418          | 4.408                      | 4.487                     | 4.189                          |
| 33        | 1.973          | 1.958                      | 2.035                     | 1.739                          | 75        | 4.478          | 4.468                      | 4.546                     | 4.249                          |
| 34        | 2.032          | 2.017                      | 2.097                     | 1.798                          | 76        | 4.537          | 4.527                      | 4.607                     | 4.308                          |
| 35        | 2.092          | 2.077                      | 2.154                     | 1.858                          | 77        | 4.597          | 4.587                      | 4.665                     | 4.368                          |
| 36        | 2.151          | 2.137                      | 2.216                     | 1.918                          | 78        | 4.657          | 4.647                      | 4.726                     | 4.428                          |
| 37        | 2.211          | 2.197                      | 2.274                     | 1.978                          | 79        | 4.716          | 4.706                      | 4.785                     | 4.487                          |
| 38        | 2.271          | 2.257                      | 2.336                     | 2.038                          | 80        | 4.776          | 4.766                      | 4.845                     | 4.547                          |
| 39        | 2.330          | 2.317                      | 2.394                     | 2.098                          | 81        | 4.836          | 4.826                      | 4.904                     | 4.607                          |
| 40        | 2.390          | 2.376                      | 2.456                     | 2.157                          | 82        | 4.895          | 4.886                      | 4.965                     | 4.667                          |
| 41        | 2.449          | 2.436                      | 2.514                     | 2.217                          | 83        | 4.955          | 4.945                      | 5.024                     | 4.726                          |
| 42        | 2.509          | 2.496                      | 2.575                     | 2.277                          | 84        | 5.015          | 5.005                      | 5.084                     | 4.786                          |
| 43        | 2.569          | 2.556                      | 2.633                     | 2.337                          | 85        | 5.074          | 5.065                      | 5.143                     | 4.846                          |
| 44        | 2.628          | 2.616                      | 2.695                     | 2.397                          | 86        | 5.134          | 5.124                      | 5.204                     | 4.905                          |
| 45        | 2.688          | 2.675                      | 2.753                     | 2.456                          | 87        | 5.194          | 5.184                      | 5.263                     | 4.965                          |
| 46        | 2.748          | 2.735                      | 2.815                     | 2.516                          | 88        | 5.253          | 5.244                      | 5.323                     | 5.025                          |
| 47        | 2.807          | 2.795                      | 2.873                     | 2.576                          | 89        | 5.313          | 5.304                      | 5.382                     | 5.085                          |
| 48        | 2.867          | 2.855                      | 2.934                     | 2.636                          | 90        | 5.373          | 5.363                      | 5.443                     | 5.144                          |
| 49        | 2.926          | 2.914                      | 2.992                     | 2.695                          | 91        | 5.432          | 5.423                      | 5.501                     | 5.204                          |
| 50        | 2.986          | 2.974                      | 3.054                     | 2.755                          | 92        | 5.492          | 5.483                      | 5.562                     | 5.264                          |
| 51        | 3.046          | 3.034                      | 3.112                     | 2.815                          | 93        | 5.552          | 5.542                      | 5.621                     | 5.323                          |
| 52        | 3.105          | 3.094                      | 3.173                     | 2.875                          | 94        | 5.611          | 5.602                      | 5.681                     | 5.383                          |

**Table 3b. American National Standard Silent Chain Sprocket Diameters for  $\frac{3}{16}$ -in. Pitch Chain ANSI B29.2M-1982, R1987**

| No. Teeth | Pitch Diameter | Outside Diameter           |                           |                                | No. Teeth | Pitch Diameter | Outside Diameter           |                           |                                |
|-----------|----------------|----------------------------|---------------------------|--------------------------------|-----------|----------------|----------------------------|---------------------------|--------------------------------|
|           |                | Rounded Teeth <sup>b</sup> | Square Teeth <sup>c</sup> | Over Pin Diameter <sup>a</sup> |           |                | Rounded Teeth <sup>b</sup> | Square Teeth <sup>c</sup> | Over Pin Diameter <sup>a</sup> |
| 95        | 5.671          | 5.662                      | 5.740                     | 5.443                          | 108       | 6.447          | 6.438                      | 6.517                     | 6.219                          |
| 96        | 5.731          | 5.722                      | 5.801                     | 5.503                          | 109       | 6.506          | 6.498                      | 6.576                     | 6.279                          |
| 97        | 5.790          | 5.781                      | 5.860                     | 5.562                          | 110       | 6.566          | 6.557                      | 6.637                     | 6.338                          |
| 98        | 5.850          | 5.841                      | 5.920                     | 5.622                          | 111       | 6.626          | 6.617                      | 6.696                     | 6.398                          |
| 99        | 5.910          | 5.901                      | 5.979                     | 5.682                          | 112       | 6.685          | 6.677                      | 6.756                     | 6.458                          |
| 100       | 5.969          | 5.960                      | 6.040                     | 5.741                          | 113       | 6.745          | 6.736                      | 6.815                     | 6.517                          |
| 101       | 6.029          | 6.020                      | 6.099                     | 5.801                          | 114       | 6.805          | 6.796                      | 6.875                     | 6.577                          |
| 102       | 6.089          | 6.080                      | 6.159                     | 5.861                          | 115       | 6.864          | 6.856                      | 6.934                     | 6.637                          |
| 103       | 6.148          | 6.139                      | 6.218                     | 5.920                          | 116       | 6.924          | 6.916                      | 6.995                     | 6.697                          |
| 104       | 6.208          | 6.199                      | 6.278                     | 5.980                          | 117       | 6.984          | 6.975                      | 7.054                     | 6.756                          |
| 105       | 6.268          | 6.259                      | 6.337                     | 6.040                          | 118       | 7.043          | 7.035                      | 7.114                     | 6.816                          |
| 106       | 6.327          | 6.319                      | 6.398                     | 6.100                          | 119       | 7.103          | 7.095                      | 7.173                     | 6.876                          |
| 107       | 6.387          | 6.378                      | 6.457                     | 6.159                          | 120       | 7.163          | 7.154                      | 7.233                     | 6.935                          |

<sup>a</sup>For tolerances on over-pin diameters, see table 4.

<sup>b</sup>Blank diameters are 0.020 inch larger and maximum guide groove diameters G are 1.240 inches smaller than these outside diameters.

<sup>c</sup>These diameters are maximum; tolerance is +0, -0.50 × pitch, inches.

Tolerance for maximum eccentricity (total indicator reading) of pitch diameter with respect to bore is 0.004 in. up to and including 4 in. diameter; and 0.008 in., over 4 in. diameter.

**Table 4a. Over-Pin Diameter Tolerances for American National Standard  $\frac{3}{8}$ -in. Pitch and Larger Silent Chain Sprocket Measurement ANSI B29.2M-1982, 1987**

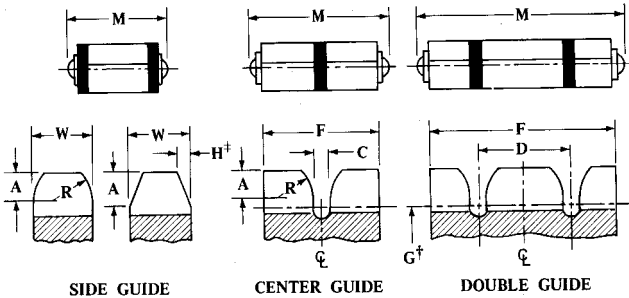
| Pitch                          | Number of Teeth |       |       |       |       |       |       |         |         |        |
|--------------------------------|-----------------|-------|-------|-------|-------|-------|-------|---------|---------|--------|
|                                | Up to 15        | 16-24 | 25-35 | 36-48 | 49-63 | 64-80 | 81-99 | 100-120 | 121-143 | 144 up |
| Tolerance, <sup>a</sup> Inches |                 |       |       |       |       |       |       |         |         |        |
| 0.375                          | 0.005           | 0.006 | 0.006 | 0.006 | 0.007 | 0.007 | 0.008 | 0.008   | 0.008   | 0.009  |
| 0.500                          | 0.006           | 0.006 | 0.007 | 0.007 | 0.008 | 0.008 | 0.009 | 0.009   | 0.010   | 0.010  |
| 0.625                          | 0.006           | 0.007 | 0.007 | 0.008 | 0.009 | 0.009 | 0.010 | 0.011   | 0.011   | 0.012  |
| 0.750                          | 0.006           | 0.007 | 0.008 | 0.009 | 0.010 | 0.010 | 0.011 | 0.012   | 0.013   | 0.013  |
| 1.000                          | 0.008           | 0.009 | 0.010 | 0.011 | 0.012 | 0.013 | 0.014 | 0.015   | 0.016   | 0.016  |
| 1.250                          | 0.008           | 0.009 | 0.010 | 0.012 | 0.013 | 0.015 | 0.016 | 0.017   | 0.018   | 0.019  |
| 1.500                          | 0.009           | 0.010 | 0.012 | 0.014 | 0.015 | 0.017 | 0.018 | 0.020   | 0.021   | 0.022  |
| 2.000                          | 0.012           | 0.014 | 0.017 | 0.019 | 0.021 | 0.023 | 0.025 | 0.027   | 0.028   | 0.028  |
| Tolerances, Millimeters        |                 |       |       |       |       |       |       |         |         |        |
| 9.52                           | 0.13            | 0.13  | 0.13  | 0.15  | 0.15  | 0.18  | 0.18  | 0.18    | 0.20    | 0.20   |
| 2.70                           | 0.13            | 0.15  | 0.15  | 0.18  | 0.18  | 0.20  | 0.20  | 0.23    | 0.23    | 0.25   |
| 15.88                          | 0.15            | 0.15  | 0.18  | 0.20  | 0.23  | 0.25  | 0.25  | 0.25    | 0.28    | 0.30   |
| 19.05                          | 0.15            | 0.18  | 0.20  | 0.23  | 0.25  | 0.28  | 0.28  | 0.30    | 0.33    | 0.36   |
| 25.40                          | 0.18            | 0.20  | 0.23  | 0.25  | 0.28  | 0.30  | 0.33  | 0.36    | 0.38    | 0.40   |
| 31.75                          | 0.20            | 0.23  | 0.25  | 0.28  | 0.33  | 0.36  | 0.38  | 0.43    | 0.46    | 0.48   |
| 38.10                          | 0.20            | 0.25  | 0.28  | 0.33  | 0.36  | 0.40  | 0.43  | 0.48    | 0.51    | 0.56   |
| 50.80                          | 0.25            | 0.30  | 0.36  | 0.40  | 0.46  | 0.51  | 0.56  | 0.61    | 0.66    | 0.71   |

<sup>a</sup>All tolerances are negative. Tolerances =  $(0.004 + 0.001P\sqrt{N})$ , where P= chain pitch, N= number of teeth. See 3A for over pin diameters.

**Table 4b. Over-Pin Diameter Tolerances for ANSI  $\frac{3}{16}$ -in. Pitch and Larger Silent Chain Sprocket Measurement (ANSI B29.2M-1982, R1987)**

| Pitch                                | Number of Teeth |         |         |         |         |         |         |           |          |        |
|--------------------------------------|-----------------|---------|---------|---------|---------|---------|---------|-----------|----------|--------|
|                                      | Up to 15        | 16 - 24 | 25 - 35 | 36 - 48 | 49 - 63 | 64 - 80 | 81 - 99 | 100 - 120 | 121- 143 | 144 up |
| Tolerances, <sup>a</sup> Inches      |                 |         |         |         |         |         |         |           |          |        |
| 0.1875                               | 0.004           | 0.004   | 0.004   | 0.004   | 0.004   | 0.005   | 0.005   | 0.005     | 0.005    | 0.005  |
| Tolerances, <sup>a</sup> Millimeters |                 |         |         |         |         |         |         |           |          |        |
| 4.76                                 | 0.10            | 0.10    | 0.10    | 0.10    | 0.10    | 0.13    | 0.13    | 0.13      | 0.13     | 0.13   |

<sup>a</sup>All tolerances are negative.



Grooving tool may be either square or round end but groove must be full width down to diameter of G. For values of G (max.) see footnote to Table 3a

Values of H ( $\pm 0.003$  in.) = 0.051 in. are given only for chain numbers SC302 and SC402. M = Max. overall width of chain. The maximum radius over a new chain engaged on a sprocket will not exceed the sprocket pitch radius plus 75 per cent of the chain pitch. To obtain the chain widths and sprocket face dimensions in millimeters, multiply each entry by 25.4.



**Table 4c. ANSI  $\frac{3}{8}$ - in. Pitch and Larger Silent Chain Widths and Sprocket Face Dimensions (ANSI B29.2M-1982, R1987)**

| Chain No | Chain Pitch | Type                    | M <sup>a</sup><br>Max. | A     | C<br>±0.005 | D<br>±0.010 | F<br>+0.125<br>-0.000 | R<br>±0.003 | W<br>+0.010<br>-0.000 |       |     |
|----------|-------------|-------------------------|------------------------|-------|-------------|-------------|-----------------------|-------------|-----------------------|-------|-----|
| SC302    | 0.375       | Side Guide <sup>b</sup> | 0.594                  | 0.133 | ...         | ...         | ...                   | 0.200       | 0.410                 |       |     |
| SC303    |             | Center Guide            | 0.844                  |       | 0.100       | ...         | 0.750                 |             |                       | ...   |     |
| SC304    |             |                         | 1.094                  |       |             | ...         | 1.000                 |             |                       | ...   |     |
| SC305    |             |                         | 1.344                  |       |             | ...         | 1.250                 |             |                       | ...   |     |
| SC306    |             |                         | 1.594                  |       |             | ...         | 1.500                 |             |                       | ...   |     |
| SC307    |             |                         | 1.844                  |       |             | ...         | 1.750                 |             |                       | ...   |     |
| SC308    |             |                         | 2.094                  |       |             | ...         | 2.000                 |             |                       | ...   |     |
| SC309    |             |                         | 2.344                  |       |             | ...         | 2.250                 |             |                       | ...   |     |
| SC310    |             |                         | 2.594                  |       |             | ...         | 2.500                 |             |                       | ...   |     |
| SC312    |             |                         | Double-Guide           |       |             | 3.094       | 1.000                 |             |                       | 3.000 | ... |
| SC316    |             |                         |                        |       |             | 4.094       |                       |             |                       | 4.000 | ... |
| SC320    |             | 5.094                   |                        |       | 5.000       | ...         |                       |             |                       |       |     |
| SC324    | 6.094       | 6.000                   |                        | ...   |             |             |                       |             |                       |       |     |
| SC402    | 0.500       | Side Guide <sup>b</sup> | 0.750                  | 0.133 | ...         | ...         | ...                   | 0.200       | 0.410                 |       |     |
| SC403    |             | Center Guide            | 0.875                  |       | 0.100       | ...         | 0.750                 |             |                       | ...   |     |
| SC404    |             |                         | 1.125                  |       |             | ...         | 1.000                 |             |                       | ...   |     |
| SC405    |             |                         | 1.375                  |       |             | ...         | 1.250                 |             |                       | ...   |     |
| SC406    |             |                         | 1.625                  |       |             | ...         | 1.500                 |             |                       | ...   |     |
| SC407    |             |                         | 1.875                  |       |             | ...         | 1.750                 |             |                       | ...   |     |
| SC408    |             |                         | 2.125                  |       |             | ...         | 2.000                 |             |                       | ...   |     |
| SC409    |             |                         | 2.375                  |       |             | ...         | 2.250                 |             |                       | ...   |     |
| SC410    |             |                         | 2.625                  |       |             | ...         | 2.500                 |             |                       | ...   |     |
| SC411    |             |                         | 2.875                  |       |             | ...         | 2.750                 |             |                       | ...   |     |
| SC412    |             |                         | 3.125                  |       |             | ...         | 3.000                 |             |                       | ...   |     |
| SC414    |             |                         | 3.625                  |       |             | ...         | 3.500                 |             |                       | ...   |     |
| SC416    |             |                         | Double-Guide           |       |             | 4.125       | 1.000                 |             |                       | 4.000 | ... |
| SC420    |             |                         |                        |       |             | 5.125       |                       |             |                       | 5.000 | ... |
| SC424    |             |                         |                        |       |             | 6.125       |                       |             |                       | 6.000 | ... |
| SC432    |             | 8.125                   |                        |       | 8.000       | ...         |                       |             |                       |       |     |
| SC504    | 0.625       | Center-Guide            | 1.156                  | 0.177 | 0.125       | ...         | 1.000                 | 0.250       | ...                   |       |     |
| SC505    |             |                         | 1.406                  |       |             | ...         | 1.250                 |             |                       | ...   |     |
| SC506    |             |                         | 1.656                  |       |             | ...         | 1.500                 |             |                       | ...   |     |
| SC507    |             |                         | 1.906                  |       |             | ...         | 1.750                 |             |                       | ...   |     |
| SC508    |             |                         | 2.156                  |       |             | ...         | 2.000                 |             |                       | ...   |     |
| SC510    |             |                         | 2.656                  |       |             | ...         | 2.500                 |             |                       | ...   |     |
| SC512    |             |                         | 3.156                  |       |             | ...         | 3.000                 |             |                       | ...   |     |
| SC516    |             |                         | 4.156                  |       |             | ...         | 4.000                 |             |                       | ...   |     |
| SC520    |             | Double-Guide            | 5.156                  |       |             | 2.000       | 5.000                 |             |                       | ...   |     |
| SC524    |             |                         | 6.156                  |       |             |             | 6.000                 |             |                       | ...   |     |
| SC528    |             |                         | 7.156                  |       |             |             | 7.000                 |             |                       | ...   |     |
| SC532    |             |                         | 8.156                  |       |             |             | 8.000                 |             |                       | ...   |     |
| SC540    |             |                         | 10.156                 |       |             |             | 10.000                |             |                       | ...   |     |

**Table 4c. (Continued) ANSI  $\frac{3}{8}$ -in. Pitch and Larger Silent Chain Widths and Sprocket Face Dimensions (ANSI B29.2M-1982, R1987)**

| Chain No | Chain Pitch | Type         | M <sup>a</sup> Max. | A      | C ±0.005 | D ±0.010     | F +0.125 -0.000 | R ±0.003 | W +0.010 -0.000 |       |       |
|----------|-------------|--------------|---------------------|--------|----------|--------------|-----------------|----------|-----------------|-------|-------|
| SC604    | 0.750       | Center-Guide | 1.187               | 0.274  | 0.180    | ...          | 1.000           | 0.360    | ...             |       |       |
| SC605    |             |              | 1.437               |        |          | ...          | 1.250           |          | ...             |       |       |
| SC606    |             |              | 1.687               |        |          | ...          | 1.500           |          | ...             |       |       |
| SC608    |             |              | 2.187               |        |          | ...          | 2.000           |          | ...             |       |       |
| SC610    |             |              | 2.687               |        |          | ...          | 2.500           |          | ...             |       |       |
| SC612    |             |              | 3.187               |        |          | ...          | 3.000           |          | ...             |       |       |
| SC614    |             |              | 3.687               |        |          | ...          | 3.500           |          | ...             |       |       |
| SC616    |             |              | 4.187               |        |          | ...          | 4.000           |          | ...             |       |       |
| SC620    |             |              | 5.187               |        |          | ...          | 5.000           |          | ...             |       |       |
| SC624    |             |              | 6.187               |        |          | Double guide | 6.187           |          | 4.000           | 6.000 | ...   |
| SC628    |             |              | 7.187               |        |          |              | 7.000           |          |                 | ...   |       |
| SC632    |             |              | 8.187               |        |          |              | 8.000           |          |                 | ...   |       |
| SC636    |             |              | 9.187               |        |          |              | 9.000           |          |                 | ...   |       |
| SC640    |             |              | 10.187              |        |          |              | 10.000          |          |                 | ...   |       |
| SC648    | 12.187      | 12.000       | ...                 |        |          |              |                 |          |                 |       |       |
| SC808    | 1.000       | Center Guide | 2.250               | 0.177  | 0.125    |              | ...             | 2.000    |                 | 0.250 | ...   |
| SC810    |             |              | 2.750               |        |          | ...          | 2.500           | ...      |                 |       |       |
| SC812    |             |              | 3.250               |        |          | ...          | 3.000           | ...      |                 |       |       |
| SC816    |             |              | 4.250               |        |          | ...          | 4.000           | ...      |                 |       |       |
| SC820    |             |              | 5.250               |        |          | ...          | 5.000           | ...      |                 |       |       |
| SC824    |             |              | 6.250               |        |          | ...          | 6.000           | ...      |                 |       |       |
| SC828    |             |              | 7.250               |        |          | ...          | 7.000           | ...      |                 |       |       |
| SC832    |             |              | 8.250               |        |          | Double guide | 8.250           | ...      | 8.000           |       | ...   |
| SC836    |             |              | 9.250               |        |          |              | 9.000           | ...      |                 |       |       |
| SC840    |             |              | 10.250              |        |          |              | 10.000          | ...      |                 |       |       |
| SC848    |             |              | 12.250              |        |          |              | 12.000          | ...      |                 |       |       |
| SC856    |             |              | 14.250              |        |          |              | 14.000          | ...      |                 |       |       |
| SC864    |             |              | 16.250              |        |          |              | 16.000          | ...      |                 |       |       |
| SC1010   |             |              | 1.25                |        |          |              | Center Guide    | 2.812    | 0.274           |       | 0.180 |
| SC1012   | 3.312       | ...          |                     | 3.000  | ...      |              |                 |          |                 |       |       |
| SC1016   | 4.312       | ...          |                     | 4.000  | ...      |              |                 |          |                 |       |       |
| SC1020   | 5.312       | ...          |                     | 5.000  | ...      |              |                 |          |                 |       |       |
| SC1024   | 6.312       | ...          |                     | 6.000  | ...      |              |                 |          |                 |       |       |
| SC1028   | 7.312       | ...          |                     | 7.000  | ...      |              |                 |          |                 |       |       |
| SC1032   | 8.312       | Double guide |                     | 8.312  | 4.000    | 8.000        |                 | ...      |                 |       |       |
| SC1036   | 9.312       |              |                     | 9.000  |          | ...          |                 |          |                 |       |       |
| SC1040   | 10.312      |              |                     | 10.000 |          | ...          |                 |          |                 |       |       |
| SC1048   | 12.312      |              |                     | 12.000 |          | ...          |                 |          |                 |       |       |
| SC1056   | 14.312      |              |                     | 14.000 |          | ...          |                 |          |                 |       |       |
| SC1064   | 16.312      |              |                     | 16.000 |          | ...          |                 |          |                 |       |       |
| SC1072   | 18.312      |              |                     | 18.000 |          | ...          |                 |          |                 |       |       |
| SC1080   | 20.312      | 20.000       |                     | ...    |          |              |                 |          |                 |       |       |

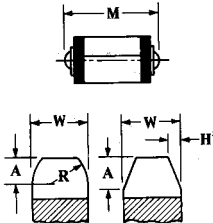
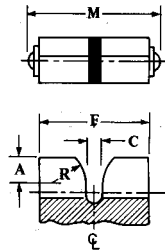
**Table 4c. (Continued) ANSI  $\frac{3}{8}$ -in. Pitch and Larger Silent Chain Widths and Sprocket Face Dimensions (ANSI B29.2M-1982, R1987)**

| Chain No | Chain Pitch | Type         | M <sup>a</sup> Max. | A     | C<br>±0.005 | D<br>±0.010 | F<br>+0.125<br>-0.000 | R<br>±0.003 | W<br>+0.010<br>-0.000 |     |
|----------|-------------|--------------|---------------------|-------|-------------|-------------|-----------------------|-------------|-----------------------|-----|
| SC1212   | 1.500       | Center Guide | 3.375               | 0.274 | 0.180       | ...         | 3.000                 | 0.360       | ...                   |     |
| SC1216   |             |              | 4.375               |       |             | ...         | 4.000                 |             | ...                   |     |
| SC1220   |             |              | 5.375               |       |             | ...         | 5.000                 |             | ...                   |     |
| SC1224   |             |              | 6.375               |       |             | ...         | 6.000                 |             | ...                   |     |
| SC1228   |             |              | 7.375               |       |             | ...         | 7.000                 |             | ...                   |     |
| SC1232   |             |              | 8.375               |       |             | ...         | 8.000                 |             | ...                   |     |
| SC1236   |             | Double guide | 9.375               |       |             | ...         | 4.000                 |             | 9.000                 | ... |
| SC1240   |             |              | 10.375              |       |             | ...         | 10.000                |             | ...                   |     |
| SC1248   |             |              | 12.375              |       |             | ...         | 12.000                |             | ...                   |     |
| SC1256   |             |              | 14.375              |       |             | ...         | 14.000                |             | ...                   |     |
| SC1264   |             |              | 16.375              |       |             | ...         | 16.000                |             | ...                   |     |
| SC1272   |             |              | 18.375              |       |             | ...         | 18.000                |             | ...                   |     |
| SC1280   |             |              | 20.375              |       |             | ...         | 20.000                |             | ...                   |     |
| SC1288   |             |              | 22.375              |       |             | ...         | 22.000                |             | ...                   |     |
| SC1296   | 24.375      | ...          | 24.000              | ...   |             |             |                       |             |                       |     |
| SC1616   | 2.000       | Center Guide | 4.500               | 0.274 | 0.218       | ...         | 4.000                 | 0.360       | ...                   |     |
| SC1620   |             |              | 5.500               |       |             | ...         | 5.000                 |             | ...                   |     |
| SC1624   |             |              | 6.500               |       |             | ...         | 6.000                 |             | ...                   |     |
| SC1628   |             |              | 7.500               |       |             | ...         | 4.000                 |             | 7.000                 | ... |
| SC1632   |             | Double guide | 8.500               |       |             | ...         | 8.000                 |             | ...                   |     |
| SC1640   |             |              | 10.500              |       |             | ...         | 10.000                |             | ...                   |     |
| SC1648   |             |              | 12.500              |       |             | ...         | 12.000                |             | ...                   |     |
| SC1656   |             |              | 14.500              |       |             | ...         | 14.000                |             | ...                   |     |
| SC1664   |             |              | 16.500              |       |             | ...         | 16.000                |             | ...                   |     |
| SC1672   |             |              | 18.500              |       |             | ...         | 18.000                |             | ...                   |     |
| SC1680   |             |              | 20.500              |       |             | ...         | 20.000                |             | ...                   |     |
| SC1688   |             |              | 22.500              |       |             | ...         | 22.000                |             | ...                   |     |
| SC1696   |             |              | 24.500              |       |             | ...         | 24.000                |             | ...                   |     |
| SC16120  |             |              | 30.500              |       |             | ...         | 30.000                |             | ...                   |     |

<sup>a</sup> Specify side guide or center guide type.

<sup>b</sup> Side Guide chains have single outside guides of same thickness as toothed links. All dimensions in inches. M Max. overall width of chain.

**Table 4d. American National Standard  $\frac{3}{16}$ -in. Pitch and Larger Silent Chain Widths and Sprocket Face Dimensions ANSI B29.2M-1982, 1987**

|  |             | SIDE GUIDE  |        | CENTER GUIDE  |        |        |       |          |  |
|--|-------------|---|--------|---|--------|--------|-------|----------|--|
|  |             |  |        |  |        |        |       |          |  |
|  |             | <b>SIDE GUIDE</b>   |        | <b>CENTER GUIDE</b>   |        |        |       |          |  |
| Values of H = 0.025 in. are given for chain numbers SC0305 through SC0315. |             |   |        |   |        |        |       |          |  |
| Chain No   | Chain Pitch | Type  | M Max. | A   | C Max. | F Min. | R     | W ±0.003 |  |
| SC0305   | 0.1875      | Side Guide  | 0.216  | 0.06  | ...    | ...    | 0.09  | 0.075    |  |
| SC0307   |             |   | 0.278  |   | ...    | ...    |       | 0.138    |  |
| SC0309   |             |   | 0.341  |   | ...    | ...    |       | 0.201    |  |
| SC0311   |             | Side Guide/<br>Center Guide   | 0.403  |   | 0.050  | 0.334  | 0.264 |          |  |
| SC0313   |             |   | 0.466  |   |        |        | 0.396 | 0.327    |  |
| SC0315   |             |   | 0.528  |   |        |        | 0.459 | 0.390    |  |
| SC0317   |             | Center Guide  | 0.591  |   | 0.521  | ...    |       |          |  |
| SC0319   |             |   | 0.653  |   | 0.584  | ...    |       |          |  |
| SC0321   |             |   | 0.716  |   | 0.646  | ...    |       |          |  |
| SC0323   |             |   | 0.778  |   | 0.709  | ...    |       |          |  |
| SC0325   |             |   | 0.850  |   | 0.771  | ...    |       |          |  |
| SC0327   |             |   | 0.903  |   | 0.834  | ...    |       |          |  |
| SC0329   |             |   | 0.966  |   | 0.896  | ...    |       |          |  |
| SC0331   |             |   | 1.028  |   | 0.959  | ...    |       |          |  |

All dimensions in inches. M = Max. overall width of chain.

To obtain chain width and sprocket face dimensions in millimeters, multiply each entry by 25.4.

**Sprocket Hub Dimensions.**—The important hub dimensions are the outside diameter, the bore, and the length. The maximum hub diameter is limited by the need to clear the chain guides and is of particular importance for sprockets with low numbers of teeth. The American National Standard for inverted tooth chains and sprocket teeth ANSI B29.2M-1982 (R1987) provides the following formulas for calculating maximum hub diameters, *MHD*.

$$MHD(\text{for hobbled teeth}) = P \left[ \cot \left( \frac{180^\circ}{N} \right) - 1.33 \right]$$

$$MHD(\text{for straddle cut teeth}) = P \left[ \cot \left( \frac{180^\circ}{N} \right) - 1.25 \right]$$

Maximum hub diameters for sprockets with from 17 to 31 teeth are given in Table 5. Maximum hub diameters for other methods of cutting teeth may differ from these values. Recommended maximum bores are given in Table 6.

**Table 5. American National Standard Minimum Hub Diameters for Silent chain Sprockets (17 to 31 Teeth) ANSI B29.2M-1982, 1987**

| No. Teeth | Hob cut        | Straddle Cut | No. Teeth | Hob cut        | Straddle Cut | No. Teeth | Hob cut        | Straddle Cut |
|-----------|----------------|--------------|-----------|----------------|--------------|-----------|----------------|--------------|
|           | Min. Hub Diam. |              |           | Min. Hub Diam. |              |           | Min. Hub Diam. |              |
| 17        | 4.019          | 4.099        | 22        | 5.626          | 5.706        | 27        | 7.226          | 7.306        |
| 18        | 4.341          | 4.421        | 23        | 5.946          | 6.026        | 28        | 7.546          | 7.626        |
| 19        | 4.662          | 4.742        | 24        | 6.265          | 6.345        | 29        | 7.865          | 7.945        |
| 20        | 4.983          | 5.063        | 25        | 6.586          | 6.666        | 30        | 8.185          | 8.265        |
| 21        | 5.304          | 5.384        | 26        | 6.905          | 6.985        | 31        | 8.503          | 8.583        |

All dimensions in inches.

Values shown are 1-inch pitch chain. For other pitches ( $\frac{3}{8}$ -inch and larger) multiply the values given by the pitch.

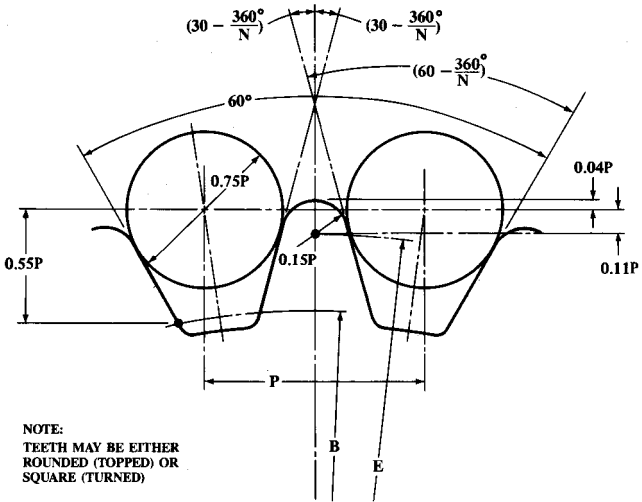
Good practice indicates that teeth of sprockets up to and including 31 teeth should have a Rockwell hardness of C50 min.

**Table 6. Recommended maximum Sprocket Bores for Silent Chains**

| Number of Teeth | Chain Pitch, Inches           |                  |                |                |                |                |                |                 |
|-----------------|-------------------------------|------------------|----------------|----------------|----------------|----------------|----------------|-----------------|
|                 | $\frac{3}{8}$                 | $\frac{1}{2}$    | $\frac{5}{8}$  | $\frac{3}{4}$  | 1              | $1\frac{1}{4}$ | $1\frac{1}{2}$ | 2               |
|                 | Maximum Sprocket Bore, Inches |                  |                |                |                |                |                |                 |
| 17              | 1                             | $1\frac{3}{8}$   | $1\frac{3}{4}$ | 2              | $2\frac{3}{4}$ | $3\frac{3}{8}$ | $4\frac{1}{8}$ | $5\frac{1}{4}$  |
| 19              | $1\frac{1}{4}$                | $1\frac{5}{8}$   | 2              | $2\frac{3}{8}$ | $3\frac{1}{4}$ | 4              | $4\frac{7}{8}$ | $6\frac{3}{4}$  |
| 21              | $1\frac{3}{8}$                | $1\frac{7}{8}$   | $2\frac{1}{4}$ | $2\frac{3}{4}$ | $3\frac{3}{4}$ | $4\frac{1}{2}$ | $5\frac{1}{2}$ | $7\frac{3}{4}$  |
| 23              | $1\frac{5}{8}$                | $2\frac{1}{8}$   | $2\frac{5}{8}$ | $3\frac{1}{4}$ | $4\frac{3}{8}$ | $5\frac{1}{2}$ | $6\frac{1}{2}$ | 9               |
| 25              | $1\frac{3}{4}$                | $2\frac{3}{8}$   | 3              | $3\frac{5}{8}$ | $4\frac{3}{4}$ | 6              | $7\frac{1}{4}$ | 10              |
| 27              | 2                             | $2\frac{5}{8}$   | $3\frac{3}{8}$ | $3\frac{7}{8}$ | $5\frac{3}{8}$ | $6\frac{3}{4}$ | $8\frac{1}{8}$ | $11\frac{1}{4}$ |
| 29              | $2\frac{1}{8}$                | $2\frac{13}{16}$ | $3\frac{5}{8}$ | $4\frac{3}{8}$ | $5\frac{3}{4}$ | $7\frac{3}{8}$ | $9\frac{1}{8}$ | $12\frac{1}{4}$ |
| 31              | $2\frac{5}{16}$               | $3\frac{1}{16}$  | $3\frac{7}{8}$ | $4\frac{5}{8}$ | $6\frac{3}{8}$ | 8              | $9\frac{7}{8}$ | $13\frac{1}{4}$ |

American Chain Association.

**Table 7a. Tooth Form for ANSI  $\frac{3}{8}$ -inch and larger Silent Tooth Sprocket  
ANSI B29.2M-1982, R1987**



$P$  = Chain Pitch

$N$  = Number of Teeth

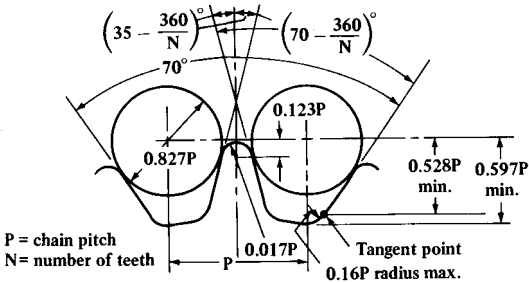
$E$  = Diameter to Center of Topping Curve

$B$  = Diameter to Base of Working Face

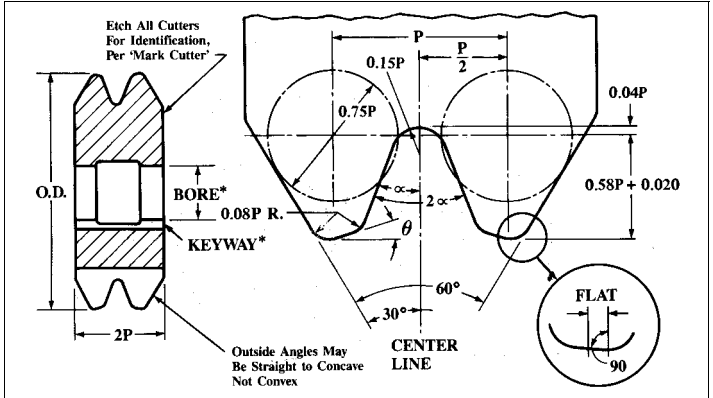
$$E = P \left( \cot \frac{180^\circ}{N} - 0.22 \right)$$

$$B = P \sqrt{1.515213 + \left( \cot \frac{180^\circ}{N} - 1.1 \right)^2}$$

**Table 7b. Tooth Form for ANSI  $\frac{3}{16}$ -inch and larger Silent Tooth Sprocket ANSI  
B29.2M-1982, R1987**



**Table 8. Straddle Cutters for American National Standard  $\frac{3}{8}$  in. Pitch and Larger Silent Chain Sprocket Teeth**



| Chain Pitch P | Mark Cutter <sup>a</sup>      | Outside Diam. | 0.75P  | $\alpha$           | $\theta$  | Bore <sup>b</sup> |
|---------------|-------------------------------|---------------|--------|--------------------|-----------|-------------------|
| 0.375         | SC3-15 thru 35<br>SC3-36 up   | 3.625         | 0.2813 | 22°-30'<br>27°-30' | 12°<br>5° | 1.250             |
| 0.500         | SC4-15 thru 35<br>SC4-36 up   | 3.875         | 0.3750 | 22°-30'<br>27°-30' | 12°<br>5° | 1.250             |
| 0.625         | SC5-15 thru 35<br>SC5-36 up   | 4.250         | 0.4688 | 22°-30'<br>27°-30' | 2°<br>5°  | 1.250             |
| 0.750         | SC6-15 thru 35<br>SC6-36 up   | 4.625         | 0.5625 | 22°-30'<br>27°-30' | 12°<br>5° | 1.250             |
| 1.000         | SC8-15 thru 35<br>SC8-36 up   | 5.250         | 0.7500 | 22°-30'<br>27°-30' | 12°<br>5° | 1.500             |
| 1.250         | SC10-15 thru 35<br>SC10-36 up | 5.750         | 0.9375 | 22°-30'<br>27°-30' | 12°<br>5° | 1.500             |
| 1.500         | SC12-15 thru 35<br>SC12-36 up | 6.250         | 1.1250 | 22°-30'<br>27°-30' | 12°<br>5° | 1.750             |
| 2.000         | SC16-15 thru 35<br>SC16-36 up | 6.500         | 1.5000 | 22°-30'<br>27°-30' | 12°<br>5° | 1.750             |

<sup>a</sup> Range of teeth is indicated in the cutter marking.

<sup>b</sup> Suggested standard. Bores other than standard must be specified.

All dimensions in inches. To obtain values in millimeters, multiply inch values by 25.4. These data are given as supplementary information in ANSI B29.2M-1982, R1987 and are made available by the American Chain Association.

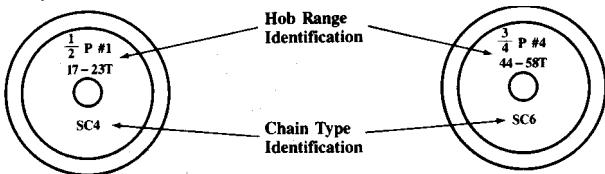
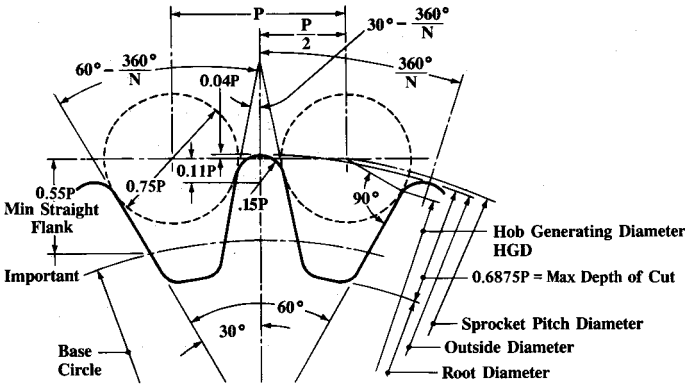


Fig. 3. Identification of Inverted Tooth Chain Hobs.

Table 9. Hobs for ANSI  $\frac{3}{8}$ -inch and larger Silent Tooth Sprocket\*

$P$  = Chain Pitch

$N$  = Number of Teeth

$$HGD = P \sqrt{\frac{1}{\sin \frac{180^\circ}{N}} + 0.5625 - \frac{1.5 \sin \left( 30 - \frac{180^\circ}{N} \right)}{\sin \frac{180^\circ}{N}}}$$

**Sprocket Design and Tooth Form.**—Except for tooth form, silent chain sprocket design parallels the general design practice of roller chain sprockets as covered in the previous section.

As shown in Tables 7a and 7b, sprockets for American National Standard silent chains have teeth with straight-line working faces. The tops of teeth for  $\frac{3}{8}$ -in. and larger pitch chains may be rounded or square. Bottom clearance below the working face is not specified but must be sufficient to clear the chain teeth. The standard tooth form for  $\frac{3}{8}$ -in. and larger pitch chains is designed to mesh with link plate contours having an included angle of 60 degrees as shown in the diagram of Table 7a. The standard tooth form for  $\frac{3}{16}$ -in. pitch chains has an included angle of 70 degrees as shown in Table 7b. It will be seen from these tables that the angle between the faces of a given tooth [ $60^\circ - 720^\circ/N$  for  $\frac{3}{8}$ -in. pitch and larger;  $70^\circ - 720^\circ/N$  for  $\frac{3}{16}$ -in. pitch] becomes smaller as the number of teeth decreases. Therefore, for a  $\frac{3}{8}$ -in. pitch or larger 12-tooth sprocket it will be zero. In other words the tooth faces will be parallel.

For smaller tooth numbers the teeth would be undercut. For best results, 21 or more teeth are recommended; less than 17 should not be used.

**Cutting Silent Chain Sprocket Teeth.**—Sprocket teeth may be cut by either a straddle cutter or a hob. Essential dimensions for straddle cutters are given in Table 8 and for hobs in Table 9 and 10. American National Standard silent chain hobs are stamped for identification as shown on page 2375.

\* Source: American Chain Association.



**Table 10. Hobs for American National Standard  $\frac{3}{8}$ -in. Pitch and Larger Silent Chain Sprocket Teeth\***

| Chain Pitch                    | Hob Number | Basic Number of Teeth | Tooth Range of Hob | Generating Diameter |             |
|--------------------------------|------------|-----------------------|--------------------|---------------------|-------------|
|                                |            |                       |                    | Inches              | Millimeters |
| SC3 = 0.375 in.<br>= 9.52 mm   | 1          | 20                    | 17 - 23            | 2.311               | 58.70       |
|                                | 2          | 28                    | 24 - 32            | 3.247               | 82.47       |
|                                | 3          | 38                    | 33 - 43            | 4.428               | 112.47      |
|                                | 4          | 51                    | 44 - 58            | 5.971               | 151.66      |
|                                | 5          | 69                    | 29 - 79            | 8.114               | 206.10      |
|                                | 6          | 95                    | 80 - 110           | 11.212              | 284.78      |
|                                | 7          | 130                   | 111 - 150          | 15.385              | 390.78      |
| SC4 = 0.500 in.<br>= 12.70 mm  | 1          | 20                    | 17 - 23            | 3.082               | 78.28       |
|                                | 2          | 28                    | 24 - 32            | 4.329               | 109.96      |
|                                | 3          | 38                    | 33 - 43            | 5.904               | 149.96      |
|                                | 4          | 51                    | 44 - 58            | 7.962               | 202.23      |
|                                | 5          | 69                    | 29 - 79            | 10.818              | 274.78      |
|                                | 6          | 95                    | 80 - 110           | 14.950              | 379.73      |
|                                | 7          | 130                   | 111 - 150          | 20.513              | 521.03      |
| SC5 = 0.625 in.<br>= 15.88 mm  | 1          | 20                    | 17 - 23            | 3.852               | 97.84       |
|                                | 2          | 28                    | 24 - 32            | 5.412               | 137.46      |
|                                | 3          | 38                    | 33 - 43            | 7.381               | 187.48      |
|                                | 4          | 51                    | 44 - 58            | 9.952               | 252.78      |
|                                | 5          | 69                    | 29 - 79            | 13.522              | 343.46      |
|                                | 6          | 95                    | 80 - 110           | 18.687              | 474.65      |
|                                | 7          | 130                   | 111 - 150          | 25.641              | 651.28      |
| SC6 = 0.750 in.<br>= 19.05 mm  | 1          | 20                    | 17 - 23            | 4.623               | 117.42      |
|                                | 2          | 28                    | 24 - 32            | 6.494               | 164.95      |
|                                | 3          | 38                    | 33 - 43            | 8.857               | 224.97      |
|                                | 4          | 51                    | 44 - 58            | 11.943              | 303.35      |
|                                | 5          | 69                    | 29 - 79            | 16.227              | 412.17      |
|                                | 6          | 95                    | 80 - 110           | 22.424              | 569.57      |
|                                | 7          | 130                   | 111 - 150          | 30.770              | 781.56      |
| SC8 = 1.000 in.<br>= 25.40 mm  | 1          | 20                    | 17 - 23            | 6.163               | 156.54      |
|                                | 2          | 28                    | 24 - 32            | 8.659               | 219.94      |
|                                | 3          | 38                    | 33 - 43            | 11.809              | 299.95      |
|                                | 4          | 51                    | 44 - 58            | 15.924              | 404.47      |
|                                | 5          | 69                    | 29 - 79            | 21.636              | 549.55      |
|                                | 6          | 95                    | 80 - 110           | 29.899              | 759.43      |
|                                | 7          | 130                   | 111 - 150          | 41.026              | 1042.06     |
| SC10 = 1.250 in.<br>= 31.75 mm | 1          | 20                    | 17 - 23            | 7.704               | 195.68      |
|                                | 2          | 28                    | 24 - 32            | 10.823              | 274.90      |
|                                | 3          | 38                    | 33 - 43            | 14.761              | 374.93      |
|                                | 4          | 51                    | 44 - 58            | 19.905              | 505.59      |
|                                | 5          | 69                    | 29 - 79            | 27.045              | 686.94      |
|                                | 6          | 95                    | 80 - 110           | 37.374              | 949.30      |
|                                | 7          | 130                   | 111 - 150          | 51.283              | 1302.59     |
| SC12 = 1.500 in.<br>= 38.10 mm | 1          | 20                    | 17-23              | 9.245               | 234.82      |
|                                | 2          | 28                    | 24 - 32            | 12.988              | 329.90      |
|                                | 3          | 38                    | 33 - 43            | 17.713              | 449.91      |
|                                | 4          | 51                    | 44 - 58            | 23.886              | 606.70      |
|                                | 5          | 69                    | 29 - 79            | 32.454              | 824.33      |
|                                | 6          | 95                    | 80 - 110           | 44.849              | 1139.16     |
|                                | 7          | 130                   | 111 - 150          | 61.539              | 1563.09     |
| SC16 = 2.000 in.<br>= 50.80 mm | 1          | 20                    | 17 - 23            | 12.327              | 313.11      |
|                                | 2          | 28                    | 24 - 32            | 17.317              | 439.85      |
|                                | 3          | 38                    | 33 - 43            | 23.618              | 599.90      |
|                                | 4          | 51                    | 44 - 58            | 31.848              | 808.94      |
|                                | 5          | 69                    | 29 - 79            | 43.272              | 1099.11     |
|                                | 6          | 95                    | 80 - 110           | 59.798              | 1518.87     |
|                                | 7          | 130                   | 111 - 150          | 82.052              | 2.84.12     |

\* Source: American Chain Association.

**Design of Silent Chain Drives.**—The design of silent chain transmissions must be based not only upon the power to be transmitted and the ratio between driving and driven shafts, but also upon such factors as the speed of the faster running shaft, the available space, assuming that it affects the sprocket diameters, the character of the load and certain other factors. Determining the pitch of the chain and the number of teeth on the smallest sprocket are the important initial steps. Usually any one of several combinations of pitches and sprocket sizes may be employed for a given installation. In attempting to select the best combination, it is advisable to consult with the manufacturer of the chain to be used. Some of the more important fundamental points governing the design of silent chain transmissions will be summarized.

The design of a silent chain drive consists, primarily, of the selection of the chain size, sprockets, determination of chain length, center distance, lubrication method, and arrangement of casings.

**Pitch of Silent Chain.**—The pitch is selected with reference to the speed of the faster running shaft which ordinarily is the driver and holds the smaller sprocket. The following pitches are recommended: for a faster running shaft of 2000 to 5000 rpm,  $\frac{3}{8}$ -inch pitch; for 1500 to 2000 rpm,  $\frac{1}{2}$ -inch pitch; for 1200 to 1500 rpm,  $\frac{5}{8}$ -inch pitch, for 1000 to 1200 rpm,  $\frac{3}{4}$ -inch pitch; for 800 to 1000 rpm, 1-inch pitch; for 650 to 800 rpm,  $1\frac{1}{4}$ -inch pitch; for 300 to 600 rpm,  $1\frac{1}{2}$ -inch pitch; for 300 to 500 rpm, 2-inch pitch; and for below 300 rpm,  $2\frac{1}{2}$ -inch pitch. As the normal operating speeds increase, the allowable pitch decreases. Recommendations relating to the relationship between pitch and operating speed are intended for normal or average conditions. Speeds for a given pitch may be exceeded under favorable conditions and may have to be reduced when conditions are unfavorable. In general, smoother or quieter operation will result from using the smallest pitch suitable for a given speed and load. However, a larger pitch which might be applicable under the same conditions, will result in a narrower chain and a less expensive transmission. This relationship usually is true when there is a small speed reduction and comparatively long center distance. If there is a large speed reduction and short center distance, drives having the smaller pitches may be less expensive.

**Maximum Ratios for Silent Chain Drives.**—The maximum permissible ratios between driving and driven sprockets vary somewhat for different conditions and usually range from 6- or 7-to-1 up to 10-to-1. Some drives have even higher ratios, especially when the operating conditions are exceptionally favorable. When a large speed reduction is necessary, it is preferable as a general rule to use a double reduction or compound type of transmission instead of obtaining the entire reduction with two sprockets. Drives should be so proportioned that the angle between the two strands of a tight chain does not exceed 45 degrees. When the angle is larger, the chain does not have sufficient contact with the driving sprocket.

*Sprocket Size and Chain Speed:* A driving sprocket with not less than 17 teeth is generally recommended. For the driven sprocket, one manufacturer recommends 127 teeth as a maximum limit and less than 100 as preferable. If practicable, the sprocket sizes should be small enough to limit the chain speed to from 1200 to 1400 feet per minute. If the chain speed exceeds these figures, this may indicate that the pitch is too large or that a smaller pitch, and, consequently, a reduction in sprocket diameters (and chain speed) will result in better operating conditions. Both sprockets should preferably have a "hunting tooth ratio" relative to the number of chain links for uniform wear. See "Hunting Tooth Ratios," page 1867.

If there is a small reduction in speed between the driving and driven shafts, both sprockets may be made as small as is consistent with satisfactory operation, either to obtain a compact drive or possibly to avoid excessive chain speed in cases where the rotative speed is high for a given horsepower. Under such conditions, one manufacturer recommends driving sprockets ranging from 17 to 30 teeth, and driven sprockets ranging from 19 to 33

teeth. If the number of revolutions per minute is low for a given horsepower and the center distance comparatively long, then the recommended range for driving sprockets is from 23 to iii teeth, and driven sprockets from 27 to 129 teeth. The preferable range is from 17 to 75 teeth for the driving sprockets, and 19 to 102 teeth for the driven sprockets.

**Center Distance for Silent Chain Drives.**—If the ratio of the drive is small, it is possible to locate the sprockets so close—that the teeth just clear; however, as a general rule, the minimum center-to-center distance should equal the sum of the diameters of both sprockets. According to the Whitney Chain & Mfg. Co., if the speed ratio is not over  $2\frac{1}{2}$ -to-1, the center distance may be equal to one-half the sum of the sprocket diameters plus tooth clearance, providing this distance is not less than the minimum given in Table 11. If the speed ratio is greater than  $2\frac{1}{2}$ -to-1, the center distance should not be less than the sum of the sprocket diameters.

**Table 11. Minimum Center Distances for Various Pitches**

| Pitch, inches                    | $\frac{3}{8}$ | $\frac{1}{2}$ | $\frac{5}{8}$ | $\frac{3}{4}$ | 1  | $1\frac{1}{4}$ | $1\frac{1}{2}$ |
|----------------------------------|---------------|---------------|---------------|---------------|----|----------------|----------------|
| Minimum Center Distances, inches | 6             | 9             | 12            | 15            | 21 | 27             | 33             |

When the chain length in pitches is known, the equivalent center distance for a tight chain may be determined by the formula for roller chain found on page 2348.

In selecting chain length, factors determining length should be adjusted so that the use of offset links may be avoided wherever possible. Chain lengths of an uneven number of pitches are also to be avoided.

**Silent Tooth Chain Horsepower Capacity.**—The horsepower ratings given in Tables 12a, 12b, and 12c have been established on a life expectancy of approximately 15,000 hours under optimum drive conditions, i.e. for a uniform rate of work where there is relatively little shock or load variation throughout a single revolution of a driven sprocket. Using these horsepower ratings as a basis, engineering judgment should be exercised as to the severity of the operating conditions for the intended installation, taking into consideration the source of power, the nature of the load, and the resulting effects of inertia, strain, and shock. Thus, for other than optimum drive conditions, the specified horsepower must be multiplied by the applicable service factor to obtain a “design” horsepower value. This is the value used to enter Table 13 to obtain the required size of chain.

*Service Factors:* For a uniform type of load, a service factor of 1.0 for a 10-hour day and 1.3 for a 24-hour day are recommended. For a moderate shock load, service factors of 1.4 for a 10-hour day and 1.7 for a 24-hour day are recommended. For heavy shock loads, service factors of 1.7 for a 10-hour day and 2.0 for a 24-hour day are recommended. For extensive table of service factor applications, see supplementary information in ANSI B29.2M-1982.

**Installation of Silent Chain Drives.**—In installing chain transmissions of any kind, horizontal drives are those having driving and driven shafts in a horizontal plane. These are always preferable to vertical drives, which have a vertical center line intersecting the driving and driven shafts. If one sprocket must be higher than the other, avoid a vertical drive if possible by so locating the two sprockets that the common center line inclines from the vertical as far as is permitted by other conditions which might govern the installation. If practicable, an adjustment should be provided for the center distance between the driving and driven shafts.

*Slack Side of Chain:* As a general rule, the slack strand of a chain should be on the lower side of a horizontal drive. If the drive is not horizontal but angular or at some angle less than 90 degrees from the vertical, the slack should preferably be on that side which causes the strand to curve outward or away from the center line of the driving and driven shafts. Whenever the slack strand is on the upper side of either a horizontal or inclined drive,

adjustment for the center distance is especially important to compensate for possible chain elongation.

*Lubrication:* The life of a silent chain subjected to conditions such as are common to automobile drives, depends largely upon the wear of the joints. On account of the high speed and whipping action, it is important to have the chains well oiled. When splash lubrication is employed, the supply pipe should be placed so that the oil will be directed against the inside of the chain. It is preferable that silent chains be operated in an oil-retaining casing with provisions for lubrication. Avoid using greases of any kind. The viscosity of the oil depends on temperature, as follows:

| Ambient Temp.<br>°F   | Chain Pitch                         |                             | Ambient Temp.<br>°F   | Chain Pitch                         |                             |
|-----------------------|-------------------------------------|-----------------------------|-----------------------|-------------------------------------|-----------------------------|
|                       | $\frac{3}{16}$ & $\frac{3}{8}$ inch | $\frac{1}{2}$ inch & larger |                       | $\frac{3}{16}$ & $\frac{3}{8}$ inch | $\frac{1}{2}$ inch & larger |
| Recommended Lubricant |                                     |                             | Recommended Lubricant |                                     |                             |
| 20-40                 | SAE 10                              | SAE 20                      | 20-40                 | SAE 10                              | SAE 20                      |
| 40-100                | SAE 20                              | SAE 30                      | 40-100                | SAE 20                              | SAE 30                      |

**Double-Flexure Silent Chain.**—In double-flexure chain, the teeth of the link plates project on both sides of the chain and the chain flexes in both directions. This chain is used where the drive arrangements require that sprockets contact both sides of the chain. Neither double-flexure chain nor sprockets are covered in American National Standard ANSI B29.2M-1982.

#### **Horsepower Ratings Per Inch of Chain Width for Silent Chain Drives — 1982.**—

The following industrial standard horsepower ratings for silent chain drives have been supplied by the American Chain Association. These ratings are for American National Standard silent chain as covered by ANSI B29.2M-1982. These values may require modification by using the appropriate service factors (see page 2379). These factors, which apply to typical drives, are intended as a general guide only, and engineering judgment and experience may indicate different modifications to suit the nature of the load.

$$\text{Horsepower capacity of chain per inch of width} = \frac{\text{Rating in Table 12A, 12B}}{\text{Service Factor}}$$

$$\text{chainwidth for given total hp capacity} = \frac{\text{hp} \times \text{Service factor}}{\text{Rating per inch, Table 12A, 12B}}$$

*Lubrication:* The horsepower established from the sprocket and speed combinations of the drive under consideration will indicate a method of lubrication. This method or a better one must be used to obtain optimum chain life. The types of lubrication as indicated on the tables are: Type I, manual, brush, or oil cup; Type II, bath or disk; Type III, circulating pump.

SILENT OF INVERTED TOOTH CHAIN

**Table 12a. Horse Power Ratings per Inch of Chain Width for Silent Chain Drives—1982**

| No. of Teeth Small Sprkt. | $\frac{3}{16}$ Inch Pitch Chain       |      |      |      |      |      |         |      |      |          |      |      |
|---------------------------|---------------------------------------|------|------|------|------|------|---------|------|------|----------|------|------|
|                           | Revolutions per Minute—Small Sprocket |      |      |      |      |      |         |      |      |          |      |      |
|                           | 500                                   | 600  | 700  | 800  | 900  | 1200 | 1800    | 2000 | 3500 | 5000     | 7000 | 9000 |
| 15                        | 0.28                                  | 0.33 | 0.38 | 0.43 | 0.47 | 0.60 | 0.80    | 0.90 | 1.33 | 1.66     | 1.94 | 1.96 |
| 17                        | 0.33                                  | 0.39 | 0.44 | 0.50 | 0.55 | 0.70 | 0.96    | 1.05 | 1.60 | 2.00     | 2.40 | 2.52 |
| 19                        | 0.37                                  | 0.43 | 0.50 | 0.55 | 0.61 | 0.80 | 1.10    | 1.20 | 1.80 | 2.30     | 2.76 | 2.92 |
| 21                        | 0.41                                  | 0.48 | 0.55 | 0.62 | 0.68 | 0.87 | 1.22    | 1.33 | 2.03 | 2.58     | 3.12 | 3.35 |
| 23                        | 0.45                                  | 0.53 | 0.60 | 0.68 | 0.75 | 0.96 | 1.35    | 1.47 | 2.25 | 2.88     | 3.50 | 3.78 |
| 25                        | 0.49                                  | 0.58 | 0.66 | 0.74 | 0.82 | 1.05 | 1.47    | 1.60 | 2.45 | 3.13     | 3.80 | 4.10 |
| 27                        | 0.53                                  | 0.62 | 0.71 | 0.80 | 0.88 | 1.15 | 1.58    | 1.72 | 2.63 | 3.35     | 4.06 | 4.37 |
| 29                        | 0.57                                  | 0.67 | 0.76 | 0.86 | 0.95 | 1.21 | 1.70    | 1.85 | 2.83 | 3.61     | 4.40 | 4.72 |
| 31                        | 0.60                                  | 0.72 | 0.81 | 0.91 | 1.01 | 1.30 | 1.81    | 1.97 | 3.02 | 3.84     | 4.66 | 5.00 |
| 33                        | 0.64                                  | 0.75 | 0.86 | 0.97 | 1.07 | 1.37 | 1.90    | 2.08 | 3.17 | 4.02     | 4.85 | ...  |
| 35                        | 0.68                                  | 0.80 | 0.92 | 1.03 | 1.14 | 1.45 | 2.03    | 2.21 | 3.41 | 4.27     | 5.16 | ...  |
| 37                        | 0.71                                  | 0.84 | 0.96 | 1.08 | 1.19 | 1.52 | 2.11    | 2.30 | 3.48 | 4.39     | 5.24 | ...  |
| 40                        | 0.77                                  | 0.91 | 1.04 | 1.16 | 1.29 | 1.64 | 2.28    | 2.50 | 3.77 | 4.76     | ...  | ...  |
| 45                        | 0.86                                  | 1.02 | 1.15 | 1.30 | 1.43 | 1.83 | 2.53    | 2.75 | 4.15 | 5.21     | ...  | ...  |
| 50                        | 0.95                                  | 1.12 | 1.27 | 1.37 | 1.58 | 2.00 | 2.78    | 3.02 | 4.52 | 5.65     | ...  | ...  |
|                           | Type I                                |      |      |      |      |      | Type II |      |      | Type III |      |      |

| No. of Teeth Small Sprkt. | $\frac{3}{8}$ Inch Pitch Chain        |     |      |         |      |      |      |          |      |      |      |      |      |
|---------------------------|---------------------------------------|-----|------|---------|------|------|------|----------|------|------|------|------|------|
|                           | Revolutions per Minute—Small Sprocket |     |      |         |      |      |      |          |      |      |      |      |      |
|                           | 100                                   | 500 | 1000 | 1200    | 1500 | 1800 | 2000 | 2500     | 3000 | 3500 | 4000 | 5000 | 6000 |
| 17                        | 0.46                                  | 2.1 | 4.6  | 4.9     | 5.3  | 6.5  | 6.9  | 7.9      | 8.5  | 8.8  | 8.8  | ...  | ...  |
| 19                        | 0.53                                  | 2.5 | 4.8  | 5.4     | 6.5  | 7.4  | 7.9  | 9.1      | 9.9  | 10   | 11   | 9.8  | ...  |
| 21                        | 0.58                                  | 2.8 | 5.1  | 6.0     | 7.3  | 8.3  | 9.0  | 10       | 11   | 12   | 12   | 12   | 10   |
| 23                        | 0.63                                  | 3.0 | 5.6  | 6.6     | 8.0  | 9.3  | 10   | 12       | 13   | 14   | 14   | 14   | 12   |
| 25                        | 0.69                                  | 3.3 | 6.1  | 7.3     | 8.8  | 10   | 11   | 13       | 14   | 15   | 15   | 15   | 14   |
| 27                        | 0.74                                  | 3.5 | 6.8  | 7.9     | 9.5  | 11   | 12   | 14       | 15   | 16   | 18   | 18   | 16   |
| 29                        | 0.80                                  | 3.8 | 7.3  | 8.5     | 10   | 12   | 13   | 15       | 16   | 18   | 19   | 19   | 18   |
| 31                        | 0.85                                  | 4.1 | 7.8  | 9.1     | 11   | 13   | 14   | 16       | 18   | 19   | 20   | 20   | 19   |
| 33                        | 0.90                                  | 4.4 | 8.3  | 9.8     | 12   | 14   | 15   | 18       | 19   | 21   | 21   | 21   | 20   |
| 35                        | 0.96                                  | 4.6 | 8.8  | 10      | 13   | 15   | 16   | 19       | 20   | 23   | 23   | 23   | 21   |
| 37                        | 1.0                                   | 4.9 | 9.1  | 11      | 14   | 15   | 16   | 20       | 21   | 24   | 24   | 24   | ...  |
| 40                        | 1.1                                   | 5.3 | 10   | 12      | 15   | 16   | 18   | 21       | 24   | 25   | 26   | 26   | ...  |
| 45                        | 1.3                                   | 6.0 | 11   | 13      | 16   | 19   | 20   | 24       | 26   | 28   | 29   | ...  | ...  |
| 50                        | 1.4                                   | 6.6 | 13   | 15      | 18   | 20   | 23   | 26       | 29   | 30   | ...  | ...  | ...  |
|                           | Type I                                |     |      | Type II |      |      |      | Type III |      |      |      |      |      |

| No. of Teeth Small Sprkt. | $\frac{1}{2}$ Inch Pitch Chain        |     |     |         |      |      |      |          |      |      |      |
|---------------------------|---------------------------------------|-----|-----|---------|------|------|------|----------|------|------|------|
|                           | Revolutions per Minute—Small Sprocket |     |     |         |      |      |      |          |      |      |      |
|                           | 100                                   | 500 | 700 | 1000    | 1200 | 1800 | 2000 | 2500     | 3000 | 3500 | 4000 |
| 17                        | 0.83                                  | 3.8 | 5.0 | 6.3     | 7.5  | 10   | 11   | 11       | 11   | 11   | ...  |
| 19                        | 0.93                                  | 3.8 | 5.0 | 7.5     | 8.8  | 11   | 13   | 14       | 14   | 14   | ...  |
| 21                        | 1.0                                   | 5.0 | 6.3 | 8.8     | 10   | 14   | 14   | 15       | 16   | 16   | ...  |
| 23                        | 1.1                                   | 5.0 | 7.5 | 10      | 11   | 15   | 16   | 18       | 19   | 19   | 18   |
| 25                        | 1.2                                   | 5.0 | 7.5 | 10      | 13   | 16   | 18   | 20       | 21   | 21   | 20   |
| 27                        | 1.3                                   | 6.3 | 8.8 | 11      | 13   | 18   | 19   | 21       | 24   | 24   | 23   |
| 29                        | 1.4                                   | 6.3 | 8.8 | 13      | 14   | 19   | 21   | 24       | 25   | 25   | 25   |
| 31                        | 1.5                                   | 7.5 | 10  | 13      | 15   | 21   | 23   | 25       | 28   | 28   | 28   |
| 33                        | 1.6                                   | 7.5 | 10  | 14      | 16   | 23   | 24   | 28       | 29   | 30   | 29   |
| 35                        | 1.8                                   | 7.5 | 11  | 15      | 18   | 24   | 25   | 29       | 31   | 31   | 30   |
| 37                        | 1.9                                   | 8.8 | 11  | 16      | 19   | 25   | 26   | 30       | 33   | 33   | ...  |
| 40                        | 2.0                                   | 8.8 | 13  | 18      | 20   | 28   | 29   | 33       | 35   | 35   | ...  |
| 45                        | 2.5                                   | 10  | 14  | 19      | 23   | 30   | 30   | 36       | 39   | ...  | ...  |
| 50                        | 2.5                                   | 11  | 15  | 21      | 25   | 34   | 36   | 40       | ...  | ...  | ...  |
|                           | Type I                                |     |     | Type II |      |      |      | Type III |      |      |      |

<sup>a</sup> For best results, smaller sprocket should have at least 21 teeth.

**Table 12b. Horse Power Ratings per Inch of Chain Width for Silent Chain Drives—1982**

| No. of Teeth Small Sprkt. | $\frac{3}{8}$ - Inch Pitch Chain      |     |     |         |      |      |          |      |      |      |
|---------------------------|---------------------------------------|-----|-----|---------|------|------|----------|------|------|------|
|                           | Revolutions per Minute—Small Sprocket |     |     |         |      |      |          |      |      |      |
|                           | 100                                   | 500 | 700 | 1000    | 1200 | 1800 | 2000     | 2500 | 3000 | 3500 |
| *17                       | 1.3                                   | 6.3 | 7.5 | 10      | 11   | 14   | 15       | 14   | ...  | ...  |
| *19                       | 1.4                                   | 6.3 | 8.8 | 13      | 14   | 16   | 18       | 18   | ...  | ...  |
| 21                        | 1.6                                   | 7.5 | 10  | 13      | 15   | 19   | 20       | 20   | 20   | ...  |
| 23                        | 1.8                                   | 7.5 | 11  | 15      | 16   | 21   | 23       | 24   | 23   | ...  |
| 25                        | 1.9                                   | 8.8 | 11  | 16      | 19   | 24   | 25       | 26   | 26   | 24   |
| 27                        | 2.0                                   | 10  | 13  | 18      | 20   | 26   | 28       | 29   | 29   | 26   |
| 29                        | 2.1                                   | 10  | 14  | 19      | 21   | 28   | 30       | 31   | 31   | 29   |
| 31                        | 2.4                                   | 11  | 15  | 20      | 23   | 30   | 31       | 34   | 34   | 31   |
| 33                        | 2.5                                   | 11  | 16  | 21      | 25   | 33   | 34       | 36   | 36   | 34   |
| 35                        | 2.6                                   | 13  | 16  | 23      | 26   | 34   | 36       | 39   | 39   | 35   |
| 37                        | 2.8                                   | 13  | 18  | 24      | 28   | 36   | 39       | 43   | 41   | ...  |
| 40                        | 3.0                                   | 14  | 19  | 26      | 30   | 39   | 41       | 44   | ...  | ...  |
| 45                        | 3.4                                   | 16  | 21  | 29      | 34   | 44   | 46       | ...  | ...  | ...  |
| 50                        | 3.8                                   | 18  | 24  | 33      | 38   | 48   | 50       | ...  | ...  | ...  |
|                           | Type I                                |     |     | Type II |      |      | Type III |      |      |      |

| No. of Teeth Small Sprkt. | $\frac{1}{2}$ - Inch Pitch Chain       |     |     |         |      |      |          |      |      |     |
|---------------------------|--|-----|-----|---------|------|------|----------|------|------|-----|
|                           | Revolutions per Minute- Small Sprocket |     |     |         |      |      |          |      |      |     |
|                           | 100                                    | 500 | 700 | 1000    | 1200 | 1500 | 1800     | 2000 | 2500 |     |
| *17                       | 1.9                                    | 8.1 | 11  | 14      | 15   | 16   | 18       | 18   | ...  | ... |
| *19                       | 2.0                                    | 9.3 | 13  | 15      | 18   | 20   | 21       | 21   | ...  | ... |
| 21                        | 2.3                                    | 10  | 14  | 18      | 20   | 23   | 24       | 25   | 24   | ... |
| 23                        | 2.5                                    | 11  | 15  | 20      | 23   | 25   | 28       | 28   | 28   | ... |
| 25                        | 2.8                                    | 13  | 16  | 21      | 25   | 29   | 31       | 31   | 30   | ... |
| 27                        | 2.9                                    | 14  | 18  | 24      | 28   | 31   | 34       | 35   | 35   | ... |
| 29                        | 3.1                                    | 15  | 20  | 26      | 30   | 34   | 36       | 38   | 38   | ... |
| 31                        | 3.4                                    | 15  | 21  | 28      | 31   | 36   | 40       | 41   | 41   | ... |
| 33                        | 3.6                                    | 16  | 23  | 30      | 34   | 39   | 43       | 44   | 44   | ... |
| 35                        | 3.8                                    | 18  | 24  | 31      | 36   | 41   | 45       | 46   | 46   | ... |
| 37                        | 4.0                                    | 19  | 25  | 34      | 39   | 44   | 48       | 49   | 49   | ... |
| 40                        | 4.4                                    | 20  | 28  | 36      | 41   | 48   | 51       | 53   | 53   | ... |
| 45                        | 4.9                                    | 23  | 30  | 40      | 46   | 53   | 56       | 58   | ...  | ... |
| 50                        | 5.4                                    | 25  | 34  | 45      | 51   | 58   | 61       | ...  | ...  | ... |
|                           | Type I                                 |     |     | Type II |      |      | Type III |      |      |     |

| No. of Teeth Small Sprkt. | 1- Inch Pitch Chain                    |     |     |         |     |     |      |          |      |      |      |
|---------------------------|--|-----|-----|---------|-----|-----|------|----------|------|------|------|
|                           | Revolutions per Minute- Small Sprocket |     |     |         |     |     |      |          |      |      |      |
|                           | 100                                    | 200 | 300 | 400     | 500 | 700 | 1000 | 1200     | 1500 | 1800 | 2000 |
| *17                       | 3.8                                    | 6.3 | 8.8 | 11      | 14  | 18  | 21   | 23       | ...  | ...  | ...  |
| *19                       | 3.8                                    | 7.5 | 10  | 13      | 15  | 20  | 25   | 26       | 28   | ...  | ...  |
| 21                        | 3.8                                    | 7.5 | 11  | 15      | 18  | 23  | 29   | 31       | 33   | 33   | ...  |
| 23                        | 3.8                                    | 8.8 | 13  | 16      | 19  | 25  | 31   | 35       | 38   | 38   | ...  |
| 25                        | 5.0                                    | 8.8 | 14  | 18      | 21  | 28  | 35   | 39       | 41   | 41   | 41   |
| 27                        | 5.0                                    | 10  | 15  | 19      | 24  | 30  | 39   | 43       | 46   | 46   | 45   |
| 29                        | 5.0                                    | 11  | 16  | 20      | 25  | 33  | 41   | 46       | 50   | 51   | 50   |
| 31                        | 6.3                                    | 11  | 16  | 23      | 28  | 35  | 45   | 50       | 54   | 55   | 54   |
| 33                        | 6.3                                    | 13  | 18  | 24      | 29  | 38  | 49   | 54       | 59   | 59   | 58   |
| 35                        | 6.3                                    | 13  | 19  | 25      | 30  | 40  | 51   | 56       | 61   | 63   | 61   |
| 37                        | 6.8                                    | 14  | 20  | 26      | 33  | 43  | 54   | 60       | 65   | 66   | ...  |
| 40                        | 7.5                                    | 15  | 23  | 29      | 35  | 45  | 59   | 65       | 70   | ...  | ...  |
| 45                        | 8.8                                    | 16  | 25  | 31      | 39  | 51  | 65   | 71       | 76   | ...  | ...  |
| 50                        | 10                                     | 19  | 28  | 35      | 43  | 56  | 71   | 78       | ...  | ...  | ...  |
|                           | Type I                                 |     |     | Type II |     |     |      | Type III |      |      |      |

<sup>a</sup> For best results, smaller sprocket should have at least 21 teeth.

SILENT OF INVERTED TOOTH CHAIN

**Table 12c. Horse Power Ratings per Inch of Chain Width for Silent Chain Drives –1982**

| No. of Teeth Small Sprkt. | 1/4 Inch Pitch Chain                   |     |     |         |     |     |     |          |      |      |      |
|---------------------------|--|-----|-----|---------|-----|-----|-----|----------|------|------|------|
|                           | Revolutions per Minute- Small Sprocket |     |     |         |     |     |     |          |      |      |      |
|                           | 100                                    | 200 | 300 | 400     | 500 | 600 | 700 | 800      | 1000 | 1200 | 1500 |
| 19                        | 5.6                                    | 10  | 15  | 20      | 24  | 26  | 29  | 31       | 34   | 35   | ...  |
| 21                        | 6.3                                    | 11  | 18  | 23      | 26  | 30  | 33  | 36       | 40   | 41   | ...  |
| 23                        | 6.9                                    | 13  | 19  | 24      | 29  | 34  | 36  | 40       | 45   | 46   | 46   |
| 25                        | 7.5                                    | 14  | 20  | 26      | 31  | 36  | 40  | 44       | 50   | 53   | 53   |
| 27                        | 8.0                                    | 15  | 23  | 29      | 35  | 40  | 44  | 49       | 54   | 58   | 58   |
| 29                        | 8.6                                    | 16  | 24  | 31      | 38  | 43  | 48  | 53       | 59   | 63   | 64   |
| 31                        | 9.3                                    | 18  | 26  | 34      | 40  | 46  | 51  | 56       | 64   | 68   | 69   |
| 33                        | 9.9                                    | 19  | 28  | 35      | 43  | 49  | 55  | 60       | 69   | 73   | 74   |
| 35                        | 11                                     | 20  | 29  | 38      | 45  | 53  | 59  | 64       | 73   | 78   | 78   |
| 37                        | 11                                     | 21  | 30  | 40      | 48  | 55  | 63  | 68       | 76   | 81   | ...  |
| 40                        | 12                                     | 24  | 34  | 44      | 53  | 60  | 68  | 74       | 83   | 88   | ...  |
| 45                        | 13                                     | 26  | 38  | 49      | 59  | 68  | 75  | 81       | 91   | ...  | ...  |
| 50                        | 15                                     | 29  | 43  | 54      | 65  | 74  | 83  | 90       | 100  | ...  | ...  |
|                           | Type I                                 |     |     | Type II |     |     |     | Type III |      |      |      |

| No. of Teeth Small Sprkt. | 1/2 Inch Pitch Chain                   |     |     |         |     |     |     |          |     |      |      |
|---------------------------|--|-----|-----|---------|-----|-----|-----|----------|-----|------|------|
|                           | Revolutions per Minute- Small Sprocket |     |     |         |     |     |     |          |     |      |      |
|                           | 100                                    | 200 | 300 | 400     | 500 | 600 | 700 | 800      | 900 | 1000 | 1200 |
| 19                        | 8.0                                    | 15  | 21  | 28      | 31  | 35  | 39  | 40       | 41  | 43   | ...  |
| 21                        | 8.8                                    | 16  | 24  | 30      | 36  | 40  | 44  | 46       | 49  | 49   | ...  |
| 23                        | 10                                     | 19  | 26  | 34      | 40  | 45  | 49  | 53       | 55  | 56   | 55   |
| 25                        | 10                                     | 20  | 29  | 38      | 44  | 50  | 55  | 59       | 61  | 65   | 64   |
| 27                        | 11                                     | 23  | 31  | 40      | 48  | 54  | 60  | 64       | 68  | 70   | 70   |
| 29                        | 13                                     | 24  | 34  | 44      | 51  | 59  | 65  | 70       | 74  | 75   | 76   |
| 31                        | 14                                     | 25  | 36  | 46      | 55  | 64  | 70  | 75       | 79  | 81   | 83   |
| 33                        | 14                                     | 28  | 39  | 50      | 59  | 68  | 75  | 80       | 85  | 88   | 89   |
| 35                        | 15                                     | 29  | 41  | 53      | 63  | 71  | 79  | 85       | 90  | 93   | 94   |
| 37                        | 16                                     | 30  | 44  | 59      | 66  | 76  | 84  | 90       | 96  | 99   | ...  |
| 40                        | 18                                     | 33  | 48  | 66      | 73  | 83  | 90  | 98       | 105 | ...  | ...  |
| 45                        | 19                                     | 38  | 54  | 68      | 81  | 93  | 101 | 108      | 113 | ...  | ...  |
| 50                        | 21                                     | 41  | 59  | 75      | 89  | 101 | 111 | 118      | ... | ...  | ...  |
|                           | Type I                                 |     |     | Type II |     |     |     | Type III |     |      |      |

| No. of Teeth Small Sprkt. | 2- Inch Pitch Chain                    |     |         |     |     |          |     |     |     |     |
|---------------------------|--|-----|---------|-----|-----|----------|-----|-----|-----|-----|
|                           | Revolutions per Minute- Small Sprocket |     |         |     |     |          |     |     |     |     |
|                           | 100                                    | 200 | 300     | 400 | 500 | 600      | 700 | 800 | 900 | ... |
| 19                        | 14                                     | 26  | 36      | 44  | 50  | 54       | 56  | ... | ... | ... |
| 21                        | 16                                     | 29  | 40      | 50  | 53  | 63       | 65  | ... | ... | ... |
| 23                        | 17                                     | 33  | 45      | 55  | 64  | 70       | 74  | 75  | ... | ... |
| 25                        | 18                                     | 35  | 49      | 61  | 70  | 78       | 83  | 85  | 85  | 85  |
| 27                        | 20                                     | 38  | 54      | 66  | 78  | 85       | 91  | 94  | 94  | 94  |
| 29                        | 21                                     | 41  | 58      | 73  | 84  | 93       | 99  | 103 | 103 | 103 |
| 31                        | 23                                     | 44  | 63      | 78  | 90  | 100      | 106 | 110 | 110 | 110 |
| 33                        | 25                                     | 46  | 66      | 83  | 96  | 106      | 114 | 118 | 118 | 118 |
| 35                        | 26                                     | 50  | 71      | 88  | 103 | 114      | 121 | 125 | 125 | 125 |
| 37                        | 28                                     | 53  | 75      | 93  | 110 | 124      | 128 | 131 | ... | ... |
| 40                        | 30                                     | 58  | 81      | 101 | 118 | 129      | 138 | 141 | ... | ... |
| 45                        | 34                                     | 64  | 90      | 113 | 131 | 144      | 151 | ... | ... | ... |
| 50                        | 38                                     | 71  | 100     | 125 | 144 | 156      | ... | ... | ... | ... |
|                           | Type I                                 |     | Type II |     |     | Type III |     |     |     |     |

<sup>a</sup> For best results, smaller sprocket should have at least 21 teeth.

## GEARS AND GEARING

### Geometry Factors For Gear Teeth

**Contact and Bending Stresses.**—To calculate the contact and bending stresses acting between the teeth of a pair of gears meshing under load, it is necessary to include in the stress formulas a number of factors that account for the geometry of the teeth, the physical properties of the materials used, and the nature of the specific application.

AGMA 908-B89 Information Sheet\* gives equations for calculating the pitting resistance geometry factor,  $I$ , for external and internal spur and helical gears; and the bending strength geometry factor,  $J$ , for external spur and helical gears that are generated by rack-type tools (hobs, rack cutters, or generating grinding wheels) or pinion-type tools (shaper cutters). The document includes 66 tables of geometry factors,  $I$  and  $J$ , for a range of typical gear sets and tooth forms of  $14\frac{1}{2}$ -, 20-, and 25-deg pressure angles and 0-, 10-, 15-, 20-, 25-, and 30-deg helix angles.

The Information sheet was prepared to assist designers making preliminary design studies and to present data useful to those without access to computer programs. Not all tooth forms, pressure angles, and pinion and gear modifications are covered. Neither are these data applicable to all gear designs; however, the data should be helpful to the majority of gear designers. Data from this Information Sheet are used with the rating procedures described in AGMA 2001-B88, *Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth*, for evaluating various spur and helical gear designs produced by using a generating process (see page 1834).

**Geometry Factors for Pitting Resistance and Bending Strength.**—The AGMA Information Sheet includes a mathematical procedure to determine the pitting resistance geometry factor,  $I$ , for internal and external gear sets of spur, conventional helical, and low-axial-contact-ratio (LACR) helical design. A mathematical procedure is also included to determine the bending strength geometry factor,  $J$ , for external gear sets of spur, conventional helical, and low-axial-contact-ratio (LACR) helical designs. The calculation procedure is valid for generated root fillets produced by both rack- and pinion-type tools.

**Exceptions to the Information Sheet Data and Procedures.**—The formulas in the Information Sheet are not valid when any of the following conditions exist:

1) Spur gears with transverse contact ratio less than one,  $m_p < 1.0$ ; 2) spur or helical gears with transverse contact ratio equal or greater than two,  $m_p \geq 2.0$ ; 3) interference exists between the tips of teeth and root fillets; 4) the teeth are pointed; 5) backlash is zero; 6) undercut exists in an area above the theoretical start of the active profile (the effect of this undercut is to move the highest point of single tooth contact, negating the assumption of this calculation method; however, the reduction in tooth thickness due to protuberance below the active profile is handled correctly by this method); 7) the root profiles are stepped or irregular (the  $J$  factor calculation uses the stress correction factors developed by Dolan and Broghamer; the factors may not be valid for root forms that are not smooth curves; for root profiles that are stepped or irregular, other stress correction factors may be appropriate); 8) where root fillets of the gear teeth are produced by a process other than generating; and 9) the helix angle at the standard (reference) diameter is greater than 50 deg.

In addition to these exceptions, it is assumed that 1) the friction effect on the direction of force is neglected; and 2) the fillet radius is smooth (it is actually a series of scallops).

**Basic Gear Geometry of Spur and Helical Gears.**—The equations that follow apply to spur and helical gears. Where double signs are used (e.g.,  $\pm$ ), the upper sign applies to exter-

\* Extracted from AGMA 908-B89, Information Sheet, *Geometry Factors for Determining the Pitting Resistance and Bending Strength of Spur, Helical, and Herringbone Gear Teeth*, with the permission of the publisher, American Gear Manufacturers Association, 1500 King Street, Suite 201, Alexandria, Virginia 22314.



nal gears and the lower sign to internal gears. The equations given are based on unity normal module ( $m_n = 1$ ) or unity normal diametral pitch ( $P_{nd} = 1$ ) and are valid for any consistent set of units. All angles are in radians unless otherwise specified. *In using the given equations, certain variables must be made dimensionless by dividing by the normal module  $m_n$  or multiplying by the normal diametral pitch  $P_{nd}$ .* For example, if a face width  $F$  0.5 in. and the normal diametral pitch is 4, then the value of  $F$  to be used in the equations is  $0.5 \times 4 = 2$ . The variables to be so adjusted are  $F, R_{o1}, R_{o2}, R_{oc}, R_c, h_{ao}, \delta_{ao}, \rho_{ao},$  and  $\Delta_{sn}$ .

$$\text{Gear ratio, } m_G = \frac{n_2}{n_1}, \text{ Where } n_1 \text{ and } n_2 \text{ are pinion and gear tooth numbers} \quad (1)$$

$$\text{Standard (reference) pinion pitch radius, } R_1 = \frac{n_1}{2 \cos \psi} \quad (2)$$

Where  $\psi$  = standard helix angle.

$$\text{Standard (reference) gear pitch radius, } R_2 = R_1 m_G \quad (3)$$

$$\text{Standard transverse pressure angle, } \phi = \arctan\left(\frac{\tan \phi_n}{\cos \psi}\right) \quad (4)$$

Where  $\phi_n$  = standard normal pressure angle.

$$\text{Pinion base radius, } R_{b1} = R_1 \cos \phi \quad (5)$$

$$\text{Gear base radius, } R_{b2} = R_{b1} m_G \quad (6)$$

$$\text{Operating transverse pressure angle, } \phi_r = \arccos\left(\frac{R_{b2} \pm R_{b1}}{C_r}\right) \quad (7)$$

Where  $C_r$  = Operating center distance.

$$\text{Transverse base pitch, } P_b = \frac{2\pi R_{b1}}{n_1} \quad (8)$$

$$\text{Normal base pitch, } P_N = \pi \cos \phi_n \quad (9)$$

$$\text{Base helix angle, } \psi_b = \arccos\left(\frac{P_N}{P_b}\right) \quad (10)$$

Fig. 1 shows a view of the line of action in the transverse plane of two meshing gears. The distances  $C_1$ , through  $C_6$  are derived from this figure taking into account the exceptions noted previously with regard to undercut.

$$C_6 = C_r \sin \phi_r \quad (11)$$

$$C_1 = \pm [C_6 - (R_{o2}^2 - R_{b2}^2)^{0.5}] \quad (12)$$

where  $R_{o2}$  = addendum radius of gear, for internal or external gears.

$$C_3 = \frac{C_6}{(m_G \pm 1)} \quad (13)$$

$$C_4 = C_1 + P_b \quad (14)$$

$$C_5 = (R_{o1}^2 - R_{b1}^2)^{0.50} \tag{15}$$

Where  $R_{o1}$  = addendum radius of pinion.

$$C_2 = C_5 - P_b \tag{16}$$

$$\text{Active length of line of contact, } Z = C_5 - C_1 \tag{17}$$

Distance  $C_2$  locates the lowest point of single tooth contact (LPSTC); distance  $C_4$  locates the highest point of single tooth contact (HPSTC), where  $C_r$ ,  $R_{o1}$ , and  $R_{o2}$  are values for  $m_n = 1$  or  $P_{nd} = 1$ .

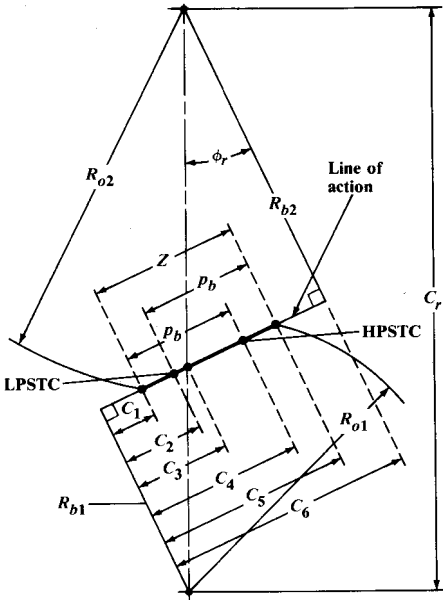


Fig. 1. Transverse Plane View of the Line of Action

**Contact Ratios.**—The contact ratios are as follows:

$$\text{Transverse Contact ratio, } m_p = \frac{Z}{P_b} \tag{18}$$

$$\text{Axial pitch, } P_x = \frac{\pi}{\sin \psi} \tag{19}$$

$$\text{Axial contact ratio, } m_F = \frac{F}{P_x} \tag{20}$$

where  $F$  = effective face width at  $m_n = 1$  or  $P_{nd} = 1$ . For spur gears,  $m_F = 0$ .

**Minimum Lengths of Lines of Contact.**—For spur gears with  $m_p < 2.0$  the minimum length of contact lines,  $L_{min}$ ,

$$L_{min} = F \quad (21)$$

For helical gears, two cases must be considered:

$$\text{Case I: For } n_a \leq 1 - n_r, L_{min} = \frac{(m_p F - n_a n_r p_x)}{\cos \psi_b} \quad (22)$$

$$\text{Case II: For } n_a > 1 - n_r, L_{min} = \frac{[m_p F - (1 - n_a)(1 - n_r)p_x]}{\cos \psi_b} \quad (23)$$

where  $n_r$  = fractional part of  $m_p$ , and  $n_a$  = fractional part of  $m_F$ . For example, if  $m_p = 1.4$ , then  $n_r = 0.4$ .

**Load Sharing Ratio,  $m_N$ .**—The load sharing ratio  $m_N$  is calculated as follows:

$$\text{For helical gears, } m_N = \frac{F}{L_{min}} \quad (24)$$

$$\text{For spur gears with } m_p \leq 2.0, \text{ Eq. (21) has } L_{min} = F \text{ so that } m_N = 1.0 \quad (25)$$

For low axial contact ratio (LACR) helicals,  $m_F \leq 1.0$ . Load sharing is accommodated by the helical overlap factor  $C_\psi$  [Equation (36)]; therefore,

$$m_N = 1.0 \quad (26)$$

$$\text{Operating helix angle, } \psi_r = \arctan\left(\frac{\tan \psi_b}{\cos \phi_r}\right) \quad (27)$$

$$\text{Operating normal pressure angle, } \phi_{nr} = \arcsin(\cos \psi_b \sin \phi_r) \quad (28)$$

**Calculating the Pitting Resistance Geometry Factor,  $I$ .**—The pitting resistance geometry factor  $I$  is a dimensionless number that takes into account the effects of the radii of curvature of the gear tooth surfaces, load sharing, and the normal component of the transmitted load:

$$I = \frac{\cos \phi_r C_\psi^2}{[(1/\rho_1 + 1/\rho_2)(dm_N)]} \quad (29)$$

where

$\phi_r$  = operating transverse pressure angle [Equation (7)];

$C_\psi$  = helical overlap factor [Equation (36)];

$d$  = pinion operating pitch diameter [Equation (30)];

$m_N$  = load sharing ratio [Equation (24), (25), or (26)]; and

$\rho_1$  and  $\rho_2$  = radii of curvature of pinion and gear profiles, respectively, at point of stress calculation.

$$\text{Operating pitch diameter of pinion, } d = \frac{2c_r}{(m_G + 1)} \quad (30)$$

**Radii of Curvature of Profiles at Contact Stress Calculation Point:** For conventional helical gears ( $m_F > 1$ ) the radii of curvature are calculated at the mean radius or middle of the working profile of the pinion where

$$\text{Mean radius of pinion, } R_{m1} = \frac{1}{2}[R_{O1} \pm (C_r - R_{O2})] \quad (31)$$

where

$R_{O1}$  = addendum radius of pinion and;

$R_{O2}$  = addendum radius of gear, internal or external.

$$\text{radius of curvature of pinion profile, } \rho_1 = (R_{m1}^2 - R_{b1}^2)^{0.50} \quad (32)$$

Where  $R_{b1}$  = base radius of pinion.

$$\text{Radius of curvature of gear profile, } \rho_2 = C_6 \mp \rho_1 \quad (33)$$

For spurs and LACR helicals ( $m_F \leq 1$ ), the radii of curvature are calculated at the LPSTC:

$$\rho_1 = C_2 \quad (34)$$

$$\rho_2 = C_6 \mp \rho_1 \quad (35)$$

Helical overlap factor for LACR ( $m_F \leq 1$ ), helical gears,

$$C_\psi = \left[ 1 - m_F \left( 1 - \frac{\rho_{m1} \rho_{m2} Z}{\rho_1 \rho_2 \rho_N} \right) \right]^{0.50} \quad (36)$$

where  $Z$  = Equation (17);  $\rho_N$  = Equation (9);  $\rho_{m1}$  = Equation (37) and,  $\rho_{m2}$  = Equation (38).  
radius of curvature of pinion profile at mean radius of profile,

$$\rho_{m1} = (R_{m1}^2 - R_{b1}^2)^{0.50} \quad (37)$$

Radius of curvature of gear profile at mean radius of gear,

$$\rho_{m2} = C_6 \mp \rho_{m1} \quad (38)$$

$$\text{For spur and conventional helicals, } C_\psi = 1 \quad (39)$$

**Bending Strength Geometry Factor,  $J$ .**—The bending strength geometry factor is a dimensionless number that takes into account: 1) shape of the tooth; 2) worst load position; 3) stress concentration; and 4) load sharing between oblique lines of contact in helical gears.

Both tangential (bending) and radial (compressive) components of the tooth load are included. The equations and calculation procedures for the bending stress geometry factor are not given here, but may be found in AGMA 908-B89. The procedures apply only to external gears and must be repeated for both the pinion and the gear using the appropriate dimensions for each.

*Generating Tool Geometry:* Details of the methods for calculating the geometry of the tools used to generate tooth profiles are provided in the Information Sheet as part of the  $J$ -factor calculation procedure.

\*Included in the AGMA Information Sheet are the equations needed to write a computer program to calculate values not given in the tables of  $J$  factors.

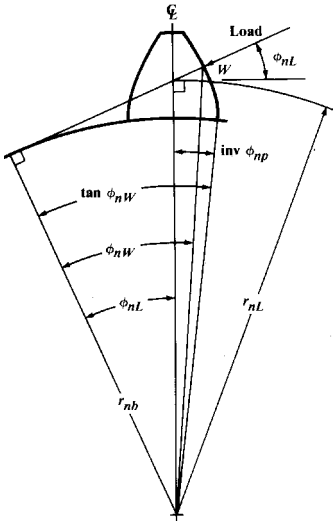


Fig. 2. Load Angle and Load Radius

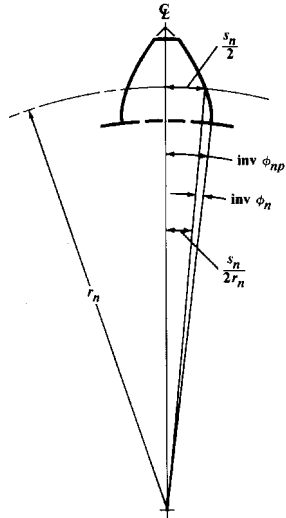


Fig. 3. Pressure Angle Where Tooth Comes to Point

*Virtual Spur Gear:* Helical gears are considered to be virtual spur gears with the following virtual geometry:

$$\text{Virtual tooth number, } n = \frac{n_1}{\cos^3 \psi} \quad (40)$$

$$\text{Standard (ref) pitch radius of virtual spur gear, } r_n = \frac{n}{2} \quad (41)$$

$$\text{Virtual base radius, } r_{nb} = r_n \cos \phi_n \quad (42)$$

$$\text{Virtual outside radius, } r_{na} = r_n + R_{01} - R_1 \quad (43)$$

For spur gears, the virtual geometry is the same as the actual geometry:

$$n = n_1 \quad (44)$$

$$r_n = R_1 \quad (45)$$

$$r_{nb} = R_{b1} \quad (46)$$

$$r_{na} = R_{01} \quad (47)$$

**Pressure Angle at Load Application Point.**—The critical bending stress on a spur gear tooth develops when all the applied load is carried at the highest point of single tooth contact on the tooth. Spur gears having variations that prevent two pairs of teeth from sharing the load may be stressed most heavily when the load is applied at the tips of the teeth. Table 1 has been used in previous standards to establish the variation in base pitch between the

gear and pinion, which determines whether load sharing exists in steel spur gears. Values greater than those in the table require the use of tip loading in determining bending stress geometry factors described in AGMA 908-B89.

**Table 1. Maximum Allowable Variation in Action for Steel Spur Gears for Load Sharing (Variation in Base Pitch)**

| Number of Pinion Teeth | Load Pounds per Inch of Face (Newtons Per Millimeter of Face)               |                |                |                |                 |
|------------------------|---|----------------|----------------|----------------|-----------------|
|                        | 500 lb (90N)  | 1000 lb (175N) | 2000 lb (350N) | 4000 lb (700N) | 8000 lb (1400N) |
|                        | Maximum Allowable Variation in Inches and Millimeters when Teeth Share Load |                |                |                |                 |
| 15                     | 0.0004 in.  | 0.0007 in.     | 0.0014 in.     | 0.0024 in.     | 0.0042 in.      |
|                        | 0.01 mm   | 0.02 mm        | 0.04 mm        | 0.06 mm        | 0.11 mm         |
| 20                     | 0.0003 in.  | 0.0006 in.     | 0.0011 in.     | 0.0020 in.     | 0.0036 in.      |
|                        | 0.01 mm   | 0.02 mm        | 0.03 mm        | 0.05 mm        | 0.09 mm         |
| 25                     | 0.0002 in.  | 0.0005 in.     | 0.0009 in.     | 0.0017 in.     | 0.0030 in.      |
|                        | 0.01 mm   | 0.01 mm        | 0.02 mm        | 0.04 mm        | 0.08 mm         |

For helical gears and spur gears that are analyzed with the load applied at the tip of the tooth, the pressure angle at the load application point,  $\phi_{nW}$ , is found from

$$\tan \phi_{nW} = \left[ \left( \frac{r_{na}}{r_{nb}} \right)^2 - 1 \right]^{0.50} \quad (48)$$

For spur gears, where the highest bending stress occurs when the load is at the highest point of single tooth contact (HPSTC), the pressure angle is found from

$$\tan \phi_{nW} = \frac{C_4}{r_{nb}} \quad (49)$$

Equation (49) may also be used for LACR helical gears, but distance  $C_4$  must be based on the virtual spur gear. The following equations are from analogy with Equation (3), (6), (11), (12), (14), (44), and (49):

$$\text{Standard (ref) pitch radius of virtual spur gear, } r_{n2} = r_n m_G \quad (50)$$

$$\text{Virtual base radius, } r_{nb2} = r_{nb} m_G \quad (51)$$

$$\text{Virtual outside radius, } r_{na2} = r_{n2} + R_{02} - R_2 \quad (52)$$

$$\text{Sixth distance along line of action of virtual gear, } C_{n6} = (r_{nb2} + r_{nb}) \tan \phi_{nr} \quad (53)$$

$$\text{First distance along line of action of virtual gear, } C_{n1} = [C_{n6} - (r_{na2}^2 - r_{nb2}^2)^{0.50}] \quad (54)$$

$$\text{Fourth distance along line of action of virtual gear, } C_{n4} = C_{n1} + \rho_N \quad (55)$$

The pressure angle at the load application point (tip),  $\phi_{nW}$

$$\tan \phi_{nW} = \frac{C_{n4}}{r_{nb}} \quad (56)$$

**Generating-Rack Shift Coefficient.**—The generating-rack shift coefficient,  $x_g$ , applies to the completely finished teeth. It includes the rack shift for addendum modification plus the rack shift for thinning the teeth to obtain backlash:

$$x_g = x - \frac{\Delta s_n}{2 \tan \phi_n} \quad (57)$$

where  $\Delta S_n$  = amount gear tooth is thinned for backlash and  $x$  = addendum modification coefficient at zero backlash,

$$x = \frac{\left(S_n + \Delta S_n - \frac{\pi}{2}\right)}{(2 \tan \phi_n)} \quad (58)$$

where  $S_n$  = normal circular tooth thickness measured on the standard (ref) pitch cylinder,

$$S_n = \frac{\pi}{2} + 2x_g \tan \phi_n \quad (59)$$

*Load Angle and Load Radius:* Fig. 2 defines the load angle  $\phi_{nl}$  and the load radius  $r_{nl}$ . The applied load is shown at an arbitrary point  $W$  such that:

$$\phi_{nl} = \tan \phi_{nw} - \text{INV} \phi_{np} \quad (60)$$

where  $\phi_{np}$  = pressure angle where gear tooth is pointed, Fig. 3.

$$\text{INV} \phi_{np} = \text{INV} \phi_n + \frac{S_n}{2r_n} \quad (61)$$

but,

$$\text{INV} \phi_n = \tan \phi_n - \phi \quad (62)$$

and

$$2r_n = n \quad (63)$$

so that

$$\text{INV} \phi_{np} = \tan \phi_n - \phi_n + \frac{S_n}{n} \quad (64)$$

Then Equation (60) can be expressed as

$$\phi_{nl} = \tan \phi_{nw} - \tan \phi_n + \phi_n - \frac{S_n}{n} \quad (65)$$

Equation (65) gives the load angle  $\phi_{nL}$  for any load position specified by  $\tan \phi_{nw}$  found from Equation (48) and (49).

As may be seen from Fig. 3, the virtual radius is

$$r_{nl} = \frac{r_{nb}}{\cos \phi_{nL}} \quad (66)$$

**Tables of Geometry Factors,  $I$  and  $J$ .**—Included here are some of the tables of precalculated values of  $I$  and  $J$  extracted from the Information Sheet. For additional data, tables, and related information for other combinations of gear sets, tooth forms, pressure angles, helix angles, cutting tool dimensions, and addendum coefficients, refer to the Information Sheet. It should be noted that the formulas and data in the Information Sheet are not applicable to bending stresses in internal gears, since no simplified model for calculating bending stresses in internal gears is available.

**Using the Tables.**—Each of the tables in the Information Sheet and those presented here were generated for a specific tool form (basic rack) defined by whole depth factor, normal pressure (profile) angle, and tool tip radius. Only those tables applicable to spur gears are presented here; those for helical gear sets are available in the Information Sheet.

*Whole Depth:* Whole depth is expressed in the tables as a “whole depth factor” and is the whole depth of a basic rack for  $I$  normal module or  $I$  normal diametral pitch. The actual generated depths will be slightly greater due to tooth thinning for backlash

*Outside Diameter:* The tabulated values are for gears having an outside diameter (for normal module or normal diametral pitch = 1), equal to

$$D_{a1} = \frac{n_1}{\cos \psi} + 2(1 + x_1) \quad (67)$$

$$D_{a2} = \frac{n_2}{\cos \psi} + 2(1 + x_2) \quad (68)$$

where  $n_1$  and  $n_2$  are the pinion and gear tooth numbers, respectively;  $\psi$  = standard helix angle, deg.; and  $D_{a1}$  and  $D_{a2}$  are the pinion and gear addendum, respectively.

*Center Distance:* The tables apply to gearsets that operate at standard center distance. This center distance is the tight-mesh center distance for gears not yet thinned for backlash:

$$C = \frac{(n_1 + n_2)}{2 \cos \psi} \quad (69)$$

where  $C$  = standard center distance. For this center distance the sum of the addendum modification coefficients for pinion and gear is zero:

$$x_1 + x_2 = 0 \quad (70)$$

*Tooth Thickness Backlash Allowance:* Values in the tables were calculated based on a backlash allowance. The circular tooth thickness for the pinion and gear are each thinned by an amount  $\Delta s_n$ :

$$\Delta s_n = \frac{0.024}{P_{nd}} = 0.024 \text{ for } P_{nd} = 1 \quad (71)$$

If the gears being evaluated have different minimum tooth thicknesses than from Equation (71), the bending strength geometry factor,  $J$ , can be approximated by using Equation (72). The pitting resistance geometry factor,  $I$ , is unaffected by variations in tooth thickness:

$$J_1 = J_s \left( \frac{s_{n1}}{s_{ns}} \right)^2 \quad (72)$$

where  $J_1$  = adjusted geometry factor;  $J_s$  = geometry factor from table;  $s_{n1}$  = adjusted circular tooth thickness; and  $s_{ns}$  = standard tooth thickness thinned per Equation (71).

As an example, from Table 4, for 20-deg pressure angle spur gears loaded at the highest point of single tooth contact, the  $J$  factor for a 21-tooth pinion operating with a 35-tooth gear is found to be 0.31. The table values are based on a circular tooth thickness of  $\pi/2 - 0.024 = 3.1416/2 - 0.024 = 1.547$  for diametral pitch.

For a 10 normal diametral pitch pinion or gear, the equivalent circular tooth thickness would be  $1.547/10 = 0.155$ .

If a  $J$  value for a 0.010 in. thinner pinion, having a circular thickness of  $0.155 - 0.010 = 0.145$  in. is required, the approximate value is  $0.34(0.145/0.155)^2 = 0.30 = J_1$  so that a 6.5 per cent reduction in tooth thickness reduces the  $J$  factor by 12 percent.

*Undercutting:* The tables do not include geometry factors that may be needed if an undercutting condition exists in either of the two gears. Undercutting can be evaluated using Equation (73) and Fig. 4 where the generating-rack shift coefficient,  $x_g$ , must be equal to or greater than the expression in Equation (73):

$$x_{gmin} = h_{ao} - \rho_{ao}(1 - \sin \phi_n) - \left( \frac{n}{2} \right) \sin \phi_n^2 \quad (73)$$



where  $h_{ao}$  = nominal tool addendum;  $\rho_{ao}$  = tool tip radius; and  $n$  = pinion or gear tooth number.

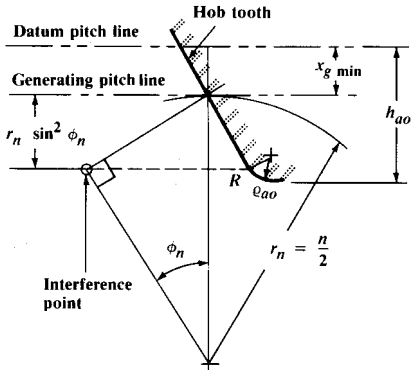


Fig. 4. Undercutting Criteria

*Top Land:* The tables do not include geometry factors when either the pinion or the gear tooth top land is less than the value expressed in Equation (74) or (74a):

$$s_{namin} \geq \frac{0.3}{P_{nd}} \text{ in.} \tag{74}$$

$$s_{namin} \geq 0.3m_n \text{ mm} \tag{74a}$$

in which  $s_{na}$  = tooth thickness at outside diameter.

*Cutter Geometry:* The hob geometry used in the calculation of  $I$  and  $J$  is as follows: Tool tooth number,  $n_c = 10,000$ ; reference normal circular tooth thickness of tool,  $s_{no} = 1.5708$ ; addendum modification coefficient of tool,  $x_o = 0.0$ ; amount of protuberance,  $\delta_o = 0.0$ .

**Table 2. Geometry Factors  $I$  and  $J$  for Various Number Combinations for Module = 1 or Normal Diametral Pitch = 1**

|  |                          |       |        |       |                                   |       |        |       |        |       |      |
|--|--------------------------|-------|--------|-------|-----------------------------------|-------|--------|-------|--------|-------|------|
| Number of Gear Teeth                             | 14.5 -deg Pressure Angle |       |        |       | 2.157 Whole Depth Factor          |       |        |       |        |       |      |
|  | 0.0-deg Helix Angle      |       |        |       | 0.024 Tooth Thinning for Backlash |       |        |       |        |       |      |
|  | 0.0157 Tool Edge Radius  |       |        |       | Loaded at Tip of Gears            |       |        |       |        |       |      |
|  | Number of Pinion Teeth   |       |        |       |                                   |       |        |       |        |       |      |
|  | 21                       |       | 26     |       | 35                                |       | 55     |       | 135    |       |      |
|  | Pinion                   | Gear  | Pinion | Gear  | Pinion                            | Gear  | Pinion | Gear  | Pinion | Gear  |      |
| Equal Addendum Coefficients ( $x_1 = x_2 = 0$ )  |                          |       |        |       |                                   |       |        |       |        |       |      |
| 35   | $I$                      |       |        |       | 0.061                             |       |        |       |        |       |      |
|  | $J$                      |       |        |       | 0.29                              | 0.29  |        |       |        |       |      |
| 55   | $I$                      |       |        |       | 0.074                             |       | 0.061  |       |        |       |      |
|  | $J$                      |       |        |       | 0.30                              | 0.31  | 0.33   | 0.33  |        |       |      |
| 135  | $I$                      |       |        |       | 0.096                             |       | 0.088  |       | 0.061  |       |      |
|  | $J$                      |       |        |       | 0.31                              | 0.34  | 0.35   | 0.35  | 0.38   | 0.38  |      |
| 25 percent Long Addendum Pinion ( $x_1 = 0.25$ ) |                          |       |        |       |                                   |       |        |       |        |       |      |
| 25 percent Short Addendum Gear ( $x_2 = -0.25$ ) |                          |       |        |       |                                   |       |        |       |        |       |      |
| 26   | $I$                      |       |        | 0.060 |                                   |       |        |       |        |       |      |
|  | $J$                      |       |        | 0.32  | 0.22                              |       |        |       |        |       |      |
| 35   | $I$                      |       |        | 0.071 |                                   | 0.059 |        |       |        |       |      |
|  | $J$                      |       |        | 0.32  | 0.24                              | 0.34  | 0.24   |       |        |       |      |
| 55   | $I$                      |       |        | 0.087 |                                   | 0.077 |        | 0.060 |        |       |      |
|  | $J$                      |       |        | 0.33  | 0.27                              | 0.35  | 0.27   | 0.37  | 0.29   |       |      |
| 135  | $I$                      |       |        | 0.111 |                                   | 0.106 |        | 0.092 |        | 0.060 |      |
|  | $J$                      |       |        | 0.35  | 0.29                              | 0.36  | 0.30   | 0.39  | 0.32   | 0.41  | 0.35 |
| 50 percent Long Addendum Pinion ( $x_1 = 0.50$ ) |                          |       |        |       |                                   |       |        |       |        |       |      |
| 50 percent Short Addendum Gear ( $x_2 = -0.50$ ) |                          |       |        |       |                                   |       |        |       |        |       |      |
| 21   | $I$                      | 0.056 |        |       |                                   |       |        |       |        |       |      |
|  | $J$                      | 0.35  | 0.15   |       |                                   |       |        |       |        |       |      |
| 26   | $I$                      | 0.067 |        | 0.056 |                                   |       |        |       |        |       |      |
|  | $J$                      | 0.36  | 0.17   | 0.37  | 0.17                              |       |        |       |        |       |      |
| 35   | $I$                      | 0.081 |        | 0.071 |                                   | 0.056 |        |       |        |       |      |
|  | $J$                      | 0.36  | 0.19   | 0.37  | 0.20                              | 0.38  | 0.20   |       |        |       |      |
| 55   | $I$                      | 0.100 |        | 0.091 |                                   | 0.078 |        | 0.057 |        |       |      |
|  | $J$                      | 0.37  | 0.22   | 0.38  | 0.23                              | 0.39  | 0.24   | 0.41  | 0.25   |       |      |
| 135  | $I$                      | 0.127 |        | 0.123 |                                   | 0.114 |        | 0.096 |        | 0.060 |      |
|  | $J$                      | 0.38  | 0.26   | 0.39  | 0.26                              | 0.40  | 0.27   | 0.42  | 0.29   | 0.43  | 0.32 |

The addendum modification coefficients  $x_1$  and  $x_2$  are for zero backlash gears meshing at standard center distance.

**Table 3. Geometry Factors  $I$  and  $J$  for Various Number Combinations for Module = 1 or Normal Diametral Pitch = 1**

|  |                          |        |      |        |       |        |                                   |        |       |           |
|--|--------------------------|--------|------|--------|-------|--------|-----------------------------------|--------|-------|-----------|
| Number of Gear Teeth                             | 14.5 -deg Pressure Angle |        |      |        |       |        | 2.157 Whole Depth Factor          |        |       |           |
|  | 0.0-deg Helix Angle      |        |      |        |       |        | 0.024 Tooth Thinning for Backlash |        |       |           |
|  | 0.0157 Tool Edge Radius  |        |      |        |       |        | Loaded at HPSTC of Gears          |        |       |           |
|  | Number of Pinion Teeth   |        |      |        |       |        |                                   |        |       |           |
|  | 21                       |        | 26   |        | 35    |        | 55                                |        | 135   |           |
| Pinion   | Gear                     | Pinion | Gear | Pinion | Gear  | Pinion | Gear                              | Pinion | Gear  |           |
| Equal Addendum Coefficients ( $x_1 = x_2 = 0$ )  |                          |        |      |        |       |        |                                   |        |       |           |
| 35   | $I$                      |        |      |        | 0.061 |        |                                   |        |       |           |
|  | $J$                      |        |      |        | 0.29  | 0.29   |                                   |        |       |           |
| 55   | $I$                      |        |      |        | 0.074 |        | 0.061                             |        |       |           |
|  | $J$                      |        |      |        | 0.30  | 0.31   | 0.33                              | 0.33   |       |           |
| 135  | $I$                      |        |      |        | 0.096 |        | 0.088                             |        | 0.061 |           |
|  | $J$                      |        |      |        | 0.31  | 0.34   | 0.35                              | 0.35   | 0.38  | 0.38      |
| 25 percent Long Addendum Pinion ( $x_1 = 0.25$ ) |                          |        |      |        |       |        |                                   |        |       |           |
| 25 percent Short Addendum Gear ( $x_2 = -0.25$ ) |                          |        |      |        |       |        |                                   |        |       |           |
| 26   | $I$                      |        |      | 0.060  |       |        |                                   |        |       |           |
|  | $J$                      |        |      | 0.32   | 0.22  |        |                                   |        |       |           |
| 35   | $I$                      |        |      | 0.071  |       | 0.059  |                                   |        |       |           |
|  | $J$                      |        |      | 0.32   | 0.24  | 0.34   | 0.24                              |        |       |           |
| 55   | $I$                      |        |      | 0.087  |       | 0.077  |                                   | 0.060  |       |           |
|  | $J$                      |        |      | 0.33   | 0.27  | 0.35   | 0.27                              | 0.37   | 0.29  |           |
| 135  | $I$                      |        |      | 0.111  |       | 0.106  |                                   | 0.092  |       | 0.060     |
|  | $J$                      |        |      | 0.35   | 0.29  | 0.36   | 0.30                              | 0.39   | 0.32  | 0.41 0.35 |
| 50 percent Long Addendum Pinion ( $x_1 = 0.50$ ) |                          |        |      |        |       |        |                                   |        |       |           |
| 50 percent Short Addendum Gear ( $x_2 = -0.50$ ) |                          |        |      |        |       |        |                                   |        |       |           |
| 21   | $I$                      | 0.056  |      |        |       |        |                                   |        |       |           |
|  | $J$                      | 0.35   | 0.15 |        |       |        |                                   |        |       |           |
| 26   | $I$                      | 0.067  |      | 0.056  |       |        |                                   |        |       |           |
|  | $J$                      | 0.36   | 0.17 | 0.37   | 0.17  |        |                                   |        |       |           |
| 35   | $I$                      | 0.081  |      | 0.071  |       | 0.056  |                                   |        |       |           |
|  | $J$                      | 0.36   | 0.19 | 0.37   | 0.20  | 0.38   | 0.20                              |        |       |           |
| 55   | $I$                      | 0.100  |      | 0.091  |       | 0.078  |                                   | 0.057  |       |           |
|  | $J$                      | 0.37   | 0.22 | 0.38   | 0.23  | 0.39   | 0.24                              | 0.41   | 0.25  |           |
| 135  | $I$                      | 0.127  |      | 0.123  |       | 0.114  |                                   | 0.096  |       | 0.060     |
|  | $J$                      | 0.38   | 0.26 | 0.39   | 0.26  | 0.40   | 0.27                              | 0.42   | 0.29  | 0.43 0.32 |

The addendum modification coefficients  $x_1$  and  $x_2$  are for zero backlash gears meshing at standard center distance.

**Table 4. Geometry Factors  $I$  and  $J$  for Various Number Combinations for Module = 1 or Normal Diametral Pitch = 1**

| Number of Gear Teeth                             | 14.5 -deg Pressure Angle |       |      |       |      |       |      |       | 2.157 Whole Depth Factor          |       |      |       |      |  |  |  |
|--|--------------------------|-------|------|-------|------|-------|------|-------|-----------------------------------|-------|------|-------|------|--|--|--|
|  | 0.0-deg Helix Angle      |       |      |       |      |       |      |       | 0.024 Tooth Thinning for Backlash |       |      |       |      |  |  |  |
|  | 0.0157 Tool Edge Radius  |       |      |       |      |       |      |       | Loaded at Tip of Gears            |       |      |       |      |  |  |  |
| Number of Pinion Teeth                           |                          |       |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 14   |                          | 17    |      | 21    |      | 26    |      | 35    |                                   | 55    |      | 135   |      |  |  |  |
| P  | G                        | P     | G    | P     | G    | P     | G    | P     | G                                 | P     | G    | P     | G    |  |  |  |
| Equal Addendum Coefficients ( $x_1 = x_2 = 0$ )  |                          |       |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 21   | $I$                      |       |      |       |      | 0.078 |      |       |                                   |       |      |       |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.24  | 0.24 |       |                                   |       |      |       |      |  |  |  |
| 26   | $I$                      |       |      |       |      | 0.084 |      | 0.079 |                                   |       |      |       |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.24  | 0.25 | 0.25  | 0.25                              |       |      |       |      |  |  |  |
| 35   | $I$                      |       |      |       |      | 0.091 |      | 0.088 |                                   | 0.080 |      |       |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.24  | 0.26 | 0.25  | 0.26                              | 0.26  | 0.26 |       |      |  |  |  |
| 55   | $I$                      |       |      |       |      | 0.102 |      | 0.101 |                                   | 0.095 |      | 0.080 |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.24  | 0.28 | 0.25  | 0.28                              | 0.26  | 0.28 | 0.28  | 0.28 |  |  |  |
| 135  | $I$                      |       |      |       |      | 0.118 |      | 0.121 |                                   | 0.120 |      | 0.112 |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.24  | 0.29 | 0.25  | 0.29                              | 0.26  | 0.29 | 0.28  | 0.29 |  |  |  |
| 25 percent Long Addendum Pinion ( $x_1 = 0.25$ ) |                          |       |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 25 percent Short Addendum Gear ( $x_2 = -0.25$ ) |                          |       |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 17   | $I$                      |       |      |       |      | 0.080 |      |       |                                   |       |      |       |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.27  | 0.19 |       |                                   |       |      |       |      |  |  |  |
| 21   | $I$                      |       |      |       |      | 0.087 |      | 0.080 |                                   |       |      |       |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.27  | 0.21 | 0.27  | 0.21                              |       |      |       |      |  |  |  |
| 26   | $I$                      |       |      |       |      | 0.094 |      | 0.088 |                                   | 0.080 |      |       |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.27  | 0.22 | 0.27  | 0.22                              | 0.27  | 0.22 |       |      |  |  |  |
| 35   | $I$                      |       |      |       |      | 0.103 |      | 0.098 |                                   | 0.092 |      | 0.080 |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.27  | 0.24 | 0.27  | 0.24                              | 0.28  | 0.24 | 0.28  | 0.24 |  |  |  |
| 55   | $I$                      |       |      |       |      | 0.115 |      | 0.113 |                                   | 0.108 |      | 0.099 |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.27  | 0.26 | 0.27  | 0.26                              | 0.28  | 0.26 | 0.28  | 0.26 |  |  |  |
| 135  | $I$                      |       |      |       |      | 0.131 |      | 0.134 |                                   | 0.133 |      | 0.129 |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.27  | 0.28 | 0.27  | 0.28                              | 0.28  | 0.28 | 0.28  | 0.28 |  |  |  |
| 50 percent Long Addendum Pinion ( $x_1 = 0.50$ ) |                          |       |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 50 percent Short Addendum Gear ( $x_2 = -0.50$ ) |                          |       |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 14   | $I$                      | 0.080 |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
|  | $J$                      | 0.30  | 0.12 |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 17   | $I$                      | 0.088 |      | 0.080 |      |       |      |       |                                   |       |      |       |      |  |  |  |
|  | $J$                      | 0.30  | 0.15 | 0.30  | 0.15 |       |      |       |                                   |       |      |       |      |  |  |  |
| 21   | $I$                      | 0.097 |      | 0.090 |      | 0.080 |      |       |                                   |       |      |       |      |  |  |  |
|  | $J$                      | 0.30  | 0.17 | 0.30  | 0.17 | 0.31  | 0.17 |       |                                   |       |      |       |      |  |  |  |
| 26   | $I$                      | 0.105 |      | 0.099 |      | 0.090 |      | 0.080 |                                   |       |      |       |      |  |  |  |
|  | $J$                      | 0.30  | 0.19 | 0.30  | 0.19 | 0.31  | 0.19 | 0.31  | 0.19                              |       |      |       |      |  |  |  |
| 35   | $I$                      | 0.116 |      | 0.111 |      | 0.103 |      | 0.094 |                                   | 0.080 |      |       |      |  |  |  |
|  | $J$                      | 0.30  | 0.21 | 0.30  | 0.21 | 0.31  | 0.21 | 0.31  | 0.21                              | 0.30  | 0.21 |       |      |  |  |  |
| 55   | $I$                      | 0.130 |      | 0.127 |      | 0.122 |      | 0.114 |                                   | 0.101 |      | 0.080 |      |  |  |  |
|  | $J$                      | 0.30  | 0.24 | 0.30  | 0.24 | 0.31  | 0.24 | 0.31  | 0.24                              | 0.30  | 0.24 | 0.30  | 0.24 |  |  |  |
| 135  | $I$                      | 0.148 |      | 0.149 |      | 0.148 |      | 0.145 |                                   | 0.136 |      | 0.120 |      |  |  |  |
|  | $J$                      | 0.30  | 0.27 | 0.30  | 0.27 | 0.31  | 0.27 | 0.31  | 0.27                              | 0.30  | 0.27 | 0.30  | 0.27 |  |  |  |

The addendum modification coefficients  $x_1$  and  $x_2$  are for zero backlash gears meshing at standard center distance.

GEOMETRY FACTORS FOR GEAR TEETH

**Table 5. Geometry Factors  $I$  and  $J$  for Various Number Combinations for Module = 1 or Normal Diametral Pitch = 1**

| Number of Gear Teeth                             | 14.5 -deg Pressure Angle |       |      |       |      |       |      |       | 2.25 Whole Depth Factor           |       |      |       |      |  |  |  |
|--|--------------------------|-------|------|-------|------|-------|------|-------|-----------------------------------|-------|------|-------|------|--|--|--|
|  | 0.0-deg Helix Angle      |       |      |       |      |       |      |       | 0.024 Tooth Thinning for Backlash |       |      |       |      |  |  |  |
|  | 0.250 Tool Edge Radius   |       |      |       |      |       |      |       | Loaded at HPSTC of Gears          |       |      |       |      |  |  |  |
| Number of Pinion Teeth                           |                          |       |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 14   |                          | 17    |      | 21    |      | 26    |      | 35    |                                   | 55    |      | 135   |      |  |  |  |
| P  | G                        | P     | G    | P     | G    | P     | G    | P     | G                                 | P     | G    | P     | G    |  |  |  |
| Equal Addendum Coefficients ( $x_1 = x_2 = 0$ )  |                          |       |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 21   | $I$                      |       |      |       |      | 0.078 |      |       |                                   |       |      |       |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.33  | 0.33 |       |                                   |       |      |       |      |  |  |  |
| 26   | $I$                      |       |      |       |      | 0.084 |      | 0.079 |                                   |       |      |       |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.33  | 0.35 | 0.35  | 0.35                              |       |      |       |      |  |  |  |
| 35   | $I$                      |       |      |       |      | 0.091 |      | 0.088 |                                   | 0.080 |      |       |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.34  | 0.37 | 0.36  | 0.38                              | 0.39  | 0.39 |       |      |  |  |  |
| 55   | $I$                      |       |      |       |      | 0.102 |      | 0.101 |                                   | 0.095 |      | 0.080 |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.34  | 0.40 | 0.37  | 0.41                              | 0.40  | 0.42 | 0.43  | 0.43 |  |  |  |
| 135  | $I$                      |       |      |       |      | 0.118 |      | 0.121 |                                   | 0.120 |      | 0.112 |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.35  | 0.43 | 0.38  | 0.44                              | 0.41  | 0.45 | 0.45  | 0.47 |  |  |  |
| 25 percent Long Addendum Pinion ( $x_1 = 0.25$ ) |                          |       |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 25 percent Short Addendum Gear ( $x_2 = -0.25$ ) |                          |       |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 17   | $I$                      |       |      |       |      | 0.080 |      |       |                                   |       |      |       |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.36  | 0.24 |       |                                   |       |      |       |      |  |  |  |
| 21   | $I$                      |       |      |       |      | 0.087 |      | 0.080 |                                   |       |      |       |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.37  | 0.26 | 0.39  | 0.27                              |       |      |       |      |  |  |  |
| 26   | $I$                      |       |      |       |      | 0.094 |      | 0.088 |                                   | 0.080 |      |       |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.37  | 0.29 | 0.39  | 0.29                              | 0.41  | 0.30 |       |      |  |  |  |
| 35   | $I$                      |       |      |       |      | 0.103 |      | 0.106 |                                   | 0.092 |      | 0.080 |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.37  | 0.32 | 0.40  | 0.32                              | 0.41  | 0.33 | 0.43  | 0.34 |  |  |  |
| 55   | $I$                      |       |      |       |      | 0.115 |      | 0.113 |                                   | 0.108 |      | 0.099 |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.38  | 0.35 | 0.40  | 0.36                              | 0.42  | 0.36 | 0.44  | 0.37 |  |  |  |
| 135  | $I$                      |       |      |       |      | 0.131 |      | 0.134 |                                   | 0.133 |      | 0.129 |      |  |  |  |
|  | $J$                      |       |      |       |      | 0.39  | 0.39 | 0.41  | 0.40                              | 0.43  | 0.41 | 0.45  | 0.42 |  |  |  |
| 50 percent Long Addendum Pinion ( $x_1 = 0.50$ ) |                          |       |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 50 percent Short Addendum Gear ( $x_2 = -0.50$ ) |                          |       |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 14   | $I$                      | 0.080 |      |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
|  | $J$                      | 0.40  | 0.14 |       |      |       |      |       |                                   |       |      |       |      |  |  |  |
| 17   | $I$                      | 0.088 |      | 0.080 |      |       |      |       |                                   |       |      |       |      |  |  |  |
|  | $J$                      | 0.41  | 0.17 | 0.42  | 0.18 |       |      |       |                                   |       |      |       |      |  |  |  |
| 21   | $I$                      | 0.097 |      | 0.090 |      | 0.080 |      |       |                                   |       |      |       |      |  |  |  |
|  | $J$                      | 0.41  | 0.20 | 0.43  | 0.21 | 0.44  | 0.21 |       |                                   |       |      |       |      |  |  |  |
| 26   | $I$                      | 0.105 |      | 0.099 |      | 0.090 |      | 0.080 |                                   |       |      |       |      |  |  |  |
|  | $J$                      | 0.41  | 0.23 | 0.43  | 0.23 | 0.45  | 0.24 | 0.46  | 0.24                              |       |      |       |      |  |  |  |
| 35   | $I$                      | 0.116 |      | 0.111 |      | 0.103 |      | 0.094 |                                   | 0.080 |      |       |      |  |  |  |
|  | $J$                      | 0.42  | 0.26 | 0.43  | 0.27 | 0.45  | 0.27 | 0.46  | 0.28                              | 0.48  | 0.29 |       |      |  |  |  |
| 55   | $I$                      | 0.130 |      | 0.127 |      | 0.122 |      | 0.114 |                                   | 0.101 |      | 0.080 |      |  |  |  |
|  | $J$                      | 0.42  | 0.30 | 0.44  | 0.31 | 0.45  | 0.31 | 0.47  | 0.32                              | 0.48  | 0.33 | 0.50  | 0.34 |  |  |  |
| 135  | $I$                      | 0.148 |      | 0.149 |      | 0.148 |      | 0.145 |                                   | 0.136 |      | 0.120 |      |  |  |  |
|  | $J$                      | 0.43  | 0.34 | 0.44  | 0.35 | 0.46  | 0.36 | 0.47  | 0.37                              | 0.49  | 0.38 | 0.50  | 0.40 |  |  |  |

The addendum modification coefficients  $x_1$  and  $x_2$  are for zero backlash gears meshing at standard center distance.

**Table 6. Geometry Factors  $I$  and  $J$  for Various Number Combinations for Module = 1 or Normal Diametral Pitch = 1**

| Number of Gear Teeth                             | 25-deg Pressure Angle<br>0.0-deg Helix Angle<br>0.027 Tool Edge Radius |       |      |       | 2.350 Whole Depth Factor<br>0.024 Tooth Thinning for Backlash<br>Loaded at Tip of Gears |       |      |       |      |       |      |       |      |       |      |       |      |
|--|--|-------|------|-------|---|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|
|  | Number of Pinion Teeth   |       |      |       |   |       |      |       |      |       |      |       |      |       |      |       |      |
|  | 12   |       | 14   |       | 17  |       | 21   |       | 26   |       | 35   |       | 55   |       | 135  |       |      |
|  | P  | G     | P    | G     | P   | G     | P    | G     | P    | G     | P    | G     | P    | G     | P    | G     |      |
| Equal Addendum Coefficients ( $x_1 = x_2 = 0$ )  |  |       |      |       |   |       |      |       |      |       |      |       |      |       |      |       |      |
| 14   | $I$  |       |      | 0.086 |   |       |      |       |      |       |      |       |      |       |      |       |      |
|  | $J$  |       |      | 0.28  | 0.28  |       |      |       |      |       |      |       |      |       |      |       |      |
| 17   | $I$  |       |      | 0.091 |   | 0.090 |      |       |      |       |      |       |      |       |      |       |      |
|  | $J$  |       |      | 0.28  | 0.30  | 0.30  | 0.30 |       |      |       |      |       |      |       |      |       |      |
| 21   | $I$  |       |      | 0.095 |   | 0.096 |      | 0.092 |      |       |      |       |      |       |      |       |      |
|  | $J$  |       |      | 0.28  | 0.31  | 0.30  | 0.31 | 0.31  | 0.31 |       |      |       |      |       |      |       |      |
| 26   | $I$  |       |      | 0.100 |   | 0.101 |      | 0.099 |      | 0.094 |      |       |      |       |      |       |      |
|  | $J$  |       |      | 0.28  | 0.33  | 0.30  | 0.33 | 0.31  | 0.33 | 0.33  | 0.33 |       |      |       |      |       |      |
| 35   | $I$  |       |      | 0.106 |   | 0.109 |      | 0.108 |      | 0.104 |      | 0.095 |      |       |      |       |      |
|  | $J$  |       |      | 0.28  | 0.34  | 0.30  | 0.34 | 0.31  | 0.34 | 0.33  | 0.34 | 0.34  | 0.34 |       |      |       |      |
| 55   | $I$  |       |      | 0.113 |   | 0.119 |      | 0.121 |      | 0.119 |      | 0.112 |      | 0.095 |      |       |      |
|  | $J$  |       |      | 0.28  | 0.36  | 0.30  | 0.36 | 0.31  | 0.36 | 0.33  | 0.36 | 0.34  | 0.36 | 0.36  | 0.36 |       |      |
| 135  | $I$  |       |      | 0.123 |   | 0.132 |      | 0.139 |      | 0.142 |      | 0.141 |      | 0.131 |      | 0.096 |      |
|  | $J$  |       |      | 0.28  | 0.38  | 0.30  | 0.38 | 0.31  | 0.38 | 0.33  | 0.38 | 0.34  | 0.38 | 0.36  | 0.38 | 0.49  | 0.49 |
| 25 percent Long Addendum Pinion ( $x_1 = 0.25$ ) |  |       |      |       |   |       |      |       |      |       |      |       |      |       |      |       |      |
| 25 percent Short Addendum Gear ( $x_2 = -0.25$ ) |  |       |      |       |   |       |      |       |      |       |      |       |      |       |      |       |      |
| 14   | $I$  | 0.095 |      | 0.093 |   |       |      |       |      |       |      |       |      |       |      |       |      |
|  | $J$  | 0.32  | 0.22 | 0.33  | 0.22  |       |      |       |      |       |      |       |      |       |      |       |      |
| 17   | $I$  | 0.100 |      | 0.099 |   | 0.094 |      |       |      |       |      |       |      |       |      |       |      |
|  | $J$  | 0.32  | 0.25 | 0.33  | 0.25  | 0.34  | 0.25 |       |      |       |      |       |      |       |      |       |      |
| 21   | $I$  | 0.106 |      | 0.106 |   | 0.102 |      | 0.095 |      |       |      |       |      |       |      |       |      |
|  | $J$  | 0.32  | 0.27 | 0.33  | 0.27  | 0.34  | 0.27 | 0.36  | 0.27 |       |      |       |      |       |      |       |      |
| 26   | $I$  | 0.111 |      | 0.112 |   | 0.109 |      | 0.103 |      | 0.095 |      | 0.095 |      |       |      |       |      |
|  | $J$  | 0.32  | 0.29 | 0.33  | 0.29  | 0.34  | 0.29 | 0.36  | 0.29 | 0.36  | 0.29 | 0.36  | 0.29 |       |      |       |      |
| 35   | $I$  | 0.118 |      | 0.120 |   | 0.119 |      | 0.115 |      | 0.108 |      | 0.096 |      |       |      |       |      |
|  | $J$  | 0.32  | 0.31 | 0.33  | 0.31  | 0.34  | 0.31 | 0.36  | 0.31 | 0.36  | 0.31 | 0.37  | 0.31 |       |      |       |      |
| 55   | $I$  | 0.127 |      | 0.131 |   | 0.133 |      | 0.131 |      | 0.126 |      | 0.116 |      | 0.096 |      |       |      |
|  | $J$  | 0.32  | 0.34 | 0.33  | 0.34  | 0.34  | 0.34 | 0.36  | 0.34 | 0.36  | 0.34 | 0.37  | 0.34 | 0.38  | 0.34 |       |      |
| 135  | $I$  | 0.138 |      | 0.145 |   | 0.151 |      | 0.153 |      | 0.153 |      | 0.148 |      | 0.135 |      | 0.096 |      |
|  | $J$  | 0.32  | 0.37 | 0.33  | 0.37  | 0.34  | 0.27 | 0.36  | 0.37 | 0.36  | 0.37 | 0.37  | 0.37 | 0.38  | 0.37 | 0.39  | 0.37 |
| 50 percent Long Addendum Pinion ( $x_1 = 0.50$ ) |  |       |      |       |   |       |      |       |      |       |      |       |      |       |      |       |      |
| 50 percent Short Addendum Gear ( $x_2 = -0.50$ ) |  |       |      |       |   |       |      |       |      |       |      |       |      |       |      |       |      |
| 21   | $I$  |       |      |       |   | 0.096 |      |       |      |       |      |       |      |       |      |       |      |
|  | $J$  |       |      |       |   | 0.40  | 0.23 |       |      |       |      |       |      |       |      |       |      |
| 26   | $I$  |       |      |       |   | 0.106 |      | 0.096 |      |       |      |       |      |       |      |       |      |
|  | $J$  |       |      |       |   | 0.40  | 0.25 | 0.40  | 0.25 |       |      |       |      |       |      |       |      |
| 35   | $I$  |       |      |       |   | 0.120 |      | 0.110 |      | 0.096 |      |       |      |       |      |       |      |
|  | $J$  |       |      |       |   | 0.40  | 0.28 | 0.40  | 0.28 | 0.40  | 0.28 |       |      |       |      |       |      |
| 55   | $I$  |       |      |       |   | 0.139 |      | 0.131 |      | 0.118 |      | 0.096 |      |       |      |       |      |
|  | $J$  |       |      |       |   | 0.40  | 0.32 | 0.40  | 0.32 | 0.40  | 0.32 | 0.40  | 0.32 | 0.40  | 0.32 |       |      |
| 135  | $I$  |       |      |       |   | 0.167 |      | 0.163 |      | 0.155 |      | 0.138 |      | 0.096 |      |       |      |
|  | $J$  |       |      |       |   | 0.40  | 0.36 | 0.40  | 0.36 | 0.40  | 0.36 | 0.40  | 0.36 | 0.40  | 0.36 | 0.40  | 0.36 |

The addendum modification coefficients  $x_1$  and  $x_2$  are for zero backlash gears meshing at standard center distance.

**Table 7. Geometry Factors  $I$  and  $J$  for Various Number Combinations for Module = 1 or Normal Diametral Pitch = 1**

| Number of Gear Teeth                             | 25-deg Pressure Angle<br>0.0-deg Helix Angle<br>0.270 Tool Edge Radius |       |       |       | 2.350 Whole Depth Factor<br>0.024 Tooth Thinning for Backlash<br>Loaded at HPSTC of Gears |       |       |       |       |       |       |       |       |       |       |       |      |
|--|--|-------|-------|-------|---|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|
|  | Number of Pinion Teeth   |       |       |       |   |       |       |       |       |       |       |       |       |       |       |       |      |
|  | 12   |       | 14    |       | 17  |       | 21    |       | 26    |       | 35    |       | 55    |       | 135   |       |      |
|  | P  | G     | P     | G     | P   | G     | P     | G     | P     | G     | P     | G     | P     | G     | P     | G     |      |
| Equal Addendum Coefficients ( $x_f = x_2 = 0$ )  |  |       |       |       |   |       |       |       |       |       |       |       |       |       |       |       |      |
| 14   | $I$  |       | 0.086 |       |   |       |       |       |       |       |       |       |       |       |       |       |      |
|  | $J$  |       | 0.33  | 0.33  |   |       |       |       |       |       |       |       |       |       |       |       |      |
| 17   | $I$  |       | 0.091 |       | 0.090   |       |       |       |       |       |       |       |       |       |       |       |      |
|  | $J$  |       | 0.33  | 0.36  | 0.36  | 0.36  |       |       |       |       |       |       |       |       |       |       |      |
| 21   | $I$  |       | 0.095 |       | 0.096   |       | 0.092 |       |       |       |       |       |       |       |       |       |      |
|  | $J$  |       | 0.33  | 0.39  | 0.36  | 0.39  | 0.39  | 0.39  |       |       |       |       |       |       |       |       |      |
| 26   | $I$  |       | 0.100 |       | 0.101   |       | 0.099 |       | 0.094 |       |       |       |       |       |       |       |      |
|  | $J$  |       | 0.33  | 0.41  | 0.37  | 0.42  | 0.40  | 0.42  | 0.43  | 0.43  |       |       |       |       |       |       |      |
| 35   | $I$  |       | 0.106 |       | 0.109   |       | 0.108 |       | 0.104 |       | 0.095 |       |       |       |       |       |      |
|  | $J$  |       | 0.34  | 0.44  | 0.37  | 0.45  | 0.40  | 0.45  | 0.43  | 0.46  | 0.46  | 0.46  |       |       |       |       |      |
| 55   | $I$  |       | 0.113 |       | 0.119   |       | 0.121 |       | 0.119 |       | 0.112 |       | 0.095 |       |       |       |      |
|  | $J$  |       | 0.34  | 0.47  | 0.38  | 0.48  | 0.41  | 0.49  | 0.43  | 0.49  | 0.47  | 0.50  | 0.51  | 0.51  |       |       |      |
| 135  | $I$  |       | 0.123 |       | 0.132   |       | 0.139 |       | 0.142 |       | 0.141 |       | 0.131 |       | 0.096 |       |      |
|  | $J$  |       | 0.35  | 0.51  | 0.38  | 0.52  | 0.42  | 0.53  | 0.45  | 0.53  | 0.48  | 0.54  | 0.53  | 0.56  | 0.57  | 0.57  |      |
| 25 percent Long Addendum Pinion ( $x_f = 0.25$ ) |  |       |       |       |   |       |       |       |       |       |       |       |       |       |       |       |      |
| 25 percent Short Addendum Gear ( $x_2 = -0.25$ ) |  |       |       |       |   |       |       |       |       |       |       |       |       |       |       |       |      |
| 14   | $I$  | 0.095 |       | 0.093 |   |       |       |       |       |       |       |       |       |       |       |       |      |
|  | $J$  | 0.38  | 0.25  | 0.40  | 0.25  |       |       |       |       |       |       |       |       |       |       |       |      |
| 17   | $I$  | 0.100 |       | 0.099 |   | 0.094 |       |       |       |       |       |       |       |       |       |       |      |
|  | $J$  | 0.38  | 0.29  | 0.40  | 0.29  | 0.43  | 0.29  |       |       |       |       |       |       |       |       |       |      |
| 21   | $I$  | 0.106 |       | 0.106 |   | 0.102 |       | 0.095 |       |       |       |       |       |       |       |       |      |
|  | $J$  | 0.38  | 0.32  | 0.41  | 0.32  | 0.43  | 0.33  | 0.46  | 0.33  |       |       |       |       |       |       |       |      |
| 26   | $I$  | 0.111 |       | 0.112 |   | 0.109 |       | 0.103 |       | 0.095 |       |       |       |       |       |       |      |
|  | $J$  | 0.39  | 0.35  | 0.41  | 0.35  | 0.44  | 0.36  | 0.46  | 0.36  | 0.48  | 0.37  |       |       |       |       |       |      |
| 35   | $I$  | 0.118 |       | 0.120 |   | 0.119 |       | 0.115 |       | 0.108 |       | 0.096 |       |       |       |       |      |
|  | $J$  | 0.39  | 0.38  | 0.41  | 0.39  | 0.44  | 0.39  | 0.47  | 0.40  | 0.49  | 0.41  | 0.51  | 0.41  |       |       |       |      |
| 55   | $I$  | 0.127 |       | 0.131 |   | 0.133 |       | 0.131 |       | 0.126 |       | 0.116 |       | 0.096 |       |       |      |
|  | $J$  | 0.39  | 0.42  | 0.42  | 0.43  | 0.44  | 0.44  | 0.47  | 0.44  | 0.49  | 0.45  | 0.52  | 0.46  | 0.55  | 0.47  |       |      |
| 135  | $I$  | 0.138 |       | 0.145 |   | 0.151 |       | 0.153 |       | 0.153 |       | 0.148 |       | 0.135 |       | 0.096 |      |
|  | $J$  | 0.40  | 0.47  | 0.42  | 0.48  | 0.45  | 0.49  | 0.48  | 0.49  | 0.50  | 0.50  | 0.53  | 0.51  | 0.56  | 0.53  | 0.59  | 0.55 |
| 50 percent Long Addendum Pinion ( $x_f = 0.50$ ) |  |       |       |       |   |       |       |       |       |       |       |       |       |       |       |       |      |
| 50 percent Short Addendum Gear ( $x_2 = -0.50$ ) |  |       |       |       |   |       |       |       |       |       |       |       |       |       |       |       |      |
| 21   | $I$  |       |       |       |   | 0.096 |       |       |       |       |       |       |       |       |       |       |      |
|  | $J$  |       |       |       |   | 0.52  | 0.27  |       |       |       |       |       |       |       |       |       |      |
| 26   | $I$  |       |       |       |   | 0.106 |       | 0.096 |       |       |       |       |       |       |       |       |      |
|  | $J$  |       |       |       |   | 0.52  | 0.30  | 0.53  | 0.31  |       |       |       |       |       |       |       |      |
| 35   | $I$  |       |       |       |   | 0.120 |       | 0.110 |       | 0.096 |       |       |       |       |       |       |      |
|  | $J$  |       |       |       |   | 0.52  | 0.35  | 0.53  | 0.35  | 0.55  | 0.36  |       |       |       |       |       |      |
| 55   | $I$  |       |       |       |   | 0.139 |       | 0.131 |       | 0.118 |       | 0.096 |       |       |       |       |      |
|  | $J$  |       |       |       |   | 0.52  | 0.40  | 0.54  | 0.41  | 0.56  | 0.42  | 0.58  | 0.43  |       |       |       |      |
| 135  | $I$  |       |       |       |   | 0.167 |       | 0.163 |       | 0.155 |       | 0.138 |       | 0.096 |       |       |      |
|  | $J$  |       |       |       |   | 0.53  | 0.46  | 0.54  | 0.47  | 0.56  | 0.48  | 0.58  | 0.50  | 0.60  | 0.53  |       |      |

The addendum modification coefficients  $x_f$  and  $x_2$  are for zero backlash gears meshing at standard center distance.

### Power-Transmitting Capacity of Spur Gears

**Modes of Failure.**—When sets of spur gears are made, installed, and lubricated properly, they normally may be subject to three primary modes of failure, as discussed below.

**Tooth Scoring:** Tooth scoring is a scuffing or welding type of tooth failure, caused by high sliding speed combined with high contact stress. Scoring is not a fatigue failure but rather a failure of the lubricant caused by increases in lubricant viscosity with pressure. The lubricant must provide cooling to the gears as well as reducing friction. Well proportioned commercial gears with a pitchline velocity of less than 7000 ft/min will normally not score if they have a reasonably good surface finish and are properly lubricated. If scoring does occur or if it is suspected to be critical in a new high speed design, the scoring temperature index should be determined by the method shown in American Gear Manufacturers Standard AGMA 217.01 or by some similar method.

**Pitting:** In surface pitting, small cracks first develop on and under the surfaces of gear teeth as a result of metal fatigue. Pieces of the surface then break away, and those that do not fall clear cause further damage or broken teeth. Vacuum-melted steels have gone far toward reducing pitting. Failure usually occurs at a point just below the pitch surface on the driving pinion and may be anticipated in the gear design by a determination of the gear set contact compressive stress.

**Tooth Breakage:** Tooth breakage is usually a tensile fatigue failure at the weakest section of the gear tooth when considered as a cantilever beam. The weakest point is normally the tensile side of the gear tooth fillet, and it may be anticipated in the gear design by determining the stress at this weakest section of the gear tooth.

**Strength Calculations for Spur and Helical Gears.**—Many standards and procedures for the design, manufacture, inspection, and application of gears have been published for the guidance of both the users and the manufacturers of gears and gear products. Among such publications, those of the American Gear Manufacturers Association (AGMA) represent an authoritative resource for information and standards on all phases of design, inspection, manufacture, application, and other aspects of gear technology.

American Gear Manufacturers Association Standard, AGMA 2001–B88, *Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth*, is a revision of, and supersedes, AGMA 218.01. The Standard presents general formulas for rating the pitting resistance and the bending strength of spur and helical involute gear teeth and is intended to establish a common base for rating various types of gears for differing applications and to encourage the maximum practical degree of uniformity and consistency between rating practices in the gear industry. Standard 2001–B88 provides the basis from which more detailed AGMA Application Standards are developed and is a means for calculation of approximate ratings in the absence of such standards. Where applicable AGMA standards exist, they should be used in preference to this Standard. Where no applicable standards exist, numerical values may be estimated for the factors used in the general equations presented in the standard. The values of these factors may vary significantly, depending on the application, system effects, gear accuracy, manufacturing practice, and definition of what constitutes gear failure. Proper evaluation of these factors is essential for realistic ratings.

Information on the geometry factors,  $I$  and  $J$ , used in pitting resistance and bending strength calculations has been amplified, and moved from the old AGMA 218.01 standard to AGMA 908–B89, *Geometry Factors for Determining the Pitting Resistance and Bending Strength of Spur, Helical, and Herringbone Gear Teeth*. AGMA Standard 908–B89 is covered on Handbook pages 1853–1866.



**Rating Formulas\*.**—AGMA 2001–B88 provides a method whereby different gear designs can be compared but it is not intended to ensure the performance of assembled gear drive systems. The formulas are applicable for rating the pitting resistance and bending strength of internal and external spur and helical involute gear teeth operating on parallel axes. Gear tooth capacity is influenced by the major factors that affect gear tooth pitting and gear tooth fracture at the fillet radius can be evaluated with these formulas.

Knowledge and judgment required to evaluate the various rating factors can be gained only from years of accumulated experience in designing, manufacturing, and operating gear units. Empirical factors given in the AGMA 2001–B88 standard are general in nature, and other AGMA application standards may use other empirical factors that are more closely suited to the particular field of application. AGMA 2001–B88 is intended for use by the experienced gear designer capable of selecting suitable values for the factors and not for use by engineers inexperienced in gear design and applications.

**Exceptions.**—The formulas in this Standard are not applicable to other types of gear tooth deterioration such as plastic yielding, wear, case crushing, and welding and are not applicable when vibratory conditions exceed the limits for the normal operation of the gears (see AGMA 6000–A88, *Specification for Measurement of Lateral Vibration on Gear Units*). The formulas are not applicable when any of the following conditions exist:

5) spur gears with transverse contact ratio less than 1.0; 6) spur or helical gears with transverse contact ratio equal to or greater than 2.0; 7) interference exists between the tips of the teeth and the root fillets; 8) the teeth are pointed; and 9) backlash is zero.

**Additional Considerations.**—When suitable test results or field data are not available, values for the rating factors should be chosen conservatively. Among other considerations, the following should be taken into account:

*Manufacturing Tolerances:* Rating factors should be evaluated on the basis of the expected variation of component parts in the production run.

*Accuracy:* Experimental data from actual gear unit measurements are seldom repeatable within a plus or minus 10 per cent band. Calculated gear ratings are intended to be conservative but the scatter in actual results may exceed 20 per cent.

*Misalignment and Deflection of Foundations:* Misalignment and deflection of foundations, on which many gear systems depend to maintain alignment of the gear mesh, will adversely affect overall performance.

*Deflection due to External Loads:* Deflection of supporting housings, shafts, and bearings, due to external overhang, transverse and thrust loads affects tooth contact across the mesh. Deflection varies with load, so it is difficult to obtain good tooth contact at different loads. Generally, deflection due to external loads reduces capacity.

*Metallurgy:* The allowable stress numbers included in the Standard are a function of melting, casting, forging, and heat treating practices. Hardness, tensile strength, and cleanliness are some of the criteria for determining allowable stress numbers; the allowable values in this Standard are based on 10,000,000 cycles of loading, 99 percent reliability, and unidirectional loading.

Variations in microstructure account for some variation in gear capacity. Higher levels of cleanliness and better metallurgical controls permit use of higher allowable stress values and, conversely, lower quality levels require the use of lower values.

*Residual Stress:* Any material having a case—core relationship is likely to have residual stresses. Properly managed, these stresses will be compressive at the surface and will enhance the bending strength performance of the gear teeth. Shot peening, case carburiz-

\*Extracted from AGMA 2001–B88, Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth, with the permission of the publisher, American Gear Manufacturers Association, 1500 King Street, Suite 201, Alexandria, Virginia 22314.

ing, nitriding, and induction hardening are common methods of inducing compressive prestress in the surfaces of gear teeth.

Grinding the tooth surfaces after heat treatment reduces residual compressive stresses; and grinding the tooth surfaces and the root fillet areas may introduce tensile stresses and possibly cracks in these areas if done incorrectly. Care is needed to avoid excessive reductions in hardness and changes in microstructure during the grinding process, and shot peening after grinding is often performed to ensure the presence of residual compressive stresses.

*Lubrication:* The ratings determined by the formulas in the Standard are only valid when a lubricant of proper viscosity for the load, gear-tooth surface finish, temperature, and pitchline velocity is used. Gears with pitchline velocities of less than 100 ft/min require special design considerations to avoid premature failure from inadequate lubrication.

Velocities greater than 100 ft/min but less than 1000 ft/min frequently require special design considerations even when the lubricants used conform to AGMA 250 recommendations.

With velocities in the range of 1000–0,000 ft/min, lubrication problems may be caused by high temperatures, unsuitable additives in the oil, size of the pinion, inadequate oil viscosity, or tooth finish characteristics. Problems in this speed range are not common in industrial gears but sometimes occur in aerospace and in marine gearing.

From a lubrication standpoint, the design of slower gears should be based on application criteria such as hours of life, degree of reliability needed, and acceptable increases in vibration and noise as the gear teeth wear or deform. At pitchline velocities below 100 ft/min, or 20 rpm input speed, the gear designer may allow for acceptable pitting and wear to occur during the gear life when using these rating practices for other than surface-hardened gearing. Rating of gear teeth due to wear is not covered by this Standard.

*System Dynamics:* The dynamic response of the system results in additional gear tooth loads due to the relative motions of the connected masses of the driver and the driven equipment. Application factors,  $C_a$  and  $K_a$ , are intended to account for the operating characteristics of the driving and driven equipment. However, if the operating roughness of the driver, gearbox, or driven equipment causes an excitation with a frequency near to one of the system's major natural frequencies, resonant vibrations may cause severe overloads that may be several times higher than the nominal load. For more information, refer to AGMA 427.01, *Information Sheet—Systems Considerations for Critical Service Gear Drives*.

*Corrosion:* Corrosion of the gear tooth surface can have significant detrimental effects on the bending strength and pitting resistance of the teeth. The extent of these corrosion effects is not included in the Standard.

*Cold Temperature Operation:* For gears operated at temperatures below 320F, special care must be taken to select materials that will have adequate impact properties at the operating temperature. Consideration should be given to

1) low-temperature Charpy impact specification; 2) fracture appearance transition or nil ductility temperature specification; 3) reduction of carbon content to less than 0.4 per cent; and 4) use of higher nickel alloy steels.

### Criteria for Gear Tooth Capacity

**Relationship of Pitting Resistance and Bending Strength Ratings.**—There are two major differences between the pitting resistance and the bending strength ratings. Pitting is a function of the Hertzian contact (compressive) stresses between two cylinders and is proportional to the square root of the applied load. Bending strength is measured in terms of the bending (tensile) stress in a cantilever plate and is directly proportional to this same load. The difference in the nature of the stresses induced in the tooth surface areas and at

the tooth root is reflected in a corresponding difference in allowable limits of contact and bending stress numbers for identical materials and load intensities.

Analysis of the load and stress modifying factors is similar in each instance, so many of these factors have identical numerical values. The term "gear failure" is itself subjective and a source of considerable disagreement. One observer's "failure" may be another observer's "wearing in." A more complete discussion of "failure" is given in AGMA 110.04, Nomenclature of Gear Tooth Failure Modes.

**Pitting Resistance:** In most industrial practice, corrective and nonprogressive initial pitting is not deemed serious. Initial pitting is characterized by small pits that do not extend over the entire face width or profile height of the affected teeth. The definition of acceptable pitting varies widely with gear application. Initial pitting occurs in localized, overstressed areas and tends to redistribute the load by progressively removing high contact spots. Generally, when the load has been reduced or redistributed, the pitting stops.

The pitting resistance formula aims to determine a load rating at which destructive pitting of the teeth does not occur during their design life. The ratings for pitting resistance are based on the formulas developed by Hertz for contact pressure between two curved surfaces, modified for the effect of load sharing between adjacent teeth.

**Bending Strength:** The bending strength of gear teeth is a fatigue phenomenon related to the resistance to cracking at the tooth root fillet in external gears and at the critical section in internal gears. The basic theory employed in this analysis assumes the gear tooth to be rigidly fixed at its base, thus, the critical stress occurs in the fillet. If the rim supporting the gear tooth is thin relative to the size of the tooth and the gear pitch diameter, another critical stress may occur not at the fillet but in the root area. The rim thickness factor,  $K_B$ , adjusts the calculated bending stress number for thin rimmed gears.

The strength ratings determined by this Standard are based on plate theory that is modified to consider:

- 1) the compressive stress at tooth roots caused by the radial component of tooth loading;
- 2) nonuniform moment distribution resulting from the inclined angle of the load lines on the teeth; 3) stress concentrations at the tooth root fillets; and 4) the load sharing between adjacent teeth in contact.

The intent of the AGMA strength rating formula is to determine the load that can be transmitted for the design life of the gear drive without causing cracking or failure. Occasionally, wear, surface fatigue, or plastic flow may limit bending strength due to stress concentrations around large, sharp cornered pits or wear steps on the tooth surface.

**Fundamental Rating Formulas.**—The symbols and definitions used in the pitting resistance and bending strength formulas are shown in [Table 1](#). SI units are shown in parentheses in [Table 1](#) and in the text. Where equations require a different format or constant for use with SI units, a second expression is shown after the first and with  $M$  included in the equation number at the right.

**Pitting Resistance.**—The fundamental formula for pitting resistance of gear teeth is

$$S_c = C_p \sqrt{\frac{W_t \times C_a \cdot C_s \cdot C_m \times C_f}{C_v \cdot dF \cdot I}} \quad (1)$$

where the meaning of the symbols is as shown in [Table 1](#) and,

$$d = \frac{2C}{m_G + 1.0} \quad \text{for external gears} \quad (2)$$

$$d = \frac{2C}{m_G - 1.0} \quad \text{for internal gears} \quad (3)$$

**Table 1. Symbols Used in Gear Rating Equations**

| Symbol   | Description of Symbols and Units   | Symbol   | Description of Symbols and Units                                 |
|----------|--|----------|--|
| $C$      | Operating center distance, in. (mm)  | $K_R$    | Reliability factor for bending strength                          |
| $C_a$    | Application factor for pitting resistance                                      | $K_s$    | Size factor for bending strength                                 |
| $C_c$    | Curvature factor at pitchline  | $K_{SF}$ | Service factor for bending strength                              |
| $C_e$    | Mesh alignment correction factor   | $K_T$    | Temperature factor for bending strength                          |
| $C_f$    | Surface condition factor for pitting resistance                                | $K_v$    | Dynamic factor for bending strength                              |
| $C_G$    | Gear ratio factor  | $K_y$    | Yield strength factor  |
| $C_H$    | Hardness ratio factor for pitting resistance                                   | $m$      | Metric module, nominal in plane of rotation (mm)                 |
| $C_L$    | Life factor for pitting resistance   | $m_B$    | Back up ratio  |
| $C_m$    | Load distribution factor for pitting resistance                                | $m_G$    | Gear ratio (never less than 1.0)                                 |
| $C_{ma}$ | Mesh alignment factor  | $m_N$    | Load sharing ratio   |
| $C_{mc}$ | Lead correction factor   | $m_n$    | Normal metric module, nominal (mm)                               |
| $C_{mf}$ | Face load distribution factor  | $N$      | Number of load cycles  |
| $C_{mt}$ | Transverse load distribution factor  | $N_G$    | Number of teeth in gear  |
| $C_p$    | Elastic coefficient [lb/in. <sup>2</sup> ] <sup>0.5</sup> (MPa) <sup>0.5</sup> | $N_p$    | Number of teeth in pinion  |
| $C_{pf}$ | Pinion proportion factor   | $n_p$    | Pinion speed rpm   |
| $C_{pm}$ | Pinion proportion modifier   | $P$      | Transmitted power, hp (kW)                                       |
| $C_R$    | Reliability factor for pitting resistance                                      | $P_{ac}$ | Allowable transmitted power for pitting resistance, hp (kW)      |
| $C_s$    | Size factor for pitting resistance   | $P_{at}$ | Allowable transmitted power for bending strength, hp (kW)        |
| $C_{SF}$ | Service factor for pitting resistance  | $P_d$    | Diametral pitch, nominal, in plane of rotation, in <sup>-1</sup> |
| $C_T$    | Temperature factor for pitting resistance                                      | $P_{nd}$ | Normal diametral pitch, nominal, in <sup>-1</sup>                |
| $C_v$    | Dynamic factor for pitting resistance  | $P_b$    | Transverse base pitch, in. (mm)                                  |
| $C_x$    | Contact height factor  | $P_x$    | Axial pitch, in. (mm)  |
| $C_\psi$ | Helical overlap factor   | $Q_v$    | Transmission accuracy level number                               |
| $d$      | Operating pitch diameter of pinion, in. (mm)                                   | $S$      | Bearing span, in. (mm)   |
| $E_G$    | Modulus of elasticity for gear, lb/in. <sup>2</sup> (MPa)                      | $S_l$    | Pinion offset, in. (mm)  |
| $E_p$    | Modulus of elasticity for pinion, lb/in. <sup>2</sup> (MPa)                    | $S_{ac}$ | Allowable contact stress number, lb/in. <sup>2</sup> (MPa)       |
| $e_t$    | Total lead mismatch, in. (mm)  | $S_{at}$ | Allowable bending stress number, lb/in. <sup>2</sup> (MPa)       |

**Table 1. (Continued) Symbols Used in Gear Rating Equations**

| Symbol       | Description of Symbols and Units                                      | Symbol       | Description of Symbols and Units                                      |
|--------------|---|--------------|---|
| $f_p$        | Pinion surface finish, microinches rms                                | $S_{ay}$     | Allowable yield stress number, lb/in. <sup>2</sup> (MPa)              |
| $F$          | Net face width of narrowest member, in. (mm)                          | $S_c$        | Contact stress number, lb/in. <sup>2</sup> (MPa)                      |
| $G$          | Tooth stiffness constant, lb/in. <sup>2</sup> (MPa)                   | $S_t$        | Bending stress number, lb/in. <sup>2</sup> (MPa)                      |
| $H_{BG}$     | Brinell hardness of gear  | $T$          | Transmitted pinion torque, lb-in. (N-m)                               |
| $H_{BP}$     | Brinell hardness of pinion  | $t_R$        | Gear rim thickness, in. (mm)  |
| $h_c$        | Minimum total case depth for nitrided gears, in. (mm)                 | $t_o$        | Normal tooth thickness at top land of gear, in. (mm)                  |
| $h_e$        | Minimum effective case depth for carburized gears, in. (mm)           | $U_{at}$     | Allowable unit load for bending strength, lb/in. <sup>2</sup> (MPa)   |
| $h_{e\ max}$ | Maximum effective case depth, in. (mm)                                | $U_c$        | Core hardness coefficient   |
| $h_t$        | Gear tooth whole depth, in. (mm)                                      | $U_H$        | Hardening process factor  |
| $I$          | Geometry factor for pitting resistance                                | $U_L$        | Unit load for bending strength, lb/in. <sup>2</sup> (MPa)             |
| $J$          | Geometry factor for bending strength                                  | $v_t$        | Pitch line velocity at operating pitch diameter, ft/min (m/s)         |
| $K$          | Contact load factor for pitting resistance, lb/in. <sup>2</sup> (MPa) | $v_{t\ max}$ | Pitch line velocity maximum at operating pitch diameter, ft/min (m/s) |
| $K_a$        | Application factor for bending strength                               | $W_d$        | Incremental dynamic tooth load, lb (N)                                |
| $K_{ac}$     | Allowable contact load factor, lb/in. <sup>2</sup> (MPa)              | $W_{max}$    | Maximum peak tangential load, lb (N)                                  |
| $K_B$        | Rim thickness factor  | $W_t$        | Transmitted tangential load, lb (N)                                   |
| $K_f$        | Stress correction factor  | $Y$          | Tooth form factor   |
| $K_L$        | Life factor for bending strength                                      | $Z$          | Length of action in transverse plane, in. (mm)                        |
| $K_m$        | Load distribution factor for bending strength                         | $\mu_G$      | Poisson's ratio for gear  |
|              |   | $\mu_P$      | Poisson's ratio for pinion  |
|              |   | $\phi_t$     | Operating transverse pressure angle                                   |
|              |   | $\psi_s$     | Helix angle at standard pitch diameter                                |
|              |   | $\psi_b$     | Base helix angle  |

**Allowable Contact Stress Number:** The relation of calculated contact stress number (graphed in Fig. 1) to the allowable contact stress number is

$$S_c \leq S_{ac} \frac{C_L C_H}{C_T C_R} \quad (4)$$

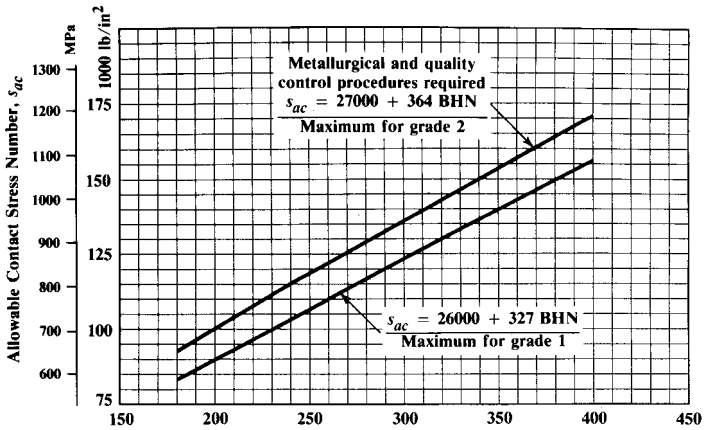


Fig. 1. Allowable Contact Stress Number for Steel Gears,  $S_{ac}$

**Pitting Resistance Power Rating.**—The pitting resistance power rating is given by

$$P_{ac} = \frac{n_p \times F}{12600 C_s \times C_m \times C_f \times C_a} \frac{I \times C_v}{C_p \times C_T \times C_R} \left( \frac{d \times S_{ac} C_L \times C_H}{C_p \times C_T \times C_R} \right)^2 \quad (5)$$

$$P_{ac} = \frac{n_p \times F}{1.91 \times 10^7 C_s \times C_m \times C_f \times C_a} \frac{I \times C_v}{C_p \times C_T \times C_R} \left( \frac{d \times S_{ac} C_L \times C_H}{C_p \times C_T \times C_R} \right)^2 \quad (5a)$$

In using Formula (5) and (5a), the ratings of both pinion and gear must be calculated to evaluate differences in material properties and the number of cycles under load. The pitting resistance power rating is based on the lowest value of the product  $S_{ac} C_L C_H$  for each of the mating gears.

**Contact Load Factor,  $K$ .**—In some industries, pitting resistance is rated in terms of a  $K$  factor:

$$K = \frac{W_t}{dF} \times \frac{1}{C_G} \quad (6)$$

for external gears,  $C_G = \frac{N_G}{N_G + N_P}$  (7)

for internal gears,  $C_G = \frac{N_G}{N_G - N_P}$  (8)

In terms of this Standard, the allowable  $K$  factor is defined as

$$K_{ac} = \frac{I}{C_G C_a \times C_s \times C_m \times C_f} \frac{C_v}{C_p \times C_T \times C_R} \left( \frac{S_{ac} \times C_L \times C_H}{C_p \times C_T \times C_R} \right)^2 \quad (9)$$

The allowable contact load factor,  $K_{ac}$ , is the lowest of the ratings calculated using the different values of  $s_{ac}$ ,  $C_L$ , and  $C_H$  for pinion and gear.

**Bending Strength.**—The fundamental formula for bending stress number in a gear tooth is

$$s_t = \frac{W_t \times K_a P_d K_s \times K_m \times K_B}{K_v F J} \tag{10}$$

where  $P_d = P_{nd}$  for spur gears. For helical gears,  $P_d$  is given by Equation (11),

$$s_t = \frac{W_t \times K_a I K_s \times K_m \times K_B}{K_v F \times m J} \tag{10a}$$

where  $m = m_n$  for spur gears. For helical gears  $m$  is given by Equation (11a):

$$P_d = \frac{\pi}{p_x \tan \psi_s} = P_{nd} \cos \psi_s \tag{11}$$

$$m = \frac{P_x \times \tan \psi_s}{\pi} = \frac{m_n}{\cos \psi_s} \tag{11a}$$

where  $\psi_s$  is given by Equation (12) or (12a)

$$\psi_s = \text{asin} \left( \frac{\pi}{p_x \times P_{nd}} \right) \tag{12}$$

$$\psi_s = \text{asin} \left( \frac{\pi \times m_n}{p_x} \right) \tag{12a}$$

**Allowable Bending Stress Number.**—The relation of calculated bending stress number to allowable bending stress number is

$$S_t \leq \frac{S_{at} \times K_L}{K_T \times K_R} \tag{13}$$

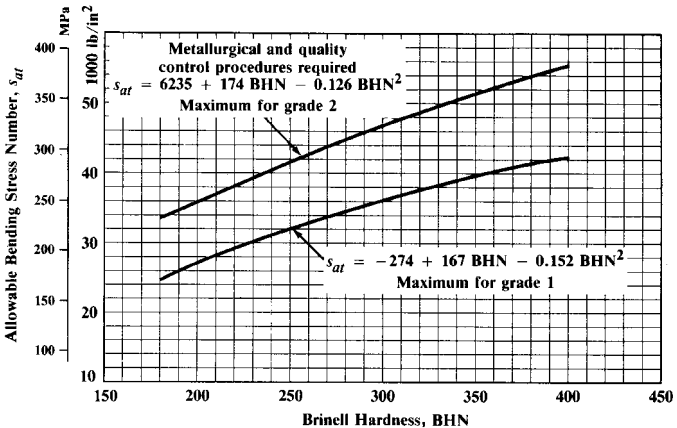


Fig. 2. Allowable Bending Stress Number for Steel Gears  $s_{at}$

**Bending Strength Power Rating.**—The bending strength power rating is

$$P_{at} = \frac{n_p \times d \times K_v}{126000 \times K_a P_d K_s \times K_m \times K_B K_R \times K_T} \frac{F}{J} \frac{s_{at} \times K_L}{K_T} \quad (14)$$

$$P_{at} = \frac{n_p \times d \times K_v}{1.91 \times 10^7 \times K_a} \frac{F \times m \times J}{K_s \times K_m \times K_B K_R \times K_T} \frac{s_{at} \times K_L}{K_T} \quad (14a)$$

The ratings of both pinion and gear must be calculated to evaluate differences in geometry factors, number of load cycles, and material properties. The bending strength power rating is based on the lowest value of the term  $s_{at} K_L J / K_B$  for each of the mating gears.

In some industries, the bending strength is rated in terms of unit load:

$$U_L = \frac{(W_t \times P_{nd})}{F} \quad (15)$$

$$U_L = \frac{W_t}{(F \times m)} \quad (15a)$$

The allowable unit load,  $U_{at}$ , is the lowest of the ratings calculated using the different values of  $s_{at}$ ,  $K_B$ ,  $K_L$ , and  $J$  for pinion and gear in Equation (16):

$$U_{at} = \frac{J}{\cos \psi K_a \times K_m \times K_s \times K_B K_R \times K_T} \frac{K_v}{s_{at} \times K_L} \quad (16)$$

**Values for Factors Applied in Fundamental Equations.**—Values for the various factors used in the pitting resistance and bending strength rating equations are discussed and explained in greater detail in the Standard and its appendices than can be provided here. The following paragraphs are intended by the Editors to provide values for some of these factors suitable for making approximations to the ratings of pairs of mating gears without the refinements used by experienced gear designers.

**Rim Thickness Factor  $K_B$ .**—The rim thickness factor,  $K_B$ , is used to adjust the calculated bending stress number for thin rimmed gears, the value of the factor depending upon the backup ratio,

$$m_B = \frac{t_R}{h_t} \quad (17)$$

If  $m_B$  is equal to or greater than 1.2, then  $K_B$  may be taken as 1.0. For values of  $m_B$  less than 1.2, see the information in Appendix C following the Standard.

**Geometry Factors  $I$  and  $J$ .**—The geometry factors  $I$  and  $J$  for pitting resistance and bending strength, respectively, are described, along with selected typical values, beginning on page 1853.

**Transmitted Tangential Load,  $W_t$ .**—In most gear applications the torque is not constant, so the transmitted tangential load will vary. To obtain values of the operating transmitted tangential load,  $W_t$ , the values of power and speed at which the driven device will operate should be used. If the rating is calculated on the basis of uniform load, then the transmitted tangential load is

$$W_t = \frac{33000 \times P}{v_t} = \frac{2 \times T}{d} = \frac{126000 \times P}{n_p \times d} \quad (18)$$

$$W_t = \frac{1000 \times P}{v_t} = \frac{2000 \times T}{d} = \frac{1.91 \times 10^7 \times P}{n_p \times d} \quad (18a)$$



where,

$$v_t = \frac{(\pi \times n_p \times d)}{12} \quad (19)$$

$$v_t = \frac{(\pi \times n_p \times d)}{60000} \quad (19a)$$

**Nonuniform Load:** When the transmitted load is not uniform, consideration should be given not only to the peak load and its anticipated number of cycles, but also to intermediate loads and their duration. This type of load is often considered a duty cycle and may be represented by a load spectrum. The cumulative fatigue effect of the duty cycle is then considered in rating the gearset. A method of calculating the effects of the loads under such conditions is given in Appendix B of the Standard.

**Dynamic Factors,  $C_v$  and  $K_d$ .**—Dynamic factors account for internally generated gear tooth loads, which are induced by nonconjugate meshing action of the gear teeth. Even if the input torque and speed are constant, significant vibration of the gear masses, and therefore dynamic tooth forces, can exist. These forces result from the relative displacements between the gears as they vibrate in response to an excitation known as “transmission error.” Ideally, a gearset would have a uniform velocity ratio between the input and output rotation. Transmission error is defined as the departure from uniform relative angular motion of the pair of meshing gears. It is influenced by all the deviations from the ideal gear tooth form.

The dynamic factor relates the total tooth load, including internal dynamic effects, to the transmitted tangential tooth load:

$$C_v = K_v = \frac{W_t}{W_d \times W_t} \quad (20)$$

where  $W_d$  = incremental dynamic tooth load due to the dynamic response of the gear pair to the transmission error excitation, excluding the transmitted tangential load  $W_t$ .

**Excitation:** The transmission error contributing to the dynamic factors is influenced by:

- 1) Manufacturing variations such as spacing, profile, lead, and runout.
- 2) Gear mesh stiffness variation as the gear teeth pass through the meshing cycle. This source of excitation is especially pronounced in spur gears without profile modification. Spur gears with properly designed profile modification, and helical gears with axial contact ratios greater than 1.0, have a smaller stiffness variation.
- 3) Transmitted load. Since elastic deflections are load dependent, gear tooth profile modifications can be designed to give a uniform velocity ratio at only one load magnitude.
- 4) Pitchline velocity. The frequencies of the excitation depend on the pitchline velocity.
- 5) Dynamic imbalance of the gears and shafts.
- 6) Excessive wear and plastic deformation of the gear tooth profiles increase the amount of transmission error.
- 7) Shaft alignment. Gear tooth alignment is influenced by load and thermal distortions of the gears, shafts, bearings, and housings, and by manufacturing variations.
- 8) Tooth friction induced excitation.

**Dynamic Response:** The dynamic tooth forces are influenced by:

- 1) Mass of the gears, shafts, and other major internal components.
- 2) Stiffness of the gear teeth, gear blanks, shafts, bearings, and gear housings.
- 3) Damping. The principal source of coulomb or viscous damping is the shaft bearings. Generally, oil film bearings provide greater damping than rolling element bearings. Other sources of damping include the hysteresis of the gear shafts, and viscous damping at sliding interfaces and shaft couplings.

*Resonance:* When an excitation frequency coincides with a natural frequency, the resonant response is limited only by the damping, and high dynamic loads may result. The dynamic factors  $C_v$  and  $K_d$  do not apply to resonance.

*Gear Pair Resonance:* If a particular frequency of the transmission error excitation is close to the natural frequency of the gear masses, or some multiple of the natural frequency such as  $\frac{1}{2}$  or 2, a resonant vibration may cause high dynamic tooth forces due to large relative displacements of the gear masses. The dynamic factors  $C_v$  and  $K_d$  do not account for gear pair resonance and operation in this regime is to be avoided.

*Gear Blank Resonance:* Gear blanks may have natural frequencies within the operating speed range. If the gear blank is excited by a frequency that is close to one of its natural frequencies, the resonant deflections may cause high dynamic tooth loads. This phenomenon occurs more frequently in high speed, light weight gear blanks, but can also occur in other thin rimmed or thinwebbed blanks. The dynamic factors  $C_v$  and  $K_d$  do not account for gear blank resonance. A separate investigation is recommended when these conditions arise.

*System Resonance:* The gearbox is one component of a system comprised of a power source, gearbox, driven equipment, and interconnecting shafts and couplings. The dynamic response of this system depends on the distribution of the masses, stiffness, and damping. In certain designs, a system may possess a torsional natural frequency close to an excitation frequency associated with an operating speed. Under these resonant conditions the dynamic tooth loads may be high, and operation near such a system resonance is to be avoided. The dynamic factors  $C_v$  and  $K_d$  do not include considerations of the dynamic loads due to torsional vibration of the gear system. These loads must be included with other externally applied forces in the application factors  $C_a$  and  $K_a$ . For critical drives, a separate dynamic analysis of the entire system is recommended.

*Shaft Critical Speeds:* Owing to their high bending stiffness, the natural frequency of lateral vibrations of the gear shafts are usually much higher than the operating speeds. However, for high speed gears it is recommended that the critical speeds be analyzed to ensure that they are well removed from the operating speed range. The dynamic factors  $C_v$  and  $K_d$  do not account for the dynamic tooth loads due to this mode of vibration.

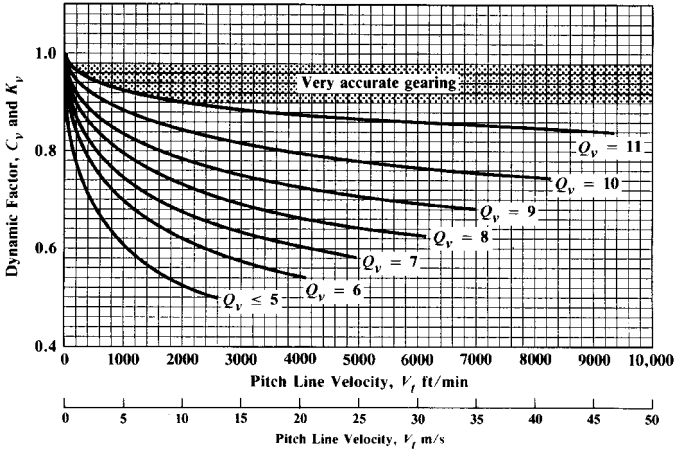
*Nonlinear Resonance:* Large cyclical variation in gear mesh stiffness and impact loads may lead to additional regions of resonance and instability. This problem appears primarily with lightly loaded, lightly damped spur gears that do not have profile modifications.

*Approximate Dynamic Factors:* Fig. 3 shows dynamic factors that can be used in the absence of specific knowledge of the dynamic loads. The curves of Fig. 3 are based on equations in the Standard derived from empirical data and do not account for resonance.

Choice of which of curves 5 through 11 of Fig. 3 to use should be based on transmission error. When transmission error data are unavailable, it is reasonable to use pitch (spacing) and profile accuracy.  $Q_v$  is the transmission accuracy level number. It can be the same as the quality number for the lowest quality member in the mesh from AGMA 2000–A88 when manufacturing techniques ensure equivalent transmission accuracy, or when the pitch (spacing) and profile accuracy are the same as AGMA 2000–A88 tolerances.

Owing to the approximate nature of the empirical curves and the lack of measured tolerance values at the design stage, the dynamic factor curve should be selected based on experience with the manufacturing methods and operating considerations of the design.

The curves in Fig. 3 are referenced only by spacing and profile, and actual dynamic load is influenced by many other factors, so slight variations from the selected tolerances are not considered significant to the gearset rating.

Fig. 3. Dynamic Factors,  $C_v$  and  $K_d$ 

**Very Accurate Gearing:** Where gearing is manufactured using process controls that correspond to  $Q_v \geq 12$  limits, or where the design and manufacturing techniques ensure a low transmission error equivalent to this accuracy, values of  $C_v$  and  $K_d$  between 0.90 and 0.98 may be used, depending on the specifier's experience with similar applications and the degree of accuracy actually achieved. To use these values, the gearing must be maintained in accurate alignment and adequately lubricated so that its accuracy is maintained under the operating conditions. Spur gears should have properly designed profile modification and helical gears should have an axial contact ratio greater than 1.0.

**Curves Numbered 6 through 11 on Fig. 3:** These curves are generated by equations in the Standard for values of  $Q_v$ , such that  $6 \leq Q_v \leq 11$ .

**Unity Dynamic Factor:** When the known dynamic loads (from analysis or experience) are added to the nominal transmitted load, then the dynamic factor can be taken to be 1.0.

**Application Factors,  $C_a$  and  $K_a$ .**—These application factors make allowance for any externally applied loads in excess of the nominal tangential load  $W_t$ . Application factors can only be established after considerable field experience is gained in a particular application.

In determining the application factor, consideration should be given to the fact that many prime movers develop momentary peak torques appreciably greater than those determined by the nominal ratings of either the prime mover or the driven equipment. Many possible sources of overload should be considered. Some of these are system vibrations, acceleration torques, overspeeds, variations in system operation, split path load sharing among multiple prime movers, and changes in process load conditions. When operating near a critical speed of the drive system, a careful analysis of conditions must be made.

**Service Factors,  $C_{SF}$  and  $K_{SF}$ .**—These service factors have been used to include the combined effects of  $C_L$ ,  $C_R$ ,  $C_a$  and  $K_L$ ,  $K_R$ ,  $K_a$ , respectively, in an empirically determined single factor. The mathematical contribution of each of these factors has not been established, so that, in the absence of more specific load data, a service factor may be used. When a ser-

vice factor is used, the power rating formulas [Equation (5) and (5a)] would be modified as follows:

$$P_{ac} = \frac{n_p \times F}{126000 C_{sf} \times C_s \times C_m \times C_f} \frac{I \times C_v}{C_p} \left( \frac{d \times s_{ac} C_H}{C_T} \right) \quad (21)$$

$$P_{ac} = \frac{n_p \times F}{1.91 \times 10^7 C_{sf} \times C_s \times C_m \times C_f} \frac{I \times C_v}{C_p} \left( \frac{d \times s_{ac} C_H}{C_T} \right) \quad (21a)$$

$$P_{at} = \frac{n_p \times d \times K_v}{126000 \times K_{SF} P_d K_s \times K_m \times K_B K_T} \frac{F}{J} \frac{s_{at}}{K_T} \quad (22)$$

$$P_{at} = \frac{n_p \times d \times K_v}{1.91 \times 10^7 \times K_{SF} K_s \times K_m \times K_B K_T} \frac{F \times m \times J}{s_{at}} \quad (22a)$$

where  $C_{SF}$  and  $K_{SF}$  are service factors for pitting resistance and bending strength, respectively.

Teeth of both the pinion and the gear must be checked to account for differences in material properties, geometry factors, and the number of cycles under load. The power rating is then based on the lowest values of the following expressions for each of the mating gears:

$$\text{for pitting resistance } \frac{(s_{ac} \times C_H)^2}{C_{SF}}, \text{ and for bending strength } \frac{s_{at} \times J}{K_{SF}}.$$

**Elastic Coefficient,  $C_p$ .**—The elastic coefficient,  $C_p$ , is defined by the equation

$$C_p = \sqrt{\frac{1.0}{\pi \left[ \left( \frac{1.0 - \mu_P^2}{E_P} \right) \div \left( \frac{1.0 - \mu_G^2}{E_G} \right) \right]}} \quad (23)$$

The value of  $C_p$  for a steel gear meshing with a steel pinion is 2300 [lb/in.<sup>2</sup>]<sup>0.5</sup>, or 191 (MPa)<sup>0.5</sup>, approximately. Approximate values for other combinations of materials are given in the Standard.

**Surface Condition Factor,  $C_f$ .**—The surface finish factor used only in the pitting resistance formulas has not yet been established for conditions where there is a detrimental surface finish effect. Where such effects are encountered, a surface condition factor greater than unity should be used.

**Size Factors,  $C_s$  and  $K_s$ .**—The size factor reflects nonuniformity of material properties and depends primarily on tooth size, diameter of parts, ratio of tooth size to diameter of part, face width, area of stress pattern, ratio of case depth to tooth size, and hardenability and heat treatment of materials. Size factors have not yet been established for conditions where there is a detrimental size effect, but the factor may be taken as unity for most gears provided that a proper choice of steel is made for the size of the part and its heat treatment and hardening processes.

**Load Distribution Factors,  $C_m$  and  $K_m$ .**—The load distribution factor modifies the rating equations to reflect the nonuniform distribution of the load along the lines of contact. The amount of nonuniformity of the load distribution is caused by, and is dependent on the following influences:

- 1) The gear tooth manufacturing accuracy: lead, profile, and spacing;
- 2) alignment of the axes of rotation of the pitch cylinders of the mating gear elements;

## 3000 POWER TRANSMITTING CAPACITY OF SPUR GEARS

- 3) elastic deflections of gear unit elements: shafts, bearings, housings, and foundations that support the gear elements;
- 4) bearing clearances;
- 5) Hertzian contact and bending deformations at the tooth surface;
- 6) thermal expansion and distortion due to operating temperature (especially on wide face gearing);
- 7) centrifugal deflections due to operating speed;
- 8) tooth crowning and end relief.

Any of these influences that affect a given application should be evaluated by appropriate analysis when possible.

*Values for  $C_m$  and  $K_m$ :* The load distribution factor is defined to be the peak load intensity divided by the average, or uniformly distributed load intensity; i.e., the ratio of peak to mean loading. The magnitude is influenced by two components, namely,  $C_{mf}$  = face load distribution factor and  $C_{mt}$  = transverse load distribution factor that accounts for nonuniform load sharing among load sharing teeth. The load distribution factor is affected primarily by the correctness of the profiles of mating teeth, i.e., profile modification and profile error. The value of the factor may be taken as 1.0 because the Standard has not yet established procedures to evaluate its influence. If  $C_{mt}$  is taken as 1.0, then  $C_m = K_m = C_{mf}$ .

The face load distribution factor  $C_{mf}$  accounts for the nonuniform distribution of load across the gearing face width. The magnitude of  $C_{mf}$  is defined as the peak load intensity divided by the average load intensity across the face width. Two methods of determining  $C_{mf}$  are given in the Standard, an empirical method and an analytical method. These two methods sometimes yield significantly different results.

*Empirical Method:* The empirical method requires a minimum amount of information and is recommended for relatively stiff designs that meet the following requirements:

- 1) Ratio of net face width to pinion pitch diameter is less than or equal to 2.0;
- 2) the gear elements are mounted between bearings (not overhung);
- 3) face width up to 40 in.; and
- 4) contact across full face width of narrowest member when loaded.

Other restrictions apply to the use of this method. For details of these restrictions and how the method is applied, the Standard should be consulted.

*Analytical Method:* This method is based on theoretical calculation of values of elastic tooth deformation under load and lead mismatch. Knowledge of the design, manufacturing, and mounting are required to evaluate the load distribution factor. Calculated results should be compared with past experience as it may be necessary to reevaluate other rating factors to arrive at a rating consistent with past experience. As explained in the Standard, the analytical method assumes that mismatch between the teeth is a straight line. This approach usually yields load distribution factors larger than those used in the past. Another method, using true deflection between the teeth (which is not straight line deflection), has resulted in calculated values closer to those used in the past, but it has not been demonstrated that either method is more accurate. Further study may produce other, more accurate, methods.

In using the analytical method, if high values of the gear tooth stiffness constant are used ( $G = 2,000,000$ ) or high values of total lead mismatch  $e_t$  are assumed, the  $C_{mf}$  values calculated will be much more conservative than those obtained by the empirical method. If  $C_{mf}$  values calculated are in excess of 2.0, indicating less than full face contact, it may be desirable to revise the design by improving the configuration of bearings, shaft diameters, aspect ratio, and center distance to lower  $C_{mf}$ . It may be possible to lower  $C_{mf}$  by modifying leads of the parts. The assumed values of  $e_t$  and  $G$  have a large effect on  $C_{mf}$ , so there are times when experimental verification of  $C_{mf}$  may be necessary.

The analytical method is valid for any gear design and is recommended for the following conditions:

1) ratio of net face width to pinion pitch diameter,  $F/D$ , is equal or greater than 2.0 (for double helical gears the gap is not included in the face width); 2) applications with overhanging gear elements; 3) applications with long shafts subject to large deflections or where deflections under load reduce width of contact; and 4) applications where contact does not extend across the full face of narrowest member when loaded.

For designs that have high crowns to centralize tooth contact under deflected conditions, the factors  $C_m$  and  $K_m$  may be conservatively approximated by this method. For the most commonly encountered condition, contact across the entire face width under normal operating load, the face load distribution factor expressions are

$$\text{for spur gearing: } C_{mf} = 1.0 + \frac{G \times e_t \times F}{2 \times W_t} \quad (24)$$

$$\text{and, for helical gearing: } C_{mf} = 1.0 + \frac{G \times e_t \times Z \times F}{1.8 \times W_t} \quad (25)$$

If the total contact length under normal operating load is less than the face width, the expressions for the load distribution factor are

$$\text{for spur gearing: } C_{mf} = \sqrt{\frac{2.0 \times G \times e_t \times F}{W_t}} \quad (26)$$

$$\text{and, for helical gearing: } C_{mf} = \sqrt{\frac{2.0 \times G \times e_t \times Z \times F}{W_t \times P_b}} \quad (27)$$

where  $G$  = tooth stiffness constant, lb/in./in. of face (MPa), the average mesh stiffness of a single pair of teeth in the normal direction. The usual range of this value that is compatible with this analysis is  $1.5\text{--}2.0 \times 10^6$  lb/in.<sup>2</sup> ( $1.0\text{--}1.4 \times 10^4$  MPa). The most conservative value is the highest.  $e_t$  = total lead mismatch between mating teeth, in loaded condition, in. (mm).  $Z$  = length of action in transverse plane, from Equation (17) on page 2995, in. (mm).  $P_b$  = transverse base pitch, in. (mm).

The total mismatch,  $e_p$ , is a virtual separation between the tooth profiles at the end of the face width which is composed of the static, no load separation plus a component due to the elastic load deformations. This total mismatch is influenced by all the items listed under Load Distribution Factors except the Hertzian contact stress and bending deformations of the gear teeth, which are accounted for by the tooth stiffness constant  $G$ . Evaluation of  $e_p$  is difficult but it is critical to the reliability of the analytical method. An iterative computer program may be used, but in critical applications full scale testing may be desirable.

**Allowable Stress Numbers,  $S_{ac}$  and  $S_{at}$ .**—The allowable stress numbers depend on

1) material composition and cleanliness; 2) mechanical properties; 3) residual stress; 4) hardness and; and 5) type of heat treatment, surface or through hardened.

An allowable stress number for unity application factor, 10 million cycles of load application, 99 per cent reliability and unidirectional loading, is determined or estimated from laboratory and field experience for each material and condition of that material. This stress number is designated  $S_{ac}$  and  $S_{at}$ . The allowable stress numbers are adjusted for design life cycles by the use of life factors.

The allowable stress numbers for gear materials vary with material composition, cleanliness, quality, heat treatment, and processing practices. For materials other than steel, a range is shown, and the lower values should be used for general design purposes. Data for materials other than steel are given in the Standard.

Allowable stress numbers for steel gears are established by specific quality control requirements for each material type and grade. All requirements for the quality grade must be met in order to use the stress values for that grade. Details of these quality requirements are given in the Standard.

*Reverse Loading:* For idler gears and other gears where the teeth are completely reverse loaded on every cycle, 70 per cent of the  $S_{at}$  values should be used.

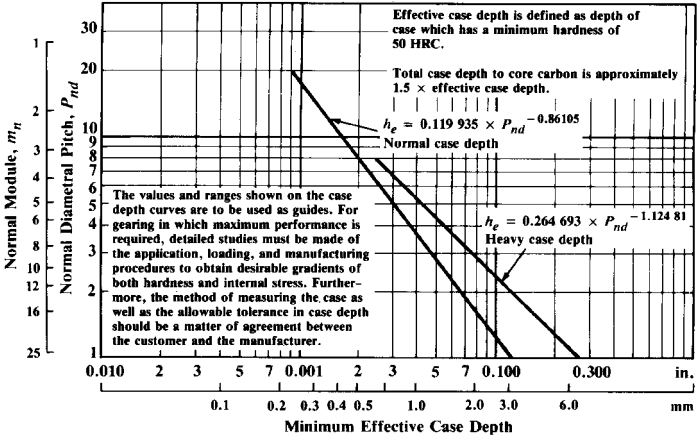


Fig. 4. Effective Case Depth for Carburized Gears,  $h_e$

**Case Depth of Surface-Hardened Gears.**—The Standard provides formulas to guide the selection of minimum effective case depth at the pitchline for carburized and induction hardened teeth based on the maximum shear from contact loading.

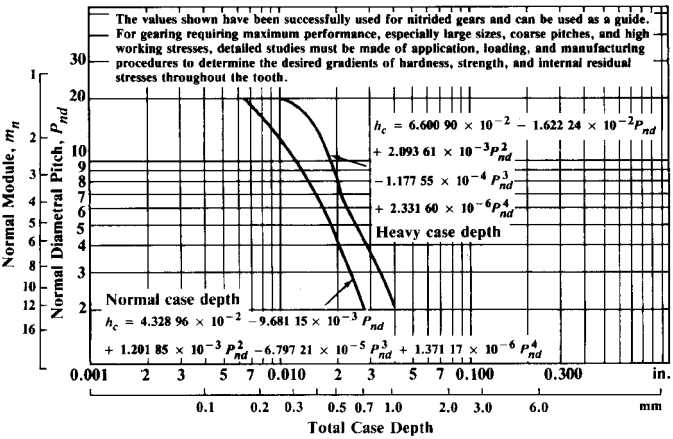


Fig. 5. Minimum Total Case Depth for Nitrided Gears,  $h_c$

Fig. 5 shows values that have a long history of successful use for carburized gears and can be used for such gears.

For nitrided gears, case depth is specified as the total case depth  $h_c$ , which is defined as the depth below the surface at which the hardness has dropped to 10 per cent of the core hardness. Minimum total case depths for nitrided gears are shown in Fig. 5.

**Momentary Overloads.**—When the gear is subjected to less than 100 cycles of momentary overloads, the maximum allowable stress is determined by the allowable yield properties rather than the bending fatigue strength of the material. Fig. 6 shows suggested values of the allowable yield strength  $S_{ay}$  for through hardened steel. For case hardened gears, the core hardness should be used in conjunction with the table of metallurgical factors affecting the bending stress number for carburized gears shown in the Standard.

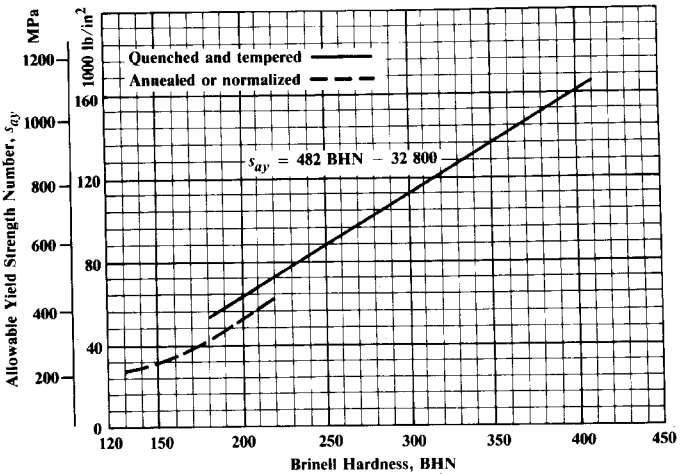


Fig. 6. Allowable Yield Strength Number for Steel Gears,  $S_{ay}$

The design should be checked to make sure that the teeth are not permanently deformed. Also, when yield is the governing stress, the stress correction factor  $K_f$  is considered ineffective and therefore taken as unity.

**Yield Strength.**—For through hardened gears up to 400 BHN, a yield strength factor  $K_y$  can be applied to the allowable yield strength taken from Fig. 6. This factor is applied at the maximum peak load to which the gear is subjected:

$$S_{ay} \times K_y \geq \frac{W_{max} \times K_a P_d K_s \times K_m}{K_v F J \times K_f} \quad (28)$$

$$S_{ay} \times K_y \geq \frac{W_{max} \times K_a \times K_s \times K_m}{K_v \times F \times m \times J \times K_f} \quad (28a)$$

For conservative practice,  $K_y$  is taken as 0.5 and for industrial practice,  $K_y$  is 0.75.

**Hardness Ratio Factor  $C_H$ .**—The hardness ratio factor depends on (1) gear ratio and (2) Brinell hardness numbers of gear and pinion. When the pinion is substantially harder than the gear, the work hardening effect increases the gear capacity. Typical values of the hard-



ness ratio factor,  $C_H$ , for through hardened gears are shown in Fig. 7. These values apply to the gear only, not to the pinion.

When surface hardened pinions (48 HRC or harder) are run with through hardened gears (180–400 BHN), a work hardening effect is achieved. The  $C_H$  factor varies with the surface finish of the pinion,  $K_p$ , and the mating gear hardness as shown in Fig. 8.

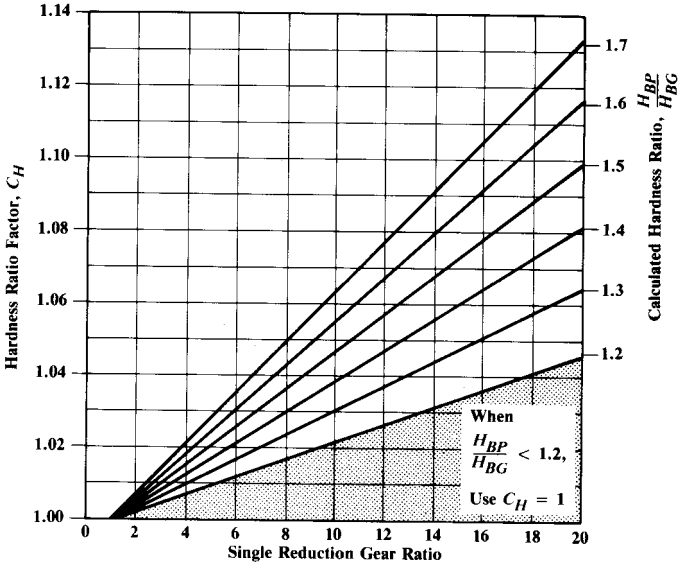


Fig. 7. Hardness Ratio Factor,  $C_H$  (Through Hardened)

**Life Factors  $C_L$  and  $K_L$ .**— These life factors adjust the allowable stress numbers for the required number of cycles of operation. In the Standard, the number of cycles,  $N$ , is defined as the number of mesh contacts under load of the gear tooth being analyzed. Allowable stress numbers are established for 10,000,000 tooth load cycles at 99 per cent reliability. The life cycle factors adjust the allowable stress numbers for design lives other than 10,000,000 cycles.

The life factor accounts for the  $S/N$  characteristics of the gear material as well as for the gradually increased tooth stress that may occur from tooth wear, resulting in increased dynamic effects and from shifting load distributions that may occur during the design life of the gearing. A  $C_L$  or  $K_L$  value of 1.0 may be used beyond 10,000,000 cycles, where justified by experience.

*Life Factors for Steel Gears:* Insufficient data exist to provide accurate life curves for every gear and gear application. However, experience suggests life curves for pitting and strength of steel gears are as shown in Figs. 9 and 10. These figures do not include data for nitrided gears. The upper portions of the shaded zones are for general commercial applications. The lower portions of the shaded zones are typically used for critical service applications where little pitting and tooth wear are permissible and where smoothness of operation and low vibration levels are required. When gear service ratings are established by the use

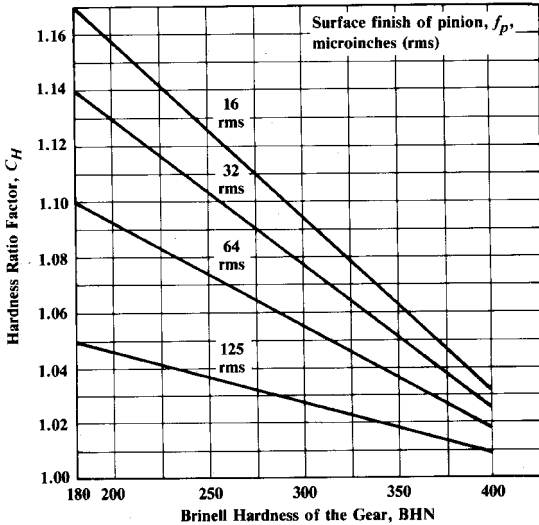


Fig. 8. Hardness Ratio Factor,  $C_H$  (Surface Hardened Pinions)

of service factors, life factors  $C_L$  and  $K_L$  should be set equal to 1.0 for the determination of the gear tooth rating.

**Localized Yielding.**—If the product of  $S_{at} K_L$  exceeds the allowable yield stress  $S_{ay}$  of Fig. 6, localized yielding of the teeth may occur. In some applications this yielding is not acceptable. In others, where profile and motion transmission accuracies are not critical, the yielding may be acceptable for limited life.

**Reliability Factors,  $C_R$  and  $K_R$ .**—These reliability factors account for the effect of the normal statistical distribution of failures found in materials testing. The allowable stress numbers given in the tables in the Standard are based on a statistical probability of 1 failure in 100 at 10,000,000 cycles. Table 2 contains reliability factors which may be used to modify these allowable stresses to change that probability. These numbers are based on data developed for bending and pitting failure by the U.S. Navy. Other values may be used if specific data are available.

When strength rating is based on yield strength,  $S_{ay}$  the values of  $K_y$  given in the paragraph, Yield Strength, should be used instead of  $K_R$ .

**Temperature Factors  $C_T$  and  $K_T$ .**—The temperature factor is generally taken as 1 when gears operate with temperatures of oil or gear blank not over 250°F (120°C). At temperatures above 250°F, the factors are given a value greater than 1.0 to allow for the effect of temperature on oil film and material properties. Consideration must be given to the loss of hardness and strength of some materials due to the tempering effect of temperatures over 350°F (175°C).

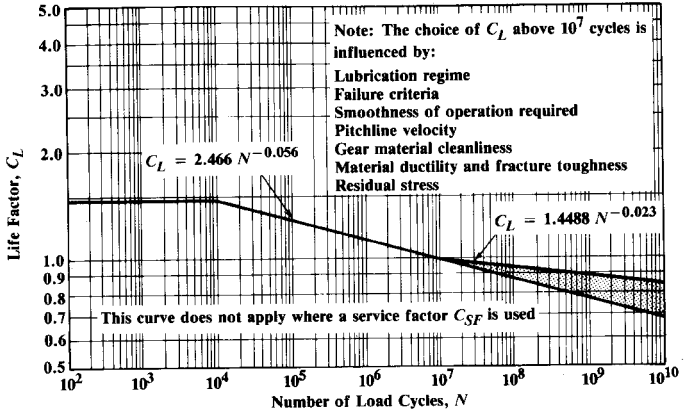


Fig. 9. Pitting Resistance Life Factor,  $C_L$

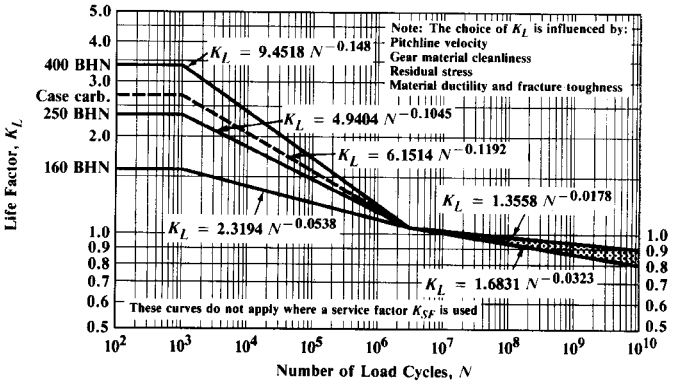


Fig. 10. Bending Strength Life Factor,  $K_L$

Table 2. Reliability Factors,  $C_R$  and  $K_R$

| Requirement of Application     | $C_R, K_R^a$ | Requirement of Application  | $C_R, K_R$        |
|--------------------------------|--------------|-----------------------------|-------------------|
| Fewer than 1 failure in 10,000 | 1.50         | Fewer than 1 failure in 100 | 1.00              |
| Fewer than 1 failure in 1,000  | 1.25         | Fewer than 1 failure in 10  | 0.85 <sup>b</sup> |

<sup>a</sup>Tooth breakage is sometimes considered a greater hazard than pitting. In such instances a value of  $K_R$  greater than  $C_R$  is selected.

<sup>b</sup>At this value plastic flow might occur rather than pitting.

### Worm Gearing

**Worm Gearing Classification.**—Worm gearing may be divided into two general classes, fine-pitch worm gearing, and coarse-pitch worm gearing. Fine-pitch worm gearing is segregated from coarse-pitch worm gearing for the following reasons:

- 1) Fine-pitch worms and wormgears are used largely to transmit motion rather than power. Tooth strength except at the coarser end of the fine-pitch range is seldom an important factor; durability and accuracy, as they affect the transmission of uniform angular motion, are of greater importance.
- 2) Housing constructions and lubricating methods are, in general, quite different for fine-pitch worm gearing.
- 3) Because fine-pitch worms and wormgears are so small, profile deviations and tooth bearings cannot be measured with the same accuracy as can those of coarse pitches.
- 4) Equipment generally available for cutting fine-pitch wormgears has restrictions which limit the diameter, the lead range, the degree of accuracy attainable, and the kind of tooth bearing obtainable.
- 5) Special consideration must be given to top lands in fine-pitch hardened worms and wormgear-cutting tools.
- 6) Interchangeability and high production are important factors in fine-pitch worm gearing; individual matching of the worm to the gear, as often practiced with coarse-pitch precision worms, is impractical in the case of fine-pitch worm drives.

**American Standard Design for Fine-pitch Worm Gearing (ANSI B6.9-1977).**—This standard is intended as a design procedure for fine-pitch worms and wormgears having axes at right angles. It covers cylindrical worms with helical threads, and wormgears hobbled for fully conjugate tooth surfaces. It does not cover helical gears used as wormgears.

*Hobs:* The hob for producing the gear is a duplicate of the mating worm with regard to tooth profile, number of threads, and lead. The hob differs from the worm principally in that the outside diameter of the hob is larger to allow for resharpening and to provide bottom clearance in the wormgear.

*Pitches:* Eight standard axial pitches have been established to provide adequate coverage of the pitch range normally required: 0.030, 0.040, 0.050, 0.065, 0.080, 0.100, 0.130, and 0.160 inch.

Axial pitch is used as a basis for this design standard because: 1) Axial pitch establishes lead which is a basic dimension in the production and inspection of worms; 2) the axial pitch of the worm is equal to the circular pitch of the gear in the central plane; and 3) only one set of change gears or one master lead cam is required for a given lead, regardless of lead angle, on commonly-used worm-producing equipment.

*Lead Angles:* Fifteen standard lead angles have been established to provide adequate coverage: 0.5, 1, 1.5, 2, 3, 4, 5, 7, 9, 11, 14, 17, 21, 25, and 30 degrees.

This series of lead angles has been standardized to: 1) Minimize tooling; 2) permit obtaining geometric similarity between worms of different axial pitch by keeping the same lead angle; and 3) take into account the production distribution found in fine-pitch worm gearing applications.

For example, most fine-pitch worms have either one or two threads. This requires smaller increments at the low end of the lead angle series. For the less frequently used thread numbers, proportionately greater increments at the high end of the lead angle series are sufficient.

**Table 1. Formulas for Proportions of American Standard Fine-pitch Worms and Wormgears ANSI B6.9-1977**

|   |  |
|---|--|
| <p style="text-align: center;">LETTER SYMBOLS</p> <p><math>P</math> = Circular pitch of wormgear<br/> <math>P</math> = axial pitch of the worm, <math>P_x</math>, in the central plane<br/> <math>P_x</math> = Axial pitch of worm<br/> <math>P_n</math> = Normal circular pitch of worm and wormgear = <math>P_x</math><br/> <math>\cos \lambda = P \cos \psi</math><br/> <math>\lambda</math> = Lead angle of worm<br/> <math>\psi</math> = Helix angle of wormgear<br/> <math>n</math> = Number of threads in worm<br/> <math>N</math> = Number of teeth in wormgear<br/> <math>N = nm_G</math><br/> <math>m_G</math> = Ratio of gearing = <math>N \div n</math></p> |  |
|---|--|

| Item   | Formula                         | Item   | Formula  |
|--|---------------------------------|--|--|
| WORM DIMENSIONS  |                                 | WORMGEAR DIMENSIONS <sup>a</sup>               |  |
| Lead   | $l = nP_x$                      | Pitch Diameter                                 | $D = NP \div \pi = NP_x \div \pi$                            |
| Pitch Diameter   | $d = l \div (\pi \tan \lambda)$ | Outside Diameter                               | $D_o = 2C - d + 2a$  |
| Outside Diameter   | $d_o = d + 2a$                  | Face Width                                     | $F_{Gmin} = 1.125 \times \sqrt{(d_o + 2c)^2 - (d_o - 4a)^2}$ |
| Safe Minimum Length of Threaded Portion of Worm <sup>b</sup> | $F_W = \sqrt{D_o^2 - D^2}$      |  |  |
| DIMENSIONS FOR BOTH WORM AND WORMGEAR                        |                                 |  |  |
| Addendum   | $a = 0.3183P_n$                 | Tooth thickness                                | $t_n = 0.5P_n$   |
| Whole Depth  | $h_t = 0.7003P_n + 0.002$       | Approximate normal pressure angle <sup>c</sup> | $\phi_n = 20$ degrees  |
| Working Depth  | $h_k = 0.6366P_n$               |  |  |
| Clearance  | $c = h_t - h_k$                 | Center distance                                | $C = 0.5(d + D)$   |

<sup>a</sup> Current practice for fine-pitch worm gearing does not require the use of throated blanks. This results in the much simpler blank shown in the diagram which is quite similar to that for a spur or helical gear. The slight loss in contact resulting from the use of non-throated blanks has little effect on the load-carrying capacity of fine-pitch worm gears. It is sometimes desirable to use topping hobs for producing wormgears in which the size relation between the outside and pitch diameters must be closely controlled. In such cases the blank is made slightly larger than  $D_o$  by an amount (usually from 0.010 to 0.020) depending on the pitch. Topped wormgears will appear to have a small throat which is the result of the hobbing operation. For all intents and purposes, the throating is negligible and a blank so made is not to be considered as being a throated blank.

<sup>b</sup> This formula allows a sufficient length for fine-pitch worms.

<sup>c</sup> As stated in the text on page 3008, the actual pressure angle will be slightly greater due to the manufacturing process.

All dimensions in inches unless otherwise indicated.

**Pressure Angle of Worm:** A pressure angle of 20 degrees has been selected as standard for cutters and grinding wheels used to produce worms within the scope of this Standard because it avoids objectionable undercutting regardless of lead angle.

Although the pressure angle of the cutter or grinding wheel used to produce the worm is 20 degrees, the normal pressure angle produced in the worm will actually be slightly greater, and will vary with the worm diameter, lead angle, and diameter of cutter or grinding wheel. A method for calculating the pressure angle change is given under the heading *Effect of Production Method on Worm Profile and Pressure Angle*.

**Pitch Diameter Range of Worms:** The minimum recommended worm pitch diameter is 0.250 inch and the maximum is 2.000 inches. Pitch diameters for all possible combinations of lead and lead angle, together with the number of threads for each lead, are given in [Table 2a](#) and [2b](#).

**Tooth Form of Worm and Wormgear:** The shape of the worm thread in the normal plane is defined as that which is produced by a symmetrical double-conical cutter or grinding wheel having straight elements and an included angle of 40 degrees.

Because worms and wormgears are closely related to their method of manufacture, it is impossible to specify clearly the tooth form of the wormgear without referring to the mating worm. For this reason, worm specifications should include the method of manufacture and the diameter of cutter or grinding wheel used. Similarly, for determining the shape of the generating tool, information about the method of producing the worm threads must be given to the manufacturer if the tools are to be designed correctly.

The worm profile will be a curve that departs from a straight line by varying amounts, depending on the worm diameter, lead angle, and the cutter or grinding wheel diameter. A method for calculating this deviation is given in the Standard. The tooth form of the wormgear is understood to be made fully conjugate to the mating worm thread.

**Proportions of Fine-pitch Worms and Wormgears.**—Hardened worms and cutting tools for wormgears should have adequate top lands. To automatically provide sufficient top lands, regardless of lead angle or axial pitch, the addendum and whole depth proportions of fine-pitch worm gearing are based on the normal circular pitch. Tooth proportions based on normal pitch for all combinations of standard axial pitches and lead angles are given in [Table 3](#). Formulas for the proportions of worms and worm gears are given in [Table 1](#).

**Example 1:** Determine the design of a worm and wormgear for a center distance of approximately 3 inches if the ratio is to be 10 to 1; axial pitch, 0.1600 inch; and lead angle, 30 degrees.

From [Table 2a](#) and [2b](#) it can be determined that there are eight possible worm diameters that will satisfy the given conditions of lead angle and pitch. These worms have from 3 to 10 threads.

To satisfy the 3-inch center distance requirement it is now necessary to determine which of these eight worms, together with its mating wormgear, will come closest to making up this center distance. One way of doing this is as follows:

First use the formula given below to obtain the approximate number of threads necessary. Then from the eight possible worms in [Table 2a](#) and [2b](#), choose the one whose number of threads is nearest this approximate value:

Approximate number of threads needed for required center distance =

$$\frac{2\pi \times \text{required center distance}}{P_x (\cot \lambda + m_G)}$$

Approximate number of threads =

$$\frac{2 \times 3.1416 \times 3}{0.1600 \times (1.7320 + 10)} = 10.04 \text{ threads}$$

Of the eight possible worms in [Table 2a](#) and [2b](#), the one having a number of threads nearest this value is the 10-thread worm with a pitch diameter of 0.8821 inch. Since the ratio of gearing is given as 10,  $N$  may now be computed as follows:  $N = 10 \times 10 = 100$  teeth (from [Table 1](#))

Other worm and wormgear dimensions may now be calculated using the formulas given in [Table](#) or may be taken from the data presented in [Table 2a](#), [2b](#), and [3](#).

$l = 1.600$  inches (from [Table 2b](#))

$$d = 0.8821 \text{ inch (from Table 2b)}$$

$$D = 100 \times 0.1600 + 3.1416 = 5.0930 \text{ inches (from Table 1)}$$

$$C = 0.5(0.8821 + 5.0930) = 2.9876 \text{ inches (from Table 1)}$$

$$P_n = 0.1386 \text{ inch (from Table 3)}$$

$$a = 0.0441 \text{ inch (from Table 3)}$$

$$h_t = 0.0990 \text{ inch (from Table 3)}$$

$$h_k = 0.6366 \times 0.1386 = 0.0882 \text{ inch (from Table 1)}$$

$$c = 0.0990 - 0.0882 = 0.0108 \text{ inch (from Table 1)}$$

$$t_n = 0.5 \times 0.1386 = 0.0693 \text{ inch (from Table 1)}$$

$$d_o = 0.8821 + (2 \times 0.0441) = 0.9703 \text{ inch (from Table 1)}$$

$$D_o = (2 \times 2.9876) - 0.8821 + (2 \times 0.0441) = 5.1813 \text{ (from Table 1)}$$

$$F_G = 1.125 \sqrt{(0.9703 + 2 \times 0.0108)^2 - (0.9703 - 4 \times 0.0441)^2} = 0.6689 \text{ inch}$$

$$F_W = \sqrt{5.1813^2 - 5.0930^2} = 0.9525 \text{ inch}$$

*Example 2:* Determine the design of a worm and wormgear for a center distance of approximately 0.550 inch if the ratio is to be 50 to 1 and the axial pitch is to be 0.050 inch.

Assume that  $n = 1$  (since most fine-pitch worms have either one or two threads). The lead of the worm will then be  $nP_x = 1 \times 0.050 = 0.050$  inch. From Table 2a and 2b it can be determined that there are six possible lead angles and corresponding worm diameters that will satisfy this lead. The approximate lead angle required to meet the conditions of the example can be computed from the following formula:

$$\text{Cotangent of approx. lead angle} = \frac{2\pi \times \text{approximate center distance required}}{\text{assumed number of threads} \times \text{axial pitch}} - m_G$$

Using letter symbols, this formula becomes:

Of the six possible worms in Table 2a and 2b, the one with the 3-degree lead angle is closest to the calculated  $2^\circ 59'$  lead angle. This worm, which has a pitch diameter of 0.3037 inch, is therefore selected.

The remaining worm and wormgear dimensions may now be determined from the data in Table 2a, 2b and 3 and by computation using the formulas given in Table 1.

$$N = 50 \times 1 = 50 \text{ teeth (from Table 1)}$$

$$d = 0.3037 \text{ inch (from Table 2b)}$$

$$D = 50 \times 0.050 \div 3.1416 = 0.7958 \text{ inch (from Table 1)}$$

$$C = 0.5(0.3037 + 0.7958) = 0.5498 \text{ inch (from Table 1)}$$

$$P_n = 0.0499 \text{ inch (from Table 3)}$$

$$a = 0.0159 \text{ inch (from Table 3)}$$

$$h_t = 0.0370 \text{ inch (from Table 3)}$$

$$h_k = 0.6366 \times 0.0499 = 0.0318 \text{ inch (from Table 1)}$$

$$c = 0.0370 - 0.0318 = 0.0052 \text{ inch (from Table 1)}$$

$$t_n = 0.5 \times 0.0499 = 0.0250 \text{ inch (from Table 1)}$$

$$d_o = 0.3037 + (2 \times 0.0159) = 0.3355 \text{ inch (from Table 1)}$$

$$D_o = (2 \times 0.5498) - 0.3037 + (2 \times 0.0159) = 5.1813 \text{ (from Table 1)}$$

$$F_{Gmin} = 1.125 \sqrt{(0.3355 + 2 \times 0.0052)^2 - (0.3355 - 4 \times 0.0159)^2} = 0.2405 \text{ inch}$$

$$F_W = \sqrt{0.8277^2 - 0.7958^2} = 0.2276 \text{ inch}$$

**Table 2a. Pitch Diameters of Fine-pitch Worms for American Standard Combinations of Lead and Lead Angle (ANSI B6.9-1977)**

| Lead in Inches, <i>l</i> | Number of Threads <i>n</i> | Lead Angle in Degrees             |        |        |        |        |        |        |        |
|--------------------------|----------------------------|-----------------------------------|--------|--------|--------|--------|--------|--------|--------|
|                          |                            | 0.5                               | 1      | 1.5    | 2      | 3      | 4      | 5      | 7      |
|                          |                            | Pitch Diameter <i>d</i> in inches |        |        |        |        |        |        |        |
| 0.030                    | 1                          | 1.0942                            | 0.5471 | 0.3647 | 0.2735 | ...    | ...    | ...    | ...    |
| 0.040                    | 1                          | 1.4590                            | 0.7294 | 0.4862 | 0.3646 | 0.2429 | ...    | ...    | ...    |
| 0.050                    | 1                          | 1.8237                            | 0.9118 | 0.6078 | 0.4558 | 0.3037 | 0.2276 | ...    | ...    |
| 0.060                    | 2                          | 2.1885                            | 1.0942 | 0.7293 | 0.5469 | 0.3644 | 0.2731 | ...    | ...    |
| 0.065                    | 1                          | ...                               | 1.1853 | 0.7901 | 0.5925 | 0.3948 | 0.2959 | 0.2365 | ...    |
| 0.080                    | 1                          | ...                               | 1.4589 | 0.9725 | 0.7292 | 0.4859 | 0.3642 | 0.2911 | ...    |
| 0.090                    | 3                          | ...                               | 1.6412 | 1.0940 | 0.8204 | 0.5466 | 0.4097 | 0.3274 | 0.2333 |
| 0.100                    | 1                          | ...                               | 1.8236 | 1.2156 | 0.9115 | 0.6074 | 0.4552 | 0.3638 | 0.2592 |
| 0.120                    | 3                          | ...                               | 2.1883 | 1.4587 | 1.0938 | 0.7288 | 0.5462 | 0.4366 | 0.3111 |
| 0.130                    | 1                          | ...                               | ...    | 1.5802 | 1.1850 | 0.7896 | 0.5918 | 0.4730 | 0.3370 |
| 0.150                    | 3                          | ...                               | ...    | 1.8234 | 1.3673 | 0.9111 | 0.6828 | 0.5457 | 0.3889 |
| 0.160                    | 1                          | ...                               | ...    | 1.9449 | 1.4584 | 0.9718 | 0.7283 | 0.5821 | 0.4148 |
| 0.180                    | 6                          | ...                               | ...    | 2.1880 | 1.6407 | 1.0933 | 0.8194 | 0.6549 | 0.4666 |
| 0.195                    | 3                          | ...                               | ...    | ...    | 1.7775 | 1.1844 | 0.8876 | 0.7095 | 0.5055 |
| 0.200                    | 2                          | ...                               | ...    | ...    | 1.8230 | 1.2147 | 0.9104 | 0.7277 | 0.5185 |
| 0.210                    | 7                          | ...                               | ...    | ...    | 1.9142 | 1.2755 | 0.9559 | 0.7640 | 0.5444 |
| 0.240                    | 3                          | ...                               | ...    | ...    | 2.1876 | 1.4577 | 1.0925 | 0.8732 | 0.6222 |
| 0.250                    | 5                          | ...                               | ...    | ...    | ...    | 1.5184 | 1.1380 | 0.9096 | 0.6481 |
| 0.260                    | 2                          | ...                               | ...    | ...    | ...    | 1.5792 | 1.1835 | 0.9460 | 0.6740 |
| 0.270                    | 9                          | ...                               | ...    | ...    | ...    | 1.6399 | 1.2291 | 0.9823 | 0.7000 |
| 0.280                    | 7                          | ...                               | ...    | ...    | ...    | 1.7006 | 1.2746 | 1.0187 | 0.7259 |
| 0.300                    | 3                          | ...                               | ...    | ...    | ...    | 1.8221 | 1.3656 | 1.0915 | 0.7777 |
| 0.320                    | 2                          | ...                               | ...    | ...    | ...    | 1.9436 | 1.4567 | 1.1643 | 0.8296 |
| 0.325                    | 5                          | ...                               | ...    | ...    | ...    | 1.9740 | 1.4794 | 1.1824 | 0.8425 |
| 0.350                    | 7                          | ...                               | ...    | ...    | ...    | 2.1258 | 1.5932 | 1.2734 | 0.9073 |
| 0.360                    | 9                          | ...                               | ...    | ...    | ...    | ...    | 1.6387 | 1.3098 | 0.9333 |
| 0.390                    | 3                          | ...                               | ...    | ...    | ...    | ...    | 1.7753 | 1.4189 | 1.0110 |
| 0.400                    | 4                          | ...                               | ...    | ...    | ...    | ...    | 1.8208 | 1.4553 | 1.0370 |
| 0.450                    | 9                          | ...                               | ...    | ...    | ...    | ...    | 2.0484 | 1.6372 | 1.1666 |
| 0.455                    | 7                          | ...                               | ...    | ...    | ...    | ...    | ...    | 1.6554 | 1.1796 |
| 0.480                    | 3                          | ...                               | ...    | ...    | ...    | ...    | ...    | 1.7464 | 1.2444 |
| 0.500                    | 5                          | ...                               | ...    | ...    | ...    | ...    | ...    | 1.8191 | 1.2962 |
| 0.520                    | 4                          | ...                               | ...    | ...    | ...    | ...    | ...    | 1.8919 | 1.3481 |
| 0.560                    | 7                          | ...                               | ...    | ...    | ...    | ...    | ...    | 2.0374 | 1.4518 |
| 0.585                    | 9                          | ...                               | ...    | ...    | ...    | ...    | ...    | 2.1284 | 1.5166 |
| 0.600                    | 6                          | ...                               | ...    | ...    | ...    | ...    | ...    | 2.1830 | 1.5555 |
| 0.640                    | 4                          | ...                               | ...    | ...    | ...    | ...    | ...    | 2.3285 | 1.6592 |
| 0.650                    | 5                          | ...                               | ...    | ...    | ...    | ...    | ...    | ...    | 1.6851 |
| 0.700                    | 7                          | ...                               | ...    | ...    | ...    | ...    | ...    | ...    | 1.8147 |
| 0.720                    | 9                          | ...                               | ...    | ...    | ...    | ...    | ...    | ...    | 1.8665 |
| 0.780                    | 6                          | ...                               | ...    | ...    | ...    | ...    | ...    | ...    | 2.0221 |



**Table 2b. Pitch Diameters of Fine-pitch Worms for American Standard Combinations of Lead and Lead Angle ANSI B6.9-1977**

| Lead in Inches, $l$ | Number of Threads $n$ | Lead Angle in Degrees        |        |        |        |        |        |        |
|---------------------|-----------------------|------------------------------|--------|--------|--------|--------|--------|--------|
|                     |                       | 9                            | 11     | 14     | 17     | 21     | 25     | 30     |
|                     |                       | Pitch Diameter $d$ in inches |        |        |        |        |        |        |
| 0.120               | 3                     | 0.2412                       | ...    | ...    | ...    | ...    | ...    | ...    |
| 0.130               | 1                     | 0.2613                       | ...    | ...    | ...    | ...    | ...    | ...    |
| 0.150               | 3                     | 0.3015                       | 0.2456 | ...    | ...    | ...    | ...    | ...    |
| 0.160               | 1                     | 0.3216                       | 0.2620 | ...    | ...    | ...    | ...    | ...    |
| 0.180               | 6                     | 0.3618                       | 0.2948 | ...    | ...    | ...    | ...    | ...    |
| 0.195               | 3                     | 0.3919                       | 0.3193 | 0.2490 | ...    | ...    | ...    | ...    |
| 0.200               | 2                     | 0.4019                       | 0.3275 | 0.2553 | ...    | ...    | ...    | ...    |
| 0.210               | 7                     | 0.4220                       | 0.3439 | 0.2681 | 0.2186 | ...    | ...    | ...    |
| 0.240               | 3                     | 0.4823                       | 0.3930 | 0.3064 | 0.2499 | ...    | ...    | ...    |
| 0.250               | 5                     | 0.5024                       | 0.4094 | 0.3192 | 0.2603 | ...    | ...    | ...    |
| 0.260               | 2                     | 0.5225                       | 0.4258 | 0.3319 | 0.2707 | ...    | ...    | ...    |
| 0.270               | 9                     | 0.5426                       | 0.4421 | 0.3447 | 0.2811 | ...    | ...    | ...    |
| 0.280               | 7                     | 0.5627                       | 0.4585 | 0.3575 | 0.2915 | ...    | ...    | ...    |
| 0.300               | 3                     | 0.6029                       | 0.4913 | 0.3830 | 0.3123 | 0.2488 | ...    | ...    |
| 0.320               | 2                     | 0.6431                       | 0.5240 | 0.4085 | 0.3332 | 0.2654 | ...    | ...    |
| 0.325               | 5                     | 0.6532                       | 0.5322 | 0.4149 | 0.3384 | 0.2695 | ...    | ...    |
| 0.350               | 7                     | 0.7034                       | 0.5731 | 0.4468 | 0.3644 | 0.2902 | 0.2389 | ...    |
| 0.360               | 9                     | 0.7235                       | 0.5895 | 0.4596 | 0.3748 | 0.2985 | 0.2457 | ...    |
| 0.390               | 3                     | 0.7838                       | 0.6386 | 0.4979 | 0.4060 | 0.3234 | 0.2662 | ...    |
| 0.400               | 4                     | 0.8039                       | 0.6550 | 0.5107 | 0.4165 | 0.3317 | 0.2730 | ...    |
| 0.450               | 9                     | 0.9044                       | 0.7369 | 0.5745 | 0.4685 | 0.3732 | 0.3072 | 0.2481 |
| 0.455               | 7                     | 0.9144                       | 0.7451 | 0.5809 | 0.4737 | 0.3773 | 0.3106 | 0.2509 |
| 0.480               | 3                     | 0.9647                       | 0.7860 | 0.6128 | 0.4997 | 0.3980 | 0.3277 | 0.2646 |
| 0.500               | 5                     | 1.0049                       | 0.8188 | 0.6383 | 0.5206 | 0.4146 | 0.3413 | 0.2757 |
| 0.520               | 4                     | 1.0451                       | 0.8515 | 0.6639 | 0.5414 | 0.4312 | 0.3550 | 0.2867 |
| 0.560               | 7                     | 1.1254                       | 0.9170 | 0.7149 | 0.5830 | 0.4644 | 0.3823 | 0.3087 |
| 0.585               | 9                     | 1.1757                       | 0.9580 | 0.7469 | 0.6091 | 0.4851 | 0.3993 | 0.3225 |
| 0.600               | 6                     | 1.2058                       | 0.9825 | 0.7660 | 0.6247 | 0.4975 | 0.4096 | 0.3308 |
| 0.640               | 4                     | 1.2862                       | 1.0480 | 0.8171 | 0.6663 | 0.5307 | 0.4369 | 0.3529 |
| 0.650               | 5                     | 1.3063                       | 1.0644 | 0.8298 | 0.6767 | 0.5390 | 0.4437 | 0.3584 |
| 0.700               | 7                     | 1.4068                       | 1.1463 | 0.8937 | 0.7288 | 0.5805 | 0.4778 | 0.3859 |
| 0.720               | 9                     | 1.4470                       | 1.1790 | 0.9192 | 0.7496 | 0.5970 | 0.4915 | 0.3970 |
| 0.780               | 6                     | 1.5676                       | 1.2773 | 0.9958 | 0.8121 | 0.6468 | 0.5324 | 0.4300 |
| 0.800               | 5                     | 1.6078                       | 1.3100 | 1.0213 | 0.8329 | 0.6634 | 0.5461 | 0.4411 |
| 0.900               | 9                     | 1.8088                       | 1.4738 | 1.1490 | 0.9370 | 0.7463 | 0.6144 | 0.4962 |
| 0.910               | 7                     | 1.8289                       | 1.4902 | 1.1618 | 0.9474 | 0.7546 | 0.6212 | 0.5017 |
| 0.960               | 6                     | 1.9293                       | 1.5721 | 1.2256 | 0.9995 | 0.7961 | 0.6553 | 0.5293 |
| 1.000               | 10                    | 2.0097                       | 1.6376 | 1.2767 | 1.0411 | 0.8292 | 0.6826 | 0.5513 |
| 1.040               | 8                     | ...                          | 1.7031 | 1.3277 | 1.0828 | 0.8624 | 0.7099 | 0.5734 |
| 1.120               | 7                     | ...                          | 1.8341 | 1.4299 | 1.1661 | 0.9287 | 0.7645 | 0.6175 |
| 1.170               | 9                     | ...                          | 1.9159 | 1.4937 | 1.2181 | 0.9702 | 0.7987 | 0.6451 |
| 1.280               | 8                     | ...                          | 2.0961 | 1.6341 | 1.3327 | 1.0614 | 0.8738 | 0.7057 |
| 1.300               | 10                    | ...                          | ...    | 1.6597 | 1.3535 | 1.0780 | 0.8874 | 0.7167 |
| 1.440               | 9                     | ...                          | ...    | 1.8384 | 1.4992 | 1.1941 | 0.9830 | 0.7939 |
| 1.600               | 10                    | ...                          | ...    | 2.0427 | 1.6658 | 1.3268 | 1.0922 | 0.8821 |

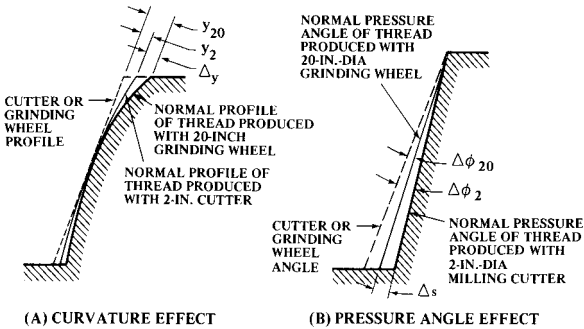
**Table 3. Tooth Proportions of American Standard Fine-Pitch Worms and WormGears ANSI B6.9-1977**

| Standard Axial Pitch in Inches, | Tooth Parts | Lead angle in $\lambda$ in degrees  |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|---------------------------------|-------------|-------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                                 |             | 0.5                                 | 1      | 1.5    | 2      | 3      | 4      | 5      | 7      | 9      | 11     | 14     | 17     | 21     | 25     | 30     |
|                                 |             | Dimensions of Tooth Parts in Inches |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| 0.030                           | $a$         | 0.0095                              | 0.0095 | 0.0095 | 0.0095 | 0.0095 | 0.0095 | 0.0095 | 0.0095 | 0.0094 | 0.0094 | 0.0093 | 0.0091 | 0.0089 | ...    | ...    |
|                                 | $h_t$       | 0.0230                              | 0.0230 | 0.0230 | 0.0230 | 0.0230 | 0.0230 | 0.0229 | 0.0229 | 0.0228 | 0.0226 | 0.0224 | 0.0221 | 0.0216 | ...    | ...    |
|                                 | $p_n$       | 0.0300                              | 0.0300 | 0.0300 | 0.0300 | 0.0300 | 0.0299 | 0.0299 | 0.0298 | 0.0296 | 0.0294 | 0.0291 | 0.0287 | 0.0280 | ...    | ...    |
| 0.040                           | $a$         | 0.0127                              | 0.0127 | 0.0127 | 0.0127 | 0.0127 | 0.0127 | 0.0127 | 0.0126 | 0.0126 | 0.0125 | 0.0124 | 0.0122 | 0.0119 | 0.0115 | ...    |
|                                 | $h_t$       | 0.0300                              | 0.0300 | 0.0300 | 0.0300 | 0.0300 | 0.0299 | 0.0299 | 0.0298 | 0.0297 | 0.0295 | 0.0292 | 0.0288 | 0.0282 | 0.0274 | ...    |
|                                 | $p_n$       | 0.0400                              | 0.0400 | 0.0400 | 0.0400 | 0.0399 | 0.0399 | 0.0398 | 0.0397 | 0.0395 | 0.0393 | 0.0388 | 0.0383 | 0.0373 | 0.0363 | ...    |
| 0.050                           | $a$         | 0.0159                              | 0.0159 | 0.0159 | 0.0159 | 0.0159 | 0.0159 | 0.0159 | 0.0158 | 0.0157 | 0.0156 | 0.0154 | 0.0152 | 0.0149 | 0.0144 | 0.0138 |
|                                 | $h_t$       | 0.0370                              | 0.0370 | 0.0370 | 0.0370 | 0.0370 | 0.0369 | 0.0369 | 0.0368 | 0.0366 | 0.0364 | 0.0360 | 0.0355 | 0.0347 | 0.0337 | 0.0323 |
|                                 | $p_n$       | 0.0500                              | 0.0500 | 0.0500 | 0.0500 | 0.0499 | 0.0499 | 0.0498 | 0.0496 | 0.0494 | 0.0491 | 0.0485 | 0.0478 | 0.0467 | 0.0453 | 0.0433 |
| 0.065                           | $a$         | 0.0207                              | 0.0207 | 0.0207 | 0.0207 | 0.0207 | 0.0206 | 0.0206 | 0.0205 | 0.0204 | 0.0203 | 0.0201 | 0.0198 | 0.0193 | 0.0188 | 0.0179 |
|                                 | $h_t$       | 0.0475                              | 0.0475 | 0.0475 | 0.0475 | 0.0475 | 0.0474 | 0.0473 | 0.0472 | 0.0470 | 0.0467 | 0.0462 | 0.0455 | 0.0445 | 0.0433 | 0.0414 |
|                                 | $p_n$       | 0.0650                              | 0.0650 | 0.0650 | 0.0650 | 0.0649 | 0.0648 | 0.0648 | 0.0645 | 0.0642 | 0.0638 | 0.0631 | 0.0622 | 0.0607 | 0.0589 | 0.0563 |
| 0.080                           | $a$         | 0.0255                              | 0.0255 | 0.0255 | 0.0254 | 0.0254 | 0.0254 | 0.0254 | 0.0253 | 0.0252 | 0.0250 | 0.0247 | 0.0244 | 0.0238 | 0.0231 | 0.0221 |
|                                 | $h_t$       | 0.0580                              | 0.0580 | 0.0580 | 0.0580 | 0.0579 | 0.0579 | 0.0578 | 0.0576 | 0.0573 | 0.0570 | 0.0564 | 0.0556 | 0.0543 | 0.0528 | 0.0505 |
|                                 | $p_n$       | 0.0800                              | 0.0800 | 0.0800 | 0.0800 | 0.0799 | 0.0798 | 0.0797 | 0.0794 | 0.0790 | 0.0785 | 0.0776 | 0.0765 | 0.0747 | 0.0725 | 0.0693 |
| 0.100                           | $a$         | 0.0318                              | 0.0318 | 0.0318 | 0.0318 | 0.0318 | 0.0318 | 0.0317 | 0.0316 | 0.0314 | 0.0312 | 0.0309 | 0.0304 | 0.0297 | 0.0288 | 0.0276 |
|                                 | $h_t$       | 0.0720                              | 0.0720 | 0.0720 | 0.0720 | 0.0719 | 0.0719 | 0.0718 | 0.0715 | 0.0712 | 0.0707 | 0.0699 | 0.0690 | 0.0674 | 0.0655 | 0.0626 |
|                                 | $p_n$       | 0.1000                              | 0.1000 | 0.1000 | 0.0999 | 0.0999 | 0.0998 | 0.0996 | 0.0993 | 0.0988 | 0.0982 | 0.0970 | 0.0956 | 0.0934 | 0.0906 | 0.0866 |
| 0.130                           | $a$         | 0.0414                              | 0.0414 | 0.0414 | 0.0414 | 0.0413 | 0.0413 | 0.0412 | 0.0411 | 0.0409 | 0.0406 | 0.0401 | 0.0396 | 0.0386 | 0.0375 | 0.0358 |
|                                 | $h_t$       | 0.0930                              | 0.0930 | 0.0930 | 0.0930 | 0.0929 | 0.0928 | 0.0927 | 0.0924 | 0.0919 | 0.0914 | 0.0903 | 0.0891 | 0.0870 | 0.0845 | 0.0808 |
|                                 | $p_n$       | 0.1300                              | 0.1300 | 0.1300 | 0.1299 | 0.1298 | 0.1297 | 0.1295 | 0.1290 | 0.1284 | 0.1276 | 0.1261 | 0.1243 | 0.1214 | 0.1178 | 0.1126 |
| 0.160                           | $a$         | 0.0509                              | 0.0509 | 0.0509 | 0.0509 | 0.0509 | 0.0508 | 0.0507 | 0.0505 | 0.0503 | 0.0500 | 0.0494 | 0.0487 | 0.0475 | 0.0462 | 0.0441 |
|                                 | $h_t$       | 0.1140                              | 0.1140 | 0.1140 | 0.1140 | 0.1139 | 0.1138 | 0.1136 | 0.1132 | 0.1127 | 0.1120 | 0.1107 | 0.1092 | 0.1066 | 0.1035 | 0.0990 |
|                                 | $p_n$       | 0.1600                              | 0.1600 | 0.1599 | 0.1599 | 0.1598 | 0.1596 | 0.1594 | 0.1588 | 0.1580 | 0.1571 | 0.1552 | 0.1530 | 0.1494 | 0.1450 | 0.1386 |

**Effect of Production Method on Worm Profile and Pressure Angle.**—In worm gearing, tooth bearing is usually used as the means of judging tooth profile accuracy since direct profile measurements on fine-pitch worms or wormgears is not practical. According to AGMA 370.01, Design Manual for Fine-Pitch Gearing, a minimum of 50 per cent initial area of contact is suitable for most fine-pitch worm gearing, although in some cases, such as when the load fluctuates widely, a more restricted initial area of contact may be desirable.

Except where single-pointed lathe tools, end mills, or cutters of special shape are used in the manufacture of worms, the pressure angle and profile produced by the cutter are different from those of the cutter itself. The amounts of these differences depend on several factors, namely, diameter and lead angle of the worm, thickness and depth of the worm thread, and diameter of the cutter or grinding wheel. The accompanying diagram shows the curvature and pressure angle effects produced in the worm by cutters and grinding wheels, and how the amount of variation in worm profile and pressure angle is influenced by the diameter of the cutting tool used.

### Effect of Diameter of Cutting on Profile and Pressure Angle of Worms



*Calculating Worm Deviations and Pressure Angle Changes:* Included in American Standard ANSI B6.9-1977 is an extensive tabulation of profile deviations and pressure angle changes produced by cutters and grinding wheels of 2-inch and 20-inch diameters. These diameters represent the limits of the range commonly used, and the data given are useful in specifying worm profile tolerances. The data also aid in the selection of the method to be used in producing the worm and in specifying the hobs for wormgears. The formulas used to compute the data in the Standard are given here in slightly modified form, and may be used to calculate the profile deviations and pressure angle changes produced in the worm by cutters or grinding wheels.

$$\rho_{ni} = \frac{r \sin \phi_n}{(\sin \lambda)^2} \text{ inches} \quad (1)$$

$$\rho_n = \rho_{ni} + \frac{r \rho_{ni}}{R(\cos \lambda)^2} \text{ inches} \quad (2)$$

$$\Delta \phi = \frac{5400r(\sin \lambda)^3}{n(R(\cos \lambda)^2 + r)} \text{ minutes} \quad (3)$$

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$$q = a \sec \phi_n \text{ inches} \quad (4)$$

$$y = \frac{q^2}{2\rho_n} \text{ inches} \quad (5)$$

$$s = 0.000582q\Delta\phi \text{ inches} \quad (6)$$

$$\Delta y = y_w - y_c \text{ inches} \quad (7)$$

$$\Delta s = s_c - s_w \text{ inches} \quad (8)$$

In these formulas,

$\rho_{ni}$  = radius of curvature of normal thread profile for involute thread;

$r$  = pitch radius of worm;

$\Phi_n$  = normal pressure angle of cutter or grinding wheel;

$\lambda$  = lead angle of worm;

$\rho_n$  = radius of curvature of normal thread profile;

$R$  = radius of cutter or grinding wheel;

$\Delta\Phi$  = difference between the normal pressure angle of the thread and the normal pressure angle of the cutter or grinding wheel in minutes (see diagram). Subscripts  $c$  and  $w$  are used to denote the cutter and grinding wheel diameters, respectively;

$n$  = number of threads in worm;

$a$  = addendum of worm;

$q$  = slant height of worm addendum;

$y$  = amount normal worm profile departs from a straight side (see diagram). Subscripts  $c$  and  $w$  are used to denote the cutter and grinding wheel diameters, respectively;

$s$  = effect along slant height of worm thread caused by change in pressure angle  $\Delta\Phi$

$\Delta y$  = difference in  $y$  values of two cutters or grinding wheels of different diameter (see diagram);

$\Delta s$  = effect of  $\Delta\Phi_c - \Delta\Phi_w$  along slant height of thread (see diagram).

*Example 3:* Assuming the worm dimensions are the same as in [Example 1](#), determine the corrections for two worms, one milled by a 2-inch diameter cutter, the other ground by a 20-inch diameter wheel, both to be assembled with identical wormgears.

To make identical worms when using a 2-inch cutter and a 20-inch wheel, the pressure angle of either the cutter or the wheel must be corrected by an amount corresponding to  $\Delta s$  and the profile of the cutter or wheel must be a curve which departs from a straight line by an amount  $\Delta y$ . The calculations are as follows:

For the 2-inch diameter cutter, using [Formula \(1\)](#) to [\(6\)](#),

$$\rho_{ni} = \frac{0.4410 \times 0.3420}{0.5000^2} = 0.6033 \text{ inch} \quad (1)$$

$$\rho_n = 0.6033 + \frac{0.4410 \times 0.6033}{1 \times 0.8660^2} = 0.9581 \text{ inch} \quad (2)$$

$$\Delta\phi_c = \frac{5400 \times 0.4410 \times 0.5000^3}{10(1 \times 0.8660^2 + 0.4410)} = 24.99 \text{ inches} \quad (3)$$

$$q = 0.0441 \times 1.0642 = 0.0469 \text{ inch} \quad (4)$$

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$$y_c = \frac{0.0469^2}{2 \times 0.6387} = 0.00172 \text{ inches} \quad (5)$$

$$s_c = 0.000582 \times 0.0469 \times 24.99 = 0.000682 \text{ inch} \quad (6)$$

For the 20-inch diameter wheel, using [Formula \(1\)](#) to [\(6\)](#)

$$\rho_{ni} = \frac{0.4410 \times 0.3420}{0.5000^2} = 0.6033 \text{ inch} \quad (1)$$

$$\rho_n = 0.6033 + \frac{0.4410 \times 0.6033}{10 \times 0.8660^2} = 0.6387 \text{ inch} \quad (2)$$

$$\Delta\phi_w = \frac{5400 \times 0.4410 \times 0.5000^3}{10(10 \times 0.8660^2 + 0.4410)} = 3.749 \text{ inches} \quad (3)$$

$$q = 0.0441 \times 1.0642 = 0.0469 \text{ inch} \quad (4)$$

$$y_w = \frac{0.0469^2}{2 \times 0.6387} = 0.00172 \text{ inches} \quad (5)$$

$$s_w = 0.000582 \times 0.0469 \times 3.749 = 0.000102 \text{ inch} \quad (6)$$

Applying [Formula \(7\)](#) to [\(8\)](#):

$$\Delta y = 0.00172 - 0.00115 = 0.00057 \text{ inch} \quad (7)$$

$$\Delta s = 0.000682 - 0.000102 = 0.000580 \text{ inch} \quad (8)$$

Therefore the pressure angle of either the cutter or the wheel must be corrected by an amount corresponding to a  $\Delta s$  of 0.00580 inch and the profile of the cutter or wheel must be a curve which departs from a straight line by 0.00057 inch.

**Industrial Worm Gearing.**—The primary considerations in industrial worm gearing are usually:

- 1) To transmit power efficiently;
- 2) to transmit power at a considerable reduction in velocity; and
- 3) to provide a considerable "mechanical advantage" when a given applied force must overcome a comparatively high resisting force.

Worm gearing for use in such applications is usually of relatively coarse pitch. The notation below is used in the formulas on the following pages.

|                      |  |                      |  |
|----------------------|--|----------------------|--|
| <i>a</i>             | addendum, worm thread                    | <i>m</i>             | module = 0.3183 × axial pitch  |
| <i>A</i>             | addendum, wormgear tooth                 | <i>N</i>             | revolutions per minute of wormgear                                   |
| <i>B</i>             | dedendum, wormgear tooth                 | <i>n</i>             | revolutions per minute of worm                                       |
| <i>b</i>             | dedendum, worm thread                    | <i>P</i>             | axial pitch of worm and circular pitch of wormgear                   |
| <i>C</i>             | center distance (Fig. 1, p. 1928)        | <i>P<sub>n</sub></i> | normal pitch of worm   |
| <i>c</i>             | clearance                                | <i>Q</i>             | arc length of wormgear tooth measured along root                     |
| <i>D</i>             | pitch diameter of wormgear               |                      | ratio of worm gearing = No. of wormgear teeth ÷ No. of worm threads. |
| <i>d</i>             | pitch diameter of worm                   | <i>S<sub>c</sub></i> | surface stress factor ( <a href="#">Table 4</a> )                    |
| <i>d<sub>o</sub></i> | outside diameter of worm                 | <i>S<sub>b</sub></i> | bending stress factors, lbs. per sq. in. ( <a href="#">Table 4</a> ) |
| <i>D<sub>o</sub></i> | outside or over-all diameter of wormgear | <i>T</i>             | number of teeth on wormgear  |

|       |   |                       |  |
|-------|---|-----------------------|--|
| $D_t$ | throat diameter of wormgear   | $t$                   | number of threads or "starts" and on worm-2 for double thread, 3 for triple thread, 4 for quadruple thread, etc. |
| $E$   | efficiency of worm gearing, per cent  | $U$                   | radius of wormgear throat (Fig. 11)  |
| $F$   | nominal face width of wormgear rim  | $V$                   | rubbing speed of worm in feet per minute   |
| $F_e$ | effective face width (Fig. 11, p. 1928)   | $W$                   | whole tooth depth (worm and-wormgear)  |
| $f$   | coefficient of friction   | $X_{cp}$ and $X_{cw}$ | speed factor when load rating is limited by wear (Fig. 11)   |
| $G$   | length of worm threaded section   | $X_{bp}$ and $X_{bw}$ | speed factor when load rating is limited by strength (Table 5)   |
| $H$   | horsepower rating   | $\phi$                | angle of friction ( $\tan \phi =$ coefficient of friction)   |
| $L$   | lead of worm thread = pitch $\times$ number of threads or "starts"                |                       |  |
| $L_a$ | lead angle of worm = helix angle measured from a plane perpendicular to worm axis |                       |  |
| $M$   | torque applied to wormgear, pound inches  |                       |  |

**Materials for Worm Gearing.**—Worm gearing, especially for power transmission, should have steel worms and phosphor bronze wormgears. This combination is used extensively. The worms should be hardened and ground to obtain accuracy and a smooth finish.

The phosphor bronze wormgears should contain from 10 to 12 per cent of tin. The S.A.E. phosphor gear bronze (No. 65) contains 88–90% copper, 10–12% tin, 0.50% lead, 0.50% zinc (but with a maximum total lead, zinc and nickel content of 1.0 percent), phosphorous 0.10–0.30%, aluminum 0.005%. The S.A.E. nickel phosphor gear bronze (No. 65 + Ni) contains 87% copper, 11% tin, 2% nickel and 0.2% phosphorous.

**Single-thread Worms.**—The ratio of the worm speed to the wormgear speed may range from 1.5 or even less up to 100 or more. Worm gearing having high ratios are not very efficient as transmitters of power; nevertheless high as well as low ratios often are required. Since the ratio equals the number of wormgear teeth divided by the number of threads or "starts" on the worm, single-thread worms are used to obtain a high ratio. As a general rule, a ratio of 50 is about the maximum recommended for a single worm and wormgear combination, although ratios up to 100 or higher are possible. When a high ratio is required, it may be preferable to use, in combination, two sets of worm gearing of the multi-thread type in preference to one set of the single-thread type in order to obtain the same total reduction and a higher combined efficiency.

Single-thread worms are comparatively inefficient because of the effect of the low lead angle; consequently, single-thread worms are not used when the primary purpose is to transmit power as efficiently as possible but they may be employed either when a large speed reduction with one set of gearing is necessary, or possibly as a means of adjustment, especially if "mechanical advantage" or self-locking are important factors.

**Multi-thread Worms.**—When worm gearing is designed primarily for transmitting power efficiently, the lead angle of the worm should be as high as is consistent with other requirements and preferably between, say, 25 or 30 and 45 degrees. This means that the worm must be multi-threaded. To obtain a given ratio, some number of wormgear teeth divided by some number of worm threads must equal the ratio. Thus, if the ratio is 6, combinations such as the following might be used:

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$$\frac{24}{4}, \frac{30}{5}, \frac{36}{6}, \frac{42}{7}$$

The numerators represent the number of wormgear teeth and the denominators, the number of worm threads or "starts." The number of wormgear teeth may not be an exact multiple of the number of threads on a multi-thread worm in order to obtain a "hunting tooth" action.

*Number of Threads or "Starts" on Worm:* The number of threads on the worm ordinarily varies from one to six or eight, depending upon the ratio of the gearing. As the ratio is increased, the number of worm threads is reduced, as a general rule. In some cases, however, the higher of two ratios may also have a larger number of threads. For example, a ratio of  $6\frac{1}{5}$  would have 5 threads whereas a ratio of  $6\frac{5}{6}$  would have 6 threads. Whenever the ratio is fractional, the number of threads on the worm equals the denominator of the fractional part of the ratio.

**Table 4. Rules and Formulas for Worm Gearing**

| No. | To Find                 | Rule  | Formula  |
|-----|-------------------------|---|--|
| 1   | Addendum                | Addendum may be affected by lead angle. See paragraph, Addendum and Dedendum.   |  |
| 2   | Center Distance         | Add pitch diameter of wormgear to pitch diameter of worm, and divide sum by 2   | $C = \frac{D+d}{2}$  |
| 3   |                         | Divide number of worm threads by tangent lead angle, add number of wormgear teeth and multiply sum by quotient obtained by dividing pitch by 6.2832 | $C = \frac{P}{6.2832} \left( \frac{t}{\tan L_a} + T \right)$ |
| 4   | Dedendum                | Dedendum may be affected by lead angle. See paragraph, Addendum and Dedendum  |  |
| 5   | Clearance               | British Standard-multiply cosine lead angle by 0.2 times module.  | $c = 0.2m \cos L_a$  |
| 6   | Face width Wormgear     | For single and double thread worms, multiply pitch by 2.38 and add 0.25. (shell type worm.)   | $F = 2.38P + 0.25$   |
| 7   |                         | For triple and quadruple thread multiply pitch by 2.15 and add 0.2. (shell type )   | $F = 2.15P + 0.20$   |
| 8   |                         | When worm threads are integral with shaft, face width of wormgear may be equal $C^{0.875}$ divided by 3.  | $F = \frac{C^{0.875}}{3}$                                    |
| 9   | Lead of Worm thread     | Multiply pitch by number of worm threads or "starts"  | $L = 1P$   |
| 10  |                         | Multiply pitch circumference of worm by tangent of lead angle.  | $L = \pi d \times \tan L_a$                                  |
| 11  |                         | Divide pitch circumference of wormgear by ratio.  | $L = \pi D \div R$   |
| 12  | Lead Angle, Worm        | Divide lead by pitch circumference of worm; quotient is tangent of lead angle.  | $\tan L_a = \frac{L}{3.1416d}$                               |
| 13  | Outside Diam., Worm     | Add to pitch diameter twice the addendum. see paragraph, pitch diameter of worm; also Addendum and Dedendum.  | $d_0 = d + 2a$   |
| 14  | Outside Diam., Wormgear | For outside or over-all diameter of wormgear, see paragraph, outside diameter of wormgear.  |  |

Table 4. (Continued) Rules and Formulas for Worm Gearing

| No. | To Find                        | Rule   | Formula  |
|-----|--------------------------------|--|--|
| 15  | Pitch of Worm and Wormgear     | Divide lead by number of threads or "starts" on worm = axial pitch of worm and circular pitch of wormgear.   | $P = \frac{L}{t}$                                    |
| 16  |                                | Subtract the worm pitch diameter from twice the center distance. Multiply by 3.1416 and divide by number of wormgear teeth.                                    | $P = \frac{(2C - d)3.1416}{T}$                       |
| 17  | Pitch of Worm, Normal          | Multiply axial pitch by cosine of lead angle to find normal pitch.   | $P_n = P \times \cos L_a$                            |
| 18  | Pitch Diameter, Worm           | Subtract pitch diameter of worm gear from twice the center distance.   | $d = 2C - D$   |
| 19  |                                | Subtract twice the addendum from outside diameter. See Addendum and Dedendum.  | $D = d_0 - 2a$                                       |
| 20  |                                | Multiply lead by cotangent lead angle and divide product by 3.1416   | $d = \frac{L \times \cot L_a}{3.1416}$               |
| 21  | Pitch Diameter, Wormgear       | Subtract pitch diameter of worm from twice the center distance.  | $D = 2C - d$   |
| 22  |                                | Multiply number of wormgear teeth by axial pitch of worm and divide product by 3.1416.   | $D = \frac{TP}{3.1416}$                              |
| 23  | Radius of Rim Corner, Wormgear | Multiply pitch by 0.25   | Radius = 0.25P                                       |
| 24  |                                | British Standard: Radius = 0.5 × module.   | Radius = 0.50m                                       |
| 25  | Ratio                          | Divide number of wormgear teeth by by number of worm threads.  | $R = T \div t$                                       |
| 26  | Rubbing speed, ft. per minute  | Divide wormgear pitch diameter by ratio; square quotient and add to square of worm pitch diameter; multiply square root of this sum by 0.262 × R.P.M. of worm. | $V = 0.262n \sqrt{d^2 + \left(\frac{D}{4}\right)^2}$ |
| 27  |                                | Multiply 0.262 × Pitch diameter of worm by worm R.P.M. of worm; then multiply product by secant of lead angle.   | $V = 0.262dn \times \sec L_a$                        |
| 28  | Throat Diameter Wormgear       | Add twice the addendum to pitch diameter. See paragraph, Addendum and Dedendum   | $D_t = D + 2A$                                       |
| 29  | Throat Radius Wormgear         | Subtract twice the addendum from outside radius of worm.   | $U = \frac{d_0}{2} - 2a$                             |
| 30  | Total Depth                    | Whole depth equals addendum + Dedendum. See paragraph, Addendum and Dedendum   | $W = a + b \quad \text{or} \quad A + B$              |
| 31  | Worm Thread Length             | Multiply the number of wormgear teeth by 0.02, add 4.5 and multiply sum by pitch.  | $G = P(4.5 + 0.02T)$                                 |
| 32  |                                | British Standard subtract square of wormgear pitch diameter from square of outside diameter and extract square root of remainder.                              | $G = \sqrt{D_0^2 - D^2}$                             |

**Ratio for Obtaining "Hunting Tooth" Action.**—In designing wormgears having multi-thread worms, it is common practice to select a number of wormgear teeth that is not an exact multiple of the number of worm threads. To illustrate, if the desired ratio is about 5 or 6, the actual ratio might be  $5\frac{1}{6}$ ,  $5\frac{5}{6}$ ,  $5\frac{2}{3}$ ,  $6\frac{1}{5}$ , etc., so that combinations such as  $\frac{31}{6}$ ,  $\frac{35}{6}$ ,  $\frac{37}{4}$  or  $\frac{31}{5}$  would be obtained. Since the number of wormgear teeth and number of worm threads do not have a common divisor, the threads of the worm will mesh with all of the wormgear teeth in succession, thus obtaining a "hunting tooth" or self-indexing action. This progressive change will also occur during the wormgear hobbing operation, and its primary purpose is to produce more accurate wormgears by uniformly distributing among all of the teeth, any slight errors which might exist in the hob teeth. Another object is to improve the



“running-in” action between the hardened and ground worm and the phosphor bronze wormgear, but in order to obtain this advantage, the threads on the worm must be accurately or uniformly spaced by precise indexing. With a “hunting tooth ratio,” if the thread spacing of a multi-thread worm is inaccurate, load distribution on the threads will be unequal and some threads might not even make contact with the wormgear teeth. For this reason, if the indexing is inaccurate, it is preferable to avoid a hunting tooth ratio, but in that case, if the gearing is disassembled, the same worm and wormgear teeth should be mated when reassembled.

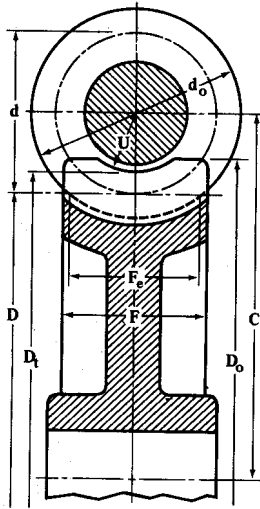


Fig. 11.

**Pitch Diameter of Worm.**—The worm must be strong enough to transmit its maximum load without excessive deflection but the diameter should be as small as is consistent with the necessary strength in order to minimize the rubbing speed. It is impracticable to give a rule or formula that is generally applicable, but the following empirical rules are based upon actual practice and may prove useful as a general guide. They apply to casehardened alloy steel worms which are integral with the shaft.

For ratios of 5, 6, or 7, the pitch diameter ranges approximately from 0.38  $C$  when center distance  $C$  is 4 inches to 0.33  $C$  when  $C$  is 20 inches.

For ratios of 8, 9, 10, the pitch diameter ranges approximately from 0.38  $C$  when center distance  $C$  is 4 inches to 0.25  $C$  when  $C$  is 30 inches.

For ratios of 10 to 20, the pitch diameter ranges approximately from 0.37  $C$  when center distance  $C$  is 4 inches to 0.24  $C$  when  $C$  is 30 inches.

For ratios of 20 to 40, the pitch diameter ranges approximately from 0.36  $C$  when center distance  $C$  is 4 inches to 0.23  $C$  when  $C$  is 30 inches.

According to another empirical formula pitch diameter  $d = C^{0.75} + 2.2$ .

**Addendum and Dedendum.**—The following A.G.M.A. formulas are applicable to industrial worm gearing. For single and double thread worms, addendum  $a = 0.318 P$  and whole depth  $W = 0.686 P$ ; for triple and quadruple threads, addendum  $a = 0.286 P$  and whole depth  $W = 0.623 P$ .

According to the British standard,  $a = \text{module } m = 0.3183 P$ ;  $b = m(2.2 \cos L_a - 1)$ ;  $A = m(2.2 \cos L_a - 1)$ ;  $B = m(1 + 0.2 \cos L_a)$ .

**Outside Diameter of Wormgear.**—Practice varies somewhat in determining the outside or over-all diameter of the wormgear, as indicated by the following formulas. For usual rim shape, see Fig. 11.

- 1) For lead angles up to about 15 or 20 degrees,  $D_o = D + (3 \times 0.3183 P)$
- 2) For lead angles over 20 degrees,  $D_o = D + (3 \times 0.3183 P \times \cos L_a)$
- 3) For single and double thread,  $D_o = D_t + 0.4775 P$
- 4) For triple and quadruple thread,  $D_o = D_t + 0.3183 P$

**Pressure Angles.**—The pressure angle (one-half the included thread angle) ranges from  $14\frac{1}{2}$  to 30 degrees. While the practice varies somewhat, the following relationship between lead angle and pressure angle may be used as a general guide.

For lead angles up to about 10 or 12 degrees, pressure angle =  $14\frac{1}{2}$  degrees.

For lead angles from 10 or 12 to about 20 or 25 degrees, pressure angle = 20 degrees.

For lead angles from 25 to about 35 degrees, pressure angle = 25 degrees.

For lead angles over 35 degrees, pressure angle = 30 degrees.

In the British Standard specifications, the recommended thread form has a normal pressure angle of 20 degrees.

**Designing Worm Gearing Relative to Center Distance and Ratio.**—In designing worm gearing, three general cases or types of problems may be encountered in establishing the proportions of the worm and wormgear.

*When Center Distance is Fixed and Ratio may be Varied:* The ratio in this case is nominal and may be varied somewhat to meet other conditions. Assume that the required center distance is 6 inches, the desired ratio is about 7, and the pitch of the worm and wormgears is to be approximately 1 inch. Combinations of wormgears and worms such as the following might be used in this case:

$$\frac{28}{4}, \frac{35}{5}, \frac{42}{6}, \frac{56}{8}, \text{ etc.}$$

Suppose we select the  $\frac{28}{4}$  combination for trial but change the number of worm-gear teeth from 28 to 29 to obtain a self-indexing or "hunting tooth" action. The ratio now equals  $\frac{29}{4}$  or 7.25. Then, for trial purposes

$$\text{Pitch diameter } D \text{ of wormgear} = \frac{T \times P}{\pi} = \frac{29 \times 1}{3.1416} = 9.231 \text{ inches}$$

$$\text{Pitch diameter } d \text{ of wormgear} = 2C - D = 2 \times 6 - 9.231 = 2.769 \text{ inches}$$

Assume that experience, tests, or calculations show that a worm of smaller diameter will have the necessary bending and torsional strength and that a pitch of 1.0625 will be satisfactory. Then the pitch diameter of the worm will be decreased to 2.192 inches and the pitch diameter of the wormgear will be increased to 9.808 inches. A check of the lead-angle will show that it equals  $31^\circ 41'$  which is conducive to high efficiency.

*When Ratio is Fixed and Center Distance may be Varied:* Assume that the required ratio is  $7\frac{1}{4}$  and that the center distance may be any value consistent with approved designing practice. This ratio may be obtained with a number of different worm and wormgear sizes. For example, in a series of commercial wormgears, the following combinations are employed for gearing having a ratio of  $7\frac{1}{4}$  with center distances varying from 4 to 8.25 inches. The number of worm threads is 4 and the number of teeth on the wormgear is 29 in all cases.

$$\text{When } C = 4 \text{ inches, } d = 1.654; D = 6.346; P = 0.6875; L_a = 27^\circ 54'$$

When  $C = 5$  inches,  $d = 1.923$ ;  $D = 8.077$ ;  $P = 0.875$ ;  $L_a = 30^\circ 5'$

When  $C = 6$  inches,  $d = 2.192$ ;  $D = 9.808$ ;  $P = 1.0625$ ;  $L_a = 31^\circ 41'$

When  $C = 7$  inches,  $d = 2.461$ ;  $D = 11.539$ ;  $P = 1.25$ ;  $L_a = 32^\circ 53'$

When  $C = 8.25$  inches,  $d = 2.942$ ;  $D = 13.558$ ;  $P = 1.4687$ ;  $L_a = 32^\circ 27'$

The horsepower rating increases considerably as the proportions of the worm gearing increase; hence if the gears are intended primarily for power transmission, the general proportions must be selected with reference to the power-transmitting capacity, and, usually the smallest and most compact design that will give satisfactory performance should be selected. The power capacity of the transmission, however, does not depend solely upon the proportions of the worm and wormgear. For example, the quality and viscosity of the lubricant is an important factor. The load transmitting capacity of the lubricant may also be increased decidedly when excessive temperature rises are prevented by special means such as forced air cooling. (See "Water and Forced-Air Cooling.")

*When Both Ratio and Center Distance are Fixed:* When both ratio and center distance are fixed, the problem usually is to obtain the best proportions of worm and wormgear conforming to these fixed values.

*Example:* The required ratio is 6 (6 to 1) and the center distance is fixed at 3.600 inches. Assume that experience or tests show that an axial pitch of 0.50 inch will meet strength requirements. If normal pitch  $P_n$  is given, change to axial pitch ( $P = P_n \div \cos L_a$ ). With a

ratio of 6, some of the combinations for trial are:  $\frac{30}{5}, \frac{36}{6}, \frac{42}{7}$

Trial calculations will show that the  $\frac{36}{6}$  combination gives the best proportions of worm and wheel for the center distance and pitch specified. Thus

$$D = \frac{TP}{\pi} = \frac{36 \times 0.5}{3.1416} = 5.729; \quad d = 2C - D = 2 \times 3.6 - 5.729 = 1.471$$

The lead angle is about 33 degrees. The effect of lead angle on efficiency is dealt with in a following paragraph. The total obtained by adding the number of worm-gear teeth to the number of worm threads, equals  $36 + 6 = 42$  (a total of 40 is a desirable minimum). With the  $\frac{42}{7}$  combination of the same pitch, the worm would be too small (0.516 inch); and with the  $\frac{30}{5}$  combination it would be too large (2.426 inches). The present trend in gear designing practice is to use finer pitches than in the past. In the case of worm gearing, the pitch may, in certain instances, be changed somewhat either to permit cutting with available equipment or to improve the proportions of worm and wheel.

*When Ratio, Pitch and Lead Angle are Fixed:* Assume that  $R = 10$ , axial pitch  $P = 0.16$  inch,  $L_a = 30$  degrees and  $C = 3$  inches, approximately.

The first step is to determine for the given ratio, pitch and lead angle, the number of worm threads  $t$  which will give a center distance nearest 3 inches.

The whole number nearest 10.04, or 10, is the required number of worm threads; hence number of teeth on wormgear equals  $R \times 10 = 100$

$$d = (L \cot L_a) \div \pi = (10 \times 0.16 \times 1.732) \div \pi = 0.8821 \text{ inches}$$

$$D = (TP) \div \pi = (100 \times 0.16) \div \pi = 5.0929 \text{ inches}$$

$$C = (D + d) \div 2 = (5.0929 + 0.8821) \div 2 = 2.9875 \text{ inches}$$

**Efficiency of Worm Gearing.**—The efficiency at a given speed, depends upon the worm lead angle, the workmanship, the lubrication, and the general design of the transmission. When worm gearing consists of a hardened and ground worm running with an accurately hobbled wormgear properly lubricated, the efficiency depends chiefly upon the lead angle

and coefficient of friction between the worm and worm-gear. In the lower range of lead angles, the efficiency increases considerably as the lead angle increases, as shown by Table 5 and . This increase in efficiency remains practically constant for lead angles between 30 and 45 degrees. Several formulas for obtaining efficiency percentage follow:  
*With worm driving:*

$$E = 100 - \frac{R}{2} \text{ (empirical rule); } E = \frac{100 \times \tan L_a}{\tan(L_a + \phi)}; E = \frac{100 \times L}{L + f\pi d}$$

*With wormgear driving*

$$E = 100 - 2R \text{ (empirical rule); } E = \frac{100 \times \tan(L_a - \phi)}{\tan L_a}$$

The efficiencies obtained by these formulas and other modifications of them differ somewhat and do not take into account bearing and oil-churning losses. The efficiency may be improved somewhat after the "running in" period.

**Table 5. Efficiency of Worm Gearing for Different Lead Angles and Frictional Coefficients**

| Coefficient of friction | Lead angle of worm in degrees |         |         |         |         |         |         |         |         |
|-------------------------|-------------------------------|---------|---------|---------|---------|---------|---------|---------|---------|
|                         | 5 Deg.                        | 10 Deg. | 15 Deg. | 20 Deg. | 25 Deg. | 30 Deg. | 35 Deg. | 40 Deg. | 45 Deg. |
| 0.01                    | 89.7                          | 94.5    | 96.1    | 97.0    | 97.4    | 97.7    | 97.9    | 98.0    | 98.0    |
| 0.02                    | 81.3                          | 89.5    | 92.6    | 94.1    | 95.0    | 95.5    | 95.9    | 96.0    | 96.1    |
| 0.03                    | 74.3                          | 85.0    | 89.2    | 91.4    | 92.6    | 93.4    | 93.9    | 94.1    | 94.2    |
| 0.04                    | 68.4                          | 80.9    | 86.1    | 88.8    | 90.4    | 91.4    | 91.9    | 92.2    | 92.3    |
| 0.05                    | 63.4                          | 77.2    | 83.1    | 86.3    | 88.2    | 89.4    | 90.1    | 90.4    | 90.5    |
| 0.06                    | 59.0                          | 73.8    | 80.4    | 84.0    | 86.1    | 87.4    | 88.2    | 88.6    | 88.7    |
| 0.07                    | 55.2                          | 70.7    | 77.8    | 81.7    | 84.1    | 85.6    | 86.5    | 86.9    | 86.9    |
| 0.08                    | 51.9                          | 67.8    | 75.4    | 79.6    | 82.2    | 83.8    | 84.7    | 85.2    | 85.2    |
| 0.09                    | 48.9                          | 65.2    | 73.1    | 77.5    | 80.3    | 82.0    | 83.0    | 83.5    | 83.5    |
| 0.1                     | 46.3                          | 62.7    | 70.9    | 75.6    | 78.5    | 80.3    | 81.4    | 81.9    | 81.8    |

**Table 6. AGMA Input Mechanical Horsepower Ratings of Cone-Drive Worm Gearing<sup>a</sup>**

| Ratio                  | Worm Speed, RPM |      |      |      |      |      |
|------------------------|-----------------|------|------|------|------|------|
|                        | 100             | 300  | 720  | 870  | 1150 | 1750 |
| 2-Inch Center Distance |                 |      |      |      |      |      |
| 5:1                    | 0.40            | 1.04 | 2.18 | 2.51 | 3.02 | 3.81 |
| 10:1                   | 0.25            | 0.66 | 1.40 | 1.62 | 1.98 | 2.52 |
| 15:1                   | 0.18            | 0.47 | 0.99 | 1.15 | 1.40 | 1.79 |
| 20:1                   | 0.13            | 0.36 | 0.76 | 0.88 | 1.07 | 1.38 |
| 25:1                   | 0.11            | 0.29 | 0.61 | 0.71 | 0.87 | 1.11 |
| 30:1                   | 0.09            | 0.24 | 0.51 | 0.59 | 0.73 | 0.93 |
| 40:1                   | 0.07            | 0.18 | 0.38 | 0.45 | 0.55 | 0.70 |
| 50:1                   | 0.05            | 0.15 | 0.31 | 0.36 | 0.44 | 0.56 |

**Table 6. (Continued) AGMA Input Mechanical Horsepower Ratings of Cone-Drive Worm Gearing<sup>a</sup>**

| Ratio                    | Worm Speed, RPM |      |       |       |       |       |
|--------------------------|-----------------|------|-------|-------|-------|-------|
|                          | 100             | 300  | 720   | 870   | 1150  | 1750  |
| 2.5-Inch Center Distance |                 |      |       |       |       |       |
| 5:1                      | 0.78            | 2.04 | 4.13  | 4.68  | 5.48  | 6.87  |
| 10:1                     | 0.49            | 1.30 | 2.67  | 3.05  | 3.62  | 4.54  |
| 15:1                     | 0.35            | 0.91 | 1.89  | 2.16  | 2.57  | 3.22  |
| 20:1                     | 0.27            | 0.70 | 1.44  | 1.65  | 1.97  | 2.48  |
| 25:1                     | 0.21            | 0.56 | 1.16  | 1.33  | 1.59  | 2.00  |
| 30:1                     | 0.18            | 0.47 | 0.98  | 1.12  | 1.33  | 1.68  |
| 40:1                     | 0.13            | 0.35 | 0.73  | 0.84  | 1.00  | 1.26  |
| 50:1                     | 0.11            | 0.28 | 0.59  | 0.68  | 0.81  | 1.01  |
| 3-Inch Center Distance   |                 |      |       |       |       |       |
| 5:1                      | 1.38            | 3.60 | 6.99  | 7.79  | 9.06  | 11.30 |
| 10:1                     | 0.88            | 2.31 | 4.65  | 5.26  | 6.16  | 7.72  |
| 15:1                     | 0.62            | 1.62 | 3.29  | 3.74  | 4.38  | 5.49  |
| 20:1                     | 0.47            | 1.24 | 2.52  | 2.87  | 3.37  | 4.22  |
| 25:1                     | 0.38            | 1.00 | 2.04  | 2.31  | 2.72  | 3.41  |
| 30:1                     | 0.32            | 0.84 | 1.71  | 1.94  | 2.28  | 2.86  |
| 40:1                     | 0.24            | 0.63 | 1.28  | 1.46  | 1.72  | 2.15  |
| 50:1                     | 0.19            | 0.51 | 1.03  | 1.17  | 1.38  | 1.73  |
| 60:1                     | 0.16            | 0.42 | 0.86  | 0.98  | 1.15  | 1.44  |
| 3.5-Inch Center Distance |                 |      |       |       |       |       |
| 5:1                      | 2.55            | 6.60 | 12.30 | 13.70 | 15.90 | 19.70 |
| 10:1                     | 1.63            | 4.24 | 8.27  | 9.21  | 10.70 | 13.40 |
| 15:1                     | 1.14            | 2.99 | 5.85  | 6.54  | 7.62  | 9.53  |
| 20:1                     | 0.88            | 2.28 | 4.49  | 5.03  | 5.86  | 7.33  |
| 25:1                     | 0.71            | 1.84 | 3.62  | 4.06  | 4.73  | 5.92  |
| 30:1                     | 0.59            | 1.54 | 3.04  | 3.40  | 3.96  | 4.96  |
| 40:1                     | 0.44            | 1.16 | 2.29  | 2.56  | 2.99  | 3.74  |
| 50:1                     | 0.36            | 0.93 | 1.83  | 2.06  | 2.40  | 3.00  |
| 60:1                     | 0.30            | 0.78 | 1.53  | 1.72  | 2.00  | 2.51  |
| 4-Inch Center Distance   |                 |      |       |       |       |       |
| 5:1                      | 3.66            | 9.40 | 16.90 | 18.70 | 21.70 | 26.70 |
| 10:1                     | 2.35            | 6.09 | 11.50 | 12.70 | 14.80 | 18.40 |
| 15:1                     | 1.65            | 4.29 | 8.15  | 9.06  | 10.50 | 13.10 |
| 20:1                     | 1.26            | 3.28 | 6.26  | 6.96  | 8.09  | 10.10 |
| 25:1                     | 1.02            | 2.65 | 5.05  | 5.62  | 6.53  | 8.13  |
| 30:1                     | 0.85            | 2.22 | 4.24  | 4.71  | 5.48  | 6.82  |
| 40:1                     | 0.64            | 1.67 | 3.19  | 3.55  | 4.12  | 5.14  |
| 50:1                     | 0.51            | 1.34 | 2.56  | 2.85  | 3.31  | 4.12  |
| 60:1                     | 0.43            | 1.12 | 2.14  | 2.38  | 2.76  | 3.44  |

**Table 6. (Continued) AGMA Input Mechanical Horsepower Ratings of Cone-Drive Worm Gearing<sup>a</sup>**

| Ratio                  | Worm Speed, RPM |       |       |        |        |        |
|------------------------|-----------------|-------|-------|--------|--------|--------|
|                        | 100             | 300   | 720   | 870    | 1150   | 1750   |
| 5-Inch Center Distance |                 |       |       |        |        |        |
| 5:1                    | 7.21            | 18.20 | 31.00 | 34.30  | 39.60  | 47.40  |
| 10:1                   | 4.63            | 11.80 | 21.10 | 23.40  | 27.20  | 33.30  |
| 15:1                   | 3.25            | 8.36  | 15.00 | 16.70  | 19.30  | 23.80  |
| 20:1                   | 2.49            | 6.40  | 11.60 | 12.80  | 14.90  | 18.30  |
| 25:1                   | 2.01            | 5.16  | 9.34  | 10.30  | 12.00  | 14.80  |
| 30:1                   | 1.68            | 4.32  | 7.83  | 8.67   | 10.10  | 12.40  |
| 40:1                   | 1.27            | 3.25  | 5.90  | 6.53   | 7.58   | 9.34   |
| 50:1                   | 1.02            | 2.61  | 4.73  | 5.24   | 6.09   | 7.50   |
| 60:1                   | 0.85            | 2.18  | 3.95  | 4.37   | 5.08   | 6.26   |
| 70:1                   | 0.73            | 1.87  | 3.39  | 3.76   | 4.36   | 5.38   |
| 6-Inch Center Distance |                 |       |       |        |        |        |
| 5:1                    | 11.10           | 27.30 | 45.30 | 50.10  | 57.50  | 66.80  |
| 10:1                   | 7.08            | 17.80 | 30.40 | 33.70  | 38.80  | 46.40  |
| 15:1                   | 4.98            | 12.60 | 21.60 | 23.90  | 27.60  | 33.20  |
| 20:1                   | 3.81            | 9.64  | 16.60 | 18.40  | 21.20  | 25.60  |
| 25:1                   | 3.07            | 7.78  | 13.40 | 14.90  | 17.20  | 20.70  |
| 30:1                   | 2.57            | 6.52  | 11.30 | 12.50  | 14.40  | 17.40  |
| 40:1                   | 1.94            | 4.90  | 8.47  | 9.38   | 10.80  | 13.10  |
| 50:1                   | 1.55            | 3.93  | 6.80  | 7.53   | 8.70   | 10.50  |
| 60:1                   | 1.30            | 3.28  | 5.68  | 6.29   | 7.26   | 8.79   |
| 70:1                   | 1.11            | 2.82  | 4.87  | 5.40   | 6.23   | 7.55   |
| 7-Inch Center Distance |                 |       |       |        |        |        |
| 5:1                    | 17.50           | 41.60 | 67.30 | 73.90  | 83.60  | 96.40  |
| 10:1                   | 11.20           | 27.70 | 46.20 | 51.20  | 58.70  | 68.40  |
| 15:1                   | 7.88            | 19.60 | 32.90 | 36.50  | 41.90  | 49.20  |
| 20:1                   | 6.03            | 15.00 | 25.30 | 28.00  | 32.20  | 37.90  |
| 25:1                   | 4.86            | 12.20 | 20.50 | 22.60  | 26.00  | 30.70  |
| 30:1                   | 4.07            | 10.20 | 17.20 | 19.00  | 21.80  | 25.80  |
| 40:1                   | 3.06            | 7.66  | 12.90 | 14.30  | 16.40  | 19.40  |
| 50:1                   | 2.46            | 6.15  | 10.40 | 11.50  | 13.20  | 15.60  |
| 60:1                   | 2.05            | 5.13  | 8.66  | 9.58   | 11.00  | 13.00  |
| 70:1                   | 1.76            | 4.41  | 7.43  | 8.23   | 9.46   | 11.20  |
| 8-Inch Center Distance |                 |       |       |        |        |        |
| 5:1                    | 25.90           | 59.60 | 95.20 | 104.00 | 116.00 | 134.00 |
| 10:1                   | 16.70           | 40.90 | 67.40 | 74.40  | 85.10  | 98.70  |
| 15:1                   | 11.80           | 29.00 | 48.20 | 53.20  | 61.20  | 71.00  |
| 20:1                   | 9.00            | 22.20 | 37.00 | 40.90  | 47.00  | 54.70  |
| 25:1                   | 7.26            | 18.00 | 29.90 | 33.10  | 38.00  | 44.30  |
| 30:1                   | 6.08            | 15.10 | 25.10 | 27.80  | 31.90  | 37.20  |
| 40:1                   | 4.58            | 11.30 | 18.90 | 20.90  | 24.00  | 28.00  |
| 50:1                   | 3.67            | 9.10  | 15.20 | 16.80  | 19.30  | 22.50  |
| 60:1                   | 3.07            | 7.59  | 12.70 | 14.00  | 16.10  | 18.80  |
| 70:1                   | 2.63            | 6.52  | 10.90 | 12.00  | 13.80  | 16.10  |

**Table 6. (Continued) AGMA Input Mechanical Horsepower Ratings of Cone-Drive Worm Gearing<sup>a</sup>**

| Ratio                   | Worm Speed, RPM |        |        |        |        |        |
|-------------------------|-----------------|--------|--------|--------|--------|--------|
|                         | 100             | 300    | 720    | 870    | 1150   | 1750   |
| 10-Inch Center Distance |                 |        |        |        |        |        |
| 5:1                     | 48.50           | 105.00 | 164.00 | 178.00 | 194.00 | 226.00 |
| 10:1                    | 31.40           | 73.20  | 117.00 | 129.00 | 144.00 | 166.00 |
| 15:1                    | 22.10           | 52.10  | 83.70  | 91.90  | 104.00 | 119.00 |
| 20:1                    | 16.90           | 40.00  | 64.40  | 70.70  | 79.80  | 91.80  |
| 25:1                    | 13.60           | 32.30  | 52.10  | 57.20  | 64.60  | 74.30  |
| 30:1                    | 11.40           | 27.10  | 43.70  | 48.00  | 54.20  | 62.40  |
| 40:1                    | 8.60            | 20.40  | 32.90  | 36.10  | 40.90  | 47.00  |
| 50:1                    | 6.90            | 16.40  | 26.40  | 29.00  | 32.80  | 37.80  |
| 60:1                    | 5.76            | 13.70  | 22.10  | 24.20  | 27.40  | 31.60  |
| 70:1                    | 4.94            | 11.70  | 18.90  | 20.80  | 23.50  | 27.10  |
| 12-Inch Center Distance |                 |        |        |        |        |        |
| 5:1                     | 81.30           | 167.00 | 257.00 | 271.00 | 300.00 | ...    |
| 10:1                    | 53.20           | 118.00 | 186.00 | 202.00 | 221.00 | ...    |
| 15:1                    | 37.50           | 83.90  | 133.00 | 145.00 | 159.00 | ...    |
| 20:1                    | 28.70           | 64.40  | 102.00 | 111.00 | 122.00 | ...    |
| 25:1                    | 23.10           | 52.10  | 82.70  | 90.10  | 99.10  | ...    |
| 30:1                    | 19.40           | 43.70  | 69.40  | 75.70  | 83.20  | ...    |
| 40:1                    | 14.60           | 32.90  | 52.20  | 57.00  | 62.70  | ...    |
| 50:1                    | 11.70           | 26.40  | 41.90  | 45.80  | 50.40  | ...    |
| 60:1                    | 9.77            | 22.10  | 35.00  | 38.20  | 42.10  | ...    |
| 70:1                    | 8.39            | 18.90  | 30.10  | 32.80  | 36.10  | ...    |

<sup>a</sup> These values for different rubbing speeds are based upon the use of phosphor bronze wormgears with case-hardened ground and polished steel worms lubricated with mineral oil.

**Self-locking or Irreversible Worm Gearing.**—Neglecting friction in the bearings, worm gearing is irreversible when the efficiency is zero or negative, the lead angle being equal to or less than the angle  $\phi$  of friction ( $\tan \phi =$  coefficient of friction). When worm gearing is self-locking or irreversible, this means that the worm-gear cannot drive the worm. Since the angle of friction changes rapidly with the rubbing speed, and the static angle of friction may be reduced by external vibration, it is usually impracticable to design irreversible worm gearing with any security. If irreversibility is desired, it is recommended that some form of brake be employed.

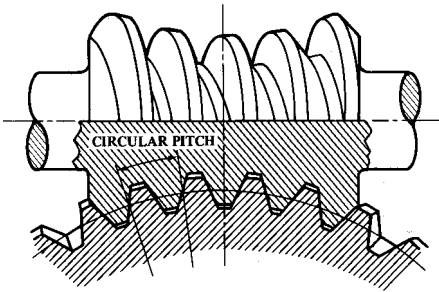
**Worm Gearing Operating Temperatures.**—The load capacity of a worm gearing lubricant at operating temperature is an important factor in establishing the continuous power-transmitting capacity of the gearing. If the churning or turbulence of the oil generates excessive heat, the viscosity of the lubricant may be reduced below its load-supporting capacity. The temperature measured in the oil sump should not, as a rule, exceed 180 to 200 degrees F. or rise more than 120 to 140 degrees F. above a surrounding air temperature of 60 degrees F. In rear axle motor vehicle transmissions, the maximum operating temperature may be somewhat higher than the figures given and usually is limited to about 220 degrees F.

**Thermal Rating.**—In some cases, especially when the worm speed is comparatively high, the horsepower capacity of worm gearing should be based upon its thermal rating instead of the mechanical rating. To illustrate, worm gearing may have a thermal rating of, say, 60 H.P., and mechanical ratings which are considerably higher than 60 for the higher

speed ranges. This means that the gearing is capable of transmitting more than 60 H.P. so far as wear and strength are concerned but not without overheating; hence, in this case a rating of 60 should be considered maximum. Of course, if the power to be transmitted is less than the thermal rating for a given ratio, then the thermal rating may be ignored.

**Water and Forced-Air Cooling.**—One method of increasing the thermal rating of a speed-reducing unit of the worm gearing type, is by installing a water-cooling coil through which water is circulated to prevent an excessive rise of the oil temperature. According to one manufacturer, the thermal rating may be increased as much as 35 per cent in this manner. Much larger increases have been obtained by means of a forced air cooling system incorporated in the design of the speed-reducing unit. A fan which is mounted on the worm shaft draws air through a double walled housing, thus maintaining a comparatively low oil bath temperature. A fan cooling system makes it possible to transmit a given amount of power through a worm-gearing unit that is much smaller than one not equipped with a fan.

**Double-enveloping Worm Gearing.**—Contact between the worm and wormgear of the conventional type of worm gearing is theoretically a line contact; however, due to deflection of the materials under load, the line is increased to a narrow band or contact zone. In attempting to produce a double-enveloping type of worm gearing (with the worm curved longitudinally to fit the curvature of the gear as shown by illustration), the problem primarily was that of generating the worm and worm-gear in such a manner as to obtain area contact between the engaging teeth. A practical method of obtaining such contact was developed by Samuel I. Cone at the Norfolk Navy Yard, and this is known as "Cone-Drive" worm gearing. The Cone generating method makes it possible to cut the worm and wormgear without any interference which would alter the required tooth form. The larger tooth bearing area and multiple tooth contact obtained with this type of worm gearing, increases the load-carrying or horsepower capacity so that as compared with a conventional worm drive a double-enveloping worm drive may be considerably smaller in size. [Table 6](#), which is intended as a general guide, gives input horsepower ratings for Cone-Drive worm gearing for various center distances of from 2 to 12 inches. These ratings are based on AGMA specifications 341, 441, and 641. They allow for starting and momentary peak overloads of up to 300 per cent of the values shown in [Table 5](#) using a service factor of 1. Factors for various types of service are given in [Table 7](#). To obtain the mechanical horsepower rating required, multiply the appropriate rating given in [Table 6](#) by the service factor taken from [Table 7](#).



\*Horsepower ratings are for Class 1 service, using splash lubrication, except for that shown in italics, for which force feed lubrication is required. Other ratios and center distances are available.



**Table 7. Service Factors for Cone-Drive Worm Gearing**

| Hours/Day | Uniform Motion | Moderate Shock | Heavy Shock | Extreme Shock |
|-----------|----------------|----------------|-------------|---------------|
| 0.5       | 0.6            | 0.8            | 0.9         | 1.1           |
| 1         | 0.7            | 0.9            | 1           | 1.2           |
| 2         | 0.9            | 1              | 1.2         | 1.3           |
| 10        | 1              | 1.2            | 1.3         | 1.5           |
| 24        | 1.2            | 1.3            | 1.5         | 1.75          |

**Thermal Horsepower Rating:** When the operation is to be continuous, consideration must be given to the possibility of overheating. For this possibility, the thermal horsepower rating given in Ex-Cell-O Corporation, Cone Drive Operations catalog must be checked. The thermal rating defines the maximum horsepower which can be transmitted continuously (30 minutes or longer). This is based on an oil sump temperature rise of 100 deg. F above the ambient temperature. This rise must not exceed 200 deg. F. If the thermal rating is lower than the mechanical rating, the unit must be selected on the basis of the thermal rating.

**Type of Drive Connection:** If either input or output shaft is connected to driver or driven mechanism by other than a direct shaft coupling, the overhead load requirement (chain pull) must be calculated by dividing the torque demand by the pitch radius of the sprocket, sheave, spur gear, or helical gear used. The result is multiplied by the overhung load factor which is: for a chain sprocket, 1.00; for spur or helical gearing, 1.25; for a V-belt sheave, 1.50; and for a flat belt sheave, 2.50. As modified by the applicable overhung load factor, this load may not exceed the overhung load rating given in the company catalog.

**Locking Considerations:** It is a common misconception that all worm gears are self-locking or non-overhauling. Actually, wormgear ratios up 15 to 1 will overhaul quite freely. Ratios from 20:1 to 40:1 can generally be considered as overhauling with difficulty, particularly from rest. Ratios above 40:1 may or may not overhaul depending on the loading, lubrication, and amount of vibration present. Therefore it is not acceptable to rely on a wormgear to prevent movement in a system. Whenever a load must be stopped or held in place, a positive mechanical device must be incorporated into the system to prevent rotation of the gearset.

**Backdriving or Overhauling:** Applications such as wheel drives that require a brake on the motor or input shaft to decelerate a high inertial load require special attention to brake selection. Wherever possible, these applications should utilize freely overhauling ratios (15:1 or less). If higher ratios are used with a brake, the gearset can, under certain conditions, lockup during deceleration and impose severe shock loading on the reducer and driven equipment.

**Stairstepping:** Self-locking ratios (generally 40:1 and higher) are susceptible to the phenomenon of "stair stepping" when back driving or overhauling. This erratic rotation of the gear set occasionally occurs when the gear set is back driven at worm speeds less than the theoretical lockup speed of the gear set and can be amplified by the rest of the drive train creating a very undesirable operating condition. "Stair stepping" can occur on drives where there is a high inertial load at the output shaft.

**Backlash:** Defined as the amount of movement at the pitch line of the gear with the worm locked and the gear set on exact center distance, backlash normally ranges from 0.003 to 0.008 inch for a 2-inch center distance set up to 0.012 to 0.020 inch for a 12-inch center distance set. When the gear set is assembled into a machine or reducer, the assembled backlash may fall outside these limits depending upon worm and gear bearing looseness and the actual center distance used.

**Lubrication:** Lubricating oils for use in double-enveloping worm drive units should be well refined petroleum oils of high quality. They should not be corrosive to gears or bear-

ings and they must be neutral in reaction and free from grit or abrasives. They should have good defoaming properties and good resistance to oxidation. For worm gears, add up to 3 to 10 per cent of acid less tallow or similar animal fat.

The oil bath temperature should not exceed 200 degrees F. Where worm speed exceeds 3600 revolutions per minute, or 2000 feet per minute rubbing speed, a force feed lubrication may be required. Auxiliary cooling by forced air, water coils in sump, or an oil heat exchanger may be provided in a unit where mechanical horsepower rating is in excess of the thermal rating, if full advantage of mechanical capacity is to be realized. The rubbing speed ( $V$ ), in feet per minute, may be calculated from the formula:  $V = 0.262 \times \text{worm thread diameter in inches} \times \text{worm RPM} \div \cos \text{lead angle}$ .

**Worm Thread Cutting.**—Worm threads are cut either by using some form of thread-cutting lathe and a single-point tool, by using a thread milling machine and a disk type of cutter, or by using a gear-hobbing machine. Single-thread worms usually have an included angle of 29 degrees. Many worm gears used at the present time, especially for power transmission, have thread angles larger than 29 degrees because multiple-thread worms are used to obtain higher efficiency, and larger thread angles are necessary in order to avoid excessive under-cutting of the worm-wheel teeth. According to the recommended practice of the American Gear Manufacturers' Association, worms having triple and quadruple threads should have a thread angle of 40 degrees, and some manufacturers of worm gearing, especially when the helix or lead angle of the thread is quite large, use a thread angle of 60 degrees.

If the helix or lead angle of the worm thread exceeds 15 or 20 degrees, it is common practice to reduce the depth of the thread by using the normal instead of the axial pitch of the worm in the formulas. Thus, if  $P_n$  equals normal pitch, the total depth equals  $P_n \times 0.6866$  instead of  $P_n = 0.6866$ . This normal pitch  $P_n$ , equals  $P_n \times \cos$ ine of the helix angle. According to the recommended practice of the American Gear Manufacturers' Association, the whole depth for single- and double-thread worms equals  $P_n \times 0.686$ , and for triple and quadruple-thread worms equals  $P_n \times 0.623$ .

**Wormgear Hobs.**—An ideal hob would have exactly the same pitch diameter and lead angle as the worm; repeated sharpening, however, would reduce the hob size because of the form-relieved teeth. Hence, the general practice is to make hobs (especially the radial or in-feed type) "over-size" to provide a grinding allowance and increase the hob life. An over-size hob has a larger pitch diameter and smaller lead angle than the worm, but repeated sharpenings gradually reduce these differences. To compensate for the smaller lead angle of an over-size hob, the hob axis may be set 90-degrees relative to the wormgear axis plus the difference between the lead angle of the worm at the pitch line, and the lead angle of the over-size hob at its pitch line. This angular adjustment is in the direction required to increase the inclination of the wormgear teeth so that the axis of the assembled worm will be 90 degrees from the wormgear axis. ("Lead angle" is measured from a plane perpendicular to worm or hob axis.)

*Hob Diameter Formulas:* If

$D$  = pitch diameter of worm;

$D_h$  = pitch diameter of hob;

$A$  = addendum of worm and wormgear;

$C$  = clearance between worm and worm-gear;

$S$  = increase in hob diameter or "over-size" allowance for sharpening.

Outside diameter  $O$  of hob =  $D + 2A + 2C + S$

Root diameter of hob =  $D - 2A$

Pitch diameter  $D_h$  of hob =  $O - (2A + 2C)$

*Sharpening Allowance:* Hobs for ordinary commercial work are given the following sharpening allowance, according to the recommended practice of the AGMA: In this for-

mula,  $h$  = helix angle of hob at outside diameter measured from axis;  $H$  = helix angle of hob at pitch diameter measured from axis.

$$\text{Sharpening allowance} = 0.075 \times \text{normal pitch} \times \left[ \frac{16 - (h - H)}{16} \right] + 0.010$$

*Number of Flutes or Gashes in Hobs:* For finding the approximate number of flutes in a hob, the following rule may be used: Multiply the diameter of the hob by 3, and divide this product by twice the linear pitch. This rule gives suitable results for hobs for general purposes. Certain modifications, however, are necessary as explained in the following paragraph.

It is important that the number of flutes or gashes in hobs bear a certain relation to the number of threads in the hob and the number of teeth in the wormgear to be hobbled. In the first place, avoid having a common factor between the number of threads in the hob and the number of flutes; that is, if the worm is double-threaded, the number of gashes should be, say, 7 or 9, rather than 8. If it is triple threaded, the number of gashes should be 7 or 11, rather than 6 or 9. The second requirement is to avoid having a common factor between the number of threads in the hob and the number of teeth in the wormgear. For example, if the number of teeth in the wheel is 28, it would be best to have the hob triple-threaded, as 3 is not a factor of 28. Again, if there were to be 36 threads in the wormgear, it would be preferable to have 5 threads in the hob.

The cutter used in gashing hobs should be from  $\frac{1}{8}$  to  $\frac{1}{4}$  inch thick at the periphery, according to the pitch of the thread of the hob. The width of the gash at the periphery of the hob should be about 0.4 times the pitch of the flutes. The cutter should be sunk into the hob blank so that it reaches from  $\frac{3}{16}$  to  $\frac{1}{4}$  inch below the root of the thread.

**Helical Fluted Hobs.**—Hobs are generally fluted parallel with the axis, but it is obvious that the cutting action will be better if they are fluted on a helix at right angles with the thread helix. The difficulty of relieving the teeth with the ordinary backing-off attachment is the cause for using a flute parallel with the axis. Flutes cut at right angles to the direction of the thread can, however, also be relieved, if the angle of the flutes is slightly modified. In order to relieve hobs with a regular relieving attachment, it is necessary that the number of teeth in one revolution along the thread helix be such that the relieving attachment can be geared to suit it. The following method makes it possible to select an angle of flute that will make the flute come approximately at right angles to the thread, and at the same time the angle is so selected that the relieving attachment can be properly geared for relieving the hob.

Let

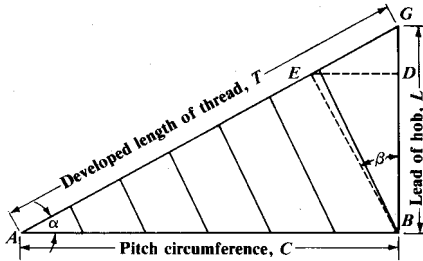
$C$  = pitch circumference

$T$  = developed length of thread in one turn;

$N$  = number of teeth in one turn along thread helix;

$F$  = number of flutes;

$\alpha$  = angle of thread helix.



Then  $C \div F =$  length of each small division on pitch circumference;  
 $(C \div F) \times \cos \alpha =$  length of division on developed thread;  
 $C \div \cos \alpha = T$

Hence

$$\frac{T}{(C \div F) \cos \alpha} = N = \frac{F}{\cos \alpha^2}$$

Now, if

$$\alpha = 30 \text{ degrees}, N = 1\frac{1}{3}F;$$

$$\alpha = 45 \text{ degrees}, N = 2F;$$

$$\alpha = 60 \text{ degrees}, N = 4F.$$

In most cases, however, such simple relations are not obtained. Suppose for example that  $F = 7$ , and  $\alpha = 35$  degrees. Then  $N = 10.432$ , and no gears could be selected that would relieve this hob. By a very slight change in the helix angle of the flute, however, we can change  $N$  to 10 or  $10\frac{1}{2}$ ; in either case we can find suitable gears for the relieving attachment.

The rule for finding the modified helical lead of the flute is: Multiply the lead of the hob by  $F$ , and divide the product by the difference between the desired values of  $N$  and  $F$ .

Hence, the lead of flute required to make  $N = 10$  is:

$$\text{Lead of hob} \times (7 \div 3).$$

To make  $N = 10\frac{1}{2}$ , we have:

$$\text{Lead of flute} = \text{lead of hob} \times (7 \div 3.5).$$

From this the angle of the flute can easily be found.

That the rule given is correct will be understood from the following consideration. Change the angle of the flute helix  $\beta$  so that  $AG$  contains the required number of parts  $N$  desired. Then  $EG$  contains  $N - F$  parts. But  $\cot \beta = BD \div ED$  and by the law of similar triangles,

$$BD = \frac{F}{N} \times BG, \text{ and } ED = \frac{N - F}{N} C$$

The lead of the helix of the flute, however, is  $C \times \cot \beta$ .

Hence, the required lead of the helix of the flute:

$$C \times \cot \beta = \frac{F}{N - F} L$$

This formula makes it possible always to flute hobs so that they can be conveniently relieved, and at the same time have the flutes at approximately right angles to the thread.

**Gear Shaving**

The purpose of gear shaving is to correct errors in indexing, helix angle, tooth profile, and eccentricity by removing small amounts of material from the working surfaces of gear teeth. Special shaving cutters are used and have tooth flanks with sharp-edged grooves that traverse the tooth surfaces of the gear to be corrected as the hardened, driven cutter and the softer (30-35 Rockwell C) free-running gear are rotated in mesh on crossed axes in a special machine. The crossed angle is usually between 10 and 15 degrees, or half the difference between the helix angles of cutter and gear. In conventional shaving, the gear is held between live centers on the machine table, which is moved parallel to the gear axis, and is fed into contact with the cutter at each successive stroke of the table. Cutter speeds of up to 450 surface feet/min are commonly used.

The crossed axes cause the sharp-edged grooves on the cutter to traverse the tooth surfaces on the gear as cutter and gear rotate, resulting in a shearing action that cuts fine slivers from the gear tooth surfaces. At the same time, contact between the meshing sets of teeth has a burnishing action on the gear teeth, improving the surface finish. Shaving can remove 60-80 per cent of errors in a gear, and can produce accuracies of 0.0002 in. on the involute profile, 0.0003 in. on tooth-to-tooth spacing, and 0.0002 in. on lead or parallelism.

Gear-shaving machines have built-in mechanisms that can be used to rock the table as it traverses, producing crowned gear teeth that are slightly thicker at the center than at the ends. In the faster diagonal shaving method, the traversing movement of the table is at an angle to the gear axis, so that the cutter grooves move more rapidly across the gear, increasing the shaving action.

**MISCELLANEOUS TOPICS****Mathematics**

**Catenary Curve.**—The catenary is the curve assumed by a string or chain of uniform weight hanging freely between two supports. The cables of a suspension bridge, if uniformly loaded, assume the form of the catenary curve. It has, therefore, considerable importance in structural engineering.

**Mechanics**

**Running Balance.**—When a part such as a drum, rotor, crankshaft, pulley, etc., is properly tested for balance while revolving, and any appreciable lack of balance is corrected on the basis of such test, the part is said to be in running or dynamic balance. Special balancing machines are used to determine the magnitude and location of unbalanced masses while the part is revolving; hence, the test is applied under operating conditions, which is not true of the test for static or standing balance.

**Properties of Materials**

**Copper-Clad Steel.**—A material generally used in the form of wire, in which a steel wire is covered with a coating of copper. It is produced either by alloying the copper with the surface of the metal or by welding it onto the surface. When the copper is alloyed with the surface, it is brought to a molten state before being applied, while, when welded to the surface, it is merely in a plastic state.

**Truflex.**—Thermostatic bimetal made in different types for automatically controlling temperature ranges of from —50 degrees F. to 1000 degrees F. Used for automatically controlling the operation of devices either heated or cooled by electricity, oil, or gas, as, for example: electric refrigerators, irons, toasters, gas ranges, water heaters, and domestic oil burners. Available in helical and spiral coils, rings, flat pieces, U-shapes, and in sheets up to 8 inches wide.

**Firebrick Properties.**—Brick intended for use in furnaces, flues, and cupolas, where the brickwork is subjected to very high temperatures, is generally known as "firebrick." There are several classes of firebrick, such as fireclay brick, silica brick, bauxite brick, chrome brick, and magnesia brick.

Ordinary firebricks are made from fireclay; that is, clays which will stand a high temperature without fusion, excessive shrinkage, or warping. There is no fixed standard of refractoriness for fireclay, but, as a general rule, no clay is classed as a fireclay that fuses below 2900 degrees F.

Fireclays vary in composition, but they all contain high percentages of alumina and silica, and only small percentages of such constituents as oxide of iron, magnesia, lime, soda, and potash. A great number of different kinds of firebrick are manufactured to meet the various conditions to which firebricks are subjected. Different classes of bricks are required to withstand different temperatures, as well as the corrosive action of gases, the chemical action of furnace charges, etc.

The most common firebrick will melt at a temperature ranging from 2830 to 3140 degrees F.; bauxite brick, from 2950 to 3245 degrees F.; silica brick, from 3090 to 3100 degrees F.; chromite brick, at 3720 degrees F.; and magnesia brick, at 4950 degrees F.

**Inconel.**—This heat resistant alloy retains its strength at high heats, resists oxidation and corrosion, has a high creep strength and is non-magnetic. It is used for high temperature applications (up to 2000 degrees F.) such as engine exhaust manifolds and furnace and heat treating equipment. Springs operating at temperatures up to 700 degrees F. are also made from it.

*Approximate Composition:* Nickel, 76; copper, 0.20; iron, 7.5; chromium, 15.5; silicon, 0.25; manganese, 0.25; carbon, 0.08; and sulphur, 0.007.

*Physical Properties:* Wrought Inconel in the annealed, hot-rolled, cold-drawn, and hard temper cold-rolled conditions exhibits yield strengths (0.2 per cent offset) of 35,000, 60,000, 90,000, and 110,000 pounds per square inch, respectively; tensile strengths of 85,000, 100,000, 115,000, and 135,000 pounds per square inch, respectively; elongations in 2 inches of 45, 35, 20, and 5 per cent, respectively; and Brinell hardnesses of 150, 180, 200, and 260, respectively.

**Inconel "X".**—This alloy has a low creep rate, is age-hardenable and non-magnetic, resists oxidation and exhibits a high strength at elevated temperatures. Uses include the making of bolts and turbine rotors used at temperatures up to 1500 degrees F., aviation brake drum springs and relief valve and turbine springs with low load loss or relaxation for temperatures up to 1000 degrees F.

*Approximate Composition:* Nickel, 73; copper, 0.2 maximum; iron, 7; chromium, 15; aluminum, 0.7; silicon, 0.4; manganese, 0.5; carbon, 0.04; sulphur, 0.007; columbium, 1; and titanium, 2.5.

*Average Physical Properties:* Wrought Inconel "X" in the annealed and age-hardened hot-rolled conditions exhibits yield strengths (0.2 per cent offset) of 50,000 and 120,000 pounds per square inch, respectively; tensile strengths of 115,000 and 180,000 pounds per square inch, respectively; elongations in 2 inches of 50 and 25 per cent, respectively; and Brinell hardnesses of 200 and 360, respectively.

**Lodestone.**—The most highly magnetic substances are iron and steel. Nickel and cobalt are also magnetic, but in a less degree. The name "magnet" has been derived from that of Magnesia, a town in Asia Minor, where an iron ore was found in early days which had the power of attracting iron.

This ore is known as magnetite and consists of about 72 per cent, by weight, of iron and 28 per cent of oxygen, the chemical formula being  $Fe_3O_4$ . The ore possessing this magnetic property is also known as lodestone. If a bar of hardened steel is rubbed with a piece of lodestone, it will acquire magnetic properties similar to those of the lodestone itself.

**Metallography.**—The science or study of the microstructure of metal is known by most metallurgists as "metallography." The name "crystallography" is also used to some extent. The examination of metals and metal alloys by the aid of the microscope has become one of the most effective methods of studying their properties, and it is also a valuable means of controlling the quality of manufactured metallic articles and of testing the finished product. In preparing the specimen to be examined, a flat surface is first formed by filing or grinding, and this surface is then given a high polish, which is later subjected to the action of a suitable acid or etching reagent, in order to reveal clearly the internal structure of the metal when the specimen is examined under the microscope. This process shows clearly to an experienced observer the effect of variation in composition, heat-treatment, etc., and in many cases it has proved a correct means of determining certain properties of industrial products that a chemical analysis has failed to reveal.

*Preparing Hardened Steel for Microscopic Study:* To cause the constituents of the specimen to contrast with one another as seen through the microscope is the desired end, and a reagent is used which acts differently towards these elements; generally this reagent acts on one element more than on another so that the one least affected reflects the light from the faces of its crystals while the etched part absorbs the light, and, therefore, appears dark when photographed.

In etching specimens to develop the constituents of hardened anti tempered steels, very good results are obtained with sulphurous acid that is composed of 4 parts of sulphur dioxide to 96 parts of distilled water. The specimens are immersed in this, face upward, and removed as soon as the polished surface is frosted. This takes from 7 seconds to 1 minute.

They are then rinsed with water and dried with alcohol. Very thin layers of iron sulphide are deposited on the different constituents in different thicknesses, and this gives them different colors. Austenite remains a pale brown; martensite is given a pale blue and deep blue and brown color; troostite is made very dark; sorbite is uncolored; cementite exhibits a brilliant white; and ferrite is made dark brown. When the etching has proceeded to the desired extent, the specimen is at once washed thoroughly in order to remove all trace of the etching reagent. Usually it is simply rinsed with water, but frequently the washing is done with absolute alcohol, while ether and chloroform are also sometimes used.

The apparatus used for examining the etched surfaces of metals is composed of a microscope and camera combined with an arc lamp or other means of illumination.

*Microscopic Study of Steel:* Steel, in particular, shows many changes of structure due to the mechanical and thermal treatment, so that the microscope has become a very valuable instrument with which to inspect steel. To one who understands what the different formations of crystalline structure denote, the magnified surface reveals the temperature at which the steel was hardened, or at which it was drawn, and the depth to which the hardness penetrated. It also shows whether the steel was annealed or casehardened, as well as the depth to which the carbon penetrated. The carbon content can be closely judged, when the steel is annealed, and also how much of it is in the graphitic state in the high carbon steels. The quantity of special elements that is added to steel, such as nickel, chromium, tungsten, etc., can also be estimated, when the alloy to be examined has been put through its prescribed heat-treatment. Likewise, the impurities that may be present are clearly seen, regardless of whether they are of solid or gaseous origin.

**Micarta.**—Micarta is a non-metallic laminated product of specially treated woven fabric. By means of the various processes through which it is passed, it becomes a homogenous structure with physical properties which make it especially adapted for use as gears and pinions. Micarta can be supplied either in plate form or cut into blanks. It may also be molded into rings or on metal hubs for applications such as timing gears, where quantity production is attained. Micarta may be machined in the ordinary manner with standard tools and equipment.

Micarta gears do not require shrouds or end plates except where it is desired to provide additional strength for keyway support or to protect the keyway and bore against rough usage in mounting drive fits and the like. When end plates for hub support are employed they should extend only to the root of the tooth or slightly less.

*Properties:* The physical and mechanical properties of Micarta are as follows: weight per cubic inch, 0.05 pound; specific gravity, 1.4; oil absorption, practically none; shrinkage, swelling or warping, practically none up to 100 degrees C.; coefficient of expansion per inch per degree Centigrade, 0.00002 inch in the direction parallel to the laminations (edgewise), 0.00009 inch in the direction perpendicular to the laminations (flat wise); tensile strength, edgewise, 10,000 pounds per square inch; compressive strength, flat wise, 40,000 pounds per square inch; compressive strength, edgewise, 20,000 pounds per square inch; bending strength, flatwise, 22,000 pounds per square inch; bending strength, edgewise, 20,000 pounds per square inch.

**Monel.**—This general purpose alloy is corrosion-resistant, strong, tough and has a silvery-white color. It is used for making abrasion- and heat-resistant valves and pump parts, propeller shafts, laundry machines, chemical processing equipment, etc.

*Approximate Composition:* Nickel, 67; copper, 30; iron, 1.4; silicon, 0.1; manganese, 1; carbon, 0.15; and sulphur 0.01.

*Average Physical Properties:* Wrought Monel in the annealed, hot-rolled, cold-drawn, and hard temper cold-rolled conditions exhibits yield strengths (0.2 per cent offset) of 35,000, 50,000, 80,000, and 100,000 pounds per square inch, respectively; tensile strengths of 75,000, 90,000, 100,000, and 110,000 pounds per square inch, respectively;



elongations in 2 inches of 40, 35, 25, and 5 per cent, respectively; and Brinell hardnesses of 125, 150, 190, and 240, respectively.

**“R” Monel.**—This free-cutting, corrosion resistant alloy is used for automatic screw machine products such as bolts, screws and precision parts.

*Approximate Composition:* Nickel, 67; copper, 30; iron, 1.4; silicon, 0.05; manganese, 1; carbon, 0.15; and sulphur, 0.035.

*Average Physical Properties:* In the hot-rolled and cold-drawn conditions this alloy exhibits yield strengths (0.2 per cent offset) of 45,000 and 75,000 pounds per square inch, respectively; tensile strengths of 85,000 and 90,000 pounds per square inch, respectively; elongations in 2 inches of 35, and 25 per cent, respectively; and Brinell hardnesses of 145 and 180, respectively.

**“K” Monel.**—This strong and hard alloy, comparable to heat-treated alloy steel, is age-hardenable, non-magnetic and has low-sparking properties. It is used for corrosive applications where the material is to be machined or formed, then age hardened. Pump and valve parts, scrapers, and instrument parts are made from this alloy.

*Approximate Composition:* Nickel, 66; copper, 29; iron, 0.9; aluminum, 2.75; silicon, 0.5; manganese, 0.75; carbon, 0.15; and sulphur, 0.005.

*Average Physical Properties:* In the hot-rolled, hot-rolled and age-hardened, cold-drawn, and cold-drawn and age-hardened conditions the alloy exhibits yield strengths (0.2 per cent offset) of 45,000, 110,000, 85,000, and 115,000 pounds per square inch, respectively; tensile strengths of 100,000, 150,000, 115,000, and 155,000 pounds per square inch, respectively; elongations in 2 inches of 40, 25, 25, and 20 per cent, respectively; and Brinell hardnesses of 160, 280, 210, and 290, respectively.

**“KR” Monel.**—This strong, hard, age-hardenable and non-magnetic alloy is more readily machinable than “K” Monel. It is used for making valve stems, small parts for pumps, and screw machine products requiring an age-hardening material that is corrosion-resistant.

*Approximate Composition:* Nickel, 66; copper, 29; iron, 0.9; aluminum, 2.75; silicon, 0.5; manganese, 0.75; carbon, 0.28; and sulphur, 0.005.

*Average Physical Properties:* Essentially the same as “K” Monel.

**“S” Monel.**—This extra hard casting alloy is non-galling, corrosion-resisting, non-magnetic, age-hardenable and has low-sparking properties. It is used for gall-resistant pump and valve parts which have to withstand high temperatures, corrosive chemicals and severe abrasion.

*Approximate Composition:* Nickel, 63; copper, 30; iron, 2; silicon, 4; manganese, 0.75; carbon, 0.1; and sulphur, 0.015.

*Average Physical Properties:* In the annealed sand-cast, as-cast sand-cast, and age-hardened sand-cast conditions it exhibits yield strengths (0.2 per cent offset) of 70,000, 100,000, and 100,000 pounds per square inch, respectively; tensile strengths of 90,000, 130,000, and 130,000 pounds per square inch, respectively; elongations in 2 inches of and 3, 2, and 2 per cent, respectively; and Brinell hardnesses of 275, 320, and 350, respectively.

**“H” Monel.**—An extra hard casting alloy with good ductility, intermediate strength and hardness that is used for pumps, impellers and steam nozzles.

*Approximate Composition:* Nickel, 63; copper, 31; iron, 2; silicon, 3; manganese, 0.75; carbon, 0.1; and sulphur, 0.015.

*Average Physical Properties:* In the as-cast sand-cast condition this alloy exhibits a yield strength (0.2 per cent offset) of 60,000 pounds per square inch, a tensile strength of 100,000 pounds per square inch, an elongation in 2 inches of 15 per cent and a Brinell hardness of 210.

**Nichrome.**—“Nichrome” is the trade name of an alloy composed of nickel and chromium, which is practically non-corrosive and far superior to nickel in its ability to withstand high

temperatures. Its melting point is about 1550 degrees C. (about 2800 degrees F.). Nichrome shows a remarkable resistance to sulphuric and lactic acids. In general, nichrome is adapted for annealing and carburizing boxes, heating retorts of various kinds, conveyor chains subjected to high temperatures, valves and valve seats of internal combustion engines, molds, plungers and conveyors for use in the working of glass, wire baskets or receptacles of other form that must resist the action of acids, etc. Nichrome may be used as a substitute for other materials, especially where there is difficulty from oxidation, pitting of surfaces, corrosion, change of form, or lack of strength at high temperatures. It can be used in electrically-heated appliances and resistance elements. Large plates of this alloy are used by some manufacturers for containers and furnace parts, and when perforated, as screens for use in chemical sifting and ore roasting apparatus, for services where temperatures between 1700 degrees F. and 2200 degrees F. are encountered.

*Strength of Nichrome:* The strength of a nichrome casting, when cold, varies from 45,000 to 50,000 pounds per square inch. The ultimate strength at 200 degrees F. is 94,000 pounds per square inch; at 400 degrees F., 91,000 pounds per square inch; at 600 degrees F., 59,000 pounds per square inch; and at 800 degrees F., 32,000 pounds per square inch. At a temperature of 1800 degrees F., nichrome has a tensile strength of about 30,000 pounds per square inch, and it is tough and will bend considerably before breaking, even when heated red or white hot.

*Nichrome in Cast Iron:* Because of the irregularity of the castings, the numerous cores required, and the necessity for sound castings, gray iron with a high silicon content has been the best cast iron available to the automotive industry. Attempts have been made to alloy this metal in such a way that the strength and hardness would be increased, but considerable difficulty has been experienced in obtaining uniform results. Nickel has been added to the cupola with success, but in the case of automotive castings, where a large quantity of silicon is present, the nickel has combined with the silicon in forming large flakes of graphite, which, of course, softens the product. To offset this, chromium has also been added, but it has been uncertain just what the chromium content of the poured mixture should be, as a considerable amount of the chromium oxidizes.

Nichrome (Grade B) may be added to the ladle to obtain chromium and nickel in definite controllable amounts. The analysis of this nichrome is, approximately: Nickel, 60 per cent; chromium, 12 per cent; and iron, 24 per cent. It is claimed that the process produces castings of closer grain, greater hardness, greater resistance to abrasion, increased durability, improved machinability, and decreased brittleness. Nichrome-processed iron is suitable for casting internal-combustion engine cylinders; electrical equipment, where a control of the magnetic properties is desired; cast-iron cams; iron castings of thin sections where machinability and durability are factors; electrical resistance grids; pistons; piston-rings; and water, steam, gas, and other valves.

**Nickel Alloy for Resisting Acids.**—The resistance of nickel to acids is considerably increased by an addition of tantalum. Ordinarily from 5 to 10 per cent may be added, but the resistance increases with an increasing percentage of tantalum. An alloy of nickel with 30 per cent tantalum, for example, can be boiled in aqua regia or any other acid without being affected. The alloy is claimed to be tough, easily rolled, capable of being hammered or drawn into wire. The nickel loses its magnetic quality when alloyed with tantalum. The alloy can be heated in the open air at a high temperature without oxidizing. The method of producing the alloy consists in mixing the two metals in a powdered form, compressing them at high pressure, and bringing them to a high heat in a crucible or quartz tube in a vacuum. For general purposes, the alloy is too expensive.

**Duronze.**—An alloy of high resistance to wear and corrosion, composed of aluminum, copper, and silicon, with a tensile strength of 90,000 pounds per square inch. Developed for the manufacture of valve bushings for valves that must operate satisfactorily at high pressures and high temperatures without lubrication.

**Aluminum Alloys, Wrought, Sheet.**—*Physical Properties:* In the form of sheets, the tensile strength varies from 35,000 for soft temper to 62,000 pounds per square inch for heat-treated sheets, and the elongation in 2 inches from 12 to 18 per cent. The yield strength of a heat-treated sheet is about 40,000 pounds per square inch minimum.

**Plow-steel Wire Rope.**—The name “plow” steel originated in England and was applied to a strong grade of steel wire used in the construction of very strong ropes employed in the mechanical operation of plows. The name “plow” steel, however, has become a commercial trade name, and, applied to wire, simply means a high-grade open-hearth steel of a tensile strength in wire of from 200,000 to 260,000 pounds per square inch of sectional area. A strength of 200,000 pounds per square inch is obtained in wire about 0.200 inch in diameter. Plow steel when used for wire ropes has the advantage of combining lightness and great strength. It is a tough material, but not as pliable as crucible steel. The very highest grade of steel wire used for wire rope is made from special steels ranging in tensile strength in wire from 220,000 to 280,000 pounds per square inch of sectional area. This steel is especially useful when great strength, lightness, and abrasive resisting qualities are required.

**Type Metal.**—Antimony gives to metals the property of expansion on solidification, and hence, is used in type metal for casting type for the printing trades to insure completely filling the molds. Type metals are generally made with from 5 to 25 per cent of antimony, and with lead, tin and sometimes a small percentage of copper as the other alloying metals.

The compositions of a number of type metal alloys are as follows (figures given are percentages): lead 77.5, tin 6.5, antimony 16; lead 70, tin, 10, antimony 18, copper, 2; lead 63.2, tin 12, antimony 24, copper 0.8; lead 60.5, tin 14.5, antimony 24-25, copper 0.75; lead 60, tin 35, antimony 5; and lead 55.5, tin 40, antimony 4.5.

A high grade of type metal is composed of the following percentages: lead 50; tin 25; and antimony 25.

**Vanadium Steel.**—The two most marked characteristics of vanadium steel are its high tensile strength and its high elastic limit. Another equally important characteristic is its great resistance to shocks; vanadium steel is essentially a non-fatigue metal, and, therefore, does not become crystallized and break under repeated shocks like other steels. Tests of the various spring steels show that, when subjected to successive shocks for a considerable length of time, a crucible carbon-steel spring was broken by 125,000 alternations of the testing machine, while a chrome-vanadium steel spring withstood 5,000,000 alternations, remaining unbroken. Another characteristic of vanadium steel is its great ductility. Highly-tempered vanadium-steel springs may be bent sharply, in the cold state, to an angle of 90 degrees or more, and even straightened again, cold, without a sign of fracture; vanadium-steel shafts and axles may be twisted around several complete turns, in the cold state, without fracture. This property, combined with its great tensile strength, makes vanadium steel highly desirable for this class of work, as well as for gears which are subjected to heavy strains or shocks upon the teeth. Chromium gives to steel a brittle hardness which makes it very difficult to forge, machine, or work, but vanadium, when added to chrome-steel, reduces this brittle hardness to such an extent that it can be machined as readily as an 0.40-per-cent carbon steel, and it forges much more easily. Vanadium steels ordinarily contain from 0.16 to 0.25 per cent of vanadium. Steels of this composition are especially adapted for springs, car axles, gears subjected to severe service, and for all parts which must withstand constant vibration and varying stresses. Vanadium steels containing chromium are used for many automobile parts, particularly springs, axles, driving-shafts, and gears.

**Wood's Metal.**—The composition of Wood's metal, which is a so-called “fusible metal,” is as follows: 50 parts of bismuth, 25 parts of lead, 12.5 parts of tin and 12.5 parts of cadmium. The melting point of this alloy is from 66 to 71 degrees centigrade (151 to 160 degrees F. approximately).

**Lumber.**—Lumber is the product of the saw and planing mill not further manufactured than by sawing, resawing, and passing lengthwise through a standard planing machine, cross-cutting to length and working. When not in excess of one-quarter inch thickness and intended for use as veneering it is classified as veneer. According to the Simplified Practice Recommendations promulgated by the National Bureau of Standards, lumber is classified by its principal use as: yard lumber, factory and shop lumber, and structural lumber.

*Yard lumber* is defined as lumber of all sizes and patterns which is intended for general building purposes. Its grading is based on intended use and is applied to each piece without reference to size and length when graded and without consideration to further manufacture. As classified by size it includes: strips, which are yard lumber less than 2 inches thick and less than 8 inches wide; boards, which are yard lumber less than 2 inches thick but 8 inches or more wide; dimension, which includes all yard lumber except strips, boards and timbers; and timbers, which are yard lumber of 5 or more inches in the least dimension.

*Factory and shop lumber* is defined as lumber intended to be cut up for use in further manufacture. It is graded on the basis of the percentage of the area which will produce a limited number of cuttings of a specified, or of a given minimum, size and quality.

*Structural lumber* is defined as lumber that is 2 or more inches thick and 4 or more inches wide, intended for use where working stresses are required. The grading of structural lumber is based on the strength of the piece and the use of the entire piece. As classified by size and use it includes *joists* and *planks*—lumber from 2 inches to but not including 5 inches thick, and 4 or more inches wide, of rectangular cross section and graded with respect to its strength in bending, when loaded either on the narrow face as joist or on the wide face as plank; *beams* and *stringers*—lumber of rectangular cross section 5 or more inches thick and 8 or more inches wide and graded with respect to its strength in bending when loaded on the narrow face; and *posts* and *timbers*—pieces of square or approximately square cross section 5 by 5 inches and larger and graded primarily for use as posts or columns carrying longitudinal load, but adapted to miscellaneous uses in which strength in bending is not especially important.

**Lumber, Manufactured.**—According to the Simplified Practice Recommendations promulgated by the National Bureau of Standards, lumber may be classified according to the extent which it is manufactured as:

*Rough lumber* which is lumber that is undressed as it comes from the saw.

*Surfaced lumber* which is lumber that is dressed by running it through a planer and may be surfaced on one or more sizes and edges.

*Worked lumber* which is lumber that has been run through a matching machine, sticker or molder and includes: *matched lumber* which has been worked to provide a close tongue-and-groove joint at the edges or, in the case of end-matched lumber, at the ends also; *ship-lapped lumber* which has been worked to provide a close rabbetted or lapped joint at the edges; and *patterned lumber* which has been shaped to a patterned or molded form.

**Lumber Water Content.**—The origin of lumber has a noticeable effect on its water content. Lumber or veneer (thin lumber produced usually by rotary cutting or flat slicing, sometimes by sawing), when produced from the log, contains a large proportion of water, ranging from 25 to 75 per cent of the total weight. One square foot (board measure, one inch thick) of gum lumber, weighing approximately five pounds when sawed, will be reduced to about three pounds when its water content of approximately one quart has been evaporated. Oak grown on a hillside may contain only a pint (approximately 1 lb.) and swamp gum may have from 2 to 4 pints of water per square foot, board measure. This water content of wood exists in two forms—free moisture and cell moisture. The former is readily evaporable in ordinary air drying, but the latter requires extensive air drying (several years) or artificial treatment in kilns. It is possible to use artificial means to remove the free moisture, but a simple air exposure is usually more economical.

## Dimensioning, Gaging, and Measuring

**Transfer Calipers.**—Calipers provided with an auxiliary arm which can be located so that the calipers may be opened or closed to the original setting, if required. Calipers of this type are generally used for inside measurements, and are employed for measuring recesses where it is necessary to move the caliper points in order to remove the calipers from the place where the measurement is taken.

**Wheatstone Bridge.**—The most generally used method for the measurement of the ohmic resistance of conductors is by the use of the *Wheatstone bridge*. In a simple form (See Fig. 1.) it comprises two resistance coils the ratio of the resistances of which is known, and a third, generally adjustable, resistance of known value. These are connected in circuit with the unknown resistance to be measured, a galvanometer, and a source of current, as in the diagram.

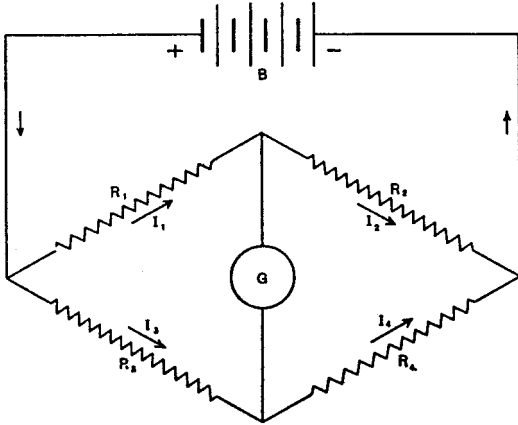


Fig. 1. Wheatstone Bridge

The adjustable resistance and the "bridge arms," if necessary, are adjusted until the galvanometer indicates no flow of current. The value of the unknown resistance is thus measured in terms of the known resistance and the known ratio of the bridge arms. In the diagram,  $R_1$ ,  $R_2$ ,  $R_3$ , and  $R_4$  are resistances;  $B$  a source of electromotive force and  $I_1$ ,  $I_2$ ,  $I_3$  and  $I_4$  currents through the resistances;  $G$  is a galvanometer. If the relation of the various resistances is such that no current flows through  $G$ , then  $I_1$  equals  $I_2$ , and  $I_3$  equals  $I_4$ ; also  $I_1R_1$  equals  $I_3R_3$ , and  $I_2R_2$  equals  $I_4R_4$ , there being no electromotive forces in the triangles  $R_1R_3G$  and  $R_2R_4G$ . It follows, therefore, that

$$\frac{I_1}{I_3} = \frac{R_3}{R_1}, \quad \text{and} \quad \frac{I_2}{I_4} = \frac{R_4}{R_2}$$

and hence, as

$$\frac{I_1}{I_3} = \frac{I_2}{I_4}, \quad \text{it follows that} \quad \frac{R_3}{R_1} = \frac{R_4}{R_2}$$

If one of these resistances,  $R_1$  for instance, is unknown, it may then be found through the equation:

$$R_1 = \frac{R_2 R_3}{R_4}$$

Wheatstone bridges are made in many forms. The three known resistances are made adjustable and are usually made of many spools of special resistance wire. The resistances are usually varied by short-circuiting a greater or smaller number of these spools.

### Tools and Tooling

**Rotary Files and Burs.**—Rotary files and burs are used with power-operated tools, such as flexible- or stationary-shaft machines, drilling machines, lathes, and portable electric or pneumatic tools, for abrading or smoothing metals and other materials. Corners can be broken and chamfered, burs and fins removed, holes and slots enlarged or elongated, and scale removed in die-sinking, metal patternmaking, mold finishing, toolmaking and casting operations.

The difference between rotary files and rotary burs, as defined by most companies, is that the former have teeth cut by hand with hammer and chisel, whereas the latter have teeth or flutes ground from the solid blank after hardening, or milled from the solid blank before hardening. (At least one company, however prefers to differentiate the two by use and size: The larger-sized general purpose tools with  $\frac{1}{4}$ -inch shanks, whether hand cut or ground, are referred to as rotary files; the smaller shanked  $\frac{1}{8}$ -inch – and correspondingly smaller-headed tools used by diesinkers and jewelers are referred to as burs.) Rotary files are made from high-speed steel and rotary burs from high-speed steel or cemented carbide in various cuts such as double extra coarse, extra coarse or rough, coarse or standard, medium, fine, and smooth. Standard shanks are  $\frac{1}{4}$  inch in diameter.

There is very little difference in the efficiency of rotary files or burs when used in electric tools and when used in air tools, provided the speeds have been reasonably well selected. Flexible-shaft and other machines used as a source of power for these tools have a limited number of speeds which govern the revolutions per minute at which the tools can be operated.

The carbide bur may be used on hard or soft materials with equally good results. The principal difference in construction of the carbide bur is that its teeth or flutes are provided with negative rather than a radial rake. Carbide burs are relatively brittle and must be treated more carefully than ordinary burs. They should be kept cutting freely, in order to prevent too much pressure, which might result in crumbling of the cutting edges.

At the same speeds, both high-speed steel and carbide burs remove approximately the same amount of metal. However, when carbide burs are used at their most efficient speeds, the rate of stock removal may be as much as four times that of ordinary burs. It has been demonstrated that a carbide bur will last up to 100 times as long as a high-speed steel bur of corresponding size and shape.

**Tooth-rest for Cutter Grinding.**—A tooth-rest is used to support a cutter while grinding the teeth. For grinding a cylindrical cutter having helical or "spiral" teeth, the tooth-rest must remain in a fixed position relative to the grinding wheel. The tooth being ground will then slide over the tooth-rest, thus causing the cutter to turn as it moves longitudinally, so that the edge of the helical tooth is ground to a uniform distance from the center, throughout its length. For grinding a straight-fluted cutter, it is also preferable to have the tooth-rest in a fixed position relative to the wheel, unless the cutter is quite narrow, because any warping of the cutter in hardening will result in inaccurate grinding, if the toothrest moves with the work. The tooth-rest should be placed as close to the cutting edge of the cutter as is practicable, and bear against the face of the tooth being ground.

### Machining Operations

**Feed Rate on Machine Tools.**— The rate of feed as applied to machine tools in general, usually indicates (1) the movement of a tool per work revolution, (2) the movement of a tool per tool revolution, (3) or the movement of the work per tool revolution.

*Rate of Feed in Turning:* The term "feed" as applied to a lathe indicates the distance that the tool moves during each revolution of the work. There are two ways of expressing the rate of feed. One is to give the actual tool movement per work revolution in thousandths of an inch. For example, the range of feeds may be given as 0.002 to 0.125 inch. This is the usual method. Another way of indicating a feed range is to give the number of cuts per inch or the number of ridges that would be left by a pointed tool after turning a length of one inch. For example, the feed range might be given as 8 to 400. In connection with turning and other lathe operations, the feed is regulated to suit the kind of material, depth of cut, and in some cases the finish desired.

*Rate of Feed in Milling:* The feed rate of milling indicates the movement of the work per cutter revolution.

*Rate of Feed in Drilling:* The rate of feed on drilling machines ordinarily indicates the feeding movement of the drill per drill revolution.

*Rate of Feed in Planing:* On planers, the rate of feed represents the tool movement per cutting stroke. On shapers, which are also machines of the planing type, the rate of feed represents the work movement per cutting stroke.

*Rate of Feed on Gear Hobbing:* The feed rate of a gear hobbing machine represents the feeding movement of the hob per revolution of the gear being hobbled.

*Feed on Grinding Machines:* The traversing movement in grinding is equivalent to the feeding movement on other types of machine tools and represents either the axial movement of the work per work revolution or the traversing movement of the wheel per work revolution, depending upon the design of the machine.

**Billet.**— A "billet," as the term is applied in rolling mill practice, is square or round in section and from 1½ inches in diameter or square to almost 6 inches in diameter or square. Rolling mills used to prepare the ingot for the forming mills are termed "blooming mills," "billet mills," etc.

**Milling Machines, Lincoln Type.**—The well-known Lincoln type of milling machine is named after George S. Lincoln of the firm then known as George S. Lincoln & Co., Hartford, Conn. Mr. Lincoln, however, did not originate this type but he introduced an improved design. Milling machines constructed along the same general lines had previously been built by the Phoenix Iron Works of Hartford, Conn., and also by Robbins & Lawrence Co., of Windsor, Vt. Milling machines of this class are intended especially for manufacturing and are not adapted to a great variety of milling operations, but are designed for machining large numbers of duplicate parts. Some milling machines which are designed along the same lines as the Lincoln type are referred to as the *manufacturing type*. The distinguishing features of the Lincoln type are as follows: The work table, instead of being carried by an adjustable knee, is mounted on the solid bed of the machine and the outer arbor support is also attached directly to the bed. This construction gives a very rigid support both for the work and the cutter. The work is usually held in a fixture or vise attached to the table, and the milling is done as the table feeds longitudinally. The table is not adjustable vertically but the spindle head and spindles can be raised or lowered as may be required.

**Saddle.**—A machine tool saddle is a slide which is mounted upon the ways of a bed, cross-rail, arm, or other guiding surfaces, and the saddle metal-cutting tools or a work-holding table. On holding either metal-cutting tools or a work-holding table. On a knee-type milling machine the saddle is that part which slides upon the knee and which supports the work-holding table. The saddle of a planer or boring mill is mounted upon the cross-rail

and supports the tool-holding slide. The saddle of a lathe is that part of a carriage which slide. The saddle of a lathe is that part of a carriage which slides directly upon the lathe bed and supports the cross-slide.

**Cold Extrusion.**—In simplest terms, cold extrusion can be defined as the forcing of unheated metal to flow through a shape-forming die. It is a method of shaping metal by plastically deforming it under compression at room temperature while the metal is within a die cavity formed by the tools. The metal issues from the die in at least one direction with the desired cross-sectional contour, as permitted by the orifice created by the tools.

Cold extrusion is always performed at a temperature well below the recrystallization temperature of the metal (about 1100 to 1300 degrees F. for steel) so that work-hardening always occurs. In hot extrusion, recrystallization eliminates the effects of work-hardening, unless rapid cooling of the extrusion prevents recrystallization from being completed.

Extrusion differs from other processes, such as drawing, in that the metal is always being pushed under compression and never pulled in tension. As a result, the material suffers much less from cracking. While coining is closely related to extrusion, it differs in that metal is completely confined in the die cavity instead of being forced through openings in the die. Some forging operations combine both coining and extrusion.

The pressure of the punch against the metal in an open die, and the resultant shaped part obtained by displacing the metal along paths of least resistance through an orifice formed between the punch and die, permits considerably higher deformation rates without tearing and large changes in the shape. Extrusion is characterized by a thorough kneading of the material. The cross-sectional shape of the part will not change due to expansion or contraction as it leaves the tool orifice. The term "cold extrusion" is not too descriptive and is not universally accepted. Other names for the same process include impact extrusion, extrusion-forging, cold forging, extrusion pressing, and heavy cold forming. Impact extrusion, however, is more frequently used to describe the production of non-ferrous parts, such as collapsible tubes and other components, while cold extrusion seems to be preferred by manufacturers of steel parts. In Germany, the practice is called *Kaltspritzen*—a literal translation of which is "cold-squirting."

One probable reason for not using impact extrusion in referring to the cold extrusion of steel is that the term implies plastic deformation by striking the metal an impact blow. Actually, the metal must be pushed through the die orifice, with pressure required over a definite period of time. One disadvantage of the terminology "cold extrusion" is the possible confusion with the older, more conventional direct extrusion process in which billets of hot metal are placed in a cylinder and pushed by a ram through a die (usually in a large, horizontal hydraulic press) to form rods, bars, tubes, or irregular shapes of considerable length.

Another possible disadvantage is the connotation of the word "cold." While the process is started with blanks, slugs, tubular sections, or pre-formed cups at room temperature, the internal, frictional resistance of the metal to plastic flow raises the surface temperature of the part to 400 degrees F. or more, and the internal temperature even higher (depending on the severity of the operation). These are still below the recrystallization temperature and the extrusions retain the advantages of improved physical properties resulting from the cold working.

**Transfer Machines.**—These specialized machine tools are used to perform various machining operations on parts or parts in fixtures as the parts are moved along on an automatic conveyor which is part of the machine tool set-up. In a set-up, the parts can move in a straight line from their entry point to their exit point, or the setup may be constructed in a U-shape so that the parts are expelled near where they start.



## Fasteners

**Stove Bolt.**— This bolt has been so named because of its use in stove building. It is made in a number of different forms, either with a round button, or flat countersunk head, the head having a slot for a screwdriver and the threaded end being provided with a square or hexagon nut.

**Flattening Test.**— This term as applied to tubing refers to a method of testing a section of tubing by flattening it until the inside walls are parallel and separated by a given distance—usually equal to three times the wall thickness for seamless tubes and five times the wall thickness for lap-welded tubes. Boiler tubes subjected to this test should show no cracks or flaws. The flattening test applied to rivets, consists in flattening a rivet head while hot to a diameter equal to  $2\frac{1}{2}$  times the diameter of the shank or body of the rivet. Good rivet steel must not crack at the edges of the flattened head.

**Rivets, Cold Formed.**— In permanently assembling various Light parts, it is often possible to greatly reduce the cost and yet secure sufficient strength by cold forming in an assembling die, the rivet or rivets as an integral part of one of the assembled sections. Figures 1a, 1b, and 1c illustrate how a steel spring is cold riveted to the heavier section. Plain round punches descend and form the rivets by forcing metal down through the holes in the spring (see Fig. 1b); the metal at the edge is then turned back by the die as shown in Fig. 1c, thus completing the riveting at one stroke of the press. In this particular case, about sixty assemblies per minute are obtained.

*Embossed Dowels and Hubs:* When dowel-pins are required to insure the accurate location of parts relative to each other, small projections or bosses may be formed directly on many die-made products, the projection being an integral part of the work and serving as a dowel-pin. Figure 1d illustrates how the dowel is formed. The method may be described as a partial punching operation, as a punch penetrate about one-half the stock thickness and forces the boss into a pocket in the die which controls the diameter and compresses the metal, thus forming a stronger projection than would be obtained otherwise. The height  $h$  of the dowel or boss should not exceed one-half of the dowel diameter  $d$  and  $h$ . should not exceed one-half of the stock thickness  $t$ . This is a practical rule which may be applied either to steel or non-ferrous metals, such as brass.

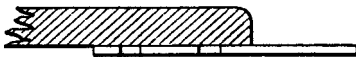


Fig. 1a.



Fig. 1b.



Fig. 1c.

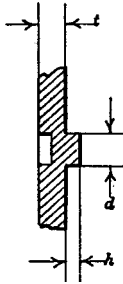


Fig. 1d.

**Expansion Bolt.**—When a through bolt cannot be used for attaching a pipe hanger, bracket, or other part, to a wall or ceiling of brick or concrete, what are known as *expansion bolts* are often used. The body of an expansion bolt is divided and the arrangement is such that, when the head of the bolt is turned, the sections forming the body of the bolt are forced outward and against the wall of the hole which has been drilled into the brick, concrete, or stone, as the case may be. Bolts of this type are made in quite a variety of designs. The nominal size represents the diameter of the bolt proper and not the diameter of the casing or expansion member.

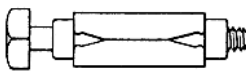


Fig. 2. Expansion Bolt

**Washers.**—Plain washers are made in standard sizes to suit standard screw threads, bolts and screws. The manufacturers' regular standard, adopted in 1935, is for bolt sizes ranging from  $\frac{1}{4}$  inch up to 3 inches, inclusive. There is also an S.A.E. standard for plain washers. This includes screw and bolt sizes ranging from No. 2 machine screw up to, and including,  $1\frac{1}{2}$ -inch bolts. These washers are somewhat smaller than the manufacturers' standard and also have smaller inside diameters or clearance spaces between the bolt and washer.

### Threads and Threading

**History of Briggs Pipe Thread (NPT).**—The USA (American) Standard for Pipe Threads, originally known as the Briggs Standard, was formulated by Mr. Robert Briggs. For several years around 1862 Mr. Briggs was superintendent of the Pascal Iron Works of Morris, Tasker & Company, Philadelphia, Pa., and later engineering editor of the "Journal" of the Franklin Institute. After his death on July 24, 1882, a paper by Mr. Briggs containing detailed information regarding American pipe and pipe thread practice, as developed by him when superintendent of the Pascal Iron Works, was read before the Institution of Civil Engineers of Great Britain. This is recorded in the Excerpt Minutes, Volume LXXI, Session 1882–1883, Part 1, of that Society.

It is of interest to note that the nominal sizes (diameters) of pipe ten (10) inches and under, and the pitches of the thread were for the most part established between 1820 and 1840.

By publishing his data, based on years of practice, Mr. Briggs was the means of establishing definite detail dimensions. The Briggs formula did not provide for the internal threads or gaging requirements for making taper threaded joints. It established only the external thread on pipe, with no tolerance.

In 1886 the large majority of American manufacturers threaded pipe to practically the Briggs Standard, and acting jointly with The American Society of Mechanical Engineers they adopted it as a standard practice that year, and master plug and ring gages were made.

Later at various conferences representatives of the manufacturers and the ASME established additional sizes, certain details of gaging, tolerances, special applications of the standard, and in addition tabulated the formulas and dimensions more completely than was done by Mr. Briggs.

Until the manufacturers adopted the Briggs thread in 1886, it seems that each manufacturer of necessity threaded his pipe and fittings according to his best judgment. After 1886 there was some attempt to work toward better interchangeability. However, the need for a better gaging practice resulted in the adoption of the thin ring gage and the truncation of the plug and ring gages to gage the flanks of the thread. This practice of threading fittings and couplings which provides threads to make up joints with a wrench was standardized about 1913.

In 1913 a Committee on the Standardization of Pipe Threads was organized for the purpose of re-editing and expanding the Briggs Standard. The American Gas Association and The American Society of Mechanical Engineers served as joint sponsors. After six years of work, this committee completed the revised standard for taper pipe thread which was published in the ASME "*Transactions*" of 1919, and was approved as an American Standard by the American Engineering Standards Committee, later named the American Standards Association in December 1919. It was the first standard to receive this designation under the ASA procedure, and was later published in pamphlet form.

In the years which followed, the need for a further revision of this American Standard became evident as well as the necessity of adding to it the recent developments in pipe threading practice. Accordingly, the Sectional Committee on the Standardization of Pipe Threads, B2, was organized in 1927 under the joint sponsorship of the A.G.A. and the ASME.

During the following 15 years, several meetings were held leading to approval by the members of the Sectional Committee, of the April 1941 draft. The revision was approved by the sponsors and ASA and published as an American Standard in October, 1942.

Shortly after publication of the 1942 standard, the Committee undertook preparation of a complete revision. The text and tables were rearranged and expanded to include Dryseal pipe threads, and an extensive appendix was added to provide additional data on the application of pipe threads and to record in abbreviated form the several special methods which were established for gaging some of the various applications of pipe threads.

The resulting proposal was approved by letter ballot of the Sectional Committee. Following its acceptance by the sponsor bodies, the draft was submitted to the American Standards Association and designated an American Standard on December 11, 1945.

At a subsequent meeting of the Sectional Committee it was agreed that for the convenience of users, the standards covering Dryseal pipe threads should be published under separate cover. Consequently, the section included in ASA B2.1-1945 on Dryseal pipe threads was deleted from the 1960 revision to that standard and used as a basis for the development of a separate proposal for Dryseal pipe threads. The text and tables were expanded to completely document the various series threads and gages, and appendices covering formulas, drilled hole sizes and special series threads were added. The  $E_j$  internal diameter and the  $L_j$  hand type engagements for the  $\frac{1}{8}$  and  $\frac{1}{4}$  inch sizes were revised to correct for a disproportionate number of threads for hand tight engagement. This proposal was approved by letter ballot vote of the Sectional Committee and submitted to the A.G.A. and the ASME. Following approval by the sponsor organizations, it was approved by the American Standards Association on April 29, 1960, and designated as ASA B2.1-1960, Pipe Threads (Except Dryseal).

The present revision of this standard constitutes a general updating. In line with their current policy, the A.G.A. has withdrawn sponsorship of this standard, while remaining active in the work of the standards committee. In compliance with the rules of the United States of America Standards Institute (formerly ASA) the previously designated Sectional Committees are now called Standards Committees.

Following approval by the Standards Committee B2 and the sponsor, ASME, the revision was approved by the United States of America Standards Institute on November 29, 1968.

**Lock-Nut Pipe Thread.**—The lock-nut pipe thread is a straight thread of the largest diameter which can be cut on a pipe. Its form is identical with that of the American or Briggs standard taper pipe thread. In general, “Go” gages only are required. These consist of a straight-threaded plug representing the minimum female lock-nut thread, and a straight-threaded ring representing the maximum male lock-nut thread. This thread is used only to hold parts together, or to retain a collar on the pipe. It is never used where a tight threaded joint is required.

**Thread Grinding.**—Thread grinding is applied both in the manufacture of duplicate parts and also in connection with precision thread work in the tool-room.

*Single-edged Grinding Wheel:* In grinding a thread, the general practice in the United States is to use a large grinding wheel (for external threads) having a diameter of possibly 18 to 20 inches. The width may be  $5/16$  or  $3/8$  inch. The face or edge of this comparatively narrow wheel is accurately formed to the cross-sectional shape of the thread to be ground. The thread is ground to the correct shape and lead by traversing it relative to the grinding wheel. This traversing movement, which is equivalent to the lead of the screw thread for each of its revolutions, is obtained from a lead-screw. On one type of thread grinder, this lead-screw is attached directly to the work-spindle and has the same lead as the screw thread to be ground; hence, there is a separate lead-screw for each different lead of thread to be ground. On another design of machine, the lead-screw arrangement is similar to that on a lathe in that the required lead on the ground thread is obtained by selection of the proper change gears. The grinding wheel may have a surface speed of 7000 feet a minute, whereas the work speed may range from 3 to 10 feet per minute. The grinding wheel is inclined to suit the helix angle of the thread and either right- or left-hand threads may be ground. Provision is also made for grinding multiple threads and for relieving taps and hobs. The wheel shape is accurately maintained by means of diamond truing tools. On one type of machine, this truing is done automatically and the grinding wheel is also adjusted automatically to compensate for whatever slight reduction in wheel size may result from the truing operation.

An internal thread may also be ground with a single-edged wheel. The operation is the same in principle as external thread grinding. The single-edged wheel is used whenever the highest precision is required, grinding the work either from the solid or as a finishing operation.

*Grinding “from the Solid”:* On some classes of work, the entire thread is formed by grinding “from the solid,” especially if the time required is less than would be needed for a rough thread-cutting operation followed by finish-grinding after hardening. Grinding threads from the solid is applied to the finer pitches. In some plants, threads with pitches up to about  $1/16$  inch are always ground by this method.

*Multi-edged Grinding Wheel:* An entire screw thread, if not too long, may be ground completely in one revolution by using a multi-edged type of grinding wheel. The face of this wheel is formed of a series of annular thread-shaped ridges so that it is practically a number of wheels combined in one. The principle is the same as that of milling screw threads by the multiple-cutter method. If the length of the thread to be ground is less than the width of the wheel, it is possible to complete the grinding in practically one work revolution as in thread milling. A grinding wheel having a width of, say,  $2\frac{1}{2}$  inches, is provided

with annual ridges or threads across its entire width. The wheel is fed in to the thread depth, and, while the work makes one single revolution, the wheel moves axially a distance equal to the thread lead along the face of the work. Most threads which require grinding are not longer than the width of the wheel; hence, the thread is completed by one turn of the work.

If the thread is longer than the wheel width, one method is to grind part of the thread and then shift the wheel axially one or more times for grinding the remaining part. For example, with a wheel  $2\frac{1}{2}$  inches in width, a thread approximately 12 inches long might be ground in five successive steps. A second method is that of using a multi-edged tapering wheel which is fed axially along the work. The taper is to distribute the work of grinding over the different edges or ridges as the wheel feeds along.

**Hand Chaser.**—A hand chaser is a type of threading tool used either for cutting or chasing external or internal threads. The tool is supported upon a rest and is guided by the hand; it is used mainly on brass work, for slightly reducing the size of a thread that has been cut either by a die or threading tool. A hand chaser may also be used for truing up battered threads in repair work and for similar purposes.

**Thread-Cutting Methods.**—The two general methods of forming screw threads may be defined as the cutting method and the rolling or displacement method. The cutting methods as applied to external threads are briefly as follows:

1) By taking a number of successive cuts with a single-point tool that is traversed along the part to be threaded at a rate per revolution of the work depending upon the lead of the thread. (Common method of cutting screw threads in the engine lathe.)

2) By taking successive cuts with a multiple-point tool or chaser of the type used to some extent in conjunction with the engine lathe and on lathes of the Fox or monitor types.

3) By using a tool of the die class, which usually has four or more multiple-point cutting edges or chasers and generally finishes the thread in one cut or passage of the tool.

4) By a single rotating milling cutter, which forms the thread groove as either the cutter or the work is traversed axially at a rate depending upon the thread lead.

5) By a multiple rotating milling cutter which completes a thread in approximately one revolution of the work.

6) By a multiple rotating cutter which also has a planetary rotating movement about the work which is held stationary. See Planamilling and Planathreading.

7) By a grinding wheel having its edge shaped to conform to the groove of the screw thread.

8) By a multi-edged grinding wheel which, within certain limits as to thread length, will grind the complete thread in practically one revolution of the work.

Internal screw threads, or those in holes, may or may not be produced by the same general method that is applied to external work. There are three commercial methods of importance, namely:

1) By the use of a single-point traversing tool in the engine lathe or a multiple-point chaser in some cases.

2) By means of a tap which, in machine tapping, usually finishes the thread in one cut or passage of the tool.

3) By a rotating milling cutter of either the single or the multiple type.

Dies operated by hand are frequently used for small and medium-sized parts, especially when accuracy as to the lead of the thread and its relation to the screw axis is not essential and comparatively few parts need to be threaded at a time. When a large number of pieces must be threaded, power-driven machines equipped with dies are commonly employed. If the operation is simply that of threading the ends of bolts, studs, rods, etc., a "bolt cutter" would generally be used, but if cutting the thread were only one of several other operations necessary to complete the work, the thread would probably be cut in the same machine performing the additional operations. For instance, parts are threaded in turret lathes and automatic screw machines by means of dies and in conjunction with other operations. When

screws are required which must be accurate as to the pitch or lead of the thread, and be true relative to the axis of the work, a lathe is generally used; lathes are also employed, ordinarily, when the threaded part is comparatively long and large in diameter. Many threads which formerly were cut in the lathe are now produced by the milling process in special thread-milling machines. The method often depends upon the equipment at hand and the number of parts to be threaded. Very precise threads may be produced by grinding.

**Taps.**—A tap is an internal thread-cutting tool having teeth which conform to the shape of the thread. Taps may be classified according to the kind of thread with which they are provided, as U. S. Standard thread taps, square thread taps, and Acme thread taps, etc. The most important classification of taps, however, is according to their use.

*Hand taps:* as the name implies, are intended primarily for tapping holes by hand but are often used in machines. All taps used by hand are not termed “hand” taps as there are many special taps used by hand which are known by specific names.

*Tapper taps:* are used for tapping nuts in tapping machines. They are provided with a long chamfered part on the end of the threaded portion, and a long shank.

*Machine nut taps:* are also used for tapping nuts in tapping machines. This type is designed for more severe duty than the tapper tap and is especially adapted for tapping holes in materials of tough structure. Machine nut taps are chamfered and relieved in a different manner from tapper taps.

*Machine screw taps:* may be either hand taps or machine nut taps, but are known by the name “machine screw tap,” because they constitute a class of special taps used for tapping holes for standard machine screw sizes.

*Screw machine taps:* for tapping in the screw machine are provided with shanks fitting either the turret holes of the machine or bushings inserted in these holes. As these taps ordinarily cut threads down to the bottom of the hole, they are provided with a very short chamfer.

*Pulley taps:* are simply a special type of taps used for tapping holes which cannot be reached by ordinary hand taps, as, for instance, the set-screw or oil-cup holes in the hubs of pulleys. They are simply hand taps with a very long shank.

*Die taps:* also known as long taper die taps, are used for cutting the thread in a die in a single operation from the blank, and are intended to be followed by a sizing hob tap. Die taps are similar to machine nut taps.

*Hob taps:* are used for sizing dies. They are intended only for the final finishing of the thread and can only take a slight chip. They are made to the same dimensions as regular hand taps, but fluted differently.

*Pipe taps:* are used for tapping holes for standard pipe sizes. These taps are taper taps. There is also a special form of pipe tap termed *straight* pipe tap, which is simply a hand corresponding in diameter and number of threads per inch to standard pipe sizes.

*Pipe hobs:* are similar to pipe taps, but are intended only for sizing pipe dies after the thread has been cut either by a pipe tap or in a lathe.

*Boiler taps:* are used in steam boiler work where a steam-tight fit is required. They are made either straight or tapered. The straight boiler tap is practically only a hand tap.

*Mud or washout taps:* are used in boiler or locomotive work. They are sometimes also called arch pipe taps. Patch bolt taps are used in boiler and locomotive work. These are taper taps similar to mud or washout taps.

*Staybolt taps:* are used on locomotive boiler work. They are usually provided with a reamer portion preceding the threaded part, and have generally a long threaded portion and a long shank. A special form of staybolt tap is known as a spindle staybolt tap which revolves on a central spindle with a taper guide on the front end.

*Stove-bolt taps* and *carriage-bolt taps* are taps which have derived their names from the uses to which they were originally put. These taps have special forms of threads.

*Bit-brace taps* differ in no essential from the hand tap on the threaded portion, but are provided with a special shank for use in a bit brace.

*Blacksmiths' taper taps* are made for general rough threading and are used especially in repair work, where an accurately fitting thread is not required.

*Inserted cutter taps* may belong to any of the classes mentioned and constitute a separate type only because they are not solid, but have the cutting teeth on blades inserted and held rigidly in a tap body.

### Machine Elements

**Nordberg Key.**—This is a taper key of circular cross-section. This type of key may be used for attaching hand wheels to their shafts or for other similar light work requiring an inexpensive type of key. The Nordberg key has a taper of 1/16 inch per foot. The center of the key hole is located at the joint line between the shaft and hub. A small hole may be drilled first to prevent the larger drill from crowding over into the cast-iron hub. A general rule for determining the size of the key is to make the large key diameter equal to one-fourth the shaft diameter.

**Woodruff Keys.**—In the Woodruff key system, half-circular disks of steel are used as keys, the half-circular side of the key being inserted into the keyseat. Part of the key projects and enters into a keyway in the part to be keyed to the shaft in the ordinary way. The advantage of this method of keys is that the keyway is easily milled by simply sinking a milling cutter, of the same diameter as the diameter of the stock from which the keys are made, into the shaft. The keys are also very cheaply made, as they are simply cut off from round bar stock and milled apart in the center. Dimensions of Woodruff keys are given in engineering handbooks.

**Saddle Key.**—This form of key has parallel sides and is curved on its under side to fit the shaft. It is slightly tapered on top so that, when it is driven tightly in place, the shaft is held by frictional resistance. This key should be fitted so that it bears lightly on the sides and heavily between the shaft and hub throughout its entire length. As the drive with this type of key is not positive, it is only used where there is little power to transmit. It is an inexpensive method of keying, as the shaft does not need to be machined.

**Locomotive Development.**—The first steam locomotive which ever ran on rails was built in 1804 by Richard Trevithick, an Englishman, and the first one to be used on a commercial basis was built by Matthew Murray, another Englishman. In 1811, Blenkinsop of Leeds, had several locomotives built by Murray in order to operate a railway extending from Middletown Colliers to Leeds, a distance of three and one-half miles. Trevithick's impracticable design had a single cylinder only, but Murray used two cylinders which were utilized in driving the same shaft on which cranks were set at right angles an important arrangement common to all modern locomotives. A cog-wheel, or gear, meshing with a continuous rack laid along the road-bed was employed. These locomotives were used daily for years and were examined by George Stephenson when he began his work on locomotive development. Several years after the construction of Murray's locomotives Hedley and Stephenson demonstrated that the gear and rack method of propulsion was unnecessary, and that the frictional resistance of smooth drivers would supply adequate tractive power. Stephenson's name will always be associated with locomotive development owing to his accomplishments in perfecting the locomotive and in establishing it on a commercial basis. His first locomotive was tried on the Killingworth Railway in 1814. The first locomotive to be used in the United States was imported from England in 1829.

**Percentages of Radial and Thrust Loads.**—There are three types of bearing that are combined load carriers: First, the annular ball bearing, which is primarily designed for radial loads and has no angle of contact incorporated in its design, therefore having minimum thrust capacity (approximately 20 per cent of its radial capacity). Second, the one-direction angular contact bearing, which has a thrust capacity depending upon race design and the angle incorporated, which is generally made so that the thrust capacity is 100 per cent of the radial capacity. (This bearing, however, when used for combined loads, can

only be used in pairs, and must have a threaded or shim adjustment incorporated in the mounting design to allow for initial adjustment.) Third, the double angular type bearing which is really two of the previously mentioned bearings built as a self-contained unit. The functioning of this bearing is not dependent on any exterior adjustment, and the angle of contact is generally such that it will sustain approximately 150 per cent of its radial capacity as thrust.

**Roller Bearing.**—The load on roller bearings is supported by cylindrical or conical rollers interposed between two races, one race being mounted on the shaft and one other in the bearing proper. There are three principal designs of roller bearings. One is for straight radial loads, the lines of contact of the rollers with the races being parallel with the shaft axis, as shown by the left-hand diagram; another design is for combined radial and thrust loads (See Fig. 3b.). With this design, the rollers are tapering so that the lines of contact of the rollers with the races, and the axis of the rollers, will intersect, if extended, at the same point on the shaft axis. A third design is intended for thrust or axial loads exclusively. Bearings for radial loads may have solid rollers, or the hollow helically-wound type such as is used in the Hyatt bearing. Although anti-friction bearings have replaced a great many plain or sliding bearings, the trend is toward a much wider application, and evidently will include eventually the heaviest classes of service since modern anti-friction bearings not only greatly reduce friction losses, but lower maintenance and repair costs.

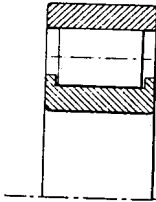


Fig. 3a. Bearing for Radial Load

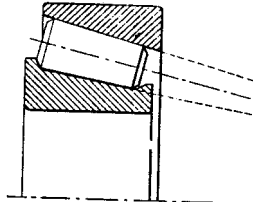


Fig. 3b. Bearing for Radial and Thrust Loads

**Ball Bearing Lubrication.**—To obtain the full measure of efficiency and service from ball and roller bearing equipment, the kind and quality of the lubricant, as well as the system of applying it, must be adapted to the design of the bearing, the design of the machine, and the operating conditions.

*Operating Temperatures:* Under ordinary conditions the temperature of a bearing while running will be from 10 to 60 degrees F. above that of the room. If it exceeds 125 degrees F., ordinary greases will frequently prove unsatisfactory. They will tend to soften and flow continuously into the path of the rolling elements, causing a rise in the normal operating temperature due to the increased frictional resistance introduced. This may eventually result in the separation of the oil and soap base, with a complete loss of lubricating qualities. In some cases, greases developed for use at high temperatures may be employed. Care should be taken, however, to see that they meet all the requirements for adequate lubrication.

Mineral oil of proper physical and chemical properties is an ideal lubricant for ball and roller bearings when the housing is designed to control the quantity entering the bearing and to prevent leakage and protect the bearing from the entrance of foreign matter. A ball or roller bearing should not be subjected to temperature in excess of 300 degrees F., because of the danger of drawing the temper of the hardened steel races and balls.

*Quantity of Lubricant Required:* In no case does a ball or roller bearing require a large quantity of lubricant. On the contrary, a few drops of oil, or a corresponding amount of grease, properly distributed over the running surfaces of the bearing, will provide satisfactory lubrication for a considerable period of time. A large volume of lubricant within a



bearing will usually result in high operating temperatures, due to the working or churning of the lubricant by the rolling elements and retainer. This may seriously impair the useful life of the lubricant through oxidation or sludging of the oil or actual disintegration of greases.

*Use of Grease:* If grease is used, the housing should not be kept more than one-fourth to one-half full of the lubricant. Unlike oil, there is no way of controlling with any degree of exactness the quantity of grease in a housing, and greater care must therefore be taken to avoid overloading. A bearing that runs at too high a temperature will often return to normal temperature if some of the lubricating grease is removed.

Grease is being used successfully for the lubrication of ball bearings at high speeds, but great care is necessary, both from the standpoint of housing design and selection of the lubricant, in order to obtain satisfactory results. Any system employed must be designed to feed only a limited amount of grease to the bearing. For the average application at operating speeds up to 3600 revolutions per minute, a grease of soft consistency, such as a No. 2 grease, will usually be found satisfactory, provided it is suitable in other respects. Hard greases, such as No. 3, may be used if the grease is to serve as a packing medium around the shaft to prevent the entrance of dirt, water, or other corrosive substances.

*Sealed Bearings:* Bearings for certain classes of service must operate over long periods without relubrication, as, for example, a motor installation on an airplane beacon; hence the efforts of ball-bearing manufacturers to produce bearings so completely sealed as to enable them to retain their original charge of grease for many months. In appreciation of this requirement, the petroleum industry has developed lubricants that will maintain lubrication for a long period without change in structure, homogeneity, lubricating properties, or leakage.

**Engine Governors.**—Governors may be of a purely centrifugal type such as the fly-ball or pendulum design previously referred to, or the principle of inertia may be introduced to secure better speed regulation. Thus, there are two general classes of governors known as centrifugal and inertia governors. The method of utilizing the motion of the governing element for regulating the speed varies; as applied to steam engines, there is the general type of governor which controls the speed by operating a throttling valve which increases or diminishes the amount of steam admitted to the steam-chest, and another general type which regulates the speed by changing the point of cut-off and consequently the amount of expansion in the cylinders.

In the design of governors, the sensitiveness, effort, and stability of the governor are important factors. The sensitiveness of a fly-ball governor is indicated by the amount that the governing sleeve is displaced for a given change in speed, the displacement being relatively large for a given speed change if the governor is sensitive.

The term "effort" as applied to a governor relates to the energy it is capable of exerting upon the governing mechanism. Thus, in the case of a fly-ball governor, the effort indicates the energy exerted on the sleeve while the governor speed is increasing or diminishing. If the energy stored in a revolving governor is small, its sensitiveness will be reduced, because a larger speed change is necessary to obtain the power for operating the governing mechanism than would be required with a governor which exerts greater energy for a given speed change.

When a governor occupies a definite position of equilibrium for any speed within the range of speeds controlled by the governor, it is said to be "stable." If the load on an engine having a fly-ball governor is diminished, the balls of a stable governor will move outward to a new position as the speed increases, although there will usually be a temporary oscillating movement on each side of this new position, the oscillations gradually diminishing. If the governor were unstable (and therefore useless) the oscillations would increase until the limiting points were reached.

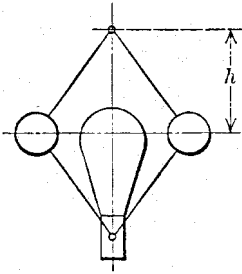


Fig. 1.

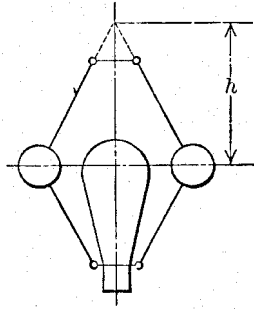


Fig. 2.

**Loaded or Weighted Fly-ball Governors.**—As the arms of a governor of the conical pendulum type swing outward toward the horizontal position as the result of increasing speed, the change in height  $h$  (see Fig. 1) is small for given changes in speed. For instance, if the speed is changed from 50 to 70 revolutions per minute, the difference between the values of  $h$  is nearly 7 inches, whereas if the speed changes from 200 to 300 revolutions per minute, the difference in height  $h$  for the two speeds is only about  $\frac{1}{2}$  inch. Hence, the simple pendulum governor is not suitable for the higher speeds, because then the movement which accompanies the speed changes is too small to secure proper regulation through the governing mechanism. Fly-ball governors are adapted for much higher speeds by loading them. The load may be in the form of a weight which surrounds the spindle, as illustrated by Fig. 1. This is known as a Porter governor.

In the following formula,  $w$  = the weight of one governor ball in pounds;  $c$  = the weight of the additional load;  $h$  = the height in feet indicated by the diagram, Fig. 1;  $n$  = speed of governor in revolutions per minute:

$$h = \frac{2933}{n^2} \times \frac{e + w}{w}$$

If the governor is constructed as indicated by the diagram Fig. 2, the height  $h$  is not measured from the points at which the arms or rods are suspended, but from the point where the axes of the rods intersect with the vertical center line. The outward movement of the balls may be resisted by a spring instead of a weight, as in the case of the Hartnell governor, which is known as a spring-loaded type.

**Sensitiveness and Stability of Governors.**—The sensitiveness of one governor may be compared with that of another by determining the *coefficient of speed variations*. If  $C$  = the coefficient of speed variations,  $M$  = maximum speed within limits of the governor action;  $M_1$  = minimum speed within limits of governor action;  $m$  = mean speed within these limits; then,

$$C = \frac{M - M_1}{m}$$

The minimum value of coefficient  $C$  necessary to obtain stability in a pendulum type of governor is given by the following formula in which  $y$  = distance the fly-balls move horizontally in feet;  $F$  = mean centrifugal force of fly-balls in pounds;  $H$  = indicated horsepower of engine;  $W$  = the weight of engine flywheel in pounds;  $S$  = revolutions per minute of main shaft;  $R$  = the flywheel radius in feet.

## ROPE SPLICING

$$C = 4000 \sqrt[3]{\frac{xy}{F}} \times 8 \sqrt[4]{\frac{H^2}{S^4 R^4 W^2}}$$

The factor  $x$  in this formula represents that weight which would be equivalent to the weights of the various moving parts, if it were centered at a point corresponding to the center of gravity of the fly-balls. To determine the value of  $x$ , first determine the weights of the different moving parts of the governor, such as the balls, the central weight or load (in the case of a Porter governor), the sleeve, etc.; multiply the weight of each part by the square of the distance it moves from one position to the other; add the various products thus obtained, and divide the total sum by the square of the corresponding movement of the fly-balls at right angles to the governor spindle.

**Shaft Governors.**—Shaft governors are so named because the governing mechanism is carried by the main shaft and is commonly attached in some way to the flywheel. One type is so arranged that, in the case of a steam engine, the action of centrifugal force on a pivoted and weighted lever, to which a spring is attached, changes the position of the eccentric which operates the slide valve, thus increasing or decreasing the valve travel and changing the point of cut-off. Another type is so designed that the inertia of a pivoted “weight arm” accelerates the governing action by acting in conjunction with the effect of centrifugal force, thus increasing the sensitiveness of the governor. With the inertia governor, the effort or force needed to actuate the governing mechanism increases as the rate of velocity change increases; hence this type is adapted to engines liable to sudden load changes. When the load remains practically constant, the centrifugal type of shaft governor is often employed in preference to the inertia type. The design of these governors depends upon the arrangement of the governing mechanism and upon varying factors.

**Rope Splicing.**—Splicing is the operation when two pieces of rope are joined by unlaying the strands and weaving or intertwining the strands of one end with those of the other.

*Short Splice:* The first step in making a short splice is to unlay or untwist the strands at the end of each rope. After the ropes are placed together, as shown at A, Fig. 1a, the strands on one side, as shown at  $d$ ,  $e$ , and  $f$ , are either held together by the left hand or are fastened together with twine, in case the rope is too large to be held by the hand. The splicing operation is started by taking one of the strands as at  $a$ , and passing it across or over the adjacent strand  $d$  and then under the next strand  $e$ , after having made an opening beneath strand  $e$ . The strands  $b$  and  $c$  are next treated in the same manner, first one and then the other being passed over its adjoining strand and then under the next successive one. These same operations are then repeated for the strands  $d$ ,  $e$  and  $f$  of the other rope. The splice will now appear as shown at B, Fig. 1b. In order to make it stronger and more secure, the projecting strands of each rope are again passed diagonally over the adjoining strands and under the next successive ones. The splice should then be subjected to a strong pull, in order to tighten the strands and make them more compact. The projecting ends of the strands should then be cut off, thus completing the splice as shown at C. For making the openings beneath the strands on the rope, what is known as a marlin spike is generally used. This is merely a tapering, pointed pin made of wood or iron.

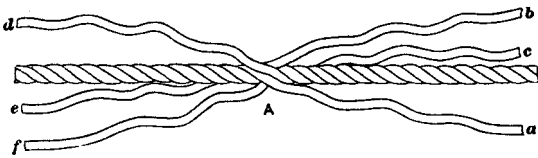


Fig. 1a. Method of Making a Short Splice

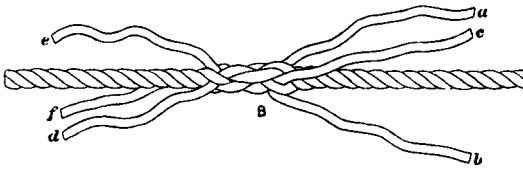


Fig. 1b. Method of Making a Short Splice



Fig. 1c. Method of Making a Short Splice

**Long Splice:** When a rope has to pass through pulley blocks, or in case any increase in the size of the rope would be objectionable, the short splice is not suitable and the long splice should be employed. The diameter of a long splice is the same as that of the rope and, if the work is done carefully, the place where the ends are joined can scarcely be distinguished from the rest of the rope. The ends of each rope are first unlaied or untwisted the same as when making a short splice, but for a distance about three times as long. These ends are then placed together so that each strand lies between two strands of the other rope, the same as for a short splice. One of the strands is next unlaied and then a strand from the other rope is curled around into the groove thus made, as indicated at A Fig. 2a, strand a having been unlaied and strand b from the other rope end, put into its place. Care should be taken to twist strand b so that it will lie in its natural position into the groove previously occupied by strand a, as the neatness of the splice will depend partly upon the care with which this part of the work is done. This operation is then repeated in connection with strands c and d, strand c being unlaied and strand d twisted around to occupy the groove thus made. The splice will now be as shown at B, Fig. 2b, and the next step is that of disposing of the protruding ends of the strands. After these strands have been cut to about the length shown at B, two of the strands, as at a and b, are first reduced in size by removing about one-third of the fiber; these ends are then tied by an overhand knot as shown at e. After tightening this knot, the protruding ends may be disposed of the same as when making a short splice, or by passing them over the adjoining strand and through the rope, under the next one. By gradually removing the fiber each time the end is passed across an adjoining strand, the enlargement of the rope at this point may be made very slight and scarcely noticeable. The strands f and g which remain in their original positions in the center of the splice, and the strands c and d are disposed of in a similar manner, thus completing the splice as shown at Fig. 2c.

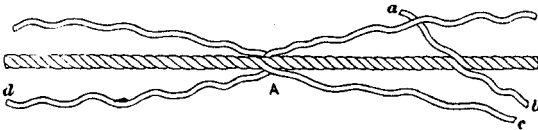


Fig. 2a. How a Long Splice is Made

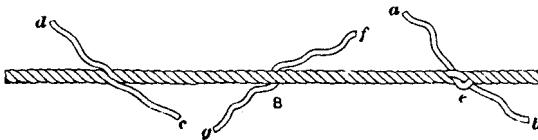


Fig. 2b. How a Long Splice is Made

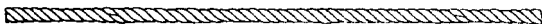


Fig. 2c. How a Long Splice is Made

*Eye-Splice:* When a loop is formed at the end of a rope by splicing the free end to the main or standing part of the rope, this is known as an *eye-splice*. The end of the rope is first unlaidd about as far as it would be for making a short splice. After bending the end around to form a loop of the required size, the middle strand *a*, Fig. 3a, is tucked under a strand on the main part of the rope. The strand *b* is next inserted from the rear side under the strand on the main part which is just above the strand under which *a* was inserted. Since strand *b* is pushed under the strand on the main part from the rear side, it will come out at the point where strand *a* went in, as Fig. 3b. The third strand *c* is now passed over the strand under which strand *a* was inserted, and then under the next successive one, as Fig. 3c. These three strands are next pulled taut and then about one-third of the fiber should be cut from them; they are next tucked away by passing a strand over its adjoining one and under the next successive strand. Cutting away part of the fiber or yarns is to reduce the size of the splice and give it a neater appearance. By gradually thinning out the fiber, the over-lapping strands may be given a gradual taper, as Fig. 3d which shows the completed eye-splice.



Fig. 3a. Eye -Splice



Fig. 3b. Eye -Splice



Fig. 3c. Eye -Splice



Fig. 3d. Eye -Splice

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## NUMBERS, FRACTIONS, AND DECIMALS

Table 1. Fractional and Decimal Inch to Millimeter, Exact<sup>a</sup> Values

| Fractional Inch | Decimal Inch                      | Millimeters           | Fractional Inch | Decimal Inch         | Millimeters           |
|-----------------|-----------------------------------|-----------------------|-----------------|----------------------|-----------------------|
| 1/64            | 0.015625                          | 0.396875              |                 | 0.511811024          | 13                    |
| 1/32            | 0.03125                           | 0.79375               | 33/64           | 0.515625             | 13.096875             |
|                 | 0.039370079                       | 1                     | 17/32           | 0.53125              | 13.49375              |
| 3/64            | 0.046875                          | 1.190625              | 35/64           | 0.546875             | 13.890625             |
| 1/16            | 0.0625                            | 1.5875                |                 | 0.551181102          | 14                    |
| 5/64            | 0.078125                          | 1.984375              | 9/16            | 0.5625               | 14.2875               |
|                 | 0.078740157                       | 2                     | 37/64           | 0.578125             | 14.684375             |
| 1/12            | 0.08 $\overline{33}$ <sup>b</sup> | 2.11 $\overline{66}$  | 7/12            | 0.58 $\overline{33}$ | 14.81 $\overline{66}$ |
| 3/32            | 0.09375                           | 2.38125               |                 | 0.590551181          | 15                    |
| 7/64            | 0.109375                          | 2.778125              | 19/32           | 0.59375              | 15.08125              |
|                 | 0.118110236                       | 3                     | 39/64           | 0.609375             | 15.478125             |
| 1/8             | 0.125                             | 3.175                 | 5/8             | 0.625                | 15.875                |
| 9/64            | 0.140625                          | 3.571875              |                 | 0.62992126           | 16                    |
| 5/32            | 0.15625                           | 3.96875               | 41/64           | 0.640625             | 16.271875             |
|                 | 0.157480315                       | 4                     | 21/32           | 0.65625              | 16.66875              |
| 1/6             | 0.166                             | 4.23 $\overline{3}$   | 2/3             | 0.66                 | 16.93 $\overline{3}$  |
| 11/64           | 0.171875                          | 4.365625              |                 | 0.669291339          | 17                    |
| 3/16            | 0.1875                            | 4.7625                | 43/64           | 0.671875             | 17.065625             |
|                 | 0.196850394                       | 5                     | 11/16           | 0.6875               | 17.4625               |
| 13/64           | 0.203125                          | 5.159375              | 45/64           | 0.703125             | 17.859375             |
| 7/32            | 0.21875                           | 5.55625               |                 | 0.708661417          | 18                    |
| 15/64           | 0.234375                          | 5.953125              | 23/32           | 0.71875              | 18.25625              |
|                 | 0.236220472                       | 6                     | 47/64           | 0.734375             | 18.653125             |
| 1/4             | 0.25                              | 6.35                  |                 | 0.748031496          | 19                    |
| 17/64           | 0.265625                          | 6.746875              | 3/4             | 0.75                 | 19.05                 |
|                 | 0.275590551                       | 7                     | 49/64           | 0.765625             | 19.446875             |
| 9/32            | 0.28125                           | 7.14375               | 25/32           | 0.78125              | 19.84375              |
| 19/64           | 0.296875                          | 7.540625              |                 | 0.787401575          | 20                    |
| 5/16            | 0.3125                            | 7.9375                | 51/64           | 0.796875             | 20.240625             |
|                 | 0.31496063                        | 8                     | 13/16           | 0.8125               | 20.6375               |
| 21/64           | 0.328125                          | 8.334375              |                 | 0.826771654          | 21                    |
| 1/3             | 0.3 $\overline{3}$                | 8.466                 | 53/64           | 0.828125             | 21.034375             |
| 11/32           | 0.34375                           | 8.73125               | 27/32           | 0.84375              | 21.43125              |
|                 | 0.354330709                       | 9                     | 55/64           | 0.859375             | 21.828125             |
| 23/64           | 0.359375                          | 9.128125              |                 | 0.866141732          | 22                    |
| 3/8             | 0.375                             | 9.525                 | 7/8             | 0.875                | 22.225                |
| 25/64           | 0.390625                          | 9.921875              | 57/64           | 0.890625             | 22.621875             |
|                 | 0.393700787                       | 10                    |                 | 0.905511811          | 23                    |
| 13/32           | 0.40625                           | 10.31875              | 29/32           | 0.90625              | 23.01875              |
| 5/12            | 0.41 $\overline{66}$              | 10.58 $\overline{33}$ | 11/12           | 0.91 $\overline{66}$ | 23.28 $\overline{33}$ |
| 27/64           | 0.421875                          | 10.715625             | 59/64           | 0.921875             | 23.415625             |
|                 | 0.433070866                       | 11                    | 15/16           | 0.9375               | 23.8125               |
| 7/16            | 0.4375                            | 11.1125               |                 | 0.94488189           | 24                    |
| 29/64           | 0.453125                          | 11.509375             | 61/64           | 0.953125             | 24.209375             |
| 15/32           | 0.46875                           | 11.90625              | 31/32           | 0.96875              | 24.60625              |
|                 | 0.472440945                       | 12                    |                 | 0.984251969          | 25                    |
| 31/64           | 0.484375                          | 12.303125             | 63/64           | 0.984375             | 25.003125             |
| 1/2             | 0.5                               | 12.7                  |                 |                      |                       |

<sup>a</sup>Table data are based on 1 inch = 25.4 mm, exactly. Inch to millimeter conversion values are exact. Whole number millimeter to inch conversions are rounded to 9 decimal places.

<sup>b</sup>Numbers with an overbar, repeat indefinitely after the last figure, for example 0.08 $\overline{33}$  = 0.08333...



### Numbers

Numbers are the basic instrumentation of computation. Calculations are made by operations of numbers. The whole numbers greater than zero are called natural numbers. The first ten numbers 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 are called numerals. Numbers follow certain formulas. The following properties hold true:

*Associative law:*  $x + (y + z) = (x + y) + z$ ,  $x(yz) = (xy)z$

*Distributive law:*  $x(y + z) = xy + xz$

*Commutative law:*  $x + y = y + x$

*Identity law:*  $0 + x = x$ ,  $1x = x$

*Inverse law:*  $x - x = 0$ ,  $x/x = 1$

**Positive and Negative Numbers.**—The degrees on a thermometer scale extending upward from the zero point may be called *positive* and may be preceded by a plus sign; thus +5 degrees means 5 degrees above zero. The degrees below zero may be called *negative* and may be preceded by a minus sign; thus, -5 degrees means 5 degrees below zero. In the same way, the ordinary numbers 1, 2, 3, etc., which are larger than 0, are called positive numbers; but numbers can be conceived of as extending in the other direction from 0, numbers that, in fact, are less than 0, and these are called negative. As these numbers must be expressed by the same figures as the positive numbers they are designated by a minus sign placed before them, thus: (-3). A negative number should always be enclosed within parentheses whenever it is written in line with other numbers; for example:  $17 + (-13) - 3 \times (-0.76)$ .

Negative numbers are most commonly met with in the use of logarithms and natural trigonometric functions. The following rules govern calculations with negative numbers.

A negative number can be added to a positive number by subtracting its numerical value from the positive number.

*Example:*  $4 + (-3) = 4 - 3 = 1$

A negative number can be subtracted from a positive number by adding its numerical value to the positive number.

*Example:*  $4 - (-3) = 4 + 3 = 7$

A negative number can be added to a negative number by adding the numerical values and making the sum negative.

*Example:*  $(-4) + (-3) = -7$

A negative number can be subtracted from a larger negative number by subtracting the numerical values and making the difference negative.

*Example:*  $(-4) - (-3) = -1$

A negative number can be subtracted from a smaller negative number by subtracting the numerical values and making the difference positive.

*Example:*  $(-3) - (-4) = 1$

If in a subtraction the number to be subtracted is larger than the number from which it is to be subtracted, the calculation can be carried out by subtracting the smaller number from the larger, and indicating that the remainder is negative.

*Example:*  $3 - 5 = -(5 - 3) = -2$

When a positive number is to be multiplied or divided by a negative numbers, multiply or divide the numerical values as usual; the product or quotient, respectively, is negative. The same rule is true if a negative number is multiplied or divided by a positive number.

*Examples:*  $4 \times (-3) = -12$   $(-4) \times 3 = -12$

$15 \div (-3) = -5$   $(-15) \div 3 = -5$

When two negative numbers are to be multiplied by each other, the product is positive. When a negative number is divided by a negative number, the quotient is positive.

Examples:  $(-4) \times (-3) = 12$ ;  $(-4) \div (-3) = 1.333$

The two last rules are often expressed for memorizing as follows: "Equal signs make plus, unequal signs make minus."

**Sequence of Performing Arithmetic Operations.**—When several numbers or quantities in a formula are connected by signs indicating that additions, subtractions, multiplications, and divisions are to be made, the multiplications and divisions should be carried out first, in the sequence in which they appear, before the additions or subtractions are performed.

Example:

$$10 + 26 \times 7 - 2 = 10 + 182 - 2 = 190$$

$$18 \div 6 + 15 \times 3 = 3 + 45 = 48$$

$$12 + 14 \div 2 - 4 = 12 + 7 - 4 = 15$$

When it is required that certain additions and subtractions should precede multiplications and divisions, use is made of parentheses ( ) and brackets [ ]. These signs indicate that the calculation inside the parentheses or brackets should be carried out completely by itself before the remaining calculations are commenced. If one bracket is placed inside another, the one inside is first calculated.

Example:

$$(6 - 2) \times 5 + 8 = 4 \times 5 + 8 = 20 + 8 = 28$$

$$6 \times (4 + 7) \div 22 = 6 \times 11 \div 22 = 66 \div 22 = 3$$

$$2 + [10 \times 6(8 + 2) - 4] \times 2 = 2 + [10 \times 6 \times 10 - 4] \times 2$$

$$= 2 + [600 - 4] \times 2 = 2 + 596 \times 2 = 2 + 1192 = 1194$$

The parentheses are considered as a sign of multiplication; for example:

$$6(8 + 2) = 6 \times (8 + 2).$$

The line or bar between the numerator and denominator in a fractional expression is to be considered as a division sign. For example,

$$\frac{12 + 16 + 22}{10} = (12 + 16 + 22) \div 10 = 50 \div 10 = 5$$

In formulas, the multiplication sign ( $\times$ ) is often left out between symbols or letters, the values of which are to be multiplied. Thus,

$$AB = A \times B \quad \text{and} \quad \frac{ABC}{D} = (A \times B \times C) \div D$$

**Ratio and Proportion.**—The *ratio* between two quantities is the quotient obtained by dividing the first quantity by the second. For example, the ratio between 3 and 12 is  $\frac{1}{4}$ , and the ratio between 12 and 3 is 4. Ratio is generally indicated by the sign (:); thus, 12 : 3 indicates the ratio of 12 to 3.

A *reciprocal*, or *inverse* ratio, is the opposite of the original ratio. Thus, the inverse ratio of 5 : 7 is 7 : 5.

In a *compound* ratio, each term is the product of the corresponding terms in two or more simple ratios. Thus, when

$$8:2 = 4 \quad 9:3 = 3 \quad 10:5 = 2$$

then the compound ratio is

$$8 \times 9 \times 10 : 2 \times 3 \times 5 = 4 \times 3 \times 2$$

$$720:30 = 24$$

*Proportion* is the equality of ratios. Thus,

$$6:3 = 10:5 \quad \text{or} \quad 6:3::10:5$$

The first and last terms in a proportion are called the *extremes*; the second and third, the *means*. The product of the extremes is equal to the product of the means. Thus,

$$25:2 = 100:8 \quad \text{and} \quad 25 \times 8 = 2 \times 100$$

If three terms in a proportion are known, the remaining term may be found by the following rules:

The first term is equal to the product of the second and third terms, divided by the fourth. The second term is equal to the product of the first and fourth terms, divided by the third. The third term is equal to the product of the first and fourth terms, divided by the second. The fourth term is equal to the product of the second and third terms, divided by the first.

*Example:* Let  $x$  be the term to be found, then,

$$x : 12 = 3.5 : 21 \quad x = \frac{12 \times 3.5}{21} = \frac{42}{21} = 2$$

$$\frac{1}{4} : x = 14 : 42 \quad x = \frac{\frac{1}{4} \times 42}{14} = \frac{1}{4} \times 3 = \frac{3}{4}$$

$$5 : 9 = x : 63 \quad x = \frac{5 \times 63}{9} = \frac{315}{9} = 35$$

$$\frac{1}{4} : \frac{7}{8} = 4 : x \quad x = \frac{\frac{7}{8} \times 4}{\frac{1}{4}} = \frac{3\frac{1}{2}}{\frac{1}{4}} = 14$$

If the second and third terms are the same, that number is the *mean proportional* between the other two. Thus,  $8 : 4 = 4 : 2$ , and 4 is the mean proportional between 8 and 2. The mean proportional between two numbers may be found by multiplying the numbers together and extracting the square root of the product. Thus, the mean proportional between 3 and 12 is found as follows:

$$3 \times 12 = 36 \quad \text{and} \quad \sqrt{36} = 6$$

which is the mean proportional.

*Practical Examples Involving Simple Proportion:* If it takes 18 days to assemble 4 lathes, how long would it take to assemble 14 lathes?

Let the number of days to be found be  $x$ . Then write out the proportion as follows:

$$4:18 = 14:x$$

$$(\text{lathes} : \text{days} = \text{lathes} : \text{days})$$

Now find the fourth term by the rule given:

$$x = \frac{18 \times 14}{4} = 63 \text{ days}$$

Thirty-four linear feet of bar stock are required for the blanks for 100 clamping bolts. How many feet of stock would be required for 912 bolts?

Let  $x$  = total length of stock required for 912 bolts.

$$34:100 = x:912$$

$$(\text{feet} : \text{bolts} = \text{feet} : \text{bolts})$$

Then, the third term  $x = (34 \times 912)/100 = 310$  feet, approximately.

*Inverse Proportion:* In an inverse proportion, as one of the items involved *increases*, the corresponding item in the proportion *decreases*, or vice versa. For example, a factory employing 270 men completes a given number of typewriters weekly, the number of working hours being 44 per week. How many men would be required for the same production if the working hours were reduced to 40 per week?

The time per week is in an inverse proportion to the number of men employed; the shorter the time, the more men. The inverse proportion is written:

$$270 : x = 40 : 44$$

(men, 44-hour basis: men, 40-hour basis = time, 40-hour basis: time, 44-hour basis)  
Thus

$$\frac{270}{x} = \frac{40}{44} \quad \text{and} \quad x = \frac{270 \times 44}{40} = 297 \text{ men}$$

*Problems Involving Both Simple and Inverse Proportions:* If two groups of data are related both by direct (simple) and inverse proportions among the various quantities, then a simple mathematical relation that may be used in solving problems is as follows:

$$\begin{aligned} & \frac{\text{Product of all directly proportional items in first group}}{\text{Product of all inversely proportional items in first group}} \\ &= \frac{\text{Product of all directly proportional items in second group}}{\text{Product of all inversely proportional items in second group}} \end{aligned}$$

*Example:* If a man capable of turning 65 studs in a day of 10 hours is paid \$6.50 per hour, how much per hour ought a man be paid who turns 72 studs in a 9-hour day, if compensated in the same proportion?

The first group of data in this problem consists of the number of hours worked by the first man, his hourly wage, and the number of studs which he produces per day; the second group contains similar data for the second man except for his unknown hourly wage, which may be indicated by  $x$ .

The labor cost per stud, as may be seen, is directly proportional to the number of hours worked and the hourly wage. These quantities, therefore, are used in the numerators of the fractions in the formula. The labor cost per stud is inversely proportional to the number of studs produced per day. (The greater the number of studs produced in a given time the less the cost per stud.) The numbers of studs per day, therefore, are placed in the denominators of the fractions in the formula. Thus,

$$\begin{aligned} \frac{10 \times 6.50}{65} &= \frac{9 \times x}{72} \\ x &= \frac{10 \times 6.50 \times 72}{65 \times 9} = \$8.00 \text{ per hour} \end{aligned}$$

**Percentage.**—If out of 100 pieces made, 12 do not pass inspection, it is said that 12 per cent (12 of the hundred) are rejected. If a quantity of steel is bought for \$100 and sold for \$140, the profit is 28.6 per cent of the selling price.

The per cent of gain or loss is found by dividing the amount of gain or loss by the *original* number of which the percentage is wanted, and multiplying the quotient by 100.

*Example:* Out of a total output of 280 castings a day, 30 castings are, on an average, rejected. What is the percentage of bad castings?

$$\frac{30}{280} \times 100 = 10.7 \text{ per cent}$$

If by a new process 100 pieces can be made in the same time as 60 could formerly be made, what is the gain in output of the new process over the old, expressed in per cent?

Original number, 60; gain  $100 - 60 = 40$ . Hence,

$$\frac{40}{60} \times 100 = 66.7 \text{ per cent}$$

Care should be taken always to use the original number, or the number of which the percentage is wanted, as the divisor in all percentage calculations. In the example just given, it

is the percentage of gain over the old output 60 that is wanted and not the percentage with relation to the new output too. Mistakes are often made by overlooking this important point.

### Fractions

**Common Fractions.**— Common fractions consist of two basic parts, a denominator, or bottom number, and a numerator, or top number. The denominator shows how many parts the whole unit has been divided into. The numerator indicates the number of parts of the whole that are being considered. A fraction having a value of  $\frac{5}{32}$ , means the whole unit has been divided into 32 equal parts and 5 of these parts are considered in the value of the fraction.

The following are the basic facts, rules, and definitions concerning common fractions.

A common fraction having the same numerator and denominator is equal to 1. For example,  $\frac{2}{2}$ ,  $\frac{4}{4}$ ,  $\frac{8}{8}$ ,  $\frac{16}{16}$ ,  $\frac{32}{32}$ , and  $\frac{64}{64}$  all equal 1.

**Proper Fraction:** A proper fraction is a common fraction having a numerator smaller than its denominator, such as  $\frac{1}{4}$ ,  $\frac{1}{2}$ , and  $\frac{47}{64}$ .

**Improper Fraction:** An improper fraction is a common fraction having a numerator larger than its denominator. For example,  $\frac{3}{2}$ ,  $\frac{5}{4}$ , and  $\frac{10}{8}$ . To convert a whole number to an improper fraction place the whole number over 1, as in  $4 = \frac{4}{1}$  and  $3 = \frac{3}{1}$ .

**Reducible Fraction:** A reducible fraction is a common fraction that can be reduced to lower terms. For example,  $\frac{2}{4}$  can be reduced to  $\frac{1}{2}$ , and  $\frac{28}{32}$  can be reduced to  $\frac{7}{8}$ . To reduce a common fraction to lower terms, divide both the numerator and the denominator by the same number. For example,  $\frac{24}{32} \div \frac{8}{8} = \frac{3}{4}$  and  $\frac{6}{8} \div \frac{2}{2} = \frac{3}{4}$ .

**Least Common Denominator:** A least common denominator is the smallest denominator value that is evenly divisible by the other denominator values in the problem. For example, given the following numbers,  $\frac{1}{2}$ ,  $\frac{1}{4}$ , and  $\frac{3}{8}$ , the least common denominator is 8.

**Mixed Number:** A mixed number is a combination of a whole number and a common fraction, such as  $2\frac{1}{2}$ ,  $1\frac{7}{8}$ ,  $3\frac{15}{16}$  and  $1\frac{9}{32}$ .

To convert mixed numbers to improper fractions, multiply the whole number by the denominator and add the numerator to obtain the new numerator. The denominator remains the same. For example,

$$2\frac{1}{2} = \frac{2 \times 2 + 1}{2} = \frac{5}{2}$$

$$3\frac{7}{16} = \frac{3 \times 16 + 7}{16} = \frac{55}{16}$$

To convert an improper fraction to a mixed number, divide the numerator by the denominator and reduce the remaining fraction to its lowest terms. For example,

$$\frac{17}{8} = 17 \div 8 = 2\frac{1}{8} \text{ and } \frac{26}{16} = 26 \div 16 = 1\frac{10}{16} = 1\frac{5}{8}$$

A fraction may be converted to higher terms by multiplying the numerator and denominator by the same number. For example,  $\frac{1}{4}$  in 16ths =  $\frac{1}{4} \times \frac{4}{4} = \frac{4}{16}$  and  $\frac{3}{8}$  in 32nds =  $\frac{3}{8} \times \frac{4}{4} = \frac{12}{32}$ .

To change a whole number to a common fraction with a specific denominator value, convert the whole number to a fraction and multiply the numerator and denominator by the desired denominator value.

*Example:*  $4$  in 16ths =  $\frac{4}{1} \times \frac{16}{16} = \frac{64}{16}$  and  $3$  in 32nds =  $\frac{3}{1} \times \frac{32}{32} = \frac{96}{32}$

**Reciprocals.**— The *reciprocal*  $R$  of a number  $N$  is obtained by dividing 1 by the number;  $R = 1/N$ . Reciprocals are useful in some calculations because they avoid the use of negative characteristics as in calculations with logarithms and in trigonometry. In trigonometry, the

values *cosecant*, *secant*, and *cotangent* are often used for convenience and are the reciprocals of the *sine*, *cosine*, and *tangent*, respectively (see page 88). The reciprocal of a fraction, for instance  $\frac{3}{4}$ , is the fraction inverted, since  $1 \div \frac{3}{4} = 1 \times \frac{4}{3} = \frac{4}{3}$ .

### Adding Fractions and Mixed Numbers

*To Add Common Fractions:* 1) Find and convert to the least common denominator; 2) Add the numerators; 3) Convert the answer to a mixed number, if necessary; and 4) Reduce the fraction to its lowest terms.

*To Add Mixed Numbers:* 1) Find and convert to the least common denominator; 2) Add the numerators; 3) Add the whole numbers; and 4) Reduce the answer to its lowest terms.

*Example, Addition of Common Fractions:*

$$\begin{aligned}\frac{1}{4} + \frac{3}{16} + \frac{7}{8} &= \\ \frac{1}{4}\left(\frac{4}{4}\right) + \frac{3}{16} + \frac{7}{8}\left(\frac{2}{2}\right) &= \\ \frac{4}{16} + \frac{3}{16} + \frac{14}{16} &= \frac{21}{16}\end{aligned}$$

*Example, Addition of Mixed Numbers:*

$$\begin{aligned}2\frac{1}{2} + 4\frac{1}{4} + 1\frac{15}{32} &= \\ 2\frac{1}{2}\left(\frac{16}{16}\right) + 4\frac{1}{4}\left(\frac{8}{8}\right) + 1\frac{15}{32} &= \\ 2\frac{16}{32} + 4\frac{8}{32} + 1\frac{15}{32} &= 7\frac{39}{32} = 8\frac{7}{32}\end{aligned}$$

### Subtracting Fractions and Mixed Numbers

*To Subtract Common Fractions:* 1) Convert to the least common denominator; 2) Subtract the numerators; and 3) Reduce the answer to its lowest terms.

*To Subtract Mixed Numbers:* 1) Convert to the least common denominator; 2) Subtract the numerators; 3) Subtract the whole numbers; and 4) Reduce the answer to its lowest terms.

*Example, Subtraction of Common Fractions:*

$$\begin{aligned}\frac{15}{16} - \frac{7}{32} &= \\ \frac{15}{16}\left(\frac{2}{2}\right) - \frac{7}{32} &= \\ \frac{30}{32} - \frac{7}{32} &= \frac{23}{32}\end{aligned}$$

*Example, Subtraction of Mixed Numbers:*

$$\begin{aligned}2\frac{3}{8} - 1\frac{1}{16} &= \\ 2\frac{3}{8}\left(\frac{2}{2}\right) - 1\frac{1}{16} &= \\ 2\frac{6}{16} - 1\frac{1}{16} &= 1\frac{5}{16}\end{aligned}$$

### Multiplying Fractions and Mixed Numbers

*To Multiply Common Fractions:* 1) Multiply the numerators; 2) Multiply the denominators; and 3) Convert improper fractions to mixed numbers, if necessary.

*To Multiply Mixed Numbers:* 1) Convert the mixed numbers to improper fractions; 2) Multiply the numerators; 3) Multiply the denominators; and 4) Convert improper fractions to mixed numbers, if necessary.

*Example, Multiplication of Common Fractions:*

$$\frac{3}{4} \times \frac{7}{16} = \frac{3 \times 7}{4 \times 16} = \frac{21}{64}$$

*Example, Multiplication of Mixed Numbers:*

$$2\frac{1}{4} \times 3\frac{1}{2} = \frac{9 \times 7}{4 \times 2} = \frac{63}{8} = 7\frac{7}{8}$$

### Dividing Fractions and Mixed Numbers

*To Divide Common Fractions:* 1) Write the fractions to be divided; 2) Invert (switch) the numerator and denominator in the dividing fraction; 3) Multiply the numerators and denominators; and 4) Convert improper fractions to mixed numbers, if necessary.

*To Divide Mixed Numbers:* 1) Convert the mixed numbers to improper fractions; 2) Write the improper fraction to be divided; 3) Invert (switch) the numerator and denominator in the dividing fraction; 4) Multiplying numerators and denominators; and 5) Convert improper fractions to mixed numbers, if necessary.

*Example, Division of Common Fractions:*

$$\frac{3}{4} \div \frac{1}{2} = \frac{3 \times 2}{4 \times 1} = \frac{6}{4} = 1\frac{1}{2}$$

*Example, Division of Mixed Numbers:*

$$2\frac{1}{2} \div 1\frac{7}{8} = \frac{5 \times 8}{2 \times 15} = \frac{40}{30} = 1\frac{1}{3}$$

**Decimal Fractions.**—Decimal fractions are fractional parts of a whole unit, which have implied denominators that are multiples of 10. A decimal fraction of 0.1 has a value of 1/10th, 0.01 has a value of 1/100th, and 0.001 has a value of 1/1000th. As the number of decimal place values increases, the value of the decimal number changes by a multiple of 10. A single number placed to the right of a decimal point has a value expressed in tenths; two numbers to the right of a decimal point have a value expressed in hundredths; three numbers to the right have a value expressed in thousandths; and four numbers are expressed in ten-thousandths. Since the denominator is implied, the number of decimal places in the numerator indicates the value of the decimal fraction. So a decimal fraction expressed as a 0.125 means the whole unit has been divided into 1000 parts and 125 of these parts are considered in the value of the decimal fraction.

In industry, most decimal fractions are expressed in terms of thousandths rather than tenths or hundredths. So a decimal fraction of 0.2 is expressed as 200 thousandths, not 2 tenths, and a value of 0.75 is expressed as 750 thousandths, rather than 75 hundredths. In the case of four place decimals, the values are expressed in terms of ten-thousandths. So a value of 0.1875 is expressed as 1 thousand 8 hundred and 75 ten-thousandths. When whole numbers and decimal fractions are used together, whole units are shown to the left of a decimal point, while fractional parts of a whole unit are shown to the right.

*Example:*

|                |                   |
|----------------|-------------------|
| 10.125         |                   |
| Whole<br>Units | Fraction<br>Units |

*Adding Decimal Fractions:* 1) Write the problem with all decimal points aligned vertically; 2) Add the numbers as whole number values; and 3) Insert the decimal point in the same vertical column in the answer.

*Subtracting Decimal Fractions:* 1) Write the problem with all decimal points aligned vertically; 2) Subtract the numbers as whole number values; and 3) Insert the decimal point in the same vertical column in the answer.

*Multiplying Decimal Fractions:* 1) Write the problem with the decimal points aligned; 2) Multiply the values as whole numbers; 3) Count the number of decimal places in both multiplied values; and 4) Counting from right to left in the answer, insert the decimal point so the number of decimal places in the answer equals the total number of decimal places in the numbers multiplied.

*Example, Adding Decimal Fractions:*

$$\begin{array}{r} 0.125 \\ 1.0625 \\ 2.50 \\ \hline 0.1875 \\ 3.8750 \end{array} \quad \text{or} \quad \begin{array}{r} 1.750 \\ 0.875 \\ 0.125 \\ \hline 2.0005 \\ 4.7505 \end{array}$$

*Example, Subtracting Decimal Fractions:*

$$\begin{array}{r} 1.750 \\ -0.250 \\ \hline 1.500 \end{array} \quad \text{or} \quad \begin{array}{r} 2.625 \\ -1.125 \\ \hline 1.500 \end{array}$$

Example, Multiplying Decimal Fractions:

|             |                       |              |
|-------------|-----------------------|--------------|
| 0.75        |                       | 1.625        |
| <u>0.25</u> |                       | <u>0.033</u> |
| 375         | (four decimal places) | 4875         |
| <u>150</u>  |                       | <u>4875</u>  |
| 0.1875      |                       | 0.053625     |

**Continued Fractions.**—In dealing with a cumbersome fraction, or one which does not have satisfactory factors, it may be possible to substitute some other, approximately equal, fraction which is simpler or which can be factored satisfactorily. Continued fractions provide a means of computing a series of fractions each of which is a closer approximation to the original fraction than the one preceding it in the series.

A continued fraction is a proper fraction (one whose numerator is smaller than its denominator) expressed in the form shown at the left below; or, it may be convenient to write the left expression as shown at the right below.

$$\frac{N}{D} = \frac{1}{D_1 + \frac{1}{D_2 + \frac{1}{D_3 + \dots}}} \qquad \frac{N}{D} = \frac{1}{D_1} + \frac{1}{D_2} + \frac{1}{D_3} + \frac{1}{D_4} + \dots$$

The continued fraction is produced from a proper fraction  $N/D$  by dividing the numerator  $N$  both into itself and into the denominator  $D$ . Dividing the numerator into itself gives a result of 1; dividing the numerator into the denominator gives a whole number  $D_1$  plus a remainder fraction  $R_1$ . The process is then repeated on the remainder fraction  $R_1$  to obtain  $D_2$  and  $R_2$ ; then  $D_3, R_3$ , etc., until a remainder of zero results. As an example, using  $N/D = 2153/9277$ ,

$$\frac{2153}{9277} = \frac{2153 \div 2153}{9277 \div 2153} = \frac{1}{4 + \frac{665}{2153}} = \frac{1}{D_1 + R_1}$$

$$R_1 = \frac{665}{2153} = \frac{1}{3 + \frac{158}{665}} = \frac{1}{D_2 + R_2} \text{ etc.}$$

from which it may be seen that  $D_1 = 4, R_1 = 665/2153; D_2 = 3, R_2 = 158/665$ ; and, continuing as was explained previously, it would be found that:  $D_3 = 4, R_3 = 33/158; \dots; D_9 = 2, R_9 = 0$ . The complete set of continued fraction elements representing  $2153/9277$  may then be written as

$$\frac{2153}{9277} = \frac{1}{4 + \frac{1}{3 + \frac{1}{4 + \frac{1}{4 + \frac{1}{1 + \frac{1}{3 + \frac{1}{1 + \frac{1}{2 + \frac{1}{2}}}}}}}}}$$

$$D_1 \dots \dots \dots D_5 \dots \dots \dots D_9$$

By following a simple procedure, together with a table organized similar to the one below for the fraction  $2153/9277$ , the denominators  $D_1, D_2, \dots$  of the elements of a continued fraction may be used to calculate a series of fractions, each of which is a successively closer approximation, called a *convergent*, to the original fraction  $N/D$ .

1) The first row of the table contains column numbers numbered from 1 through 2 plus the number of elements,  $2 + 9 = 11$  in this example.



CONJUGATE FRACTIONS

2) The second row contains the denominators of the continued fraction elements in sequence but beginning in column 3 instead of column 1 because columns 1 and 2 must be blank in this procedure.

3) The third row contains the convergents to the original fraction as they are calculated and entered. Note that the fractions 1/0 and 0/1 have been inserted into columns 1 and 2. These are two arbitrary convergents, the first equal to infinity, the second to zero, which are used to facilitate the calculations.

4) The convergent in column 3 is now calculated. To find the numerator, multiply the denominator in column 3 by the numerator of the convergent in column 2 and add the numerator of the convergent in column 1. Thus,  $4 \times 0 + 1 = 1$ .

5) The denominator of the convergent in column 3 is found by multiplying the denominator in column 3 by the denominator of the convergent in column 2 and adding the denominator of the convergent in column 1. Thus,  $4 \times 1 + 0 = 4$ , and the convergent in column 3 is then  $\frac{1}{4}$  as shown in the table.

6) Finding the remaining successive convergents can be reduced to using the simple equation

$$\text{CONVERGENT}_n = \frac{(D_n)(\text{NUM}_{n-1}) + \text{NUM}_{n-2}}{(D_n)(\text{DEN}_{n-1}) + \text{DEN}_{n-2}}$$

in which  $n$  = column number in the table;  $D_n$  = denominator in column  $n$ ;  $\text{NUM}_{n-1}$  and  $\text{NUM}_{n-2}$  are numerators and  $\text{DEN}_{n-1}$  and  $\text{DEN}_{n-2}$  are denominators of the convergents in the columns indicated by their subscripts; and  $\text{CONVERGENT}_n$  is the convergent in column  $n$ .

**Convergents of the Continued Fraction for 2153/9277**

| Column Number, $n$            | 1             | 2             | 3             | 4              | 5               | 6                | 7                | 8                  | 9                  | 10                 | 11                  |
|-------------------------------|---------------|---------------|---------------|----------------|-----------------|------------------|------------------|--------------------|--------------------|--------------------|---------------------|
| Denominator, $D_n$            | —             | —             | 4             | 3              | 4               | 4                | 1                | 3                  | 1                  | 2                  | 2                   |
| Convergent, $\frac{NUM}{DEN}$ | $\frac{1}{0}$ | $\frac{0}{1}$ | $\frac{1}{4}$ | $\frac{3}{13}$ | $\frac{13}{56}$ | $\frac{55}{237}$ | $\frac{68}{293}$ | $\frac{259}{1116}$ | $\frac{327}{1409}$ | $\frac{913}{3934}$ | $\frac{2153}{9277}$ |

Notes: The decimal values of the successive convergents in the table are alternately larger and smaller than the value of the original fraction 2153/9277. If the last convergent in the table has the same value as the original fraction 2153/9277, then all of the other calculated convergents are correct.

**Conjugate Fractions.**—In addition to finding approximate ratios by the use of continued fractions and logarithms of ratios, conjugate fractions may be used for the same purpose, independently, or in combination with the other methods.

Two fractions  $a/b$  and  $c/d$  are said to be conjugate if  $ad - bc = \pm 1$ . Examples of such pairs are: 0/1 and 1/1; 1/2 and 1/1; and 9/10 and 8/9. Also, every successive pair of the convergents of a continued fraction are conjugate. Conjugate fractions have certain properties that are useful for solving ratio problems:

1) No fraction between two conjugate fractions  $a/b$  and  $c/d$  can have a denominator smaller than either  $b$  or  $d$ .

2) A new fraction,  $e/f$ , conjugate to both fractions of a given pair of conjugate fractions,  $a/b$  and  $c/d$ , and lying between them, may be created by adding respective numerators,  $a + c$ , and denominators,  $b + d$ , so that  $e/f = (a + c)/(b + d)$ .

3) The denominator  $f = b + d$  of the new fraction  $e/f$  is the smallest of any possible fraction lying between  $a/b$  and  $c/d$ . Thus, 17/19 is conjugate to both 8/9 and 9/10 and no fraction with denominator smaller than 19 lies between them. This property is important if it is desired to minimize the size of the factors of the ratio to be found.

The following example shows the steps to approximate a ratio for a set of gears to any desired degree of accuracy within the limits established for the allowable size of the factors in the ratio.

*Example:* Find a set of four change gears,  $ab/cd$ , to approximate the ratio 2.105399 accurate to within  $\pm 0.0001$ ; no gear is to have more than 120 teeth.

Step 1. Convert the given ratio  $R$  to a number  $r$  between 0 and 1 by taking its reciprocal:  $1/R = 1/2.105399 = 0.4749693 = r$ .

Step 2. Select a pair of conjugate fractions  $a/b$  and  $c/d$  that bracket  $r$ . The pair  $a/b = 0/1$  and  $c/d = 1/1$ , for example, will bracket 0.4749693.

Step 3. Add the respective numerators and denominators of the conjugates  $0/1$  and  $1/1$  to create a new conjugate  $e/f$  between 0 and 1:  $e/f = (a + c)/(b + d) = (0 + 1)/(1 + 1) = 1/2$ .

Step 4. Since 0.4749693 lies between  $0/1$  and  $1/2$ ,  $e/f$  must also be between  $0/1$  and  $1/2$ :  $e/f = (0 + 1)/(1 + 2) = 1/3$ .

Step 5. Since 0.4749693 now lies between  $1/3$  and  $1/2$ ,  $e/f$  must also be between  $1/3$  and  $1/2$ :  $e/f = (1 + 1)/(3 + 2) = 2/5$ .

Step 6. Continuing as above to obtain successively closer approximations of  $e/f$  to 0.4749693, and using a handheld calculator and a scratch pad to facilitate the process, the fractions below, each of which has factors less than 120, were determined:

| Fraction | Numerator Factors  | Denominator Factors             | Error       |
|----------|--|---------------------------------|-------------|
| 19/40    | 19   | $2 \times 2 \times 2 \times 5$  | + .000031   |
| 28/59    | $2 \times 2 \times 7$  | 59                              | - .00039    |
| 47/99    | 47   | $3 \times 3 \times 11$          | - .00022    |
| 104/219  | $2 \times 2 \times 2 \times 13$                                    | $3 \times 73$                   | - .000083   |
| 123/259  | $3 \times 41$  | $7 \times 37$                   | - .000066   |
| 142/299  | $2 \times 71$  | $13 \times 23$                  | - .000053   |
| 161/339  | $7 \times 23$  | $3 \times 113$                  | - .000043   |
| 218/459  | $2 \times 109$   | $3 \times 3 \times 3 \times 17$ | - .000024   |
| 256/539  | $2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2$ | $7 \times 7 \times 11$          | - .000016   |
| 370/779  | $2 \times 5 \times 37$   | $19 \times 41$                  | - .0000014  |
| 759/1598 | $3 \times 11 \times 23$  | $2 \times 17 \times 47$         | - .00000059 |

Factors for the numerators and denominators of the fractions shown above were found with the aid of the Prime Numbers and Factors tables beginning on page 20. Since in Step 1 the desired ratio of 2.105399 was converted to its reciprocal 0.4749693, all of the above fractions should be inverted. Note also that the last fraction, 759/1598, when inverted to become 1598/759, is in error from the desired value by approximately one-half the amount obtained by trial and error using earlier methods.

**Using Continued Fraction Convergents as Conjugates.**—Since successive convergents of a continued fraction are also conjugate, they may be used to find a series of additional fractions in between themselves. As an example, the successive convergents 55/237 and 68/293 from the table of convergents for 2153/9277 on page 12 will be used to demonstrate the process for finding the first few in-between ratios.

#### Desired Fraction $N/D = 2153/9277 = 0.2320793$

| $ab$                      | $ef$   | $cd$                  |
|---------------------------|--|-----------------------|
| (1) $55/237 = .2320675$   | $^{a}123/530 = .2320755$ error = - .0000039  | $68/293 = .2320819$   |
| (2) $123/530 = .2320755$  | $191/823 = .2320778$ error = - .0000016      | $68/293 = .2320819$   |
| (3) $191/823 = .2320778$  | $^{a}259/1116 = .2320789$ error = - .0000005 | $68/293 = .2320819$   |
| (4) $259/1116 = .2320789$ | $327/1409 = .2320795$ error = + .0000002     | $68/293 = .2320819$   |
| (5) $259/1116 = .2320789$ | $586/2525 = .2320792$ error = - .0000001     | $327/1409 = .2320795$ |
| (6) $586/2525 = .2320792$ | $913/3934 = .2320793$ error = - .0000000     | $327/1409 = .2320795$ |

<sup>a</sup> Only these ratios had suitable factors below 120.

Step 1. Check the convergents for conjugateness:  $55 \times 293 - 237 \times 68 = 16115 - 16116 = -1$  proving the pair to be conjugate.

Step 2. Set up a table as shown above. The leftmost column of line (1) contains the convergent of lowest value,  $a/b$ ; the rightmost the higher value,  $c/d$ ; and the center column the derived value  $e/f$  found by adding the respective numerators and denominators of  $a/b$  and  $c/d$ . The error or difference between  $e/f$  and the desired value  $N/D$ ,  $\text{error} = N/D - e/f$ , is also shown.

Step 3. On line (2), the process used on line (1) is repeated with the  $e/f$  value from line (1) becoming the new value of  $a/b$  while the  $c/d$  value remains unchanged. Had the error in  $e/f$  been + instead of -, then  $e/f$  would have been the new  $c/d$  value and  $a/b$  would be unchanged.

Step 4. The process is continued until, as seen on line (4), the error changes sign to + from the previous -. When this occurs, the  $e/f$  value becomes the  $c/d$  value on the next line instead of  $a/b$  as previously and the  $a/b$  value remains unchanged.

### Powers and Roots

The *square* of a number (or quantity) is the product of that number multiplied by itself. Thus, the square of 9 is  $9 \times 9 = 81$ . The square of a number is indicated by the *exponent* (<sup>2</sup>), thus:  $9^2 = 9 \times 9 = 81$ .

The *cube* or *third power* of a number is the product obtained by using that number as a factor three times. Thus, the cube of 4 is  $4 \times 4 \times 4 = 64$ , and is written  $4^3$ .

If a number is used as a factor four or five times, respectively, the product is the fourth or fifth power. Thus,  $3^4 = 3 \times 3 \times 3 \times 3 = 81$ , and  $2^5 = 2 \times 2 \times 2 \times 2 \times 2 = 32$ . A number can be raised to any power by using it as a factor the required number of times.

The *square root* of a given number is that number which, when multiplied by itself, will give a product equal to the given number. The square root of 16 (written  $\sqrt{16}$ ) equals 4, because  $4 \times 4 = 16$ .

The *cube root* of a given number is that number which, when used as a factor three times, will give a product equal to the given number. Thus, the cube root of 64 (written  $\sqrt[3]{64}$ ) equals 4, because  $4 \times 4 \times 4 = 64$ .

The fourth, fifth, etc., roots of a given number are those numbers which when used as factors four, five, etc., times, will give as a product the given number. Thus,  $\sqrt[4]{16} = 2$ , because  $2 \times 2 \times 2 \times 2 = 16$ .

In some formulas, there may be such expressions as  $(a^2)^3$  and  $a^{3/2}$ . The first of these,  $(a^2)^3$ , means that the number  $a$  is first to be squared,  $a^2$ , and the result then cubed to give  $a^6$ . Thus,  $(a^2)^3$  is equivalent to  $a^6$  which is obtained by *multiplying* the exponents 2 and 3. Similarly,  $a^{3/2}$  may be interpreted as the cube of the square root of  $a$ ,  $(\sqrt{a})^3$ , or  $(a^{1/2})^3$ , so that, for example,  $16^{3/2} = (\sqrt{16})^3 = 64$ .

The multiplications required for raising numbers to powers and the extracting of roots are greatly facilitated by the use of logarithms. Extracting the square root and cube root by the regular arithmetical methods is a slow and cumbersome operation, and any roots can be more rapidly found by using logarithms.

When the power to which a number is to be raised is not an integer, say 1.62, the use of either logarithms or a scientific calculator becomes the only practical means of solution.

**Powers of Ten Notation.**—Powers of ten notation is used to simplify calculations and ensure accuracy, particularly with respect to the position of decimal points, and also simplifies the expression of numbers which are so large or so small as to be unwieldy. For example, the metric (SI) pressure unit pascal is equivalent to 0.0000986923 atmosphere or 0.0001450377 pound/inch<sup>2</sup>. In powers of ten notation, these figures are  $9.86923 \times 10^{-6}$

atmosphere and  $1.450377 \times 10^{-4}$  pound/inch<sup>2</sup>. The notation also facilitates adaptation of numbers for electronic data processing and computer readout.

**Expressing Numbers in Powers of Ten Notation.**—In this system of notation, every number is expressed by two factors, one of which is some integer from 1 to 9 followed by a decimal and the other is some power of 10.

Thus, 10,000 is expressed as  $1.0000 \times 10^4$  and 10,463 as  $1.0463 \times 10^4$ . The number 43 is expressed as  $4.3 \times 10$  and 568 is expressed as  $5.68 \times 10^2$ .

In the case of decimals, the number 0.0001, which as a fraction is  $\frac{1}{10,000}$  and is expressed as  $1 \times 10^{-4}$  and 0.0001463 is expressed as  $1.463 \times 10^{-4}$ . The decimal 0.498 is expressed as  $4.98 \times 10^{-1}$  and 0.03146 is expressed as  $3.146 \times 10^{-2}$ .

**Rules for Converting Any Number to Powers of Ten Notation.**—Any number can be converted to the powers of ten notation by means of one of two rules.

*Rule 1:* If the number is a whole number or a whole number and a decimal so that it has digits to the left of the decimal point, the decimal point is moved a sufficient number of places to the *left* to bring it to the immediate right of the first digit. With the decimal point shifted to this position, the number so written comprises the *first* factor when written in powers of ten notation.

The number of places that the decimal point is moved to the left to bring it immediately to the right of the first digit is the *positive* index or power of 10 that comprises the *second* factor when written in powers of ten notation.

Thus, to write 4639 in this notation, the decimal point is moved three places to the left giving the two factors:  $4.639 \times 10^3$ . Similarly,

$$431.412 = 4.31412 \times 10^2 \quad 986388 = 9.86388 \times 10^5$$

*Rule 2:* If the number is a decimal, i.e., it has digits entirely to the right of the decimal point, then the decimal point is moved a sufficient number of places to the *right* to bring it immediately to the right of the first digit. With the decimal point shifted to this position, the number so written comprises the *first* factor when written in powers of ten notation.

The number of places that the decimal point is moved to the *right* to bring it immediately to the right of the first digit is the *negative* index or power of 10 that follows the number when written in powers of ten notation.

Thus, to bring the decimal point in 0.005721 to the immediate right of the first digit, which is 5, it must be moved *three* places to the right, giving the two factors:  $5.721 \times 10^{-3}$ . Similarly,

$$0.469 = 4.69 \times 10^{-1} \quad 0.0000516 = 5.16 \times 10^{-5}$$

**Multiplying Numbers Written in Powers of Ten Notation.**—When multiplying two numbers written in the powers of ten notation together, the procedure is as follows:

1) Multiply the first factor of one number by the first factor of the other to obtain the first factor of the product.

2) Add the index of the second factor (which is some power of 10) of one number to the index of the second factor of the other number to obtain the index of the second factor (which is some power of 10) in the product. Thus:

$$(4.31 \times 10^{-2}) \times (9.0125 \times 10) = (4.31 \times 9.0125) \times 10^{-2+1} = 38.844 \times 10^{-1}$$

$$(5.986 \times 10^4) \times (4.375 \times 10^3) = (5.986 \times 4.375) \times 10^{4+3} = 26.189 \times 10^7$$

In the preceding calculations, neither of the results shown are in the conventional powers of ten form since the first factor in each has two digits. In the conventional powers of ten notation, the results would be

$38.844 \times 10^{-1} = 3.884 \times 10^0 = 3.884$ , since  $10^0 = 1$ , and  $26.189 \times 10^7 = 2.619 \times 10^8$  in each case rounding off the first factor to three decimal places.

When multiplying several numbers written in this notation together, the procedure is the same. All of the first factors are multiplied together to get the first factor of the product and all of the indices of the respective powers of ten are added together, taking into account their respective signs, to get the index of the second factor of the product. Thus,  $(4.02 \times 10^{-3}) \times (3.987 \times 10) \times (4.863 \times 10^5) = (4.02 \times 3.987 \times 4.863) \times 10^{(-3+1+5)} = 77.94 \times 10^3 = 7.79 \times 10^4$  rounding off the first factor to two decimal places.

**Dividing Numbers Written in Powers of Ten Notation.**—When dividing one number by another when both are written in this notation, the procedure is as follows:

1) Divide the first factor of the dividend by the first factor of the divisor to get the first factor of the quotient.

2) Subtract the index of the second factor of the divisor from the index of the second factor of the dividend, taking into account their respective signs, to get the index of the second factor of the quotient. Thus:

$$(4.31 \times 10^{-2}) \div (9.0125 \times 10) = \\ (4.31 \div 9.0125) \times (10^{-2-1}) = 0.4782 \times 10^{-3} = 4.782 \times 10^{-4}$$

It can be seen that this system of notation is helpful where several numbers of different magnitudes are to be multiplied and divided.

*Example:* Find the quotient of  $\frac{250 \times 4698 \times 0.00039}{43678 \times 0.002 \times 0.0147}$

*Solution:* Changing all these numbers to powers of ten notation and performing the operations indicated:

$$\frac{(2.5 \times 10^2) \times (4.698 \times 10^3) \times (3.9 \times 10^{-4})}{(4.3678 \times 10^4) \times (2 \times 10^{-3}) \times (1.47 \times 10^{-2})} = \\ = \frac{(2.5 \times 4.698 \times 3.9)(10^{2+3-4})}{(4.3678 \times 2 \times 1.47)(10^{4-3-2})} = \frac{45.8055 \times 10}{12.8413 \times 10^{-1}} \\ = 3.5670 \times 10^{1-(-1)} = 3.5670 \times 10^2 = 356.70$$

### Constants Frequently Used in Mathematical Expressions

|   |                                   |                                   |                               |
|---|-----------------------------------|-----------------------------------|-------------------------------|
| $0.00872665 = \frac{\pi}{360}$          | $0.8660254 = \frac{\sqrt{3}}{2}$  | $2.0943951 = \frac{2\pi}{3}$      | $4.712389 = \frac{3\pi}{2}$   |
| $0.01745329 = \frac{\pi}{180}$          | $1.0471975 = \frac{\pi}{3}$       | $2.3561945 = \frac{3\pi}{4}$      | $5.2359878 = \frac{5\pi}{3}$  |
| $0.26179939 = \frac{\pi}{12}$           | $1.1547005 = \frac{2\sqrt{3}}{3}$ | $2.5980762 = \frac{3\sqrt{3}}{2}$ | $5.4977871 = \frac{7\pi}{4}$  |
| $0.39269908 = \frac{\pi}{8}$            | $1.2247449 = \sqrt{\frac{3}{2}}$  | $2.6179939 = \frac{5\pi}{6}$      | $5.7595865 = \frac{11\pi}{6}$ |
| $0.52359878 = \frac{\pi}{6}$            | $1.4142136 = \sqrt{2}$            | $3.1415927 = \pi$                 | $6.2831853 = 2\pi$            |
| $0.57735027 = \frac{\sqrt{3}}{3}$       | $1.5707963 = \frac{\pi}{2}$       | $3.6651914 = \frac{7\pi}{6}$      | $9.8696044 = \pi^2$           |
| $0.62035049 = \sqrt[3]{\frac{3}{4\pi}}$ | $1.7320508 = \sqrt{3}$            | $3.9269908 = \frac{5\pi}{4}$      | $9.424778 = 3\pi$             |
| $0.78539816 = \frac{\pi}{4}$            | $2.4674011 = \frac{\pi^2}{4}$     | $4.1887902 = \frac{4\pi}{3}$      | $12.566371 = 4\pi$            |
|   |                                   |                                   | $57.29578 = \frac{180}{\pi}$  |
|   |                                   |                                   | $114.59156 = \frac{360}{\pi}$ |

### Imaginary and Complex Numbers

**Complex or Imaginary Numbers.**—Complex or imaginary numbers represent a class of mathematical objects that are used to simplify certain problems, such as the solution of polynomial equations. The basis of the complex number system is the unit imaginary number  $i$  that satisfies the following relations:

$$i^2 = (-i)^2 = -1 \quad i = \sqrt{-1} \quad -i = -\sqrt{-1}$$

In electrical engineering and other fields, the unit imaginary number is often represented by  $j$  rather than  $i$ . However, the meaning of the two terms is identical.

**Rectangular or Trigonometric Form:** Every complex number,  $Z$ , can be written as the sum of a real number and an imaginary number. When expressed as a sum,  $Z = a + bi$ , the complex number is said to be in rectangular or trigonometric form. The real part of the number is  $a$ , and the imaginary portion is  $bi$  because it has the imaginary unit assigned to it.

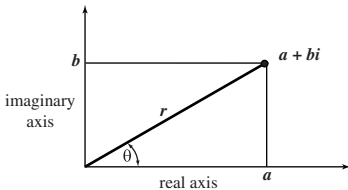
**Polar Form:** A complex number  $Z = a + bi$  can also be expressed in polar form, also known as phasor form. In polar form, the complex number  $Z$  is represented by a magnitude  $r$  and an angle  $\theta$  as follows:

$$Z = r \angle \theta$$

$\angle \theta$  = a direction, the angle whose tangent is  $b \div a$ , thus  $\theta = \text{atan} \frac{b}{a}$  and

$$r = \sqrt{a^2 + b^2} \text{ is the magnitude}$$

A complex number can be plotted on a real-imaginary coordinate system known as the complex plane. The figure below illustrates the relationship between the rectangular coordinates  $a$  and  $b$ , and the polar coordinates  $r$  and  $\theta$ .



Complex Number in the Complex Plane

The rectangular form can be determined from  $r$  and  $\theta$  as follows:

$$a = r \cos \theta \quad b = r \sin \theta \quad a + bi = r \cos \theta + ir \sin \theta = r(\cos \theta + i \sin \theta)$$

The rectangular form can also be written using Euler's Formula:

$$e^{\pm i\theta} = \cos \theta \pm i \sin \theta \quad \sin \theta = \frac{e^{i\theta} - e^{-i\theta}}{2i} \quad \cos \theta = \frac{e^{i\theta} + e^{-i\theta}}{2}$$

**Complex Conjugate:** Complex numbers commonly arise in finding the solution of polynomials. A polynomial of  $n^{\text{th}}$  degree has  $n$  solutions, an even number of which are complex and the rest are real. The complex solutions always appear as complex conjugate pairs in the form  $a + bi$  and  $a - bi$ . The product of these two conjugates,  $(a + bi) \times (a - bi) = a^2 + b^2$ , is the square of the magnitude  $r$  illustrated in the previous figure.

### Operations on Complex Numbers

**Example 1, Addition:** When adding two complex numbers, the real parts and imaginary parts are added separately, the real parts added to real parts and the imaginary to imaginary parts. Thus,

$$(a_1 + ib_1) + (a_2 + ib_2) = (a_1 + a_2) + i(b_1 + b_2)$$

$$(a_1 + ib_1) - (a_2 + ib_2) = (a_1 - a_2) + i(b_1 - b_2)$$

$$(3 + 4i) + (2 + i) = (3 + 2) + (4 + 1)i = 5 + 5i$$

*Example 2, Multiplication:* Multiplication of two complex numbers requires the use of the imaginary unit,  $i^2 = -1$  and the algebraic distributive law.

$$\begin{aligned}(a_1 + ib_1)(a_2 + ib_2) &= a_1a_2 + ia_1b_2 + ia_2b_1 + i^2b_1b_2 \\ &= a_1a_2 + ia_1b_2 + ia_2b_1 - b_1b_2\end{aligned}$$

$$\begin{aligned}(7 + 2i) \times (5 - 3i) &= (7)(5) - (7)(3i) + (2i)(5) - (2i)(3i) \\ &= 35 - 21i + 10i - 6i^2 \\ &= 35 - 21i + 10i - (6)(-1) = 41 - 11i\end{aligned}$$

Multiplication of two complex numbers,  $Z_1 = r_1(\cos\theta_1 + i\sin\theta_1)$  and  $Z_2 = r_2(\cos\theta_2 + i\sin\theta_2)$ , results in the following:

$$Z_1 \times Z_2 = r_1(\cos\theta_1 + i\sin\theta_1) \times r_2(\cos\theta_2 + i\sin\theta_2) = r_1r_2[\cos(\theta_1 + \theta_2) + i\sin(\theta_1 + \theta_2)]$$

*Example 3, Division:* Divide the following two complex numbers,  $2 + 3i$  and  $4 - 5i$ . Dividing complex numbers makes use of the complex conjugate.

$$\frac{2 + 3i}{4 - 5i} = \frac{(2 + 3i)(4 + 5i)}{(4 - 5i)(4 + 5i)} = \frac{8 + 12i + 10i + 15i^2}{16 + 20i - 20i - 25i^2} = \frac{-7 + 22i}{16 + 25} = \left(\frac{-7}{41}\right) + i\left(\frac{22}{41}\right)$$

*Example 4:* Convert the complex number  $8+6i$  into phasor form.

First find the magnitude of the phasor vector and then the direction.

$$\text{magnitude} = \sqrt{8^2 + 6^2} = 10 \quad \text{direction} = \text{atan}\frac{6}{8} = 36.87^\circ$$

$$\text{phasor} = 10 \angle 36.87^\circ$$

**Factorial.**—A factorial is a mathematical shortcut denoted by the symbol ! following a number (for example, 3! is three factorial). A factorial is found by multiplying together all the integers greater than zero and less than or equal to the factorial number wanted, except for zero factorial (0!), which is defined as 1. For example: 3! = 1 × 2 × 3 = 6; 4! = 1 × 2 × 3 × 4 = 24; 7! = 1 × 2 × 3 × 4 × 5 × 6 × 7 = 5040; etc.

*Example:* How many ways can the letters X, Y, and Z be arranged?

*Solution:* The numbers of possible arrangements for the three letters are 3! = 3 × 2 × 1 = 6.

**Permutations.**—The number of ways  $r$  objects may be arranged from a set of  $n$  elements

$$\text{is given by } {}^n P_r = \frac{n!}{(n-r)!}$$

*Example:* There are 10 people are participating in the final run. In how many different ways can these people come in first, second and third.

*Solution:* Here  $r$  is 3 and  $n$  is 10. So the possible numbers of winning number will be

$${}^{10} P_3 = \frac{10!}{(10-3)!} = \frac{10!}{7!} = 10 \times 9 \times 8 = 720$$

**Combinations.**—The number of ways  $r$  distinct objects may be chosen from a set of  $n$  elements is given by

$${}^n C_r = \frac{n!}{(n-r)!r!}$$

*Example:* How many possible sets of 6 winning numbers can be picked from 52 numbers.

*Solution:* Here  $r$  is 6 and  $n$  is 52. So the possible number of winning combinations will be

$${}^{52}C_6 = \frac{52!}{(52-6)!6!} = \frac{52!}{46!6!} = \frac{52 \times 51 \times 50 \times 49 \times 48 \times 47}{1 \times 2 \times 3 \times 4 \times 5 \times 6} = 20358520$$

### Prime Numbers and Factors of Numbers

The *factors* of a given number are those numbers which when multiplied together give a product equal to that number; thus, 2 and 3 are factors of 6; and 5 and 7 are factors of 35.

A *prime number* is one which has no factors except itself and 1. Thus, 2, 3, 5, 7, 11, etc., are prime numbers. A factor which is a prime number is called a *prime factor*.

The accompanying "Prime Number and Factor Tables," starting on page 20, give the smallest prime factor of all odd numbers from 1 to 9600, and can be used for finding all the factors for numbers up to this limit. For example, find the factors of 931. In the column headed "900" and in the line indicated by "31" in the left-hand column, the smallest prime factor is found to be 7. As this leaves another factor 133 (since  $931 \div 7 = 133$ ), find the smallest prime factor of this number. In the column headed "100" and in the line "33", this is found to be 7, leaving a factor 19. This latter is a prime number; hence, the factors of 931 are  $7 \times 7 \times 19$ . Where no factor is given for a number in the factor table, it indicates that the number is a prime number.

The last page of the tables lists all prime numbers from 9551 through 18691; and can be used to identify quickly all unfactorable numbers in that range.

For factoring, the following general rules will be found useful:

2 is a factor of any number the right-hand figure of which is an even number or 0. Thus,  $28 = 2 \times 14$ , and  $210 = 2 \times 105$ .

3 is a factor of any number the sum of the figures of which is evenly divisible by 3. Thus, 3 is a factor of 1869, because  $1 + 8 + 6 + 9 = 24 \div 3 = 8$ .

4 is a factor of any number the two right-hand figures of which, considered as one number, are evenly divisible by 4. Thus, 1844 has a factor 4, because  $44 \div 4 = 11$ .

5 is a factor of any number the right-hand figure of which is 0 or 5. Thus,  $85 = 5 \times 17$ ;  $70 = 5 \times 14$ .

Tables of prime numbers and factors of numbers are particularly useful for calculations involving change-gear ratios for compound gearing, dividing heads, gear-generating machines, and mechanical designs having gear trains.

*Example 1:* A set of four gears is required in a mechanical design to provide an overall gear ratio of  $4104 \div 1200$ . Furthermore, no gear in the set is to have more than 120 teeth or less than 24 teeth. Determine the tooth numbers.

First, as explained previously, the factors of 4104 are determined to be:  $2 \times 2 \times 2 \times 3 \times 3 \times 57 = 4104$ . Next, the factors of 1200 are determined:  $2 \times 2 \times 2 \times 2 \times 5 \times 5 \times 3 = 1200$ .

Therefore  $\frac{4104}{1200} = \frac{2 \times 2 \times 2 \times 3 \times 3 \times 57}{2 \times 2 \times 2 \times 2 \times 5 \times 5 \times 3} = \frac{72 \times 57}{24 \times 50}$ . If the factors had been com-

bined differently, say, to give  $\frac{72 \times 57}{16 \times 75}$ , then the 16-tooth gear in the denominator would

not satisfy the requirement of no less than 24 teeth.

*Example 2:* Factor the number 25078 into two numbers neither of which is larger than 200.

The first factor of 25078 is obviously 2, leaving  $25078 \div 2 = 12539$  to be factored further. However, from the last table, *Prime Numbers from 9551 to 18691*, it is seen that 12539 is a prime number; therefore, no solution exists.



FACTORS AND PRIME NUMBERS

Prime Number and Factor Table for 1 to 1199

| From To | 0 100 | 100 200 | 200 300 | 300 400 | 400 500 | 500 600 | 600 700 | 700 800 | 800 900 | 900 1000 | 1000 1100 | 1100 1200 |
|---------|-------|---------|---------|---------|---------|---------|---------|---------|---------|----------|-----------|-----------|
| 1       | P     | P       | 3       | 7       | P       | 3       | P       | P       | 3       | 17       | 7         | 3         |
| 2       | P     | 2       | 2       | 2       | 2       | 2       | 2       | 2       | 2       | 2        | 2         | 2         |
| 3       | P     | P       | 7       | 3       | 13      | P       | 3       | 19      | 11      | 3        | 17        | P         |
| 5       | P     | 3       | 5       | 5       | 3       | 5       | 5       | 3       | 5       | 5        | 3         | 5         |
| 7       | P     | P       | 3       | P       | 11      | 3       | P       | 7       | 3       | P        | 19        | 3         |
| 9       | 3     | P       | 11      | 3       | P       | P       | 3       | P       | P       | 3        | P         | P         |
| 11      | P     | 3       | P       | P       | 3       | 7       | 13      | 3       | P       | P        | 3         | 11        |
| 13      | P     | P       | 3       | P       | 7       | 3       | P       | 23      | 3       | 11       | P         | 3         |
| 15      | 3     | 5       | 5       | 3       | 5       | 5       | 3       | 5       | 5       | 3        | 5         | 5         |
| 17      | P     | 3       | 7       | P       | 3       | 11      | P       | 3       | 19      | 7        | 3         | P         |
| 19      | P     | 7       | 3       | 11      | P       | 3       | P       | P       | 3       | P        | P         | 3         |
| 21      | 3     | 11      | 13      | 3       | P       | P       | 3       | 7       | P       | 3        | P         | 19        |
| 23      | P     | 3       | P       | 17      | 3       | P       | 7       | 3       | P       | 13       | 3         | P         |
| 25      | 5     | 5       | 3       | 5       | 5       | 3       | 5       | 5       | 3       | 5        | 5         | 3         |
| 27      | 3     | P       | P       | 3       | 7       | 17      | 3       | P       | P       | 3        | 13        | 7         |
| 29      | P     | 3       | P       | 7       | 3       | 23      | 17      | 3       | P       | P        | 3         | P         |
| 31      | P     | P       | 3       | P       | P       | 3       | P       | 17      | 3       | 7        | P         | 3         |
| 33      | 3     | 7       | P       | 3       | P       | 13      | 3       | P       | 7       | 3        | P         | 11        |
| 35      | 5     | 3       | 5       | 5       | 3       | 5       | 5       | 3       | 5       | 5        | 3         | 5         |
| 37      | P     | P       | 3       | P       | 19      | 3       | 7       | 11      | 3       | P        | 17        | 3         |
| 39      | 3     | P       | P       | 3       | P       | 7       | 3       | P       | P       | 3        | P         | 17        |
| 41      | P     | 3       | P       | 11      | 3       | P       | P       | 3       | 29      | P        | 3         | 7         |
| 43      | P     | 11      | 3       | 7       | P       | 3       | P       | P       | 3       | 23       | 7         | 3         |
| 45      | 3     | 5       | 5       | 3       | 5       | 5       | 3       | 5       | 5       | 3        | 5         | 5         |
| 47      | P     | 3       | 13      | P       | 3       | P       | P       | 3       | 7       | P        | 3         | 31        |
| 49      | 7     | P       | 3       | P       | P       | 3       | 11      | 7       | 3       | 13       | P         | 3         |
| 51      | 3     | P       | P       | 3       | 11      | 19      | 3       | P       | 23      | 3        | P         | P         |
| 53      | P     | 3       | 11      | P       | 3       | 7       | P       | 3       | P       | P        | 3         | P         |
| 55      | 5     | 5       | 3       | 5       | 5       | 3       | 5       | 5       | 3       | 5        | 5         | 3         |
| 57      | 3     | P       | P       | 3       | P       | P       | 3       | P       | P       | 3        | 7         | 13        |
| 59      | P     | 3       | 7       | P       | 3       | 13      | P       | 3       | P       | 7        | 3         | 19        |
| 61      | P     | 7       | 3       | 19      | P       | 3       | P       | P       | 3       | 31       | P         | 3         |
| 63      | 3     | P       | P       | 3       | P       | P       | 3       | 7       | P       | 3        | P         | P         |
| 65      | 5     | 3       | 5       | 5       | 3       | 5       | 5       | 3       | 5       | 5        | 3         | 5         |
| 67      | P     | P       | 3       | P       | P       | 3       | 23      | 13      | 3       | P        | 11        | 3         |
| 69      | 3     | 13      | P       | 3       | 7       | P       | 3       | P       | 11      | 3        | P         | 7         |
| 71      | P     | 3       | P       | 7       | 3       | P       | 11      | 3       | 13      | P        | 3         | P         |
| 73      | P     | P       | 3       | P       | 11      | 3       | P       | P       | 3       | 7        | 29        | 3         |
| 75      | 3     | 5       | 5       | 3       | 5       | 5       | 3       | 5       | 5       | 3        | 5         | 5         |
| 77      | 7     | 3       | P       | 13      | 3       | P       | P       | 3       | P       | P        | 3         | 11        |
| 79      | P     | P       | 3       | P       | P       | 3       | 7       | 19      | 3       | 11       | 13        | 3         |
| 81      | 3     | P       | P       | 3       | 13      | 7       | 3       | 11      | P       | 3        | 23        | P         |
| 83      | P     | 3       | P       | P       | 3       | 11      | P       | 3       | P       | P        | 3         | 7         |
| 85      | 5     | 5       | 3       | 5       | 5       | 3       | 5       | 5       | 3       | 5        | 5         | 3         |
| 87      | 3     | 11      | 7       | 3       | P       | P       | 3       | P       | P       | 3        | P         | P         |
| 89      | P     | 3       | 17      | P       | 3       | 19      | 13      | 3       | 7       | 23       | 3         | 29        |
| 91      | 7     | P       | 3       | 17      | P       | 3       | P       | 7       | 3       | P        | P         | 3         |
| 93      | 3     | P       | P       | 3       | 17      | P       | 3       | 13      | 19      | 3        | P         | P         |
| 95      | 5     | 3       | 5       | 5       | 3       | 5       | 5       | 3       | 5       | 5        | 3         | 5         |
| 97      | P     | P       | 3       | P       | 7       | 3       | 17      | P       | 3       | P        | P         | 3         |
| 99      | 3     | P       | 13      | 3       | P       | P       | 3       | 17      | 29      | 3        | 7         | 11        |

Prime Number and Factor Table for 1201 to 2399

| From<br>To | 1200<br>1300 | 1300<br>1400 | 1400<br>1500 | 1500<br>1600 | 1600<br>1700 | 1700<br>1800 | 1800<br>1900 | 1900<br>2000 | 2000<br>2100 | 2100<br>2200 | 2200<br>2300 | 2300<br>2400 |
|------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| 1          | P            | P            | 3            | 19           | P            | 3            | P            | P            | 3            | 11           | 31           | 3            |
| 3          | 3            | P            | 23           | 3            | 7            | 13           | 3            | 11           | P            | 3            | P            | 7            |
| 5          | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            |
| 7          | 17           | P            | 3            | 11           | P            | 3            | 13           | P            | 3            | 7            | P            | 3            |
| 9          | 3            | 7            | P            | 3            | P            | P            | 3            | 23           | 7            | 3            | 47           | P            |
| 11         | 7            | 3            | 17           | P            | 3            | 29           | P            | 3            | P            | P            | 3            | P            |
| 13         | P            | 13           | 3            | 17           | P            | 3            | 7            | P            | 3            | P            | P            | 3            |
| 15         | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            |
| 17         | P            | 3            | 13           | 37           | 3            | 17           | 23           | 3            | P            | 29           | 3            | 7            |
| 19         | 23           | P            | 3            | 7            | P            | 3            | 17           | 19           | 3            | 13           | 7            | 3            |
| 21         | 3            | P            | 7            | 3            | P            | P            | 3            | 17           | 43           | 3            | P            | 11           |
| 23         | P            | 3            | P            | P            | 3            | P            | P            | 3            | 7            | 11           | 3            | 23           |
| 25         | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            |
| 27         | 3            | P            | P            | 3            | P            | 11           | 3            | 41           | P            | 3            | 17           | 13           |
| 29         | P            | 3            | P            | 11           | 3            | 7            | 31           | 3            | P            | P            | 3            | 17           |
| 31         | P            | 11           | 3            | P            | 7            | 3            | P            | P            | 3            | P            | 23           | 3            |
| 33         | 3            | 31           | P            | 3            | 23           | P            | 3            | P            | 19           | 3            | 7            | P            |
| 35         | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            |
| 37         | P            | 7            | 3            | 29           | P            | 3            | 11           | 13           | 3            | P            | P            | 3            |
| 39         | 3            | 13           | P            | 3            | 11           | 37           | 3            | 7            | P            | 3            | P            | P            |
| 41         | 17           | 3            | 11           | 23           | 3            | P            | 7            | 3            | 13           | P            | 3            | P            |
| 43         | 11           | 17           | 3            | P            | 31           | 3            | 19           | 29           | 3            | P            | P            | 3            |
| 45         | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            |
| 47         | 29           | 3            | P            | 7            | 3            | P            | P            | 3            | 23           | 19           | 3            | P            |
| 49         | P            | 19           | 3            | P            | 17           | 3            | 43           | P            | 3            | 7            | 13           | 3            |
| 51         | 3            | 7            | P            | 3            | 13           | 17           | 3            | P            | 7            | 3            | P            | P            |
| 53         | 7            | 3            | P            | P            | 3            | P            | 17           | 3            | P            | P            | 3            | 13           |
| 55         | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            |
| 57         | 3            | 23           | 31           | 3            | P            | 7            | 3            | 19           | 11           | 3            | 37           | P            |
| 59         | P            | 3            | P            | P            | 3            | P            | 11           | 3            | 29           | 17           | 3            | 7            |
| 61         | 13           | P            | 3            | 7            | 11           | 3            | P            | 37           | 3            | P            | 7            | 3            |
| 63         | 3            | 29           | 7            | 3            | P            | 41           | 3            | 13           | P            | 3            | 31           | 17           |
| 65         | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            |
| 67         | 7            | P            | 3            | P            | P            | 3            | P            | 7            | 3            | 11           | P            | 3            |
| 69         | 3            | 37           | 13           | 3            | P            | 29           | 3            | 11           | P            | 3            | P            | 23           |
| 71         | 31           | 3            | P            | P            | 3            | 7            | P            | 3            | 19           | 13           | 3            | P            |
| 73         | 19           | P            | 3            | 11           | 7            | 3            | P            | P            | 3            | 41           | P            | 3            |
| 75         | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            |
| 77         | P            | 3            | 7            | 19           | 3            | P            | P            | 3            | 31           | 7            | 3            | P            |
| 79         | P            | 7            | 3            | P            | 23           | 3            | P            | P            | 3            | P            | 43           | 3            |
| 81         | 3            | P            | P            | 3            | 41           | 13           | 3            | 7            | P            | 3            | P            | P            |
| 83         | P            | 3            | P            | P            | 3            | P            | 7            | 3            | P            | 37           | 3            | P            |
| 85         | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            |
| 87         | 3            | 19           | P            | 3            | 7            | P            | 3            | P            | P            | 3            | P            | 7            |
| 89         | P            | 3            | P            | 7            | 3            | P            | P            | 3            | P            | 11           | 3            | P            |
| 91         | P            | 13           | 3            | 37           | 19           | 3            | 31           | 11           | 3            | 7            | 29           | 3            |
| 93         | 3            | 7            | P            | 3            | P            | 11           | 3            | P            | 7            | 3            | P            | P            |
| 95         | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            |
| 97         | P            | 11           | 3            | P            | P            | 3            | 7            | P            | 3            | 13           | P            | 3            |
| 99         | 3            | P            | P            | 3            | P            | 7            | 3            | P            | P            | 3            | 11           | P            |

FACTORS AND PRIME NUMBERS

Prime Number and Factor Table for 2401 to 3599

| From To | 2400 2500 | 2500 2600 | 2600 2700 | 2700 2800 | 2800 2900 | 2900 3000 | 3000 3100 | 3100 3200 | 3200 3300 | 3300 3400 | 3400 3500 | 3500 3600 |
|---------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1       | 7         | 41        | 3         | 37        | P         | 3         | P         | 7         | 3         | P         | 19        | 3         |
| 3       | 3         | P         | 19        | 3         | P         | P         | 3         | 29        | P         | 3         | 41        | 31        |
| 5       | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 7       | 29        | 23        | 3         | P         | 7         | 3         | 31        | 13        | 3         | P         | P         | 3         |
| 9       | 3         | 13        | P         | 3         | 53        | P         | 3         | P         | P         | 3         | 7         | 11        |
| 11      | P         | 3         | 7         | P         | 3         | 41        | P         | 3         | 13        | 7         | 3         | P         |
| 13      | 19        | 7         | 3         | P         | 29        | 3         | 23        | 11        | 3         | P         | P         | 3         |
| 15      | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         |
| 17      | P         | 3         | P         | 11        | 3         | P         | 7         | 3         | P         | 31        | 3         | P         |
| 19      | 41        | 11        | 3         | P         | P         | 3         | P         | P         | 3         | P         | 13        | 3         |
| 21      | 3         | P         | P         | 3         | 7         | 23        | 3         | P         | P         | 3         | 11        | 7         |
| 23      | P         | 3         | 43        | 7         | 3         | 37        | P         | 3         | 11        | P         | 3         | 13        |
| 25      | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         |
| 27      | 3         | 7         | 37        | 3         | 11        | P         | 3         | 53        | 7         | 3         | 23        | P         |
| 29      | 7         | 3         | 11        | P         | 3         | 29        | 13        | 3         | P         | P         | 3         | P         |
| 31      | 11        | P         | 3         | P         | 19        | 3         | 7         | 31        | 3         | P         | 47        | 3         |
| 33      | 3         | 17        | P         | 3         | P         | 7         | 3         | 13        | 53        | 3         | P         | P         |
| 35      | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 37      | P         | 43        | 3         | 7         | P         | 3         | P         | P         | 3         | 47        | 7         | 3         |
| 39      | 3         | P         | 7         | 3         | 17        | P         | 3         | 43        | 41        | 3         | 19        | P         |
| 41      | P         | 3         | 19        | P         | 3         | 17        | P         | 3         | 7         | 13        | 3         | P         |
| 43      | 7         | P         | 3         | 13        | P         | 3         | 17        | 7         | 3         | P         | 11        | 3         |
| 45      | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         |
| 47      | P         | 3         | P         | 41        | 3         | 7         | 11        | 3         | 17        | P         | 3         | P         |
| 49      | 31        | P         | 3         | P         | 7         | 3         | P         | 47        | 3         | 17        | P         | 3         |
| 51      | 3         | P         | 11        | 3         | P         | 13        | 3         | 23        | P         | 3         | 7         | 53        |
| 53      | 11        | 3         | 7         | P         | 3         | P         | 43        | 3         | P         | 7         | 3         | 11        |
| 55      | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         |
| 57      | 3         | P         | P         | 3         | P         | P         | 3         | 7         | P         | 3         | P         | P         |
| 59      | P         | 3         | P         | 31        | 3         | 11        | 7         | 3         | P         | P         | 3         | P         |
| 61      | 23        | 13        | 3         | 11        | P         | 3         | P         | 29        | 3         | P         | P         | 3         |
| 63      | 3         | 11        | P         | 3         | 7         | P         | 3         | P         | 13        | 3         | P         | 7         |
| 65      | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 67      | P         | 17        | 3         | P         | 47        | 3         | P         | P         | 3         | 7         | P         | 3         |
| 69      | 3         | 7         | 17        | 3         | 19        | P         | 3         | P         | 7         | 3         | P         | 43        |
| 71      | 7         | 3         | P         | 17        | 3         | P         | 37        | 3         | P         | P         | 3         | P         |
| 73      | P         | 31        | 3         | 47        | 13        | 3         | 7         | 19        | 3         | P         | 23        | 3         |
| 75      | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         |
| 77      | P         | 3         | P         | P         | 3         | 13        | 17        | 3         | 29        | 11        | 3         | 7         |
| 79      | 37        | P         | 3         | 7         | P         | 3         | P         | 11        | 3         | 31        | 7         | 3         |
| 81      | 3         | 29        | 7         | 3         | 43        | 11        | 3         | P         | 17        | 3         | 59        | P         |
| 83      | 13        | 3         | P         | 11        | 3         | 19        | P         | 3         | 7         | 17        | 3         | P         |
| 85      | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         |
| 87      | 3         | 13        | P         | 3         | P         | 29        | 3         | P         | 19        | 3         | 11        | 17        |
| 89      | 19        | 3         | P         | P         | 3         | 7         | P         | 3         | 11        | P         | 3         | 37        |
| 91      | 47        | P         | 3         | P         | 7         | 3         | 11        | P         | 3         | P         | P         | 3         |
| 93      | 3         | P         | P         | 3         | 11        | 41        | 3         | 31        | 37        | 3         | 7         | P         |
| 95      | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 97      | 11        | 7         | 3         | P         | P         | 3         | 19        | 23        | 3         | 43        | 13        | 3         |
| 99      | 3         | 23        | P         | 3         | 13        | P         | 3         | 7         | P         | 3         | P         | 59        |

## Prime Number and Factor Table for 3601 to 4799

| From<br>To | 3600<br>3700 | 3700<br>3800 | 3800<br>3900 | 3900<br>4000 | 4000<br>4100 | 4100<br>4200 | 4200<br>4300 | 4300<br>4400 | 4400<br>4500 | 4500<br>4600 | 4600<br>4700 | 4700<br>4800 |
|------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| 1          | 13           | P            | 3            | 47           | P            | 3            | P            | 11           | 3            | 7            | 43           | 3            |
| 3          | 3            | 7            | P            | 3            | P            | 11           | 3            | 13           | 7            | 3            | P            | P            |
| 5          | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            |
| 7          | P            | 11           | 3            | P            | P            | 3            | 7            | 59           | 3            | P            | 17           | 3            |
| 9          | 3            | P            | 13           | 3            | 19           | 7            | 3            | 31           | P            | 3            | 11           | 17           |
| 11         | 23           | 3            | 37           | P            | 3            | P            | P            | 3            | 11           | 13           | 3            | 7            |
| 13         | P            | 47           | 3            | 7            | P            | 3            | 11           | 19           | 3            | P            | 7            | 3            |
| 15         | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            |
| 17         | P            | 3            | 11           | P            | 3            | 23           | P            | 3            | 7            | P            | 3            | 53           |
| 19         | 7            | P            | 3            | P            | P            | 3            | P            | 7            | 3            | P            | 31           | 3            |
| 21         | 3            | 61           | P            | 3            | P            | 13           | 3            | 29           | P            | 3            | P            | P            |
| 23         | P            | 3            | P            | P            | 3            | 7            | 41           | 3            | P            | P            | 3            | P            |
| 25         | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            |
| 27         | 3            | P            | 43           | 3            | P            | P            | 3            | P            | 19           | 3            | 7            | 29           |
| 29         | 19           | 3            | 7            | P            | 3            | P            | P            | 3            | 43           | 7            | 3            | P            |
| 31         | P            | 7            | 3            | P            | 29           | 3            | P            | 61           | 3            | 23           | 11           | 3            |
| 33         | 3            | P            | P            | 3            | 37           | P            | 3            | 7            | 11           | 3            | 41           | P            |
| 35         | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            |
| 37         | P            | 37           | 3            | 31           | 11           | 3            | 19           | P            | 3            | 13           | P            | 3            |
| 39         | 3            | P            | 11           | 3            | 7            | P            | 3            | P            | 23           | 3            | P            | 7            |
| 41         | 11           | 3            | 23           | 7            | 3            | 41           | P            | 3            | P            | 19           | 3            | 11           |
| 43         | P            | 19           | 3            | P            | 13           | 3            | P            | 43           | 3            | 7            | P            | 3            |
| 45         | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            |
| 47         | 7            | 3            | P            | P            | 3            | 11           | 31           | 3            | P            | P            | 3            | 47           |
| 49         | 41           | 23           | 3            | 11           | P            | 3            | 7            | P            | 3            | P            | P            | 3            |
| 51         | 3            | 11           | P            | 3            | P            | 7            | 3            | 19           | P            | 3            | P            | P            |
| 53         | 13           | 3            | P            | 59           | 3            | P            | P            | 3            | 61           | 29           | 3            | 7            |
| 55         | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            |
| 57         | 3            | 13           | 7            | 3            | P            | P            | 3            | P            | P            | 3            | P            | 67           |
| 59         | P            | 3            | 17           | 37           | 3            | P            | P            | 3            | 7            | 47           | 3            | P            |
| 61         | 7            | P            | 3            | 17           | 31           | 3            | P            | 7            | 3            | P            | 59           | 3            |
| 63         | 3            | 53           | P            | 3            | 17           | 23           | 3            | P            | P            | 3            | P            | 11           |
| 65         | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            |
| 67         | 19           | P            | 3            | P            | 7            | 3            | 17           | 11           | 3            | P            | 13           | 3            |
| 69         | 3            | P            | 53           | 3            | 13           | 11           | 3            | 17           | 41           | 3            | 7            | 19           |
| 71         | P            | 3            | 7            | 11           | 3            | 43           | P            | 3            | 17           | 7            | 3            | 13           |
| 73         | P            | 7            | 3            | 29           | P            | 3            | P            | P            | 3            | 17           | P            | 3            |
| 75         | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            |
| 77         | P            | 3            | P            | 41           | 3            | P            | 7            | 3            | 11           | 23           | 3            | 17           |
| 79         | 13           | P            | 3            | 23           | P            | 3            | 11           | 29           | 3            | 19           | P            | 3            |
| 81         | 3            | 19           | P            | 3            | 7            | 37           | 3            | 13           | P            | 3            | 31           | 7            |
| 83         | 29           | 3            | 11           | 7            | 3            | 47           | P            | 3            | P            | P            | 3            | P            |
| 85         | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            |
| 87         | 3            | 7            | 13           | 3            | 61           | 53           | 3            | 41           | 7            | 3            | 43           | P            |
| 89         | 7            | 3            | P            | P            | 3            | 59           | P            | 3            | 67           | 13           | 3            | P            |
| 91         | P            | 17           | 3            | 13           | P            | 3            | 7            | P            | 3            | P            | P            | 3            |
| 93         | 3            | P            | 17           | 3            | P            | 7            | 3            | 23           | P            | 3            | 13           | P            |
| 95         | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            |
| 97         | P            | P            | 3            | 7            | 17           | 3            | P            | P            | 3            | P            | 7            | 3            |
| 99         | 3            | 29           | 7            | 3            | P            | 13           | 3            | 53           | 11           | 3            | 37           | P            |

FACTORS AND PRIME NUMBERS

Prime Number and Factor Table for 4801 to 5999

| From To | 4800 4900 | 4900 5000 | 5000 5100 | 5100 5200 | 5200 5300 | 5300 5400 | 5400 5500 | 5500 5600 | 5600 5700 | 5700 5800 | 5800 5900 | 5900 6000 |
|---------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1       | P         | 13        | 3         | P         | 7         | 3         | 11        | P         | 3         | P         | P         | 3         |
| 3       | 3         | P         | P         | 3         | 11        | P         | 3         | P         | 13        | 3         | 7         | P         |
| 5       | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 7       | 11        | 7         | 3         | P         | 41        | 3         | P         | P         | 3         | 13        | P         | 3         |
| 9       | 3         | P         | P         | 3         | P         | P         | 3         | 7         | 71        | 3         | 37        | 19        |
| 11      | 17        | 3         | P         | 19        | 3         | 47        | 7         | 3         | 31        | P         | 3         | 23        |
| 13      | P         | 17        | 3         | P         | 13        | 3         | P         | 37        | 3         | 29        | P         | 3         |
| 15      | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         |
| 17      | P         | 3         | 29        | 7         | 3         | 13        | P         | 3         | 41        | P         | 3         | 61        |
| 19      | 61        | P         | 3         | P         | 17        | 3         | P         | P         | 3         | 7         | 11        | 3         |
| 21      | 3         | 7         | P         | 3         | 23        | 17        | 3         | P         | 7         | 3         | P         | 31        |
| 23      | 7         | 3         | P         | 47        | 3         | P         | 11        | 3         | P         | 59        | 3         | P         |
| 25      | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         |
| 27      | 3         | 13        | 11        | 3         | P         | 7         | 3         | P         | 17        | 3         | P         | P         |
| 29      | 11        | 3         | 47        | 23        | 3         | 73        | 61        | 3         | 13        | 17        | 3         | 7         |
| 31      | P         | P         | 3         | 7         | P         | 3         | P         | P         | 3         | 11        | 7         | 3         |
| 33      | 3         | P         | 7         | 3         | P         | P         | 3         | 11        | 43        | 3         | 19        | 17        |
| 35      | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 37      | 7         | P         | 3         | 11        | P         | 3         | P         | 7         | 3         | P         | 13        | 3         |
| 39      | 3         | 11        | P         | 3         | 13        | 19        | 3         | 29        | P         | 3         | P         | P         |
| 41      | 47        | 3         | 71        | 53        | 3         | 7         | P         | 3         | P         | P         | 3         | 13        |
| 43      | 29        | P         | 3         | 37        | 7         | 3         | P         | 23        | 3         | P         | P         | 3         |
| 45      | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         |
| 47      | 37        | 3         | 7         | P         | 3         | P         | 13        | 3         | P         | 7         | 3         | 19        |
| 49      | 13        | 7         | 3         | 19        | 29        | 3         | P         | 31        | 3         | P         | P         | 3         |
| 51      | 3         | P         | P         | 3         | 59        | P         | 3         | 7         | P         | 3         | P         | 11        |
| 53      | 23        | 3         | 31        | P         | 3         | 53        | 7         | 3         | P         | 11        | 3         | P         |
| 55      | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         |
| 57      | 3         | P         | 13        | 3         | 7         | 11        | 3         | P         | P         | 3         | P         | 7         |
| 59      | 43        | 3         | P         | 7         | 3         | 23        | 53        | 3         | P         | 13        | 3         | 59        |
| 61      | P         | 11        | 3         | 13        | P         | 3         | 43        | 67        | 3         | 7         | P         | 3         |
| 63      | 3         | 7         | 61        | 3         | 19        | 31        | 3         | P         | 7         | 3         | 11        | 67        |
| 65      | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 67      | 31        | P         | 3         | P         | 23        | 3         | 7         | 19        | 3         | 73        | P         | 3         |
| 69      | 3         | P         | 37        | 3         | 11        | 7         | 3         | P         | P         | 3         | P         | 47        |
| 71      | P         | 3         | 11        | P         | 3         | 41        | P         | 3         | 53        | 29        | 3         | 7         |
| 73      | 11        | P         | 3         | 7         | P         | 3         | 13        | P         | 3         | 23        | 7         | 3         |
| 75      | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         |
| 77      | P         | 3         | P         | 31        | 3         | 19        | P         | 3         | 7         | 53        | 3         | 43        |
| 79      | 7         | 13        | 3         | P         | P         | 3         | P         | 7         | 3         | P         | P         | 3         |
| 81      | 3         | 17        | P         | 3         | P         | P         | 3         | P         | 13        | 3         | P         | P         |
| 83      | 19        | 3         | 13        | 71        | 3         | 7         | P         | 3         | P         | P         | 3         | 31        |
| 85      | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         |
| 87      | 3         | P         | P         | 3         | 17        | P         | 3         | 37        | 11        | 3         | 7         | P         |
| 89      | P         | 3         | 7         | P         | 3         | 17        | 11        | 3         | P         | 7         | 3         | 53        |
| 91      | 67        | 7         | 3         | 29        | 11        | 3         | 17        | P         | 3         | P         | 43        | 3         |
| 93      | 3         | P         | 11        | 3         | 67        | P         | 3         | 7         | P         | 3         | 71        | 13        |
| 95      | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 97      | 59        | 19        | 3         | P         | P         | 3         | 23        | 29        | 3         | 11        | P         | 3         |
| 99      | 3         | P         | P         | 3         | 7         | P         | 3         | 11        | 41        | 3         | 17        | 7         |

Prime Number and Factor Table for 6001 to 7199

| From To | 6000 6100 | 6100 6200 | 6200 6300 | 6300 6400 | 6400 6500 | 6500 6600 | 6600 6700 | 6700 6800 | 6800 6900 | 6900 7000 | 7000 7100 | 7100 7200 |
|---------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1       | 17        | P         | 3         | P         | 37        | 3         | 7         | P         | 3         | 67        | P         | 3         |
| 3       | 3         | 17        | P         | 3         | 19        | 7         | 3         | P         | P         | 3         | 47        | P         |
| 5       | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 7       | P         | 31        | 3         | 7         | 43        | 3         | P         | 19        | 3         | P         | 7         | 3         |
| 9       | 3         | 41        | 7         | 3         | 13        | 23        | 3         | P         | 11        | 3         | 43        | P         |
| 11      | P         | 3         | P         | P         | 3         | 17        | 11        | 3         | 7         | P         | 3         | 13        |
| 13      | 7         | P         | 3         | 59        | 11        | 3         | 17        | 7         | 3         | 31        | P         | 3         |
| 15      | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         |
| 17      | 11        | 3         | P         | P         | 3         | 7         | 13        | 3         | 17        | P         | 3         | 11        |
| 19      | 13        | 29        | 3         | 71        | 7         | 3         | P         | P         | 3         | 11        | P         | 3         |
| 21      | 3         | P         | P         | 3         | P         | P         | 3         | 11        | 19        | 3         | 7         | P         |
| 23      | 19        | 3         | 7         | P         | 3         | 11        | 37        | 3         | P         | 7         | 3         | 17        |
| 25      | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         |
| 27      | 3         | 11        | 13        | 3         | P         | 61        | 3         | 7         | P         | 3         | P         | P         |
| 29      | P         | 3         | P         | P         | 3         | P         | 7         | 3         | P         | 13        | 3         | P         |
| 31      | 37        | P         | 3         | 13        | 59        | 3         | 19        | 53        | 3         | 29        | 79        | 3         |
| 33      | 3         | P         | 23        | 3         | 7         | 47        | 3         | P         | P         | 3         | 13        | 7         |
| 35      | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 37      | P         | 17        | 3         | P         | 41        | 3         | P         | P         | 3         | 7         | 31        | 3         |
| 39      | 3         | 7         | 17        | 3         | 47        | 13        | 3         | 23        | 7         | 3         | P         | 11        |
| 41      | 7         | 3         | 79        | 17        | 3         | 31        | 29        | 3         | P         | 11        | 3         | 37        |
| 43      | P         | P         | 3         | P         | 17        | 3         | 7         | 11        | 3         | 53        | P         | 3         |
| 45      | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         |
| 47      | P         | 3         | P         | 11        | 3         | P         | 17        | 3         | 41        | P         | 3         | 7         |
| 49      | 23        | 11        | 3         | 7         | P         | 3         | 61        | 17        | 3         | P         | 7         | 3         |
| 51      | 3         | P         | 7         | 3         | P         | P         | 3         | 43        | 13        | 3         | 11        | P         |
| 53      | P         | 3         | 13        | P         | 3         | P         | P         | 3         | 7         | 17        | 3         | 23        |
| 55      | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         |
| 57      | 3         | 47        | P         | 3         | 11        | 79        | 3         | 29        | P         | 3         | P         | 17        |
| 59      | 73        | 3         | 11        | P         | 3         | 7         | P         | 3         | 19        | P         | 3         | P         |
| 61      | 11        | 61        | 3         | P         | 7         | 3         | P         | P         | 3         | P         | 23        | 3         |
| 63      | 3         | P         | P         | 3         | 23        | P         | 3         | P         | P         | 3         | 7         | 13        |
| 65      | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 67      | P         | 7         | 3         | P         | 29        | 3         | 59        | 67        | 3         | P         | 37        | 3         |
| 69      | 3         | 31        | P         | 3         | P         | P         | 3         | 7         | P         | 3         | P         | 67        |
| 71      | 13        | 3         | P         | 23        | 3         | P         | 7         | 3         | P         | P         | 3         | 71        |
| 73      | P         | P         | 3         | P         | P         | 3         | P         | 13        | 3         | 19        | 11        | 3         |
| 75      | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         |
| 77      | 59        | 3         | P         | 7         | 3         | P         | 11        | 3         | 13        | P         | 3         | P         |
| 79      | P         | 37        | 3         | P         | 11        | 3         | P         | P         | 3         | 7         | P         | 3         |
| 81      | 3         | 7         | 11        | 3         | P         | P         | 3         | P         | 7         | 3         | 73        | 43        |
| 83      | 7         | 3         | 61        | 13        | 3         | 29        | 41        | 3         | P         | P         | 3         | 11        |
| 85      | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         |
| 87      | 3         | 23        | P         | 3         | 13        | 7         | 3         | 11        | 71        | 3         | 19        | P         |
| 89      | P         | 3         | 19        | P         | 3         | 11        | P         | 3         | 83        | 29        | 3         | 7         |
| 91      | P         | 41        | 3         | 7         | P         | 3         | P         | P         | 3         | P         | 7         | 3         |
| 93      | 3         | 11        | 7         | 3         | 43        | 19        | 3         | P         | 61        | 3         | 41        | P         |
| 95      | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 97      | 7         | P         | 3         | P         | 73        | 3         | 37        | 7         | 3         | P         | 47        | 3         |
| 99      | 3         | P         | P         | 3         | 67        | P         | 3         | 13        | P         | 3         | 31        | 23        |

FACTORS AND PRIME NUMBERS

Prime Number and Factor Table for 7201 to 8399

| From To | 7200 7300 | 7300 7400 | 7400 7500 | 7500 7600 | 7600 7700 | 7700 7800 | 7800 7900 | 7900 8000 | 8000 8100 | 8100 8200 | 8200 8300 | 8300 8400 |
|---------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1       | 19        | 7         | 3         | 13        | 11        | 3         | 29        | P         | 3         | P         | 59        | 3         |
| 3       | 3         | 67        | 11        | 3         | P         | P         | 3         | 7         | 53        | 3         | 13        | 19        |
| 5       | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 7       | P         | P         | 3         | P         | P         | 3         | 37        | P         | 3         | 11        | 29        | 3         |
| 9       | 3         | P         | 31        | 3         | 7         | 13        | 3         | 11        | P         | 3         | P         | 7         |
| 11      | P         | 3         | P         | 7         | 3         | 11        | 73        | 3         | P         | P         | 3         | P         |
| 13      | P         | 71        | 3         | 11        | 23        | 3         | 13        | 41        | 3         | 7         | 43        | 3         |
| 15      | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         |
| 17      | 7         | 3         | P         | P         | 3         | P         | P         | 3         | P         | P         | 3         | P         |
| 19      | P         | 13        | 3         | 73        | 19        | 3         | 7         | P         | 3         | 23        | P         | 3         |
| 21      | 3         | P         | 41        | 3         | P         | 7         | 3         | 89        | 13        | 3         | P         | 53        |
| 23      | 31        | 3         | 13        | P         | 3         | P         | P         | 3         | 71        | P         | 3         | 7         |
| 25      | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         |
| 27      | 3         | 17        | 7         | 3         | 29        | P         | 3         | P         | 23        | 3         | 19        | 11        |
| 29      | P         | 3         | 17        | P         | 3         | 59        | P         | 3         | 7         | 11        | 3         | P         |
| 31      | 7         | P         | 3         | 17        | 13        | 3         | 41        | 7         | 3         | 47        | P         | 3         |
| 33      | 3         | P         | P         | 3         | 17        | 11        | 3         | P         | 29        | 3         | P         | 13        |
| 35      | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 37      | P         | 11        | 3         | P         | 7         | 3         | 17        | P         | 3         | 79        | P         | 3         |
| 39      | 3         | 41        | 43        | 3         | P         | 71        | 3         | 17        | P         | 3         | 7         | 31        |
| 41      | 13        | 3         | 7         | P         | 3         | P         | P         | 3         | 11        | 7         | 3         | 19        |
| 43      | P         | 7         | 3         | 19        | P         | 3         | 11        | 13        | 3         | 17        | P         | 3         |
| 45      | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         |
| 47      | P         | 3         | 11        | P         | 3         | 61        | 7         | 3         | 13        | P         | 3         | 17        |
| 49      | 11        | P         | 3         | P         | P         | 3         | 47        | P         | 3         | 29        | 73        | 3         |
| 51      | 3         | P         | P         | 3         | 7         | 23        | 3         | P         | 83        | 3         | 37        | 7         |
| 53      | P         | 3         | 29        | 7         | 3         | P         | P         | 3         | P         | 31        | 3         | P         |
| 55      | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         |
| 57      | 3         | 7         | P         | 3         | 13        | P         | 3         | 73        | 7         | 3         | 23        | 61        |
| 59      | 7         | 3         | P         | P         | 3         | P         | 29        | 3         | P         | 41        | 3         | 13        |
| 61      | 53        | 17        | 3         | P         | 47        | 3         | 7         | 19        | 3         | P         | 11        | 3         |
| 63      | 3         | 37        | 17        | 3         | 79        | 7         | 3         | P         | 11        | 3         | P         | P         |
| 65      | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 67      | 13        | 53        | 3         | 7         | 11        | 3         | P         | 31        | 3         | P         | 7         | 3         |
| 69      | 3         | P         | 7         | 3         | P         | 17        | 3         | 13        | P         | 3         | P         | P         |
| 71      | 11        | 3         | 31        | 67        | 3         | 19        | 17        | 3         | 7         | P         | 3         | 11        |
| 73      | 7         | 73        | 3         | P         | P         | 3         | P         | 7         | 3         | 11        | P         | 3         |
| 75      | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         |
| 77      | 19        | 3         | P         | P         | 3         | 7         | P         | 3         | 41        | 13        | 3         | P         |
| 79      | 29        | 47        | 3         | 11        | 7         | 3         | P         | 79        | 3         | P         | 17        | 3         |
| 81      | 3         | 11        | P         | 3         | P         | 31        | 3         | 23        | P         | 3         | 7         | 17        |
| 83      | P         | 3         | 7         | P         | 3         | 43        | P         | 3         | 59        | 7         | 3         | 83        |
| 85      | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         |
| 87      | 3         | 83        | P         | 3         | P         | 13        | 3         | 7         | P         | 3         | P         | P         |
| 89      | 37        | 3         | P         | P         | 3         | P         | 7         | 3         | P         | 19        | 3         | P         |
| 91      | 23        | 19        | 3         | P         | P         | 3         | 13        | 61        | 3         | P         | P         | 3         |
| 93      | 3         | P         | 59        | 3         | 7         | P         | 3         | P         | P         | 3         | P         | 7         |
| 95      | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         | 5         | 3         | 5         |
| 97      | P         | 13        | 3         | 71        | 43        | 3         | 53        | 11        | 3         | 7         | P         | 3         |
| 99      | 3         | 7         | P         | 3         | P         | 11        | 3         | 19        | 7         | 3         | 43        | 37        |

## Prime Number and Factor Table for 8401 to 9599

| From<br>To | 8400<br>8500 | 8500<br>8600 | 8600<br>8700 | 8700<br>8800 | 8800<br>8900 | 8900<br>9000 | 9000<br>9100 | 9100<br>9200 | 9200<br>9300 | 9300<br>9400 | 9400<br>9500 | 9500<br>9600 |
|------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| 1          | 31           | P            | 3            | 7            | 13           | 3            | P            | 19           | 3            | 71           | 7            | 3            |
| 3          | 3            | 11           | 7            | 3            | P            | 29           | 3            | P            | P            | 3            | P            | 13           |
| 5          | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            |
| 7          | 7            | 47           | 3            | P            | P            | 3            | P            | 7            | 3            | 41           | 23           | 3            |
| 9          | 3            | 67           | P            | 3            | 23           | 59           | 3            | P            | P            | 3            | 97           | 37           |
| 11         | 13           | 3            | 79           | 31           | 3            | 7            | P            | 3            | 61           | P            | 3            | P            |
| 13         | 47           | P            | 3            | P            | 7            | 3            | P            | 13           | 3            | 67           | P            | 3            |
| 15         | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            |
| 17         | 19           | 3            | 7            | 23           | 3            | 37           | 71           | 3            | 13           | 7            | 3            | 31           |
| 19         | P            | 7            | 3            | P            | P            | 3            | 29           | 11           | 3            | P            | P            | 3            |
| 21         | 3            | P            | 37           | 3            | P            | 11           | 3            | 7            | P            | 3            | P            | P            |
| 23         | P            | 3            | P            | 11           | 3            | P            | 7            | 3            | 23           | P            | 3            | 89           |
| 25         | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            |
| 27         | 3            | P            | P            | 3            | 7            | 79           | 3            | P            | P            | 3            | 11           | 7            |
| 29         | P            | 3            | P            | 7            | 3            | P            | P            | 3            | 11           | 19           | 3            | 13           |
| 31         | P            | 19           | 3            | P            | P            | 3            | 11           | 23           | 3            | 7            | P            | 3            |
| 33         | 3            | 7            | 89           | 3            | 11           | P            | 3            | P            | 7            | 3            | P            | P            |
| 35         | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            |
| 37         | 11           | P            | 3            | P            | P            | 3            | 7            | P            | 3            | P            | P            | 3            |
| 39         | 3            | P            | 53           | 3            | P            | 7            | 3            | 13           | P            | 3            | P            | P            |
| 41         | 23           | 3            | P            | P            | 3            | P            | P            | 3            | P            | P            | 3            | 7            |
| 43         | P            | P            | 3            | 7            | 37           | 3            | P            | 41           | 3            | P            | 7            | 3            |
| 45         | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            |
| 47         | P            | 3            | P            | P            | 3            | 23           | 83           | 3            | 7            | 13           | 3            | P            |
| 49         | 7            | 83           | 3            | 13           | P            | 3            | P            | 7            | 3            | P            | 11           | 3            |
| 51         | 3            | 17           | 41           | 3            | 53           | P            | 3            | P            | 11           | 3            | 13           | P            |
| 53         | 79           | 3            | 17           | P            | 3            | 7            | 11           | 3            | 19           | 47           | 3            | 41           |
| 55         | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            |
| 57         | 3            | 43           | 11           | 3            | 17           | 13           | 3            | P            | P            | 3            | 7            | 19           |
| 59         | 11           | 3            | 7            | 19           | 3            | 17           | P            | 3            | 47           | 7            | 3            | 11           |
| 61         | P            | 7            | 3            | P            | P            | 3            | 13           | P            | 3            | 11           | P            | 3            |
| 63         | 3            | P            | P            | 3            | P            | P            | 3            | 7            | 59           | 3            | P            | 73           |
| 65         | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            |
| 67         | P            | 13           | 3            | 11           | P            | 3            | P            | 89           | 3            | 17           | P            | 3            |
| 69         | 3            | 11           | P            | 3            | 7            | P            | 3            | 53           | 13           | 3            | 17           | 7            |
| 71         | 43           | 3            | 13           | 7            | 3            | P            | 47           | 3            | 73           | P            | 3            | 17           |
| 73         | 37           | P            | 3            | 31           | 19           | 3            | 43           | P            | 3            | 7            | P            | 3            |
| 75         | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            |
| 77         | 7            | 3            | P            | 67           | 3            | 47           | 29           | 3            | P            | P            | 3            | 61           |
| 79         | 61           | 23           | 3            | P            | 13           | 3            | 7            | 67           | 3            | 83           | P            | 3            |
| 81         | 3            | P            | P            | 3            | 83           | 7            | 3            | P            | P            | 3            | 19           | 11           |
| 83         | 17           | 3            | 19           | P            | 3            | 13           | 31           | 3            | P            | 11           | 3            | 7            |
| 85         | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            |
| 87         | 3            | 31           | 7            | 3            | P            | 11           | 3            | P            | 37           | 3            | 53           | P            |
| 89         | 13           | 3            | P            | 11           | 3            | 89           | 61           | 3            | 7            | 41           | 3            | 43           |
| 91         | 7            | 11           | 3            | 59           | 17           | 3            | P            | 7            | 3            | P            | P            | 3            |
| 93         | 3            | 13           | P            | 3            | P            | 17           | 3            | 29           | P            | 3            | 11           | 53           |
| 95         | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            | 5            | 3            | 5            |
| 97         | 29           | P            | 3            | 19           | 7            | 3            | 11           | 17           | 3            | P            | P            | 3            |
| 99         | 3            | P            | P            | 3            | 11           | P            | 3            | P            | 17           | 3            | 7            | 29           |



## Prime Numbers from 9551 to 18691

|       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 9551  | 10181 | 10853 | 11497 | 12157 | 12763 | 13417 | 14071 | 14747 | 15361 | 16001 | 16693 | 17387 | 18043 |
| 9587  | 10193 | 10859 | 11503 | 12161 | 12781 | 13421 | 14081 | 14753 | 15373 | 16007 | 16699 | 17389 | 18047 |
| 9601  | 10211 | 10861 | 11519 | 12163 | 12791 | 13441 | 14083 | 14759 | 15377 | 16033 | 16703 | 17393 | 18049 |
| 9613  | 10223 | 10867 | 11527 | 12197 | 12799 | 13451 | 14087 | 14767 | 15383 | 16057 | 16729 | 17401 | 18059 |
| 9619  | 10243 | 10883 | 11549 | 12203 | 12809 | 13457 | 14107 | 14771 | 15391 | 16061 | 16741 | 17417 | 18061 |
| 9623  | 10247 | 10889 | 11551 | 12211 | 12821 | 13463 | 14143 | 14779 | 15401 | 16063 | 16747 | 17419 | 18077 |
| 9629  | 10253 | 10891 | 11579 | 12227 | 12823 | 13469 | 14149 | 14783 | 15413 | 16067 | 16759 | 17431 | 18089 |
| 9631  | 10259 | 10903 | 11587 | 12239 | 12829 | 13477 | 14153 | 14797 | 15427 | 16069 | 16763 | 17443 | 18097 |
| 9643  | 10267 | 10909 | 11593 | 12241 | 12841 | 13487 | 14159 | 14813 | 15439 | 16073 | 16787 | 17449 | 18119 |
| 9649  | 10271 | 10937 | 11597 | 12251 | 12853 | 13499 | 14173 | 14821 | 15443 | 16087 | 16811 | 17467 | 18121 |
| 9661  | 10273 | 10939 | 11617 | 12253 | 12889 | 13513 | 14177 | 14827 | 15451 | 16091 | 16823 | 17471 | 18127 |
| 9677  | 10289 | 10949 | 11621 | 12263 | 12893 | 13523 | 14197 | 14831 | 15461 | 16097 | 16829 | 17477 | 18131 |
| 9679  | 10301 | 10957 | 11633 | 12269 | 12899 | 13537 | 14207 | 14843 | 15467 | 16103 | 16831 | 17483 | 18133 |
| 9689  | 10303 | 10973 | 11657 | 12277 | 12907 | 13553 | 14221 | 14851 | 15473 | 16111 | 16843 | 17489 | 18143 |
| 9697  | 10313 | 10979 | 11677 | 12281 | 12911 | 13567 | 14243 | 14867 | 15493 | 16127 | 16871 | 17491 | 18149 |
| 9719  | 10321 | 10987 | 11681 | 12289 | 12917 | 13577 | 14249 | 14869 | 15497 | 16139 | 16879 | 17497 | 18169 |
| 9721  | 10331 | 10993 | 11689 | 12301 | 12919 | 13591 | 14251 | 14879 | 15511 | 16141 | 16883 | 17509 | 18181 |
| 9733  | 10333 | 11003 | 11699 | 12323 | 12923 | 13597 | 14281 | 14887 | 15527 | 16183 | 16889 | 17519 | 18191 |
| 9739  | 10337 | 11027 | 11701 | 12329 | 12941 | 13613 | 14293 | 14891 | 15541 | 16187 | 16901 | 17539 | 18199 |
| 9743  | 10343 | 11047 | 11717 | 12343 | 12953 | 13619 | 14303 | 14897 | 15551 | 16189 | 16903 | 17551 | 18211 |
| 9749  | 10357 | 11057 | 11719 | 12347 | 12959 | 13627 | 14321 | 14923 | 15559 | 16193 | 16921 | 17569 | 18217 |
| 9767  | 10369 | 11059 | 11731 | 12373 | 12967 | 13633 | 14323 | 14929 | 15569 | 16217 | 16927 | 17573 | 18223 |
| 9769  | 10391 | 11069 | 11743 | 12377 | 12973 | 13649 | 14327 | 14939 | 15581 | 16223 | 16931 | 17579 | 18229 |
| 9781  | 10399 | 11071 | 11777 | 12379 | 12979 | 13669 | 14341 | 14947 | 15583 | 16229 | 16937 | 17581 | 18233 |
| 9787  | 10427 | 11083 | 11779 | 12391 | 12983 | 13679 | 14347 | 14951 | 15601 | 16231 | 16943 | 17597 | 18251 |
| 9791  | 10429 | 11087 | 11783 | 12401 | 13001 | 13681 | 14369 | 14957 | 15607 | 16249 | 16963 | 17599 | 18253 |
| 9803  | 10433 | 11093 | 11789 | 12409 | 13003 | 13687 | 14387 | 14969 | 15619 | 16253 | 16979 | 17609 | 18257 |
| 9811  | 10453 | 11113 | 11801 | 12413 | 13007 | 13691 | 14389 | 14983 | 15629 | 16267 | 16981 | 17623 | 18269 |
| 9817  | 10457 | 11117 | 11807 | 12421 | 13009 | 13693 | 14401 | 15013 | 15641 | 16273 | 16987 | 17627 | 18287 |
| 9829  | 10459 | 11119 | 11813 | 12433 | 13033 | 13697 | 14407 | 15017 | 15643 | 16301 | 16993 | 17657 | 18289 |
| 9833  | 10463 | 11131 | 11821 | 12437 | 13037 | 13709 | 14411 | 15031 | 15647 | 16319 | 17011 | 17659 | 18301 |
| 9839  | 10477 | 11149 | 11827 | 12451 | 13043 | 13711 | 14419 | 15053 | 15649 | 16333 | 17021 | 17669 | 18307 |
| 9851  | 10487 | 11159 | 11831 | 12457 | 13049 | 13721 | 14423 | 15061 | 15661 | 16339 | 17027 | 17681 | 18311 |
| 9857  | 10499 | 11161 | 11833 | 12473 | 13063 | 13723 | 14431 | 15073 | 15667 | 16349 | 17029 | 17683 | 18313 |
| 9859  | 10501 | 11171 | 11839 | 12479 | 13093 | 13729 | 14437 | 15077 | 15671 | 16361 | 17033 | 17707 | 18329 |
| 9871  | 10513 | 11173 | 11863 | 12487 | 13099 | 13751 | 14447 | 15083 | 15679 | 16363 | 17041 | 17713 | 18341 |
| 9883  | 10529 | 11177 | 11867 | 12491 | 13103 | 13757 | 14449 | 15091 | 15683 | 16369 | 17047 | 17729 | 18353 |
| 9887  | 10531 | 11197 | 11887 | 12497 | 13109 | 13759 | 14461 | 15101 | 15727 | 16381 | 17053 | 17737 | 18367 |
| 9901  | 10559 | 11213 | 11897 | 12503 | 13121 | 13763 | 14479 | 15107 | 15731 | 16411 | 17077 | 17747 | 18371 |
| 9907  | 10567 | 11239 | 11903 | 12511 | 13127 | 13767 | 14489 | 15121 | 15733 | 16417 | 17093 | 17749 | 18379 |
| 9923  | 10589 | 11243 | 11909 | 12517 | 13147 | 13789 | 14503 | 15131 | 15737 | 16421 | 17099 | 17761 | 18397 |
| 9929  | 10597 | 11251 | 11923 | 12527 | 13151 | 13799 | 14519 | 15137 | 15739 | 16427 | 17107 | 17783 | 18401 |
| 9931  | 10601 | 11257 | 11927 | 12539 | 13159 | 13807 | 14533 | 15139 | 15749 | 16433 | 17117 | 17789 | 18413 |
| 9941  | 10607 | 11261 | 11933 | 12541 | 13163 | 13829 | 14537 | 15149 | 15761 | 16447 | 17123 | 17791 | 18427 |
| 9949  | 10613 | 11273 | 11939 | 12547 | 13171 | 13831 | 14543 | 15161 | 15767 | 16451 | 17137 | 17807 | 18433 |
| 9967  | 10627 | 11279 | 11941 | 12553 | 13177 | 13841 | 14549 | 15173 | 15773 | 16453 | 17159 | 17827 | 18439 |
| 9973  | 10631 | 11287 | 11953 | 12569 | 13183 | 13859 | 14551 | 15187 | 15787 | 16477 | 17167 | 17837 | 18443 |
| 10007 | 10639 | 11299 | 11959 | 12577 | 13187 | 13873 | 14557 | 15193 | 15791 | 16481 | 17183 | 17839 | 18451 |
| 10009 | 10651 | 11311 | 11969 | 12583 | 13217 | 13877 | 14561 | 15199 | 15797 | 16487 | 17189 | 17851 | 18457 |
| 10037 | 10657 | 11317 | 11971 | 12589 | 13219 | 13879 | 14563 | 15217 | 15803 | 16493 | 17191 | 17863 | 18461 |
| 10039 | 10663 | 11321 | 11981 | 12601 | 13229 | 13883 | 14591 | 15227 | 15809 | 16519 | 17203 | 17881 | 18481 |
| 10061 | 10667 | 11329 | 11987 | 12611 | 13241 | 13901 | 14593 | 15233 | 15817 | 16529 | 17207 | 17891 | 18493 |
| 10067 | 10687 | 11351 | 12007 | 12613 | 13249 | 13903 | 14621 | 15241 | 15823 | 16547 | 17209 | 17903 | 18503 |
| 10069 | 10691 | 11353 | 12011 | 12619 | 13259 | 13907 | 14627 | 15259 | 15859 | 16553 | 17231 | 17909 | 18517 |
| 10079 | 10709 | 11369 | 12037 | 12637 | 13267 | 13913 | 14629 | 15263 | 15877 | 16561 | 17239 | 17911 | 18521 |
| 10091 | 10711 | 11383 | 12041 | 12641 | 13291 | 13921 | 14633 | 15269 | 15881 | 16567 | 17257 | 17921 | 18523 |
| 10093 | 10723 | 11393 | 12043 | 12647 | 13297 | 13931 | 14639 | 15271 | 15887 | 16573 | 17291 | 17923 | 18539 |
| 10099 | 10729 | 11399 | 12049 | 12653 | 13309 | 13933 | 14653 | 15277 | 15889 | 16603 | 17293 | 17929 | 18541 |
| 10103 | 10733 | 11411 | 12071 | 12659 | 13313 | 13963 | 14657 | 15287 | 15901 | 16607 | 17299 | 17939 | 18553 |
| 10111 | 10739 | 11423 | 12073 | 12671 | 13327 | 13967 | 14669 | 15289 | 15907 | 16619 | 17317 | 17957 | 18583 |
| 10133 | 10753 | 11437 | 12097 | 12689 | 13331 | 13997 | 14683 | 15299 | 15913 | 16631 | 17321 | 17959 | 18587 |
| 10139 | 10771 | 11443 | 12101 | 12697 | 13337 | 13999 | 14699 | 15307 | 15919 | 16633 | 17327 | 17971 | 18593 |
| 10141 | 10781 | 11447 | 12107 | 12703 | 13339 | 14009 | 14713 | 15313 | 15923 | 16649 | 17333 | 17977 | 18617 |
| 10151 | 10789 | 11467 | 12109 | 12713 | 13367 | 14011 | 14717 | 15319 | 15937 | 16651 | 17341 | 17981 | 18637 |
| 10159 | 10799 | 11471 | 12113 | 12721 | 13381 | 14029 | 14723 | 15329 | 15959 | 16657 | 17351 | 17987 | 18661 |
| 10163 | 10831 | 11483 | 12119 | 12739 | 13397 | 14033 | 14731 | 15331 | 15971 | 16661 | 17359 | 17989 | 18671 |
| 10169 | 10837 | 11489 | 12143 | 12743 | 13399 | 14051 | 14737 | 15349 | 15973 | 16673 | 17377 | 18013 | 18679 |
| 10177 | 10847 | 11491 | 12149 | 12757 | 13411 | 14057 | 14741 | 15359 | 15991 | 16691 | 17383 | 18041 | 18691 |

## ALGEBRA AND EQUATIONS

An unknown number can be represented by a symbol or a letter which can be manipulated like an ordinary numeral within an arithmetic expression. The rules of arithmetic are also applicable in algebra.

**Rearrangement and Transposition of Terms in Formulas**

A formula is a rule for a calculation expressed by using letters and signs instead of writing out the rule in words; by this means, it is possible to condense, in a very small space, the essentials of long and cumbersome rules. The letters used in formulas simply stand in place of the figures that are to be substituted when solving a specific problem.

As an example, the formula for the horsepower transmitted by belting may be written

$$P = \frac{SVW}{33,000}$$

where  $P$  = horsepower transmitted;  $S$  = working stress of belt per inch of width in pounds;  $V$  = velocity of belt in feet per minute; and,  $W$  = width of belt in inches.

If the working stress  $S$ , the velocity  $V$ , and the width  $W$  are known, the horsepower can be found directly from this formula by inserting the given values. Assume  $S = 33$ ;  $V = 600$ ; and  $W = 5$ . Then

$$P = \frac{33 \times 600 \times 5}{33,000} = 3$$

Assume that the horsepower  $P$ , the stress  $S$ , and the velocity  $V$  are known, and that the width of belt,  $W$ , is to be found. The formula must then be rearranged so that the symbol  $W$  will be on one side of the equals sign and all the known quantities on the other. The rearranged formula is as follows:

$$\frac{P \times 33,000}{SV} = W$$

The quantities ( $S$  and  $V$ ) that were in the numerator on the right side of the equals sign are moved to the denominator on the left side, and "33,000," which was in the denominator on the right side of the equals sign, is moved to the numerator on the other side. Symbols that are not part of a fraction, like " $P$ " in the formula first given, are to be considered as being numerators (having the denominator 1).

Thus, any formula of the form  $A = B/C$  can be rearranged as follows:

$$A \times C = B \quad \text{and} \quad C = \frac{B}{A}$$

Suppose a formula to be of the form  $A = \frac{B \times C}{D}$

$$\text{Then} \quad D = \frac{B \times C}{A} \quad \frac{A \times D}{C} = B \quad \frac{A \times D}{B} = C$$

The method given is only directly applicable when all the quantities in the numerator or denominator are standing independently or are *factors of a product*. If connected by + or - signs, the entire numerator or denominator must be moved as a unit, thus,

$$\text{Given:} \quad \frac{B+C}{A} = \frac{D+E}{F}$$

To solve for  $F$ , rearrange in two steps as follows:  $\frac{F}{A} = \frac{D+E}{B+C}$  and  $F = \frac{A(D+E)}{B+C}$

A quantity preceded by a + or - sign can be transposed to the opposite side of the equals sign by changing its sign; if the sign is +, change it to - on the other side; if it is -, change it to +. This process is called *transposition* of terms.

*Example:*  $B + C = A - D$  then  $A = B + C + D$   
 $B = A - D - C$   
 $C = A - D - B$

### Principal Algebraic Expressions and Formulas

$$a \times a = aa = a^2$$

$$a \times a \times a = aaa = a^3$$

$$a \times b = ab$$

$$a^2 b^2 = (ab)^2$$

$$a^2 a^3 = a^{2+3} = a^5$$

$$a^4 \div a^3 = a^{4-3} = a$$

$$a^0 = 1$$

$$a^2 - b^2 = (a+b)(a-b)$$

$$(a+b)^2 = a^2 + 2ab + b^2$$

$$(a-b)^2 = a^2 - 2ab + b^2$$

$$ab = \left(\frac{a+b}{2}\right)^2 - \left(\frac{a-b}{2}\right)^2$$

$$\sqrt{a} \times \sqrt{a} = a$$

$$\sqrt[3]{a} \times \sqrt[3]{a} \times \sqrt[3]{a} = a$$

$$(\sqrt[3]{a})^3 = a$$

$$\sqrt[3]{a^2} = (\sqrt[3]{a})^2 = a^{2/3}$$

$$\sqrt[4]{\sqrt[3]{a}} = 4 \times \sqrt[3]{a} = \sqrt[3]{4\sqrt{a}}$$

$$\sqrt{a} + \sqrt{b} = \sqrt{a+b+2\sqrt{ab}}$$

$$\frac{a^3}{b^3} = \left(\frac{a}{b}\right)^3$$

$$\frac{1}{a^3} = \left(\frac{1}{a}\right)^3 = a^{-3}$$

$$(a^2)^3 = a^{2 \times 3} = (a^3)^2 = a^6$$

$$a^3 + b^3 = (a+b)(a^2 - ab + b^2)$$

$$a^3 - b^3 = (a-b)(a^2 + ab + b^2)$$

$$(a+b)^3 = a^3 + 3a^2b + 3ab^2 + b^3$$

$$(a-b)^3 = a^3 - 3a^2b + 3ab^2 - b^3$$

$$a^3 + b^3 = (a+b)^3 - 3ab(a+b)$$

$$a^3 - b^3 = (a-b)^3 + 3ab(a-b)$$

$$\sqrt[3]{ab} = \sqrt[3]{a} \times \sqrt[3]{b}$$

$$\sqrt[3]{\frac{a}{b}} = \frac{\sqrt[3]{a}}{\sqrt[3]{b}}$$

$$\sqrt[3]{\frac{1}{a}} = \frac{1}{\sqrt[3]{a}} = a^{-1/3}$$

When  $a \times b = x$  then  $\log a + \log b = \log x$

$a \div b = x$  then  $\log a - \log b = \log x$

$a^3 = x$  then  $3 \log a = \log x$

$\sqrt[3]{a} = x$  then  $\frac{\log a}{3} = \log x$

## Equation Solving

An equation is a statement of equality between two expressions, as  $5x = 105$ . The unknown quantity in an equation is frequently designated by the letter such as  $x$ . If there is more than one unknown quantity, the others are designated by letters also usually selected from the end of the alphabet, as  $y, z, u, t$ , etc.

An equation of the first degree is one which contains the unknown quantity only in the first power, as in  $3x = 9$ . A quadratic equation is one which contains the unknown quantity in the second, but no higher, power, as in  $x^2 + 3x = 10$ .

**Solving Equations of the First Degree with One Unknown.**—Transpose all the terms containing the unknown  $x$  to one side of the equals sign, and all the other terms to the other side. Combine and simplify the expressions as far as possible, and divide both sides by the coefficient of the unknown  $x$ . (See the rules given for transposition of formulas.)

*Example:*

$$\begin{aligned} 22x - 11 &= 15x + 10 \\ 22x - 15x &= 10 + 11 \\ 7x &= 21 \\ x &= 3 \end{aligned}$$

**Solution of Equations of the First Degree with Two Unknowns.**—The form of the simplified equations is

$$\begin{aligned} a_1x + b_1y &= c_1 \\ a_2x + b_2y &= c_2 \end{aligned}$$

Then,

$$x = \frac{c_1b_2 - c_2b_1}{a_1b_2 - a_2b_1} \qquad y = \frac{a_1c_2 - a_2c_1}{a_1b_2 - a_2b_1}$$

*Example:*

$$\begin{aligned} 3x + 4y &= 17 \\ 5x - 2y &= 11 \\ x &= \frac{17 \times (-2) - 11 \times 4}{3 \times (-2) - 5 \times 4} = \frac{-34 - 44}{-6 - 20} = \frac{-78}{-26} = 3 \end{aligned}$$

The value of  $y$  can now be most easily found by inserting the value of  $x$  in one of the equations:

$$5 \times 3 - 2y = 11 \qquad 2y = 15 - 11 = 4 \qquad y = 2$$

**Solution of Quadratic Equations with One Unknown.**—If the form of the equation is  $ax^2 + bx + c = 0$ , then

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

*Example:* Given the equation,  $1x^2 + 6x + 5 = 0$ , then  $a = 1$ ,  $b = 6$ , and  $c = 5$ .

$$x = \frac{-6 \pm \sqrt{6^2 - 4 \times 1 \times 5}}{2 \times 1} = \frac{(-6) + 4}{2} = -1 \quad \text{or} \quad \frac{(-6) - 4}{2} = -5$$

If the form of the equation is  $ax^2 + bx = c$ , then

$$x = \frac{-b \pm \sqrt{b^2 + 4ac}}{2a}$$

*Example:* A right-angle triangle has a hypotenuse 5 inches long and one side which is one inch longer than the other; find the lengths of the two sides.

Let  $x =$  one side and  $x + 1 =$  other side; then  $x^2 + (x + 1)^2 = 5^2$  or  $x^2 + x^2 + 2x + 1 = 25$ ; or  $2x^2 + 2x = 24$ ; or  $x^2 + x = 12$ . Now referring to the basic formula,  $ax^2 + bx = c$ , we find that  $a = 1$ ,  $b = 1$ , and  $c = 12$ ; hence,

$$x = \frac{-1 \pm \sqrt{1 + 4 \times 1 \times 12}}{2 \times 1} = \frac{(-1) + 7}{2} = 3 \quad \text{or} \quad x = \frac{(-1) - 7}{2} = -4$$

Since the positive value (3) would apply in this case, the lengths of the two sides are  $x = 3$  inches and  $x + 1 = 4$  inches.

**Factoring a Quadratic Expression.**—The method described below is useful in determining factors of the quadratic equation in the form  $ax^2 + bx + c = 0$ . First, obtain the product  $ac$  from the coefficients  $a$  and  $c$ , and then determine two numbers,  $f_1$  and  $f_2$ , such that  $f_1 \times f_2 = |ac|$ , and  $f_1 + f_2 = b$  if  $ac$  is positive, or  $f_1 - f_2 = b$  if  $ac$  is negative.

The numbers  $f_1$  and  $f_2$  are used to modify or rearrange the  $bx$  term to simplify factoring the quadratic expression. The roots of the quadratic equation can be easily obtained from the factors.

*Example:* Factor  $8x^2 + 22x + 5 = 0$  and find the values of  $x$  that satisfy the equation.

*Solution:* In this example,  $a = 8$ ,  $b = 22$ , and  $c = 5$ . Therefore,  $ac = 8 \times 5 = 40$ , and  $ac$  is positive, so we are looking for two factors of  $ac$ ,  $f_1$  and  $f_2$ , such that  $f_1 \times f_2 = 40$ , and  $f_1 + f_2 = 22$ .

The  $ac$  term can be written as  $2 \times 2 \times 2 \times 5 = 40$ , and the possible combination of numbers for  $f_1$  and  $f_2$  are (20 and 2), (8 and 5), (4 and 10) and (40 and 1). The requirements for  $f_1$  and  $f_2$  are satisfied by  $f_1 = 20$  and  $f_2 = 2$ , i.e.,  $20 \times 2 = 40$  and  $20 + 2 = 22$ . Using  $f_1$  and  $f_2$ , the original quadratic expression is rewritten and factored as follows:

$$\begin{aligned} 8x^2 + 22x + 5 &= 0 \\ 8x^2 + 20x + 2x + 5 &= 0 \\ 4x(2x + 5) + 1(2x + 5) &= 0 \\ (2x + 5)(4x + 1) &= 0 \end{aligned}$$

If the product of the two factors equals zero, then each of the factors equals zero, thus,  $2x + 5 = 0$  and  $4x + 1 = 0$ . Rearranging and solving,  $x = -\frac{5}{2}$  and  $x = -\frac{1}{4}$ .

*Example:* Factor  $8x^2 + 3x - 5 = 0$  and find the solutions for  $x$ .

*Solution:* Here  $a = 8$ ,  $b = 3$ ,  $c = -5$ , and  $ac = 8 \times (-5) = -40$ . Because  $ac$  is negative, the required numbers,  $f_1$  and  $f_2$ , must satisfy  $f_1 \times f_2 = |ac| = 40$  and  $f_1 - f_2 = 3$ .

As in the previous example, the possible combinations for  $f_1$  and  $f_2$  are (20 and 2), (8 and 5), (4 and 10) and (40 and 1). The numbers  $f_1 = 8$  and  $f_2 = 5$  satisfy the requirements because  $8 \times 5 = 40$  and  $8 - 5 = 3$ . In the second line below,  $5x$  is both added to and subtracted from the original equation, making it possible to rearrange and simplify the expression.

$$\begin{aligned} 8x^2 + 3x - 5 &= 0 \\ 8x^2 + 8x - 5x - 5 &= 0 \\ 8x(x + 1) - 5(x + 1) &= 0 \\ (x + 1)(8x - 5) &= 0 \end{aligned}$$

Solving, for  $x + 1 = 0$ ,  $x = -1$ ; and, for  $8x - 5 = 0$ ,  $x = \frac{5}{8}$ .

**Cubic Equations.**—If the given equation has the form:  $x^3 + ax + b = 0$  then

$$x = \left(-\frac{b}{2} + \sqrt{\frac{a^3}{27} + \frac{b^2}{4}}\right)^{1/3} + \left(-\frac{b}{2} - \sqrt{\frac{a^3}{27} + \frac{b^2}{4}}\right)^{1/3}$$

The equation  $x^3 + px^2 + qx + r = 0$ , may be reduced to the form  $x_1^3 + ax_1 + b = 0$  by substituting  $x_1 = x - \frac{p}{3}$  for  $x$  in the given equation.

**Solving Numerical Equations Having One Unknown.**—The Newton-Raphson method is a procedure for solving various kinds of numerical algebraic and transcendental equations in one unknown. The steps in the procedure are simple and can be used with either a handheld calculator or as a subroutine in a computer program.

Examples of types of equations that can be solved to any desired degree of accuracy by this method are

$$f(x) = x^2 - 101 = 0, \quad f(x) = x^3 - 2x^2 - 5 = 0$$

$$\text{and } f(x) = 2.9x - \cos x - 1 = 0$$

The procedure begins with an estimate,  $r_1$ , of the root satisfying the given equation. This estimate is obtained by judgment, inspection, or plotting a rough graph of the equation and observing the value  $r_1$  where the curve crosses the  $x$  axis. This value is then used to calculate values  $r_2, r_3, \dots, r_n$  progressively closer to the exact value.

Before continuing, it is necessary to calculate the first derivative,  $f'(x)$ , of the function. In the above examples,  $f'(x)$  is, respectively,  $2x$ ,  $3x^2 - 4x$ , and  $2.9 + \sin x$ . These values were found by the methods described in *Derivatives and Integrals of Functions* on page 34.

In the steps that follow,

$r_1$  is the first estimate of the value of the root of  $f(x) = 0$ ;

$f(r_1)$  is the value of  $f(x)$  for  $x = r_1$ ;

$f'(x)$  is the first derivative of  $f(x)$ ;

$f'(r_1)$  is the value of  $f'(x)$  for  $x = r_1$ .

The second approximation of the root of  $f(x) = 0$ ,  $r_2$ , is calculated from

$$r_2 = r_1 - [f(r_1)/f'(r_1)]$$

and, to continue further approximations,

$$r_n = r_{n-1} - [f(r_{n-1})/f'(r_{n-1})]$$

*Example:* Find the square root of 101 using the Newton-Raphson method. This problem can be restated as an equation to be solved, i.e.,  $f(x) = x^2 - 101 = 0$

Step 1. By inspection, it is evident that  $r_1 = 10$  may be taken as the first approximation of the root of this equation. Then,  $f(r_1) = f(10) = 10^2 - 101 = -1$

Step 2. The first derivative,  $f'(x)$ , of  $x^2 - 101$  is  $2x$  as stated previously, so that

$$f'(10) = 2(10) = 20.$$

Then,  $r_2 = r_1 - f(r_1)/f'(r_1) = 10 - (-1)/20 = 10 + 0.05 = 10.05$

$$\text{Check: } 10.05^2 = 101.0025; \text{ error} = 0.0025$$

Step 3. The next, better approximation is

$$r_3 = r_2 - [f(r_2)/f'(r_2)] = 10.05 - [f(10.05)/f'(10.05)]$$

$$= 10.05 - [(10.05^2 - 101)/2(10.05)] = 10.049875$$

$$\text{Check: } 10.049875^2 = 100.9999875; \text{ error} = 0.0000125$$

**Series.**—Some hand calculations, as well as computer programs of certain types of mathematical problems, may be facilitated by the use of an appropriate series. For example, in some gear problems, the angle corresponding to a given or calculated involute function is found by using a series together with an iterative procedure such as the Newton-Raphson method described on page 33. The following are those series most commonly used for such purposes. In the series for trigonometric functions, the angles  $x$  are in radians (1 radian =  $180/\pi$  degrees). The expression  $\exp(-x^2)$  means that the base  $e$  of the natural logarithm system is raised to the  $-x^2$  power;  $e = 2.7182818$ .

- (1)  $\sin x = x - x^3/3! + x^5/5! - x^7/7! + \dots$  for all values of  $x$ .
- (2)  $\cos x = 1 - x^2/2! + x^4/4! - x^6/6! + \dots$  for all values of  $x$ .
- (3)  $\tan x = x + x^3/3 + 2x^5/15 + 17x^7/315 + 62x^9/2835 + \dots$  for  $|x| < \pi/2$ .
- (4)  $\arcsin x = x + x^3/6 + 1 \cdot 3 \cdot x^5/(2 \cdot 4 \cdot 5) + 1 \cdot 3 \cdot 5 \cdot x^7/(2 \cdot 4 \cdot 6 \cdot 7) + \dots$  for  $|x| \leq 1$ .
- (5)  $\arccos x = \pi/2 - \arcsin x$
- (6)  $\arctan x = x - x^3/3 + x^5/5 - x^7/7 + \dots$  for  $|x| \leq 1$ .
- (7)  $\pi/4 = 1 - 1/3 + 1/5 - 1/7 + 1/9 \dots \pm 1/(2x - 1) \mp \dots$  for all values of  $x$ .
- (8)  $e = 1 + 1/1! + 2/2! + 1/3! + \dots$  for all values of  $x$ .
- (9)  $e^x = 1 + x + x^2/2! + x^3/3! + \dots$  for all values of  $x$ .
- (10)  $\exp(-x^2) = 1 - x^2 + x^4/2! - x^6/3! + \dots$  for all values of  $x$ .
- (11)  $a^x = 1 + x \log_e a + (x \log_e a)^2/2! + (x \log_e a)^3/3! + \dots$  for all values of  $x$ .
- (12)  $1/(1+x) = 1 - x + x^2 - x^3 + x^4 - \dots$  for  $|x| < 1$ .
- (13)  $1/(1-x) = 1 + x + x^2 + x^3 + x^4 + \dots$  for  $|x| < 1$ .
- (14)  $1/(1+x)^2 = 1 - 2x + 3x^2 - 4x^3 + 5x^4 - \dots$  for  $|x| < 1$ .
- (15)  $1/(1-x)^2 = 1 + 2x + 3x^2 + 4x^3 + 5x^4 + \dots$  for  $|x| < 1$ .
- (16)  $\sqrt{1+x} = 1 + x/2 - x^2/(2 \cdot 4) + 1 \cdot 3 \cdot x^3/(2 \cdot 4 \cdot 6) - 1 \cdot 3 \cdot 5 \cdot x^4/(2 \cdot 4 \cdot 6 \cdot 8) - \dots$  for  $|x| < 1$ .
- (17)  $1/(\sqrt{1+x}) = 1 - x/2 + 1 \cdot 3 \cdot x^2/(2 \cdot 4) - 1 \cdot 3 \cdot 5 \cdot x^3/(2 \cdot 4 \cdot 6) + \dots$  for  $|x| < 1$ .
- (18)  $(a+x)^n = a^n + na^{n-1}x + n(n-1)a^{n-2}x^2/2! + n(n-1)(n-2)a^{n-3}x^3/3! + \dots$  for  $x^2 < a^2$ .

**Derivatives and Integrals of Functions.**—The following are formulas for obtaining the derivatives and integrals of basic mathematical functions. In these formulas, the letters  $a$  and  $c$  denotes constants; the letter  $x$  denotes a variable; and the letters  $u$  and  $v$  denote functions of the variable  $x$ . The expression  $d/dx$  means the derivative with respect to  $x$ , and as such applies to whatever expression in parentheses follows it. Thus,  $d/dx(ax)$  means the derivative with respect to  $x$  of the product  $(ax)$  of the constant  $a$  and the variable  $x$ .

**Formulas for Differential and Integral Calculus**

| Derivative                       | Value   | Integral                  | Value                           |
|----------------------------------|---|---------------------------|---------------------------------|
| $\frac{d}{dx}(c)$                | 0   | $\int c dx$               | $cx$                            |
| $\frac{d}{dx}(x)$                | 1   | $\int 1 dx$               | $x$                             |
| $\frac{d}{dx}(x^n)$              | $nx^{n-1}$                                      | $\int x^n dx$             | $\frac{x^{n+1}}{n+1}$           |
| $\frac{d}{dx}(g(u))$             | $\frac{d}{du}g(u) \frac{du}{dx}$                | $\int \frac{dx}{ax+b}$    | $\frac{1}{a} \log ax+b $        |
| $\frac{d}{dx}(u(x) + v(x))$      | $\frac{d}{dx}u(x) + \frac{d}{dx}v(x)$           | $\int (u(x) \pm v(x)) dx$ | $\int u(x) dx \pm \int v(x) dx$ |
| $\frac{d}{dx}(u(x) \times v(x))$ | $u(x) \frac{d}{dx}v(x) + v(x) \frac{d}{dx}u(x)$ | $\int u(x)v(x) dx$        | $u(x)v(x) - \int v(x) du(x)$    |

## Formulas for Differential and Integral Calculus (Continued)

| Derivative                                   | Value  | Integral                         | Value  |
|--|--|----------------------------------|--|
| $\frac{d}{dx}\left(\frac{u(x)}{v(x)}\right)$ | $\frac{v(x)\frac{d}{dx}u(x) - u(x)\frac{d}{dx}v(x)}{v(x)^2}$ | $\int \frac{dx}{\sqrt{x}}$       | $2\sqrt{x}$  |
| $\frac{d}{dx}(\sin x)$                       | $\cos x$   | $\int \cos x dx$                 | $\sin x$   |
| $\frac{d}{dx}(\cos x)$                       | $-\sin x$  | $\int \sin x dx$                 | $-\cos x$  |
| $\frac{d}{dx}(\tan x)$                       | $\sec^2 x$   | $\int \tan x dx$                 | $-\log \cos x$   |
| $\frac{d}{dx}(\cot x)$                       | $-\operatorname{cosec}^2 x$                                  | $\int \cot x dx$                 | $\log \sin x$  |
| $\frac{d}{dx}(\sec x)$                       | $\sec x \tan x$  | $\int \sin^2 x dx$               | $\left(-\frac{1}{4}\right) \sin(2x) + \frac{1}{2}x$  |
| $\frac{d}{dx}(\csc x)$                       | $-\csc x \cot x$   | $\int \cos^2 x dx$               | $\frac{1}{4} \sin(2x) + \frac{1}{2}x$  |
| $\frac{d}{dx}(e^x)$                          | $e^x$  | $\int e^x dx$                    | $e^x$  |
| $\frac{d}{dx}(\log x)$                       | $\frac{1}{x}$  | $\int \frac{1}{x} dx$            | $\log x$   |
| $\frac{d}{dx}(a^x)$                          | $a^x \log a$   | $\int a^x dx$                    | $\frac{a^x}{\log a}$   |
| $\frac{d}{dx}(\operatorname{asin} x)$        | $\frac{1}{\sqrt{1-x^2}}$                                     | $\int \frac{dx}{\sqrt{b^2-x^2}}$ | $\operatorname{asin} \frac{x}{b}$  |
| $\frac{d}{dx}(\operatorname{acos} x)$        | $\frac{-1}{\sqrt{1-x^2}}$                                    | $\int \frac{dx}{\sqrt{x^2-b^2}}$ | $\operatorname{acosh} \frac{x}{b} = \log(x + \sqrt{x^2-b^2})$  |
| $\frac{d}{dx}(\operatorname{atan} x)$        | $\frac{1}{1+x^2}$  | $\int \frac{dx}{b^2+x^2}$        | $\frac{1}{b} \operatorname{atan} \frac{x}{b}$  |
| $\frac{d}{dx}(\operatorname{acot} x)$        | $\frac{-1}{1+x^2}$   | $\int \frac{dx}{b^2-x^2}$        | $\frac{1}{b} \operatorname{atanh} \frac{x}{b} = \frac{-1}{2b} \log \left( \frac{ x-b }{ x+b } \right)$ |
| $\frac{d}{dx}(\operatorname{asec} x)$        | $\frac{1}{x\sqrt{x^2-1}}$                                    | $\int \frac{dx}{x^2-b^2}$        | $\frac{1}{b} \operatorname{acoth} \frac{x}{b} = \frac{1}{2b} \log \left( \frac{ x-b }{ x+b } \right)$  |
| $\frac{d}{dx}(\operatorname{acsc} x)$        | $\frac{-1}{x\sqrt{x^2-1}}$                                   | $\int \frac{dx}{ax^2+bx+c}$      | $\frac{2}{\sqrt{4ac-b^2}} \operatorname{atan} \left( \frac{2ax+b}{\sqrt{4ac-b^2}} \right)$             |
| $\frac{d}{dx}(\log \sin x)$                  | $\cot x$   | $\int e^{ax} \sin bx dx$         | $\frac{(\operatorname{asin} bx - b \cos bx) e^{ax}}{a^2 + b^2}$  |
| $\frac{d}{dx}(\log \cos x)$                  | $-\tan x$  | $\int e^{ax} \cos (bx) dx$       | $\frac{(\operatorname{acos} (bx) + b \sin (bx)) e^{ax}}{a^2 + b^2}$                                    |
| $\frac{d}{dx}(\log \tan x)$                  | $\frac{2}{\sin 2x}$  | $\int \frac{1}{\sin x} dx$       | $\log \tan \frac{x}{2}$  |
| $\frac{d}{dx}(\log \cot x)$                  | $\frac{-2}{\sin 2x}$   | $\int \frac{1}{\cos x} dx$       | $\log \tan \left( \frac{\pi}{4} + \frac{x}{2} \right)$   |
| $\frac{d}{dx}(\sqrt{x})$                     | $\frac{1}{2\sqrt{x}}$  | $\int \frac{1}{1+\cos x} dx$     | $\tan \frac{x}{2}$   |
| $\frac{d}{dx}(\log_{10} x)$                  | $\frac{\log_{10} e}{x}$                                      | $\int \log x dx$                 | $x \log x - x$   |



## GEOMETRY

### Arithmetical Progression

An arithmetical progression is a series of numbers in which each consecutive term differs from the preceding one by a fixed amount called the *common difference*,  $d$ . Thus, 1, 3, 5, 7, etc., is an arithmetical progression where the difference  $d$  is 2. The difference here is *added* to the preceding term, and the progression is called increasing. In the series 13, 10, 7, 4, etc., the difference is (-3), and the progression is called decreasing. In any arithmetical progression (or part of progression), let

$a$  = first term considered

$l$  = last term considered

$n$  = number of terms

$d$  = common difference

$S$  = sum of  $n$  terms

Then the general formulas are  $l = a + (n - 1)d$       and       $S = \frac{a + l}{2} \times n$

In these formulas,  $d$  is positive in an increasing and negative in a decreasing progression. When any three of the preceding five quantities are given, the other two can be found by the formulas in the accompanying table of arithmetical progression.

*Example:* In an arithmetical progression, the first term equals 5, and the last term 40. The difference is 7. Find the sum of the progression.

$$S = \frac{a + l}{2d}(l + d - a) = \frac{5 + 40}{2 \times 7}(40 + 7 - 5) = 135$$

### Geometrical Progression

A geometrical progression or a geometrical series is a series in which each term is derived by multiplying the preceding term by a constant multiplier called the *ratio*. When the ratio is greater than 1, the progression is increasing; when less than 1, it is decreasing. Thus, 2, 6, 18, 54, etc., is an increasing geometrical progression with a ratio of 3, and 24, 12, 6, etc., is a decreasing progression with a ratio of 1/2.

In any geometrical progression (or part of progression), let

$a$  = first term

$l$  = last (or  $n$ th) term

$n$  = number of terms

$r$  = ratio of the progression

$S$  = sum of  $n$  terms

Then the general formulas are  $l = ar^{n-1}$       and       $S = \frac{rl - a}{r - 1}$

When any three of the preceding five quantities are given, the other two can be found by the formulas in the accompanying table. For instance, geometrical progressions are used for finding the successive speeds in machine tool drives, and in interest calculations.

*Example:* The lowest speed of a lathe is 20 rpm. The highest speed is 225 rpm. There are 18 speeds. Find the ratio between successive speeds.

$$\text{Ratio } r = \sqrt[n-1]{\frac{l}{a}} = \sqrt[17]{\frac{225}{20}} = 17\sqrt{11.25} = 1.153$$

## Formulas for Arithmetical Progression

| To Find | Given               | Use Equation   |
|---------|---------------------|--|
| $a$     | $d \quad l \quad n$ | $a = l - (n - 1)d$   |
|         | $d \quad n \quad S$ | $a = \frac{S}{n} - \frac{n-1}{2} \times d$                                 |
|         | $d \quad l \quad S$ | $a = \frac{d \pm 1}{2} \sqrt{(2l + d)^2 - 8dS}$                            |
|         | $l \quad n \quad S$ | $a = \frac{2S}{n} - l$   |
| $d$     | $a \quad l \quad n$ | $d = \frac{l - a}{n - 1}$  |
|         | $a \quad n \quad S$ | $d = \frac{2S - 2an}{n(n - 1)}$  |
|         | $a \quad l \quad S$ | $d = \frac{l^2 - a^2}{2S - l - a}$   |
|         | $l \quad n \quad S$ | $d = \frac{2nl - 2S}{n(n - 1)}$  |
| $l$     | $a \quad d \quad n$ | $l = a + (n - 1)d$   |
|         | $a \quad d \quad S$ | $l = -\frac{d \pm 1}{2} \sqrt{8dS + (2a - d)^2}$                           |
|         | $a \quad n \quad S$ | $l = \frac{2S}{n} - a$   |
|         | $d \quad n \quad S$ | $l = \frac{S}{n} + \frac{n-1}{2} \times d$                                 |
| $n$     | $a \quad d \quad l$ | $n = 1 + \frac{l - a}{d}$  |
|         | $a \quad d \quad S$ | $n = \frac{d - 2a}{2d} \pm \frac{1}{2d} \sqrt{8dS + (2a - d)^2}$           |
|         | $a \quad l \quad S$ | $n = \frac{2S}{a + l}$   |
|         | $d \quad l \quad S$ | $n = \frac{2l + d}{2d} \pm \frac{1}{2d} \sqrt{(2l + d)^2 - 8dS}$           |
| $S$     | $a \quad d \quad n$ | $S = \frac{n}{2}[2a + (n - 1)d]$   |
|         | $a \quad d \quad l$ | $S = \frac{a + l}{2} + \frac{l^2 - a^2}{2d} = \frac{a + l}{2d}(l + d - a)$ |
|         | $a \quad l \quad n$ | $S = \frac{n}{2}(a + l)$   |
|         | $d \quad l \quad n$ | $S = \frac{n}{2}[2l - (n - 1)d]$   |

## Formulas for Geometrical Progression

| To Find | Given               | Use Equation   |
|---------|---------------------|--|
| $a$     | $l \quad n \quad r$ | $a = \frac{l}{r^{n-1}}$  |
|         | $n \quad r \quad S$ | $a = \frac{(r-1)S}{r^n - 1}$   |
|         | $l \quad r \quad S$ | $a = lr - (r-1)S$  |
|         | $l \quad n \quad S$ | $a(S-a)^{n-1} = l(S-l)^{n-1}$  |
| $l$     | $a \quad n \quad r$ | $l = ar^{n-1}$   |
|         | $a \quad r \quad S$ | $l = \frac{1}{r}[a + (r-1)S]$  |
|         | $a \quad n \quad S$ | $l(S-l)^{n-1} = a(S-a)^{n-1}$  |
|         | $n \quad r \quad S$ | $l = \frac{S(r-1)r^{n-1}}{r^n - 1}$  |
| $n$     | $a \quad l \quad r$ | $n = \frac{\log l - \log a}{\log r} + 1$   |
|         | $a \quad r \quad S$ | $n = \frac{\log[a + (r-1)S] - \log a}{\log r}$                                   |
|         | $a \quad l \quad S$ | $n = \frac{\log l - \log a}{\log(S-a) - \log(S-l)} + 1$                          |
|         | $l \quad r \quad S$ | $n = \frac{\log l - \log[lr - (r-1)S]}{\log r} + 1$                              |
| $r$     | $a \quad l \quad n$ | $r = \frac{n-1}{\sqrt[n]{\frac{l}{a}}}$  |
|         | $a \quad n \quad S$ | $r^n = \frac{Sr}{a} + \frac{a-S}{a}$   |
|         | $a \quad l \quad S$ | $r = \frac{S-a}{S-l}$  |
|         | $l \quad n \quad S$ | $r^n = \frac{Sr^{n-1}}{S-l} - \frac{l}{S-l}$                                     |
| $S$     | $a \quad n \quad r$ | $S = \frac{a(r^n - 1)}{r - 1}$   |
|         | $a \quad l \quad r$ | $S = \frac{lr - a}{r - 1}$   |
|         | $a \quad l \quad n$ | $S = \frac{n-1\sqrt[n]{ln} - n-1\sqrt[n]{a^n}}{n-1\sqrt[n]{l} - n-1\sqrt[n]{a}}$ |
|         | $l \quad n \quad r$ | $S = \frac{l(r^n - 1)}{(r-1)r^{n-1}}$  |

## Analytical Geometry

**Straight Line.**—A straight line is a line between two points with the minimum distance.

*Coordinate System:* It is possible to locate any point on a plane by a pair of numbers called the coordinates of the point. If P is a point on a plane, and perpendiculars are drawn from P to the coordinate axes, one perpendicular meets the X-axis at the  $x$ -coordinate of P and the other meets the Y-axis at the  $y$ -coordinate of P. The pair of numbers  $(x_1, y_1)$ , in that order, is called the coordinates or coordinate pair for P.

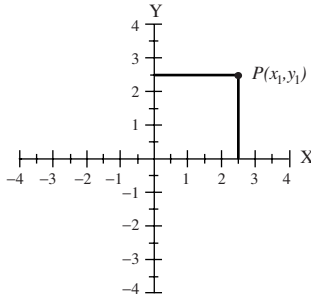


Fig. 1. Coordinate Plan

*Distance Between Two Points:* The distance  $d$  between two points  $P_1(x_1, y_1)$  and  $P_2(x_2, y_2)$  is given by the formula:

$$d(P_1, P_2) = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

*Example 1:* What is the distance AB between points A(4,5) and B(7,8)?

*Solution:* The length of line AB is

$$d = \sqrt{(7-4)^2 + (8-5)^2} = \sqrt{3^2 + 3^2} = \sqrt{18} = 3\sqrt{2}$$

*Intermediate Point:* An intermediate point, P( $x, y$ ) on a line between two points,  $P_1(x_1, y_1)$  and  $P_2(x_2, y_2)$ , Fig. 2, can be obtained by linear interpolation as follows,

$$x = \frac{r_1 x_1 + r_2 x_2}{r_1 + r_2} \quad \text{and} \quad y = \frac{r_1 y_1 + r_2 y_2}{r_1 + r_2}$$

where  $r_1$  is the ratio of the distance of  $P_1$  to P to the distance of  $P_1$  to  $P_2$ , and  $r_2$  is the ratio of the distance of  $P_2$  to P to the distance of  $P_1$  to  $P_2$ . If the desired point is the midpoint of line  $P_1P_2$ , then  $r_1 = r_2 = 1$ , and the coordinates of P are:

$$x = \frac{x_1 + x_2}{2} \quad \text{and} \quad y = \frac{y_1 + y_2}{2}$$

*Example 2:* What is the coordinate of point P( $x, y$ ), if P divides the line defined by points A(0,0) and B(8,6) at the ratio of 5:3.

$$\text{Solution:} \quad x = \frac{5 \times 0 + 3 \times 8}{5 + 3} = \frac{24}{8} = 3 \quad y = \frac{5 \times 0 + 3 \times 6}{5 + 3} = \frac{18}{8} = 2.25$$

*External Point:* A point,  $Q(x, y)$  on the line  $P_1P_2$ , and beyond the two points,  $P_1(x_1, y_1)$  and  $P_2(x_2, y_2)$ , can be obtained by external interpolation as follows,

$$x = \frac{r_1 x_1 - r_2 x_2}{r_1 - r_2} \quad \text{and} \quad y = \frac{r_1 y_1 - r_2 y_2}{r_1 - r_2}$$

where  $r_1$  is the ratio of the distance of  $P_1$  to  $Q$  to the distance of  $P_1$  to  $P_2$ , and  $r_2$  is the ratio of the distance of  $P_2$  to  $Q$  to the distance of  $P_1$  to  $P_2$ .

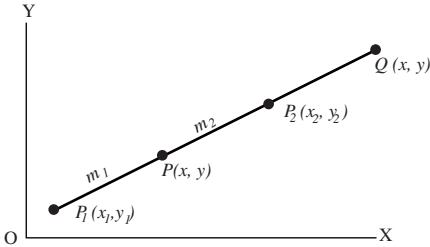


Fig. 2. Finding Intermediate and External Points on a Line

*Equation of a line  $P_1P_2$ :* The general equation of a line passing through points  $P_1(x_1, y_1)$  and  $P_2(x_2, y_2)$  is  $\frac{y - y_1}{y_1 - y_2} = \frac{x - x_1}{x_1 - x_2}$ .

The previous equation is frequently written in the form  $y - y_1 = \frac{y_1 - y_2}{x_1 - x_2}(x - x_1)$

where  $\frac{y_1 - y_2}{x_1 - x_2}$  is the slope of the line,  $m$ , and thus becomes  $y - y_1 = m(x - x_1)$  where  $y_1$  is the coordinate of the  $y$ -intercept  $(0, y_1)$  and  $x_1$  is the coordinate of the  $x$ -intercept  $(x_1, 0)$ . If the line passes through point  $(0, 0)$ , then  $x_1 = y_1 = 0$  and the equation becomes  $y = mx$ . The  $y$ -intercept is the  $y$ -coordinate of the point at which a line intersects the  $Y$ -axis at  $x = 0$ . The  $x$ -intercept is the  $x$ -coordinate of the point at which a line intersects the  $X$ -axis at  $y = 0$ . If a line  $AB$  intersects the  $X$ -axis at point  $A(a, 0)$  and the  $Y$ -axis at point  $B(0, b)$  then the equation of line  $AB$  is

$$\frac{x}{a} + \frac{y}{b} = 1$$

*Slope:* The equation of a line in a Cartesian coordinate system is  $y = mx + b$ , where  $x$  and  $y$  are coordinates of a point on a line,  $m$  is the slope of the line, and  $b$  is the  $y$ -intercept. The slope is the rate at which the  $x$  coordinates are increasing or decreasing relative to the  $y$  coordinates.

Another form of the equation of a line is the point-slope form  $(y - y_1) = m(x - x_1)$ . The slope,  $m$ , is defined as a ratio of the change in the  $y$  coordinates,  $y_2 - y_1$ , to the change in the  $x$  coordinates,  $x_2 - x_1$ ,

$$m = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1}$$

*Example 3:* What is the equation of a line AB between points A(4,5) and B(7,8)?

*Solution:*

$$\frac{y - y_1}{y_1 - y_2} = \frac{x - x_1}{x_1 - x_2}$$

$$\frac{y - 5}{5 - 8} = \frac{x - 4}{4 - 7}$$

$$y - 5 = x - 4$$

$$y - x = 1$$

*Example 4:* Find the general equation of a line passing through the points (3, 2) and (5, 6), and its intersection point with the y-axis.

First, find the slope using the equation above

$$m = \frac{\Delta y}{\Delta x} = \frac{6 - 2}{5 - 3} = \frac{4}{2} = 2$$

The line has a general form of  $y = 2x + b$ , and the value of the constant  $b$  can be determined by substituting the coordinates of a point on the line into the general form. Using point (3,2),  $2 = 2 \times 3 + b$  and rearranging,  $b = 2 - 6 = -4$ . As a check, using another point on the line, (5,6), yields equivalent results,  $y = 6 = 2 \times 5 + b$  and  $b = 6 - 10 = -4$ .

The equation of the line, therefore, is  $y = 2x - 4$ , indicating that line  $y = 2x - 4$  intersects the y-axis at point (0,-4), the y-intercept.

*Example 5:* Use the point-slope form to find the equation of the line passing through the point (3,2) and having a slope of 2.

$$(y - 2) = 2(x - 3)$$

$$y = 2x - 6 + 2$$

$$y = 2x - 4$$

The slope of this line is positive and crosses the y-axis at the y-intercept, point (0,-4).

*Parallel Lines:* The two lines,  $P_1P_2$  and  $Q_1Q_2$ , are parallel if both lines have the same slope, that is, if  $m_1 = m_2$ .

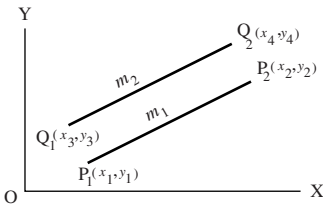


Fig. 3. Parallel Lines

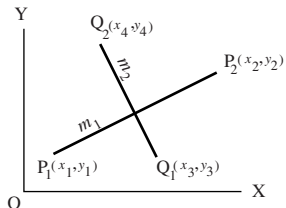


Fig. 4. Perpendicular Lines

*Perpendicular Lines:* The two lines  $P_1P_2$  and  $Q_1Q_2$  are perpendicular if the product of their slopes equal  $-1$ , that is,  $m_1m_2 = -1$ .

*Example 6:* Find an equation of a line that passes through the point (3,4) and is (a) parallel to and (b) perpendicular to the line  $2x - 3y = 16$ ?

*Solution (a):* Line  $2x - 3y = 16$  in standard form is  $y = \frac{2}{3}x - \frac{16}{3}$ , and the equation of a line passing through (3,4) is  $y - 4 = m(x - 3)$ .

If the lines are parallel, their slopes are equal. Thus,  $y - 4 = \frac{2}{3}(x - 3)$  is parallel to line  $2x - 3y = -6$  and passes through point (3,4).

*Solution (b):* As illustrated in part (a), line  $2x - 3y = -6$  has a slope of  $\frac{2}{3}$ . The product of the slopes of perpendicular lines = -1, thus the slope  $m$  of a line passing through point (4,3) and perpendicular to  $2x - 3y = -6$  must satisfy the following:

$$m = \frac{-1}{m_1} = \frac{-1}{\frac{2}{3}} = -\frac{3}{2}$$

The equation of a line passing through point (4,3) and perpendicular to the line  $2x - 3y = -6$  is  $y - 4 = -\frac{3}{2}(x - 3)$ , which rewritten is  $3x + 2y = 17$ .

*Angle Between Two Lines:* For two non-perpendicular lines with slopes  $m_1$  and  $m_2$ , the angle between the two lines is given by

$$\tan \theta = \left| \frac{m_1 - m_2}{1 + m_1 m_2} \right|$$

*Note:* The straight brackets surrounding a symbol or number, as in  $|x|$ , stands for absolute value and means use the positive value of the bracketed quantity, irrespective of its sign.

*Example 7:* Find the angle between the following two lines:  $2x - y = 4$  and  $3x + 4y = 12$

*Solution:* The slopes are 2 and  $-\frac{3}{4}$ , respectively. The angle between two lines is given by

$$\tan \theta = \left| \frac{m_1 - m_2}{1 + m_1 m_2} \right| = \left| \frac{2 - \left(-\frac{3}{4}\right)}{1 + 2\left(-\frac{3}{4}\right)} \right| = \left| \frac{2 + \frac{3}{4}}{1 - \frac{6}{4}} \right| = \left| \frac{\frac{8 + 3}{4}}{\frac{4 - 6}{4}} \right| = \left| \frac{11}{-2} \right| = \frac{11}{2}$$

$$\theta = \text{atan} \frac{11}{2} = 79.70^\circ$$

*Distance Between a Point and a Line:* The distance between a point  $(x_1, y_1)$  and a line given by  $Ax + By + C = 0$  is

$$d = \frac{|Ax_1 + By_1 + C|}{\sqrt{A^2 + B^2}}$$

*Example 8:* Find the distance between the point (4,6) and the line  $2x + 3y - 9 = 0$ .

*Solution:* The distance between a point and the line is

$$d = \frac{|Ax_1 + By_1 + C|}{\sqrt{A^2 + B^2}} = \frac{|2 \times 4 + 3 \times 6 - 9|}{\sqrt{2^2 + 3^2}} = \frac{|8 + 18 - 9|}{\sqrt{4 + 9}} = \frac{17}{\sqrt{13}}$$

**Coordinate Systems.**—*Rectangular, Cartesian Coordinates:* In a Cartesian coordinate system the coordinate axes are perpendicular to one another, and the same unit of length is chosen on the two axes. This rectangular coordinate system is used in the majority of cases.

*Polar Coordinates:* Another coordinate system is determined by a fixed point O, the origin or pole, and a zero direction or axis through it, on which positive lengths can be laid off and measured, as a number line. A point P can be fixed to the zero direction line at a distance  $r$  away and then rotated in a positive sense at an angle  $\theta$ . The angle,  $\theta$ , in polar coordinates can take on values from  $0^\circ$  to  $360^\circ$ . A point in polar coordinates takes the form of  $(r, \theta)$ .

*Changing Coordinate Systems:* For simplicity it may be assumed that the origin on a Cartesian coordinate system coincides with the pole on a polar coordinate system, and its axis with the x-axis. Then, if point P has polar coordinates of  $(r, \theta)$  and Cartesian coordinates of  $(x, y)$ , by trigonometry  $x = r \times \cos(\theta)$  and  $y = r \times \sin(\theta)$ . By the Pythagorean theorem and trigonometry

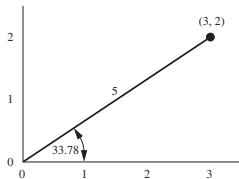
$$r = \sqrt{x^2 + y^2} \quad \theta = \operatorname{atan} \frac{y}{x}$$

*Example 1:* Convert the Cartesian coordinate (3, 2) into polar coordinates.

$$r = \sqrt{3^2 + 2^2} = \sqrt{9 + 4} = \sqrt{13} = 3.6 \quad \theta = \operatorname{atan} \frac{2}{3} = 33.69^\circ$$

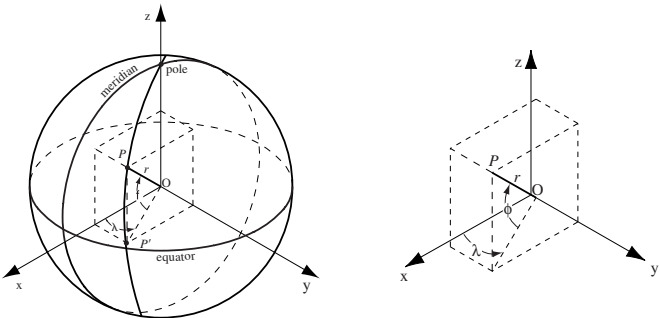
Therefore the point (3.6, 33.69) is the polar form of the Cartesian point (3, 2).

Graphically, the polar and Cartesian coordinates are related in the following figure



*Example 2:* Convert the polar form (5, 608) to Cartesian coordinates. By trigonometry,  $x = r \times \cos(\theta)$  and  $y = r \times \sin(\theta)$ . Then  $x = 5 \cos(608) = -1.873$  and  $y = 5 \sin(608) = -4.636$ . Therefore, the Cartesian point equivalent is  $(-1.873, -4.636)$ .

*Spherical Coordinates:* It is convenient in certain problems, for example, those concerned with spherical surfaces, to introduce non-parallel coordinates. An arbitrary point P in space can be expressed in terms of the distance  $r$  between point P and the origin O, the angle  $\phi$  that  $OP'$  makes with the x-y plane, and the angle  $\lambda$  that the projection  $OP'$  (of the segment  $OP$  onto the x-y plane) makes with the positive x-axis.



The rectangular coordinates of a point in space can therefore be calculated by the formulas in the following table.



## Relationship Between Spherical and Rectangular Coordinates

| Spherical to Rectangular  | Rectangular to Spherical  |
|---|---|
| $x = r \cos \phi \cos \lambda$<br>$y = r \cos \phi \sin \lambda$<br>$z = r \sin \phi$ | $r = \sqrt{x^2 + y^2 + z^2}$  |
|   | $\phi = \operatorname{atan} \frac{z}{\sqrt{x^2 + y^2}}$ (for $x^2 + y^2 \neq 0$ ) |
|   | $\lambda = \operatorname{atan} \frac{y}{x}$ (for $x > 0, y > 0$ )                 |
|   | $\lambda = \pi + \operatorname{atan} \frac{y}{x}$ (for $x < 0$ )                  |
|   | $\lambda = 2\pi + \operatorname{atan} \frac{y}{x}$ (for $x > 0, y < 0$ )          |

*Example 3:* What are the spherical coordinates of the point  $P(3, -4, -12)$ ?

$$r = \sqrt{3^2 + (-4)^2 + (-12)^2} = 13$$

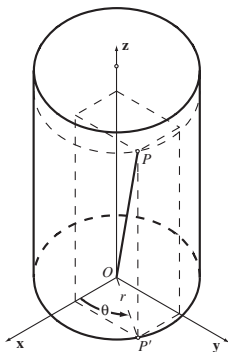
$$\phi = \operatorname{atan} \frac{-12}{\sqrt{3^2 + (-4)^2}} = \operatorname{atan} \frac{-12}{5} = -67.38^\circ$$

$$\lambda = 360^\circ + \operatorname{atan} \frac{-4}{3} = 360^\circ - 53.13^\circ = 306.87^\circ$$

The spherical coordinates of  $P$  are therefore  $r = 13$ ,  $\phi = -67.38^\circ$ , and  $\lambda = 306.87^\circ$ .

*Cylindrical Coordinates:* For problems on the surface of a cylinder it is convenient to use cylindrical coordinates. The cylindrical coordinates  $r$ ,  $\theta$ ,  $z$ , of  $P$  coincide with the polar coordinates of the point  $P'$  in the  $x$ - $y$  plane and the rectangular  $z$ -coordinate of  $P$ . This gives the conversion formula. Those for  $\theta$  hold only if  $x^2 + y^2 \neq 0$ ;  $\theta$  is undetermined if  $x = y = 0$ .

| Cylindrical to Rectangular                            | Rectangular to Cylindrical                 |
|---|--|
| $x = r \cos \theta$<br>$y = r \sin \theta$<br>$z = z$ | $r = \frac{1}{\sqrt{x^2 + y^2}}$           |
|   | $\cos \theta = \frac{x}{\sqrt{x^2 + y^2}}$ |
|   | $\sin \theta = \frac{y}{\sqrt{x^2 + y^2}}$ |
|   | $z = z$                                    |



*Example 4:* Given the cylindrical coordinates of a point  $P$ ,  $r = 3$ ,  $\theta = -30^\circ$ ,  $z = 51$ , find the rectangular coordinates. Using the above formulas  $x = 3 \cos(-30^\circ) = 3 \cos(30^\circ) = 2.598$ ;  $y = 3 \sin(-30^\circ) = -3 \sin(30^\circ) = -1.5$ ; and  $z = 51$ . Therefore, the rectangular coordinates of point  $P$  are  $x = 2.598$ ,  $y = -1.5$ , and  $z = 51$ .

**Circle.**—The general form for the equation of a circle is  $x^2 + y^2 + 2gx + 2fy + c = 0$ , where  $-g$  and  $-f$  are the coordinates of the center and the radius is  $r = \sqrt{g^2 + f^2 - c}$ .

The center radius form of the circle equation is

$$(x - h)^2 + (y - k)^2 = r^2$$

where  $r$  = radius and point  $(h, k)$  is the center.

When the center of circle is at point  $(0,0)$ , the equation of circle reduces to  $x^2 + y^2 = r^2$  or  $r = \sqrt{x^2 + y^2}$

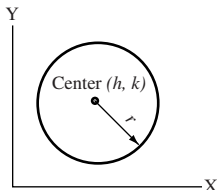
*Example:* Point  $(4,6)$  lies on a circle whose center is at  $(-2,3)$ . Find the circle equation?

*Solution:* The radius is the distance between the center  $(-2,3)$  and point  $(4,6)$ , found using the method of [Example 1](#) on page 39.

$$r = \sqrt{[4 - (-2)]^2 + (6 - 3)^2} = \sqrt{6^2 + 3^2} = \sqrt{45}$$

The equation of the circle is

$$\begin{aligned}(x - h)^2 + (y - k)^2 &= r^2 \\(x + 2)^2 + (y - 3)^2 &= x^2 + 4x + 4 + y^2 - 6y + 9 = 45 \\x^2 + y^2 + 4x - 6y - 32 &= 0\end{aligned}$$



**Parabola.**—A parabola is the set of all points  $P$  in the plane that are equidistant from focus  $F$  and a line called the directrix. A parabola is symmetric with respect to its parabolic axis. The line perpendicular to the parabolic axis which passing through the focus is known as latus rectum.

The general equation of a parabola is given by  $(y - k)^2 = 4p(x - h)$ , where the vertex is located at point  $(h, k)$ , the focus  $F$  is located at point  $(h + p, k)$ , the directrix is located at  $x = h - p$ , and the latus rectum is located at  $x = h + p$ .

*Example:* Determine the focus, directrix, axis, vertex, and latus rectum of the parabola

$$4y^2 - 8x - 12y + 1 = 0$$

*Solution:* Format the equation into the general form of a parabolic equation

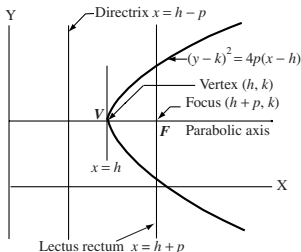
$$4y^2 - 8x - 12y + 1 = 0$$

$$4y^2 - 12y = 8x - 1$$

$$y^2 - 3y = 2x - \frac{1}{4}$$

$$y^2 - 2y\left(\frac{3}{2}\right) + \left(\frac{3}{2}\right)^2 = 2x - \frac{1}{4} + \frac{9}{4}$$

$$\left(y - \frac{3}{2}\right)^2 = 2\left(x + \frac{1}{2}\right)$$



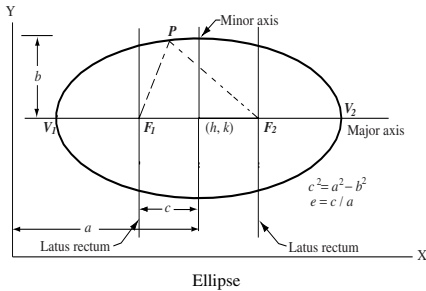
Parabola

Thus,  $k = \frac{3}{2}$ ,  $h = -\frac{1}{2}$  and  $p = \frac{1}{2}$ . Focus  $F$  is located at point  $(h + p, k) = (\frac{1}{2}, \frac{3}{2})$ ; the directrix is located at  $x = h - p = -1 - \frac{1}{2} = -\frac{3}{2}$ ; the parabolic axis is the horizontal line  $y = \frac{3}{2}$ ; the vertex  $V(h, k)$  is located at point  $(-\frac{1}{2}, \frac{3}{2})$ ; and the latus rectum is located at  $x = h + p = -\frac{1}{2}$ .

**Ellipse.**—The ellipse with eccentricity  $e$ , focus  $F$  and a directrix  $L$  is the set of all points  $P$  such that the distance  $PF$  is  $e$  times the distance from  $P$  to the line  $L$ . The general equation of an ellipse is

$$Ax^2 + Cy^2 + Dx + Ey + F = 0 \Big|_{AC > 0 \text{ and } A \neq C$$

The ellipse has two foci separated along the major axis by a distance  $2c$ . The line passing through the focus perpendicular to the major axis is called the latus rectum. The line passing through the center, perpendicular to the major axis, is called the minor axis. The distances  $2a$  and  $2b$  are the major distance, and the minor distance. The ellipse is the locus of points such that the sum of the distances from the two foci to a point on the ellipse is  $2a$ , thus,  $PF_1 + PF_2 = 2a$



If  $(h, k)$  are the center, the general equation of an ellipse is  $\frac{(x-h)^2}{a^2} + \frac{(y-k)^2}{b^2} = 1$

The eccentricity of the ellipse,  $e = \frac{\sqrt{a^2 - b^2}}{a}$ , is always less than 1.

The distance between the two foci is  $2c = 2\sqrt{a^2 - b^2}$ .

The aspect ratio of the ellipse is  $a/b$ .

The equation of an ellipse centered at  $(0, 0)$  with foci at  $(\pm c, 0)$  is  $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$ , and the

ellipse is symmetric about both coordinate axes. Its  $x$ -intercepts are  $(\pm a, 0)$  and  $y$ -intercepts are  $(0, \pm b)$ . The line joining  $(0, b)$  and  $(0, -b)$  is called the minor axis. The vertices of the ellipse are  $(\pm a, 0)$ , and the line joining vertices is the major axis of the ellipse.

*Example:* Determine the values of  $h, k, a, b, c$ , and  $e$  of the ellipse

$$3x^2 + 5y^2 - 12x + 30y + 42 = 0$$

*Solution:* Rearrange the ellipse equation into the general form as follows:

$$3x^2 + 5y^2 - 12x + 30y + 42 = 3x^2 - 12x + 5y^2 + 30y + 42 = 0$$

$$3(x^2 - 4x + 2^2) + 5(y^2 + 6y + 3^2) = 15$$

$$\frac{3(x-2)^2}{15} + \frac{5(y+3)^2}{15} = \frac{(x-2)^2}{(\sqrt{5})^2} + \frac{(y+3)^2}{(\sqrt{3})^2} = 1$$

Comparing the result with the general form,  $\frac{(x-h)^2}{a^2} + \frac{(y-k)^2}{b^2} = 1$ , and solving for  $c$  and  $e$  gives

$$h = 2 \quad k = -3 \quad a = \sqrt{5} \quad b = \sqrt{3} \quad c = \sqrt{2} \quad e = \sqrt{\frac{2}{5}}$$

**Four-Arc Oval that Approximates an Ellipse\*.**—The method of constructing an approximate ellipse by circular arcs, described on page 57, fails when the ratio of the major to minor diameter equals four or greater. Additionally, it is reported that the method always draws a somewhat larger minor axes than intended. The method described below presents an alternative.

An oval that approximates an ellipse, illustrated in Fig. 1, can be constructed from the following equations:

$$r = \frac{B^2 \left(\frac{A}{B}\right)^{0.38}}{2A} \quad (1)$$

where  $A$  and  $B$  are dimensions of the major and minor axis, respectively, and  $r$  is the radius of the curve at the long ends.

The radius  $R$  and its location are found from Equations (2) and (3):

$$X = \frac{\frac{A^2}{4} - Ar + Br - \frac{B^2}{4}}{B - 2r} \quad (2) \quad R = \frac{B}{2 + X} \quad (3)$$

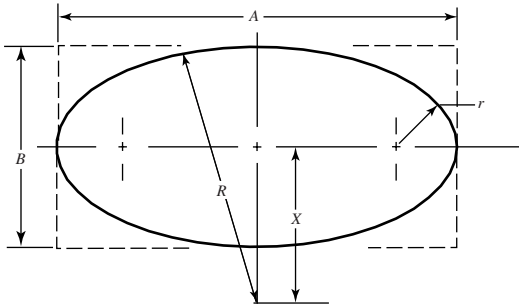


Fig. 1.

To make an oval thinner or fatter than that given, select a smaller or larger radius  $r$  than calculated by Equation (1) and then find  $X$  and  $R$  using Equations (2) and (3).

**Hyperbola.**—The hyperbola with eccentricity  $e$ , focus  $F$  and a directrix  $L$  is the set of all points  $P$  such that the distance  $PF$  is  $e$  times the distance from  $P$  to the line  $L$ . The general equation of an hyperbola is

$$Ax^2 + Cy^2 + Dx + Ey + F = 0 \quad \left|_{AC < 0 \text{ and } AC \neq 0}\right.$$

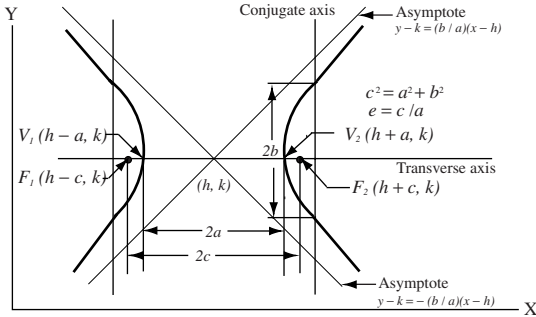
The hyperbola has two foci separated along the transverse axis by a distance  $2c$ . Lines perpendicular to the transverse axis passing through the foci are the conjugate axis. The distance between two vertices is  $2a$ . The distance along a conjugate axis between two

\* Four-Arc Oval material contributed by Manfred K. Brueckner

## HYPERBOLA

points on the hyperbola is  $2b$ . The hyperbola is the locus of points such that the difference of the distances from the two foci is  $2a$ , thus,  $PF_2 - PF_1 = 2a$

If point  $(h, k)$  is the center, the general equation of an ellipse is  $\frac{(x-h)^2}{a^2} - \frac{(y-k)^2}{b^2} = 1$



Hyperbola

The eccentricity of hyperbola,  $e = \frac{\sqrt{a^2 + b^2}}{a}$  is always less than 1.

The distance between the two foci is  $2c = 2\sqrt{a^2 + b^2}$ .

The equation of a hyperbola with center at  $(0, 0)$  and focus at  $(\pm c, 0)$  is  $\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$ .

*Example:* Determine the values of  $h, k, a, b, c,$  and  $e$  of the hyperbola

$$9x^2 - 4y^2 - 36x + 8y - 4 = 0$$

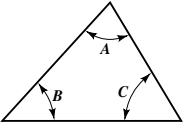
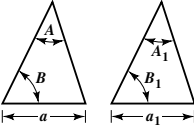
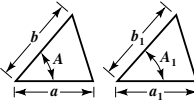
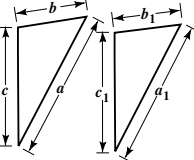
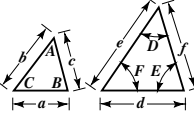
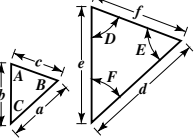
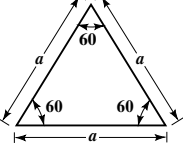
*Solution:* Convert the hyperbola equation into the general form

$$\begin{aligned} 9x^2 - 4y^2 - 36x + 8y - 4 &= (9x^2 - 36x) - (4y^2 - 8y) - 4 = 0 \\ 9(x^2 - 4x + 4) - 4(y^2 - 2y + 1) &= 36 \\ 9\frac{(x-2)^2}{36} - 4\frac{(y-1)^2}{36} &= \frac{(x-2)^2}{2^2} - \frac{(y-1)^2}{3^2} = 1 \end{aligned}$$

Comparing the results above with the general form  $\frac{(x-h)^2}{a^2} - \frac{(y-k)^2}{b^2} = 1$  and calculating the eccentricity from  $e = \frac{\sqrt{a^2 + b^2}}{a}$  and  $c$  from  $c = \sqrt{a^2 + b^2}$  gives

$$h = 2 \quad k = 1 \quad a = 2 \quad b = 3 \quad c = \sqrt{13} \quad e = \frac{\sqrt{13}}{2}$$

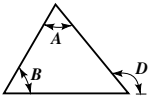
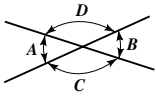
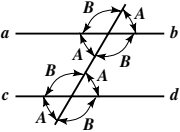
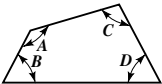
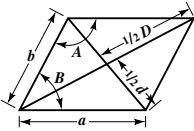
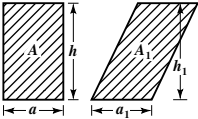
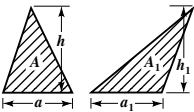
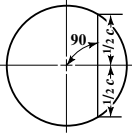
## Geometrical Propositions

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|---|---|
|    | <p>The sum of the three angles in a triangle always equals 180 degrees. Hence, if two angles are known, the third angle can always be found.</p> $A + B + C = 180^\circ \quad A = 180^\circ - (B + C)$ $B = 180^\circ - (A + C) \quad C = 180^\circ - (A + B)$  |
|     | <p>If one side and two angles in one triangle are equal to one side and similarly located angles in another triangle, then the remaining two sides and angle also are equal.</p> <p>If <math>a = a_1</math>, <math>A = A_1</math>, and <math>B = B_1</math>, then the two other sides and the remaining angle also are equal.</p>       |
|     | <p>If two sides and the angle between them in one triangle are equal to two sides and a similarly located angle in another triangle, then the remaining side and angles also are equal.</p> <p>If <math>a = a_1</math>, <math>b = b_1</math>, and <math>A = A_1</math>, then the remaining side and angles also are equal.</p>          |
|     | <p>If the three sides in one triangle are equal to the three sides of another triangle, then the angles in the two triangles also are equal.</p> <p>If <math>a = a_1</math>, <math>b = b_1</math>, and <math>c = c_1</math>, then the angles between the respective sides also are equal.</p>   |
|   | <p>If the three sides of one triangle are proportional to corresponding sides in another triangle, then the triangles are called <i>similar</i>, and the angles in the one are equal to the angles in the other.</p> <p>If <math>a : b : c = d : e : f</math>, then <math>A = D</math>, <math>B = E</math>, and <math>C = F</math>.</p> |
|   | <p>If the angles in one triangle are equal to the angles in another triangle, then the triangles are similar and their corresponding sides are proportional.</p> <p>If <math>A = D</math>, <math>B = E</math>, and <math>C = F</math>, then <math>a : b : c = d : e : f</math>.</p>   |
|  | <p>If the three sides in a triangle are equal—that is, if the triangle is <i>equilateral</i>—then the three angles also are equal.</p> <p>Each of the three equal angles in an equilateral triangle is 60 degrees.</p> <p>If the three angles in a triangle are equal, then the three sides also are equal.</p>                         |

## Geometrical Propositions

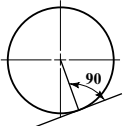
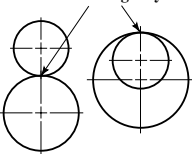
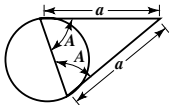
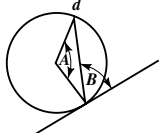
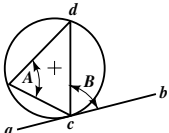
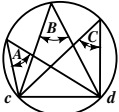

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|  | <p>A line in an equilateral triangle that bisects or divides any of the angles into two equal parts also bisects the side opposite the angle and is at right angles to it.</p> <p>If line <math>AB</math> divides angle <math>CAD</math> into two equal parts, it also divides line <math>CD</math> into two equal parts and is at right angles to it.</p>                                   |
|  | <p>If two sides in a triangle are equal—that is, if the triangle is an <i>isosceles</i> triangle—then the angles opposite these sides also are equal.</p> <p>If side <math>a</math> equals side <math>b</math>, then angle <math>A</math> equals angle <math>B</math>.</p>   |
|  | <p>If two angles in a triangle are equal, the sides opposite these angles also are equal.</p> <p>If angles <math>A</math> and <math>B</math> are equal, then side <math>a</math> equals side <math>b</math>.</p>   |
|  | <p>In an isosceles triangle, if a straight line is drawn from the point where the two equal sides meet, so that it bisects the third side or base of the triangle, then it also bisects the angle between the equal sides and is perpendicular to the base.</p>  |
|  | <p>In every triangle, that angle is greater that is opposite a longer side. In every triangle, that side is greater which is opposite a greater angle.</p> <p>If <math>a</math> is longer than <math>b</math>, then angle <math>A</math> is greater than <math>B</math>. If angle <math>A</math> is greater than <math>B</math>, then side <math>a</math> is longer than <math>b</math>.</p> |
|  | <p>In every triangle, the sum of the lengths of two sides is always greater than the length of the third.</p> <p>Side <math>a +</math> side <math>b</math> is always greater than side <math>c</math>.</p>   |
|  | <p>In a right-angle triangle, the square of the hypotenuse or the side opposite the right angle is equal to the sum of the squares on the two sides that form the right angle.</p> $a^2 = b^2 + c^2$   |

**Geometrical Propositions**



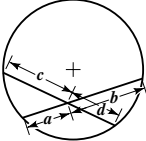
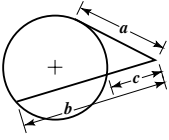
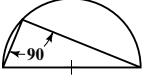
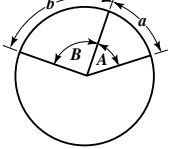
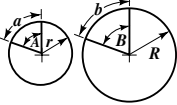


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|---|--|
|    | <p>If one side of a triangle is produced, then the exterior angle is equal to the sum of the two interior opposite angles.</p> <p style="text-align: center;"><math>\text{Angle } D = \text{angle } A + \text{angle } B</math></p>   |
|    | <p>If two lines intersect, then the opposite angles formed by the intersecting lines are equal.</p> <p style="text-align: center;"><math>\text{Angle } A = \text{angle } B</math><br/><math>\text{Angle } C = \text{angle } D</math></p>   |
|    | <p>If a line intersects two parallel lines, then the corresponding angles formed by the intersecting line and the parallel lines are equal.</p> <p style="text-align: center;">Lines <math>ab</math> and <math>cd</math> are parallel. Then all the angles designated <math>A</math> are equal, and all those designated <math>B</math> are equal.</p> |
|    | <p>In any figure having four sides, the sum of the interior angles equals 360 degrees.</p> <p style="text-align: center;"><math>A + B + C + D = 360 \text{ degrees}</math></p>   |
|    | <p>The sides that are opposite each other in a parallelogram are equal; the angles that are opposite each other are equal; the diagonal divides it into two equal parts. If two diagonals are drawn, they bisect each other.</p>   |
|   | <p>The areas of two parallelograms that have equal base and equal height are equal.</p> <p style="text-align: center;">If <math>a = a_1</math> and <math>h = h_1</math>, then<br/><math>\text{Area } A = \text{area } A_1</math></p>   |
|   | <p>The areas of triangles having equal base and equal height are equal.</p> <p style="text-align: center;">If <math>a = a_1</math> and <math>h = h_1</math>, then<br/><math>\text{Area } A = \text{area } A_1</math></p>   |
|  | <p>If a diameter of a circle is at right angles to a chord, then it bisects or divides the chord into two equal parts.</p>   |



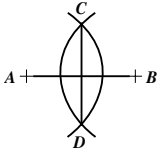
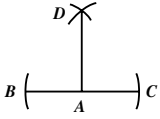
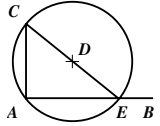
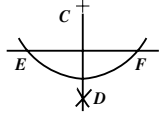
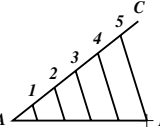
## Geometrical Propositions

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|                                 | <p>If a line is tangent to a circle, then it is also at right angles to a line drawn from the center of the circle to the point of tangency—that is, to a radial line through the point of tangency.</p>   |
| <p><b>Point of Tangency</b></p>  | <p>If two circles are tangent to each other, then the straight line that passes through the centers of the two circles must also pass through the point of tangency.</p>   |
|                                 | <p>If from a point outside a circle, tangents are drawn to a circle, the two tangents are equal and make equal angles with the chord joining the points of tangency.</p>   |
|                                 | <p>The angle between a tangent and a chord drawn from the point of tangency equals one-half the angle at the center subtended by the chord.</p> $\text{Angle } B = \frac{1}{2} \text{ angle } A$   |
|                               | <p>The angle between a tangent and a chord drawn from the point of tangency equals the angle at the periphery subtended by the chord.</p> <p>Angle <math>B</math>, between tangent <math>ab</math> and chord <math>cd</math>, equals angle <math>A</math> subtended at the periphery by chord <math>cd</math>.</p> |
|                               | <p>All angles having their vertex at the periphery of a circle and subtended by the same chord are equal.</p> <p>Angles <math>A</math>, <math>B</math>, and <math>C</math>, all subtended by chord <math>cd</math>, are equal.</p>   |
|                               | <p>If an angle at the circumference of a circle, between two chords, is subtended by the same arc as the angle at the center, between two radii, then the angle at the circumference is equal to one-half of the angle at the center.</p> $\text{Angle } A = \frac{1}{2} \text{ angle } B$                         |

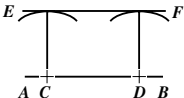
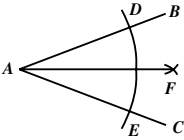
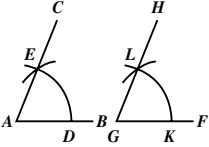
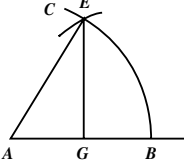
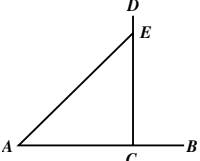
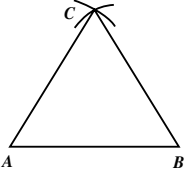
**Geometrical Propositions**

|   |  |
|---|--|
| <p><b>A = Less than 90</b></p>  <p><b>B = More than 90</b></p>   | <p>An angle subtended by a chord in a circular segment larger than one-half the circle is an acute angle—an angle less than 90 degrees. An angle subtended by a chord in a circular segment less than one-half the circle is an obtuse angle—an angle greater than 90 degrees.</p>   |
|    | <p>If two chords intersect each other in a circle, then the rectangle of the segments of the one equals the rectangle of the segments of the other.</p> $a \times b = c \times d$  |
|    | <p>If from a point outside a circle two lines are drawn, one of which intersects the circle and the other is tangent to it, then the rectangle contained by the total length of the intersecting line, and that part of it that is between the outside point and the periphery, equals the square of the tangent.</p> $a^2 = b \times c$ |
|    | <p>If a triangle is inscribed in a semicircle, the angle opposite the diameter is a right (90-degree) angle.</p> <p>All angles at the periphery of a circle, subtended by the diameter, are right (90-degree) angles.</p>  |
|   | <p>The lengths of circular arcs of the same circle are proportional to the corresponding angles at the center.</p> $A : B = a : b$   |
|   | <p>The lengths of circular arcs having the same center angle are proportional to the lengths of the radii.</p> <p>If <math>A = B</math>, then <math>a : b = r : R</math>.</p>  |
| <p>{ Circumf. = <math>c</math><br/>Area = <math>a</math></p>  <p>{ Circumf. = <math>C</math><br/>Area = <math>A</math></p>  | <p>The circumferences of two circles are proportional to their radii.</p> <p>The areas of two circles are proportional to the squares of their radii.</p> $c : C = r : R$ $a : A = r^2 : R^2$  |

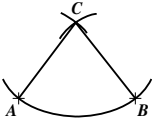
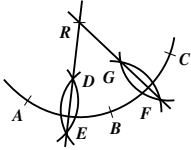
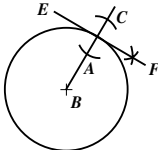
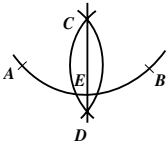
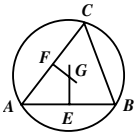
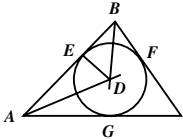
## Geometrical Constructions

|   |   |
|---|---|
|    | <p>To divide a line <math>AB</math> into two equal parts:</p> <p>With the ends <math>A</math> and <math>B</math> as centers and a radius greater than one-half the line, draw circular arcs. Through the intersections <math>C</math> and <math>D</math>, draw line <math>CD</math>. This line divides <math>AB</math> into two equal parts and is also perpendicular to <math>AB</math>.</p>   |
|    | <p>To draw a perpendicular to a straight line from a point <math>A</math> on that line:</p> <p>With <math>A</math> as a center and with any radius, draw circular arcs intersecting the given line at <math>B</math> and <math>C</math>. Then, with <math>B</math> and <math>C</math> as centers and a radius longer than <math>AB</math>, draw circular arcs intersecting at <math>D</math>. Line <math>DA</math> is perpendicular to <math>BC</math> at <math>A</math>.</p>                                       |
|    | <p>To draw a perpendicular line from a point <math>A</math> at the end of a line <math>AB</math>:</p> <p>With any point <math>D</math>, outside of the line <math>AB</math>, as a center, and with <math>AD</math> as a radius, draw a circular arc intersecting <math>AB</math> at <math>E</math>. Draw a line through <math>E</math> and <math>D</math> intersecting the arc at <math>C</math>; then join <math>AC</math>. This line is the required perpendicular.</p>   |
|  | <p>To draw a perpendicular to a line <math>AB</math> from a point <math>C</math> at a distance from it:</p> <p>With <math>C</math> as a center, draw a circular arc intersecting the given line at <math>E</math> and <math>F</math>. With <math>E</math> and <math>F</math> as centers, draw circular arcs with a radius longer than one-half the distance between <math>E</math> and <math>F</math>. These arcs intersect at <math>D</math>. Line <math>CD</math> is the required perpendicular.</p>              |
|  | <p>To divide a straight line <math>AB</math> into a number of equal parts:</p> <p>Let it be required to divide <math>AB</math> into five equal parts. Draw line <math>AC</math> at an angle with <math>AB</math>. Set off on <math>AC</math> five equal parts of any convenient length. Draw <math>B-5</math> and then draw lines parallel with <math>B-5</math> through the other division points on <math>AC</math>. The points where these lines intersect <math>AB</math> are the required division points.</p> |

## Geometrical Constructions

|  |  |
|--|--|
|    | <p>To draw a straight line parallel to a given line <math>AB</math>, at a given distance from it:</p> <p>With any points <math>C</math> and <math>D</math> on <math>AB</math> as centers, draw circular arcs with the given distance as radius. Line <math>EF</math>, drawn to touch the circular arcs, is the required parallel line.</p>   |
|    | <p>To bisect or divide an angle <math>BAC</math> into two equal parts:</p> <p>With <math>A</math> as a center and any radius, draw arc <math>DE</math>. With <math>D</math> and <math>E</math> as centers and a radius greater than one-half <math>DE</math>, draw circular arcs intersecting at <math>F</math>. Line <math>AF</math> divides the angle into two equal parts.</p>  |
|    | <p>To draw an angle upon a line <math>AB</math>, equal to a given angle <math>FGH</math>:</p> <p>With point <math>G</math> as a center and with any radius, draw arc <math>KL</math>. With <math>A</math> as a center and with the same radius, draw arc <math>DE</math>. Make arc <math>DE</math> equal to <math>KL</math> and draw <math>AC</math> through <math>E</math>. Angle <math>BAC</math> then equals angle <math>FGH</math>.</p>  |
|   | <p>To lay out a 60-degree angle:</p> <p>With <math>A</math> as a center and any radius, draw an arc <math>BC</math>. With point <math>B</math> as a center and <math>AB</math> as a radius, draw an arc intersecting at <math>E</math> the arc just drawn. <math>EAB</math> is a 60-degree angle.</p> <p>A 30-degree angle may be obtained either by dividing a 60-degree angle into two equal parts or by drawing a line <math>EG</math> perpendicular to <math>AB</math>. Angle <math>AEG</math> is then 30 degrees.</p> |
|  | <p>To draw a 45-degree angle:</p> <p>From point <math>A</math> on line <math>AB</math>, set off a distance <math>AC</math>. Draw the perpendicular <math>DC</math> and set off a distance <math>CE</math> equal to <math>AC</math>. Draw <math>AE</math>. Angle <math>EAC</math> is a 45-degree angle.</p>   |
|  | <p>To draw an equilateral triangle, the length of the sides of which equals <math>AB</math>:</p> <p>With <math>A</math> and <math>B</math> as centers and <math>AB</math> as radius, draw circular arcs intersecting at <math>C</math>. Draw <math>AC</math> and <math>BC</math>. Then <math>ABC</math> is an equilateral triangle.</p>  |

## Geometrical Constructions

|   |   |
|---|---|
|    | <p>To draw a circular arc with a given radius through two given points <math>A</math> and <math>B</math>:</p> <p>With <math>A</math> and <math>B</math> as centers, and the given radius as radius, draw circular arcs intersecting at <math>C</math>. With <math>C</math> as a center, and the same radius, draw a circular arc through <math>A</math> and <math>B</math>.</p>   |
|     | <p>To find the center of a circle or of an arc of a circle:</p> <p>Select three points on the periphery of the circle, as <math>A</math>, <math>B</math>, and <math>C</math>. With each of these points as a center and the same radius, describe arcs intersecting each other. Through the points of intersection, draw lines <math>DE</math> and <math>FG</math>. Point <math>H</math>, where these lines intersect, is the center of the circle.</p> |
|    | <p>To draw a tangent to a circle from a given point on the circumference:</p> <p>Through the point of tangency <math>A</math>, draw a radial line <math>BC</math>. At point <math>A</math>, draw a line <math>EF</math> at right angles to <math>BC</math>. This line is the required tangent.</p>  |
|   | <p>To divide a circular arc <math>AB</math> into two equal parts:</p> <p>With <math>A</math> and <math>B</math> as centers, and a radius larger than half the distance between <math>A</math> and <math>B</math>, draw circular arcs intersecting at <math>C</math> and <math>D</math>. Line <math>CD</math> divides arc <math>AB</math> into two equal parts at <math>E</math>.</p>  |
|  | <p>To describe a circle about a triangle:</p> <p>Divide the sides <math>AB</math> and <math>AC</math> into two equal parts, and from the division points <math>E</math> and <math>F</math>, draw lines at right angles to the sides. These lines intersect at <math>G</math>. With <math>G</math> as a center and <math>GA</math> as a radius, draw circle <math>ABC</math>.</p>  |
|   | <p>To inscribe a circle in a triangle:</p> <p>Bisect two of the angles, <math>A</math> and <math>B</math>, by lines intersecting at <math>D</math>. From <math>D</math>, draw a line <math>DE</math> perpendicular to one of the sides, and with <math>DE</math> as a radius, draw circle <math>EFG</math>.</p>   |


**Geometrical Constructions**

|  |  |
|--|--|
|  | <p>To describe a circle about a square and to inscribe a circle in a square:</p> <p>The centers of both the circumscribed and inscribed circles are located at the point <math>E</math>, where the two diagonals of the square intersect. The radius of the circumscribed circle is <math>AE</math>, and of the inscribed circle, <math>EF</math>.</p>   |
|  | <p>To inscribe a hexagon in a circle:</p> <p>Draw a diameter <math>AB</math>. With <math>A</math> and <math>B</math> as centers and with the radius of the circle as radius, describe circular arcs intersecting the given circle at <math>D, E, F</math>, and <math>G</math>. Draw lines <math>AD, DE</math>, etc., forming the required hexagon.</p>   |
|  | <p>To describe a hexagon about a circle:</p> <p>Draw a diameter <math>AB</math>, and with <math>A</math> as a center and the radius of the circle as radius, cut the circumference of the given circle at <math>D</math>. Join <math>AD</math> and bisect it with radius <math>CE</math>. Through <math>E</math>, draw <math>FG</math> parallel to <math>AD</math> and intersecting line <math>AB</math> at <math>F</math>. With <math>C</math> as a center and <math>CF</math> as radius, draw a circle. Within this circle, inscribe the hexagon as in the preceding problem.</p>  |
|  | <p>To describe an ellipse with the given axes <math>AB</math> and <math>CD</math>:</p> <p>Describe circles with <math>O</math> as a center and <math>AB</math> and <math>CD</math> as diameters. From a number of points, <math>E, F, G</math>, etc., on the outer circle, draw radii intersecting the inner circle at <math>e, f, g</math>. From <math>E, F</math>, and <math>G</math>, draw lines perpendicular to <math>AB</math>, and from <math>e, f</math>, and <math>g</math>, draw lines parallel to <math>AB</math>. The intersections of these perpendicular and parallel lines are points on the curve of the ellipse.</p>  |
|  | <p>To construct an approximate ellipse by circular arcs:</p> <p>Let <math>AC</math> be the major axis and <math>BN</math> the minor. Draw half circle <math>ADC</math> with <math>O</math> as a center. Divide <math>BD</math> into three equal parts and set off <math>BE</math> equal to one of these parts. With <math>A</math> and <math>C</math> as centers and <math>OE</math> as radius, describe circular arcs <math>KLM</math> and <math>FGH</math>; with <math>G</math> and <math>L</math> as centers, and the same radius, describe arcs <math>FCH</math> and <math>KAM</math>. Through <math>F</math> and <math>G</math>, draw line <math>FP</math>, and with <math>P</math> as a center, draw the arc <math>FBK</math>. Arc <math>HNM</math> is drawn in the same manner.</p> |

**Geometrical Constructions**

|  |  |
|--|--|
|  | <p>To construct a parabola:</p> <p>Divide line <math>AB</math> into a number of equal parts and divide <math>BC</math> into the same number of parts. From the division points on <math>AB</math>, draw horizontal lines. From the division points on <math>BC</math>, draw lines to point <math>A</math>. The points of intersection between lines drawn from points numbered alike are points on the parabola.</p>   |
|  | <p>To construct a hyperbola:</p> <p>From focus <math>F</math>, lay off a distance <math>FD</math> equal to the transverse axis, or the distance <math>AB</math> between the two branches of the curve. With <math>F</math> as a center and any distance <math>FE</math> greater than <math>FB</math> as a radius, describe a circular arc. Then with <math>F_1</math> as a center and <math>DE</math> as a radius, describe arcs intersecting at <math>C</math> and <math>G</math> the arc just described. <math>C</math> and <math>G</math> are points on the hyperbola. Any number of points can be found in a similar manner.</p> |
|  | <p>To construct an involute:</p> <p>Divide the circumference of the base circle <math>ABC</math> into a number of equal parts. Through the division points 1, 2, 3, etc., draw tangents to the circle and make the lengths <math>D-1</math>, <math>E-2</math>, <math>F-3</math>, etc., of these tangents equal to the actual length of the arcs <math>A-1</math>, <math>A-2</math>, <math>A-3</math>, etc.</p>   |
|  | <p>To construct a helix:</p> <p>Divide half the circumference of the cylinder, on the surface of which the helix is to be described, into a number of equal parts. Divide half the lead of the helix into the same number of equal parts. From the division points on the circle representing the cylinder, draw vertical lines, and from the division points on the lead, draw horizontal lines as shown. The intersections between lines numbered alike are points on the helix.</p>   |

## Areas and Volumes

**The Prismoidal Formula.**—The prismoidal formula is a general formula by which the volume of any prism, pyramid, or frustum of a pyramid may be found. 

$A_1$  = area at one end of the body

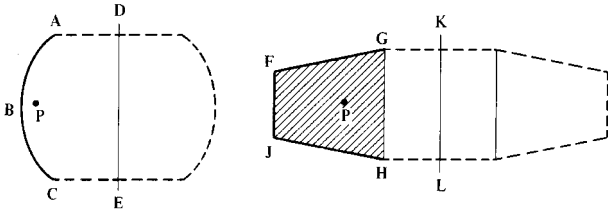
$A_2$  = area at the other end

$A_m$  = area of middle section between the two end surfaces

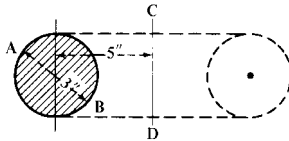
$h$  = height of body

Then, volume  $V$  of the body is  $V = \frac{h}{6}(A_1 + 4A_m + A_2)$

**Pappus or Guldinus Rules.**—By means of these rules the area of any surface of revolution and the volume of any solid of revolution may be found. The area of the surface swept out by the revolution of a line  $ABC$  (see illustration) about the axis  $DE$  equals the length of the line multiplied by the length of the path of its center of gravity,  $P$ . If the line is of such a shape that it is difficult to determine its center of gravity, then the line may be divided into a number of short sections, each of which may be considered as a straight line, and the areas swept out by these different sections, as computed by the rule given, may be added to find the total area. The line must lie wholly on one side of the axis of revolution and must be in the same plane.



The volume of a solid body formed by the revolution of a surface  $FGHJ$  about axis  $KL$  equals the area of the surface multiplied by the length of the path of its center of gravity. The surface must lie wholly on one side of the axis of revolution and in the same plane.



*Example:* By means of these rules, the area and volume of a cylindrical ring or torus may be found. The torus is formed by a circle  $AB$  being rotated about axis  $CD$ . The center of gravity of the circle is at its center. Hence, with the dimensions given in the illustration, the length of the path of the center of gravity of the circle is  $3.1416 \times 10 = 31.416$  inches. Multiplying by the length of the circumference of the circle, which is  $3.1416 \times 3 = 9.4248$  inches, gives  $31.416 \times 9.4248 = 296.089$  square inches which is the area of the torus.

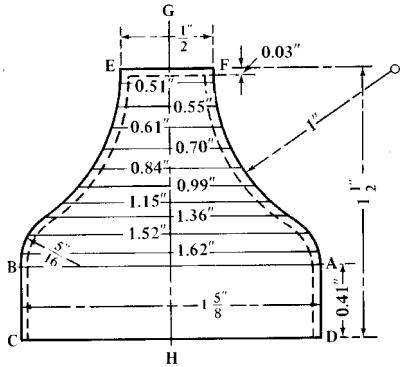
The volume equals the area of the circle, which is  $0.7854 \times 9 = 7.0686$  square inches, multiplied by the path of the center of gravity, which is 31.416, as before; hence,

$$\text{Volume} = 7.0686 \times 31.416 = 222.067 \text{ cubic inches}$$



**Approximate Method for Finding the Area of a Surface of Revolution.**—The accompanying illustration is shown in order to give an example of the approximate method based on Guldinus' rule, that can be used for finding the area of a symmetrical body. In the illustration, the dimensions in common fractions are the known dimensions; those in decimals are found by actual measurements on a figure drawn to scale.

The method for finding the area is as follows: First, separate such areas as are cylindrical, conical, or spherical, as these can be found by exact formulas. In the illustration  $ABCD$  is a cylinder, the area of the surface of which can be easily found. The top area  $EF$  is simply a circular area, and can thus be computed separately. The remainder of the surface generated by rotating line  $AF$  about the axis  $GH$  is found by the approximate method explained in the previous section. From point  $A$ , set off equal distances on line  $AF$ . In the illustration, each division indicated is  $\frac{1}{8}$  inch long. From the central or middle point of each of these parts draw a line at right angles to the axis of rotation  $GH$ , measure the length of these lines or diameters (the length of each is given in decimals), add all these lengths together and multiply the sum by the length of one division set off on line  $AF$  (in this case,  $\frac{1}{8}$  inch), and multiply this product by  $\pi$  to find the approximate area of the surface of revolution.



In setting off divisions  $\frac{1}{8}$  inch long along line  $AF$ , the last division does not reach exactly to point  $F$ , but only to a point 0.03 inch below it. The part 0.03 inch high at the top of the cup can be considered as a cylinder of  $\frac{1}{2}$  inch diameter and 0.03 inch height, the area of the cylindrical surface of which is easily computed. By adding the various surfaces together, the total surface of the cup is found as follows:

|   |                            |
|---|----------------------------|
| Cylinder, $1 \frac{5}{8}$ inch diameter, 0.41 inch high | 2.093 square inches        |
| Circle, $\frac{1}{2}$ inch diameter                     | 0.196 square inch          |
| Cylinder, $\frac{1}{2}$ inch diameter, 0.03 inch high   | 0.047 square inch          |
| Irregular surface                                       | <u>3.868</u> square inches |
| Total   | 6.204 square inches        |

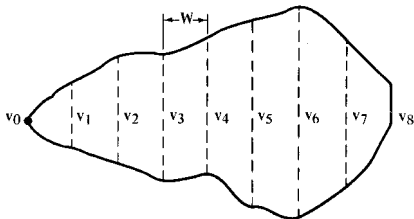
**Area of Plane Surfaces of Irregular Outline.**—One of the most useful and accurate methods for determining the approximate area of a plane figure or irregular outline is known as *Simpson's Rule*. In applying Simpson's Rule to find an area the work is done in four steps:

- 1) Divide the area into an *even* number,  $N$ , of parallel strips of equal width  $W$ ; for example, in the accompanying diagram, the area has been divided into 8 strips of equal width.
- 2) Label the sides of the strips  $V_0, V_1, V_2, \dots, V_N$ .
- 3) Measure the heights  $V_0, V_1, V_2, \dots, V_N$  of the sides of the strips.
- 4) Substitute the heights  $V_0, V_1, \dots$ , in the following formula to find the area  $A$  of the figure:

$$A = \frac{W}{3}[(V_0 + V_N) + 4(V_1 + V_3 + \dots + V_{N-1}) + 2(V_2 + V_4 + \dots + V_N).$$

*Example:* The area of the accompanying figure was divided into 8 strips on a full-size drawing and the following data obtained. Calculate the area using Simpson's Rule.

- $W = \frac{1}{2}''$
- $V_0 = 0''$
- $V_1 = \frac{3}{4}''$
- $V_2 = 1\frac{1}{4}''$
- $V_3 = 1\frac{1}{2}''$
- $V_4 = 1\frac{5}{8}''$
- $V_5 = 2\frac{1}{4}''$
- $V_6 = 2\frac{1}{2}''$
- $V_7 = 1\frac{3}{4}''$
- $V_8 = \frac{1}{2}''$



Substituting the given data in the Simpson formula,

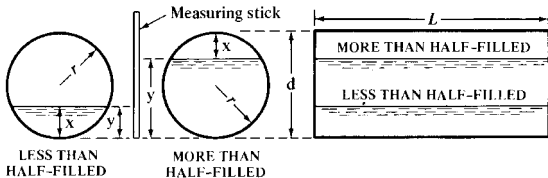
$$\begin{aligned} A &= \frac{1/2}{3}[(0 + 1/2) + 4(3/4 + 1\frac{1}{2} + 2\frac{1}{4} + 1\frac{3}{4}) + 2(1\frac{1}{4} + 1\frac{5}{8} + 2\frac{1}{2})] \\ &= \frac{1}{6}[(1/2) + 4(6\frac{1}{4}) + 2(5\frac{3}{8})] = \frac{1}{6}[36\frac{1}{4}] \\ &= 6.04 \text{ square inches} \end{aligned}$$

In applying Simpson's Rule, it should be noted that the larger the number of strips into which the area is divided the more accurate the results obtained.

**Areas Enclosed by Cycloidal Curves.**—The area between a cycloid and the straight line upon which the generating circle rolls, equals three times the area of the generating circle (see diagram, page 66). The areas between epicycloidal and hypocycloidal curves and the “fixed circle” upon which the generating circle is rolled, may be determined by the following formulas, in which  $a$  = radius of the fixed circle upon which the generating circle rolls;  $b$  = radius of the generating circle;  $A$  = the area for the epicycloidal curve; and  $A_1$  = the area for the hypocycloidal curve.

$$A = \frac{3.1416b^2(3a + 2b)}{a} \qquad A_1 = \frac{3.1416b^2(3a - 2b)}{a}$$

**Find the Contents of Cylindrical Tanks at Different Levels.**—In conjunction with the table *Segments of Circles for Radius = 1* starting on page 71, the following relations can give a close approximation of the liquid contents, at any level, in a cylindrical tank.



A long measuring rule calibrated in length units or simply a plain stick can be used for measuring contents at a particular level. In turn, the rule or stick can be graduated to serve as a volume gauge for the tank in question. The only requirements are that the cross-section of the tank is circular; the tank's dimensions are known; the gauge rod is inserted vertically through the top center of the tank so that it rests on the exact bottom of the tank; and that consistent English or metric units are used throughout the calculations.

$$K = Cr^2L = \text{Tank Constant (remains the same for any given tank)} \quad (1)$$

$$V_T = \pi K, \text{ for a tank that is completely full} \quad (2)$$

$$V_s = KA \quad (3)$$

$$V = V_s \text{ when tank is less than half full} \quad (4)$$

$$V = V_T - V_s = V_T - KA, \text{ when tank is more than half full} \quad (5)$$

where  $C$  = liquid volume conversion factor, the exact value of which depends on the length and liquid volume units being used during measurement: 0.00433 U.S. gal/in<sup>3</sup>; 7.48 U.S. gal/ft<sup>3</sup>; 0.00360 U.K. gal/in<sup>3</sup>; 6.23 U.K. gal/ft<sup>3</sup>; 0.001 liter/cm<sup>3</sup>; or 1000 liters/m<sup>3</sup>

$V_T$  = total volume of liquid tank can hold

$V_s$  = volume formed by segment of circle having depth =  $x$  in given tank (see diagram)

$V$  = volume of liquid at particular level in tank

$d$  = diameter of tank;  $L$  = length of tank;  $r$  = radius of tank ( $= \frac{1}{2}$  diameter)

$A$  = segment area of a corresponding unit circle taken from the table starting on page 71

$y$  = actual depth of contents in tank as shown on a gauge rod or stick

$x$  = depth of the segment of a circle to be considered in given tank. As can be seen in above diagram,  $x$  is the actual depth of contents ( $y$ ) when the tank is less than half full, and is the depth of the void ( $d - y$ ) above the contents when the tank is more than half full. From pages 71 and 74 it can also be seen that  $h$ , the height of a segment of a corresponding unit circle, is  $x/r$

*Example:* A tank is 20 feet long and 6 feet in diameter. Convert a long inch-stick into a gauge that is graduated at 1000 and 3000 U.S. gallons.

$$L = 20 \times 12 = 240 \text{ in.} \quad r = \frac{6}{2} \times 12 = 36 \text{ in.}$$

From [Formula \(1\)](#):  $K = 0.00433(36)^2(240) = 1346.80$

From [Formula \(2\)](#):  $V_T = 3.1416 \times 1347 = 4231.1$  US gal.

The 72-inch mark from the bottom on the inch-stick can be graduated for the rounded full volume "4230"; and the halfway point 36" for 4230/2 or "2115." It can be seen that the 1000-gal mark would be below the halfway mark. From [Formulas \(3\) and \(4\)](#):

$$A_{1000} = \frac{1000}{1347} = 0.7424 \text{ from the table starting on page 71, } h \text{ can be interpolated as}$$

0.5724; and  $x = y = 36 \times 0.5724 = 20.61$ . If the desired level of accuracy permits, interpolation can be omitted by choosing  $h$  directly from the table on page 71 for the value of  $A$  nearest that calculated above.

Therefore, the 1000-gal mark is graduated  $20\frac{5}{8}$ " from bottom of rod.

It can be seen that the 3000 mark would be above the halfway mark. Therefore, the circular segment considered is the cross-section of the void space at the top of the tank. From [Formulas \(3\) and \(5\)](#):

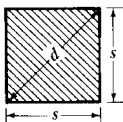
$$A_{3000} = \frac{4230 - 3000}{1347} = 0.9131; h = 0.6648; x = 36 \times 0.6648 = 23.93''$$

Therefore, the 3000-gal mark is  $72.00 - 23.93 = 48.07$ , or at the  $48\frac{1}{16}$ " mark from the bottom.

## Areas and Dimensions of Plane Figures

In the following tables are given formulas for the areas of plane figures, together with other formulas relating to their dimensions and properties; the surfaces of solids; and the volumes of solids. The notation used in the formulas is, as far as possible, given in the illustration accompanying them; where this has not been possible, it is given at the beginning of each set of formulas.

Examples are given with each entry, some in English and some in metric units, showing the use of the preceding formula.

*Square:*

$$\begin{aligned} \text{Area} = A &= s^2 = \frac{1}{2}d^2 \\ s &= 0.7071d = \sqrt{A} \\ d &= 1.414s = 1.414\sqrt{A} \end{aligned}$$

*Example:* Assume that the side  $s$  of a square is 15 inches. Find the area and the length of the diagonal.

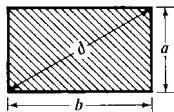
$$\text{Area} = A = s^2 = 15^2 = 225 \text{ square inches}$$

$$\text{Diagonal} = d = 1.414s = 1.414 \times 15 = 21.21 \text{ inches}$$

*Example:* The area of a square is 625 square inches. Find the length of the side  $s$  and the diagonal  $d$ .

$$s = \sqrt{A} = \sqrt{625} = 25 \text{ inches}$$

$$d = 1.414\sqrt{A} = 1.414 \times 25 = 35.35 \text{ inches}$$

*Rectangle:*

$$\begin{aligned} \text{Area} = A &= ab = a\sqrt{d^2 - a^2} = b\sqrt{d^2 - b^2} \\ d &= \sqrt{a^2 + b^2} \\ a &= \sqrt{d^2 - b^2} = A \div b \\ a &= \sqrt{d^2 - a^2} = A \div a \end{aligned}$$

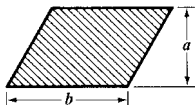
*Example:* The side  $a$  of a rectangle is 12 centimeters, and the area 70.5 square centimeters. Find the length of the side  $b$ , and the diagonal  $d$ .

$$b = A \div a = 70.5 \div 12 = 5.875 \text{ centimeters}$$

$$d = \sqrt{a^2 + b^2} = \sqrt{12^2 + 5.875^2} = \sqrt{178.516} = 13.361 \text{ centimeters}$$

*Example:* The sides of a rectangle are 30.5 and 11 centimeters long. Find the area.

$$\text{Area} = A = a \times b = 30.5 \times 11 = 335.5 \text{ square centimeters}$$

*Parallelogram:*

$$\begin{aligned} \text{Area} = A &= ab \\ a &= A \div b \\ b &= A \div a \end{aligned}$$

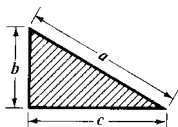
*Note:* The dimension  $a$  is measured at right angles to line  $b$ .

*Example:* The base  $b$  of a parallelogram is 16 feet. The height  $a$  is 5.5 feet. Find the area.

$$\text{Area} = A = a \times b = 5.5 \times 16 = 88 \text{ square feet}$$

*Example:* The area of a parallelogram is 12 square inches. The height is 1.5 inches. Find the length of the base  $b$ .

$$b = A \div a = 12 \div 1.5 = 8 \text{ inches}$$

**Right-Angled Triangle:**

$$\text{Area} = A = \frac{bc}{2}$$

$$a = \sqrt{b^2 + c^2}$$

$$b = \sqrt{a^2 - c^2}$$

$$c = \sqrt{a^2 - b^2}$$

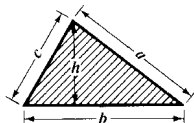
*Example:* The sides  $b$  and  $c$  in a right-angled triangle are 6 and 8 inches. Find side  $a$  and the area

$$a = \sqrt{b^2 + c^2} = \sqrt{6^2 + 8^2} = \sqrt{36 + 64} = \sqrt{100} = 10 \text{ inches}$$

$$A = \frac{b \times c}{2} = \frac{6 \times 8}{2} = \frac{48}{2} = 24 \text{ square inches}$$

*Example:* If  $a = 10$  and  $b = 6$  had been known, but not  $c$ , the latter would have been found as follows:

$$c = \sqrt{a^2 - b^2} = \sqrt{10^2 - 6^2} = \sqrt{100 - 36} = \sqrt{64} = 8 \text{ inches}$$

**Acute-Angled Triangle:**

$$\text{Area} = A = \frac{bh}{2} = \frac{b}{2} \sqrt{a^2 - \left(\frac{a^2 + b^2 - c^2}{2b}\right)^2}$$

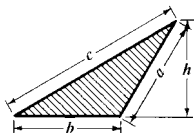
If  $S = \frac{1}{2}(a + b + c)$ , then

$$A = \sqrt{S(S-a)(S-b)(S-c)}$$

*Example:* If  $a = 10$ ,  $b = 9$ , and  $c = 8$  centimeters, what is the area of the triangle?

$$A = \frac{b}{2} \sqrt{a^2 - \left(\frac{a^2 + b^2 - c^2}{2b}\right)^2} = \frac{9}{2} \sqrt{10^2 - \left(\frac{10^2 + 9^2 - 8^2}{2 \times 9}\right)^2} = 4.5 \sqrt{100 - \left(\frac{117}{18}\right)^2}$$

$$= 4.5 \sqrt{100 - 42.25} = 4.5 \sqrt{57.75} = 4.5 \times 7.60 = 34.20 \text{ square centimeters}$$

**Obtuse-Angled Triangle:**

$$\text{Area} = A = \frac{bh}{2} = \frac{b}{2} \sqrt{a^2 - \left(\frac{c^2 - a^2 - b^2}{2b}\right)^2}$$

If  $S = \frac{1}{2}(a + b + c)$ , then

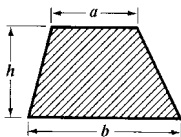
$$A = \sqrt{S(S-a)(S-b)(S-c)}$$

*Example:* The side  $a = 5$ , side  $b = 4$ , and side  $c = 8$  inches. Find the area.

$$S = \frac{1}{2}(a + b + c) = \frac{1}{2}(5 + 4 + 8) = \frac{1}{2} \times 17 = 8.5$$

$$A = \sqrt{S(S-a)(S-b)(S-c)} = \sqrt{8.5(8.5-5)(8.5-4)(8.5-8)}$$

$$= \sqrt{8.5 \times 3.5 \times 4.5 \times 0.5} = \sqrt{66.937} = 8.18 \text{ square inches}$$

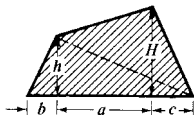
**Trapezoid:**

$$\text{Area} = A = \frac{(a+b)h}{2}$$

*Note:* In Britain, this figure is called a *trapezium* and the one below it is known as a *trapezoid*, the terms being reversed.

*Example:* Side  $a = 23$  meters, side  $b = 32$  meters, and height  $h = 12$  meters. Find the area.

$$A = \frac{(a+b)h}{2} = \frac{(23+32)12}{2} = \frac{55 \times 12}{2} = 330 \text{ square meters}$$

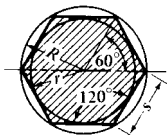
**Trapezium:**

$$\text{Area} = A = \frac{(H+h)a + bh + cH}{2}$$

A trapezium can also be divided into two triangles as indicated by the dashed line. The area of each of these triangles is computed, and the results added to find the area of the trapezium.

*Example:* Let  $a = 10$ ,  $b = 2$ ,  $c = 3$ ,  $h = 8$ , and  $H = 12$  inches. Find the area.

$$\begin{aligned} A &= \frac{(H+h)a + bh + cH}{2} = \frac{(12+8)10 + 2 \times 8 + 3 \times 12}{2} \\ &= \frac{20 \times 10 + 16 + 36}{2} = \frac{252}{2} = 126 \text{ square inches} \end{aligned}$$

**Regular Hexagon:**

$$A = 2.598s^2 = 2.598R^2 = 3.464r^2$$

$$R = s = \text{radius of circumscribed circle} = 1.155r$$

$$r = \text{radius of inscribed circle} = 0.866s = 0.866R$$

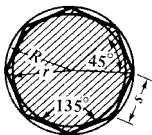
$$s = R = 1.155r$$

*Example:* The side  $s$  of a regular hexagon is 40 millimeters. Find the area and the radius  $r$  of the inscribed circle.

$$A = 2.598s^2 = 2.598 \times 40^2 = 2.598 \times 1600 = 4156.8 \text{ square millimeters}$$

$$r = 0.866s = 0.866 \times 40 = 34.64 \text{ millimeters}$$

*Example:* What is the length of the side of a hexagon that is drawn around a circle of 50 millimeters radius? — Here  $r = 50$ . Hence,  $s = 1.155r = 1.155 \times 50 = 57.75$  millimeters

**Regular Octagon:**

$$A = \text{area} = 4.828s^2 = 2.828R^2 = 3.314r^2$$

$$R = \text{radius of circumscribed circle} = 1.307s = 1.082r$$

$$r = \text{radius of inscribed circle} = 1.207s = 0.924R$$

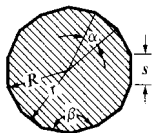
$$s = 0.765R = 0.828r$$

*Example:* Find the area and the length of the side of an octagon that is inscribed in a circle of 12 inches diameter.

Diameter of circumscribed circle = 12 inches; hence,  $R = 6$  inches.

$$A = 2.828R^2 = 2.828 \times 6^2 = 2.828 \times 36 = 101.81 \text{ square inches}$$

$$s = 0.765R = 0.765 \times 6 = 4.590 \text{ inches}$$

**Regular Polygon:**

$$A = \text{area} \quad n = \text{number of sides}$$

$$\alpha = 360^\circ \div n \quad \beta = 180^\circ - \alpha$$

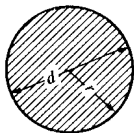
$$A = \frac{nsr}{2} = \frac{ns}{2} \sqrt{R^2 - \frac{s^2}{4}}$$

$$R = \sqrt{r^2 + \frac{s^2}{4}} \quad r = \sqrt{R^2 - \frac{s^2}{4}} \quad s = 2\sqrt{R^2 - r^2}$$

*Example:* Find the area of a polygon having 12 sides, inscribed in a circle of 8 centimeters radius. The length of the side  $s$  is 4.141 centimeters.

$$\begin{aligned} A &= \frac{ns}{2} \sqrt{R^2 - \frac{s^2}{4}} = \frac{12 \times 4.141}{2} \sqrt{8^2 - \frac{4.141^2}{4}} = 24.846 \sqrt{59.713} \\ &= 24.846 \times 7.727 = 191.98 \text{ square centimeters} \end{aligned}$$

## Circle:



$$\begin{aligned} \text{Area} = A &= \pi r^2 = 3.1416r^2 = 0.7854d^2 \\ \text{Circumference} = C &= 2\pi r = 6.2832r = 3.1416d \\ r &= C \div 6.2832 = \sqrt{A \div 3.1416} = 0.564\sqrt{A} \\ d &= C \div 3.1416 = \sqrt{A \div 0.7854} = 1.128\sqrt{A} \\ \text{Length of arc for center angle of } 1^\circ &= 0.008727d \\ \text{Length of arc for center angle of } n^\circ &= 0.008727nd \end{aligned}$$

*Example:* Find the area  $A$  and circumference  $C$  of a circle with a diameter of  $2\frac{3}{4}$  inches.

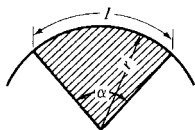
$$A = 0.7854d^2 = 0.7854 \times 2.75^2 = 0.7854 \times 2.75 \times 2.75 = 5.9396 \text{ square inches}$$

$$C = 3.1416d = 3.1416 \times 2.75 = 8.6394 \text{ inches}$$

*Example:* The area of a circle is 16.8 square inches. Find its diameter.

$$d = 1.128\sqrt{A} = 1.128\sqrt{16.8} = 1.128 \times 4.099 = 4.624 \text{ inches}$$

## Circular Sector:



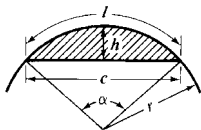
$$\begin{aligned} \text{Length of arc} = l &= \frac{r \times \alpha \times 3.1416}{180} = 0.01745r\alpha = \frac{2A}{r} \\ \text{Area} = A &= \frac{1}{2}rl = 0.008727r^2\alpha \\ \text{Angle, in degrees} = \alpha &= \frac{57.296 l}{r} \quad r = \frac{2A}{l} = \frac{57.296 l}{\alpha} \end{aligned}$$

*Example:* The radius of a circle is 35 millimeters, and angle  $\alpha$  of a sector of the circle is 60 degrees. Find the area of the sector and the length of arc  $l$ .

$$A = 0.008727r^2\alpha = 0.008727 \times 60 \times 35^2 = 641.41 \text{ mm}^2 = 6.41 \text{ cm}^2$$

$$l = 0.01745r\alpha = 0.01745 \times 35 \times 60 = 36.645 \text{ millimeters}$$

## Circular Segment:



$$\begin{aligned} A &= \text{area} \quad l = \text{length of arc} \quad \alpha = \text{angle, in degrees} \\ c &= 2\sqrt{h(2r-h)} \quad A = \frac{1}{2}[rl - c(r-h)] \\ r &= \frac{c^2 + 4h^2}{8h} \quad l = 0.01745r\alpha \\ h &= r - \frac{1}{2}\sqrt{4r^2 - c^2} = r[1 - \cos(\alpha/2)] \quad \alpha = \frac{57.296 l}{r} \end{aligned}$$

See also, *Circular Segments* starting on page 70.

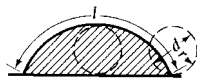
*Example:* The radius  $r$  is 60 inches and the height  $h$  is 8 inches. Find the length of the chord  $c$ .

$$c = 2\sqrt{h(2r-h)} = 2\sqrt{8 \times (2 \times 60 - 8)} = 2\sqrt{896} = 2 \times 29.93 = 59.86 \text{ inches}$$

*Example:* If  $c = 16$ , and  $h = 6$  inches, what is the radius of the circle of which the segment is a part?

$$r = \frac{c^2 + 4h^2}{8h} = \frac{16^2 + 4 \times 6^2}{8 \times 6} = \frac{256 + 144}{48} = \frac{400}{48} = 8\frac{1}{3} \text{ inches}$$

## Cycloid:

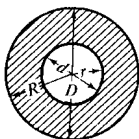


$$\begin{aligned} \text{Area} = A &= 3\pi r^2 = 9.4248r^2 = 2.3562d^2 \\ &= 3 \times \text{area of generating circle} \\ \text{Length of cycloid} = l &= 8r = 4d \end{aligned}$$

See also, *Areas Enclosed by Cycloidal Curves* on page 61.

*Example:* The diameter of the generating circle of a cycloid is 6 inches. Find the length  $l$  of the cycloidal curve, and the area enclosed between the curve and the base line.

$$l = 4d = 4 \times 6 = 24 \text{ inches} \quad A = 2.3562d^2 = 2.3562 \times 6^2 = 84.82 \text{ square inches}$$

**Circular Ring:**

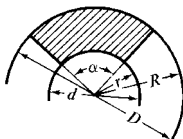
$$\begin{aligned} \text{Area} = A &= \pi(R^2 - r^2) = 3.1416(R^2 - r^2) \\ &= 3.1416(R + r)(R - r) \\ &= 0.7854(D^2 - d^2) = 0.7854(D + d)(D - d) \end{aligned}$$

*Example:* Let the outside diameter  $D = 12$  centimeters and the inside diameter  $d = 8$  centimeters. Find the area of the ring.

$$\begin{aligned} A &= 0.7854(D^2 - d^2) = 0.7854(12^2 - 8^2) = 0.7854(144 - 64) = 0.7854 \times 80 \\ &= 62.83 \text{ square centimeters} \end{aligned}$$

By the alternative formula:

$$\begin{aligned} A &= 0.7854(D + d)(D - d) = 0.7854(12 + 8)(12 - 8) = 0.7854 \times 20 \times 4 \\ &= 62.83 \text{ square centimeters} \end{aligned}$$

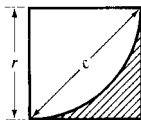
**Circular Ring Sector:**

$A = \text{area}$       $\alpha = \text{angle, in degrees}$

$$\begin{aligned} A &= \frac{\alpha\pi}{360}(R^2 - r^2) = 0.00873\alpha(R^2 - r^2) \\ &= \frac{\alpha\pi}{4 \times 360}(D^2 - d^2) = 0.00218\alpha(D^2 - d^2) \end{aligned}$$

*Example:* Find the area, if the outside radius  $R = 5$  inches, the inside radius  $r = 2$  inches, and  $\alpha = 72$  degrees.

$$\begin{aligned} A &= 0.00873\alpha(R^2 - r^2) = 0.00873 \times 72(5^2 - 2^2) \\ &= 0.6286(25 - 4) = 0.6286 \times 21 = 13.2 \text{ square inches} \end{aligned}$$

**Spandrel or Fillet:**

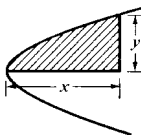
$$\text{Area} = A = r^2 - \frac{\pi r^2}{4} = 0.215r^2 = 0.1075c^2$$

*Example:* Find the area of a spandrel, the radius of which is 0.7 inch.

$$A = 0.215r^2 = 0.215 \times 0.7^2 = 0.105 \text{ square inch}$$

*Example:* If chord  $c$  were given as 2.2 inches, what would be the area?

$$A = 0.1075c^2 = 0.1075 \times 2.2^2 = 0.520 \text{ square inch}$$

**Parabola:**

$$\text{Area} = A = \frac{2}{3}xy$$

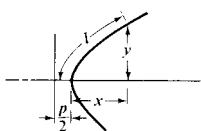
(The area is equal to two-thirds of a rectangle which has  $x$  for its base and  $y$  for its height.)

*Example:* Let  $x$  in the illustration be 15 centimeters, and  $y$ , 9 centimeters. Find the area of the shaded portion of the parabola.

$$A = \frac{2}{3} \times xy = \frac{2}{3} \times 15 \times 9 = 10 \times 9 = 90 \text{ square centimeters}$$



## Parabola:



$$l = \text{length of arc} = \frac{p}{2} \left[ \sqrt{\frac{2x}{p} \left( 1 + \frac{2x}{p} \right)} + \ln \left( \sqrt{\frac{2x}{p}} + \sqrt{1 + \frac{2x}{p}} \right) \right]$$

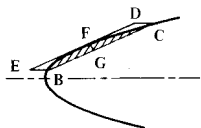
When  $x$  is small in proportion to  $y$ , the following is a close approximation:

$$l = y \left[ 1 + \frac{2}{3} \left( \frac{x}{y} \right)^2 - \frac{2}{5} \left( \frac{x}{y} \right)^4 \right] \text{ or } l = \sqrt{y^2 + \frac{4}{3}x^2}$$

*Example:* If  $x = 2$  and  $y = 24$  feet, what is the approximate length  $l$  of the parabolic curve?

$$\begin{aligned} l &= y \left[ 1 + \frac{2}{3} \left( \frac{x}{y} \right)^2 - \frac{2}{5} \left( \frac{x}{y} \right)^4 \right] = 24 \left[ 1 + \frac{2}{3} \left( \frac{2}{24} \right)^2 - \frac{2}{5} \left( \frac{2}{24} \right)^4 \right] \\ &= 24 \left[ 1 + \frac{2}{3} \times \frac{1}{144} - \frac{2}{5} \times \frac{1}{20,736} \right] = 24 \times 1.0046 = 24.11 \text{ feet} \end{aligned}$$

## Segment of Parabola:



$$\text{Area BFC} = A = \frac{2}{3} \text{ area of parallelogram BCDE}$$

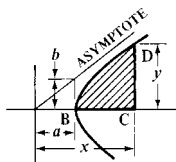
If  $FG$  is the height of the segment, measured at right angles to  $BC$ , then:

$$\text{Area of segment BFC} = \frac{2}{3} BC \times FG$$

*Example:* The length of the chord  $BC = 19.5$  inches. The distance between lines  $BC$  and  $DE$ , measured at right angles to  $BC$ , is 2.25 inches. This is the height of the segment. Find the area.

$$\text{Area} = A = \frac{2}{3} BC \times FG = \frac{2}{3} \times 19.5 \times 2.25 = 29.25 \text{ square inches}$$

## Hyperbola:



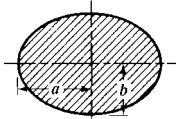
$$\text{Area BCD} = A = \frac{xy}{2} - \frac{ab}{2} \ln \left( \frac{x}{a} + \frac{y}{b} \right)$$

*Example:* The half-axes  $a$  and  $b$  are 3 and 2 inches, respectively. Find the area shown shaded in the illustration for  $x = 8$  and  $y = 5$ .

Inserting the known values in the formula:

$$\begin{aligned} A &= \frac{8 \times 5}{2} - \frac{3 \times 2}{2} \times \ln \left( \frac{8}{3} + \frac{5}{2} \right) = 20 - 3 \times \ln 5.167 \\ &= 20 - 3 \times 1.6423 = 20 - 4.927 = 15.073 \text{ square inches} \end{aligned}$$

## Ellipse:



$$\text{Area} = A = \pi ab = 3.1416ab$$

An approximate formula for the perimeter is

$$\text{Perimeter} = P = 3.1416 \sqrt{2(a^2 + b^2)}$$

A closer approximation is

$$P = 3.1416 \sqrt{2(a^2 + b^2) - \frac{(a-b)^2}{2.2}}$$

*Example:* The larger or major axis is 200 millimeters. The smaller or minor axis is 150 millimeters. Find the area and the approximate circumference. Here, then,  $a = 100$ , and  $b = 75$ .

$$A = 3.1416ab = 3.1416 \times 100 \times 75 = 23,562 \text{ square millimeters} = 235.62 \text{ square centimeters}$$

$$P = 3.1416 \sqrt{2(a^2 + b^2)} = 3.1416 \sqrt{2(100^2 + 75^2)} = 3.1416 \sqrt{2 \times 15,625}$$

$$= 3.1416 \sqrt{31,250} = 3.1416 \times 176.78 = 555.37 \text{ millimeters} = (55.537 \text{ centimeters})$$

**Formulas and Table for Regular Polygons.**—The following formulas and table can be used to calculate the area, length of side, and radii of the inscribed and circumscribed circles of regular polygons (equal sided).

$$A = NS^2 \cot \alpha \div 4 = NR^2 \sin \alpha \cos \alpha = Nr^2 \tan \alpha$$

$$r = R \cos \alpha = (S \cot \alpha) \div 2 = \sqrt{(A \times \cot \alpha) \div N}$$

$$R = S \div (2 \sin \alpha) = r \div \cos \alpha = \sqrt{A \div (N \sin \alpha \cos \alpha)}$$

$$S = 2R \sin \alpha = 2r \tan \alpha = 2\sqrt{(A \times \tan \alpha) \div N}$$

where  $N$  = number of sides;  $S$  = length of side;  $R$  = radius of circumscribed circle;  $r$  = radius of inscribed circle;  $A$  = area of polygon; and,  $\alpha = 180^\circ \div N$  = one-half center angle of one side. See also *Regular Polygon* on page 65.

#### Area, Length of Side, and Inscribed and Circumscribed Radii of Regular Polygons

| No. of Sides | $\frac{A}{S^2}$ | $\frac{A}{R^2}$ | $\frac{A}{r^2}$ | $\frac{R}{S}$ | $\frac{R}{r}$ | $\frac{S}{R}$ | $\frac{S}{r}$ | $\frac{r}{R}$ | $\frac{r}{S}$ |
|--------------|-----------------|-----------------|-----------------|---------------|---------------|---------------|---------------|---------------|---------------|
| 3            | 0.4330          | 1.2990          | 5.1962          | 0.5774        | 2.0000        | 1.7321        | 3.4641        | 0.5000        | 0.2887        |
| 4            | 1.0000          | 2.0000          | 4.0000          | 0.7071        | 1.4142        | 1.4142        | 2.0000        | 0.7071        | 0.5000        |
| 5            | 1.7205          | 2.3776          | 3.6327          | 0.8507        | 1.2361        | 1.1756        | 1.4531        | 0.8090        | 0.6882        |
| 6            | 2.5981          | 2.5981          | 3.4641          | 1.0000        | 1.1547        | 1.0000        | 1.1547        | 0.8660        | 0.8660        |
| 7            | 3.6339          | 2.7364          | 3.3710          | 1.1524        | 1.1099        | 0.8678        | 0.9631        | 0.9010        | 1.0383        |
| 8            | 4.8284          | 2.8284          | 3.3137          | 1.3066        | 1.0824        | 0.7654        | 0.8284        | 0.9239        | 1.2071        |
| 9            | 6.1818          | 2.8925          | 3.2757          | 1.4619        | 1.0642        | 0.6840        | 0.7279        | 0.9397        | 1.3737        |
| 10           | 7.6942          | 2.9389          | 3.2492          | 1.6180        | 1.0515        | 0.6180        | 0.6498        | 0.9511        | 1.5388        |
| 12           | 11.196          | 3.0000          | 3.2154          | 1.9319        | 1.0353        | 0.5176        | 0.5359        | 0.9659        | 1.8660        |
| 16           | 20.109          | 3.0615          | 3.1826          | 2.5629        | 1.0196        | 0.3902        | 0.3978        | 0.9808        | 2.5137        |
| 20           | 31.569          | 3.0902          | 3.1677          | 3.1962        | 1.0125        | 0.3129        | 0.3168        | 0.9877        | 3.1569        |
| 24           | 45.575          | 3.1058          | 3.1597          | 3.8306        | 1.0086        | 0.2611        | 0.2633        | 0.9914        | 3.7979        |
| 32           | 81.225          | 3.1214          | 3.1517          | 5.1011        | 1.0048        | 0.1960        | 0.1970        | 0.9952        | 5.0766        |
| 48           | 183.08          | 3.1326          | 3.1461          | 7.6449        | 1.0021        | 0.1308        | 0.1311        | 0.9979        | 7.6285        |
| 64           | 325.69          | 3.1365          | 3.1441          | 10.190        | 1.0012        | 0.0981        | 0.0983        | 0.9988        | 10.178        |

*Example 1:* A regular hexagon is inscribed in a circle of 6 inches diameter. Find the area and the radius of an inscribed circle. Here  $R = 3$ . From the table, area  $A = 2.5981R^2 = 2.5981 \times 9 = 23.3829$  square inches. Radius of inscribed circle,  $r = 0.866R = 0.866 \times 3 = 2.598$  inches.

*Example 2:* An octagon is inscribed in a circle of 100 millimeters diameter. Thus  $R = 50$ . Find the area and radius of an inscribed circle.  $A = 2.8284R^2 = 2.8284 \times 2500 = 7071 \text{ mm}^2 = 70.7 \text{ cm}^2$ . Radius of inscribed circle,  $r = 0.9239R = 0.9239 \times 50 = 46.195 \text{ mm}$ .

*Example 3:* Thirty-two bolts are to be equally spaced on the periphery of a bolt-circle, 16 inches in diameter. Find the chordal distance between the bolts. Chordal distance equals the side  $S$  of a polygon with 32 sides.  $R = 8$ . Hence,  $S = 0.196R = 0.196 \times 8 = 1.568$  inch.

*Example 4:* Sixteen bolts are to be equally spaced on the periphery of a bolt-circle, 250 millimeters diameter. Find the chordal distance between the bolts. Chordal distance equals the side  $S$  of a polygon with 16 sides.  $R = 125$ . Thus,  $S = 0.3902R = 0.3902 \times 125 = 48.775$  millimeters.

**Circular Segments.**—The table that follows gives the principle formulas for dimensions of circular segments. The dimensions are illustrated in the figures on pages 66 and 71. When two of the dimensions found together in the first column are known, the other dimensions are found by using the formulas in the corresponding row. For example, if radius  $r$  and chord  $c$  are known, solve for angle  $\alpha$  using Equation (13), then use Equations (14) and (15) to solve for  $h$  and  $l$ , respectively. In these formulas, the value of  $\alpha$  is in degrees between 0 and 180°.

**Formulas for Circular Segments**

| Given       | Formulas  |   |  |
|-------------|---|---|--|
| $\alpha, r$ | $c = 2r \sin \frac{\alpha}{2}$ (1)                          | $h = r \left( 1 - \cos \frac{\alpha}{2} \right)$ (2)      | $l = \frac{\pi r \alpha}{180}$ (3)   |
| $\alpha, c$ | $r = \frac{c}{2 \sin \alpha}$ (4)                           | $h = -\frac{c}{2} \tan \alpha$ (5)                        | $l = \frac{\pi c \alpha}{360 \sin \frac{\alpha}{2}}$ (6)                               |
| $\alpha, h$ | $r = \frac{h}{1 - \cos \frac{\alpha}{2}}$ (7)               | $c = \frac{2h}{\tan \frac{\alpha}{4}}$ (8)                | $l = \frac{\pi H \alpha}{180 \left( 1 - \cos \frac{\alpha}{2} \right)}$ (9)            |
| $\alpha, l$ | $r = \frac{180 l}{\pi \alpha}$ (10)                         | $c = \frac{360 l \sin \frac{\alpha}{2}}{\pi \alpha}$ (11) | $h = \frac{180 l \left( 1 - \cos \frac{\alpha}{2} \right)}{\pi \alpha}$ (12)           |
| $r, c$      | $\alpha = \arccos \left( \frac{1 - c^2}{2R^2} \right)$ (13) | $h = r - \frac{\sqrt{4r^2 - c^2}}{2}$ (14)                | $l = \frac{\pi}{90} r \sin \left( \frac{c}{2r} \right)$ (15)                           |
| $r, h$      | $\alpha = 2 \arccos \left( 1 - \frac{h}{r} \right)$ (16)    | $c = 2 \sqrt{h(2r - h)}$ (17)                             | $l = \frac{\pi}{90} r \arccos \left( 1 - \frac{h}{r} \right)$ (18)                     |
| $r, l$      | $\alpha = \frac{180 l}{\pi r}$ (19)                         | $c = 2r \sin \frac{90l}{\pi R}$ (20)                      | $h = r \left( 1 - \cos \frac{90l}{\pi r} \right)$ (21)                                 |
| $c, h$      | $\alpha = 4 \operatorname{atan} \frac{2h}{c}$ (22)          | $r = \frac{c^2 + 4h^2}{8H}$ (23)                          | $l = \pi \left( \frac{c^2 + 4h^2}{360h} \right) \operatorname{atan} \frac{2h}{c}$ (24) |

| Given  | Formula To Find   | Given  | Formula To Find  |
|--------|---|--------|--|
| $c, l$ | $\frac{360 l}{\pi c} = \frac{\alpha}{\sin \frac{\alpha}{2}}$ (25)<br>Solve Equation (25) for $\alpha$ by iteration <sup>a</sup> , then<br>$r =$ Equation (10)<br>$h =$ Equation (5) | $h, l$ | $\frac{180 l}{\pi h} = \frac{\alpha}{1 - \cos \frac{\alpha}{2}}$ (26)<br>Solve Equation (26) for $\alpha$ by iteration <sup>a</sup> , then<br>$r =$ Equation (10)<br>$c =$ Equation (11) |

<sup>a</sup>Equations (25) and (26) can not be easily solved by ordinary means. To solve these equations, test various values of  $\alpha$  until the left side of the equation equals the right side. For example, if given  $c = 4$  and  $l = 5$ , the left side of Equation (25) equals 143.24, and by testing various values of  $\alpha$  it will be found that the right side equals 143.24 when  $\alpha = 129.62^\circ$ .

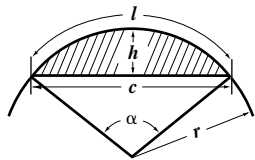
Angle  $\alpha$  is in degrees,  $0 < \alpha < 180$

Formulas for Circular Segments contributed by Manfred Brueckner

**Segments of Circles for Radius = 1.**—Formulas for segments of circles are given on pages 66 and 70. When the central angle  $\alpha$  and radius  $r$  are known, the tables on this and the following page can be used to find the length of arc  $l$ , height of segment  $h$ , chord length  $c$ , and segment area  $A$ .

When angle  $\alpha$  and radius  $r$  are not known, but segment height  $h$  and chord length  $c$  are known or can be measured, the ratio  $h/c$  can be used to enter the table and find  $\alpha$ ,  $l$ , and  $A$  by linear interpolation. Radius  $r$  is found by the formula on page 66 or 70. The value of  $l$  is then multiplied by the radius  $r$  and the area  $A$  by  $r^2$ , the square of the radius.

Angle  $\alpha$  can be found thus with an accuracy of about 0.001 degree; arc length  $l$  with an error of about 0.02 per cent; and area  $A$  with an error ranging from about 0.02 per cent for the highest entry value of  $h/c$  to about 1 per cent for values of  $h/c$  of about 0.050. For lower values of  $h/c$ , and where greater accuracy is required, area  $A$  should be found by the formula on page 66.



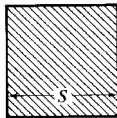
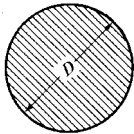
**Segments of Circles for Radius = 1 (English or metric units)**

| $\theta$ , Deg. | $l$     | $h$     | $c$     | Area $A$ | $h/c$   | $\theta$ , Deg. | $l$     | $h$     | $c$     | Area $A$ | $h/c$   |
|-----------------|---------|---------|---------|----------|---------|-----------------|---------|---------|---------|----------|---------|
| 1               | 0.01745 | 0.00004 | 0.01745 | 0.0000   | 0.00218 | 41              | 0.71558 | 0.06333 | 0.70041 | 0.0298   | 0.09041 |
| 2               | 0.03491 | 0.00015 | 0.03490 | 0.0000   | 0.00436 | 42              | 0.73304 | 0.06642 | 0.71674 | 0.0320   | 0.09267 |
| 3               | 0.05236 | 0.00034 | 0.05235 | 0.0000   | 0.00655 | 43              | 0.75049 | 0.06958 | 0.73300 | 0.0342   | 0.09493 |
| 4               | 0.06981 | 0.00061 | 0.06980 | 0.0000   | 0.00873 | 44              | 0.76794 | 0.07282 | 0.74921 | 0.0366   | 0.09719 |
| 5               | 0.08727 | 0.00095 | 0.08724 | 0.0001   | 0.01091 | 45              | 0.78540 | 0.07612 | 0.76537 | 0.0391   | 0.09946 |
| 6               | 0.10472 | 0.00137 | 0.10467 | 0.0001   | 0.01309 | 46              | 0.80285 | 0.07950 | 0.78146 | 0.0418   | 0.10173 |
| 7               | 0.12217 | 0.00187 | 0.12210 | 0.0002   | 0.01528 | 47              | 0.82030 | 0.08294 | 0.79750 | 0.0445   | 0.10400 |
| 8               | 0.13963 | 0.00244 | 0.13951 | 0.0002   | 0.01746 | 48              | 0.83776 | 0.08645 | 0.81347 | 0.0473   | 0.10628 |
| 9               | 0.15708 | 0.00308 | 0.15692 | 0.0003   | 0.01965 | 49              | 0.85521 | 0.09004 | 0.82939 | 0.0503   | 0.10856 |
| 10              | 0.17453 | 0.00381 | 0.17431 | 0.0004   | 0.02183 | 50              | 0.87266 | 0.09369 | 0.84524 | 0.0533   | 0.11085 |
| 11              | 0.19199 | 0.00460 | 0.19169 | 0.0006   | 0.02402 | 51              | 0.89012 | 0.09741 | 0.86102 | 0.0565   | 0.11314 |
| 12              | 0.20944 | 0.00548 | 0.20906 | 0.0008   | 0.02620 | 52              | 0.90757 | 0.10121 | 0.87674 | 0.0598   | 0.11543 |
| 13              | 0.22689 | 0.00643 | 0.22641 | 0.0010   | 0.02839 | 53              | 0.92502 | 0.10507 | 0.89240 | 0.0632   | 0.11773 |
| 14              | 0.24435 | 0.00745 | 0.24374 | 0.0012   | 0.03058 | 54              | 0.94248 | 0.10899 | 0.90798 | 0.0667   | 0.12004 |
| 15              | 0.26180 | 0.00856 | 0.26105 | 0.0015   | 0.03277 | 55              | 0.95993 | 0.11299 | 0.92350 | 0.0704   | 0.12235 |
| 16              | 0.27925 | 0.00973 | 0.27835 | 0.0018   | 0.03496 | 56              | 0.97738 | 0.11705 | 0.93894 | 0.0742   | 0.12466 |
| 17              | 0.29671 | 0.01098 | 0.29562 | 0.0022   | 0.03716 | 57              | 0.99484 | 0.12118 | 0.95432 | 0.0781   | 0.12698 |
| 18              | 0.31416 | 0.01231 | 0.31287 | 0.0026   | 0.03935 | 58              | 1.01229 | 0.12538 | 0.96962 | 0.0821   | 0.12931 |
| 19              | 0.33161 | 0.01371 | 0.33010 | 0.0030   | 0.04155 | 59              | 1.02974 | 0.12964 | 0.98485 | 0.0863   | 0.13164 |
| 20              | 0.34907 | 0.01519 | 0.34730 | 0.0035   | 0.04374 | 60              | 1.04720 | 0.13397 | 1.00000 | 0.0906   | 0.13397 |
| 21              | 0.36652 | 0.01675 | 0.36447 | 0.0041   | 0.04594 | 61              | 1.06465 | 0.13837 | 1.01508 | 0.0950   | 0.13632 |
| 22              | 0.38397 | 0.01837 | 0.38162 | 0.0047   | 0.04814 | 62              | 1.08210 | 0.14283 | 1.03008 | 0.0996   | 0.13866 |
| 23              | 0.40143 | 0.02008 | 0.39874 | 0.0053   | 0.05035 | 63              | 1.09956 | 0.14736 | 1.04500 | 0.1043   | 0.14101 |
| 24              | 0.41888 | 0.02185 | 0.41582 | 0.0061   | 0.05255 | 64              | 1.11701 | 0.15195 | 1.05984 | 0.1091   | 0.14337 |
| 25              | 0.43633 | 0.02370 | 0.43288 | 0.0069   | 0.05476 | 65              | 1.13446 | 0.15661 | 1.07460 | 0.1141   | 0.14574 |
| 26              | 0.45379 | 0.02563 | 0.44990 | 0.0077   | 0.05697 | 66              | 1.15192 | 0.16133 | 1.08928 | 0.1192   | 0.14811 |
| 27              | 0.47124 | 0.02763 | 0.46689 | 0.0086   | 0.05918 | 67              | 1.16937 | 0.16611 | 1.10387 | 0.1244   | 0.15048 |
| 28              | 0.48869 | 0.02970 | 0.48384 | 0.0096   | 0.06139 | 68              | 1.18682 | 0.17096 | 1.11839 | 0.1298   | 0.15287 |
| 29              | 0.50615 | 0.03185 | 0.50076 | 0.0107   | 0.06361 | 69              | 1.20428 | 0.17587 | 1.13281 | 0.1353   | 0.15525 |
| 30              | 0.52360 | 0.03407 | 0.51764 | 0.0118   | 0.06583 | 70              | 1.22173 | 0.18085 | 1.14715 | 0.1410   | 0.15765 |
| 31              | 0.54105 | 0.03637 | 0.53448 | 0.0130   | 0.06805 | 71              | 1.23918 | 0.18588 | 1.16141 | 0.1468   | 0.16005 |
| 32              | 0.55851 | 0.03874 | 0.55127 | 0.0143   | 0.07027 | 72              | 1.25664 | 0.19098 | 1.17557 | 0.1528   | 0.16246 |
| 33              | 0.57596 | 0.04118 | 0.56803 | 0.0157   | 0.07250 | 73              | 1.27409 | 0.19614 | 1.18965 | 0.1589   | 0.16488 |
| 34              | 0.59341 | 0.04370 | 0.58474 | 0.0171   | 0.07473 | 74              | 1.29154 | 0.20136 | 1.20363 | 0.1651   | 0.16730 |
| 35              | 0.61087 | 0.04628 | 0.60141 | 0.0186   | 0.07696 | 75              | 1.30900 | 0.20665 | 1.21752 | 0.1715   | 0.16973 |
| 36              | 0.62832 | 0.04894 | 0.61803 | 0.0203   | 0.07919 | 76              | 1.32645 | 0.21199 | 1.23132 | 0.1781   | 0.17216 |
| 37              | 0.64577 | 0.05168 | 0.63461 | 0.0220   | 0.08143 | 77              | 1.34390 | 0.21739 | 1.24503 | 0.1848   | 0.17461 |
| 38              | 0.66323 | 0.05448 | 0.65114 | 0.0238   | 0.08367 | 78              | 1.36136 | 0.22285 | 1.25864 | 0.1916   | 0.17706 |
| 39              | 0.68068 | 0.05736 | 0.66761 | 0.0257   | 0.08592 | 79              | 1.37881 | 0.22838 | 1.27216 | 0.1986   | 0.17952 |
| 40              | 0.69813 | 0.06031 | 0.68404 | 0.0277   | 0.08816 | 80              | 1.39626 | 0.23396 | 1.28558 | 0.2057   | 0.18199 |

## Segments of Circles for Radius = 1 (English or metric units) (Continued)

| $\theta$ ,<br>Deg. | $l$     | $h$     | $c$     | Area $A$ | $h/c$   | $\theta$ ,<br>Deg. | $l$     | $h$     | $c$     | Area $A$ | $h/c$   |
|--------------------|---------|---------|---------|----------|---------|--------------------|---------|---------|---------|----------|---------|
| 81                 | 1.41372 | 0.23959 | 1.29890 | 0.2130   | 0.18446 | 131                | 2.28638 | 0.58531 | 1.81992 | 0.7658   | 0.32161 |
| 82                 | 1.43117 | 0.24529 | 1.31212 | 0.2205   | 0.18694 | 132                | 2.30383 | 0.59326 | 1.82709 | 0.7803   | 0.32470 |
| 83                 | 1.44862 | 0.25104 | 1.32524 | 0.2280   | 0.18943 | 133                | 2.32129 | 0.60125 | 1.83412 | 0.7950   | 0.32781 |
| 84                 | 1.46608 | 0.25686 | 1.33826 | 0.2358   | 0.19193 | 134                | 2.33874 | 0.60927 | 1.84101 | 0.8097   | 0.33094 |
| 85                 | 1.48353 | 0.26272 | 1.35118 | 0.2437   | 0.19444 | 135                | 2.35619 | 0.61732 | 1.84776 | 0.8245   | 0.33409 |
| 86                 | 1.50098 | 0.26865 | 1.36400 | 0.2517   | 0.19696 | 136                | 2.37365 | 0.62539 | 1.85437 | 0.8395   | 0.33725 |
| 87                 | 1.51844 | 0.27463 | 1.37671 | 0.2599   | 0.19948 | 137                | 2.39110 | 0.63350 | 1.86084 | 0.8546   | 0.34044 |
| 88                 | 1.53589 | 0.28066 | 1.38932 | 0.2682   | 0.20201 | 138                | 2.40855 | 0.64163 | 1.86716 | 0.8697   | 0.34364 |
| 89                 | 1.55334 | 0.28675 | 1.40182 | 0.2767   | 0.20456 | 139                | 2.42601 | 0.64979 | 1.87334 | 0.8850   | 0.34686 |
| 90                 | 1.57080 | 0.29289 | 1.41421 | 0.2854   | 0.20711 | 140                | 2.44346 | 0.65798 | 1.87939 | 0.9003   | 0.35010 |
| 91                 | 1.58825 | 0.29909 | 1.42650 | 0.2942   | 0.20967 | 141                | 2.46091 | 0.66619 | 1.88528 | 0.9158   | 0.35337 |
| 92                 | 1.60570 | 0.30534 | 1.43868 | 0.3032   | 0.21224 | 142                | 2.47837 | 0.67443 | 1.89104 | 0.9314   | 0.35665 |
| 93                 | 1.62316 | 0.31165 | 1.45075 | 0.3123   | 0.21482 | 143                | 2.49582 | 0.68270 | 1.89665 | 0.9470   | 0.35995 |
| 94                 | 1.64061 | 0.31800 | 1.46271 | 0.3215   | 0.21741 | 144                | 2.51327 | 0.69098 | 1.90211 | 0.9627   | 0.36327 |
| 95                 | 1.65806 | 0.32441 | 1.47455 | 0.3309   | 0.22001 | 145                | 2.53073 | 0.69929 | 1.90743 | 0.9786   | 0.36662 |
| 96                 | 1.67552 | 0.33087 | 1.48629 | 0.3405   | 0.22261 | 146                | 2.54818 | 0.70763 | 1.91261 | 0.9945   | 0.36998 |
| 97                 | 1.69297 | 0.33738 | 1.49791 | 0.3502   | 0.22523 | 147                | 2.56563 | 0.71598 | 1.91764 | 1.0105   | 0.37337 |
| 98                 | 1.71042 | 0.34394 | 1.50942 | 0.3601   | 0.22786 | 148                | 2.58309 | 0.72436 | 1.92252 | 1.0266   | 0.37678 |
| 99                 | 1.72788 | 0.35055 | 1.52081 | 0.3701   | 0.23050 | 149                | 2.60054 | 0.73276 | 1.92726 | 1.0428   | 0.38021 |
| 100                | 1.74533 | 0.35721 | 1.53209 | 0.3803   | 0.23315 | 150                | 2.61799 | 0.74118 | 1.93185 | 1.0590   | 0.38366 |
| 101                | 1.76278 | 0.36392 | 1.54325 | 0.3906   | 0.23582 | 151                | 2.63545 | 0.74962 | 1.93630 | 1.0753   | 0.38714 |
| 102                | 1.78024 | 0.37068 | 1.55429 | 0.4010   | 0.23849 | 152                | 2.65290 | 0.75808 | 1.94059 | 1.0917   | 0.39064 |
| 103                | 1.79769 | 0.37749 | 1.56522 | 0.4117   | 0.24117 | 153                | 2.67035 | 0.76655 | 1.94474 | 1.1082   | 0.39417 |
| 104                | 1.81514 | 0.38434 | 1.57602 | 0.4224   | 0.24387 | 154                | 2.68781 | 0.77505 | 1.94874 | 1.1247   | 0.39772 |
| 105                | 1.83260 | 0.39124 | 1.58671 | 0.4333   | 0.24657 | 155                | 2.70526 | 0.78356 | 1.95259 | 1.1413   | 0.40129 |
| 106                | 1.85005 | 0.39818 | 1.59727 | 0.4444   | 0.24929 | 156                | 2.72271 | 0.79209 | 1.95630 | 1.1580   | 0.40489 |
| 107                | 1.86750 | 0.40518 | 1.60771 | 0.4556   | 0.25202 | 157                | 2.74017 | 0.80063 | 1.95985 | 1.1747   | 0.40852 |
| 108                | 1.88496 | 0.41221 | 1.61803 | 0.4669   | 0.25476 | 158                | 2.75762 | 0.80919 | 1.96325 | 1.1915   | 0.41217 |
| 109                | 1.90241 | 0.41930 | 1.62823 | 0.4784   | 0.25752 | 159                | 2.77507 | 0.81776 | 1.96651 | 1.2084   | 0.41585 |
| 110                | 1.91986 | 0.42642 | 1.63830 | 0.4901   | 0.26028 | 160                | 2.79253 | 0.82635 | 1.96962 | 1.2253   | 0.41955 |
| 111                | 1.93732 | 0.43359 | 1.64825 | 0.5019   | 0.26306 | 161                | 2.80998 | 0.83495 | 1.97257 | 1.2422   | 0.42328 |
| 112                | 1.95477 | 0.44081 | 1.65808 | 0.5138   | 0.26585 | 162                | 2.82743 | 0.84357 | 1.97538 | 1.2592   | 0.42704 |
| 113                | 1.97222 | 0.44806 | 1.66777 | 0.5259   | 0.26866 | 163                | 2.84489 | 0.85219 | 1.97803 | 1.2763   | 0.43083 |
| 114                | 1.98968 | 0.45536 | 1.67734 | 0.5381   | 0.27148 | 164                | 2.86234 | 0.86083 | 1.98054 | 1.2934   | 0.43464 |
| 115                | 2.00713 | 0.46270 | 1.68678 | 0.5504   | 0.27431 | 165                | 2.87979 | 0.86947 | 1.98289 | 1.3105   | 0.43849 |
| 116                | 2.02458 | 0.47008 | 1.69610 | 0.5629   | 0.27715 | 166                | 2.89725 | 0.87813 | 1.98509 | 1.3277   | 0.44236 |
| 117                | 2.04204 | 0.47750 | 1.70528 | 0.5755   | 0.28001 | 167                | 2.91470 | 0.88680 | 1.98714 | 1.3449   | 0.44627 |
| 118                | 2.05949 | 0.48496 | 1.71433 | 0.5883   | 0.28289 | 168                | 2.93215 | 0.89547 | 1.98904 | 1.3621   | 0.45020 |
| 119                | 2.07694 | 0.49246 | 1.72326 | 0.6012   | 0.28577 | 169                | 2.94961 | 0.90415 | 1.99079 | 1.3794   | 0.45417 |
| 120                | 2.09440 | 0.50000 | 1.73205 | 0.6142   | 0.28868 | 170                | 2.96706 | 0.91284 | 1.99239 | 1.3967   | 0.45817 |
| 121                | 2.11185 | 0.50758 | 1.74071 | 0.6273   | 0.29159 | 171                | 2.98451 | 0.92154 | 1.99383 | 1.4140   | 0.46220 |
| 122                | 2.12930 | 0.51519 | 1.74924 | 0.6406   | 0.29452 | 172                | 3.00197 | 0.93024 | 1.99513 | 1.4314   | 0.46626 |
| 123                | 2.14675 | 0.52284 | 1.75763 | 0.6540   | 0.29747 | 173                | 3.01942 | 0.93895 | 1.99627 | 1.4488   | 0.47035 |
| 124                | 2.16421 | 0.53053 | 1.76590 | 0.6676   | 0.30043 | 174                | 3.03687 | 0.94766 | 1.99726 | 1.4662   | 0.47448 |
| 125                | 2.18166 | 0.53825 | 1.77402 | 0.6813   | 0.30341 | 175                | 3.05433 | 0.95638 | 1.99810 | 1.4836   | 0.47865 |
| 126                | 2.19911 | 0.54601 | 1.78201 | 0.6950   | 0.30640 | 176                | 3.07178 | 0.96510 | 1.99878 | 1.5010   | 0.48284 |
| 127                | 2.21657 | 0.55380 | 1.78987 | 0.7090   | 0.30941 | 177                | 3.08923 | 0.97382 | 1.99931 | 1.5184   | 0.48708 |
| 128                | 2.23402 | 0.56163 | 1.79759 | 0.7230   | 0.31243 | 178                | 3.10669 | 0.98255 | 1.99970 | 1.5359   | 0.49135 |
| 129                | 2.25147 | 0.56949 | 1.80517 | 0.7372   | 0.31548 | 179                | 3.12414 | 0.99127 | 1.99992 | 1.5533   | 0.49566 |
| 130                | 2.26893 | 0.57738 | 1.81262 | 0.7514   | 0.31854 | 180                | 3.14159 | 1.00000 | 2.00000 | 1.5708   | 0.50000 |

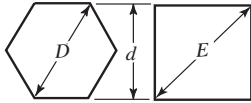
## Diameters of Circles and Sides of Squares of Equal Area



The table below will be found useful for determining the diameter of a circle of an area equal to that of a square, the side of which is known, or for determining the side of a square which has an area equal to that of a circle, the area or diameter of which is known. For example, if the diameter of a circle is  $17\frac{1}{2}$  inches, it is found from the table that the side of a square of the same area is 15.51 inches.

| Diam. of Circle, $D$ | Side of Square, $S$ | Area of Circle or Square | Diam. of Circle, $D$ | Side of Square, $S$ | Area of Circle or Square | Diam. of Circle, $D$ | Side of Square, $S$ | Area of Circle or Square |
|----------------------|---------------------|--------------------------|----------------------|---------------------|--------------------------|----------------------|---------------------|--------------------------|
| $\frac{1}{2}$        | 0.44                | 0.196                    | $20\frac{1}{2}$      | 18.17               | 330.06                   | $40\frac{1}{2}$      | 35.89               | 1288.25                  |
| 1                    | 0.89                | 0.785                    | 21                   | 18.61               | 346.36                   | 41                   | 36.34               | 1320.25                  |
| $1\frac{1}{2}$       | 1.33                | 1.767                    | $21\frac{1}{2}$      | 19.05               | 363.05                   | $41\frac{1}{2}$      | 36.78               | 1352.65                  |
| 2                    | 1.77                | 3.142                    | 22                   | 19.50               | 380.13                   | 42                   | 37.22               | 1385.44                  |
| $2\frac{1}{2}$       | 2.22                | 4.909                    | $22\frac{1}{2}$      | 19.94               | 397.61                   | $42\frac{1}{2}$      | 37.66               | 1418.63                  |
| 3                    | 2.66                | 7.069                    | 23                   | 20.38               | 415.48                   | 43                   | 38.11               | 1452.20                  |
| $3\frac{1}{2}$       | 3.10                | 9.621                    | $23\frac{1}{2}$      | 20.83               | 433.74                   | $43\frac{1}{2}$      | 38.55               | 1486.17                  |
| 4                    | 3.54                | 12.566                   | 24                   | 21.27               | 452.39                   | 44                   | 38.99               | 1520.53                  |
| $4\frac{1}{2}$       | 3.99                | 15.904                   | $24\frac{1}{2}$      | 21.71               | 471.44                   | $44\frac{1}{2}$      | 39.44               | 1555.28                  |
| 5                    | 4.43                | 19.635                   | 25                   | 22.16               | 490.87                   | 45                   | 39.88               | 1590.43                  |
| $5\frac{1}{2}$       | 4.87                | 23.758                   | $25\frac{1}{2}$      | 22.60               | 510.71                   | $45\frac{1}{2}$      | 40.32               | 1625.97                  |
| 6                    | 5.32                | 28.274                   | 26                   | 23.04               | 530.93                   | 46                   | 40.77               | 1661.90                  |
| $6\frac{1}{2}$       | 5.76                | 33.183                   | $26\frac{1}{2}$      | 23.49               | 551.55                   | $46\frac{1}{2}$      | 41.21               | 1698.23                  |
| 7                    | 6.20                | 38.485                   | 27                   | 23.93               | 572.56                   | 47                   | 41.65               | 1734.94                  |
| $7\frac{1}{2}$       | 6.65                | 44.179                   | $27\frac{1}{2}$      | 24.37               | 593.96                   | $47\frac{1}{2}$      | 42.10               | 1772.05                  |
| 8                    | 7.09                | 50.265                   | 28                   | 24.81               | 615.75                   | 48                   | 42.54               | 1809.56                  |
| $8\frac{1}{2}$       | 7.53                | 56.745                   | $28\frac{1}{2}$      | 25.26               | 637.94                   | $48\frac{1}{2}$      | 42.98               | 1847.45                  |
| 9                    | 7.98                | 63.617                   | 29                   | 25.70               | 660.52                   | 49                   | 43.43               | 1885.74                  |
| $9\frac{1}{2}$       | 8.42                | 70.882                   | $29\frac{1}{2}$      | 26.14               | 683.49                   | $49\frac{1}{2}$      | 43.87               | 1924.42                  |
| 10                   | 8.86                | 78.540                   | 30                   | 26.59               | 706.86                   | 50                   | 44.31               | 1963.50                  |
| $10\frac{1}{2}$      | 9.31                | 86.590                   | $30\frac{1}{2}$      | 27.03               | 730.62                   | $50\frac{1}{2}$      | 44.75               | 2002.96                  |
| 11                   | 9.75                | 95.033                   | 31                   | 27.47               | 754.77                   | 51                   | 45.20               | 2042.82                  |
| $11\frac{1}{2}$      | 10.19               | 103.87                   | $31\frac{1}{2}$      | 27.92               | 779.31                   | $51\frac{1}{2}$      | 45.64               | 2083.07                  |
| 12                   | 10.63               | 113.10                   | 32                   | 28.36               | 804.25                   | 52                   | 46.08               | 2123.72                  |
| $12\frac{1}{2}$      | 11.08               | 122.72                   | $32\frac{1}{2}$      | 28.80               | 829.58                   | $52\frac{1}{2}$      | 46.53               | 2164.75                  |
| 13                   | 11.52               | 132.73                   | 33                   | 29.25               | 855.30                   | 53                   | 46.97               | 2206.18                  |
| $13\frac{1}{2}$      | 11.96               | 143.14                   | $33\frac{1}{2}$      | 29.69               | 881.41                   | $53\frac{1}{2}$      | 47.41               | 2248.01                  |
| 14                   | 12.41               | 153.94                   | 34                   | 30.13               | 907.92                   | 54                   | 47.86               | 2290.22                  |
| $14\frac{1}{2}$      | 12.85               | 165.13                   | $34\frac{1}{2}$      | 30.57               | 934.82                   | $54\frac{1}{2}$      | 48.30               | 2332.83                  |
| 15                   | 13.29               | 176.71                   | 35                   | 31.02               | 962.11                   | 55                   | 48.74               | 2375.83                  |
| $15\frac{1}{2}$      | 13.74               | 188.69                   | $35\frac{1}{2}$      | 31.46               | 989.80                   | $55\frac{1}{2}$      | 49.19               | 2419.22                  |
| 16                   | 14.18               | 201.06                   | 36                   | 31.90               | 1017.88                  | 56                   | 49.63               | 2463.01                  |
| $16\frac{1}{2}$      | 14.62               | 213.82                   | $36\frac{1}{2}$      | 32.35               | 1046.35                  | $56\frac{1}{2}$      | 50.07               | 2507.19                  |
| 17                   | 15.07               | 226.98                   | 37                   | 32.79               | 1075.21                  | 57                   | 50.51               | 2551.76                  |
| $17\frac{1}{2}$      | 15.51               | 240.53                   | $37\frac{1}{2}$      | 33.23               | 1104.47                  | $57\frac{1}{2}$      | 50.96               | 2596.72                  |
| 18                   | 15.95               | 254.47                   | 38                   | 33.68               | 1134.11                  | 58                   | 51.40               | 2642.08                  |
| $18\frac{1}{2}$      | 16.40               | 268.80                   | $38\frac{1}{2}$      | 34.12               | 1164.16                  | $58\frac{1}{2}$      | 51.84               | 2687.83                  |
| 19                   | 16.84               | 283.53                   | 39                   | 34.56               | 1194.59                  | 59                   | 52.29               | 2733.97                  |
| $19\frac{1}{2}$      | 17.28               | 298.65                   | $39\frac{1}{2}$      | 35.01               | 1225.42                  | $59\frac{1}{2}$      | 52.73               | 2780.51                  |
| 20                   | 17.72               | 314.16                   | 40                   | 35.45               | 1256.64                  | 60                   | 53.17               | 2827.43                  |

**Distance Across Corners of Squares and Hexagons.**—The table below gives values of dimensions  $D$  and  $E$  described in the figures and equations that follow.



$$D = \frac{2\sqrt{3}}{3}d = 1.154701d$$

$$E = d\sqrt{2} = 1.414214d$$

A desired value not given directly in the table can be obtained directly from the equations above, or by the simple addition of two or more values taken directly from the table. Further values can be obtained by shifting the decimal point.

*Example 1:* Find  $D$  when  $d = 2 \frac{5}{16}$  inches. From the table,  $2 = 2.3094$ , and  $\frac{5}{16} = 0.3608$ . Therefore,  $D = 2.3094 + 0.3608 = 2.6702$  inches.

*Example 2:* Find  $E$  when  $d = 20.25$  millimeters. From the table,  $20 = 28.2843$ ;  $0.2 = 0.2828$ ; and  $0.05 = 0.0707$  (obtained by shifting the decimal point one place to the left at  $= 0.5$ ). Thus,  $E = 28.2843 + 0.2828 + 0.0707 = 28.6378$  millimeters.

### Distance Across Corners of Squares and Hexagons (English and metric units)

| $d$             | $D$    | $E$    | $d$             | $D$     | $E$     | $d$ | $D$     | $E$     | $d$ | $D$     | $E$     |
|-----------------|--------|--------|-----------------|---------|---------|-----|---------|---------|-----|---------|---------|
| $\frac{1}{32}$  | 0.0361 | 0.0442 | 0.9             | 1.0392  | 1.2728  | 32  | 36.9504 | 45.2548 | 67  | 77.3650 | 94.7523 |
| $\frac{1}{16}$  | 0.0722 | 0.0884 | $\frac{29}{32}$ | 1.0464  | 1.2816  | 33  | 38.1051 | 46.6691 | 68  | 78.5197 | 96.1666 |
| $\frac{3}{32}$  | 0.1083 | 0.1326 | $\frac{15}{16}$ | 1.0825  | 1.3258  | 34  | 39.2598 | 48.0833 | 69  | 79.6744 | 97.5808 |
| 0.1             | 0.1155 | 0.1414 | $\frac{31}{32}$ | 1.1186  | 1.3700  | 35  | 40.4145 | 49.4975 | 70  | 80.8291 | 98.9950 |
| $\frac{1}{8}$   | 0.1443 | 0.1768 | 1.0             | 1.1547  | 1.4142  | 36  | 41.5692 | 50.9117 | 71  | 81.9838 | 100.409 |
| $\frac{5}{32}$  | 0.1804 | 0.2210 | 2.0             | 2.3094  | 2.8284  | 37  | 42.7239 | 52.3259 | 72  | 83.1385 | 101.823 |
| $\frac{3}{16}$  | 0.2165 | 0.2652 | 3.0             | 3.4641  | 4.2426  | 38  | 43.8786 | 53.7401 | 73  | 84.2932 | 103.238 |
| 0.2             | 0.2309 | 0.2828 | 4.0             | 4.6188  | 5.6569  | 39  | 45.0333 | 55.1543 | 74  | 85.4479 | 104.652 |
| $\frac{7}{32}$  | 0.2526 | 0.3094 | 5.0             | 5.7735  | 7.0711  | 40  | 46.1880 | 56.5686 | 75  | 86.6026 | 106.066 |
| $\frac{1}{4}$   | 0.2887 | 0.3536 | 6.0             | 6.9282  | 8.4853  | 41  | 47.3427 | 57.9828 | 76  | 87.7573 | 107.480 |
| $\frac{9}{32}$  | 0.3248 | 0.3977 | 7.0             | 8.0829  | 9.8995  | 42  | 48.4974 | 59.3970 | 77  | 88.9120 | 108.894 |
| 0.3             | 0.3464 | 0.4243 | 8.0             | 9.2376  | 11.3137 | 43  | 49.6521 | 60.8112 | 78  | 90.0667 | 110.309 |
| $\frac{5}{16}$  | 0.3608 | 0.4419 | 9.0             | 10.3923 | 12.7279 | 44  | 50.8068 | 62.2254 | 79  | 91.2214 | 111.723 |
| $\frac{11}{32}$ | 0.3969 | 0.4861 | 10              | 11.5470 | 14.1421 | 45  | 51.9615 | 63.6396 | 80  | 92.3761 | 113.137 |
| $\frac{3}{8}$   | 0.4330 | 0.5303 | 11              | 12.7017 | 15.5564 | 46  | 53.1162 | 65.0538 | 81  | 93.5308 | 114.551 |
| 0.4             | 0.4619 | 0.5657 | 12              | 13.8564 | 16.9706 | 47  | 54.2709 | 66.4681 | 82  | 94.6855 | 115.966 |
| $\frac{13}{32}$ | 0.4691 | 0.5745 | 13              | 15.0111 | 18.3848 | 48  | 55.4256 | 67.8823 | 83  | 95.8402 | 117.380 |
| $\frac{7}{16}$  | 0.5052 | 0.6187 | 14              | 16.1658 | 19.7990 | 49  | 56.5803 | 69.2965 | 84  | 96.9949 | 118.794 |
| $\frac{15}{32}$ | 0.5413 | 0.6629 | 15              | 17.3205 | 21.2132 | 50  | 57.7351 | 70.7107 | 85  | 98.1496 | 120.208 |
| 0.5             | 0.5774 | 0.7071 | 16              | 18.4752 | 22.6274 | 51  | 58.8898 | 72.1249 | 86  | 99.3043 | 121.622 |
| $\frac{17}{32}$ | 0.6134 | 0.7513 | 17              | 19.6299 | 24.0416 | 52  | 60.0445 | 73.5391 | 87  | 100.459 | 123.037 |
| $\frac{9}{16}$  | 0.6495 | 0.7955 | 18              | 20.7846 | 25.4559 | 53  | 61.1992 | 74.9533 | 88  | 101.614 | 124.451 |
| $\frac{19}{32}$ | 0.6856 | 0.8397 | 19              | 21.9393 | 26.8701 | 54  | 62.3539 | 76.3676 | 89  | 102.768 | 125.865 |
| 0.6             | 0.6928 | 0.8485 | 20              | 23.0940 | 28.2843 | 55  | 63.5086 | 77.7818 | 90  | 103.923 | 127.279 |
| $\frac{5}{8}$   | 0.7217 | 0.8839 | 21              | 24.2487 | 29.6985 | 56  | 64.6633 | 79.1960 | 91  | 105.078 | 128.693 |
| $\frac{21}{32}$ | 0.7578 | 0.9281 | 22              | 25.4034 | 31.1127 | 57  | 65.8180 | 80.6102 | 92  | 106.232 | 130.108 |
| $\frac{11}{16}$ | 0.7939 | 0.9723 | 23              | 26.5581 | 32.5269 | 58  | 66.9727 | 82.0244 | 93  | 107.387 | 131.522 |
| 0.7             | 0.8083 | 0.9899 | 24              | 27.7128 | 33.9411 | 59  | 68.1274 | 83.4386 | 94  | 108.542 | 132.936 |
| $\frac{23}{32}$ | 0.8299 | 1.0165 | 25              | 28.8675 | 35.3554 | 60  | 69.2821 | 84.8528 | 95  | 109.697 | 134.350 |
| $\frac{3}{4}$   | 0.8660 | 1.0607 | 26              | 30.0222 | 36.7696 | 61  | 70.4368 | 86.2671 | 96  | 110.851 | 135.765 |
| $\frac{25}{32}$ | 0.9021 | 1.1049 | 27              | 31.1769 | 38.1838 | 62  | 71.5915 | 87.6813 | 97  | 112.006 | 137.179 |
| 0.8             | 0.9238 | 1.1314 | 28              | 32.3316 | 39.5980 | 63  | 72.7462 | 89.0955 | 98  | 113.161 | 138.593 |
| $\frac{13}{16}$ | 0.9382 | 1.1490 | 29              | 33.4863 | 41.0122 | 64  | 73.9009 | 90.5097 | 99  | 114.315 | 140.007 |
| $\frac{27}{32}$ | 0.9743 | 1.1932 | 30              | 34.6410 | 42.4264 | 65  | 75.0556 | 91.9239 | 100 | 115.470 | 141.421 |
| $\frac{7}{8}$   | 1.0104 | 1.2374 | 31              | 35.7957 | 43.8406 | 66  | 76.2103 | 93.3381 | ... | ...     | ...     |

## Volumes of Solids

## Cube:



$$\text{Diagonal of cube face} = d = s\sqrt{2}$$

$$\text{Diagonal of cube} = D = \sqrt{3d^2} = s\sqrt{3} = 1.732s$$

$$\text{Volume} = V = s^3$$

$$s = \sqrt[3]{V}$$

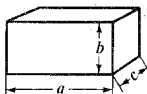
*Example:* The side of a cube equals 9.5 centimeters. Find its volume.

$$\text{Volume} = V = s^3 = 9.5^3 = 9.5 \times 9.5 \times 9.5 = 857.375 \text{ cubic centimeters}$$

*Example:* The volume of a cube is 231 cubic centimeters. What is the length of the side?

$$s = \sqrt[3]{V} = \sqrt[3]{231} = 6.136 \text{ centimeters}$$

## Square Prism:



$$\text{Volume} = V = abc$$

$$a = \frac{V}{bc} \quad b = \frac{V}{ac} \quad c = \frac{V}{ab}$$

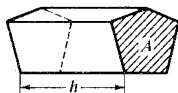
*Example:* In a square prism,  $a = 6$ ,  $b = 5$ ,  $c = 4$ . Find the volume.

$$V = a \times b \times c = 6 \times 5 \times 4 = 120 \text{ cubic inches}$$

*Example:* How high should a box be made to contain 25 cubic feet, if it is 4 feet long and  $2\frac{1}{2}$  feet wide? Here,  $a = 4$ ,  $c = 2.5$ , and  $V = 25$ . Then,

$$b = \text{depth} = \frac{V}{ac} = \frac{25}{4 \times 2.5} = \frac{25}{10} = 2.5 \text{ feet}$$

## Prism:



$$V = \text{volume}$$

$$A = \text{area of end surface}$$

$$V = h \times A$$

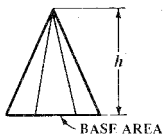
The area  $A$  of the end surface is found by the formulas for areas of plane figures on the preceding pages. Height  $h$  must be measured perpendicular to the end surface.

*Example:* A prism, having for its base a regular hexagon with a side  $s$  of 7.5 centimeters, is 25 centimeters high. Find the volume.

$$\text{Area of hexagon} = A = 2.598s^2 = 2.598 \times 56.25 = 146.14 \text{ square centimeters}$$

$$\text{Volume of prism} = h \times A = 25 \times 146.14 = 3653.5 \text{ cubic centimeters}$$

## Pyramid:



$$\text{Volume} = V = \frac{1}{3}h \times \text{area of base}$$

If the base is a regular polygon with  $n$  sides, and  $s =$  length of side,  $r =$  radius of inscribed circle, and  $R =$  radius of circumscribed circle, then:

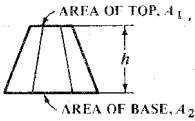
$$V = \frac{nsrh}{6} = \frac{ns}{6} \sqrt{R^2 - \frac{s^2}{4}}$$

*Example:* A pyramid, having a height of 9 feet, has a base formed by a rectangle, the sides of which are 2 and 3 feet, respectively. Find the volume.

$$\text{Area of base} = 2 \times 3 = 6 \text{ square feet; } h = 9 \text{ feet}$$

$$\text{Volume} = V = \frac{1}{3}h \times \text{area of base} = \frac{1}{3} \times 9 \times 6 = 18 \text{ cubic feet}$$



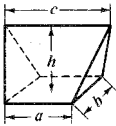
*Frustum of Pyramid:*

$$\text{Volume} = V = \frac{h}{3}(A_1 + A_2 + \sqrt{A_1 \times A_2})$$

*Example:* The pyramid in the previous example is cut off  $4\frac{1}{2}$  feet from the base, the upper part being removed. The sides of the rectangle forming the top surface of the frustum are, then, 1 and  $1\frac{1}{2}$  feet long, respectively. Find the volume of the frustum.

$$\text{Area of top} = A_1 = 1 \times 1\frac{1}{2} = 1\frac{1}{2} \text{ sq. ft.} \quad \text{Area of base} = A_2 = 2 \times 3 = 6 \text{ sq. ft.}$$

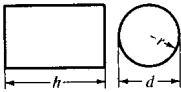
$$V = \frac{4.5}{3}(1.5 + 6 + \sqrt{1.5 \times 6}) = 1.5(7.5 + \sqrt{9}) = 1.5 \times 10.5 = 15.75 \text{ cubic feet}$$

*Wedge:*

$$\text{Volume} = V = \frac{(2a + c)bh}{6}$$

*Example:* Let  $a = 4$  inches,  $b = 3$  inches, and  $c = 5$  inches. The height  $h = 4.5$  inches. Find the volume.

$$V = \frac{(2a + c)bh}{6} = \frac{(2 \times 4 + 5) \times 3 \times 4.5}{6} = \frac{(8 + 5) \times 13.5}{6} \\ = \frac{175.5}{6} = 29.25 \text{ cubic inches}$$

*Cylinder:*

$$\text{Volume} = V = 3.1416r^2h = 0.7854d^2h$$

$$\text{Area of cylindrical surface} = S = 6.2832rh = 3.1416dh$$

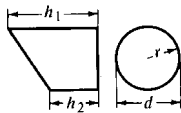
Total area  $A$  of cylindrical surface and end surfaces:

$$A = 6.2832r(r + h) = 3.1416d(\frac{1}{2}d + h)$$

*Example:* The diameter of a cylinder is 2.5 inches. The length or height is 20 inches. Find the volume and the area of the cylindrical surface  $S$ .

$$V = 0.7854d^2h = 0.7854 \times 2.5^2 \times 20 = 0.7854 \times 6.25 \times 20 = 98.17 \text{ cubic inches}$$

$$S = 3.1416dh = 3.1416 \times 2.5 \times 20 = 157.08 \text{ square inches}$$

*Portion of Cylinder:*

$$\text{Volume} = V = 1.5708r^2(h_1 + h_2)$$

$$= 0.3927d^2(h_1 + h_2)$$

$$\text{Cylindrical surface area} = S = 3.1416r(h_1 + h_2)$$

$$= 1.5708d(h_1 + h_2)$$

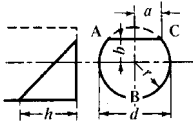
*Example:* A cylinder 125 millimeters in diameter is cut off at an angle, as shown in the illustration. Dimension  $h_1 = 150$ , and  $h_2 = 100$  mm. Find the volume and the area  $S$  of the cylindrical surface.

$$V = 0.3927d^2(h_1 + h_2) = 0.3927 \times 125^2 \times (150 + 100)$$

$$= 0.3927 \times 15,625 \times 250 = 1,533,984 \text{ cubic millimeters} = 1534 \text{ cm}^3$$

$$S = 1.5708d(h_1 + h_2) = 1.5708 \times 125 \times 250$$

$$= 49,087.5 \text{ square millimeters} = 490.9 \text{ square centimeters}$$

*Portion of Cylinder:*

$$\text{Volume} = V = \left(\frac{2}{3}a^3 \pm b \times \text{area } ABC\right) \frac{h}{r \pm b}$$

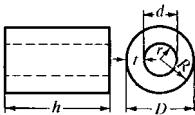
$$\text{Cylindrical surface area} = S = (ad \pm b \times \text{length of arc } ABC) \frac{h}{r \pm b}$$

Use + when base area is larger, and - when base area is less than one-half the base circle.

*Example:* Find the volume of a cylinder so cut off that line AC passes through the center of the base circle — that is, the base area is a half-circle. The diameter of the cylinder = 5 inches, and the height  $h = 2$  inches.

In this case,  $a = 2.5$ ;  $b = 0$ ;  $\text{area } ABC = 0.5 \times 0.7854 \times 5^2 = 9.82$ ;  $r = 2.5$ .

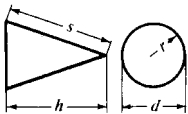
$$V = \left(\frac{2}{3} \times 2.5^3 + 0 \times 9.82\right) \frac{2}{2.5 + 0} = \frac{2}{3} \times 15.625 \times 0.8 = 8.33 \text{ cubic inches}$$

*Hollow Cylinder:*

$$\begin{aligned} \text{Volume} = V &= 3.1416h(R^2 - r^2) = 0.7854h(D^2 - d^2) \\ &= 3.1416ht(2R - t) = 3.1416ht(D - t) \\ &= 3.1416ht(2r + t) = 3.1416ht(d + t) \\ &= 3.1416ht(R + r) = 1.5708ht(D + d) \end{aligned}$$

*Example:* A cylindrical shell, 28 centimeters high, is 36 centimeters in outside diameter, and 4 centimeters thick. Find its volume.

$$\begin{aligned} V &= 3.1416ht(D - t) = 3.1416 \times 28 \times 4(36 - 4) = 3.1416 \times 28 \times 4 \times 32 \\ &= 11,259.5 \text{ cubic centimeters} \end{aligned}$$

*Cone:*

$$\text{Volume} = V = \frac{3.1416r^2h}{3} = 1.0472r^2h = 0.2618d^2h$$

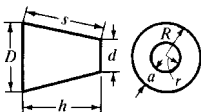
$$\begin{aligned} \text{Conical surface area} = A &= 3.1416r\sqrt{r^2 + h^2} = 3.1416rs \\ &= 1.5708ds \end{aligned}$$

$$s = \sqrt{r^2 + h^2} = \sqrt{\frac{d^2}{4} + h^2}$$

*Example:* Find the volume and area of the conical surface of a cone, the base of which is a circle of 6 inches diameter, and the height of which is 4 inches.

$$V = 0.2618d^2h = 0.2618 \times 6^2 \times 4 = 0.2618 \times 36 \times 4 = 37.7 \text{ cubic inches}$$

$$\begin{aligned} A &= 3.1416r\sqrt{r^2 + h^2} = 3.1416 \times 3 \times \sqrt{3^2 + 4^2} = 9.4248 \times \sqrt{25} \\ &= 47.124 \text{ square inches} \end{aligned}$$

*Frustum of Cone:*

$$V = \text{volume} \quad A = \text{area of conical surface}$$

$$V = 1.0472h(R^2 + Rr + r^2) = 0.2618h(D^2 + Dd + d^2)$$

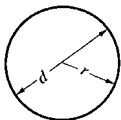
$$A = 3.1416s(R + r) = 1.5708s(D + d)$$

$$a = R - r \quad s = \sqrt{a^2 + h^2} = \sqrt{(R - r)^2 + h^2}$$

*Example:* Find the volume of a frustum of a cone of the following dimensions:  $D = 8$  centimeters;  $d = 4$  centimeters;  $h = 5$  centimeters.

$$\begin{aligned} V &= 0.2618 \times 5(8^2 + 8 \times 4 + 4^2) = 0.2618 \times 5(64 + 32 + 16) \\ &= 0.2618 \times 5 \times 112 = 146.61 \text{ cubic centimeters} \end{aligned}$$

## Sphere:



$$\text{Volume} = V = \frac{4\pi r^3}{3} = \frac{\pi d^3}{6} = 4.1888r^3 = 0.5236d^3$$

$$\text{Surface area} = A = 4\pi r^2 = \pi d^2 = 12.5664r^2 = 3.1416d^2$$

$$r = \sqrt[3]{\frac{3V}{4\pi}} = 0.6204\sqrt[3]{V}$$

*Example:* Find the volume and the surface of a sphere 6.5 centimeters diameter.

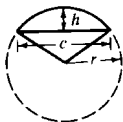
$$V = 0.5236d^3 = 0.5236 \times 6.5^3 = 0.5236 \times 6.5 \times 6.5 \times 6.5 = 143.79 \text{ cm}^3$$

$$A = 3.1416d^2 = 3.1416 \times 6.5^2 = 3.1416 \times 6.5 \times 6.5 = 132.73 \text{ cm}^2$$

*Example:* The volume of a sphere is 64 cubic centimeters. Find its radius.

$$r = 0.6204\sqrt[3]{64} = 0.6204 \times 4 = 2.4816 \text{ centimeters}$$

## Spherical Sector:



$$V = \frac{2\pi r^2 h}{3} = 2.0944r^2 h = \text{Volume}$$

$$A = 3.1416r(2h + \frac{1}{2}c)$$

= total area of conical and spherical surface

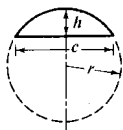
$$c = 2\sqrt{h(2r-h)}$$

*Example:* Find the volume of a sector of a sphere 6 inches in diameter, the height  $h$  of the sector being 1.5 inch. Also find the length of chord  $c$ . Here  $r = 3$  and  $h = 1.5$ .

$$V = 2.0944r^2 h = 2.0944 \times 3^2 \times 1.5 = 2.0944 \times 9 \times 1.5 = 28.27 \text{ cubic inches}$$

$$c = 2\sqrt{h(2r-h)} = 2\sqrt{1.5(2 \times 3 - 1.5)} = 2\sqrt{6.75} = 2 \times 2.598 = 5.196 \text{ inches}$$

## Spherical Segment:



$$V = \text{volume} \quad A = \text{area of spherical surface}$$

$$V = 3.1416h^2\left(r - \frac{h}{3}\right) = 3.1416h\left(\frac{c^2}{8} + \frac{h^2}{6}\right)$$

$$A = 2\pi rh = 6.2832rh = 3.1416\left(\frac{c^2}{4} + h^2\right)$$

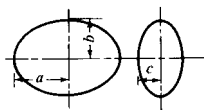
$$c = 2\sqrt{h(2r-h)}; \quad r = \frac{c^2 + 4h^2}{8h}$$

*Example:* A segment of a sphere has the following dimensions:  $h = 50$  millimeters;  $c = 125$  millimeters. Find the volume  $V$  and the radius of the sphere of which the segment is a part.

$$V = 3.1416 \times 50 \times \left(\frac{125^2}{8} + \frac{50^2}{6}\right) = 157.08 \times \left(\frac{15,625}{8} + \frac{2500}{6}\right) = 372,247 \text{ mm}^3 = 372 \text{ cm}^3$$

$$r = \frac{125^2 + 4 \times 50^2}{8 \times 50} = \frac{15,625 + 10,000}{400} = \frac{25,625}{400} = 64 \text{ millimeters}$$

## Ellipsoid:



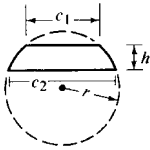
$$\text{Volume} = V = \frac{4\pi}{3}abc = 4.1888abc$$

In an ellipsoid of revolution, or spheroid, where  $c = b$ :

$$V = 4.1888ab^2$$

*Example:* Find the volume of a spheroid in which  $a = 5$ , and  $b = c = 1.5$  inches.

$$V = 4.1888 \times 5 \times 1.5^2 = 47.124 \text{ cubic inches}$$

**Spherical Zone:**

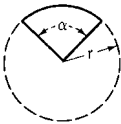
$$\text{Volume} = V = 0.5236h \left( \frac{3c_1^2}{4} + \frac{3c_2^2}{4} + h^2 \right)$$

$$A = 2\pi rh = 6.2832rh = \text{area of spherical surface}$$

$$r = \sqrt{\frac{c_2^2}{4} + \left( \frac{c_2^2 - c_1^2 - 4h^2}{8h} \right)^2}$$

*Example:* In a spherical zone, let  $c_1 = 3$ ;  $c_2 = 4$ ; and  $h = 1.5$  inch. Find the volume.

$$V = 0.5236 \times 1.5 \times \left( \frac{3 \times 3^2}{4} + \frac{3 \times 4^2}{4} + 1.5^2 \right) = 0.5236 \times 1.5 \times \left( \frac{27}{4} + \frac{48}{4} + 2.25 \right) = 16.493 \text{ in}^3$$

**Spherical Wedge:**

$$V = \text{volume} \quad A = \text{area of spherical surface}$$

$$\alpha = \text{center angle in degrees}$$

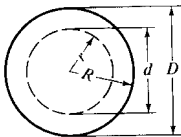
$$V = \frac{\alpha}{360} \times \frac{4\pi r^3}{3} = 0.0116\alpha r^3$$

$$A = \frac{\alpha}{360} \times 4\pi r^2 = 0.0349\alpha r^2$$

*Example:* Find the area of the spherical surface and the volume of a wedge of a sphere. The diameter of the sphere is 100 millimeters, and the center angle  $\alpha$  is 45 degrees.

$$V = 0.0116 \times 45 \times 50^3 = 0.0116 \times 45 \times 125,000 = 65,250 \text{ mm}^3 = 65.25 \text{ cm}^3$$

$$A = 0.0349 \times 45 \times 50^2 = 3926.25 \text{ square millimeters} = 39.26 \text{ cm}^2$$

**Hollow Sphere:**

$V =$  volume of material used  
to make a hollow sphere

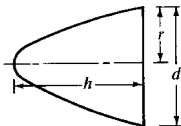
$$V = \frac{4\pi}{3}(R^3 - r^3) = 4.1888(R^3 - r^3)$$

$$= \frac{\pi}{6}(D^3 - d^3) = 0.5236(D^3 - d^3)$$

*Example:* Find the volume of a hollow sphere, 8 inches in outside diameter, with a thickness of material of 1.5 inch.

Here  $R = 4$ ;  $r = 4 - 1.5 = 2.5$ .

$$V = 4.1888(4^3 - 2.5^3) = 4.1888(64 - 15.625) = 4.1888 \times 48.375 = 202.63 \text{ cubic inches}$$

**Paraboloid:**

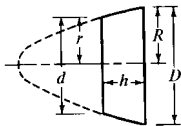
$$\text{Volume} = V = \frac{1}{2}\pi r^2 h = 0.3927d^2 h$$

$$\text{Area} = A = \frac{2\pi}{3} p \left[ \sqrt{\left( \frac{d^2}{4} + p^2 \right)^3} - p^3 \right]$$

$$\text{in which } p = \frac{d^2}{8h}$$

*Example:* Find the volume of a paraboloid in which  $h = 300$  millimeters and  $d = 125$  millimeters.

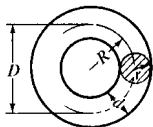
$$V = 0.3927d^2 h = 0.3927 \times 125^2 \times 300 = 1,840,781 \text{ mm}^3 = 1,840.8 \text{ cm}^3$$

*Paraboloidal Segment:*

$$\begin{aligned} \text{Volume} = V &= \frac{\pi}{2}h(R^2 + r^2) = 1.5708h(R^2 + r^2) \\ &= \frac{\pi}{8}h(D^2 + d^2) = 0.3927h(D^2 + d^2) \end{aligned}$$

*Example:* Find the volume of a segment of a paraboloid in which  $D = 5$  inches,  $d = 3$  inches, and  $h = 6$  inches.

$$\begin{aligned} V &= 0.3927h(D^2 + d^2) = 0.3927 \times 6 \times (5^2 + 3^2) \\ &= 0.3927 \times 6 \times 34 = 80.11 \text{ cubic inches} \end{aligned}$$

*Torus:*

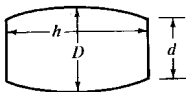
$$\begin{aligned} \text{Volume} = V &= 2\pi^2 Rr^2 = 19.739Rr^2 \\ &= \frac{\pi^2}{4}Dd^2 = 2.4674Dd^2 \end{aligned}$$

$$\begin{aligned} \text{Area of surface} = A &= 4\pi^2 Rr = 39.478Rr \\ &= \pi^2 Dd = 9.8696Dd \end{aligned}$$

*Example:* Find the volume and area of surface of a torus in which  $d = 1.5$  and  $D = 5$  inches.

$$V = 2.4674 \times 5 \times 1.5^2 = 2.4674 \times 5 \times 2.25 = 27.76 \text{ cubic inches}$$

$$A = 9.8696 \times 5 \times 1.5 = 74.022 \text{ square inches}$$

*Barrel:*

$V =$  approximate volume.

If the sides are bent to the arc of a circle:

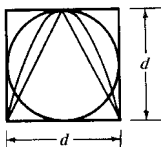
$$V = \frac{1}{12}\pi h(2D^2 + d^2) = 0.262h(2D^2 + d^2)$$

If the sides are bent to the arc of a parabola:

$$V = 0.209h(2D^2 + Dd + \frac{3}{4}d^2)$$

*Example:* Find the approximate contents of a barrel, the inside dimensions of which are  $D = 60$  centimeters,  $d = 50$  centimeters;  $h = 120$  centimeters.

$$\begin{aligned} V &= 0.262h(2D^2 + d^2) = 0.262 \times 120 \times (2 \times 60^2 + 50^2) \\ &= 0.262 \times 120 \times (7200 + 2500) = 0.262 \times 120 \times 9700 \\ &= 304,968 \text{ cubic centimeters} = 0.305 \text{ cubic meter} \end{aligned}$$

*Ratio of Volumes:*

If  $d =$  base diameter and height of a cone, a paraboloid and a cylinder, and the diameter of a sphere, then the volumes of these bodies are to each other as follows:

$$\text{Cone:paraboloid:sphere:cylinder} = \frac{1}{3} : \frac{1}{2} : \frac{2}{3} : 1$$

*Example:* Assume, as an example, that the diameter of the base of a cone, paraboloid, and cylinder is 2 inches, that the height is 2 inches, and that the diameter of a sphere is 2 inches. Then the volumes, written in formula form, are as follows:

$$\frac{\text{Cone}}{12} \times 2^2 \times 2 : \frac{\text{Paraboloid}}{8} \times (2p)^2 \times 2 : \frac{\text{Sphere}}{6} \times 2^3 : \frac{\text{Cylinder}}{4} \times 2^2 \times 2 = \frac{1}{3} : \frac{1}{2} : \frac{2}{3} : 1$$

## Packing Circles in Circles and Rectangles

**Diameter of Circle Enclosing a Given Number of Smaller Circles.**—Four of many possible compact arrangements of circles within a circle are shown at A, B, C, and D in Fig. 1. To determine the diameter of the smallest enclosing circle for a particular number of enclosed circles all of the same size, three factors that influence the size of the enclosing circle should be considered. These are discussed in the paragraphs that follow, which are based on the article "How Many Wires Can Be Packed into a Circular Conduit," by Jacques Dutka, *Machinery*, October 1956.

1) *Arrangement of Center or Core Circles:* The four most common arrangements of center or core circles are shown cross-sectioned in Fig. 1. It may seem, offhand, that the "A" pattern would require the smallest enclosing circle for a given number of enclosed circles but this is not always the case since the most compact arrangement will, in part, depend on the number of circles to be enclosed.

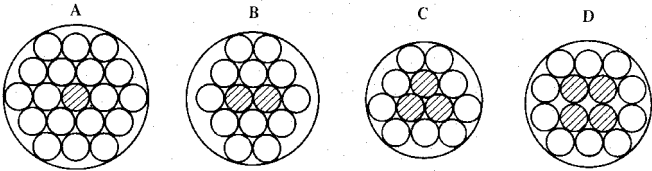


Fig. 1. Arrangements of Circles within a Circle

2) *Diameter of Enclosing Circle When Outer Layer of Circles Is Complete:* Successive, complete "layers" of circles may be placed around each of the central cores, Fig. 1, of 1, 2, 3, or 4 circles as the case may be. The number of circles contained in arrangements of complete "layers" around a central core of circles, as well as the diameter of the enclosing circle, may be obtained using the data in Table 1. Thus, for example, the "A" pattern in Fig. 1 shows, by actual count, a total of 19 circles arranged in two complete "layers" around a central core consisting of one circle; this agrees with the data shown in the left half of Table 1 for  $n = 2$ .

To determine the diameter of the enclosing circle, the data in the right half of Table 1 is used. Thus, for  $n = 2$  and an "A" pattern, the diameter  $D$  is 5 times the diameter  $d$  of the enclosed circles.

3) *Diameter of Enclosing Circle When Outer Layer of Circles Is Not Complete:* In most cases, it is possible to reduce the size of the enclosing circle from that required if the outer layer were complete. Thus, for example, the "B" pattern in Fig. 1 shows that the central core consisting of 2 circles is surrounded by 1 complete layer of 8 circles and 1 partial, outer layer of 4 circles, so that the total number of circles enclosed is 14. If the outer layer were complete, then (from Table 1) the total number of enclosed circles would be 24 and the diameter of the enclosing circle would be  $6d$ ; however, since the outer layer is composed of only 4 circles out of a possible 14 for a complete second layer, a smaller diameter of enclosing circle may be used. Table 2 shows that for a total of 14 enclosed circles arranged in a "B" pattern with the outer layer of circles incomplete, the diameter for the enclosing circle is  $4.606d$ .

Table 2 can be used to determine the smallest enclosing circle for a given number of circles to be enclosed by direct comparison of the "A," "B," and "C" columns. For data outside the range of Table 2, use the formulas in Dr. Dutka's article.

**Table 1. Number of Circles Contained in Complete Layers of Circles and Diameter of Enclosing Circle (English or metric units)**

| No. Complete Layers Over Core, <i>n</i> | Number of Circles in Center Pattern                   |          |          |   |             |             |                 |                 |
|---|---|----------|----------|---|-------------|-------------|-----------------|-----------------|
|   | 1   | 2        | 3        | 4   | 1           | 2           | 3               | 4               |
|   | Arrangement of Circles in Center Pattern (see Fig. 1) |          |          |   |             |             |                 |                 |
|   | "A"   | "B"      | "C"      | "D"   | "A"         | "B"         | "C"             | "D"             |
| Number of Circles, <i>N</i> , Enclosed  |   |          |          | Diameter, <i>D</i> , of Enclosing Circle <sup>a</sup> |             |             |                 |                 |
| 0                                       | 1   | 2        | 3        | 4   | <i>d</i>    | <i>2d</i>   | 2.155 <i>d</i>  | 2.414 <i>d</i>  |
| 1                                       | 7   | 10       | 12       | 14  | 3 <i>d</i>  | 4 <i>d</i>  | 4.055 <i>d</i>  | 4.386 <i>d</i>  |
| 2                                       | 19  | 24       | 27       | 30  | 5 <i>d</i>  | 6 <i>d</i>  | 6.033 <i>d</i>  | 6.379 <i>d</i>  |
| 3                                       | 37  | 44       | 48       | 52  | 7 <i>d</i>  | 8 <i>d</i>  | 8.024 <i>d</i>  | 8.375 <i>d</i>  |
| 4                                       | 61  | 70       | 75       | 80  | 9 <i>d</i>  | 10 <i>d</i> | 10.018 <i>d</i> | 10.373 <i>d</i> |
| 5                                       | 91  | 102      | 108      | 114   | 11 <i>d</i> | 12 <i>d</i> | 12.015 <i>d</i> | 12.372 <i>d</i> |
| <i>n</i>                                | <i>b</i>  | <i>b</i> | <i>b</i> | <i>b</i>  | <i>b</i>    | <i>b</i>    | <i>b</i>        | <i>b</i>        |

<sup>a</sup>Diameter *D* is given in terms of *d*, the diameter of the enclosed circles.

<sup>b</sup>For *n* complete layers over core, the number of enclosed circles *N* for the "A" center pattern is  $3n^2 + 3n + 1$ ; for "B,"  $3n^2 + 5n + 2$ ; for "C,"  $3n^2 + 6n + 3$ ; for "D,"  $3n^2 + 7n + 4$ . The diameter *D* of the enclosing circle for "A" center pattern is  $(2n + 1)d$ ; for "B,"  $(2n + 2)d$ ; for "C,"  $(1 + 2\sqrt{n^2 + n + \frac{1}{2}})d$  and for "D,"  $(1 + \sqrt{4n^2 + 5.644n + 2})d$ .

**Table 2. Factors for Determining Diameter, *D*, of Smallest Enclosing Circle for Various Numbers, *N*, of Enclosed Circles (English or metric units)**

| No. <i>N</i> | Center Circle Pattern    |       |       | No. <i>N</i> | Center Circle Pattern    |       |       | No. <i>N</i> | Center Circle Pattern    |        |        |
|--------------|--------------------------|-------|-------|--------------|--------------------------|-------|-------|--------------|--------------------------|--------|--------|
|              | "A"                      | "B"   | "C"   |              | "A"                      | "B"   | "C"   |              | "A"                      | "B"    | "C"    |
|              | Diameter Factor <i>K</i> |       |       |              | Diameter Factor <i>K</i> |       |       |              | Diameter Factor <i>K</i> |        |        |
| 2            | 3                        | 2     | ...   | 34           | 7.001                    | 7.083 | 7.111 | 66           | 9.718                    | 9.545  | 9.327  |
| 3            | 3                        | 2.733 | 2.155 | 35           | 7.001                    | 7.245 | 7.111 | 67           | 9.718                    | 9.545  | 9.327  |
| 4            | 3                        | 2.733 | 3.310 | 36           | 7.001                    | 7.245 | 7.111 | 68           | 9.718                    | 9.545  | 9.327  |
| 5            | 3                        | 3.646 | 3.310 | 37           | 7.001                    | 7.245 | 7.430 | 69           | 9.718                    | 9.661  | 9.327  |
| 6            | 3                        | 3.646 | 3.310 | 38           | 7.929                    | 7.245 | 7.430 | 70           | 9.718                    | 9.661  | 10.019 |
| 7            | 3                        | 3.646 | 4.056 | 39           | 7.929                    | 7.558 | 7.430 | 71           | 9.718                    | 9.889  | 10.019 |
| 8            | 4.465                    | 3.646 | 4.056 | 40           | 7.929                    | 7.558 | 7.430 | 72           | 9.718                    | 9.889  | 10.019 |
| 9            | 4.465                    | 4     | 4.056 | 41           | 7.929                    | 7.558 | 7.430 | 73           | 9.718                    | 9.889  | 10.019 |
| 10           | 4.465                    | 4     | 4.056 | 42           | 7.929                    | 7.558 | 7.430 | 74           | 10.166                   | 9.889  | 10.019 |
| 11           | 4.465                    | 4.606 | 4.056 | 43           | 7.929                    | 8.001 | 8.024 | 75           | 10.166                   | 10     | 10.019 |
| 12           | 4.465                    | 4.606 | 4.056 | 44           | 8.212                    | 8.001 | 8.024 | 76           | 10.166                   | 10     | 10.238 |
| 13           | 4.465                    | 4.606 | 5.164 | 45           | 8.212                    | 8.001 | 8.024 | 77           | 10.166                   | 10.540 | 10.238 |
| 14           | 5                        | 4.606 | 5.164 | 46           | 8.212                    | 8.001 | 8.024 | 78           | 10.166                   | 10.540 | 10.238 |
| 15           | 5                        | 5.359 | 5.164 | 47           | 8.212                    | 8.001 | 8.024 | 79           | 10.166                   | 10.540 | 10.452 |
| 16           | 5                        | 5.359 | 5.164 | 48           | 8.212                    | 8.001 | 8.024 | 80           | 10.166                   | 10.540 | 10.452 |
| 17           | 5                        | 5.359 | 5.164 | 49           | 8.212                    | 8.550 | 8.572 | 81           | 10.166                   | 10.540 | 10.452 |
| 18           | 5                        | 5.359 | 5.164 | 50           | 8.212                    | 8.550 | 8.572 | 82           | 10.166                   | 10.540 | 10.452 |
| 19           | 5                        | 5.583 | 5.619 | 51           | 8.212                    | 8.550 | 8.572 | 83           | 10.166                   | 10.540 | 10.452 |
| 20           | 6.292                    | 5.583 | 5.619 | 52           | 8.212                    | 8.550 | 8.572 | 84           | 10.166                   | 10.540 | 10.452 |
| 21           | 6.292                    | 5.583 | 5.619 | 53           | 8.212                    | 8.811 | 8.572 | 85           | 10.166                   | 10.644 | 10.866 |
| 22           | 6.292                    | 5.583 | 6.034 | 54           | 8.212                    | 8.811 | 8.572 | 86           | 11                       | 10.644 | 10.866 |
| 23           | 6.292                    | 6.001 | 6.034 | 55           | 8.212                    | 8.811 | 9.083 | 87           | 11                       | 10.644 | 10.866 |
| 24           | 6.292                    | 6.001 | 6.034 | 56           | 9.001                    | 8.811 | 9.083 | 88           | 11                       | 10.644 | 10.866 |
| 25           | 6.292                    | 6.197 | 6.034 | 57           | 9.001                    | 8.938 | 9.083 | 89           | 11                       | 10.849 | 10.866 |
| 26           | 6.292                    | 6.197 | 6.034 | 58           | 9.001                    | 8.938 | 9.083 | 90           | 11                       | 10.849 | 10.866 |
| 27           | 6.292                    | 6.568 | 6.034 | 59           | 9.001                    | 8.938 | 9.083 | 91           | 11                       | 10.849 | 11.067 |
| 28           | 6.292                    | 6.568 | 6.774 | 60           | 9.001                    | 8.938 | 9.083 | 92           | 11.393                   | 10.849 | 11.067 |
| 29           | 6.292                    | 6.568 | 6.774 | 61           | 9.001                    | 9.186 | 9.083 | 93           | 11.393                   | 11.149 | 11.067 |
| 30           | 6.292                    | 6.568 | 6.774 | 62           | 9.718                    | 9.186 | 9.083 | 94           | 11.393                   | 11.149 | 11.067 |
| 31           | 6.292                    | 7.083 | 7.111 | 63           | 9.718                    | 9.186 | 9.083 | 95           | 11.393                   | 11.149 | 11.067 |
| 32           | 7.001                    | 7.083 | 7.111 | 64           | 9.718                    | 9.186 | 9.327 | 96           | 11.393                   | 11.149 | 11.067 |
| 33           | 7.001                    | 7.083 | 7.111 | 65           | 9.718                    | 9.545 | 9.327 | 97           | 11.393                   | 11.441 | 11.264 |

**Table 2. (Continued) Factors for Determining Diameter,  $D$ , of Smallest Enclosing Circle for Various Numbers,  $N$ , of Enclosed Circles (English or metric units)**

| No.<br>$N$ | Center Circle Pattern |        |        | No.<br>$N$ | Center Circle Pattern |        |        | No.<br>$N$ | Center Circle Pattern |        |        |
|------------|-----------------------|--------|--------|------------|-----------------------|--------|--------|------------|-----------------------|--------|--------|
|            | "A"                   | "B"    | "C"    |            | "A"                   | "B"    | "C"    |            | "A"                   | "B"    | "C"    |
|            | Diameter Factor $K$   |        |        |            | Diameter Factor $K$   |        |        |            | Diameter Factor $K$   |        |        |
| 98         | 11.584                | 11.441 | 11.264 | 153        | 14.115                | 14     | 14.013 | 208        | 16.100                | 16     | 16.144 |
| 99         | 11.584                | 11.441 | 11.264 | 154        | 14.115                | 14     | 14.013 | 209        | 16.100                | 16.133 | 16.144 |
| 100        | 11.584                | 11.441 | 11.264 | 155        | 14.115                | 14.077 | 14.013 | 210        | 16.100                | 16.133 | 16.144 |
| 101        | 11.584                | 11.536 | 11.264 | 156        | 14.115                | 14.077 | 14.013 | 211        | 16.100                | 16.133 | 16.144 |
| 102        | 11.584                | 11.536 | 11.264 | 157        | 14.115                | 14.077 | 14.317 | 212        | 16.621                | 16.133 | 16.144 |
| 103        | 11.584                | 11.536 | 12.016 | 158        | 14.115                | 14.077 | 14.317 | 213        | 16.621                | 16.395 | 16.144 |
| 104        | 11.584                | 11.536 | 12.016 | 159        | 14.115                | 14.229 | 14.317 | 214        | 16.621                | 16.395 | 16.276 |
| 105        | 11.584                | 11.817 | 12.016 | 160        | 14.115                | 14.229 | 14.317 | 215        | 16.621                | 16.395 | 16.276 |
| 106        | 11.584                | 11.817 | 12.016 | 161        | 14.115                | 14.229 | 14.317 | 216        | 16.621                | 16.395 | 16.276 |
| 107        | 11.584                | 11.817 | 12.016 | 162        | 14.115                | 14.229 | 14.317 | 217        | 16.621                | 16.525 | 16.276 |
| 108        | 11.584                | 11.817 | 12.016 | 163        | 14.115                | 14.454 | 14.317 | 218        | 16.621                | 16.525 | 16.276 |
| 109        | 11.584                | 12     | 12.016 | 164        | 14.857                | 14.454 | 14.317 | 219        | 16.621                | 16.525 | 16.276 |
| 110        | 12.136                | 12     | 12.016 | 165        | 14.857                | 14.454 | 14.317 | 220        | 16.621                | 16.525 | 16.535 |
| 111        | 12.136                | 12.270 | 12.016 | 166        | 14.857                | 14.454 | 14.317 | 221        | 16.621                | 16.589 | 16.535 |
| 112        | 12.136                | 12.270 | 12.016 | 167        | 14.857                | 14.528 | 14.317 | 222        | 16.621                | 16.589 | 16.535 |
| 113        | 12.136                | 12.270 | 12.016 | 168        | 14.857                | 14.528 | 14.317 | 223        | 16.621                | 16.716 | 16.535 |
| 114        | 12.136                | 12.270 | 12.016 | 169        | 14.857                | 14.528 | 14.614 | 224        | 16.875                | 16.716 | 16.535 |
| 115        | 12.136                | 12.358 | 12.373 | 170        | 15                    | 14.528 | 14.614 | 225        | 16.875                | 16.716 | 16.535 |
| 116        | 12.136                | 12.358 | 12.373 | 171        | 15                    | 14.748 | 14.614 | 226        | 16.875                | 16.716 | 17.042 |
| 117        | 12.136                | 12.358 | 12.373 | 172        | 15                    | 14.748 | 14.614 | 227        | 16.875                | 16.716 | 17.042 |
| 118        | 12.136                | 12.358 | 12.373 | 173        | 15                    | 14.748 | 14.614 | 228        | 16.875                | 16.716 | 17.042 |
| 119        | 12.136                | 12.533 | 12.373 | 174        | 15                    | 14.748 | 14.614 | 229        | 16.875                | 16.716 | 17.042 |
| 120        | 12.136                | 12.533 | 12.373 | 175        | 15                    | 14.893 | 15.048 | 230        | 16.875                | 16.716 | 17.042 |
| 121        | 12.136                | 12.533 | 12.548 | 176        | 15                    | 14.893 | 15.048 | 231        | 16.875                | 17.094 | 17.042 |
| 122        | 13                    | 12.533 | 12.548 | 177        | 15                    | 14.893 | 15.048 | 232        | 16.875                | 17.094 | 17.166 |
| 123        | 13                    | 12.533 | 12.548 | 178        | 15                    | 14.893 | 15.048 | 233        | 16.875                | 17.094 | 17.166 |
| 124        | 13                    | 12.533 | 12.719 | 179        | 15                    | 15.107 | 15.048 | 234        | 16.875                | 17.094 | 17.166 |
| 125        | 13                    | 12.533 | 12.719 | 180        | 15                    | 15.107 | 15.048 | 235        | 16.875                | 17.094 | 17.166 |
| 126        | 13                    | 12.533 | 12.719 | 181        | 15                    | 15.107 | 15.190 | 236        | 17                    | 17.094 | 17.166 |
| 127        | 13                    | 12.790 | 12.719 | 182        | 15                    | 15.107 | 15.190 | 237        | 17                    | 17.094 | 17.166 |
| 128        | 13.166                | 12.790 | 12.719 | 183        | 15                    | 15.178 | 15.190 | 238        | 17                    | 17.094 | 17.166 |
| 129        | 13.166                | 12.790 | 12.719 | 184        | 15                    | 15.178 | 15.190 | 239        | 17                    | 17.463 | 17.166 |
| 130        | 13.166                | 12.790 | 13.056 | 185        | 15                    | 15.178 | 15.190 | 240        | 17                    | 17.463 | 17.166 |
| 131        | 13.166                | 13.125 | 13.056 | 186        | 15                    | 15.178 | 15.190 | 241        | 17                    | 17.463 | 17.290 |
| 132        | 13.166                | 13.125 | 13.056 | 187        | 15                    | 15.526 | 15.469 | 242        | 17.371                | 17.463 | 17.290 |
| 133        | 13.166                | 13.125 | 13.056 | 188        | 15.423                | 15.526 | 15.469 | 243        | 17.371                | 17.523 | 17.290 |
| 134        | 13.166                | 13.125 | 13.056 | 189        | 15.423                | 15.526 | 15.469 | 244        | 17.371                | 17.523 | 17.290 |
| 135        | 13.166                | 13.125 | 13.056 | 190        | 15.423                | 15.526 | 15.469 | 245        | 17.371                | 17.523 | 17.290 |
| 136        | 13.166                | 13.125 | 13.221 | 191        | 15.423                | 15.731 | 15.469 | 246        | 17.371                | 17.523 | 17.290 |
| 137        | 13.166                | 13.289 | 13.221 | 192        | 15.423                | 15.731 | 15.469 | 247        | 17.371                | 17.523 | 17.654 |
| 138        | 13.166                | 13.289 | 13.221 | 193        | 15.423                | 15.731 | 15.743 | 248        | 17.371                | 17.523 | 17.654 |
| 139        | 13.166                | 13.289 | 13.221 | 194        | 15.423                | 15.731 | 15.743 | 249        | 17.371                | 17.523 | 17.654 |
| 140        | 13.490                | 13.289 | 13.221 | 195        | 15.423                | 15.731 | 15.743 | 250        | 17.371                | 17.523 | 17.654 |
| 141        | 13.490                | 13.530 | 13.221 | 196        | 15.423                | 15.731 | 15.743 | 251        | 17.371                | 17.644 | 17.654 |
| 142        | 13.490                | 13.530 | 13.702 | 197        | 15.423                | 15.731 | 15.743 | 252        | 17.371                | 17.644 | 17.654 |
| 143        | 13.490                | 13.530 | 13.702 | 198        | 15.423                | 15.731 | 15.743 | 253        | 17.371                | 17.644 | 17.773 |
| 144        | 13.490                | 13.530 | 13.702 | 199        | 15.423                | 15.799 | 16.012 | 254        | 18.089                | 17.644 | 17.773 |
| 145        | 13.490                | 13.768 | 13.859 | 200        | 16.100                | 15.799 | 16.012 | 255        | 18.089                | 17.704 | 17.773 |
| 146        | 13.490                | 13.768 | 13.859 | 201        | 16.100                | 15.799 | 16.012 | 256        | 18.089                | 17.704 | 17.773 |
| 147        | 13.490                | 13.768 | 13.859 | 202        | 16.100                | 15.799 | 16.012 | 257        | 18.089                | 17.704 | 17.773 |
| 148        | 13.490                | 13.768 | 13.859 | 203        | 16.100                | 15.934 | 16.012 | 258        | 18.089                | 17.704 | 17.773 |
| 149        | 13.490                | 14     | 13.859 | 204        | 16.100                | 15.934 | 16.012 | 259        | 18.089                | 17.823 | 18.010 |
| 150        | 13.490                | 14     | 13.859 | 205        | 16.100                | 15.934 | 16.012 | 260        | 18.089                | 17.823 | 18.010 |
| 151        | 13.490                | 14     | 14.013 | 206        | 16.100                | 15.934 | 16.012 | 261        | 18.089                | 17.823 | 18.010 |
| 152        | 14.115                | 14     | 14.013 | 207        | 16.100                | 16     | 16.012 | 262        | 18.089                | 17.823 | 18.010 |



The diameter  $D$  of the enclosing circle is equal to the diameter factor,  $K$ , multiplied by  $d$ , the diameter of the enclosed circles, or  $D = K \times d$ . For example, if the number of circles to be enclosed,  $N$ , is 12, and the center circle arrangement is "C," then for  $d = 1\frac{1}{2}$  inches,  $D = 4.056 \times 1\frac{1}{2} = 6.084$  inches. If  $d = 50$  millimeters, then  $D = 4.056 \times 50 = 202.9$  millimeters.

*Approximate Formula When Number of Enclosed Circles Is Large:* When a large number of circles are to be enclosed, the arrangement of the center circles has little effect on the diameter of the enclosing circle. For numbers of circles greater than 10,000, the diameter of the enclosing circle may be calculated within 2 per cent from the formula  $D = d(1 + \sqrt{N \div 0.907})$ . In this formula,  $D$  = diameter of the enclosing circle;  $d$  = diameter of the enclosed circles; and  $N$  is the number of enclosed circles.

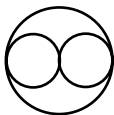
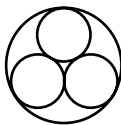
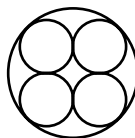
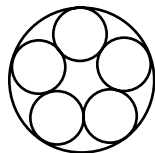
An alternative approach relates the area of each of the same-sized circles to be enclosed to the area of the enclosing circle (or container), as shown in Figs. 1 through 27. The table shows efficient ways for packing various numbers of circles  $N$ , from 2 up to 97.

In the table,  $D$  = the diameter of each circle to be enclosed,  $d$  = the diameter of the enclosing circle or container, and  $\Phi = Nd^2/D^2$  = ratio of the area of the  $N$  circles to the area of the enclosing circle or container, which is the packing efficiency. Cross-hatching in the diagrams indicates loose circles that may need packing constraints.

Data for Numbers of Circles in Circles

| $N$ | $D/d$  | $\Phi$ | Fig. | $N$ | $D/d$   | $\Phi$ | Fig. |
|-----|--------|--------|------|-----|---------|--------|------|
| 2   | 2.0000 | 0.500  | 1    | 17  | 4.7920  | 0.740  | 15   |
| 3   | 2.1547 | 0.646  | 2    | 18  | 4.8637  | 0.761  | 16   |
| 4   | 2.4142 | 0.686  | 3    | 19  | 4.8637  | 0.803  | 16   |
| 5   | 2.7013 | 0.685  | 4    | 20  | 5.1223  | 0.762  | 17   |
| 6   | 3.0000 | 0.667  | 5    | 21  | 5.2523  | 0.761  | 18   |
| 7   | 3.0000 | 0.778  | 5    | 22  | 5.4397  | 0.743  | 19   |
| 8   | 3.3048 | 0.733  | 6    | 23  | 5.5452  | 0.748  | 20   |
| 9   | 3.6131 | 0.689  | 7    | 24  | 5.6517  | 0.751  | 21   |
| 10  | 3.8130 | 0.688  | 8    | 25  | 5.7608  | 0.753  | 22   |
| 11  | 3.9238 | 0.714  | 9    | 31  | 6.2915  | 0.783  | 23   |
| 12  | 4.0296 | 0.739  | 10   | 37  | 6.7588  | 0.810  | 24   |
| 13  | 4.2361 | 0.724  | 11   | 55  | 8.2111  | 0.816  | 25   |
| 14  | 4.3284 | 0.747  | 12   | 61  | 8.6613  | 0.813  | 26   |
| 15  | 4.5214 | 0.734  | 13   | 97  | 11.1587 | 0.779  | 27   |
| 16  | 4.6154 | 0.751  | 14   | ... | ...     | ...    | ...  |

Packing of large numbers of circles, such as the 97 in Fig. 27, may be approached by drawing a triangular pattern of circles, as shown in Fig. 28, which represents three circles near the center of the array. The point of a compass is then placed at  $A$ ,  $B$ , or  $C$ , or anywhere within triangle  $ABC$ , and the radius of the compass is gradually enlarged until it encompasses the number of circles to be enclosed. As a first approximation of the diameter,  $D = 1.14d\sqrt{N}$  may be tried.

Fig. 1.  $N = 2$ Fig. 2.  $N = 3$ Fig. 3.  $N = 4$ Fig. 4.  $N = 5$

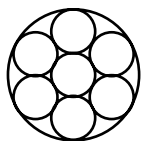
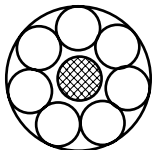
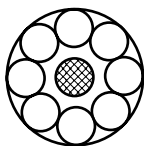
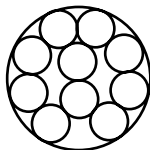
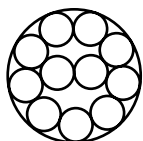
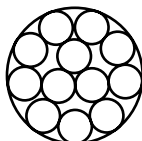
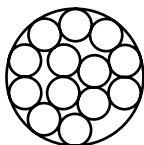
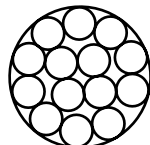
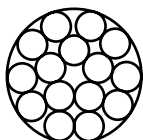
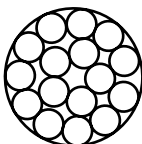
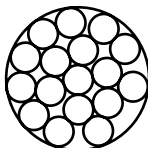
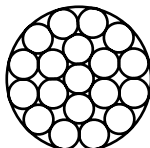
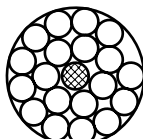
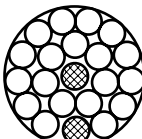
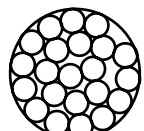
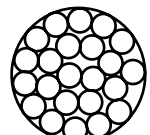
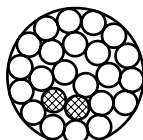
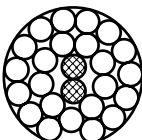
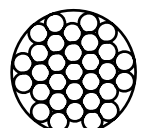
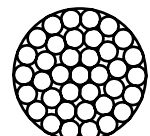
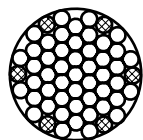
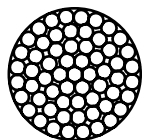
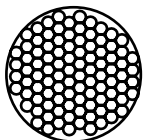
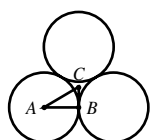
Fig. 5.  $N=7$ Fig. 6.  $N=8$ Fig. 7.  $N=9$ Fig. 8.  $N=10$ Fig. 9.  $N=11$ Fig. 10.  $N=12$ Fig. 11.  $N=13$ Fig. 12.  $N=14$ Fig. 13.  $N=15$ Fig. 14.  $N=16$ Fig. 15.  $N=17$ Fig. 16.  $N=19$ Fig. 17.  $N=20$ Fig. 18.  $N=21$ Fig. 19.  $N=22$ Fig. 20.  $N=23$ Fig. 21.  $N=24$ Fig. 22.  $N=25$ Fig. 23.  $N=31$ Fig. 24.  $N=37$ Fig. 25.  $N=55$ Fig. 26.  $N=61$ Fig. 27.  $N=97$ 

Fig. 28.

**Circles within Rectangles.**—For small numbers  $N$  of circles, packing (for instance, of cans) is less vital than for larger numbers and the number will usually govern the decision whether to use a rectangular or a triangular pattern, examples of which are seen in Figs. 29 and 30.

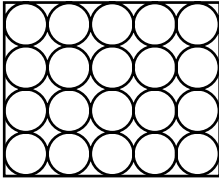


Fig. 29. Rectangular Pattern ( $r = 4, c = 5$ )

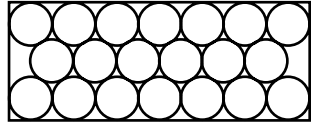


Fig. 30. Triangular Pattern ( $r = 3, c = 7$ )

If  $D$  is the can diameter and  $H$  its height, the arrangement in Fig. 29 will hold 20 circles or cans in a volume of  $5D \times 4D \times H = 20D^2 H$ . The arrangement in Fig. 30 will pack the same 20 cans into a volume of  $7D \times 2.732D \times H = 19.124D^2 H$ , a reduction of 4.4 per cent. When the ratio of  $H/D$  is less than 1.196:1, the rectangular pattern requires less surface area (therefore less material) for the six sides of the box, but for greater ratios, the triangular pattern is better. Some numbers, such as 19, can be accommodated only in a triangular pattern.

The following table shows possible patterns for 3 to 25 cans, where  $N$  = number of circles,  $P$  = pattern ( $R$  rectangular or  $T$  triangular), and  $r$  and  $c$  = numbers of rows and columns, respectively. The final table column shows the most economical application, where  $V$  = best volume,  $S$  = best surface area (sometimes followed by a condition on  $H/D$ ). For the rectangular pattern, the area of the container is  $rD \times cD$ , and for the triangular pattern, the area is  $cD \times [1 + (r - 1)\sqrt{3}/2]D$ , or  $cD^2[1 + 0.866(r - 1)]$ .

**Numbers of Circles in Rectangular Arrangements**

| $N$ | $P$ | $r$ | $c$ | Application           | $N$ | $P$ | $r$ | $c$                   | Application                |
|-----|-----|-----|-----|-----------------------|-----|-----|-----|-----------------------|----------------------------|
| 3   | $T$ | 2   | 2   | $V, S$                | 15  | $R$ | 3   | 5                     | $(S, H/D > 0.038)$         |
|     |     |     |     |                       |     | $T$ | 2   | 8                     | $V, (S, H/D < 0.038)$      |
| 4   | $R$ | 2   | 2   | $V, S$                | 16  | $R$ | 4   | 4                     | $V, S$                     |
| 5   | $T$ | 3   | 2   | $V, S$                | 17  | $T$ | 3   | 6                     | $V, S$                     |
| 6   | $R$ | 2   | 3   | $V, S$                | 18  | $T$ | 5   | 4                     | $V, S$                     |
| 7   | $T$ | 2   | 4   | $V, S$                | 19  | $T$ | 2   | 10                    | $V, S$                     |
| 8   | $R$ | 4   | 2   | $V, (S, H/D < 0.732)$ | 20  | $R$ | 4   | 5                     | $(S, H/D > 1.196)$         |
|     | $T$ | 3   | 3   | $(S, H/D > 0.732)$    |     | $T$ | 3   | 7                     | $V, (S, H/D < 1.196)$      |
| 9   | $R$ | 3   | 3   | $V, S$                | 21  | $R$ | 3   | 7                     | $(S, 0.165 < H/D < 0.479)$ |
| 10  | $R$ | 5   | 2   | $V, (S, H/D > 1.976)$ |     | $T$ | 6   | 4                     | $(S, H/D > 0.479)$         |
|     | $T$ | 4   | 3   | $(S, H/D > 1.976)$    | $T$ | 2   | 11  | $V, (S, H/D < 0.165)$ |                            |
| 11  | $T$ | 3   | 4   | $V, S$                | 22  | $T$ | 4   | 6                     | $V, S$                     |
| 12  | $R$ | 3   | 4   | $V, S$                | 23  | $T$ | 5   | 5                     | $(S, H/D > 0.366)$         |
| 13  | $T$ | 5   | 3   | $(S, H/D > 0.236)$    |     | $T$ | 3   | 8                     | $V, (S, H/D < 0.366)$      |
|     | $T$ | 2   | 7   | $V, (S, H/D < 0.236)$ | 24  | $R$ | 4   | 6                     | $V, S$                     |
| 14  | $T$ | 4   | 4   | $(S, H/D > 5.464)$    | 25  | $R$ | 5   | 5                     | $(S, H/D > 1.10)$          |
|     | $T$ | 3   | 5   | $V, (S, H/D < 5.464)$ |     | $T$ | 7   | 4                     | $(S, 0.113 < H/D < 1.10)$  |
|     |     |     |     |                       |     | $T$ | 2   | 13                    | $V, (S, H/D < 0.133)$      |

**Rollers on a Shaft\*.**—The following formulas illustrate the geometry of rollers on a shaft. In Fig. 31,  $D$  is the diameter of the center line of the roller circle,  $d$  is the diameter of a roller,  $D_S = D - d$  is the shaft diameter, and  $C$  is the clearance along the center line of the roller circle. In the equations that follow,  $N$  is the number of rollers, and  $N > 3$ .

Equation (1a) applies when the clearance  $C = 0$

$$D = \frac{d}{\sin\left(\frac{180}{N}\right)} \quad (1a)$$

Equation (1b) applies when clearance  $C > 0$  then

$$C = D \sin\left(180^\circ - (N - 1) \operatorname{asin}\left(\frac{d}{D}\right)\right) - d \quad (1b)$$

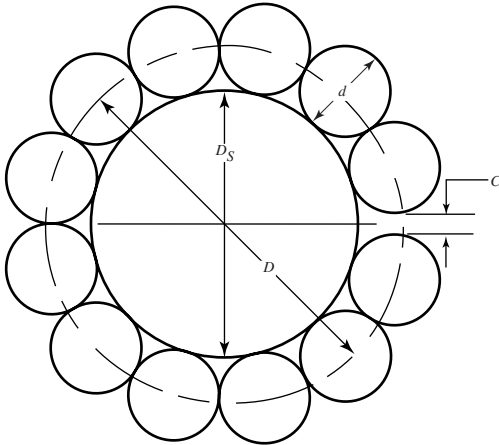


Fig. 31.

*Example:* Forty bearings are to be placed around a 3-inch diameter shaft with no clearance. What diameter bearings are needed?

*Solution:* Rearrange Equation (1a), and substitute in the value of  $N$ . Use the result to eliminate  $d$ , using  $D_S = D - d$ . Finally, solve for  $D$  and  $d$ .

$$d = D \sin\left(\frac{180}{N}\right) = D \sin\left(\frac{180}{40}\right) = 0.078459D$$

$$D = D_S + d = 3 + 0.078459D$$

$$D = \frac{3}{0.92154} = 3.2554$$

$$d = D - D_S = 0.2554$$

\*Rollers on a Shaft contributed by Manfred K. Brueckner.

## SOLUTION OF TRIANGLES

Any figure bounded by three straight lines is called a triangle. Any one of the three lines may be called the base, and the line drawn from the angle opposite the base at right angles to it is called the height or altitude of the triangle.

If all three sides of a triangle are of equal length, the triangle is called *equilateral*. Each of the three angles in an equilateral triangle equals 60 degrees. If two sides are of equal length, the triangle is an *isosceles* triangle. If one angle is a right or 90-degree angle, the triangle is a *right* or *right-angled* triangle. The side opposite the right angle is called the *hypotenuse*.

If all the angles are less than 90 degrees, the triangle is called an *acute* or *acute-angled* triangle. If one of the angles is larger than 90 degrees, the triangle is called an *obtuse-angled* triangle. Both acute and obtuse-angled triangles are known under the common name of *oblique-angled* triangles. The sum of the three angles in every triangle is 180 degrees.

The sides and angles of any triangle that are not known can be found when: 1) all the three sides; 2) two sides and one angle; and 3) one side and two angles are given.

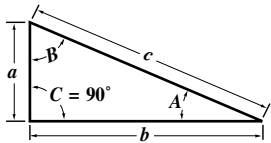
In other words, if a triangle is considered as consisting of six parts, three angles and three sides, the unknown parts can be determined when any three parts are given, provided at least one of the given parts is a side.

## Functions of Angles

For every right triangle, a set of six ratios is defined; each is the length of one side of the triangle divided by the length of another side. The six ratios are the trigonometric (trig) functions sine, cosine, tangent, cosecant, secant, and cotangent (abbreviated sin, cos, tan, csc, sec, and cot). Trig functions are usually expressed in terms of an angle in degree or radian measure, as in  $\cos 60^\circ = 0.5$ . "Arc" in front of a trig function name, as in arcsin or arccos, means find the angle whose function value is given. For example,  $\arcsin 0.5 = 30^\circ$  means that  $30^\circ$  is the angle whose sin is equal to 0.5. Electronic calculators frequently use  $\sin^{-1}$ ,  $\cos^{-1}$ , and  $\tan^{-1}$  to represent the arc functions.

*Example:*  $\tan 53.1^\circ = 1.332$ ;  $\arctan 1.332 = \tan^{-1} 1.332 = 53.1^\circ = 53^\circ 6'$

The *sine* of an angle equals the opposite side divided by the hypotenuse. Hence,  $\sin B = b \div c$ , and  $\sin A = a \div c$ .



The *cosine* of an angle equals the adjacent side divided by the hypotenuse. Hence,  $\cos B = a \div c$ , and  $\cos A = b \div c$ .

The *tangent* of an angle equals the opposite side divided by the adjacent side. Hence,  $\tan B = b \div a$ , and  $\tan A = a \div b$ .

The *cotangent* of an angle equals the adjacent side divided by the opposite side. Hence,  $\cot B = a \div b$ , and

$\cot A = b \div a$ .

The *secant* of an angle equals the hypotenuse divided by the adjacent side. Hence,  $\sec B = c \div a$ , and  $\sec A = c \div b$ .

The *cosecant* of an angle equals the hypotenuse divided by the opposite side. Hence,  $\csc B = c \div b$ , and  $\csc A = c \div a$ .

It should be noted that the functions of the angles can be found in this manner only when the triangle is right-angled.

If in a right-angled triangle (see preceding illustration), the lengths of the three sides are represented by  $a$ ,  $b$ , and  $c$ , and the angles opposite each of these sides by  $A$ ,  $B$ , and  $C$ , then the side  $c$  opposite the right angle is the hypotenuse; side  $b$  is called the *side adjacent* to angle  $A$  and is also the *side opposite* to angle  $B$ ; side  $a$  is the side adjacent to angle  $B$  and the

side opposite to angle  $A$ . The meanings of the various functions of angles can be explained with the aid of a right-angled triangle. Note that the cosecant, secant, and cotangent are the reciprocals of, respectively, the sine, cosine, and tangent.

The following relation exists between the angular functions of the two acute angles in a right-angled triangle: The sine of angle  $B$  equals the cosine of angle  $A$ ; the tangent of angle  $B$  equals the cotangent of angle  $A$ , and *vice versa*. The sum of the two acute angles in a right-angled triangle always equals 90 degrees; hence, when one angle is known, the other can easily be found. When any two angles together make 90 degrees, one is called the *complement* of the other, and the sine of the one angle equals the cosine of the other, and the tangent of the one equals the cotangent of the other.

**The Law of Sines.**—In any triangle, any side is to the sine of the angle opposite that side as any other side is to the sine of the angle opposite that side. If  $a$ ,  $b$ , and  $c$  are the sides, and  $A$ ,  $B$ , and  $C$  their opposite angles, respectively, then:

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}, \quad \text{so that:}$$

$$a = \frac{b \sin A}{\sin B} \quad \text{or} \quad a = \frac{c \sin A}{\sin C}$$

$$b = \frac{a \sin B}{\sin A} \quad \text{or} \quad b = \frac{c \sin B}{\sin C}$$

$$c = \frac{a \sin C}{\sin A} \quad \text{or} \quad c = \frac{b \sin C}{\sin B}$$

**The Law of Cosines.**—In any triangle, the square of any side is equal to the sum of the squares of the other two sides minus twice their product times the cosine of the included angle; or if  $a$ ,  $b$  and  $c$  are the sides and  $A$ ,  $B$ , and  $C$  are the opposite angles, respectively, then:

$$a^2 = b^2 + c^2 - 2bc \cos A$$

$$b^2 = a^2 + c^2 - 2ac \cos B$$

$$c^2 = a^2 + b^2 - 2ab \cos C$$

These two laws, together with the proposition that the sum of the three angles equals 180 degrees, are the basis of all formulas relating to the solution of triangles.

Formulas for the solution of right-angled and oblique-angled triangles, arranged in tabular form, are given on the following pages.

**Signs of Trigonometric Functions.**—The diagram, Fig. 1 on page 98, shows the proper sign (+ or -) for the trigonometric functions of angles in each of the four quadrants, 0 to 90, 90 to 180, 180 to 270, and 270 to 360 degrees. Thus, the cosine of an angle between 90 and 180 degrees is negative; the sine of the same angle is positive.

**Trigonometric Identities.**—Trigonometric identities are formulas that show the relationship between different trigonometric functions. They may be used to change the form of some trigonometric expressions to simplify calculations. For example, if a formula has a term,  $2\sin A \cos A$ , the equivalent but simpler term  $\sin 2A$  may be substituted. The identities that follow may themselves be combined or rearranged in various ways to form new identities.

**Basic**

$$\tan A = \frac{\sin A}{\cos A} = \frac{1}{\cot A} \quad \sec A = \frac{1}{\cos A} \quad \csc A = \frac{1}{\sin A}$$

**Negative Angle**

$$\sin(-A) = -\sin A \quad \cos(-A) = \cos A \quad \tan(-A) = -\tan A$$

**Pythagorean**

$$\sin^2 A + \cos^2 A = 1 \quad 1 + \tan^2 A = \sec^2 A \quad 1 + \cot^2 A = \csc^2 A$$

**Sum and Difference of Angles**

$$\tan(A + B) = \frac{\tan A + \tan B}{1 - \tan A \tan B} \quad \tan(A - B) = \frac{\tan A - \tan B}{1 + \tan A \tan B}$$

$$\cot(A + B) = \frac{\cot A \cot B - 1}{\cot B + \cot A} \quad \cot(A - B) = \frac{\cot A \cot B + 1}{\cot B - \cot A}$$

$$\sin(A + B) = \sin A \cos B + \cos A \sin B \quad \sin(A - B) = \sin A \cos B - \cos A \sin B$$

$$\cos(A + B) = \cos A \cos B - \sin A \sin B \quad \cos(A - B) = \cos A \cos B + \sin A \sin B$$

**Double-Angle**

$$\cos 2A = \cos^2 A - \sin^2 A = 2 \cos^2 A - 1 = 1 - 2 \sin^2 A$$

$$\sin 2A = 2 \sin A \cos A \quad \tan 2A = \frac{2 \tan A}{1 - \tan^2 A} = \frac{2}{\cot A - \tan A}$$

**Half-Angle**

$$\sin \frac{1}{2}A = \sqrt{\frac{1 - \cos A}{2}} \quad \cos \frac{1}{2}A = \sqrt{\frac{1 + \cos A}{2}}$$

$$\tan \frac{1}{2}A = \frac{\sqrt{1 - \cos A}}{\sqrt{1 + \cos A}} = \frac{1 - \cos A}{\sin A} = \frac{\sin A}{1 + \cos A}$$

**Product-to-Sum**

$$\sin A \cos B = \frac{1}{2}[\sin(A + B) + \sin(A - B)]$$

$$\cos A \cos B = \frac{1}{2}[\cos(A + B) + \cos(A - B)]$$

$$\sin A \sin B = \frac{1}{2}[\cos(A - B) - \cos(A + B)]$$

$$\tan A \tan B = \frac{\tan A + \tan B}{\cot A + \cot B}$$

**Sum and Difference of Functions**

$$\sin A + \sin B = 2[\sin \frac{1}{2}(A + B) \cos \frac{1}{2}(A - B)]$$

$$\sin A - \sin B = 2[\sin \frac{1}{2}(A - B) \cos \frac{1}{2}(A + B)]$$

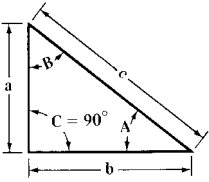
$$\cos A + \cos B = 2[\cos \frac{1}{2}(A + B) \cos \frac{1}{2}(A - B)]$$

$$\cos A - \cos B = -2[\sin \frac{1}{2}(A + B) \sin \frac{1}{2}(A - B)]$$

$$\tan A + \tan B = \frac{\sin(A + B)}{\cos A \cos B} \quad \tan A - \tan B = \frac{\sin(A - B)}{\cos A \cos B}$$

$$\cot A + \cot B = \frac{\sin(B + A)}{\sin A \sin B} \quad \cot A - \cot B = \frac{\sin(B - A)}{\sin A \sin B}$$

## Solution of Right-Angled Triangles

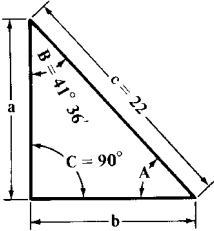
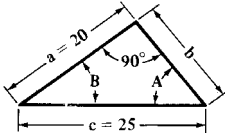
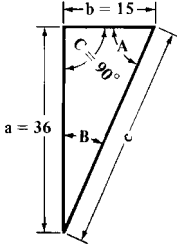
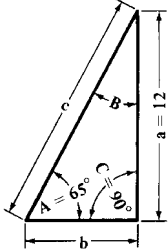
|  |   |                        |                    |
|--|---|------------------------|--------------------|
|  | <p>As shown in the illustration, the sides of the right-angled triangle are designated <math>a</math> and <math>b</math> and the hypotenuse, <math>c</math>. The angles opposite each of these sides are designated <math>A</math> and <math>B</math>, respectively.</p> <p>Angle <math>C</math>, opposite the hypotenuse <math>c</math> is the right angle, and is therefore always one of the known quantities.</p> |                        |                    |
| Sides and Angles Known   | Formulas for Sides and Angles to be Found   |                        |                    |
| Side $a$ ; side $b$  | $c = \sqrt{a^2 + b^2}$  | $\tan A = \frac{a}{b}$ | $B = 90^\circ - A$ |
| Side $a$ ; hypotenuse $c$  | $b = \sqrt{c^2 - a^2}$  | $\sin A = \frac{a}{c}$ | $B = 90^\circ - A$ |
| Side $b$ ; hypotenuse $c$  | $a = \sqrt{c^2 - b^2}$  | $\sin B = \frac{b}{c}$ | $A = 90^\circ - B$ |
| Hypotenuse $c$ ; angle $B$   | $b = c \times \sin B$   | $a = c \times \cos B$  | $A = 90^\circ - B$ |
| Hypotenuse $c$ ; angle $A$   | $b = c \times \cos A$   | $a = c \times \sin A$  | $B = 90^\circ - A$ |
| Side $b$ ; angle $B$   | $c = \frac{b}{\sin B}$  | $a = b \times \cot B$  | $A = 90^\circ - B$ |
| Side $b$ ; angle $A$   | $c = \frac{b}{\cos A}$  | $a = b \times \tan A$  | $B = 90^\circ - A$ |
| Side $a$ ; angle $B$   | $c = \frac{a}{\cos B}$  | $b = a \times \tan B$  | $A = 90^\circ - B$ |
| Side $a$ ; angle $A$   | $c = \frac{a}{\sin A}$  | $b = a \times \cot A$  | $B = 90^\circ - A$ |

## Trig Functions Values for Common Angles

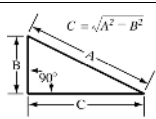
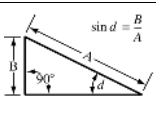
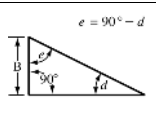
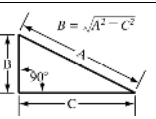
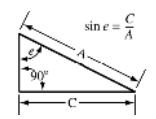
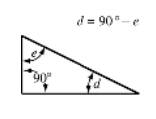
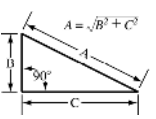
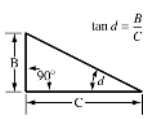
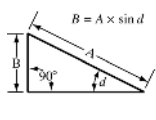
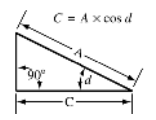
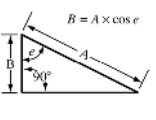
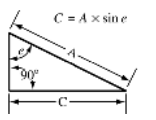
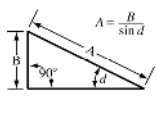
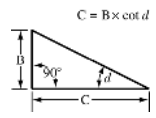
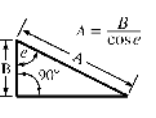
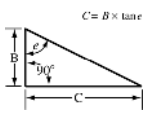
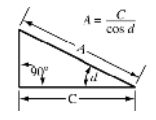
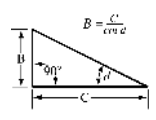
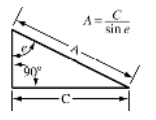
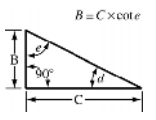
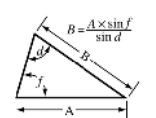
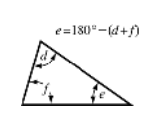
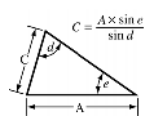
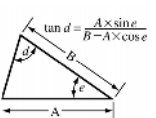
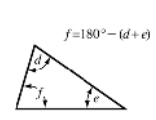

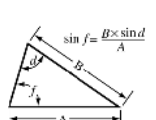
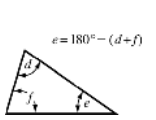
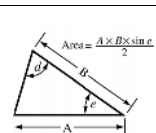
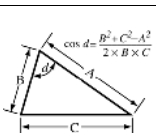
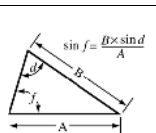
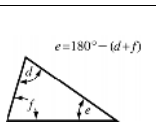
|   |   |   |
|---|---|---|
| $\sin 0^\circ = 0$                                | $\cos 0^\circ = 1$                                | $\tan 0^\circ = 0$                                |
| $\sin 30^\circ = \sin \frac{\pi}{6} = 0.5$        | $\cos 30^\circ = \cos \frac{\pi}{6} = 0.8660254$  | $\tan 30^\circ = \tan \frac{\pi}{6} = 0.57735027$ |
| $\sin 45^\circ = \sin \frac{\pi}{4} = 0.70710678$ | $\cos 45^\circ = \cos \frac{\pi}{4} = 0.70710678$ | $\tan 45^\circ = \tan \frac{\pi}{4} = 1$          |
| $\sin 60^\circ = \sin \frac{\pi}{3} = 0.8660254$  | $\cos 60^\circ = \cos \frac{\pi}{3} = 0.5$        | $\tan 60^\circ = \tan \frac{\pi}{3} = 1.7320508$  |
| $\sin 90^\circ = \sin \frac{\pi}{2} = 1$          | $\cos 90^\circ = \cos \frac{\pi}{2} = 0$          | $\tan 90^\circ = \tan \frac{\pi}{2} = \infty$     |



## Examples of the Solution of Right-Angled Triangles (English and metric units)

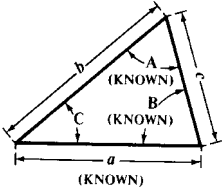
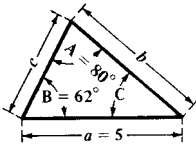
|   |  |
|---|--|
|  <p>Hypotenuse and One Angle Known</p>  | $c = 22 \text{ inches}; B = 41^\circ 36'$<br>$a = c \times \cos B = 22 \times \cos 41^\circ 36' = 22 \times 0.74780$<br>$= 16.4516 \text{ inches}$<br>$b = c \times \sin B = 22 \times \sin 41^\circ 36' = 22 \times 0.66393$<br>$= 14.6065 \text{ inches}$<br>$A = 90^\circ - B = 90^\circ - 41^\circ 36' = 48^\circ 24'$ |
|  <p>Hypotenuse and One Side Known</p>   | $c = 25 \text{ centimeters}; a = 20 \text{ centimeters.}$<br>$b = \sqrt{c^2 - a^2} = \sqrt{25^2 - 20^2} = \sqrt{625 - 400}$<br>$= \sqrt{225} = 15 \text{ centimeters}$<br>$\sin A = \frac{a}{c} = \frac{20}{25} = 0.8$<br>$A = 53^\circ 8'$<br>Hence,<br>$B = 90^\circ - A = 90^\circ - 53^\circ 8' = 36^\circ 52'$        |
|  <p>Two Sides Known</p>               | $a = 36 \text{ inches}; b = 15 \text{ inches.}$<br>$c = \sqrt{a^2 + b^2} = \sqrt{36^2 + 15^2} = \sqrt{1296 + 225}$<br>$= \sqrt{1521} = 39 \text{ inches}$<br>$\tan A = \frac{a}{b} = \frac{36}{15} = 2.4$<br>Hence,<br>$A = 67^\circ 23'$<br>$B = 90^\circ - A = 90^\circ - 67^\circ 23' = 22^\circ 37'$                   |
|  <p>One Side and One Angle Known</p> | $a = 12 \text{ meters}; A = 65^\circ.$<br>$c = \frac{a}{\sin A} = \frac{12}{\sin 65^\circ} = \frac{12}{0.90631} = 13.2405 \text{ meters}$<br>$b = a \times \cot A = 12 \times \cot 65^\circ = 12 \times 0.46631$<br>$= 5.5957 \text{ meters}$<br>$B = 90^\circ - A = 90^\circ - 65^\circ = 25^\circ$                       |

## Chart For The Rapid Solution of Right-Angle and Oblique-Angle Triangles

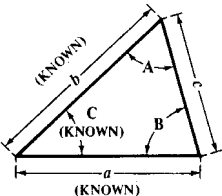
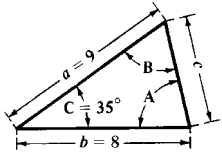
|  |   |   |   |
|--|---|---|---|
| <br>$C = \sqrt{A^2 - B^2}$                               | <br>$\sin d = \frac{B}{A}$                                   | <br>$e = 90^\circ - d$                     | <br>$B = \sqrt{A^2 - C^2}$                                   |
| <br>$\sin e = \frac{C}{A}$                               | <br>$d = 90^\circ - e$                                       | <br>$A = \sqrt{B^2 + C^2}$                 | <br>$\tan d = \frac{B}{C}$                                   |
| <br>$B = A \times \sin d$                                | <br>$C = A \times \cos d$                                    | <br>$B = A \times \cos e$                  | <br>$C = A \times \sin e$                                    |
| <br>$A = \frac{B}{\sin d}$                               | <br>$C = B \times \cot d$                                    | <br>$A = \frac{B}{\cos e}$                 | <br>$C = B \times \tan e$                                    |
| <br>$A = \frac{C}{\cos d}$                              | <br>$B = \frac{C}{\tan d}$                                  | <br>$A = \frac{C}{\sin e}$                | <br>$B = C \times \cot e$                                   |
| <br>$B = \frac{A \times \sin f}{\sin d}$               | <br>$e = 180^\circ - (d + f)$                              | <br>$C = \frac{A \times \sin e}{\sin d}$ | <br>$\tan d = \frac{A \times \sin e}{B - A \times \cos e}$ |
| <br>$f = 180^\circ - (d + e)$                          | <br>$C = \frac{A \times \sin e}{\sin d}$                   | <br>$\sin f = \frac{B \times \sin d}{A}$ | <br>$e = 180^\circ - (d + f)$                              |
| <br>$\text{Area} = \frac{A \times B \times \sin e}{2}$ | <br>$\cos d = \frac{B^2 + C^2 - A^2}{2 \times B \times C}$ | <br>$\sin f = \frac{B \times \sin d}{A}$ | <br>$e = 180^\circ - (d + f)$                              |

## Solution of Oblique-Angled Triangles

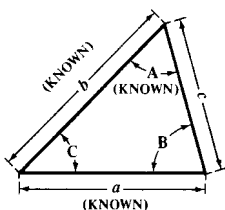
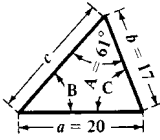
## One Side and Two Angles Known (Law of Sines):

|   |  |
|---|--|
|  <p>One Side and Two Angles Known</p> | <p>Call the known side <math>a</math>, the angle opposite it <math>A</math>, and the other known angle <math>B</math>. Then, <math>C = 180^\circ - (A + B)</math>. If angles <math>B</math> and <math>C</math> are given, but not <math>A</math>, then <math>A = 180^\circ - (B + C)</math>.</p> $C = 180^\circ - (A + B)$ $b = \frac{a \times \sin B}{\sin A} \quad c = \frac{a \times \sin C}{\sin A}$ $\text{Area} = \frac{a \times b \times \sin C}{2}$                      |
|  <p>Side and Angles Known</p>         | <p><math>a = 5</math> centimeters; <math>A = 80^\circ</math>; <math>B = 62^\circ</math></p> $C = 180^\circ - (80^\circ + 62^\circ) = 180^\circ - 142^\circ = 38^\circ$ $b = \frac{a \times \sin B}{\sin A} = \frac{5 \times \sin 62^\circ}{\sin 80^\circ} = \frac{5 \times 0.88295}{0.98481}$ $= 4.483 \text{ centimeters}$ $c = \frac{a \times \sin C}{\sin A} = \frac{5 \times \sin 38^\circ}{\sin 80^\circ} = \frac{5 \times 0.61566}{0.98481}$ $= 3.126 \text{ centimeters}$ |

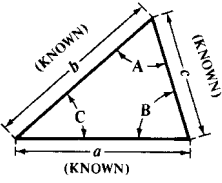
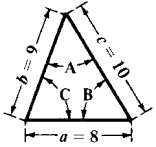
## Two Sides and the Angle Between Them Known:

|   |  |
|---|--|
|  <p>Two Sides and the Angle Between Them Known</p> | <p>Call the known sides <math>a</math> and <math>b</math>, and the known angle between them <math>C</math>. Then,</p> $\tan A = \frac{a \times \sin C}{b - (a \times \cos C)}$ $B = 180^\circ - (A + C) \quad c = \frac{a \times \sin C}{\sin A}$ <p>Side <math>c</math> may also be found directly as below:</p> $c = \sqrt{a^2 + b^2 - (2ab \times \cos C)}$ $\text{Area} = \frac{a \times b \times \sin C}{2}$  |
|  <p>Sides and Angle Known</p>                     | <p><math>a = 9</math> inches; <math>b = 8</math> inches; <math>C = 35^\circ</math>.</p> $\tan A = \frac{a \times \sin C}{b - (a \times \cos C)} = \frac{9 \times \sin 35^\circ}{8 - (9 \times \cos 35^\circ)}$ $= \frac{9 \times 0.57358}{8 - (9 \times 0.81915)} = \frac{5.16222}{0.62765} = 8.22468$ <p>Hence, <math>A = 83^\circ 4'</math></p> $B = 180^\circ - (A + C) = 180^\circ - 118^\circ 4' = 61^\circ 56'$ $c = \frac{a \times \sin C}{\sin A} = \frac{9 \times 0.57358}{0.99269} = 5.2 \text{ inches}$ |

## Two Sides and the Angle Opposite One of the Sides Known:

|   |  |
|---|--|
|  <p>Two Sides and the Angle Opposite One of the Sides Known</p> | <p>Call the known angle <math>A</math>, the side opposite it <math>a</math>, and the other known side <math>b</math>. Then,</p> $\sin B = \frac{b \times \sin A}{a} \quad C = 180^\circ - (A + B)$ $c = \frac{a \times \sin C}{\sin A} \quad \text{Area} = \frac{a \times b \times \sin C}{2}$ <p>If, in the above, angle <math>B &gt; \text{angle } A</math> but <math>&lt; 90^\circ</math>, then a second solution <math>B_2, C_2, c_2</math> exists for which: <math>B_2 = 180^\circ - B</math>; <math>C_2 = 180^\circ - (A + B_2)</math>; <math>c_2 = (a \times \sin C_2) \div \sin A</math>; area = <math>(a \times b \times \sin C_2) \div 2</math>. If <math>a \geq b</math>, then the first solution only exists. If <math>a &lt; b \times \sin A</math>, then no solution exists.</p> |
|  <p>Sides and Angle Known</p>                                  | <p><math>a = 20</math> centimeters; <math>b = 17</math> centimeters; <math>A = 61^\circ</math>.</p> $\sin B = \frac{b \times \sin A}{a} = \frac{17 \times \sin 61^\circ}{20}$ $= \frac{17 \times 0.87462}{20} = 0.74343$ <p>Hence, <math>B = 48^\circ 1'</math></p> $C = 180^\circ - (A + B) = 180^\circ - 109^\circ 1' = 70^\circ 59'$ $c = \frac{a \times \sin C}{\sin A} = \frac{20 \times \sin 70^\circ 59'}{\sin 61^\circ} = \frac{20 \times 0.94542}{0.87462}$ $= 21.62 \text{ centimeters}$   |

## All Three Sides are Known:

|  |  |
|--|--|
|  <p>All Three Sides Known</p>   | <p>Call the sides <math>a, b</math>, and <math>c</math>, and the angles opposite them, <math>A, B</math>, and <math>C</math>. Then,</p> $\cos A = \frac{b^2 + c^2 - a^2}{2bc} \quad \sin B = \frac{b \times \sin A}{a}$ $C = 180^\circ - (A + B) \quad \text{Area} = \frac{a \times b \times \sin C}{2}$   |
|  <p>Sides and Angle Known</p> | <p><math>a = 8</math> inches; <math>b = 9</math> inches; <math>c = 10</math> inches.</p> $\cos A = \frac{b^2 + c^2 - a^2}{2bc} = \frac{9^2 + 10^2 - 8^2}{2 \times 9 \times 10}$ $= \frac{81 + 100 - 64}{180} = \frac{117}{180} = 0.65000$ <p>Hence, <math>A = 49^\circ 27'</math></p> $\sin B = \frac{b \times \sin A}{a} = \frac{9 \times 0.75984}{8} = 0.85482$ <p>Hence, <math>B = 58^\circ 44'</math></p> $C = 180^\circ - (A + B) = 180^\circ - 108^\circ 11' = 71^\circ 49'$ |

ANGULAR CONVERSIONS

**Conversion Tables of Angular Measure.**—The accompanying tables of degrees, minutes, and seconds into radians; radians into degrees, minutes, and seconds; radians into degrees and decimals of a degree; and minutes and seconds into decimals of a degree and vice versa facilitate the conversion of measurements.

*Example 1:* The Degrees, Minutes, and Seconds into Radians table is used to find the number of radians in 324 degrees, 25 minutes, 13 seconds as follows:

|             |                    |
|-------------|--------------------|
| 300 degrees | = 5.235988 radians |
| 20 degrees  | = 0.349066 radian  |
| 4 degrees   | = 0.069813 radian  |
| 25 minutes  | = 0.007272 radian  |
| 13 seconds  | = 0.000063 radian  |
| 324°25'13"  | = 5.662202 radians |

*Example 2:* The Radians into Degrees and Decimals of a Degree, and Radians into Degrees, Minutes and Seconds tables are used to find the number of decimal degrees or degrees, minutes and seconds in 0.734 radian as follows:

|                                |                                      |
|--------------------------------|--------------------------------------|
| 0.7 radian = 40.1070 degrees   | 0.7 radian = 40° 6'25"               |
| 0.03 radian = 1.7189 degrees   | 0.03 radian = 1°43'8"                |
| 0.004 radian = 0.2292 degree   | 0.004 radian = 0°13'45"              |
| 0.734 radian = 42.0551 degrees | 0.734 radian = 41°62'78" or 42°3'18" |

**Degrees, Minutes, and Seconds into Radians (Based on 180 degrees = π radians)**

| Degrees into Radians |            |      |           |      |          |      |          |      |          |
|----------------------|------------|------|-----------|------|----------|------|----------|------|----------|
| Deg.                 | Rad.       | Deg. | Rad.      | Deg. | Rad.     | Deg. | Rad.     | Deg. | Rad.     |
| 1000                 | 17.453293  | 100  | 1.745329  | 10   | 0.174533 | 1    | 0.017453 | 0.1  | 0.001745 |
| 2000                 | 34.906585  | 200  | 3.490659  | 20   | 0.349066 | 2    | 0.034907 | 0.2  | 0.003491 |
| 3000                 | 52.359878  | 300  | 5.235988  | 30   | 0.523599 | 3    | 0.052360 | 0.3  | 0.005236 |
| 4000                 | 69.813170  | 400  | 6.981317  | 40   | 0.698132 | 4    | 0.069813 | 0.4  | 0.006981 |
| 5000                 | 87.266463  | 500  | 8.726646  | 50   | 0.872665 | 5    | 0.087266 | 0.5  | 0.008727 |
| 6000                 | 104.719755 | 600  | 10.471976 | 60   | 1.047198 | 6    | 0.104720 | 0.6  | 0.010472 |
| 7000                 | 122.173048 | 700  | 12.217305 | 70   | 1.221730 | 7    | 0.122173 | 0.7  | 0.012217 |
| 8000                 | 139.626340 | 800  | 13.962634 | 80   | 1.396263 | 8    | 0.139626 | 0.8  | 0.013963 |
| 9000                 | 157.079633 | 900  | 15.707963 | 90   | 1.570796 | 9    | 0.157080 | 0.9  | 0.015708 |
| 10000                | 174.532925 | 1000 | 17.453293 | 100  | 1.745329 | 10   | 0.174533 | 1.0  | 0.017453 |
| Minutes into Radians |            |      |           |      |          |      |          |      |          |
| Min.                 | Rad.       | Min. | Rad.      | Min. | Rad.     | Min. | Rad.     | Min. | Rad.     |
| 1                    | 0.000291   | 11   | 0.003200  | 21   | 0.006109 | 31   | 0.009018 | 41   | 0.011926 |
| 2                    | 0.000582   | 12   | 0.003491  | 22   | 0.006400 | 32   | 0.009308 | 42   | 0.012217 |
| 3                    | 0.000873   | 13   | 0.003782  | 23   | 0.006690 | 33   | 0.009599 | 43   | 0.012508 |
| 4                    | 0.001164   | 14   | 0.004072  | 24   | 0.006981 | 34   | 0.009890 | 44   | 0.012799 |
| 5                    | 0.001454   | 15   | 0.004363  | 25   | 0.007272 | 35   | 0.010181 | 45   | 0.013090 |
| 6                    | 0.001745   | 16   | 0.004654  | 26   | 0.007563 | 36   | 0.010472 | 46   | 0.013381 |
| 7                    | 0.002036   | 17   | 0.004945  | 27   | 0.007854 | 37   | 0.010763 | 47   | 0.013672 |
| 8                    | 0.002327   | 18   | 0.005236  | 28   | 0.008145 | 38   | 0.011054 | 48   | 0.013963 |
| 9                    | 0.002618   | 19   | 0.005527  | 29   | 0.008436 | 39   | 0.011345 | 49   | 0.014254 |
| 10                   | 0.002909   | 20   | 0.005818  | 30   | 0.008727 | 40   | 0.011636 | 50   | 0.014544 |
| Seconds into Radians |            |      |           |      |          |      |          |      |          |
| Sec.                 | Rad.       | Sec. | Rad.      | Sec. | Rad.     | Sec. | Rad.     | Sec. | Rad.     |
| 1                    | 0.000005   | 11   | 0.000053  | 21   | 0.000102 | 31   | 0.000150 | 41   | 0.000199 |
| 2                    | 0.000010   | 12   | 0.000058  | 22   | 0.000107 | 32   | 0.000155 | 42   | 0.000204 |
| 3                    | 0.000015   | 13   | 0.000063  | 23   | 0.000112 | 33   | 0.000160 | 43   | 0.000208 |
| 4                    | 0.000019   | 14   | 0.000068  | 24   | 0.000116 | 34   | 0.000165 | 44   | 0.000213 |
| 5                    | 0.000024   | 15   | 0.000073  | 25   | 0.000121 | 35   | 0.000170 | 45   | 0.000218 |
| 6                    | 0.000029   | 16   | 0.000078  | 26   | 0.000126 | 36   | 0.000175 | 46   | 0.000223 |
| 7                    | 0.000034   | 17   | 0.000082  | 27   | 0.000131 | 37   | 0.000179 | 47   | 0.000228 |
| 8                    | 0.000039   | 18   | 0.000087  | 28   | 0.000136 | 38   | 0.000184 | 48   | 0.000233 |
| 9                    | 0.000044   | 19   | 0.000092  | 29   | 0.000141 | 39   | 0.000189 | 49   | 0.000238 |
| 10                   | 0.000048   | 20   | 0.000097  | 30   | 0.000145 | 40   | 0.000194 | 50   | 0.000242 |

**Radians into Degrees and Decimals of a Degree  
(Based on  $\pi$  radians = 180 degrees)**

| Rad. | Deg.      | Rad. | Deg.     | Rad. | Deg.    | Rad. | Deg.   | Rad.  | Deg.   | Rad.   | Deg.   |
|------|-----------|------|----------|------|---------|------|--------|-------|--------|--------|--------|
| 10   | 572.9578  | 1    | 57.2958  | 0.1  | 5.7296  | 0.01 | 0.5730 | 0.001 | 0.0573 | 0.0001 | 0.0057 |
| 20   | 1145.9156 | 2    | 114.5916 | 0.2  | 11.4592 | 0.02 | 1.1459 | 0.002 | 0.1146 | 0.0002 | 0.0115 |
| 30   | 1718.8734 | 3    | 171.8873 | 0.3  | 17.1887 | 0.03 | 1.7189 | 0.003 | 0.1719 | 0.0003 | 0.0172 |
| 40   | 2291.8312 | 4    | 229.1831 | 0.4  | 22.9183 | 0.04 | 2.2918 | 0.004 | 0.2292 | 0.0004 | 0.0229 |
| 50   | 2864.7890 | 5    | 286.4789 | 0.5  | 28.6479 | 0.05 | 2.8648 | 0.005 | 0.2865 | 0.0005 | 0.0286 |
| 60   | 3437.7468 | 6    | 343.7747 | 0.6  | 34.3775 | 0.06 | 3.4377 | 0.006 | 0.3438 | 0.0006 | 0.0344 |
| 70   | 4010.7046 | 7    | 401.0705 | 0.7  | 40.1070 | 0.07 | 4.0107 | 0.007 | 0.4011 | 0.0007 | 0.0401 |
| 80   | 4583.6624 | 8    | 458.3662 | 0.8  | 45.8366 | 0.08 | 4.5837 | 0.008 | 0.4584 | 0.0008 | 0.0458 |
| 90   | 5156.6202 | 9    | 515.6620 | 0.9  | 51.5662 | 0.09 | 5.1566 | 0.009 | 0.5157 | 0.0009 | 0.0516 |
| 100  | 5729.5780 | 10   | 572.9578 | 1.0  | 57.2958 | 0.10 | 5.7296 | 0.010 | 0.5730 | 0.0010 | 0.0573 |

**Radians into Degrees, Minutes, and Seconds  
(Based on  $\pi$  radians = 180 degrees)**

| Rad. | Angle       | Rad. | Angle      | Rad. | Angle     | Rad. | Angle    | Rad.  | Angle    | Rad.   | Angle   |
|------|-------------|------|------------|------|-----------|------|----------|-------|----------|--------|---------|
| 10   | 572°57'28"  | 1    | 57°17'45"  | 0.1  | 5°43'46"  | 0.01 | 0°34'23" | 0.001 | 0°3'26"  | 0.0001 | 0°0'21" |
| 20   | 1145°54'56" | 2    | 114°35'30" | 0.2  | 11°27'33" | 0.02 | 1°8'45"  | 0.002 | 0°6'53"  | 0.0002 | 0°0'41" |
| 30   | 1718°52'24" | 3    | 171°53'14" | 0.3  | 17°11'19" | 0.03 | 1°43'8"  | 0.003 | 0°10'19" | 0.0003 | 0°1' 2" |
| 40   | 2291°49'52" | 4    | 229°10'59" | 0.4  | 22°55'6"  | 0.04 | 2°17'31" | 0.004 | 0°13'45" | 0.0004 | 0°1'23" |
| 50   | 2864°47'20" | 5    | 286°28'44" | 0.5  | 28°38'52" | 0.05 | 2°51'53" | 0.005 | 0°17'11" | 0.0005 | 0°1'43" |
| 60   | 3437°44'48" | 6    | 343°46'29" | 0.6  | 34°22'39" | 0.06 | 3°26'16" | 0.006 | 0°20'38" | 0.0006 | 0°2' 4" |
| 70   | 4010°42'16" | 7    | 401°4'14"  | 0.7  | 40°6'25"  | 0.07 | 4°0'39"  | 0.007 | 0°24'4"  | 0.0007 | 0°2'24" |
| 80   | 4583°39'44" | 8    | 458°21'58" | 0.8  | 45°50'12" | 0.08 | 4°35'1"  | 0.008 | 0°27'30" | 0.0008 | 0°2'45" |
| 90   | 5156°37'13" | 9    | 515°39'43" | 0.9  | 51°33'58" | 0.09 | 5°9'24"  | 0.009 | 0°30'56" | 0.0009 | 0°3'6"  |
| 100  | 5729°34'41" | 10   | 572°57'28" | 1.0  | 57°17'45" | 0.10 | 5°43'46" | 0.010 | 0°34'23" | 0.0010 | 0°3'26" |

**Minutes and Seconds into Decimal of a Degree and Vice Versa  
(Based on 1 second = 0.00027778 degree)**

| Minutes into Decimals of a Degree |        |      |        | Seconds into Decimals of a Degree |        |      |        |
|-----------------------------------|--------|------|--------|-----------------------------------|--------|------|--------|
| Min.                              | Deg.   | Min. | Deg.   | Sec.                              | Deg.   | Sec. | Deg.   |
| 1                                 | 0.0167 | 21   | 0.3500 | 41                                | 0.6833 | 1    | 0.0003 |
| 2                                 | 0.0333 | 22   | 0.3667 | 42                                | 0.7000 | 2    | 0.0006 |
| 3                                 | 0.0500 | 23   | 0.3833 | 43                                | 0.7167 | 3    | 0.0008 |
| 4                                 | 0.0667 | 24   | 0.4000 | 44                                | 0.7333 | 4    | 0.0011 |
| 5                                 | 0.0833 | 25   | 0.4167 | 45                                | 0.7500 | 5    | 0.0014 |
| 6                                 | 0.1000 | 26   | 0.4333 | 46                                | 0.7667 | 6    | 0.0017 |
| 7                                 | 0.1167 | 27   | 0.4500 | 47                                | 0.7833 | 7    | 0.0019 |
| 8                                 | 0.1333 | 28   | 0.4667 | 48                                | 0.8000 | 8    | 0.0022 |
| 9                                 | 0.1500 | 29   | 0.4833 | 49                                | 0.8167 | 9    | 0.0025 |
| 10                                | 0.1667 | 30   | 0.5000 | 50                                | 0.8333 | 10   | 0.0028 |
| 11                                | 0.1833 | 31   | 0.5167 | 51                                | 0.8500 | 11   | 0.0031 |
| 12                                | 0.2000 | 32   | 0.5333 | 52                                | 0.8667 | 12   | 0.0033 |
| 13                                | 0.2167 | 33   | 0.5500 | 53                                | 0.8833 | 13   | 0.0036 |
| 14                                | 0.2333 | 34   | 0.5667 | 54                                | 0.9000 | 14   | 0.0039 |
| 15                                | 0.2500 | 35   | 0.5833 | 55                                | 0.9167 | 15   | 0.0042 |
| 16                                | 0.2667 | 36   | 0.6000 | 56                                | 0.9333 | 16   | 0.0044 |
| 17                                | 0.2833 | 37   | 0.6167 | 57                                | 0.9500 | 17   | 0.0047 |
| 18                                | 0.3000 | 38   | 0.6333 | 58                                | 0.9667 | 18   | 0.0050 |
| 19                                | 0.3167 | 39   | 0.6500 | 59                                | 0.9833 | 19   | 0.0053 |
| 20                                | 0.3333 | 40   | 0.6667 | 60                                | 1.0000 | 20   | 0.0056 |
|                                   |        |      |        |                                   |        | 21   | 0.0058 |
|                                   |        |      |        |                                   |        | 22   | 0.0061 |
|                                   |        |      |        |                                   |        | 23   | 0.0064 |
|                                   |        |      |        |                                   |        | 24   | 0.0067 |
|                                   |        |      |        |                                   |        | 25   | 0.0069 |
|                                   |        |      |        |                                   |        | 26   | 0.0072 |
|                                   |        |      |        |                                   |        | 27   | 0.0075 |
|                                   |        |      |        |                                   |        | 28   | 0.0078 |
|                                   |        |      |        |                                   |        | 29   | 0.0081 |
|                                   |        |      |        |                                   |        | 30   | 0.0083 |
|                                   |        |      |        |                                   |        | 31   | 0.0086 |
|                                   |        |      |        |                                   |        | 32   | 0.0089 |
|                                   |        |      |        |                                   |        | 33   | 0.0092 |
|                                   |        |      |        |                                   |        | 34   | 0.0094 |
|                                   |        |      |        |                                   |        | 35   | 0.0097 |
|                                   |        |      |        |                                   |        | 36   | 0.0100 |
|                                   |        |      |        |                                   |        | 37   | 0.0103 |
|                                   |        |      |        |                                   |        | 38   | 0.0106 |
|                                   |        |      |        |                                   |        | 39   | 0.0108 |
|                                   |        |      |        |                                   |        | 40   | 0.0111 |
|                                   |        |      |        |                                   |        | 41   | 0.0114 |
|                                   |        |      |        |                                   |        | 42   | 0.0117 |
|                                   |        |      |        |                                   |        | 43   | 0.0119 |
|                                   |        |      |        |                                   |        | 44   | 0.0122 |
|                                   |        |      |        |                                   |        | 45   | 0.0125 |
|                                   |        |      |        |                                   |        | 46   | 0.0128 |
|                                   |        |      |        |                                   |        | 47   | 0.0131 |
|                                   |        |      |        |                                   |        | 48   | 0.0133 |
|                                   |        |      |        |                                   |        | 49   | 0.0136 |
|                                   |        |      |        |                                   |        | 50   | 0.0139 |
|                                   |        |      |        |                                   |        | 51   | 0.0142 |
|                                   |        |      |        |                                   |        | 52   | 0.0144 |
|                                   |        |      |        |                                   |        | 53   | 0.0147 |
|                                   |        |      |        |                                   |        | 54   | 0.0150 |
|                                   |        |      |        |                                   |        | 55   | 0.0153 |
|                                   |        |      |        |                                   |        | 56   | 0.0156 |
|                                   |        |      |        |                                   |        | 57   | 0.0158 |
|                                   |        |      |        |                                   |        | 58   | 0.0161 |
|                                   |        |      |        |                                   |        | 59   | 0.0164 |
|                                   |        |      |        |                                   |        | 60   | 0.0167 |

*Example 3:* Convert 11°37" to decimals of a degree. From the left table, 11° = 0.1833 degree. From the right table, 37" = 0.0103 degree. Adding, 11°37" = 0.1833 + 0.0103 = 0.1936 degree.

*Example 4:* Convert 0.1234 degree to minutes and seconds. From the left table, 0.1167 degree = 7'. Subtracting 0.1167 from 0.1234 gives 0.0067. From the right table, 0.0067 = 24" so that 0.1234 = 7°24".

## SOLUTION OF TRIANGLES

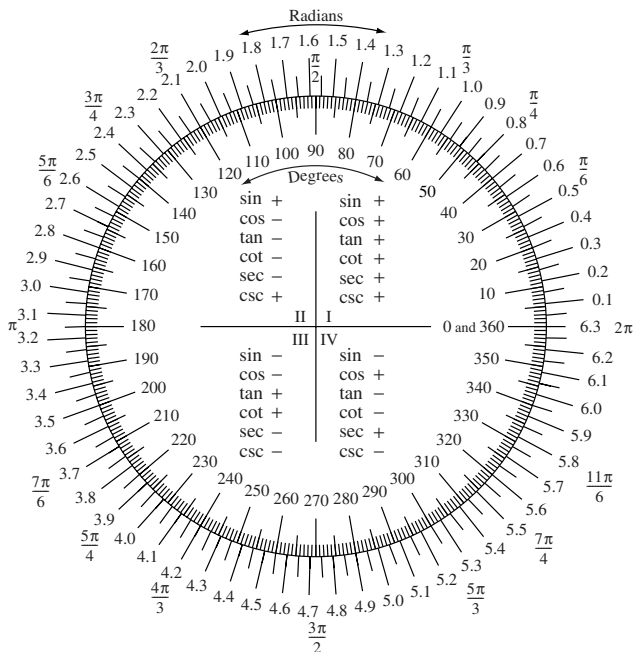
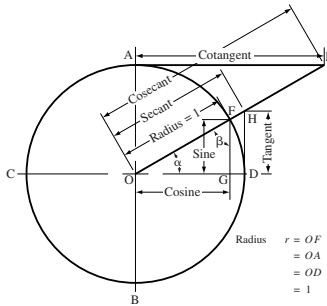


Fig. 1. Signs of Trigonometric Functions, Fractions of  $\pi$ , and Degree-Radian Conversion

**Graphic Illustrations of the Functions of Angles.**—In graphically illustrating the functions of angles, it is assumed that all distances measured in the horizontal direction to the right of line  $AB$  are positive. Those measured horizontally to the left of  $AB$  are negative. All distances measured vertically, are positive above line  $CD$  and negative below it. It can then be readily seen that the sine is positive for all angles less than 180 degrees. For angles larger than 180 degrees, the sine would be measured below  $CD$ , and is negative. The cosine is positive up to 90 degrees, but for angles larger than 90 but less than 270 degrees, the cosine is measured to the left of line  $AB$  and is negative.

The table *Useful Relationships Among Angles* that follows is arranged to show directly whether the function of any given angle is positive or negative. It also gives the limits between which the numerical values of the function vary. For example, it will be seen from the table that the cosine of an angle between 90 and 180 degrees is negative, and that its value will be somewhere between 0 and  $-1$ . In the same way, the cotangent of an angle between 180 and 270 degrees is positive and has a value between infinity and 0; in other words, the cotangent for 180 degrees is infinitely large and then the cotangent gradually decreases for increasing angles, so that the cotangent for 270 degrees equals 0.

The sine is positive for all angles up to 180 degrees. The cosine, tangent and cotangent for angles between 90 and 180 degrees, while they have the same numerical values as for angles from 0 to 90 degrees, are negative. These should be preceded by a minus sign; thus  $\tan 123$  degrees 20 minutes  $= -1.5204$ .



Graphic Illustration of the Functions of Angles

**Tables of Trigonometric Functions.**—The trigonometric (trig) tables on the following pages give numerical values for sine, cosine, tangent, and cotangent functions of angles from 0 to 90 degrees. Function values for all other angles can be obtained from the tables by applying the rules for signs of trigonometric functions and the useful relationships among angles given in the following. Secant and cosecant functions can be found from  $\sec A = 1/\cos A$  and  $\csc A = 1/\sin A$ .

The trig tables are divided by a double line. The body of each half table consists of four labeled columns of data between columns listing angles. The angles listed to the left of the data increase moving down the table, and angles listed to the right of the data increase moving up the table. Labels above the data identify the trig functions corresponding to angles listed in the left column of each half table. Labels below the data correspond to angles listed in the right column of each half table. To find the value of a function for a particular angle, first locate the angle in the table, then find the appropriate function label across the top or bottom row of the table, and find the function value at the intersection of the angle row and label column. Angles opposite each other are complementary angles (i.e., their sum equals  $90^\circ$ ) and related. For example,  $\sin 10^\circ = \cos 80^\circ$  and  $\cos 10^\circ = \sin 80^\circ$ .

All the trig functions of angles between  $0^\circ$  and  $90^\circ$  have positive values. For other angles, consult the chart below to find the sign of the function in the quadrant where the angle is located. To determine trig functions of angles greater than  $90^\circ$  subtract 90, 180, 270, or 360 from the angle to get an angle less than  $90^\circ$  and use Table 1 to find the equivalent first-quadrant function and angle to look up in the trig tables.

**Table 1. Useful Relationships Among Angles**

| Angle Function | $\theta$      | $-\theta$      | $90^\circ \pm \theta$ | $180^\circ \pm \theta$ | $270^\circ \pm \theta$ | $360^\circ \pm \theta$ |
|----------------|---------------|----------------|-----------------------|------------------------|------------------------|------------------------|
| sin            | $\sin \theta$ | $-\sin \theta$ | $+\cos \theta$        | $\mp \sin \theta$      | $-\cos \theta$         | $\pm \sin \theta$      |
| cos            | $\cos \theta$ | $+\cos \theta$ | $\mp \sin \theta$     | $-\cos \theta$         | $\pm \sin \theta$      | $+\cos \theta$         |
| tan            | $\tan \theta$ | $-\tan \theta$ | $\mp \cot \theta$     | $\pm \tan \theta$      | $\mp \cot \theta$      | $\pm \tan \theta$      |
| cot            | $\cot \theta$ | $-\cot \theta$ | $\mp \tan \theta$     | $\pm \cot \theta$      | $\mp \tan \theta$      | $\pm \cot \theta$      |
| sec            | $\sec \theta$ | $+\sec \theta$ | $\mp \csc \theta$     | $-\sec \theta$         | $\pm \csc \theta$      | $+\sec \theta$         |
| csc            | $\csc \theta$ | $-\csc \theta$ | $+\sec \theta$        | $\mp \csc \theta$      | $-\sec \theta$         | $\pm \csc \theta$      |

Examples:  $\cos (270^\circ - \theta) = -\sin \theta$ ;  $\tan (90^\circ + \theta) = -\cot \theta$ .

**Example:** Find the cosine of  $336^\circ 40'$ . The diagram in *Signs of Trigonometric Functions, Fractions of  $p$ , and Degree–Radian Conversion* shows that the cosine of every angle in Quadrant IV ( $270^\circ$  to  $360^\circ$ ) is positive. To find the angle and trig function to use when entering the trig table, subtract 270 from 336 to get  $\cos 336^\circ 40' = \cos (270^\circ + 66^\circ 40')$  and then find the intersection of the cos row and the  $270 \pm \theta$  column in Table 1. Because  $\cos (270 \pm \theta)$  in the fourth quadrant is equal to  $\pm \sin \theta$  in the first quadrant, find  $\sin 66^\circ 40'$  in the trig table. Therefore,  $\cos 336^\circ 40' = \sin 66^\circ 40' = 0.918216$ .



## Trigonometric Functions of Angles from 0° to 15° and 75° to 90°

| Angle  | sin      | cos      | tan      | cot      | Angle   | sin    | cos      | tan      | cot      | Angle    |         |
|--------|----------|----------|----------|----------|---------|--------|----------|----------|----------|----------|---------|
| 0° 0'  | 0.000000 | 1.000000 | 0.000000 | —        | 90° 0'  | 7° 30' | 0.130526 | 0.991445 | 0.131652 | 7.595754 | 82° 30' |
| 10     | 0.002909 | 0.999996 | 0.002909 | 343.7737 | 50      | 40     | 0.133410 | 0.991061 | 0.134613 | 7.428706 | 20      |
| 20     | 0.005818 | 0.999983 | 0.005818 | 171.8854 | 40      | 50     | 0.136292 | 0.990669 | 0.137576 | 7.268725 | 10      |
| 30     | 0.008727 | 0.999962 | 0.008727 | 114.5887 | 30      | 8° 0'  | 0.139173 | 0.990268 | 0.140541 | 7.115370 | 82° 0'  |
| 40     | 0.011635 | 0.999932 | 0.011636 | 85.93979 | 20      | 10     | 0.142053 | 0.989859 | 0.143508 | 6.968234 | 50      |
| 50     | 0.014544 | 0.999894 | 0.014545 | 68.75009 | 10      | 20     | 0.144932 | 0.989442 | 0.146478 | 6.826944 | 40      |
| 1° 0'  | 0.017452 | 0.999848 | 0.017455 | 57.28996 | 89° 0'  | 30     | 0.147809 | 0.989016 | 0.149451 | 6.691156 | 30      |
| 10     | 0.020361 | 0.999793 | 0.020365 | 49.10388 | 50      | 40     | 0.150686 | 0.988582 | 0.152426 | 6.560554 | 20      |
| 20     | 0.023269 | 0.999729 | 0.023275 | 42.96408 | 40      | 50     | 0.153561 | 0.988139 | 0.155404 | 6.434843 | 10      |
| 30     | 0.026177 | 0.999657 | 0.026186 | 38.18846 | 30      | 9° 0'  | 0.156434 | 0.987688 | 0.158384 | 6.313752 | 81° 0'  |
| 40     | 0.029085 | 0.999577 | 0.029097 | 34.36777 | 20      | 10     | 0.159307 | 0.987229 | 0.161368 | 6.197028 | 50      |
| 50     | 0.031992 | 0.999488 | 0.032009 | 31.24158 | 10      | 20     | 0.162178 | 0.986762 | 0.164354 | 6.084438 | 40      |
| 2° 0'  | 0.034899 | 0.999391 | 0.034921 | 28.63625 | 88° 0'  | 30     | 0.165048 | 0.986286 | 0.167343 | 5.975764 | 30      |
| 10     | 0.037806 | 0.999285 | 0.037834 | 26.43160 | 50      | 40     | 0.167916 | 0.985801 | 0.170334 | 5.870804 | 20      |
| 20     | 0.040713 | 0.999171 | 0.040747 | 24.54176 | 40      | 50     | 0.170783 | 0.985309 | 0.173329 | 5.769369 | 10      |
| 30     | 0.043619 | 0.999048 | 0.043661 | 22.90377 | 30      | 10° 0' | 0.173648 | 0.984808 | 0.176327 | 5.671282 | 80° 0'  |
| 40     | 0.046525 | 0.998917 | 0.046576 | 21.47040 | 20      | 10     | 0.176512 | 0.984298 | 0.179328 | 5.576379 | 50      |
| 50     | 0.049431 | 0.998778 | 0.049491 | 20.20555 | 10      | 20     | 0.179375 | 0.983781 | 0.182332 | 5.484505 | 40      |
| 3° 0'  | 0.052336 | 0.998630 | 0.052408 | 19.08114 | 87° 0'  | 30     | 0.182236 | 0.983255 | 0.185339 | 5.395517 | 30      |
| 10     | 0.055241 | 0.998473 | 0.055325 | 18.07498 | 50      | 40     | 0.185095 | 0.982721 | 0.188349 | 5.309279 | 20      |
| 20     | 0.058145 | 0.998308 | 0.058243 | 17.16934 | 40      | 50     | 0.187953 | 0.982178 | 0.191363 | 5.225665 | 10      |
| 30     | 0.061049 | 0.998135 | 0.061163 | 16.34986 | 30      | 11° 0' | 0.190809 | 0.981627 | 0.194380 | 5.144554 | 79° 0'  |
| 40     | 0.063952 | 0.997953 | 0.064083 | 15.60478 | 20      | 10     | 0.193664 | 0.981068 | 0.197401 | 5.065835 | 50      |
| 50     | 0.066854 | 0.997763 | 0.067004 | 14.92442 | 10      | 20     | 0.196517 | 0.980500 | 0.200425 | 4.989403 | 40      |
| 4° 0'  | 0.069756 | 0.997564 | 0.069927 | 14.30067 | 86° 0'  | 30     | 0.199368 | 0.979925 | 0.203452 | 4.915157 | 30      |
| 10     | 0.072658 | 0.997357 | 0.072851 | 13.72674 | 50      | 40     | 0.202218 | 0.979341 | 0.206483 | 4.843005 | 20      |
| 20     | 0.075559 | 0.997141 | 0.075775 | 13.19688 | 40      | 50     | 0.205065 | 0.978748 | 0.209518 | 4.772857 | 10      |
| 30     | 0.078459 | 0.996917 | 0.078702 | 12.70621 | 30      | 12° 0' | 0.207912 | 0.978148 | 0.212557 | 4.704630 | 78° 0'  |
| 40     | 0.081359 | 0.996685 | 0.081629 | 12.25051 | 20      | 10     | 0.210756 | 0.977539 | 0.215599 | 4.638246 | 50      |
| 50     | 0.084258 | 0.996444 | 0.084558 | 11.82617 | 10      | 20     | 0.213599 | 0.976921 | 0.218645 | 4.573629 | 40      |
| 5° 0'  | 0.087156 | 0.996195 | 0.087489 | 11.43005 | 85° 0'  | 30     | 0.216440 | 0.976296 | 0.221695 | 4.510709 | 30      |
| 10     | 0.090053 | 0.995937 | 0.090421 | 11.05943 | 50      | 40     | 0.219279 | 0.975662 | 0.224748 | 4.449418 | 20      |
| 20     | 0.092950 | 0.995671 | 0.093354 | 10.71191 | 40      | 50     | 0.222116 | 0.975020 | 0.227806 | 4.389694 | 10      |
| 30     | 0.095846 | 0.995396 | 0.096289 | 10.38540 | 30      | 13° 0' | 0.224951 | 0.974370 | 0.230868 | 4.331476 | 77° 0'  |
| 40     | 0.098741 | 0.995113 | 0.099226 | 10.07803 | 20      | 10     | 0.227784 | 0.973712 | 0.233934 | 4.274707 | 50      |
| 50     | 0.101635 | 0.994822 | 0.102164 | 9.788173 | 10      | 20     | 0.230616 | 0.973045 | 0.237004 | 4.219332 | 40      |
| 6° 0'  | 0.104528 | 0.994522 | 0.105104 | 9.514364 | 84° 0'  | 30     | 0.233445 | 0.972370 | 0.240079 | 4.165300 | 30      |
| 10     | 0.107421 | 0.994214 | 0.108046 | 9.255304 | 50      | 40     | 0.236273 | 0.971687 | 0.243157 | 4.112561 | 20      |
| 20     | 0.110313 | 0.993897 | 0.110990 | 9.009826 | 40      | 50     | 0.239098 | 0.970995 | 0.246241 | 4.061070 | 10      |
| 30     | 0.113203 | 0.993572 | 0.113936 | 8.776887 | 30      | 14° 0' | 0.241922 | 0.970296 | 0.249328 | 4.010781 | 76° 0'  |
| 40     | 0.116093 | 0.993238 | 0.116883 | 8.555547 | 20      | 10     | 0.244743 | 0.969588 | 0.252420 | 3.961652 | 50      |
| 50     | 0.118982 | 0.992896 | 0.119833 | 8.344956 | 10      | 20     | 0.247563 | 0.968872 | 0.255516 | 3.913642 | 40      |
| 7° 0'  | 0.121869 | 0.992546 | 0.122785 | 8.144346 | 83° 0'  | 30     | 0.250380 | 0.968148 | 0.258618 | 3.866713 | 30      |
| 10     | 0.124756 | 0.992187 | 0.125738 | 7.953022 | 50      | 40     | 0.253195 | 0.967415 | 0.261723 | 3.820828 | 20      |
| 20     | 0.127642 | 0.991820 | 0.128694 | 7.770351 | 40      | 50     | 0.256008 | 0.966675 | 0.264834 | 3.775952 | 10      |
| 7° 30' | 0.130526 | 0.991445 | 0.131652 | 7.595754 | 82° 30' | 15° 0' | 0.258819 | 0.965926 | 0.267949 | 3.732051 | 75° 0'  |
|        | cos      | sin      | cot      | tan      | Angle   |        | cos      | sin      | cot      | tan      | Angle   |

For angles 0° to 15° 0' (angles found in a column to the left of the data), use the column labels at the top of the table; for angles 75° to 90° 0' (angles found in a column to the right of the data), use the column labels at the bottom of the table.

## Trigonometric Functions of Angles from 15° to 30° and 60° to 75°

| Angle   | sin      | cos      | tan      | cot      | Angle   | sin      | cos      | tan      | cot      | Angle    |        |
|---------|----------|----------|----------|----------|---------|----------|----------|----------|----------|----------|--------|
| 15° 0'  | 0.258819 | 0.965926 | 0.267949 | 3.732051 | 75° 0'  | 0.382683 | 0.923880 | 0.414214 | 2.414214 | 67° 30'  |        |
| 10      | 0.261628 | 0.965169 | 0.271069 | 3.689093 | 50      | 0.385369 | 0.922762 | 0.417626 | 2.394489 | 20       |        |
| 20      | 0.264434 | 0.964404 | 0.274194 | 3.647047 | 40      | 0.388052 | 0.921638 | 0.421046 | 2.375037 | 10       |        |
| 30      | 0.267238 | 0.963630 | 0.277325 | 3.605884 | 30      | 23° 0'   | 0.390731 | 0.920505 | 0.424475 | 2.355852 | 67° 0' |
| 40      | 0.270040 | 0.962849 | 0.280460 | 3.565575 | 20      | 10       | 0.393407 | 0.919364 | 0.427912 | 2.336929 | 50     |
| 50      | 0.272840 | 0.962059 | 0.283600 | 3.526094 | 10      | 20       | 0.396080 | 0.918216 | 0.431358 | 2.318261 | 40     |
| 16° 0'  | 0.275637 | 0.961262 | 0.286745 | 3.487414 | 74° 0'  | 30       | 0.398749 | 0.917060 | 0.434812 | 2.299843 | 30     |
| 10      | 0.278432 | 0.960456 | 0.289896 | 3.449512 | 50      | 40       | 0.401415 | 0.915896 | 0.438276 | 2.281669 | 20     |
| 20      | 0.281225 | 0.959642 | 0.293052 | 3.412363 | 40      | 50       | 0.404078 | 0.914725 | 0.441748 | 2.263736 | 10     |
| 30      | 0.284015 | 0.958820 | 0.296213 | 3.375943 | 30      | 24° 0'   | 0.406737 | 0.913545 | 0.445229 | 2.246037 | 66° 0' |
| 40      | 0.286803 | 0.957990 | 0.299380 | 3.340233 | 20      | 10       | 0.409392 | 0.912358 | 0.448719 | 2.228568 | 50     |
| 50      | 0.289589 | 0.957151 | 0.302553 | 3.305209 | 10      | 20       | 0.412045 | 0.911164 | 0.452218 | 2.211323 | 40     |
| 17° 0'  | 0.292372 | 0.956305 | 0.305731 | 3.270853 | 73° 0'  | 30       | 0.414693 | 0.909961 | 0.455726 | 2.194300 | 30     |
| 10      | 0.295152 | 0.955450 | 0.308914 | 3.237144 | 50      | 40       | 0.417338 | 0.908751 | 0.459244 | 2.177492 | 20     |
| 20      | 0.297930 | 0.954588 | 0.312104 | 3.204064 | 40      | 50       | 0.419980 | 0.907533 | 0.462771 | 2.160896 | 10     |
| 30      | 0.300706 | 0.953717 | 0.315299 | 3.171595 | 30      | 25° 0'   | 0.422618 | 0.906308 | 0.466308 | 2.144507 | 65° 0' |
| 40      | 0.303479 | 0.952838 | 0.318500 | 3.139719 | 20      | 10       | 0.425253 | 0.905075 | 0.469854 | 2.128321 | 50     |
| 50      | 0.306249 | 0.951951 | 0.321707 | 3.108421 | 10      | 20       | 0.427884 | 0.903834 | 0.473410 | 2.112335 | 40     |
| 18° 0'  | 0.309017 | 0.951057 | 0.324920 | 3.077684 | 72° 0'  | 30       | 0.430511 | 0.902585 | 0.476976 | 2.096544 | 30     |
| 10      | 0.311782 | 0.950154 | 0.328139 | 3.047492 | 50      | 40       | 0.433135 | 0.901329 | 0.480551 | 2.080944 | 20     |
| 20      | 0.314545 | 0.949243 | 0.331364 | 3.017830 | 40      | 50       | 0.435755 | 0.900065 | 0.484137 | 2.065532 | 10     |
| 30      | 0.317305 | 0.948324 | 0.334595 | 2.988685 | 30      | 26° 0'   | 0.438371 | 0.898794 | 0.487733 | 2.050304 | 64° 0' |
| 40      | 0.320062 | 0.947397 | 0.337833 | 2.960042 | 20      | 10       | 0.440984 | 0.897515 | 0.491339 | 2.035256 | 50     |
| 50      | 0.322816 | 0.946462 | 0.341077 | 2.931888 | 10      | 20       | 0.443593 | 0.896229 | 0.494955 | 2.020386 | 40     |
| 19° 0'  | 0.325568 | 0.945519 | 0.344328 | 2.904211 | 71° 0'  | 30       | 0.446198 | 0.894934 | 0.498582 | 2.005690 | 30     |
| 10      | 0.328317 | 0.944568 | 0.347585 | 2.876997 | 50      | 40       | 0.448799 | 0.893633 | 0.502219 | 1.991164 | 20     |
| 20      | 0.331063 | 0.943609 | 0.350848 | 2.850235 | 40      | 50       | 0.451397 | 0.892323 | 0.505867 | 1.976805 | 10     |
| 30      | 0.333807 | 0.942641 | 0.354119 | 2.823913 | 30      | 27° 0'   | 0.453990 | 0.891007 | 0.509525 | 1.962611 | 63° 0' |
| 40      | 0.336547 | 0.941666 | 0.357396 | 2.798020 | 20      | 10       | 0.456580 | 0.889682 | 0.513195 | 1.948577 | 50     |
| 50      | 0.339285 | 0.940684 | 0.360679 | 2.772545 | 10      | 20       | 0.459166 | 0.888350 | 0.516875 | 1.934702 | 40     |
| 20° 0'  | 0.342020 | 0.939693 | 0.363970 | 2.747477 | 70° 0'  | 30       | 0.461749 | 0.887011 | 0.520567 | 1.920982 | 30     |
| 10      | 0.344752 | 0.938694 | 0.367268 | 2.722808 | 50      | 40       | 0.464327 | 0.885664 | 0.524270 | 1.907415 | 20     |
| 20      | 0.347481 | 0.937687 | 0.370573 | 2.698525 | 40      | 50       | 0.466901 | 0.884309 | 0.527984 | 1.893997 | 10     |
| 30      | 0.350207 | 0.936672 | 0.373885 | 2.674621 | 30      | 28° 0'   | 0.469472 | 0.882948 | 0.531709 | 1.880726 | 62° 0' |
| 40      | 0.352931 | 0.935650 | 0.377204 | 2.651087 | 20      | 10       | 0.472038 | 0.881578 | 0.535446 | 1.867600 | 50     |
| 50      | 0.355651 | 0.934619 | 0.380530 | 2.627912 | 10      | 20       | 0.474600 | 0.880201 | 0.539195 | 1.854616 | 40     |
| 21° 0'  | 0.358368 | 0.933580 | 0.383864 | 2.605089 | 69° 0'  | 30       | 0.477159 | 0.878817 | 0.542956 | 1.841771 | 30     |
| 10      | 0.361082 | 0.932534 | 0.387205 | 2.582609 | 50      | 40       | 0.479713 | 0.877425 | 0.546728 | 1.829063 | 20     |
| 20      | 0.363793 | 0.931480 | 0.390554 | 2.560465 | 40      | 50       | 0.482263 | 0.876026 | 0.550513 | 1.816489 | 10     |
| 30      | 0.366501 | 0.930418 | 0.393910 | 2.538648 | 30      | 29° 0'   | 0.484810 | 0.874620 | 0.554309 | 1.804048 | 61° 0' |
| 40      | 0.369206 | 0.929348 | 0.397275 | 2.517151 | 20      | 10       | 0.487352 | 0.873206 | 0.558118 | 1.791736 | 50     |
| 50      | 0.371908 | 0.928270 | 0.400646 | 2.495966 | 10      | 20       | 0.489890 | 0.871784 | 0.561939 | 1.779552 | 40     |
| 22° 0'  | 0.374607 | 0.927184 | 0.404026 | 2.475087 | 68° 0'  | 30       | 0.492424 | 0.870356 | 0.565773 | 1.767494 | 30     |
| 10      | 0.377302 | 0.926090 | 0.407414 | 2.454506 | 50      | 40       | 0.494953 | 0.868920 | 0.569619 | 1.755559 | 20     |
| 20      | 0.379994 | 0.924989 | 0.410810 | 2.434217 | 40      | 50       | 0.497479 | 0.867476 | 0.573478 | 1.743745 | 10     |
| 22° 30' | 0.382683 | 0.923880 | 0.414214 | 2.414214 | 67° 30' | 30° 0'   | 0.500000 | 0.866025 | 0.577350 | 1.732051 | 60° 0' |
|         | cos      | sin      | cot      | tan      | Angle   |          | cos      | sin      | cot      | tan      | Angle  |

For angles 15° to 30° 0' (angles found in a column to the left of the data), use the column labels at the top of the table; for angles 60° to 75° 0' (angles found in a column to the right of the data), use the column labels at the bottom of the table.

## Trigonometric Functions of Angles from 30° to 60°

| Angle   | sin      | cos      | tan      | cot      |       | Angle   | sin      | cos      | tan      | cot      |         |
|---------|----------|----------|----------|----------|-------|---------|----------|----------|----------|----------|---------|
| 30° 0'  | 0.500000 | 0.866025 | 0.577350 | 1.732051 |       | 60° 0'  | 0.608761 | 0.793353 | 0.767327 | 1.303225 | 52° 30' |
| 10      | 0.502517 | 0.864567 | 0.581235 | 1.720474 |       | 50      | 0.611067 | 0.791579 | 0.771959 | 1.295406 | 20      |
| 20      | 0.505030 | 0.863102 | 0.585134 | 1.709012 |       | 40      | 0.613367 | 0.789798 | 0.776612 | 1.287645 | 10      |
| 30      | 0.507538 | 0.861629 | 0.589045 | 1.697663 |       | 30      | 0.615661 | 0.788011 | 0.781286 | 1.279942 | 52° 0'  |
| 40      | 0.510043 | 0.860149 | 0.592970 | 1.686426 |       | 20      | 0.617951 | 0.786217 | 0.785981 | 1.272296 | 50      |
| 50      | 0.512543 | 0.858662 | 0.596908 | 1.675299 |       | 10      | 0.620235 | 0.784416 | 0.790697 | 1.264706 | 40      |
| 31° 0'  | 0.515038 | 0.857167 | 0.600861 | 1.664279 |       | 59° 0'  | 0.622515 | 0.782608 | 0.795436 | 1.257172 | 30      |
| 10      | 0.517529 | 0.855665 | 0.604827 | 1.653366 |       | 50      | 0.624789 | 0.780794 | 0.800196 | 1.249693 | 20      |
| 20      | 0.520016 | 0.854156 | 0.608807 | 1.642558 |       | 40      | 0.627057 | 0.778973 | 0.804979 | 1.242268 | 10      |
| 30      | 0.522499 | 0.852640 | 0.612801 | 1.631852 |       | 30      | 0.629320 | 0.777146 | 0.809784 | 1.234897 | 51° 0'  |
| 40      | 0.524977 | 0.851117 | 0.616809 | 1.621247 |       | 20      | 0.631578 | 0.775312 | 0.814612 | 1.227579 | 50      |
| 50      | 0.527450 | 0.849586 | 0.620832 | 1.610742 |       | 10      | 0.633831 | 0.773472 | 0.819463 | 1.220312 | 40      |
| 32° 0'  | 0.529919 | 0.848048 | 0.624869 | 1.600335 |       | 58° 0'  | 0.636078 | 0.771625 | 0.824336 | 1.213097 | 30      |
| 10      | 0.532384 | 0.846503 | 0.628921 | 1.590024 |       | 50      | 0.638320 | 0.769771 | 0.829234 | 1.205933 | 20      |
| 20      | 0.534844 | 0.844951 | 0.632988 | 1.579808 |       | 40      | 0.640557 | 0.767911 | 0.834155 | 1.198818 | 10      |
| 30      | 0.537300 | 0.843391 | 0.637070 | 1.569686 |       | 30      | 0.642788 | 0.766044 | 0.839100 | 1.191754 | 50° 0'  |
| 40      | 0.539751 | 0.841825 | 0.641167 | 1.559655 |       | 20      | 0.645013 | 0.764171 | 0.844069 | 1.184738 | 50      |
| 50      | 0.542197 | 0.840251 | 0.645280 | 1.549715 |       | 10      | 0.647233 | 0.762292 | 0.849062 | 1.177770 | 40      |
| 33° 0'  | 0.544639 | 0.838671 | 0.649408 | 1.539865 |       | 57° 0'  | 0.649448 | 0.760406 | 0.854081 | 1.170850 | 30      |
| 10      | 0.547076 | 0.837083 | 0.653551 | 1.530102 |       | 50      | 0.651657 | 0.758514 | 0.859124 | 1.163976 | 20      |
| 20      | 0.549509 | 0.835488 | 0.657710 | 1.520426 |       | 40      | 0.653861 | 0.756615 | 0.864193 | 1.157149 | 10      |
| 30      | 0.551937 | 0.833886 | 0.661886 | 1.510835 |       | 30      | 0.656059 | 0.754710 | 0.869287 | 1.150368 | 49° 0'  |
| 40      | 0.554360 | 0.832277 | 0.666077 | 1.501328 |       | 20      | 0.658252 | 0.752798 | 0.874407 | 1.143633 | 40      |
| 50      | 0.556779 | 0.830661 | 0.670284 | 1.491904 |       | 10      | 0.660439 | 0.750880 | 0.879553 | 1.136941 | 50      |
| 34° 0'  | 0.559193 | 0.829038 | 0.674509 | 1.482561 |       | 56° 0'  | 0.662620 | 0.748956 | 0.884725 | 1.130294 | 30      |
| 10      | 0.561602 | 0.827407 | 0.678749 | 1.473298 |       | 50      | 0.664796 | 0.747025 | 0.889924 | 1.123691 | 20      |
| 20      | 0.564007 | 0.825770 | 0.683007 | 1.464115 |       | 40      | 0.666966 | 0.745088 | 0.895151 | 1.117130 | 10      |
| 30      | 0.566406 | 0.824126 | 0.687281 | 1.455009 |       | 30      | 0.669131 | 0.743145 | 0.900404 | 1.110613 | 48° 0'  |
| 40      | 0.568801 | 0.822475 | 0.691572 | 1.445980 |       | 20      | 0.671289 | 0.741195 | 0.905685 | 1.104137 | 50      |
| 50      | 0.571191 | 0.820817 | 0.695881 | 1.437027 |       | 10      | 0.673443 | 0.739239 | 0.910994 | 1.097702 | 40      |
| 35° 0'  | 0.573576 | 0.819152 | 0.700208 | 1.428148 |       | 55° 0'  | 0.675590 | 0.737277 | 0.916331 | 1.091309 | 30      |
| 10      | 0.575957 | 0.817480 | 0.704551 | 1.419343 |       | 50      | 0.677732 | 0.735309 | 0.921697 | 1.084955 | 20      |
| 20      | 0.578332 | 0.815801 | 0.708913 | 1.410610 |       | 40      | 0.679868 | 0.733334 | 0.927091 | 1.078642 | 10      |
| 30      | 0.580703 | 0.814116 | 0.713293 | 1.401948 |       | 30      | 0.681998 | 0.731354 | 0.932515 | 1.072369 | 47° 0'  |
| 40      | 0.583069 | 0.812423 | 0.717691 | 1.393357 |       | 20      | 0.684123 | 0.729367 | 0.937968 | 1.066134 | 50      |
| 50      | 0.585429 | 0.810723 | 0.722108 | 1.384835 |       | 10      | 0.686242 | 0.727374 | 0.943451 | 1.059938 | 40      |
| 36° 0'  | 0.587785 | 0.809017 | 0.726543 | 1.376382 |       | 54° 0'  | 0.688355 | 0.725374 | 0.948965 | 1.053780 | 30      |
| 10      | 0.590136 | 0.807304 | 0.730996 | 1.367996 |       | 50      | 0.690462 | 0.723369 | 0.954508 | 1.047660 | 20      |
| 20      | 0.592482 | 0.805584 | 0.735469 | 1.359676 |       | 40      | 0.692563 | 0.721357 | 0.960083 | 1.041577 | 10      |
| 30      | 0.594823 | 0.803857 | 0.739961 | 1.351422 |       | 30      | 0.694658 | 0.719340 | 0.965689 | 1.035530 | 46° 0'  |
| 40      | 0.597159 | 0.802123 | 0.744472 | 1.343233 |       | 20      | 0.696748 | 0.717316 | 0.971326 | 1.029520 | 50      |
| 50      | 0.599489 | 0.800383 | 0.749003 | 1.335108 |       | 10      | 0.698832 | 0.715286 | 0.976996 | 1.023546 | 40      |
| 37° 0'  | 0.601815 | 0.798636 | 0.753554 | 1.327045 |       | 53° 0'  | 0.700909 | 0.713250 | 0.982697 | 1.017607 | 30      |
| 10      | 0.604136 | 0.796882 | 0.758125 | 1.319044 |       | 50      | 0.702981 | 0.711209 | 0.988432 | 1.011704 | 20      |
| 20      | 0.606451 | 0.795121 | 0.762716 | 1.311105 |       | 40      | 0.705047 | 0.709161 | 0.994199 | 1.005835 | 10      |
| 37° 30' | 0.608761 | 0.793353 | 0.767327 | 1.303225 |       | 52° 30' | 0.707107 | 0.707107 | 1.000000 | 1.000000 | 45° 0'  |
|         | cos      | sin      | cot      | tan      | Angle |         | cos      | sin      | cot      | tan      | Angle   |

For angles 30° to 45° 0' (angles found in a column to the left of the data), use the column labels at the top of the table; for angles 45° to 60° 0' (angles found in a column to the right of the data), use the column labels at the bottom of the table.

**Using a Calculator to Find Trig Functions.**—A scientific calculator is quicker and more accurate than tables for finding trig functions and angles corresponding to trig functions. On scientific calculators, the keys labeled **sin**, **cos**, and **tan** are used to find the common trig functions. The other functions can be found by using the same keys and the **1/x** key, noting that  $\csc A = 1/\sin A$ ,  $\sec A = 1/\cos A$ , and  $\cot A = 1/\tan A$ . The specific keystrokes used will vary slightly from one calculator to another. To find the angle corresponding to a given trig function use the keys labeled **sin<sup>-1</sup>**, **cos<sup>-1</sup>**, and **tan<sup>-1</sup>**. On some other calculators, the **sin**, **cos**, and **tan** are used in combination with the **INV**, or inverse, key to find the number corresponding to a given trig function.

If a scientific calculator or computer is not available, tables are the easiest way to find trig values. However, trig function values can be calculated very accurately without a scientific calculator by using the following formulas:

$$\begin{aligned}\sin A &= A - \frac{A^3}{3!} + \frac{A^5}{5!} - \frac{A^7}{7!} \pm \dots & \cos A &= 1 - \frac{A^2}{2!} + \frac{A^4}{4!} - \frac{A^6}{6!} \pm \dots \\ \sin^{-1} A &= \frac{1}{2} \times \frac{A^3}{3} + \frac{1}{2} \times \frac{3}{4} \times \frac{A^5}{5} + \dots & \tan^{-1} A &= A - \frac{A^3}{3} + \frac{A^5}{5} - \frac{A^7}{7} \pm \dots\end{aligned}$$

where the angle  $A$  is expressed in radians (convert degrees to radians by multiplying degrees by  $\pi/180 = 0.0174533$ ). The three dots at the ends of the formulas indicate that the expression continues with more terms following the sequence established by the first few terms. Generally, calculating just three or four terms of the expression is sufficient for accuracy. In these formulas, a number followed by the symbol **!** is called a factorial (for example,  $3!$  is three factorial). Except for  $0!$ , which is defined as 1, a factorial is found by multiplying together all the integers greater than zero and less than or equal to the factorial number wanted. For example:  $3! = 1 \times 2 \times 3 = 6$ ;  $4! = 1 \times 2 \times 3 \times 4 = 24$ ;  $7! = 1 \times 2 \times 3 \times 4 \times 5 \times 6 \times 7 = 5040$ ; etc.

**Versed Sine and Versed Cosine.**—These functions are sometimes used in formulas for segments of a circle and may be obtained using the relationships:

$$\text{versed } \sin \theta = 1 - \cos \theta; \text{ versed } \cos \theta = 1 - \sin \theta.$$

**Sevolute Functions.**—Sevolute functions are used in calculating the form diameter of involute splines. They are computed by subtracting the involute function of an angle from the secant of the angle ( $1/\cosine = \text{secant}$ ). Thus, sevolute of 20 degrees = secant of 20 degrees - involute function of 20 degrees =  $1.064178 - 0.014904 = 1.049274$ .

**Involute Functions.**—Involute functions are used in certain formulas relating to the design and measurement of gear teeth as well as measurement of threads over wires. See, for example, pages 1901 through 1904, 2111, and 2175.

The tables on the following pages provide values of involute functions for angles from 14 to 51 degrees in increments of 1 minute. These involute functions were calculated from the following formulas: Involute of  $\theta = \tan \theta - \theta$ , for  $\theta$  in radians, and involute of  $\theta = \tan \theta - \pi \times \theta/180$ , for  $\theta$  in degrees.

*Example:* For an angle of 14 degrees and 10 minutes, the involute function is found as follows: 10 minutes =  $10/60 = 0.166666$  degrees,  $14 + 0.166666 = 14.166666$  degree, so that the involute of 14.166666 degrees =  $\tan 14.166666 - \pi \times 14.166666/180 = 0.252420 - 0.247255 = 0.005165$ . This value is the same as that in the table *Involute Functions for Angles from 14 to 23 Degrees* for 14 degrees and 10 minutes. The same result would be obtained from using the conversion tables beginning on page 96 to convert 14 degrees and 10 minutes to radians and then applying the first of the formulas given above.

## INVOLUTE FUNCTIONS

## Involute Functions for Angles from 14 to 23 Degrees

| Minutes | Degrees            |          |          |          |          |          |          |          |          |
|---------|--------------------|----------|----------|----------|----------|----------|----------|----------|----------|
|         | 14                 | 15       | 16       | 17       | 18       | 19       | 20       | 21       | 22       |
|         | Involute Functions |          |          |          |          |          |          |          |          |
| 0       | 0.004982           | 0.006150 | 0.007493 | 0.009025 | 0.010760 | 0.012715 | 0.014904 | 0.017345 | 0.020054 |
| 1       | 0.005000           | 0.006171 | 0.007517 | 0.009052 | 0.010791 | 0.012750 | 0.014943 | 0.017388 | 0.020101 |
| 2       | 0.005018           | 0.006192 | 0.007541 | 0.009079 | 0.010822 | 0.012784 | 0.014982 | 0.017431 | 0.020149 |
| 3       | 0.005036           | 0.006213 | 0.007565 | 0.009107 | 0.010853 | 0.012819 | 0.015020 | 0.017474 | 0.020197 |
| 4       | 0.005055           | 0.006234 | 0.007589 | 0.009134 | 0.010884 | 0.012854 | 0.015059 | 0.017517 | 0.020244 |
| 5       | 0.005073           | 0.006255 | 0.007613 | 0.009161 | 0.010915 | 0.012888 | 0.015098 | 0.017560 | 0.020292 |
| 6       | 0.005091           | 0.006276 | 0.007637 | 0.009189 | 0.010946 | 0.012923 | 0.015137 | 0.017603 | 0.020340 |
| 7       | 0.005110           | 0.006297 | 0.007661 | 0.009216 | 0.010977 | 0.012958 | 0.015176 | 0.017647 | 0.020388 |
| 8       | 0.005128           | 0.006318 | 0.007686 | 0.009244 | 0.011008 | 0.012993 | 0.015215 | 0.017690 | 0.020436 |
| 9       | 0.005146           | 0.006340 | 0.007710 | 0.009272 | 0.011039 | 0.013028 | 0.015254 | 0.017734 | 0.020484 |
| 10      | 0.005165           | 0.006361 | 0.007735 | 0.009299 | 0.011071 | 0.013063 | 0.015293 | 0.017777 | 0.020533 |
| 11      | 0.005184           | 0.006382 | 0.007759 | 0.009327 | 0.011102 | 0.013098 | 0.015333 | 0.017821 | 0.020581 |
| 12      | 0.005202           | 0.006404 | 0.007784 | 0.009355 | 0.011133 | 0.013134 | 0.015372 | 0.017865 | 0.020629 |
| 13      | 0.005221           | 0.006425 | 0.007808 | 0.009383 | 0.011165 | 0.013169 | 0.015411 | 0.017908 | 0.020678 |
| 14      | 0.005239           | 0.006447 | 0.007833 | 0.009411 | 0.011196 | 0.013204 | 0.015451 | 0.017952 | 0.020726 |
| 15      | 0.005258           | 0.006469 | 0.007857 | 0.009439 | 0.011228 | 0.013240 | 0.015490 | 0.017996 | 0.020775 |
| 16      | 0.005277           | 0.006490 | 0.007882 | 0.009467 | 0.011260 | 0.013275 | 0.015530 | 0.018040 | 0.020824 |
| 17      | 0.005296           | 0.006512 | 0.007907 | 0.009495 | 0.011291 | 0.013311 | 0.015570 | 0.018084 | 0.020873 |
| 18      | 0.005315           | 0.006534 | 0.007932 | 0.009523 | 0.011323 | 0.013346 | 0.015609 | 0.018129 | 0.020921 |
| 19      | 0.005334           | 0.006555 | 0.007957 | 0.009552 | 0.011355 | 0.013382 | 0.015649 | 0.018173 | 0.020970 |
| 20      | 0.005353           | 0.006577 | 0.007982 | 0.009580 | 0.011387 | 0.013418 | 0.015689 | 0.018217 | 0.021019 |
| 21      | 0.005372           | 0.006599 | 0.008007 | 0.009608 | 0.011419 | 0.013454 | 0.015729 | 0.018262 | 0.021069 |
| 22      | 0.005391           | 0.006621 | 0.008032 | 0.009637 | 0.011451 | 0.013490 | 0.015769 | 0.018306 | 0.021118 |
| 23      | 0.005410           | 0.006643 | 0.008057 | 0.009665 | 0.011483 | 0.013526 | 0.015809 | 0.018351 | 0.021167 |
| 24      | 0.005429           | 0.006665 | 0.008082 | 0.009694 | 0.011515 | 0.013562 | 0.015850 | 0.018395 | 0.021217 |
| 25      | 0.005448           | 0.006687 | 0.008107 | 0.009722 | 0.011547 | 0.013598 | 0.015890 | 0.018440 | 0.021266 |
| 26      | 0.005467           | 0.006709 | 0.008133 | 0.009751 | 0.011580 | 0.013634 | 0.015930 | 0.018485 | 0.021316 |
| 27      | 0.005487           | 0.006732 | 0.008158 | 0.009780 | 0.011612 | 0.013670 | 0.015971 | 0.018530 | 0.021365 |
| 28      | 0.005506           | 0.006754 | 0.008183 | 0.009808 | 0.011644 | 0.013707 | 0.016011 | 0.018575 | 0.021415 |
| 29      | 0.005525           | 0.006776 | 0.008209 | 0.009837 | 0.011677 | 0.013743 | 0.016052 | 0.018620 | 0.021465 |
| 30      | 0.005545           | 0.006799 | 0.008234 | 0.009866 | 0.011709 | 0.013779 | 0.016092 | 0.018665 | 0.021514 |
| 31      | 0.005564           | 0.006821 | 0.008260 | 0.009895 | 0.011742 | 0.013816 | 0.016133 | 0.018710 | 0.021564 |
| 32      | 0.005584           | 0.006843 | 0.008285 | 0.009924 | 0.011775 | 0.013852 | 0.016174 | 0.018755 | 0.021614 |
| 33      | 0.005603           | 0.006866 | 0.008311 | 0.009953 | 0.011807 | 0.013889 | 0.016215 | 0.018800 | 0.021665 |
| 34      | 0.005623           | 0.006888 | 0.008337 | 0.009982 | 0.011840 | 0.013926 | 0.016255 | 0.018846 | 0.021715 |
| 35      | 0.005643           | 0.006911 | 0.008362 | 0.010011 | 0.011873 | 0.013963 | 0.016296 | 0.018891 | 0.021765 |
| 36      | 0.005662           | 0.006934 | 0.008388 | 0.010041 | 0.011906 | 0.013999 | 0.016337 | 0.018937 | 0.021815 |
| 37      | 0.005682           | 0.006956 | 0.008414 | 0.010070 | 0.011939 | 0.014036 | 0.016379 | 0.018983 | 0.021866 |
| 38      | 0.005702           | 0.006979 | 0.008440 | 0.010100 | 0.011972 | 0.014073 | 0.016420 | 0.019028 | 0.021916 |
| 39      | 0.005722           | 0.007002 | 0.008466 | 0.010129 | 0.012005 | 0.014110 | 0.016461 | 0.019074 | 0.021967 |
| 40      | 0.005742           | 0.007025 | 0.008492 | 0.010158 | 0.012038 | 0.014148 | 0.016502 | 0.019120 | 0.022018 |
| 41      | 0.005762           | 0.007048 | 0.008518 | 0.010188 | 0.012071 | 0.014185 | 0.016544 | 0.019166 | 0.022068 |
| 42      | 0.005782           | 0.007071 | 0.008544 | 0.010217 | 0.012105 | 0.014222 | 0.016585 | 0.019212 | 0.022119 |
| 43      | 0.005802           | 0.007094 | 0.008571 | 0.010247 | 0.012138 | 0.014259 | 0.016627 | 0.019258 | 0.022170 |
| 44      | 0.005822           | 0.007117 | 0.008597 | 0.010277 | 0.012172 | 0.014297 | 0.016669 | 0.019304 | 0.022221 |
| 45      | 0.005842           | 0.007140 | 0.008623 | 0.010307 | 0.012205 | 0.014334 | 0.016710 | 0.019350 | 0.022272 |
| 46      | 0.005862           | 0.007163 | 0.008650 | 0.010336 | 0.012239 | 0.014372 | 0.016752 | 0.019397 | 0.022324 |
| 47      | 0.005882           | 0.007186 | 0.008676 | 0.010366 | 0.012272 | 0.014409 | 0.016794 | 0.019443 | 0.022375 |
| 48      | 0.005903           | 0.007209 | 0.008702 | 0.010396 | 0.012306 | 0.014447 | 0.016836 | 0.019490 | 0.022426 |
| 49      | 0.005923           | 0.007233 | 0.008729 | 0.010426 | 0.012340 | 0.014485 | 0.016878 | 0.019536 | 0.022478 |
| 50      | 0.005943           | 0.007256 | 0.008756 | 0.010456 | 0.012373 | 0.014523 | 0.016920 | 0.019583 | 0.022529 |
| 51      | 0.005964           | 0.007280 | 0.008782 | 0.010486 | 0.012407 | 0.014560 | 0.016962 | 0.019630 | 0.022581 |
| 52      | 0.005984           | 0.007303 | 0.008809 | 0.010517 | 0.012441 | 0.014598 | 0.017004 | 0.019676 | 0.022633 |
| 53      | 0.006005           | 0.007327 | 0.008836 | 0.010547 | 0.012475 | 0.014636 | 0.017047 | 0.019723 | 0.022684 |
| 54      | 0.006025           | 0.007350 | 0.008863 | 0.010577 | 0.012509 | 0.014674 | 0.017089 | 0.019770 | 0.022736 |
| 55      | 0.006046           | 0.007374 | 0.008889 | 0.010608 | 0.012543 | 0.014713 | 0.017132 | 0.019817 | 0.022788 |
| 56      | 0.006067           | 0.007397 | 0.008916 | 0.010638 | 0.012578 | 0.014751 | 0.017174 | 0.019864 | 0.022840 |
| 57      | 0.006087           | 0.007421 | 0.008943 | 0.010669 | 0.012612 | 0.014789 | 0.017217 | 0.019912 | 0.022892 |
| 58      | 0.006108           | 0.007445 | 0.008970 | 0.010699 | 0.012646 | 0.014827 | 0.017259 | 0.019959 | 0.022944 |
| 59      | 0.006129           | 0.007469 | 0.008998 | 0.010730 | 0.012681 | 0.014866 | 0.017302 | 0.020006 | 0.022997 |
| 60      | 0.006150           | 0.007493 | 0.009025 | 0.010760 | 0.012715 | 0.014904 | 0.017345 | 0.020054 | 0.023049 |

## INVOLUTE FUNCTIONS

## Involute Functions for Angles from 23 to 32 Degrees

| Minutes | Degrees            |          |          |          |          |          |          |          |          |
|---------|--------------------|----------|----------|----------|----------|----------|----------|----------|----------|
|         | 23                 | 24       | 25       | 26       | 27       | 28       | 29       | 30       | 31       |
|         | Involute Functions |          |          |          |          |          |          |          |          |
| 0       | 0.023049           | 0.026350 | 0.029975 | 0.033947 | 0.038287 | 0.043017 | 0.048164 | 0.053752 | 0.059809 |
| 1       | 0.023102           | 0.026407 | 0.030039 | 0.034016 | 0.038362 | 0.043100 | 0.048253 | 0.053849 | 0.059914 |
| 2       | 0.023154           | 0.026465 | 0.030102 | 0.034086 | 0.038438 | 0.043182 | 0.048343 | 0.053946 | 0.060019 |
| 3       | 0.023207           | 0.026523 | 0.030166 | 0.034155 | 0.038514 | 0.043264 | 0.048432 | 0.054043 | 0.060124 |
| 4       | 0.023259           | 0.026581 | 0.030229 | 0.034225 | 0.038590 | 0.043347 | 0.048522 | 0.054140 | 0.060230 |
| 5       | 0.023312           | 0.026639 | 0.030293 | 0.034294 | 0.038666 | 0.043430 | 0.048612 | 0.054238 | 0.060335 |
| 6       | 0.023365           | 0.026697 | 0.030357 | 0.034364 | 0.038742 | 0.043513 | 0.048702 | 0.054336 | 0.060441 |
| 7       | 0.023418           | 0.026756 | 0.030420 | 0.034434 | 0.038818 | 0.043596 | 0.048792 | 0.054433 | 0.060547 |
| 8       | 0.023471           | 0.026814 | 0.030484 | 0.034504 | 0.038894 | 0.043679 | 0.048883 | 0.054531 | 0.060653 |
| 9       | 0.023524           | 0.026872 | 0.030549 | 0.034574 | 0.038971 | 0.043762 | 0.048973 | 0.054629 | 0.060759 |
| 10      | 0.023577           | 0.026931 | 0.030613 | 0.034644 | 0.039047 | 0.043845 | 0.049064 | 0.054728 | 0.060866 |
| 11      | 0.023631           | 0.026989 | 0.030677 | 0.034714 | 0.039124 | 0.043929 | 0.049154 | 0.054826 | 0.060972 |
| 12      | 0.023684           | 0.027048 | 0.030741 | 0.034785 | 0.039201 | 0.044012 | 0.049245 | 0.054924 | 0.061079 |
| 13      | 0.023738           | 0.027107 | 0.030806 | 0.034855 | 0.039278 | 0.044096 | 0.049336 | 0.055023 | 0.061186 |
| 14      | 0.023791           | 0.027166 | 0.030870 | 0.034926 | 0.039355 | 0.044180 | 0.049427 | 0.055122 | 0.061292 |
| 15      | 0.023845           | 0.027225 | 0.030935 | 0.034997 | 0.039432 | 0.044264 | 0.049518 | 0.055221 | 0.061400 |
| 16      | 0.023899           | 0.027284 | 0.031000 | 0.035067 | 0.039509 | 0.044348 | 0.049609 | 0.055320 | 0.061507 |
| 17      | 0.023952           | 0.027343 | 0.031065 | 0.035138 | 0.039586 | 0.044432 | 0.049701 | 0.055419 | 0.061614 |
| 18      | 0.024006           | 0.027402 | 0.031130 | 0.035209 | 0.039664 | 0.044516 | 0.049792 | 0.055518 | 0.061721 |
| 19      | 0.024060           | 0.027462 | 0.031195 | 0.035280 | 0.039741 | 0.044601 | 0.049884 | 0.055617 | 0.061829 |
| 20      | 0.024114           | 0.027521 | 0.031260 | 0.035352 | 0.039819 | 0.044685 | 0.049976 | 0.055717 | 0.061937 |
| 21      | 0.024169           | 0.027581 | 0.031325 | 0.035423 | 0.039897 | 0.044770 | 0.050068 | 0.055817 | 0.062045 |
| 22      | 0.024223           | 0.027640 | 0.031390 | 0.035494 | 0.039974 | 0.044855 | 0.050160 | 0.055916 | 0.062153 |
| 23      | 0.024277           | 0.027700 | 0.031456 | 0.035566 | 0.040052 | 0.044940 | 0.050252 | 0.056016 | 0.062261 |
| 24      | 0.024332           | 0.027760 | 0.031521 | 0.035637 | 0.040131 | 0.045024 | 0.050344 | 0.056116 | 0.062369 |
| 25      | 0.024386           | 0.027820 | 0.031587 | 0.035709 | 0.040209 | 0.045110 | 0.050437 | 0.056217 | 0.062478 |
| 26      | 0.024441           | 0.027880 | 0.031653 | 0.035781 | 0.040287 | 0.045195 | 0.050529 | 0.056317 | 0.062586 |
| 27      | 0.024495           | 0.027940 | 0.031718 | 0.035853 | 0.040366 | 0.045280 | 0.050622 | 0.056417 | 0.062695 |
| 28      | 0.024550           | 0.028000 | 0.031784 | 0.035925 | 0.040444 | 0.045366 | 0.050715 | 0.056518 | 0.062804 |
| 29      | 0.024605           | 0.028060 | 0.031850 | 0.035997 | 0.040523 | 0.045451 | 0.050808 | 0.056619 | 0.062913 |
| 30      | 0.024660           | 0.028121 | 0.031917 | 0.036069 | 0.040602 | 0.045537 | 0.050901 | 0.056720 | 0.063022 |
| 31      | 0.024715           | 0.028181 | 0.031983 | 0.036142 | 0.040680 | 0.045623 | 0.050994 | 0.056821 | 0.063131 |
| 32      | 0.024770           | 0.028242 | 0.032049 | 0.036214 | 0.040759 | 0.045709 | 0.051087 | 0.056922 | 0.063241 |
| 33      | 0.024825           | 0.028302 | 0.032116 | 0.036287 | 0.040839 | 0.045795 | 0.051181 | 0.057023 | 0.063350 |
| 34      | 0.024881           | 0.028363 | 0.032182 | 0.036359 | 0.040918 | 0.045881 | 0.051274 | 0.057124 | 0.063460 |
| 35      | 0.024936           | 0.028424 | 0.032249 | 0.036432 | 0.040997 | 0.045967 | 0.051368 | 0.057226 | 0.063570 |
| 36      | 0.024992           | 0.028485 | 0.032315 | 0.036505 | 0.041077 | 0.046054 | 0.051462 | 0.057328 | 0.063680 |
| 37      | 0.025047           | 0.028546 | 0.032382 | 0.036578 | 0.041156 | 0.046140 | 0.051556 | 0.057429 | 0.063790 |
| 38      | 0.025103           | 0.028607 | 0.032449 | 0.036651 | 0.041236 | 0.046227 | 0.051650 | 0.057531 | 0.063901 |
| 39      | 0.025159           | 0.028668 | 0.032516 | 0.036724 | 0.041316 | 0.046313 | 0.051744 | 0.057633 | 0.064011 |
| 40      | 0.025214           | 0.028729 | 0.032583 | 0.036798 | 0.041395 | 0.046400 | 0.051838 | 0.057736 | 0.064122 |
| 41      | 0.025270           | 0.028791 | 0.032651 | 0.036871 | 0.041475 | 0.046487 | 0.051933 | 0.057838 | 0.064232 |
| 42      | 0.025326           | 0.028852 | 0.032718 | 0.036945 | 0.041556 | 0.046575 | 0.052027 | 0.057940 | 0.064343 |
| 43      | 0.025382           | 0.028914 | 0.032785 | 0.037018 | 0.041636 | 0.046662 | 0.052122 | 0.058043 | 0.064454 |
| 44      | 0.025439           | 0.028976 | 0.032853 | 0.037092 | 0.041716 | 0.046749 | 0.052217 | 0.058146 | 0.064565 |
| 45      | 0.025495           | 0.029037 | 0.032920 | 0.037166 | 0.041797 | 0.046837 | 0.052312 | 0.058249 | 0.064677 |
| 46      | 0.025551           | 0.029099 | 0.032988 | 0.037240 | 0.041877 | 0.046924 | 0.052407 | 0.058352 | 0.064788 |
| 47      | 0.025608           | 0.029161 | 0.033056 | 0.037314 | 0.041958 | 0.047012 | 0.052502 | 0.058455 | 0.064900 |
| 48      | 0.025664           | 0.029223 | 0.033124 | 0.037388 | 0.042039 | 0.047100 | 0.052597 | 0.058558 | 0.065012 |
| 49      | 0.025721           | 0.029285 | 0.033192 | 0.037462 | 0.042120 | 0.047188 | 0.052693 | 0.058662 | 0.065123 |
| 50      | 0.025778           | 0.029348 | 0.033260 | 0.037537 | 0.042201 | 0.047276 | 0.052788 | 0.058765 | 0.065236 |
| 51      | 0.025834           | 0.029410 | 0.033328 | 0.037611 | 0.042282 | 0.047364 | 0.052884 | 0.058869 | 0.065348 |
| 52      | 0.025891           | 0.029472 | 0.033397 | 0.037686 | 0.042363 | 0.047452 | 0.052980 | 0.058973 | 0.065460 |
| 53      | 0.025948           | 0.029535 | 0.033465 | 0.037761 | 0.042444 | 0.047541 | 0.053076 | 0.059077 | 0.065573 |
| 54      | 0.026005           | 0.029598 | 0.033534 | 0.037835 | 0.042526 | 0.047630 | 0.053172 | 0.059181 | 0.065685 |
| 55      | 0.026062           | 0.029660 | 0.033602 | 0.037910 | 0.042608 | 0.047718 | 0.053268 | 0.059285 | 0.065798 |
| 56      | 0.026120           | 0.029723 | 0.033671 | 0.037985 | 0.042689 | 0.047807 | 0.053365 | 0.059390 | 0.065911 |
| 57      | 0.026177           | 0.029786 | 0.033740 | 0.038060 | 0.042771 | 0.047896 | 0.053461 | 0.059494 | 0.066024 |
| 58      | 0.026235           | 0.029849 | 0.033809 | 0.038136 | 0.042853 | 0.047985 | 0.053558 | 0.059599 | 0.066137 |
| 59      | 0.026292           | 0.029912 | 0.033878 | 0.038211 | 0.042935 | 0.048074 | 0.053655 | 0.059704 | 0.066251 |
| 60      | 0.026350           | 0.029975 | 0.033947 | 0.038287 | 0.043017 | 0.048164 | 0.053752 | 0.059809 | 0.066364 |

## INVOLUTE FUNCTIONS

## Involute Functions for Angles from 32 to 41 Degrees

| Minutes | Degrees            |          |          |          |          |          |          |          |          |
|---------|--------------------|----------|----------|----------|----------|----------|----------|----------|----------|
|         | 32                 | 33       | 34       | 35       | 36       | 37       | 38       | 39       | 40       |
|         | Involute Functions |          |          |          |          |          |          |          |          |
| 0       | 0.066364           | 0.073449 | 0.081097 | 0.089342 | 0.098224 | 0.107782 | 0.118061 | 0.129106 | 0.140968 |
| 1       | 0.066478           | 0.073572 | 0.081229 | 0.089485 | 0.098378 | 0.107948 | 0.118238 | 0.129297 | 0.141173 |
| 2       | 0.066591           | 0.073695 | 0.081362 | 0.089628 | 0.098532 | 0.108113 | 0.118416 | 0.129488 | 0.141378 |
| 3       | 0.066705           | 0.073818 | 0.081494 | 0.089771 | 0.098686 | 0.108279 | 0.118594 | 0.129679 | 0.141584 |
| 4       | 0.066820           | 0.073941 | 0.081627 | 0.089914 | 0.098840 | 0.108445 | 0.118773 | 0.129870 | 0.141789 |
| 5       | 0.066934           | 0.074064 | 0.081760 | 0.090058 | 0.098994 | 0.108611 | 0.118951 | 0.130062 | 0.141995 |
| 6       | 0.067048           | 0.074188 | 0.081894 | 0.090201 | 0.099149 | 0.108777 | 0.119130 | 0.130254 | 0.142201 |
| 7       | 0.067163           | 0.074312 | 0.082027 | 0.090345 | 0.099303 | 0.108943 | 0.119309 | 0.130446 | 0.142408 |
| 8       | 0.067277           | 0.074435 | 0.082161 | 0.090489 | 0.099458 | 0.109110 | 0.119488 | 0.130639 | 0.142614 |
| 9       | 0.067392           | 0.074559 | 0.082294 | 0.090633 | 0.099614 | 0.109277 | 0.119667 | 0.130832 | 0.142821 |
| 10      | 0.067507           | 0.074684 | 0.082428 | 0.090777 | 0.099769 | 0.109444 | 0.119847 | 0.131025 | 0.143028 |
| 11      | 0.067622           | 0.074808 | 0.082562 | 0.090922 | 0.099924 | 0.109611 | 0.120027 | 0.131218 | 0.143236 |
| 12      | 0.067738           | 0.074932 | 0.082697 | 0.091067 | 0.100080 | 0.109779 | 0.120207 | 0.131411 | 0.143443 |
| 13      | 0.067853           | 0.075057 | 0.082831 | 0.091211 | 0.100236 | 0.109947 | 0.120387 | 0.131605 | 0.143651 |
| 14      | 0.067969           | 0.075182 | 0.082966 | 0.091356 | 0.100392 | 0.110114 | 0.120567 | 0.131799 | 0.143859 |
| 15      | 0.068084           | 0.075307 | 0.083101 | 0.091502 | 0.100549 | 0.110283 | 0.120748 | 0.131993 | 0.144068 |
| 16      | 0.068200           | 0.075432 | 0.083235 | 0.091647 | 0.100705 | 0.110451 | 0.120929 | 0.132187 | 0.144276 |
| 17      | 0.068316           | 0.075557 | 0.083371 | 0.091793 | 0.100862 | 0.110619 | 0.121110 | 0.132381 | 0.144485 |
| 18      | 0.068432           | 0.075683 | 0.083506 | 0.091938 | 0.101019 | 0.110788 | 0.121291 | 0.132576 | 0.144694 |
| 19      | 0.068549           | 0.075808 | 0.083641 | 0.092084 | 0.101176 | 0.110957 | 0.121473 | 0.132771 | 0.144903 |
| 20      | 0.068665           | 0.075934 | 0.083777 | 0.092230 | 0.101333 | 0.111126 | 0.121655 | 0.132966 | 0.145113 |
| 21      | 0.068782           | 0.076060 | 0.083913 | 0.092377 | 0.101490 | 0.111295 | 0.121837 | 0.133162 | 0.145323 |
| 22      | 0.068899           | 0.076186 | 0.084049 | 0.092523 | 0.101648 | 0.111465 | 0.122019 | 0.133358 | 0.145533 |
| 23      | 0.069016           | 0.076312 | 0.084185 | 0.092670 | 0.101806 | 0.111635 | 0.122201 | 0.133553 | 0.145743 |
| 24      | 0.069133           | 0.076439 | 0.084321 | 0.092816 | 0.101964 | 0.111805 | 0.122384 | 0.133750 | 0.145954 |
| 25      | 0.069250           | 0.076565 | 0.084458 | 0.092963 | 0.102122 | 0.111975 | 0.122567 | 0.133946 | 0.146165 |
| 26      | 0.069367           | 0.076692 | 0.084594 | 0.093111 | 0.102280 | 0.112145 | 0.122750 | 0.134143 | 0.146376 |
| 27      | 0.069485           | 0.076819 | 0.084731 | 0.093258 | 0.102439 | 0.112316 | 0.122933 | 0.134339 | 0.146587 |
| 28      | 0.069602           | 0.076946 | 0.084868 | 0.093406 | 0.102598 | 0.112486 | 0.123117 | 0.134537 | 0.146799 |
| 29      | 0.069720           | 0.077073 | 0.085005 | 0.093553 | 0.102757 | 0.112657 | 0.123300 | 0.134734 | 0.147010 |
| 30      | 0.069838           | 0.077200 | 0.085142 | 0.093701 | 0.102916 | 0.112829 | 0.123484 | 0.134931 | 0.147222 |
| 31      | 0.069956           | 0.077328 | 0.085280 | 0.093849 | 0.103075 | 0.113000 | 0.123668 | 0.135129 | 0.147435 |
| 32      | 0.070075           | 0.077455 | 0.085418 | 0.093998 | 0.103235 | 0.113172 | 0.123853 | 0.135327 | 0.147647 |
| 33      | 0.070193           | 0.077583 | 0.085555 | 0.094146 | 0.103395 | 0.113343 | 0.124037 | 0.135525 | 0.147860 |
| 34      | 0.070312           | 0.077711 | 0.085693 | 0.094295 | 0.103555 | 0.113515 | 0.124222 | 0.135724 | 0.148073 |
| 35      | 0.070430           | 0.077839 | 0.085832 | 0.094443 | 0.103715 | 0.113688 | 0.124407 | 0.135923 | 0.148286 |
| 36      | 0.070549           | 0.077968 | 0.085970 | 0.094593 | 0.103875 | 0.113860 | 0.124592 | 0.136122 | 0.148500 |
| 37      | 0.070668           | 0.078096 | 0.086108 | 0.094742 | 0.104036 | 0.114033 | 0.124778 | 0.136321 | 0.148714 |
| 38      | 0.070788           | 0.078225 | 0.086247 | 0.094891 | 0.104196 | 0.114205 | 0.124964 | 0.136520 | 0.148928 |
| 39      | 0.070907           | 0.078354 | 0.086386 | 0.095041 | 0.104357 | 0.114378 | 0.125150 | 0.136720 | 0.149142 |
| 40      | 0.071026           | 0.078483 | 0.086525 | 0.095190 | 0.104518 | 0.114552 | 0.125336 | 0.136920 | 0.149357 |
| 41      | 0.071146           | 0.078612 | 0.086664 | 0.095340 | 0.104680 | 0.114725 | 0.125522 | 0.137120 | 0.149572 |
| 42      | 0.071266           | 0.078741 | 0.086804 | 0.095490 | 0.104841 | 0.114899 | 0.125709 | 0.137320 | 0.149787 |
| 43      | 0.071386           | 0.078871 | 0.086943 | 0.095641 | 0.105003 | 0.115073 | 0.125896 | 0.137521 | 0.150002 |
| 44      | 0.071506           | 0.079000 | 0.087083 | 0.095791 | 0.105165 | 0.115247 | 0.126083 | 0.137722 | 0.150218 |
| 45      | 0.071626           | 0.079130 | 0.087223 | 0.095942 | 0.105327 | 0.115421 | 0.126270 | 0.137923 | 0.150434 |
| 46      | 0.071747           | 0.079260 | 0.087363 | 0.096093 | 0.105489 | 0.115595 | 0.126457 | 0.138124 | 0.150650 |
| 47      | 0.071867           | 0.079390 | 0.087503 | 0.096244 | 0.105652 | 0.115770 | 0.126645 | 0.138326 | 0.150866 |
| 48      | 0.071988           | 0.079520 | 0.087644 | 0.096395 | 0.105814 | 0.115945 | 0.126833 | 0.138528 | 0.151083 |
| 49      | 0.072109           | 0.079651 | 0.087784 | 0.096546 | 0.105977 | 0.116120 | 0.127021 | 0.138730 | 0.151299 |
| 50      | 0.072230           | 0.079781 | 0.087925 | 0.096698 | 0.106140 | 0.116296 | 0.127209 | 0.138932 | 0.151517 |
| 51      | 0.072351           | 0.079912 | 0.088066 | 0.096850 | 0.106304 | 0.116471 | 0.127398 | 0.139134 | 0.151734 |
| 52      | 0.072473           | 0.080043 | 0.088207 | 0.097002 | 0.106467 | 0.116647 | 0.127587 | 0.139337 | 0.151952 |
| 53      | 0.072594           | 0.080174 | 0.088348 | 0.097154 | 0.106631 | 0.116823 | 0.127776 | 0.139540 | 0.152169 |
| 54      | 0.072716           | 0.080306 | 0.088490 | 0.097306 | 0.106795 | 0.116999 | 0.127965 | 0.139743 | 0.152388 |
| 55      | 0.072838           | 0.080437 | 0.088631 | 0.097459 | 0.106959 | 0.117175 | 0.128155 | 0.139947 | 0.152606 |
| 56      | 0.072960           | 0.080569 | 0.088773 | 0.097611 | 0.107123 | 0.117352 | 0.128344 | 0.140151 | 0.152825 |
| 57      | 0.073082           | 0.080700 | 0.088915 | 0.097764 | 0.107288 | 0.117529 | 0.128534 | 0.140355 | 0.153044 |
| 58      | 0.073204           | 0.080832 | 0.089057 | 0.097917 | 0.107452 | 0.117706 | 0.128725 | 0.140559 | 0.153263 |
| 59      | 0.073326           | 0.080964 | 0.089200 | 0.098071 | 0.107617 | 0.117883 | 0.128915 | 0.140763 | 0.153482 |
| 60      | 0.073449           | 0.081097 | 0.089342 | 0.098224 | 0.107782 | 0.118061 | 0.129106 | 0.140968 | 0.153702 |

## INVOLUTE FUNCTIONS

## Involute Functions for Angles from 41 to 50 Degrees

| Minutes | Degrees            |          |          |          |          |          |          |          |          |
|---------|--------------------|----------|----------|----------|----------|----------|----------|----------|----------|
|         | 41                 | 42       | 43       | 44       | 45       | 46       | 47       | 48       | 49       |
|         | Involute Functions |          |          |          |          |          |          |          |          |
| 0       | 0.153702           | 0.167366 | 0.182024 | 0.197744 | 0.214602 | 0.232679 | 0.252064 | 0.272855 | 0.295157 |
| 1       | 0.153922           | 0.167602 | 0.182277 | 0.198015 | 0.214893 | 0.232991 | 0.252399 | 0.273214 | 0.295542 |
| 2       | 0.154142           | 0.167838 | 0.182530 | 0.198287 | 0.215184 | 0.233304 | 0.252734 | 0.273573 | 0.295928 |
| 3       | 0.154362           | 0.168075 | 0.182784 | 0.198559 | 0.215476 | 0.233616 | 0.253069 | 0.273933 | 0.296314 |
| 4       | 0.154583           | 0.168311 | 0.183038 | 0.198832 | 0.215768 | 0.233930 | 0.253405 | 0.274293 | 0.296701 |
| 5       | 0.154804           | 0.168548 | 0.183292 | 0.199104 | 0.216061 | 0.234243 | 0.253742 | 0.274654 | 0.297088 |
| 6       | 0.155025           | 0.168786 | 0.183547 | 0.199377 | 0.216353 | 0.234557 | 0.254078 | 0.275015 | 0.297475 |
| 7       | 0.155247           | 0.169023 | 0.183801 | 0.199651 | 0.216646 | 0.234871 | 0.254415 | 0.275376 | 0.297863 |
| 8       | 0.155469           | 0.169261 | 0.184057 | 0.199924 | 0.216940 | 0.235186 | 0.254753 | 0.275738 | 0.298251 |
| 9       | 0.155691           | 0.169500 | 0.184312 | 0.200198 | 0.217234 | 0.235501 | 0.255091 | 0.276101 | 0.298640 |
| 10      | 0.155913           | 0.169738 | 0.184568 | 0.200473 | 0.217528 | 0.235816 | 0.255429 | 0.276464 | 0.299029 |
| 11      | 0.156135           | 0.169977 | 0.184824 | 0.200747 | 0.217822 | 0.236132 | 0.255767 | 0.276827 | 0.299419 |
| 12      | 0.156358           | 0.170216 | 0.185080 | 0.201022 | 0.218117 | 0.236448 | 0.256106 | 0.277191 | 0.299809 |
| 13      | 0.156581           | 0.170455 | 0.185337 | 0.201297 | 0.218412 | 0.236765 | 0.256446 | 0.277555 | 0.300200 |
| 14      | 0.156805           | 0.170695 | 0.185594 | 0.201573 | 0.218708 | 0.237082 | 0.256786 | 0.277919 | 0.300591 |
| 15      | 0.157028           | 0.170935 | 0.185851 | 0.201849 | 0.219004 | 0.237399 | 0.257126 | 0.278284 | 0.300983 |
| 16      | 0.157252           | 0.171175 | 0.186109 | 0.202125 | 0.219300 | 0.237717 | 0.257467 | 0.278649 | 0.301375 |
| 17      | 0.157476           | 0.171415 | 0.186367 | 0.202401 | 0.219596 | 0.238035 | 0.257808 | 0.279015 | 0.301767 |
| 18      | 0.157701           | 0.171656 | 0.186625 | 0.202678 | 0.219893 | 0.238353 | 0.258149 | 0.279381 | 0.302160 |
| 19      | 0.157925           | 0.171897 | 0.186883 | 0.202956 | 0.220190 | 0.238672 | 0.258491 | 0.279748 | 0.302553 |
| 20      | 0.158150           | 0.172138 | 0.187142 | 0.203233 | 0.220488 | 0.238991 | 0.258833 | 0.280115 | 0.302947 |
| 21      | 0.158375           | 0.172380 | 0.187401 | 0.203511 | 0.220786 | 0.239310 | 0.259176 | 0.280483 | 0.303342 |
| 22      | 0.158601           | 0.172621 | 0.187661 | 0.203789 | 0.221084 | 0.239630 | 0.259519 | 0.280851 | 0.303736 |
| 23      | 0.158826           | 0.172864 | 0.187920 | 0.204067 | 0.221383 | 0.239950 | 0.259862 | 0.281219 | 0.304132 |
| 24      | 0.159052           | 0.173106 | 0.188180 | 0.204346 | 0.221682 | 0.240271 | 0.260206 | 0.281588 | 0.304527 |
| 25      | 0.159279           | 0.173349 | 0.188440 | 0.204625 | 0.221981 | 0.240592 | 0.260550 | 0.281957 | 0.304924 |
| 26      | 0.159505           | 0.173592 | 0.188701 | 0.204905 | 0.222281 | 0.240913 | 0.260895 | 0.282327 | 0.305320 |
| 27      | 0.159732           | 0.173835 | 0.188962 | 0.205185 | 0.222581 | 0.241235 | 0.261240 | 0.282697 | 0.305718 |
| 28      | 0.159959           | 0.174078 | 0.189223 | 0.205465 | 0.222881 | 0.241557 | 0.261585 | 0.283067 | 0.306115 |
| 29      | 0.160186           | 0.174322 | 0.189485 | 0.205745 | 0.223182 | 0.241879 | 0.261931 | 0.283438 | 0.306513 |
| 30      | 0.160414           | 0.174566 | 0.189746 | 0.206026 | 0.223483 | 0.242202 | 0.262277 | 0.283810 | 0.306912 |
| 31      | 0.160642           | 0.174811 | 0.190009 | 0.206307 | 0.223784 | 0.242525 | 0.262624 | 0.284182 | 0.307311 |
| 32      | 0.160870           | 0.175055 | 0.190271 | 0.206588 | 0.224086 | 0.242849 | 0.262971 | 0.284554 | 0.307710 |
| 33      | 0.161098           | 0.175300 | 0.190534 | 0.206870 | 0.224388 | 0.243173 | 0.263318 | 0.284927 | 0.308110 |
| 34      | 0.161327           | 0.175546 | 0.190797 | 0.207152 | 0.224690 | 0.243497 | 0.263666 | 0.285300 | 0.308511 |
| 35      | 0.161555           | 0.175791 | 0.191060 | 0.207434 | 0.224993 | 0.243822 | 0.264014 | 0.285673 | 0.308911 |
| 36      | 0.161785           | 0.176037 | 0.191324 | 0.207717 | 0.225296 | 0.244147 | 0.264363 | 0.286047 | 0.309313 |
| 37      | 0.162014           | 0.176283 | 0.191588 | 0.208000 | 0.225600 | 0.244472 | 0.264712 | 0.286422 | 0.309715 |
| 38      | 0.162244           | 0.176529 | 0.191852 | 0.208284 | 0.225904 | 0.244798 | 0.265062 | 0.286797 | 0.310117 |
| 39      | 0.162474           | 0.176776 | 0.192116 | 0.208567 | 0.226208 | 0.245125 | 0.265412 | 0.287172 | 0.310520 |
| 40      | 0.162704           | 0.177023 | 0.192381 | 0.208851 | 0.226512 | 0.245451 | 0.265762 | 0.287548 | 0.310923 |
| 41      | 0.162934           | 0.177270 | 0.192646 | 0.209136 | 0.226817 | 0.245778 | 0.266113 | 0.287924 | 0.311327 |
| 42      | 0.163165           | 0.177518 | 0.192912 | 0.209420 | 0.227123 | 0.246106 | 0.266464 | 0.288301 | 0.311731 |
| 43      | 0.163396           | 0.177766 | 0.193178 | 0.209705 | 0.227428 | 0.246433 | 0.266815 | 0.288678 | 0.312136 |
| 44      | 0.163628           | 0.178014 | 0.193444 | 0.209991 | 0.227734 | 0.246761 | 0.267167 | 0.289056 | 0.312541 |
| 45      | 0.163859           | 0.178262 | 0.193710 | 0.210276 | 0.228041 | 0.247090 | 0.267520 | 0.289434 | 0.312947 |
| 46      | 0.164091           | 0.178511 | 0.193977 | 0.210562 | 0.228347 | 0.247419 | 0.267872 | 0.289812 | 0.313353 |
| 47      | 0.164323           | 0.178760 | 0.194244 | 0.210849 | 0.228654 | 0.247748 | 0.268225 | 0.290191 | 0.313759 |
| 48      | 0.164556           | 0.179009 | 0.194511 | 0.211136 | 0.228962 | 0.248078 | 0.268579 | 0.290570 | 0.314166 |
| 49      | 0.164788           | 0.179259 | 0.194779 | 0.211423 | 0.229270 | 0.248408 | 0.268933 | 0.290950 | 0.314574 |
| 50      | 0.165021           | 0.179509 | 0.195047 | 0.211710 | 0.229578 | 0.248738 | 0.269287 | 0.291330 | 0.314982 |
| 51      | 0.165254           | 0.179759 | 0.195315 | 0.211998 | 0.229886 | 0.249069 | 0.269642 | 0.291711 | 0.315391 |
| 52      | 0.165488           | 0.180009 | 0.195584 | 0.212286 | 0.230195 | 0.249400 | 0.269998 | 0.292092 | 0.315800 |
| 53      | 0.165722           | 0.180260 | 0.195853 | 0.212574 | 0.230504 | 0.249732 | 0.270353 | 0.292474 | 0.316209 |
| 54      | 0.165956           | 0.180511 | 0.196122 | 0.212863 | 0.230814 | 0.250064 | 0.270709 | 0.292856 | 0.316619 |
| 55      | 0.166190           | 0.180763 | 0.196392 | 0.213152 | 0.231124 | 0.250396 | 0.271066 | 0.293238 | 0.317029 |
| 56      | 0.166425           | 0.181014 | 0.196661 | 0.213441 | 0.231434 | 0.250729 | 0.271423 | 0.293621 | 0.317440 |
| 57      | 0.166660           | 0.181266 | 0.196932 | 0.213731 | 0.231745 | 0.251062 | 0.271780 | 0.294004 | 0.317852 |
| 58      | 0.166895           | 0.181518 | 0.197202 | 0.214021 | 0.232056 | 0.251396 | 0.272138 | 0.294388 | 0.318264 |
| 59      | 0.167130           | 0.181771 | 0.197473 | 0.214311 | 0.232367 | 0.251730 | 0.272496 | 0.294772 | 0.318676 |
| 60      | 0.167366           | 0.182024 | 0.197744 | 0.214602 | 0.232679 | 0.252064 | 0.272855 | 0.295157 | 0.319089 |



## Compound Angles

Three types of compound angles are illustrated by Figs. 1 through 6. The first type is shown in Figs. 1, 2, and 3; the second in Fig. 4; and the third in Figs. 5 and 6.

In Fig. 1 is shown what might be considered as a thread-cutting tool without front clearance.  $A$  is a known angle in plane  $y-y$  of the top surface.  $C$  is the corresponding angle in plane  $x-x$  that is at some given angle  $B$  with plane  $y-y$ . Thus, angles  $A$  and  $B$  are components of the compound angle  $C$ .

*Example Problem Referring to Fig. 1:* Angle  $2A$  in plane  $y-y$  is known, as is also angle  $B$  between planes  $x-x$  and  $y-y$ . It is required to find compound angle  $2C$  in plane  $x-x$ .

*Solution:* Let  $2A = 60$  and  $B = 15$

$$\begin{aligned} \text{Then} \quad \tan C &= \tan A \cos B = \tan 30 \cos 15 \\ \tan C &= 0.57735 \times 0.96592 = 0.55767 \\ C &= 29 \text{ } 8.8' & 2C &= 58 \text{ } 17.6' \end{aligned}$$

Fig. 2 shows a thread-cutting tool with front clearance angle  $B$ . Angle  $A$  equals one-half the angle between the cutting edges in plane  $y-y$  of the top surface and compound angle  $C$  is one-half the angle between the cutting edges in a plane  $x-x$  at right angles to the inclined front edge of the tool. The angle between planes  $y-y$  and  $x-x$  is, therefore, equal to clearance angle  $B$ .

*Example Problem Referring to Fig. 2:* Find the angle  $2C$  between the front faces of a thread-cutting tool having a known clearance angle  $B$ , which will permit the grinding of these faces so that their top edges will form the desired angle  $2A$  for cutting the thread.

*Solution:* Let  $2A = 60$  and  $B = 15$

$$\begin{aligned} \text{Then} \quad \tan C &= \frac{\tan A}{\cos B} = \frac{\tan 30^\circ}{\cos 15^\circ} = \frac{0.57735}{0.96592} \\ \tan C &= 0.59772 \\ C &= 30 \text{ } 52' & 2C &= 61 \text{ } 44' \end{aligned}$$

In Fig. 3 is shown a form-cutting tool in which the angle  $A$  is one-half the angle between the cutting edges in plane  $y-y$  of the top surface;  $B$  is the front clearance angle; and  $C$  is one-half the angle between the cutting edges in plane  $x-x$  at right angles to the front edges of the tool. The formula for finding angle  $C$  when angles  $A$  and  $B$  are known is the same as that for Fig. 2.

*Example Problem Referring to Fig. 3:* Find the angle  $2C$  between the front faces of a form-cutting tool having a known clearance angle  $B$  that will permit the grinding of these faces so that their top edges will form the desired angle  $2A$  for form cutting.

*Solution:* Let  $2A = 46$  and  $B = 12$

$$\begin{aligned} \text{Then} \quad \tan C &= \frac{\tan A}{\cos B} = \frac{\tan 23^\circ}{\cos 12^\circ} = \frac{0.42447}{0.97815} \\ \tan C &= 0.43395 \\ C &= 23 \text{ } 27.5' & 2C &= 46 \text{ } 55' \end{aligned}$$

In Fig. 4 is shown a wedge-shaped block, the top surface of which is inclined at compound angle  $C$  with the base in a plane at right angles with the base and at angle  $R$  with the front edge. Angle  $A$  in the vertical plane of the front of the plate and angle  $B$  in the vertical plane of one side that is at right angles to the front are components of angle  $C$ .

*Example Problem Referring to Fig. 4:* Find the compound angle  $C$  of a wedge-shaped block having known component angles  $A$  and  $B$  in sides at right angles to each other.

Formulas for Compound Angles

|  |  |
|--|--|
| <p>Fig. 1.                  Fig. 2.                  Fig. 3.</p> | <p>For given angles <math>A</math> and <math>B</math>, find the resultant angle <math>C</math> in plane <math>x-x</math>. Angle <math>B</math> is measured in vertical plane <math>y-y</math> of midsection.</p> <p>(Fig. 1) <math>\tan C = \tan A \times \cos B</math></p> <p>(Fig. 2) <math>\tan C = \frac{\tan A}{\cos B}</math></p> <p>(Fig. 3) (Same formula as for Fig. 2)</p>   |
| <p>Fig. 4.</p>   | <p>Fig. 4. In machining plate to angles <math>A</math> and <math>B</math>, it is held at angle <math>C</math> in plane <math>x-x</math>. Angle of rotation <math>R</math> in plane parallel to base (or complement of <math>R</math>) is for locating plate so that plane <math>x-x</math> is perpendicular to axis of pivot on angle-plate or work-holding vise.</p> $\tan R = \frac{\tan B}{\tan A}; \quad \tan C = \frac{\tan A}{\cos R}$   |
| <p>Fig. 5.</p>   | <p>Fig. 5. Angle <math>R</math> in horizontal plane parallel to base is angle from plane <math>x-x</math> to side having angle <math>A</math>.</p> $\tan R = \frac{\tan A}{\tan B}$ <p><math>\tan C = \tan A \cos R = \tan B \sin R</math></p> <p>Compound angle <math>C</math> is angle in plane <math>x-x</math> from base to corner formed by intersection of planes inclined to angles <math>A</math> and <math>B</math>. This formula for <math>C</math> may be used to find cot of complement of <math>C_1</math>, Fig. 6.</p> |
| <p>Fig. 6.</p>   | <p>Fig. 6. Angles <math>A_1</math> and <math>B_1</math> are measured in vertical planes of front and side elevations. Plane <math>x-x</math> is located by angle <math>R</math> from centerline or from plane of angle <math>B_1</math>.</p> $\tan R = \frac{\tan A_1}{\tan B_1}$ $\tan C_1 = \frac{\tan A_1}{\sin R} = \frac{\tan B_1}{\cos R}$ <p>The resultant angle <math>C_1</math> would be required in drilling hole for pin.</p>   |

$C$  = compound angle in plane  $x-x$  and is the resultant of angles  $A$  and  $B$

*Solution:* Let  $A = 47^{\circ}14'$  and  $B = 38^{\circ}10'$

Then

$$\tan R = \frac{\tan B}{\tan A} = \frac{\tan 38^{\circ}10'}{\tan 47^{\circ}14'} = \frac{0.78598}{1.0812} = 0.72695 \quad R = 36^{\circ}09'$$

$$\tan C = \frac{\tan A}{\cos R} = \frac{\tan 47^{\circ}14'}{\cos 36^{\circ}09'} = \frac{1.0812}{0.80887} = 1.3367 \quad C = 53^{\circ}12'$$

In Fig. 5 is shown a four-sided block, two sides of which are at right angles to each other and to the base of the block. The other two sides are inclined at an oblique angle with the base. Angle  $C$  is a compound angle formed by the intersection of these two inclined sides and the intersection of a vertical plane passing through  $x-x$ , and the base of the block. The components of angle  $C$  are angles  $A$  and  $B$  and angle  $R$  is the angle in the base plane of the block between the plane of angle  $C$  and the plane of angle  $A$ .

*Example Problem Referring to Fig. 5:* Find the angles  $C$  and  $R$  in the block shown in Fig. 5 when angles  $A$  and  $B$  are known.

*Solution:* Let angle  $A = 27^{\circ}$  and  $B = 36^{\circ}$

Then

$$\cot C = \sqrt{\cot^2 A + \cot^2 B} = \sqrt{1.9626^2 + 1.3764^2} = \sqrt{5.74627572} = 2.3971$$

$$C = 22^{\circ}38.6'$$

$$\tan R = \frac{\cot B}{\cot A} = \frac{\cot 36^{\circ}}{\cot 27^{\circ}} = \frac{1.3764}{1.9626} = 0.70131 \quad R = 35^{\circ}2.5'$$

*Example Problem Referring to Fig. 6:* A rod or pipe is inserted into a rectangular block at an angle. Angle  $C_1$  is the compound angle of inclination (measured from the vertical) in a plane passing through the center line of the rod or pipe and at right angles to the top surface of the block. Angles  $A_1$  and  $B_1$  are the angles of inclination of the rod or pipe when viewed respectively in the front and side planes of the block. Angle  $R$  is the angle between the plane of angle  $C_1$  and the plane of angle  $B_1$ . Find angles  $C_1$  and  $R$  when a rod or pipe is inclined at known angles  $A_1$  and  $B_1$ .

*Solution:* Let  $A_1 = 39^{\circ}$  and  $B_1 = 34^{\circ}$

Then

$$\tan C_1 = \sqrt{\tan^2 A_1 + \tan^2 B_1} = \sqrt{0.80978^2 + 0.67451^2} = 1.0539$$

$$C_1 = 46^{\circ}30.2'$$

$$\tan R = \frac{\tan A_1}{\tan B_1} = \frac{0.80978}{0.67451} = 1.2005 \quad R = 50^{\circ}12.4'$$

**Interpolation.**—In mathematics, interpolation is the process of finding a value in a table or in a mathematical expression which falls between two given tabulated or known values. In engineering handbooks, the values of trigonometric functions are usually given to degrees and minutes; hence, if the given angle is to degrees, minutes and seconds, the value of the function is determined from the nearest given values, by interpolation.

*Interpolation to Find Functions of an Angle:* Assume that the sine of  $14^{\circ}22'26''$  is to be determined. It is evident that this value lies between the sine of  $14^{\circ}22'$  and the sine of  $14^{\circ}23'$ . Sine  $14^{\circ}23' = 0.24841$  and sine  $14^{\circ}22' = 0.24813$ . The difference =  $0.24841 - 0.24813 = 0.00028$ . Consider this difference as a whole number (28) and multiply it by a fraction having as its numerator the number of seconds (26) in the given angle, and as its denominator 60 (number of seconds in one minute). Thus  $\frac{26}{60} \times 28 = 12$  nearly; hence, by adding 0.00012 to sine of  $14^{\circ}22'$  we find that sine  $14^{\circ}22'26'' = 0.24813 + 0.00012 = 0.24825$ . The correction value (represented in this example by 0.00012) is *added* to the function of the *smaller* angle nearest the given angle in dealing with *sines* or *tangents* but this correction value is *subtracted* in dealing with *cosines* or *cotangents*.

## LOGARITHMS

Logarithms have long been used to facilitate and shorten calculations involving multiplication, division, the extraction of roots, and obtaining powers of numbers; however, since the advent of hand-held calculators logarithms are rarely used for multiplication and division problems. Logarithms still come up in other problems, and the following properties of logarithms are useful:

$$\begin{aligned} \log_c c &= 1 & \log_c c^p &= p & \log_c 1 &= 0 \\ \log_c (a \times b) &= \log_c a + \log_c b & \log_c (a \div b) &= \log_c a - \log_c b \\ \log_c (a^p) &= p \log_c a & \log_c (\sqrt[p]{a}) &= 1/p \log_c a \end{aligned}$$

The logarithm of a number is defined as the exponent of a base number raised to a power. For example,  $\log_{10} 3.162277 = 0.500$  means the logarithm of 3.162277 is equal to 0.500. Another way of expressing the same relationship is  $10^{0.500} = 3.162277$ , where 10 is the base number and the exponent 0.500 is the logarithm of 3.162277. A common example of a logarithmic expression  $10^2 = 100$  means that the base 10 logarithm of 100 is 2, that is,  $\log_{10} 100 = 2.00$ . There are two standard systems of logarithms in use: the "common" system (base 10) and the so-called "natural" system (base  $e = 2.71828\dots$ ). Logarithms to base  $e$  are frequently written using "ln" instead of " $\log_e$ " such as  $\ln 6.1 = 1.808289$ . Logarithms of a number can be converted between the natural- and common-based systems as follows:  $\ln_e A = 2.3026 \times \log_{10} A$  and  $\log_{10} A = 0.43430 \times \ln_e A$ . Additional information on the use of "natural logarithms" is given at the end of this section.

A logarithm consists of two parts, a whole number and a decimal. The whole number, which may be positive, negative, or zero, is called the characteristic; the decimal is called the mantissa. As a rule, only the decimal or mantissa is given in tables of common logarithms; tables of natural logarithms give both the characteristic and mantissa. The tables given in this section are abbreviated, but very accurate results can be obtained by using the method of interpolation described in *Interpolation from the Tables* on page 112. These tables are especially useful for finding logarithms and calculating powers and roots of numbers on calculators without these functions built in.

## Evaluating Logarithms

**Common Logarithms.**—For common logarithms, the characteristic is prefixed to the mantissa according to the following rules: For numbers greater than or equal to 1, the characteristic is one less than the number of places to the left of the decimal point. For example, the characteristic of the logarithm of 237 is 2, and of 2536.5 is 3. For numbers smaller than 1 and greater than 0, the characteristic is negative and its numerical value is one more than the number of zeros immediately to the right of the decimal point. For example, the characteristic of the logarithm of 0.036 is  $-2$ , and the characteristic of the logarithm of 0.0006 is  $-4$ . The minus sign is usually written over the figure, as in  $\bar{2}$  to indicate that the minus sign refers only to the characteristic and not to the mantissa, which is never negative. The logarithm of 0 does not exist.

The table of common logarithms in this section gives the mantissas of the logarithms of numbers from 1 to 10 and from 1.00 to 1.01. When finding the mantissa, the decimal point in a number is disregarded. The mantissa of the logarithms of 2716, 271.6, 27.16, 2.716, or 0.02716, for example, is the same. The tables give directly the mantissas of logarithms of numbers with three figures or less; the logarithms for numbers with four or more figures can be found by interpolation, as described in *Interpolation from the Tables* on page 112 and illustrated in the examples. All the mantissas in the common logarithmic tables are decimals and the decimal point has been omitted in the table. However, a decimal point should always be put before the mantissa as soon as it is taken from the table. Logarithmic

tables are sufficient for many purposes, but electronic calculators and computers are faster, simpler, and more accurate than tables.

To find the common logarithm of a number from the tables, find the left-hand column of the table and follow down to locate the first two figures of the number. Then look at the top row of the table, on the same page, and follow across it to find the third figure of the number. Follow down the column containing this last figure until opposite the row on which the first two figures were found. The number at the intersection of the row and column is the mantissa of the logarithm. If the logarithm of a number with less than three figures is being obtained, add extra zeros to the right of the number so as to obtain three figures. For example, if the mantissa of the logarithm of 6 is required, find the mantissa of 600.

**Interpolation from the Tables.**—If the logarithm of a number with more than three figures is needed, linear interpolation is a method of using two values from the table to estimate the value of the logarithm desired. To find the logarithm of a number not listed in the tables, find the mantissa corresponding to the first three digits of the given number (disregarding the decimal point and leading zeros) and find the mantissa of the first three digits of the given number plus one. For example, to find the logarithm of 601.2, 60.12, or 0.006012, find the mantissa of 601 and find the mantissa of 602 from the tables. Then subtract the mantissa of the smaller number from the mantissa of the larger number and multiply the result by a decimal number made from the remaining (additional greater than 3) figures of the original number. Add the result to the mantissa of the smaller number. Find the characteristic as described previously.

*Example:* Find the logarithm of 4032. The characteristic portion of the logarithm found in the manner described before is 3. Find the mantissa by locating 40 in the left-hand column of the logarithmic tables and then follow across the top row of the table to the column headed 3. Follow down the 3 column to the intersection with the 40 row and read the mantissa. The mantissa of the logarithm of 4030 is 0.605305. Because 4032 is between 4030 and 4040, the logarithm of 4032 is the logarithm of 4030 plus two tenths of the difference in the logarithms of 4030 and 4040. Find the mantissa of 4040 and then subtract from it the mantissa of 4030. Multiply the difference obtained by 0.2 and add the result to the mantissa of the logarithm of 4030. Finally, add the characteristic portion of the logarithm. The result is  $\log_{10} 4032 = 3 + 0.605305 + 0.2 \times (0.606381 - 0.605305) = 3.60552$ .

**Finding a Number Whose Logarithm Is Given.**—When a logarithm is given and it is required to find the corresponding number, find the number in the body of the table equal to the value of the mantissa. This value may appear in any column 0 to 9. Follow the row on which the mantissa is found across to the left to read the first two digits of the number sought. Read the third digit of the number from the top row of the table by following up the column on which the mantissa is found to the top. If the characteristic of the logarithm is positive, the number of figures to the left of the decimal in the number is one greater than the value of the characteristic. For example, if the figures corresponding to a given mantissa are 376 and the characteristic is 5, then the number sought has six figures to the left of the decimal point and is 376,000. If the characteristic had been  $\bar{3}$ , then the number sought would have been 0.00376. If the mantissa is not exactly obtainable in the tables, find the mantissa in the table that is nearest to the one given and determine the corresponding number. This procedure usually gives sufficiently accurate results. If more accuracy is required, find the two mantissas in the tables nearest to the mantissa given, one smaller and the other larger. For each of the two mantissas, read the three corresponding digits from the left column and top row to obtain the first three figures of the number as described before. The exact number sought lies between the two numbers found in this manner.

Next: 1) subtract the smaller mantissa from the given mantissa and; and 2) subtract the smaller mantissa from the larger mantissa.

Divide the result of (1) by the result of (2) and add the quotient to the number corresponding to the smaller mantissa.

*Example:* Find the number whose logarithm is 2.70053. First, find the number closest to the mantissa 70053 in the body of the tables. The closest mantissa listed in the tables is 700704, so read across the table to the left to find the first two digits of the number sought (50) and up the column to find the third digit of the number (2). The characteristic of the logarithm given is 2, so the number sought has three digits to the left of the decimal point. Therefore, the number sought is slightly less than 502 and greater than 501. If greater accuracy is required, find the two mantissas in the table closest to the given mantissa (699838 and 700704). Subtract the smaller mantissa from the mantissa of the given logarithm and divide the result by the smaller mantissa subtracted from the larger mantissa. Add the result to the number corresponding to the smaller mantissa. The resulting answer is  $501 + (700530 - 699838) \div (700704 - 699838) = 501 + 0.79 = 501.79$ .

**Natural Logarithms.**—In certain formulas and in some branches of mathematical analysis, use is made of logarithms (formerly also called Napierian or hyperbolic logarithms). As previously mentioned, the base of this system,  $e = 2.7182818284\dots$ , is the limit of certain mathematical series. The logarithm of a number  $A$  to the base  $e$  is usually written  $\log_e A$  or  $\ln A$ . Tables of natural logarithms for numbers ranging from 1 to 10 and 1.00 to 1.01 are given in this Handbook after the table of common logarithms. To obtain natural logs of numbers less than 1 or greater than 10, proceed as in the following examples:  $\log_e 0.239 = \log_e 2.39 - \log_e 10$ ;  $\log_e 0.0239 = \log_e 2.39 - 2 \log_e 10$ ;  $\log_e 239 = \log_e 2.39 + 2 \log_e 10$ ;  $\log_e 2390 = \log_e 2.39 + 3 \log_e 10$ , etc.

**Using Calculators to Find Logarithms.**—A scientific calculator is usually the quickest and most accurate method of finding logarithms and numbers corresponding to given logarithms. On most scientific calculators, the key labeled **log** is used to find common logarithms (base 10) and the key labeled **ln** is used for finding natural logarithms (base  $e$ ). The keystrokes to find a logarithm will vary slightly from one calculator to another, so specific instructions are not given. To find the number corresponding to a given logarithm: use the key labeled **10<sup>x</sup>** if a common logarithm is given or use the key labeled **e<sup>x</sup>** if a natural logarithm is given; calculators without the **10<sup>x</sup>** or **e<sup>x</sup>** keys may have a key labeled **x<sup>y</sup>** that can be used by substituting 10 or  $e$  (2.718281...), as required, for  $x$  and substituting the logarithm whose corresponding number is sought for  $y$ . On some other calculators, the **log** and **ln** keys are used to find common and natural logarithms, and the same keys in combination with the **INV**, or inverse, key are used to find the number corresponding to a given logarithm.

**Obtaining the Powers of Numbers.**—A number may be raised to any power by simply multiplying the logarithm of the number by the exponent of the number. The product gives the logarithm of the value of the power.

*Example 1:* Find the value of  $6.51^3$

$$\begin{aligned}\log 6.51 &= 0.81358 \\ 3 \times 0.81358 &= 2.44074\end{aligned}$$

The logarithm 2.44074 is the logarithm of  $6.51^3$ . Hence,  $6.51^3$  equals the number corresponding to this logarithm, as found from the tables, or  $6.51^3 = 275.9$ .

*Example 2:* Find the value of  $12^{1.29}$

$$\begin{aligned}\log 12 &= 1.07918 \\ 1.29 \times 1.07918 &= 1.39214\end{aligned}$$

Hence,  $12^{1.29} = 24.67$ .

Raising a decimal to a decimal power presents a somewhat more difficult problem because of the negative characteristic of the logarithm and the fact that the logarithm must be multiplied by a decimal exponent. The method for avoiding the use of negative charac-

teristics, that is adding a number to and subtracting it from the characteristic, as shown below, is helpful here.

*Example 3:* Find the value of  $0.0813^{0.46}$

$$\log 0.0813 = \bar{2}.91009 = 8.91009 - 10$$

$$\log 0.0813^{0.46} = 0.46 \times (8.91009 - 10) = 4.09864 - 4.6$$

Subtract and add 0.6 to make the characteristic a whole number:

$$\begin{array}{r} 4.09864 - 4.6 \\ \underline{-0.6} \quad + 0.6 \end{array}$$

$$\log 0.0813^{0.46} = 3.49864 - 4 = \bar{1}.49864$$

Hence,  $0.0813^{0.46} = 0.3152$ .

**Extracting Roots by Logarithms.**—Roots of numbers, for example,  $\sqrt[5]{37}$ , can be extracted easily by means of logarithms. The small (<sup>5</sup>) in the radical ( $\sqrt{\quad}$ ) of the root sign is called the index of the root. Any root of a number may be found by dividing its logarithm by the index of the root; the quotient is the logarithm of the root.

*Example 1:* Find  $\sqrt[3]{276}$

$$\begin{array}{r} \log 276 \quad = 2.44091 \\ 2.44091 \div 3 = 0.81364 \end{array}$$

Hence,  $\log \sqrt[3]{276} = 0.81364$       and       $\sqrt[3]{276} = 6.511$

*Example 2:* Find  $\sqrt[3]{0.67}$

$$\log 0.67 = \bar{1}.82607$$

Here it is not possible to divide directly, because there is a negative characteristic and a positive mantissa, another instance where the method of avoiding the use of negative characteristics, previously outlined, is helpful. The preferred procedure is to add and subtract some number to the characteristic that is evenly divisible by the index of the root. The root index is 3, so 9 can be added to and subtracted from the characteristic, and the resulting logarithm divided by 3.

$$\log 0.67 = \bar{1}.82607 = 8.82607 - 9$$

$$\log \sqrt[3]{0.67} = \frac{8.82607 - 9}{3} = 2.94202 - 3$$

$$\log \sqrt[3]{0.67} = 2.94202 - 3 = \bar{1}.94202$$

Hence,  $\sqrt[3]{0.67} = 0.875$

*Example 3:* Find  $\sqrt[1.7]{0.2}$

$$\log 0.2 = \bar{1}.30103 = 16.30103 - 17$$

$$\log \sqrt[1.7]{0.2} = \frac{16.30103 - 17}{1.7} = 9.58884 - 10 = \bar{1}.58884$$

Hence,

$$\sqrt[1.7]{0.2} = 0.388$$

## LOGARITHMS

## Table of Logarithms

## Table of Common Logarithms

|    | 0      | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      |
|----|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10 | 000000 | 004321 | 008600 | 012837 | 017033 | 021189 | 025306 | 029384 | 033424 | 037426 |
| 11 | 041393 | 045323 | 049218 | 053078 | 056905 | 060698 | 064458 | 068186 | 071882 | 075547 |
| 12 | 079181 | 082785 | 086360 | 089905 | 093422 | 096910 | 100371 | 103804 | 107210 | 110590 |
| 13 | 113943 | 117271 | 120574 | 123852 | 127105 | 130334 | 133539 | 136721 | 139879 | 143015 |
| 14 | 146128 | 149219 | 152288 | 155336 | 158362 | 161368 | 164353 | 167317 | 170262 | 173186 |
| 15 | 176091 | 178977 | 181844 | 184691 | 187521 | 190332 | 193125 | 195900 | 198657 | 201397 |
| 16 | 204120 | 206826 | 209515 | 212188 | 214844 | 217484 | 220108 | 222716 | 225309 | 227887 |
| 17 | 230449 | 232996 | 235528 | 238046 | 240549 | 243038 | 245513 | 247973 | 250420 | 252853 |
| 18 | 255273 | 257679 | 260071 | 262451 | 264818 | 267172 | 269513 | 271842 | 274158 | 276462 |
| 19 | 278754 | 281033 | 283301 | 285557 | 287802 | 290035 | 292256 | 294466 | 296665 | 298853 |
| 20 | 301030 | 303196 | 305351 | 307496 | 309630 | 311754 | 313867 | 315970 | 318063 | 320146 |
| 21 | 322219 | 324282 | 326336 | 328380 | 330414 | 332438 | 334454 | 336460 | 338456 | 340444 |
| 22 | 342423 | 344392 | 346353 | 348305 | 350248 | 352183 | 354108 | 356026 | 357935 | 359835 |
| 23 | 361728 | 363612 | 365488 | 367356 | 369216 | 371068 | 372912 | 374748 | 376577 | 378398 |
| 24 | 380211 | 382017 | 383815 | 385606 | 387390 | 389166 | 390935 | 392697 | 394452 | 396199 |
| 25 | 397940 | 399674 | 401401 | 403121 | 404834 | 406540 | 408240 | 409933 | 411620 | 413300 |
| 26 | 414973 | 416641 | 418301 | 419956 | 421604 | 423246 | 424882 | 426511 | 428135 | 429752 |
| 27 | 431364 | 432969 | 434569 | 436163 | 437751 | 439333 | 440909 | 442480 | 444045 | 445604 |
| 28 | 447158 | 448706 | 450249 | 451786 | 453318 | 454845 | 456366 | 457882 | 459392 | 460898 |
| 29 | 462398 | 463893 | 465383 | 466868 | 468347 | 469822 | 471292 | 472756 | 474216 | 475671 |
| 30 | 477121 | 478566 | 480007 | 481443 | 482874 | 484300 | 485721 | 487138 | 488551 | 489958 |
| 31 | 491362 | 492760 | 494155 | 495544 | 496930 | 498311 | 499687 | 501059 | 502427 | 503791 |
| 32 | 505150 | 506505 | 507856 | 509203 | 510545 | 511883 | 513218 | 514548 | 515874 | 517196 |
| 33 | 518514 | 519828 | 521138 | 522444 | 523746 | 525045 | 526339 | 527630 | 528917 | 530200 |
| 34 | 531479 | 532754 | 534026 | 535294 | 536558 | 537819 | 539076 | 540329 | 541579 | 542825 |
| 35 | 544068 | 545307 | 546543 | 547775 | 549003 | 550228 | 551450 | 552668 | 553883 | 555094 |
| 36 | 556303 | 557507 | 558709 | 559907 | 561101 | 562293 | 563481 | 564666 | 565848 | 567026 |
| 37 | 568202 | 569374 | 570543 | 571709 | 572872 | 574031 | 575188 | 576341 | 577492 | 578639 |
| 38 | 579784 | 580925 | 582063 | 583199 | 584331 | 585461 | 586587 | 587711 | 588832 | 589950 |
| 39 | 591065 | 592177 | 593286 | 594393 | 595496 | 596597 | 597695 | 598791 | 599883 | 600973 |
| 40 | 602060 | 603144 | 604226 | 605305 | 606381 | 607455 | 608526 | 609594 | 610660 | 611723 |
| 41 | 612784 | 613842 | 614897 | 615950 | 617000 | 618048 | 619093 | 620136 | 621176 | 622214 |
| 42 | 623249 | 624282 | 625312 | 626340 | 627366 | 628389 | 629410 | 630428 | 631444 | 632457 |
| 43 | 633468 | 634477 | 635484 | 636488 | 637490 | 638489 | 639486 | 640481 | 641474 | 642465 |
| 44 | 643453 | 644439 | 645422 | 646404 | 647383 | 648360 | 649335 | 650308 | 651278 | 652246 |
| 45 | 653213 | 654177 | 655138 | 656098 | 657056 | 658011 | 658965 | 659916 | 660865 | 661813 |
| 46 | 662758 | 663701 | 664642 | 665581 | 666518 | 667453 | 668386 | 669317 | 670246 | 671173 |
| 47 | 672098 | 673021 | 673942 | 674861 | 675778 | 676694 | 677607 | 678518 | 679428 | 680336 |
| 48 | 681241 | 682145 | 683047 | 683947 | 684845 | 685742 | 686636 | 687529 | 688420 | 689309 |
| 49 | 690196 | 691081 | 691965 | 692847 | 693727 | 694605 | 695482 | 696356 | 697229 | 698101 |
| 50 | 698970 | 699838 | 700704 | 701568 | 702431 | 703291 | 704151 | 705008 | 705864 | 706718 |
| 51 | 707570 | 708421 | 709270 | 710117 | 710963 | 711807 | 712650 | 713491 | 714330 | 715167 |
| 52 | 716003 | 716838 | 717671 | 718502 | 719331 | 720159 | 720986 | 721811 | 722634 | 723456 |
| 53 | 724276 | 725095 | 725912 | 726727 | 727541 | 728354 | 729165 | 729974 | 730782 | 731589 |
| 54 | 732394 | 733197 | 733999 | 734800 | 735599 | 736397 | 737193 | 737987 | 738781 | 739572 |
| 55 | 740363 | 741152 | 741939 | 742725 | 743510 | 744293 | 745075 | 745855 | 746634 | 747412 |
| 56 | 748188 | 748963 | 749736 | 750508 | 751279 | 752048 | 752816 | 753583 | 754348 | 755112 |
| 57 | 755875 | 756636 | 757396 | 758155 | 758912 | 759668 | 760422 | 761176 | 761928 | 762679 |
| 58 | 763428 | 764176 | 764923 | 765669 | 766413 | 767156 | 767898 | 768638 | 769377 | 770115 |
| 59 | 770852 | 771587 | 772322 | 773055 | 773786 | 774517 | 775246 | 775974 | 776701 | 777427 |



Table of Common Logarithms

|     | 0      | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      |
|-----|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 60  | 778151 | 778874 | 779596 | 780317 | 781037 | 781755 | 782473 | 783189 | 783904 | 784617 |
| 61  | 785330 | 786041 | 786751 | 787460 | 788168 | 788875 | 789581 | 790285 | 790988 | 791691 |
| 62  | 792392 | 793092 | 793790 | 794488 | 795185 | 795880 | 796574 | 797268 | 797960 | 798651 |
| 63  | 799341 | 800029 | 800717 | 801404 | 802089 | 802774 | 803457 | 804139 | 804821 | 805501 |
| 64  | 806180 | 806858 | 807535 | 808211 | 808886 | 809560 | 810233 | 810904 | 811575 | 812245 |
| 65  | 812913 | 813581 | 814248 | 814913 | 815578 | 816241 | 816904 | 817565 | 818226 | 818885 |
| 66  | 819544 | 820201 | 820858 | 821514 | 822168 | 822822 | 823474 | 824126 | 824776 | 825426 |
| 67  | 826075 | 826723 | 827369 | 828015 | 828660 | 829304 | 829947 | 830589 | 831230 | 831870 |
| 68  | 832509 | 833147 | 833784 | 834421 | 835056 | 835691 | 836324 | 836957 | 837588 | 838219 |
| 69  | 838849 | 839478 | 840106 | 840733 | 841359 | 841985 | 842609 | 843233 | 843855 | 844477 |
| 70  | 845098 | 845718 | 846337 | 846955 | 847573 | 848189 | 848805 | 849419 | 850033 | 850646 |
| 71  | 851258 | 851870 | 852480 | 853090 | 853698 | 854306 | 854913 | 855519 | 856124 | 856729 |
| 72  | 857332 | 857935 | 858537 | 859138 | 859739 | 860338 | 860937 | 861534 | 862131 | 862728 |
| 73  | 863323 | 863917 | 864511 | 865104 | 865696 | 866287 | 866878 | 867467 | 868056 | 868644 |
| 74  | 869232 | 869818 | 870404 | 870989 | 871573 | 872156 | 872739 | 873321 | 873902 | 874482 |
| 75  | 875061 | 875640 | 876218 | 876795 | 877371 | 877947 | 878522 | 879096 | 879669 | 880242 |
| 76  | 880814 | 881385 | 881955 | 882525 | 883093 | 883661 | 884229 | 884795 | 885361 | 885926 |
| 77  | 886491 | 887054 | 887617 | 888179 | 888741 | 889302 | 889862 | 890421 | 890980 | 891537 |
| 78  | 892095 | 892651 | 893207 | 893762 | 894316 | 894870 | 895423 | 895975 | 896526 | 897077 |
| 79  | 897627 | 898176 | 898725 | 899273 | 899821 | 900367 | 900913 | 901458 | 902003 | 902547 |
| 80  | 903090 | 903633 | 904174 | 904716 | 905256 | 905796 | 906335 | 906874 | 907411 | 907949 |
| 81  | 908485 | 909021 | 909556 | 910091 | 910624 | 911158 | 911690 | 912222 | 912753 | 913284 |
| 82  | 913814 | 914343 | 914872 | 915400 | 915927 | 916454 | 916980 | 917506 | 918030 | 918555 |
| 83  | 919078 | 919601 | 920123 | 920645 | 921166 | 921686 | 922206 | 922725 | 923244 | 923762 |
| 84  | 924279 | 924796 | 925312 | 925828 | 926342 | 926857 | 927370 | 927883 | 928396 | 928908 |
| 85  | 929419 | 929930 | 930440 | 930949 | 931458 | 931966 | 932474 | 932981 | 933487 | 933993 |
| 86  | 934498 | 935003 | 935507 | 936011 | 936514 | 937016 | 937518 | 938019 | 938520 | 939020 |
| 87  | 939519 | 940018 | 940516 | 941014 | 941511 | 942008 | 942504 | 943000 | 943495 | 943989 |
| 88  | 944483 | 944976 | 945469 | 945961 | 946452 | 946943 | 947434 | 947924 | 948413 | 948902 |
| 89  | 949390 | 949878 | 950365 | 950851 | 951338 | 951823 | 952308 | 952792 | 953276 | 953760 |
| 90  | 954243 | 954725 | 955207 | 955688 | 956168 | 956649 | 957128 | 957607 | 958086 | 958564 |
| 91  | 959041 | 959518 | 959995 | 960471 | 960946 | 961421 | 961895 | 962369 | 962843 | 963316 |
| 92  | 963788 | 964260 | 964731 | 965202 | 965672 | 966142 | 966611 | 967080 | 967548 | 968016 |
| 93  | 968483 | 968950 | 969416 | 969882 | 970347 | 970812 | 971276 | 971740 | 972203 | 972666 |
| 94  | 973128 | 973590 | 974051 | 974512 | 974972 | 975432 | 975891 | 976350 | 976808 | 977266 |
| 95  | 977724 | 978181 | 978637 | 979093 | 979548 | 980003 | 980458 | 980912 | 981366 | 981819 |
| 96  | 982271 | 982723 | 983175 | 983626 | 984077 | 984527 | 984977 | 985426 | 985875 | 986324 |
| 97  | 986772 | 987219 | 987666 | 988113 | 988559 | 989005 | 989450 | 989895 | 990339 | 990783 |
| 98  | 991226 | 991669 | 992111 | 992554 | 992995 | 993436 | 993877 | 994317 | 994757 | 995196 |
| 99  | 995635 | 996074 | 996512 | 996949 | 997386 | 997823 | 998259 | 998695 | 999131 | 999565 |
| 100 | 000000 | 000434 | 000868 | 001301 | 001734 | 002166 | 002598 | 003029 | 003461 | 003891 |
| 101 | 004321 | 004751 | 005181 | 005609 | 006038 | 006466 | 006894 | 007321 | 007748 | 008174 |
| 102 | 008600 | 009026 | 009451 | 009876 | 010300 | 010724 | 011147 | 011570 | 011993 | 012415 |
| 103 | 012837 | 013259 | 013680 | 014100 | 014521 | 014940 | 015360 | 015779 | 016197 | 016616 |
| 104 | 017033 | 017451 | 017868 | 018284 | 018700 | 019116 | 019532 | 019947 | 020361 | 020775 |
| 105 | 021189 | 021603 | 022016 | 022428 | 022841 | 023252 | 023664 | 024075 | 024486 | 024896 |
| 106 | 025306 | 025715 | 026125 | 026533 | 026942 | 027350 | 027757 | 028164 | 028571 | 028978 |
| 107 | 029384 | 029789 | 030195 | 030600 | 031004 | 031408 | 031812 | 032216 | 032619 | 033021 |
| 108 | 033424 | 033826 | 034227 | 034628 | 035029 | 035430 | 035830 | 036230 | 036629 | 037028 |
| 109 | 037426 | 037825 | 038223 | 038620 | 039017 | 039414 | 039811 | 040207 | 040602 | 040998 |

Table of Natural Logarithms

|     | 0        | 1        | 2        | 3        | 4        | 5        | 6        | 7        | 8        | 9        |
|-----|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 1.0 | 0.00000  | 0.009950 | 0.019803 | 0.029559 | 0.039221 | 0.048790 | 0.058269 | 0.067659 | 0.076961 | 0.086178 |
| 1.1 | 0.09531  | 0.104360 | 0.113329 | 0.122218 | 0.131028 | 0.139762 | 0.148420 | 0.157004 | 0.165514 | 0.173953 |
| 1.2 | 0.18232  | 0.190620 | 0.198851 | 0.207014 | 0.215111 | 0.223144 | 0.231112 | 0.239017 | 0.246860 | 0.254642 |
| 1.3 | 0.26236  | 0.270027 | 0.277632 | 0.285179 | 0.292670 | 0.300105 | 0.307485 | 0.314811 | 0.322083 | 0.329304 |
| 1.4 | 0.33647  | 0.343590 | 0.350657 | 0.357674 | 0.364643 | 0.371564 | 0.378436 | 0.385262 | 0.392042 | 0.398776 |
| 1.5 | 0.40546  | 0.412110 | 0.418710 | 0.425268 | 0.431782 | 0.438255 | 0.444686 | 0.451076 | 0.457425 | 0.463734 |
| 1.6 | 0.47000  | 0.476234 | 0.482426 | 0.488580 | 0.494696 | 0.500775 | 0.506818 | 0.512824 | 0.518794 | 0.524729 |
| 1.7 | 0.53062  | 0.536493 | 0.542324 | 0.548121 | 0.553885 | 0.559616 | 0.565314 | 0.570980 | 0.576613 | 0.582216 |
| 1.8 | 0.58778  | 0.593327 | 0.598837 | 0.604316 | 0.609766 | 0.615186 | 0.620576 | 0.625938 | 0.631272 | 0.636577 |
| 1.9 | 0.64185  | 0.647103 | 0.652325 | 0.657520 | 0.662688 | 0.667829 | 0.672944 | 0.678034 | 0.683097 | 0.688135 |
| 2.0 | 0.69314  | 0.698135 | 0.703098 | 0.708036 | 0.712950 | 0.717840 | 0.722706 | 0.727549 | 0.732368 | 0.737164 |
| 2.1 | 0.74193  | 0.746688 | 0.751416 | 0.756122 | 0.760806 | 0.765468 | 0.770108 | 0.774727 | 0.779325 | 0.783902 |
| 2.2 | 0.78845  | 0.792993 | 0.797507 | 0.802002 | 0.806476 | 0.810930 | 0.815365 | 0.819780 | 0.824175 | 0.828552 |
| 2.3 | 0.83290  | 0.837248 | 0.841567 | 0.845868 | 0.850151 | 0.854415 | 0.858662 | 0.862890 | 0.867100 | 0.871293 |
| 2.4 | 0.87546  | 0.879627 | 0.883768 | 0.887891 | 0.891998 | 0.896088 | 0.900161 | 0.904218 | 0.908259 | 0.912283 |
| 2.5 | 0.91629  | 0.920283 | 0.924259 | 0.928219 | 0.932164 | 0.936093 | 0.940007 | 0.943906 | 0.947789 | 0.951658 |
| 2.6 | 0.95551  | 0.959350 | 0.963174 | 0.966984 | 0.970779 | 0.974560 | 0.978326 | 0.982078 | 0.985817 | 0.989541 |
| 2.7 | 0.99325  | 0.996949 | 1.000632 | 1.004302 | 1.007958 | 1.011601 | 1.015231 | 1.018847 | 1.022451 | 1.026042 |
| 2.8 | 1.02961  | 1.033184 | 1.036737 | 1.040277 | 1.043804 | 1.047319 | 1.050822 | 1.054312 | 1.057790 | 1.061257 |
| 2.9 | 1.06471  | 1.068153 | 1.071584 | 1.075002 | 1.078410 | 1.081805 | 1.085189 | 1.088562 | 1.091923 | 1.095273 |
| 3.0 | 1.09861  | 1.101940 | 1.105257 | 1.108563 | 1.111858 | 1.115142 | 1.118415 | 1.121678 | 1.124930 | 1.128171 |
| 3.1 | 1.13140  | 1.134623 | 1.137833 | 1.141033 | 1.144223 | 1.147402 | 1.150572 | 1.153732 | 1.156881 | 1.160021 |
| 3.2 | 1.16315  | 1.166271 | 1.169381 | 1.172482 | 1.175573 | 1.178655 | 1.181727 | 1.184790 | 1.187843 | 1.190888 |
| 3.3 | 1.19392  | 1.196948 | 1.199965 | 1.202972 | 1.205971 | 1.208960 | 1.211941 | 1.214913 | 1.217876 | 1.220830 |
| 3.4 | 1.22377  | 1.226712 | 1.229641 | 1.232560 | 1.235471 | 1.238374 | 1.241269 | 1.244155 | 1.247032 | 1.249902 |
| 3.5 | 1.25276  | 1.255616 | 1.258461 | 1.261298 | 1.264127 | 1.266948 | 1.269761 | 1.272566 | 1.275363 | 1.278152 |
| 3.6 | 1.28093  | 1.283708 | 1.286474 | 1.289233 | 1.291984 | 1.294727 | 1.297463 | 1.300192 | 1.302913 | 1.305626 |
| 3.7 | 1.30833  | 1.311032 | 1.313724 | 1.316400 | 1.319086 | 1.321756 | 1.324419 | 1.327075 | 1.329724 | 1.332366 |
| 3.8 | 1.33500  | 1.337629 | 1.340250 | 1.342865 | 1.345472 | 1.348073 | 1.350667 | 1.353255 | 1.355835 | 1.358409 |
| 3.9 | 1.36097  | 1.363537 | 1.366092 | 1.368639 | 1.371181 | 1.373716 | 1.376244 | 1.378766 | 1.381282 | 1.383791 |
| 4.0 | 1.38629  | 1.388791 | 1.391282 | 1.393766 | 1.396245 | 1.398717 | 1.401183 | 1.403643 | 1.406097 | 1.408545 |
| 4.1 | 1.41098  | 1.413423 | 1.415853 | 1.418277 | 1.420696 | 1.423108 | 1.425515 | 1.427916 | 1.430311 | 1.432701 |
| 4.2 | 1.43508  | 1.437463 | 1.439835 | 1.442202 | 1.444563 | 1.446919 | 1.449269 | 1.451614 | 1.453953 | 1.456287 |
| 4.3 | 1.45861  | 1.460938 | 1.463255 | 1.465568 | 1.467874 | 1.470176 | 1.472472 | 1.474763 | 1.477049 | 1.479329 |
| 4.4 | 1.48160  | 1.483875 | 1.486140 | 1.488400 | 1.490654 | 1.492904 | 1.495149 | 1.497388 | 1.499623 | 1.501853 |
| 4.5 | 1.50407  | 1.506297 | 1.508512 | 1.510722 | 1.512927 | 1.515127 | 1.517323 | 1.519513 | 1.521699 | 1.523880 |
| 4.6 | 1.52605  | 1.528228 | 1.530395 | 1.532557 | 1.534714 | 1.536867 | 1.539015 | 1.541159 | 1.543298 | 1.545433 |
| 4.7 | 1.54756  | 1.549688 | 1.551809 | 1.553925 | 1.556037 | 1.558145 | 1.560248 | 1.562346 | 1.564441 | 1.566530 |
| 4.8 | 1.56861  | 1.570697 | 1.572774 | 1.574846 | 1.576915 | 1.578979 | 1.581038 | 1.583094 | 1.585145 | 1.587192 |
| 4.9 | 1.58923  | 1.591274 | 1.593309 | 1.595339 | 1.597365 | 1.599388 | 1.601406 | 1.603420 | 1.605430 | 1.607436 |
| 5.0 | 1.60943  | 1.611436 | 1.613430 | 1.615420 | 1.617406 | 1.619388 | 1.621366 | 1.623341 | 1.625311 | 1.627278 |
| 5.1 | 1.62924  | 1.631199 | 1.633154 | 1.635106 | 1.637053 | 1.638997 | 1.640937 | 1.642873 | 1.644805 | 1.646734 |
| 5.2 | 1.64865  | 1.650580 | 1.652497 | 1.654411 | 1.656321 | 1.658228 | 1.660131 | 1.662030 | 1.663926 | 1.665818 |
| 5.3 | 1.66770  | 1.669592 | 1.671473 | 1.673351 | 1.675226 | 1.677097 | 1.678964 | 1.680828 | 1.682688 | 1.684545 |
| 5.4 | 1.68639  | 1.688249 | 1.690096 | 1.691939 | 1.693779 | 1.695616 | 1.697449 | 1.699279 | 1.701105 | 1.702928 |
| 5.5 | 1.70474  | 1.706565 | 1.708378 | 1.710188 | 1.711995 | 1.713798 | 1.715598 | 1.717395 | 1.719189 | 1.720979 |
| 5.6 | 1.722767 | 1.724551 | 1.726332 | 1.728110 | 1.729884 | 1.731656 | 1.733424 | 1.735189 | 1.736951 | 1.738710 |
| 5.7 | 1.74046  | 1.742219 | 1.743969 | 1.745716 | 1.747459 | 1.749200 | 1.750937 | 1.752672 | 1.754404 | 1.756132 |
| 5.8 | 1.75785  | 1.759581 | 1.761300 | 1.763017 | 1.764731 | 1.766442 | 1.768150 | 1.769855 | 1.771557 | 1.773256 |
| 5.9 | 1.77495  | 1.776646 | 1.778336 | 1.780024 | 1.781709 | 1.783391 | 1.785070 | 1.786747 | 1.788421 | 1.790091 |

Table of Natural Logarithms

|      | 0        | 1        | 2        | 3        | 4        | 5        | 6        | 7        | 8        | 9        |
|------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 6.0  | 1.791759 | 1.793425 | 1.795087 | 1.796747 | 1.798404 | 1.800058 | 1.801710 | 1.803359 | 1.805005 | 1.806648 |
| 6.1  | 1.808289 | 1.809927 | 1.811562 | 1.813195 | 1.814825 | 1.816452 | 1.818077 | 1.819699 | 1.821318 | 1.822935 |
| 6.2  | 1.824549 | 1.826161 | 1.827770 | 1.829376 | 1.830980 | 1.832581 | 1.834180 | 1.835776 | 1.837370 | 1.838961 |
| 6.3  | 1.840550 | 1.842136 | 1.843719 | 1.845300 | 1.846879 | 1.848455 | 1.850028 | 1.851599 | 1.853168 | 1.854734 |
| 6.4  | 1.856298 | 1.857859 | 1.859418 | 1.860975 | 1.862529 | 1.864080 | 1.865629 | 1.867176 | 1.868721 | 1.870263 |
| 6.5  | 1.871802 | 1.873339 | 1.874874 | 1.876407 | 1.877937 | 1.879465 | 1.880991 | 1.882514 | 1.884035 | 1.885553 |
| 6.6  | 1.887070 | 1.888584 | 1.890095 | 1.891605 | 1.893112 | 1.894617 | 1.896119 | 1.897620 | 1.899118 | 1.900614 |
| 6.7  | 1.902108 | 1.903599 | 1.905088 | 1.906575 | 1.908060 | 1.909543 | 1.911023 | 1.912501 | 1.913977 | 1.915451 |
| 6.8  | 1.916923 | 1.918392 | 1.919859 | 1.921325 | 1.922788 | 1.924249 | 1.925707 | 1.927164 | 1.928619 | 1.930071 |
| 6.9  | 1.931521 | 1.932970 | 1.934416 | 1.935860 | 1.937302 | 1.938742 | 1.940179 | 1.941615 | 1.943049 | 1.944481 |
| 7.0  | 1.945910 | 1.947338 | 1.948763 | 1.950187 | 1.951608 | 1.953028 | 1.954445 | 1.955860 | 1.957274 | 1.958685 |
| 7.1  | 1.960095 | 1.961502 | 1.962908 | 1.964311 | 1.965713 | 1.967112 | 1.968510 | 1.969906 | 1.971299 | 1.972691 |
| 7.2  | 1.974081 | 1.975469 | 1.976855 | 1.978239 | 1.979621 | 1.981001 | 1.982380 | 1.983756 | 1.985131 | 1.986504 |
| 7.3  | 1.987874 | 1.989243 | 1.990610 | 1.991976 | 1.993339 | 1.994700 | 1.996060 | 1.997418 | 1.998774 | 2.000128 |
| 7.4  | 2.001480 | 2.002830 | 2.004179 | 2.005526 | 2.006871 | 2.008214 | 2.009555 | 2.010895 | 2.012233 | 2.013569 |
| 7.5  | 2.014903 | 2.016235 | 2.017566 | 2.018895 | 2.020222 | 2.021548 | 2.022871 | 2.024193 | 2.025513 | 2.026832 |
| 7.6  | 2.028148 | 2.029463 | 2.030776 | 2.032088 | 2.033398 | 2.034706 | 2.036012 | 2.037317 | 2.038620 | 2.039921 |
| 7.7  | 2.041220 | 2.042518 | 2.043814 | 2.045109 | 2.046402 | 2.047693 | 2.048982 | 2.050270 | 2.051556 | 2.052841 |
| 7.8  | 2.054124 | 2.055405 | 2.056685 | 2.057963 | 2.059239 | 2.060514 | 2.061787 | 2.063058 | 2.064328 | 2.065596 |
| 7.9  | 2.066863 | 2.068128 | 2.069391 | 2.070653 | 2.071913 | 2.073172 | 2.074429 | 2.075684 | 2.076938 | 2.078191 |
| 8.0  | 2.079442 | 2.080691 | 2.081938 | 2.083185 | 2.084429 | 2.085672 | 2.086914 | 2.088153 | 2.089392 | 2.090629 |
| 8.1  | 2.091864 | 2.093098 | 2.094330 | 2.095561 | 2.096790 | 2.098018 | 2.099244 | 2.100469 | 2.101692 | 2.102914 |
| 8.2  | 2.104134 | 2.105353 | 2.106570 | 2.107786 | 2.109000 | 2.110213 | 2.111425 | 2.112635 | 2.113843 | 2.115050 |
| 8.3  | 2.116256 | 2.117460 | 2.118662 | 2.119863 | 2.121063 | 2.122262 | 2.123458 | 2.124654 | 2.125848 | 2.127041 |
| 8.4  | 2.128232 | 2.129421 | 2.130610 | 2.131797 | 2.132982 | 2.134166 | 2.135349 | 2.136531 | 2.137710 | 2.138889 |
| 8.5  | 2.140066 | 2.141242 | 2.142416 | 2.143589 | 2.144761 | 2.145931 | 2.147100 | 2.148268 | 2.149434 | 2.150599 |
| 8.6  | 2.151762 | 2.152924 | 2.154085 | 2.155245 | 2.156403 | 2.157559 | 2.158715 | 2.159869 | 2.161022 | 2.162173 |
| 8.7  | 2.163323 | 2.164472 | 2.165619 | 2.166765 | 2.167910 | 2.169054 | 2.170196 | 2.171337 | 2.172476 | 2.173615 |
| 8.8  | 2.174752 | 2.175887 | 2.177022 | 2.178155 | 2.179287 | 2.180417 | 2.181547 | 2.182675 | 2.183802 | 2.184927 |
| 8.9  | 2.186051 | 2.187174 | 2.188296 | 2.189416 | 2.190536 | 2.191654 | 2.192770 | 2.193886 | 2.195000 | 2.196113 |
| 9.0  | 2.197225 | 2.198335 | 2.199444 | 2.200552 | 2.201659 | 2.202765 | 2.203869 | 2.204972 | 2.206074 | 2.207175 |
| 9.1  | 2.208274 | 2.209373 | 2.210470 | 2.211566 | 2.212660 | 2.213754 | 2.214846 | 2.215937 | 2.217027 | 2.218116 |
| 9.2  | 2.219203 | 2.220290 | 2.221375 | 2.222459 | 2.223542 | 2.224624 | 2.225704 | 2.226783 | 2.227862 | 2.228939 |
| 9.3  | 2.230014 | 2.231089 | 2.232163 | 2.233235 | 2.234306 | 2.235376 | 2.236445 | 2.237513 | 2.238580 | 2.239645 |
| 9.4  | 2.240710 | 2.241773 | 2.242835 | 2.243896 | 2.244956 | 2.246015 | 2.247072 | 2.248129 | 2.249184 | 2.250239 |
| 9.5  | 2.251292 | 2.252344 | 2.253395 | 2.254445 | 2.255493 | 2.256541 | 2.257588 | 2.258633 | 2.259678 | 2.260721 |
| 9.6  | 2.261763 | 2.262804 | 2.263844 | 2.264883 | 2.265921 | 2.266958 | 2.267994 | 2.269028 | 2.270062 | 2.271094 |
| 9.7  | 2.272126 | 2.273156 | 2.274186 | 2.275214 | 2.276241 | 2.277267 | 2.278292 | 2.279316 | 2.280339 | 2.281361 |
| 9.8  | 2.282382 | 2.283402 | 2.284421 | 2.285439 | 2.286456 | 2.287471 | 2.288486 | 2.289500 | 2.290513 | 2.291524 |
| 9.9  | 2.292535 | 2.293544 | 2.294553 | 2.295560 | 2.296567 | 2.297573 | 2.298577 | 2.299581 | 2.300583 | 2.301585 |
| 1.00 | 0.000000 | 0.001000 | 0.001998 | 0.002996 | 0.003992 | 0.004988 | 0.005982 | 0.006976 | 0.007968 | 0.008960 |
| 1.01 | 0.009950 | 0.010940 | 0.011929 | 0.012916 | 0.013903 | 0.014889 | 0.015873 | 0.016857 | 0.017840 | 0.018822 |
| 1.02 | 0.019803 | 0.020783 | 0.021761 | 0.022739 | 0.023717 | 0.024693 | 0.025668 | 0.026642 | 0.027615 | 0.028587 |
| 1.03 | 0.029559 | 0.030529 | 0.031499 | 0.032467 | 0.033435 | 0.034401 | 0.035367 | 0.036332 | 0.037296 | 0.038259 |
| 1.04 | 0.039221 | 0.040182 | 0.041142 | 0.042101 | 0.043059 | 0.044017 | 0.044973 | 0.045929 | 0.046884 | 0.047837 |
| 1.05 | 0.048790 | 0.049742 | 0.050693 | 0.051643 | 0.052592 | 0.053541 | 0.054488 | 0.055435 | 0.056380 | 0.057325 |
| 1.06 | 0.058269 | 0.059212 | 0.060154 | 0.061095 | 0.062035 | 0.062975 | 0.063913 | 0.064851 | 0.065788 | 0.066724 |
| 1.07 | 0.067659 | 0.068593 | 0.069526 | 0.070458 | 0.071390 | 0.072321 | 0.073250 | 0.074179 | 0.075107 | 0.076035 |
| 1.08 | 0.076961 | 0.077887 | 0.078811 | 0.079735 | 0.080658 | 0.081580 | 0.082501 | 0.083422 | 0.084341 | 0.085260 |
| 1.09 | 0.086178 | 0.087095 | 0.088011 | 0.088926 | 0.089841 | 0.090754 | 0.091667 | 0.092579 | 0.093490 | 0.094401 |

## MATRICES

A matrix is a set of real numbers arranged in rows and columns to form a rectangular array. A matrix with  $m$  rows and  $n$  columns is an  $m \times n$  matrix ( $m$  by  $n$ ) and may be written as

$$A_{mn} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$

The  $a_{ij}$  terms are called the entries or elements of the matrix. The first subscript  $i$  identifies the row position of an entry, and the second subscript  $j$  identifies the column position in the matrix.

Some common matrix types have special names, as follows:

*Column Matrix:* A matrix that has only one column ( $m \times 1$ ).

*Diagonal Matrix:* A square matrix in which all values are zero except for those on one of the diagonals. If the diagonal entries are all 1, the matrix is an *identity* matrix.

*Identity Matrix:* A diagonal matrix in which the diagonal entries are all 1.

*Row Matrix:* A matrix that has only one row ( $1 \times n$ ).

*Square Matrix:* A matrix in which the number of rows and columns are equal, i.e.,  $m = n$ .

*Zero Matrix:* A matrix in which all the entries of the matrix are zero. The zero matrix is also called the *null* matrix.

## Matrix Operations

**Matrix Addition and Subtraction.**—Matrices can be added or subtracted if they have the same shape, that is, if number of columns in each matrix is the same, and the number of rows in each matrix is the same. The sum or difference of the matrices are determined by adding or subtracting the corresponding elements of each matrix. Thus, each element in the resultant matrix is formed using  $c_{ij} = a_{ij} \pm b_{ij}$  as illustrated below:

$$\begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \pm \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} = \begin{bmatrix} (a_{11} \pm b_{11}) & (a_{12} \pm b_{12}) & (a_{13} \pm b_{13}) \\ (a_{21} \pm b_{21}) & (a_{22} \pm b_{22}) & (a_{23} \pm b_{23}) \\ (a_{31} \pm b_{31}) & (a_{32} \pm b_{32}) & (a_{33} \pm b_{33}) \end{bmatrix}$$

## Example 1

$$\begin{bmatrix} 4 & 6 & -5 \\ 5 & -7 & 8 \\ -8 & 6 & -7 \end{bmatrix} + \begin{bmatrix} 8 & -2 & 6 \\ -6 & 9 & 5 \\ 9 & -2 & 2 \end{bmatrix} = \begin{bmatrix} (4+8) & (6-2) & (-5+6) \\ (5-6) & (-7+9) & (8+5) \\ (-8+9) & (6-2) & (-7+2) \end{bmatrix} = \begin{bmatrix} 12 & 4 & 1 \\ -1 & 2 & 13 \\ 1 & 4 & -5 \end{bmatrix}$$

**Matrix Multiplication.**—Two matrices can be multiplied *only* when the number of columns in the first matrix is equal to the number of rows of the second matrix. Matrix multiplication is not commutative, thus,  $A \times B$  is not necessarily equal to  $B \times A$ .

Each resulting entry  $c_{ij}$  in the product matrix,  $C = A \times B$ , is the sum of the products of each element in the  $i^{\text{th}}$  row of matrix  $A$  multiplied by the corresponding element in the  $j^{\text{th}}$  column of matrix  $B$ , as illustrated in the following:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \times \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix}$$

$$= \begin{bmatrix} (a_{11}b_{11} + a_{12}b_{21} + a_{13}b_{31}) & (a_{11}b_{12} + a_{12}b_{22} + a_{13}b_{32}) & (a_{11}b_{13} + a_{12}b_{23} + a_{13}b_{33}) \\ (a_{21}b_{11} + a_{22}b_{21} + a_{23}b_{31}) & (a_{21}b_{12} + a_{22}b_{22} + a_{23}b_{32}) & (a_{21}b_{13} + a_{22}b_{23} + a_{23}b_{33}) \\ (a_{31}b_{11} + a_{32}b_{21} + a_{33}b_{31}) & (a_{31}b_{12} + a_{32}b_{22} + a_{33}b_{32}) & (a_{31}b_{13} + a_{32}b_{23} + a_{33}b_{33}) \end{bmatrix}$$

**Example 2**

$$\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 3 & 2 & 1 \end{bmatrix} \times \begin{bmatrix} 7 & 8 & 9 \\ 1 & 2 & 3 \\ 4 & 5 & 7 \end{bmatrix} = \begin{bmatrix} (1 \cdot 7 + 2 \cdot 1 + 3 \cdot 4) & (1 \cdot 8 + 2 \cdot 2 + 3 \cdot 5) & (1 \cdot 9 + 2 \cdot 3 + 3 \cdot 7) \\ (4 \cdot 7 + 5 \cdot 1 + 6 \cdot 4) & (4 \cdot 8 + 5 \cdot 2 + 6 \cdot 5) & (4 \cdot 9 + 5 \cdot 3 + 6 \cdot 7) \\ (3 \cdot 7 + 2 \cdot 1 + 1 \cdot 4) & (3 \cdot 8 + 2 \cdot 2 + 1 \cdot 5) & (3 \cdot 9 + 2 \cdot 3 + 1 \cdot 7) \end{bmatrix}$$

$$= \begin{bmatrix} (7 + 2 + 12) & (8 + 4 + 15) & (9 + 6 + 21) \\ (28 + 5 + 24) & (32 + 10 + 30) & (36 + 15 + 42) \\ (21 + 2 + 4) & (24 + 4 + 5) & (27 + 6 + 7) \end{bmatrix} = \begin{bmatrix} 21 & 27 & 36 \\ 57 & 72 & 93 \\ 27 & 33 & 40 \end{bmatrix}$$

**Transpose of a Matrix.**— If the rows of a matrix  $A_{mn}$  are interchanged with its columns, the new matrix is called the transpose of matrix  $A$ , or  $A^T_{nm}$ . The first row of the matrix becomes the first column in the transposed matrix, the second row of the matrix becomes second column, and the third row of the matrix becomes third column.

**Example 3:**

$$A = \begin{bmatrix} 21 & 27 & 36 \\ 57 & 72 & 93 \\ 27 & 33 & 40 \end{bmatrix} \quad A^T = \begin{bmatrix} 21 & 57 & 27 \\ 27 & 72 & 33 \\ 36 & 93 & 40 \end{bmatrix}$$

**Determinant of a Square Matrix.**— Every square matrix  $A$  is associated with a real number, its determinant, which may be written  $\det(A)$  or  $|A|$ .

For  $A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$ , the determinant of  $A$  is

$$\det(A) = |A| = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = a_{11}a_{22} - a_{12}a_{21}$$

For a  $3 \times 3$  matrix  $B$ , the determinant is

$$\det(B) = \begin{vmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{vmatrix}$$

$$= (b_{11}b_{22}b_{33} - b_{11}b_{23}b_{32}) - (b_{12}b_{23}b_{31} - b_{12}b_{21}b_{33}) + (b_{13}b_{21}b_{32} - b_{13}b_{22}b_{31})$$

$$= b_{11}(b_{22}b_{33} - b_{23}b_{32}) - b_{12}(b_{23}b_{31} - b_{21}b_{33}) + b_{13}(b_{21}b_{32} - b_{22}b_{31})$$

The determinant of an  $n \times n$  matrix results in  $n$  successive terms with alternating signs (+ or -). The troublesome task of keeping track of the proper sign for each term can be avoided by multiplying each term by  $(-1)^{i+j}$  and adding all the terms. For example, using this rule, the last line of the previous equation can be rewritten as follows:

$$= (-1)^{(1+1)}b_{11}(b_{22}b_{33} - b_{23}b_{32}) + (-1)^{(1+2)}b_{12}(b_{23}b_{31} - b_{21}b_{33}) + (-1)^{(1+3)}b_{13}(b_{21}b_{32} - b_{22}b_{31})$$

**Example 4:** Find the determinant of the following matrix.

$$A = \begin{bmatrix} 5 & 6 & 7 \\ 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix}$$

*Solution:*

$$\begin{aligned} \det(A) &= (-1)^{(1+1)} \cdot 5 \cdot [(2 \times 6) - (5 \times 3)] \\ &\quad + (-1)^{(1+2)} \cdot 6 \cdot [(1 \times 6) - (4 \times 3)] \\ &\quad + (-1)^{(1+3)} \cdot 7 \cdot [(1 \times 5) - (2 \times 4)] \\ \det(A) &= 5(12 - 15) - 6(6 - 12) + 7(5 - 8) \\ &= 5(-3) - 6(-6) + 7(-3) = -15 + 36 - 21 = 0 \end{aligned}$$

**Minors and Cofactors.**— The minor  $M_{ij}$  of a matrix  $A$  is the determinant of a submatrix resulting from the elimination of row  $i$  and of column  $j$ . If  $A$  is a square matrix, the minor  $M_{ij}$  of the entry  $a_{ij}$  is the determinant of the matrix obtained by deleting the  $i^{\text{th}}$  row and  $j^{\text{th}}$  column of  $A$ .

The cofactor  $C_{ij}$  of the entry  $a_{ij}$  is given by  $C_{ij} = (-1)^{(i+j)}M_{ij}$ . When the matrix is formed by the cofactors, then it is called a cofactors matrix.

*Example 5:* Find the minors and cofactors of

$$A = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 3 & 2 & 1 \end{bmatrix}$$

*Solution:* To determine the minor  $M_{11}$ , delete the first row and first column of  $A$  and find the determinant of the resulting matrix.

$$M_{11} = \begin{vmatrix} 5 & 6 \\ 2 & 1 \end{vmatrix} = (5 \times 1) - (6 \times 2) = 5 - 12 = -7$$

Similarly to find  $M_{12}$ , delete the first row and second column of  $A$  and find the determinant of the resulting matrix.

$$M_{12} = \begin{vmatrix} 4 & 6 \\ 3 & 1 \end{vmatrix} = (4 \times 1) - (6 \times 3) = 4 - 18 = -14$$

Continuing this way, we obtain the following minors:

$$\begin{array}{lll} M_{11} = -7 & M_{12} = -14 & M_{13} = -7 \\ M_{21} = -4 & M_{22} = -8 & M_{23} = -4 \\ M_{31} = -3 & M_{32} = -6 & M_{33} = -3 \end{array}$$

To find the cofactor  $C_{ij} = (-1)^{(i+j)} \times M_{ij}$ , thus  $C_{11} = (-1)^{(1+1)} \times M_{11} = 1 \times (-7) = -7$

Similarly  $C_{12} = (-1)^{(1+2)} \times M_{12} = -1 \times -14 = 14$ , and continuing this way we obtain the following cofactors

$$\begin{array}{lll} C_{11} = -7 & C_{12} = 14 & C_{13} = -7 \\ C_{21} = 4 & C_{22} = -8 & C_{23} = 4 \\ C_{31} = -3 & C_{32} = 6 & C_{33} = -3 \end{array}$$

**Adjoint of a Matrix.**— The transpose of cofactor matrix is called the adjoint matrix. First determine the cofactor matrix and then transpose it to obtain the adjoint matrix.

*Example 6:* Find the adjoint matrix of  $A$

$$A = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 3 & 2 & 1 \end{bmatrix}$$

**Solution:** The cofactor matrix from the above example is shown below at the left, and the adjoint matrix on the right.

$$\text{Cofactor}(A) = \begin{bmatrix} -7 & 14 & -7 \\ 4 & -8 & 4 \\ -3 & 6 & -3 \end{bmatrix} \quad \text{Adjoint}(A) = \begin{bmatrix} -7 & 14 & -7 \\ 4 & -8 & 4 \\ -3 & 6 & -3 \end{bmatrix}^T = \begin{bmatrix} -7 & 4 & -3 \\ 14 & -8 & 6 \\ -7 & 4 & -3 \end{bmatrix}$$

**Singularity and Rank of a Matrix.**—A singular matrix is one whose determinant is zero. The rank of a matrix is the maximum number of linearly independent row or column vectors.

**Inverse of a Matrix.**—A square non-singular matrix  $A$  has an inverse  $A^{-1}$  such that the product of matrix  $A$  and inverse matrix  $A^{-1}$ , is the identity matrix  $I$ . Thus,  $AA^{-1} = I$ . The inverse is the ratio of adjoint of the matrix and the determinant of that matrix.

$$A^{-1} = \frac{\text{Adjoint}(A)}{|A|}$$

**Example 7:** What is the inverse of the following matrix?

$$A = \begin{bmatrix} 2 & 3 & 5 \\ 4 & 1 & 6 \\ 1 & 4 & 0 \end{bmatrix}$$

**Solution:** The basic formula of an inverse of a matrix is

$$A^{-1} = \frac{\text{Adjoint}(A)}{|A|}$$

The determinant of  $A$  is

$$\begin{aligned} |A| &= 2(1 \times 0 - 4 \times 6) - 3(4 \times 0 - 1 \times 6) + 5(4 \times 4 - 1 \times 1) \\ &= 2(0 - 24) - 3(0 - 6) + 5(16 - 1) \\ &= -48 + 18 + 75 = 45 \end{aligned}$$

The cofactors are

$$\begin{aligned} a_{11} &= (-1)^{1+1} \begin{vmatrix} 1 & 6 \\ 4 & 0 \end{vmatrix} = -24 & a_{12} &= (-1)^{1+2} \begin{vmatrix} 4 & 6 \\ 1 & 0 \end{vmatrix} = 6 & a_{13} &= (-1)^{1+3} \begin{vmatrix} 4 & 1 \\ 1 & 4 \end{vmatrix} = 15 \\ a_{21} &= (-1)^{2+1} \begin{vmatrix} 3 & 5 \\ 4 & 0 \end{vmatrix} = 20 & a_{22} &= (-1)^{2+2} \begin{vmatrix} 2 & 5 \\ 1 & 0 \end{vmatrix} = -5 & a_{23} &= (-1)^{2+3} \begin{vmatrix} 2 & 3 \\ 1 & 4 \end{vmatrix} = -5 \\ a_{31} &= (-1)^{3+1} \begin{vmatrix} 3 & 5 \\ 1 & 6 \end{vmatrix} = 13 & a_{32} &= (-1)^{3+2} \begin{vmatrix} 2 & 5 \\ 4 & 6 \end{vmatrix} = 8 & a_{33} &= (-1)^{3+3} \begin{vmatrix} 2 & 3 \\ 4 & 1 \end{vmatrix} = -10 \end{aligned}$$

The matrix of cofactors is  $\begin{bmatrix} -24 & 6 & 15 \\ 20 & -5 & -5 \\ 13 & 8 & -10 \end{bmatrix}$  and the adjoint matrix is  $\begin{bmatrix} -24 & 20 & 13 \\ 6 & -5 & 8 \\ 15 & -5 & -10 \end{bmatrix}$

Then the inverse of matrix  $A$  is

$$A^{-1} = \frac{\text{Adjoint}(A)}{|A|} = \frac{1}{45} \begin{bmatrix} -24 & 20 & 13 \\ 6 & -5 & 8 \\ 15 & -5 & -10 \end{bmatrix}$$

**Simultaneous Equations.**—Matrices can be used to solve systems of simultaneous equations with a large number of unknowns. Generally, this method is less cumbersome than

using substitution methods. The coefficients of the equations are placed in matrix form. The matrix is then manipulated into the Identity matrix, see below, to yield a solution.

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Identity Matrix

*Example 8:* Solve the three simultaneous equations using matrix operations.

$$-4x_1 + 8x_2 + 12x_3 = 16$$

$$3x_1 - x_2 + 2x_3 = 5$$

$$x_1 + 7x_2 + 6x_3 = 10$$

*Solution:* First, place the equation coefficients and constants into matrix form. The object is to transform the coefficient matrix into the form shown below, thereby obtaining a solution to the system of equations.

$$\begin{bmatrix} -4 & 8 & 12 & 16 \\ 3 & -1 & 2 & 5 \\ 1 & 7 & 6 & 10 \end{bmatrix} \Leftrightarrow \begin{bmatrix} 1 & 0 & 0 & x_1 \\ 0 & 1 & 0 & x_2 \\ 0 & 0 & 1 & x_3 \end{bmatrix}$$

Transform the coefficient matrix so that element  $c_{11}$  is 1 and all other elements in the first column are 0, as follows: a) Divide *Row 1* ( $R_1$ ) by  $-4$ ; b) multiply new  $R_1$  by  $-3$ , then add to  $R_2$ ; and c) multiply  $R_1$  by  $-1$ , then add to  $R_3$ .

$$\begin{bmatrix} -4 & 8 & 12 & 16 \\ -4 & -4 & -4 & -4 \\ 3 & -1 & 2 & 5 \\ 1 & 7 & 6 & 10 \end{bmatrix} \Rightarrow \begin{bmatrix} 1 & -2 & -3 & -4 \\ (3-3) & (-1+6) & (2+9) & (5+12) \\ (1-1) & (7+2) & (6+3) & (10+4) \end{bmatrix} \Rightarrow \begin{bmatrix} 1 & -2 & -3 & -4 \\ 0 & 5 & 11 & 17 \\ 0 & 9 & 9 & 14 \end{bmatrix}$$

Transform the resulting matrix so that element  $c_{22}$  is 1 and all other elements in the second column are 0, as follows: a) Divide  $R_2$  by 9; b) multiply new  $R_2$  by  $-5$ , then add to  $R_1$ ; c) multiply  $R_2$  by 2, then add to  $R_3$ ; and d) swap  $R_2$  and  $R_3$ .

$$\begin{bmatrix} 1 & -2 & -3 & -4 \\ 0 & 5 & 11 & 17 \\ 0 & 9 & 9 & 14 \\ \frac{9}{9} & \frac{9}{9} & \frac{9}{9} & \frac{9}{9} \end{bmatrix} \Rightarrow \begin{bmatrix} 1 & (-2+2) & (-3+2) & (-4+\frac{28}{9}) \\ 0 & (5-5) & (11-5) & (17-\frac{70}{9}) \\ 0 & 1 & 1 & \frac{14}{9} \end{bmatrix} \Rightarrow \begin{bmatrix} 1 & 0 & -1 & -\frac{8}{9} \\ 0 & 0 & 6 & \frac{83}{9} \\ 0 & 1 & 1 & \frac{14}{9} \end{bmatrix} \Rightarrow \begin{bmatrix} 1 & 0 & -1 & -\frac{8}{9} \\ 0 & 1 & 1 & \frac{14}{9} \\ 0 & 0 & 6 & \frac{83}{9} \end{bmatrix}$$

Transform the resulting matrix so that element  $c_{33}$  is 1 and all other elements in the third column are 0, as follows: a) Divide  $R_3$  by 6; b) multiply new  $R_3$  by  $-1$ , then add to  $R_2$ ; and c) add  $R_3$  to  $R_1$ .

$$\begin{bmatrix} 1 & 0 & -1 & -\frac{8}{9} \\ 0 & 1 & 1 & \frac{14}{9} \\ 0 & 0 & \frac{6}{6} & \frac{83}{9(6)} \end{bmatrix} \Rightarrow \begin{bmatrix} 1 & 0 & (-1+1) & (-\frac{8}{9} + \frac{83}{54}) \\ 0 & 1 & (1-1) & (\frac{14}{9} - \frac{83}{54}) \\ 0 & 0 & 1 & \frac{83}{54} \end{bmatrix} \Rightarrow \begin{bmatrix} 1 & 0 & 0 & \frac{35}{54} \\ 0 & 1 & 0 & \frac{1}{54} \\ 0 & 0 & 1 & \frac{83}{54} \end{bmatrix}$$



Finally, when the identity matrix has been formed, the last column contains the values of  $x_1$ ,  $x_2$ , and  $x_3$  that satisfy the original equations.

$$x_1 = \frac{35}{54} \quad x_2 = \frac{1}{54} \quad x_3 = \frac{83}{54}$$

Checking the solutions:

$$\begin{array}{rcl} -4x_1 + 8x_2 + 12x_3 = 16 & 3x_1 - x_2 + 2x_3 = 5 & x_1 + 7x_2 + 6x_3 = 10 \\ 16 = 16 & 5 = 5 & 10 = 10 \end{array}$$

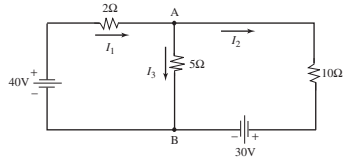
**Example 9:** Use matrix operations to find the currents ( $I_1$ ,  $I_2$ ,  $I_3$ ) in the following electrical network.

By Kirchoff's Current Law:

$$\begin{array}{l} I_2 + I_3 = I_1 \\ I_1 - I_2 - I_3 = 0 \end{array}$$

By Kirchoff's Voltage Law, and Ohm's Law:

$$\begin{array}{l} 2I_1 + 5I_3 - 40 = 0 \\ 10I_2 + 5I_3 - 30 = 0 \end{array}$$



By combining all the above equations, a linear system of three independent equations is formed. Solve the system for the currents  $I_1$ ,  $I_2$ , and  $I_3$ .

$$\begin{array}{l} I_1 - I_2 - I_3 = 0 \\ 2I_1 + 5I_3 = 40 \\ 10I_2 - 5I_3 = 30 \end{array}$$

**Solution:** If  $A$  is the matrix of coefficients of the currents,  $B$  is the matrix of currents (variables), and  $C$  be the matrix of constants from the right side of the equations, then the problem can be written in the following form:  $AB = C$ , and  $B = A^{-1}C$ , where  $A^{-1}$  is the inverse of matrix  $A$ .

Thus,

$$A = \begin{bmatrix} 1 & -1 & -1 \\ 2 & 0 & 5 \\ 0 & 10 & -5 \end{bmatrix} \quad B = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \quad C = \begin{bmatrix} 0 \\ 40 \\ 30 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} 1 & -1 & -1 \\ 2 & 0 & 5 \\ 0 & 10 & -5 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 40 \\ 50 \end{bmatrix}$$

Using the method of [Example 7](#), the inverse of matrix  $A$  is

$$A^{-1} = \begin{bmatrix} 1 & -1 & -1 \\ 2 & 0 & 5 \\ 0 & 10 & -5 \end{bmatrix}^{-1} = -\frac{1}{80} \begin{bmatrix} -50 & -15 & -5 \\ 10 & -5 & -7 \\ 20 & -10 & 2 \end{bmatrix} = \begin{bmatrix} \frac{5}{8} & \frac{3}{16} & \frac{1}{16} \\ -\frac{1}{8} & \frac{1}{16} & \frac{7}{80} \\ -\frac{1}{4} & \frac{1}{8} & -\frac{1}{40} \end{bmatrix}$$

and finally, matrix  $B$  can be found as follows:

$$B = A^{-1}C = \begin{bmatrix} \frac{5}{8} & \frac{3}{16} & \frac{1}{16} \\ -\frac{1}{8} & \frac{1}{16} & \frac{7}{80} \\ -\frac{1}{4} & \frac{1}{8} & -\frac{1}{40} \end{bmatrix} \begin{bmatrix} 0 \\ 40 \\ 50 \end{bmatrix} = \begin{bmatrix} 9.375 \\ 5.125 \\ 4.25 \end{bmatrix}$$

Thus,  $I_1 = 9.375$  amps,  $I_2 = 5.125$  amps, and  $I_3 = 4.25$  amps

## ENGINEERING ECONOMICS

Engineers, managers, purchasing agents, and others are often required to plan and evaluate project alternatives, and make economic decisions that may greatly affect the success or failure of a project.

The goals of a project, such as reducing manufacturing cost or increasing production, selection of machine tool alternatives, or reduction of tooling, labor and other costs, determine which of the available alternatives may bring the most attractive economic return.

Various cost analysis techniques that may be used to obtain the desired outcome are discussed in the material that follows.

### Interest

Interest is money paid for the use of money lent for a certain time. *Simple* interest is the interest paid on the principal (money lent) only. When simple interest that is due is not paid, and its amount is added to the interest-bearing principal, the interest calculated on this new principal is called *compound* interest. The compounding of the interest into the principal may take place yearly or more often, according to circumstances.

**Interest Formulas.**—The symbols used in the formulas to calculate various types of interest are:

$P$  = principal or amount of money lent

$I$  = nominal annual interest rate stated as a percentage, i.e., 10 per cent per annum

$I_e$  = effective annual interest rate when interest is compounded more often than once a year (see *Nominal vs. Effective Interest Rates*)

$i$  = nominal annual interest rate per cent expressed as a decimal, i.e., if  $I = 12$  per cent, then  $i = 12/100 = 0.12$

$n$  = number of annual interest periods

$m$  = number of interest compounding periods in one year

$F$  = a sum of money at the end of  $n$  interest periods from the present date that is equivalent to  $P$  with added interest  $i$

$A$  = the payment at the end of each period in a uniform series of payments continuing for  $n$  periods, the entire series equivalent to  $P$  at interest rate  $i$

*Note:* The exact amount of interest for one day is  $1/365$  of the interest for one year. Banks, however, customarily take the year as composed of 12 months of 30 days, making a total of 360 days to a year. This method is also used for home-mortgage-type payments, so that the interest rate per month is  $30/360 = 1/12$  of the annual interest rate. For example, if  $I$  is a 12 per cent per annum nominal interest rate, then for a 30-day period, the interest rate is  $(12 \times 1/12) = 1.0$  per cent per month. The decimal rate per month is then  $1.0/100 = 0.01$ .

**Simple Interest.**—The formulas for simple interest are:

$$\text{Interest for } n \text{ years} = P \times i \times n$$

$$\text{Total amount after } n \text{ years, } S = P + P \times i \times n$$

*Example:* For \$250 that has been lent for three years at 6 per cent simple interest:  $P = 250$ ;  $I = 6$ ;  $i = I/100 = 0.06$ ;  $n = 3$ .

$$F = 250 + (250 \times 0.06 \times 3) = 250 + 45 = \$295$$

**Compound Interest.**—The following formulas apply when compound interest is to be computed and assuming that the interest is compounded annually.

$$F = P(1 + i)^n$$

$$P = F/(1 + i)^n$$

$$i = (F/P)^{1/n} - 1$$

$$n = (\log F - \log P)/\log(1 + i)$$

*Example:* At 10 per cent interest compounded annually for 10 years, a principal amount  $P$  of \$1000 becomes a sum  $F$  of

$$F = 1000(1 + 10/100)^{10} = \$2,593.74$$

If a sum  $F = \$2593.74$  is to be accumulated, beginning with a principal  $P = \$1,000$  over a period  $n = 10$  years, the interest rate  $i$  to accomplish this would have to be  $i = (2593.74/1000)^{1/10} - 1 = 0.09999$ , which rounds to 0.1, or 10 per cent.

For a principal  $P = \$500$  to become  $F = \$1,000$  at 6 per cent interest compounded annually, the number of years  $n$  would have to be

$$\begin{aligned} n &= (\log 1000 - \log 500)/\log(1 + 0.06) \\ &= (3 - 2.69897)/0.025306 = 11.9 \text{ years} \end{aligned}$$

To triple the principal  $P = \$500$  to become  $F = \$1,500$ , the number of years would have to be

$$\begin{aligned} n &= (\log 1500 - \log 500)/\log(1 + 0.06) \\ &= (3.17609 - 2.69897)/0.025306 = 18.85 \text{ years} \end{aligned}$$

**Interest Compounded More Often Than Annually.**—If interest is payable  $m$  times a year, it will be computed  $m$  times during each year, or  $nm$  times during  $n$  years. The rate for each compounding period will be  $i/m$  if  $i$  is the nominal annual decimal interest rate. Therefore, at the end of  $n$  years, the amount  $F$  will be:  $F = P(1 + i/m)^{nm}$ .

As an example, if  $P = \$1,000$ ;  $n$  is 5 years, the interest payable quarterly, and the annual rate is 6 per cent, then  $n = 5$ ;  $m = 4$ ;  $i = 0.06$ ;  $i/m = 0.06/4 = 0.015$ ; and  $nm = 5 \times 4 = 20$ , so that

$$F = 1000(1 + 0.015)^{20} = \$1,346.86$$

**Nominal vs. Effective Interest Rates.**—Deposits in savings banks, automobile loans, interest on bonds, and many other transactions of this type involve computation of interest due and payable more often than once a year. For such instances, there is a difference between the *nominal* annual interest rate stated to be the cost of borrowed money and the *effective* rate that is actually charged.

For example, a loan with interest charged at 1 per cent per month is described as having an interest rate of 12 per cent per annum. To be precise, this rate should be stated as being a *nominal* 12 per cent per annum compounded monthly; the actual or *effective* rate for monthly payments is 12.7 per cent. For quarterly compounding, the effective rate would be 12.6 per cent:

$$I_e = (1 + I/m)^m - 1$$

In this formula,  $I_e$  is the effective annual rate,  $I$  is the nominal annual rate, and  $m$  is the number of times per year the money is compounded.

*Example:* For a nominal per annum rate of 12 per cent, with monthly compounding, the effective per annum rate is

$$I_e = (1 + 0.12/12)^{12} - 1 = 0.1268 = 12.7 \text{ per cent effective per annum rate}$$

*Example:* Same as before but with quarterly compounding:

$$I_e = (1 + 0.12/4)^4 - 1 = 0.1255 = 12.6 \text{ per cent effective per annum rate}$$

**Finding Unknown Interest Rates.**—If a single payment of  $P$  dollars is to produce a sum of  $F$  dollars after  $n$  annual compounding periods, the per annum decimal interest rate is found using:

$$i = \sqrt[n]{\frac{F}{P}} - 1$$

### Cash Flow and Equivalence

The sum of money receipts or disbursement in a project's financial report are called cash flows. Due to the time value of money, the timing of cash flows over the project life plays a vital role in project success. Engineering economy problems involve the following four patterns of cash flow, both separately and in combination. Two cash flow patterns are said to be equivalent if they have the same value at a particular time.

**Present Value and Discount.**—The present value or present worth  $P$  of a given amount  $F$  is the amount  $P$  that, when placed at interest  $i$  for a given time  $n$ , will produce the given amount  $F$ .

$$\text{At simple interest, } P = F / (1 + ni)$$

$$\text{At compound interest, } P = F / (1 + i)^n$$

The *true discount*  $D$  is the difference between  $F$  and  $P$ :  $D = F - P$ .

These formulas are for an annual interest rate. If interest is payable other than annually, modify the formulas as indicated in the formulas in the section *Interest Compounded More Often Than Annually* on page 126.

*Example:* Find the present value and discount of \$500 due in six months at 6 per cent simple interest. Here,  $F = 500$ ;  $n = 6/12 = 0.5$  year;  $i = 0.06$ . Then,  $P = 500 / (1 + 0.5 \times 0.06) = \$485.44$ .

*Example:* Find the sum that, placed at 5 per cent compound interest, will in three years produce \$5,000. Here,  $F = 5000$ ;  $i = 0.05$ ;  $n = 3$ . Then,

$$P = 5000 / (1 + 0.05)^3 = \$4,319.19$$

**Annuities.**—An annuity is a fixed sum paid at regular intervals. In the formulas that follow, yearly payments are assumed. It is customary to calculate annuities on the basis of compound interest. If an annuity  $A$  is to be paid out for  $n$  consecutive years, the interest rate being  $i$ , then the present value  $P$  of the annuity is

$$P = A \frac{(1+i)^n - 1}{i(1+i)^n}$$

If at the *beginning* of each year a sum  $A$  is set aside at an interest rate  $i$ , the total value  $F$  of the sum set aside, with interest, at the end of  $n$  years, will be

$$F = A \frac{(1+i)[(1+i)^n - 1]}{i}$$

If at the *end* of each year a sum  $A$  is set aside at an interest rate  $i$ , then the total value  $F$  of the principal, with interest, at the end of  $n$  years will be

$$F = A \frac{(1+i)^n - 1}{i}$$

If a principal  $P$  is increased or decreased by a sum  $A$  at the end of each year, then the value of the principal after  $n$  years will be

$$F = P(1+i)^n \pm A \frac{(1+i)^n - 1}{i}$$

If the sum  $A$  by which the principal  $P$  is decreased each year is greater than the total yearly interest on the principal, then the principal, with the accumulated interest, will be entirely used up in  $n$  years:

$$n = \frac{\log A - \log(A - iP)}{\log(1 + i)}$$

*Example:* If an annuity of \$200 is to be paid for 10 years, what is the present amount of money that needs to be deposited if the interest is 5 per cent. Here,  $A = 200$ ;  $i = 0.05$ ;  $n = 10$ :

$$P = 200 \frac{(1 + 0.05)^{10} - 1}{0.05(1 + 0.05)^{10}} = \$1,544.35$$

The annuity a principal  $P$  drawing interest at the rate  $i$  will give for a period of  $n$  years is

$$A = P \frac{i(1 + i)^n}{(1 + i)^n - 1}$$

*Example:* A sum of \$10,000 is placed at 4 per cent. What is the amount of the annuity payable for 20 years out of this sum: Here,  $P = 10000$ ;  $i = 0.04$ ;  $n = 20$ :

$$A = 10,000 \frac{0.04(1 + 0.04)^{20}}{(1 + 0.04)^{20} - 1} = \$735.82$$

**Sinking Funds.**—Amortization is “the extinction of debt, usually by means of a sinking fund.” The sinking fund is created by a fixed investment  $A$  placed each year at compound interest for a term of years  $n$ , and is therefore an annuity of sufficient size to produce at the end of the term of years the amount  $F$  necessary for the repayment of the principal of the debt, or to provide a definite sum for other purposes. Then,

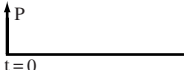

$$F = A \frac{(1 + i)^n - 1}{i} \quad \text{and} \quad A = F \frac{i}{(1 + i)^n - 1}$$

*Example:* If \$2,000 is invested annually for 10 years at 4 per cent compound interest, as a sinking fund, what would be the total amount of the fund at the expiration of the term? Here,  $A = 2000$ ;  $n = 10$ ;  $i = 0.04$ :

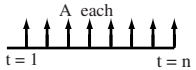
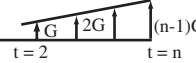
$$F = 2000 \frac{(1 + 0.04)^{10} - 1}{0.04} = \$24,012.21$$

**Cash Flow Diagrams.**—The following conventions are used to standardize cash flow diagrams. The horizontal (time) axis is marked off in equal increments, one per period, up to the duration of the project. Receipts are represented by arrows directed upwards and disbursements are represented by arrows directed downwards. The arrow length is proportional to the magnitude of cash flow. In the following,  $i$  = interest rate, and  $n$  = number of payments or periods.

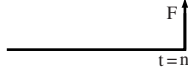
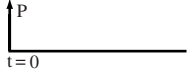
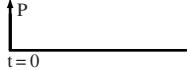
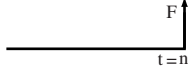
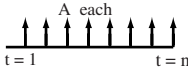
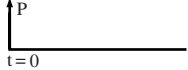
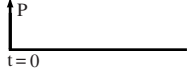
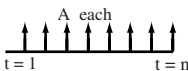
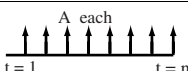
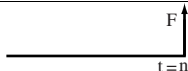
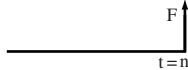
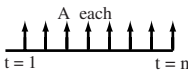
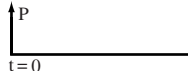
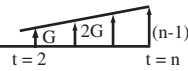
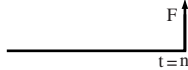
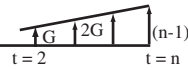
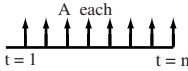
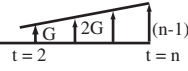
**Table 1. Cash Flow Patterns**

|                                     |   |   |
|-------------------------------------|---|---|
| $P$ -pattern<br>$P$ = present value | A single amount $P$ occurring at the beginning of $n$ years. $P$ represents “Present” amount. |  |
| $F$ -pattern<br>$F$ = future value  | A single amount $F$ occurring at the end of $n$ years. $F$ represents “Future” amount.        |  |

**Table 1. (Continued) Cash Flow Patterns**

|  |   |   |
|--|---|---|
| <p>A-pattern<br/>A = annual value</p>                | <p>Equal amounts <i>A</i> occurring at the end of each of <i>n</i> years. <i>A</i> represents "annual" amount.</p>        |  |
| <p>G-pattern<br/>G = uniform gradient of expense</p> | <p><i>G</i> is increasing by an equal amount over the period of life <i>n</i>. <i>G</i> represents "Gradient" amount.</p> |  |

**Table 2. Standard Cash Flow Factors**

| Symbol   | To Find | Formula   | Given | Symbol  |
|--|---------|---|-------|---|
|    | F       | $(P/F, i\%, n)$ $F = P(1+i)^n$  | P     |    |
|    | P       | $(F/P, i\%, n)$ $P = \frac{F}{(1+i)^n}$   | F     |    |
|    | A       | $(A/P, i\%, n)$ $A = P \frac{i(1+i)^n}{(1+i)^n - 1}$  | P     |    |
|    | P       | $(P/A, i\%, n)$ $P = A \frac{(1+i)^n - 1}{i(1+i)^n}$  | A     |    |
|   | A       | $(A/F, i\%, n)$ $A = F \frac{i}{(1+i)^n - 1}$   | F     |   |
|  | F       | $(F/A, i\%, n)$ $F = A \left[ \frac{(1+i)^n - 1}{i} \right]$  | A     |  |
|  | P       | $(P/G, i\%, n)$ $P = G \frac{1}{i} \left[ \frac{(1+i)^n - 1}{i(1+i)^n} - \frac{n}{(1+i)^n} \right]$ | G     |  |
|  | F       | $(F/G, i\%, n)$ $F = G \frac{1}{i} \left[ \frac{(1+i)^n - 1}{i} - n \right]$                        | G     |  |
|  | A       | $(A/G, i\%, n)$ $A = G \left[ \frac{1}{i} - \frac{n}{(1+i)^n - 1} \right]$                          | G     |  |

*Example:* A rental property pays \$2000/month with a \$10 per month increase starting the second year. Based on 10 year period and 8% annual interest, compute the unified average annuity, considering the gradient.

*Solution*

$$\begin{aligned} \text{Average rental} &= G \left[ \frac{1}{i} - \frac{n}{(1+i)^n - 1} \right] + A \\ &= 10 \left[ \frac{1}{(8/1200)} - \frac{120}{(1+8/1200)^{120} - 1} \right] + 2000 \\ &= 516 + 2000 = \$2516 \end{aligned}$$

**Depreciation**

Depreciation is the allocation of the cost of an asset over its depreciable life. A machine may decline in value because it is wearing out and no longer performing its function as well as when it is new. Depreciation is an economical technique that spreads the purchase price of an asset or other property over a number of years. Tax regulations do not allow the cost of an asset to be treated as a deductible expense in the year of purchase. Portions of the expense must be allocated to each of the years of the asset's depreciation period. The amount that is allocated each year is called the depreciation.

**Straight Line Depreciation.**—Straight line depreciation is a constant depreciation charge over the period of life. If  $P$  is the principal value,  $L$  is the salvage value and  $n$  is the period of life. The depreciation will be

$$\text{Depreciation at } x\text{th year} \quad D_x = \frac{P-L}{n}$$

$$\text{Book Value after } x \text{ years} \quad BV_x = \frac{(P-L)(n-x)}{n} + L$$

$$\text{After Tax Depreciation Recovery} \quad ATDR = TR \left( \frac{P-L}{n} \right) \left( \frac{(1+i)^n - 1}{i(1+i)^n} \right)$$

**Sum of the Years Digits.**—Another method for allocating the cost of an asset minus salvage value over its useful life is called sum of the years digits depreciation. This method results in larger than straight line depreciation charges during the early years of an asset and smaller charges near the end period.

$$\text{Depreciation at } x\text{th year} \quad D_x = \frac{2(P-L)(n-x+1)}{n(n+1)}$$

$$\text{Book Value after } x \text{ years} \quad BV_x = P - (P-L)(2n-x+1) \frac{x}{n(n+1)}$$

**Double Declining Balance Method.**—A constant depreciation is applied to the book value of the property.

$$\text{Depreciation at } x\text{th year} \quad D_x = 2 \left( \frac{P}{n} \right) \left( \frac{n-2}{n} \right)^{(x-1)}$$

$$\text{Book Value after } x \text{ years} \quad BV_x = P \left( \frac{n-2}{n} \right)^x$$

**Statutory Depreciation System.**—The latest depreciation method is used in U.S. income tax purpose is called accelerated cost recovery system (ACRS) depreciation. The first step in ACRS is to determine the property class of the asset being depreciated. All personal property falls into one of six classes.

$$\text{Depreciation at } x\text{th year} \quad D_x = P \times \text{Factor}$$

**Table 3. Property Class and Factor**

| ACRS Classes of Depreciable Property |  | Year<br>(x) | Depreciation Rate for Recovery Period (n) |         |         |          |
|--------------------------------------|--|-------------|---|---------|---------|----------|
| Property<br>Class                    | Personal Property  |             | 3 Years                                   | 5 Years | 7 Years | 10 Years |
| 3                                    | Handling device for food and beverage manufacture, plastic products, fabricated metal products             | 1           | 33.33%                                    | 20.00%  | 14.29%  | 10.00%   |
|                                      |  | 2           | 44.45%                                    | 32.00%  | 24.49%  | 18.00%   |
|                                      |  | 3           | 14.81%                                    | 19.20%  | 17.49%  | 14.40%   |
| 5                                    | Automobiles, trucks, computer, aircraft, petroleum drilling equipment, research and experimentation equip. | 4           | 7.41%                                     | 11.52%  | 12.49%  | 11.52%   |
|                                      |  | 5           |   | 11.52%  | 8.93%   | 9.22%    |
| 7                                    | Office furniture, fixtures, and equip.   | 6           |   | 5.76%   | 8.92%   | 7.37%    |
| 10                                   | Railroad cars, manufacture of tobacco products   | 7           |   |         | 8.93%   | 6.55%    |
|                                      |  | 8           |   |         | 4.46%   | 6.55%    |
| 15                                   | Telephone distribution line, municipal sewers plant  | 9           |   |         |         | 6.56%    |
|                                      |  | 10          |   |         |         | 6.55%    |
| 20                                   | Municipal sewers   | 11          |   |         |         | 3.28%    |

### Evaluating Alternatives

Two or more mutually exclusive investments compete for limited funds. There are a number of ways for selecting the superior alternative from a group of proposals. This section concerns strategies for selecting alternatives in such a way that net value is maximized.

**Net Present Value.**—One of the easiest way to compare mutually exclusive alternatives is to resolve their consequences to the present time. It is most frequently used to determine the present value of future money receipts and disbursements. There are three economic criteria for present worth analysis described in the table that follows. If investment cost is same, consider only the output money. If the output result is known, then minimize the investment cost. If neither input nor output is fixed, then maximize the output minus the input. This method is widely applied when alternatives have the same period of time.

$$\text{With uniform annual expense before tax} \quad NPV = -P + (AR - AE) \left( \frac{(1+i)^n - 1}{i(1+i)^n} \right) + \frac{L}{(1+i)^n}$$

$$\text{With uniform gradient on annual expense before tax} \quad NPV = -P + (AR - AE - (A/G, i, n)G) \left( \frac{(1+i)^n - 1}{i(1+i)^n} \right) + \frac{L}{(1+i)^n}$$

$$\text{With uniform annual expense after tax} \quad NPV = -P + (AR - AE)(1 - TR) \left( \frac{(1+i)^n - 1}{i(1+i)^n} \right) + \frac{L}{(1+i)^n}$$

$$\text{With uniform gradient on annual expense after tax} \quad NPV = -P + (AR - AE - (A/G, i, n)G)(1 - TR) \left( \frac{(1+i)^n - 1}{i(1+i)^n} \right) + \frac{L}{(1+i)^n}$$

The symbol used in this table are defined as follows:

$P$  = Present value     $NPV$  = Net present value     $AR$  = Annual revenue  
 $AE$  = Annual expense     $G$  = Uniform gradient of expense     $TR$  = Tax rate as percentage  
 $i$  = Interest rate     $n$  = Number of payments or periods

The previous formulas do not consider depreciation. To include depreciation, the after tax depreciation recovery (ATDR) must be added to get the net present value.

**Example 10:** A pharmaceutical company produces a product from different chemical compositions. Two mixing processes, batch and continuous, are available.



## INVESTMENTS

| Process                | Continuous | Batch   |
|------------------------|------------|---------|
| Initial cost           | \$75000    | \$35000 |
| Lifetime (years)       | 10         | 10      |
| Maintenance (per year) | \$5000     | \$8000  |
| Capacity (units/year)  | 25000      | 20000   |

The company uses straight line depreciation, pays 40% of its net income as income tax, and has an after tax minimum attractive rate of return of 15%. The company can sell the product at \$1.00 per unit. Which manufacturing process should the company invest in?

**Solution:** Because the lifetimes are equal, we can make a comparison using the present worth method by applying the formulas for  $NPV$  and also for  $ATDR$ .

$$\begin{aligned}
 NPV_{Continuous} &= -P + (AR - AE)(1 - TR) \left( \frac{(1+i)^n - 1}{i(1+i)^n} \right) + TR \left( \frac{P-L}{n} \right) \left( \frac{(1+i)^n - 1}{i(1+i)^n} \right) \\
 &= -75000 + (25000 \times 1 - 5000)(1 - 0.40) \left( \frac{\left(1 + \frac{15}{100}\right)^{10} - 1}{\left(\frac{15}{100}\right)\left(1 + \frac{15}{100}\right)^{10}} \right) + 0.40 \left( \frac{75000}{10} \right) \left( \frac{\left(1 + \frac{15}{100}\right)^{10} - 1}{\left(\frac{15}{100}\right)\left(1 + \frac{15}{100}\right)^{10}} \right) \\
 &= -14775 + 15056 = 281
 \end{aligned}$$

$$\begin{aligned}
 NPV_{Batch} &= -P + (AR - AE)(1 - TR) \left( \frac{(1+i)^n - 1}{i(1+i)^n} \right) + TR \left( \frac{P-L}{n} \right) \left( \frac{(1+i)^n - 1}{i(1+i)^n} \right) \\
 &= -35000 + [(20000 \times 1) - 8000](1 - 0.40) \left( \frac{\left(1 + \frac{15}{100}\right)^{10} - 1}{\left(\frac{15}{100}\right)\left(1 + \frac{15}{100}\right)^{10}} \right) + 0.40 \left( \frac{35000}{10} \right) \left( \frac{\left(1 + \frac{15}{100}\right)^{10} - 1}{\left(\frac{15}{100}\right)\left(1 + \frac{15}{100}\right)^{10}} \right) \\
 &= 1135 + 7026 = 8161
 \end{aligned}$$

Based on above calculations, the batch production process is selected because it gives a greater net present value ( $NPV$ ) than the continuous process.

**Capitalized Cost.**—In governmental analyses, there are some circumstances where a service is required for an infinite period of time such as with roads, dams, pipelines, etc. Present worth of a project with an infinite life is known as capitalized cost. Capitalized cost is the amount of money at  $n = 0$  needed to perpetually support the projection the earned interest only. Capitalized cost is the present sum of money that would need to be set aside now, at some interest rate, to yield the funds required to provide the service.

$$CC = P + A(P/A, i\%, n) - L(P/F, i\%, n) + G(P/G, i\%, n)$$

$$\text{Without Periodical Replacement} \quad CC = P + \frac{A}{i}$$

$$\text{With 100\% Periodical Replacement} \quad CC = P + \frac{P-L}{(1+i)^n - 1} + \frac{A}{i}$$

$$\text{With Periodical Renovation Cost} \quad CC = P + \frac{RC}{(1+i)^n - 1} + \frac{A}{i}$$

where  $CC$  = capitalized cost;  $P$  = initial cost;  $L$  = salvage value;  $A$  = annual cost;  $RC$  = renovation cost;  $i$  = interest rate; and,  $n$  = effective period of time.

**Equivalent Uniform Annual Cost.**—This method is applied when the alternatives have unequal periods of life. To avoid unequal periods of time, the present value and future value is converted to an annual value. The alternatives must be mutually exclusive and repeatedly renewed up to the duration of the longest lived alternative.

$$A = P(A/P, i\%, n) - L(A/F, i\%, n) + G(A/G, i\%, n) + AE$$

$$\text{With Sinking Fund Depreciation} \quad A = (P - L) \frac{i(1+i)^n}{(1+i)^n - 1} + Li + AE$$

$$\text{With Sinking Fund Depreciation and Uniform Gradient G} \quad A = (P - L) \frac{i(1+i)^n}{(1+i)^n - 1} + Li + AE + G \left( \frac{1}{i} - \frac{n}{(1+i)^n - 1} \right)$$

$$\text{Straight Line Depreciation} \quad A = \frac{P - L}{n} + Li + AE + \frac{(P - L)(n + 1)i}{2n}$$

*Example 11:* An investment of \$15,000 is being considered to reduce labor and labor-associated costs in a materials handling operation from \$8,200 a year to \$3,300. This operation is expected to be used for 10 years before being changed or discontinued entirely. In addition to the initial investment of \$15,000 and the annual cost of \$3,300 for labor, there are additional annual costs for power, maintenance, insurance, and property taxes of \$1,800 associated with the revised operation. Based on comparisons of annual costs, should the \$15,000 investment be made or the present operation continued?

The present annual cost of the operation is \$8,200 for labor and labor-associated costs. The proposed operation has an annual cost of \$3,300 for labor and labor extras plus \$1,800 for additional power, maintenance, insurance, and taxes, plus the annual cost of recovering the initial investment of \$15,000 at some interest rate (minimum acceptable rate of return).

Assuming that 10 per cent would be an acceptable rate of return on this investment over a period of 10 years, the annual amount to be recovered on the initial investment would be \$15,000 multiplied by the capital recovery factor.

Putting this value into  $(A/P, i\%, n)$  yields:

$$A = \frac{i(1+i)^n}{(1+i)^n - 1} P + AE = \frac{(10/100)(1 + 10/100)^{10}}{(1 + 10/100)^{10} - 1} 15000 + 5100 = 7541.18$$

Adding this amount to the \$5,100 annual cost associated with the investment (\$3,300 + \$1,800 = \$5,100) gives a total annual cost of \$7,542, which is less than the present annual cost of \$8,200. Thus, the investment is justified unless there are other considerations such as the effects of income taxes, salvage values, expected life, uncertainty about the required rate of return, changes in the cost of borrowed funds, and others.

A tabulation of annual costs of alternative plans A, B, C, etc., is a good way to compare costs item by item. For this example:

| Item |                                    | Plan A     | Plan B     |
|------|------------------------------------|------------|------------|
| 1    | Labor and labor extras             | \$8,200.00 | \$3,300.00 |
| 2    | Annual cost of \$15,000 investment |            | 2,442.00   |
| 3    | Power                              |            | 400.00     |
| 4    | Maintenance                        |            | 1,100.00   |
| 5    | Property taxes and insurance       |            | 300.00     |
|      | Total annual cost                  | \$8,200.00 | \$7,542.00 |

*Example 12, (Annual Cost Considering Salvage Value):* If in [Example 11](#) the salvage value of the equipment installed was \$5,000 at the end of 10 years, what effect does this have on the annual cost of the proposed investment of \$15,000?

The only item in the annual cost of [Example 11](#) that will be affected is the capital recovery amount of \$2,442. The following formula gives the amount of annual capital recovery when salvage value is considered:

$$A = (P - L) \frac{i(1+i)^n}{(1+i)^n - 1} + Li + AE$$

$$= (15000 - 5000) \frac{\left(\frac{10}{100}\right) \left(1 + \frac{10}{100}\right)^{10}}{\left(1 + \frac{10}{100}\right)^{10} - 1} + 5000 \left(\frac{10}{100}\right) + 5100 = 7227.45$$

Adding this amount to the \$5,100 annual cost determined previously gives a total annual cost of \$7,227, which is \$315 less than the previous annual cost of \$7,542 for the proposed investment.

**Rate of Return.**—The estimated interest rate produced by an investment. Rate of return is the interest rate at which the benefits are equivalent to the costs. It is defined as the interest rate paid on the unpaid balance of a loan such that the payment schedule makes the unpaid loan balance equal to zero when the final payment is made. It may be computed by finding the interest rate in such a way that the estimated expenditures are equal to the capital gain. *Net Present Worth = 0, or PW of benefits - PW of costs = 0*

$$\frac{((1 + ror)^n - 1)}{ror(1 + ror)^n} (AR - AE) + \frac{L}{(1 + ror)^n} = P$$

The rate of return can only be calculated by trial and error solution. To find out the present worth, select a reasonable interest rate, calculate the present worth. Choose another rate, calculate the present worth. Interpolate or extrapolate the value of *ROR* to find the zero value of present worth.

**Benefit-Cost Ratio.**—It is the ratio of present worth of benefit and present worth of cost. This method is applied to municipal project evaluations where benefits (*B*) and costs (*C*) accrue to different segments of the community. The project is considered acceptable if the ratio equals or exceeds 1. For fixed input maximize the  $B/C \geq 1$  and for fixed output maximize the  $B/C \geq 1$  and if neither input nor output is fixed, to compute the incremental benefit cost ratio ( $\Delta B/\Delta C$ ), choose  $\Delta B/\Delta C \geq 1$ .

*Example 13:* To build a bridge over a river costs \$1,200,000, benefits of \$2,000,000, and disbenefits of \$500,000. (a) What is the benefit cost ratio? (b) What is the excess of benefits over costs?

$$\text{Solution: The benefit cost ratio is } B/C = \frac{B - D}{D} = \frac{2,000,000 - 500,000}{500,000} = 3$$

The excess of benefits over cost equal  $2,000,000 - 1,200,000 - 500,000 = 300,000$ .

**Payback Period.**—This is the period of time required for the profit or other benefits of an investment to equal the cost of investment. The criterion in all situations is to minimize the payback period.

**Break-Even Analysis.**—Break-even analysis is a method of comparing two or more alternatives to determine which works best. Frequently, cost is the basis of the comparison, with the least expensive alternative being the most desirable. Break-even analysis can be applied in situations such as: to determine if it is more efficient and cost effective to use HSS, carbide, or ceramic tooling; to compare coated versus uncoated carbide tooling; to

decide which of several machines should be used to produce a part; or to decide whether to buy a new machine for a particular job or to continue to use an older machine. The techniques used to solve any of these problems are the same; however, the details will be different, depending on the type of comparison being made. The remainder of this section deals with break-even analysis based on comparing the costs of manufacturing a product using different machines.

*Choosing a Manufacturing Method:* The object of this analysis is to decide which of several machines can produce parts at the lowest cost. In order to compare the cost of producing a part, all the costs involved in making that part must be considered. The cost of manufacturing any number of parts can be expressed as the sum:  $C_T = C_F + n \times C_V$ , where  $C_T$  is the total cost of manufacturing one part,  $C_F$  is the sum of the fixed costs of making the parts,  $n$  is the number of parts made, and  $C_V$  is the total variable costs per piece made.

Fixed costs are manufacturing costs that have to be paid whatever the number of parts is produced and usually before any parts can be produced. They include the cost of drafting and CNC part programs, the cost of special tools and equipment required to make the part, and the cost of setting up the machine for the job. Fixed costs are generally one-time charges that occur at the beginning of a job or are recurrent charges that do not depend on the number of pieces made, such as those that might occur each time a job is run again.

Variable costs depend on the number of parts produced and are expressed as the cost per part made. The variable costs include the cost of materials, the cost of machine time, the cost of the labor directly involved in making the part, and the portion of the overhead that is attributable to production of the part. Variable costs can be expressed as:  $C_V =$  material cost + machine cost + labor cost + overhead cost. When comparing alternatives, if the same cost is incurred by each alternative, then that cost can be eliminated from the analysis without affecting the result. For example, the cost of material is frequently omitted from a manufacturing analysis if each machine is going to make parts from the same stock and if there is not going to be a significant difference in the amount of scrap produced by each method. The time to produce one part is needed to determine the machine, labor, and overhead costs. The total time expressed in hours per part is  $t_T = t_f + t_s$ , where  $t_f$  equals the floor-to-floor production time for one part and  $t_s$  the setup time per part. The setup time,  $t_s$ , is the time spent setting up the machine and periodically reconditioning tooling, divided by the number of parts made per setup.

*Material cost* equals the cost of the materials divided by the number of parts made.

*Machine cost* is the portion of a machine's total cost that is charged toward the production of each part. It is found by multiplying the machine rate (cost of the machine per hour) by the machine time per part,  $t_f$ . The machine hourly rate is calculated by dividing the lifetime costs (including purchase price, insurance, maintenance, etc.) by the estimated lifetime hours of operation of the machine. The total operating hours may be difficult to determine but a reasonable number can be based on experience and dealer information.

*Labor costs* are the wages paid to people who are directly involved in the manufacture of the part. The labor cost per part is the labor rate per hour multiplied by the time needed to manufacture each part,  $t_T$ . Indirect labor, which supports but is not directly involved in the manufacture of the part, is charged as overhead.

*Overhead cost* is the cost of producing an item that is not directly related to the cost of manufacture. Overhead includes the cost of management and other support personnel, building costs, heating and cooling, and similar expenses. Often, overhead is estimated as a percentage of the largest component cost of producing a part. For example, if direct labor is the largest expense in producing a part, the overhead can be estimated as a percentage of the direct labor costs. On the other hand, if equipment costs are higher, the overhead would be based on a percentage of the machine cost. Depending on the company, typical overhead charges range from about 150 to 800 per cent of the highest variable cost.

Most of the time, the decision to use one machine or another for making parts depends on how many pieces are needed. For example, given three machines *A*, *B*, and *C*, if only a few parts need to be produced, then, in terms of cost, machine *A* might be the best; if hundreds of parts are needed, then machine *B* might be best; and, if thousands of components are to be manufactured, then machine *C* may result in the lowest cost per part. Break-even analysis reveals how many components need to be produced before a particular machine becomes more cost effective than another.

To use break-even analysis, the cost of operating each machine needs to be established. The costs are plotted on a graph as a function of the number of components to be manufactured to learn which machine can make the required parts for the least cost. The following graph is a plot of the fixed and variable costs of producing a quantity of parts on two different machines, *Machine 1* and *Machine 2*. Fixed costs for each machine are plotted on the vertical *cost* axis. Variable costs for each machine are plotted as a line that intersects the cost axis at the fixed cost for each respective machine. The variable cost line is constructed with a slope that is equal to the cost per part, that is, for each part made, the line rises by an amount equal to the cost per part. If the calculations necessary to produce the graph are done carefully, the total cost of producing any quantity of parts can be found from the data plotted on the graph.

As an example, the graph shown in Fig. 7 is a comparison of the cost of manufacturing a quantity of a small part on a manually operated milling machine (*Machine 1*) and on a CNC machining center (*Machine 2*). The fixed costs (fixed costs = lead time  $\times$  lead time rate + setup time  $\times$  setup rate) for the manual machine are \$190 and the fixed costs for the CNC machine are higher at \$600. The fixed cost for each machine is the starting point of the line representing the cost of manufacturing a quantity of parts with that machine. The variable costs plotted are: \$18 per piece for the manual machine and \$5 per piece for the CNC mill.

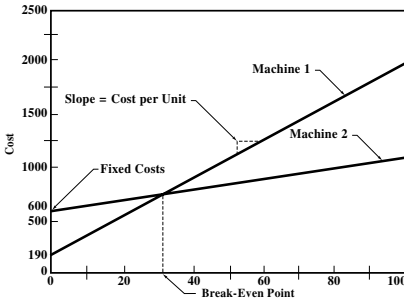


Fig. 7. Quantity of Parts

The variable costs are calculated using the machine, labor, and overhead costs. The cost of materials is not included because it is assumed that materials cost will be the same for parts made on either machine and there will be no appreciable difference in the amount of scrap generated. The original cost of *Machine 1* (the manual milling machine) is \$19,000 with an estimated operating life of 16,000 hours, so the hourly operating cost is  $19,000/16,000 = \$1.20$  per hour. The labor rate is \$17 per hour and the overhead is estimated as 1.6 times the labor rate, or  $17 \times 1.6 = \$27.20$  per hour. The time,  $t_p$ , needed to complete each part on *Machine 1* is estimated as 24 minutes (0.4 hour). Therefore, by using *Machine 1*, the variable cost per part excluding material is  $(1.20 + 17.00 + 27.20) \text{ \$/h} \times 0.4 \text{ h/part} = \$18$  per part. For *Machine 2* (the CNC machining center), the machine cost is calculated at \$3 per hour, which is based on a \$60,000 initial cost (including installation, maintenance,

insurance, etc.) and 20,000 hours of estimated lifetime. The cost of labor is \$15 per hour for *Machine 2* and the overhead is again calculated at 1.6 times the labor rate, or \$24 per hour. Each part is estimated to take 7.2 minutes (0.12 h) to make, so the variable cost per part made on *Machine 2* is  $(3 + 15 + 24) \$/h \times 0.12 \text{ h/part} = \$5$  per part.

The lines representing the variable cost of operating each machine intersect at only one point on the graph. The intersection point corresponds to a quantity of parts that can be made by either the CNC or manual machine for the same cost, which is the break-even point. In the figure, the break-even point is 31.5 parts and the cost of those parts is \$757, or about \$24 apiece, excluding materials. The graph shows that if fewer than 32 parts need to be made, the total cost will be lowest if the manual machine is used because the line representing *Machine 1* is lower (representing lower cost) than the line representing *Machine 2*. On the other hand, if more than 31 parts are going to be made, the CNC machine will produce them for a lower cost. It is easy to see that the per piece cost of manufacturing is lower on the CNC machine because the line for *Machine 2* rises at a slower rate than the line for *Machine 1*. For producing only a few parts, the manual machine will make them less expensively than the CNC because the fixed costs are lower, but once the CNC part program has been written, the CNC can also run small batches efficiently because very little setup work is required.

The quantity of parts corresponding to the break-even point is known as the break-even quantity  $Q_b$ . The break-even quantity can be found without the use of the graph by using the following break-even equation:  $Q_b = (C_{F1} - C_{F2}) / (C_{V2} - C_{V1})$ . In this equation, the  $C_{F1}$  and  $C_{F2}$  are the fixed costs for *Machine 1* and *Machine 2*, respectively;  $C_{V1}$  and  $C_{V2}$  are the variable costs for *Machine 1* and *Machine 2*, respectively.

Break-even analysis techniques are also useful for comparing performance of more than two machines. Plot the manufacturing costs for each machine on a graph as before and then compare the costs of the machines in pairs using the techniques described. For example, if an automatic machine such as a rotary transfer machine is included as *Machine 3* in the preceding analysis, then three lines representing the costs of operating each machine would be plotted on the graph. The equation to find the break-even quantities is applied three times in succession, for *Machines 1* and 2, for *Machines 1* and 3, and again for *Machines 2* and 3. The result of this analysis will show the region (range of quantities) within which each machine is most profitable.

**Overhead Expenses.—Machine-Hour Distribution:** The machine-hour rate method consists of distributing all the manufacturing expenses of an establishment by a charge to each job of the overhead cost of operating the machines and other facilities used on that job. This overhead charge is not an average for the whole plant or department, but is, as nearly as possible, the actual overhead cost of maintaining and operating each of the machines, group of machines, benches, etc., which are found in the plant. By the proper use of this method it is possible to show the difference between the expense cost of a boring mill and a lathe, a gear-cutter and a splining machine, etc.

**Man-Hour Distribution:** The man-hour method of distributing overhead has for its base the number of hours spent on a job instead of the amount of wages paid. The assumption is made that the overhead expenses have a fixed ratio to the number of hours of time spent on a job. Certain items of expense bear a direct relation to the number of hours worked, and include the expenses of the payroll, compensation, insurance, and supervision.

**Man-Rate Distribution:** The man-rate method of distributing overhead costs is the one in most general use because of its simplicity. To use this method, find the ratio of total expenses to total labor for a given business, and to apply this ratio to the labor cost of each job. For a factory making one kind of product, this method of distributing overhead is quite satisfactory, but where the product itself is varied and the tools used are different for each of the products, this method is incorrect and misleading as to final results.

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## MECHANICS

Throughout this section in this Handbook, both English and metric SI data and formulas are given to cover the requirements of working in either system of measurement. Except for the passage entitled *The Use of the Metric SI System in Mechanics Calculations*, formulas and text relating exclusively to SI are given in bold face type.

### Terms and Definitions

**Definitions.**—The science of mechanics deals with the effects of forces in causing or preventing motion. *Statics* is the branch of mechanics that deals with bodies in equilibrium, i.e., the forces acting on them cause them to remain at rest or to move with uniform velocity. *Dynamics* is the branch of mechanics that deals with bodies not in equilibrium, i.e., the forces acting on them cause them to move with non-uniform velocity. *Kinetics* is the branch of dynamics that deals with both the forces acting on bodies and the motions that they cause. *Kinematics* is the branch of dynamics that deals only with the motions of bodies without reference to the forces that cause them.

Definitions of certain terms and quantities as used in mechanics follow:

*Force* may be defined simply as a push or a pull; the push or pull may result from the force of contact between bodies or from a force, such as magnetism or gravitation, in which no direct contact takes place.

*Matter* is any substance that occupies space; gases, liquids, solids, electrons, atoms, molecules, etc., all fit this definition.

*Inertia* is the property of matter that causes it to resist any change in its motion or state of rest.

*Mass* is a measure of the inertia of a body.

*Work*, in mechanics, is the product of force times distance and is expressed by a combination of units of force and distance, as foot-pounds, inch-pounds, meter-kilograms, etc. **The metric SI unit of work is the joule, which is the work done when the point of application of a force of one newton is displaced through a distance of one meter in the direction of the force.**

*Power*, in mechanics, is the product of force times distance divided by time; it measures the performance of a given amount of work in a given time. It is the rate of doing work and as such is expressed in foot-pounds per minute, foot-pounds per second, kilogram-meters per second, etc. **The metric SI unit is the watt, which is one joule per second.**

*Horsepower* is the unit of power that has been adopted for engineering work. One horsepower is equal to 33,000 foot-pounds per minute or 550 foot-pounds per second. The *kilowatt*, used in electrical work, equals 1.34 horsepower; or 1 horsepower equals 0.746 kilowatt. **However, in the metric SI, the term horsepower is not used, and the basic unit of power is the watt. This unit, and the derived units milliwatt and kilowatt, for example, are the same as those used in electrical work.**

*Torque or moment* of a force is a measure of the tendency of the force to rotate the body upon which it acts about an axis. The magnitude of the moment due to a force acting in a plane perpendicular to some axis is obtained by multiplying the force by the perpendicular distance from the axis to the line of action of the force. (If the axis of rotation is not perpendicular to the plane of the force, then the components of the force in a plane perpendicular to the axis of rotation are used to find the resultant moment of the force by finding the moment of each component and adding these component moments algebraically.) Moment or torque is commonly expressed in pound-feet, pound-inches, kilogram-meters, etc. **The metric SI unit is the newton-meter (N · m).**

*Velocity* is the time-rate of change of distance and is expressed as distance divided by time, that is, feet per second, miles per hour, centimeters per second, meters per second, etc.

*Acceleration* is defined as the time-rate of change of velocity and is expressed as velocity divided by time or as distance divided by time squared, that is, in feet per second, per second or feet per second squared; inches per second, per second or inches per second squared; centimeters per second, per second or centimeters per second squared; etc. **The metric SI unit is the meter per second squared.**

**Unit Systems.**—In mechanics calculations, both *absolute* and *gravitational* systems of units are employed. The fundamental units in absolute systems are *length*, *time*, and *mass*, and from these units, the dimension of force is derived. Two absolute systems which have been in use for many years are the cgs (centimeter-gram-second) and the MKS (meter-kilogram-second) systems. Another system, known as MKSA (meter-kilogram-second-ampere), links the MKS system of units of mechanics with electro magnetic units.

**The Conference General des Poids et Mesures (CGPM), which is the body responsible for all international matters concerning the metric system, adopted in 1954 a rationalized and coherent system of units based on the four MKSA units and including the kelvin as the unit of temperature, and the candela as the unit of luminous intensity. In 1960, the CGPM formally named this system the 'Système International d'Unites,' for which the abbreviation is SI in all languages. In 1971, the 14th CGPM adopted a seventh base unit, the mole, which is the unit of quantity ("amount of substance"). Further details of the SI are given in the section *MEASURING UNITS* starting on page 2544, and its application in mechanics calculations, contrasted with the use of the English system, is considered on page 142.**

The fundamental units in gravitational systems are *length*, *time*, and *force*, and from these units, the dimension of mass is derived. In the gravitational system most widely used in English measure countries, the units of length, time, and force are, respectively, the foot, the second, and the pound. The corresponding unit of mass, commonly called the *slug*, is equal to 1 pound second<sup>2</sup> per foot and is derived from the formula,  $M = W \div g$  in which  $M$  = mass in slugs,  $W$  = weight in pounds, and  $g$  = acceleration due to gravity, commonly taken as 32.16 feet per second<sup>2</sup>. A body that weighs 32.16 lbs. on the surface of the earth has, therefore, a mass of one slug.

Many engineering calculations utilize a system of units consisting of the inch, the second, and the pound. The corresponding units of mass are pounds second<sup>2</sup> per inch and the value of  $g$  is taken as 386 inches per second<sup>2</sup>.

In a gravitational system that has been widely used in metric countries, the units of length, time, and force are, respectively, the meter, the second, and the kilogram. The corresponding units of mass are kilograms second<sup>2</sup> per meter and the value of  $g$  is taken as 9.81 meters per second<sup>2</sup>.

**Acceleration of Gravity  $g$  Used in Mechanics Formulas.**—The acceleration of a freely falling body has been found to vary according to location on the earth's surface as well as with height, the value at the equator being 32.09 feet per second, per second while at the poles it is 32.26 ft/sec<sup>2</sup>. In the United States it is customary to regard 32.16 as satisfactory for most practical purposes in engineering calculations.

*Standard Pound Force:* For use in defining the magnitude of a standard unit of force, known as the *pound force*, a fixed value of 32.1740 ft/sec<sup>2</sup>, designated by the symbol  $g_0$ , has been adopted by international agreement. As a result of this agreement, whenever the term mass,  $M$ , appears in a mechanics formula and the substitution  $M = W/g$  is made, use of the standard value  $g_0 = 32.1740$  ft/sec<sup>2</sup> is implied although as stated previously, it is customary to use approximate values for  $g$  except where extreme accuracy is required.

**The Use of the Metric SI System in Mechanics Calculations.**—The SI system is a development of the traditional metric system based on decimal arithmetic; fractions are avoided. For each physical quantity, units of different sizes are formed by multiplying or dividing a single base value by powers of 10. Thus, changes can be made very simply by

adding zeros or shifting decimal points. For example, the meter is the basic unit of length; the kilometer is a multiple (1,000 meters); and the millimeter is a sub-multiple (one-thousandth of a meter).

In the older metric system, the simplicity of a series of units linked by powers of 10 is an advantage for plain quantities such as length, but this simplicity is lost as soon as more complex units are encountered. For example, in different branches of science and engineering, energy may appear as the erg, the calorie, the kilogram-meter, the liter-atmosphere, or the horsepower-hour. In contrast, the SI provides only one basic unit for each physical quantity, and universality is thus achieved.

There are seven base-units, and in mechanics calculations three are used, which are for the basic quantities of length, mass, and time, expressed as the meter (m), the kilogram (kg), and the second (s). The other four base-units are the ampere (A) for electric current, the kelvin (K) for thermodynamic temperature, the candela (cd) for luminous intensity, and the mole (mol) for amount of substance.

The SI is a coherent system. A system of units is said to be coherent if the product or quotient of any two unit quantities in the system is the unit of the resultant quantity. For example, in a coherent system in which the foot is a unit of length, the square foot is the unit of area, whereas the acre is not. Further details of the SI, and definitions of the units, are given in the section *MEASURING UNITS* starting on page 2544, near the end of the book.

Other physical quantities are derived from the base-units. For example, the unit of velocity is the meter per second (m/s), which is a combination of the base-units of length and time. The unit of acceleration is the meter per second squared ( $m/s^2$ ). By applying Newton's second law of motion — force is proportional to mass multiplied by acceleration — the unit of force is obtained, which is the  $kg \cdot m/s^2$ . This unit is known as the newton, or N. Work, or force times distance, is the  $kg \cdot m^2/s^2$ , which is the joule, (1 joule = 1 newton-meter) and energy is also expressed in these terms. The abbreviation for joule is J. Power, or work per unit time, is the  $kg \cdot m^2/s^3$ , which is the watt (1 watt = 1 joule per second = 1 newton-meter per second). The abbreviation for watt is W.

More information on Newton's laws may be found in the section *Newton's Laws of Motion* on page 167.

The coherence of SI units has two important advantages. The first, that of uniqueness and therefore universality, has been explained. The second is that it greatly simplifies technical calculations. Equations representing physical principles can be applied without introducing such numbers as 550 in power calculations, which, in the English system of measurement have to be used to convert units. Thus conversion factors largely disappear from calculations carried out in SI units, with a great saving in time and labor.

*Mass, Weight, Force, Load:* SI is an absolute system (see *Unit Systems* on page 142), and consequently it is necessary to make a clear distinction between mass and weight. The *mass* of a body is a measure of its inertia, whereas the *weight* of a body is the *force* exerted on it by gravity. In a fixed gravitational field, weight is directly proportional to mass, and the distinction between the two can be easily overlooked. However, if a body is moved to a different gravitational field, for example, that of the moon, its weight alters, but its mass remains unchanged. Since the gravitational field on earth varies from place to place by only a small amount, and weight is proportional to mass, it is practical to use the weight of unit mass as a unit of force, and this procedure is adopted in both the English and older metric systems of measurement. In common usage, they are given the same names, and we say that a mass of 1 pound has a weight of 1 pound. In the former case the pound is being used as a unit of mass, and in the latter case, as a unit of force. This procedure is convenient in some branches of engineering, but leads to confusion in others.

As mentioned earlier, Newton's second law of motion states that force is proportional to mass times acceleration. Because an unsupported body on the earth's surface falls with acceleration  $g$  ( $32 \text{ ft/s}^2$  approximately), the pound (force) is that force which will impart an

acceleration of  $g$  ft/s<sup>2</sup> to a pound (mass). Similarly, the kilogram (force) is that force which will impart an acceleration of  $g$  (9.8 meters per second<sup>2</sup> approximately), to a mass of one kilogram. In the SI, the *newton* is that force which will impart unit acceleration (1 m/s<sup>2</sup>) to a mass of one kilogram. It is therefore smaller than the kilogram (force) in the ratio 1: $g$  (about 1:9.8). This fact has important consequences in engineering calculations. The factor  $g$  now disappears from a wide range of formulas in dynamics, but appears in many formulas in statics where it was formerly absent. It is however not quite the same  $g$ , for reasons which will now be explained.

In the article on page 171, the mass of a body is referred to as  $M$ , but it is immediately replaced in subsequent formulas by  $W/g$ , where  $W$  is the weight in pounds (force), which leads to familiar expressions such as  $WV^2/2g$  for kinetic energy. In this treatment, the  $M$  which appears briefly is really expressed in terms of the slug (page 142), a unit normally used only in aeronautical engineering. In everyday engineers' language, weight and mass are regarded as synonymous and expressions such as  $WV^2/2g$  are used without pondering the distinction. Nevertheless, on reflection it seems odd that  $g$  should appear in a formula which has nothing to do with gravity at all. In fact the  $g$  used here is not the true, local value of the acceleration due to gravity, but an arbitrary standard value which has been chosen as part of the definition of the pound (force) and is more properly designated  $g_0$  (page 142). Its function is not to indicate the strength of the local gravitational field, but to convert from one unit to another.

In the SI the unit of mass is the *kilogram*, and the unit of force (and therefore weight) is the *newton*.

The following are typical statements in dynamics expressed in SI units:

A force of  $R$  newtons acting on a mass of  $M$  kilograms produces an acceleration of  $R/M$  meters per second<sup>2</sup>. The kinetic energy of a mass of  $M$  kg moving with velocity  $V$  m/s is  $\frac{1}{2}MV^2$  kg (m/s)<sup>2</sup> or  $\frac{1}{2}MV^2$  joules. The work done by a force of  $R$  newtons moving a distance  $L$  meters is  $RL$  Nm, or  $RL$  joules. If this work were converted entirely into kinetic energy we could write  $RL = \frac{1}{2}MV^2$  and it is instructive to consider the units. Remembering that the N is the same as the kg · m/s<sup>2</sup>, we have (kg · m/s<sup>2</sup>) × m = kg (m/s)<sup>2</sup>, which is obviously correct. It will be noted that  $g$  does not appear anywhere in these statements.

In contrast, in many branches of engineering where the weight of a body is important, rather than its mass, using SI units,  $g$  does appear where formerly it was absent. Thus, if a rope hangs vertically supporting a mass of  $M$  kilograms the tension in the rope is  $Mg$  N. Here  $g$  is the acceleration due to gravity, and its units are m/s<sup>2</sup>. The ordinary numerical value of 9.81 will be sufficiently accurate for most purposes on earth. The expression is still valid elsewhere, for example, on the moon, provided the proper value of  $g$  is used. The maximum tension the rope can safely withstand (and other similar properties) will also be specified in terms of the newton, so that direct comparison may be made with the tension predicted.

Words like load and weight have to be used with greater care. In everyday language we might say "a lift carries a load of five people of average weight 70 kg," but in precise technical language we say that if the average mass is 70 kg, then the average weight is 70g N, and the total load (that is force) on the lift is 350g N.

If the lift starts to rise with acceleration  $a$  · m/s<sup>2</sup>, the load becomes 350( $g + a$ ) N; both  $g$  and  $a$  have units of m/s<sup>2</sup>, the mass is in kg, so the load is in terms of kg · m/s<sup>2</sup>, which is the same as the newton.

*Pressure and stress:* These quantities are expressed in terms of force per unit area. In the SI the unit is the pascal (Pa), which expressed in terms of SI derived and base units is the newton per meter squared (N/m<sup>2</sup>). The pascal is very small—it is only equivalent to 0.15 × 10<sup>-3</sup> lb/in<sup>2</sup>—hence the kilopascal (kPa = 1000 pascals), and the megapascal (MPa = 10<sup>6</sup>

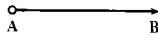
pascals) may be more convenient multiples in practice. Thus, note: 1 newton per millimeter squared = 1 meganewton per meter squared = 1 megapascal.

In addition to the pascal, the bar, a non-SI unit, is in use in the field of pressure measurement in some countries, including England. Thus, in view of existing practice, the International Committee of Weights and Measures (CIPM) decided in 1969 to retain this unit for a limited time for use with those of SI. The bar =  $10^5$  pascals and the hectobar =  $10^7$  pascals.

### Force Systems

**Scalar and Vector Quantities.**—The quantities dealt with in mechanics are of two kinds according to whether magnitude alone or direction as well as magnitude must be known in order to completely specify them. Quantities such as time, volume and density are completely specified when their magnitude is known. Such quantities are called *scalar* quantities. Quantities such as force, velocity, acceleration, moment, and displacement which must, in order to be specified completely, have a specific direction as well as magnitude, are called *vector* quantities.

**Graphical Representation of Forces.**—A force has three characteristics which, when known, determine it. They are *direction*, *point of application*, and *magnitude*. The direction of a force is the direction in which it tends to move the body upon which it acts. The point of application is the place on the line of action where the force is applied. Forces may conveniently be represented by straight lines and arrow heads. The arrow head indicates the direction of the force, and the length of the line, its magnitude to any suitable scale. The point of application may be at any point on the line, but it is generally convenient to assume it to be at one end. In the accompanying illustration, a force is supposed to act along line *AB* in a direction from left to right. The length of line *AB* shows the magnitude of the force. If point *A* is the point of application, the force is exerted as a pull, but if point *B* be assumed to be the point of application, it would indicate that the force is exerted as a push.



Vector

Velocities, moments, displacements, etc. may similarly be represented and manipulated graphically because they are all of the same class of quantities called vectors. (See *Scalar and Vector Quantities*.)

**Addition and Subtraction of Forces:** The resultant of two forces applied at the same point and acting in the same direction, is equal to the sum of the forces. For example, if the two forces *AB* and *AC*, one equal to two and the other equal to three pounds, are applied at point *A*, then their resultant *AD* equals the sum of these forces, or five pounds.

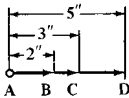


Fig. 1.

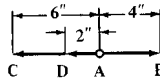


Fig. 2.

If two forces act in opposite directions, then their resultant is equal to their difference, and the direction of the resultant is the same as the direction of the greater of the two forces. For example: *AB* and *AC* are both applied at point *A*; then, if *AB* equals four and *AC* equals six pounds, the resultant *AD* equals two pounds and acts in the direction of *AC*.

**Parallelogram of Forces:** If two forces applied at a point are represented in magnitude and direction by the adjacent sides of a parallelogram (*AB* and *AC* in Fig. 3), their resultant

will be represented in magnitude and direction by the diagonal  $AR$  drawn from the intersection of the two component forces.

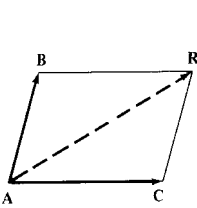


Fig. 3.

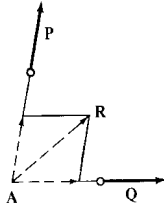


Fig. 4.

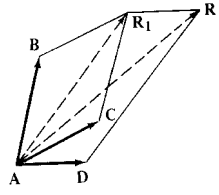


Fig. 5.

If two forces  $P$  and  $Q$  do not have the same point of application, as in Fig. 4, but the lines indicating their directions intersect, the forces may be imagined as applied at the point of intersection between the lines (as at  $A$ ), and the resultant of the two forces may be found by constructing the parallelogram of forces. Line  $AR$  shows the direction and magnitude of the resultant, the point of application of which may be assumed to be at any point on line  $AR$  or its extension.

If the resultant of three or more forces having the same point of application is to be found, as in Fig. 5, first find the resultant of any two of the forces ( $AB$  and  $AC$ ) and then find the resultant of the resultant just found ( $AR_1$ ) and the third force ( $AD$ ). If there are more than three forces, continue in this manner until the resultant of all the forces has been found.

**Parallel Forces:** If two forces are parallel and act in the same direction, as in Fig. 6, then their resultant is parallel to both lines, is located between them, and is equal to the sum of the two components. The point of application of the resultant divides the line joining the points of application of the components inversely as the magnitude of the components. Thus,

$$AB : CE = CD : AD$$

The resultant of two parallel and unequal forces acting in opposite directions, Fig. 7, is parallel to both lines, is located outside of them on the side of the greater of the components, has the same direction as the greater component, and is equal in magnitude to the difference between the two components. The point of application on the line  $AC$  produced is found from the proportion:

$$AB : CD = CE : AE$$

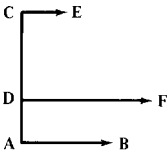


Fig. 6.

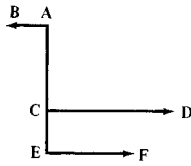


Fig. 7.

**Polygon of Forces:** When several forces are applied at a point and act in a single plane, Fig. 8, their resultant may be found more simply than by the method just described, as follows: From the extreme end of the line representing the first force, draw a line representing the second force, parallel to it and of the same length and in the direction of the second force. Then through the extreme end of this line draw a line parallel to, and of the same length and direction as the third force, and continue this until all the forces have been thus

represented. Then draw a line from the point of application of the forces (as  $A$ ) to the extreme point (as  $5_1$ ) of the line last drawn. This line ( $A 5_1$ ) is the resultant of the forces.

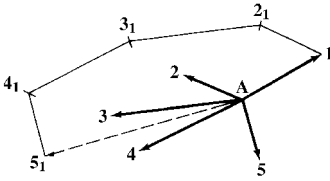


Fig. 8.

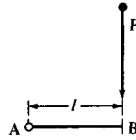
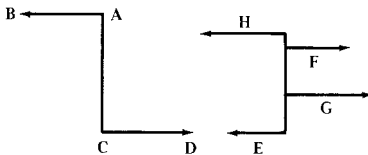


Fig. 9.

**Moment of a Force:** The moment of a force with respect to a point is the product of the force multiplied by the perpendicular distance from the given point to the direction of the force. In Fig. 9, the moment of the force  $P$  with relation to point  $A$  is  $P \times AB$ . The perpendicular distance  $AB$  is called the lever-arm of the force. The moment is the measure of the tendency of the force to produce rotation about the given point, which is termed the center of moments. If the force is measured in pounds and the distance in inches, the moment is expressed in inch-pounds. **In metric SI units, the moment is expressed in newton-meters ( $N \cdot m$ ), or newton-millimeters ( $N \cdot mm$ ).**

The moment of the resultant of any number of forces acting together in the same plane is equal to the algebraic sum of the moments of the separate forces.

**Couples.**—If the forces  $AB$  and  $CD$  are equal and parallel but act in opposite directions, then the resultant equals 0, or, in other words, the two forces have no resultant and are called a couple. A couple tends to produce rotation. The measure of this tendency is called the moment of the couple and is the product of one of the forces multiplied by the distance between the two.



Two Examples of Couples

As a couple has no resultant, no single force can balance or counteract the tendency of the couple to produce rotation. To prevent the rotation of a body acted upon by a couple, two other forces are therefore required, forming a second couple. In the illustration,  $E$  and  $F$  form one couple and  $G$  and  $H$  are the balancing couple. The body on which they act is in equilibrium if the moments of the two couples are equal and tend to rotate the body in opposite directions. A couple may also be represented by a vector in the direction of the axis about which the couple acts. The length of the vector, to some scale, represents the magnitude of the couple, and the direction of the vector is that in which a right-hand screw would advance if it were to be rotated by the couple.

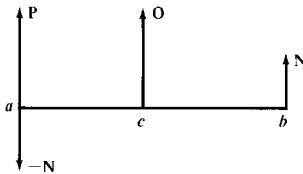


**Composition of a Single Force and Couple.**—A single force and a couple in the same plane or in parallel planes may be replaced by another single force equal and parallel to the first force, at a distance from it equal to the moment of the couple divided by the magnitude of the force. The new single force is located so that the moment of the resultant about the point of application of the original force is of the same sign as the moment of the couple.

In the next figure, with the couple  $N-N$  in the position shown, the resultant of  $P, -N$ , and  $N$  is  $O$  (which equals  $P$ ) acting on a line through point  $c$  so that  $(P-N) \times ac = N \times bc$ .

Thus, it follows that,

$$ac = \frac{N(ac + bc)}{P} = \frac{\text{Moment of Couple}}{P}$$



Single Force and Couple Composition

**Algebraic Composition and Resolution of Force Systems.**—The graphical methods given beginning on page 145 are convenient for solving problems involving force systems in which all of the forces lie in the same plane and only a few forces are involved. If many forces are involved, however, or the forces do not lie in the same plane, it is better to use algebraic methods to avoid complicated space diagrams. Systematic procedures for solving force problems by algebraic methods are outlined beginning on page 148. In connection with the use of these procedures, it is necessary to define several terms applicable to force systems in general.

The single force which produces the same effect upon a body as two or more forces acting together is called their *resultant*. The separate forces which can be so combined are called the *components*. Finding the resultant of two or more forces is called the *composition of forces*, and finding two or more components of a given force, the *resolution of forces*. Forces are said to be *concurrent* when their lines of action can be extended to meet at a common point; forces that are *parallel* are, of course, *nonconcurrent*. Two forces having the same line of action are said to be *collinear*. Two forces equal in magnitude, parallel, and in opposite directions constitute a *couple*. Forces all in the same plane are said to be *coplanar*; if not in the same plane, they are called *noncoplanar* forces.

The *resultant* of a system of forces is the simplest equivalent system that can be determined. It may be a single force, a couple, or a noncoplanar force and a couple. This last type of resultant, a noncoplanar force and a couple, may be replaced, if desired, by two *skewed* forces (forces that are nonconcurrent, nonparallel, and noncoplanar). When the resultant of a system of forces is zero, the system is in equilibrium, that is, the body on which the force system acts remains at rest or continues to move with uniform velocity.

**Algebraic Solution of Force Systems—All Forces in the Same Plane**

*Finding Two Concurrent Components of a Single Force:*

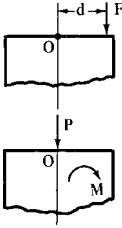
|  |   |
|--|---|
|  | <p>Case I: To find two components <math>F_1</math> and <math>F_2</math> at angles <math>\theta</math> and <math>\phi</math>, <math>\phi</math> not being <math>90^\circ</math>.</p> $F_1 = \frac{F \sin \theta}{\sin \phi}$ $F_2 = \frac{F \sin(\phi - \theta)}{\sin \phi}$ |
|  | <p>Case II: Components <math>F_1</math> and <math>F_2</math> form <math>90^\circ</math> angle.</p> $F_1 = F \sin \theta$ $F_2 = F \cos \theta$  |

*Finding the Resultant of Two Concurrent Forces:*

|  |  |
|--|--|
|  | <p>Case I: Forces <math>F_1</math> and <math>F_2</math> do not form <math>90^\circ</math> angle.</p> $R = \frac{F_1 \sin \phi}{\sin \theta} \text{ or } R = \frac{F_2 \sin \phi}{\sin(\phi - \theta)} \text{ or}$ $R = \sqrt{F_1^2 + F_2^2 + 2F_1F_2 \cos \phi}$ $\tan \theta = \frac{F_1 \sin \phi}{F_1 \cos \phi + F_2}$ |
|  | <p>Case II: Forces <math>F_1</math> and <math>F_2</math> form <math>90^\circ</math> angle.</p> $R = \frac{F_2}{\cos \theta} \text{ or } R = \frac{F_1}{\sin \theta} \text{ or}$ $R = \sqrt{F_1^2 + F_2^2}$ $\tan \theta = \frac{F_1}{F_2}$   |

*Finding the Resultant of Three or More Concurrent Forces:*

|       | <p>To determine resultant of forces <math>F_1, F_2, F_3</math>, etc. making angles, respectively, of <math>\theta_1, \theta_2, \theta_3</math>, etc. with the <math>x</math> axis, find the <math>x</math> and <math>y</math> components <math>F_x</math> and <math>F_y</math> of each force and arrange in a table similar to that shown below for a system of three forces. Find the algebraic sum of the <math>F_x</math> and <math>F_y</math> components (<math>\Sigma F_x</math> and <math>\Sigma F_y</math>) and use these to determine resultant <math>R</math>.</p> <table border="1"> <thead> <tr> <th>Force</th> <th><math>F_x</math></th> <th><math>F_y</math></th> </tr> </thead> <tbody> <tr> <td><math>F_1</math></td> <td><math>F_1 \cos \theta_1</math></td> <td><math>F_1 \sin \theta_1</math></td> </tr> <tr> <td><math>F_2</math></td> <td><math>F_2 \cos \theta_2</math></td> <td><math>F_2 \sin \theta_2</math></td> </tr> <tr> <td><math>F_3</math></td> <td><math>F_3 \cos \theta_3</math></td> <td><math>F_3 \sin \theta_3</math></td> </tr> <tr> <td></td> <td><math>\Sigma F_x</math></td> <td><math>\Sigma F_y</math></td> </tr> </tbody> </table> $R = \sqrt{(\Sigma F_x)^2 + (\Sigma F_y)^2}$ $\cos \theta_R = \frac{\Sigma F_x}{R}$ <p>or <math>\tan \theta_R = \frac{\Sigma F_y}{\Sigma F_x}</math></p> | Force               | $F_x$ | $F_y$ | $F_1$ | $F_1 \cos \theta_1$ | $F_1 \sin \theta_1$ | $F_2$ | $F_2 \cos \theta_2$ | $F_2 \sin \theta_2$ | $F_3$ | $F_3 \cos \theta_3$ | $F_3 \sin \theta_3$ |  | $\Sigma F_x$ | $\Sigma F_y$ |
|-------|--|---------------------|-------|-------|-------|---------------------|---------------------|-------|---------------------|---------------------|-------|---------------------|---------------------|--|--------------|--------------|
| Force | $F_x$  | $F_y$               |       |       |       |                     |                     |       |                     |                     |       |                     |                     |  |              |              |
| $F_1$ | $F_1 \cos \theta_1$  | $F_1 \sin \theta_1$ |       |       |       |                     |                     |       |                     |                     |       |                     |                     |  |              |              |
| $F_2$ | $F_2 \cos \theta_2$  | $F_2 \sin \theta_2$ |       |       |       |                     |                     |       |                     |                     |       |                     |                     |  |              |              |
| $F_3$ | $F_3 \cos \theta_3$  | $F_3 \sin \theta_3$ |       |       |       |                     |                     |       |                     |                     |       |                     |                     |  |              |              |
|       | $\Sigma F_x$   | $\Sigma F_y$        |       |       |       |                     |                     |       |                     |                     |       |                     |                     |  |              |              |

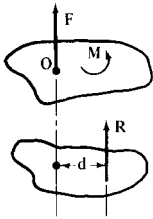
*Finding a Force and a Couple Which Together are Equivalent to a Single Force:*

To resolve a single force  $F$  into a couple of moment  $M$  and a force  $P$  passing through any chosen point  $O$  at a distance  $d$  from the original force  $F$ , use the relations

$$P = F$$

$$M = F \times d$$

The moment  $M$  must, of course, tend to produce rotation about  $O$  in the same direction as the original force. Thus, as seen in the diagram,  $F$  tends to produce clockwise rotation; hence  $M$  is shown clockwise.

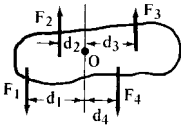
*Finding the Resultant of a Single Force and a Couple:*

The resultant of a single force  $F$  and a couple  $M$  is a single force  $R$  equal in magnitude and direction to  $F$  and parallel to it at a distance  $d$  to the left or right of  $F$ .

$$R = F$$

$$d = M \div R$$

Resultant  $R$  is placed to the left or right of point of application  $O$  of the original force  $F$  depending on which position will give  $R$  the same direction of moment about  $O$  as the original couple  $M$ .

*Finding the Resultant of a System of Parallel Forces:*

To find the resultant of a system of coplanar parallel forces, proceed as indicated below.

1) Select any convenient point  $O$  from which perpendicular distances  $d_1, d_2, d_3$ , etc. to parallel forces  $F_1, F_2, F_3$ , etc. can be specified or calculated.

2) Find the algebraic sum of all the forces; this will give the magnitude of the resultant of the system.

$$R = \Sigma F = F_1 + F_2 + F_3 + \dots$$

3) Find the algebraic sum of the moments of the forces about  $O$ ; clockwise moments may be taken as negative and counterclockwise moments as positive:

$$\Sigma M_O = F_1 d_1 + F_2 d_2 + \dots$$

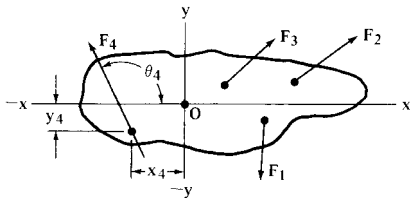
4) Calculate the distance  $d$  from  $O$  to the line of action of resultant  $R$ :

$$d = \Sigma M_O \div R$$

This distance is measured to the left or right from  $O$  depending on which position will give the moment of  $R$  the same direction of rotation about  $O$  as the couple  $\Sigma M_O$ , that is, if  $\Sigma M_O$  is negative, then  $d$  is left or right of  $O$  depending on which direction will make  $R \times d$  negative.

*Note Concerning Interpretation of Results:* If  $R = 0$ , then the resultant of the system is a couple  $\Sigma M_O$ ; if  $\Sigma M_O = 0$  then the resultant is a single force  $R$ ; if both  $R$  and  $\Sigma M_O = 0$ , then the system is in equilibrium.

## Finding the Resultant of Forces Not Intersecting at a Common Point:



To determine the resultant of a coplanar, nonconcurrent, nonparallel force system as shown in the diagram, proceed as shown below.

1) Draw a set of  $x$  and  $y$  coordinate axes through any convenient point  $O$  in the plane of the forces as shown in the diagram.

2) Determine the  $x$  and  $y$  coordinates of any convenient point on the line of action of each force and the angle  $\theta$ , measured in a counterclockwise direction, that each line of action makes with the positive  $x$  axis. For example, in the diagram, coordinates  $x_4, y_4$ , and  $\theta_4$  are shown for  $F_4$ . Similar data should be known for each of the forces of the system.

3) Calculate the  $x$  and  $y$  components ( $F_x, F_y$ ) of each force and the moment of each component about  $O$ . Counterclockwise moments are considered positive and clockwise moments are negative. Tabulate all results in a manner similar to that shown below for a system of three forces and find  $\Sigma F_x, \Sigma F_y, \Sigma M_O$  by algebraic addition.

| Force<br>$F$ | Coordinates of $F$ |       |            | Components of $F$   |                     | Moment of $F$ about $O$                         |
|--------------|--------------------|-------|------------|---------------------|---------------------|---|
|              | $x$                | $y$   | $\theta$   | $F_x$               | $F_y$               | $M_O = xF_y - yF_x$                             |
| $F_1$        | $x_1$              | $y_1$ | $\theta_1$ | $F_1 \cos \theta_1$ | $F_1 \sin \theta_1$ | $x_1 F_1 \sin \theta_1 - y_1 F_1 \cos \theta_1$ |
| $F_2$        | $x_2$              | $y_2$ | $\theta_2$ | $F_2 \cos \theta_2$ | $F_2 \sin \theta_2$ | $x_2 F_2 \sin \theta_2 - y_2 F_2 \cos \theta_2$ |
| $F_3$        | $x_3$              | $y_3$ | $\theta_3$ | $F_3 \cos \theta_3$ | $F_3 \sin \theta_3$ | $x_3 F_3 \sin \theta_3 - y_3 F_3 \cos \theta_3$ |
|              |                    |       |            | $\Sigma F_x$        | $\Sigma F_y$        | $\Sigma M_O$                                    |

4. Compute the resultant of the system and the angle  $\theta_R$  it makes with the  $x$  axis by using the formulas:

$$R = \sqrt{(\Sigma F_x)^2 + (\Sigma F_y)^2}$$

$$\cos \theta_R = \Sigma F_x \div R \text{ or } \tan \theta_R = \Sigma F_y \div \Sigma F_x$$

5. Calculate the distance  $d$  from  $O$  to the line of action of the resultant  $R$ :

$$d = \Sigma M_O \div R$$

Distance  $d$  is in such direction from  $O$  as will make the moment of  $R$  about  $O$  have the same sign as  $\Sigma M_O$ .

*Note Concerning Interpretation of Results:* If  $R = 0$ , then the resultant is a couple  $\Sigma M_O$ ; if  $\Sigma M_O = 0$ , then  $R$  passes through  $O$ ; if both  $R = 0$  and  $\Sigma M_O = 0$ , then the system is in equilibrium.

*Example:* Find the resultant of three coplanar nonconcurrent forces for which the following data are given.

$$F_1 = 10 \text{ lbs; } x_1 = 5 \text{ in.; } y_1 = -1 \text{ in.; } \theta_1 = 270^\circ$$

$$F_2 = 20 \text{ lbs; } x_2 = 4 \text{ in.; } y_2 = 1.5 \text{ in.; } \theta_2 = 50^\circ$$

$$F_3 = 30 \text{ lbs; } x_3 = 2 \text{ in.; } y_3 = 2 \text{ in.; } \theta_3 = 60^\circ$$

$$F_{x_1} = 10 \cos 270^\circ = 10 \times 0 = 0 \text{ lbs.}$$

$$F_{x_2} = 20 \cos 50^\circ = 20 \times 0.64279 = 12.86 \text{ lbs.}$$

$$F_{x_3} = 30 \cos 60^\circ = 30 \times 0.5000 = 15.00 \text{ lbs.}$$

$$F_{y_1} = 10 \times \sin 270^\circ = 10 \times (-1) = -10.00 \text{ lbs.}$$

$$F_{y_2} = 20 \times \sin 50^\circ = 20 \times 0.76604 = 15.32 \text{ lbs.}$$

$$F_{y_3} = 30 \times \sin 60^\circ = 30 \times 0.86603 = 25.98 \text{ lbs.}$$

$$M_{o_1} = 5 \times (-10) - (-1) \times 0 = -50 \text{ in. lbs.}$$

$$M_{o_2} = 4 \times 15.32 - 1.5 \times 12.86 = 41.99 \text{ in. lbs.}$$

$$M_{o_3} = 2 \times 25.98 - 2 \times 15 = 21.96 \text{ in. lbs.}$$

**Note:** When working in metric SI units, pounds are replaced by newtons (N); inches by meters or millimeters, and inch-pounds by newton-meters (N · m) or newton-millimeters (N · mm).

| Force<br>$F$ | Coordinates of $F$ |     |             | Components of $F$    |                      | Moment<br>of $F$ about $O$ |
|--------------|--------------------|-----|-------------|----------------------|----------------------|----------------------------|
|              | $x$                | $y$ | $\theta$    | $F_x$                | $F_y$                |                            |
| $F_1 = 10$   | 5                  | -1  | $270^\circ$ | 0                    | -10.00               | -50.00                     |
| $F_2 = 20$   | 4                  | 1.5 | $50^\circ$  | 12.86                | 15.32                | 41.99                      |
| $F_3 = 30$   | 2                  | 2   | $60^\circ$  | 15.00                | 25.98                | 21.96                      |
|              |                    |     |             | $\Sigma F_x = 27.86$ | $\Sigma F_y = 31.30$ | $\Sigma M_O = 13.95$       |

$$R = \sqrt{(27.86)^2 + (31.30)^2}$$

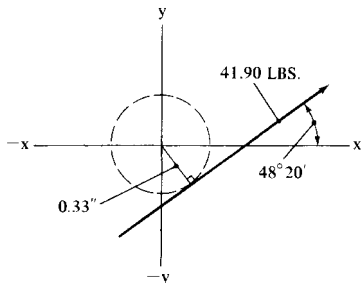
$$= 41.90 \text{ lbs.}$$

$$\tan \theta_R = \frac{31.30}{27.86} = 1.1235$$

$$\theta_R = 48^\circ 20'$$

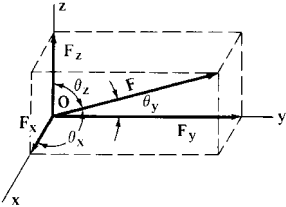
$$d = \frac{13.95}{41.90} = 0.33 \text{ inches}$$

measured as shown on the diagram.



### Algebraic Solution of Force Systems — Forces Not in Same Plane

#### Resolving a Single Force Into Its Three Rectangular Components:

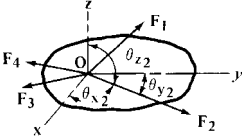


$F_x = F \cos \theta_x$   
 $F_y = F \cos \theta_y$   
 $F_z = F \cos \theta_z$   
 $F = \sqrt{F_x^2 + F_y^2 + F_z^2}$

The diagram shows how a force  $F$  may be resolved at any point  $O$  on its line of action into three concurrent components each of which is perpendicular to the other two.

The  $x, y, z$  components  $F_x, F_y, F_z$  of force  $F$  are determined from the accompanying relations in which  $\theta_x, \theta_y, \theta_z$  are the angles that the force  $F$  makes with the  $x, y, z$  axes.

#### Finding the Resultant of Any Number of Concurrent Forces:



To find the resultant of any number of noncoplanar concurrent forces  $F_1, F_2, F_3$ , etc., use the procedure outlined below.

- 1) Draw a set of  $x, y, z$  axes at  $O$ , the point of concurrency of the forces. The angles each force makes measured counterclockwise from the positive  $x, y$ , and  $z$  coordinate axes must be known in addition to the magnitudes of the forces. For force  $F_2$ , for example, the angles are  $\theta_{x2}, \theta_{y2}, \theta_{z2}$  as indicated on the diagram.
- 2) Apply the first three formulas given under the heading "Resolving a Single Force Into Its Three Rectangular Components" to each force to find its  $x, y$ , and  $z$  components. Tabulate these calculations as shown below for a system of three forces. Algebraically add the calculated components to find  $\Sigma F_x, \Sigma F_y$ , and  $\Sigma F_z$  which are the components of the resultant.

| Force<br>$F$ | Angles        |               |               | Components of Forces   |                        |                        |
|--------------|---------------|---------------|---------------|------------------------|------------------------|------------------------|
|              | $\theta_x$    | $\theta_y$    | $\theta_z$    | $F_x$                  | $F_y$                  | $F_z$                  |
| $F_1$        | $\theta_{x1}$ | $\theta_{y1}$ | $\theta_{z1}$ | $F_1 \cos \theta_{x1}$ | $F_1 \cos \theta_{y1}$ | $F_1 \cos \theta_{z1}$ |
| $F_2$        | $\theta_{x2}$ | $\theta_{y2}$ | $\theta_{z2}$ | $F_2 \cos \theta_{x2}$ | $F_2 \cos \theta_{y2}$ | $F_2 \cos \theta_{z2}$ |
| $F_3$        | $\theta_{x3}$ | $\theta_{y3}$ | $\theta_{z3}$ | $F_3 \cos \theta_{x3}$ | $F_3 \cos \theta_{y3}$ | $F_3 \cos \theta_{z3}$ |
|              |               |               |               | $\Sigma F_x$           | $\Sigma F_y$           | $\Sigma F_z$           |

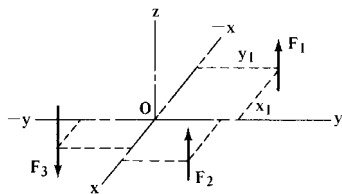
3. Find the resultant of the system from the formula  $R = \sqrt{(\Sigma F_x)^2 + (\Sigma F_y)^2 + (\Sigma F_z)^2}$

4. Calculate the angles  $\theta_{xR}, \theta_{yR}$ , and  $\theta_{zR}$  that the resultant  $R$  makes with the respective coordinate axes:

$$\cos \theta_{xR} = \frac{\Sigma F_x}{R}$$

$$\cos \theta_{yR} = \frac{\Sigma F_y}{R}$$

$$\cos \theta_{zR} = \frac{\Sigma F_z}{R}$$

*Finding the Resultant of Parallel Forces Not in the Same Plane:*

In the diagram, forces  $F_1, F_2$ , etc. represent a system of noncoplanar parallel forces. To find the resultant of such systems, use the procedure shown below.

1) Draw a set of  $x, y$ , and  $z$  coordinate axes through any point  $O$  in such a way that one of these axes, say the  $z$  axis, is parallel to the lines of action of the forces. The  $x$  and  $y$  axes then will be perpendicular to the forces.

2) Set the distances of each force from the  $x$  and  $y$  axes in a table as shown below. For example,  $x_1$  and  $y_1$  are the  $x$  and  $y$  distances for  $F_1$  shown in the diagram.

3) Calculate the moment of each force about the  $x$  and  $y$  axes and set the results in the table as shown for a system consisting of three forces. The algebraic sums of the moments  $\sum M_x$  and  $\sum M_y$  are then obtained. (In taking moments about the  $x$  and  $y$  axes, assign counterclockwise moments a plus (+) sign and clockwise moments a minus (-) sign. In deciding whether a moment is counterclockwise or clockwise, look from the positive side of the axis in question toward the negative side.)

| Force      | Coordinates of Force $F$ |       | Moments $M_x$ and $M_y$ due to $F$ |              |
|------------|--------------------------|-------|------------------------------------|--------------|
|            | $x$                      | $y$   | $M_x$                              | $M_y$        |
| $F_1$      | $x_1$                    | $y_1$ | $F_1 y_1$                          | $F_1 x_1$    |
| $F_2$      | $x_2$                    | $y_2$ | $F_2 y_2$                          | $F_2 x_2$    |
| $F_3$      | $x_3$                    | $y_3$ | $F_3 y_3$                          | $F_3 x_3$    |
| $\Sigma F$ |                          |       | $\Sigma M_x$                       | $\Sigma M_y$ |

4. Find the algebraic sum  $\Sigma F$  of all the forces; this will be the resultant  $R$  of the system.

$$R = \Sigma F = F_1 + F_2 + \dots$$

5. Calculate  $x_R$  and  $y_R$ , the moment arms of the resultant:

$$x_R = \Sigma M_y \div R$$

$$y_R = \Sigma M_x \div R$$

These moment arms are measured in such direction along the  $x$  and  $y$  axes as will give the resultant a moment of the same direction of rotation as  $\Sigma M_x$  and  $\Sigma M_y$ .

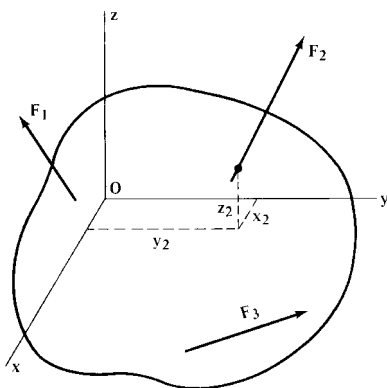
*Note Concerning Interpretation of Results:* If  $\Sigma M_x$  and  $\Sigma M_y$  are both 0, then the resultant is a single force  $R$  along the  $z$  axis; if  $R$  is also 0, then the system is in equilibrium. If  $R$  is 0 but  $\Sigma M_x$  and  $\Sigma M_y$  are not both 0, then the resultant is a couple

$$M_R = \sqrt{(\Sigma M_x)^2 + (\Sigma M_y)^2}$$

that lies in a plane parallel to the  $z$  axis and making an angle  $\theta_R$  measured in a counterclockwise direction from the positive  $x$  axis and calculated from the following formula:

$$\sin \theta_R = \frac{\Sigma M_x}{M_R}$$

## Finding the Resultant of Nonparallel Forces Not Meeting at a Common Point:



The diagram shows a system of noncoplanar, nonparallel, nonconcurrent forces  $F_1, F_2$ , etc. for which the resultant is to be determined. Generally speaking, the resultant will be a noncoplanar force and a couple which may be further combined, if desired, into two forces that are skewed.

This is the most general force system that can be devised, so each of the other systems so far described represents a special, simpler case of this general force system. The method of solution described below for a system of three forces applies for any number of forces.

- 1) Select a set of coordinate  $x, y$ , and  $z$  axes at any desired point  $O$  in the body as shown in the diagram.
- 2) Determine the  $x, y$ , and  $z$  coordinates of any convenient point on the line of action of each force as shown for  $F_2$ . Also determine the angles,  $\theta_x, \theta_y, \theta_z$  that each force makes with each coordinate axis. These angles are measured counterclockwise from the positive direction of the  $x, y$ , and  $z$  axes. The data is tabulated, as shown in the table accompanying Step 3, for convenient use in subsequent calculations.
- 3) Calculate the  $x, y$ , and  $z$  components of each force using the formulas given in the accompanying table. Add these components algebraically to get  $\Sigma F_x, \Sigma F_y$  and  $\Sigma F_z$  which are the components of the resultant,  $R$ , given by the formula,

$$R = \sqrt{(\Sigma F_x)^2 + (\Sigma F_y)^2 + (\Sigma F_z)^2}$$

| Force<br>$F$ | Coordinates of Force $F$ |       |       |               |               |               | Components of $F$      |                        |                        |
|--------------|--------------------------|-------|-------|---------------|---------------|---------------|------------------------|------------------------|------------------------|
|              | $x$                      | $y$   | $z$   | $\theta_x$    | $\theta_y$    | $\theta_z$    | $F_x$                  | $F_y$                  | $F_z$                  |
| $F_1$        | $x_1$                    | $y_1$ | $z_1$ | $\theta_{x1}$ | $\theta_{y1}$ | $\theta_{z1}$ | $F_1 \cos \theta_{x1}$ | $F_1 \cos \theta_{y1}$ | $F_1 \cos \theta_{z1}$ |
| $F_2$        | $x_2$                    | $y_2$ | $z_2$ | $\theta_{x2}$ | $\theta_{y2}$ | $\theta_{z2}$ | $F_2 \cos \theta_{x2}$ | $F_2 \cos \theta_{y2}$ | $F_2 \cos \theta_{z2}$ |
| $F_3$        | $x_3$                    | $y_3$ | $z_3$ | $\theta_{x3}$ | $\theta_{y3}$ | $\theta_{z3}$ | $F_3 \cos \theta_{x3}$ | $F_3 \cos \theta_{y3}$ | $F_3 \cos \theta_{z3}$ |
|              |                          |       |       |               |               |               | $\Sigma F_x$           | $\Sigma F_y$           | $\Sigma F_z$           |

The resultant force  $R$  makes angles of  $\theta_{xR}, \theta_{yR}$ , and  $\theta_{zR}$  with the  $x, y$ , and  $z$  axes, respectively, and passes through the selected point  $O$ . These angles are determined from the formulas,

$$\cos \theta_{xR} = \Sigma F_x \div R$$

$$\cos \theta_{yR} = \Sigma F_y \div R$$

$$\cos \theta_{zR} = \Sigma F_z \div R$$



4. Calculate the moments  $M_x, M_y, M_z$  about  $x, y,$  and  $z$  axes, respectively, due to the  $F_x, F_y,$  and  $F_z$  components of each force and set them in tabular form. The formulas to use are given in the accompanying table.

In interpreting moments about the  $x, y,$  and  $z$  axes, consider counterclockwise moments a plus (+) sign and clockwise moments a minus (-) sign. In deciding whether a moment is counterclockwise or clockwise, look from the positive side of the axis in question toward the negative side.

| Force | Moments of Components of $F (F_x, F_y, F_z)$ about $x, y, z$ axes |                                  |                                  |
|-------|---|----------------------------------|----------------------------------|
| $F$   | $M_x = yF_z - zF_y$   | $M_y = zF_x - xF_z$              | $M_z = xF_y - yF_x$              |
| $F_1$ | $M_{x1} = y_1F_{z1} - z_1F_{y1}$                                  | $M_{y1} = z_1F_{x1} - x_1F_{z1}$ | $M_{z1} = x_1F_{y1} - y_1F_{x1}$ |
| $F_2$ | $M_{x2} = y_2F_{z2} - z_2F_{y2}$                                  | $M_{y2} = z_2F_{x2} - x_2F_{z2}$ | $M_{z2} = x_2F_{y2} - y_2F_{x2}$ |
| $F_3$ | $M_{x3} = y_3F_{z3} - z_3F_{y3}$                                  | $M_{y3} = z_3F_{x3} - x_3F_{z3}$ | $M_{z3} = x_3F_{y3} - y_3F_{x3}$ |
|       | $\Sigma M_x$  | $\Sigma M_y$                     | $\Sigma M_z$                     |

5. Add the component moments algebraically to get  $\Sigma M_x, \Sigma M_y,$  and  $\Sigma M_z$  which are the components of the resultant couple,  $M$ , given by the formula,

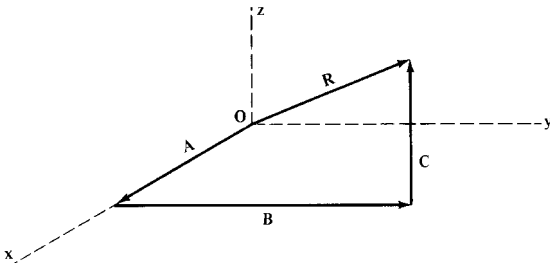
$$M = \sqrt{(\Sigma M_x)^2 + (\Sigma M_y)^2 + (\Sigma M_z)^2}$$

The resultant couple  $M$  will tend to produce rotation about an axis making angles of  $\beta_x, \beta_y,$  and  $\beta_z$  with the  $x, y, z$  axes, respectively. These angles are determined from the formulas,

$$\cos \beta_x = \frac{\Sigma M_x}{M} \quad \cos \beta_y = \frac{\Sigma M_y}{M} \quad \cos \beta_z = \frac{\Sigma M_z}{M}$$

*General Method of Locating Resultant When Its Components are Known:* To determine the position of the resultant force of a system of forces, proceed as follows:

From the origin, point  $O$ , of a set of coordinate axes  $x, y, z,$  lay off on the  $x$  axis a length  $A$  representing the algebraic sum  $\Sigma F_x$  of the  $x$  components of all the forces. From the end of line  $A$  lay off a line  $B$  representing  $\Sigma F_y$ , the algebraic sum of the  $y$  components; this line  $B$  is drawn in a direction parallel to the  $y$  axis. From the end of line  $B$  lay off a line  $C$  representing  $\Sigma F_z$ . Finally, draw a line  $R$  from  $O$  to the end of  $C$ ;  $R$  will be the resultant of the system.



### Friction

**Properties of Friction.**—Friction is the resistance to motion that takes place when one body is moved upon another, and is generally defined as “that force which acts between two bodies at their surface of contact, so as to resist their sliding on each other.” According to the conditions under which sliding occurs, the force of friction,  $F$ , bears a certain relation to the force between the two bodies called the normal force  $N$ . The relation between force of friction and normal force is given by the *coefficient of friction*, generally denoted by the Greek letter  $\mu$ . Thus:

$$F = \mu \times N \quad \text{and} \quad \mu = \frac{F}{N}$$

*Example:* A body weighing 28 pounds rests on a horizontal surface. The force required to keep it in motion along the surface is 7 pounds. Find the coefficient of friction.

$$\mu = \frac{F}{N} = \frac{7}{28} = 0.25$$

If a body is placed on an inclined plane, the friction between the body and the plane will prevent it from sliding down the inclined surface, provided the angle of the plane with the horizontal is not too great. There will be a certain angle, however, at which the body will just barely be able to remain stationary, the frictional resistance being very nearly overcome by the tendency of the body to slide down. This angle is termed the angle of repose, and the tangent of this angle equals the coefficient of friction. The angle of repose is frequently denoted by the Greek letter  $\theta$ . Thus,  $\mu = \tan \theta$ .

A greater force is required to start a body moving from a state of rest than to merely keep it in motion, because the *friction of rest* is greater than the *friction of motion*.

**Laws of Friction.**—The laws of friction for unlubricated or dry surfaces are summarized in the following statements.

1) For low pressures (normal force per unit area) the friction is directly proportional to the normal force between the two surfaces. As the pressure increases, the friction does not rise proportionally; but when the pressure becomes abnormally high, the friction increases at a rapid rate until seizing takes place.

2) The friction both in its total amount and its coefficient is independent of the areas in contact, so long as the normal force remains the same. This is true for moderate pressures only. For high pressures, this law is modified in the same way as in the first case.

3) At very low velocities the friction is independent of the velocity of rubbing. As the velocities increase, the friction decreases.

*Lubricated Surfaces:* For well lubricated surfaces, the laws of friction are considerably different from those governing dry or poorly lubricated surfaces.

1) The frictional resistance is almost independent of the pressure (normal force per unit area) if the surfaces are flooded with oil.

2) The friction varies directly as the speed, at low pressures; but for high pressures the friction is very great at low velocities, approaching a minimum at about two feet per second linear velocity, and afterwards increasing approximately as the square root of the speed.

3) For well lubricated surfaces the frictional resistance depends, to a very great extent, on the temperature, partly because of the change in the viscosity of the oil and partly because, for a journal bearing, the diameter of the bearing increases with the rise of temperature more rapidly than the diameter of the shaft, thus relieving the bearing of side pressure.

4) If the bearing surfaces are flooded with oil, the friction is almost independent of the nature of the material of the surfaces in contact. As the lubrication becomes less ample, the coefficient of friction becomes more dependent upon the material of the surfaces.

**Influence of Friction on the Efficiency of Small Machine Elements.**—Friction between machine parts lowers the efficiency of a machine. Average values of the efficiency, in per cent, of the most common machine elements when carefully made are ordi-

nary bearings, 95 to 98; roller bearings, 98; ball bearings, 99; spur gears with cut teeth, including bearings, 99; bevel gears with cut teeth, including bearings, 98; belting, from 96 to 98; high-class silent power transmission chain, 97 to 99; roller chains, 95 to 97.

**Coefficients of Friction.**—Tables 1 and 2 provide representative values of static friction for various combinations of materials with dry (clean, unlubricated) and lubricated surfaces. The values for static or breakaway friction shown in these tables will generally be higher than the subsequent or sliding friction. Typically, the steel-on-steel static coefficient of 0.8 unlubricated will drop to 0.4 when sliding has been initiated; with oil lubrication, the value will drop from 0.16 to 0.03.

Many factors affect friction, and even slight deviations from normal or test conditions can produce wide variations. Accordingly, when using friction coefficients in design calculations, due allowance or factors of safety should be considered, and in critical applications, specific tests conducted to provide specific coefficients for material, geometry, and/or lubricant combinations.

**Table 1. Coefficients of Static Friction for Steel on Various Materials**

| Material          | Coefficient of Friction, $\mu$ |            | Material         | Coefficient of Friction, $\mu$ |            |
|-------------------|--------------------------------|------------|------------------|--------------------------------|------------|
|                   | Clean                          | Lubricated |                  | Clean                          | Lubricated |
| Steel             | 0.8                            | 0.16       | Hard carbon      | 0.14                           | 0.11–0.14  |
| Copper-lead alloy | 0.22                           | ...        | Graphite         | 0.1                            | 0.1        |
| Phosphor-bronze   | 0.35                           | ...        | Tungsten carbide | 0.4–0.6                        | 0.1–0.2    |
| Aluminum-bronze   | 0.45                           | ...        | Plexiglas        | 0.4–0.5                        | 0.4–0.5    |
| Brass             | 0.35                           | 0.19       | Polystyrene      | 0.3–0.35                       | 0.3–0.35   |
| Cast iron         | 0.4                            | 0.21       | Polythene        | 0.2                            | 0.2        |
| Bronze            | ...                            | 0.16       | Teflon           | 0.04                           | 0.04       |
| Sintered bronze   | ...                            | 0.13       |                  |                                |            |

Tables 1 and 2 used with permission from *The Friction and Lubrication of Solids*, Vol. 1, by Bowden and Tabor, Clarendon Press, Oxford, 1950.

**Table 2. Coefficients of Static Friction for Various Materials Combinations**

| Material Combination          | Coefficient of Friction, $\mu$ |            | Material Combination              | Coefficient of Friction, $\mu$ |            |
|-------------------------------|--------------------------------|------------|-----------------------------------|--------------------------------|------------|
|                               | Clean                          | Lubricated |                                   | Clean                          | Lubricated |
| Aluminum-aluminum             | 1.35                           | 0.30       | Tungsten carbide-tungsten carbide | 0.2–0.25                       | 0.12       |
| Cadmium-cadmium               | 0.5                            | 0.05       | Plexiglas-Plexiglas               | 0.8                            | 0.8        |
| Chromium-chromium             | 0.41                           | 0.34       | Polystyrene-polystyrene           | 0.5                            | 0.5        |
| Copper-copper                 | 1.0                            | 0.08       | Teflon-Teflon                     | 0.04                           | 0.04       |
| Iron-iron                     | 1.0                            | 0.15–0.20  | Nylon-nylon                       | 0.15–0.25                      | ...        |
| Magnesium-magnesium           | 0.6                            | 0.08       | Solids on rubber                  | 1–4                            | ...        |
| Nickel-nickel                 | 0.7                            | 0.28       | Wood on wood (clean)              | 0.25–0.5                       | ...        |
| Platinum-platinum             | 1.2                            | 0.25       | Wood on wood (wet)                | 0.2                            | ...        |
| Silver-silver                 | 1.4                            | 0.55       | Wood on metals (clean)            | 0.2–0.6                        | ...        |
| Zinc-zinc                     | 0.6                            | 0.04       | Wood on metals (wet)              | 0.2                            | ...        |
| Glass-glass                   | 0.9–1.0                        | 0.1–0.6    | Brick on wood                     | 0.6                            | ...        |
| Glass-metal                   | 0.5–0.7                        | 0.2–0.3    | Leather on wood                   | 0.3–0.4                        | ...        |
| Diamond-diamond               | 0.1                            | 0.05–0.1   | Leather on metal (clean)          | 0.6                            | ...        |
| Diamond-metal                 | 0.1–0.15                       | 0.1        | Leather on metal (wet)            | 0.4                            | ...        |
| Sapphire-sapphire             | 0.2                            | 0.2        | Leather on metal (greasy)         | 0.2                            | ...        |
| Hard carbon on carbon         | 0.16                           | 0.12–0.14  | Brake material on cast iron       | 0.4                            | ...        |
| Graphite-graphite (in vacuum) | 0.5–0.8                        | ...        | Brake material on cast iron (wet) | 0.2                            | ...        |
| Graphite-graphite             | 0.1                            | 0.1        |                                   |                                |            |

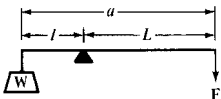
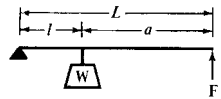
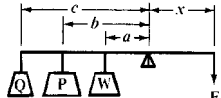
**Rolling Friction.**—When a body rolls on a surface, the force resisting the motion is termed *rolling friction* or *rolling resistance*. Let  $W$  = total weight of rolling body or load on wheel, in pounds;  $r$  = radius of wheel, in inches;  $f$  = coefficient of rolling resistance, in inches. Then: resistance to rolling, in pounds =  $(W \times f) \div r$ .

The coefficient of rolling resistance varies with the conditions. For wood on wood it may be assumed as 0.06 inch; for iron on iron, 0.02 inch; iron on granite, 0.085 inch; iron on asphalt, 0.15 inch; and iron on wood, 0.22 inch.

The coefficient of rolling resistance,  $f$ , is in inches and is not the same as the sliding or static coefficient of friction given in Tables 1 and 2, which is a dimensionless ratio between frictional resistance and normal load. Various investigators are not in close agreement on the true values for these coefficients and the foregoing values should only be used for the approximate calculation of rolling resistance.

## Mechanisms

### Lever

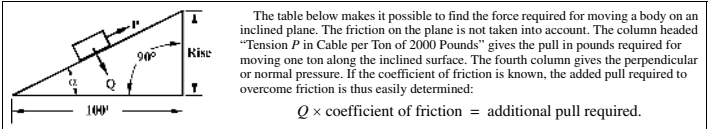
| Types of Levers   | Examples   |
|---|--|
|  <p> <math>F:W = l:L</math> <math>F \times L = W \times l</math><br/> <math>F = \frac{W \times l}{L}</math> <math>W = \frac{F \times L}{l}</math><br/> <math>L = \frac{W \times a}{W + F} = \frac{W \times l}{F}</math> <math>l = \frac{F \times a}{W + F} = \frac{F \times L}{W}</math> </p>  | <p>A pull of 80 pounds is exerted at the end of the lever, at <math>W</math>; <math>l = 12</math> inches and <math>L = 32</math> inches.</p> <p>Find the value of force <math>F</math> required to balance the lever.</p> $F = \frac{80 \times 12}{32} = \frac{960}{32} = 30 \text{ pounds}$ <p>If <math>F = 20</math>; <math>W = 180</math>; and <math>l = 3</math>; how long must <math>L</math> be made to secure equilibrium?</p> $L = \frac{180 \times 3}{20} = 27$                                   |
|  <p> <math>F:W = l:L</math> <math>F \times L = W \times l</math><br/> <math>F = \frac{W \times l}{L}</math> <math>W = \frac{F \times L}{l}</math><br/> <math>L = \frac{W \times a}{W - F} = \frac{W \times l}{F}</math> <math>l = \frac{F \times a}{W - F} = \frac{F \times L}{W}</math> </p> | <p>Total length <math>L</math> of a lever is 25 inches. A weight of 90 pounds is supported at <math>W</math>; <math>l</math> is 10 inches.</p> <p>Find the value of <math>F</math>.</p> $F = \frac{90 \times 10}{25} = 36 \text{ pounds}$ <p>If <math>F = 100</math> pounds, <math>W = 2200</math> pounds, and <math>a = 5</math> feet, what should <math>L</math> equal to secure equilibrium?</p> $L = \frac{2200 \times 5}{2200 - 100} = 5.24 \text{ feet}$   |
|  <p>When three or more forces act on lever:</p> $F \times x = W \times a + P \times b + Q \times c$ $x = \frac{W \times a + P \times b + Q \times c}{F}$ $F = \frac{W \times a + P \times b + Q \times c}{x}$  | <p>Let <math>W = 20</math>, <math>P = 30</math>, and <math>Q = 15</math> pounds; <math>a = 4</math>, <math>b = 7</math>, and <math>c = 10</math> inches.</p> <p>If <math>x = 6</math> inches, find <math>F</math>.</p> $F = \frac{20 \times 4 + 30 \times 7 + 15 \times 10}{6} = 73\frac{1}{3} \text{ lbs}$ <p>Assuming <math>F = 20</math> pounds in the example above, how long must lever arm <math>x</math> be made?</p> $x = \frac{20 \times 4 + 30 \times 7 + 15 \times 10}{20} = 22 \text{ inches}$ |

The above formulas are valid using metric SI units, with forces expressed in newtons, and lengths in meters. However, it should be noted that the weight of a mass  $W$  kilograms is equal to a force of  $Wg$  newtons, where  $g$  is approximately  $9.81 \text{ m/s}^2$ . Thus, supposing that in the first

example  $l = 0.4$  m,  $L = 1.2$  m, and  $W = 30$  kg, then the weight of  $W$  is 30g newtons, so that the force  $F$  required to balance the lever is  $F = \frac{30g \times 0.4}{1.2} = 10g = 98.1$  newtons.

This force could be produced by suspending a mass of 10 kg at  $F$ .

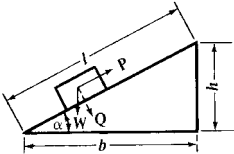
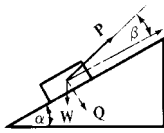
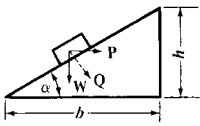
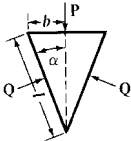
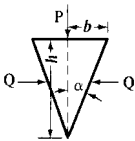
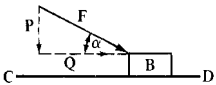
**Table of Forces on Inclined Planes**



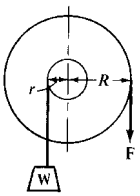
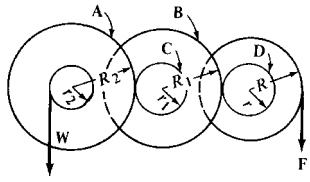
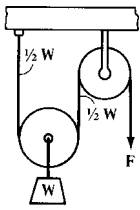
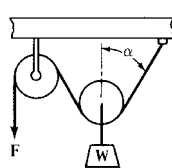
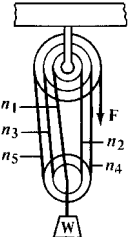
| Per Cent of Grade. Rise, Ft. per 100 Ft. | Angle $\alpha$ | Tension $P$ in Cable per Ton of 2000 Lbs. | Perpendicular Pressure $Q$ on Plane per Ton of 2000 Lbs. | Per Cent of Grade. Rise, Ft. per 100 Ft. | Angle $\alpha$ | Tension $P$ in Cable per Ton of 2000 Lbs. | Perpendicular Pressure $Q$ on Plane per Ton of 2000 Lbs. |
|--|----------------|---|--|--|----------------|---|--|
| 1  | 0.57           | 20.00                                     | 1999.90  | 51                                       | 27.02          | 976.35                                    | 1745.49  |
| 2  | 1.15           | 40.00                                     | 1999.60  | 52                                       | 27.47          | 993.76                                    | 1735.64  |
| 3  | 1.72           | 59.99                                     | 1999.10  | 53                                       | 27.92          | 1011.07                                   | 1725.61  |
| 4  | 2.29           | 79.98                                     | 1998.40  | 54                                       | 28.37          | 1028.27                                   | 1715.42  |
| 5  | 2.86           | 99.96                                     | 1997.50  | 55                                       | 28.81          | 1045.37                                   | 1705.05  |
| 6  | 3.43           | 119.93                                    | 1996.40  | 56                                       | 29.25          | 1062.37                                   | 1694.51  |
| 7  | 4.00           | 139.89                                    | 1995.10  | 57                                       | 29.68          | 1079.26                                   | 1683.80  |
| 8  | 4.57           | 159.83                                    | 1993.60  | 58                                       | 30.11          | 1096.05                                   | 1672.93  |
| 9  | 5.14           | 179.76                                    | 1991.91  | 59                                       | 30.54          | 1112.72                                   | 1661.88  |
| 10                                       | 5.71           | 199.67                                    | 1990.01  | 60                                       | 30.96          | 1129.28                                   | 1650.67  |
| 11                                       | 6.28           | 219.56                                    | 1987.91  | 61                                       | 31.38          | 1145.73                                   | 1639.30  |
| 12                                       | 6.84           | 239.42                                    | 1985.62  | 62                                       | 31.80          | 1162.07                                   | 1627.76  |
| 13                                       | 7.41           | 259.27                                    | 1983.12  | 63                                       | 32.21          | 1178.29                                   | 1616.06  |
| 14                                       | 7.97           | 279.09                                    | 1980.43  | 64                                       | 32.62          | 1194.39                                   | 1604.19  |
| 15                                       | 8.53           | 298.88                                    | 1977.54  | 65                                       | 33.02          | 1210.37                                   | 1592.17  |
| 16                                       | 9.09           | 318.64                                    | 1974.45  | 66                                       | 33.42          | 1226.23                                   | 1579.98  |
| 17                                       | 9.65           | 338.36                                    | 1971.17  | 67                                       | 33.82          | 1241.97                                   | 1567.64  |
| 18                                       | 10.20          | 358.06                                    | 1967.69  | 68                                       | 34.22          | 1257.59                                   | 1555.15  |
| 19                                       | 10.76          | 377.72                                    | 1964.01  | 69                                       | 34.61          | 1273.07                                   | 1542.49  |
| 20                                       | 11.31          | 397.34                                    | 1960.13  | 70                                       | 34.99          | 1288.44                                   | 1529.68  |
| 21                                       | 11.86          | 416.92                                    | 1956.06  | 71                                       | 35.37          | 1303.67                                   | 1516.72  |
| 22                                       | 12.41          | 436.46                                    | 1951.79  | 72                                       | 35.75          | 1318.77                                   | 1503.61  |
| 23                                       | 12.95          | 455.96                                    | 1947.33  | 73                                       | 36.13          | 1333.74                                   | 1490.35  |
| 24                                       | 13.50          | 475.41                                    | 1942.68  | 74                                       | 36.50          | 1348.58                                   | 1476.94  |
| 25                                       | 14.04          | 494.81                                    | 1937.82  | 75                                       | 36.87          | 1363.28                                   | 1463.38  |
| 26                                       | 14.57          | 514.16                                    | 1932.78  | 76                                       | 37.23          | 1377.84                                   | 1449.67  |
| 27                                       | 15.11          | 533.46                                    | 1927.54  | 77                                       | 37.60          | 1392.27                                   | 1435.82  |
| 28                                       | 15.64          | 552.71                                    | 1922.11  | 78                                       | 37.95          | 1406.56                                   | 1421.83  |
| 29                                       | 16.17          | 571.90                                    | 1916.49  | 79                                       | 38.31          | 1420.71                                   | 1407.69  |
| 30                                       | 16.70          | 591.04                                    | 1910.67  | 80                                       | 38.66          | 1434.71                                   | 1393.41  |
| 31                                       | 17.22          | 610.12                                    | 1904.67  | 81                                       | 39.01          | 1448.57                                   | 1379.00  |
| 32                                       | 17.74          | 629.13                                    | 1898.47  | 82                                       | 39.35          | 1462.29                                   | 1364.44  |
| 33                                       | 18.26          | 648.09                                    | 1892.08  | 83                                       | 39.69          | 1475.86                                   | 1349.75  |
| 34                                       | 18.78          | 666.97                                    | 1885.51  | 84                                       | 40.03          | 1489.29                                   | 1334.93  |
| 35                                       | 19.29          | 685.80                                    | 1878.75  | 85                                       | 40.36          | 1502.56                                   | 1319.97  |
| 36                                       | 19.80          | 704.55                                    | 1871.79  | 86                                       | 40.70          | 1515.69                                   | 1304.87  |
| 37                                       | 20.30          | 723.23                                    | 1864.65  | 87                                       | 41.02          | 1528.66                                   | 1289.65  |
| 38                                       | 20.81          | 741.84                                    | 1857.33  | 88                                       | 41.35          | 1541.48                                   | 1274.30  |
| 39                                       | 21.31          | 760.38                                    | 1849.82  | 89                                       | 41.67          | 1554.14                                   | 1258.82  |
| 40                                       | 21.80          | 778.84                                    | 1842.12  | 90                                       | 41.99          | 1566.65                                   | 1243.22  |
| 41                                       | 22.29          | 797.22                                    | 1834.24  | 91                                       | 42.30          | 1579.01                                   | 1227.49  |
| 42                                       | 22.78          | 815.52                                    | 1826.18  | 92                                       | 42.61          | 1591.20                                   | 1211.64  |
| 43                                       | 23.27          | 833.74                                    | 1817.93  | 93                                       | 42.92          | 1603.24                                   | 1195.67  |
| 44                                       | 23.75          | 851.88                                    | 1809.50  | 94                                       | 43.23          | 1615.12                                   | 1179.58  |
| 45                                       | 24.23          | 869.93                                    | 1800.89  | 95                                       | 43.53          | 1626.83                                   | 1163.37  |
| 46                                       | 24.70          | 887.90                                    | 1792.10  | 96                                       | 43.83          | 1638.38                                   | 1147.04  |
| 47                                       | 25.17          | 905.77                                    | 1783.14  | 97                                       | 44.13          | 1649.77                                   | 1130.60  |
| 48                                       | 25.64          | 923.56                                    | 1773.99  | 98                                       | 44.42          | 1660.99                                   | 1114.05  |
| 49                                       | 26.10          | 941.25                                    | 1764.67  | 99                                       | 44.71          | 1672.05                                   | 1097.38  |
| 50                                       | 26.57          | 958.85                                    | 1755.17  | 100                                      | 45.00          | 1682.94                                   | 1080.60  |

Tensions and pressures in pounds.

**Inclined Plane—Wedge**

|  |  |
|--|--|
| <p><math>W =</math> weight of body</p>  <p>Neglecting friction:</p> $P = W \times \frac{h}{l} = W \times \sin \alpha$ $W = P \times \frac{l}{h} = \frac{P}{\sin \alpha} = P \times \operatorname{cosec} \alpha$ $Q = W \times \frac{b}{l} = W \times \cos \alpha$   | <p>If friction is taken into account, then<br/>Force <math>P</math> to pull body up is:</p> $P = W(\mu \cos \alpha + \sin \alpha)$ <p>Force <math>P_1</math> to pull body down is:</p> $P_1 = W(\mu \cos \alpha - \sin \alpha)$ <p>Force <math>P_2</math> to hold body stationary:</p> $P_2 = W(\sin \alpha - \mu \cos \alpha)$ <p>in which <math>\mu</math> is the coefficient of friction.</p>                         |
| <p><math>W =</math> weight of body</p>  <p>Neglecting friction:</p> $P = W \times \frac{\sin \alpha}{\cos \beta}$ $W = P \times \frac{\cos \beta}{\sin \alpha}$ $Q = W \times \frac{\cos(\alpha + \beta)}{\cos \beta}$ <p>With friction:<br/>Coefficient of friction <math>= \mu = \tan \phi</math></p> $P = W \times \frac{\sin(\alpha + \phi)}{\cos(\beta - \phi)}$ | <p><math>W =</math> weight of body</p>  <p>Neglecting friction:</p> $P = W \times \frac{h}{b} = W \times \tan \alpha$ $W = P \times \frac{b}{h} = P \times \cot \alpha$ $Q = \frac{W}{\cos \alpha} = W \times \sec \alpha$ <p>With friction:<br/>Coefficient of friction <math>= \mu = \tan \phi</math></p> $P = W \tan(\alpha + \phi)$ |
|  <p>Neglecting friction:</p> $P = 2Q \times \frac{b}{l} = 2Q \times \sin \alpha$ $Q = P \times \frac{l}{2b} = \frac{1}{2} P \times \operatorname{cosec} \alpha$ <p>With friction:<br/>Coefficient of friction <math>= \mu</math>.</p> $P = 2Q(\mu \cos \alpha + \sin \alpha)$   |  <p>Neglecting friction:</p> $P = 2Q \times \frac{b}{h} = 2Q \times \tan \alpha$ $Q = P \times \frac{h}{2b} = \frac{1}{2} P \times \cot \alpha$ <p>With friction:<br/>Coefficient of friction <math>= \mu = \tan \phi</math>.</p> $P = 2Q \tan(\alpha + \phi)$  |
|   | <p><b>Force Moving Body on Horizontal Plane.</b>—<math>F</math> tends to move <math>B</math> along line <math>CD</math>; <math>Q</math> is the component which actually moves <math>B</math>; <math>P</math> is the pressure, due to <math>F</math>, of the body on <math>CD</math>.</p> $Q = F \times \cos \alpha \quad P = \sqrt{F^2 - Q^2}$   |

**Wheels and Pulleys**

|  |  |
|--|--|
|  $F:W = r:R$ $F \times R = W \times r$ $F = \frac{W \times r}{R}$ $W = \frac{F \times R}{r}$ $R = \frac{W \times r}{F}$ $r = \frac{F \times R}{W}$   | <p>The radius of a drum on which is wound the lifting rope of a windlass is 2 inches. What force will be exerted at the periphery of a gear of 24 inches diameter, mounted on the same shaft as the drum and transmitting power to it, if one ton (2000 pounds) is to be lifted? Here <math>W = 2000</math>; <math>R = 12</math>; <math>r = 2</math>.</p> $F = \frac{2000 \times 2}{12} = 333 \text{ pounds}$  |
|  <p>A, B, C and D are the pitch circles of gears.</p> $F = \frac{W \times r \times r_1 \times r_2}{R \times R_1 \times R_2}$ $W = \frac{F \times R \times R_1 \times R_2}{r \times r_1 \times r_2}$  | <p>Let the pitch diameters of gears A, B, C and D be 30, 28, 12 and 10 inches, respectively. Then <math>R_2 = 15</math>; <math>R_1 = 14</math>; <math>r_1 = 6</math>; and <math>r = 5</math>. Let <math>R = 12</math>, and <math>r_2 = 4</math>. Then the force <math>F</math> required to lift a weight <math>W</math> of 2000 pounds, friction being neglected, is:</p> $F = \frac{2000 \times 5 \times 6 \times 4}{12 \times 14 \times 15} = 95 \text{ pounds}$ |
|  $F = \frac{1}{2} W$ <p>The velocity with which weight <math>W</math> will be raised equals one-half the velocity of the force applied at <math>F</math>.</p>   |  $F:W = \sec \alpha:2$ $F = \frac{W \times \sec \alpha}{2}$ $W = 2F \times \cos \alpha$  |
|  <p><math>n</math> = number of strands or parts of rope (<math>n_1, n_2</math>, etc.).</p> $F = \frac{1}{n} \times W$ <p>The velocity with which <math>W</math> will be raised equals <math>\frac{1}{n}</math> of the velocity of the force applied at <math>F</math>.</p> | <p>In the illustration is shown a combination of a double and triple block. The pulleys each turn freely on a pin as axis, and are drawn with different diameters, to show the parts of the rope more clearly. There are 5 parts of rope. Therefore, if 200 pounds is to be lifted, the force <math>F</math> required at the end of the rope is:</p> $F = \frac{1}{5} \times 200 = 40 \text{ pounds}$  |

Note: The above formulas are valid using metric SI units, with forces expressed in newtons, and lengths in meters or millimeters. (See note on page 159 concerning weight and mass.)

Differential Pulley

|  |   |
|--|---|
|  | <p>In the differential pulley a chain must be used, engaging sprockets, so as to prevent the chain from slipping over the pulley faces.</p> $P \times R = \frac{1}{2} W(R - r)$ $P = \frac{W(R - r)}{2R}$ $W = \frac{2PR}{R - r}$ |
|--|---|

|   |  |
|---|--|
| <p style="text-align: center;">Chinese Windlass</p> | <p>The Chinese windlass is of the differential motion principle, in that the resultant motion is the difference between two original motions. The hoisting rope is arranged to unwind from one part of a drum or pulley onto another part differing somewhat in diameter. The distance that the load or hook moves for one revolution of the compound hoisting drum is equal to half the difference between the circumferences of the two drum sections.</p> |
|---|--|

Screw

|  |  |
|--|--|
|  | <p><math>F</math> = force at end of handle or wrench; <math>R</math> = lever-arm of <math>F</math>; <math>r</math> = pitch radius of screw; <math>p</math> = lead of thread; <math>Q</math> = load. Then, neglecting friction:</p> $F = Q \times \frac{p}{6.2832R} \quad Q = F \times \frac{6.2832R}{p}$ <p>If <math>\mu</math> is the coefficient of friction, then:<br/>         For motion in direction of load <math>Q</math> which <i>assists</i> it:</p> $F = Q \times \frac{6.2832\mu r - p}{6.2832r + \mu p} \times \frac{r}{R}$ <p>For motion opposite load <math>Q</math> which <i>resists</i> it:</p> $F = Q \times \frac{p + 6.2832\mu r}{6.2832r - \mu p} \times \frac{r}{R}$ |
|--|--|

Geneva Wheel

|  |  |
|--|--|
|  | <p>Geneva wheels are frequently used on machine tools for indexing or rotating some part of the machine through a fractional part of a revolution.</p> <p>The driven wheel shown in the illustration has four radial slots located 90 degrees apart, and the driver carries a roller <math>k</math> which engages one of these slots each time it makes a revolution, thus turning the driven wheel one-quarter revolution. The concentric surface <math>b</math> engages the concave surface <math>c</math> between each pair of slots before the driving roller is disengaged from the driven wheel, which prevents the latter from rotating while the roller is moving around to engage the next successive slot. The circular boss <math>b</math> on the driver is cut away at <math>d</math> to provide a clearance space for the projecting arms of the driven wheel. In designing gearing of the general type illustrated, it is advisable to so proportion the driving and driven members that the angle <math>a</math> will be approximately 90 degrees.</p> <p>The radial slots in the driven part will then be tangent to the circular path of the driving roller at the time the roller enters and leaves the slot. When the gearing is designed in this way, the driven wheel is started gradually from a state of rest and the motion is also gradually checked.</p> |
|--|--|



**Toggle Joint**

A link mechanism commonly known as a toggle joint is applied to machines of different types, such as drawing and embossing presses, stone crushers, etc., for securing great pressure. The principle of the toggle joint is shown by Fig. 10. There are two links, *b* and *c*, which are connected at the center. Link *b* is free to swivel about a fixed pin or bearing at *d*, and link *e* is connected to a sliding member *e*. Rod *f* joins links *b* and *c* at the central connection. When force is applied to rod *f* in a direction at right angles to center-line *xx*, along which the driven member *e* moves, this force is greatly multiplied at *e*, because a movement at the joint *g* produces a relatively slight movement at *e*. As the angle  $\alpha$  becomes less, motion at *e* decreases and the force increases until the links are in line. If *R* = the resistance at *e*, *P* = the applied power or force, and  $\alpha$  = the angle between each link, and a line *x-x* passing through the axes of the pins, then:

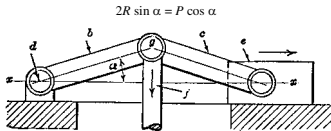
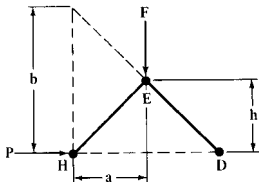
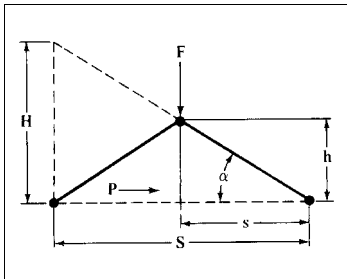


Fig. 10. Toggle Joint Principle

If arms *ED* and *EH* are of unequal length then  
 $P = (F \times a) \div b$   
 The relation between *P* and *F* changes constantly as *F* moves downward.  
 If arms *ED* and *EH* are equal, then  
 $P = (F \times a) \div 2h$   
 A double toggle-joint does not increase the pressure exerted so long as the relative distances moved by *F* and *P* remain the same.



**Toggle-joints with Equal Arms**



$2P \sin \alpha = F \cos \alpha$   
 $\frac{P}{F} = \frac{\cos \alpha}{2 \sin \alpha} = \text{coefficient}$   
 $P = F \times \text{coefficient}$   
 where *F* = force applied; *P* = resistance; and,  $\alpha$  = given angle.

Equivalent expressions (see diagram):  
 $P = \frac{FS}{4h} \quad P = \frac{Fs}{H}$

To use the table, measure angle  $\alpha$ , and find the coefficient in the table corresponding to the angle found. The coefficient is the ratio of the resistance to the force applied, and multiplying the force applied by the coefficient gives the resistance, neglecting friction.

| Angle ° | Coefficient | Angle ° | Coefficient | Angle ° | Coefficient | Angle ° | Coefficient |
|---------|-------------|---------|-------------|---------|-------------|---------|-------------|
| 0.01    | 2864.79     | 1.00    | 28.64       | 5.25    | 5.44        | 23      | 1.18        |
| 0.02    | 1432.39     | 1.10    | 26.04       | 5.50    | 5.19        | 24      | 1.12        |
| 0.03    | 954.93      | 1.20    | 23.87       | 5.75    | 4.97        | 25      | 1.07        |
| 0.04    | 716.20      | 1.30    | 22.03       | 6.00    | 4.76        | 26      | 1.03        |
| 0.05    | 572.96      | 1.40    | 20.46       | 6.50    | 4.39        | 27      | 0.98        |
| 0.10    | 286.48      | 1.50    | 19.09       | 7.00    | 4.07        | 28      | 0.94        |
| 0.15    | 190.99      | 1.60    | 17.90       | 7.50    | 3.80        | 29      | 0.90        |
| 0.20    | 143.24      | 1.70    | 16.85       | 8.00    | 3.56        | 30      | 0.87        |
| 0.25    | 114.59      | 1.80    | 15.91       | 8.50    | 3.35        | 31      | 0.83        |
| 0.30    | 95.49       | 1.90    | 15.07       | 9.00    | 3.16        | 32      | 0.80        |
| 0.35    | 81.85       | 2.00    | 14.32       | 10.00   | 2.84        | 33      | 0.77        |
| 0.40    | 71.62       | 2.25    | 12.73       | 11.00   | 2.57        | 34      | 0.74        |
| 0.45    | 63.66       | 2.50    | 11.45       | 12.00   | 2.35        | 35      | 0.71        |
| 0.50    | 57.29       | 2.75    | 10.41       | 13.00   | 2.17        | 36      | 0.69        |
| 0.55    | 52.09       | 3.00    | 9.54        | 14.00   | 2.01        | 37      | 0.66        |
| 0.60    | 47.74       | 3.25    | 8.81        | 15.00   | 1.87        | 38      | 0.64        |
| 0.65    | 44.07       | 3.50    | 8.17        | 16.00   | 1.74        | 39      | 0.62        |
| 0.70    | 40.92       | 3.75    | 7.63        | 17.00   | 1.64        | 40      | 0.60        |
| 0.75    | 38.20       | 4.00    | 7.15        | 18.00   | 1.54        | 41      | 0.58        |
| 0.80    | 35.81       | 4.25    | 6.73        | 19.00   | 1.45        | 42      | 0.56        |
| 0.85    | 33.70       | 4.50    | 6.35        | 20.00   | 1.37        | 43      | 0.54        |
| 0.90    | 31.83       | 4.75    | 6.02        | 21.00   | 1.30        | 44      | 0.52        |
| 0.95    | 30.15       | 5.00    | 5.72        | 22.00   | 1.24        | 45      | 0.50        |

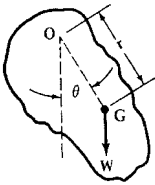
### Pendulums

A *compound* or *physical* pendulum consists of any rigid body suspended from a fixed horizontal axis about which the body may oscillate in a vertical plane due to the action of gravity.

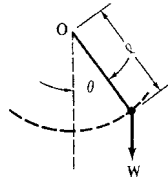
A *simple* or *mathematical* pendulum is similar to a compound pendulum except that the mass of the body is concentrated at a single point which is suspended from a fixed horizontal axis by a weightless cord. Actually, a simple pendulum cannot be constructed since it is impossible to have either a weightless cord or a body whose mass is entirely concentrated at one point. A good approximation, however, consists of a small, heavy bob suspended by a light, fine wire. If these conditions are not met by the pendulum, it should be considered as a compound pendulum.

A *conical* pendulum is similar to a simple pendulum except that the weight suspended by the cord moves at a uniform speed around the circumference of a circle in a horizontal plane instead of oscillating back and forth in a vertical plane. The principle of the conical pendulum is employed in the Watt fly-ball governor.

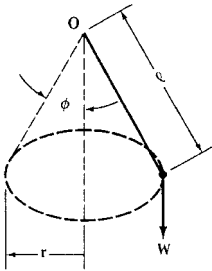
#### Four Types of Pendulum



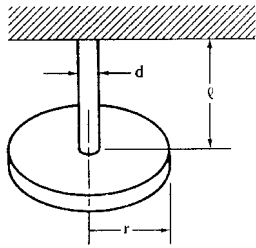
Physical Pendulum



Simple Pendulum



Conical Pendulum



Torsional Pendulum

$W$  = Weight of Disk

A *torsional* pendulum in its simplest form consists of a disk fixed to a slender rod, the other end of which is fastened to a fixed frame. When the disk is twisted through some angle and released, it will then oscillate back and forth about the axis of the rod because of the torque exerted by the rod.

**Pendulum Formulas.**—From the formulas that follow, the period of vibration or time required for one complete cycle back and forth may be determined for the types of pendulums shown in the accompanying diagram.

For a *simple* pendulum,

$$T = 2\pi \sqrt{\frac{l}{g}} \quad (1)$$

where  $T$  = period in seconds for one complete cycle;  $g$  = acceleration due to gravity = 32.17 feet per second per second (approximately); and  $l$  is the length of the pendulum in feet as shown on the accompanying diagram.

For a *physical* or *compound* pendulum,

$$T = 2\pi \sqrt{\frac{k_o^2}{gr}} \quad (2)$$

where  $k_o$  = radius of gyration of the pendulum about the axis of rotation, in feet, and  $r$  is the distance from the axis of rotation to the center of gravity, in feet.

**The metric SI units that can be used in the two above formulas are  $T$  = seconds;  $g$  = approximately 9.81 meters per second squared, which is the value for acceleration due to gravity;  $l$  = the length of the pendulum in meters;  $k_o$  = the radius of gyration in meters, and  $r$  = the distance from the axis of rotation to the center of gravity, in meters.**

**Formulas (1) and (2)** are accurate when the angle of oscillation  $\theta$  shown in the diagram is very small. For  $\theta$  equal to 22 degrees, these formulas give results that are too small by 1 per cent; for  $\theta$  equal to 32 degrees, by 2 per cent.

For a *conical* pendulum, the time in seconds for one revolution is:

$$T = 2\pi \sqrt{\frac{l \cos \phi}{g}} \quad (3a) \quad \text{or} \quad T = 2\pi \sqrt{\frac{r \cot \phi}{g}} \quad (3b)$$

For a *torsional* pendulum consisting of a thin rod and a disk as shown in the figure

$$T = \frac{2}{3} \sqrt{\frac{\pi W r^2 l}{g d^4 G}} \quad (4)$$

where  $W$  = weight of disk in pounds;  $r$  = radius of disk in feet;  $l$  = length of rod in feet;  $d$  = diameter of rod in feet; and  $G$  = modulus of elasticity in shear of the rod material in pounds per square inch.

**The formula using metric SI units is:**

$$T = 8 \sqrt{\frac{\pi M r^2 l}{d^4 G}}$$

where  $T$  = time in seconds for one complete oscillation;  $M$  = mass in kilograms;  $r$  = radius in meters;  $l$  = length of rod in meters;  $d$  = diameter of rod in meters;  $G$  = modulus of elasticity in shear of the rod material in pascals (newtons per meter squared). **The same formula can be applied using millimeters, providing dimensions are expressed in millimeters throughout, and the modulus of elasticity in megapascals (newtons per millimeter squared).**

**Harmonic.**—A harmonic is any component of a periodic quantity which is an integral multiple of the fundamental frequency. For example, a component the frequency of which is twice the fundamental frequency is called the second harmonic.

A harmonic, in electricity, is an alternating-current electromotive force wave of higher frequency than the fundamental, and superimposed on the same so as to distort it from a true sine-wave shape. It is caused by the slots, the shape of the pole pieces, and the pulsation of the armature reaction. The third and the fifth harmonics, i.e., with a frequency three and five times the fundamental, are generally the predominating ones in three-phase machines.

## VELOCITY, ACCELERATION, WORK, AND ENERGY

### Velocity and Acceleration

Motion is a progressive change of position of a body. Velocity is the rate of motion, that is, the rate of change of position. When the velocity of a body is the same at every moment during which the motion takes place, the latter is called *uniform* motion. When the velocity is variable and constantly increasing, the rate at which it changes is called *acceleration*; that is, acceleration is the rate at which the velocity of a body changes in a unit of time, as the change in feet per second, in one second. When the motion is decreasing instead of increasing, it is called *retarded* motion, and the rate at which the motion is retarded is frequently called the *deceleration*. If the acceleration is uniform, the motion is called *uniformly accelerated* motion. An example of such motion is found in that of falling bodies.

**Newton's Laws of Motion.**—The first clear statement of the fundamental relations existing between force and motion was made in the seventeenth century by Sir Isaac Newton, the English mathematician and physicist. It was put in the form of three laws, which are given as originally stated by Newton:

- 1) Every body continues in its state of rest, or uniform motion in a straight line, except in so far as it may be compelled by force to change that state.
- 2) Change of motion is proportional to the force applied and takes place in the direction in which that force acts.
- 3) To every action there is always an equal reaction; or, the mutual actions of two bodies are always equal and oppositely directed.

**Motion with Constant Velocity.**—In the formulas that follow,  $S$  = distance moved;  $V$  = velocity;  $t$  = time of motion,  $\theta$  = angle of rotation, and  $\omega$  = angular velocity; the usual units for these quantities are, respectively, feet, feet per second, seconds, radians, and radians per second. Any other consistent set of units may be employed.

*Constant Linear Velocity:*

$$S = V \times t \quad V = S \div t \quad t = S \div V$$

*Constant Angular Velocity:*

$$\theta = \omega t \quad \omega = \theta \div t \quad t = \theta \div \omega$$

*Relation between Angular Motion and Linear Motion:* The relation between the angular velocity of a rotating body and the linear velocity of a point at a distance  $r$  feet from the center of rotation is:

$$V(\text{ft per sec}) = r(\text{ft}) \times \omega(\text{radians per sec})$$

Similarly, the distance moved by the point during rotation through angle  $\theta$  is:

$$S(\text{ft}) = r(\text{ft}) \times \theta(\text{radians})$$

**Linear Motion with Constant Acceleration.**—The relations between distance, velocity, and time for linear motion with constant or uniform acceleration are given by the formulas in the accompanying Table 1. In these formulas, the acceleration is assumed to be in the same direction as the initial velocity; hence, if the acceleration in a particular problem should happen to be in a direction opposite that of the initial velocity, then  $a$  should be replaced by  $-a$ . Thus, for example, the formula  $V_f = V_o + at$  becomes  $V_f = V_o - at$  when  $a$  and  $V_o$  are opposite in direction.

*Example:* A car is moving at 60 mph when the brakes are suddenly locked and the car begins to skid. If it takes 2 seconds to slow the car to 30 mph, at what rate is it being decelerated, how long is it before the car comes to a halt, and how far will it have traveled?

The initial velocity  $V_o$  of the car is 60 mph or 88 ft/sec and the acceleration  $a$  due to braking is opposite in direction to  $V_o$ , since the car is slowed to 30 mph or 44 ft/sec.

**Table 1. Linear Motion with Constant Acceleration**

| To Find   | Known                                  | Formula                            | To Find  | Known                                  | Formula                       |
|---|--|------------------------------------|--|--|-------------------------------|
| Motion Uniformly Accelerated From Rest                                  |  |                                    |  |  |                               |
| <i>S</i>  | <i>a, t</i>                            | $S = \frac{1}{2}at^2$              | <i>t</i>   | <i>S, V<sub>f</sub></i>                | $t = 2S \div V_f$             |
|   | <i>V<sub>f</sub>, t</i>                | $S = \frac{1}{2}V_f t$             |  | <i>S, a</i>                            | $t = \sqrt{2S \div a}$        |
|   | <i>V<sub>f</sub>, a</i>                | $S = V_f^2 \div 2a$                |  | <i>a, V<sub>f</sub></i>                | $t = V_f \div a$              |
| <i>V<sub>f</sub></i>  | <i>a, t</i>                            | $V_f = at$                         | <i>a</i>   | <i>S, t</i>                            | $a = 2S \div t^2$             |
|   | <i>S, t</i>                            | $V_f = 2S \div t$                  |  | <i>S, V</i>                            | $a = V_f^2 \div 2S$           |
|   | <i>a, S</i>                            | $V_f = \sqrt{2aS}$                 |  | <i>V<sub>f</sub>, t</i>                | $a = V_f \div t$              |
| Motion Uniformly Accelerated From Initial Velocity <i>V<sub>o</sub></i> |  |                                    |  |  |                               |
| <i>S</i>  | <i>a, t, V<sub>o</sub></i>             | $S = V_o t + \frac{1}{2}at^2$      | <i>t</i>   | <i>V<sub>o</sub>, V<sub>f</sub>, a</i> | $t = (V_f - V_o) \div a$      |
|   | <i>V<sub>o</sub>, V<sub>f</sub>, t</i> | $S = (V_f + V_o)t \div 2$          |  | <i>V<sub>o</sub>, V<sub>f</sub>, S</i> | $t = 2S \div (V_f + V_o)$     |
|   | <i>V<sub>o</sub>, V<sub>f</sub>, a</i> | $S = (V_f^2 - V_o^2) \div 2a$      | <i>a</i>   | <i>V<sub>o</sub>, V<sub>f</sub>, S</i> | $a = (V_f^2 - V_o^2) \div 2S$ |
|   | <i>V<sub>f</sub>, a, t</i>             | $S = V_f t - \frac{1}{2}at^2$      |  | <i>V<sub>o</sub>, V<sub>f</sub>, t</i> | $a = (V_f - V_o) \div t$      |
| <i>V<sub>f</sub></i>  | <i>V<sub>o</sub>, a, t</i>             | $V_f = V_o + at$                   |  | <i>V<sub>o</sub>, S, t</i>             | $a = 2(S - V_o t) \div t^2$   |
|   | <i>V<sub>o</sub>, S, t</i>             | $V_f = (2S \div t) - V_o$          |  | <i>V<sub>f</sub>, S, t</i>             | $a = 2(V_f t - S) \div t^2$   |
|   | <i>V<sub>o</sub>, a, S</i>             | $V_f = \sqrt{V_o^2 + 2aS}$         | <i>Meanings of Symbols</i>   |  |                               |
| <i>V<sub>o</sub></i>  | <i>S, a, t</i>                         | $V_f = (S \div t) + \frac{1}{2}at$ | <i>S</i> = distance moved in feet<br><i>V<sub>f</sub></i> = final velocity, feet per second<br><i>V<sub>o</sub></i> = initial velocity, feet per second<br><i>a</i> = acceleration, feet per second per second<br><i>t</i> = time of acceleration in seconds |  |                               |
|   | <i>V<sub>f</sub>, a, S</i>             | $V_o = \sqrt{V_f^2 - 2aS}$         |  |  |                               |
|   | <i>V<sub>f</sub>, S, t</i>             | $V_o = (2S \div t) - V_f$          |  |  |                               |
|   | <i>V<sub>f</sub>, a, t</i>             | $V_o = V_f - at$                   |  |  |                               |
|   | <i>S, a, t</i>                         | $V_o = (S \div t) - \frac{1}{2}at$ |  |  |                               |

Since  $V_o$ ,  $V_f$ , and  $t$  are known,  $a$  can be determined from the formula

$$a = (V_f - V_o) \div t = (44 - 88) \div 2 = -22 \text{ ft/sec}^2$$

The time required to stop the car can be determined from the formula

$$t = (V_f - V_o) \div a = (0 - 88) \div (-22) = 4 \text{ seconds}$$

The distance traveled by the car is obtained from the formula

$$S = V_o t + \frac{1}{2}at^2 = (88 \times 4) + \left(\frac{1}{2} \times (-22) \times 4^2\right) = (352 - 176) = 176 \text{ feet}$$

**Angular Velocity of Rotating Bodies.**—The angular velocity of a rotating body is the angle through which the body turns in a unit of time. Angular velocity is commonly expressed in terms of revolutions per minute, but in certain engineering applications it is necessary to express it as radians per second. By definition there are  $2\pi$  radians in 360 degrees, or one revolution, so that one radian =  $360 \div 2\pi = 57.3$  degrees. To convert angular velocity in revolutions per minute,  $n$ , to angular velocity in radians per second,  $\omega$ , multiply by  $\pi$  and divide by 30:

$$\omega = \frac{\pi n}{30} \quad (1)$$

The following Table 2 may be used to obtain angular velocity in radians per second for all numbers of revolutions per minute from 1 to 239.

**Table 2. Angular Velocity in Revolutions per Minute  
Converted to Radians per Second**

| R.P.M. | Angular Velocity in Radians per Second |       |       |       |       |       |       |       |       |       |
|--------|--|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|        | 0                                      | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     |
| 0      | 0.00                                   | 0.10  | 0.21  | 0.31  | 0.42  | 0.52  | 0.63  | 0.73  | 0.84  | 0.94  |
| 10     | 1.05                                   | 1.15  | 1.26  | 1.36  | 1.47  | 1.57  | 1.67  | 1.78  | 1.88  | 1.99  |
| 20     | 2.09                                   | 2.20  | 2.30  | 2.41  | 2.51  | 2.62  | 2.72  | 2.83  | 2.93  | 3.04  |
| 30     | 3.14                                   | 3.25  | 3.35  | 3.46  | 3.56  | 3.66  | 3.77  | 3.87  | 3.98  | 4.08  |
| 40     | 4.19                                   | 4.29  | 4.40  | 4.50  | 4.61  | 4.71  | 4.82  | 4.92  | 5.03  | 5.13  |
| 50     | 5.24                                   | 5.34  | 5.44  | 5.55  | 5.65  | 5.76  | 5.86  | 5.97  | 6.07  | 6.18  |
| 60     | 6.28                                   | 6.39  | 6.49  | 6.60  | 6.70  | 6.81  | 6.91  | 7.02  | 7.12  | 7.23  |
| 70     | 7.33                                   | 7.43  | 7.54  | 7.64  | 7.75  | 7.85  | 7.96  | 8.06  | 8.17  | 8.27  |
| 80     | 8.38                                   | 8.48  | 8.59  | 8.69  | 8.80  | 8.90  | 9.01  | 9.11  | 9.21  | 9.32  |
| 90     | 9.42                                   | 9.53  | 9.63  | 9.74  | 9.84  | 9.95  | 10.05 | 10.16 | 10.26 | 10.37 |
| 100    | 10.47                                  | 10.58 | 10.68 | 10.79 | 10.89 | 11.00 | 11.10 | 11.20 | 11.31 | 11.41 |
| 110    | 11.52                                  | 11.62 | 11.73 | 11.83 | 11.94 | 12.04 | 12.15 | 12.25 | 12.36 | 12.46 |
| 120    | 12.57                                  | 12.67 | 12.78 | 12.88 | 12.98 | 13.09 | 13.19 | 13.30 | 13.40 | 13.51 |
| 130    | 13.61                                  | 13.72 | 13.82 | 13.93 | 14.03 | 14.14 | 14.24 | 14.35 | 14.45 | 14.56 |
| 140    | 14.66                                  | 14.76 | 14.87 | 14.97 | 15.08 | 15.18 | 15.29 | 15.39 | 15.50 | 15.60 |
| 150    | 15.71                                  | 15.81 | 15.92 | 16.02 | 16.13 | 16.23 | 16.34 | 16.44 | 16.55 | 16.65 |
| 160    | 16.75                                  | 16.86 | 16.96 | 17.07 | 17.17 | 17.28 | 17.38 | 17.49 | 17.59 | 17.70 |
| 170    | 17.80                                  | 17.91 | 18.01 | 18.12 | 18.22 | 18.33 | 18.43 | 18.53 | 18.64 | 18.74 |
| 180    | 18.85                                  | 18.95 | 19.06 | 19.16 | 19.27 | 19.37 | 19.48 | 19.58 | 19.69 | 19.79 |
| 190    | 19.90                                  | 20.00 | 20.11 | 20.21 | 20.32 | 20.42 | 20.52 | 20.63 | 20.73 | 20.84 |
| 200    | 20.94                                  | 21.05 | 21.15 | 21.26 | 21.36 | 21.47 | 21.57 | 21.68 | 21.78 | 21.89 |
| 210    | 21.99                                  | 22.10 | 22.20 | 22.30 | 22.41 | 22.51 | 22.62 | 22.72 | 22.83 | 22.93 |
| 220    | 23.04                                  | 23.14 | 23.25 | 23.35 | 23.46 | 23.56 | 23.67 | 23.77 | 23.88 | 23.98 |
| 230    | 24.09                                  | 24.19 | 24.29 | 24.40 | 24.50 | 24.61 | 24.71 | 24.82 | 24.92 | 25.03 |

*Example:* To find the angular velocity in radians per second of a flywheel making 97 revolutions per minute, locate 90 in the left-hand column and 7 at the top of the columns; at the intersection of the two lines, the angular velocity is read off as equal to 10.16 radians per second.

**Linear Velocity of Points on a Rotating Body.**—The linear velocity,  $v$ , of any point on a rotating body expressed in feet per second may be found by multiplying the angular velocity of the body in radians per second,  $\omega$ , by the radius,  $r$ , in feet from the center of rotation to the point:

$$v = \omega r \quad (2)$$

**The metric SI units are  $v$  = meters per second;  $\omega$  = radians per second,  $r$  = meters.**

**Rotary Motion with Constant Acceleration.**—The relations among angle of rotation, angular velocity, and time for rotation with constant or uniform acceleration are given in the accompanying Table 3.

In these formulas, the acceleration is assumed to be in the same direction as the initial angular velocity; hence, if the acceleration in a particular problem should happen to be in a direction opposite that of the initial angular velocity, then  $\alpha$  should be replaced by  $-\alpha$ . Thus, for example, the formula  $\omega_f = \omega_o + \alpha t$  becomes  $\omega_f = \omega_o - \alpha t$  when  $\alpha$  and  $\omega_o$  are opposite in direction.

*Linear Acceleration of a Point on a Rotating Body:* A point on a body rotating about a fixed axis has a linear acceleration  $a$  that is the resultant of two component accelerations. The first component is the centripetal or normal acceleration which is directed from the point  $P$  toward the axis of rotation; its magnitude is  $\omega^2 r$  where  $r$  is the radius from the axis to the point  $P$  and  $\omega$  is the angular velocity of the body at the time acceleration  $a$  is to be

**Table 3. Rotary Motion with Constant Acceleration**

| To Find   | Known                                    | Formula  | To Find  | Known                        | Formula   |
|---|--|--|--|------------------------------|---|
| Motion Uniformly Accelerated From Rest ( $\omega_o = 0$ )     |  |  |  |                              |   |
| $\theta$  | $\alpha, t$                              | $\theta = \frac{1}{2}\alpha t^2$                   | $t$  | $\theta, \omega_f$           | $t = 2\theta \div \omega_f$                       |
|   | $\omega_f, t$                            | $\theta = \frac{1}{2}\omega_f t$                   |  | $\theta, \alpha$             | $t = \sqrt{2\theta \div \alpha}$                  |
|   | $\omega_f, \alpha$                       | $\theta = \omega_f^2 \div 2\alpha$                 |  | $\alpha, \omega_f$           | $t = \omega_f \div \alpha$                        |
| $\omega_f$  | $\alpha, t$                              | $\omega_f = \alpha t$                              | $\alpha$   | $\theta, t$                  | $\alpha = 2\theta \div t^2$                       |
|   | $\theta, t$                              | $\omega_f = 2\theta \div t$                        |  | $\theta, \omega_f$           | $\alpha = \omega_f^2 \div 2\theta$                |
|   | $\alpha, \theta$                         | $\omega_f = \sqrt{2\alpha\theta}$                  |  | $\omega_f, t$                | $\alpha = \omega_f \div t$                        |
| Motion Uniformly Accelerated From Initial Velocity $\omega_o$ |  |  |  |                              |   |
| $\theta$  | $\alpha, t, \omega_o$                    | $\theta = \omega_o t + \frac{1}{2}\alpha t^2$      | $\alpha$   | $\omega_o, \omega_f, \theta$ | $\alpha = (\omega_f^2 - \omega_o^2) \div 2\theta$ |
|   | $\omega_o, \omega_f, t$                  | $\theta = (\omega_f + \omega_o)t \div 2$           |  | $\omega_o, \omega_f, t$      | $\alpha = (\omega_f - \omega_o) \div t$           |
|   | $\omega_o, \omega_f, \alpha$             | $\theta = (\omega_f^2 - \omega_o^2) \div 2\alpha$  |  | $\omega_o, \theta, t$        | $\alpha = 2(\theta - \omega_o t) \div t^2$        |
|   | $\omega_f, \alpha, t$                    | $\theta = \omega_f t - \frac{1}{2}\alpha t^2$      |  | $\omega_f, \theta, t$        | $\alpha = 2(\omega_f t - \theta) \div t^2$        |
| $\omega_f$  | $\omega_o, \alpha, t$                    | $\omega_f = \omega_o + \alpha t$                   | <i>Meanings of Symbols</i><br><br>$\theta$ = angle of rotation, radians<br>$\omega_f$ = final angular velocity, radians per second<br>$\omega_o$ = initial angular velocity, radians per second<br>$\alpha$ = angular acceleration, radians per second, per second<br>$t$ = time in seconds<br><br>1 degree = 0.01745 radians<br>(See conversion table on page 96) |                              |   |
|   | $\omega_o, \theta, t$                    | $\omega_f = (2\theta \div t) - \omega_o$           |  |                              |   |
|   | $\omega_o, \alpha, \theta$               | $\omega_f = \sqrt{\omega_o^2 + 2\alpha\theta}$     |  |                              |   |
| $\omega_o$  | $\theta, \alpha, t$                      | $\omega_f = (\theta \div t) + \frac{1}{2}\alpha t$ |  |                              |   |
|   | $\omega_f, \alpha, \theta$               | $\omega_o = \sqrt{\omega_f^2 - 2\alpha\theta}$     |  |                              |   |
|   | $\omega_f, \theta, t$                    | $\omega_o = (2\theta \div t) - \omega_f$           |  |                              |   |
|   | $\omega_f, \alpha, t$                    | $\omega_o = \omega_f - \alpha t$                   |  |                              |   |
| $t$   | $\theta, \alpha, t$                      | $\omega_o = (\theta \div t) - \frac{1}{2}\alpha t$ |  |                              |   |
|   | $\omega_o, \omega_f, \alpha$             | $t = (\omega_f - \omega_o) \div \alpha$            |  |                              |   |
| $\omega_o, \omega_f, \theta$                                  | $t = 2\theta \div (\omega_f + \omega_o)$ |  |  |                              |   |

determined. The second component of  $a$  is the tangential acceleration which is equal to  $r\alpha$  where  $\alpha$  is the angular acceleration of the body.

The acceleration of point  $P$  is the resultant of  $r\omega^2$  and  $r\alpha$  and is given by the formula

$$a = \sqrt{(r\omega^2)^2 + (r\alpha)^2}$$

When  $\alpha = 0$ , this formula reduces to:  $a = r\omega^2$

*Example:* A flywheel on a press rotating at 120 rpm is slowed to 102 rpm during a punching operation that requires  $\frac{3}{4}$  second for the punching portion of the cycle. What angular deceleration does the flywheel experience?

From the table on page 169, the angular velocities corresponding to 120 rpm and 102 rpm, respectively, are 12.57 and 10.68 radians per second. Therefore, using the formula

$$\alpha = (\omega_f - \omega_o) \div t$$

$$\alpha = (10.68 - 12.57) \div \frac{3}{4} = -1.89 \div \frac{3}{4}$$

$$\alpha = -2.52 \text{ radians per second per second}$$

which is, from the table on page 169, -24 rpm per second. The minus sign in the answer indicates that the acceleration  $\alpha$  acts to slow the flywheel, that is, the flywheel is being decelerated.

### Force, Work, Energy, and Momentum

**Accelerations Resulting from Unbalanced Forces.**—In the section describing the resolution and composition of forces it was stated that when the resultant of a system of forces is zero, the system is in equilibrium, that is, the body on which the force system acts remains at rest or continues to move with uniform velocity. If, however, the resultant of a system of forces is not zero, the body on which the forces act will be accelerated in the direction of the unbalanced force. To determine the relation between the unbalanced force and the resulting acceleration, Newton's laws of motion must be applied. These laws may be stated as follows:

*First Law:* Every body continues in a state of rest or in uniform motion in a straight line, until it is compelled by a force to change its state of rest or motion.

*Second Law:* Change of motion is proportional to the force applied, and takes place along the straight line in which the force acts. The "force applied" represents the resultant of *all* the forces acting on the body. This law is sometimes worded: An unbalanced force acting on a body causes an acceleration of the body in the direction of the force and of magnitude proportional to the force and inversely proportional to the mass of the body. Stated as a formula,  $R = Ma$  where  $R$  is the resultant of *all* the forces acting on the body,  $M$  is the mass of the body (mass = weight  $W$  divided by acceleration due to gravity  $g$ ), and  $a$  is the acceleration of the body resulting from application of force  $R$ .

*Third Law:* To every action there is always an equal reaction, or, in other words, if a force acts to change the state of motion of a body, the body offers a resistance equal and directly opposite to the force.

Newton's second law may be used to calculate linear and angular accelerations of a body produced by unbalanced forces and torques acting on the body; however, it is necessary first to use the methods described under *Algebraic Composition and Resolution of Force Systems* starting on page 148 to determine the magnitude and direction of the resultant of *all* forces acting on the body. Then, for a body moving with pure translation,

$$R = Ma = \frac{W}{g}a$$

where  $R$  is the resultant force in pounds acting on a body weighing  $W$  pounds;  $g$  is the gravitational constant, usually taken as 32.16 ft/sec<sup>2</sup>, approximately; and  $a$  is the resulting acceleration in ft/sec<sup>2</sup> of the body due to  $R$  and in the same direction as  $R$ .

**Using metric SI units, the formula is  $R = Ma$ , where  $R$  = force in newtons (N),  $M$  = mass in kilograms, and  $a$  = acceleration in meters/second squared. It should be noted that the weight of a body of mass  $M$  kg is  $Mg$  newtons, where  $g$  is approximately 9.81 m/s<sup>2</sup>.**

*Free Body Diagram:* In order to correctly determine the effect of forces on the motion of a body it is necessary to resort to what is known as a *free body diagram*. This diagram shows 1) the body removed or isolated from contact with all other bodies that exert force on the body and; and 2) *all* the forces acting on the body.

Thus, for example, in Fig. 1a the block being pulled up the plane is acted upon by certain forces; the free body diagram of this block is shown at Fig. 1b. Note that all forces acting on the block are indicated. These forces include: 1) the force of gravity (weight); 2) the pull of the cable,  $P$ ; 3) the normal component,  $W \cos \phi$ , of the force exerted on the block by the plane; and 4) the friction force,  $\mu W \cos \phi$ , of the plane on the block.



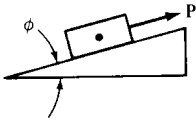


Fig. 1a.

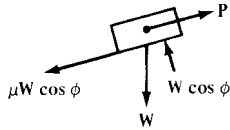


Fig. 1b.

In preparing a free body diagram, it is important to realize that only those forces exerted on the body being considered are shown; forces exerted by the body on other bodies are disregarded. This feature makes the free body diagram an invaluable aid in the solution of problems in mechanics.

*Example:* A 100-pound body is being hoisted by a winch, the tension in the hoisting cable being kept constant at 110 pounds. At what rate is the body accelerated?

Two forces are acting on the body, its weight, 100 pounds downward, and the pull of the cable, 110 pounds upward. The resultant force  $R$ , from a free body diagram, is therefore  $110 - 100$ . Thus, applying Newton's second law,

$$110 - 100 = \frac{100}{32.16}a$$

$$a = \frac{32.16 \times 10}{100} = 3.216 \text{ ft/sec}^2 \text{ upward}$$

It should be noted that since in this problem the resultant force  $R$  was positive ( $110 - 100 = +10$ ), the acceleration  $a$  is also positive, that is,  $a$  is in the same direction as  $R$ , which is in accord with Newton's second law.

*Example using SI metric units:* A body of mass 50 kilograms is being hoisted by a winch, and the tension in the cable is 600 newtons. What is the acceleration? The weight of the 50 kg body is 50g newtons, where  $g =$  approximately  $9.81 \text{ m/s}^2$  (see *Note* on page 179). Applying the formula  $R = Ma$ , the calculation is:  $(600 - 50g) = 50a$ . Thus,

$$a = \frac{600 - 50g}{50} = \frac{600 - (50 \times 9.81)}{50} = 2.19 \text{ m/s}^2$$

*Formulas Relating Torque and Angular Acceleration:* For a body rotating about a fixed axis the relation between the unbalanced torque acting to produce rotation and the resulting angular acceleration may be determined from any one of the following formulas, each based on Newton's second law:

$$T_o = J_M \alpha$$

$$T_o = M k_o^2 \alpha$$

$$T_o = \frac{W k_o^2 \alpha}{g} = \frac{W k_o^2 \alpha}{32.16}$$

where  $T_o$  is the unbalanced torque in pounds-feet;  $J_M$  in ft-lbs-sec<sup>2</sup> is the moment of inertia of the body about the axis of rotation;  $k_o$  in feet is the radius of gyration of the body with respect to the axis of rotation, and  $\alpha$  in radians per second, per second is the angular acceleration of the body.

*Example:* A flywheel has a diameter of 3 feet and weighs 1000 pounds. What torque must be applied, neglecting bearing friction, to accelerate the flywheel at the rate of 100 revolutions per minute, per second?

From page 250 the moment of inertia of a solid cylinder with respect to a gravity axis at right angles to the circular cross-section is given as  $\frac{1}{2}Mr^2$ . From page 169, 100 rpm = 10.47 radians per second, hence an acceleration of 100 rpm per second = 10.47 radians per second, per second. Therefore, using the first of the preceding formulas,

$$T_o = J_M\alpha = \left(\frac{1}{2}\right)\frac{1000}{32.16}\left(\frac{3}{2}\right)^2 \times 10.47 = 366 \text{ ft-lbs}$$

Using metric SI units, the formulas are:  $T_o = J_M\alpha = Mk_o^2\alpha$ , where  $T_o$  = torque in newton-meters;  $J_M$  = the moment of inertia in  $\text{kg} \cdot \text{m}^2$ , and  $\alpha$  = the angular acceleration in radians per second squared.

**Example:** A flywheel has a diameter of 1.5 m, and a mass of 800 kg. What torque is needed to produce an angular acceleration of 100 revolutions per minute, per second? As in the preceding example,  $\alpha = 10.47 \text{ rad/s}^2$ . Thus:

$$J_M = \frac{1}{2}Mr^2 = \frac{1}{2} \times 800 \times 0.75^2 = 225 \text{ kg} \cdot \text{m}^2$$

Therefore:  $T_o = J_M\alpha = 225 \times 10.47 = 2356 \text{ N} \cdot \text{m}$ .

**Energy.**—A body is said to possess energy when it is capable of doing work or overcoming resistance. The energy may be either mechanical or non-mechanical, the latter including chemical, electrical, thermal, and atomic energy.

Mechanical energy includes *kinetic energy* (energy possessed by a body because of its motion) and *potential energy* (energy possessed by a body because of its position in a field of force and/or its elastic deformation).

**Kinetic Energy:** The motion of a body may be one of pure translation, pure rotation, or a combination of rotation and translation. By translation is meant motion in which every line in the body remains parallel to its original position throughout the motion, that is, no rotation is associated with the motion of the body.

The kinetic energy of a translating body is given by the formula

$$\text{Kinetic Energy in ft-lbs due to translation} = E_{KT} = \frac{1}{2}MV^2 = \frac{WV^2}{2g} \quad (3a)$$

where  $M$  = mass of body ( $= W \div g$ );  $V$  = velocity of the center of gravity of the body in feet per second;  $W$  = weight of body in pounds; and  $g$  = acceleration due to gravity = 32.16 feet per second, per second.

The kinetic energy of a body rotating about a fixed axis  $O$  is expressed by the formula:

$$\text{Kinetic Energy in ft-lbs due to rotation} = E_{KR} = \frac{1}{2}J_{MO}\omega^2 \quad (3b)$$

where  $J_{MO}$  is the moment of inertia of the body about the fixed axis  $O$  in pounds-feet-seconds<sup>2</sup>, and  $\omega$  = angular velocity in radians per second.

For a body that is moving with both translation and rotation, the total kinetic energy is given by the following formula as the sum of the kinetic energy due to translation of the center of gravity and the kinetic energy due to rotation about the center of gravity:

$$\begin{aligned} \text{Total Kinetic Energy in ft-lbs} &= E_T = \frac{1}{2}MV^2 + \frac{1}{2}J_{MG}\omega^2 \\ &= \frac{WV^2}{2g} + \frac{1}{2}J_{MG}\omega^2 = \frac{WV^2}{2g} + \frac{1}{2}\frac{Wk^2\omega^2}{g} = \frac{W}{2g}(V^2 + k^2\omega^2) \end{aligned} \quad (3c)$$

where  $J_{MG}$  is the moment of inertia of the body about its gravity axis in pounds-feet-seconds<sup>2</sup>,  $k$  is the radius of gyration in feet with respect to an axis through the center of gravity, and the other quantities are as previously defined.

**In the metric SI system, energy is expressed as the joule (J). One joule = 1 newton-meter. The kinetic energy of a translating body is given by the formula  $E_{KT} = \frac{1}{2}MV^2$ ,**

where  $M$  = mass in kilograms, and  $V$  = velocity in meters per second. Kinetic energy due to rotation is expressed by the formula  $E_{KR} = \frac{1}{2}J_{MO}\omega^2$ , where  $J_{MO}$  = moment of inertia in  $\text{kg} \cdot \text{m}^2$ , and  $\omega$  = the angular velocity in radians per second. Total kinetic energy  $ET = \frac{1}{2}MV^2 + \frac{1}{2}J_{MO}\omega^2$  joules =  $\frac{1}{2}M(V^2 + k^2\omega^2)$  joules, where  $k$  = radius of gyration in meters.

*Potential Energy:* The most common example of a body having potential energy because of its position in a field of force is that of a body elevated to some height above the earth. Here the field of force is the gravitational field of the earth and the potential energy  $E_{PF}$  of a body weighing  $W$  pounds elevated to some height  $S$  in feet above the surface of the earth is  $WS$  foot-pounds. If the body is permitted to drop from this height its potential energy  $E_{PF}$  will be converted to kinetic energy. Thus, after falling through height  $S$  the kinetic energy of the body will be  $WS$  ft-lbs.

**In metric SI units, the potential energy  $E_{PF}$  of a body of mass  $M$  kilograms elevated to a height of  $S$  meters, is  $MgS$  joules. After it has fallen a distance  $S$ , the kinetic energy gained will thus be  $MgS$  joules.**

Another type of potential energy is elastic potential energy, such as possessed by a spring that has been compressed or extended. The amount of work in ft lbs done in compressing the spring  $S$  feet is equal to  $KS^2/2$ , where  $K$  is the spring constant in pounds per foot. Thus, when the spring is released to act against some resistance, it can perform  $KS^2/2$  ft-lbs of work which is the amount of elastic potential energy  $E_{PE}$  stored in the spring.

**Using metric SI units, the amount of work done in compressing the spring a distance  $S$  meters is  $KS^2/2$  joules, where  $K$  is the spring constant in newtons per meter.**

**Work Performed by Forces and Couples.**—The work  $U$  done by a force  $F$  in moving an object along some path is the product of the distance  $S$  the body is moved and the component  $F \cos \alpha$  of the force  $F$  in the direction of  $S$ .

$$U = FS \cos \alpha$$

where  $U$  = work in ft-lbs;  $S$  = distance moved in feet;  $F$  = force in lbs; and  $\alpha$  = angle between line of action of force and the path of  $S$ .

If the force is in the same direction as the motion, then  $\cos \alpha = \cos 0 = 1$  and this formula reduces to:

$$U = FS$$

Similarly, the work done by a couple  $T$  turning an object through an angle  $\theta$  is:

$$U = T\theta$$

where  $T$  = torque of couple in pounds-feet and  $\theta$  = the angular rotation in radians.

**The above formulas can be used with metric SI units:  $U$  is in joules;  $S$  is in meters;  $F$  is in newtons, and  $T$  is in newton-meters.**

**Relation between Work and Energy.**—Theoretically, when work is performed on a body and there are no energy losses (such as due to friction, air resistance, etc.), the energy acquired by the body is equal to the work performed on the body; this energy may be either potential, kinetic, or a combination of both.

In actual situations, however, there may be energy losses that must be taken into account. Thus, the relation between work done on a body, energy losses, and the energy acquired by the body can be stated as:

$$\text{Work Performed} - \text{Losses} = \text{Energy Acquired}$$

$$U - \text{Losses} = E_T$$

*Example 1:* A 12-inch cube of steel weighing 490 pounds is being moved on a horizontal conveyor belt at a speed of 6 miles per hour (8.8 feet per second). What is the kinetic energy of the cube?

Since the block is not rotating, **Formula (3a)** for the kinetic energy of a body moving with pure translation applies:

$$\text{Kinetic Energy} = \frac{WV^2}{2g} = \frac{490 \times (8.8)^2}{2 \times 32.16} = 590 \text{ ft-lbs}$$

**A similar example using metric SI units is as follows: If a cube of mass 200 kg is being moved on a conveyor belt at a speed of 3 meters per second, what is the kinetic energy of the cube? It is:**

$$\text{Kinetic Energy} = \frac{1}{2}MV^2 = \frac{1}{2} \times 200 \times 3^2 = 900 \text{ joules}$$

*Example 2:* If the conveyor in **Example 1** is brought to an abrupt stop, how long would it take for the steel block to come to a stop and how far along the belt would it slide before stopping if the coefficient of friction  $\mu$  between the block and the conveyor belt is 0.2 and the block slides without tipping over?

The only force acting to slow the motion of the block is the friction force between the block and the belt. This force  $F$  is equal to the weight of the block,  $W$ , multiplied by the coefficient of friction;  $F = \mu W = 0.2 \times 490 = 98 \text{ lbs}$ .

The time required to bring the block to a stop can be determined from the impulse-momentum **Formula (4c)** on page 176.

$$R \times t = \frac{W}{g}(V_f - V_o) = (-98)t = \frac{490}{32.16} \times (0 - 8.8)$$

$$t = \frac{490 \times 8.8}{98 \times 32.16} = 1.37 \text{ seconds}$$

The distance the block slides before stopping can be determined by equating the kinetic energy of the block and the work done by friction in stopping it:

$$\text{Kinetic energy of block} (WV^2/2g) = \text{Work done by friction} (F \times S)$$

$$590 = 98 \times S$$

$$S = \frac{590}{98} = 6.0 \text{ feet}$$

**If metric SI units are used, the calculation is as follows (for the cube of 200 kg mass): The friction force =  $\mu$  multiplied by the weight  $Mg$  where  $g =$  approximately  $9.81 \text{ m/s}^2$ . Thus,  $\mu Mg = 0.2 \times 200g = 392.4$  newtons. The time  $t$  required to bring the block to a stop is  $(-392.4)t = 200(0 - 3)$ . Therefore,**

$$t = \frac{200 \times 3}{392.4} = 1.53 \text{ seconds}$$

**The kinetic energy of the block is equal to the work done by friction, that is  $392.4 \times S = 900$  joules. Thus, the distance  $S$  which the block moves before stopping is**

$$S = \frac{900}{392.4} = 2.29 \text{ meters}$$

**Force of a Blow.**—A body that weighs  $W$  pounds and falls  $S$  feet from an initial position of rest is capable of doing  $WS$  foot-pounds of work. The work performed during its fall may be, for example, that necessary to drive a pile a distance  $d$  into the ground. Neglecting losses in the form of dissipated heat and strain energy, the work done in driving the pile is equal to the product of the impact force acting on the pile and the distance  $d$  which the pile is driven. Since the impact force is not accurately known, an average value, called the

"average force of the blow," may be assumed. Equating the work done on the pile and the work done by the falling body, which in this case is a pile driver:

$$\text{Average force of blow} \times d = WS$$

$$\text{or,} \quad \text{Average force of blow} = \frac{WS}{d}$$

where,  $S$  = total height in feet through which the driver falls, including the distance  $d$  that the pile is driven

$W$  = weight of driver in pounds

$d$  = distance in feet which pile is driven

**When using metric SI units, it should be noted that a body of mass  $M$  kilograms has a weight of  $Mg$  newtons, where  $g$  = approximately  $9.81 \text{ m/s}^2$ . If the body falls a distance  $S$  meters, it can do work equal to  $MgS$  joules. The average force of the blow is  $MgS/d$  newtons, where  $d$  is the distance in meters that the pile is driven.**

*Example:* A pile driver weighing 200 pounds strikes the top of the pile after having fallen from a height of 20 feet. It forces the pile into the ground a distance of  $\frac{1}{2}$  foot. Before the ram is brought to rest, it will  $200 \times (20 + \frac{1}{2}) = 4100$  foot-pounds of work, and as this energy is expended in a distance of one-half foot, the average force of the blow equals  $4100 \div \frac{1}{2} = 8200$  pounds.

**A similar example using metric SI units is as follows: A pile driver of mass 100 kilograms falls 10 meters and moves the pile a distance of 0.3 meters. The work done =  $100g(10 + 0.3)$  joules, and it is expended in 0.3 meters. Thus, the average force is**

$$\frac{100g \times 10.3}{0.3} = 33680 \text{ newtons or } 33.68 \text{ kN}$$

**Impulse and Momentum.**—The *linear momentum* of a body is defined as the product of the mass  $M$  of the body and the velocity  $V$  of the center of gravity of the body:

$$\text{Linear momentum} = MV \text{ or since } M = W \div g$$

$$\text{Linear momentum} = \frac{WV}{g} \quad (4a)$$

It should be noted that linear momentum is a vector quantity, the momentum being in the same direction as  $V$ .

*Linear impulse* is defined as the product of the resultant  $R$  of all the forces acting on a body and the time  $t$  that the resultant acts:

$$\text{Linear Impulse} = Rt \quad (4b)$$

The change in the linear momentum of a body is numerically equal to the linear impulse that causes the change in momentum:

$$\text{Linear Impulse} = \text{change in Linear Momentum}$$

$$Rt = \frac{W}{g}V_f - \frac{W}{g}V_o = \frac{W}{g}(V_f - V_o) \quad (4c)$$

where  $V_f$ , the final velocity of the body after time  $t$ , and  $V_o$ , the initial velocity of the body, are both in the same direction as the applied force  $R$ . If  $V_o$ , and  $V_f$  are in opposite directions, then the minus sign in the formula becomes a plus sign.

**In metric SI units, the formulas are: Linear Momentum =  $MV$  kg · m/s, where  $M$  = mass in kg, and  $V$  = velocity in meters per second; and Linear Impulse =  $Rt$  newton-seconds, where  $R$  = force in newtons, and  $t$  = time in seconds. In [Formula \(4c\)](#) above,  $W/g$  is replaced by  $M$  when SI units are used.**

*Example:* A 1000-pound block is pulled up a 2-degree incline by a cable exerting a constant force  $F$  of 600 pounds. If the coefficient of friction  $\mu$  between the block and the plane is 0.5, how fast will the block be moving up the plane 10 seconds after the pull is applied?

The resultant force  $R$  causing the body to be accelerated up the plane is the difference between  $F$ , the force acting up the plane, and  $P$ , the force acting to resist motion up the plane. This latter force for a body on a plane is given by the formula at the top of page 161 as  $P = W(\mu \cos \alpha + \sin \alpha)$  where  $\alpha$  is the angle of the incline.

$$\begin{aligned}\text{Thus, } R &= F - P = F - W(\mu \cos \alpha + \sin \alpha) \\ &= 600 - 1000(0.5 \cos 2^\circ + \sin 2^\circ) = 600 - 1000(0.5 \times 0.99939 + 0.03490) \\ R &= 600 - 535 = 65 \text{ pounds.}\end{aligned}$$

**Formula (4c)** can now be applied to determine the speed at which the body will be moving up the plane after 10 seconds.

$$\begin{aligned}Rt &= \frac{W}{g}V_f - \frac{W}{g}V_o \\ 65 \times 10 &= \frac{1000}{32.2}V_f - \frac{1000}{32.2} \times 0 \\ V_f &= \frac{65 \times 10 \times 32.2}{1000} = 20.9 \text{ ft per sec} = 14.3 \text{ miles per hour}\end{aligned}$$

**A similar example using metric SI units is as follows: A 500 kg block is pulled up a 2 degree incline by a constant force  $F$  of 4 kN. The coefficient of friction  $\mu$  between the block and the plane is 0.5. How fast will the block be moving 10 seconds after the pull is applied?**

The resultant force  $R$  is:

$$\begin{aligned}R &= F - Mg(\mu \cos \alpha + \sin \alpha) \\ &= 4000 - 500 \times 9.81(0.5 \times 0.99939 + 0.03490) = 1378\text{N or } 1.378 \text{ kN}\end{aligned}$$

**Formula (4c)** can now be applied to determine the speed at which the body will be moving up the plane after 10 seconds. Replacing  $W/g$  by  $M$  in the formula, the calculation is:

$$\begin{aligned}Rt &= MV_f - MV_o \\ 1378 \times 10 &= 500(V_f - 0) \\ V_f &= \frac{1378 \times 10}{500} = 27.6 \text{ m/s}\end{aligned}$$

*Angular Impulse and Momentum:* In a manner similar to that for linear impulse and moment, the formulas for angular impulse and momentum for a body rotating about a fixed axis are:

$$\text{Angular momentum} = J_M \omega \quad (5a)$$

$$\text{Angular impulse} = T_o t \quad (5b)$$

where  $J_M$  is the moment of inertia of the body about the axis of rotation in pounds-feet-seconds<sup>2</sup>,  $\omega$  is the angular velocity in radians per second,  $T_o$  is the torque in pounds-feet about the axis of rotation, and  $t$  is the time in seconds that  $T_o$  acts.

The change in angular momentum of a body is numerically equal to the angular impulse that causes the change in angular momentum:

$$\begin{aligned}\text{Angular Impulse} &= \text{Change in Angular Momentum} \\ T_o t &= J_M \omega_f - J_M \omega_o = J_M (\omega_f - \omega_o)\end{aligned} \quad (5c)$$

where  $\omega_f$  and  $\omega_o$  are the final and initial angular velocities, respectively.

*Example:* A flywheel having a moment of inertia of 25 lbs-ft-sec<sup>2</sup> is revolving with an angular velocity of 10 radians per second when a constant torque of 20 lbs-ft is applied to reverse its direction of rotation. For what length of time must this constant torque act to stop the flywheel and bring it up to a reverse speed of 5 radians per second?

Applying [Formula \(5c\)](#),

$$\begin{aligned} T_o t &= J_M(\omega_f - \omega_o) \\ 20t &= 25(10 - [-5]) = 250 + 125 \\ t &= 375 \div 20 = 18.8 \text{ seconds} \end{aligned}$$

A similar example using metric SI units is as follows: A flywheel with a moment of inertia of 20 kilogram-meters<sup>2</sup> is revolving with an angular velocity of 10 radians per second when a constant torque of 30 newton-meters is applied to reverse its direction of rotation. For what length of time must this constant torque act to stop the flywheel and bring it up to a reverse speed of 5 radians per second? Applying [Formula \(5c\)](#), the calculation is:

$$\begin{aligned} T_o t &= J_M(\omega_f - \omega_o), \\ 30t &= 20(10 - [-5]). \end{aligned}$$

Thus,  $t = \frac{20 \times 15}{30} = 10 \text{ seconds}$

**Formulas for Work and Power.**—The formulas in the accompanying [Table 4](#) may be used to determine work and power in terms of the applied force and the velocity at the point of application of the force.

**Table 4. Formulas<sup>a</sup> for Work and Power**

| To Find | Known    | Formula                               | To Find   | Known                        | Formula                               |
|---------|----------|---------------------------------------|---|------------------------------|---------------------------------------|
| S       | P, t, F  | $S = P \times t \div F$               | K   | F, S                         | $K = F \times S$                      |
|         | K, F     | $S = K \div F$                        |   | P, t                         | $K = P \times t$                      |
| V       | t, F, hp | $S = 550 \times t \times hp \div F$   | hp  | F, V, t                      | $K = F \times V \times t$             |
|         | P, F     | $V = P \div F$                        |   | t, hp                        | $K = 550 \times t \times hp$          |
| t       | K, F, t  | $V = K \div (F \times t)$             | F, S, t   | P                            | $hp = F \times S \div (550 \times t)$ |
|         | F, hp    | $V = 550 \times hp \div F$            |   | P                            | $hp = P \div 550$                     |
| F       | F, S, P  | $t = F \times S \div P$               | F, V  | $hp = F \times V \div 550$   |                                       |
|         | K, F, V  | $t = K \div (F \times V)$             | K, t  | $hp = K \div (550 \times t)$ |                                       |
| P       | F, S, hp | $t = F \times S \div (550 \times hp)$ | <p><i>Meanings of Symbols:</i></p> <p>S = distance in feet<br/> V = constant or average velocity in feet per second<br/> t = time in seconds<br/> F = constant or average force in pounds<br/> P = power in foot-pounds per second<br/> hp = horsepower</p> |                              |                                       |
|         | P, V     | $F = P \div V$                        |   |                              |                                       |
| K       | K, S     | $F = K \div S$                        |   |                              |                                       |
|         | K, V, t  | $F = K \div (V \times t)$             |   |                              |                                       |
| V       | V, hp    | $F = 550 \times hp \div V$            |   |                              |                                       |
|         | F, V     | $P = F \times V$                      |   |                              |                                       |
| P       | F, S, t  | $P = F \times S \div t$               |   |                              |                                       |
|         | K, t     | $P = K \div t$                        |   |                              |                                       |
|         | hp       | $P = 550 \times hp$                   |   |                              |                                       |

<sup>a</sup> *Note:* The metric SI unit of work is the joule (one joule = 1 newton-meter), and the unit of power is the watt (one watt = 1 joule per second = 1 N · m/s). The term horsepower is not used. Thus, those formulas above that involve horsepower and the factor 550 are not applicable when working in SI units. The remaining formulas can be used, and the units are:  $S$  = distance in meters;  $V$  = constant or average velocity in meters per second;  $t$  = time in seconds;  $F$  = force in newtons;  $P$  = power in watts;  $K$  = work in joules.

*Example:* A casting weighing 300 pounds is to be lifted by means of an overhead crane. The casting is lifted 10 feet in 12 seconds. What is the horsepower developed? Here  $F = 300$ ;  $S = 10$ ;  $t = 12$ .

$$\text{hp} = \frac{F \times S}{550t} = \frac{300 \times 10}{550 \times 12} = 0.45$$

A similar example using metric SI units is as follows: A casting of mass 150 kg is lifted 4 meters in 15 seconds by means of a crane. What is the power? Here  $F = 150g$  N,  $S = 4$  m, and  $t = 15$  s. Thus:

$$\text{Power} = \frac{FS}{t} = \frac{150g \times 4}{15} = \frac{150 \times 9.81 \times 4}{15} = 392 \text{ watts or } 0.392 \text{ kW}$$

### Centrifugal Force

**Centrifugal Force.**—When a body rotates about any axis other than one at its center of mass, it exerts an outward radial force called centrifugal force upon the axis or any arm or cord from the axis that restrains it from moving in a straight (tangential) line. In the following formulas:

$F$  = centrifugal force in pounds

$W$  = weight of revolving body in pounds

$v$  = velocity at radius  $R$  on body in feet per second

$n$  = number of revolutions per minute

$g$  = acceleration due to gravity = 32.16 feet per second per second

$R$  = perpendicular distance in feet from axis of rotation to center of mass, or for practical use, to center of gravity of revolving body

*Note:* If a body rotates about its own center of mass,  $R$  equals zero and  $v$  equals zero. This means that the *resultant* of the centrifugal forces of all the elements of the body is equal to zero or, in other words, no centrifugal force is exerted on the axis of rotation. The centrifugal force of any part or element of such a body is found by the equations given below, where  $R$  is the radius to the center of gravity of the part or element. In a flywheel rim,  $R$  is the mean radius of the rim because it is the radius to the center of gravity of a thin radial section.

$$F = \frac{Wv^2}{gR} = \frac{Wv^2}{32.16R} = \frac{4WR\pi^2n^2}{60 \times 60g} = \frac{WRn^2}{2933} = 0.000341 WRn^2$$

$$W = \frac{FRg}{v^2} = \frac{2933F}{Rn^2} \qquad v = \sqrt{\frac{FRg}{W}}$$

$$R = \frac{Wv^2}{Fg} = \frac{2933F}{Wn^2} \qquad n = \sqrt{\frac{2933F}{WR}}$$

(If  $n$  is the number of revolutions per second instead of per minute, then  $F = 1227WRn^2$ .)

If metric SI units are used in the foregoing formulas,  $W/g$  is replaced by  $M$ , which is the mass in kilograms;  $F$  = centrifugal force in newtons;  $v$  = velocity in meters per second;  $n$  = number of revolutions per minute; and  $R$  = the radius in meters. Thus:



$$F = Mv^2/R = \frac{Mn^2(2\pi R^2)}{60^2 R} = 0.01097 MRn^2$$

If the rate of rotation is expressed as  $n_1 =$  revolutions per second, then  $F = 39.48 MRn_1^2$ ; if it is expressed as  $\omega$  radians per second, then  $F = MR\omega^2$ .

**Calculating Centrifugal Force.**—In the ordinary formula for centrifugal force,  $F = 0.000341 WRn^2$ ; the mean radius  $R$  of the flywheel or pulley rim is given in feet. For small dimensions, it is more convenient to have the formula in the form:

$$F = 0.2842 \times 10^{-4} Wrn^2$$

in which  $F$  = centrifugal force, in pounds;  $W$  = weight of rim, in pounds;  $r$  = mean radius of rim, in inches;  $n$  = number of revolutions per minute.

In this formula let  $C = 0.000028416n^2$ . This, then, is the centrifugal force of one pound, one inch from the axis. The formula can now be written in the form,

$$F = WrC$$

$C$  is calculated for various values of the revolutions per minute  $n$ , and the calculated values of  $C$  are given in Table 5. To find the centrifugal force in any given case, simply find the value of  $C$  in the table and multiply it by the product of  $W$  and  $r$ , the four multiplications in the original formula given thus having been reduced to two.

*Example:* A cast-iron flywheel with a mean rim radius of 9 inches, is rotated at a speed of 800 revolutions per minute. If the weight of the rim is 20 pounds, what is the centrifugal force?

From Table 5, for  $n = 800$  revolutions per minute, the value of  $C$  is 18.1862.

Thus,

$$F = WrC = 20 \times 9 \times 18.1862 = 3273.52 \text{ pounds}$$

Using metric SI units,  $0.01097n^2$  is the centrifugal force acting on a body of 1 kilogram mass rotating at  $n$  revolutions per minute at a distance of 1 meter from the axis. If this value is designated  $C_1$ , then the centrifugal force of mass  $M$  kilograms rotating at this speed at a distance from the axis of  $R$  meters, is  $C_1MR$  newtons. To simplify calculations, values for  $C_1$  are given in Table 6. If it is required to work in terms of millimeters, the force is  $0.001 C_1MR_1$  newtons, where  $R_1$  is the radius in millimeters.

*Example:* A steel pulley with a mean rim radius of 120 millimeters is rotated at a speed of 1100 revolutions per minute. If the mass of the rim is 5 kilograms, what is the centrifugal force?

From Table 6, for  $n = 1100$  revolutions per minute, the value of  $C_1$  is 13,269.1.

Thus,

$$F = 0.001 C_1MR_1 = 0.001 \times 13,269.1 \times 5 \times 120 = 7961.50 \text{ newtons}$$

**Centrifugal Casting.**—The centrifugal casting of metals is an old art. This process has become important in such work as the manufacture of paper-mill rolls, railroad car wheels, and cast-iron pipe. The centrifugal casting process has been successfully applied in the production of non-metallic tubes, such as concrete pipe, in the production of solid castings by locating the molds around the rim of a spinning wheel, and to a limited extent in the production of solid ingots by a largely similar process. Hollow objects such as cast-iron pipe are cast by introducing molten metal into a spinning mold. If the chilling of the metal is extremely rapid, for example in casting cast-iron pipe against a water-cooled chilled mold, it is imperative to use a movable spout. The particular feature that determines the field of application of hot-mold centrifugal casting is the ability to produce long cast shapes of comparatively thin metal.

**Table 5. Factors *C* for Calculating Centrifugal Force (English units)**

| <i>n</i> | <i>C</i> | <i>n</i> | <i>C</i> | <i>n</i> | <i>C</i> | <i>n</i> | <i>C</i> |
|----------|----------|----------|----------|----------|----------|----------|----------|
| 50       | 0.07104  | 100      | 0.28416  | 470      | 6.2770   | 5200     | 768.369  |
| 51       | 0.07391  | 101      | 0.28987  | 480      | 6.5470   | 5300     | 798.205  |
| 52       | 0.07684  | 102      | 0.29564  | 490      | 6.8227   | 5400     | 828.611  |
| 53       | 0.07982  | 103      | 0.30147  | 500      | 7.1040   | 5500     | 859.584  |
| 54       | 0.08286  | 104      | 0.30735  | 600      | 10.2298  | 5600     | 891.126  |
| 55       | 0.08596  | 105      | 0.31328  | 700      | 13.9238  | 5700     | 923.236  |
| 56       | 0.08911  | 106      | 0.31928  | 800      | 18.1862  | 5800     | 955.914  |
| 57       | 0.09232  | 107      | 0.32533  | 900      | 23.0170  | 5900     | 989.161  |
| 58       | 0.09559  | 108      | 0.33144  | 1000     | 28.4160  | 6000     | 1022.980 |
| 59       | 0.09892  | 109      | 0.33761  | 1100     | 34.3834  | 6100     | 1057.360 |
| 60       | 0.10230  | 110      | 0.34383  | 1200     | 40.9190  | 6200     | 1092.310 |
| 61       | 0.10573  | 115      | 0.37580  | 1300     | 48.0230  | 6300     | 1127.830 |
| 62       | 0.10923  | 120      | 0.40921  | 1400     | 55.6954  | 6400     | 1163.920 |
| 63       | 0.11278  | 125      | 0.44400  | 1500     | 63.9360  | 6500     | 1200.580 |
| 64       | 0.11639  | 130      | 0.48023  | 1600     | 72.7450  | 6600     | 1237.800 |
| 65       | 0.12006  | 135      | 0.51788  | 1700     | 82.1222  | 6700     | 1275.590 |
| 66       | 0.12378  | 140      | 0.55695  | 1800     | 92.0678  | 6800     | 1313.960 |
| 67       | 0.12756  | 145      | 0.59744  | 1900     | 102.5820 | 6900     | 1352.890 |
| 68       | 0.13140  | 150      | 0.63936  | 2000     | 113.6640 | 7000     | 1392.380 |
| 69       | 0.13529  | 160      | 0.72745  | 2100     | 125.3150 | 7100     | 1432.450 |
| 70       | 0.13924  | 170      | 0.82122  | 2200     | 137.5330 | 7200     | 1473.090 |
| 71       | 0.14325  | 180      | 0.92067  | 2300     | 150.3210 | 7300     | 1514.290 |
| 72       | 0.14731  | 190      | 1.02590  | 2400     | 163.6760 | 7400     | 1556.060 |
| 73       | 0.15143  | 200      | 1.1367   | 2500     | 177.6000 | 7500     | 1598.400 |
| 74       | 0.15561  | 210      | 1.2531   | 2600     | 192.0920 | 7600     | 1641.310 |
| 75       | 0.15984  | 220      | 1.3753   | 2700     | 207.1530 | 7700     | 1684.780 |
| 76       | 0.16413  | 230      | 1.5032   | 2800     | 222.7810 | 7800     | 1728.830 |
| 77       | 0.16848  | 240      | 1.6358   | 2900     | 238.9790 | 7900     | 1773.440 |
| 78       | 0.17288  | 250      | 1.7760   | 3000     | 255.7400 | 8000     | 1818.620 |
| 79       | 0.17734  | 260      | 1.9209   | 3100     | 273.0780 | 8100     | 1864.370 |
| 80       | 0.18186  | 270      | 2.0715   | 3200     | 290.9800 | 8200     | 1910.690 |
| 81       | 0.18644  | 280      | 2.2278   | 3300     | 309.4500 | 8300     | 1957.580 |
| 82       | 0.19107  | 290      | 2.3898   | 3400     | 328.4890 | 8400     | 2005.030 |
| 83       | 0.19576  | 300      | 2.5574   | 3500     | 348.0960 | 8500     | 2053.060 |
| 84       | 0.20050  | 310      | 2.7308   | 3600     | 368.2710 | 8600     | 2101.650 |
| 85       | 0.20530  | 320      | 2.9098   | 3700     | 389.0150 | 8700     | 2150.810 |
| 86       | 0.21016  | 330      | 3.0945   | 3800     | 410.3270 | 8800     | 2200.540 |
| 87       | 0.21508  | 340      | 3.2849   | 3900     | 432.2070 | 8900     | 2250.830 |
| 88       | 0.22005  | 350      | 3.4809   | 4000     | 454.6560 | 9000     | 2301.700 |
| 89       | 0.22508  | 360      | 3.6823   | 4100     | 477.6730 | 9100     | 2353.130 |
| 90       | 0.23017  | 370      | 3.8901   | 4200     | 501.2580 | 9200     | 2405.130 |
| 91       | 0.23531  | 380      | 4.1032   | 4300     | 525.4120 | 9300     | 2457.700 |
| 92       | 0.24051  | 390      | 4.3220   | 4400     | 550.1340 | 9400     | 2510.840 |
| 93       | 0.24577  | 400      | 4.5466   | 4500     | 575.4240 | 9500     | 2564.540 |
| 94       | 0.25108  | 410      | 4.7767   | 4600     | 601.2830 | 9600     | 2618.820 |
| 95       | 0.25645  | 420      | 5.0126   | 4700     | 627.7090 | 9700     | 2673.660 |
| 96       | 0.26188  | 430      | 5.2541   | 4800     | 654.7050 | 9800     | 2729.070 |
| 97       | 0.26737  | 440      | 5.5013   | 4900     | 682.2680 | 9900     | 2785.050 |
| 98       | 0.27291  | 450      | 5.7542   | 5000     | 710.4000 | 10000    | 2841.600 |
| 99       | 0.27851  | 460      | 6.0128   | 5100     | 739.1000 | ...      | ...      |

Table 6. Factors  $C_1$  for Calculating Centrifugal Force (Metric SI units)

| $n$ | $C_1$   | $n$ | $C_1$    | $n$  | $C_1$    | $n$   | $C_1$     |
|-----|---------|-----|----------|------|----------|-------|-----------|
| 50  | 27.4156 | 100 | 109.662  | 470  | 2,422.44 | 5200  | 296,527   |
| 51  | 28.5232 | 101 | 111.867  | 480  | 2,526.62 | 5300  | 308,041   |
| 52  | 29.6527 | 102 | 114.093  | 490  | 2,632.99 | 5400  | 319,775   |
| 53  | 30.8041 | 103 | 116.341  | 500  | 2,741.56 | 5500  | 331,728   |
| 54  | 31.9775 | 104 | 118.611  | 600  | 3,947.84 | 5600  | 343,901   |
| 55  | 33.1728 | 105 | 120.903  | 700  | 5,373.45 | 5700  | 356,293   |
| 56  | 34.3901 | 106 | 123.217  | 800  | 7,018.39 | 5800  | 368,904   |
| 57  | 35.6293 | 107 | 125.552  | 900  | 8,882.64 | 5900  | 381,734   |
| 58  | 36.8904 | 108 | 127.910  | 1000 | 10,966.2 | 6000  | 394,784   |
| 59  | 38.1734 | 109 | 130.290  | 1100 | 13,269.1 | 6100  | 408,053   |
| 60  | 39.4784 | 110 | 132.691  | 1200 | 15,791.4 | 6200  | 421,542   |
| 61  | 40.8053 | 115 | 145.028  | 1300 | 18,532.9 | 6300  | 435,250   |
| 62  | 42.1542 | 120 | 157.914  | 1400 | 21,493.8 | 6400  | 449,177   |
| 63  | 43.5250 | 125 | 171.347  | 1500 | 24,674.0 | 6500  | 463,323   |
| 64  | 44.9177 | 130 | 185.329  | 1600 | 28,073.5 | 6600  | 477,689   |
| 65  | 46.3323 | 135 | 199.860  | 1700 | 31,692.4 | 6700  | 492,274   |
| 66  | 47.7689 | 140 | 214.938  | 1800 | 35,530.6 | 6800  | 507,078   |
| 67  | 49.2274 | 145 | 230.565  | 1900 | 39,588.1 | 6900  | 522,102   |
| 68  | 50.7078 | 150 | 246.740  | 2000 | 43,864.9 | 7000  | 537,345   |
| 69  | 52.2102 | 160 | 280.735  | 2100 | 48,361.1 | 7100  | 552,808   |
| 70  | 53.7345 | 170 | 316.924  | 2200 | 53,076.5 | 7200  | 568,489   |
| 71  | 55.2808 | 180 | 355.306  | 2300 | 58,011.3 | 7300  | 584,390   |
| 72  | 56.8489 | 190 | 395.881  | 2400 | 63,165.5 | 7400  | 600,511   |
| 73  | 58.4390 | 200 | 438.649  | 2500 | 68,538.9 | 7500  | 616,850   |
| 74  | 60.0511 | 210 | 483.611  | 2600 | 74,131.7 | 7600  | 633,409   |
| 75  | 61.6850 | 220 | 530.765  | 2700 | 79,943.8 | 7700  | 650,188   |
| 76  | 63.3409 | 230 | 580.113  | 2800 | 85,975.2 | 7800  | 667,185   |
| 77  | 65.0188 | 240 | 631.655  | 2900 | 92,226.0 | 7900  | 684,402   |
| 78  | 66.7185 | 250 | 685.389  | 3000 | 98,696.0 | 8000  | 701,839   |
| 79  | 68.4402 | 260 | 741.317  | 3100 | 105,385  | 8100  | 719,494   |
| 80  | 70.1839 | 270 | 799.438  | 3200 | 112,294  | 8200  | 737,369   |
| 81  | 71.9494 | 280 | 859.752  | 3300 | 119,422  | 8300  | 755,463   |
| 82  | 73.7369 | 290 | 922.260  | 3400 | 126,770  | 8400  | 773,777   |
| 83  | 75.5463 | 300 | 986.960  | 3500 | 134,336  | 8500  | 792,310   |
| 84  | 77.3777 | 310 | 1,053.85 | 3600 | 142,122  | 8600  | 811,062   |
| 85  | 79.2310 | 320 | 1,122.94 | 3700 | 150,128  | 8700  | 830,034   |
| 86  | 81.1062 | 330 | 1,194.22 | 3800 | 158,352  | 8800  | 849,225   |
| 87  | 83.0034 | 340 | 1,267.70 | 3900 | 166,796  | 8900  | 868,635   |
| 88  | 84.9225 | 350 | 1,343.36 | 4000 | 175,460  | 9000  | 888,264   |
| 89  | 86.8635 | 360 | 1,421.22 | 4100 | 184,342  | 9100  | 908,113   |
| 90  | 88.8264 | 370 | 1,501.28 | 4200 | 193,444  | 9200  | 928,182   |
| 91  | 90.8113 | 380 | 1,583.52 | 4300 | 202,766  | 9300  | 948,469   |
| 92  | 92.8182 | 390 | 1,667.96 | 4400 | 212,306  | 9400  | 968,976   |
| 93  | 94.8469 | 400 | 1,754.60 | 4500 | 222,066  | 9500  | 989,702   |
| 94  | 96.8976 | 410 | 1,843.42 | 4600 | 232,045  | 9600  | 1,010,650 |
| 95  | 98.9702 | 420 | 1,934.44 | 4700 | 242,244  | 9700  | 1,031,810 |
| 96  | 101.065 | 430 | 2,027.66 | 4800 | 252,662  | 9800  | 1,053,200 |
| 97  | 103.181 | 440 | 2,123.06 | 4900 | 263,299  | 9900  | 1,074,800 |
| 98  | 105.320 | 450 | 2,220.66 | 5000 | 274,156  | 10000 | 1,096,620 |
| 99  | 107.480 | 460 | 2,320.45 | 5100 | 285,232  | ...   | ...       |

## FLYWHEELS

### Classification of Flywheels

Flywheels may be classified as *balance wheels* or as *flywheel pulleys*. The object of all flywheels is to equalize the energy exerted and the work done and thereby prevent excessive or sudden changes of speed. The permissible speed variation is an important factor in all flywheel designs. The allowable speed change varies considerably for different classes of machinery; for instance, it is about 1 or 2 per cent in steam engines, while in punching and shearing machinery a speed variation of 20 per cent may be allowed.

The function of a balance wheel is to absorb and equalize energy in case the resistance to motion, or driving power, varies throughout the cycle. Therefore, the rim section is generally quite heavy and is designed with reference to the energy that must be stored in it to prevent excessive speed variations and, with reference to the strength necessary to withstand safely the stresses resulting from the required speed. The rims of most balance wheels are either square or nearly square in section, but flywheel pulleys are commonly made wide to accommodate a belt and relatively thin in a radial direction, although this is not an invariable rule.

Flywheels, in general, may either be formed of a solid or one-piece section, or they may be of sectional construction. Flywheels in diameters up to about eight feet are usually cast solid, the hubs sometimes being divided to relieve cooling stresses. Flywheels ranging from, say, eight feet to fifteen feet in diameter, are commonly cast in half sections, and the larger sizes in several sections, the number of which may equal the number of arms in the wheel. Sectional flywheels may be divided into two general classes. One class includes cast wheels which are formed of sections principally because a solid casting would be too large to transport readily. The second class includes wheels of sectional construction which, by reason of the materials used and the special arrangement of the sections, enables much higher peripheral speeds to be obtained safely than would be possible with ordinary sectional wheels of the type not designed especially for high speeds. Various designs have been built to withstand the extreme stresses encountered in some classes of service. The rims in some designs are laminated, being partly or entirely formed of numerous segment-shaped steel plates. Another type of flywheel, which is superior to an ordinary sectional wheel, has a solid cast-iron rim connected to the hub by disk-shaped steel plates instead of cast spokes.

Steel wheels may be divided into three distinct types, including 1) those having the center and rim built up entirely of steel plates; 2) those having a cast-iron center and steel rim; and 3) those having a cast-steel center and rim formed of steel plates.

Wheels having wire-wound rims have been used to a limited extent when extremely high speeds have been necessary.

When the rim is formed of sections held together by joints it is very important to design these joints properly. The ordinary bolted and flanged rim joints located between the arms average about 20 per cent of the strength of a solid rim and about 25 per cent is the maximum strength obtainable for a joint of this kind. However, by placing the joints at the ends of the arms instead of between them, an efficiency of 50 per cent of the strength of the rim may be obtained, because the joint is not subjected to the outward bending stresses between the arms but is directly supported by the arm, the end of which is secured to the rim just beneath the joint. When the rim sections of heavy balance wheels are held together by steel links shrunk into place, an efficiency of 60 per cent may be obtained; and by using a rim of box or I-section, a link type of joint connection may have an efficiency of 100 per cent.

## Flywheel Calculations

**Energy Due to Changes of Velocity.**—When a flywheel absorbs energy from a variable driving force, as in a steam engine, the velocity increases; and when this stored energy is given out, the velocity diminishes. When the driven member of a machine encounters a variable resistance in performing its work, as when the punch of a punching machine is passing through a steel plate, the flywheel gives up energy while the punch is at work, and, consequently, the speed of the flywheel is reduced. The total energy that a flywheel would give out if brought to a standstill is given by the formula:

$$E = \frac{Wv^2}{2g} = \frac{Wv^2}{64.32}$$

in which  $E$  = total energy of flywheel, in foot-pounds

$W$  = weight of flywheel rim, in pounds

$v$  = velocity at mean radius of flywheel rim, in feet per second

$g$  = acceleration due to gravity = 32.16 ft/s<sup>2</sup>

If the velocity of a flywheel changes, the energy it will absorb or give up is proportional to the difference between the squares of its initial and final speeds, and is equal to the difference between the energy that it would give out if brought to a full stop and the energy that is still stored in it at the reduced velocity. Hence:

$$E_1 = \frac{Wv_1^2}{2g} - \frac{Wv_2^2}{2g} = \frac{W(v_1^2 - v_2^2)}{64.32}$$

in which  $E_1$  = energy in foot-pounds that a flywheel will give out while the speed is reduced from  $v_1$  to  $v_2$

$W$  = weight of flywheel rim, in pounds

$v_1$  = velocity at mean radius of flywheel rim before any energy has been given out, in feet per second

$v_2$  = velocity of flywheel rim at end of period during which the energy has been given out, in feet per second

Ordinarily, the effects of the arms and hub do not enter into flywheel calculations, and only the weight of the rim is considered. In computing the velocity, the mean radius of the rim is commonly used.

**Using metric SI units, the formulas are  $E = \frac{1}{2}Mv^2$ , and  $E_1 = \frac{1}{2}M(v_1^2 - v_2^2)$ , where  $E$  and  $E_1$  are in joules;  $M$  = the mass of the rim in kilograms; and  $v$ ,  $v_1$ , and  $v_2$  = velocities in meters per second. Note: In the SI, the unit of mass is the kilogram. If the weight of the flywheel rim is given in kilograms, the value referred to is the mass,  $M$ . Should the weight be given in newtons,  $N$ , then**

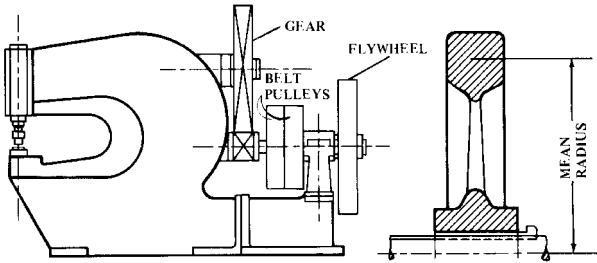
$$M = \frac{W(\text{newtons})}{g}$$

where  $g$  is approximately 9.81 meters per second squared.

**General Procedure in Flywheel Design.**—The general method of designing a flywheel is to determine first the value of  $E_1$  or the energy the flywheel must either supply or absorb for a given change in velocity, which, in turn, varies for different classes of service. The mean diameter of the flywheel may be assumed, or it may be fixed within certain limits by the general design of the machine. Ordinarily the speed of the flywheel shaft is known, at least approximately; the values of  $v_1$  and  $v_2$  can then be determined, the latter depending upon the allowable percentage of speed variation. When these values are known, the weight of the rim and the cross-sectional area required to obtain this weight may be computed. The general procedure will be illustrated more in detail by considering the design of flywheels for punching and shearing machinery.

**Flywheels for Presses, Punches, Shears, Etc.**—In these classes of machinery, the work that the machine performs is of an intermittent nature and is done during a small part of the time required for the driving shaft of the machine to make a complete revolution. To distribute the work of the machine over the entire period of revolution of the driving shaft, a heavy-rimmed flywheel is placed on the shaft, giving the belt an opportunity to perform an almost uniform amount of work during the whole revolution. During the greater part of the revolution of the driving shaft, the belt power is used to accelerate the speed of the flywheel. During the part of the revolution when the work is done, the energy thus stored up in the flywheel is given out at the expense of its velocity. The problem is to determine the weight and cross-sectional area of the rim when the conditions affecting the design of the flywheel are known.

*Example:* A flywheel is required for a punching machine capable of punching  $\frac{3}{4}$ -inch holes through structural steel plates  $\frac{3}{4}$  inch thick. This machine (see accompanying diagram) is of the general type having a belt-driven shaft at the rear which carries a flywheel and a pinion that meshes with a large gear on the main shaft at the top of the machine. It is assumed that the relative speeds of the pinion and large gear are 7 to 1, respectively, and that the slide is to make 30 working strokes per minute. The preliminary layout shows that the flywheel should have a mean diameter (see enlarged detail) of about 30 inches. Find the weight of the flywheel and the remaining rim dimensions.



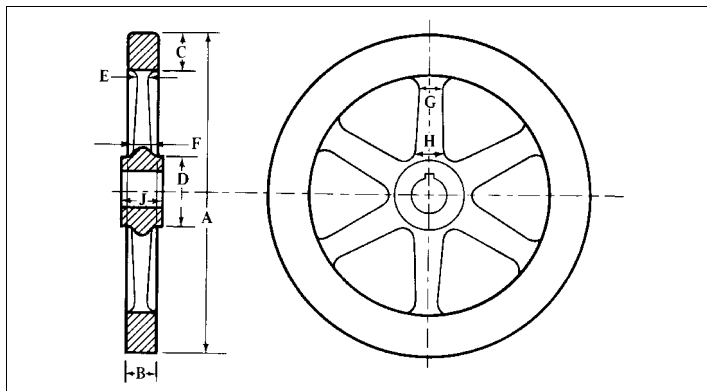
Punch Press and Flywheel Detail

*Energy Supplied by Flywheel:* The energy that the flywheel must give up for a given change in velocity, and the weight of rim necessary to supply that energy, must be determined. The maximum force for shearing a  $\frac{3}{4}$ -inch hole through  $\frac{3}{4}$ -inch structural steel equals approximately the circumference of the hole multiplied by the thickness of the stock multiplied by the tensile strength, which is nearly the same as the shearing resistance of the steel. Thus, in this case,  $3.1416 \times \frac{3}{4} \times \frac{3}{4} \times 60,000 = 106,000$  pounds. The average force will be much less than the maximum. Some designers assume that the average force is about one-half the maximum, although experiments show that the material is practically sheared off when the punch has entered the sheet a distance equal to about one-third the sheet thickness. On this latter basis, the average energy  $E_a$  is 2200 foot-pounds for the example given. Thus:

$$E_a = \frac{106,000 \times \frac{1}{3} \times \frac{3}{4}}{12} = \frac{106,000}{4 \times 12} = 2200 \text{ foot-pounds.}$$

If the efficiency of the machine is taken as 85 per cent, the energy required will equal  $2200/0.85 = 2600$  foot-pounds nearly. Assume that the energy supplied by the belt while the punch is at work is determined by calculation to equal 175 foot-pounds. Then the flywheel must supply  $2600 - 175 = 2425$  foot-pounds =  $E_1$ .

## Dimensions of Flywheels for Punches and Shears



| A   | B  | C  | D   | E  | F  | G  | H   | J  | Max.<br>R.P.M. |
|-----|----|----|-----|----|----|----|-----|----|----------------|
| 24  | 3  | 3½ | 6   | 1¼ | 1⅜ | 2¾ | 3¼  | 3½ | 955            |
| 30  | 3½ | 4  | 7   | 1⅜ | 1½ | 3  | 3¾  | 4  | 796            |
| 36  | 4  | 4½ | 8   | 1½ | 1¾ | 3¼ | 4¼  | 4½ | 637            |
| 42  | 4¼ | 4¾ | 9   | 1¾ | 2  | 3½ | 4½  | 5  | 557            |
| 48  | 4½ | 5  | 10  | 1¾ | 2  | 3¾ | 4¾  | 5½ | 478            |
| 54  | 4¾ | 5½ | 11  | 2  | 2¼ | 4  | 5   | 6  | 430            |
| 60  | 5  | 6  | 12  | 2¼ | 2½ | 4½ | 5½  | 6½ | 382            |
| 72  | 5½ | 7  | 13  | 2½ | 2¾ | 5  | 6½  | 7  | 318            |
| 84  | 6  | 8  | 14  | 3  | 3½ | 5½ | 7½  | 8  | 273            |
| 96  | 7  | 9  | 15  | 3½ | 4  | 6  | 9   | 9  | 239            |
| 108 | 8  | 10 | 16½ | 3¾ | 4½ | 6½ | 10½ | 10 | 212            |
| 120 | 9  | 11 | 18  | 4  | 5  | 7½ | 12  | 12 | 191            |

The maximum number of revolutions per minute given in this table should never be exceeded for cast-iron flywheels.

**Rim Velocity at Mean Radius:** When the mean radius of the flywheel is known, the velocity of the rim at the mean radius, in feet per second, is:

$$v = \frac{2 \times 3.1416 \times R \times n}{60}$$

in which  $v$  = velocity at mean radius of flywheel, in feet per second

$R$  = mean radius of flywheel rim, in feet

$n$  = number of revolutions per minute

According to the preliminary layout the mean diameter in this example should be about 30 inches and the driving shaft is to make 210 rpm, hence,

$$v = \frac{2 \times 3.1416 \times 1.25 \times 210}{60} = 27.5 \text{ feet per second}$$

*Weight of Flywheel Rim:* Assuming that the allowable variation in velocity when punching is about 15 per cent, and values of  $v_1$  and  $v_2$  are respectively 27.5 and 23.4 feet per second ( $27.5 \times 0.85 = 23.4$ ), the weight of a flywheel rim necessary to supply a given amount of energy in foot-pounds while the speed is reduced from  $v_1$  to  $v_2$  would be:

$$W = \frac{E_1 \times 64.32}{v_1^2 - v_2^2} = \frac{2425 \times 64.32}{27.5^2 - 23.4^2} = 750 \text{ pounds}$$

*Size of Rim for Given Weight:* Since 1 cubic inch of cast iron weighs 0.26 pound, a flywheel rim weighing 750 pounds contains  $750/0.26 = 2884$  cubic inches. The cross-sectional area of the rim in square inches equals the total number of cubic inches divided by the mean circumference, or  $2884/94.25 = 31$  square inches nearly, which is approximately the area of a rim  $5\frac{1}{8}$  inches wide and 6 inches deep.

**Simplified Flywheel Calculations.**—Calculations for designing the flywheels of punches and shears are simplified by the following formulas and the accompanying table of constants applying to different percentages of speed reduction. In these formulas let:

HP = horsepower required

N = number of strokes per minute

E = total energy required per stroke, in foot-pounds

$E_1$  = energy given up by flywheel, in foot-pounds

T = time in seconds per stroke

$T_1$  = time in seconds of actual cut

W = weight of flywheel rim, in pounds

D = mean diameter of flywheel rim, in feet

R = maximum allowable speed of flywheel in revolutions per minute

C and  $C_1$  = speed reduction values as given in table

a = width of flywheel rim

b = depth of flywheel rim

y = ratio of depth to width of rim

$$HP = \frac{EN}{33,000} = \frac{E}{T \times 550} \quad E_1 = E \left(1 - \frac{T_1}{T}\right)$$

$$W = \frac{E_1}{CD^2R^2} \quad a = \sqrt{\frac{1.22W}{12Dy}} \quad b = ay$$

For cast-iron flywheels, with a maximum stress of 1000 pounds per square inch:

$$W = C_1 E_1 \quad R = 1940 \div D$$

#### Values of C and $C_1$ in the Previous Formulas

| Per Cent Reduction | C          | $C_1$  | Per Cent Reduction | C          | $C_1$  |
|--------------------|------------|--------|--------------------|------------|--------|
| 2½                 | 0.00000213 | 0.1250 | 10                 | 0.00000810 | 0.0328 |
| 5                  | 0.00000426 | 0.0625 | 15                 | 0.00001180 | 0.0225 |
| 7½                 | 0.00000617 | 0.0432 | 20                 | 0.00001535 | 0.0173 |

*Example 1:* A hot slab shear is required to cut a slab  $4 \times 15$  inches which, at a shearing stress of 6000 pounds per square inch, gives a force between the knives of 360,000 pounds. The total energy required for the cut will then be  $360,000 \times \frac{1}{2} = 120,000$  foot-pounds. The shear is to make 20 strokes per minute; the actual cutting time is 0.75 second, and the balance of the stroke is 2.25 seconds.



The flywheel is to have a mean diameter of 6 feet 6 inches and is to run at a speed of 200 rpm; the reduction in speed to be 10 per cent per stroke when cutting.

$$HP = \frac{120,000 \times 20}{33,000} = 72.7 \text{ horsepower}$$

$$E_1 = 120,000 \times \left(1 - \frac{0.75}{3}\right) = 90,000 \text{ foot-pounds}$$

$$W = \frac{90,000}{0.0000081 \times 6.5^2 \times 200^2} = 6570 \text{ pounds}$$

Assuming a ratio of 1.22 between depth and width of rim,

$$a = \sqrt{\frac{6570}{12 \times 6.5}} = 9.18 \text{ inches}$$

$$b = 1.22 \times 9.18 = 11.2 \text{ inches}$$

or size of rim, say,  $9 \times 11\frac{1}{2}$  inches.

*Example 2:* Suppose that the flywheel in [Example 1](#) is to be made with a stress due to centrifugal force of 1000 pounds per square inch of rim section.

$$C_1 \text{ for 10 per cent} = 0.0328$$

$$W = 0.0328 \times 90,000 = 2950 \text{ pounds}$$

$$R = \frac{1940}{D} \quad \text{If } D = 6 \text{ feet,} \quad R = \frac{1940}{6} = 323 \text{ rpm}$$

Assuming a ratio of 1.22 between depth and width of rim, as before:

$$a = \sqrt{\frac{2950}{12 \times 6}} = 6.4 \text{ inches}$$

$$b = 1.22 \times 6.4 = 7.8 \text{ inches}$$

or size of rim, say,  $6\frac{1}{4} \times 8$  inches.

**Centrifugal Stresses in Flywheel Rims.**—In general, high speed is desirable for flywheels in order to avoid using wheels that are unnecessarily large and heavy. The centrifugal tension or hoop tension stress, that tends to rupture a flywheel rim of given area, depends solely upon the rim velocity and is independent of the rim radius. The bursting velocity of a flywheel, based on hoop stress alone (not considering bending stresses), is related to the tensile stress in the flywheel rim by the following formula which is based on the centrifugal force formula from mechanics.

$$V = \sqrt{10 \times s} \quad \text{or,} \quad s = V^2 \div 10$$

where  $V$  = velocity of outside circumference of rim in feet per second, and  $s$  is the tensile strength of the rim material in pounds per square inch.

For cast iron having a tensile strength of 19,000 pounds per square inch the bursting speed would be:

$$V = \sqrt{10 \times 19,000} = 436 \text{ feet per second}$$

*Built-up Flywheels:* Flywheels built up of solid disks of rolled steel plate stacked and bolted together on a through shaft have greater speed capacity than other types. The maximum hoop stress is at the bore and is given by the formula,

$$s = 0.0194V^2[4.333 + (d/D)^2]$$

In this formula,  $s$  and  $V$  are the stress and velocity as previously defined and  $d$  and  $D$  are the bore and outside diameters, respectively.

Assuming the plates to be of steel having a tensile strength of 60,000 pounds per square inch and a safe working stress of 24,000 pounds per square inch (using a factor of safety of 2.5 on stress or  $\sqrt{2.5}$  on speed) and taking the worst condition (when  $d$  approaches  $D$ ), the safe rim speed for this type of flywheel is 500 feet per second or 30,000 feet per minute.

**Combined Stresses in Flywheels.**—The bending stresses in the rim of a flywheel may exceed the centrifugal (hoop tension) stress predicted by the simple formula  $s = V^2/10$  by a considerable amount. By taking into account certain characteristics of flywheels, relatively simple formulas have been developed to determine the stress due to the combined effect of hoop tension and bending stress. Some of the factors that influence the magnitude of the maximum combined stress acting at the rim of a flywheel are:

1) *The number of spokes.* Increasing the number of spokes decreases the rim span between spokes and hence decreases the bending moment. Thus an eight-spoke wheel can be driven to a considerably higher speed before bursting than a six-spoke wheel having the same rim.

2) *The relative thickness of the spokes.* If the spokes were extremely thin, like wires, they could offer little constraint to the rim in expanding to its natural diameter under centrifugal force, and hence would cause little bending stress. Conversely, if the spokes were extremely heavy in proportion to the rim, they would restrain the rim thereby setting up heavy bending stresses at the junctions of the rim and spokes.

3) *The relative thickness of the rim to the diameter.* If the rim is quite thick (i.e., has a large section modulus in proportion to span), its resistance to bending will be great and bending stress small. Conversely, thin rims with a section modulus small in comparison with diameter or span have little resistance to bending, thus are subject to high bending stresses.

4) *Residual stresses.* These include shrinkage stresses, impact stresses, and stresses caused by operating torques and imperfections in the material. Residual stresses are taken into account by the use of a suitable factor of safety. (See *Factors of Safety for Flywheels.*)

The formulas that follow give the maximum combined stress at the rim of flywheels having 6, 8, and 10 spokes. These formulas are for flywheels with *rectangular rim sections* and take into account the first three of the four factors listed as influencing the magnitude of the combined stress in flywheels.

$$\text{For 6 spokes:} \quad s = \frac{V^2}{10} \left[ 1 + \left( \frac{0.56B - 1.81}{3Q + 3.14} \right) Q \right]$$

$$\text{For 8 spokes:} \quad s = \frac{V^2}{10} \left[ 1 + \left( \frac{0.42B - 2.53}{4Q + 3.14} \right) Q \right]$$

$$\text{For 10 spokes:} \quad s = \frac{V^2}{10} \left[ 1 + \left( \frac{0.33B - 3.22}{5Q + 3.14} \right) Q \right]$$

In these formulas,  $s$  = maximum combined stress in pounds per square inch;  $Q$  = ratio of mean spoke cross-section area to rim cross-section area;  $B$  = ratio of outside diameter of rim to rim thickness; and  $V$  = velocity of flywheel rim in feet per second.

**Thickness of Cast Iron Flywheel Rims.**—The mathematical analysis of the stresses in flywheel rims is not conclusive owing to the uncertainty of shrinkage stresses in castings or the strength of the joint in sectional wheels. When a flywheel of ordinary design is revolving at high speed, the tendency of the rim is to bend or bow outward between the arms, and the bending stresses may be serious, especially if the rim is wide and thin and the spokes are rather widely spaced. When the rims are thick, this tendency does not need to be considered, but in a thin rim running at high speed, the stress in the middle might become suf-

ficiently great to cause the wheel to fail. The proper thickness of a cast-iron rim to resist this tendency is given for solid rims by [Formula \(1\)](#) and for a jointed rim by [Formula \(2\)](#).

$$t = \frac{0.475d}{n^2 \left( \frac{6000}{v^2} - \frac{1}{10} \right)} \quad (1)$$

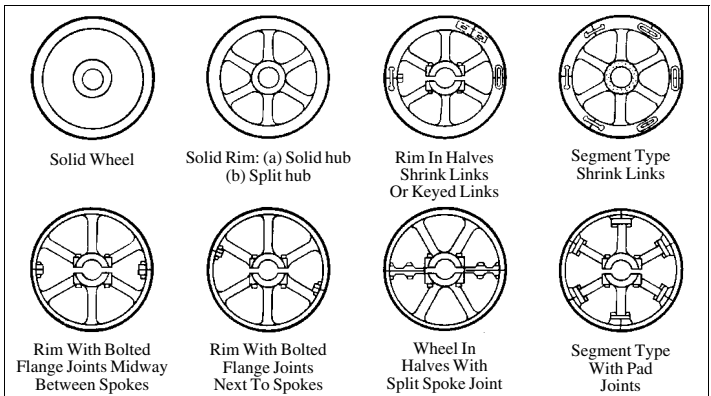
$$t = \frac{0.95d}{n^2 \left( \frac{6000}{v^2} - \frac{1}{10} \right)} \quad (2)$$

In these formulas,  $t$  = thickness of rim, in inches;  $d$  = diameter of flywheel, in inches;  $n$  = number of arms;  $v$  = peripheral speed, in feet per second.

**Factors of Safety for Flywheels.**—Cast-iron flywheels are commonly designed with a factor of safety of 10 to 13. A factor of safety of 10 applied to the tensile strength of a flywheel material is equivalent to a factor of safety of  $\sqrt{10}$  or 3.16 on the speed of the flywheel because the stress on the rim of a flywheel increases as the square of the speed. Thus, a flywheel operating at a speed twice that for which it was designed would undergo rim stresses four times as great as at the design speed.

**Tables of Safe Speeds for Flywheels.**—The accompanying [Table 1](#), prepared by T. C. Rathbone of The Fidelity and Casualty Company of New York, gives general recommendations for safe rim speeds for flywheels of various constructions. [Table 2](#) shows the number of revolutions per minute corresponding to the rim speeds in [Table 1](#).

**Table 1. Safe Rim Speeds for Flywheels**



| Type of Wheel                               | Safe Rim Speed |               |
|---|----------------|---------------|
|   | Feet per Sec.  | Feet per Min. |
| Solid cast iron (balance wheels—heavy rims) | 110            | 6,600         |
| Solid cast iron (pulley wheels—thin rims)   | 85             | 5,100         |
| Wheels with shrink link joints              | 77.5           | 4,650         |
| Wheels with pad type joints                 | 70.7           | 4,240         |
| Wheels with bolted flange joints            | 50             | 3,000         |
| Solid cast steel wheels                     | 200            | 12,000        |
| Wheels built up of stacked steel plates     | 500            | 30,000        |

To find the safe speed in revolutions per minute, divide the safe rim speed in feet per minute by 3.14 times the outside diameter of the flywheel rim in feet. For flywheels up to 15 feet in diameter, see [Table 2](#).

**Table 2. Safe Speeds of Rotation for Flywheels**

| Outside Diameter of Rim (feet) | Safe Rim Speed in Feet per Minute (from Table 1) |       |       |       |       |        |        |
|--------------------------------|--|-------|-------|-------|-------|--------|--------|
|                                | 6,600  | 5,100 | 4,650 | 4,240 | 3,000 | 12,000 | 30,000 |
|                                | Safe Speed of Rotation in Revolutions per Minute |       |       |       |       |        |        |
| 1                              | 2100   | 1623  | 1480  | 1350  | 955   | 3820   | 9549   |
| 2                              | 1050   | 812   | 740   | 676   | 478   | 1910   | 4775   |
| 3                              | 700  | 541   | 493   | 450   | 318   | 1273   | 3183   |
| 4                              | 525  | 406   | 370   | 338   | 239   | 955    | 2387   |
| 5                              | 420  | 325   | 296   | 270   | 191   | 764    | 1910   |
| 6                              | 350  | 271   | 247   | 225   | 159   | 637    | 1592   |
| 7                              | 300  | 232   | 211   | 193   | 136   | 546    | 1364   |
| 8                              | 263  | 203   | 185   | 169   | 119   | 478    | 1194   |
| 9                              | 233  | 180   | 164   | 150   | 106   | 424    | 1061   |
| 10                             | 210  | 162   | 148   | 135   | 96    | 382    | 955    |
| 11                             | 191  | 148   | 135   | 123   | 87    | 347    | 868    |
| 12                             | 175  | 135   | 123   | 113   | 80    | 318    | 796    |
| 13                             | 162  | 125   | 114   | 104   | 73    | 294    | 735    |
| 14                             | 150  | 116   | 106   | 97    | 68    | 273    | 682    |
| 15                             | 140  | 108   | 99    | 90    | 64    | 255    | 637    |

Safe speeds of rotation are based on safe rim speeds shown in Table 1.

**Safe Speed Formulas for Flywheels and Pulleys.**—No simple formula can accommodate all the various types and proportions of flywheels and pulleys and at the same time provide a uniform factor of safety for each. Because of considerations of safety, such a formula would penalize the better constructions to accommodate the weaker designs.

One formula that has been used to check the maximum rated operating speed of flywheels and pulleys and which takes into account material properties, construction, rim thickness, and joint efficiencies is the following:

$$N = \frac{CAMEK}{D}$$

In this formula,

$N$  = maximum rated operating speed in revolutions per minute

$C$  = 1.0 for wheels driven by a constant speed electric motor (i.e., a-c squirrel-cage induction motor or a-c synchronous motor, etc.)

0.90 for wheels driven by variable speed motors, engines or turbines where overspeed is not over 110 per cent of rated operating speed

$A$  = 0.90 for 4 arms or spokes

1.00 for 6 arms or spokes

1.08 for 8 arms or spokes

1.50 for disc type

$M$  = 1.00 for cast iron of 20,000 psi tensile strength, or unknown

1.12 for cast iron of 25,000 psi tensile strength

1.22 for cast iron of 30,000 psi tensile strength

1.32 for cast iron of 35,000 psi tensile strength

2.20 for nodular iron of 60,000 psi tensile strength

2.45 for cast steel of 60,000 psi tensile strength

2.75 for plate or forged steel of 60,000 psi tensile strength

$E$  = joint efficiency

1.0 for solid rim

0.85 for link or prison joints

0.75 for split rim — bolted joint at arms

0.70 for split rim — bolted joint between arms

|  |
|--|
| $K = 1355$ for rim thickness equal to 1 per cent of outside diameter |
| 1650 for rim thickness equal to 2 per cent of outside diameter       |
| 1840 for rim thickness equal to 3 per cent of outside diameter       |
| 1960 for rim thickness equal to 4 per cent of outside diameter       |
| 2040 for rim thickness equal to 5 per cent of outside diameter       |
| 2140 for rim thickness equal to 7 per cent of outside diameter       |
| 2225 for rim thickness equal to 10 per cent of outside diameter      |
| 2310 for rim thickness equal to 15 per cent of outside diameter      |
| 2340 for rim thickness equal to 20 per cent of outside diameter      |

$D$  = outside diameter of rim in feet

*Example:* A six-spoke solid cast iron balance wheel 8 feet in diameter has a rectangular rim 10 inches thick. What is the safe speed, in revolutions per minute, if driven by a constant motor?

In this instance,  $C = 1$ ;  $A = 1$ ;  $M = 1$ , since tensile strength is unknown;  $E = 1$ ;  $K = 2225$  since the rim thickness is approximately 10 per cent of the wheel diameter; and  $D = 8$  feet. Thus,

$$N = \frac{1 \times 1 \times 1 \times 2225}{8} = 278 \text{ rpm}$$

(*Note:* This safe speed is slightly greater than the value of 263 rpm obtainable directly from Tables 1 and 2.)

**Tests to Determine Flywheel Bursting Speeds.**—Tests made by Prof. C. H. Benjamin, to determine the bursting speeds of flywheels, showed the following results:

*Cast-iron Wheels with Solid Rims:* Cast-iron wheels having solid rims burst at a rim speed of 395 feet per second, corresponding to a centrifugal tension of about 15,600 pounds per square inch.

*Wheels with Jointed Rims:* Four wheels were tested with joints and bolts inside the rim, using the familiar design ordinarily employed for band wheels, but with the joints located at points one-fourth of the distance from one arm to the next. These locations represent the points of least bending moment, and, consequently, the points at which the deflection due to centrifugal force would be expected to have the least effect. The tests, however, did not bear out this conclusion. The wheels burst at a rim speed of 194 feet per second, corresponding to a centrifugal tension of about 3750 pounds per square inch. These wheels, therefore, were only about one-quarter as strong as the wheels with solid rims, and burst at practically the same speed as wheels in a previous series of tests in which the rim joints were midway between the arms.

*Bursting Speed for Link Joints:* Another type of wheel with deep rim, fastened together at the joints midway between the arms by links shrunk into recesses, after the manner of flywheels for massive engines, gave much superior results. This wheel burst at a speed of 256 feet per second, indicating a centrifugal tension of about 6600 pounds per square inch.

*Wheel having Tie-rods:* Tests were made on a band wheel having joints inside the rim, midway between the arms, and in all respects like others of this design previously tested, except that tie-rods were used to connect the joints with the hub. This wheel burst at a speed of 225 feet per second, showing an increase of strength of from 30 to 40 per cent over similar wheels without the tie-rods.

*Wheel Rim of I-section:* Several wheels of special design, not in common use, were also tested, the one giving the greatest strength being an English wheel, with solid rim of I-section, made of high-grade cast iron and with the rim tied to the hub by steel wire spokes. These spokes were adjusted to have a uniform tension. The wheel gave way at a rim speed of 424 feet per second, which is slightly higher than the speed of rupture of the solid rim wheels with ordinary style of spokes.

*Tests on Flywheel of Special Construction:* A test was made on a flywheel 49 inches in diameter and weighing about 900 pounds. The rim was  $6\frac{3}{4}$  inches wide and  $1\frac{1}{8}$  inches thick, and was built of ten segments, the material being cast steel. Each joint was secured by three "prisoners" of an I-section on the outside face, by link prisoners on each edge, and by a dovetailed bronze clamp on the inside, fitting over lugs on the rim. The arms were of phosphor-bronze, twenty in number, ten on each side, and were cross-shaped in section. These arms came midway between the rim joints and were bolted to plane faces on the polygonal hub. The rim was further reinforced by a system of diagonal bracing, each section of the rim being supported at five points on each side, in such a way as to relieve it almost entirely from bending. The braces, like the arms, were of phosphor-bronze, and all bolts and connecting links were of steel. This wheel was designed as a model of a proposed 30-foot flywheel. On account of the excessive air resistance the wheel was enclosed at the sides between sheet-metal disks. This wheel burst at 1775 revolutions per minute or at a linear speed of 372 feet per second. The hub and main spokes of the wheel remained nearly in place, but parts of the rim were found 200 feet away. This sudden failure of the rim casting was unexpected, as it was thought the flange bolts would be the parts to give way first. The tensile strength of the casting at the point of fracture was about four times the strength of the wheel rim at a solid section.

**Stresses in Rotating Disks.**—When a disk of uniform width is rotated, the maximum stress  $S_t$  is tangential and at the bore of the hub, and the tangential stress is always greater than the radial stress at the same point on the disk. If  $S_t$  = maximum tangential stress in pounds per sq. in.;  $w$  = weight of material, lb. per cu. in.;  $N$  = rev. per min.;  $m$  = Poisson's ratio = 0.3 for steel;  $R$  = outer radius of disk, inches;  $r$  = inner radius of disk or radius of bore, inches.

$$S_t = 0.000071 w N^2 [(3 + m)R^2 + (1 - m)r^2]$$

**Steam Engine Flywheels.**—The variable amount of energy during each stroke and the allowable percentage of speed variation are of special importance in designing steam engine flywheels. The earlier the point of cut-off, the greater the variation in energy and the larger the flywheel that will be required. The weight of the reciprocating parts and the length of the connecting-rod also affect the variation. The following formula is used for computing the weight of the flywheel rim:

Let  $W$  = weight of rim in pounds

$D$  = mean diameter of rim in feet

$N$  = number of revolutions per minute

$\frac{1}{n}$  = allowable variation in speed (from  $\frac{1}{50}$  to  $\frac{1}{100}$ )

$E$  = excess and deficiency of energy in foot-pounds

$c$  = factor of energy excess, from the accompanying table

$HP$  = indicated horsepower

Then, if the indicated horsepower is given:

$$W = \frac{387,587,500 \times cn \times HP}{D^2 N^3} \quad (1)$$

If the work in foot-pounds is given, then:

$$W = \frac{11,745nE}{D^2 N^2} \quad (2)$$

In the second formula,  $E$  equals the average work in foot-pounds done by the engine in one revolution, multiplied by the decimal given in the accompanying table, "*Factors for Engine Flywheel Calculations*," which covers both condensing and non-condensing engines:

## Factors for Engine Flywheel Calculations

| Condensing Engines                           |               |               |               |               |               |               |
|--|---------------|---------------|---------------|---------------|---------------|---------------|
| Fraction of stroke at which steam is cut off | $\frac{1}{3}$ | $\frac{1}{4}$ | $\frac{1}{5}$ | $\frac{1}{6}$ | $\frac{1}{7}$ | $\frac{1}{8}$ |
| Factor of energy excess                      | 0.163         | 0.173         | 0.178         | 0.184         | 0.189         | 0.191         |
| Non-condensing Engines                       |               |               |               |               |               |               |
| Steam cut off at                             |               | $\frac{1}{2}$ | $\frac{1}{3}$ | $\frac{1}{4}$ | $\frac{1}{5}$ |               |
| Factor of energy excess                      |               | 0.160         | 0.186         | 0.209         | 0.232         |               |

*Example 1:* A non-condensing engine of 150 indicated horsepower is to make 200 revolutions per minute, with a speed variation of 2 per cent. The average cut-off is to be at one-quarter stroke, and the flywheel is to have a mean diameter of 6 feet. Find the necessary weight of the rim in pounds.

From the table  $c = 0.209$ , and from the data given  $HP = 150$ ;  $N = 200$ ;  $1/n = 1/50$  or  $n = 50$ ; and,  $D = 6$ .

Substituting these values in [Equation \(1\)](#):

$$W = \frac{387,587,500 \times 0.209 \times 50 \times 150}{6^2 \times 200^3} = 2110 \text{ pounds, nearly}$$

*Example 2:* A condensing engine,  $24 \times 42$  inches, cuts off at one-third stroke and has a mean effective pressure of 50 pounds per square inch. The flywheel is to be 18 feet in mean diameter and make 75 revolutions per minute with a variation of 1 per cent. Find the required weight of the rim.

The work done on the piston in one revolution is equal to the pressure on the piston multiplied by the distance traveled or twice the stroke in feet. The area of the piston is 452.4 square inches, and twice the stroke is 7 feet. The work done on the piston in one revolution is, therefore,  $452.4 \times 50 \times 7 = 158,340$  foot-pounds. From the table  $c = 0.163$ , and therefore:

$$E = 158,340 \times 0.163 = 25,810 \text{ foot-pounds}$$

From the data given:  $n = 100$ ;  $D = 18$ ;  $N = 75$ . Substituting these values in [Equation \(2\)](#):

$$W = \frac{11,745 \times 100 \times 25,810}{18^2 \times 75^2} = 16,650 \text{ pounds, nearly}$$

**Spokes or Arms of Flywheels.**—Flywheel arms are usually of elliptical cross-section. The major axis of the ellipse is in the plane of rotation to give the arms greater resistance to bending stresses and reduce the air resistance which may be considerable at high velocity. The stresses in the arms may be severe, due to the inertia of a heavy rim when sudden load changes occur. The strength of the arms should equal three-fourths the strength of the shaft in torsion.

If  $W$  equals the width of the arm at the hub (length of major axis) and  $D$  equals the shaft diameter, then  $W$  equals  $1.3D$  for a wheel having 6 arms; and for an 8-arm wheel  $W$  equals  $1.2D$ . The thickness of the arm at the hub (length of minor axis) equals one-half the width. The arms usually taper toward the rim. The cross-sectional area at the rim should not be less than two-thirds the area at the hub.

### Critical Speeds

**Critical Speeds of Rotating Bodies and Shafts.**—If a body or disk mounted upon a shaft rotates about it, the center of gravity of the body or disk must be at the center of the shaft, if a perfect running balance is to be obtained. In most cases, however, the center of gravity of the disk will be slightly removed from the center of the shaft, owing to the difficulty of perfect balancing. Now, if the shaft and disk be rotated, the centrifugal force generated by the heavier side will be greater than that generated by the lighter side geometrically opposite to it, and the shaft will deflect toward the heavier side, causing the center of the disk to rotate in a small circle. A rotating shaft without a body or disk mounted on it can also become dynamically unstable, and the resulting vibrations and deflections can result in damage not only to the shaft but to the machine of which it is a part. These conditions hold true up to a comparatively high speed; but a point is eventually reached (at several thousand revolutions per minute) when momentarily there will be excessive vibration, and then the parts will run quietly again. The speed at which this occurs is called the *critical speed* of the wheel or shaft, and the phenomenon itself for the shaft-mounted disk or body is called the *settling* of the wheel. The explanation of the settling is that at this speed the axis of rotation changes, and the wheel and shaft, instead of rotating about their geometrical center, begin to rotate about an axis through their center of gravity. The shaft itself is then deflected so that for every revolution its geometrical center traces a circle around the center of gravity of the rotating mass.

Critical speeds depend upon the magnitude or location of the load or loads carried by the shaft, the length of the shaft, its diameter and the kind of supporting bearings. The normal operating speed of a machine may or may not be higher than the critical speed. For instance, some steam turbines exceed the critical speed, although they do not run long enough at the critical speed for the vibrations to build up to an excessive amplitude. The practice of the General Electric Co. at Schenectady is to keep below the critical speeds. It is assumed that the maximum speed of a machine may be within 20 per cent high or low of the critical speed without vibration troubles. Thus, in a design of steam turbine sets, critical speed is a factor that determines the size of the shafts for both the generators and turbines. Although a machine may run very close to the critical speed, the alignment and play of the bearings, the balance and construction generally, will require extra care, resulting in a more expensive machine; moreover, while such a machine may run smoothly for a considerable time, any looseness or play that may develop later, causing a slight imbalance, will immediately set up excessive vibrations.

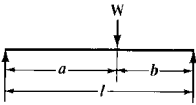
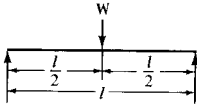
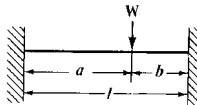
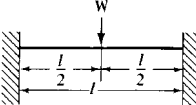
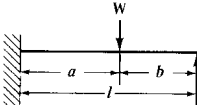
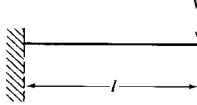
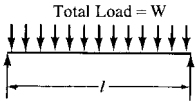
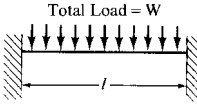
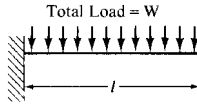
The formulas commonly used to determine critical speeds are sufficiently accurate for general purposes. There are cases, however, where the torque applied to a shaft has an important effect on its critical speed. Investigations have shown that the critical speeds of a uniform shaft are decreased as the applied torque is increased, and that there exist critical torques which will reduce the corresponding critical speed of the shaft to zero. A detailed analysis of the effects of applied torques on critical speeds may be found in a paper, "Critical Speeds of Uniform Shafts under Axial Torque," by Golumb and Rosenberg, presented at the First U.S. National Congress of Applied Mechanics in 1951.

**Formulas for Critical Speeds.**—The critical speed formulas given in the accompanying table (from the paper on Critical Speed Calculation presented before the ASME by S. H. Weaver) apply to (1) shafts with single concentrated loads and (2) shafts carrying uniformly distributed loads. These formulas also cover different conditions as regards bearings. If the bearings are self-aligning or very short, the shaft is considered supported at the ends; whereas, if the bearings are long and rigid, the shaft is considered fixed. These formulas, for both concentrated and distributed loads, apply to vertical shafts as well as horizontal shafts, the critical speeds having the same value in both cases. The data required for the solution of critical speed problems are the same as for shaft deflection. As the shaft is usually of variable diameter and its stiffness is increased by a long hub, an ideal shaft of uniform diameter and equal stiffness must be assumed.



**CRITICAL SPEEDS**

**Critical Speed Formulas**

| Formulas for Single Concentrated Load  |  |   |
|--|--|---|
|  $N = 387,000 \frac{d^2}{ab} \sqrt{\frac{l}{W}}$ <p>Bearings supported</p>   |  $N = 1,550,500 \frac{d^2}{l \sqrt{Wl}}$ <p>Bearings supported</p>  |  $N = 387,000 \frac{d^2 l}{ab} \sqrt{\frac{l}{Wab}}$ <p>Bearings fixed</p>   |
|  $N = 3,100,850 \frac{d^2}{l \sqrt{Wl}}$ <p>Bearings fixed</p>   |  $N = 775,200 \frac{d^2 l}{ab} \sqrt{\frac{l}{Wa(3l+b)}}$ <p>One-fixed — One supported</p>                            |  $N = 387,000 \frac{d^2}{l \sqrt{Wl}}$ <p>One fixed — One free end</p>   |
| Formulas for Distributed Loads—First Critical Speed  |  |   |
| <p>Total Load = W</p>  $N = 2,232,500 \frac{d^2}{l \sqrt{Wl}}$ $N_1 = 4,760,000 \frac{d}{l^2}$ <p>Bearings supported</p> | <p>Total Load = W</p>  $N = 4,979,250 \frac{d^2}{l \sqrt{Wl}}$ $N_1 = 10,616,740 \frac{d}{l^2}$ <p>Bearings fixed</p> | <p>Total Load = W</p>  $N = 795,200 \frac{d^2}{l \sqrt{Wl}}$ $N_1 = 1,695,500 \frac{d}{l^2}$ <p>One fixed—One free end</p> |

$N$  = critical speed, RPM

$N_1$  = critical speed of shaft alone

$d$  = diameter of shaft, in inches

$W$  = load applied to shaft, in pounds

$l$  = distance between centers of bearings, in inches

$a$  and  $b$  = distances from bearings to load

In calculating critical speeds, the weight of the shaft is either neglected or, say, one-half to two-thirds of the weight is added to the concentrated load. The formulas apply to steel shafts having a modulus of elasticity  $E = 29,000,000$ . Although a shaft carrying a number of loads or a distributed load may have an infinite number of critical speeds, ordinarily it is the first critical speed that is of importance in engineering work. The first critical speed is obtained by the formulas given in the distributed loads portion of the table [Critical Speed Formulas](#).

### Balancing Rotating Parts

**Static Balancing.**—There are several methods of testing the standing or static balance of a rotating part. A simple method that is sometimes used for flywheels, etc., is illustrated by the diagram, Fig. 1. An accurate shaft is inserted through the bore of the finished wheel, which is then mounted on carefully leveled "parallels" A. If the wheel is in an unbalanced state, it will turn until the heavy side is downward. When it will stand in any position as the result of counterbalancing and reducing the heavy portions, it is said to be in standing or static balance. Another test which is used for disk-shaped parts is shown in Fig. 2. The disk D is mounted on a vertical arbor attached to an adjustable cross-slide B. The latter is carried by a table C, which is supported by a knife-edged bearing. A pendulum having an adjustable screw-weight W at the lower end is suspended from cross-slide B. To test the static balance of disk D, slide B is adjusted until pointer E of the pendulum coincides with the center of a stationary scale F. Disk D is then turned halfway around without moving the slide, and if the indicator remains stationary, it shows that the disk is in balance for this particular position. The test is then repeated for ten or twelve other positions, and the heavy sides are reduced, usually by drilling out the required amount of metal. Several other devices for testing static balance are designed on this same principle.

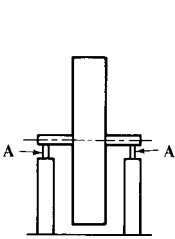


Fig. 1.

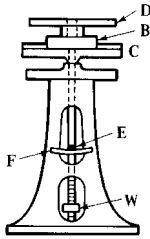


Fig. 2.

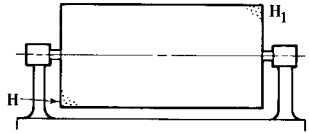


Fig. 3.

**Running or Dynamic Balance.**—A cylindrical body may be in perfect static balance and not be in a balanced state when rotating at high speed. If the part is in the form of a thin disk, static balancing, if carefully done, may be accurate enough for high speeds, but if the rotating part is long in proportion to its diameter, and the unbalanced portions are at opposite ends or in different planes, the balancing must be done so as to counteract the centrifugal force of these heavy parts when they are rotating rapidly. This process is known as a running balance or dynamic balancing. To illustrate, if a heavy section is located at H (Fig. 3), and another correspondingly heavy section at  $H_1$ , one may exactly counterbalance the other when the cylinder is stationary, and this static balance may be sufficient for a part rigidly mounted and rotating at a comparatively slow speed; but when the speed is very high, as in turbine rotors, etc., the heavy masses H and  $H_1$ , being in different planes, are in an unbalanced state owing to the effect of centrifugal force, which results in excessive strains and injurious vibrations. Theoretically, to obtain a perfect running balance, the exact positions of the heavy sections should be located and the balancing effected either by reducing their weight or by adding counterweights opposite each section and in the same plane at the proper radius; but if the rotating part is rigidly mounted on a stiff shaft, a running balance that is sufficiently accurate for practical purposes can be obtained by means of comparatively few counterbalancing weights located with reference to the unbalanced parts.

**Balancing Calculations.**—As indicated previously, centrifugal forces caused by an unbalanced mass or masses in a rotating machine member cause additional loads on the bearings which are transmitted to the housing or frame and to other machine members. Such dynamically unbalanced conditions can occur even though static balance (balance at

zero speed) exists. Dynamic balance can be achieved by the addition of one or two masses rotating about the same axis and at the same speed as the unbalanced masses. A single unbalanced mass can be balanced by one counterbalancing mass located 180 degrees opposite and in the same plane of rotation as the unbalanced mass, if the product of their respective radii and masses are equal; i.e.,  $M_1r_1 = M_2r_2$ . Two or more unbalanced masses rotating in the same plane can be balanced by a single mass rotating in the same plane, or by two masses rotating about the same axis in two separate planes. Likewise, two or more unbalanced masses rotating in different planes about a common axis can be balanced by two masses rotating about the same axis in separate planes. When the unbalanced masses are in separate planes they may be in static balance but not in dynamic balance; i.e., they may be balanced when not rotating but unbalanced when rotating. If a system is in dynamic balance, it will remain in balance at all speeds, although this is not strictly true at the critical speed of the system. (See *Critical Speeds* on page 195.)

In all the equations that follow, the symbol  $M$  denotes either mass in kilograms or in slugs, or weight in pounds. Either mass or weight units may be used and the equations may be used with metric or with customary English units without change; however, in a given problem the units must be all metric or all customary English.

**Counterbalancing Several Masses Located in a Single Plane.**—In all balancing problems, it is the product of counterbalancing mass (or weight) and its radius that is calculated; it is thus necessary to select either the mass or the radius and then calculate the other value from the product of the two quantities. Design considerations usually make this decision self-evident. The angular position of the counterbalancing mass must also be calculated. Referring to Fig. 4:

$$M_B r_B = \sqrt{(\sum Mr \cos \theta)^2 + (\sum Mr \sin \theta)^2} \quad (1)$$

$$\tan \theta_B = \frac{-\sum Mr \sin \theta}{-\sum Mr \cos \theta} = \frac{y}{x} \quad (2)$$

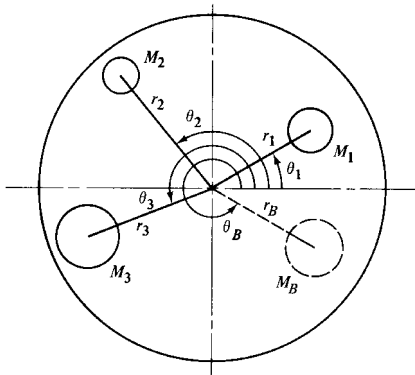


Fig. 4.

**Table 1. Relationship of the Signs of the Functions of the Angle with Respect to the Quadrant in Which They Occur**

|        |                        |                 |                 |                 |                 |
|--------|------------------------|-----------------|-----------------|-----------------|-----------------|
|        | Angle $\theta$         |                 |                 |                 |                 |
|        |                        | 0° to 90°       | 90° to 180°     | 180° to 270°    | 270° to 360°    |
|        | Signs of the Functions |                 |                 |                 |                 |
|        | tan                    | $\frac{+y}{+x}$ | $\frac{+y}{-x}$ | $\frac{-y}{-x}$ | $\frac{-y}{+x}$ |
| sine   | $\frac{+y}{+r}$        | $\frac{+y}{+r}$ | $\frac{-y}{+r}$ | $\frac{-y}{+r}$ |                 |
| cosine | $\frac{+x}{+r}$        | $\frac{-x}{+r}$ | $\frac{-x}{+r}$ | $\frac{+x}{+r}$ |                 |

where:

$M_1, M_2, M_3, \dots M_n$  = any unbalanced mass or weight, kg or lb

$M_B$  = counterbalancing mass or weight, kg or lb

$r$  = radius to center of gravity of any unbalanced mass or weight, mm or inch

$r_B$  = radius to center of gravity of counterbalancing mass or weight, mm or inch

$\theta$  = angular position of  $r$  of any unbalanced mass or weight, degrees

$\theta_B$  = angular position of  $r_B$  of counterbalancing mass or weight, degrees

$x$  and  $y$  = see Table 1

Table 1 is helpful in finding the angular position of the counterbalancing mass or weight. It indicates the range of the angles within which this angular position occurs by noting the plus and minus signs of the numerator and the denominator of the terms in Equation (2). In a like manner, Table 1 is helpful in determining the sign of the sine or cosine functions for angles ranging from 0 to 360 degrees. Balancing problems are usually solved most conveniently by arranging the arithmetical calculations in a tabular form.

Example: Referring to Fig. 4, the particular values of the unbalanced weights have been entered in the table below. Calculate the magnitude of the counterbalancing weight if its radius is to be 10 inches.

| $M$ |     | $r$<br>in. | $\theta$<br>deg. | cos $\theta$ | sin $\theta$ | $Mr \cos \theta$                 | $Mr \sin \theta$               |
|-----|-----|------------|------------------|--------------|--------------|----------------------------------|--------------------------------|
| No. | lb. |            |                  |              |              |                                  |                                |
| 1   | 10  | 10         | 30               | 0.8660       | 0.5000       | 86.6                             | 50.0                           |
| 2   | 5   | 20         | 120              | -0.5000      | 0.8660       | -50.0                            | 86.6                           |
| 3   | 15  | 15         | 200              | -0.9397      | -0.3420      | -211.4                           | -77.0                          |
|     |     |            |                  |              |              | -174.8 = $\Sigma Mr \cos \theta$ | 59.6 = $\Sigma Mr \sin \theta$ |

$$M_B = \frac{\sqrt{(\Sigma Mr \cos \theta)^2 + (\Sigma Mr \sin \theta)^2}}{r_B} = \frac{\sqrt{(-174.8)^2 + (59.6)^2}}{10}$$

$$M_B = 18.5 \text{ lb}$$

$$\tan \theta_B = \frac{-\Sigma Mr \sin \theta}{-\Sigma Mr \cos \theta} = \frac{-(59.6)}{-(-174.8)} = \frac{-y}{+x}; \theta_B = 341^\circ 10'$$

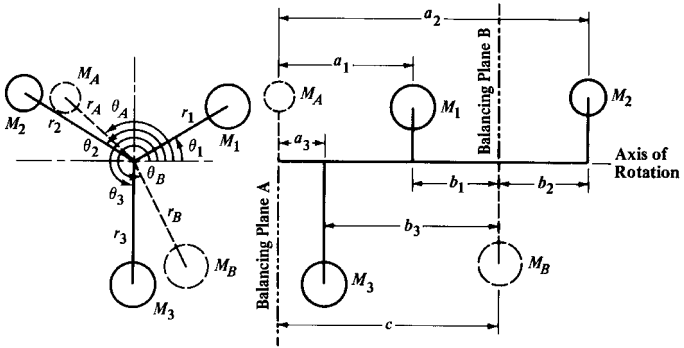


Fig. 5.

**Counterbalancing Masses Located in Two or More Planes.**—Unbalanced masses or weights rotating about a common axis in two separate planes of rotation form a couple, which must be counterbalanced by masses or weights, also located in two separate planes, call them planes A and B, and rotating about the same common axis (see *Couples*, page 147). In addition, they must be balanced in the direction perpendicular to the axis, as before. Since two counterbalancing masses are required, two separate equations are required to calculate the product of each mass or weight and its radius, and two additional equations are required to calculate the angular positions. The planes A and B selected as balancing planes may be any two planes separated by any convenient distance  $c$ , along the axis of rotation. In Fig. 5:

For balancing plane A:

$$M_A r_A = \frac{\sqrt{(\sum M r b \cos \theta)^2 + (\sum M r b \sin \theta)^2}}{c} \quad (3)$$

$$\tan \theta_A = \frac{-(\sum M r b \sin \theta)}{-(\sum M r b \cos \theta)} = \frac{y}{x} \quad (4)$$

For balancing plane B:

$$M_B r_B = \frac{\sqrt{(\sum M r a \cos \theta)^2 + (\sum M r a \sin \theta)^2}}{c} \quad (5)$$

$$\tan \theta_B = \frac{-(\sum M r a \sin \theta)}{-(\sum M r a \cos \theta)} = \frac{y}{x} \quad (6)$$

Where:  $M_A$  and  $M_B$  are the mass or weight of the counterbalancing masses in the balancing planes A and B, respectively;  $r_A$  and  $r_B$  are the radii; and  $\theta_A$  and  $\theta_B$  are the angular positions of the balancing masses in these planes.  $M$ ,  $r$ , and  $\theta$  are the mass or weight, radius, and angular positions of the unbalanced masses, with the subscripts defining the particular mass to which the values are assigned. The length  $c$ , the distance between the balancing planes, is always a positive value. The axial dimensions,  $a$  and  $b$ , may be either positive or negative, depending upon their position relative to the balancing plane; for example, in Fig. 5, the dimension  $b_2$  would be negative.

*Example:* Referring to Fig. 5, a set of values for the masses and dimensions has been selected and put into convenient table form below. The separation of balancing planes,  $c$ , is assumed as being 15 inches. If in balancing plane A, the radius of the counterbalancing

weight is selected to be 10 inches; calculate the magnitude of the counterbalancing mass and its position. If in balancing plane *B*, the counterbalancing mass is selected to be 10 lb; calculate its radius and position.

For balancing plane *A*:

| Plane    | <i>M</i><br>lb | <i>r</i><br>in. | $\theta$<br>deg. | Balancing Plane <i>A</i> |            |                             |                             |
|----------|----------------|-----------------|------------------|--------------------------|------------|-----------------------------|-----------------------------|
|          |                |                 |                  | <i>b</i><br>in.          | <i>Mrb</i> | <i>Mrb</i> cos $\theta$     | <i>Mrb</i> sin $\theta$     |
| 1        | 10             | 8               | 30               | 6                        | 480        | 415.7                       | 240.0                       |
| 2        | 8              | 10              | 135              | -6                       | -480       | 339.4                       | -339.4                      |
| 3        | 12             | 9               | 270              | 12                       | 1296       | <u>0.0</u>                  | <u>-1296.0</u>              |
| <i>A</i> | ?              | 10              | ?                | 15 <sup>a</sup>          | ...        | 755.1                       | -1395.4                     |
| <i>B</i> | 10             | ?               | ?                | 0                        | ...        | = $\Sigma Mrb$ cos $\theta$ | = $\Sigma Mrb$ sin $\theta$ |

<sup>a</sup> 15 inches = distance *c* between planes *A* and *B*.

$$M_A = \frac{\sqrt{(\Sigma Mrb \cos \theta)^2 + (\Sigma Mrb \sin \theta)^2}}{r_A c} = \frac{\sqrt{(755.1)^2 + (-1395.4)^2}}{10(15)}$$

$$M_A = 10.6 \text{ lb}$$

$$\tan \theta_A = \frac{-\Sigma Mrb \sin \theta}{-\Sigma Mrb \cos \theta} = \frac{-(-1395.4)}{-(755.1)} = \frac{+y}{-x}$$

$$\theta_A = 118^\circ 25'$$

For balancing plane *B*:

| Plane    | <i>M</i><br>lb | <i>r</i><br>in. | $\theta$<br>deg. | Balancing Plane <i>B</i> |            |                             |                             |
|----------|----------------|-----------------|------------------|--------------------------|------------|-----------------------------|-----------------------------|
|          |                |                 |                  | <i>a</i><br>in.          | <i>Mra</i> | <i>Mra</i> cos $\theta$     | <i>Mra</i> sin $\theta$     |
| 1        | 10             | 8               | 30               | 9                        | 720        | 623.5                       | 360.0                       |
| 2        | 8              | 10              | 135              | 21                       | 1680       | -1187.9                     | 1187.9                      |
| 3        | 12             | 9               | 270              | 3                        | 324        | <u>0.0</u>                  | <u>-324.0</u>               |
| <i>A</i> | ?              | 10              | ?                | 0                        | ...        | -564.4                      | 1223.9                      |
| <i>B</i> | 10             | ?               | ?                | 15 <sup>a</sup>          | ...        | = $\Sigma Mra$ cos $\theta$ | = $\Sigma Mra$ sin $\theta$ |

<sup>a</sup> 15 inches = distance *c* between planes *A* and *B*.

$$r_B = \frac{\sqrt{(\Sigma Mra \cos \theta)^2 + (\Sigma Mra \sin \theta)^2}}{M_B c} = \frac{\sqrt{(-564.4)^2 + (1223.9)^2}}{10(15)}$$

$$= 8.985 \text{ in.}$$

$$\tan \theta_B = \frac{-\Sigma Mra \sin \theta}{-\Sigma Mra \cos \theta} = \frac{-(1223.9)}{-(-564.4)} = \frac{-y}{+x}$$

$$\theta_B = 294^\circ 45'$$

**Balancing Lathe Fixtures.**—Lathe fixtures rotating at a high speed require balancing. Often it is assumed that the center of gravity of the workpiece and fixture, and of the counterbalancing masses are in the same plane; however, this is not usually the case. Counterbalancing masses are required in two separate planes to prevent excessive vibration or bearing loads at high speeds.

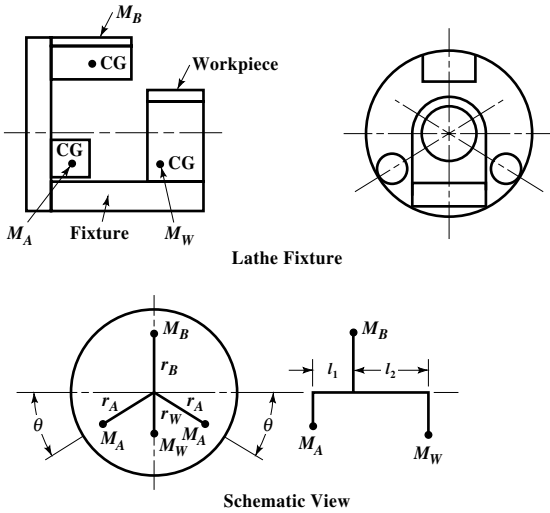


Fig. 6.

Usually a single counterbalancing mass is placed in one plane selected to be 180 degrees directly opposite the combined center of gravity of the workpiece and the fixture. Two equal counterbalancing masses are then placed in the second counterbalancing plane, equally spaced on each side of the fixture. Referring to Fig. 6, the two counterbalancing masses  $M_A$  and the two angles  $\theta$  are equal. For the design in this illustration, the following formulas can be used to calculate the magnitude of the counterbalancing masses. Since their angular positions are fixed by the design, they are not calculated.

$$M_B = \frac{M_w r_w (l_1 + l_2)}{r_B l_1} \quad (7)$$

$$M_A = \frac{M_B r_B - M_w r_w}{2 r_A \sin \theta} \quad (8)$$

In these formulas  $M_w$  and  $r_w$  denote the mass or weight and the radius of the combined center of gravity of the workpiece and the fixture.

In Fig. 6 the combined weight of the workpiece and the fixture is 18.5 lb. The following dimensions were determined from the layout of the fixture and by calculating the centers of gravity:  $r_w = 2$  in.;  $r_A = 6.25$  in.;  $r_B = 6$  in.;  $l_1 = 3$  in.;  $l_2 = 5$  in.; and  $\theta = 30^\circ$ . Calculate the weights of the counterbalancing masses.

$$M_B = \frac{M_w r_w (l_1 + l_2)}{r_B l_1} = \frac{18.5 \times 2 \times 8}{6 \times 3} = 16.44 \text{ lb}$$

$$M_A = \frac{M_B r_B - M_w r_w}{2 r_A \sin \theta} = \frac{(16.44 \times 6) - (18.5 \times 2)}{(2 \times 6.25) \sin 30^\circ} = 9.86 \text{ lb (each weight)}$$

## STRENGTH OF MATERIALS

### Introduction

Strength of materials deals with the relations between the external forces applied to elastic bodies and the resulting deformations and stresses. In the design of structures and machines, the application of the principles of strength of materials is necessary if satisfactory materials are to be utilized and adequate proportions obtained to resist functional forces.

Forces are produced by the action of gravity, by accelerations and impacts of moving parts, by gasses and fluids under pressure, by the transmission of mechanical power, etc. In order to analyze the stresses and deflections of a body, the magnitudes, directions and points of application of forces acting on the body must be known. Information given in the Mechanics section provides the basis for evaluating force systems.

The time element in the application of a force on a body is an important consideration. Thus a force may be static or change so slowly that its maximum value can be treated as if it were static; it may be suddenly applied, as with an impact; or it may have a repetitive or cyclic behavior.

The environment in which forces act on a machine or part is also important. Such factors as high and low temperatures; the presence of corrosive gases, vapors and liquids; radiation, etc. may have a marked effect on how well parts are able to resist stresses.

**Throughout the Strength of Materials section in this Handbook, both English and metric SI data and formulas are given to cover the requirements of working in either system of measurement. Formulas and text relating exclusively to SI units are given in bold-face type.**

**Mechanical Properties of Materials.**—Many mechanical properties of materials are determined from tests, some of which give relationships between stresses and strains as shown by the curves in the accompanying figures.

*Stress* is force per unit area and is usually expressed in pounds per square inch. If the stress tends to stretch or lengthen the material, it is called *tensile* stress; if to compress or shorten the material, a *compressive* stress; and if to shear the material, a *shearing* stress. Tensile and compressive stresses always act at right-angles to (normal to) the area being considered; shearing stresses are always in the plane of the area (at right-angles to compressive or tensile stresses).

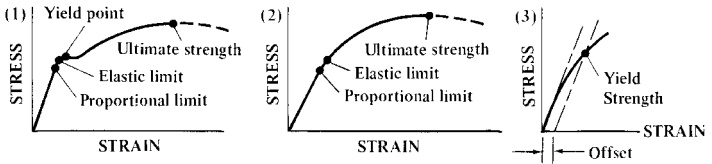


Fig. 1. Stress-strain curves

**In the SI, the unit of stress is the pascal (Pa), the newton per meter squared ( $\text{N}/\text{m}^2$ ). The megapascal (newtons per millimeter squared) is often an appropriate sub-multiple for use in practice.**

*Unit strain* is the amount by which a dimension of a body changes when the body is subjected to a load, divided by the original value of the dimension. The simpler term *strain* is often used instead of unit strain.

*Proportional limit* is the point on a stress-strain curve at which it begins to deviate from the straight-line relationship between stress and strain.



*Elastic limit* is the maximum stress to which a test specimen may be subjected and still return to its original length upon release of the load. A material is said to be stressed within the *elastic region* when the working stress does not exceed the elastic limit, and to be stressed in the *plastic region* when the working stress does exceed the elastic limit. The elastic limit for steel is for all practical purposes the same as its proportional limit.

*Yield point* is a point on the stress-strain curve at which there is a sudden increase in strain without a corresponding increase in stress. Not all materials have a yield point. Some representative values of the yield point (in ksi) are as follows:

|                            |       |   |        |
|----------------------------|-------|---|--------|
| Aluminum, wrought, 2014-T6 | 60    | Titanium, pure                                      | 55-70  |
| Aluminum, wrought, 6061-T6 | 35    | Titanium, alloy, 5Al, 2.5Sn                         | 110    |
| Beryllium copper           | 140   | Steel for bridges and buildings,                    | 33     |
| Brass, naval               | 25-50 | ASTM A7-61T, all shapes                             |        |
| Cast iron, malleable       | 32-45 | Steel, castings, high strength, for structural pur- | 40-145 |
| Cast iron, nodular         | 45-65 | poses, ASTM A148.60 (seven grades)                  |        |
| Magnesium, AZ80A-T5        | 38    | Steel, stainless (0.08-0.2C, 17Cr, 7Ni) 1/4 hard    | 78     |

*Yield strength,  $S_y$* , is the maximum stress that can be applied without permanent deformation of the test specimen. This is the value of the stress at the elastic limit for materials for which there is an elastic limit. Because of the difficulty in determining the elastic limit, and because many materials do not have an elastic region, yield strength is often determined by the offset method as illustrated by the accompanying figure at (3). Yield strength in such a case is the stress value on the stress-strain curve corresponding to a definite amount of permanent set or strain, usually 0.1 or 0.2 per cent of the original dimension. Yield strength data for various materials are given in tables starting on pages 417, 419, 463, 464, 466, 468, 472, 554, 556, 560, 569, 570, 575, 580, 588, 590, 591, and elsewhere.

*Ultimate strength,  $S_u$* , (also called *tensile strength*) is the maximum stress value obtained on a stress-strain curve.

*Modulus of elasticity,  $E$* , (also called *Young's modulus*) is the ratio of unit stress to unit strain within the proportional limit of a material in tension or compression. Some representative values of Young's modulus (in  $10^6$  psi) are as follows:

|                             |      |  |      |
|-----------------------------|------|--|------|
| Aluminum, cast, pure        | 9    | Magnesium, AZ80A-T5                            | 6.5  |
| Aluminum, wrought, 2014-T6  | 10.6 | Titanium, pure                                 | 15.5 |
| Beryllium copper            | 19   | Titanium, alloy, 5 Al, 2.5 Sn                  | 17   |
| Brass, naval                | 15   | Steel for bridges and buildings,               | 29   |
| Bronze, phosphor, ASTM B159 | 15   | ASTM A7-61T, all shapes                        |      |
| Cast iron, malleable        | 26   | Steel, castings, high strength, for structural | 29   |
| Cast iron, nodular          | 23.5 | purposes, ASTM A148-60 (seven grades)          |      |

*Modulus of elasticity in shear,  $G$* , is the ratio of unit stress to unit strain within the proportional limit of a material in shear.

*Poisson's ratio,  $\mu$* , is the ratio of lateral strain to longitudinal strain for a given material subjected to uniform longitudinal stresses within the proportional limit. The term is found in certain equations associated with strength of materials. Values of Poisson's ratio for common materials are as follows:

|                  |       |                 |       |
|------------------|-------|-----------------|-------|
| Aluminum         | 0.334 | Nickel silver   | 0.322 |
| Beryllium copper | 0.285 | Phosphor bronze | 0.349 |
| Brass            | 0.340 | Rubber          | 0.500 |
| Cast iron, gray  | 0.211 | Steel, cast     | 0.265 |
| Copper           | 0.340 | high carbon     | 0.295 |
| Inconel          | 0.290 | mild            | 0.303 |
| Lead             | 0.431 | nickel          | 0.291 |
| Magnesium        | 0.350 | Wrought iron    | 0.278 |
| Monel metal      | 0.320 | Zinc            | 0.331 |

**Compressive Properties.**—From compression tests, *compressive yield strength*,  $S_{cy}$ , and *compressive ultimate strength*,  $S_{cu}$ , are determined. Ductile materials under compression loading merely swell or buckle without fracture, hence do not have a compressive ultimate strength.

**Shear Properties.**—The properties of *shear yield strength*,  $S_{sy}$ , *shear ultimate strength*,  $S_{su}$ , and the *modulus of rigidity*,  $G$ , are determined by direct shear and torsional tests. The modulus of rigidity is also known as the modulus of elasticity in shear. It is the ratio of the shear stress,  $\tau$ , to the shear strain,  $\gamma$ , in radians, within the proportional limit:  $G = \tau/\gamma$ .

**Creep.**—Continuing changes in dimensions of a stressed material over time is called creep, and it varies with different materials and periods under stress, also with temperature. Creep tests may take some time as it is necessary to apply a constant tensile load to a specimen under a selected temperature. Measurements are taken to record the resulting elongation at time periods sufficiently long for a relationship to be established. The data are then plotted as elongation against time. The load is applied to the specimen only after it has reached the testing temperature, and causes an initial elastic elongation that includes some plastic deformation if the load is above the proportional limit for the material.

Some combinations of stress and temperature may cause failure of the specimen. Others show initial high rates of deformation, followed by decreasing, then constant, rates over long periods. Generally testing times to arrive at the constant rate of deformation are over 1000 hours.

**Creep Rupture.**—Tests for creep rupture are similar to creep tests but are prolonged until the specimen fails. Further data to be obtained from these tests include time to rupture, amount of elongation, and reduction of area. Stress-rupture tests are performed without measuring the elongation, so that no strain data are recorded, time to failure, elongation and reduction of area being sufficient. Sometimes, a V-notch is cut in the specimen to allow measurement of notch sensitivity under the testing conditions.

**Stress Analysis.**—Stresses, deflections, strains, and loads may be determined by application of strain gages or lacquers to the surface of a part, then applying loads simulating those to be encountered in service. Strain gages are commercially available in a variety of configurations and are usually cemented to the part surface. The strain gages are then calibrated by application of a known moment, load, torque, or pressure. The electrical characteristics of the strain gages change in proportion to the amount of strain, and the magnitude of changes in these characteristics under loads to be applied in service indicate changes caused by stress in the shape of the components being tested.

Lacquers are compounded especially for stress analysis and are applied to the entire part surface. When the part is loaded, and the lacquer is viewed under light of specific wavelength, stresses are indicated by color shading in the lacquer. The presence and intensity of the strains can then be identified and measured on the part(s) or on photographs of the setup. From such images, it is possible to determine the need for thicker walls, strengthening ribs and other modifications to component design that will enable the part to withstand stresses in service.

Most of these tests have been standardized by the American Society for Testing and Materials (ASTM), and are published in their *Book of Standards* in separate sections for metals, plastics, rubber, and wood. Many of the test methods are also adopted by the American National Standards Institute (ANSI).

**Fatigue Properties.**—When a material is subjected to many cycles of stress reversal or fluctuation (variation in magnitude without reversal), failure may occur, even though the maximum stress at any cycle is considerably less than the value at which failure would occur if the stress were constant. Fatigue properties are determined by subjecting test specimens to stress cycles and counting the number of cycles to failure. From a series of such tests in which maximum stress values are progressively reduced, S-N diagrams can be

plotted as illustrated by the accompanying figures. The S-N diagram Fig. 2a shows the behavior of a material for which there is an *endurance limit*,  $S_{en}$ . Endurance limit is the stress value at which the number of cycles to failure is infinite. Steels have endurance limits that vary according to hardness, composition, and quality; but many non-ferrous metals do not. The S-N diagram Fig. 2b does not have an endurance limit. For a metal that does not have an endurance limit, it is standard practice to specify fatigue strength as the stress value corresponding to a specific number of stress reversals, usually 100,000,000 or 500,000,000.

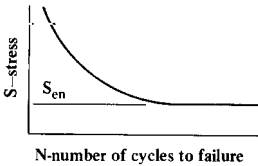


Fig. 2a. S-N endurance limit



Fig. 2b. S-N no endurance limit

**The Influence of Mean Stress on Fatigue.**—Most published data on the fatigue properties of metals are for completely reversed alternating stresses, that is, the mean stress of the cycle is equal to zero. However, if a structure is subjected to stresses that fluctuate between different values of tension and compression, then the mean stress is not zero.

When fatigue data for a specified mean stress and design life are not available for a material, the influence of nonzero mean stress can be estimated from empirical relationships that relate failure at a given life, under zero mean stress, to failure at the same life under zero mean cyclic stress. One widely used formula is Goodman's linear relationship, which is

$$S_a = S(1 - S_m/S_u)$$

where  $S_a$  is the alternating stress associated with some nonzero mean stress,  $S_m$ .  $S$  is the alternating fatigue strength at zero mean stress.  $S_u$  is the ultimate tensile strength.

Goodman's linear relationship is usually represented graphically on a so-called *Goodman Diagram*, shown in Fig. 3a. The alternating fatigue strength or the alternating stress for a given number of endurance cycles is plotted on the ordinate (y-axis) and the static tensile strength is plotted on the abscissa (x-axis). The straight line joining the alternating fatigue strength,  $S$ , and the tensile strength,  $S_u$ , is the Goodman line.

The value of an alternating stress  $S_{ax}$  at a known value of mean stress  $S_{mx}$  is determined as shown by the dashed lines on the diagram.

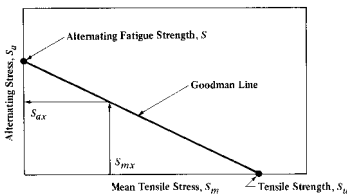


Fig. 3a. Goodman Diagram

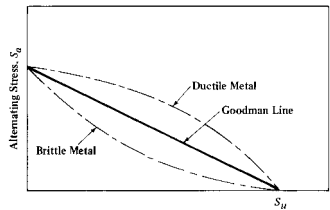


Fig. 3b. Mean Tensile Stress

For ductile materials, the Goodman law is usually conservative, since approximately 90 per cent of actual test data for most ferrous and nonferrous alloys fall above the Goodman line, even at low endurance values where the yield strength is exceeded. For many brittle

materials, however, actual test values can fall below the Goodman line, as illustrated in Fig. 3b

As a rule of thumb, materials having an elongation of less than 5 per cent in a tensile test may be regarded as brittle. Those having an elongation of 5 per cent or more may be regarded as ductile.

**Cumulative Fatigue Damage.**—Most data are determined from tests at a constant stress amplitude. This is easy to do experimentally, and the data can be presented in a straightforward manner. In actual engineering applications, however, the alternating stress amplitude usually changes in some way during service operation. Such changes, referred to as “spectrum loading,” make the direct use of standard S-N fatigue curves inappropriate. A problem exists, therefore, in predicting the fatigue life under varying stress amplitude from conventional, constant-amplitude S-N fatigue data.

The assumption in predicting spectrum loading effects is that operation at a given stress amplitude and number of cycles will produce a certain amount of permanent fatigue damage and that subsequent operation at different stress amplitude and number of cycles will produce additional fatigue damage and a sequential accumulation of total damage, which at a critical value will cause fatigue failure. Although the assumption appears simple, the amount of damage incurred at any stress amplitude and number of cycles has proven difficult to determine, and several “cumulative damage” theories have been advanced.

One of the first and simplest methods for evaluating cumulative damage is known as Miner's law or the linear damage rule, where it is assumed that  $n_1$  cycles at a stress of  $S_1$ , for which the average number of cycles to failure is  $N_1$ , cause an amount of damage  $n_1/N_1$ . Failure is predicted to occur when

$$\Sigma n/N = 1$$

The term  $n/N$  is known as the “cycle ratio” or the damage fraction.

The greatest advantages of the Miner rule are its simplicity and prediction reliability, which approximates that of more complex theories. For these reasons the rule is widely used. It should be noted, however, that it does not account for all influences, and errors are to be expected in failure prediction ability.

**Modes of Fatigue Failure.**—Several modes of fatigue failure are:

*Low/High-Cycle Fatigue:* This fatigue process covers cyclic loading in two significantly different domains, with different physical mechanisms of failure. One domain is characterized by relatively low cyclic loads, strain cycles confined largely to the elastic range, and long lives or a high number of cycles to failure; traditionally, this has been called “high-cycle fatigue.” The other domain has cyclic loads that are relatively high, significant amounts of plastic strain induced during each cycle, and short lives or a low number of cycles to failure. This domain has commonly been called “low-cycle fatigue” or cyclic strain-controlled fatigue.

The transition from low- to high-cycle fatigue behavior occurs in the range from approximately 10,000 to 100,000 cycles. Many define low-cycle fatigue as failure that occurs in 50,000 cycles or less.

*Thermal Fatigue:* Cyclic temperature changes in a machine part will produce cyclic stresses and strains if natural thermal expansions and contractions are either wholly or partially constrained. These cyclic strains produce fatigue failure just as though they were produced by external mechanical loading. When strain cycling is produced by a fluctuating temperature field, the failure process is termed “thermal fatigue.”

While thermal fatigue and mechanical fatigue phenomena are very similar, and can be mathematically expressed by the same types of equations, the use of mechanical fatigue results to predict thermal fatigue performance must be done with care. For equal values of plastic strain range, the number of cycles to failure is usually up to 2.5 times lower for thermally cycled than for mechanically cycled samples.

**Corrosion Fatigue:** Corrosion fatigue is a failure mode where cyclic stresses and a corrosion-producing environment combine to initiate and propagate cracks in fewer stress cycles and at lower stress amplitudes than would be required in a more inert environment. The corrosion process forms pits and surface discontinuities that act as stress raisers to accelerate fatigue cracking. The cyclic loads may also cause cracking and flaking of the corrosion layer, baring fresh metal to the corrosive environment. Each process accelerates the other, making the cumulative result more serious.

**Surface or Contact Fatigue:** Surface fatigue failure is usually associated with rolling surfaces in contact, and results in pitting, cracking, and spalling of the contacting surfaces from cyclic Hertz contact stresses that cause the maximum values of cyclic shear stresses to be slightly below the surface. The cyclic subsurface shear stresses generate cracks that propagate to the contacting surface, dislodging particles in the process.

**Combined Creep and Fatigue:** In this failure mode, all of the conditions for both creep failure and fatigue failure exist simultaneously. Each process influences the other in producing failure, but this interaction is not well understood.

**Factors of Safety.**—There is always a risk that the working stress to which a member is subjected will exceed the strength of its material. The purpose of a factor of safety is to minimize this risk.

Factors of safety can be incorporated into design calculations in many ways. For most calculations the following equation is used:

$$s_w = S_m / f_s \quad (1)$$

where  $f_s$  is the factor of safety,  $S_m$  is the strength of the material in pounds per square inch, and  $S_w$  is the allowable working stress, also in pounds per square inch. Since the factor of safety is greater than 1, the allowable working stress will be less than the strength of the material.

In general,  $S_m$  is based on yield strength for ductile materials, ultimate strength for brittle materials, and fatigue strength for parts subjected to cyclic stressing. Most strength values are obtained by testing standard specimens at 68°F. in normal atmospheres. If, however, the character of the stress or environment differs significantly from that used in obtaining standard strength data, then special data must be obtained. If special data are not available, standard data must be suitably modified.

General recommendations for values of factors of safety are given in the following list.

| $f_s$   | Application  |
|---------|--|
| 1.3–1.5 | For use with highly reliable materials where loading and environmental conditions are not severe, and where weight is an important consideration.  |
| 1.5–2   | For applications using reliable materials where loading and environmental conditions are not severe.   |
| 2–2.5   | For use with ordinary materials where loading and environmental conditions are not severe.   |
| 2.5–3   | For less tried and for brittle materials where loading and environmental conditions are not severe.  |
| 3–4     | For applications in which material properties are not reliable and where loading and environmental conditions are not severe, or where reliable materials are to be used under difficult loading and environmental conditions. |

**Working Stress.**—Calculated working stresses are the products of calculated nominal stress values and stress concentration factors. Calculated nominal stress values are based on the assumption of idealized stress distributions. Such nominal stresses may be simple stresses, combined stresses, or cyclic stresses. Depending on the nature of the nominal stress, one of the following equations applies:

$$s_w = K\sigma \quad (2) \qquad s_w = K\sigma' \quad (4) \qquad s_w = K\sigma_{cy} \quad (6)$$

$$s_w = K\tau \quad (3) \qquad s_w = K\tau' \quad (5) \qquad s_w = K\tau_{cy} \quad (7)$$

where  $K$  is a stress concentration factor;  $\sigma$  and  $\tau$  are, respectively, simple normal (tensile or compressive) and shear stresses;  $\sigma'$  and  $\tau'$  are combined normal and shear stresses;  $\sigma_{cy}$  and  $\tau_{cy}$  are cyclic normal and shear stresses.

Where there is uneven stress distribution, as illustrated in the table (on page 213) of simple stresses for Cases 3, 4 and 6, the maximum stress is the one to which the stress concentration factor is applied in computing working stresses. The location of the maximum stress in each case is discussed under the section *Simple Stresses* and the formulas for these maximum stresses are given in the *Table of Simple Stresses* on page 213.

**Stress Concentration Factors.**—Stress concentration is related to type of material, the nature of the stress, environmental conditions, and the geometry of parts. When stress concentration factors that specifically match all of the foregoing conditions are not available, the following equation may be used:

$$K = 1 + q(K_t - 1) \quad (8)$$

$K_t$  is a theoretical stress concentration factor that is a function only of the geometry of a part and the nature of the stress;  $q$  is the *index of sensitivity* of the material. If the geometry is such as to provide no theoretical stress concentration,  $K_t = 1$ .

Curves for evaluating  $K_t$  are on pages 209 through 212. For constant stresses in cast iron and in ductile materials,  $q = 0$  (hence  $K = 1$ ). For constant stresses in brittle materials such as hardened steel,  $q$  may be taken as 0.15; for very brittle materials such as steels that have been quenched but not drawn,  $q$  may be taken as 0.25. When stresses are suddenly applied (impact stresses)  $q$  ranges from 0.4 to 0.6 for ductile materials; for cast iron it is taken as 0.5; and, for brittle materials, 1.

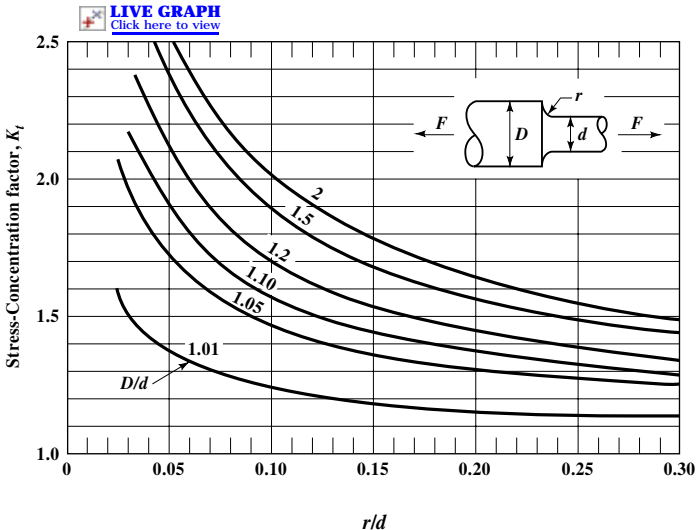


Fig. 4. Stress-concentration factor,  $K_t$ , for a filleted shaft in tension

STRESS CONCENTRATION FACTORS

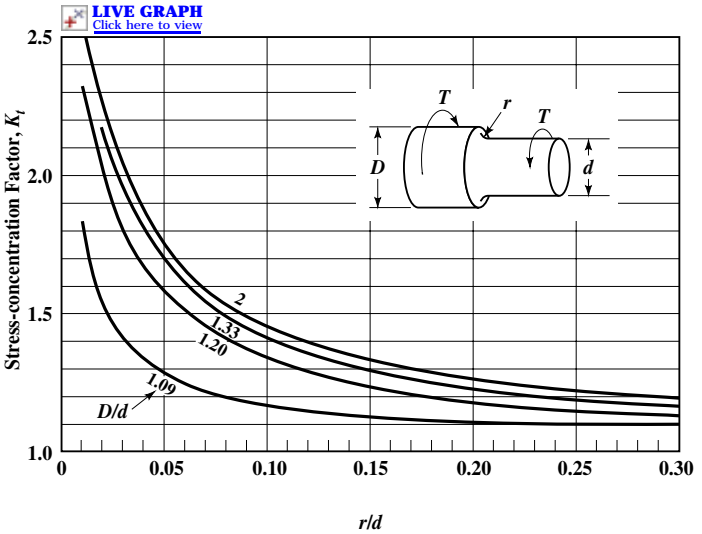


Fig. 5. Stress-concentration factor,  $K_t$ , for a filleted shaft in torsion<sup>a</sup>

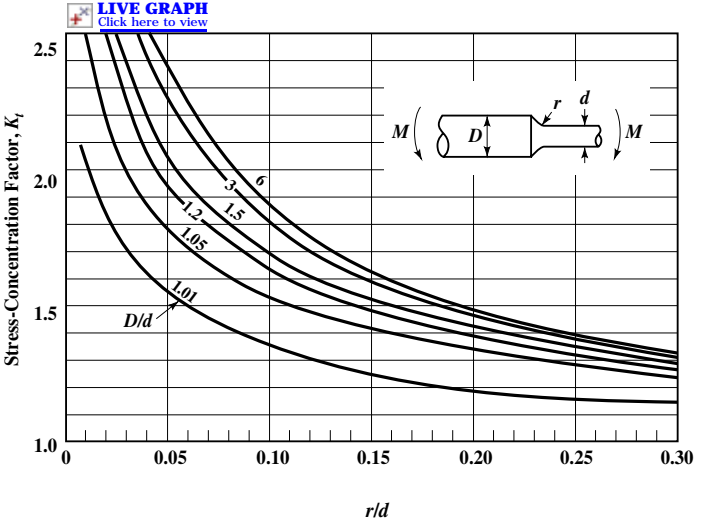


Fig. 6. Stress-concentration factor,  $K_t$ , for a shaft with shoulder fillet in bending<sup>a</sup>

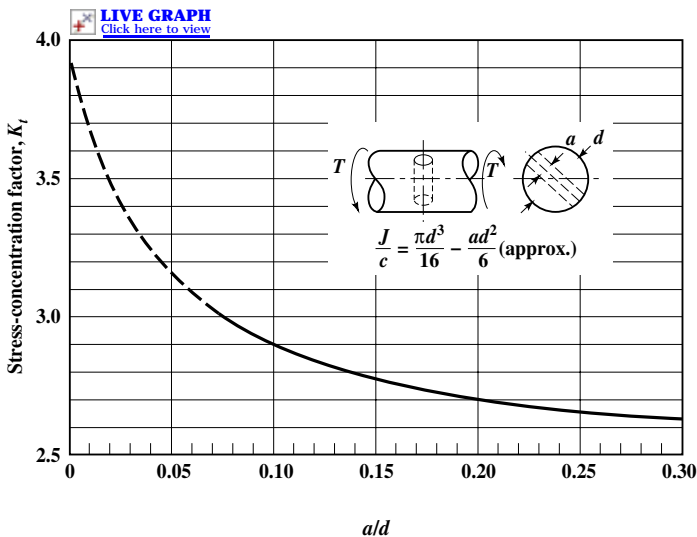


Fig. 7. Stress-concentration factor,  $K_t$ , for a shaft, with a transverse hole, in torsion<sup>a</sup>

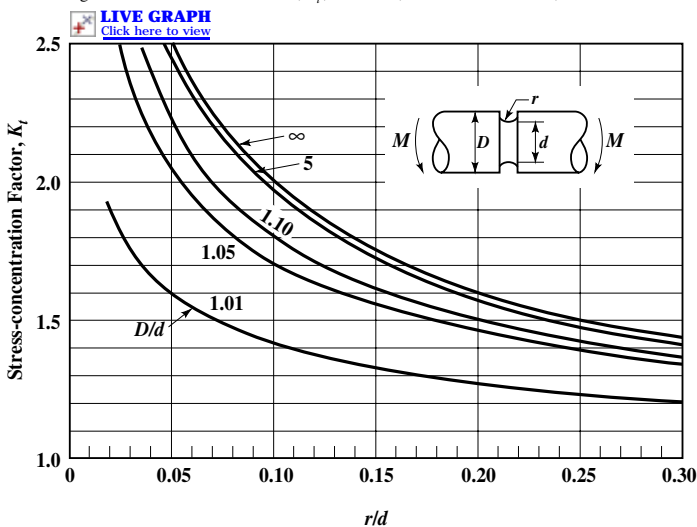
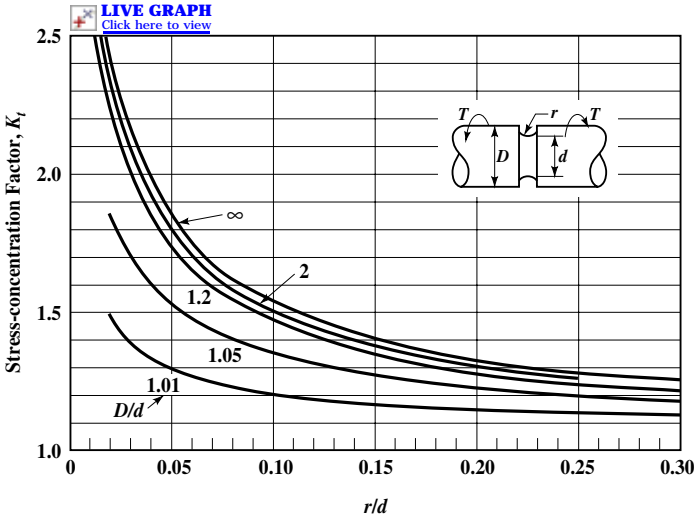
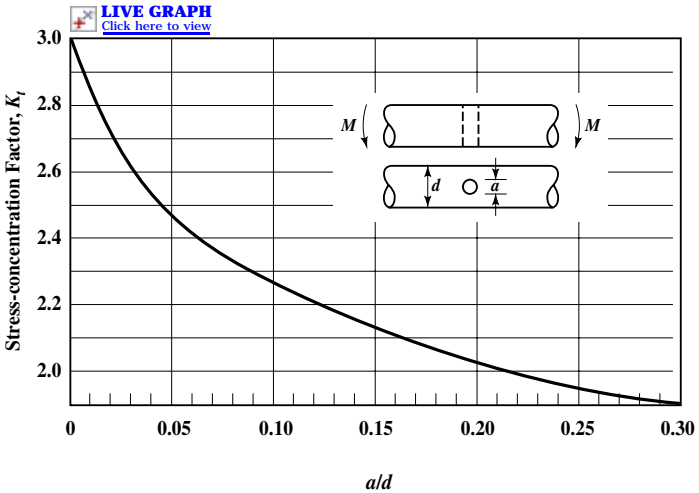


Fig. 8. Stress-concentration factor,  $K_t$ , for a grooved shaft in bending<sup>a</sup>



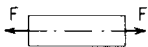
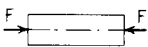
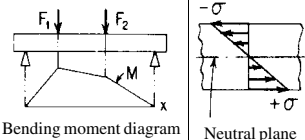
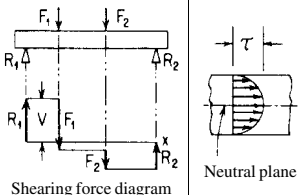
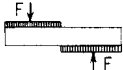
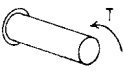
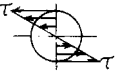
## STRESS CONCENTRATION FACTORS

Fig. 9. Stress-concentration factor,  $K_t$ , for a grooved shaft in torsion<sup>a</sup>Fig. 10. Stress-concentration factor,  $K_t$ , for a shaft, with a transverse hole, in bending<sup>a</sup>

<sup>a</sup> Source: R. E. Peterson, Design Factors for Stress Concentration, *Machine Design*, vol. 23, 1951. For other stress concentration charts, see Lipson and Juvinall, *The Handbook of Stress and Strength*, The Macmillan Co., 1963.

**Simple Stresses.**—Simple stresses are produced by constant conditions of loading on elements that can be represented as beams, rods, or bars. The table on page 213 summarizes information pertaining to the calculation of simple stresses. Following is an explanation of the symbols used in simple stress formulae:  $\sigma$  = simple normal (tensile or compressive) stress in pounds per square inch;  $\tau$  = simple shear stress in pounds per square inch;  $F$  = external force in pounds;  $V$  = shearing force in pounds;  $M$  = bending moment in inch-pounds;  $T$  = torsional moment in inch-pounds;  $A$  = cross-sectional area in square inches;  $Z$  = section modulus in inches<sup>3</sup>;  $Z_p$  = polar section modulus in inches<sup>3</sup>;  $I$  = moment of inertia in inches<sup>4</sup>;  $J$  = polar moment of inertia in inches<sup>4</sup>;  $a$  = area of the web of wide flange and I beams in square inches;  $y$  = perpendicular distance from axis through center of gravity of cross-sectional area to stressed fiber in inches;  $c$  = radial distance from center of gravity to stressed fiber in inches.

Table 2. Table of Simple Stresses

| Case | Type of Loading    | Illustration  | Stress Distribution   | Stress Equations   |
|------|--------------------|---|---|--|
| 1    | Direct tension     |    | Uniform   | $\sigma = \frac{F}{A}$ (9)   |
| 2    | Direct compression |    | Uniform   | $\sigma = -\frac{F}{A}$ (10)   |
| 3    | Bending            |    | Neutral plane   | $\sigma = \pm \frac{M}{Z} = \pm \frac{My}{I}$ (11)   |
| 4    | Shear              |   | Neutral plane   | For beams of rectangular cross-section:<br>$\tau = \frac{3V}{2A}$ (12)<br>For beams of solid circular cross-section:<br>$\tau = \frac{4V}{3A}$ (13)<br>For wide flange and I beams (approximately):<br>$\tau = \frac{V}{a}$ (14) |
| 5    | Direct shear       |  | Uniform   | $\tau = \frac{F}{A}$ (15)  |
| 6    | Torsion            |  |  | $\tau = \frac{T}{Z_p} = \frac{Tc}{J}$ (16)   |

SI metric units can be applied in the calculations in place of the English units of measurement without changes to the formulas. The SI units are the newton (N), which is the unit of force; the meter; the meter squared; the pascal (Pa) which is the

newton per meter squared ( $\text{N}/\text{m}^2$ ); and the newton-meter ( $\text{N} \cdot \text{m}$ ) for moment of force. Often in design work using the metric system, the millimeter is employed rather than the meter. In such instances, the dimensions can be converted to meters before the stress calculations are begun. Alternatively, the same formulas can be applied using millimeters in place of the meter, providing the treatment is consistent throughout. In such instances, stress and strength properties must be expressed in megapascals (MPa), which is the same as newtons per millimeter squared ( $\text{N}/\text{mm}^2$ ), and moments in newton-millimeters ( $\text{N} \cdot \text{mm}^2$ ). *Note:*  $1 \text{ N}/\text{mm}^2 = 1 \text{ N}/10^{-6}\text{m}^2 = 10^6 \text{ N}/\text{m}^2 = 1 \text{ meganewton}/\text{m}^2 = 1 \text{ megapascal}$ .

For direct tension and direct compression loading, Cases 1 and 2 in the table on page 213, the force  $F$  must act along a line through the center of gravity of the section at which the stress is calculated. The equation for direct compression loading applies only to members for which the ratio of length to least radius of gyration is relatively small, approximately 20, otherwise the member must be treated as a column.

The table *Stresses and Deflections in Beams* starting on page 261 give equations for calculating stresses due to bending for common types of beams and conditions of loading. Where these tables are not applicable, stress may be calculated using Equation (11) in the table on page 213. In using this equation it is necessary to determine the value of the bending moment at the point where the stress is to be calculated. For beams of constant cross-section, stress is ordinarily calculated at the point coinciding with the maximum value of bending moment. Bending loading results in the characteristic stress distribution shown in the table for Case 3. It will be noted that the maximum stress values are at the surfaces farthest from the neutral plane. One of the surfaces is stressed in tension and the other in compression. It is for this reason that the  $\pm$  sign is used in Equation (11). Numerous tables for evaluating section moduli are given in the section starting on page 236.

Shear stresses caused by bending have maximum values at neutral planes and zero values at the surfaces farthest from the neutral axis, as indicated by the stress distribution diagram shown for Case 4 in the *Table of Simple Stresses*. Values for  $V$  in Equations (12), (13) and (14) can be determined from shearing force diagrams. The shearing force diagram shown in Case 4 corresponds to the bending moment diagram for Case 3. As shown in this diagram, the value taken for  $V$  is represented by the greatest vertical distance from the  $x$  axis. The shear stress caused by direct shear loading, Case 5, has a uniform distribution. However, the shear stress caused by torsion loading, Case 6, has a zero value at the axis and a maximum value at the surface farthest from the axis.

**Deflections.**—For direct tension and direct compression loading on members with uniform cross sections, deflection can be calculated using Equation (17). For direct tension loading,  $e$  is an elongation; for direct compression loading,  $e$  is a contraction. Deflection is in inches when the load  $F$  is in pounds, the length  $L$  over which deflection occurs is in inches, the cross-sectional area  $A$  is in square inches, and the modulus of elasticity  $E$  is in pounds per square inch. The angular deflection of members with uniform circular cross sections subject to torsion loading can be calculated with Equation (18).

$$e = FL/AE \qquad (17) \qquad \theta = TL/GJ \qquad (18)$$

The angular deflection  $\theta$  is in radians when the torsional moment  $T$  is in inch-pounds, the length  $L$  over which the member is twisted is in inches, the modulus of rigidity  $G$  is in pounds per square inch, and the polar moment of inertia  $J$  is in inches<sup>4</sup>.

**Metric SI units can be used in Equations (17) and (18), where  $F$  = force in newtons (N);  $L$  = length over which deflection or twisting occurs in meters;  $A$  = cross-sectional area in meters squared;  $E$  = the modulus of elasticity in (newtons per meter squared);  $\theta$  = radians;  $T$  = the torsional moment in newton-meters (N·m);  $G$  = modulus of rigidity, in pascals; and  $J$  = the polar moment of inertia in meters<sup>4</sup>. If the load ( $F$ ) is applied as a weight, it should be noted that the weight of a mass  $M$  kilograms is  $Mg$  newtons,**

where  $g = 9.81 \text{ m/s}^2$ . Millimeters can be used in the calculations in place of meters, providing the treatment is consistent throughout.

**Combined Stresses.**—A member may be loaded in such a way that a combination of simple stresses acts at a point. Three general cases occur, examples of which are shown in the accompanying illustration Fig. 11.

*Superposition of Stresses:* Fig. 11 at (1) illustrates a common situation that results in simple stresses combining by superposition at points **a** and **b**. The equal and opposite forces  $F_1$  will cause a compressive stress  $\sigma_1 = -F_1/A$ . Force  $F_2$  will cause a bending moment  $M$  to exist in the plane of points **a** and **b**. The resulting stress  $\sigma_2 = \pm M/Z$ . The combined stress at point **a**,

$$\sigma'_a = -\frac{F_1}{A} - \frac{M}{Z} \quad (19) \quad \text{and at } \mathbf{b}, \quad \sigma'_b = -\frac{F_1}{A} + \frac{M}{Z} \quad (20)$$

where the minus sign indicates a compressive stress and the plus sign a tensile stress. Thus, the stress at **a** will be compressive and at **b** either tensile or compressive depending on which term in the equation for  $\sigma'_b$  has the greatest value.

*Normal Stresses at Right Angles:* This is shown in Fig. 11 at (2). This combination of stresses occurs, for example, in tanks subjected to internal or external pressure. The principle normal stresses are  $\sigma_x = F_1/A_1$ ,  $\sigma_y = F_2/A_2$ , and  $\sigma_z = 0$  in this plane stress problem. Determine the values of these three stresses with their signs, order them algebraically, and then calculate the maximum shear stress:

$$\tau = (\sigma_{\text{largest}} - \sigma_{\text{smallest}})/2 \quad (21)$$

*Normal and Shear Stresses:* The example in Fig. 11 at (3) shows a member subjected to a torsional shear stress,  $\tau = T/Z_p$ , and a direct compressive stress,  $\sigma = -F/A$ . At some point **a** on the member the principal normal stresses are calculated using the equation,

$$\sigma' = \frac{\sigma}{2} \pm \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} \quad (22)$$

The maximum shear stress is calculated by using the equation,

$$\tau' = \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} \quad (23)$$

The point **a** should ordinarily be selected where stress is a maximum value. For the example shown in the figure at (3), the point **a** can be anywhere on the cylindrical surface because the combined stress has the same value anywhere on that surface.

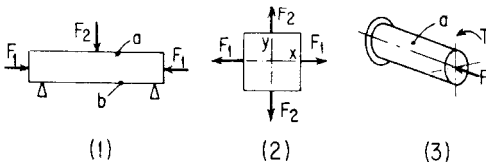


Fig. 11. Types of Combined Loading

**Tables of Combined Stresses.**—Beginning on page 216, these tables list equations for maximum nominal tensile or compressive (normal) stresses, and maximum nominal shear stresses for common machine elements. These equations were derived using general Equations (19), (20), (22), and (23). The equations apply to the critical points indicated on the

figures. Cases 1, 2, 3, and 4 are cantilever beams. These may be loaded with a combination of a vertical and horizontal force, or by a single oblique force. If the single oblique force  $F$  and the angle  $\theta$  are given, then horizontal and vertical forces can be calculated using the equations  $F_x = F \cos \theta$  and  $F_y = F \sin \theta$ . In cases 9 and 10 of the table, the equations for  $\sigma_a'$  can give a tensile and a compressive stress because of the  $\pm$  sign in front of the radical. Equations involving direct compression are valid only if machine elements have relatively short lengths with respect to their sections, otherwise column equations apply.

*Calculation of Worst Stress Condition:* Stress failure can occur at any critical point if either the tensile, compressive, or shear stress properties of the material are exceeded by the corresponding working stress. It is necessary to evaluate the factor of safety for each possible failure condition.

The following rules apply to calculations using equations in the *Table of Simple Stresses* on page 213, and to calculations based on Equations (19) and (20). *Rule 1:* For every calculated normal stress there is a corresponding induced shear stress; the value of the shear stress is equal to half that of the normal stress. *Rule 2:* For every calculated shear stress there is a corresponding induced normal stress; the value of the normal stress is equal to that of the shear stress. The tables of combined stress formulas, below, include equations for calculating both maximum nominal tensile or compressive stresses, and maximum nominal shear stresses.

**Formulas for Combined Stresses**

*(1) Circular Cantilever Beam in Direct Compression and Bending:*

| Type of Beam and Loading | Maximum Nominal Tensile or Compressive Stress  | Maximum Nominal Shear Stress                        |
|--------------------------|--|---|
|                          | $\sigma'_a = \frac{1.273}{d^2} \left( \frac{8LF_y}{d} - F_x \right)$ $\sigma'_b = -\frac{1.273}{d^2} \left( \frac{8LF_y}{d} + F_x \right)$ | $\tau'_a = 0.5 \sigma'_a$ $\tau'_b = 0.5 \sigma'_b$ |

*(2) Circular Cantilever Beam in Direct Tension and Bending:*

| Type of Beam and Loading | Maximum Nominal Tensile or Compressive Stress   | Maximum Nominal Shear Stress                        |
|--------------------------|---|---|
|                          | $\sigma'_a = \frac{1.273}{d^2} \left( F_x + \frac{8LF_y}{d} \right)$ $\sigma'_b = \frac{1.273}{d^2} \left( F_x - \frac{8LF_y}{d} \right)$ | $\tau'_a = 0.5 \sigma'_a$ $\tau'_b = 0.5 \sigma'_b$ |

*(3) Rectangular Cantilever Beam in Direct Compression and Bending:*

| Type of Beam and Loading | Maximum Nominal Tensile or Compressive Stress  | Maximum Nominal Shear Stress                        |
|--------------------------|--|---|
|                          | $\sigma'_a = \frac{1}{bh} \left( \frac{6LF_y}{h} - F_x \right)$ $\sigma'_b = -\frac{1}{bh} \left( \frac{6LF_y}{h} + F_x \right)$ | $\tau'_a = 0.5 \sigma'_a$ $\tau'_b = 0.5 \sigma'_b$ |

(4) Rectangular Cantilever Beam in Direct Tension and Bending:

| Type of Beam and Loading | Maximum Nominal Tensile or Compressive Stress   | Maximum Nominal Shear Stress                      |
|--------------------------|---|---|
|                          | $\sigma'_a = \frac{1}{bh} \left( F_x + \frac{6LF_y}{h} \right)$ $\sigma'_b = \frac{1}{bh} \left( F_x - \frac{6LF_y}{h} \right)$ | $\tau'_a = 0.5\sigma'_a$ $\tau'_b = 0.5\sigma'_b$ |

(5) Circular Beam or Shaft in Direct Compression and Bending:

| Type of Beam and Loading | Maximum Nominal Tensile or Compressive Stress  | Maximum Nominal Shear Stress                      |
|--------------------------|--|---|
|                          | $\sigma'_a = -\frac{1.273}{d^2} \left( \frac{2LF_y}{d} + F_x \right)$ $\sigma'_b = \frac{1.273}{d^2} \left( \frac{2LF_y}{d} - F_x \right)$ | $\tau'_a = 0.5\sigma'_a$ $\tau'_b = 0.5\sigma'_b$ |

(6) Circular Beam or Shaft in Direct Tension and Bending:

| Type of Beam and Loading | Maximum Nominal Tensile or Compressive Stress   | Maximum Nominal Shear Stress                      |
|--------------------------|---|---|
|                          | $\sigma'_a = \frac{1.273}{d^2} \left( F_x - \frac{2LF_y}{d} \right)$ $\sigma'_b = \frac{1.273}{d^2} \left( F_x + \frac{2LF_y}{d} \right)$ | $\tau'_a = 0.5\sigma'_a$ $\tau'_b = 0.5\sigma'_b$ |

(7) Rectangular Beam or Shaft in Direct Compression and Bending:

| Type of Beam and Loading | Maximum Nominal Tensile or Compressive Stress   | Maximum Nominal Shear Stress                      |
|--------------------------|---|---|
|                          | $\sigma'_a = -\frac{1}{bh} \left( \frac{3LF_y}{2h} + F_x \right)$ $\sigma'_b = \frac{1}{bh} \left( -\frac{3LF_y}{2h} - F_x \right)$ | $\tau'_a = 0.5\sigma'_a$ $\tau'_b = 0.5\sigma'_b$ |

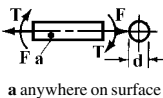
(8) Rectangular Beam or Shaft in Direct Tension and Bending:

| Type of Beam and Loading | Maximum Nominal Tensile or Compressive Stress   | Maximum Nominal Shear Stress                      |
|--------------------------|---|---|
|                          | $\sigma'_a = \frac{1}{bh} \left( F_x - \frac{3LF_y}{2h} \right)$ $\sigma'_b = \frac{1}{bh} \left( F_x + \frac{3LF_y}{2h} \right)$ | $\tau'_a = 0.5\sigma'_a$ $\tau'_b = 0.5\sigma'_b$ |

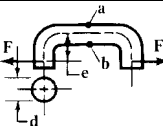
(9) Circular Shaft in Direct Compression and Torsion:

| Type of Beam and Loading     | Maximum Nominal Tensile or Compressive Stress  | Maximum Nominal Shear Stress  |
|------------------------------|--|---|
| <p>a anywhere on surface</p> | $\sigma'_a = -\frac{0.637}{d^2} \left[ F \pm \sqrt{F^2 + \left( \frac{8T}{d} \right)^2} \right]$ | $\tau'_a = -\frac{0.637}{d^2} \sqrt{F^2 + \left( \frac{8T}{d} \right)^2}$ |

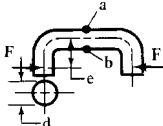
(10) Circular Shaft in Direct Tension and Torsion:

| Type of Beam and Loading   | Maximum Nominal Tensile or Compressive Stress   | Maximum Nominal Shear Stress   |
|--|---|--|
|  <p>a anywhere on surface</p> | $\sigma'_a = \frac{0.637}{d^2} \left[ F \pm \sqrt{F^2 + \left(\frac{8T}{d}\right)^2} \right]$ | $\tau'_a = \frac{0.637}{d^2} \sqrt{F^2 + \left(\frac{8T}{d}\right)^2}$ |

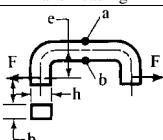
(11) Offset Link, Circular Cross Section, in Direct Tension:

| Type of Beam and Loading  | Maximum Nominal Tensile or Compressive Stress   | Maximum Nominal Shear Stress                      |
|---|---|---|
|  | $\sigma'_a = \frac{1.273F}{d^2} \left(1 - \frac{8e}{d}\right)$ $\sigma'_b = \frac{1.273F}{d^2} \left(1 + \frac{8e}{d}\right)$ | $\tau'_a = 0.5\sigma'_a$ $\tau'_b = 0.5\sigma'_b$ |

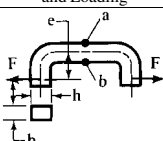
(12) Offset Link, Circular Cross Section, in Direct Compression:

| Type of Beam and Loading  | Maximum Nominal Tensile or Compressive Stress  | Maximum Nominal Shear Stress                      |
|---|--|---|
|  | $\sigma'_a = \frac{1.273F}{d^2} \left(\frac{8e}{d} - 1\right)$ $\sigma'_b = -\frac{1.273F}{d^2} \left(\frac{8e}{d} + 1\right)$ | $\tau'_a = 0.5\sigma'_a$ $\tau'_b = 0.5\sigma'_b$ |

(13) Offset Link, Rectangular Section, in Direct Tension:

| Type of Beam and Loading  | Maximum Nominal Tensile or Compressive Stress   | Maximum Nominal Shear Stress                      |
|---|---|---|
|  | $\sigma'_a = \frac{F}{bh} \left(1 - \frac{6e}{h}\right)$ $\sigma'_b = \frac{F}{bh} \left(1 + \frac{6e}{h}\right)$ | $\tau'_a = 0.5\sigma'_a$ $\tau'_b = 0.5\sigma'_b$ |

(14) Offset Link, Rectangular Section, in Direct Compression:

| Type of Beam and Loading  | Maximum Nominal Tensile or Compressive Stress  | Maximum Nominal Shear Stress                      |
|---|--|---|
|  | $\sigma'_a = \frac{F}{bh} \left(\frac{6e}{h} - 1\right)$ $\sigma'_b = -\frac{F}{bh} \left(\frac{6e}{h} + 1\right)$ | $\tau'_a = 0.5\sigma'_a$ $\tau'_b = 0.5\sigma'_b$ |

Formulas from the simple and combined stress tables, as well as tension and shear factors, can be applied without change in calculations using metric SI units. Stresses are given in newtons per meter squared (N/m<sup>2</sup>) or in N/mm<sup>2</sup>.

**Three-Dimensional Stress.**—Three-dimensional or triaxial stress occurs in assemblies such as a shaft press-fitted into a gear bore or in pipes and cylinders subjected to internal or external fluid pressure. Triaxial stress also occurs in two-dimensional stress problems if the loads produce normal stresses that are either both tensile or both compressive. In either case the calculated maximum shear stress, based on the corresponding two-dimensional theory, will be less than the true maximum value because of three-dimensional effects. Therefore, if the stress analysis is to be based on the maximum-shear-stress theory of failure, the triaxial stress cubic equation should first be used to calculate the three principal stresses and from these the true maximum shear stress. The following procedure provides the principal maximum normal tensile and compressive stresses and the true maximum shear stress at any point on a body subjected to any combination of loads.

The basis for the procedure is the stress cubic equation

$$S^3 - AS^2 + BS - C = 0$$

in which:

$$A = S_x + S_y + S_z$$

$$B = S_x S_y + S_y S_z + S_z S_x - S_{xy}^2 - S_{yz}^2 - S_{zx}^2$$

$$C = S_x S_y S_z + 2S_{xy} S_{yz} S_{zx} - S_x S_{yz}^2 - S_y S_{zx}^2 - S_z S_{xy}^2$$

and  $S_x$ ,  $S_y$ , etc., are as shown in Fig. 12.

The coordinate system  $XYZ$  in Fig. 12 shows the positive directions of the normal and shear stress components on an elementary cube of material. Only six of the nine components shown are needed for the calculations: the normal stresses  $S_x$ ,  $S_y$ , and  $S_z$  on three of the faces of the cube; and the three shear stresses  $S_{xy}$ ,  $S_{yz}$ , and  $S_{zx}$ . The remaining three shear stresses are known because  $S_{yx} = S_{xy}$ ,  $S_{zy} = S_{yz}$ , and  $S_{xz} = S_{zx}$ . The normal stresses  $S_x$ ,  $S_y$ , and  $S_z$  are shown as positive (tensile) stresses; the opposite direction is negative (compressive). The first subscript of each shear stress identifies the coordinate axis perpendicular to the plane of the shear stress; the second subscript identifies the axis to which the stress is parallel. Thus,  $S_{xy}$  is the shear stress in the  $YZ$  plane to which the  $X$  axis is perpendicular, and the stress is parallel to the  $Y$  axis.

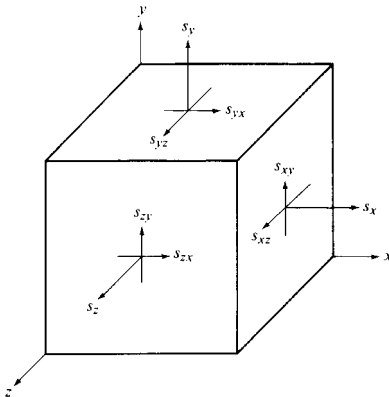


Fig. 12.  $XYZ$  Coordinate System Showing Positive Directions of Stresses

Step 1. Draw a diagram of the hardware to be analyzed, such as the shaft shown in Fig. 13, and show the applied loads  $P$ ,  $T$ , and any others.



Step 2. For any point at which the stresses are to be analyzed, draw a coordinate diagram similar to Fig. 12 and show the magnitudes of the stresses resulting from the applied loads (these stresses may be calculated by using standard basic equations from strength of materials, and should include any stress concentration factors).

Step 3. Substitute the values of the six stresses  $S_x$ ,  $S_y$ ,  $S_z$ ,  $S_{xy}$ ,  $S_{yz}$ , and  $S_{zx}$ , including zero values, into the formulas for the quantities  $A$  through  $K$ . The quantities  $I$ ,  $J$ , and  $K$  represent the principal normal stresses at the point analyzed. As a check, if the algebraic sum  $I + J + K$  equals  $A$ , within rounding errors, then the calculations up to this point should be correct.

$$D = A^2/3 - B \quad E = A \times B/3 - C - 2 \times A^3/27$$

$$F = \sqrt{(D^3/27)} \quad G = \arccos(-E/(2 \times F))$$

$$H = \sqrt{(D/3)} \quad I = 2 \times H \times \cos(G/3) + A/3$$

$$J = 2 \times H \times [\cos(G/3 + 120^\circ)] + A/3 \quad K = 2 \times H \times [\cos(G/3 + 240^\circ)] + A/3$$

Step 4. Calculate the true maximum shear stress,  $S_{s(\max)}$  using the formula

$$S_{s(\max)} = 0.5 \times (S_{\text{large}} - S_{\text{small}})$$

in which  $S_{\text{large}}$  is equal to the algebraically largest of the calculated principal stresses  $I$ ,  $J$ , or  $K$  and  $S_{\text{small}}$  is algebraically the smallest.

The maximum principal normal stresses and the maximum true shear stress calculated above may be used with any of the various theories of failure.

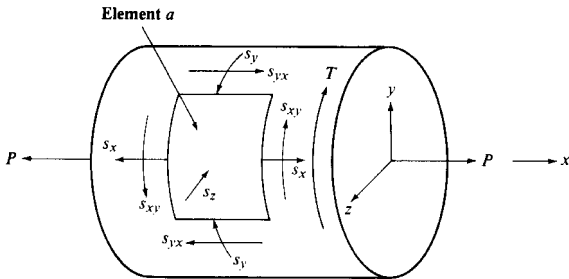


Fig. 13. Example of Triaxial Stress on an Element  $a$  of Shaft Surface Caused by Load  $P$ , Torque  $T$ , and 5000 psi Hydraulic Pressure

*Example:* A torque  $T$  on the shaft in Fig. 13 causes a shearing stress  $S_{xy}$  of 8000 psi in the outer fibers of the shaft; and the loads  $P$  at the ends of the shaft produce a tensile stress  $S_x$  of 4000 psi. The shaft passes through a hydraulic cylinder so that the shaft circumference is subjected to the hydraulic pressure of 5000 psi in the cylinder, causing compressive stresses  $S_y$  and  $S_z$  of -5000 psi on the surface of the shaft. Find the maximum shear stress at any point  $A$  on the surface of the shaft.

From the statement of the problem  $S_x = +4000$  psi,  $S_y = -5000$  psi,  $S_z = -5000$  psi,  $S_{xy} = +8000$  psi,  $S_{yz} = 0$  psi, and  $S_{zx} = 0$  psi.

$$A = 4000 - 5000 - 5000 = -6000$$

$$B = (4000 \times -5000) + (-5000 \times -5000) + (-5000 \times 4000) - 8000^2 - 0^2 - 0^2 = -7.9 \times 10^7$$

$$C = (4000 \times -5000 \times -5000) + 2 \times 8000 \times 0 \times 0 - (4000 \times 0^2) - (-5000 \times 0^2) - (-5000 \times 8000^2) = 4.2 \times 10^{11}$$

$$D = A^2/3 - B = 9.1 \times 10^7 \quad E = A \times B/3 - C - 2 \times A^3/27 = -2.46 \times 10^{11}$$

$$F = \sqrt{(D^3/27)} = 1.6706 \times 10^{11} \quad G = \arccos(-E/(2 \times F)) = 42.586 \text{ degrees}$$

$$H = \sqrt{(D/3)} = 5507.57 \quad I = 2 \times H \times \cos(G/3 + A/3) = 8678.8, \text{ say, } 8680 \text{ psi}$$

$$J = 2 \times H \times [\cos(G/3 + 120^\circ)] + A/3 = -9678.78, \text{ say, } -9680 \text{ psi}$$

$$K = 2 \times H [\cos(G/3 + 240^\circ)] + A/3 = -5000 \text{ psi}$$

Check:  $8680 + (-9680) + (-5000) = -6000$  within rounding error.

$$S_{s(\max)} = 0.5 \times (8680 - (-9680)) = 9180 \text{ psi}$$

**Sample Calculations.**—The following examples illustrate some typical strength of materials calculations, using both English and metric SI units of measurement.

*Example 1(a):* A round bar made from SAE 1025 low carbon steel is to support a direct tension load of 50,000 pounds. Using a factor of safety of 4, and assuming that the stress concentration factor  $K = 1$ , a suitable standard diameter is to be determined. Calculations are to be based on a yield strength of 40,000 psi.

Because the factor of safety and strength of the material are known, the allowable working stress  $s_w$  may be calculated using Equation (1):  $40,000/4 = 10,000$  psi. The relationship between working stress  $s_w$  and nominal stress  $\sigma$  is given by Equation (2). Since  $K = 1$ ,  $\sigma = 10,000$  psi. Applying Equation (9) in the *Table of Simple Stresses*, the area of the bar can be solved for:  $A = 50,000/10,000$  or 5 square inches. The next largest standard diameter corresponding to this area is  $2\frac{9}{16}$  inches.

*Example 1(b):* A similar example to that given in 1(a), using metric SI units is as follows. A round steel bar of 300 meganewtons/meter<sup>2</sup> yield strength, is to withstand a direct tension of 200 kilonewtons. Using a safety factor of 4, and assuming that the stress concentration factor  $K = 1$ , a suitable diameter is to be determined.

Because the factor of safety and the strength of the material are known, the allowable working stress  $s_w$  may be calculated using Equation (1):  $300/4 = 75$  mega-newtons/meter<sup>2</sup>. The relationship between working stress and nominal stress  $\sigma$  is given by Equation (2). Since  $K = 1$ ,  $\sigma = 75$  MN/m<sup>2</sup>. Applying Equation (9) in the , the area of the bar can be determined from:

$$A = \frac{200 \text{ kN}}{75 \text{ MN/m}^2} = \frac{200,000 \text{ N}}{75,000,000 \text{ N/m}^2} = 0.00267 \text{ m}^2$$

The diameter corresponding to this area is 0.058 meters, or approximately 0.06 m.

Millimeters can be employed in the calculations in place of meters, providing the treatment is consistent throughout. In this instance the diameter would be 60 mm.

*Note:* If the tension in the bar is produced by hanging a mass of  $M$  kilograms from its end, the value is  $Mg$  newtons, where  $g$  = approximately 9.81 meters per second<sup>2</sup>.

*Example 2(a):* What would the total elongation of the bar in Example 1(a) be if its length were 60 inches? Applying Equation (17),

$$e = \frac{50,000 \times 60}{5.157 \times 30,000,000} = 0.019 \text{ inch}$$

*Example 2(b):* What would be the total elongation of the bar in Example 1(b) if its length were 1.5 meters? The problem is solved by applying Equation (17) in which  $F = 200$  kilonewtons;  $L = 1.5$  meters;  $A = \pi \cdot 0.06^2/4 = 0.00283 \text{ m}^2$ . Assuming a modulus of elasticity  $E$  of 200 giganewtons/meter<sup>2</sup>, then the calculation is:

$$e = \frac{200,000 \times 1.5}{0.00283 \times 200,000,000,000} = 0.000530 \text{ m}$$

The calculation is less unwieldy if carried out using millimeters in place of meters; then  $F = 200$  kN;  $L = 1500$  mm;  $A = 2830 \text{ mm}^2$ , and  $E = 200,000 \text{ N/mm}^2$ . Thus:

$$e = \frac{200,000 \times 1500}{2830 \times 200,000} = 0.530 \text{ mm}$$

**Example 3(a):** Determine the size for the section of a square bar which is to be held firmly at one end and is to support a load of 3000 pounds at the outer end. The bar is to be 30 inches long and is to be made from SAE 1045 medium carbon steel with a yield point of 60,000 psi. A factor of safety of 3 and a stress concentration factor of 1.3 are to be used.

From Equation (1) the allowable working stress  $s_w = 60,000/3 = 20,000$  psi. The applicable equation relating working stress and nominal stress is Equation (2); hence,  $\sigma = 20,000/1.3 = 15,400$  psi. The member must be treated as a cantilever beam subject to a bending moment of  $30 \times 3000$  or 90,000 inch-pounds. Solving Equation (11) in the for section modulus:  $Z = 90,000/15,400 = 5.85$  inch<sup>3</sup>. The section modulus for a square section with neutral axis equidistant from either side is  $a^3/6$ , where  $a$  is the dimension of the square, so  $a = \sqrt[3]{35.1} = 3.27$  inches. The size of the bar can therefore be  $3\frac{5}{16}$  inches.

**Example 3(b):** A similar example to that given in Example 3(a), using metric SI units is as follows. Determine the size for the section of a square bar which is to be held firmly at one end and is to support a load of 1600 kilograms at the outer end. The bar is to be 1 meter long, and is to be made from steel with a yield strength of 500 newtons/mm<sup>2</sup>. A factor of safety of 3, and a stress concentration factor of 1.3 are to be used. The calculation can be performed using millimeters throughout.

From Equation (1) the allowable working stress  $s_w = 500 \text{ N/mm}^2/3 = 167 \text{ N/mm}^2$ . The formula relating working stress and nominal stress is Equation (2); hence  $\sigma = 167/1.3 = 128 \text{ N/mm}^2$ . Since a mass of 1600 kg equals a weight of 1600 g newtons, where  $g = 9.81$  meters/second<sup>2</sup>, the force acting on the bar is 15,700 newtons. The bending moment on the bar, which must be treated as a cantilever beam, is thus  $1000 \text{ mm} \times 15,700 \text{ N} = 15,700,000 \text{ N} \cdot \text{mm}$ . Solving Equation (11) in the for section modulus:  $Z = M/\sigma = 15,700,000/128 = 123,000 \text{ mm}^3$ . Since the section modulus for a square section with neutral axis equidistant from either side is  $a^3/6$ , where  $a$  is the dimension of the square,

$$a = \sqrt[3]{6 \times 123,000} = 90.4 \text{ mm}$$

**Example 4(a):** Find the working stress in a 2-inch diameter shaft through which a transverse hole  $\frac{1}{4}$  inch in diameter has been drilled. The shaft is subject to a torsional moment of 80,000 inch-pounds and is made from hardened steel so that the index of sensitivity  $q = 0.2$ .

The polar section modulus is calculated using the equation shown in the stress concentration curve for a Round Shaft in Torsion with Transverse Hole, Fig. 7, page 211.

$$\frac{J}{c} = Z_p = \frac{\pi \times 2^3}{16} - \frac{2^2}{4 \times 6} = 1.4 \text{ inches}^3$$

The nominal shear stress due to the torsion loading is computed using Equation (16) in the :

$$\tau = 80,000/1.4 = 57,200 \text{ psi}$$

Referring to the previously mentioned stress concentration curve on page 211,  $K_t$  is 2.82 since  $d/D$  is 0.125. The stress concentration factor may now be calculated by means of Equation (8):  $K = 1 + 0.2(2.82 - 1) = 1.36$ . Working stress calculated with Equation (3) is  $s_w = 1.36 \times 57,200 = 77,800$  psi.

**Example 4(b):** A similar example to that given in 4(a), using metric SI units is as follows. Find the working stress in a 50 mm diameter shaft through which a transverse hole 6 mm in diameter has been drilled. The shaft is subject to a torsional moment of 8000 newton-meters, and has an index of sensitivity of  $q = 0.2$ . If the calculation is made in millimeters, the torsional moment is 8,000,000 N · mm.

The polar section modulus is calculated using the equation shown in the stress concentration curve for a Round Shaft in Torsion with Transverse Hole, Fig. 7, page 211:

$$\frac{J}{c} = Z_p = \frac{\pi \times 50^3}{16} - \frac{6 \times 50^2}{6} = 24,544 - 2500 = 22,044 \text{ mm}^3$$

The nominal shear stress due to torsion loading is computed using Equation (16) in the :

$$\tau = 8,000,000/22,000 = 363 \text{ N/mm}^2 = 363 \text{ megapascals}$$

Referring to the previously mentioned stress concentration curve on page 211,  $K_t$  is 2.85, since  $a/d = 6/50 = 0.12$ . The stress concentration factor may now be calculated by means of Equation (8):  $K = 1 + 0.2(2.85 - 1) = 1.37$ . From Equation (3), working stress  $s_w = 1.37 \times 363 = 497 \text{ N/mm}^2 = 497 \text{ megapascals}$ .

Example 5(a): For Case 3 in the *Tables of Combined Stresses*, calculate the least factor of safety for a 5052-H32 aluminum beam is 10 inches long, one inch wide, and 2 inches high. Yield strengths are 23,000 psi tension; 21,000 psi compression; 13,000 psi shear. The stress concentration factor is 1.5;  $F_y$  is 600 lbs;  $F_x$  500 lbs.

From *Tables of Combined Stresses*, Case 3:

$$\sigma_b' = -\frac{1}{1 \times 2} \left( \frac{6 \times 10 \times 600}{2} + 500 \right) = -9250 \text{ psi (in compression)}$$

The other formulas for Case 3 give  $\sigma_a' = 8750$  psi (in tension);  $\tau_a' = 4375$  psi, and  $\tau_b' = 4625$  psi. Using Equation (4) for the nominal compressive stress of 9250 psi:  $S_w = 1.5 \times 9250 = 13,900$  psi. From Equation (1)  $f_s = 21,000/13,900 = 1.51$ . Applying Equations (1), (4) and (5) in appropriate fashion to the other calculated nominal stress values for tension and shear will show that the factor of safety of 1.51, governed by the compressive stress at  $b$  on the beam, is minimum.

Example 5(b): What maximum  $F$  can be applied in Case 3 if the aluminum beam is 200 mm long; 20 mm wide; 40 mm high;  $\theta = 30^\circ$ ;  $f_s = 2$ , governing for compression,  $K = 1.5$ , and  $S_m = 144 \text{ N/mm}^2$  for compression.

From Equation (1)  $S_w = -144 \text{ N/mm}^2$ . Therefore, from Equation (4),  $\sigma_b' = -72/1.5 = -48 \text{ N/mm}^2$ . Since  $F_x = F \cos 30^\circ = 0.866F$ , and  $F_y = F \sin 30^\circ = 0.5F$ :

$$-48 = -\frac{1}{20 \times 40} \left( 0.866F + \frac{6 \times 200 \times 0.5F}{40} \right) \quad F = 2420 \text{ N}$$

**Stresses and Deflections in a Loaded Ring.**—For *thin* rings, that is, rings in which the dimension  $d$  shown in the accompanying diagram is small compared with  $D$ , the maximum stress in the ring is due primarily to bending moments produced by the forces  $P$ . The maximum stress due to bending is:

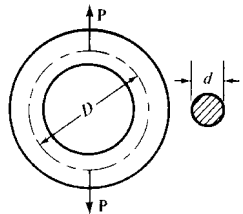
$$S = \frac{PDd}{4\pi I} \quad (24)$$

For a ring of circular cross section where  $d$  is the diameter of the bar from which the ring is made,

$$S = \frac{1.621PD}{d^3} \quad \text{or} \quad P = \frac{0.617Sd^3}{D} \quad (25)$$

The increase in the vertical diameter of the ring due to load  $P$  is:

$$\text{Increase in vertical diameter} = \frac{0.0186PD^3}{EI} \text{ inches} \quad (26)$$



The *decrease* in the horizontal diameter will be about 92% of the increase in the vertical diameter given by [Formula \(26\)](#). In the above formulas,  $P$  = load on ring in pounds;  $D$  = mean diameter of ring in inches;  $S$  = tensile stress in pounds per square inch,  $I$  = moment of inertia of section in inches<sup>4</sup>; and  $E$  = modulus of elasticity of material in pounds per square inch.

**Strength of Taper Pins.**—The mean diameter of taper pin required to safely transmit a known torque, may be found from the formulas:

$$d = 1.13 \sqrt{\frac{T}{DS}} \quad (27) \quad \text{and} \quad d = 283 \sqrt{\frac{HP}{NDS}} \quad (28a)$$

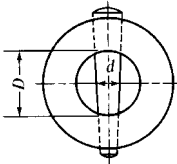
in which formulas  $T$  = torque in inch-pounds;  $S$  = safe unit stress in pounds per square inch; HP = horsepower transmitted;  $N$  = number of revolutions per minute; and  $d$  and  $D$  denote dimensions shown in the figure.

[Formula \(27\)](#) can be used with metric SI units where  $d$  and  $D$  denote dimensions shown in the figure in millimeters;  $T$  = torque in newton-millimeters ( $N \cdot \text{mm}$ ); and  $S$  = safe unit stress in newtons per millimeter<sup>2</sup> ( $\text{N}/\text{mm}^2$ ). [Formula \(28a\)](#) is replaced by:

$$d = 110.3 \sqrt{\frac{\text{Power}}{NDS}} \quad (28b)$$

where  $d$  and  $D$  denote dimensions shown in the figure in millimeters;  $S$  = safe unit stress in  $\text{N}/\text{mm}^2$ ;  $N$  = number of revolutions per minute, and Power = power transmitted in watts.

*Example 6(a):* A lever secured to a 2-inch round shaft by a steel tapered pin (dimension  $d = \frac{3}{8}$  inch) has a pull of 50 pounds at a 30-inch radius from shaft center. Find  $S$ , the unit working stress on the pin. By rearranging [Formula \(27\)](#):



$$S = \frac{1.27T}{Dd^2} = \frac{1.27 \times 50 \times 30}{2 \times \left(\frac{3}{8}\right)^2} \cong 6770 \text{ psi}$$

6770 pounds per square inch is a safe unit working stress for machine steel in shear.

Let  $P = 50$  pounds,  $R = 30$  inches,  $D = 2$  inches, and  $S = 6000$  pounds unit working stress. Using [Formula \(27\)](#) to find  $d$ :

$$d = 1.13 \sqrt{\frac{T}{DS}} = 1.13 \sqrt{\frac{50 \times 30}{2 \times 6000}} = 1.13 \sqrt{\frac{1}{8}} = 0.4 \text{ inch}$$

*Example 6(b):* A similar example using SI units is as follows: A lever secured to a 50 mm round shaft by a steel tapered pin ( $d = 10$  mm) has a pull of 200 newtons at a radius of 800 mm. Find  $S$ , the working stress on the pin. By rearranging [Formula \(27\)](#):

$$S = \frac{1.27T}{Dd^2} = \frac{1.27 \times 200 \times 800}{50 \times 10^2} = 40.6 \text{ N}/\text{mm}^2 = 40.6 \text{ megapascals}$$

If a shaft of 50 mm diameter is to transmit power of 12 kilowatts at a speed of 500 rpm, find the mean diameter of the pin for a material having a safe unit stress of 40  $\text{N}/\text{mm}^2$ . Using [Equation \(28b\)](#):

$$\begin{aligned} d &= 110.3 \sqrt{\frac{\text{Power}}{NDS}} & \text{then } d &= 110.3 \sqrt{\frac{12,000}{500 \times 50 \times 40}} \\ &= 110.3 \times 0.1096 = 12.09 \text{ mm} \end{aligned}$$

## PROPERTIES OF BODIES

### Center of Gravity

**Center of Gravity.**—The center of gravity of a body, volume, area, or line is that point at which if the body, volume, area, or line were suspended it would be perfectly balanced in all positions. For symmetrical bodies of uniform material it is at the geometric center. The center of gravity of a uniform round rod, for example, is at the center of its diameter half-way along its length; the center of gravity of a sphere is at the center of the sphere. For solids, areas, and arcs that are not symmetrical, the determination of the center of gravity may be made experimentally or may be calculated by the use of formulas.

The tables that follow give such formulas for some of the more important shapes. For more complicated and unsymmetrical shapes the methods outlined on page 231 may be used.

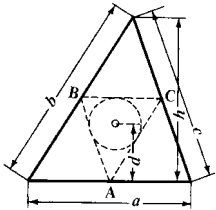
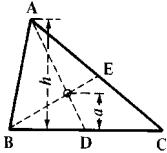
*Example:* A piece of wire is bent into the form of a semi-circular arc of 10-inch radius. How far from the center of the arc is the center of gravity located?

Accompanying the *Circular Arc* diagram on page 226 is a formula for the distance from the center of gravity of an arc to the center of the arc:  $a = 2r \div \pi$ . Therefore,

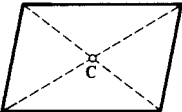
$$a = 2 \times 10 \div 3.1416 = 6.366 \text{ inches}$$

### Formulas for Center of Gravity

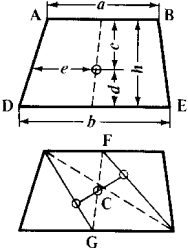
*Triangle:*

|   |   |
|---|---|
|   | <p><i>Perimeter</i></p> <p>If <math>A, B</math> and <math>C</math> are the middle points of the sides of the triangle, then the center of gravity is at the center of the circle that can be inscribed in triangle <math>ABC</math>. The distance <math>d</math> of the center of gravity from side <math>a</math> is:</p> $d = \frac{h(b+c)}{2(a+b+c)}$ <p>where <math>h</math> is the height perpendicular to <math>a</math>.</p> |
|  | <p><i>Area</i></p> <p>The center of gravity is at the intersection of lines <math>AD</math> and <math>BE</math>, which bisect the sides <math>BC</math> and <math>AC</math>. The perpendicular distance from the center of gravity to any one of the sides is equal to one-third the height perpendicular to that side. Hence, <math>a = h \div 3</math>.</p>   |

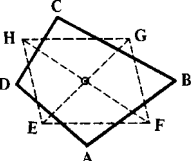
*Perimeter or Area of a Parallelogram :*

|   |   |
|---|---|
|  | <p>The center of gravity is at the intersection of the diagonals.</p> |
|---|---|

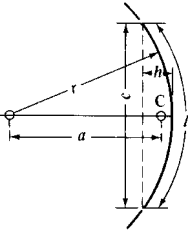
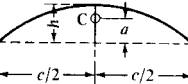
## Area of Trapezoid:

|   |  |
|---|--|
|  | <p>The center of gravity is on the line joining the middle points of parallel lines <math>AB</math> and <math>DE</math>.</p> $c = \frac{h(a+2b)}{3(a+b)} \quad d = \frac{h(2a+b)}{3(a+b)}$ $e = \frac{a^2 + ab + b^2}{3(a+b)}$ <p>The trapezoid can also be divided into two triangles. The center of gravity is at the intersection of the line joining the centers of gravity of the triangles, and the middle line <math>FG</math>.</p> |
|---|--|

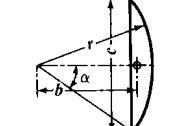
## Any Four-sided Figure :

|   |  |
|---|--|
|  | <p>Two cases are possible, as shown in the illustration. To find the center of gravity of the four-sided figure <math>ABCD</math>, each of the sides is divided into three equal parts. A line is then drawn through each pair of division points next to the points of intersection <math>A, B, C</math>, and <math>D</math> of the sides of the figure. These lines form a parallelogram <math>EFGH</math>; the intersection of the diagonals <math>EG</math> and <math>FH</math> locates center of gravity.</p> |
|---|--|

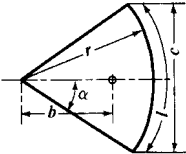
## Circular Arc:

|   |  |
|---|--|
|   | <p>The center of gravity is on the line that bisects the arc, at a distance <math>a = \frac{r \times c}{l} = \frac{c(c^2 + 4h^2)}{8lh}</math> from the center of the circle.</p> <p>For an arc equal to one-half the periphery:</p> $a = 2r \div \pi = 0.6366r$ <p>For an arc equal to one-quarter of the periphery:</p> $a = 2r \cdot \sqrt{2} \div \pi = 0.9003r$ <p>For an arc equal to one-sixth of the periphery:</p> $a = 3r \div \pi = 0.9549r$ |
|  | <p>An approximate formula is very nearly exact for all arcs less than one-quarter of the periphery is:</p> $a = \frac{2}{3}h$ <p>The error is only about one per cent for a quarter circle, and decreases for smaller arcs.</p>  |

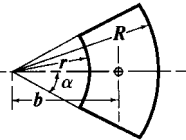
## Circle Segment :

|   |   |
|---|---|
|  | <p>The distance of the center of gravity from the center of the circle is:</p> $b = \frac{c^3}{12A} = \frac{2}{3} \times \frac{r^3 \sin^3 \alpha}{A}$ <p>in which <math>A</math> = area of segment.</p> |
|---|---|

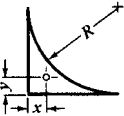
Circle Sector :

|   |   |
|---|---|
|  | <p>Distance <math>b</math> from center of gravity to center of circle is:</p> $b = \frac{2rc}{3l} = \frac{r^2c}{3A} = 38.197 \frac{r \sin \alpha}{\alpha}$ <p>in which <math>A</math> = area of sector, and <math>\alpha</math> is expressed in degrees.</p> <p>For the area of a half-circle:</p> $b = 4r \div 3\pi = 0.4244r$ <p>For the area of a quarter circle:</p> $b = 4\sqrt{2} \times r \div 3\pi = 0.6002r$ <p>For the area of a sixth of a circle:</p> $b = 2r \div \pi = 0.6366r$ |
|---|---|

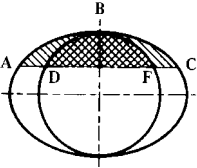
Part of Circle Ring :

|   |   |
|---|---|
|  | <p>Distance <math>b</math> from center of gravity to center of circle is:</p> $b = 38.197 \frac{(R^3 - r^3) \sin \alpha}{(R^2 - r^2) \alpha}$ <p>Angle <math>\alpha</math> is expressed in degrees.</p> |
|---|---|

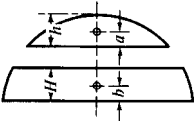
Spandrel or Fillet :

|  |  |
|--|--|
|  | <p>Area = <math>0.2146R^2</math>      <math>x = 0.2234R</math><br/> <math>y = 0.2234R</math></p> |
|--|--|

Segment of an Ellipse :

|   |  |
|---|--|
|  | <p>The center of gravity of an elliptic segment <math>ABC</math>, symmetrical about one of the axes, coincides with the center of gravity of the segment <math>DBF</math> of a circle, the diameter of which is equal to that axis of the ellipse about which the elliptic segment is symmetrical.</p> |
|---|--|

Spherical Surface of Segments and Zones of Spheres :

|   |  |
|---|--|
|  | <p>Distances <math>a</math> and <math>b</math> which determine the center of gravity, are:</p> $a = \frac{h}{2} \quad b = \frac{H}{2}$ |
|---|--|



Area of a Parabola :

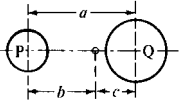
|  |   |
|--|---|
|  | <p>For the complete parabolic area, the center of gravity is on the center line or axis, and</p> $a = \frac{3h}{5}$ <p>For one-half of the parabola:</p> $a = \frac{3h}{5} \text{ and } b = \frac{3w}{8}$ <p>For the complement area ABC:</p> $c = 0.3h \text{ and } d = 0.75w$ |
|--|---|

Cylinder :

|  |  |
|--|--|
|  | <p>The center of gravity of a solid cylinder (or prism) with parallel end surfaces, is located at the middle of the line that joins the centers of gravity of the end surfaces.</p> <p>The center of gravity of a cylindrical surface or shell, with the base or end surface in one end, is found from:</p> $a = \frac{2h^2}{4h + d}$ <p>The center of gravity of a cylinder cut off by an inclined plane is located by:</p> $a = \frac{h}{2} + \frac{r^2 \tan^2 \alpha}{8h} \quad b = \frac{r^2 \tan \alpha}{4h}$ <p>where <math>\alpha</math> is the angle between the obliquely cut off surface and the base surface.</p> |
|--|--|

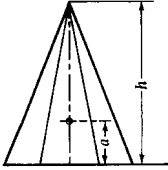
Portion of Cylinder :

|  |  |
|--|--|
|  | <p>For a solid portion of a cylinder, as shown, the center of gravity is determined by:</p> $a = \frac{3}{16} \times 3.1416r \quad b = \frac{3}{32} \times 3.1416h$ <p>For the cylindrical surface only:</p> $a = \frac{1}{4} \times 3.1416r \quad b = \frac{1}{8} \times 3.1416h$ <p>If the cylinder is hollow, the center of gravity of the solid shell is found by:</p> $a = \frac{3}{16} \times 3.1416 \frac{R^4 - r^4}{R^3 - r^3}$ $b = \frac{3}{32} \times 3.1416 \frac{H^4 - h^4}{H^3 - h^3}$ |
|--|--|

*Center of Gravity of Two Bodies :*

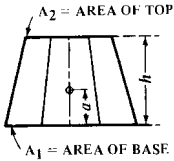
If the weights of the bodies are  $P$  and  $Q$ , and the distance between their centers of gravity is  $a$ , then:

$$b = \frac{Qa}{P+Q} \quad c = \frac{Pa}{P+Q}$$

*Pyramid :*

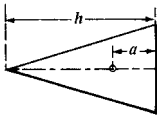
In a solid pyramid the center of gravity is located on the line joining the apex with the center of gravity of the base surface, at a distance from the base equal to one-quarter of the height; or  $a = \frac{1}{4}h$ .

The center of gravity of the triangular surfaces forming the pyramid is located on the line joining the apex with the center of gravity of the base surface, at a distance from the base equal to one-third of the height; or  $a = \frac{1}{3}h$ .

*Frustum of Pyramid :*

The center of gravity is located on the line that joins the centers of gravity of the end surfaces. If  $A_1$  = area of base surface, and  $A_2$  = area of top surface,

$$a = \frac{h(A_1 + 2\sqrt{A_1 \times A_2} + 3A_2)}{4(A_1 + \sqrt{A_1 \times A_2} + A_2)}$$

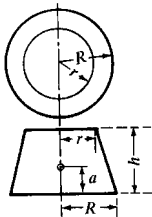
*Cone :*

The same rules apply as for the pyramid. For the solid cone:

$$a = \frac{1}{4}h$$

For the conical surface:

$$a = \frac{1}{2}h$$

*Frustum of Cone :*

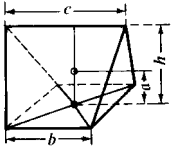
The same rules apply as for the frustum of a pyramid. For a solid frustum of a circular cone the formula below is also used:

$$a = \frac{h(R^2 + 2Rr + 3r^2)}{4(R^2 + Rr + r^2)}$$

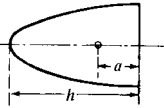
The location of the center of gravity of the conical surface of a frustum of a cone is determined by:

$$a = \frac{h(R + 2r)}{3(R + r)}$$

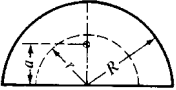
Wedge :

|   |  |
|---|--|
|  | <p>The center of gravity is on the line joining the center of gravity of the base with the middle point of the edge, and is located at:</p> $a = \frac{h(b+c)}{2(2b+c)}$ |
|---|--|

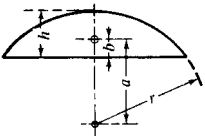
Paraboloid :

|   |  |
|---|--|
|  | <p>The center of gravity of a solid paraboloid of rotation is at:</p> $a = \frac{1}{3}h$ |
|---|--|

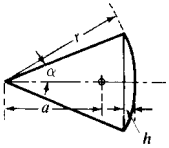
Half of a Hollow Sphere :

|   |   |
|---|---|
|  | <p>The center of gravity is located at:</p> $a = \frac{3(R^4 - r^4)}{8(R^3 - r^3)}$ |
|---|---|

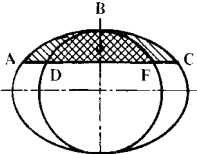
Spherical Segment :

|  |   |
|--|---|
|  | <p>The center of gravity of a solid segment is determined by:</p> $a = \frac{3(2r-h)^2}{4(3r-h)}$ $b = \frac{h(4r-h)}{4(3r-h)}$ <p>For a half-sphere, <math>a = b = \frac{3}{8}r</math></p> |
|--|---|

Spherical Sector :

|   |   |
|---|---|
|  | <p>The center of gravity of a solid sector is at:</p> $a = \frac{3}{8}(1 + \cos \alpha)r = \frac{3}{8}(2r - h)$ |
|---|---|

Segment of Ellipsoid or Spheroid :

|   |   |
|---|---|
|  | <p>The center of gravity of a solid segment <math>ABC</math>, symmetrical about the axis of rotation, coincides with the center of gravity of the segment <math>DBF</math> of a sphere, the diameter of which is equal to the axis of rotation of the spheroid.</p> |
|---|---|

**Center of Gravity of Figures of any Outline.**—If the figure is symmetrical about a center line, as in Fig. 1, the center of gravity will be located on that line. To find the exact location on that line, the simplest method is by taking moments with reference to any convenient axis at right angles to this center line. Divide the area into geometrical figures, the centers of gravity of which can be easily found. In the example shown, divide the figure into three rectangles KLMN, EFGH and OPRS. Call the areas of these rectangles  $A$ ,  $B$  and  $C$ , respectively, and find the center of gravity of each. Then select any convenient axis, as  $X-X$ , at right angles to the center line  $Y-Y$ , and determine distances  $a$ ,  $b$  and  $c$ . The distance  $y$  of the center of gravity of the complete figure from the axis  $X-X$  is then found from the equation:

$$y = \frac{Aa + Bb + Cc}{A + B + C}$$

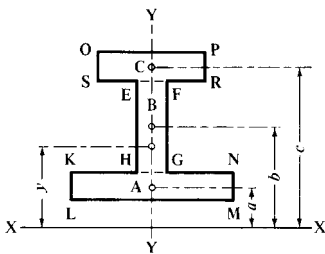


Fig. 1.

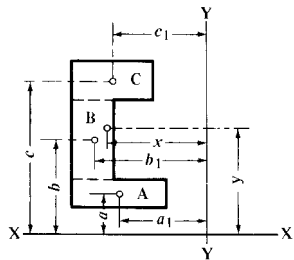


Fig. 2.

As an example, assume that the area  $A$  is 24 square inches,  $B$ , 14 square inches, and  $C$ , 16 square inches, and that  $a = 3$  inches,  $b = 7.5$  inches, and  $c = 12$  inches. Then:

$$y = \frac{24 \times 3 + 14 \times 7.5 + 16 \times 12}{24 + 14 + 16} = \frac{369}{54} = 6.83 \text{ inches}$$

If the figure, the center of gravity of which is to be found, is not symmetrical about any axis, as in Fig. 2, then moments must be taken with relation to two axes  $X-X$  and  $Y-Y$ , centers of gravity of which can be easily found, the same as before. The center of gravity is determined by the equations:

$$x = \frac{Aa_1 + Bb_1 + Cc_1}{A + B + C} \quad y = \frac{Aa + Bb + Cc}{A + B + C}$$

As an example, let  $A = 14$  square inches,  $B = 18$  square inches, and  $C = 20$  square inches. Let  $a = 3$  inches,  $b = 7$  inches, and  $c = 11.5$  inches. Let  $a_1 = 6.5$  inches,  $b_1 = 8.5$  inches, and  $c_1 = 7$  inches. Then:

$$x = \frac{14 \times 6.5 + 18 \times 8.5 + 20 \times 7}{14 + 18 + 20} = \frac{384}{52} = 7.38 \text{ inches}$$

$$y = \frac{14 \times 3 + 18 \times 7 + 20 \times 11.5}{14 + 18 + 20} = \frac{398}{52} = 7.65 \text{ inches}$$

In other words, the center of gravity is located at a distance of 7.65 inches from the axis  $X-X$  and 7.38 inches from the axis  $Y-Y$ .

RADIUS OF GYRATION

Radius of Gyration

The radius of gyration with reference to an axis is that distance from the axis at which the entire mass of a body may be considered as concentrated, the moment of inertia, meanwhile, remaining unchanged. If  $W$  is the weight of a body;  $J_M$ , its moment of inertia with respect to some axis; and  $k_o$ , the radius of gyration with respect to the same axis, then:

$$k_o = \sqrt{\frac{J_M g}{W}} \quad \text{and} \quad J_M = \frac{W k_o^2}{g}$$

When using metric SI units, the formulas are:

$$k_o = \sqrt{\frac{J_M}{M}} \quad \text{and} \quad J_M = M k_o^2$$

where  $k_o$  = the radius of gyration in meters,  $J_M$  = kilogram-meter squared, and  $M$  = mass in kilograms.

To find the radius of gyration of an area, such as for the cross-section of a beam, divide the moment of inertia of the area by the area and extract the square root.

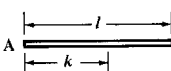
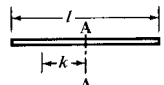
When the axis, the reference to which the radius of gyration is taken, passes through the center of gravity, the radius of gyration is the least possible and is called the *principal* radius of gyration. If  $k$  is the radius of gyration with respect to such an axis passing through the center of gravity of a body, then the radius of gyration,  $k_o$ , with respect to a parallel axis

at a distance  $d$  from the gravity axis is given by:  $k_o = \sqrt{k^2 + d^2}$

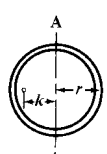
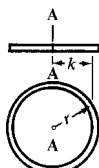
Tables of radii of gyration for various bodies and axes follows.

Formulas for Radius of Gyration

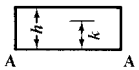
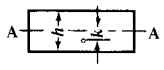
Bar of Small Diameter:

|   |  |
|---|--|
|  <p>Axis at end</p> $k = 0.5773l$ $k^2 = \frac{1}{3}l^2$ |  <p>Axis at center</p> $k = 0.2886l$ $k^2 = \frac{1}{12}l^2$ |
|---|--|

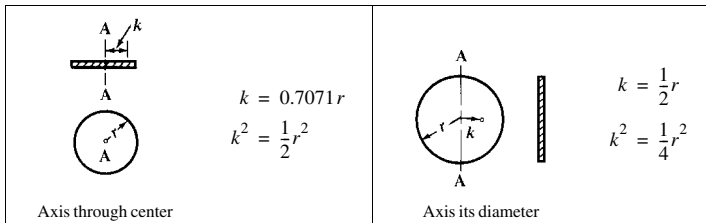
Bar of Small Diameter Bent to Circular Shape:

|  |  |
|--|--|
|  <p>Axis, a diameter of the ring</p> $k = 0.7071r$ $k^2 = \frac{1}{2}r^2$ |  <p>Axis through center of ring</p> $k = r$ $k^2 = r^2$ |
|--|--|

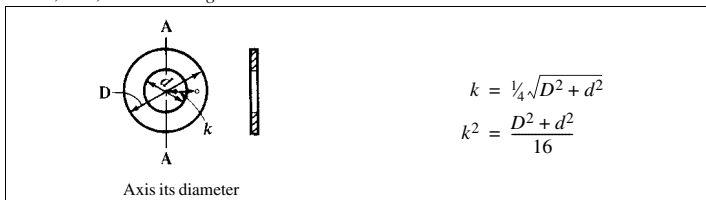
Parallelogram (Thin Flat Plate):

|   |   |
|---|---|
|  <p>Axis at base</p> $k = 0.5773h$ $k^2 = \frac{1}{3}h^2$ |  <p>Axis at mid-height</p> $k = 0.2886h$ $k^2 = \frac{1}{12}h^2$ |
|---|---|

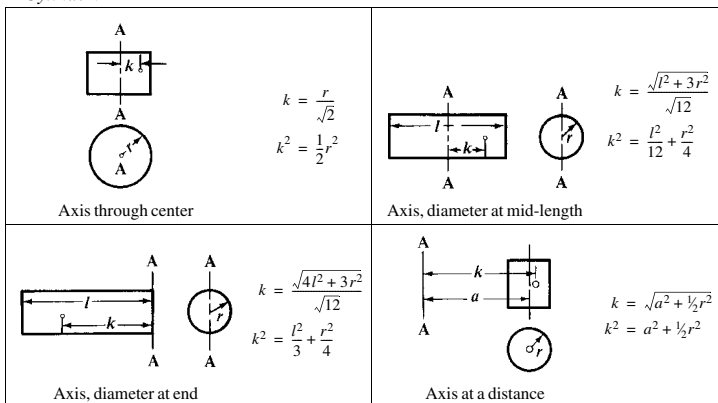
Thin Circular Disk:



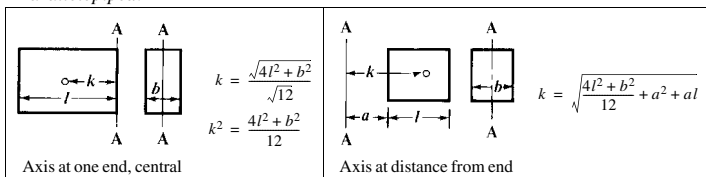
Thin, Flat, Circular Ring :



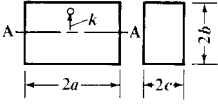
Cylinder:



Parallelepiped:



*Rectangular Prism:*

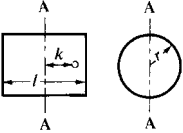


Axis through center

$$k = 0.577 \sqrt{b^2 + c^2}$$

$$k^2 = \frac{1}{3}(b^2 + c^2)$$

*Thin Hollow Cylinder:*

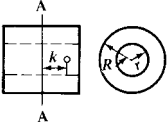


Axis, diameter at mid-length

$$k = 0.289 \sqrt{l^2 + 6r^2}$$

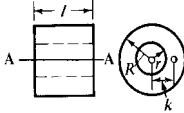
$$k^2 = \frac{l^2}{12} + \frac{r^2}{2}$$

*Hollow Cylinder:*



Axis, diameter at mid-length

$$k = \frac{\sqrt{l^2 + 3(R^2 + r^2)}}{\sqrt{12}}$$

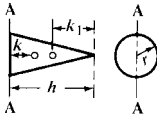
$$k^2 = \frac{l^2}{12} + \frac{R^2 + r^2}{4}$$


Longitudinal Axis

$$k = \frac{\sqrt{R^2 + r^2}}{\sqrt{2}}$$

$$k^2 = \frac{1}{2}(R^2 + r^2)$$

*Cone:*



Axis at base

$$k = \sqrt{\frac{2h^2 + 3r^2}{20}}$$

Axis at apex

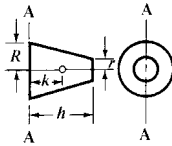
$$k_1 = \sqrt{\frac{12h^2 + 3r^2}{20}}$$


Axis through its center line

$$k = 0.5477r$$

$$k^2 = 0.3r^2$$

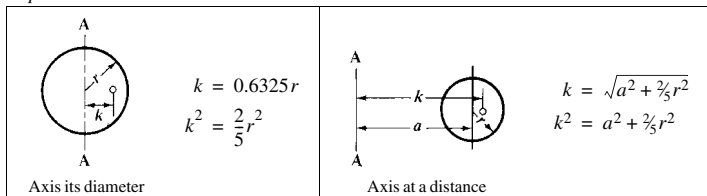
*Frustum of Cone:*



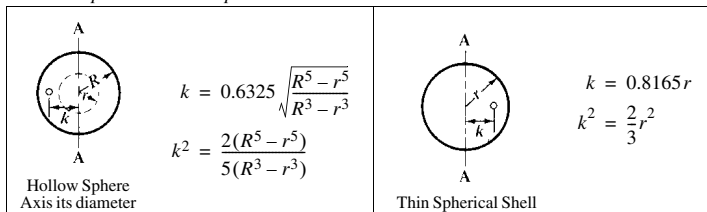
Axis at large end

$$k = \sqrt{\frac{h^2}{10} \left( \frac{R^2 + 3Rr + 6r^2}{R^2 + Rr + r^2} \right) + \frac{3}{20} \left( \frac{R^5 - r^5}{R^3 - r^3} \right)}$$

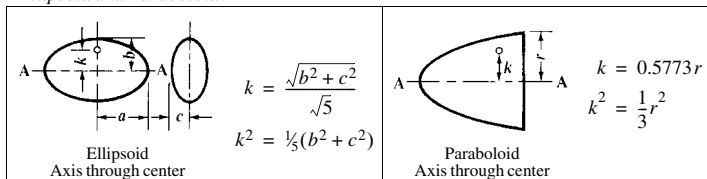
## Sphere:



## Hollow Sphere and Thin Spherical Shell:



## Ellipsoid and Paraboloid:



**Center and Radius of Oscillation.**—If a body oscillates about a horizontal axis which does not pass through its center of gravity, there will be a point on the line drawn from the center of gravity, perpendicular to the axis, the motion of which will be the same as if the whole mass were concentrated at that point. This point is called the *center of oscillation*. The *radius of oscillation* is the distance between the center of oscillation and the point of suspension. In a straight line, or in a bar of small diameter, suspended at one end and oscillating about it, the center of oscillation is at two-thirds the length of the rod from the end by which it is suspended.

When the vibrations are perpendicular to the plane of the figure, and the figure is suspended by the vertex of an angle or its uppermost point, the radius of oscillation of an isosceles triangle is equal to  $\frac{3}{4}$  of the height of the triangle; of a circle,  $\frac{5}{8}$  of the diameter; of a parabola,  $\frac{5}{7}$  of the height.

If the vibrations are in the plane of the figure, then the radius of oscillation of a circle equals  $\frac{3}{4}$  of the diameter; of a rectangle, suspended at the vertex of one angle,  $\frac{2}{3}$  of the diagonal.

**Center of Percussion.**—For a body that moves without rotation, the resultant of all the forces acting on the body passes through the center of gravity. On the other hand, for a body that rotates about some *fixed axis*, the resultant of all the forces acting on it does not pass through the center of gravity of the body but through a point called the *center of percussion*.



sion. The center of percussion is useful in determining the position of the resultant in mechanics problems involving angular acceleration of bodies about a fixed axis.

*Finding the Center of Percussion when the Radius of Gyration and the Location of the Center of Gravity are Known:* The center of percussion lies on a line drawn through the center of rotation and the center of gravity. The distance from the axis of rotation to the center of percussion may be calculated from the following formula

$$q = k_o^2 \div r$$

in which  $q$  = distance from the axis of rotation to the center of percussion;  $k_o$  = the radius of gyration of the body with respect to the axis of rotation; and  $r$  = the distance from the axis of rotation to the center of gravity of the body.

### Moment of Inertia

An important property of areas and solid bodies is the moment of inertia. Standard formulas are derived by multiplying elementary particles of area or mass by the squares of their distances from reference axes. Moments of inertia, therefore, depend on the location of reference axes. Values are minimum when these axes pass through the centers of gravity.

Three kinds of moments of inertia occur in engineering formulas:

1) *Moments of inertia of plane area,  $I$* , in which the axis is in the plane of the area, are found in formulas for calculating deflections and stresses in beams. When dimensions are given in inches, the units of  $I$  are inches<sup>4</sup>. A table of formulas for calculating the  $I$  of common areas can be found beginning on page 238.

2) *Polar moments of inertia of plane areas,  $J$* , in which the axis is at right angles to the plane of the area, occur in formulas for the torsional strength of shafting. When dimensions are given in inches, the units of  $J$  are inches<sup>4</sup>. If moments of inertia,  $I$ , are known for a plane area with respect to both  $x$  and  $y$  axes, then the polar moment for the  $z$  axis may be calculated using the equation,  $J_z = I_x + I_y$

A table of formulas for calculating  $J$  for common areas can be found on page 249 in this section.

**When metric SI units are used, the formulas referred to in (1) and (2) above, are valid if the dimensions are given consistently in meters or millimeters. If meters are used, the units of  $I$  and  $J$  are in meters<sup>4</sup>; if millimeters are used, these units are in millimeters<sup>4</sup>.**

3) *Polar moments of inertia of masses,  $J_M$* <sup>\*</sup>, appear in dynamics equations involving rotational motion.  $J_M$  bears the same relationship to angular acceleration as mass does to linear acceleration. If units are in the foot-pound-second system, the units of  $J_M$  are ft-lbs-sec<sup>2</sup> or slug-ft<sup>2</sup>. (1 slug = 1 pound second<sup>2</sup> per foot.) If units are in the inch-pound-second system, the units of  $J_M$  are inch-lbs-sec<sup>2</sup>.

**If metric SI values are used, the units of  $J_M$  are kilogram-meter squared.** Formulas for calculating  $J_M$  for various bodies are given beginning on page 250. If the polar moment of inertia  $J$  is known for the area of a body of constant cross section,  $J_M$  may be calculated using the equation,

$$J_M = \frac{\rho L}{g} J$$

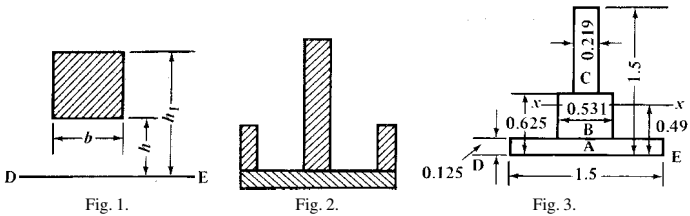
where  $\rho$  is the density of the material,  $L$  the length of the part, and  $g$  the gravitational constant. If dimensions are in the foot-pound-second system,  $\rho$  is in lbs per ft<sup>3</sup>,  $L$  is in ft,  $g$  is

<sup>\*</sup> In some books the symbol  $I$  denotes the polar moment of inertia of masses;  $J_M$  is used in this handbook to avoid confusion with moments of inertia of plane areas.

32.16 ft per sec<sup>2</sup>, and  $J$  is in ft<sup>4</sup>. If dimensions are in the inch-pound-second system,  $\rho$  is in lbs per in<sup>3</sup>,  $L$  is in inches,  $g$  is 386 inches per sec<sup>2</sup>, and  $J$  is in inches<sup>4</sup>.

Using metric SI units, the above formula becomes  $J_M = \rho L J$ , where  $\rho$  = the density in kilograms/meter<sup>3</sup>,  $L$  = the length in meters, and  $J$  = the polar moment of inertia in meters<sup>4</sup>. The units of  $J_M$  are kg · m<sup>2</sup>.

**Moment of Inertia of Built-up Sections.**—The usual method of calculating the moment of inertia of a built-up section involves the calculations of the moment of inertia for each element of the section about its own neutral axis, and the transferring of this moment of inertia to the previously found neutral axis of the whole built-up section. A much simpler method that can be used in the case of any section which can be divided into rectangular elements bounded by lines parallel and perpendicular to the neutral axis is the so-called tabular method based upon the formula:  $I = b(h_1^3 - h^3)/3$  in which  $I$  = the moment of inertia about axis  $DE$ , Fig. 1, and  $b$ ,  $h$  and  $h_1$  are dimensions as given in the same illustration.



*Example:* The method may be illustrated by applying it to the section shown in Fig. 2, and for simplicity of calculation shown “massed” in Fig. 3. The calculation may then be tabulated as shown in the accompanying table. The distance from the axis  $DE$  to the neutral axis  $xx$  (which will be designated as  $d$ ) is found by dividing the sum of the geometrical moments by the area. The moment of inertia about the neutral axis is then found in the usual way by subtracting the area multiplied by  $d^2$  from the moment of inertia about the axis  $DE$ .

**Tabulated Calculation of Moment of Inertia**

| Section | Breadth<br>$b$ | Height<br>$h_1$ | Area<br>$b(h_1 - h)$ | $h_1^2$ | Moment<br>$\frac{b(h_1^2 - h^2)}{2}$ | $h_1^3$ | $I$ about axis $DE$<br>$\frac{b(h_1^3 - h^3)}{3}$ |
|---------|----------------|-----------------|----------------------|---------|--------------------------------------|---------|---|
| A       | 1.500          | 0.125           | 0.187                | 0.016   | 0.012                                | 0.002   | 0.001   |
| B       | 0.531          | 0.625           | 0.266                | 0.391   | 0.100                                | 0.244   | 0.043   |
| C       | 0.219          | 1.500           | 0.191                | 2.250   | 0.203                                | 3.375   | 0.228   |
|         |                |                 | $\Sigma A = 0.644$   |         | $\Sigma M = 0.315$                   |         | $\Sigma I_{DE} = 0.272$                           |

The distance  $d$  from  $DE$ , the axis at the base of the configuration, to the neutral axis  $xx$  is:

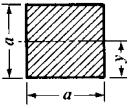
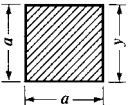
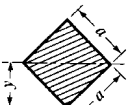
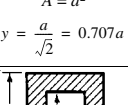
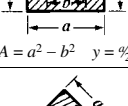
$$d = \frac{M}{A} = \frac{0.315}{0.644} = 0.49$$

The moment of inertia of the entire section with reference to the neutral axis  $xx$  is:

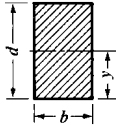
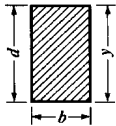
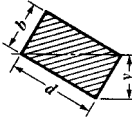
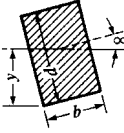
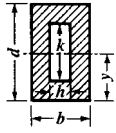
$$\begin{aligned} I_N &= I_{DE} - Ad^2 \\ &= 0.272 - 0.644 \times 0.49^2 \\ &= 0.117 \end{aligned}$$

**Formulas for Moments of Inertia, Section Moduli, etc.**—On the following pages are given formulas for the moments of inertia and other properties of forty-two different cross-sections. The formulas give the area of the section  $A$ , and the distance  $y$  from the neutral axis to the extreme fiber, for each example. Where the formulas for the section modulus and radius of gyration are very lengthy, the formula for the section modulus, for example, has been simply given as  $I \div y$ . The radius of gyration is sometimes given as  $\sqrt{I \div A}$  to save space.

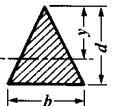

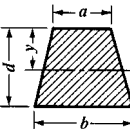
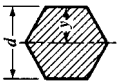
### Moments of Inertia, Section Moduli, and Radii of Gyration

| Section<br>$A = \text{area}$<br>$y = \text{distance from axis to extreme fiber}$   | Moment of Inertia<br>$I$ | Section Modulus<br>$Z = \frac{I}{y}$                              | Radius of Gyration<br>$k = \sqrt{\frac{I}{A}}$             |
|--|--------------------------|---|--|
| Square and Rectangular Sections  |                          |   |  |
| <br>$A = a^2 \quad y = \frac{a}{2}$                 | $\frac{a^4}{12}$         | $\frac{a^3}{6}$   | $\frac{a}{\sqrt{12}} = 0.289a$                             |
| <br>$A = a^2 \quad y = a$                           | $\frac{a^4}{3}$          | $\frac{a^3}{3}$   | $\frac{a}{\sqrt{3}} = 0.577a$                              |
| <br>$A = a^2$<br>$y = \frac{a}{\sqrt{2}} = 0.707a$ | $\frac{a^4}{12}$         | $\frac{a^3}{6\sqrt{2}} = 0.118a^3$                                | $\frac{a}{\sqrt{12}} = 0.289a$                             |
| <br>$A = a^2 - b^2 \quad y = \frac{a}{2}$         | $\frac{a^4 - b^4}{12}$   | $\frac{a^4 - b^4}{6a}$  | $\sqrt{\frac{a^2 + b^2}{12}}$<br>$= 0.289\sqrt{a^2 + b^2}$ |
| <br>$A = a^2 - b^2 \quad y = \frac{a}{\sqrt{2}}$  | $\frac{a^4 - b^4}{12}$   | $\frac{\sqrt{2}(a^4 - b^4)}{12a}$<br>$= 0.118\frac{a^4 - b^4}{a}$ | $\sqrt{\frac{a^2 + b^2}{12}}$<br>$= 0.289\sqrt{a^2 + b^2}$ |

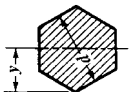
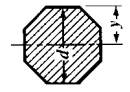
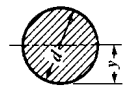
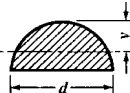
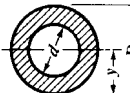
**Moments of Inertia, Section Moduli, and Radii of Gyration (Continued)**

| Section<br>$A =$ area<br>$y =$ distance from axis to<br>extreme fiber   | Moment of<br>Inertia<br>$I$                            | Section Modulus<br>$Z = \frac{I}{y}$   | Radius of Gyration<br>$k = \sqrt{\frac{I}{A}}$  |
|---|--|--|---|
| Square and Rectangular Sections (Continued)   |  |  |   |
|  <p><math>A = bd \quad y = \frac{d}{2}</math></p>  | $\frac{bd^3}{12}$                                      | $\frac{bd^2}{6}$   | $\frac{d}{\sqrt{12}} = 0.289d$  |
|  <p><math>A = bd \quad y = d</math></p>  | $\frac{bd^3}{3}$                                       | $\frac{bd^2}{3}$   | $\frac{d}{\sqrt{3}} = 0.577d$   |
|  <p><math>A = bd</math><br/> <math>y = \frac{bd}{\sqrt{b^2 + d^2}}</math></p>                  | $\frac{b^3 d^3}{6(b^2 + d^2)}$                         | $\frac{b^2 d^2}{6\sqrt{b^2 + d^2}}$  | $\frac{bd}{\sqrt{6(b^2 + d^2)}}$<br>$= 0.408 \frac{bd}{\sqrt{b^2 + d^2}}$   |
|  <p><math>A = bd</math><br/> <math>y = \frac{1}{2}(d \cos \alpha + b \sin \alpha)</math></p> | $\frac{bd}{12}(d^2 \cos^2 \alpha + b^2 \sin^2 \alpha)$ | $\frac{bd}{6} \times \left( \frac{d^2 \cos^2 \alpha + b^2 \sin^2 \alpha}{d \cos \alpha + b \sin \alpha} \right)$ | $\frac{\sqrt{d^2 \cos^2 \alpha + b^2 \sin^2 \alpha}}{\sqrt{12}} = 0.289 \times \frac{\sqrt{d^2 \cos^2 \alpha + b^2 \sin^2 \alpha}}{\sqrt{d^2 \cos^2 \alpha + b^2 \sin^2 \alpha}}$ |
|  <p><math>A = bd - hk</math><br/> <math>y = \frac{d}{2}</math></p>                           | $\frac{bd^3 - hk^3}{12}$                               | $\frac{bd^3 - hk^3}{6d}$   | $\frac{\sqrt{bd^3 - hk^3}}{\sqrt{12(bd - hk)}}$<br>$= 0.289 \sqrt{\frac{bd^3 - hk^3}{bd - hk}}$   |


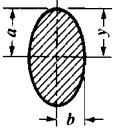
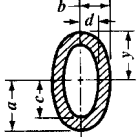
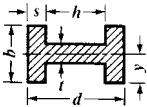
## Moments of Inertia, Section Moduli, and Radii of Gyration (Continued)

| Section   | Area of Section,<br>$A$                        | Distance from Neutral<br>Axis to Extreme Fiber, $y$ | Moment of Inertia,<br>$I$   | Section Modulus,<br>$Z = I/y$  | Radius of Gyration,<br>$k = \sqrt{I/A}$                                      |
|---|--|---|---|--|--|
| Triangular Sections   |  |   |   |  |  |
|  | $\frac{1}{2}bd$                                | $\frac{2}{3}d$                                      | $\frac{bd^3}{36}$   | $\frac{bd^2}{24}$  | $\frac{d}{\sqrt{18}} = 0.236d$   |
|  | $\frac{1}{2}bd$                                | $d$   | $\frac{bd^3}{12}$   | $\frac{bd^2}{12}$  | $\frac{d}{\sqrt{6}} = 0.408d$  |
| Polygon Sections  |  |   |   |  |  |
|  | $\frac{d(a+b)}{2}$                             | $\frac{d(a+2b)}{3(a+b)}$                            | $\frac{d^3(a^2 + 4ab + b^2)}{36(a+b)}$  | $\frac{d^2(a^2 + 4ab + b^2)}{12(a+2b)}$  | $\sqrt{\frac{d^2(a^2 + 4ab + b^2)}{18(a+b)^2}}$                              |
|  | $\frac{3d^2 \tan 30^\circ}{2}$<br>$= 0.866d^2$ | $\frac{d}{2}$                                       | $\frac{A}{12} \left[ \frac{d^2(1 + 2 \cos^2 30^\circ)}{4 \cos^2 30^\circ} \right]$<br>$= 0.06d^4$ | $\frac{A}{6} \left[ \frac{d(1 + 2 \cos^2 30^\circ)}{4 \cos^2 30^\circ} \right]$<br>$= 0.12d^3$ | $\sqrt{\frac{d^2(1 + 2 \cos^2 30^\circ)}{48 \cos^2 30^\circ}}$<br>$= 0.264d$ |

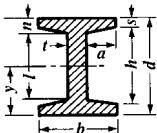
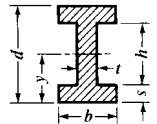
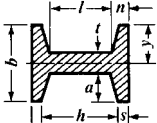
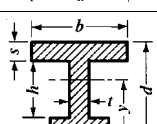
Moments of Inertia, Section Moduli, and Radii of Gyration (Continued)

| Section   | Area of Section,<br>$A$                             | Distance from Neutral<br>Axis to Extreme Fiber, $y$ | Moment of Inertia,<br>$I$  | Section Modulus,<br>$Z = I/y$   | Radius of Gyration,<br>$k = \sqrt{I/A}$  |
|---|---|---|--|---|--|
|  | $\frac{3d^2 \tan 30^\circ}{2}$<br>$= 0.866d^2$      | $\frac{d}{2 \cos 30^\circ} = 0.577d$                | $\frac{A}{12} \left[ \frac{d^2(1 + 2 \cos^2 30^\circ)}{4 \cos^2 30^\circ} \right]$<br>$= 0.06d^4$                        | $\frac{A}{6.9} \left[ \frac{d(1 + 2 \cos^2 30^\circ)}{4 \cos^2 30^\circ} \right]$<br>$= 0.104d^3$                     | $\sqrt{\frac{d^2(1 + 2 \cos^2 30^\circ)}{48 \cos^2 30^\circ}}$<br>$= 0.264d$                       |
|  | $2d^2 \tan 22\frac{1}{2}^\circ = 0.828d^2$          | $\frac{d}{2}$                                       | $\frac{A}{12} \left[ \frac{d^2(1 + 2 \cos^2 22\frac{1}{2}^\circ)}{4 \cos^2 22\frac{1}{2}^\circ} \right]$<br>$= 0.055d^4$ | $\frac{A}{6} \left[ \frac{d(1 + 2 \cos^2 22\frac{1}{2}^\circ)}{4 \cos^2 22\frac{1}{2}^\circ} \right]$<br>$= 0.109d^3$ | $\sqrt{\frac{d^2(1 + 2 \cos^2 22\frac{1}{2}^\circ)}{48 \cos^2 22\frac{1}{2}^\circ}}$<br>$= 0.257d$ |
| Circular, Elliptical, and Circular Arc Sections                                   |   |   |  |   |  |
|  | $\frac{\pi d^2}{4} = 0.7854d^2$                     | $\frac{d}{2}$                                       | $\frac{\pi d^4}{64} = 0.049d^4$  | $\frac{\pi d^3}{32} = 0.098d^3$   | $\frac{d}{4}$  |
|  | $\frac{\pi d^2}{8} = 0.393d^2$                      | $\frac{(3\pi - 4)d}{6\pi}$<br>$= 0.288d$            | $\frac{(9\pi^2 - 64)d^4}{1152\pi}$<br>$= 0.007d^4$   | $\frac{(9\pi^2 - 64)d^3}{192(3\pi - 4)}$<br>$= 0.024d^3$  | $\frac{\sqrt{(9\pi^2 - 64)d^2}}{12\pi}$<br>$= 0.132d$  |
|  | $\frac{\pi(D^2 - d^2)}{4}$<br>$= 0.7854(D^2 - d^2)$ | $\frac{D}{2}$                                       | $\frac{\pi(D^4 - d^4)}{64}$<br>$= 0.049(D^4 - d^4)$  | $\frac{\pi(D^4 - d^4)}{32D}$<br>$= 0.098 \frac{D^4 - d^4}{D}$   | $\frac{\sqrt{D^2 + d^2}}{4}$   |

## Moments of Inertia, Section Moduli, and Radii of Gyration (Continued)

| Section   | Area of Section,<br>$A$                             | Distance from Neutral<br>Axis to Extreme Fiber, $y$                            | Moment of Inertia,<br>$I$                                   | Section Modulus,<br>$Z = I/y$  | Radius of Gyration,<br>$k = \sqrt{I/A}$           |
|---|---|--|---|--|---|
|   | $\frac{\pi(R^2 - r^2)}{2}$<br>$= 1.5708(R^2 - r^2)$ | $\frac{4(R^3 - r^3)}{3\pi(R^2 - r^2)}$<br>$= 0.424\frac{R^3 - r^3}{R^2 - r^2}$ | $0.1098(R^4 - r^4)$<br>$\frac{0.283R^2r^2(R - r)}{R + r}$   | $\frac{I}{y}$  | $\sqrt{\frac{I}{A}}$                              |
|  | $\pi ab = 3.1416ab$                                 | $a$  | $\frac{\pi a^3 b}{4} = 0.7854a^3 b$                         | $\frac{\pi a^2 b}{4} = 0.7854a^2 b$                                  | $\frac{a}{2}$                                     |
|  | $\pi(ab - cd)$<br>$= 3.1416(ab - cd)$               | $a$  | $\frac{\pi}{4}(a^3 b - c^3 d)$<br>$= 0.7854(a^3 b - c^3 d)$ | $\frac{\pi(a^3 b - c^3 d)}{4a}$<br>$= 0.7854\frac{a^3 b - c^3 d}{a}$ | $\frac{1}{2}\sqrt{\frac{a^3 b - c^3 d}{ab - cd}}$ |
| I-Sections  |   |  |   |  |   |
|   | $bd - h(b - t)$                                     | $\frac{b}{2}$  | $\frac{2sb^3 + ht^3}{12}$                                   | $\frac{2sb^3 + ht^3}{6b}$  | $\sqrt{\frac{2sb^3 + ht^3}{12[bd - h(b - t)]}}$   |

## Moments of Inertia, Section Moduli, and Radii of Gyration (Continued)

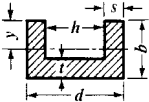
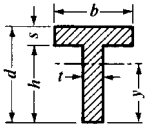
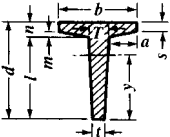
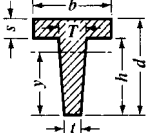
| Section  | Area of Section,<br>$A$ | Distance from Neutral<br>Axis to Extreme Fiber, $y$  | Moment of Inertia,<br>$I$   | Section Modulus,<br>$Z = I/y$   | Radius of Gyration,<br>$k = \sqrt{I/A}$  |
|--|-------------------------|--|---|---|--|
|  | $dt + 2a(s + n)$        | $\frac{d}{2}$  | $\frac{1}{12} \left[ bd^3 - \frac{1}{4g}(h^4 - t^4) \right]$<br>in which $g = \text{slope of flange} = (h - t)/(b - t) = \frac{100\%}{6}$<br>for standard I-beams.        | $\frac{1}{6d} \left[ bd^3 - \frac{1}{4g}(h^4 - t^4) \right]$            | $\sqrt{\frac{\frac{1}{12} \left[ bd^3 - \frac{1}{4g}(h^4 - t^4) \right]}{dt + 2a(s + n)}}$ |
|  | $bd - h(b - t)$         | $\frac{d}{2}$  | $\frac{bd^3 - h^3(b - t)}{12}$  | $\frac{bd^3 - h^3(b - t)}{6d}$  | $\sqrt{\frac{bd^3 - h^3(b - t)}{12[bd - h(b - t)]}}$                                       |
|  | $dt + 2a(s + n)$        | $\frac{b}{2}$  | $\frac{1}{12} \left[ b^3(d - h) + t^3 \right] + \frac{g}{4}(b^4 - t^4)$<br>in which $g = \text{slope of flange} = (h - t)/(b - t) = \frac{1}{6}$<br>for standard I-beams. | $\frac{1}{6b} \left[ b^3(d - h) + t^3 + \frac{g}{4}(b^4 - t^4) \right]$ | $\sqrt{\frac{I}{A}}$   |
|  | $bs + ht + as$          | $d - [td^2 + s^2(b - t) + s(a - t)(2d - s)] \div 2A$ | $\frac{1}{3}[b(d - y)^3 + ay^3 - (b - t)(d - y - s)^3 - (a - t)(y - s)^3]$  | $\frac{I}{y}$   | $\sqrt{\frac{I}{A}}$   |



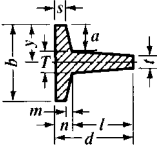
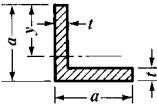
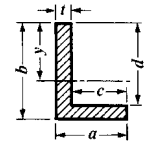
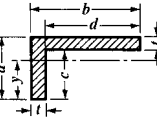
## Moments of Inertia, Section Moduli, and Radii of Gyration (Continued)

| Section    | Area of Section,<br>$A$ | Distance from Neutral<br>Axis to Extreme Fiber, $y$   | Moment of Inertia,<br>$I$   | Section Modulus,<br>$Z = I/y$                                | Radius of Gyration,<br>$k = \sqrt{I/A}$   |
|------------|-------------------------|---|---|--|---|
| C-Sections |                         |   |   |  |   |
|            | $dt + a(s + n)$         | $\frac{d}{2}$   | $\frac{1}{12} \left[ bd^3 - \frac{1}{8g}(h^4 - t^4) \right]$<br>$g = \text{slope of flange}$<br>$= \frac{h-l}{2(b-t)} = \frac{1}{6}$<br>for standard channels.                  | $\frac{1}{6d} \left[ bd^3 - \frac{1}{8g}(h^4 - t^4) \right]$ | $\sqrt{\frac{\frac{1}{12} \left[ bd^3 - \frac{1}{8g}(h^4 - t^4) \right]}{dt + a(s + n)}}$ |
|            | $dt + 2a(s + n)$        | $b - \left[ b^2 s + \frac{ht^2}{2} + \frac{g}{3}(b-t)^2 \times (b+2t) \right] \div A$<br>$g = \text{slope of flange}$<br>$= \frac{h-l}{2(b-t)}$ | $\frac{1}{3} \left[ 2sb^3 + lt^3 + \frac{g}{2}(b^4 - t^4) - A(b-y)^2 \right]$<br>$g = \text{slope of flange}$<br>$= \frac{h-l}{2(b-t)} = \frac{1}{6}$<br>for standard channels. | $\frac{I}{y}$  | $\sqrt{\frac{I}{A}}$  |
|            | $bd - h(b - t)$         | $\frac{d}{2}$   | $\frac{bd^3 - h^3(b-t)}{12}$  | $\frac{bd^3 - h^3(b-t)}{6d}$                                 | $\sqrt{\frac{bd^3 - h^3(b-t)}{12[bd - h(b-t)]}}$  |

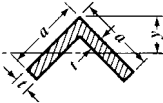
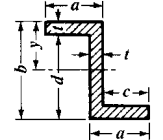
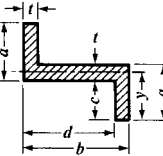
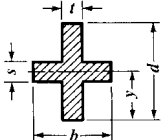
Moments of Inertia, Section Moduli, and Radii of Gyration (Continued)

| Section  | Area of Section, $A$             | Distance from Neutral Axis to Extreme Fiber, $y$                     | Moment of Inertia, $I$                                       | Section Modulus, $Z = I/y$ | Radius of Gyration, $k = \sqrt{I/A}$   |
|--|----------------------------------|--|--|----------------------------|--|
|  | $bd - h(b - t)$                  | $b - \frac{2b^2s + ht^2}{2bd - 2h(b-t)}$                             | $\frac{2sb^3 + ht^3}{3} - A(b - y)^2$                        | $\frac{I}{y}$              | $\sqrt{\frac{I}{A}}$   |
| T-Sections   |                                  |  |  |                            |  |
|  | $bs + ht$                        | $d - \frac{d^2t + s^2(b-t)}{2(bs + ht)}$                             | $\frac{1}{3}[ty^3 + b(d - y)^3 - (b - t)(d - y - s)^3]$      | $\frac{I}{y}$              | $\frac{\sqrt{\frac{1}{3(bs + ht)}[ty^3 + b(d - y)^3 - (b - t)(d - y - s)^3]}}$ |
|  | $\frac{l(T+t)}{2} + Tn + a(s+n)$ | $d - [3s^2(b - T) + 2am(m + 3s) + 3Td^2 - l(T - t)(3d - l)] \div 6A$ | $\frac{1}{12}[l^3(T + 3t) + 4bn^3 - 2am^3] - A(d - y - n)^2$ | $\frac{I}{y}$              | $\sqrt{\frac{I}{A}}$   |
|  | $bs + \frac{h(T+t)}{2}$          | $d - [3bs^2 + 3ht(d + s) + h(T - t)(h + 3s)] \div 6A$                | $\frac{1}{12}[4bs^3 + h^3(3t + T)] - A(d - y - s)^2$         | $\frac{I}{y}$              | $\sqrt{\frac{I}{A}}$   |

Moments of Inertia, Section Moduli, and Radii of Gyration (Continued)

| Section  | Area of Section, $A$             | Distance from Neutral Axis to Extreme Fiber, $y$ | Moment of Inertia, $I$  | Section Modulus, $Z = I/y$ | Radius of Gyration, $k = \sqrt{I/A}$                                       |
|--|----------------------------------|--|---|----------------------------|--|
|  | $\frac{l(T+t)}{2} + Tn + a(s+n)$ | $\frac{b}{2}$                                    | $\frac{sb^3 + mT^3 + lt^3}{12} + \frac{am[2a^2 + (2a + 3T)^2]}{36} + \frac{l(T-t)[(T-t)^2 + 2(T+2t)^2]}{144}$ | $\frac{I}{y}$              | $\sqrt{\frac{I}{A}}$   |
| L-, Z-, and X-Sections   |                                  |  |   |                            |  |
|  | $t(2a - t)$                      | $a - \frac{a^2 + at - t^2}{2(2a - t)}$           | $\frac{1}{3}[ty^3 + a(a - y)^3 - (a - t)(a - y - t)^3]$   | $\frac{I}{y}$              | $\sqrt{\frac{I}{A}}$   |
|  | $t(a + b - t)$                   | $b - \frac{t(2d + a) + d^2}{2(d + a)}$           | $\frac{1}{3}[ty^3 + a(b - y)^3 - (a - t)(b - y - t)^3]$   | $\frac{I}{y}$              | $\sqrt{\frac{1}{3t(a + b - t)}[ty^3 + a(b - y)^3 - (a - t)(b - y - t)^3]}$ |
|  | $t(a + b - t)$                   | $a - \frac{t(2c + b) + c^2}{2(c + b)}$           | $\frac{1}{3}[ty^3 + b(a - y)^3 - (b - t)(a - y - t)^3]$   | $\frac{I}{y}$              | $\sqrt{\frac{1}{3t(a + b - t)}[ty^3 + b(a - y)^3 - (b - t)(a - y - t)^3]}$ |

## Moments of Inertia, Section Moduli, and Radii of Gyration (Continued)

| Section  | Area of Section,<br>$A$ | Distance from Neutral<br>Axis to Extreme Fiber, $y$ | Moment of Inertia,<br>$I$  | Section Modulus,<br>$Z = I/y$                   | Radius of Gyration,<br>$k = \sqrt{I/A}$                        |
|--|-------------------------|---|--|---|--|
|  | $t(2a - t)$             | $\frac{a^2 + at - t^2}{2(2a - t) \cos 45^\circ}$    | $\frac{A}{12} [7(a^2 + b^2) - 12y^2]$<br>$-2ab^2(a - b)$<br>in which $b = (a - t)$ | $\frac{I}{y}$                                   | $\sqrt{\frac{I}{A}}$   |
|  | $t[b + 2(a - t)]$       | $\frac{b}{2}$                                       | $\frac{ab^3 - c(b - 2t)^3}{12}$  | $\frac{ab^3 - c(b - 2t)^3}{6b}$                 | $\sqrt{\frac{ab^3 - c(b - 2t)^3}{12t[b + 2(a - t)]}}$          |
|  | $t[b + 2(a - t)]$       | $\frac{2a - t}{2}$                                  | $\frac{b(a + c)^3 - 2c^3d - 6a^2cd}{12}$   | $\frac{b(a + c)^3 - 2c^3d - 6a^2cd}{6(2a - t)}$ | $\sqrt{\frac{b(a + c)^3 - 2c^3d - 6a^2cd}{12t[b + 2(a - t)]}}$ |
|  | $dt + s(b - t)$         | $\frac{d}{2}$                                       | $\frac{td^3 + s^3(b - t)}{12}$   | $\frac{td^3 + s^3(b - t)}{6d}$                  | $\sqrt{\frac{td^3 + s^3(b - t)}{12[td + s(b - t)]}}$           |

**Polar Area Moment of Inertia and Section Modulus.**—The *polar moment of inertia*,  $J$ , of a cross-section with respect to a polar axis, that is, an axis at right angles to the plane of the cross-section, is defined as the moment of inertia of the cross-section with respect to the point of intersection of the axis and the plane. The polar moment of inertia may be found by taking the sum of the moments of inertia about two perpendicular axes lying in the plane of the cross-section and passing through this point. Thus, for example, the polar moment of inertia of a circular or a square area with respect to a polar axis through the center of gravity is equal to two times the moment of inertia with respect to an axis lying in the plane of the cross-section and passing through the center of gravity.

The polar moment of inertia with respect to a polar axis through the center of gravity is required for problems involving the torsional strength of shafts since this axis is usually the axis about which twisting of the shaft takes place.

The *polar section modulus* (also called section modulus of torsion),  $Z_p$ , for *circular* sections may be found by dividing the polar moment of inertia,  $J$ , by the distance  $c$  from the center of gravity to the most remote fiber. This method may be used to find the *approximate* value of the polar section modulus of sections that are *nearly* round. For other than circular cross-sections, however, the polar section modulus *does not* equal the polar moment of inertia divided by the distance  $c$ .

The accompanying table *Polar Moment of Inertia and Polar Section Modulus* on page 249 gives formulas for the polar section modulus for several different cross-sections. The polar section modulus multiplied by the allowable torsional shearing stress gives the allowable twisting moment to which a shaft may be subjected, see [Formula \(7\)](#) on page 300.

**Mass Moments of Inertia\***,  $J_M$ .—Starting on page 250, formulas for mass moment of inertia of various solids are given in a series of tables. The example that follows illustrates the derivation of  $J_M$  for one of the bodies given on page 250.

*Example, Polar Mass Moment of Inertia of a Hollow Circular Section:* Referring to the figure *Hollow Cylinder* on page 250, consider a strip of width  $dr$  on a hollow circular section, whose inner radius is  $r$  and outer radius is  $R$ .

The mass of the strip =  $2\pi r dr \rho$ , where  $\rho$  is the density of material. In order to get the mass of an individual section, integrate the mass of the strip from  $r$  to  $R$ .

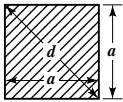
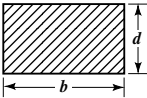
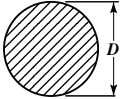
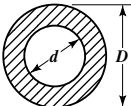
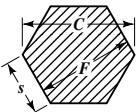
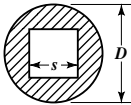
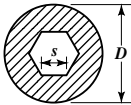
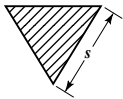
$$\begin{aligned} M &= \int_r^R 2\pi r(dr)\rho = 2\pi\rho \int_r^R r(dr) = 2\pi\rho \left[ \frac{r^2}{2} \right]_r^R \\ &= 2\pi\rho \left( \frac{R^2}{2} - \frac{r^2}{2} \right) = \pi\rho(R^2 - r^2) \end{aligned}$$

The 2nd moment of the strip about the AA axis =  $2\pi r dr \rho r^2$ . To find the polar moment of inertia about the AA axis, integrate the 2nd moment from  $r$  to  $R$ .

$$\begin{aligned} J_M &= \int_r^R 2\pi r(dr)\rho r^2 = 2\pi\rho \int_r^R r^3(dr) = 2\pi\rho \left[ \frac{r^4}{4} \right]_r^R \\ &= 2\pi\rho \left( \frac{R^4}{4} - \frac{r^4}{4} \right) = \frac{\pi\rho}{2}(R^2 - r^2)(R^2 + r^2) \\ &= \left( \pi\rho(R^2 - r^2) \right) \frac{(R^2 + r^2)}{2} = \frac{M(R^2 + r^2)}{2} \end{aligned}$$

\* In some books the symbol  $I$  denotes the polar moment of inertia of masses;  $J_M$  is used in this handbook to avoid confusion with moments of inertia of plane areas.

## Polar Moment of Inertia and Polar Section Modulus

| Section   | Polar Moment of Inertia,<br>$J$   | Polar Section Modulus,<br>$Z_p$   |
|---|---|---|
|    | $\frac{a^4}{6} = 0.1667a^4$   | $0.208a^3 = 0.074d^3$   |
|     | $\frac{bd(b^2 + d^2)}{12}$  | $\frac{bd^2}{3 + 1.8\frac{d}{b}}$<br>( $d$ is the shorter side)                               |
|    | $\frac{\pi D^4}{32} = 0.098D^4$<br>(see also footnote, page 254)          | $\frac{\pi D^3}{16} = 0.196D^3$<br>(see also footnote, page 254)                              |
|    | $\frac{\pi}{32}(D^4 - d^4)$<br>$= 0.098(D^4 - d^4)$                       | $\frac{\pi}{16}\left(\frac{D^4 - d^4}{D}\right)$<br>$= 0.196\left(\frac{D^4 - d^4}{D}\right)$ |
|   | $\frac{5\sqrt{3}}{8}s^4 = 1.0825s^4$<br>$= 0.12F^4$                       | $0.20F^3$   |
|  | $\frac{\pi D^4}{32} - \frac{s^4}{6}$<br>$= 0.098D^4 - 0.167s^4$           | $\frac{\pi D^3}{16} - \frac{s^4}{3D}$<br>$= 0.196D^3 - 0.333\frac{s^4}{D}$                    |
|  | $\frac{\pi D^4}{32} - \frac{5\sqrt{3}}{8}s^4$<br>$= 0.098D^4 - 1.0825s^4$ | $\frac{\pi D^3}{16} - \frac{5\sqrt{3}}{4D}s^4$<br>$= 0.196D^3 - 2.165\frac{s^4}{D}$           |
|  | $\frac{\sqrt{3}}{48}s^4 = 0.036s^4$                                       | $\frac{s^3}{20} = 0.05s^3$  |

Formulas for Polar Moment of Inertia of Masses,  $J_M$ 

Prism:

|  |  |
|--|--|
|  | <p>With reference to axis A - A: <math>J_M = \frac{M}{12}(h^2 + b^2)</math></p> <p>With reference to axis B - B: <math>J_M = M\left(\frac{l^2}{3} + \frac{h^2}{12}\right)</math></p> |
|--|--|

Cylinder:

|  |   |
|--|---|
|  | <p>With reference to axis A - A: <math>J_M = \frac{1}{2}Mr^2</math></p> <p>With reference to axis B - B: <math>J_M = M\left(\frac{l^2}{3} + \frac{r^2}{4}\right)</math></p> |
|--|---|

Hollow Cylinder:

|  |  |
|--|--|
|  | <p>With reference to axis A - A: <math>J_M = \frac{1}{2}M(R^2 + r^2)</math></p> <p>With reference to axis B - B:</p> $J_M = M\left(\frac{l^2}{3} + \frac{R^2 + r^2}{4}\right)$ |
|--|--|

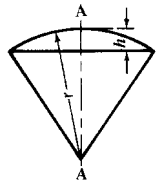
Pyramid, Rectangular Base:

|  |   |
|--|---|
|  | <p>With reference to axis A - A: <math>J_M = \frac{M}{20}(a^2 + b^2)</math></p> <p>With reference to axis B - B (through the center of gravity):</p> $J_M = M\left(\frac{3}{80}h^2 + \frac{b^2}{20}\right)$ |
|--|---|

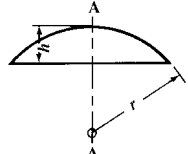
Sphere:

|  |   |
|--|---|
|  | <p>With reference to any axis through the center:</p> $J_M = \frac{2}{5}Mr^2$ |
|--|---|

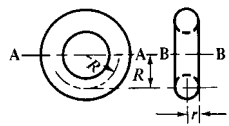
Spherical Sector:

|   |  |
|---|--|
|  | <p>With reference to axis A - A: <math>J_M = \frac{M}{5}(3rh - h^2)</math></p> |
|---|--|

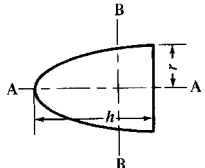
Spherical Segment:

|   |  |
|---|--|
|  | <p>Spherical Segment: With reference to axis A - A:</p> $J_M = M \left( r^2 - \frac{3rh}{4} + \frac{3h^2}{20} \right) \frac{2h}{3r - h}$ |
|---|--|

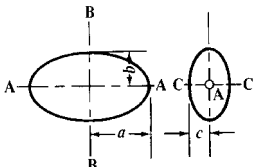
Torus:

|   |   |
|---|---|
|  | <p>With reference to axis A - A: <math>J_M = M \left( \frac{R^2}{2} + \frac{5r^2}{8} \right)</math></p> <p>With reference to axis B - B: <math>J_M = M \left( R^2 + \frac{3}{4}r^2 \right)</math></p> |
|---|---|

Paraboloid:

|  |  |
|--|--|
|  | <p>With reference to axis A - A: <math>J_M = \frac{1}{3}Mr^2</math></p> <p>With reference to axis B - B (through the center of gravity):</p> $J_M = M \left( \frac{r^2}{6} + \frac{h^2}{18} \right)$ |
|--|--|

Ellipsoid:

|  |  |
|--|--|
|  | <p>With reference to axis A - A: <math>J_M = \frac{M}{5}(b^2 + c^2)</math></p> <p>With reference to axis B - B: <math>J_M = \frac{M}{5}(a^2 + c^2)</math></p> <p>With reference to axis C - C: <math>J_M = \frac{M}{5}(a^2 + b^2)</math></p> |
|--|--|



Cone:

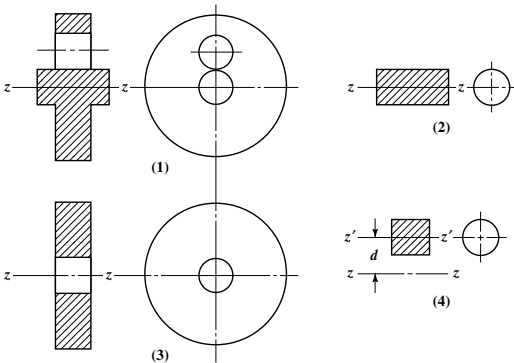
|  |   |
|--|---|
|  | <p>With reference to axis A - A: <math>J_M = \frac{3M}{10} r^2</math></p> <p>With reference to axis B - B (through the center of gravity):</p> $J_M = \frac{3M}{20} \left( r^2 + \frac{h^2}{4} \right)$ |
|--|---|

Frustrum of Cone:

|  |   |
|--|---|
|  | <p>With reference to axis A - A: <math>J_M = \frac{3M(R^5 - r^5)}{10(R^3 - r^3)}</math></p> |
|--|---|

Moments of Inertia of Complex Areas and Masses may be evaluated by the addition and subtraction of elementary areas and masses. For example, the accompanying figure shows a complex mass at (1); its mass polar moment of inertia can be determined by adding together the moments of inertia of the bodies shown at (2) and (3), and subtracting that at (4).

Thus,  $J_{M1} = J_{M2} + J_{M3} - J_{M4}$ . All of these moments of inertia are with respect to the axis of rotation  $z - z$ . Formulas for  $J_{M2}$  and  $J_{M3}$  can be obtained from the tables beginning on page 250. The moment of inertia for the body at (4) can be evaluated by using the following transfer-axis equation:  $J_{M4} = J_{M4}' + d^2M$ . The term  $J_{M4}'$  is the moment of inertia with respect to axis  $z' - z'$ ; it may be evaluated using the same equation that applies to  $J_{M2}$  where  $d$  is the distance between the  $z - z$  and the  $z' - z'$  axes, and  $M$  is the mass of the body (= weight in lbs  $\div$  g).



Moments of Inertia of Complex Masses

Similar calculations can be made when calculating  $I$  and  $J$  for complex areas using the appropriate transfer-axis equations  $I = I' + d^2A$  and  $J = J' + d^2A$ . The primed term,  $I'$  or  $J'$ , is with respect to the center of gravity of the corresponding area  $A$ ;  $d$  is the distance between the axis through the center of gravity and the axis to which  $I$  or  $J$  is referred.

**Moments of Inertia and Section Moduli  
for Rectangles and Round Shafts**

Moments of inertia and section modulus values shown here are for rectangles 1 millimeter wide. To obtain moment of inertia or section modulus for rectangle of given side length, multiply appropriate table value by given width. (See the text starting on page 238 for basic formulas.)

**Moments of Inertia and Section Moduli for Rectangles (Metric Units)**

| Length of Side (mm) | Moment of Inertia | Section Modulus | Length of Side (mm) | Moment of Inertia | Section Modulus | Length of Side (mm) | Moment of Inertia | Section Modulus |
|---------------------|-------------------|-----------------|---------------------|-------------------|-----------------|---------------------|-------------------|-----------------|
| 5                   | 10.4167           | 4.16667         | 56                  | 14634.7           | 522.667         | 107                 | 102087            | 1908.17         |
| 6                   | 18.0000           | 6.00000         | 57                  | 15432.8           | 541.500         | 108                 | 104976            | 1944.00         |
| 7                   | 28.5833           | 8.16667         | 58                  | 16259.3           | 560.667         | 109                 | 107919            | 1980.17         |
| 8                   | 42.6667           | 10.6667         | 59                  | 17114.9           | 580.167         | 110                 | 110917            | 2016.67         |
| 9                   | 60.7500           | 13.5000         | 60                  | 18000.0           | 600.000         | 111                 | 113969            | 2053.50         |
| 10                  | 83.3333           | 16.6667         | 61                  | 18915.1           | 620.167         | 112                 | 117077            | 2090.67         |
| 11                  | 110.917           | 20.1667         | 62                  | 19860.7           | 640.667         | 113                 | 120241            | 2128.17         |
| 12                  | 144.000           | 24.0000         | 63                  | 20837.3           | 661.500         | 114                 | 123462            | 2166.00         |
| 13                  | 183.083           | 28.1667         | 64                  | 21845.3           | 682.667         | 115                 | 126740            | 2204.17         |
| 14                  | 228.667           | 32.6667         | 65                  | 22885.4           | 704.167         | 116                 | 130075            | 2242.67         |
| 15                  | 281.250           | 37.5000         | 66                  | 23958.0           | 726.000         | 117                 | 133468            | 2281.50         |
| 16                  | 341.333           | 42.6667         | 67                  | 25063.6           | 748.167         | 118                 | 136919            | 2320.67         |
| 17                  | 409.417           | 48.1667         | 68                  | 26202.7           | 770.667         | 119                 | 140430            | 2360.17         |
| 18                  | 486.000           | 54.0000         | 69                  | 27375.8           | 793.500         | 120                 | 144000            | 2400.00         |
| 19                  | 571.583           | 60.1667         | 70                  | 28583.3           | 816.667         | 121                 | 147630            | 2440.17         |
| 20                  | 666.667           | 66.6667         | 71                  | 29825.9           | 840.167         | 122                 | 151321            | 2480.67         |
| 21                  | 771.750           | 73.5000         | 72                  | 31104.0           | 864.000         | 123                 | 155072            | 2521.50         |
| 22                  | 887.333           | 80.6667         | 73                  | 32418.1           | 888.167         | 124                 | 158885            | 2562.67         |
| 23                  | 1013.92           | 88.1667         | 74                  | 33768.7           | 912.667         | 125                 | 162760            | 2604.17         |
| 24                  | 1152.00           | 96.0000         | 75                  | 35156.3           | 937.500         | 126                 | 166698            | 2646.00         |
| 25                  | 1302.08           | 104.1667        | 76                  | 36581.3           | 962.667         | 127                 | 170699            | 2688.17         |
| 26                  | 1464.67           | 112.6667        | 77                  | 38044.4           | 988.167         | 128                 | 174763            | 2730.67         |
| 27                  | 1640.25           | 121.5000        | 78                  | 39546.0           | 1014.00         | 130                 | 183083            | 2816.67         |
| 28                  | 1829.33           | 130.6667        | 79                  | 41086.6           | 1040.17         | 132                 | 191664            | 2904.00         |
| 29                  | 2032.42           | 140.167         | 80                  | 42666.7           | 1066.67         | 135                 | 205031            | 3037.50         |
| 30                  | 2250.00           | 150.000         | 81                  | 44286.8           | 1093.50         | 138                 | 219006            | 3174.00         |
| 31                  | 2482.58           | 160.167         | 82                  | 45947.3           | 1120.67         | 140                 | 228667            | 3266.67         |
| 32                  | 2730.67           | 170.667         | 83                  | 47648.9           | 1148.17         | 143                 | 243684            | 3408.17         |
| 33                  | 2994.75           | 181.500         | 84                  | 49392.0           | 1176.00         | 147                 | 264710            | 3601.50         |
| 34                  | 3275.33           | 192.667         | 85                  | 51177.1           | 1204.17         | 150                 | 281250            | 3750.00         |
| 35                  | 3572.92           | 204.167         | 86                  | 53004.7           | 1232.67         | 155                 | 310323            | 4004.17         |
| 36                  | 3888.00           | 216.000         | 87                  | 54875.3           | 1261.50         | 160                 | 341333            | 4266.67         |
| 37                  | 4221.08           | 228.167         | 88                  | 56789.3           | 1290.67         | 165                 | 374344            | 4537.50         |
| 38                  | 4572.67           | 240.667         | 89                  | 58747.4           | 1320.17         | 170                 | 409417            | 4816.67         |
| 39                  | 4943.25           | 253.500         | 90                  | 60750.0           | 1350.00         | 175                 | 446615            | 5104.17         |
| 40                  | 5333.33           | 266.667         | 91                  | 62797.6           | 1380.17         | 180                 | 486000            | 5400.00         |
| 41                  | 5743.42           | 280.167         | 92                  | 64890.7           | 1410.67         | 185                 | 527635            | 5704.17         |
| 42                  | 6174.00           | 294.000         | 93                  | 67029.8           | 1441.50         | 190                 | 571583            | 6016.67         |
| 43                  | 6625.58           | 308.167         | 94                  | 69215.3           | 1472.67         | 195                 | 617906            | 6337.50         |
| 44                  | 7098.67           | 322.667         | 95                  | 71447.9           | 1504.17         | 200                 | 666667            | 6666.67         |
| 45                  | 7593.75           | 337.500         | 96                  | 73728.0           | 1536.00         | 210                 | 771750            | 7350.00         |
| 46                  | 8111.33           | 352.667         | 97                  | 76056.1           | 1568.17         | 220                 | 887333            | 8066.67         |
| 47                  | 8651.92           | 368.167         | 98                  | 78432.7           | 1600.67         | 230                 | 1013917           | 8816.67         |
| 48                  | 9216.00           | 384.000         | 99                  | 80858.3           | 1633.50         | 240                 | 1152000           | 9600.00         |
| 49                  | 9804.08           | 400.167         | 100                 | 83333.3           | 1666.67         | 250                 | 1302083           | 10416.7         |
| 50                  | 10416.7           | 416.667         | 101                 | 85858.4           | 1700.17         | 260                 | 1464667           | 11266.7         |
| 51                  | 11054.3           | 433.500         | 102                 | 88434.0           | 1734.00         | 270                 | 1640250           | 12150.0         |
| 52                  | 11717.3           | 450.667         | 103                 | 91060.6           | 1768.17         | 280                 | 1829333           | 13066.7         |
| 53                  | 12406.4           | 468.167         | 104                 | 93738.7           | 1802.67         | 290                 | 2032417           | 14016.7         |
| 54                  | 13122.0           | 486.000         | 105                 | 96468.8           | 1837.50         | 300                 | 2250000           | 15000.0         |
| 55                  | 13864.6           | 504.167         | 106                 | 99251.3           | 1872.67         | ...                 | ...               | ...             |

## Section Moduli for Rectangles

| Length of Side | Section Modulus | Length of Side  | Section Modulus | Length of Side  | Section Modulus | Length of Side | Section Modulus |
|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|-----------------|
| $\frac{1}{8}$  | 0.0026          | $2\frac{3}{4}$  | 1.26            | 12              | 24.00           | 25             | 104.2           |
| $\frac{3}{16}$ | 0.0059          | 3               | 1.50            | $12\frac{1}{2}$ | 26.04           | 26             | 112.7           |
| $\frac{1}{4}$  | 0.0104          | $3\frac{1}{4}$  | 1.76            | 13              | 28.17           | 27             | 121.5           |
| $\frac{5}{16}$ | 0.0163          | $3\frac{1}{2}$  | 2.04            | $13\frac{1}{2}$ | 30.38           | 28             | 130.7           |
| $\frac{3}{8}$  | 0.0234          | $3\frac{3}{4}$  | 2.34            | 14              | 32.67           | 29             | 140.2           |
| $\frac{7}{16}$ | 0.032           | 4               | 2.67            | $14\frac{1}{2}$ | 35.04           | 30             | 150.0           |
| $\frac{1}{2}$  | 0.042           | $4\frac{1}{2}$  | 3.38            | 15              | 37.5            | 32             | 170.7           |
| $\frac{5}{8}$  | 0.065           | 5               | 4.17            | $15\frac{1}{2}$ | 40.0            | 34             | 192.7           |
| $\frac{3}{4}$  | 0.094           | $5\frac{1}{2}$  | 5.04            | 16              | 42.7            | 36             | 216.0           |
| $\frac{7}{8}$  | 0.128           | 6               | 6.00            | $16\frac{1}{2}$ | 45.4            | 38             | 240.7           |
| 1              | 0.167           | $6\frac{1}{2}$  | 7.04            | 17              | 48.2            | 40             | 266.7           |
| $1\frac{1}{8}$ | 0.211           | 7               | 8.17            | $17\frac{1}{2}$ | 51.0            | 42             | 294.0           |
| $1\frac{1}{4}$ | 0.260           | $7\frac{1}{2}$  | 9.38            | 18              | 54.0            | 44             | 322.7           |
| $1\frac{3}{8}$ | 0.315           | 8               | 10.67           | $18\frac{1}{2}$ | 57.0            | 46             | 352.7           |
| $1\frac{1}{2}$ | 0.375           | $8\frac{1}{2}$  | 12.04           | 19              | 60.2            | 48             | 384.0           |
| $1\frac{5}{8}$ | 0.440           | 9               | 13.50           | $19\frac{1}{2}$ | 63.4            | 50             | 416.7           |
| $1\frac{3}{4}$ | 0.510           | $9\frac{1}{2}$  | 15.04           | 20              | 66.7            | 52             | 450.7           |
| $1\frac{7}{8}$ | 0.586           | 10              | 16.67           | 21              | 73.5            | 54             | 486.0           |
| 2              | 0.67            | $10\frac{1}{2}$ | 18.38           | 22              | 80.7            | 56             | 522.7           |
| $2\frac{1}{4}$ | 0.84            | 11              | 20.17           | 23              | 88.2            | 58             | 560.7           |
| $2\frac{1}{2}$ | 1.04            | $11\frac{1}{2}$ | 22.04           | 24              | 96.0            | 60             | 600.0           |

Section modulus values are shown for rectangles 1 inch wide. To obtain section modulus for rectangle of given side length, multiply value in table by given width.

## Section Moduli and Moments of Inertia for Round Shafts

| Dia.            | Section Modulus | Moment of Inertia | Dia.            | Section Modulus | Moment of Inertia | Dia.            | Section Modulus | Moment of Inertia |
|-----------------|-----------------|-------------------|-----------------|-----------------|-------------------|-----------------|-----------------|-------------------|
| $\frac{1}{8}$   | 0.00019         | 0.00001           | $\frac{27}{64}$ | 0.00737         | 0.00155           | $\frac{23}{32}$ | 0.03645         | 0.01310           |
| $\frac{9}{64}$  | 0.00027         | 0.00002           | $\frac{7}{16}$  | 0.00822         | 0.00180           | $\frac{47}{64}$ | 0.03888         | 0.01428           |
| $\frac{5}{32}$  | 0.00037         | 0.00003           | $\frac{29}{64}$ | 0.00913         | 0.00207           | $\frac{3}{4}$   | 0.04142         | 0.01553           |
| $\frac{11}{64}$ | 0.00050         | 0.00004           | $\frac{15}{32}$ | 0.01011         | 0.00237           | $\frac{49}{64}$ | 0.04406         | 0.01687           |
| $\frac{3}{16}$  | 0.00065         | 0.00006           | $\frac{31}{64}$ | 0.01116         | 0.00270           | $\frac{25}{32}$ | 0.04681         | 0.01829           |
| $\frac{13}{64}$ | 0.00082         | 0.00008           | $\frac{1}{2}$   | 0.01227         | 0.00307           | $\frac{51}{64}$ | 0.04968         | 0.01979           |
| $\frac{7}{32}$  | 0.00103         | 0.00011           | $\frac{33}{64}$ | 0.01346         | 0.00347           | $\frac{13}{16}$ | 0.05266         | 0.02139           |
| $\frac{15}{64}$ | 0.00126         | 0.00015           | $\frac{17}{32}$ | 0.01472         | 0.00391           | $\frac{53}{64}$ | 0.05576         | 0.02309           |
| $\frac{1}{4}$   | 0.00153         | 0.00019           | $\frac{35}{64}$ | 0.01606         | 0.00439           | $\frac{27}{32}$ | 0.05897         | 0.02488           |
| $\frac{17}{64}$ | 0.00184         | 0.00024           | $\frac{9}{16}$  | 0.01747         | 0.00491           | $\frac{55}{64}$ | 0.06231         | 0.02677           |
| $\frac{9}{32}$  | 0.00218         | 0.00031           | $\frac{37}{64}$ | 0.01897         | 0.00548           | $\frac{7}{8}$   | 0.06577         | 0.02877           |
| $\frac{19}{64}$ | 0.00257         | 0.00038           | $\frac{19}{32}$ | 0.02055         | 0.00610           | $\frac{57}{64}$ | 0.06936         | 0.03089           |
| $\frac{5}{16}$  | 0.00300         | 0.00047           | $\frac{39}{64}$ | 0.02222         | 0.00677           | $\frac{29}{32}$ | 0.07307         | 0.03311           |
| $\frac{21}{64}$ | 0.00347         | 0.00057           | $\frac{5}{8}$   | 0.02397         | 0.00749           | $\frac{59}{64}$ | 0.07692         | 0.03545           |
| $\frac{11}{32}$ | 0.00399         | 0.00069           | $\frac{41}{64}$ | 0.02581         | 0.00827           | $\frac{15}{16}$ | 0.08089         | 0.03792           |
| $\frac{23}{64}$ | 0.00456         | 0.00082           | $\frac{21}{32}$ | 0.02775         | 0.00910           | $\frac{61}{64}$ | 0.08501         | 0.04051           |
| $\frac{3}{8}$   | 0.00518         | 0.00097           | $\frac{43}{64}$ | 0.02978         | 0.01000           | $\frac{31}{32}$ | 0.08926         | 0.04323           |
| $\frac{25}{64}$ | 0.00585         | 0.00114           | $\frac{11}{16}$ | 0.03190         | 0.01097           | $\frac{63}{64}$ | 0.09364         | 0.04609           |
| $\frac{13}{32}$ | 0.00658         | 0.00134           | $\frac{45}{64}$ | 0.03413         | 0.01200           | ...             | ...             | ...               |

In this and succeeding tables, the *Polar Section Modulus* for a shaft of given diameter can be obtained by multiplying its section modulus by 2. Similarly, its *Polar Moment of Inertia* can be obtained by multiplying its moment of inertia by 2.

## Section Moduli and Moments of Inertia for Round Shafts (English or Metric Units)

| Dia. | Section Modulus | Moment of Inertia | Dia. | Section Modulus | Moment of Inertia | Dia. | Section Modulus | Moment of Inertia |
|------|-----------------|-------------------|------|-----------------|-------------------|------|-----------------|-------------------|
| 1.00 | 0.0982          | 0.0491            | 1.50 | 0.3313          | 0.2485            | 2.00 | 0.7854          | 0.7854            |
| 1.01 | 0.1011          | 0.0511            | 1.51 | 0.3380          | 0.2552            | 2.01 | 0.7972          | 0.8012            |
| 1.02 | 0.1042          | 0.0531            | 1.52 | 0.3448          | 0.2620            | 2.02 | 0.8092          | 0.8173            |
| 1.03 | 0.1073          | 0.0552            | 1.53 | 0.3516          | 0.2690            | 2.03 | 0.8213          | 0.8336            |
| 1.04 | 0.1104          | 0.0574            | 1.54 | 0.3586          | 0.2761            | 2.04 | 0.8335          | 0.8501            |
| 1.05 | 0.1136          | 0.0597            | 1.55 | 0.3656          | 0.2833            | 2.05 | 0.8458          | 0.8669            |
| 1.06 | 0.1169          | 0.0620            | 1.56 | 0.3727          | 0.2907            | 2.06 | 0.8582          | 0.8840            |
| 1.07 | 0.1203          | 0.0643            | 1.57 | 0.3799          | 0.2982            | 2.07 | 0.8708          | 0.9013            |
| 1.08 | 0.1237          | 0.0668            | 1.58 | 0.3872          | 0.3059            | 2.08 | 0.8835          | 0.9188            |
| 1.09 | 0.1271          | 0.0693            | 1.59 | 0.3946          | 0.3137            | 2.09 | 0.8963          | 0.9366            |
| 1.10 | 0.1307          | 0.0719            | 1.60 | 0.4021          | 0.3217            | 2.10 | 0.9092          | 0.9547            |
| 1.11 | 0.1343          | 0.0745            | 1.61 | 0.4097          | 0.3298            | 2.11 | 0.9222          | 0.9730            |
| 1.12 | 0.1379          | 0.0772            | 1.62 | 0.4174          | 0.3381            | 2.12 | 0.9354          | 0.9915            |
| 1.13 | 0.1417          | 0.0800            | 1.63 | 0.4252          | 0.3465            | 2.13 | 0.9487          | 1.0104            |
| 1.14 | 0.1455          | 0.0829            | 1.64 | 0.4330          | 0.3551            | 2.14 | 0.9621          | 1.0295            |
| 1.15 | 0.1493          | 0.0859            | 1.65 | 0.4410          | 0.3638            | 2.15 | 0.9757          | 1.0489            |
| 1.16 | 0.1532          | 0.0889            | 1.66 | 0.4491          | 0.3727            | 2.16 | 0.9894          | 1.0685            |
| 1.17 | 0.1572          | 0.0920            | 1.67 | 0.4572          | 0.3818            | 2.17 | 1.0032          | 1.0885            |
| 1.18 | 0.1613          | 0.0952            | 1.68 | 0.4655          | 0.3910            | 2.18 | 1.0171          | 1.1087            |
| 1.19 | 0.1654          | 0.0984            | 1.69 | 0.4739          | 0.4004            | 2.19 | 1.0312          | 1.1291            |
| 1.20 | 0.1696          | 0.1018            | 1.70 | 0.4823          | 0.4100            | 2.20 | 1.0454          | 1.1499            |
| 1.21 | 0.1739          | 0.1052            | 1.71 | 0.4909          | 0.4197            | 2.21 | 1.0597          | 1.1710            |
| 1.22 | 0.1783          | 0.1087            | 1.72 | 0.4996          | 0.4296            | 2.22 | 1.0741          | 1.1923            |
| 1.23 | 0.1827          | 0.1124            | 1.73 | 0.5083          | 0.4397            | 2.23 | 1.0887          | 1.2139            |
| 1.24 | 0.1872          | 0.1161            | 1.74 | 0.5172          | 0.4500            | 2.24 | 1.1034          | 1.2358            |
| 1.25 | 0.1917          | 0.1198            | 1.75 | 0.5262          | 0.4604            | 2.25 | 1.1183          | 1.2581            |
| 1.26 | 0.1964          | 0.1237            | 1.76 | 0.5352          | 0.4710            | 2.26 | 1.1332          | 1.2806            |
| 1.27 | 0.2011          | 0.1277            | 1.77 | 0.5444          | 0.4818            | 2.27 | 1.1484          | 1.3034            |
| 1.28 | 0.2059          | 0.1318            | 1.78 | 0.5537          | 0.4928            | 2.28 | 1.1636          | 1.3265            |
| 1.29 | 0.2108          | 0.1359            | 1.79 | 0.5631          | 0.5039            | 2.29 | 1.1790          | 1.3499            |
| 1.30 | 0.2157          | 0.1402            | 1.80 | 0.5726          | 0.5153            | 2.30 | 1.1945          | 1.3737            |
| 1.31 | 0.2207          | 0.1446            | 1.81 | 0.5822          | 0.5268            | 2.31 | 1.2101          | 1.3977            |
| 1.32 | 0.2258          | 0.1490            | 1.82 | 0.5919          | 0.5386            | 2.32 | 1.2259          | 1.4221            |
| 1.33 | 0.2310          | 0.1536            | 1.83 | 0.6017          | 0.5505            | 2.33 | 1.2418          | 1.4468            |
| 1.34 | 0.2362          | 0.1583            | 1.84 | 0.6116          | 0.5627            | 2.34 | 1.2579          | 1.4717            |
| 1.35 | 0.2415          | 0.1630            | 1.85 | 0.6216          | 0.5750            | 2.35 | 1.2741          | 1.4971            |
| 1.36 | 0.2470          | 0.1679            | 1.86 | 0.6317          | 0.5875            | 2.36 | 1.2904          | 1.5227            |
| 1.37 | 0.2524          | 0.1729            | 1.87 | 0.6420          | 0.6003            | 2.37 | 1.3069          | 1.5487            |
| 1.38 | 0.2580          | 0.1780            | 1.88 | 0.6523          | 0.6132            | 2.38 | 1.3235          | 1.5750            |
| 1.39 | 0.2637          | 0.1832            | 1.89 | 0.6628          | 0.6264            | 2.39 | 1.3403          | 1.6016            |
| 1.40 | 0.2694          | 0.1886            | 1.90 | 0.6734          | 0.6397            | 2.40 | 1.3572          | 1.6286            |
| 1.41 | 0.2752          | 0.1940            | 1.91 | 0.6841          | 0.6533            | 2.41 | 1.3742          | 1.6559            |
| 1.42 | 0.2811          | 0.1996            | 1.92 | 0.6949          | 0.6671            | 2.42 | 1.3914          | 1.6836            |
| 1.43 | 0.2871          | 0.2053            | 1.93 | 0.7058          | 0.6811            | 2.43 | 1.4087          | 1.7116            |
| 1.44 | 0.2931          | 0.2111            | 1.94 | 0.7168          | 0.6953            | 2.44 | 1.4262          | 1.7399            |
| 1.45 | 0.2993          | 0.2170            | 1.95 | 0.7280          | 0.7098            | 2.45 | 1.4438          | 1.7686            |
| 1.46 | 0.3055          | 0.2230            | 1.96 | 0.7392          | 0.7244            | 2.46 | 1.4615          | 1.7977            |
| 1.47 | 0.3119          | 0.2292            | 1.97 | 0.7506          | 0.7393            | 2.47 | 1.4794          | 1.8271            |
| 1.48 | 0.3183          | 0.2355            | 1.98 | 0.7621          | 0.7545            | 2.48 | 1.4975          | 1.8568            |
| 1.49 | 0.3248          | 0.2419            | 1.99 | 0.7737          | 0.7698            | 2.49 | 1.5156          | 1.8870            |

## Section Moduli and Moments of Inertia for Round Shafts (English or Metric Units)

| Dia. | Section Modulus | Moment of Inertia | Dia. | Section Modulus | Moment of Inertia | Dia. | Section Modulus | Moment of Inertia |
|------|-----------------|-------------------|------|-----------------|-------------------|------|-----------------|-------------------|
| 2.50 | 1.5340          | 1.9175            | 3.00 | 2.6507          | 3.9761            | 3.50 | 4.2092          | 7.3662            |
| 2.51 | 1.5525          | 1.9483            | 3.01 | 2.6773          | 4.0294            | 3.51 | 4.2454          | 7.4507            |
| 2.52 | 1.5711          | 1.9796            | 3.02 | 2.7041          | 4.0832            | 3.52 | 4.2818          | 7.5360            |
| 2.53 | 1.5899          | 2.0112            | 3.03 | 2.7310          | 4.1375            | 3.53 | 4.3184          | 7.6220            |
| 2.54 | 1.6088          | 2.0432            | 3.04 | 2.7582          | 4.1924            | 3.54 | 4.3552          | 7.7087            |
| 2.55 | 1.6279          | 2.0755            | 3.05 | 2.7855          | 4.2479            | 3.55 | 4.3922          | 7.7962            |
| 2.56 | 1.6471          | 2.1083            | 3.06 | 2.8130          | 4.3038            | 3.56 | 4.4295          | 7.8844            |
| 2.57 | 1.6665          | 2.1414            | 3.07 | 2.8406          | 4.3604            | 3.57 | 4.4669          | 7.9734            |
| 2.58 | 1.6860          | 2.1749            | 3.08 | 2.8685          | 4.4175            | 3.58 | 4.5054          | 8.0631            |
| 2.59 | 1.7057          | 2.2089            | 3.09 | 2.8965          | 4.4751            | 3.59 | 4.5424          | 8.1536            |
| 2.60 | 1.7255          | 2.2432            | 3.10 | 2.9247          | 4.5333            | 3.60 | 4.5804          | 8.2248            |
| 2.61 | 1.7455          | 2.2779            | 3.11 | 2.9531          | 4.5921            | 3.61 | 4.6187          | 8.3368            |
| 2.62 | 1.7656          | 2.3130            | 3.12 | 2.9817          | 4.6514            | 3.62 | 4.6572          | 8.4295            |
| 2.63 | 1.7859          | 2.3485            | 3.13 | 3.0105          | 4.7114            | 3.63 | 4.6959          | 8.5231            |
| 2.64 | 1.8064          | 2.3844            | 3.14 | 3.0394          | 4.7719            | 3.64 | 4.7348          | 8.6174            |
| 2.65 | 1.8270          | 2.4208            | 3.15 | 3.0685          | 4.8329            | 3.65 | 4.7740          | 8.7125            |
| 2.66 | 1.8478          | 2.4575            | 3.16 | 3.0979          | 4.8946            | 3.66 | 4.8133          | 8.8083            |
| 2.67 | 1.8687          | 2.4947            | 3.17 | 3.1274          | 4.9569            | 3.67 | 4.8529          | 8.9050            |
| 2.68 | 1.8897          | 2.5323            | 3.18 | 3.1570          | 5.0197            | 3.68 | 4.8926          | 9.0025            |
| 2.69 | 1.9110          | 2.5703            | 3.19 | 3.1869          | 5.0831            | 3.69 | 4.9326          | 9.1007            |
| 2.70 | 1.9324          | 2.6087            | 3.20 | 3.2170          | 5.1472            | 3.70 | 4.9728          | 9.1998            |
| 2.71 | 1.9539          | 2.6476            | 3.21 | 3.2472          | 5.2118            | 3.71 | 5.0133          | 9.2996            |
| 2.72 | 1.9756          | 2.6869            | 3.22 | 3.2777          | 5.2771            | 3.72 | 5.0539          | 9.4003            |
| 2.73 | 1.9975          | 2.7266            | 3.23 | 3.3083          | 5.3429            | 3.73 | 5.0948          | 9.5018            |
| 2.74 | 2.0195          | 2.7668            | 3.24 | 3.3391          | 5.4094            | 3.74 | 5.1359          | 9.6041            |
| 2.75 | 2.0417          | 2.8074            | 3.25 | 3.3702          | 5.4765            | 3.75 | 5.1772          | 9.7072            |
| 2.76 | 2.0641          | 2.8484            | 3.26 | 3.4014          | 5.5442            | 3.76 | 5.2187          | 9.8112            |
| 2.77 | 2.0866          | 2.8899            | 3.27 | 3.4328          | 5.6126            | 3.77 | 5.2605          | 9.9160            |
| 2.78 | 2.1093          | 2.9319            | 3.28 | 3.4643          | 5.6815            | 3.78 | 5.3024          | 10.0216           |
| 2.79 | 2.1321          | 2.9743            | 3.29 | 3.4961          | 5.7511            | 3.79 | 5.3446          | 10.1281           |
| 2.80 | 2.1551          | 3.0172            | 3.30 | 3.5281          | 5.8214            | 3.80 | 5.3870          | 10.2354           |
| 2.81 | 2.1783          | 3.0605            | 3.31 | 3.5603          | 5.8923            | 3.81 | 5.4297          | 10.3436           |
| 2.82 | 2.2016          | 3.1043            | 3.32 | 3.5926          | 5.9638            | 3.82 | 5.4726          | 10.4526           |
| 2.83 | 2.2251          | 3.1486            | 3.33 | 3.6252          | 6.0360            | 3.83 | 5.5156          | 10.5625           |
| 2.84 | 2.2488          | 3.1933            | 3.34 | 3.6580          | 6.1088            | 3.84 | 5.5590          | 10.6732           |
| 2.85 | 2.2727          | 3.2385            | 3.35 | 3.6909          | 6.1823            | 3.85 | 5.6025          | 10.7848           |
| 2.86 | 2.2967          | 3.2842            | 3.36 | 3.7241          | 6.2564            | 3.86 | 5.6463          | 10.8973           |
| 2.87 | 2.3208          | 3.3304            | 3.37 | 3.7574          | 6.3313            | 3.87 | 5.6903          | 11.0107           |
| 2.88 | 2.3452          | 3.3771            | 3.38 | 3.7910          | 6.4067            | 3.88 | 5.7345          | 11.1249           |
| 2.89 | 2.3697          | 3.4242            | 3.39 | 3.8247          | 6.4829            | 3.89 | 5.7789          | 11.2401           |
| 2.90 | 2.3944          | 3.4719            | 3.40 | 3.8587          | 6.5597            | 3.90 | 5.8236          | 11.3561           |
| 2.91 | 2.4192          | 3.5200            | 3.41 | 3.8928          | 6.6372            | 3.91 | 5.8685          | 11.4730           |
| 2.92 | 2.4443          | 3.5686            | 3.42 | 3.9272          | 6.7154            | 3.92 | 5.9137          | 11.5908           |
| 2.93 | 2.4695          | 3.6178            | 3.43 | 3.9617          | 6.7943            | 3.93 | 5.9591          | 11.7095           |
| 2.94 | 2.4948          | 3.6674            | 3.44 | 3.9965          | 6.8739            | 3.94 | 6.0047          | 11.8292           |
| 2.95 | 2.5204          | 3.7176            | 3.45 | 4.0314          | 6.9542            | 3.95 | 6.0505          | 11.9497           |
| 2.96 | 2.5461          | 3.7682            | 3.46 | 4.0666          | 7.0352            | 3.96 | 6.0966          | 12.0712           |
| 2.97 | 2.5720          | 3.8194            | 3.47 | 4.1019          | 7.1168            | 3.97 | 6.1429          | 12.1936           |
| 2.98 | 2.5981          | 3.8711            | 3.48 | 4.1375          | 7.1992            | 3.98 | 6.1894          | 12.3169           |
| 2.99 | 2.6243          | 3.9233            | 3.49 | 4.1733          | 7.2824            | 3.99 | 6.2362          | 12.4412           |

## Section Moduli and Moments of Inertia for Round Shafts (English or Metric Units)

| Dia. | Section Modulus | Moment of Inertia | Dia. | Section Modulus | Moment of Inertia | Dia. | Section Modulus | Moment of Inertia |
|------|-----------------|-------------------|------|-----------------|-------------------|------|-----------------|-------------------|
| 4.00 | 6.2832          | 12.566            | 4.50 | 8.946           | 20.129            | 5.00 | 12.272          | 30.680            |
| 4.01 | 6.3304          | 12.693            | 4.51 | 9.006           | 20.308            | 5.01 | 12.346          | 30.926            |
| 4.02 | 6.3779          | 12.820            | 4.52 | 9.066           | 20.489            | 5.02 | 12.420          | 31.173            |
| 4.03 | 6.4256          | 12.948            | 4.53 | 9.126           | 20.671            | 5.03 | 12.494          | 31.423            |
| 4.04 | 6.4736          | 13.077            | 4.54 | 9.187           | 20.854            | 5.04 | 12.569          | 31.673            |
| 4.05 | 6.5218          | 13.207            | 4.55 | 9.248           | 21.039            | 5.05 | 12.644          | 31.925            |
| 4.06 | 6.5702          | 13.337            | 4.56 | 9.309           | 21.224            | 5.06 | 12.719          | 32.179            |
| 4.07 | 6.6189          | 13.469            | 4.57 | 9.370           | 21.411            | 5.07 | 12.795          | 32.434            |
| 4.08 | 6.6678          | 13.602            | 4.58 | 9.432           | 21.599            | 5.08 | 12.870          | 32.691            |
| 4.09 | 6.7169          | 13.736            | 4.59 | 9.494           | 21.788            | 5.09 | 12.947          | 32.949            |
| 4.10 | 6.7663          | 13.871            | 4.60 | 9.556           | 21.979            | 5.10 | 13.023          | 33.209            |
| 4.11 | 6.8159          | 14.007            | 4.61 | 9.618           | 22.170            | 5.11 | 13.100          | 33.470            |
| 4.12 | 6.8658          | 14.144            | 4.62 | 9.681           | 22.363            | 5.12 | 13.177          | 33.733            |
| 4.13 | 6.9159          | 14.281            | 4.63 | 9.744           | 22.558            | 5.13 | 13.254          | 33.997            |
| 4.14 | 6.9663          | 14.420            | 4.64 | 9.807           | 22.753            | 5.14 | 13.332          | 34.263            |
| 4.15 | 7.0169          | 14.560            | 4.65 | 9.871           | 22.950            | 5.15 | 13.410          | 34.530            |
| 4.16 | 7.0677          | 14.701            | 4.66 | 9.935           | 23.148            | 5.16 | 13.488          | 34.799            |
| 4.17 | 7.1188          | 14.843            | 4.67 | 9.999           | 23.347            | 5.17 | 13.567          | 35.070            |
| 4.18 | 7.1702          | 14.986            | 4.68 | 10.063          | 23.548            | 5.18 | 13.645          | 35.342            |
| 4.19 | 7.2217          | 15.130            | 4.69 | 10.128          | 23.750            | 5.19 | 13.725          | 35.616            |
| 4.20 | 7.2736          | 15.275            | 4.70 | 10.193          | 23.953            | 5.20 | 13.804          | 35.891            |
| 4.21 | 7.3257          | 15.420            | 4.71 | 10.258          | 24.158            | 5.21 | 13.884          | 36.168            |
| 4.22 | 7.3780          | 15.568            | 4.72 | 10.323          | 24.363            | 5.22 | 13.964          | 36.446            |
| 4.23 | 7.4306          | 15.716            | 4.73 | 10.389          | 24.571            | 5.23 | 14.044          | 36.726            |
| 4.24 | 7.4834          | 15.865            | 4.74 | 10.455          | 24.779            | 5.24 | 14.125          | 37.008            |
| 4.25 | 7.5364          | 16.015            | 4.75 | 10.522          | 24.989            | 5.25 | 14.206          | 37.291            |
| 4.26 | 7.5898          | 16.166            | 4.76 | 10.588          | 25.200            | 5.26 | 14.288          | 37.576            |
| 4.27 | 7.6433          | 16.319            | 4.77 | 10.655          | 25.412            | 5.27 | 14.369          | 37.863            |
| 4.28 | 7.6972          | 16.472            | 4.78 | 10.722          | 25.626            | 5.28 | 14.451          | 38.151            |
| 4.29 | 7.7513          | 16.626            | 4.79 | 10.790          | 25.841            | 5.29 | 14.533          | 38.441            |
| 4.30 | 7.8056          | 16.782            | 4.80 | 10.857          | 26.058            | 5.30 | 14.616          | 38.732            |
| 4.31 | 7.8602          | 16.939            | 4.81 | 10.925          | 26.275            | 5.31 | 14.699          | 39.025            |
| 4.32 | 7.9150          | 17.096            | 4.82 | 10.994          | 26.495            | 5.32 | 14.782          | 39.320            |
| 4.33 | 7.9701          | 17.255            | 4.83 | 11.062          | 26.715            | 5.33 | 14.866          | 39.617            |
| 4.34 | 8.0254          | 17.415            | 4.84 | 11.131          | 26.937            | 5.34 | 14.949          | 39.915            |
| 4.35 | 8.0810          | 17.576            | 4.85 | 11.200          | 27.160            | 5.35 | 15.034          | 40.215            |
| 4.36 | 8.1369          | 17.738            | 4.86 | 11.270          | 27.385            | 5.36 | 15.118          | 40.516            |
| 4.37 | 8.1930          | 17.902            | 4.87 | 11.339          | 27.611            | 5.37 | 15.203          | 40.819            |
| 4.38 | 8.2494          | 18.066            | 4.88 | 11.409          | 27.839            | 5.38 | 15.288          | 41.124            |
| 4.39 | 8.3060          | 18.232            | 4.89 | 11.480          | 28.068            | 5.39 | 15.373          | 41.431            |
| 4.40 | 8.3629          | 18.398            | 4.90 | 11.550          | 28.298            | 5.40 | 15.459          | 41.739            |
| 4.41 | 8.4201          | 18.566            | 4.91 | 11.621          | 28.530            | 5.41 | 15.545          | 42.049            |
| 4.42 | 8.4775          | 18.735            | 4.92 | 11.692          | 28.763            | 5.42 | 15.631          | 42.361            |
| 4.43 | 8.5351          | 18.905            | 4.93 | 11.764          | 28.997            | 5.43 | 15.718          | 42.675            |
| 4.44 | 8.5931          | 19.077            | 4.94 | 11.835          | 29.233            | 5.44 | 15.805          | 42.990            |
| 4.45 | 8.6513          | 19.249            | 4.95 | 11.907          | 29.471            | 5.45 | 15.892          | 43.307            |
| 4.46 | 8.7097          | 19.423            | 4.96 | 11.980          | 29.710            | 5.46 | 15.980          | 43.626            |
| 4.47 | 8.7684          | 19.597            | 4.97 | 12.052          | 29.950            | 5.47 | 16.068          | 43.946            |
| 4.48 | 8.8274          | 19.773            | 4.98 | 12.125          | 30.192            | 5.48 | 16.156          | 44.268            |
| 4.49 | 8.8867          | 19.951            | 4.99 | 12.198          | 30.435            | 5.49 | 16.245          | 44.592            |

**Section Moduli and Moments of Inertia for Round Shafts (English or Metric Units)**

| Dia. | Section Modulus | Moment of Inertia | Dia. | Section Modulus | Moment of Inertia | Dia. | Section Modulus | Moment of Inertia |
|------|-----------------|-------------------|------|-----------------|-------------------|------|-----------------|-------------------|
| 5.5  | 16.3338         | 44.9180           | 30   | 2650.72         | 39760.8           | 54.5 | 15892.4         | 433068            |
| 6    | 21.2058         | 63.6173           | 30.5 | 2785.48         | 42478.5           | 55   | 16333.8         | 449180            |
| 6.5  | 26.9612         | 87.6241           | 31   | 2924.72         | 45333.2           | 55.5 | 16783.4         | 465738            |
| 7    | 33.6739         | 117.859           | 31.5 | 3068.54         | 48329.5           | 56   | 17241.1         | 482750            |
| 7.5  | 41.4175         | 155.316           | 32   | 3216.99         | 51471.9           | 56.5 | 17707.0         | 500223            |
| 8    | 50.2655         | 201.062           | 32.5 | 3370.16         | 54765.0           | 57   | 18181.3         | 518166            |
| 8.5  | 60.2916         | 256.239           | 33   | 3528.11         | 58213.8           | 57.5 | 18663.9         | 536588            |
| 9    | 71.5694         | 322.062           | 33.5 | 3690.92         | 61822.9           | 58   | 19155.1         | 555497            |
| 9.5  | 84.1726         | 399.820           | 34   | 3858.66         | 65597.2           | 58.5 | 19654.7         | 574901            |
| 10   | 98.1748         | 490.874           | 34.5 | 4031.41         | 69541.9           | 59   | 20163.0         | 594810            |
| 10.5 | 113.650         | 596.660           | 35   | 4209.24         | 73661.8           | 59.5 | 20680.0         | 615230            |
| 11   | 130.671         | 718.688           | 35.5 | 4392.23         | 77962.1           | 60   | 21205.8         | 636173            |
| 11.5 | 149.312         | 858.541           | 36   | 4580.44         | 82448.0           | 60.5 | 21740.3         | 657645            |
| 12   | 169.646         | 1017.88           | 36.5 | 4773.96         | 87124.7           | 61   | 22283.8         | 679656            |
| 12.5 | 191.748         | 1198.42           | 37   | 4972.85         | 91997.7           | 61.5 | 22836.3         | 702215            |
| 13   | 215.690         | 1401.98           | 37.5 | 5177.19         | 97072.2           | 62   | 23397.8         | 725332            |
| 13.5 | 241.547         | 1630.44           | 38   | 5387.05         | 102354            | 62.5 | 23968.4         | 749014            |
| 14   | 269.392         | 1885.74           | 38.5 | 5602.50         | 107848            | 63   | 24548.3         | 773272            |
| 14.5 | 299.298         | 2169.91           | 39   | 5823.63         | 113561            | 63.5 | 25137.4         | 798114            |
| 15   | 331.340         | 2485.05           | 39.5 | 6050.50         | 119497            | 64   | 25735.9         | 823550            |
| 15.5 | 365.591         | 2833.33           | 40   | 6283.19         | 125664            | 64.5 | 26343.8         | 849589            |
| 16   | 402.124         | 3216.99           | 40.5 | 6521.76         | 132066            | 65   | 26961.2         | 876241            |
| 16.5 | 441.013         | 3638.36           | 41   | 6766.30         | 138709            | 65.5 | 27588.2         | 903514            |
| 17   | 482.333         | 4099.83           | 41.5 | 7016.88         | 145600            | 66   | 28224.9         | 931420            |
| 17.5 | 526.155         | 4603.86           | 42   | 7273.57         | 152745            | 66.5 | 28871.2         | 959967            |
| 18   | 572.555         | 5153.00           | 42.5 | 7536.45         | 160150            | 67   | 29527.3         | 989166            |
| 18.5 | 621.606         | 5749.85           | 43   | 7805.58         | 167820            | 67.5 | 30193.3         | 1019025           |
| 19   | 673.381         | 6397.12           | 43.5 | 8081.05         | 175763            | 68   | 30869.3         | 1049556           |
| 19.5 | 727.954         | 7097.55           | 44   | 8362.92         | 183984            | 68.5 | 31555.2         | 1080767           |
| 20   | 785.398         | 7853.98           | 44.5 | 8651.27         | 192491            | 69   | 32251.3         | 1112670           |
| 20.5 | 845.788         | 8669.33           | 45   | 8946.18         | 201289            | 69.5 | 32957.5         | 1145273           |
| 21   | 909.197         | 9546.56           | 45.5 | 9247.71         | 210385            | 70   | 33673.9         | 1178588           |
| 21.5 | 975.698         | 10488.8           | 46   | 9555.94         | 219787            | 70.5 | 34400.7         | 1212625           |
| 22   | 1045.36         | 11499.0           | 46.5 | 9870.95         | 229499            | 71   | 35137.8         | 1247393           |
| 22.5 | 1118.27         | 12580.6           | 47   | 10192.8         | 239531            | 71.5 | 35885.4         | 1282904           |
| 23   | 1194.49         | 13736.7           | 47.5 | 10521.6         | 249887            | 72   | 36643.5         | 1319167           |
| 23.5 | 1274.10         | 14970.7           | 48   | 10857.3         | 260576            | 72.5 | 37412.3         | 1356194           |
| 24   | 1357.17         | 16286.0           | 48.5 | 11200.2         | 271604            | 73   | 38191.7         | 1393995           |
| 24.5 | 1443.77         | 17686.2           | 49   | 11550.2         | 282979            | 73.5 | 38981.8         | 1432581           |
| 25   | 1533.98         | 19174.8           | 49.5 | 11907.4         | 294707            | 74   | 39782.8         | 1471963           |
| 25.5 | 1627.87         | 20755.4           | 50   | 12271.8         | 306796            | 74.5 | 40594.6         | 1512150           |
| 26   | 1725.52         | 22431.8           | 50.5 | 12643.7         | 319253            | 75   | 41417.5         | 1553156           |
| 26.5 | 1827.00         | 24207.7           | 51   | 13023.0         | 332086            | 75.5 | 42251.4         | 1594989           |
| 27   | 1932.37         | 26087.0           | 51.5 | 13409.8         | 345302            | 76   | 43096.4         | 1637662           |
| 27.5 | 2041.73         | 28073.8           | 52   | 13804.2         | 358908            | 76.5 | 43952.6         | 1681186           |
| 28   | 2155.13         | 30171.9           | 52.5 | 14206.2         | 372913            | 77   | 44820.0         | 1725571           |
| 28.5 | 2272.66         | 32385.4           | 53   | 14616.0         | 387323            | 77.5 | 45698.8         | 1770829           |
| 29   | 2394.38         | 34718.6           | 53.5 | 15033.5         | 402147            | 78   | 46589.0         | 1816972           |
| 29.5 | 2520.38         | 37175.6           | 54   | 15459.0         | 417393            | 78.5 | 47490.7         | 1864011           |

## MOMENT OF INERTIA, SECTION MODULUS

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## Section Moduli and Moments of Inertia for Round Shafts (English or Metric Units)

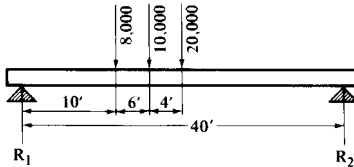
| Dia.  | Section Modulus | Moment of Inertia | Dia.  | Section Modulus | Moment of Inertia | Dia.  | Section Modulus | Moment of Inertia |
|-------|-----------------|-------------------|-------|-----------------|-------------------|-------|-----------------|-------------------|
| 79    | 48404.0         | 1911958           | 103.5 | 108848          | 5632890           | 128   | 205887          | 13176795          |
| 79.5  | 49328.9         | 1960823           | 104   | 110433          | 5742530           | 128.5 | 208310          | 13383892          |
| 80    | 50265.5         | 2010619           | 104.5 | 112034          | 5853762           | 129   | 210751          | 13593420          |
| 80.5  | 51213.9         | 2061358           | 105   | 113650          | 5966602           | 129.5 | 213211          | 13805399          |
| 81    | 52174.1         | 2113051           | 105.5 | 115281          | 6081066           | 130   | 215690          | 14019848          |
| 81.5  | 53146.3         | 2165710           | 106   | 116928          | 6197169           | 130.5 | 218188          | 14236786          |
| 82    | 54130.4         | 2219347           | 106.5 | 118590          | 6314927           | 131   | 220706          | 14456231          |
| 82.5  | 55126.7         | 2273975           | 107   | 120268          | 6434355           | 131.5 | 223243          | 14678204          |
| 83    | 56135.1         | 2329605           | 107.5 | 121962          | 6555469           | 132   | 225799          | 14902723          |
| 83.5  | 57155.7         | 2386249           | 108   | 123672          | 6678285           | 132.5 | 228374          | 15129808          |
| 84    | 58188.6         | 2443920           | 108.5 | 125398          | 6802818           | 133   | 230970          | 15359478          |
| 84.5  | 59233.9         | 2502631           | 109   | 127139          | 6929085           | 133.5 | 233584          | 15591754          |
| 85    | 60291.6         | 2562392           | 109.5 | 128897          | 7057102           | 134   | 236219          | 15826653          |
| 85.5  | 61361.8         | 2623218           | 110   | 130671          | 7186884           | 134.5 | 238873          | 16064198          |
| 86    | 62444.7         | 2685120           | 110.5 | 132461          | 7318448           | 135   | 241547          | 16304406          |
| 86.5  | 63540.1         | 2748111           | 111   | 134267          | 7451811           | 135.5 | 244241          | 16547298          |
| 87    | 64648.4         | 2812205           | 111.5 | 136089          | 7586987           | 136   | 246954          | 16792893          |
| 87.5  | 65769.4         | 2877412           | 112   | 137928          | 7723995           | 136.5 | 249688          | 17041213          |
| 88    | 66903.4         | 2943748           | 112.5 | 139784          | 7862850           | 137   | 252442          | 17292276          |
| 88.5  | 68050.2         | 3011223           | 113   | 141656          | 8003569           | 137.5 | 255216          | 17546104          |
| 89    | 69210.2         | 3079853           | 113.5 | 143545          | 8146168           | 138   | 258010          | 17802715          |
| 89.5  | 70383.2         | 3149648           | 114   | 145450          | 8290664           | 138.5 | 260825          | 18062131          |
| 90    | 71569.4         | 3220623           | 114.5 | 147372          | 8437074           | 139   | 263660          | 18324372          |
| 90.5  | 72768.9         | 3292791           | 115   | 149312          | 8585414           | 139.5 | 266516          | 18589458          |
| 91    | 73981.7         | 3366166           | 115.5 | 151268          | 8735703           | 140   | 269392          | 18857410          |
| 91.5  | 75207.9         | 3440759           | 116   | 153241          | 8887955           | 140.5 | 272288          | 19128248          |
| 92    | 76447.5         | 3516586           | 116.5 | 155231          | 9042189           | 141   | 275206          | 19401993          |
| 92.5  | 77700.7         | 3593659           | 117   | 157238          | 9198422           | 141.5 | 278144          | 19678666          |
| 93    | 78967.6         | 3671992           | 117.5 | 159262          | 9356671           | 142   | 281103          | 19958288          |
| 93.5  | 80248.1         | 3751598           | 118   | 161304          | 9516953           | 142.5 | 284083          | 20240878          |
| 94    | 81542.4         | 3832492           | 118.5 | 163363          | 9679286           | 143   | 287083          | 20526460          |
| 94.5  | 82850.5         | 3914688           | 119   | 165440          | 9843686           | 143.5 | 290105          | 20815052          |
| 95    | 84172.6         | 3998198           | 119.5 | 167534          | 10010172          | 144   | 293148          | 21106677          |
| 95.5  | 85508.6         | 4083038           | 120   | 169646          | 10178760          | 144.5 | 296213          | 21401356          |
| 96    | 86858.8         | 4169220           | 120.5 | 171775          | 10349469          | 145   | 299298          | 21699109          |
| 96.5  | 88223.0         | 4256760           | 121   | 173923          | 10522317          | 145.5 | 302405          | 21999959          |
| 97    | 89601.5         | 4345671           | 121.5 | 176088          | 10697321          | 146   | 305533          | 22303926          |
| 97.5  | 90994.2         | 4435968           | 122   | 178270          | 10874498          | 146.5 | 308683          | 22611033          |
| 98    | 92401.3         | 4527664           | 122.5 | 180471          | 11053867          | 147   | 311854          | 22921300          |
| 98.5  | 93822.8         | 4620775           | 123   | 182690          | 11235447          | 147.5 | 315047          | 23234749          |
| 99    | 95258.9         | 4715315           | 123.5 | 184927          | 11419254          | 148   | 318262          | 23551402          |
| 99.5  | 96709.5         | 4811298           | 124   | 187182          | 11605307          | 148.5 | 321499          | 23871280          |
| 100   | 98174.8         | 4908739           | 124.5 | 189456          | 11793625          | 149   | 324757          | 24194406          |
| 100.5 | 99654.8         | 5007652           | 125   | 191748          | 11984225          | 149.5 | 328037          | 24520802          |
| 101   | 101150          | 5108053           | 125.5 | 194058          | 12177126          | 150   | 331340          | 24850489          |
| 101.5 | 102659          | 5209956           | 126   | 196386          | 12372347          | ...   | ...             | ...               |
| 102   | 104184          | 5313376           | 126.5 | 198734          | 12569905          | ...   | ...             | ...               |
| 102.5 | 105723          | 5418329           | 127   | 201100          | 12769820          | ...   | ...             | ...               |
| 103   | 107278          | 5524828           | 127.5 | 203484          | 12972110          | ...   | ...             | ...               |



## BEAMS

## Beam Calculations

**Reaction at the Supports.**—When a beam is loaded by vertical loads or forces, the sum of the reactions at the supports equals the sum of the loads. In a simple beam, when the loads are symmetrically placed with reference to the supports, or when the load is uniformly distributed, the reaction at each end will equal one-half of the sum of the loads. When the loads are not symmetrically placed, the reaction at each support may be ascertained from the fact that the algebraic sum of the moments must equal zero. In the accompanying illustration, if moments are taken about the support to the left, then:  $R_2 \times 40 - 8,000 \times 10 - 10,000 \times 16 - 20,000 \times 20 = 0$ ;  $R_2 = 16,000$  pounds. In the same way, moments taken about the support at the right give  $R_1 = 22,000$  pounds.



The sum of the reactions equals 38,000 pounds, which is also the sum of the loads. If part of the load is uniformly distributed over the beam, this part is first equally divided between the two supports, or the uniform load may be considered as concentrated at its center of gravity.

**If metric SI units are used for the calculations, distances may be expressed in meters or millimeters, providing the treatment is consistent, and loads in newtons. Note: If the load is given in kilograms, the value referred to is the mass. A mass of  $M$  kilograms has a weight (applies a force) of  $Mg$  newtons, where  $g =$  approximately 9.81 meters per second<sup>2</sup>.**

**Stresses and Deflections in Beams.**—On the following pages [Table 1](#) gives an extensive list of formulas for stresses and deflections in beams, shafts, etc. It is assumed that all the dimensions are in inches, all loads in pounds, and all stresses in pounds per square inch. **The formulas are also valid using metric SI units, with all dimensions in millimeters, all loads in newtons, and stresses and moduli in newtons per millimeter<sup>2</sup> (N/mm<sup>2</sup>).** *Note: A load due to the weight of a mass of  $M$  kilograms is  $Mg$  newtons, where  $g =$  approximately 9.81 meters per second<sup>2</sup>.* In the tables:

$E$  = modulus of elasticity of the material

$I$  = moment of inertia of the cross-section of the beam

$Z$  = section modulus of the cross-section of the beam =  $I \div$  distance from neutral axis to extreme fiber

$W$  = load on beam

$s$  = stress in extreme fiber, or maximum stress in the cross-section considered, due to load  $W$ . A positive value of  $s$  denotes tension in the upper fibers and compression in the lower ones (as in a cantilever). A negative value of  $s$  denotes the reverse (as in a beam supported at the ends). The greatest safe load is that value of  $W$  which causes a maximum stress equal to, but not exceeding, the greatest safe value of  $s$

$y$  = deflection measured from the position occupied if the load causing the deflection were removed. A positive value of  $y$  denotes deflection below this position; a negative value, deflection upward

$u, v, w, x$  = variable distances along the beam from a given support to any point

**Table 1. Stresses and Deflections in Beams**

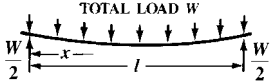
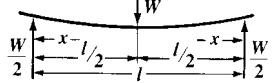
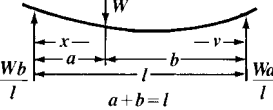
| Type of Beam  | Stresses   |  | Deflections  |  |
|---|--|--|--|--|
|   | General Formula for Stress at any Point  | Stresses at Critical Points  | General Formula for Deflection at any Point <sup>a</sup>   | Deflections at Critical Points <sup>a</sup>  |
| Case 1. — Supported at Both Ends, Uniform Load                                    |  |  |  |  |
|  | $s = -\frac{W}{2Zl}x(l-x)$   | Stress at center,<br>$-\frac{Wl}{8Z}$<br><br>If cross-section is constant, this is the maximum stress. | $y = \frac{Wx(l-x)}{24EI}[l^2 + x(l-x)]$   | Maximum deflection, at center,<br>$\frac{5}{384} \frac{Wl^3}{EI}$  |
| Case 2. — Supported at Both Ends, Load at Center                                  |  |  |  |  |
|  | Between each support and load,<br>$s = -\frac{Wx}{2Z}$   | Stress at center,<br>$-\frac{Wl}{4Z}$<br><br>If cross-section is constant, this is the maximum stress. | Between each support and load,<br>$y = \frac{Wx}{48EI}(3l^2 - 4x^2)$   | Maximum deflection, at load,<br>$\frac{Wl^3}{48EI}$  |
| Case 3. — Supported at Both Ends, Load at any Point                               |  |  |  |  |
|  | For segment of length $a$ ,<br>$s = -\frac{Wbx}{Zl}$<br><br>For segment of length $b$ ,<br>$s = -\frac{Wav}{Zl}$ | Stress at load,<br>$-\frac{Wab}{Zl}$<br><br>If cross-section is constant, this is the maximum stress.  | For segment of length $a$ ,<br>$y = \frac{Wbx}{6EI}(l^2 - x^2 - b^2)$<br><br>For segment of length $b$ ,<br>$y = \frac{Wav}{6EI}(l^2 - v^2 - a^2)$ | Deflection at load,<br>$\frac{Wa^2b^2}{3EI}$<br><br>Let $a$ be the length of the shorter segment and $b$ of the longer one. The maximum deflection $\frac{Wav^3}{3EI}$ is in the longer segment, at<br>$v = b\sqrt{\frac{1}{3} + \frac{2a}{3b}} = v_1$ |

Table 1. (Continued) Stresses and Deflections in Beams

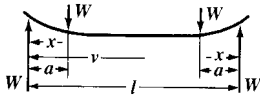
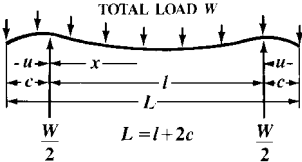
| Type of Beam  | Stresses   |  | Deflections  |  |
|---|--|--|--|--|
|   | General Formula for Stress at any Point  | Stresses at Critical Points  | General Formula for Deflection at any Point <sup>a</sup>   | Deflections at Critical Points <sup>a</sup>  |
| Case 4. — Supported at Both Ends, Two Symmetrical Loads                           |  |  |  |  |
|  | Between each support and adjacent load,<br>$s = -\frac{Wx}{Z}$<br>Between loads,<br>$s = -\frac{Wa}{Z}$                        | Stress at each load, and at all points between, $-\frac{Wa}{Z}$  | Between each support and adjacent load,<br>$y = \frac{Wx}{6EI}[3a(l-a) - x^2]$<br>Between loads,<br>$y = \frac{Wa}{6EI}[3v(l-v) - a^2]$                                | Maximum deflection at center,<br>$\frac{Wa}{24EI}(3l^2 - 4a^2)$<br>Deflection at loads<br>$\frac{Wa^2}{6EI}(3l - 4a)$  |
| Case 5. — Both Ends Overhanging Supports Symmetrically, Uniform Load              |  |  |  |  |
|   | Between each support and adjacent end,<br>$s = \frac{W}{2Zl}(c-u)^2$<br>Between supports,<br>$s = \frac{W}{2ZL}[c^2 - x(l-x)]$ | Stress at each support,<br>$\frac{Wc^2}{2ZL}$<br>Stress at center,<br>$\frac{W}{2ZL}(c^2 - \frac{1}{4}l^2)$<br>If cross-section is constant, the greater of these is the maximum stress.<br>If $l$ is greater than $2c$ , the stress is zero at points $\sqrt{\frac{1}{4}l^2 - c^2}$ on both sides of the center.<br>If cross-section is constant and if $l = 2.828c$ , the stresses at supports and center are equal and opposite, and are<br>$\pm \frac{WL}{46.62Z}$ | Between each support and adjacent end,<br>$y = \frac{Wu}{24EIL}[6c^2(l+u) - u^2(4c-u) - l^3]$<br>Between supports,<br>$y = \frac{Wx(l-x)}{24EIL}[x(l-x) + l^2 - 6c^2]$ | Deflection at ends,<br>$\frac{Wc}{24EIL}[3c^2(c+2l) - l^3]$<br>Deflection at center,<br>$\frac{Wl^2}{384EIL}(5l^2 - 24c^2)$<br>If $l$ is between $2c$ and $2.449c$ , there are maximum upward deflections at points $\sqrt{3(\frac{1}{4}l^2 - c^2)}$ on both sides of the center, which are,<br>$-\frac{W}{96EIL}(6c^2 - l^2)^2$ |

Table 1. (Continued) Stresses and Deflections in Beams

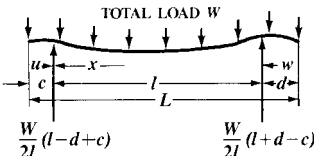
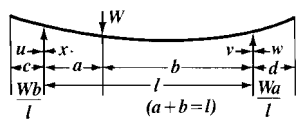
| Type of Beam  | Stresses  |   | Deflections   |  |
|---|---|---|---|--|
|   | General Formula for Stress at any Point   | Stresses at Critical Points   | General Formula for Deflection at any Point <sup>a</sup>  | Deflections at Critical Points <sup>a</sup>  |
| Case 6. — Both Ends Overhanging Supports Unsymmetrically, Uniform Load  |   |   |   |  |
|  <p style="text-align: center;">TOTAL LOAD <math>W</math></p> <p style="text-align: center;"><math>\frac{W}{2l}(l-d+c)</math>      <math>\frac{W}{2l}(l+d-c)</math></p> | <p>For overhanging end of length <math>c</math>,</p> $s = \frac{W}{2ZL}(c-u)^2$ <p>Between supports,</p> $s = \frac{W}{2ZL} \left\{ c^2 \left( \frac{l-x}{l} \right) + d^2 \frac{x}{l} - x(l-x) \right\}$ <p>For overhanging end of length <math>d</math>,</p> $s = \frac{W}{2ZL}(d-w)^2$ | <p>Stress at support next to end of length <math>c</math>, <math>\frac{Wc^2}{2ZL}</math></p> <p>Critical stress between supports is at</p> $x = \frac{l^2 + c^2 - d^2}{2l} = x_1$ <p>and is <math>\frac{W}{2ZL}(c^2 - x_1^2)</math></p> <p>Stress at support next to end of length <math>d</math>, <math>\frac{Wd^2}{2ZL}</math></p> <p>If cross-section is constant, the greatest of these three is the maximum stress.</p> <p>If <math>x_1 &gt; c</math>, the stress is zero at points <math>\sqrt{x_1^2 - c^2}</math> on both sides of <math>x = x_1</math>.</p> | <p>For overhanging end of length <math>c</math>,</p> $y = \frac{Wu}{24EIL} [2l(d^2 + 2c^2) + 6c^2u - u^2(4c-u) - l^3]$ <p>Between supports,</p> $y = \frac{Wx(l-x)}{24EIL} \{ x(l-x) + l^2 - 2(d^2 + c^2) - \frac{2}{l}[d^2x + c^2(l-x)] \}$ <p>For overhanging end of length <math>d</math>,</p> $y = \frac{Ww}{24EIL} [2l(c^2 + 2d^2) + 6d^2w - w^2(4d-w) - l^3]$ | <p>Deflection at end <math>c</math>,</p> $\frac{Wc}{24EIL} [2l(d^2 + 2c^2) + 3c^3 - l^3]$ <p>Deflection at end <math>d</math>,</p> $\frac{Wd}{24EIL} [2l(c^2 + 2d^2) + 3d^3 - l^3]$ <p>This case is so complicated that convenient general expressions for the critical deflections between supports cannot be obtained.</p> |
|   | Case 7. — Both Ends Overhanging Supports, Load at any Point Between   |   |   |  |
|  <p style="text-align: center;"><math>\frac{Wb}{l}</math>      <math>\frac{Wa}{l}</math></p> <p style="text-align: center;"><math>(a+b=l)</math></p>                    | <p>Between supports:</p> <p>For segment of length <math>a</math>,</p> $s = \frac{Wbx}{Zl}$ <p>For segment of length <math>b</math>,</p> $s = \frac{Wav}{Zl}$ <p>Beyond supports <math>s = 0</math>.</p>   | <p>Stress at load,</p> $\frac{Wab}{Zl}$ <p>If cross-section is constant, this is the maximum stress.</p>  | <p>Between supports, same as Case 3.</p> <p>For overhanging end of length <math>c</math>,</p> $y = \frac{Wabu}{6EIL}(l+b)$ <p>For overhanging end of length <math>d</math>,</p> $y = \frac{Wabw}{6EIL}(l+a)$  | <p>Between supports, same as Case 3.</p> <p>Deflection at end <math>c</math>,</p> $\frac{Wabc}{6EIL}(l+b)$ <p>Deflection at end <math>d</math>,</p> $\frac{Wabd}{6EIL}(l+a)$   |

Table 1. (Continued) Stresses and Deflections in Beams

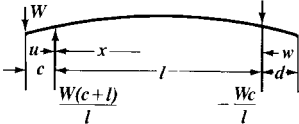
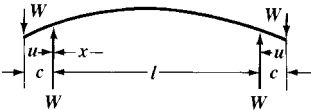
| Type of Beam  | Stresses  |   | Deflections  |  |
|---|---|---|--|--|
|   | General Formula for Stress at any Point   | Stresses at Critical Points   | General Formula for Deflection at any Point <sup>a</sup>   | Deflections at Critical Points <sup>a</sup>  |
| Case 8. — Both Ends Overhanging Supports, Single Overhanging Load   |   |   |  |  |
|   | <p>Between load and adjacent support,</p> $s = \frac{W}{Z}(c - u)$ <p>Between supports,</p> $s = \frac{Wc}{Zl}(l - x)$ <p>Between unloaded end and adjacent supports, <math>s = 0</math>.</p> | <p>Stress at support adjacent to load,</p> $\frac{Wc}{Z}$ <p>If cross-section is constant, this is the maximum stress. Stress is zero at other support.</p> | <p>Between load and adjacent support,</p> $y = \frac{Wu}{6EI}(3cu - u^2 + 2cl)$ <p>Between supports,</p> $y = -\frac{Wcx}{6EI}(l - x)(2l - x)$ <p>Between unloaded end and adjacent support, <math>y = \frac{Wcld}{6EI}</math></p> | <p>Deflection at load,</p> $\frac{Wc^2}{3EI}(c + l)$ <p>Maximum upward deflection is at <math>x = .42265l</math>, and is <math>-\frac{Wcl^2}{15.55EI}</math></p> <p>Deflection at unloaded end,</p> $\frac{Wcld}{6EI}$ |
| Case 9. — Both Ends Overhanging Supports, Symmetrical Overhanging Loads   |   |   |  |  |
|   | <p>Between each load and adjacent support,</p> $s = \frac{W}{Z}(c - u)$ <p>Between supports,</p> $s = \frac{Wc}{Z}$   | <p>Stress at supports and at all points between,</p> $\frac{Wc}{Z}$ <p>If cross-section is constant, this is the maximum stress.</p>                        | <p>Between each load and adjacent support,</p> $y = \frac{Wu}{6EI}[3c(l + u) - u^2]$ <p>Between supports,</p> $y = -\frac{Wcx}{2EI}(l - x)$  | <p>Deflections at loads,</p> $\frac{Wc^2}{6EI}(2c + 3l)$ <p>Deflection at center,</p> $\frac{Wcl^2}{8EI}$  |
| <p>The above expressions involve the usual approximations of the theory of flexure, and hold only for small deflections. Exact expressions for deflections of any magnitude are as follows:</p> <p>Between supports the curve is a circle of radius <math>r = \frac{EI}{Wc}</math></p> <p>Deflection at any point <math>x</math> between supports</p> $y = \sqrt{r^2 - \frac{1}{4}l^2} - \sqrt{r^2 - (\frac{1}{2}l - x)^2}$ <p>Deflection at center, <math>\sqrt{r^2 - \frac{1}{4}l^2} - r</math></p> |   |   |  |  |

Table 1. (Continued) Stresses and Deflections in Beams

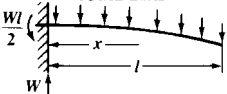
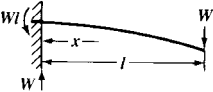
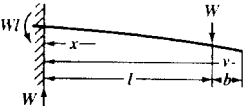
| Type of Beam   | Stresses  |   | Deflections   |   |
|--|---|---|---|---|
|  | General Formula for Stress at any Point   | Stresses at Critical Points   | General Formula for Deflection at any Point <sup>a</sup>  | Deflections at Critical Points <sup>a</sup>   |
| Case 10. — Fixed at One End, Uniform Load  |   |   |   |   |
|  <p style="text-align: center;">TOTAL LOAD <math>W</math></p> | $s = \frac{W}{2Zl}(l-x)^2$  | Stress at support,<br>$\frac{Wl}{2Z}$<br><br>If cross-section is constant,<br>this is the maximum stress. | $y = \frac{Wx^2}{24EI}[2l^2 + (2l-x)^2]$  | Maximum deflection, at end,<br>$\frac{Wl^3}{8EI}$   |
| Case 11. — Fixed at One End, Load at Other   |   |   |   |   |
|   | $s = \frac{W}{Z}(l-x)$  | Stress at support,<br>$\frac{Wl}{Z}$<br><br>If cross-section is constant,<br>this is the maximum stress.  | $y = \frac{Wx^2}{6EI}(3l-x)$  | Maximum deflection, at end,<br>$\frac{Wl^3}{3EI}$   |
| Case 12. — Fixed at One End, Intermediate Load   |   |   |   |   |
|   | Between support and load,<br>$s = \frac{W}{Z}(l-x)$<br><br>Beyond load, $s = 0$ . | Stress at support,<br>$\frac{Wl}{Z}$<br><br>If cross-section is constant,<br>this is the maximum stress.  | Between support and load,<br>$y = \frac{Wx^2}{6EI}(3l-x)$<br><br>Beyond load,<br>$y = \frac{Wl^2}{6EI}(3v-l)$ | Deflection at load,<br>$\frac{Wl^3}{3EI}$<br><br>Maximum deflection, at end,<br>$\frac{Wl^2}{6EI}(2l+3b)$ |

Table 1. (Continued) Stresses and Deflections in Beams

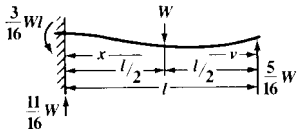
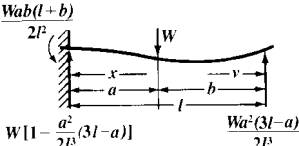
| Type of Beam   | Stresses  |   | Deflections   |   |
|--|---|---|---|---|
|  | General Formula for Stress at any Point   | Stresses at Critical Points   | General Formula for Deflection at any Point <sup>a</sup>  | Deflections at Critical Points <sup>a</sup>   |
| Case 13. — Fixed at One End, Supported at the Other, Load at Center              |   |   |   |   |
|  | Between point of fixture and load,<br>$s = \frac{W}{16Z}(3l - 11x)$<br>Between support and load,<br>$s = -\frac{5}{16} \frac{Wv}{Z}$    | Maximum stress at point of fixture, $\frac{3}{16} \frac{Wl}{Z}$<br><br>Stress is zero at $x = \frac{3}{16}l$<br>Greatest negative stress at center, $-\frac{5}{32} \frac{Wl}{Z}$  | Between point of fixture and load,<br>$y = \frac{Wx^2}{96EI}(9l - 11x)$<br>Between support and load,<br>$y = \frac{Wv}{96EI}(3l^2 - 5v^2)$                | Maximum deflection is at $v = 0.4472l$ , and is $\frac{Wl^3}{107.33EI}$<br><br>Deflection at load,<br>$\frac{7}{768} \frac{Wl^3}{EI}$   |
| Case 14. — Fixed at One End, Supported at the Other, Load at any Point           |   |   |   |   |
|  | Between point of fixture and load,<br>$s = \frac{Wb}{2Zl^3}(n - mx)$<br>Between support and load,<br>$s = -\frac{Wa^2v}{2Zl^3}(3l - a)$ | Greatest positive stress, at point of fixture,<br>$\frac{Wab}{2Zl^2}(l + b)$<br>Greatest negative stress, at load,<br>$-\frac{Wa^2b}{2Zl^3}(3l - a)$<br>If $a < 0.5858l$ , the first is the maximum stress. If $a = 0.5858l$ , the two are equal and are $\pm \frac{Wl}{5.83Z}$ If $a > 0.5858l$ , the second is the maximum stress.<br><br>Stress is zero at $x = \frac{n}{m}$ | Between point of fixture and load,<br>$y = \frac{Wx^2b}{12EI^3}(3n - mx)$<br>Between support and load,<br>$y = \frac{Wa^2v}{12EI^3}[3l^2b - v^2(3l - a)]$ | Deflection at load,<br>$\frac{Wab^3}{12EI^3}(3l + b)$<br>If $a < 0.5858l$ , maximum deflection is $\frac{Wa^2b}{6EI} \sqrt{\frac{b}{2l + b}}$ and located between load and support, at $v = l \sqrt{\frac{b}{2l + b}}$<br><br>If $a = 0.5858l$ , maximum deflection is at load and is $\frac{Wl^3}{101.9EI}$<br><br>If $a > 0.5858l$ , maximum deflection is $\frac{Wbn^3}{3EI m^2 l^3}$ and located between load and point of fixture, at $x = \frac{2n}{m}$ |

Table 1. (Continued) Stresses and Deflections in Beams

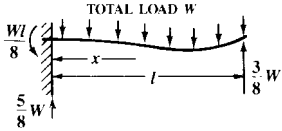
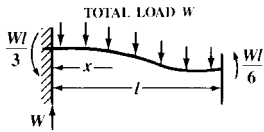
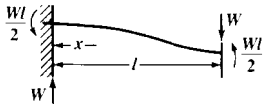
| Type of Beam  | Stresses   |   | Deflections  |  |
|---|--|---|--|--|
|   | General Formula for Stress at any Point  | Stresses at Critical Points   | General Formula for Deflection at any Point <sup>a</sup> | Deflections at Critical Points <sup>a</sup>  |
| Case 15. — Fixed at One End, Supported at the Other, Uniform Load                 |  |   |  |  |
|  | $s = \frac{W(l-x)}{2Zl}(\frac{1}{4}l-x)$   | Maximum stress at point of fixture, $\frac{Wl}{8Z}$<br><br>Stress is zero at $x = \frac{1}{4}l$ .<br>Greatest negative stress is at $x = \frac{3}{8}l$ and is $-\frac{9}{128} \frac{Wl}{Z}$ | $y = \frac{Wx^2(l-x)}{48EI}(3l-2x)$                      | Maximum deflection is at $x = 0.5785l$ , and is $\frac{Wl^3}{185EI}$<br><br>Deflection at center, $\frac{Wl^3}{192EI}$<br><br>Deflection at point of greatest negative stress, at $x = \frac{3}{8}l$ is $\frac{Wl^3}{187EI}$ |
| Case 16. — Fixed at One End, Free but Guided at the Other, Uniform Load           |  |   |  |  |
|  | $s = \frac{Wl}{Z} \left\{ \frac{1}{3} - \frac{x}{l} + \frac{1}{2} \left( \frac{x}{l} \right)^2 \right\}$ | Maximum stress, at support, $\frac{Wl}{3Z}$<br><br>Stress is zero at $x = 0.4227l$<br>Greatest negative stress, at free end, $-\frac{Wl}{6Z}$   | $y = \frac{Wx^2}{24EI}(2l-x)^2$                          | Maximum deflection, at free end, $\frac{Wl^3}{24EI}$   |
| Case 17. — Fixed at One End, Free but Guided at the Other, with Load              |  |   |  |  |
|  | $s = \frac{W}{Z}(\frac{1}{2}l-x)$  | Stress at support, $\frac{Wl}{2Z}$<br><br>Stress at free end $-\frac{Wl}{2Z}$<br><br>These are the maximum stresses and are equal and opposite.<br>Stress is zero at center.                | $y = \frac{Wx^2}{12EI}(3l-2x)$                           | Maximum deflection, at free end, $\frac{Wl^3}{12EI}$   |



Table 1. (Continued) Stresses and Deflections in Beams

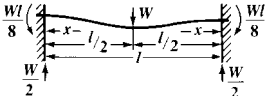
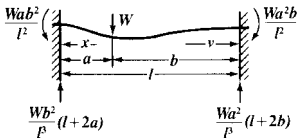
| Type of Beam  | Stresses  |  | Deflections   |  |
|---|---|--|---|--|
|   | General Formula for Stress at any Point   | Stresses at Critical Points  | General Formula for Deflection at any Point <sup>a</sup>  | Deflections at Critical Points <sup>a</sup>  |
| Case 18. — Fixed at Both Ends, Load at Center                                     |   |  |   |  |
|  | <p>Between each end and load,</p> $s = \frac{W}{2Z}(\frac{1}{4}l - x)$  | <p>Stress at ends <math>\frac{Wl}{8Z}</math></p> <p>Stress at load <math>\frac{Wl}{8Z}</math></p> <p>These are the maximum stresses and are equal and opposite.</p> <p>Stress is zero at <math>x = \frac{1}{4}l</math></p>   | $y = \frac{Wx^2}{48EI}(3l - 4x)$  | <p>Maximum deflection, at load,</p> $\frac{Wl^3}{192EI}$   |
| Case 19. — Fixed at Both Ends, Load at any Point                                  |   |  |   |  |
|   | <p>For segment of length <math>a</math>,</p> $s = \frac{Wb^2}{Zl^3}[al - x(l + 2a)]$ <p>For segment of length <math>b</math>,</p> $s = \frac{Wa^2}{Zl^3}[bl - v(l + 2b)]$ | <p>Stress at end next to segment of length <math>a</math>, <math>\frac{Wab^2}{Zl^2}</math></p> <p>Stress at end next to segment of length <math>b</math>, <math>\frac{Wa^2b}{Zl^2}</math></p> <p>Maximum stress is at end next to shorter segment.</p> <p>Stress is zero at</p> $x = \frac{al}{l + 2a}$ <p>and</p> $v = \frac{bl}{l + 2b}$ <p>Greatest negative stress, at load, <math>-\frac{2Wa^2b^2}{Zl^3}</math></p> | <p>For segment of length <math>a</math>,</p> $y = \frac{Wx^2b^2}{6EI^3}[2a(l - x) + l(a - x)]$ <p>For segment of length <math>b</math>,</p> $y = \frac{Wv^2a^2}{6EI^3}[2b(l - v) + l(b - v)]$ | <p>Deflection at load, <math>\frac{Wa^3b^3}{3EI^3}</math></p> <p>Let <math>b</math> be the length of the longer segment and <math>a</math> of the shorter one.</p> <p>The maximum deflection is in the longer segment, at</p> $v = \frac{2bl}{l + 2b} \text{ and is}$ $\frac{2Wa^2b^3}{3EI(l + 2b)^2}$ |

Table 1. (Continued) Stresses and Deflections in Beams

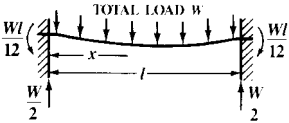
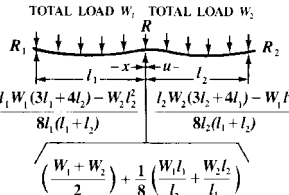
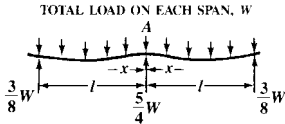
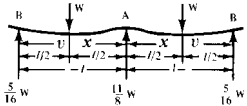
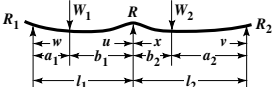
| Type of Beam   | Stresses   |  | Deflections  |  |
|--|--|--|--|--|
|  | General Formula for Stress at any Point  | Stresses at Critical Points  | General Formula for Deflection at any Point <sup>a</sup>   | Deflections at Critical Points <sup>a</sup>  |
| Case 20. — Fixed at Both Ends, Uniform Load                                      |  |  |  |  |
|  | $s = \frac{Wl}{2Z} \left\{ \frac{1}{6} - \frac{x}{l} + \left( \frac{x}{l} \right)^2 \right\}$  | Maximum stress, at ends,<br>$\frac{Wl}{12Z}$<br>Stress is zero at<br>$x = 0.7887l$ and at<br>$x = 0.2113l$<br>Greatest negative stress, at<br>center, $-\frac{Wl}{24Z}$  | $y = \frac{Wx^2}{24EI} (l-x)^2$  | Maximum deflection, at center,<br>$\frac{Wl^3}{384EI}$   |
| Case 21. — Continuous Beam, with Two Unequal Spans, Unequal Uniform Loads        |  |  |  |  |
|  | Between $R_1$ and $R$ ,<br>$s = \frac{l_1 - x}{Z} \left\{ \frac{(l_1 - x)W_1}{2l_1} - R_1 \right\}$<br>Between $R_2$ and $R$ ,<br>$s = \frac{l_2 - u}{Z} \left\{ \frac{(l_2 - u)W_2}{2l_2} - R_2 \right\}$ | Stress at support $R$ ,<br>$\frac{W_1 l_1^2 + W_2 l_2^2}{8Z(l_1 + l_2)}$<br>Greatest stress in the first span is at<br>$x = \frac{l_1}{W_1} (W_1 - R_1)$<br>and is $-\frac{R_1^2 l_1}{2ZW_1}$<br>Greatest stress in the second span is at<br>$u = \frac{l_2}{W_2} (W_2 - R_2)$<br>and is, $-\frac{R_2^2 l_2}{2ZW_2}$ | Between $R_1$ and $R$ ,<br>$y = \frac{x(l_1 - x)}{24EI} \left\{ (2l_1 - x)(4R_1 - W_1) - \frac{W_1(l_1 - x)^2}{l_1} \right\}$<br>Between $R_2$ and $R$ ,<br>$y = \frac{u(l_2 - u)}{24EI} \left\{ (2l_2 - u)(4R_2 - W_2) - \frac{W_2(l_2 - u)^2}{l_2} \right\}$ | This case is so complicated that convenient general expressions for the critical deflections cannot be obtained. |

Table 1. (Continued) Stresses and Deflections in Beams

| Type of Beam  | Stresses   |  | Deflections  |   |
|---|--|--|--|---|
|   | General Formula for Stress at any Point  | Stresses at Critical Points  | General Formula for Deflection at any Point <sup>a</sup>   | Deflections at Critical Points <sup>a</sup>   |
| Case 22. — Continuous Beam, with Two Equal Spans, Uniform Load  |  |  |  |   |
|  <p style="text-align: center;">TOTAL LOAD ON EACH SPAN, <math>W</math></p> | $s = \frac{W(l-x)}{2Zl}(\frac{1}{4}l-x)$   | <p>Maximum stress at point A, <math>\frac{Wl}{8Z}</math></p> <p>Stress is zero at <math>x = \frac{1}{2}l</math></p> <p>Greatest negative stress is at <math>x = \frac{3}{8}l</math> and is,</p> $\frac{9}{128} \frac{Wl}{Z}$ | $y = \frac{Wx^2(l-x)}{48EI}(3l-2x)$  | <p>Maximum deflection is at <math>x = 0.5785l</math>, and is <math>\frac{Wl^3}{185EI}</math></p> <p>Deflection at center of span,</p> $\frac{Wl^3}{192EI}$ <p>Deflection at point of greatest negative stress, at <math>x = \frac{3}{8}l</math> is</p> $\frac{Wl^3}{187EI}$ |
| Case 23. — Continuous Beam, with Two Equal Spans, Equal Loads at Center of Each   |  |  |  |   |
|    | <p>Between point A and load,</p> $s = \frac{W}{16Z}(3l-11x)$ <p>Between point B and load,</p> $s = -\frac{5}{16} \frac{Wv}{Z}$ | <p>Maximum stress at point A, <math>\frac{3}{16} \frac{Wl}{Z}</math></p> <p>Stress is zero at <math>x = \frac{3}{11}l</math></p> <p>Greatest negative stress at center of span,</p> $\frac{5}{32} \frac{Wl}{Z}$              | <p>Between point A and load,</p> $y = \frac{Wx^2}{96EI}(9l-11x)$ <p>Between point B and load,</p> $y = \frac{Wv}{96EI}(3l^2-5v^2)$ | <p>Maximum deflection is at <math>x = 0.4472l</math>, and is <math>\frac{Wl^3}{107.33EI}</math></p> <p>Deflection at load, <math>\frac{7}{768} \frac{Wl^3}{EI}</math></p>   |

**Table 1. (Continued) Stresses and Deflections in Beams**

| Type of Beam  | Stresses  |  | Deflections   |  |
|---|---|--|---|--|
|   | General Formula for Stress at any Point   | Stresses at Critical Points  | General Formula for Deflection at any Point <sup>a</sup>  | Deflections at Critical Points <sup>a</sup>  |
| Case 24. — Continuous Beam, with Two Unequal Spans, Unequal Loads at any Point of Each  |   |  |   |  |
|  $m = \frac{1}{2(l_1 + l_2)} \left( \frac{W_1 a_1 b_1}{l_1} (l_1 + a_1) + \frac{W_2 a_2 b_2}{l_2} (l_2 + a_2) \right)$ $\frac{W_1 b_1 - m}{l_1} = \frac{W_1 a_1 + m}{l_1} = \frac{W_2 a_2 + m}{l_2} = \frac{W_2 b_2 - m}{l_2}$ $= r_1 = r = r_2$ | <p>Between <math>R_1</math> and <math>W_1</math>,</p> $s = -\frac{w r_1}{Z}$ <p>Between <math>R</math> and <math>W_1</math>, <math>s =</math></p> $\frac{1}{l_1 Z} [m(l_1 - u) - W_1 a_1 u]$ <p>Between <math>R</math> and <math>W_2</math>, <math>s =</math></p> $\frac{1}{l_2 Z} [m(l_2 - x) - W_2 a_2 x]$ <p>Between <math>R_2</math> and <math>W_2</math>,</p> $s = -\frac{v r_2}{Z}$ | <p>Stress at load <math>W_1</math>,</p> $-\frac{a_1 r_1}{Z}$ <p>Stress at support <math>R</math>,</p> $\frac{m}{Z}$ <p>Stress at load <math>W_2</math>,</p> $-\frac{a_2 r_2}{Z}$ <p>The greatest of these is the maximum stress.</p> | <p>Between <math>R_1</math> and <math>W_1</math>,</p> $y = \frac{w}{6EI} \left\{ (l_1 - w)(l_1 + w)r_1 - \frac{W_1 b_1^3}{l_1} \right\}$ <p>Between <math>R</math> and <math>W_1</math>,</p> $y = \frac{u}{6EI l_1} [W_1 a_1 b_1 (l_1 + a_1) - W_1 a_1 u^2 - m(2l_1 - u)(l_1 - u)]$ <p>Between <math>R</math> and <math>W_2</math>,</p> $y = \frac{x}{6EI l_2} [W_2 a_2 b_2 (l_2 + a_2) - W_2 a_2 x^2 - m(2l_2 - x)(l_2 - x)]$ <p>Between <math>R_2</math> and <math>W_2</math>,</p> $y = \frac{v}{6EI} \left\{ (l_2 - v)(l_2 + v)r_2 - \frac{W_2 b_2^3}{l_2} \right\}$ | <p>Deflection at load <math>W_1</math>,</p> $\frac{a_1 b_1}{6EI l_1} [2a_1 b_1 W_1 - m(l_1 + a_1)]$ <p>Deflection at load <math>W_2</math>,</p> $\frac{a_2 b_2}{6EI l_2} [2a_2 b_2 W_2 - m(l_2 + a_2)]$ <p>This case is so complicated that convenient general expressions for the maximum deflections cannot be obtained.</p> |

<sup>a</sup>The deflections apply only to cases where the cross section of the beam is constant for its entire length.


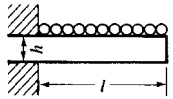
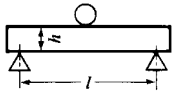
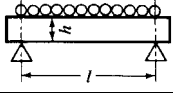
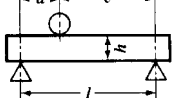
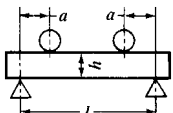
In the diagrammatical illustrations of the beams and their loading, the values indicated near, but below, the supports are the "reactions" or upward forces at the supports. For Cases 1 to 12, inclusive, the reactions, as well as the formulas for the stresses, are the same whether the beam is of constant or variable cross-section. For the other cases, the reactions and the stresses given are for constant cross-section beams only.

The bending moment at any point in inch-pounds is  $s \times Z$  and can be found by omitting the divisor  $Z$  in the formula for the stress given in the tables. A positive value of the bending moment denotes tension in the upper fibers and compression in the lower ones. A negative value denotes the reverse. The value of  $W$  corresponding to a given stress is found by transposition of the formula. For example, in Case 1, the stress at the critical point is  $s = -Wl \div 8Z$ . From this formula we find  $W = -8Zs \div l$ . Of course, the negative sign of  $W$  may be ignored.

In Table 1, if there are several kinds of loads, as, for instance, a uniform load and a load at any point, or separate loads at different points, the total stress and the total deflection at any point is found by adding together the various stresses or deflections at the point considered due to each load acting by itself. If the stress or deflection due to any one of the loads is negative, it must be subtracted instead of added.

Tables 2a and 2b give expressions for determining dimensions of rectangular and round beams in terms of beam stresses and load.

**Table 2a. Rectangular Solid Beams**

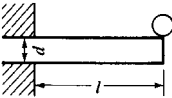
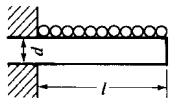
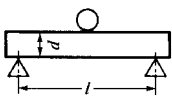
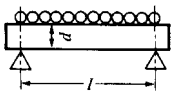
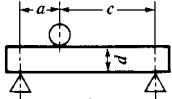
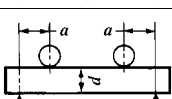
| Style of Loading and Support   | Breadth of Beam, <i>b</i><br>inch (mm) | Beam Height, <i>h</i><br>inch (mm) | Stress in Extreme Fibers, <i>f</i><br>lb/in <sup>2</sup> (N/mm <sup>2</sup> ) | Beam Length, <i>l</i><br>inch (mm)                | Total Load, <i>W</i><br>lb (N) |
|--|--|------------------------------------|---|---|--------------------------------|
| Beam fixed at one end, loaded at the other   |  |                                    |   |   |                                |
|    | $\frac{6IW}{fh^2} = b$                 | $\sqrt{\frac{6IW}{bf}} = h$        | $\frac{6IW}{bh^2} = f$  | $\frac{bfh^2}{6W} = l$                            | $\frac{bfh^2}{6l} = W$         |
| Beam fixed at one end, uniformly loaded  |  |                                    |   |   |                                |
|    | $\frac{3IW}{fh^2} = b$                 | $\sqrt{\frac{3IW}{bf}} = h$        | $\frac{3IW}{bh^2} = f$  | $\frac{bfh^2}{3W} = l$                            | $\frac{bfh^2}{3l} = W$         |
| Beam supported at both ends, single load in middle                                 |  |                                    |   |   |                                |
|    | $\frac{3IW}{2fh^2} = b$                | $\sqrt{\frac{3IW}{2bf}} = h$       | $\frac{3IW}{2bh^2} = f$   | $\frac{2bfh^2}{3W} = l$                           | $\frac{2bfh^2}{3l} = W$        |
| Beam supported at both ends, uniformly loaded                                      |  |                                    |   |   |                                |
|   | $\frac{3IW}{4fh^2} = b$                | $\sqrt{\frac{3IW}{4bf}} = h$       | $\frac{3IW}{4bh^2} = f$   | $\frac{4bfh^2}{3W} = l$                           | $\frac{4bfh^2}{3l} = W$        |
| Beam supported at both ends, single unsymmetrical load                             |  |                                    |   |   |                                |
|  | $\frac{6Wac}{fh^2l} = b$               | $\sqrt{\frac{6Wac}{bfl}} = h$      | $\frac{6Wac}{bh^2l} = f$  | $a + c = l$                                       | $\frac{bh^2fl}{6ac} = W$       |
| Beam supported at both ends, two symmetrical loads                                 |  |                                    |   |   |                                |
|  | $\frac{3Wa}{fh^2} = b$                 | $\sqrt{\frac{3Wa}{bf}} = h$        | $\frac{3Wa}{bh^2} = f$  | $l, \text{ any length}$<br>$\frac{bh^2f}{3W} = a$ | $\frac{bh^2f}{3a} = W$         |

**Deflection of Beam Uniformly Loaded for Part of Its Length.**—In the following formulas, lengths are in inches, weights in pounds. *W* = total load; *L* = total length between supports; *E* = modulus of elasticity; *I* = moment of inertia of beam section; *a* = fraction of length of beam at each end, that is not loaded = *b* ÷ *L*; and *f* = deflection.

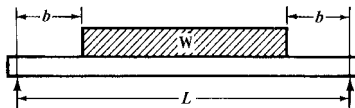
$$f = \frac{WL^3}{384EI(1 - 2a)}(5 - 24a^2 + 16a^4)$$

The expression for maximum bending moment is:  $M_{\max} = \frac{1}{8}WL(1 + 2a)$ .

Table 2b. Round Solid Beams

| Style of Loading and Support  | Diameter of Beam, $d$<br>inch (mm)                     | Stress in Extreme<br>Fibers, $f$<br>lb/in <sup>2</sup> (N/mm <sup>2</sup> ) | Beam Length, $l$<br>inch (mm)                 | Total Load, $W$<br>lb (N)   |
|---|--|---|---|-----------------------------|
|   | Beam fixed at one end, loaded at the other             |   |   |                             |
|   | $\sqrt[3]{\frac{10.18lW}{f}} = d$                      | $\frac{10.18lW}{d^3} = f$   | $\frac{d^3f}{10.18W} = l$                     | $\frac{d^3f}{10.18l} = W$   |
|   | Beam fixed at one end, uniformly loaded                |   |   |                             |
|   | $\sqrt[3]{\frac{5.092Wl}{f}} = d$                      | $\frac{5.092Wl}{d^3} = f$   | $\frac{d^3f}{5.092W} = l$                     | $\frac{d^3f}{5.092l} = W$   |
|   | Beam supported at both ends, single load in middle     |   |   |                             |
|   | $\sqrt[3]{\frac{2.546Wl}{f}} = d$                      | $\frac{2.546Wl}{d^3} = f$   | $\frac{d^3f}{2.546W} = l$                     | $\frac{d^3f}{2.546l} = W$   |
|   | Beam supported at both ends, uniformly loaded          |   |   |                             |
|   | $\sqrt[3]{\frac{1.273Wl}{f}} = d$                      | $\frac{1.273Wl}{d^3} = f$   | $\frac{d^3f}{1.273W} = l$                     | $\frac{d^3f}{1.273l} = W$   |
|   | Beam supported at both ends, single unsymmetrical load |   |   |                             |
|   | $\sqrt[3]{\frac{10.18Wac}{fl}} = d$                    | $\frac{10.18Wac}{d^3l} = f$   | $a + c = l$                                   | $\frac{d^3fl}{10.18ac} = W$ |
|  | Beam supported at both ends, two symmetrical loads     |   |   |                             |
|   | $\sqrt[3]{\frac{5.092Wa}{f}} = d$                      | $\frac{5.092Wa}{d^3} = f$   | $l$ , any length<br>$\frac{d^3f}{5.092W} = a$ | $\frac{d^3f}{5.092a} = W$   |

These formulas apply to simple beams resting on supports at the ends.

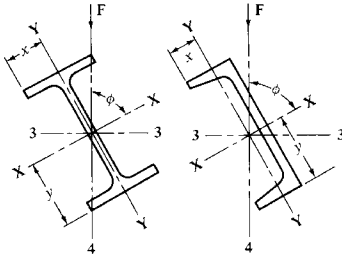


If the formulas are used with metric SI units,  $W$  = total load in newtons;  $L$  = total length between supports in millimeters;  $E$  = modulus of elasticity in newtons per millimeter<sup>2</sup>;  $I$  = moment of inertia of beam section in millimeters<sup>4</sup>;  $a$  = fraction of length of beam at each end, that is not loaded =  $b \div L$ ; and  $f$  = deflection in millimeters. The bending moment  $M_{\max}$  is in newton-millimeters (N · mm).

Note: A load due to the weight of a mass of  $M$  kilograms is  $Mg$  newtons, where  $g$  = approximately 9.81 meters per second<sup>2</sup>.

**Bending Stress Due to an Oblique Transverse Force.**—The following illustration shows a beam and a channel being subjected to a transverse force acting at an angle  $\phi$  to the center of gravity. To find the bending stress, the moments of inertia  $I$  around axes 3-3 and 4-4 are computed from the following equations:  $I_3 = I_x \sin^2 \phi + I_y \cos^2 \phi$ , and  $I_4 = I_x \cos^2 \phi + I_y \sin^2 \phi$ .

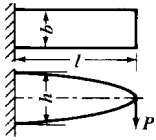
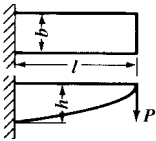
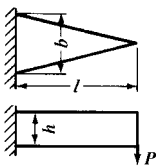
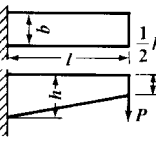
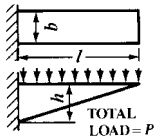
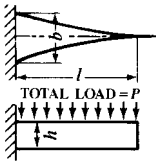
The computed bending stress  $f_b$  is then found from  $f_b = M \left( \frac{y}{I_x} \sin \phi + \frac{x}{I_y} \cos \phi \right)$  where  $M$  is the bending moment due to force  $F$ .



**Beams of Uniform Strength Throughout Their Length.**—The bending moment in a beam is generally not uniform throughout its length, but varies. Therefore, a beam of uniform cross-section which is made strong enough at its most strained section, will have an excess of material at every other section. Sometimes it may be desirable to have the cross-section uniform, but at other times the metal can be more advantageously distributed if the beam is so designed that its cross-section varies from point to point, so that it is at every point just great enough to take care of the bending stresses at that point. Tables 3a and 3b are given showing beams in which the load is applied in different ways and which are supported by different methods, and the shape of the beam required for uniform strength is indicated. It should be noted that the shape given is the theoretical shape required to resist bending only. It is apparent that sufficient cross-section of beam must also be added either at the points of support (in beams supported at both ends), or at the point of application of the load (in beams loaded at one end), to take care of the vertical shear.

It should be noted that the theoretical shapes of the beams given in the two tables that follow are based on the stated assumptions of uniformity of width or depth of cross-section, and unless these are observed in the design, the theoretical outlines do not apply without modifications. For example, in a cantilever with the load at one end, the outline is a parabola only when the width of the beam is uniform. It is not correct to use a strictly parabolic shape when the thickness is not uniform, as, for instance, when the beam is made of an I- or T-section. In such cases, some modification may be necessary; but it is evident that whatever the shape adopted, the correct depth of the section can be obtained by an investigation of the bending moment and the shearing load at a number of points, and then a line can be drawn through the points thus ascertained, which will provide for a beam of practically uniform strength whether the cross-section be of uniform width or not.

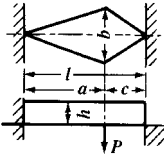
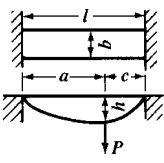
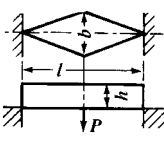
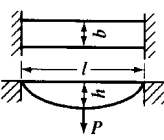
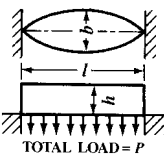
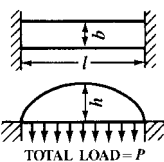
**Table 3a. Beams of Uniform Strength Throughout Their Length**

| Type of Beam   | Description   | Formula <sup>a</sup>   |
|--|---|------------------------|
|    | <p>Load at one end. Width of beam uniform. Depth of beam decreasing towards loaded end. Outline of beam-shape, parabola with vertex at loaded end.</p>  | $P = \frac{Sbh^2}{6l}$ |
|    | <p>Load at one end. Width of beam uniform. Depth of beam decreasing towards loaded end. Outline of beam, one-half of a parabola with vertex at loaded end. Beam may be reversed so that upper edge is parabolic.</p>                | $P = \frac{Sbh^2}{6l}$ |
|    | <p>Load at one end. Depth of beam uniform. Width of beam decreasing towards loaded end. Outline of beam triangular, with apex at loaded end.</p>  | $P = \frac{Sbh^2}{6l}$ |
|   | <p>Beam of <i>approximately</i> uniform strength. Load at one end. Width of beam uniform. Depth of beam decreasing towards loaded end, but not tapering to a sharp point.</p>   | $P = \frac{Sbh^2}{6l}$ |
|  | <p>Uniformly distributed load. Width of beam uniform. Depth of beam decreasing towards outer end. Outline of beam, right-angled triangle.</p>   | $P = \frac{Sbh^2}{3l}$ |
|  | <p>Uniformly distributed load. Depth of beam uniform. Width of beam gradually decreasing towards outer end. Outline of beam is formed by two parabolas which tangent each other at their vertices at the outer end of the beam.</p> | $P = \frac{Sbh^2}{3l}$ |

<sup>a</sup> In the formulas,  $P$  = load in pounds;  $S$  = safe stress in pounds per square inch; and  $a, b, c, h,$  and  $l$  are in inches. If metric SI units are used,  $P$  is in newtons;  $S$  = safe stress in  $N/mm^2$ ; and  $a, b, c, h,$  and  $l$  are in millimeters.



Table 3b. Beams of Uniform Strength Throughout Their Length

| Type of Beam   | Description  | Formula <sup>a</sup>     |
|--|--|--------------------------|
|                          | <p>Beam supported at both ends. Load concentrated at any point. Depth of beam uniform. Width of beam maximum at point of loading. Outline of beam, two triangles with apexes at points of support.</p>                     | $P = \frac{Sbh^2l}{6ac}$ |
|                          | <p>Beam supported at both ends. Load concentrated at any point. Width of beam uniform. Depth of beam maximum at point of loading. Outline of beam is formed by two parabolas with their vertexes at points of support.</p> | $P = \frac{Sbh^2l}{6ac}$ |
|                          | <p>Beam supported at both ends. Load concentrated in the middle. Depth of beam uniform. Width of beam maximum at point of loading. Outline of beam, two triangles with apexes at points of support.</p>                    | $P = \frac{2Sbh^2}{3l}$  |
|                         | <p>Beam supported at both ends. Load concentrated at center. Width of beam uniform. Depth of beam maximum at point of loading. Outline of beam, two parabolas with vertexes at points of support.</p>                      | $P = \frac{2Sbh^2}{3l}$  |
|  <p>TOTAL LOAD = P</p> | <p>Beam supported at both ends. Load uniformly distributed. Depth of beam uniform. Width of beam maximum at center. Outline of beam, two parabolas with vertexes at middle of beam.</p>                                    | $P = \frac{4Sbh^2}{3l}$  |
|  <p>TOTAL LOAD = P</p> | <p>Beam supported at both ends. Load uniformly distributed. Width of beam uniform. Depth of beam maximum at center. Outline of beam one-half of an ellipse.</p>  | $P = \frac{4Sbh^2}{3l}$  |

<sup>a</sup> For details of English and metric SI units used in the formulas, see footnote on page 275.

**Deflection as a Limiting Factor in Beam Design.**—For some applications, a beam must be stronger than required by the maximum load it is to support, in order to prevent excessive deflection. Maximum allowable deflections vary widely for different classes of service, so a general formula for determining them cannot be given. When exceptionally stiff girders are required, one rule is to limit the deflection to 1 inch per 100 feet of span; hence, if  $l$  = length of span in inches, deflection =  $l \div 1200$ . According to another formula, deflection limit =  $l \div 360$  where beams are adjacent to materials like plaster which would be broken by excessive beam deflection. Some machine parts of the beam type must be very rigid to maintain alignment under load. For example, the deflection of a punch press column may be limited to 0.010 inch or less. These examples merely illustrate variations in practice. It is impracticable to give general formulas for determining the allowable deflection in any specific application, because the allowable amount depends on the conditions governing each class of work.

*Procedure in Designing for Deflection:* Assume that a deflection equal to  $l \div 1200$  is to be the limiting factor in selecting a wide-flange (W-shape) beam having a span length of 144 inches. Supports are at both ends and load at center is 15,000 pounds. Deflection  $y$  is to be limited to  $144 \div 1200 = 0.12$  inch. According to the formula on page 261 (Case 2), in which  $W$  = load on beam in pounds,  $l$  = length of span in inches,  $E$  = modulus of elasticity of material,  $I$  = moment of inertia of cross section:

$$\text{Deflection } y = \frac{Wl^3}{48EI} \quad \text{hence, } I = \frac{Wl^3}{48yE} = \frac{15,000 \times 144^3}{48 \times 0.12 \times 29,000,000} = 268.1$$

A structural wide-flange beam, see *Steel Wide-Flange Sections* on page 2511, having a depth of 12 inches and weighing 35 pounds per foot has a moment of inertia  $I$  of 285 and a section modulus ( $Z$  or  $S$ ) of 45.6. Checking now for maximum stress  $s$  (Case 2, page 261):

$$s = \frac{Wl}{4Z} = \frac{15,000 \times 144}{4 \times 46.0} = 11,842 \text{ lbs/in}^2$$

Although deflection is the limiting factor in this case, the maximum stress is checked to make sure that it is within the allowable limit. As the limiting deflection is decreased, for a given load and length of span, the beam strength and rigidity must be increased, and, consequently, the maximum stress is decreased. Thus, in the preceding example, if the maximum deflection is 0.08 inch instead of 0.12 inch, then the calculated value for the moment of inertia  $I$  will be 402; hence a W 12  $\times$  53 beam having an  $I$  value of 426 could be used (nearest value above 402). The maximum stress then would be reduced to 7640 pounds per square inch and the calculated deflection is 0.076 inch.

A similar example using metric SI units is as follows. Assume that a deflection equal to  $l \div 1000$  millimeters is to be the limiting factor in selecting a W-beam having a span length of 5 meters. Supports are at both ends and the load at the center is 30 kilonewtons. Deflection  $y$  is to be limited to  $5000 \div 1000 = 5$  millimeters. The formula on page 261 (Case 2) is applied, and  $W$  = load on beam in newtons;  $l$  = length of span in mm;  $E$  = modulus of elasticity (assume 200,000 N/mm<sup>2</sup> in this example); and  $I$  = moment of inertia of cross-section in millimeters<sup>4</sup>. Thus,

$$\text{Deflection } y = \frac{Wl^3}{48EI}$$

hence

$$I = \frac{Wl^3}{48yE} = \frac{30,000 \times 5000^3}{48 \times 5 \times 200,000} = 78,125,000 \text{ mm}^4$$

Although deflection is the limiting factor in this case, the maximum stress is checked to make sure that it is within the allowable limit, using the formula from page 261 (Case 2):

$$s = \frac{Wl}{4Z}$$

The units of  $s$  are newtons per square millimeter;  $W$  is the load in newtons;  $l$  is the length in mm; and  $Z$  = section modulus of the cross-section of the beam =  $I \div$  distance in mm from neutral axis to extreme fiber.

**Curved Beams.**—The formula  $S = Mc/I$  used to compute stresses due to bending of beams is based on the assumption that the beams are straight before any loads are applied. In beams having initial curvature, however, the stresses may be considerably higher than predicted by the ordinary straight-beam formula because the effect of initial curvature is to shift the neutral axis of a curved member in from the gravity axis toward the center of curvature (the concave side of the beam). This shift in the position of the neutral axis causes an increase in the stress on the concave side of the beam and decreases the stress at the outside fibers.

Hooks, press frames, and other machine members which as a rule have a rather pronounced initial curvature may have a maximum stress at the inside fibers of up to about  $3\frac{1}{2}$  times that predicted by the ordinary straight-beam formula.

*Stress Correction Factors for Curved Beams:* A simple method for determining the maximum fiber stress due to bending of curved members consists of 1) calculating the maximum stress using the straight-beam formula  $S = Mc/I$ ; and; and 2) multiplying the calculated stress by a stress correction factor. Table 4 on page 279 gives stress correction factors for some of the common cross-sections and proportions used in the design of curved members.

An example in the application of the method using English units of measurement is given at the bottom of the table. **A similar example using metric SI units is as follows: The fiber stresses of a curved rectangular beam are calculated as 40 newtons per millimeter<sup>2</sup>, using the straight beam formula,  $S = Mc/I$ . If the beam is 150 mm deep and its radius of curvature is 300 mm, what are the true stresses?  $R/c = 300/75 = 4$ . From Table 4 on page 279, the  $K$  factors corresponding to  $R/c = 4$  are 1.20 and 0.85. Thus, the inside fiber stress is  $40 \times 1.20 = 48 \text{ N/mm}^2 = 48$  megapascals; and the outside fiber stress is  $40 \times 0.85 = 34 \text{ N/mm}^2 = 34$  megapascals.**

*Approximate Formula for Stress Correction Factor:* The stress correction factors given in Table 4 on page 279 were determined by Wilson and Quereau and published in the University of Illinois Engineering Experiment Station Circular No. 16, "A Simple Method of Determining Stress in Curved Flexural Members." In this same publication the authors indicate that the following empirical formula may be used to calculate the value of the stress correction factor for the *inside* fibers of sections not covered by the tabular data to within 5 per cent accuracy except in triangular sections where up to 10 per cent deviation may be expected. However, for most engineering calculations, this formula should prove satisfactory for general use in determining the factor for the inside fibers.

$$K = 1.00 + 0.5 \frac{I}{bc^2} \left[ \frac{1}{R-c} + \frac{1}{R} \right]$$

(Use 1.05 instead of 0.5 in this formula for circular and elliptical sections.)

$I$  = Moment of inertia of section about centroidal axis

$b$  = maximum width of section

$c$  = distance from centroidal axis to inside fiber, i.e., to the extreme fiber nearest the center of curvature

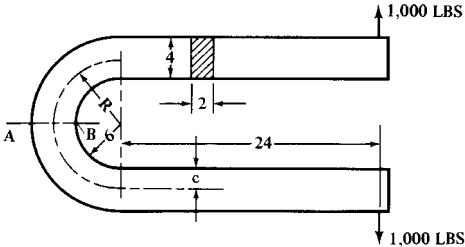
$R$  = radius of curvature of centroidal axis of beam

**Table 4. Values of Stress Correction Factor K for Various Curved Beam Sections**

| Section | $R/c$ | Factor K     |               | $y_0^a$ | Section  | $R/c$ | Factor K     |               | $y_0^a$ |
|---------|-------|--------------|---------------|---------|--|-------|--------------|---------------|---------|
|         |       | Inside Fiber | Outside Fiber |         |  |       | Inside Fiber | Outside Fiber |         |
|         | 1.2   | 3.41         | .54           | .224R   |  | 1.2   | 3.63         | .58           | .418R   |
|         | 1.4   | 2.40         | .60           | .151R   |  | 1.4   | 2.54         | .63           | .299R   |
|         | 1.6   | 1.96         | .65           | .108R   |  | 1.6   | 2.14         | .67           | .229R   |
|         | 1.8   | 1.75         | .68           | .084R   |  | 1.8   | 1.89         | .70           | .183R   |
|         | 2.0   | 1.62         | .71           | .069R   |  | 2.0   | 1.73         | .72           | .149R   |
|         | 3.0   | 1.33         | .79           | .030R   |  | 3.0   | 1.41         | .79           | .069R   |
|         | 4.0   | 1.23         | .84           | .016R   |  | 4.0   | 1.29         | .83           | .040R   |
|         | 6.0   | 1.14         | .89           | .0070R  |  | 6.0   | 1.18         | .88           | .018R   |
|         | 8.0   | 1.10         | .91           | .0039R  |  | 8.0   | 1.13         | .91           | .010R   |
|         | 10.0  | 1.08         | .93           | .0025R  |  | 10.0  | 1.10         | .92           | .0065R  |
|         | 1.2   | 2.89         | .57           | .305R   |  | 1.2   | 3.55         | .67           | .409R   |
|         | 1.4   | 2.13         | .63           | .204R   |  | 1.4   | 2.48         | .72           | .292R   |
|         | 1.6   | 1.79         | .67           | .149R   |  | 1.6   | 2.07         | .76           | .224R   |
|         | 1.8   | 1.63         | .70           | .112R   |  | 1.8   | 1.83         | .78           | .178R   |
|         | 2.0   | 1.52         | .73           | .090R   |  | 2.0   | 1.69         | .80           | .144R   |
|         | 3.0   | 1.30         | .81           | .041R   |  | 3.0   | 1.38         | .86           | .067R   |
|         | 4.0   | 1.20         | .85           | .021R   |  | 4.0   | 1.26         | .89           | .038R   |
|         | 6.0   | 1.12         | .90           | .0093R  |  | 6.0   | 1.15         | .92           | .018R   |
|         | 8.0   | 1.09         | .92           | .0052R  |  | 8.0   | 1.10         | .94           | .010R   |
|         | 10.0  | 1.07         | .94           | .0033R  |  | 10.0  | 1.08         | .95           | .0065R  |
|         | 1.2   | 3.01         | .54           | .336R   |  | 1.2   | 2.52         | .67           | .408R   |
|         | 1.4   | 2.18         | .60           | .229R   |  | 1.4   | 1.90         | .71           | .285R   |
|         | 1.6   | 1.87         | .65           | .168R   |  | 1.6   | 1.63         | .75           | .208R   |
|         | 1.8   | 1.69         | .68           | .128R   |  | 1.8   | 1.50         | .77           | .160R   |
|         | 2.0   | 1.58         | .71           | .102R   |  | 2.0   | 1.41         | .79           | .127R   |
|         | 3.0   | 1.33         | .80           | .046R   |  | 3.0   | 1.23         | .86           | .058R   |
|         | 4.0   | 1.23         | .84           | .024R   |  | 4.0   | 1.16         | .89           | .030R   |
|         | 6.0   | 1.13         | .88           | .011R   |  | 6.0   | 1.10         | .92           | .013R   |
|         | 8.0   | 1.10         | .91           | .0060R  |  | 8.0   | 1.07         | .94           | .0076R  |
|         | 10.0  | 1.08         | .93           | .0039R  |  | 10.0  | 1.05         | .95           | .0048R  |
|         | 1.2   | 3.09         | .56           | .336R   |  | 1.2   | 3.28         | .58           | .269R   |
|         | 1.4   | 2.25         | .62           | .229R   |  | 1.4   | 2.31         | .64           | .182R   |
|         | 1.6   | 1.91         | .66           | .168R   |  | 1.6   | 1.89         | .68           | .134R   |
|         | 1.8   | 1.73         | .70           | .128R   |  | 1.8   | 1.70         | .71           | .104R   |
|         | 2.0   | 1.61         | .73           | .102R   |  | 2.0   | 1.57         | .73           | .083R   |
|         | 3.0   | 1.37         | .81           | .046R   |  | 3.0   | 1.31         | .81           | .038R   |
|         | 4.0   | 1.26         | .86           | .024R   |  | 4.0   | 1.21         | .85           | .020R   |
|         | 6.0   | 1.17         | .91           | .011R   |  | 6.0   | 1.13         | .90           | .0087R  |
|         | 8.0   | 1.13         | .94           | .0060R  |  | 8.0   | 1.10         | .92           | .0049R  |
|         | 10.0  | 1.11         | .95           | .0039R  |  | 10.0  | 1.07         | .93           | .0031R  |
|         | 1.2   | 3.14         | .52           | .352R   |  | 1.2   | 2.63         | .68           | .399R   |
|         | 1.4   | 2.29         | .54           | .243R   |  | 1.4   | 1.97         | .73           | .280R   |
|         | 1.6   | 1.93         | .62           | .179R   |  | 1.6   | 1.66         | .76           | .205R   |
|         | 1.8   | 1.74         | .65           | .138R   |  | 1.8   | 1.51         | .78           | .159R   |
|         | 2.0   | 1.61         | .68           | .110R   |  | 2.0   | 1.43         | .80           | .127R   |
|         | 3.0   | 1.34         | .76           | .050R   |  | 3.0   | 1.23         | .86           | .058R   |
|         | 4.0   | 1.24         | .82           | .028R   |  | 4.0   | 1.15         | .89           | .031R   |
|         | 6.0   | 1.15         | .87           | .012R   |  | 6.0   | 1.09         | .92           | .014R   |
|         | 8.0   | 1.12         | .91           | .0060R  |  | 8.0   | 1.07         | .94           | .0076R  |
|         | 10.0  | 1.10         | .93           | .0039R  |  | 10.0  | 1.06         | .95           | .0048R  |
|         | 1.2   | 3.26         | .44           | .361R   | <p><i>Example:</i> The fiber stresses of a curved rectangular beam are calculated as 5000 psi using the straight beam formula, <math>S = Mc/I</math>. If the beam is 8 inches deep and its radius of curvature is 12 inches, what are the true stresses? <math>R/c = 12/4 = 3</math>. The factors in the table corresponding to <math>R/c = 3</math> are 0.81 and 1.30. Outside fiber stress = <math>5000 \times 0.81 = 4050</math> psi; inside fiber stress = <math>5000 \times 1.30 = 6500</math> psi.</p> |       |              |               |         |
|         | 1.4   | 2.39         | .50           | .251R   |  |       |              |               |         |
|         | 1.6   | 1.99         | .54           | .186R   |  |       |              |               |         |
|         | 1.8   | 1.78         | .57           | .144R   |  |       |              |               |         |
|         | 2.0   | 1.66         | .60           | .116R   |  |       |              |               |         |
|         | 3.0   | 1.37         | .70           | .052R   |  |       |              |               |         |
|         | 4.0   | 1.27         | .75           | .029R   |  |       |              |               |         |
|         | 6.0   | 1.16         | .82           | .013R   |  |       |              |               |         |
|         | 8.0   | 1.12         | .86           | .0060R  |  |       |              |               |         |
|         | 10.0  | 1.09         | .88           | .0039R  |  |       |              |               |         |

<sup>a</sup>  $y_0$  is the distance from the centroidal axis to the neutral axis of curved beams subjected to pure bending and is measured from the centroidal axis toward the center of curvature.

*Example:* The accompanying diagram shows the dimensions of a clamp frame of rectangular cross-section. Determine the maximum stress at points *A* and *B* due to a clamping force of 1000 pounds.



The cross-sectional area =  $2 \times 4 = 8$  square inches; the bending moment at section *AB* is  $1000(24 + 6 + 2) = 32,000$  inch pounds; the distance from the center of gravity of the section at *AB* to point *B* is  $c = 2$  inches; and using the formula on page 239, the moment of inertia of the section is  $2 \times (4)^3 \div 12 = 10.667$  inches<sup>4</sup>.

Using the straight-beam formula, page 278, the stress at points *A* and *B* due to the bending moment is:

$$S = \frac{Mc}{I} = \frac{32,000 \times 2}{10.667} = 6000 \text{ psi}$$

The stress at *A* is a compressive stress of 6000 psi and that at *B* is a tensile stress of 6000 psi.

These values must be corrected to account for the curvature effect. In Table 4 on page 279 for  $R/c = (6 + 2)/(2) = 4$ , the value of  $K$  is found to be 1.20 and 0.85 for points *B* and *A* respectively. Thus, the actual stress due to bending at point *B* is  $1.20 \times 6000 = 7200$  psi in tension and the stress at point *A* is  $0.85 \times 6000 = 5100$  psi in compression.

To these stresses at *A* and *B* must be added, algebraically, the direct stress at section *AB* due to the 1000-pound clamping force. The direct stress on section *AB* will be a tensile stress equal to the clamping force divided by the section area. Thus  $1000 \div 8 = 125$  psi in tension.

The maximum unit stress at *A* is, therefore,  $5100 - 125 = 4975$  psi in compression and the maximum unit stress at *B* is  $7200 + 125 = 7325$  psi in tension.

The following is a similar calculation using metric SI units, assuming that it is required to determine the maximum stress at points *A* and *B* due to clamping force of 4 kilonewtons acting on the frame. The frame cross-section is 50 by 100 millimeters, the radius  $R = 200$  mm, and the length of the straight portions is 600 mm. Thus, the cross-sectional area =  $50 \times 100 = 5000$  mm<sup>2</sup>; the bending moment at *AB* is  $4000(600 + 200) = 3,200,000$  newton-millimeters; the distance from the center of gravity of the section at *AB* to point *B* is  $c = 50$  mm; and the moment of inertia of the section is, using the formula on page 239,  $50 \times (100)^3 = 4,170,000$  mm<sup>4</sup>.

Using the straight-beam formula, page 278, the stress at points *A* and *B* due to the bending moment is:

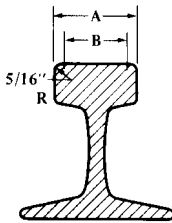
$$\begin{aligned} s &= \frac{Mc}{I} = \frac{3,200,000 \times 50}{4,170,000} \\ &= 38.4 \text{ newtons per millimeter}^2 = 38.4 \text{ megapascals} \end{aligned}$$

The stress at *A* is a compressive stress of 38.4 N/mm<sup>2</sup>, while that at *B* is a tensile stress of 38.4 N/mm<sup>2</sup>. These values must be corrected to account for the curvature

effect. From the table on page 279, the  $K$  factors are 1.20 and 0.85 for points  $A$  and  $B$  respectively, derived from  $R/c = 200/50 = 4$ . Thus, the actual stress due to bending at point  $B$  is  $1.20 \times 38.4 = 46.1 \text{ N/mm}^2$  (46.1 megapascals) in tension; and the stress at point  $A$  is  $0.85 \times 38.4 = 32.6 \text{ N/mm}^2$  (32.6 megapascals) in compression.

To these stresses at  $A$  and  $B$  must be added, algebraically, the direct stress at section  $AB$  due to the 4 kN clamping force. The direct stress on section  $AB$  will be a tensile stress equal to the clamping force divided by the section area. Thus,  $4000/5000 = 0.8 \text{ N/mm}^2$ . The maximum unit stress at  $A$  is, therefore,  $32.61 - 0.8 = 31.8 \text{ N/mm}^2$  (31.8 megapascals) in compression, and the maximum unit stress at  $B$  is  $46.1 + 0.8 = 46.9 \text{ N/mm}^2$  (46.9 megapascals) in tension.

**Size of Rail Necessary to Carry a Given Load.**—The following formulas may be employed for determining the size of rail and wheel suitable for carrying a given load. Let,  $A$  = the width of the head of the rail in inches;  $B$  = width of the tread of the rail in inches;  $C$  = the wheel-load in pounds;  $D$  = the diameter of the wheel in inches.



Then the width of the tread of the rail in inches is found from the formula:

$$B = \frac{C}{1250D} \quad (1)$$

The width  $A$  of the head equals  $B + \frac{5}{8}$  inch. The diameter  $D$  of the smallest track wheel that will safely carry the load is found from the formula:

$$D = \frac{C}{A \times K} \quad (2)$$

in which  $K = 600$  to  $800$  for steel castings;  $K = 300$  to  $400$  for cast iron.

As an example, assume that the wheel-load is 10,000 pounds; the diameter of the wheel is 20 inches; and the material is cast steel. Determine the size of rail necessary to carry this load. From [Formula \(1\)](#):

$$B = \frac{10,000}{1250 \times 20} = 0.4 \text{ inch}$$

The width of the rail required equals  $0.4 + \frac{5}{8}$  inch = 1.025 inch. Determine also whether a wheel 20 inches in diameter is large enough to safely carry the load. From [Formula \(2\)](#):

$$D = \frac{10,000}{1.025 \times 600} = 16\frac{1}{4} \text{ inches}$$

This is the smallest diameter of track wheel that will safely carry the load; hence a 20-inch wheel is ample.

**American Railway Engineering Association Formulas.**—The American Railway Engineering Association recommends for safe operation of steel cylinders rolling on steel plates that the allowable load  $p$  in pounds per inch of length of the cylinder should not exceed the value calculated from the formula

$$p = \frac{y.s. - 13,000}{20,000} 600d \text{ for diameter } d \text{ less than 25 inches}$$

This formula is based on steel having a yield strength, y.s., of 32,000 pounds per square inch. For roller or wheel diameters of up to 25 inches, the Hertz stress (contact stress) resulting from the calculated load  $p$  will be approximately 76,000 pounds per square inch.

For a 10-inch diameter roller the safe load per inch of roller length is

$$p = \frac{32,000 - 13,000}{20,000} 600 \times 10 = 5700 \text{ lbs per inch of length}$$

Therefore, to support a 10,000 pound load the roller or wheel would need to be  $10,000/5700 = 1.75$  inches wide.

### Stresses Produced by Shocks

**Stresses in Beams Produced by Shocks.**—Any elastic structure subjected to a shock will deflect until the product of the average resistance, developed by the deflection, and the distance through which it has been overcome, has reached a value equal to the energy of the shock. It follows that for a given shock, the average resisting stresses are inversely proportional to the deflection. If the structure were perfectly rigid, the deflection would be zero, and the stress infinite. The effect of a shock is, therefore, to a great extent dependent upon the elastic property (the springiness) of the structure subjected to the impact.

The energy of a body in motion, such as a falling body, may be spent in each of four ways:

- 1) In deforming the body struck as a whole.
- 2) In deforming the falling body as a whole.
- 3) In partial deformation of both bodies on the surface of contact (most of this energy will be transformed into heat).
- 4) Part of the energy will be taken up by the supports, if these are not perfectly rigid and inelastic.

How much energy is spent in the last three ways it is usually difficult to determine, and for this reason it is safest to figure as if the whole amount were spent as in Case 1. If a reliable judgment is possible as to what percentage of the energy is spent in other ways than the first, a corresponding fraction of the total energy can be assumed as developing stresses in the body subjected to shocks.

One investigation into the stresses produced by shocks led to the following conclusions:

- 1) A suddenly applied load will produce the same deflection, and, therefore, the same stress as a static load twice as great; and 2) The unit stress  $p$  (see formulas in [Table 1](#), "*Stresses Produced in Beams by Shocks*") for a given load producing a shock, varies directly as the square root of the modulus of elasticity  $E$ , and inversely as the square root of the length  $L$  of the beam and the area of the section.

Thus, for instance, if the sectional area of a beam is increased by four times, the unit stress will diminish only by half. This result is entirely different from those produced by static loads where the stress would vary inversely with the area, and within certain limits be practically independent of the modulus of elasticity.

In [Table 1](#), the expression for the approximate value of  $p$ , which is applicable whenever the deflection of the beam is small as compared with the total height  $h$  through which the body producing the shock is dropped, is always the same for beams supported at both ends and subjected to shock at *any* point between the supports. In the formulas all dimensions are in inches and weights in pounds.

**Table 1. Stresses Produced in Beams by Shocks**

| Method of Support and Point Struck by Falling Body | Fiber (Unit) Stress $p$ produced by Weight $Q$ Dropped Through a Distance $h$ | Approximate Value of $p$       |
|--|---|--------------------------------|
| Supported at both ends; struck in center.          | $p = \frac{QaL}{4I} \left( 1 + \sqrt{1 + \frac{96hEI}{QL^3}} \right)$         | $p = a \sqrt{\frac{6QhE}{LI}}$ |
| Fixed at one end; struck at the other.             | $p = \frac{QaL}{I} \left( 1 + \sqrt{1 + \frac{6hEI}{QL^3}} \right)$           | $p = a \sqrt{\frac{6QhE}{LI}}$ |
| Fixed at both ends; struck in center.              | $p = \frac{QaL}{8I} \left( 1 + \sqrt{1 + \frac{384hEI}{QL^3}} \right)$        | $p = a \sqrt{\frac{6QhE}{LI}}$ |

$I$  = moment of inertia of section;  $a$  = distance of extreme fiber from neutral axis;  $L$  = length of beam;  $E$  = modulus of elasticity.

If metric SI units are used,  $p$  is in newtons per square millimeter;  $Q$  is in newtons;  $E$  = modulus of elasticity in  $\text{N/mm}^2$ ;  $I$  = moment of inertia of section in millimeters<sup>4</sup>; and  $h$ ,  $a$ , and  $L$  in millimeters. Note: If  $Q$  is given in kilograms, the value referred to is mass. The weight  $Q$  of a mass  $M$  kilograms is  $Mg$  newtons, where  $g$  = approximately 9.81 meters per second<sup>2</sup>.

*Examples of How Formulas for Stresses Produced by Shocks are Derived:* The general formula from which specific formulas for shock stresses in beams, springs, and other machine and structural members are derived is:

$$p = p_s \left( 1 + \sqrt{1 + \frac{2h}{y}} \right) \quad (1)$$

In this formula,  $p$  = stress in pounds per square inch due to shock caused by impact of a moving load;  $p_s$  = stress in pounds per square inch resulting when moving load is applied statically;  $h$  = distance in inches that load falls before striking beam, spring, or other member;  $y$  = deflection, in inches, resulting from static load.

As an example of how Formula (1) may be used to obtain a formula for a specific application, suppose that the load  $W$  shown applied to the beam in Case 2 on page 261 were dropped on the beam from a height of  $h$  inches instead of being gradually applied (static loading). The maximum stress  $p_s$  due to load  $W$  for Case 2 is given as  $Wl \div 4Z$  and the maximum deflection  $y$  is given as  $Wl^3 \div 48EI$ . Substituting these values in Formula (1),

$$p = \frac{Wl}{4Z} \left( 1 + \sqrt{1 + \frac{2h}{Wl^3 \div 48EI}} \right) = \frac{Wl}{4Z} \left( 1 + \sqrt{1 + \frac{96hEI}{Wl^3}} \right) \quad (2)$$

If in Formula (2) the letter  $Q$  is used in place of  $W$  and if  $Z$ , the section modulus, is replaced by its equivalent,  $I \div$  distance  $a$  from neutral axis to extreme fiber of beam, then Formula (2) becomes the first formula given in the accompanying Table 1, *Stresses Produced in Beams by Shocks*

**Stresses in Helical Springs Produced by Shocks.**—A load suddenly applied on a spring will produce the same deflection, and, therefore, also the same unit stress, as a static load twice as great. When the load drops from a height  $h$ , the stresses are as given in the accompanying Table 2. The approximate values are applicable when the deflection is small as compared with the height  $h$ . The formulas show that the fiber stress for a given shock will be greater in a spring made from a square bar than in one made from a round bar, if the diameter of coil be the same and the side of the square bar equals the diameter of the round



bar. It is, therefore, more economical to use round stock for springs which must withstand shocks, due to the fact that the deflection for the same fiber stress for a square bar spring is smaller than that for a round bar spring, the ratio being as 4 to 5. The round bar spring is therefore capable of storing more energy than a square bar spring for the same stress.

**Table 2. Stresses Produced in Springs by Shocks**

| Form of Bar from Which Spring is Made | Fiber (Unit) Stress $f$ Produced by Weight $Q$ Dropped a Height $h$ on a Helical Spring | Approximate Value of $f$            |
|---------------------------------------|---|-------------------------------------|
| Round                                 | $f = \frac{8QD}{\pi d^3} \left( 1 + \sqrt{1 + \frac{Ghd^4}{4QD^3n}} \right)$            | $f = 1.27 \sqrt{\frac{QhG}{Dd^2n}}$ |
| Square                                | $f = \frac{9QD}{4d^3} \left( 1 + \sqrt{1 + \frac{Ghd^4}{0.9\pi QD^3n}} \right)$         | $f = 1.34 \sqrt{\frac{QhG}{Dd^2n}}$ |

$G$  = modulus of elasticity for torsion;  $d$  = diameter or side of bar;  $D$  = mean diameter of spring;  $n$  = number of coils in spring.

**Shocks from Bodies in Motion.**—The formulas given can be applied, in general, to shocks from bodies in motion. A body of weight  $W$  moving horizontally with the velocity of  $v$  feet per second, has a stored-up energy:

$$E_K = \frac{1}{2} \times \frac{Wv^2}{g} \text{ foot-pounds} \quad \text{or} \quad \frac{6Wv^2}{g} \text{ inch-pounds}$$

This expression may be substituted for  $Qh$  in the tables in the equations for unit stresses containing this quantity, and the stresses produced by the energy of the moving body thereby determined.

The formulas in the tables give the maximum value of the stresses, providing the designer with some definitive guidance even where there may be justification for assuming that only a part of the energy of the shock is taken up by the member under stress.

**The formulas can also be applied using metric SI units. The stored-up energy of a body of mass  $M$  kilograms moving horizontally with the velocity of  $v$  meters per second is:**

$$E_K = \frac{1}{2}Mv^2 \text{ newton-meters}$$

**This expression may be substituted for  $Qh$  in the appropriate equations in the tables. For calculation in millimeters,  $Qh = 1000 E_K$  newton-millimeters.**

**Fatigue Stresses.**—So-called "fatigue ruptures" occur in parts that are subjected to continually repeated shocks or stresses of small magnitude. Machine parts that are subjected to continual stresses in varying directions, or to repeated shocks, even if of comparatively small magnitude, may fail ultimately if designed, from a mere knowledge of the behavior of the material under a steady stress, such as is imposed upon it by ordinary tensile stress testing machines. Examinations of numerous cases of machine parts, broken under actual working conditions, indicate that at least 80 per cent of these ruptures are caused by fatigue stresses. Most fatigue ruptures are caused by bending stresses, and frequently by a revolving bending stress. Hence, to test materials for this class of stress, the tests should be made to stress the material in a manner similar to that in which it will be stressed under actual working conditions. See *Fatigue Properties* on page 205 for more on this topic.

## COLUMNS

## Strength of Columns or Struts

Structural members which are subject to compression may be so long in proportion to the diameter or lateral dimensions that failure may be the result 1) of both compression and bending; and 2) of bending or buckling to such a degree that compression stress may be ignored.

In such cases, the *slenderness ratio* is important. This ratio equals the length  $l$  of the column in inches divided by the least radius of gyration  $r$  of the cross-section. Various formulas have been used for designing columns which are too slender to be designed for compression only.

**Rankine or Gordon Formula.**—This formula is generally applied when slenderness ratios range between 20 and 100, and sometimes for ratios up to 120. The notation, in English and metric SI units of measurement, is given on page 287.

$$p = \frac{S}{1 + K\left(\frac{l}{r}\right)^2} = \text{ultimate load, lbs. per sq. in.}$$

Factor  $K$  may be established by tests with a given material and end condition, and for the probable range of  $l/r$ . If determined by calculation,  $K = S/C\pi^2E$ . Factor  $C$  equals 1 for either rounded or pivoted column ends, 4 for fixed ends, and 1 to 4 for square flat ends. The factors 25,000, 12,500, etc., in the Rankine formulas, arranged as on page 287, equal  $1/K$ , and have been used extensively.

**Straight-line Formula.**—This general type of formula is often used in designing compression members for buildings, bridges, or similar structural work. It is convenient especially in designing a number of columns that are made of the same material but vary in size, assuming that factor  $B$  is known. This factor is determined by tests.

$$p = S_y - B\left(\frac{l}{r}\right) = \text{ultimate load, lbs. per sq. in.}$$

$S_y$  equals yield point, lbs. per square inch, and factor  $B$  ranges from 50 to 100. Safe unit stress =  $p \div$  factor of safety.

**Formulas of American Railway Engineering Association.**—The formulas that follow apply to structural steel having an ultimate strength of 60,000 to 72,000 pounds per square inch.

For building columns having  $l/r$  ratios not greater than 120, allowable unit stress =  $17,000 - 0.485 l^2/r^2$ . For columns having  $l/r$  ratios greater than 120, allowable unit stress

$$\text{allowable unit stress} = \frac{18,000}{1 + l^2/18,000r^2}$$

For bridge compression members centrally loaded and with values of  $l/r$  not greater than 140:

$$\text{Allowable unit stress, riveted ends} = 15,000 - \frac{1}{4} \frac{l^2}{r^2}$$

$$\text{Allowable unit stress, pin ends} = 15,000 - \frac{1}{3} \frac{l^2}{r^2}$$

**Euler Formula.**—This formula is for columns that are so slender that bending or buckling action predominates and compressive stresses are not taken into account.

$$P = \frac{C\pi^2IE}{l^2} = \text{total ultimate load, in pounds}$$

The notation, in English and metric SI units of measurement, is given in the table *Rankine's and Euler's Formulas for Columns* on page 287. Factors  $C$  for different end conditions are included in the Euler formulas at the bottom of the table. According to a series of experiments, Euler formulas should be used if the values of  $l/r$  exceed the following ratios: Structural steel and flat ends, 195; hinged ends, 155; round ends, 120; cast iron with flat ends, 120; hinged ends, 100; round ends, 75; oak with flat ends, 130. The *critical slenderness ratio*, which marks the dividing line between the shorter columns and those slender enough to warrant using the Euler formula, depends upon the column material and its end conditions. If the Euler formula is applied when the slenderness ratio is too small, the *calculated* ultimate strength will exceed the yield point of the material and, obviously, will be incorrect.

**Eccentrically Loaded Columns.**—In the application of the column formulas previously referred to, it is assumed that the action of the load coincides with the axis of the column. If the load is offset relative to the column axis, the column is said to be eccentrically loaded, and its strength is then calculated by using a modification of the Rankine formula, the quantity  $cz/r^2$  being added to the denominator, as shown in the table on the next page. This modified formula is applicable to columns having a slenderness ratio varying from 20 or 30 to about 100.

**Machine Elements Subjected to Compressive Loads.**—As in structural compression members, an unbraced machine member that is relatively slender (i.e., its length is more than, say, six times the least dimension perpendicular to its longitudinal axis) is usually designed as a column, because failure due to overloading (assuming a compressive load centrally applied in an axial direction) may occur by buckling or a combination of buckling and compression rather than by direct compression alone. In the design of unbraced steel machine “columns” which are to carry compressive loads applied along their longitudinal axes, two formulas are in general use:

$$\text{(Euler)} \quad P_{cr} = \frac{S_y A r^2}{Q} \quad (1)$$

$$\text{(J. B. Johnson)} \quad P_{cr} = A S_y \left( 1 - \frac{Q}{4r^2} \right) \quad (2) \quad \text{where} \quad Q = \frac{S_y l^2}{n \pi^2 E} \quad (3)$$

In these formulas,  $P_{cr}$  = critical load in pounds that would result in failure of the column;  $A$  = cross-sectional area, square inches;  $S_y$  = yield point of material, pounds per square inch;  $r$  = least radius of gyration of cross-section, inches;  $E$  = modulus of elasticity, pounds per square inch;  $l$  = column length, inches; and  $n$  = coefficient for end conditions. For both ends fixed,  $n = 4$ ; for one end fixed, one end free,  $n = 0.25$ ; for one end fixed and the other end free but guided,  $n = 2$ ; for round or pinned ends, free but guided,  $n = 1$ ; and for flat ends,  $n = 1$  to 4. It should be noted that these values of  $n$  represent ideal conditions that are seldom attained in practice; for example, for both ends fixed, a value of  $n = 3$  to 3.5 may be more realistic than  $n = 4$ .

If metric SI units are used in these formulas,  $P_{cr}$  = critical load in newtons that would result in failure of the column;  $A$  = cross-sectional area, square millimeters;  $S_y$  = yield point of the material, newtons per square mm;  $r$  = least radius of gyration of cross-section, mm;  $E$  = modulus of elasticity, newtons per square mm;  $l$  = column length, mm; and  $n$  = a coefficient for end conditions. The coefficients given are valid for calculations in metric units.

**Rankine's and Euler's Formulas for Columns**

| Symbol | Quantity  | English Unit        | Metric SI Units          |
|--------|---|---------------------|--------------------------|
| $p$    | Ultimate unit load  | Lbs./sq. in.        | Newtons/sq. mm.          |
| $P$    | Total ultimate load   | Pounds              | Newtons                  |
| $S$    | Ultimate compressive strength of material   | Lbs./sq. in.        | Newtons/sq. mm.          |
| $l$    | Length of column or strut   | Inches              | Millimeters              |
| $r$    | Least radius of gyration  | Inches              | Millimeters              |
| $I$    | Least moment of inertia   | Inches <sup>4</sup> | Millimeters <sup>4</sup> |
| $r^2$  | Moment of inertia/area of section   | Inches <sup>2</sup> | Millimeters <sup>2</sup> |
| $E$    | Modulus of elasticity of material   | Lbs./sq. in.        | Newtons/sq. mm.          |
| $c$    | Distance from neutral axis of cross-section to side under compression                 | Inches              | Millimeters              |
| $z$    | Distance from axis of load to axis coinciding with center of gravity of cross-section | Inches              | Millimeters              |

**Rankine's Formulas**

| Material     | Both Ends of Column Fixed                 | One End Fixed and One End Rounded         | Both Ends Rounded                       |
|--------------|---|---|---|
| Steel        | $p = \frac{S}{1 + \frac{l^2}{25,000r^2}}$ | $p = \frac{S}{1 + \frac{l^2}{12,500r^2}}$ | $p = \frac{S}{1 + \frac{l^2}{6250r^2}}$ |
| Cast Iron    | $p = \frac{S}{1 + \frac{l^2}{5000r^2}}$   | $p = \frac{S}{1 + \frac{l^2}{2500r^2}}$   | $p = \frac{S}{1 + \frac{l^2}{1250r^2}}$ |
| Wrought Iron | $p = \frac{S}{1 + \frac{l^2}{35,000r^2}}$ | $p = \frac{S}{1 + \frac{l^2}{17,500r^2}}$ | $p = \frac{S}{1 + \frac{l^2}{8750r^2}}$ |
| Timber       | $p = \frac{S}{1 + \frac{l^2}{3000r^2}}$   | $p = \frac{S}{1 + \frac{l^2}{1500r^2}}$   | $p = \frac{S}{1 + \frac{l^2}{750r^2}}$  |

**Formulas Modified for Eccentrically Loaded Columns**

| Material | Both Ends of Column Fixed                                  | One End Fixed and One End Rounded                          | Both Ends Rounded  |
|----------|--|--|--|
| Steel    | $p = \frac{S}{1 + \frac{l^2}{25,000r^2} + \frac{cz}{r^2}}$ | $p = \frac{S}{1 + \frac{l^2}{12,500r^2} + \frac{cz}{r^2}}$ | $p = \frac{S}{1 + \frac{l^2}{6250r^2} + \frac{cz}{r^2}}$ |

For materials other than steel, such as cast iron, use the Rankine formulas given in the upper table and add to the denominator the quantity  $cz/r^2$

**Euler's Formulas for Slender Columns**

| Both Ends of Column Fixed  | One End Fixed and One End Rounded | Both Ends Rounded         | One End Fixed and One End Free |
|----------------------------|-----------------------------------|---------------------------|--------------------------------|
| $P = \frac{4\pi^2IE}{l^2}$ | $P = \frac{2\pi^2IE}{l^2}$        | $P = \frac{\pi^2IE}{l^2}$ | $P = \frac{\pi^2IE}{4l^2}$     |

*Allowable Working Loads for Columns:* To find the total allowable working load for a given section, divide the total ultimate load  $P$  (or  $p \times$  area), as found by the appropriate formula above, by a suitable factor of safety.

*Factor of Safety for Machine Columns:* When the conditions of loading and the physical qualities of the material used are accurately known, a factor of safety as low as 1.25 is sometimes used when minimum weight is important. Usually, however, a factor of safety of 2 to 2.5 is applied for steady loads. The factor of safety represents the ratio of the critical load  $P_{cr}$  to the working load.

*Application of Euler and Johnson Formulas:* To determine whether the Euler or Johnson formula is applicable in any particular case, it is necessary to determine the value of the quantity  $Q \div r^2$ . If  $Q \div r^2$  is greater than 2, then the Euler Formula (1) should be used; if  $Q \div r^2$  is less than 2, then the J. B. Johnson formula is applicable. Most compression members in machine design are in the range of proportions covered by the Johnson formula. For this reason a good procedure is to design machine elements on the basis of the Johnson formula and then as a check calculate  $Q \div r^2$  to determine whether the Johnson formula applies or the Euler formula should have been used.

*Example 1, Compression Member Design:* A rectangular machine member 24 inches long and  $\frac{1}{2} \times 1$  inch in cross-section is to carry a compressive load of 4000 pounds along its axis. What is the factor of safety for this load if the material is machinery steel having a yield point of 40,000 pounds per square inch, the load is steady, and each end of the rod has a ball connection so that  $n = 1$ ?

From Formula (3)

$$Q = \frac{40,000 \times 24 \times 24}{1 \times 3.1416 \times 3.1416 \times 30,000,000} = 0.0778$$

(The values 40,000 and 30,000,000 were obtained from the table *Strength Data for Iron and Steel* on page 474.)

The radius of gyration  $r$  for a rectangular section (page 239) is  $0.289 \times$  the dimension in the direction of bending. In columns, bending is most apt to occur in the direction in which the section is the weakest, the  $\frac{1}{2}$ -inch dimension in this example. Hence, least radius of gyration  $r = 0.289 \times \frac{1}{2} = 0.145$  inch.

$$\frac{Q}{r^2} = \frac{0.0778}{(0.145)^2} = 3.70$$

which is more than 2 so that the Euler formula will be used.

$$P_{cr} = \frac{s_y A r^2}{Q} = \frac{40,000 \times \frac{1}{2} \times 1}{3.70}$$

$$= 5400 \text{ pounds so that the factor of safety is } 5400 \div 4000 = 1.35$$

*Example 2, Compression Member Design:* In the preceding example, the column formulas were used to check the adequacy of a column of known dimensions. The more usual problem involves determining what the dimensions should be to resist a specified load. For example,:

A 24-inch long bar of rectangular cross-section with width  $w$  twice its depth  $d$  is to carry a load of 4000 pounds. What must the width and depth be if a factor of safety of 1.35 is to be used?

First determine the critical load  $P_{cr}$ :

$$\begin{aligned} P_{cr} &= \text{working load} \times \text{factor of safety} \\ &= 4000 \times 1.35 = 5400 \text{ pounds} \end{aligned}$$

Next determine  $Q$  which, as in [Example 1](#), will be 0.0778.

Assume [Formula \(2\)](#) applies:

$$P_{cr} = A s_y \left( 1 - \frac{Q}{4r^2} \right)$$

$$5400 = w \times d \times 40,000 \left( 1 - \frac{0.0778}{4r^2} \right)$$

$$= 2d^2 \times 40,000 \left( 1 - \frac{0.01945}{r^2} \right)$$

$$\frac{5400}{40,000 \times 2} = d^2 \left( 1 - \frac{0.01945}{r^2} \right)$$

As mentioned in [Example 1](#) the least radius of gyration  $r$  of a rectangle is equal to 0.289 times the least dimension,  $d$ , in this case. Therefore, substituting for  $d$  the value  $r \div 0.289$ ,

$$\frac{5400}{40,000 \times 2} = \left( \frac{r}{0.289} \right)^2 \left( 1 - \frac{0.01945}{r^2} \right)$$

$$\frac{5400 \times 0.289 \times 0.289}{40,000 \times 2} = r^2 - 0.01945$$

$$0.005638 = r^2 - 0.01945$$

$$r^2 = 0.0251$$

Checking to determine if  $Q \div r^2$  is greater or less than 2,

$$\frac{Q}{r^2} = \frac{0.0778}{0.0251} = 3.1$$

therefore [Formula \(1\)](#) should have been used to determine  $r$  and dimensions  $w$  and  $d$ . Using [Formula \(1\)](#),

$$5400 = \frac{40,000 \times 2d^2 \times r^2}{Q} = \frac{40,000 \times 2 \times \left( \frac{r}{0.289} \right)^2 r^2}{0.0778}$$

$$r^4 = \frac{5400 \times 0.0778 \times 0.289 \times 0.289}{40,000 \times 2} = 0.0004386$$

$$d = \frac{0.145}{0.289} = 0.50 \text{ inch}$$

and  $w = 2d = 1$  inch as in the previous example.

**American Institute of Steel Construction.**—For main or secondary compression members with  $l/r$  ratios up to 120, safe unit stress =  $17,000 - 0.485l^2/r^2$ . For columns and bracing or other secondary members with  $l/r$  ratios above 120,

Safe unit stress, psi =  $\frac{18,000}{1 + l^2/18,000r^2}$  for bracing and secondary members. For main

members, safe unit stress, psi =  $\frac{18,000}{1 + l^2/18,000r^2} \times \left( 1.6 - \frac{l/r}{200} \right)$

*Pipe Columns:* Allowable concentric loads for steel pipe columns based on the above formulas are given in the table on page [290](#).











## Allowable Concentric Loads for Steel Pipe Columns

| STANDARD STEEL PIPE                      |   |       |       |       |       |       |       |       |
|--|---|-------|-------|-------|-------|-------|-------|-------|
| Nominal Diameter, Inches                 | 12  | 10    | 8     | 6     | 5     | 4     | 3½    | 3     |
| Wall Thickness, Inch                     | 0.375   | 0.365 | 0.322 | 0.280 | 0.258 | 0.237 | 0.226 | 0.216 |
| Weight per Foot, Pounds                  | 49.56   | 40.48 | 28.55 | 18.97 | 14.62 | 10.79 | 9.11  | 7.58  |
| Effective Length (KL), Feet <sup>a</sup> | Allowable Concentric Loads in Thousands of Pounds |       |       |       |       |       |       |       |
| 6  | 303   | 246   | 171   | 110   | 83    | 59    | 48    | 38    |
| 7  | 301   | 243   | 168   | 108   | 81    | 57    | 46    | 36    |
| 8  | 299   | 241   | 166   | 106   | 78    | 54    | 44    | 34    |
| 9  | 296   | 238   | 163   | 103   | 76    | 52    | 41    | 31    |
| 10                                       | 293   | 235   | 161   | 101   | 73    | 49    | 38    | 28    |
| 11                                       | 291   | 232   | 158   | 98    | 71    | 46    | 35    | 25    |
| 12                                       | 288   | 229   | 155   | 95    | 68    | 43    | 32    | 22    |
| 13                                       | 285   | 226   | 152   | 92    | 65    | 40    | 29    | 19    |
| 14                                       | 282   | 223   | 149   | 89    | 61    | 36    | 25    | 16    |
| 15                                       | 278   | 220   | 145   | 86    | 58    | 33    | 22    | 14    |
| 16                                       | 275   | 216   | 142   | 82    | 55    | 29    | 19    | 12    |
| 17                                       | 272   | 213   | 138   | 79    | 51    | 26    | 17    | 11    |
| 18                                       | 268   | 209   | 135   | 75    | 47    | 23    | 15    | 10    |
| 19                                       | 265   | 205   | 131   | 71    | 43    | 21    | 14    | 9     |
| 20                                       | 261   | 201   | 127   | 67    | 39    | 19    | 12    |       |
| 22                                       | 254   | 193   | 119   | 59    | 32    | 15    | 10    |       |
| 24                                       | 246   | 185   | 111   | 51    | 27    | 13    |       |       |
| 25                                       | 242   | 180   | 106   | 47    | 25    | 12    |       |       |
| 26                                       | 238   | 176   | 102   | 43    | 23    |       |       |       |
| EXTRA STRONG STEEL PIPE                  |   |       |       |       |       |       |       |       |
| Nominal Diameter, Inches                 | 12  | 10    | 8     | 6     | 5     | 4     | 3½    | 3     |
| Wall Thickness, Inch                     | 0.500   | 0.500 | 0.500 | 0.432 | 0.375 | 0.337 | 0.318 | 0.300 |
| Weight per Foot, Pounds                  | 65.42   | 54.74 | 43.39 | 28.57 | 20.78 | 14.98 | 12.50 | 10.25 |
| Effective Length (KL), Feet <sup>a</sup> | Allowable Concentric Loads in Thousands of Pounds |       |       |       |       |       |       |       |
| 6  | 400   | 332   | 259   | 166   | 118   | 81    | 66    | 52    |
| 7  | 397   | 328   | 255   | 162   | 114   | 78    | 63    | 48    |
| 8  | 394   | 325   | 251   | 159   | 111   | 75    | 59    | 45    |
| 9  | 390   | 321   | 247   | 155   | 107   | 71    | 55    | 41    |
| 10                                       | 387   | 318   | 243   | 151   | 103   | 67    | 51    | 37    |
| 11                                       | 383   | 314   | 239   | 146   | 99    | 63    | 47    | 33    |
| 12                                       | 379   | 309   | 234   | 142   | 95    | 59    | 43    | 28    |
| 13                                       | 375   | 305   | 229   | 137   | 91    | 54    | 38    | 24    |
| 14                                       | 371   | 301   | 224   | 132   | 86    | 49    | 33    | 21    |
| 15                                       | 367   | 296   | 219   | 127   | 81    | 44    | 29    | 18    |
| 16                                       | 363   | 291   | 214   | 122   | 76    | 39    | 25    | 16    |
| 18                                       | 353   | 281   | 203   | 111   | 65    | 31    | 20    | 12    |
| 19                                       | 349   | 276   | 197   | 105   | 59    | 28    | 18    | 11    |
| 20                                       | 344   | 271   | 191   | 99    | 54    | 25    | 16    |       |
| 21                                       | 337   | 265   | 185   | 92    | 48    | 22    | 14    |       |
| 22                                       | 334   | 260   | 179   | 86    | 44    | 21    |       |       |
| 24                                       | 323   | 248   | 166   | 73    | 37    | 17    |       |       |
| 26                                       | 312   | 236   | 152   | 62    | 32    |       |       |       |
| 28                                       | 301   | 224   | 137   | 54    | 27    |       |       |       |

<sup>a</sup> With respect to radius of gyration. The effective length (KL) is the actual unbraced length, L, in feet, multiplied by the effective length factor (K) which is dependent upon the restraint at the ends of the unbraced length and the means available to resist lateral movements. K may be determined by referring to the last portion of this table.

**Allowable Concentric Loads for Steel Pipe Columns (Continued)**

| DOUBLE-EXTRA STRONG STEEL PIPE           |   |       |       |       |       |
|--|---|-------|-------|-------|-------|
| Nominal Diameter, Inches                 | 8   | 6     | 5     | 4     | 3     |
| Wall Thickness, Inch                     | 0.875   | 0.864 | 0.750 | 0.674 | 0.600 |
| Weight per Foot, Pounds                  | 72.42   | 53.16 | 38.55 | 27.54 | 18.58 |
| Effective Length (KL), Feet <sup>a</sup> | Allowable Concentric Loads in Thousands of Pounds |       |       |       |       |
| 6  | 431   | 306   | 216   | 147   | 91    |
| 7  | 424   | 299   | 209   | 140   | 84    |
| 8  | 417   | 292   | 202   | 133   | 77    |
| 9  | 410   | 284   | 195   | 126   | 69    |
| 10                                       | 403   | 275   | 187   | 118   | 60    |
| 11                                       | 395   | 266   | 178   | 109   | 51    |
| 12                                       | 387   | 257   | 170   | 100   | 43    |
| 13                                       | 378   | 247   | 160   | 91    | 37    |
| 14                                       | 369   | 237   | 151   | 81    | 32    |
| 15                                       | 360   | 227   | 141   | 70    | 28    |
| 16                                       | 351   | 216   | 130   | 62    | 24    |
| 17                                       | 341   | 205   | 119   | 55    | 22    |
| 18                                       | 331   | 193   | 108   | 49    |       |
| 19                                       | 321   | 181   | 97    | 44    |       |
| 20                                       | 310   | 168   | 87    | 40    |       |
| 22                                       | 288   | 142   | 72    | 33    |       |
| 24                                       | 264   | 119   | 61    |       |       |
| 26                                       | 240   | 102   | 52    |       |       |
| 28                                       | 213   | 88    | 44    |       |       |

| EFFECTIVE LENGTH FACTORS (K) FOR VARIOUS COLUMN CONFIGURATIONS  |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
| Buckled shape of column is shown by dashed line                 | (a)<br> | (b)<br> | (c)<br> | (d)<br> | (e)<br> | (f)<br> |
| Theoretical K value   | 0.5   | 0.7   | 1.0   | 1.0   | 2.0   | 2.0   |
| Recommended design value when ideal conditions are approximated | 0.65  | 0.80  | 1.2   | 1.0   | 2.10  | 2.0   |
| End condition code  |        | Rotation fixed and translation fixed  |   |   |   |   |
|   |        | Rotation free and translation fixed   |   |   |   |   |
|   |        | Rotation fixed and translation free   |   |   |   |   |
|   |        | Rotation free and translation free  |   |   |   |   |

Load tables are given for 36 ksi yield stress steel. No load values are given below the heavy horizontal lines, because the  $Kl/r$  ratios (where  $l$  is the actual unbraced length in inches and  $r$  is the governing radius of gyration in inches) would exceed 200.

Data from "Manual of Steel Construction," 8th ed., 1980, with permission of the American Institute of Steel Construction.



## PLATES, SHELLS, AND CYLINDERS

**Flat Stayed Surfaces.**—Large flat areas are often held against pressure by stays distributed at regular intervals over the surface. In boiler work, these stays are usually screwed into the plate and the projecting end riveted over to insure steam tightness. The U.S. Board of Supervising Inspectors and the American Boiler Makers Association rules give the following formula for flat stayed surfaces:

$$P = \frac{C \times t^2}{S^2}$$

in which  $P$  = pressure in pounds per square inch

$C$  = a constant, which equals

112 for plates  $\frac{7}{16}$  inch and under

120, for plates over  $\frac{7}{16}$  inch thick

140, for plates with stays having a nut and bolt on the inside and outside

160, for plates with stays having washers of at least one-half the thickness of the plate, and with a diameter at least one-half of the greatest pitch

$t$  = thickness of plate in 16ths of an inch (thickness =  $\frac{7}{16}$ ,  $t = 7$ )

$S$  = greatest pitch of stays in inches

**Strength and Deflection of Flat Plates.**—Generally, the formulas used to determine stresses and deflections in flat plates are based on certain assumptions that can be closely approximated in practice. These assumptions are:

- 1) the thickness of the plate is not greater than one-quarter the least width of the plate;
- 2) the greatest deflection when the plate is loaded is less than one-half the plate thickness;
- 3) the maximum tensile stress resulting from the load does not exceed the elastic limit of the material; and
- 4) all loads are perpendicular to the plane of the plate.

Plates of ductile materials fail when the maximum stress resulting from deflection under load exceeds the yield strength; for brittle materials, failure occurs when the maximum stress reaches the ultimate tensile strength of the material involved.

**Square and Rectangular Flat Plates.**—The formulas that follow give the maximum stress and deflection of flat steel plates supported in various ways and subjected to the loading indicated. These formulas are based upon a modulus of elasticity for steel of 30,000,000 pounds per square inch and a value of Poisson's ratio of 0.3. If the formulas for maximum stress,  $S$ , are applied without modification to other materials such as cast iron, aluminum, and brass for which the range of Poisson's ratio is about 0.26 to 0.34, the maximum stress calculations will be in error by not more than about 3 per cent. The deflection formulas may also be applied to materials other than steel by substituting in these formulas the appropriate value for  $E$ , the modulus of elasticity of the material (see pages 474 and 554). The deflections thus obtained will not be in error by more than about 3 per cent.

In the stress and deflection formulas that follow,

$p$  = uniformly distributed load acting on plate, pounds per square inch

$W$  = total load on plate, pounds;  $W = p \times$  area of plate

$L$  = distance between supports (length of plate), inches. For rectangular plates,  $L$  = long side,  $l$  = short side

$t$  = thickness of plate, inches

$S$  = maximum tensile stress in plate, pounds per square inch

$d$  = maximum deflection of plate, inches

$E$  = modulus of elasticity in tension.  $E = 30,000,000$  pounds per square inch for steel

If metric SI units are used in the formulas, then,

$W$  = total load on plate, newtons

$L$  = distance between supports (length of plate), millimeters. For rectangular plates,  $L$  = long side,  $l$  = short side

$t$  = thickness of plate, millimeters

$S$  = maximum tensile stress in plate, newtons per mm squared

$d$  = maximum deflection of plate, mm

$E$  = modulus of elasticity, newtons per mm squared

a) Square flat plate supported at top and bottom of all four edges and a uniformly distributed load over the surface of the plate.

$$S = \frac{0.29 W}{t^2} \quad (1)$$

$$d = \frac{0.0443 WL^2}{Et^3} \quad (2)$$

b) Square flat plate supported at the bottom only of all four edges and a uniformly distributed load over the surface of the plate.

$$S = \frac{0.28 W}{t^2} \quad (3)$$

$$d = \frac{0.0443 WL^2}{Et^3} \quad (4)$$

c) Square flat plate with all edges firmly fixed and a uniformly distributed load over the surface of the plate.

$$S = \frac{0.31 W}{t^2} \quad (5)$$

$$d = \frac{0.0138 WL^2}{Et^3} \quad (6)$$

d) Square flat plate with all edges firmly fixed and a uniform load over small circular area at the center. In Equations (7) and (9),  $r_0$  = radius of area to which load is applied. If  $r_0 < 1.7t$ , use  $r_s$  where  $r_s = \sqrt{1.6r_0^2 + t^2} - 0.675t$ .

$$S = \frac{0.62 W}{t^2} \log_e \left( \frac{L}{2r_0} \right) \quad (7)$$

$$d = \frac{0.0568 WL^2}{Et^3} \quad (8)$$

e) Square flat plate with all edges supported above and below, or below only, and a concentrated load at the center. (See Case 4, above, for definition of  $r_0$ ).

$$S = \frac{0.62 W}{t^2} \left[ \log_e \left( \frac{L}{2r_0} \right) + 0.577 \right] \quad (9)$$

$$d = \frac{0.1266 WL^2}{Et^3} \quad (10)$$

f) Rectangular plate with all edges supported at top and bottom and a uniformly distributed load over the surface of the plate.

$$S = \frac{0.75 W}{t^2 \left( \frac{L}{l} + 1.61 \frac{l^2}{L^2} \right)} \quad (11)$$

$$d = \frac{0.1422 W}{Et^3 \left( \frac{L}{l^3} + \frac{2.21}{L^2} \right)} \quad (12)$$

g) Rectangular plate with all edges fixed and a uniformly distributed load over the surface of the plate.

$$S = \frac{0.5 W}{t^2 \left( \frac{L}{l} + \frac{0.623 l^5}{L^5} \right)} \quad (13)$$

$$d = \frac{0.0284 W}{Et^3 \left( \frac{L}{l^3} + \frac{1.056 l^2}{L^4} \right)} \quad (14)$$

**Circular Flat Plates.**—In the following formulas,  $R$  = radius of plate to supporting edge in inches;  $W$  = total load in pounds; and other symbols are the same as used for square and rectangular plates.

**If metric SI units are used,  $R$  = radius of plate to supporting edge in millimeters, and the values of other symbols are the same as those used for square and rectangular plates.**

a) Edge supported around the circumference and a uniformly distributed load over the surface of the plate.

$$S = \frac{0.39W}{t^2} \quad (15) \quad d = \frac{0.221WR^2}{Et^3} \quad (16)$$

b) Edge fixed around circumference and a uniformly distributed load over the surface of the plate.

$$S = \frac{0.24W}{t^2} \quad (17) \quad d = \frac{0.0543WR^2}{Et^3} \quad (18)$$

c) Edge supported around the circumference and a concentrated load at the center.

$$S = \frac{0.48W}{t^2} \left[ 1 + 1.3 \log_e \frac{R}{0.325t} - 0.0185 \frac{t^2}{R^2} \right] \quad (19) \quad d = \frac{0.55WR^2}{Et^3} \quad (20)$$

d) Edge fixed around circumference and a concentrated load at the center.

$$S = \frac{0.62W}{t^2} \left[ \log_e \frac{R}{0.325t} + 0.0264 \frac{t^2}{R^2} \right] \quad (21) \quad d = \frac{0.22WR^2}{Et^3} \quad (22)$$

**Strength of Cylinders Subjected to Internal Pressure.**—In designing a cylinder to withstand internal pressure, the choice of formula to be used depends on 1) the kind of material of which the cylinder is made (whether brittle or ductile); 2) the construction of the cylinder ends (whether open or closed); and 3) whether the cylinder is classed as a thin- or a thick-walled cylinder.

A cylinder is considered to be thin-walled when the ratio of wall thickness to inside diameter is 0.1 or less and thick-walled when this ratio is greater than 0.1. Materials such as cast iron, hard steel, cast aluminum are considered to be brittle materials; low-carbon steel, brass, bronze, etc. are considered to be ductile.

In the formulas that follow,  $p$  = internal pressure, pounds per square inch;  $D$  = inside diameter of cylinder, inches;  $t$  = wall thickness of cylinder, inches;  $\mu$  = Poisson's ratio, = 0.3 for steel, 0.26 for cast iron, 0.34 for aluminum and brass; and  $S$  = allowable tensile stress, pounds per square inch.

**Metric SI units can be used in Formulas (23), (25), (26), and (27), where  $p$  = internal pressure in newtons per square millimeter;  $D$  = inside diameter of cylinder, millimeters;  $t$  = wall thickness, mm;  $\mu$  = Poisson's ratio, = 0.3 for steel, 0.26 for cast iron, and 0.34 for aluminum and brass; and  $S$  = allowable tensile stress, N/mm<sup>2</sup>. For the use of metric SI units in Formula (24), see below.**

*Thin-walled Cylinders:* 
$$t = \frac{Dp}{2S} \quad (23)$$

For low-pressure cylinders of cast iron such as are used for certain engine and press applications, a formula in common use is

$$t = \frac{Dp}{2500} + 0.3 \quad (24)$$

This formula is based on allowable stress of 1250 pounds per square inch and will give a wall thickness 0.3 inch greater than [Formula \(23\)](#) to allow for variations in metal thickness that may result from the casting process.

**If metric SI units are used in [Formula \(24\)](#),  $t$  = cylinder wall thickness in millimeters;  $D$  = inside diameter of cylinder, mm; and the allowable stress is in newtons per square millimeter. The value of 0.3 inches additional wall thickness is 7.62 mm, and the next highest number in preferred metric basic sizes is 8 mm.**

*Thick-walled Cylinders of Brittle Material, Ends Open or Closed:* Lamé's equation is used when cylinders of this type are subjected to internal pressure.

$$t = \frac{D}{2} \left( \sqrt{\frac{S+p}{S-p}} - 1 \right) \quad (25)$$

The table *Ratio of Outside Radius to Inside Radius, Thick Cylinders* on page 296 is for convenience in calculating the dimensions of cylinders under high internal pressure without the use of [Formula \(25\)](#).

*Example, Use of the Table:* Assume that a cylinder of 10 inches inside diameter is to withstand a pressure of 2500 pounds per square inch; the material is cast iron and the allowable stress is 6000 pounds per square inch. To solve the problem, locate the allowable stress per square inch in the left-hand column of the table and the working pressure at the top of the columns. Then find the ratio between the outside and inside radii in the body of the table. In this example, the ratio is 1.558, and hence the outside diameter of the cylinder should be  $10 \times 1.558$ , or about 15½ inches. The thickness of the cylinder wall will therefore be  $(15.558 - 10)/2 = 2.779$  inches.

Unless very high-grade material is used and sound castings assured, cast iron should not be used for pressures exceeding 2000 pounds per square inch. It is well to leave more metal in the bottom of a hydraulic cylinder than is indicated by the results of calculations, because a hole of some size must be cored in the bottom to permit the entrance of a boring bar when finishing the cylinder, and when this hole is subsequently tapped and plugged it often gives trouble if there is too little thickness.

For steady or gradually applied stresses, the maximum allowable fiber stress  $S$  may be assumed to be from 3500 to 4000 pounds per square inch for cast iron; from 6000 to 7000 pounds per square inch for brass; and 12,000 pounds per square inch for steel castings. For intermittent stresses, such as in cylinders for steam and hydraulic work, 3000 pounds per square inch for cast iron; 5000 pounds per square inch for brass; and 10,000 pounds per square inch for steel castings, is ordinarily used. These values give ample factors of safety.

**Note: In metric SI units, 1000 pounds per square inch equals 6.895 newtons per square millimeter.**

*Thick-walled Cylinders of Ductile Material, Closed Ends:* Clavarino's equation is used:

$$t = \frac{D}{2} \left[ \sqrt{\frac{S + (1 - 2\mu)p}{S - (1 + \mu)p}} - 1 \right] \quad (26)$$

*Thick-walled Cylinders of Ductile Material, Open Ends:* Birnie's equation is used:

$$t = \frac{D}{2} \left[ \sqrt{\frac{S + (1 - \mu)p}{S - (1 + \mu)p}} - 1 \right] \quad (27)$$

**Spherical Shells Subjected to Internal Pressure.—Let:**

$D$  = internal diameter of shell in inches

$p$  = internal pressure in pounds per square inch

$S$  = safe tensile stress per square inch

$t$  = thickness of metal in the shell, in inches.

**Ratio of Outside Radius to Inside Radius, Thick Cylinders**

| Allowable Stress in Metal per Sq. In. of Section | Working Pressure in Cylinder, Pounds per Square Inch |       |       |       |       |       |       |
|--|--|-------|-------|-------|-------|-------|-------|
|  | 1000   | 2000  | 3000  | 4000  | 5000  | 6000  | 7000  |
| 2,000  | 1.732  | ...   | ...   | ...   | ...   | ...   | ...   |
| 2,500  | 1.527  | ...   | ...   | ...   | ...   | ...   | ...   |
| 3,000  | 1.414  | 2.236 | ...   | ...   | ...   | ...   | ...   |
| 3,500  | 1.341  | 1.915 | ...   | ...   | ...   | ...   | ...   |
| 4,000  | 1.291  | 1.732 | 2.645 | ...   | ...   | ...   | ...   |
| 4,500  | 1.253  | 1.612 | 2.236 | ...   | ...   | ...   | ...   |
| 5,000  | 1.224  | 1.527 | 2.000 | 3.000 | ...   | ...   | ...   |
| 5,500  | 1.201  | 1.464 | 1.844 | 2.516 | ...   | ...   | ...   |
| 6,000  | 1.183  | 1.414 | 1.732 | 2.236 | 3.316 | ...   | ...   |
| 6,500  | ...  | 1.374 | 1.647 | 2.049 | 2.768 | ...   | ...   |
| 7,000  | ...  | 1.341 | 1.581 | 1.914 | 2.449 | 3.605 | ...   |
| 7,500  | ...  | 1.314 | 1.527 | 1.813 | 2.236 | 3.000 | ...   |
| 8,000  | ...  | 1.291 | 1.483 | 1.732 | 2.081 | 2.645 | 3.872 |
| 8,500  | ...  | 1.271 | 1.446 | 1.666 | 1.963 | 2.408 | 3.214 |
| 9,000  | ...  | 1.253 | 1.414 | 1.612 | 1.871 | 2.236 | 2.828 |
| 9,500  | ...  | 1.235 | 1.386 | 1.566 | 1.795 | 2.104 | 2.569 |
| 10,000   | ...  | 1.224 | 1.362 | 1.527 | 1.732 | 2.000 | 2.380 |
| 10,500   | ...  | 1.212 | 1.341 | 1.493 | 1.678 | 1.915 | 2.236 |
| 11,000   | ...  | 1.201 | 1.322 | 1.464 | 1.633 | 1.844 | 2.121 |
| 11,500   | ...  | 1.193 | 1.306 | 1.437 | 1.593 | 1.784 | 2.027 |
| 12,000   | ...  | 1.183 | 1.291 | 1.414 | 1.558 | 1.732 | 1.949 |
| 12,500   | ...  | ...   | 1.277 | 1.393 | 1.527 | 1.687 | 1.878 |
| 13,000   | ...  | ...   | 1.264 | 1.374 | 1.500 | 1.647 | 1.825 |
| 13,500   | ...  | ...   | 1.253 | 1.357 | 1.475 | 1.612 | 1.775 |
| 14,000   | ...  | ...   | 1.243 | 1.341 | 1.453 | 1.581 | 1.732 |
| 14,500   | ...  | ...   | 1.233 | 1.327 | 1.432 | 1.553 | 1.693 |
| 15,000   | ...  | ...   | 1.224 | 1.314 | 1.414 | 1.527 | 1.658 |
| 16,000   | ...  | ...   | 1.209 | 1.291 | 1.381 | 1.483 | 1.599 |

$$\text{Then, } t = \frac{pD}{4S}$$

This formula also applies to hemi-spherical shells, such as the hemi-spherical head of a cylindrical container subjected to internal pressure, etc.

**If metric SI units are used, then:**

$D$  = internal diameter of shell in millimeters

$p$  = internal pressure in newtons per square millimeter

$S$  = safe tensile stress in newtons per square millimeter

$t$  = thickness of metal in the shell in millimeters

**Meters can be used in the formula in place of millimeters, providing the treatment is consistent throughout.**

*Example:* Find the thickness of metal required in the hemi-spherical end of a cylindrical vessel, 2 feet in diameter, subjected to an internal pressure of 500 pounds per square inch. The material is mild steel and a tensile stress of 10,000 pounds per square inch is allowable.

$$t = \frac{500 \times 2 \times 12}{4 \times 10,000} = 0.3 \text{ inch}$$

**A similar example using metric SI units is as follows: find the thickness of metal required in the hemi-spherical end of a cylindrical vessel, 750 mm in diameter, subjected to an internal pressure of 3 newtons/mm<sup>2</sup>. The material is mild steel and a tensile stress of 70 newtons/mm<sup>2</sup> is allowable.**

$$t = \frac{3 \times 750}{4 \times 70} = 8.04 \text{ mm}$$

If the radius of curvature of the domed head of a boiler or container subjected to internal pressure is made equal to the diameter of the boiler, the thickness of the cylindrical shell and of the spherical head should be made the same. For example, if a boiler is 3 feet in diameter, the radius of curvature of its head should also be 3 feet, if material of the same thickness is to be used and the stresses are to be equal in both the head and cylindrical portion.

**Collapsing Pressure of Cylinders and Tubes Subjected to External Pressures.**—The following formulas may be used for finding the collapsing pressures of lap-welded Bessemer steel tubes:

$$P = 86,670 \frac{t}{D} - 1386 \quad (28)$$

$$P = 50,210,000 \left( \frac{t}{D} \right)^3 \quad (29)$$

in which  $P$  = collapsing pressure in pounds per square inch;  $D$  = outside diameter of tube or cylinder in inches;  $t$  = thickness of wall in inches.

**Formula (28)** is for values of  $P$  greater than 580 pounds per square inch, and **Formula (29)** is for values of  $P$  less than 580 pounds per square inch. These formulas are substantially correct for all lengths of pipe greater than six diameters between transverse joints that tend to hold the pipe to a circular form. The pressure  $P$  found is the actual collapsing pressure, and a suitable factor of safety must be used. Ordinarily, a factor of safety of 5 is sufficient. In cases where there are repeated fluctuations of the pressure, vibration, shocks and other stresses, a factor of safety of from 6 to 12 should be used.

**If metric SI units are used the formulas are:**

$$P = 597.6 \frac{t}{D} - 9.556 \quad (30)$$

$$P = 346,200 \left( \frac{t}{D} \right)^3 \quad (31)$$

where  $P$  = collapsing pressure in newtons per square millimeter;  $D$  = outside diameter of tube or cylinder in millimeters; and  $t$  = thickness of wall in millimeters. **Formula (30)** is for values of  $P$  greater than 4 N/mm<sup>2</sup>, and **Formula (31)** is for values of  $P$  less than 4 N/mm<sup>2</sup>.

The table *Tubes Subjected to External Pressure* is based upon the requirements of the Steam Boat Inspection Service of the Department of Commerce and Labor and gives the permissible working pressures and corresponding minimum wall thickness for long, plain, lap-welded and seamless steel flues subjected to external pressure only. The table thicknesses have been calculated from the formula:

$$t = \frac{[(F \times p) + 1386]D}{86,670}$$

in which  $D$  = outside diameter of flue or tube in inches;  $t$  = thickness of wall in inches;  $p$  = working pressure in pounds per square inch;  $F$  = factor of safety. The formula is applicable to working pressures greater than 100 pounds per square inch, to outside diameters from 7 to 18 inches, and to temperatures less than 650°F.

The preceding [Formulas \(28\) and \(29\)](#) were determined by Prof. R. T. Stewart, Dean of the Mechanical Engineering Department of the University of Pittsburgh, in a series of experiments carried out at the plant of the National Tube Co., McKeesport, Pa.

The apparent fiber stress under which the different tubes failed varied from about 7000 pounds per square inch for the relatively thinnest to 35,000 pounds per square inch for the relatively thickest walls. The average yield point of the material tested was 37,000 pounds and the tensile strength 58,000 pounds per square inch, so it is evident that the strength of a tube subjected to external fluid collapsing pressure is not dependent alone upon the elastic limit or ultimate strength of the material from which it is made.

### Tubes Subjected to External Pressure

| Outside Diameter of Tube, Inches | Working Pressure in Pounds per Square Inch    |       |       |       |       |       |       |
|----------------------------------|---|-------|-------|-------|-------|-------|-------|
|                                  | 100   | 120   | 140   | 160   | 180   | 200   | 220   |
|                                  | Thickness of Tube in Inches. Safety Factor, 5 |       |       |       |       |       |       |
| 7                                | 0.152   | 0.160 | 0.168 | 0.177 | 0.185 | 0.193 | 0.201 |
| 8                                | 0.174   | 0.183 | 0.193 | 0.202 | 0.211 | 0.220 | 0.229 |
| 9                                | 0.196   | 0.206 | 0.217 | 0.227 | 0.237 | 0.248 | 0.258 |
| 10                               | 0.218   | 0.229 | 0.241 | 0.252 | 0.264 | 0.275 | 0.287 |
| 11                               | 0.239   | 0.252 | 0.265 | 0.277 | 0.290 | 0.303 | 0.316 |
| 12                               | 0.261   | 0.275 | 0.289 | 0.303 | 0.317 | 0.330 | 0.344 |
| 13                               | 0.283   | 0.298 | 0.313 | 0.328 | 0.343 | 0.358 | 0.373 |
| 14                               | 0.301   | 0.320 | 0.337 | 0.353 | 0.369 | 0.385 | 0.402 |
| 15                               | 0.323   | 0.343 | 0.361 | 0.378 | 0.396 | 0.413 | 0.430 |
| 16                               | 0.344   | 0.366 | 0.385 | 0.404 | 0.422 | 0.440 | 0.459 |
| 16                               | 0.366   | 0.389 | 0.409 | 0.429 | 0.448 | 0.468 | 0.488 |
| 18                               | 0.387   | 0.412 | 0.433 | 0.454 | 0.475 | 0.496 | 0.516 |

### Dimensions and Maximum Allowable Pressure of Tubes Subjected to External Pressure

| Outside Dia., Inches | Thick-ness of Material, Inches | Max. Pressure Allowed, psi | Outside Dia., Inches | Thick-ness of Material, Inches | Max. Pressure Allowed, psi | Outside Dia., Inches | Thick-ness of Material, Inches | Max. Pressure Allowed, psi |
|----------------------|--------------------------------|----------------------------|----------------------|--------------------------------|----------------------------|----------------------|--------------------------------|----------------------------|
| 2                    | 0.095                          | 427                        | 3                    | 0.109                          | 327                        | 4                    | 0.134                          | 303                        |
| 2¼                   | 0.095                          | 380                        | 3¼                   | 0.120                          | 332                        | 4½                   | 0.134                          | 238                        |
| 2½                   | 0.109                          | 392                        | 3½                   | 0.120                          | 308                        | 5                    | 0.148                          | 235                        |
| 2¾                   | 0.109                          | 356                        | 3¾                   | 0.120                          | 282                        | 6                    | 0.165                          | 199                        |

## SHAFTS

## Shaft Calculations

**Torsional Strength of Shafting.**—In the formulas that follow,

$\alpha$  = angular deflection of shaft in degrees

$c$  = distance from center of gravity to extreme fiber

$D$  = diameter of shaft in inches

$G$  = torsional modulus of elasticity = 11,500,000 pounds per square inch for steel

$J$  = polar moment of inertia of shaft cross-section (see table)

$l$  = length of shaft in inches

$N$  = angular velocity of shaft in revolutions per minute

$P$  = power transmitted in horsepower

$S_s$  = allowable torsional shearing stress in pounds per square inch

$T$  = torsional or twisting moment in inch-pounds

$Z_p$  = polar section modulus (see table page 249)

The allowable twisting moment for a shaft of any cross-section such as circular, square, etc., is:

$$T = S_s \times Z_p \quad (1)$$

For a shaft delivering  $P$  horsepower at  $N$  revolutions per minute the twisting moment  $T$  being transmitted is:

$$T = \frac{63,000P}{N} \quad (2)$$

The twisting moment  $T$  as determined by this formula should be less than the value determined by using [Formula \(7\)](#) if the maximum allowable stress  $S_s$  is not to be exceeded.

The diameter of a solid circular shaft required to transmit a given torque  $T$  is:

$$D = \sqrt[3]{\frac{5.1T}{S_s}} \quad (3a) \quad \text{or} \quad D = \sqrt[3]{\frac{321,000P}{NS_s}} \quad (3b)$$

The allowable stresses that are generally used in practice are: 4000 pounds per square inch for main power-transmitting shafts; 6000 pounds per square inch for lineshafts carrying pulleys; and 8500 pounds per square inch for small, short shafts, countershafts, etc. Using these allowable stresses, the horsepower  $P$  transmitted by a shaft of diameter  $D$ , or the diameter  $D$  of a shaft to transmit a given horsepower  $P$  may be determined from the following formulas:

For main power-transmitting shafts:

$$P = \frac{D^3 N}{80} \quad (4a) \quad \text{or} \quad D = \sqrt[3]{\frac{80P}{N}} \quad (4b)$$

For lineshafts carrying pulleys:

$$P = \frac{D^3 N}{53.5} \quad (5a) \quad \text{or} \quad D = \sqrt[3]{\frac{53.5P}{N}} \quad (5b)$$



For small, short shafts:

$$P = \frac{D^3 N}{38} \quad (6a) \quad \text{or} \quad D = \sqrt[3]{\frac{38P}{N}} \quad (6b)$$

Shafts that are subjected to shocks, such as sudden starting and stopping, should be given a greater factor of safety resulting in the use of lower allowable stresses than those just mentioned.

*Example:* What should be the diameter of a lineshaft to transmit 10 horsepower if the shaft is to make 150 revolutions per minute? Using [Formula \(5b\)](#),

$$D = \sqrt[3]{\frac{53.5 \times 10}{150}} = 1.53 \text{ or, say, } 1\frac{1}{16} \text{ inches}$$

*Example:* What horsepower would be transmitted by a short shaft, 2 inches in diameter, carrying two pulleys close to the bearings, if the shaft makes 300 revolutions per minute? Using [Formula \(6a\)](#),

$$P = \frac{2^3 \times 300}{38} = 63 \text{ horsepower}$$

**Torsional Strength of Shafting, Calculations in Metric SI Units.**—The allowable twisting moment for a shaft of any cross-section such as circular, square, etc., can be calculated from:

$$T = S_s \times Z_p \quad (7)$$

where  $T$  = torsional or twisting moment in newton-millimeters;  $S_s$  = allowable torsional shearing stress in newtons per square millimeter; and  $Z_p$  = polar section modulus in millimeters<sup>3</sup>.

For a shaft delivering power of  $P$  kilowatts at  $N$  revolutions per minute, the twisting moment  $T$  being transmitted is:

$$T = \frac{9.55 \times 10^6 P}{N} \quad (8) \quad \text{or} \quad T = \frac{10^6 P}{\omega} \quad (8a)$$

where  $T$  is in newton-millimeters, and  $\omega$  = angular velocity in radians per second.

The diameter  $D$  of a solid circular shaft required to transmit a given torque  $T$  is:

$$D = \sqrt[3]{\frac{5.1T}{S_s}} \quad (9a) \quad \text{or} \quad D = \sqrt[3]{\frac{48.7 \times 10^6 P}{NS_s}} \quad (9b)$$

$$\text{or} \quad D = \sqrt[3]{\frac{5.1 \times 10^6 P}{\omega S_s}} \quad (9c)$$

where  $D$  is in millimeters;  $T$  is in newton-millimeters;  $P$  is power in kilowatts;  $N$  = revolutions per minute;  $S_s$  = allowable torsional shearing stress in newtons per square millimeter, and  $\omega$  = angular velocity in radians per second.

If 28 newtons/mm<sup>2</sup> and 59 newtons/mm<sup>2</sup> are taken as the generally allowed stresses for main power-transmitting shafts and small short shafts, respectively, then using these allowable stresses, the power  $P$  transmitted by a shaft of diameter  $D$ , or the diameter  $D$  of a shaft to transmit a given power  $P$  may be determined from the following formulas:

For main power-transmitting shafts:

$$P = \frac{D^3 N}{1.77 \times 10^6} \quad (10a) \quad \text{or} \quad D = 3\sqrt{\frac{1.77 \times 10^6 P}{N}} \quad (10b)$$

For small, short shafts:

$$P = \frac{D^3 N}{0.83 \times 10^6} \quad (11a) \quad \text{or} \quad D = 3\sqrt{\frac{0.83 \times 10^6 P}{N}} \quad (11b)$$

where  $P$  is in kilowatts,  $D$  is in millimeters, and  $N$  = revolutions per minute.

*Example:* What should be the diameter of a power-transmitting shaft to transmit 150 kW at 500 rpm?

$$D = 3\sqrt{\frac{1.77 \times 10^6 \times 150}{500}} = 81 \text{ millimeters}$$

*Example:* What power would a short shaft, 50 millimeters in diameter, transmit at 400 rpm?

$$P = \frac{50^3 \times 400}{0.83 \times 10^6} = 60 \text{ kilowatts}$$

**Torsional Deflection of Circular Shafts.**—Shafting must often be proportioned not only to provide the strength required to transmit a given torque, but also to prevent torsional deflection (twisting) through a greater angle than has been found satisfactory for a given type of service.

For a solid circular shaft the torsional deflection in degrees is given by:

$$\alpha = \frac{584 T l}{D^4 G} \quad (12)$$

*Example:* Find the torsional deflection for a solid steel shaft 4 inches in diameter and 48 inches long, subjected to a twisting moment of 24,000 inch-pounds. By [Formula \(12\)](#),

$$\alpha = \frac{584 \times 24,000 \times 48}{4^4 \times 11,500,000} = 0.23 \text{ degree}$$

**Formula (12)** can be used with metric SI units, where  $\alpha$  = angular deflection of shaft in degrees;  $T$  = torsional moment in newton-millimeters;  $l$  = length of shaft in millimeters;  $D$  = diameter of shaft in millimeters; and  $G$  = torsional modulus of elasticity in newtons per square millimeter.

*Example:* Find the torsional deflection of a solid steel shaft, 100 mm in diameter and 1300 mm long, subjected to a twisting moment of  $3 \times 10^6$  newton-millimeters. The torsional modulus of elasticity is 80,000 newtons/mm<sup>2</sup>. By [Formula \(12\)](#)

$$\alpha = \frac{584 \times 3 \times 10^6 \times 1300}{100^4 \times 80,000} = 0.285 \text{ degree}$$

The diameter of a shaft that is to have a maximum torsional deflection  $\alpha$  is given by:

$$D = 4.9 \times 4\sqrt[4]{\frac{Tl}{G\alpha}} \quad (13)$$

**Formula (13)** can be used with metric SI units, where  $D$  = diameter of shaft in millimeters;  $T$  = torsional moment in newton-millimeters;  $l$  = length of shaft in millime-

ters;  $G$  = torsional modulus of elasticity in newtons per square millimeter; and  $\alpha$  = angular deflection of shaft in degrees.

According to some authorities, the allowable twist in steel transmission shafting should not exceed 0.08 degree per foot length of the shaft. The diameter  $D$  of a shaft that will permit a maximum angular deflection of 0.08 degree per foot of length for a given torque  $T$  or for a given horsepower  $P$  can be determined from the formulas:

$$D = 0.29\sqrt[4]{T} \quad (14a) \quad \text{or} \quad D = 4.6 \times \sqrt[4]{\frac{P}{N}} \quad (14b)$$

Using metric SI units and assuming an allowable twist in steel transmission shafting of 0.26 degree per meter length, Formulas (14a) and (14b) become:

$$D = 2.26\sqrt[4]{T} \quad \text{or} \quad D = 125.7 \times \sqrt[4]{\frac{P}{N}}$$

where  $D$  = diameter of shaft in millimeters;  $T$  = torsional moment in newton-millimeters;  $P$  = power in kilowatts; and  $N$  = revolutions per minute.

Another rule that has been generally used in mill practice limits the deflection to 1 degree in a length equal to 20 times the shaft diameter. For a given torque or horsepower, the diameter of a shaft having this maximum deflection is given by:

$$D = 0.1\sqrt[3]{T} \quad (15a) \quad \text{or} \quad D = 4.0 \times \sqrt[3]{\frac{P}{N}} \quad (15b)$$

*Example:* Find the diameter of a steel lineshaft to transmit 10 horsepower at 150 revolutions per minute with a torsional deflection not exceeding 0.08 degree per foot of length. By Formula (14b),

$$D = 4.6 \times \sqrt[4]{\frac{10}{150}} = 2.35 \text{ inches}$$

This diameter is larger than that obtained for the same horsepower and rpm in the example given for Formula (5b) in which the diameter was calculated for strength considerations only. The usual procedure in the design of shafting which is to have a specified maximum angular deflection is to compute the diameter first by means of Formulas (13), (14a), (14b), (15a), or (15b) and then by means of Formulas (3a), (3b), (4b), (5b), or (6b), using the larger of the two diameters thus found.

**Linear Deflection of Shafting.**—For steel line shafting, it is considered good practice to limit the linear deflection to a maximum of 0.010 inch per foot of length. The maximum distance in feet between bearings, for average conditions, in order to avoid excessive linear deflection, is determined by the formulas:

$$L = 8.95\sqrt[3]{D^2} \text{ for shafting subject to no bending action except its own weight}$$

$$L = 5.2\sqrt[3]{D^2} \text{ for shafting subject to bending action of pulleys, etc.}$$

in which  $D$  = diameter of shaft in inches and  $L$  = maximum distance between bearings in feet. Pulleys should be placed as close to the bearings as possible.

In general, shafting up to three inches in diameter is almost always made from cold-rolled steel. This shafting is true and straight and needs no turning, but if keyways are cut in the shaft, it must usually be straightened afterwards, as the cutting of the keyways relieves the tension on the surface of the shaft produced by the cold-rolling process. Sizes of shafting from three to five inches in diameter may be either cold-rolled or turned, more frequently the latter, and all larger sizes of shafting must be turned because cold-rolled shafting is not available in diameters larger than 5 in.

**Diameters of Finished Shafting (former American Standard ASA B17.1)**

| Diameters, Inches     |                    | Minus Tolerances, Inches <sup>a</sup> | Diameters, Inches     |                    | Minus Tolerances, Inches <sup>a</sup> | Diameters, Inches     |                    | Minus Tolerances, Inches <sup>a</sup> |
|-----------------------|--------------------|---------------------------------------|-----------------------|--------------------|---------------------------------------|-----------------------|--------------------|---------------------------------------|
| Transmission Shafting | Machinery Shafting |                                       | Transmission Shafting | Machinery Shafting |                                       | Transmission Shafting | Machinery Shafting |                                       |
|                       | ½                  | 0.002                                 |                       | 1 13/16            | 0.003                                 |                       | 3 ¼                | 0.004                                 |
|                       | 9/16               | 0.002                                 |                       | 1 7/8              | 0.003                                 |                       | 3 3/8              | 0.004                                 |
|                       | 5/8                | 0.002                                 | 1 15/16               | 1 15/16            | 0.003                                 | 3 15/16               | 4                  | 0.004                                 |
|                       | 11/16              | 0.002                                 |                       | 2                  | 0.003                                 |                       | 4 ¼                | 0.005                                 |
|                       | ¾                  | 0.002                                 |                       | 2 1/16             | 0.004                                 | 4 7/16                | 4 ½                | 0.005                                 |
|                       | 13/16              | 0.002                                 |                       | 2 1/8              | 0.004                                 |                       | 4 ¾                | 0.005                                 |
|                       | 7/8                | 0.002                                 | 2 3/16                | 2 3/16             | 0.004                                 | 4 5/16                | 5                  | 0.005                                 |
| 15/16                 | 15/16              | 0.002                                 |                       | 2 ¼                | 0.004                                 |                       | 5 ¼                | 0.005                                 |
|                       | 1                  | 0.002                                 |                       | 2 5/16             | 0.004                                 | 5 7/16                | 5 ½                | 0.005                                 |
|                       | 1 1/16             | 0.003                                 |                       | 2 3/8              | 0.004                                 |                       | 5 ¾                | 0.005                                 |
|                       | 1 1/8              | 0.003                                 | 2 7/16                | 2 7/16             | 0.004                                 | 5 5/16                | 6                  | 0.005                                 |
| 1 3/16                | 1 3/16             | 0.003                                 |                       | 2 ½                | 0.004                                 |                       | 6 ¼                | 0.006                                 |
|                       | 1 ¼                | 0.003                                 |                       | 2 5/8              | 0.004                                 | 6 ½                   | 6 ½                | 0.006                                 |
|                       | 1 5/16             | 0.003                                 |                       | 2 ¾                | 0.004                                 |                       | 6 ¾                | 0.006                                 |
|                       | 1 3/8              | 0.003                                 | 2 15/16               | 2 7/8              | 0.004                                 | 7                     | 7                  | 0.006                                 |
| 1 7/16                | 1 7/16             | 0.003                                 |                       | 3                  | 0.004                                 |                       | 7 ¼                | 0.006                                 |
|                       | 1 ½                | 0.003                                 |                       | 3 1/8              | 0.004                                 | 7 ½                   | 7 ½                | 0.006                                 |
|                       | 1 9/16             | 0.003                                 |                       | 3 ¼                | 0.004                                 |                       | 7 ¾                | 0.006                                 |
|                       | 1 5/8              | 0.003                                 |                       | 3 3/8              | 0.004                                 | 8                     | 8                  | 0.006                                 |
| 1 11/16               | 1 11/16            | 0.003                                 | 3 7/16                | 3 ½                | 0.004                                 | ...                   | ...                | ...                                   |
|                       | 1 ¾                | 0.003                                 |                       | 3 5/8              | 0.004                                 | ...                   | ...                | ...                                   |

<sup>a</sup> Note:—These tolerances are *negative* or minus and represent the maximum allowable variation below the exact nominal size. For instance the maximum diameter of the 1 15/16 inch shaft is 1.938 inch and its minimum allowable diameter is 1.935 inch. Stock lengths of finished transmission shafting shall be: 16, 20 and 24 feet.

**Design of Transmission Shafting.**—The following guidelines for the design of shafting for transmitting a given amount of power under various conditions of loading are based upon formulas given in the former American Standard ASA B17c Code for the Design of Transmission Shafting. These formulas are based on the *maximum-shear theory* of failure which assumes that the elastic limit of a *ductile* ferrous material in shear is practically one-half its elastic limit in tension. This theory agrees, very nearly, with the results of tests on ductile materials and has gained wide acceptance in practice.

The formulas given apply in all shaft designs including shafts for special machinery. The limitation of these formulas is that they provide only for the strength of shafting and are not concerned with the torsional or lineal deformations which may, in shafts used in machine design, be the controlling factor (see *Torsional Deflection of Circular Shafts* on page 301 and *Linear Deflection of Shafting* on page 302 for deflection considerations). In the formulas that follow,

$$B = \sqrt[3]{1 \div (1 - K^4)} \text{ (see Table 3)}$$

$D$  = outside diameter of shaft in inches

$D_i$  = inside diameter of a hollow shaft in inches

$K_m$  = shock and fatigue factor to be applied in every case to the computed bending moment (see Table 1)

$K_t$  = combined shock and fatigue factor to be applied in every case to the computed torsional moment (see Table 1)

$M$  = maximum bending moment in inch-pounds

$N$  = revolutions per minute

$P$  = maximum power to be transmitted by the shaft in horsepower

$p_t$  = maximum allowable shearing stress under combined loading conditions in pounds per square inch (see Table 2)

$S$  = maximum allowable flexural (bending) stress, in either tension or compression in pounds per square inch (see Table 2)

$S_s$  = maximum allowable torsional shearing stress in pounds per square inch (see Table 2)

$T$  = maximum torsional moment in inch-pounds

$V$  = maximum transverse shearing load in pounds

For shafts subjected to pure torsional loads only,

$$D = B \sqrt[3]{\frac{5.1 K_t T}{S_s}} \quad (16a) \quad \text{or} \quad D = B \sqrt[3]{\frac{321,000 K_t P}{S_s N}} \quad (16b)$$

For stationary shafts subjected to bending only,

$$D = B \sqrt[3]{\frac{10.2 K_m M}{S}} \quad (17)$$

For shafts subjected to combined torsion and bending,

$$D = B \sqrt[3]{\frac{5.1}{p_t} \sqrt{(K_m M)^2 + (K_t T)^2}} \quad (18a)$$

or

$$D = B \sqrt[3]{\frac{5.1}{p_t} \sqrt{(K_m M)^2 + \left(\frac{63,000 K_t P}{N}\right)^2}} \quad (18b)$$

Formulas (16a) to (18b) may be used for solid shafts or for hollow shafts. For solid shafts the factor  $B$  is equal to 1, whereas for hollow shafts the value of  $B$  depends on the value of  $K$  which, in turn, depends on the ratio of the inside diameter of the shaft to the outside diameter ( $D_1 \div D = K$ ). Table 3 gives values of  $B$  corresponding to various values of  $K$ .

For short solid shafts subjected only to heavy transverse shear, the diameter of shaft required is:

$$D = \sqrt[3]{\frac{1.7V}{S_s}} \quad (19)$$

Formulas (16a), (17), (18a) and (19), can be used unchanged with metric SI units. Formula (16b) becomes:

$$D = B \sqrt[3]{\frac{48.7 K_t P}{S_s N}} \quad \text{and Formula (18b) becomes:}$$

$$D = B \sqrt[3]{\frac{5.1}{p_t} \sqrt{(K_m M)^2 + \left(\frac{9.55 K_t P}{N}\right)^2}}$$

Throughout the formulas,  $D$  = outside diameter of shaft in millimeters;  $T$  = maximum torsional moment in newton-millimeters;  $S_s$  = maximum allowable torsional shearing stress in newtons per millimeter squared (see Table 2);  $P$  = maximum power to be transmitted in milliwatts;  $N$  = revolutions per minute;  $M$  = maximum bending moment in newton-millimeters;  $S$  = maximum allowable flexural (bending) stress, either in tension or compression in newtons per millimeter squared (see Table 2);  $p_t$  = maximum allowable shearing stress under combined loading conditions in newtons

per millimeter squared; and  $V$  = maximum transverse shearing load in kilograms. The factors  $K_m$ ,  $K_r$ , and  $B$  are unchanged, and  $D_1$  = the inside diameter of a hollow shaft in millimeters.

**Table 1. Recommended Values of the Combined Shock and Fatigue Factors for Various Types of Load**

| Type of Load                        | Stationary Shafts |         | Rotating Shafts |         |
|-------------------------------------|-------------------|---------|-----------------|---------|
|                                     | $K_m$             | $K_r$   | $K_m$           | $K_r$   |
| Gradually applied and steady        | 1.0               | 1.0     | 1.5             | 1.0     |
| Suddenly applied, minor shocks only | 1.5–2.0           | 1.5–2.0 | 1.5–2.0         | 1.0–1.5 |
| Suddenly applied, heavy shocks      | ...               | ...     | 2.0–3.0         | 1.5–3.0 |

**Table 2. Recommended Maximum Allowable Working Stresses for Shafts Under Various Types of Load**

| Material                                       | Type of Load             |                          |                          |
|--|--------------------------|--------------------------|--------------------------|
|  | Simple Bending           | Pure Torsion             | Combined Stress          |
| "Commercial Steel" shafting without keyways    | $S = 16,000$             | $S_s = 8000$             | $p_t = 8000$             |
| "Commercial Steel" shafting with keyways       | $S = 12,000$             | $S_s = 6000$             | $p_t = 6000$             |
| Steel purchased under definite physical specs. | (See note <sup>a</sup> ) | (See note <sup>b</sup> ) | (See note <sup>b</sup> ) |

<sup>a</sup>  $S = 60$  per cent of the elastic limit in tension but not more than 36 per cent of the ultimate tensile strength.

<sup>b</sup>  $S_s$  and  $p_t = 30$  per cent of the elastic limit in tension but not more than 18 per cent of the ultimate tensile strength.

If the values in the Table are converted to metric SI units, note that 1000 pounds per square inch = 6.895 newtons per square millimeter.

**Table 3. Values of the Factor  $B$  Corresponding to Various Values of  $K$  for Hollow Shafts**

|                                  |      |      |      |      |      |      |      |      |      |      |
|----------------------------------|------|------|------|------|------|------|------|------|------|------|
| $K = \frac{D_1}{D} =$            | 0.95 | 0.90 | 0.85 | 0.80 | 0.75 | 0.70 | 0.65 | 0.60 | 0.55 | 0.50 |
| $B = \sqrt[3]{1 \div (1 - K^4)}$ | 1.75 | 1.43 | 1.28 | 1.19 | 1.14 | 1.10 | 1.07 | 1.05 | 1.03 | 1.02 |

For solid shafts,  $B = 1$  because  $K = 0$ , as follows:  $B = \sqrt[3]{1 \div (1 - K^4)} = \sqrt[3]{1 \div (1 - 0)} = 1$

**Effect of Keyways on Shaft Strength.**—Keyways cut into a shaft reduce its load carrying ability, particularly when impact loads or stress reversals are involved. To ensure an adequate factor of safety in the design of a shaft with standard keyway (width, one-quarter, and depth, one-eighth of shaft diameter), the former Code for Transmission Shafting tentatively recommended that shafts with keyways be designed on the basis of a solid circular shaft using not more than 75 per cent of the working stress recommended for the solid shaft. See also page 2363.

**Formula for Shafts of Brittle Materials.**—The preceding formulas are applicable to ductile materials and are based on the maximum-shear theory of failure which assumes that the elastic limit of a ductile material in shear is one-half its elastic limit in tension.

Brittle materials are generally stronger in shear than in tension; therefore, the maximum-shear theory is not applicable. The maximum-normal-stress theory of failure is now generally accepted for the design of shafts made from brittle materials. A material may be considered to be brittle if its elongation in a 2-inch gage length is less than 5 per cent. Materials such as cast iron, hardened tool steel, hard bronze, etc., conform to this rule. The diameter of a shaft made of a brittle material may be determined from the following formula which is based on the maximum-normal-stress theory of failure:

$$D = B \sqrt[3]{\frac{5.1}{S_t} \left[ (K_m M) + \sqrt{(K_m M)^2 + (K_t T)^2} \right]}$$

where  $S_t$  is the maximum allowable tensile stress in pounds per square inch and the other quantities are as previously defined.

**The formula can be used unchanged with metric SI units, where  $D$  = outside diameter of shaft in millimeters;  $S_t$  = the maximum allowable tensile stress in newtons per millimeter squared;  $M$  = maximum bending moment in newton-millimeters; and  $T$  = maximum torsional moment in newton-millimeters. The factors  $K_m$ ,  $K_t$ , and  $B$  are unchanged.**

**Critical Speed of Rotating Shafts.**—At certain speeds, a rotating shaft will become dynamically unstable and the resulting vibrations and deflections can result in damage not only to the shaft but to the machine of which it is a part. The speeds at which such dynamic instability occurs are called the critical speeds of the shaft. On page 196 are given formulas for the critical speeds of shafts subject to various conditions of loading and support. A shaft may be safely operated either above or below its critical speed, good practice indicating that the operating speed be at least 20 per cent above or below the critical.

The formulas commonly used to determine critical speeds are sufficiently accurate for general purposes. However, the torque applied to a shaft has an important effect on its critical speed. Investigations have shown that the critical speeds of a uniform shaft are decreased as the applied torque is increased, and that there exist critical torques which will reduce the corresponding critical speed of the shaft to zero. A detailed analysis of the effects of applied torques on critical speeds may be found in a paper, "Critical Speeds of Uniform Shafts under Axial Torque," by Golomb and Rosenberg presented at the First U.S. National Congress of Applied Mechanics in 1951.

**Shaft Couplings.**—A shaft coupling is a device for fastening together the ends of two shafts, so that the rotary motion of one causes rotary motion of the other. One of the most simple and common forms of coupling is the flange coupling **Figs. 1a** and **1b**. It consists of two flanged sleeves or hubs, each of which is keyed to the end of one of the two shafts to be connected. The sleeves are held together and prevented from rotating relative to each other by bolts through the flanges as indicated.

### Flange Coupling

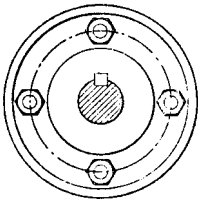


Fig. 1a.

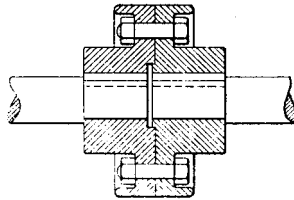


Fig. 1b.

**Flexible Couplings:** Flexible couplings are the most common mechanical means of compensating for unavoidable errors in alignment of shafts and shafting. When correctly applied, they are highly efficient for joining lengths of shafting without causing loss of power from bearing friction due to misalignment, and for use in direct motor drives for all kinds of machinery. Flexible couplings are not intended to be used for connecting a driven shaft and a driving shaft that are purposely placed in different planes or at an angle but are intended simply to overcome slight unavoidable errors in alignment that develop in service. There is a wide variety of flexible coupling designs; most of them consist essentially

of two flanged members or hubs, fastened to the shafts and connected by some yielding arrangement. Balance is an important factor in coupling selection or design; it is not sufficient that the coupling be perfectly balanced when installed, but it must remain in balance after wear has taken place.

**Comparison of Hollow and Solid Shafting with Same Outside Diameter.**—Table 4 that follows gives the per cent decrease in strength and weight of a hollow shaft relative to the strength and weight of a solid shaft of the same diameter. The upper figures in each line give the per cent decrease in strength and the lower figures give the per cent decrease in weight.

*Example:* A 4-inch shaft, with a 2-inch hole through it, has a weight 25 per cent less than a solid 4-inch shaft, but its strength is decreased only 6.25 per cent.

**Table 4. Comparative Torsional Strengths and Weights of Hollow and Solid Shafting with Same Outside Diameter**

| Dia. of Solid and Hollow Shaft, Inches | Diameter of Axial Hole in Hollow Shaft, Inches |       |       |       |       |       |       |       |       |       |
|--|--|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|  | 1  | 1¼    | 1½    | 1¾    | 2     | 2½    | 3     | 3½    | 4     | 4½    |
| 1½                                     | 19.76  | 48.23 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
|  | 44.44  | 69.44 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
| 1¾                                     | 10.67  | 26.04 | 53.98 | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
|  | 32.66  | 51.02 | 73.49 | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
| 2                                      | 6.25   | 15.26 | 31.65 | 58.62 | ...   | ...   | ...   | ...   | ...   | ...   |
|  | 25.00  | 39.07 | 56.25 | 76.54 | ...   | ...   | ...   | ...   | ...   | ...   |
| 2¼                                     | 3.91   | 9.53  | 19.76 | 36.60 | 62.43 | ...   | ...   | ...   | ...   | ...   |
|  | 19.75  | 30.87 | 44.44 | 60.49 | 79.00 | ...   | ...   | ...   | ...   | ...   |
| 2½                                     | 2.56   | 6.25  | 12.96 | 24.01 | 40.96 | ...   | ...   | ...   | ...   | ...   |
|  | 16.00  | 25.00 | 36.00 | 49.00 | 64.00 | ...   | ...   | ...   | ...   | ...   |
| 2¾                                     | 1.75   | 4.28  | 8.86  | 16.40 | 27.98 | 68.30 | ...   | ...   | ...   | ...   |
|  | 13.22  | 20.66 | 29.74 | 40.48 | 52.89 | 82.63 | ...   | ...   | ...   | ...   |
| 3                                      | 1.24   | 3.01  | 6.25  | 11.58 | 19.76 | 48.23 | ...   | ...   | ...   | ...   |
|  | 11.11  | 17.36 | 25.00 | 34.01 | 44.44 | 69.44 | ...   | ...   | ...   | ...   |
| 3¼                                     | 0.87   | 2.19  | 4.54  | 8.41  | 14.35 | 35.02 | 72.61 | ...   | ...   | ...   |
|  | 9.46   | 14.80 | 21.30 | 29.00 | 37.87 | 59.17 | 85.22 | ...   | ...   | ...   |
| 3½                                     | 0.67   | 1.63  | 3.38  | 6.25  | 10.67 | 26.04 | 53.98 | ...   | ...   | ...   |
|  | 8.16   | 12.76 | 18.36 | 25.00 | 32.66 | 51.02 | 73.49 | ...   | ...   | ...   |
| 3¾                                     | 0.51   | 1.24  | 2.56  | 4.75  | 8.09  | 19.76 | 40.96 | 75.89 | ...   | ...   |
|  | 7.11   | 11.11 | 16.00 | 21.77 | 28.45 | 44.44 | 64.00 | 87.10 | ...   | ...   |
| 4                                      | 0.40   | 0.96  | 1.98  | 3.68  | 6.25  | 15.26 | 31.65 | 58.62 | ...   | ...   |
|  | 6.25   | 9.77  | 14.06 | 19.14 | 25.00 | 39.07 | 56.25 | 76.56 | ...   | ...   |
| 4¼                                     | 0.31   | 0.74  | 1.56  | 2.89  | 4.91  | 11.99 | 24.83 | 46.00 | 78.47 | ...   |
|  | 5.54   | 8.65  | 12.45 | 16.95 | 22.15 | 34.61 | 49.85 | 67.83 | 88.59 | ...   |
| 4½                                     | 0.25   | 0.70  | 1.24  | 2.29  | 3.91  | 9.53  | 19.76 | 36.60 | 62.43 | ...   |
|  | 4.94   | 7.72  | 11.11 | 15.12 | 19.75 | 30.87 | 44.44 | 60.49 | 79.00 | ...   |
| 4¾                                     | 0.20   | 0.50  | 1.00  | 1.85  | 3.15  | 7.68  | 15.92 | 29.48 | 50.29 | 80.56 |
|  | 4.43   | 6.93  | 9.97  | 13.57 | 17.73 | 27.70 | 39.90 | 54.29 | 70.91 | 89.75 |
| 5                                      | 0.16   | 0.40  | 0.81  | 1.51  | 2.56  | 6.25  | 12.96 | 24.01 | 40.96 | 65.61 |
|  | 4.00   | 6.25  | 8.10  | 12.25 | 16.00 | 25.00 | 36.00 | 49.00 | 64.00 | 81.00 |
| 5½                                     | 0.11   | 0.27  | 0.55  | 1.03  | 1.75  | 4.27  | 8.86  | 16.40 | 27.98 | 44.82 |
|  | 3.30   | 5.17  | 7.43  | 10.12 | 13.22 | 20.66 | 29.76 | 40.48 | 52.89 | 66.94 |
| 6                                      | 0.09   | 0.19  | 0.40  | 0.73  | 1.24  | 3.02  | 6.25  | 11.58 | 19.76 | 31.65 |
|  | 2.77   | 4.34  | 6.25  | 8.50  | 11.11 | 17.36 | 25.00 | 34.02 | 44.44 | 56.25 |
| 6½                                     | 0.06   | 0.14  | 0.29  | 0.59  | 0.90  | 2.19  | 4.54  | 8.41  | 14.35 | 23.98 |
|  | 2.36   | 3.70  | 5.32  | 7.24  | 9.47  | 14.79 | 21.30 | 28.99 | 37.87 | 47.93 |
| 7                                      | 0.05   | 0.11  | 0.22  | 0.40  | 0.67  | 1.63  | 3.38  | 6.25  | 10.67 | 17.08 |
|  | 2.04   | 3.19  | 4.59  | 6.25  | 8.16  | 12.76 | 18.36 | 25.00 | 32.66 | 41.33 |
| 7½                                     | 0.04   | 0.08  | 0.16  | 0.30  | 0.51  | 1.24  | 2.56  | 4.75  | 8.09  | 12.96 |
|  | 1.77   | 2.77  | 4.00  | 5.44  | 7.11  | 11.11 | 16.00 | 21.77 | 28.45 | 36.00 |
| 8                                      | 0.03   | 0.06  | 0.13  | 0.23  | 0.40  | 0.96  | 1.98  | 3.68  | 6.25  | 10.02 |
|  | 1.56   | 2.44  | 3.51  | 4.78  | 6.25  | 9.77  | 14.06 | 19.14 | 25.00 | 31.64 |

The upper figures in each line give number of per cent decrease in strength; the lower figures give per cent decrease in weight.



## SPRINGS

## Introduction to Spring Design

Many advances have been made in the spring industry in recent years. For example: developments in materials permit longer fatigue life at higher stresses; simplified design procedures reduce the complexities of design, and improved methods of manufacture help to speed up some of the complicated fabricating procedures and increase production. New types of testing instruments and revised tolerances also permit higher standards of accuracy. Designers should also consider the possibility of using standard springs now available from stock. They can be obtained from spring manufacturing companies located in different areas, and small shipments usually can be made quickly.

Designers of springs require information in the following order of precedence to simplify design procedures.

- 1) Spring materials and their applications
- 2) Allowable spring stresses
- 3) Spring design data with tables of spring characteristics, tables of formulas, and tolerances.

Only the more commonly used types of springs are covered in detail here. Special types and designs rarely used such as torsion bars, volute springs, Belleville washers, constant force, ring and spiral springs and those made from rectangular wire are only described briefly. Belleville and disc springs are discussed in the section *DISC SPRINGS* starting on page 354

**Notation.**—The following symbols are used in spring equations:

$AC$  = Active coils

$b$  = Widest width of rectangular wire, inches

$CL$  = Compressed length, inches

$D$  = Mean coil diameter, inches =  $OD - d$

$d$  = Diameter of wire or side of square, inches

$E$  = Modulus of elasticity in tension, pounds per square inch

$F$  = Deflection, for  $N$  coils, inches

$F^\circ$  = Deflection, for  $N$  coils, rotary, degrees

$f$  = Deflection, for one active coil

$FL$  = Free length, unloaded spring, inches

$G$  = Modulus of elasticity in torsion, pounds per square inch

$IT$  = Initial tension, pounds

$K$  = Curvature stress correction factor

$L$  = Active length subject to deflection, inches

$N$  = Number of active coils, total

$P$  = Load, pounds

$p$  = pitch, inches

$R$  = Distance from load to central axis, inches

$SorS_t$  = Stress, torsional, pounds per square inch

$S_b$  = Stress, bending, pounds per square inch

$SH$  = Solid height

$S_{it}$  = Stress, torsional, due to initial tension, pounds per square inch

$T$  = Torque =  $P \times R$ , pound-inches

$TC$  = Total coils

$t$  = Thickness, inches

$U$  = Number of revolutions =  $F^\circ/360^\circ$

### Spring Materials

The spring materials most commonly used include high-carbon spring steels, alloy spring steels, stainless spring steels, copper-base spring alloys, and nickel-base spring alloys.

**High-Carbon Spring Steels in Wire Form.**—These spring steels are the most commonly used of all spring materials because they are the least expensive, are easily worked, and are readily available. However, they are not satisfactory for springs operating at high or low temperatures or for shock or impact loading. The following wire forms are available:

*Music Wire, ASTM A228* (0.80–0.95 per cent carbon): This is the most widely used of all spring materials for small springs operating at temperatures up to about 250 degrees F. It is tough, has a high tensile strength, and can withstand high stresses under repeated loading. The material is readily available in round form in diameters ranging from 0.005 to 0.125 inch and in some larger sizes up to  $\frac{3}{16}$  inch. It is not available with high tensile strengths in square or rectangular sections. Music wire can be plated easily and is obtainable pretinned or preplated with cadmium, but plating after spring manufacture is usually preferred for maximum corrosion resistance.

*Oil-Tempered MB Grade, ASTM A229* (0.60–0.70 per cent carbon): This general-purpose spring steel is commonly used for many types of coil springs where the cost of music wire is prohibitive and in sizes larger than are available in music wire. It is readily available in diameters ranging from 0.125 to 0.500 inch, but both smaller and larger sizes may be obtained. The material should not be used under shock and impact loading conditions, at temperatures above 350 degrees F., or at temperatures in the sub-zero range. Square and rectangular sections of wire are obtainable in fractional sizes. Annealed stock also can be obtained for hardening and tempering after coiling. This material has a heat-treating scale that must be removed before plating.

*Oil-Tempered HB Grade, SAE 1080* (0.75–0.85 per cent carbon): This material is similar to the MB Grade except that it has a higher carbon content and a higher tensile strength. It is obtainable in the same sizes and is used for more accurate requirements than the MB Grade, but is not so readily available. In lieu of using this material it may be better to use an alloy spring steel, particularly if a long fatigue life or high endurance properties are needed. Round and square sections are obtainable in the oil-tempered or annealed conditions.

*Hard-Drawn MB Grade, ASTM A227* (0.60–0.70 per cent carbon): This grade is used for general-purpose springs where cost is the most important factor. Although increased use in recent years has resulted in improved quality, it is best not to use it where long life and accuracy of loads and deflections are important. It is available in diameters ranging from 0.031 to 0.500 inch and in some smaller and larger sizes also. The material is available in square sections but at reduced tensile strengths. It is readily plated. Applications should be limited to those in the temperature range of 0 to 250 degrees F.

**High-Carbon Spring Steels in Flat Strip Form.**—Two types of thin, flat, high-carbon spring steel strip are most widely used although several other types are obtainable for specific applications in watches, clocks, and certain instruments. These two compositions are used for over 95 per cent of all such applications. Thin sections of these materials under 0.015 inch having a carbon content of over 0.85 per cent and a hardness of over 47 on the Rockwell C scale are susceptible to hydrogen-embrittlement even though special plating and heating operations are employed. The two types are described as follows:

*Cold-Rolled Spring Steel, Blue-Tempered or Annealed, SAE 1074, also 1064, and 1070* (0.60 to 0.80 per cent carbon): This very popular spring steel is available in thicknesses ranging from 0.005 to 0.062 inch and in some thinner and thicker sections. The material is available in the annealed condition for forming in 4-slide machines and in presses, and can

readily be hardened and tempered after forming. It is also available in the heat-treated or blue-tempered condition. The steel is obtainable in several finishes such as straw color, blue color, black, or plain. Hardnesses ranging from 42 to 46 Rockwell C are recommended for spring applications. Uses include spring clips, flat springs, clock springs, and motor, power, and spiral springs.

*Cold-Rolled Spring Steel, Blue-Tempered Clock Steel, SAE 1095* (0.90 to 1.05 per cent carbon): This popular type should be used principally in the blue-tempered condition. Although obtainable in the annealed condition, it does not always harden properly during heat-treatment as it is a "shallow" hardening type. It is used principally in clocks and motor springs. End sections of springs made from this steel are annealed for bending or piercing operations. Hardnesses usually range from 47 to 51 Rockwell C.

Other materials available in strip form and used for flat springs are brass, phosphor-bronze, beryllium-copper, stainless steels, and nickel alloys.

**Alloy Spring Steels.**—These spring steels are used for conditions of high stress, and shock or impact loadings. They can withstand both higher and lower temperatures than the high-carbon steels and are obtainable in either the annealed or pretempered conditions.

*Chromium Vanadium, ASTM A231:* This very popular spring steel is used under conditions involving higher stresses than those for which the high-carbon spring steels are recommended and is also used where good fatigue strength and endurance are needed. It behaves well under shock and impact loading. The material is available in diameters ranging from 0.031 to 0.500 inch and in some larger sizes also. In square sections it is available in fractional sizes. Both the annealed and pretempered types are available in round, square, and rectangular sections. It is used extensively in aircraft-engine valve springs and for springs operating at temperatures up to 425 degrees F.

*Silicon Manganese:* This alloy steel is quite popular in Great Britain. It is less expensive than chromium-vanadium steel and is available in round, square, and rectangular sections in both annealed and pretempered conditions in sizes ranging from 0.031 to 0.500 inch. It was formerly used for knee-action springs in automobiles. It is used in flat leaf springs for trucks and as a substitute for more expensive spring steels.

*Chromium Silicon, ASTM A401:* This alloy is used for highly stressed springs that require long life and are subjected to shock loading. It can be heat-treated to higher hardnesses than other spring steels so that high tensile strengths are obtainable. The most popular sizes range from 0.031 to 0.500 inch in diameter. Very rarely are square, flat, or rectangular sections used. Hardnesses ranging from 50 to 53 Rockwell C are quite common and the alloy may be used at temperatures up to 475 degrees F. This material is usually ordered specially for each job.

**Stainless Spring Steels.**—The use of stainless spring steels has increased and several compositions are available all of which may be used for temperatures up to 550 degrees F. They are all corrosion resistant. Only the stainless 18-8 compositions should be used at sub-zero temperatures.

*Stainless Type 302, ASTM A313* (18 per cent chromium, 8 per cent nickel): This stainless spring steel is very popular because it has the highest tensile strength and quite uniform properties. It is cold-drawn to obtain its mechanical properties and cannot be hardened by heat treatment. This material is nonmagnetic only when fully annealed and becomes slightly magnetic due to the cold-working performed to produce spring properties. It is suitable for use at temperatures up to 550 degrees F. and for sub-zero temperatures. It is very corrosion resistant. The material best exhibits its desirable mechanical properties in diameters ranging from 0.005 to 0.1875 inch although some larger diameters are available. It is also available as hard-rolled flat strip. Square and rectangular sections are available but are infrequently used.

*Stainless Type 304, ASTM A313* (18 per cent chromium, 8 per cent nickel): This material is quite similar to Type 302, but has better bending properties and about 5 per cent lower tensile strength. It is a little easier to draw, due to the slightly lower carbon content.

*Stainless Type 316, ASTM A313* (18 per cent chromium, 12 per cent nickel, 2 per cent molybdenum): This material is quite similar to Type 302 but is slightly more corrosion resistant because of its higher nickel content. Its tensile strength is 10 to 15 per cent lower than Type 302. It is used for aircraft springs.

*Stainless Type 17-7 PH ASTM A313* (17 per cent chromium, 7 per cent nickel): This alloy, which also contains small amounts of aluminum and titanium, is formed in a moderately hard state and then precipitation hardened at relatively low temperatures for several hours to produce tensile strengths nearly comparable to music wire. This material is not readily available in all sizes, and has limited applications due to its high manufacturing cost.

*Stainless Type 414, SAE 51414* (12 per cent chromium, 2 per cent nickel): This alloy has tensile strengths about 15 per cent lower than Type 302 and can be hardened by heat-treatment. For best corrosion resistance it should be highly polished or kept clean. It can be obtained hard drawn in diameters up to 0.1875 inch and is commonly used in flat cold-rolled strip for stampings. The material is not satisfactory for use at low temperatures.

*Stainless Type 420, SAE 51420* (13 per cent chromium): This is the best stainless steel for use in large diameters above 0.1875 inch and is frequently used in smaller sizes. It is formed in the annealed condition and then hardened and tempered. It does not exhibit its stainless properties until after it is hardened. Clean bright surfaces provide the best corrosion resistance, therefore the heat-treating scale must be removed. Bright hardening methods are preferred.

*Stainless Type 431, SAE 51431* (16 per cent chromium, 2 per cent nickel): This spring alloy acquires high tensile properties (nearly the same as music wire) by a combination of heat-treatment to harden the wire plus cold-drawing after heat-treatment. Its corrosion resistance is not equal to Type 302.

**Copper-Base Spring Alloys.**—Copper-base alloys are important spring materials because of their good electrical properties combined with their good resistance to corrosion. Although these materials are more expensive than the high-carbon and the alloy steels, they nevertheless are frequently used in electrical components and in sub-zero temperatures.

*Spring Brass, ASTM B 134* (70 per cent copper, 30 per cent zinc): This material is the least expensive and has the highest electrical conductivity of the copper-base alloys. It has a low tensile strength and poor spring qualities, but is extensively used in flat stampings and where sharp bends are needed. It cannot be hardened by heat-treatment and should not be used at temperatures above 150 degrees F., but is especially good at sub-zero temperatures. Available in round sections and flat strips, this hard-drawn material is usually used in the "spring hard" temper.

*Phosphor Bronze, ASTM B 159* (95 per cent copper, 5 per cent tin): This alloy is the most popular of this group because it combines the best qualities of tensile strength, hardness, electrical conductivity, and corrosion resistance with the least cost. It is more expensive than brass, but can withstand stresses 50 per cent higher. The material cannot be hardened by heat-treatment. It can be used at temperatures up to 212 degrees F. and at sub-zero temperatures. It is available in round sections and flat strip, usually in the "extra-hard" or "spring hard" tempers. It is frequently used for contact fingers in switches because of its low arcing properties. An 8 per cent tin composition is used for flat springs and a superfine grain composition called "Duraflex," has good endurance properties.

*Beryllium Copper, ASTM B 197* (98 per cent copper, 2 per cent beryllium): This alloy can be formed in the annealed condition and then precipitation hardened after forming at

temperatures around 600 degrees F, for 2 to 3 hours. This treatment produces a high hardness combined with a high tensile strength. After hardening, the material becomes quite brittle and can withstand very little or no forming. It is the most expensive alloy in the group and heat-treating is expensive due to the need for holding the parts in fixtures to prevent distortion. The principal use of this alloy is for carrying electric current in switches and in electrical components. Flat strip is frequently used for contact fingers.

**Nickel-Base Spring Alloys.**—Nickel-base alloys are corrosion resistant, withstand both elevated and sub-zero temperatures, and their non-magnetic characteristic makes them useful for such applications as gyroscopes, chronoscopes, and indicating instruments. These materials have a high electrical resistance and therefore should not be used for conductors of electrical current.

*Monel*\* (67 per cent nickel, 30 per cent copper): This material is the least expensive of the nickel-base alloys. It also has the lowest tensile strength but is useful due to its resistance to the corrosive effects of sea water and because it is nearly non-magnetic. The alloy can be subjected to stresses slightly higher than phosphor bronze and nearly as high as beryllium copper. Its high tensile strength and hardness are obtained as a result of cold-drawing and cold-rolling only, since it can not be hardened by heat-treatment. It can be used at temperatures ranging from -100 to +425 degrees F. at normal operating stresses and is available in round wires up to  $\frac{3}{16}$  inch in diameter with quite high tensile strengths. Larger diameters and flat strip are available with lower tensile strengths.

*"K" Monel*\* (66 per cent nickel, 29 per cent copper, 3 per cent aluminum): This material is quite similar to Monel except that the addition of the aluminum makes it a precipitation-hardening alloy. It may be formed in the soft or fairly hard condition and then hardened by a long-time age-hardening heat-treatment to obtain a tensile strength and hardness above Monel and nearly as high as stainless steel. It is used in sizes larger than those usually used with Monel, is non-magnetic and can be used in temperatures ranging from -100 to +450 degrees F. at normal working stresses under 45,000 pounds per square inch.

*Inconel*\* (78 per cent nickel, 14 per cent chromium, 7 per cent iron): This is one of the most popular of the non-magnetic nickel-base alloys because of its corrosion resistance and because it can be used at temperatures up to 700 degrees F. It is more expensive than stainless steel but less expensive than beryllium copper. Its hardness and tensile strength is higher than that of "K" Monel and is obtained as a result of cold-drawing and cold-rolling only. It cannot be hardened by heat treatment. Wire diameters up to  $\frac{1}{4}$  inch have the best tensile properties. It is often used in steam valves, regulating valves, and for springs in boilers, compressors, turbines, and jet engines.

*Inconel "X"*\* (70 per cent nickel, 16 per cent chromium, 7 per cent iron): This material is quite similar to Inconel but the small amounts of titanium, columbium and aluminum in its composition make it a precipitation-hardening alloy. It can be formed in the soft or partially hard condition and then hardened by holding it at 1200 degrees F. for 4 hours. It is non-magnetic and is used in larger sections than Inconel. This alloy is used at temperatures up to 850 degrees F. and at stresses up to 55,000 pounds per square inch.

*Duranickel*\* ("*Z*" Nickel) (98 per cent nickel): This alloy is non-magnetic, corrosion resistant, has a high tensile strength and is hardenable by precipitation hardening at 900 degrees F. for 6 hours. It may be used at the same stresses as Inconel but should not be used at temperatures above 500 degrees F.

**Nickel-Base Spring Alloys with Constant Moduli of Elasticity.**—Some special nickel alloys have a constant modulus of elasticity over a wide temperature range. These materials are especially useful where springs undergo temperature changes and must exhibit uniform spring characteristics. These materials have a low or zero thermo-elastic coefficient

\*Trade name of the International Nickel Company.

and therefore do not undergo variations in spring stiffness because of modulus changes due to temperature differentials. They also have low hysteresis and creep values which makes them preferred for use in food-weighing scales, precision instruments, gyroscopes, measuring devices, recording instruments and computing scales where the temperature ranges from  $-50$  to  $+150$  degrees F. These materials are expensive, none being regularly stocked in a wide variety of sizes. They should not be specified without prior discussion with spring manufacturers because some suppliers may not fabricate springs from these alloys due to the special manufacturing processes required. All of these alloys are used in small wire diameters and in thin strip only and are covered by U.S. patents. They are more specifically described as follows:

*Elinvar*\* (nickel, iron, chromium): This alloy, the first constant-modulus alloy used for hairsprings in watches, is an austenitic alloy hardened only by cold-drawing and cold-rolling. Additions of titanium, tungsten, molybdenum and other alloying elements have brought about improved characteristics and precipitation-hardening abilities. These improved alloys are known by the following trade names: Elinvar Extra, Durinval, Modular and Nivarox.

*Ni-Span C*\* (nickel, iron, chromium, titanium): This very popular constant-modulus alloy is usually formed in the 50 per cent cold-worked condition and precipitation-hardened at 900 degrees F. for 8 hours, although heating up to 1250 degrees F. for 3 hours produces hardnesses of 40 to 44 Rockwell C, permitting safe torsional stresses of 60,000 to 80,000 pounds per square inch. This material is ferromagnetic up to 400 degrees F; above that temperature it becomes non-magnetic.

*Iso-Elastic*† (nickel, iron, chromium, molybdenum): This popular alloy is relatively easy to fabricate and is used at safe torsional stresses of 40,000 to 60,000 pounds per square inch and hardnesses of 30 to 36 Rockwell C. It is used principally in dynamometers, instruments, and food-weighing scales.

*Elgiloy*‡ (nickel, iron, chromium, cobalt): This alloy, also known by the trade names 8J Alloy, Durapower, and Cobenium, is a non-magnetic alloy suitable for sub-zero temperatures and temperatures up to about 1000 degrees F., provided that torsional stresses are kept under 75,000 pounds per square inch. It is precipitation-hardened at 900 degrees F. for 8 hours to produce hardnesses of 48 to 50 Rockwell C. The alloy is used in watch and instrument springs.

*Dynavar*\*\* (nickel, iron, chromium, cobalt): This alloy is a non-magnetic, corrosion-resistant material suitable for sub-zero temperatures and temperatures up to about 750 degrees F., provided that torsional stresses are kept below 75,000 pounds per square inch. It is precipitation-hardened to produce hardnesses of 48 to 50 Rockwell C and is used in watch and instrument springs.

### Spring Stresses

**Allowable Working Stresses for Springs.**—The safe working stress for any particular spring depends to a large extent on the following items:

- 1) Type of spring — whether compression, extension, torsion, etc.
- 2) Size of spring — small or large, long or short
- 3) Spring material
- 4) Size of spring material
- 5) Type of service — light, average, or severe
- 6) Stress range — low, average, or high

\*Trade name of Soc. Anon. de Commentry Fourchambault et Decazeville, Paris, France.

†Trade name of John Chatillon & Sons.

‡Trade name of Elgin National Watch Company.

\*\*Trade name of Hamilton Watch Company.

- 7) Loading — static, dynamic, or shock
- 8) Operating temperature
- 9) Design of spring — spring index, sharp bends, hooks.

Consideration should also be given to other factors that affect spring life: corrosion, buckling, friction, and hydrogen embrittlement decrease spring life; manufacturing operations such as high-heat stress-equalizing, presetting, and shot-peening increase spring life.

Item 5, the type of service to which a spring is subjected, is a major factor in determining a safe working stress once consideration has been given to type of spring, kind and size of material, temperature, type of loading, and so on. The types of service are:

**Light Service:** This includes springs subjected to static loads or small deflections and seldom-used springs such as those in bomb fuses, projectiles, and safety devices. This service is for 1,000 to 10,000 deflections.

**Average Service:** This includes springs in general use in machine tools, mechanical products, and electrical components. Normal frequency of deflections not exceeding 18,000 per hour permit such springs to withstand 100,000 to 1,000,000 deflections.

**Severe Service:** This includes springs subjected to rapid deflections over long periods of time and to shock loading such as in pneumatic hammers, hydraulic controls and valves. This service is for 1,000,000 deflections, and above. Lowering the values 10 per cent permits 10,000,000 deflections.

Figs. 1 through 6 show curves that relate the three types of service conditions to allowable working stresses and wire sizes for compression and extension springs, and safe values are provided. Figs. 7 through 10 provide similar information for helical torsion springs. In each chart, the values obtained from the curves may be increased by 20 per cent (but not beyond the top curves on the charts if permanent set is to be avoided) for springs that are baked, and shot-peened, and compression springs that are pressed. Springs stressed slightly above the Light Service curves will take a permanent set.

A curvature correction factor is included in all curves, and is used in spring design calculations (see examples beginning page 321). The curves may be used for materials other than those designated in Figs. 1 through 10, by applying multiplication factors as given in Table 1.

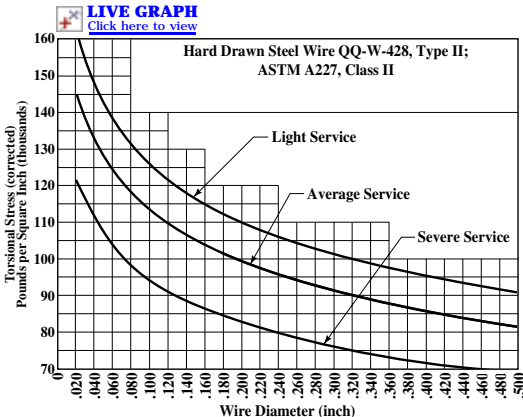
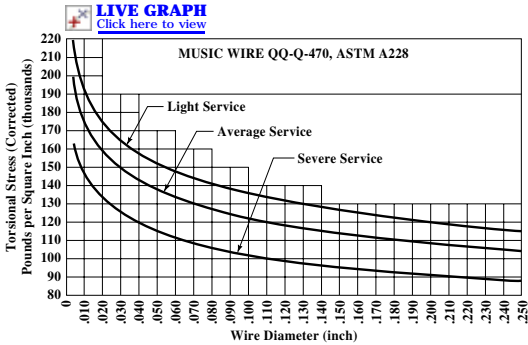
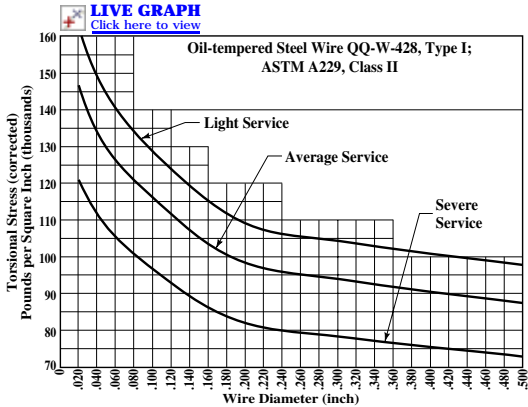
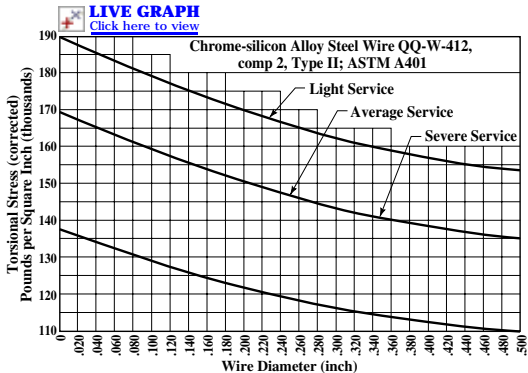


Fig. 1. Allowable Working Stresses for Compression Springs — Hard Drawn Steel Wire<sup>a</sup>

## STRESSES IN SPRINGS

Fig. 2. Allowable Working Stresses for Compression Springs — Music Wire<sup>a</sup>Fig. 3. Allowable Working Stresses for Compression Springs — Oil-Tempered<sup>a</sup>Fig. 4. Allowable Working Stresses for Compression Springs — Chrome-Silicon Alloy Steel Wire<sup>a</sup>  
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STRESSES IN SPRINGS

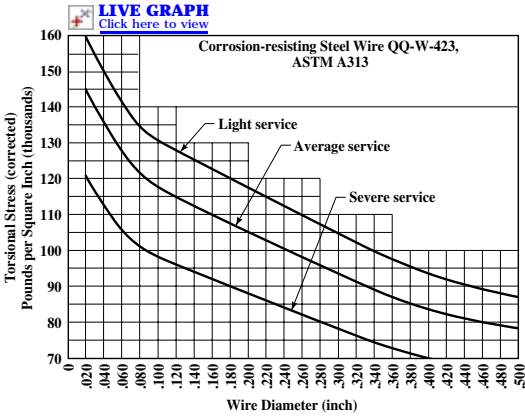


Fig. 5. Allowable Working Stresses for Compression Springs — Corrosion-Resisting Steel Wire<sup>a</sup>

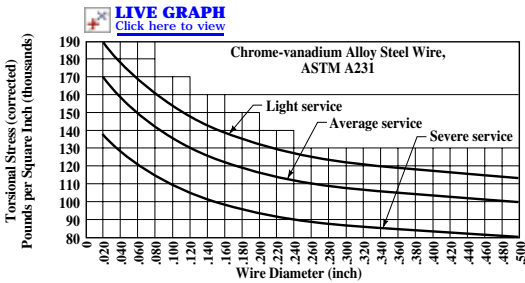


Fig. 6. Allowable Working Stresses for Compression Springs — Chrome-Vanadium Alloy Steel Wire<sup>a</sup>

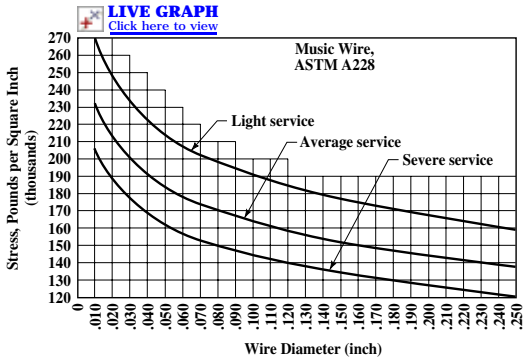


Fig. 7. Recommended Design Stresses in Bending for Helical Torsion Springs — Round Music Wire

## STRESSES IN SPRINGS

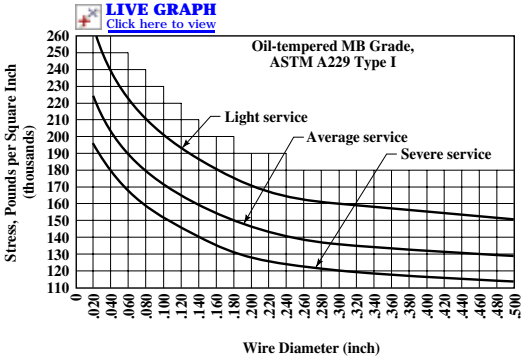


Fig. 8. Recommended Design Stresses in Bending for Helical Torsion Springs — Oil-Tempered MB Round Wire

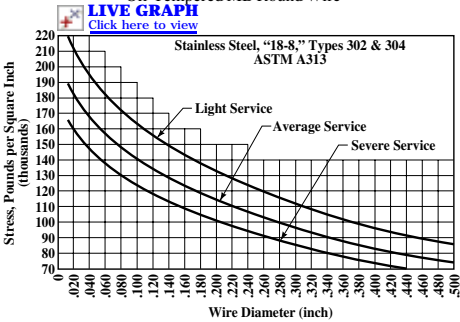


Fig. 9. Recommended Design Stresses in Bending for Helical Torsion Springs — Stainless Steel Round Wire

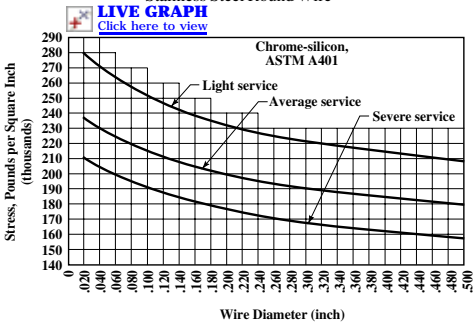


Fig. 10. Recommended Design Stresses in Bending for Helical Torsion Springs — Chrome-Silicon Round Wire

<sup>a</sup> Although Figs. 1 through 6 are for compression springs, they may also be used for extension springs; for extension springs, *reduce* the values obtained from the curves by 10 to 15 per cent.

**Table 1. Correction Factors for Other Materials**

| Compression and Tension Springs |  |                                 |  |
|---------------------------------|--|---------------------------------|--|
| Material                        | Factor   | Material                        | Factor   |
| Silicon-manganese               | Multiply the values in the chromium-vanadium curves (Fig. 6) by 0.90         | Stainless Steel, 316            | Multiply the values in the corrosion-resisting steel curves (Fig. 5) by 0.90 |
| Valve-spring quality wire       | Use the values in the chromium-vanadium curves (Fig. 6)                      |                                 |  |
| Stainless Steel, 304 and 420    | Multiply the values in the corrosion-resisting steel curves (Fig. 5) by 0.95 | Stainless Steel, 431 and 17-7PH | Multiply the values in the music wire curves (Fig. 2) by 0.90                |
| Helical Torsion Springs         |  |                                 |  |
| Material                        | Factor <sup>a</sup>  | Material                        | Factor <sup>a</sup>  |
| Hard Drawn MB                   | 0.70   | Stainless Steel, 431            |  |
| Stainless Steel, 316            |  | Up to 1/32 inch diameter        | 0.80   |
| Up to 1/32 inch diameter        | 0.75   | Over 1/32 to 1/16 inch          | 0.85   |
| Over 1/32 to 3/16 inch          | 0.70   | Over 1/16 to 1/8 inch           | 0.95   |
| Over 3/16 to 1/4 inch           | 0.65   | Over 1/8 inch                   | 1.00   |
| Over 1/4 inch                   | 0.50   | Chromium-Vanadium               |  |
| Stainless Steel, 17-7 PH        |  | Up to 1/16 inch diameter        | 1.05   |
| Up to 1/8 inch diameter         | 1.00   | Over 1/16 inch                  | 1.10   |
| Over 1/8 to 3/16 inch           | 1.07   | Phosphor Bronze                 |  |
| Over 3/16 inch                  | 1.12   | Up to 1/8 inch diameter         | 0.45   |
| Stainless Steel, 420            |  | Over 1/8 inch                   | 0.55   |
| Up to 1/32 inch diameter        | 0.70   | Beryllium Copper <sup>b</sup>   |  |
| Over 1/32 to 1/16 inch          | 0.75   | Up to 1/32 inch diameter        | 0.55   |
| Over 1/16 to 1/8 inch           | 0.80   | Over 1/32 to 1/16 inch          | 0.60   |
| Over 1/8 to 3/16 inch           | 0.90   | Over 1/16 to 1/8 inch           | 0.70   |
| Over 3/16 inch                  | 1.00   | Over 1/8 inch                   | 0.80   |

<sup>a</sup> Multiply the values in the curves for oil-tempered MB grade ASTM A229 Type 1 steel (Fig. 8) by these factors to obtain required values.

<sup>b</sup> Hard drawn and heat treated after coiling.

For use with design stress curves shown in Figs. 2, 5, 6, and 8.

**Endurance Limit for Spring Materials.**—When a spring is deflected continually it will become “tired” and fail at a stress far below its elastic limit. This type of failure is called *fatigue failure* and usually occurs without warning. *Endurance limit* is the highest stress, or range of stress, in pounds per square inch that can be repeated indefinitely without failure of the spring. Usually ten million cycles of deflection is called “infinite life” and is satisfactory for determining this limit.

For severely worked springs of long life, such as those used in automobile or aircraft engines and in similar applications, it is best to determine the allowable working stresses by referring to the endurance limit curves seen in Fig. 11. These curves are based principally upon the range or difference between the stress caused by the first or initial load and the stress caused by the final load. Experience with springs designed to stresses within the limits of these curves indicates that they should have infinite or unlimited fatigue life. All values include Wahl curvature correction factor. The stress ranges shown may be increased 20 to 30 per cent for springs that have been properly heated, pressed to remove set, and then shot peened, provided that the increased values are lower than the torsional elastic limit by at least 10 per cent.

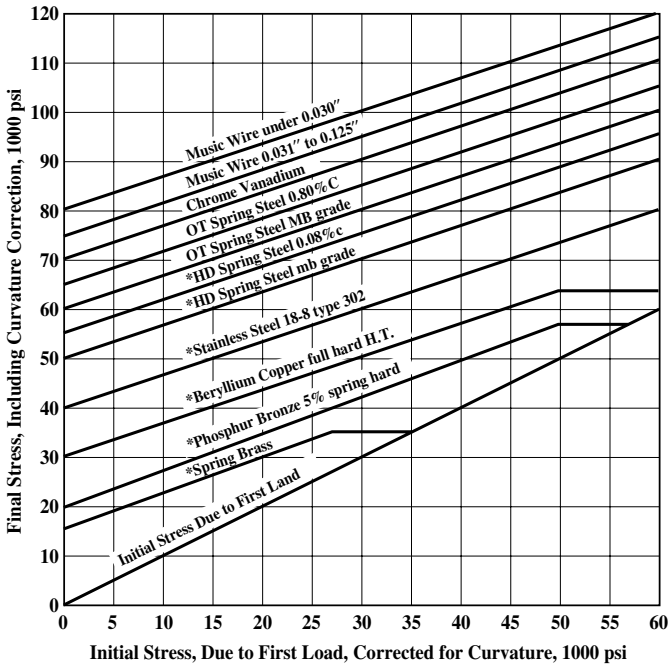


Fig. 11. Endurance Limit Curves for Compression Springs

*Notes:* For commercial spring materials with wire diameters up to  $\frac{1}{4}$  inch except as noted. Stress ranges may be increased by approximately 30 per cent for properly heated, preset, shot-peened springs.

Materials preceded by \* are not ordinarily recommended for long continued service under severe operating conditions.

**Working Stresses at Elevated Temperatures.**—Since modulus of elasticity decreases with increase in temperature, springs used at high temperatures exert less load and have larger deflections under load than at room temperature. The torsional modulus of elasticity for steel may be 11,200,000 pounds per square inch at room temperature, but it will drop to 10,600,000 pounds per square inch at 400°F. and will be only 10,000,000 pounds per square inch at 600°F. Also, the elastic limit is reduced, thereby lowering the permissible working stress.

Design stresses should be as low as possible for all springs used at elevated temperatures. In addition, corrosive conditions that usually exist at high temperatures, especially with steam, may require the use of corrosion-resistant material. Table 2 shows the permissible elevated temperatures at which various spring materials may be operated, together with the maximum recommended working stresses at these temperatures. The loss in load at the temperatures shown is less than 5 per cent in 48 hours; however, if the temperatures listed are increased by 20 to 40 degrees, the loss of load may be nearer 10 per cent. Maximum stresses shown in the table are for compression and extension springs and may be increased

by 75 per cent for torsion and flat springs. In using the data in Table 2 it should be noted that the values given are for materials in the heat-treated or spring temper condition.

**Table 2. Recommended Maximum Working Temperatures and Corresponding Maximum Working Stresses for Springs**

| Spring Material       | Max. Working Temp., °F | Max. Working Stress, psi | Spring Material              | Max. Working Temp., °F | Max. Working Stress, psi |
|-----------------------|------------------------|--------------------------|------------------------------|------------------------|--------------------------|
| Brass Spring Wire     | 150                    | 30,000                   | Permanickel <sup>a</sup>     | 500                    | 50,000                   |
| Phosphor Bronze       | 225                    | 35,000                   | Stainless Steel 18-8         | 550                    | 55,000                   |
| Music Wire            | 250                    | 75,000                   | Stainless Chromium 431       | 600                    | 50,000                   |
| Beryllium-Copper      | 300                    | 40,000                   | Inconel                      | 700                    | 50,000                   |
| Hard Drawn Steel Wire | 325                    | 50,000                   | High Speed Steel             | 775                    | 70,000                   |
| Carbon Spring Steels  | 375                    | 55,000                   | Inconel X                    | 850                    | 55,000                   |
| Alloy Spring Steels   | 400                    | 65,000                   | Chromium-Molybdenum-Vanadium | 900                    | 55,000                   |
| Monel                 | 425                    | 40,000                   | Cobenum, Elgiloy             | 1000                   | 75,000                   |
| K-Monel               | 450                    | 45,000                   |                              |                        |                          |

<sup>a</sup> Formerly called Z-Nickel, Type B.

Loss of load at temperatures shown is less than 5 per cent in 48 hours.

### Spring Design Data

**Spring Characteristics.**—This section provides tables of spring characteristics, tables of principal formulas, and other information of a practical nature for designing the more commonly used types of springs.

*Standard wire gages for springs:* Information on wire gages is given in the section beginning on page 2519, and gages in decimals of an inch are given in the table on page 2520. It should be noted that the range in this table extends from Number 7/0 through Number 80. However, in spring design, the range most commonly used extends only from Gage Number 4/0 through Number 40. When selecting wire use Steel Wire Gage or Washburn and Moen gage for all carbon steels and alloy steels except music wire; use Brown & Sharpe gage for brass and phosphor bronze wire; use Birmingham gage for flat spring steels, and cold rolled strip; and use piano or music wire gage for music wire.

*Spring index:* The spring index is the ratio of the mean coil diameter of a spring to the wire diameter ( $D/d$ ). This ratio is one of the most important considerations in spring design because the deflection, stress, number of coils, and selection of either annealed or tempered material depend to a considerable extent on this ratio. The best proportioned springs have an index of 7 through 9. Indexes of 4 through 7, and 9 through 16 are often used. Springs with values larger than 16 require tolerances wider than standard for manufacturing; those with values less than 5 are difficult to coil on automatic coiling machines.

*Direction of helix:* Unless functional requirements call for a definite hand, the helix of compression and extension springs should be specified as optional. When springs are designed to operate, one inside the other, the helices should be opposite hand to prevent intermeshing. For the same reason, a spring that is to operate freely over a threaded member should have a helix of opposite hand to that of the thread. When a spring is to engage with a screw or bolt, it should, of course, have the same helix as that of the thread.

**Helical Compression Spring Design.**—After selecting a suitable material and a safe stress value for a given spring, designers should next determine the type of end coil formation best suited for the particular application. Springs with unground ends are less expensive but they do not stand perfectly upright; if this requirement has to be met, closed ground ends are used. Helical compression springs with different types of ends are shown in Fig. 12.

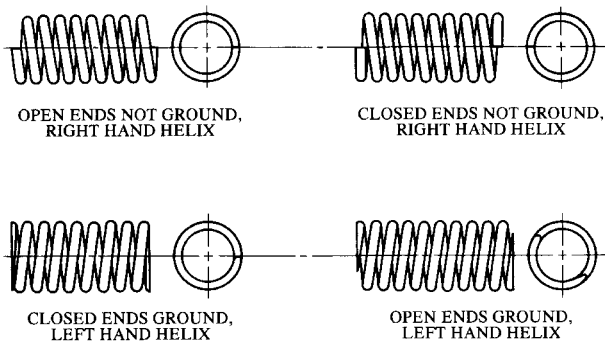


Fig. 12. Types of Helical Compression Spring Ends

*Spring design formulas:* Table 3 gives formulas for compression spring dimensional characteristics, and Table 4 gives design formulas for compression and extension springs.

*Curvature correction:* In addition to the stress obtained from the formulas for load or deflection, there is a direct shearing stress and an increased stress on the inside of the section due to curvature. Therefore, the stress obtained by the usual formulas should be multiplied by a factor  $K$  taken from the curve in Fig. 13. The corrected stress thus obtained is used only for comparison with the allowable working stress (fatigue strength) curves to determine if it is a safe stress and should not be used in formulas for deflection. The curvature correction factor  $K$  is for compression and extension springs made from round wire. For square wire reduce the  $K$  value by approximately 4 per cent.

*Design procedure:* The limiting dimensions of a spring are often determined by the available space in the product or assembly in which it is to be used. The loads and deflections on a spring may also be known or can be estimated, but the wire size and number of coils are usually unknown. Design can be carried out with the aid of the tabular data that appears later in this section (see Table 5, which is a simple method, or by calculation alone using the formulas in Tables 3 and 4.

*Example:* A compression spring with closed and ground ends is to be made from ASTM A229 high carbon steel wire, as shown in Fig. 14. Determine the wire size and number of coils.

*Method 1, using table:* Referring to Table 5, starting on page 325, locate the spring outside diameter ( $1\frac{3}{16}$  inches, from Fig. 14) in the left-hand column. Note from the drawing that the spring load is 36 pounds. Move to the right in the table to the figure nearest this value, which is 41.7 pounds. This is somewhat above the required value but safe. Immediately above the load value, the deflection  $f$  is given, which in this instance is 0.1594 inch. This is the deflection of one coil under a load of 41.7 pounds with an uncorrected torsional stress  $S$  of 100,000 pounds per square inch for ASTM A229 oil-tempered MB steel. For other spring materials, see the footnotes to Table 5 on page 325. Moving vertically in Table 5 from the load entry, the wire diameter is found to be 0.0915 inch.

The remaining spring design calculations are completed as follows:

*Step 1:* The stress with a load of 36 pounds is obtained by proportion, as follows: The 36 pound load is 86.3 per cent of the 41.7 pound load; therefore, the stress  $S$  at 36 pounds =  $0.863 \times 100,000 = 86,300$  pounds per square inch.

**Table 3. Formulas for Compression Springs**

| Feature                        | Type of End                    |                                    |                                   |                                   |
|--------------------------------|--------------------------------|------------------------------------|-----------------------------------|-----------------------------------|
|                                | Open or Plain (not ground)     | Open or Plain (with ends ground)   | Squared or Closed (not ground)    | Closed and Ground                 |
|                                | Formula <sup>a</sup>           |                                    |                                   |                                   |
| Pitch ( $p$ )                  | $\frac{FL-d}{N}$               | $\frac{FL}{TC}$                    | $\frac{FL-3d}{N}$                 | $\frac{FL-2d}{N}$                 |
| Solid Height (SH)              | $(TC+1)d$                      | $TC \times d$                      | $(TC+1)d$                         | $TC \times d$                     |
| Number of Active Coils ( $N$ ) | $N = TC$<br>$= \frac{FL-d}{p}$ | $N = TC-1$<br>$= \frac{FL}{p} - 1$ | $N = TC-2$<br>$= \frac{FL-3d}{p}$ | $N = TC-2$<br>$= \frac{FL-2d}{p}$ |
| Total Coils (TC)               | $\frac{FL-d}{p}$               | $\frac{FL}{p}$                     | $\frac{FL-3d}{p} + 2$             | $\frac{FL-2d}{p} + 2$             |
| Free Length (FL)               | $(p \times TC) + d$            | $p \times TC$                      | $(p \times N) + 3d$               | $(p \times N) + 2d$               |

<sup>a</sup>The symbol notation is given on page 308.

**Table 4. Formulas for Compression and Extension Springs**

| Feature  | Formula <sup>a, b</sup>                                 |  |
|--|---|--|
|  | Springs made from round wire                            | Springs made from square wire                            |
| Load, $P$<br>Pounds                              | $P = \frac{0.393Sd^3}{D} = \frac{Gd^4F}{8ND^3}$         | $P = \frac{0.416Sd^3}{D} = \frac{Gd^4F}{5.58ND^3}$       |
| Stress, Torsional, $S$<br>Pounds per square inch | $S = \frac{GdF}{\pi ND^2} = \frac{PD}{0.393d^3}$        | $S = \frac{GdF}{2.32ND^2} = P \frac{D}{0.416d^3}$        |
| Deflection, $F$<br>Inch                          | $F = \frac{8PND^3}{Gd^4} = \frac{\pi SND^2}{Gd}$        | $F = \frac{5.58PND^3}{Gd^4} = \frac{2.32SND^2}{Gd}$      |
| Number of Active Coils, $N$                      | $N = \frac{Gd^4F}{8PD^3} = \frac{GdF}{\pi SD^2}$        | $N = \frac{Gd^4F}{5.58PD^3} = \frac{GdF}{2.32SD^2}$      |
| Wire Diameter, $d$<br>Inch                       | $d = \frac{\pi SND^2}{GF} = \sqrt[3]{\frac{2.55PD}{S}}$ | $d = \frac{2.32SND^2}{GF} = \sqrt[3]{\frac{PD}{0.416S}}$ |
| Stress due to Initial Tension, $S_{it}$          | $S_{it} = \frac{S}{P} \times IT$                        | $S_{it} = \frac{S}{P} \times IT$                         |

<sup>a</sup>The symbol notation is given on page 308.

<sup>b</sup>Two formulas are given for each feature, and designers can use the one found to be appropriate for a given design. The end result from either of any two formulas is the same.

**Step 2:** The 86.3 per cent figure is also used to determine the deflection per coil  $f$  at 36 pounds load:  $0.863 \times 0.1594 = 0.1375$  inch.

**Step 3:** The number of active coils  $AC = \frac{F}{f} = \frac{1.25}{0.1375} = 9.1$

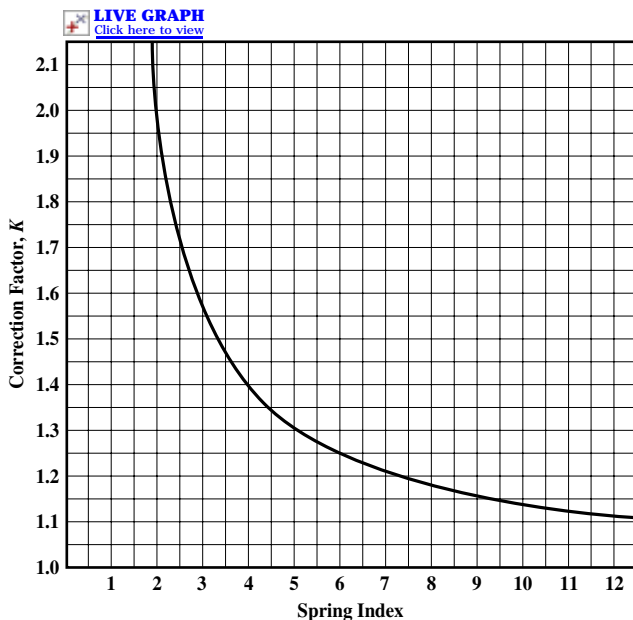


Fig. 13. Compression and Extension Spring-Stress Correction for Curvature<sup>a</sup>

<sup>a</sup> For springs made from round wire. For springs made from square wire, reduce the  $K$  factor values by approximately 4 per cent.

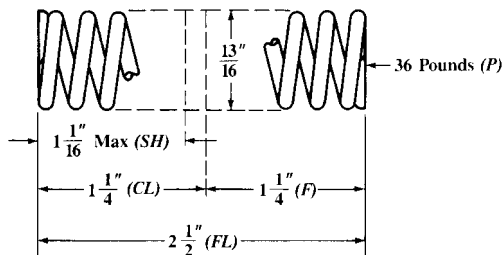


Fig. 14. Compression Spring Design Example

Step 4: Total Coils  $TC = AC + 2$  (Table 3) =  $9 + 2 = 11$

Therefore, a quick answer is: 11 coils of 0.0915 inch diameter wire. However, the design procedure should be completed by carrying out these remaining steps:

Step 5: From Table 3, Solid Height =  $SH = TC \times d = 11 \times 0.0915 \cong 1$  inch

Therefore, Total Deflection =  $FL - SH = 1.5$  inches



$$\text{Step 6: Stress Solid} = \frac{86,300}{1.25} \times 1.5 = 103,500 \text{ pounds per square inch}$$

$$\text{Step 7: Spring Index} = \frac{O.D.}{d} - 1 = \frac{0.8125}{0.0915} - 1 = 7.9$$

Step 8: From Fig. 13, the curvature correction factor  $K = 1.185$

Step 9: Total Stress at 36 pounds load =  $S \times K = 86,300 \times 1.185 = 102,300$  pounds per square inch. This stress is below the 117,000 pounds per square inch permitted for 0.0915 inch wire shown on the middle curve in Fig. 3, so it is a safe working stress.

Step 10: Total Stress at Solid =  $103,500 \times 1.185 = 122,800$  pounds per square inch. This stress is also safe, as it is below the 131,000 pounds per square inch shown on the top curve Fig. 3, and therefore the spring will not set.

*Method 2, using formulas:* The procedure for design using formulas is as follows (the design example is the same as in Method 1, and the spring is shown in Fig. 14):

Step 1: Select a safe stress  $S$  below the middle fatigue strength curve Fig. 8 for ASTM A229 steel wire, say 90,000 pounds per square inch. Assume a mean diameter  $D$  slightly below the  $\frac{13}{16}$ -inch  $O.D.$ , say 0.7 inch. Note that the value of  $G$  is 11,200,000 pounds per square inch (Table 20).

Step 2: A trial wire diameter  $d$  and other values are found by formulas from Table 4 as follows:

$$\begin{aligned} d &= \sqrt[3]{\frac{2.55PD}{S}} = \sqrt[3]{\frac{2.55 \times 36 \times 0.7}{90,000}} \\ &= \sqrt[3]{0.000714} = 0.0894 \text{ inch} \end{aligned}$$

Note: Table 21 can be used to avoid solving the cube root.

Step 3: From the table on page 2520, select the nearest wire gauge size, which is 0.0915 inch diameter. Using this value, the mean diameter  $D = \frac{13}{16}$  inch  $- 0.0915 = 0.721$  inch.

$$\text{Step 4: The stress } S = \frac{PD}{0.393d^3} = \frac{36 \times 0.721}{0.393 \times 0.0915^3} = 86,300 \text{ lb/in}^2$$

Step 5: The number of active coils is

$$N = \frac{GdF}{\pi SD^2} = \frac{11,200,000 \times 0.0915 \times 1.25}{3.1416 \times 86,300 \times 0.721^2} = 9.1 \text{ (say 9)}$$

The answer is the same as before, which is to use 11 total coils of 0.0915-inch diameter wire. The total coils, solid height, etc., are determined in the same manner as in Method 1.

**Table of Spring Characteristics.**—Table 5 gives characteristics for compression and extension springs made from ASTM A229 oil-tempered MB spring steel having a torsional modulus of elasticity  $G$  of 11,200,000 pounds per square inch, and an uncorrected torsional stress  $S$  of 100,000 pounds per square inch. The deflection  $f$  for one coil under a load  $P$  is shown in the body of the table. The method of using these data is explained in the problems for compression and extension spring design. The table may be used for other materials by applying factors to  $f$ . The factors are given in a footnote to the table.

Table 5. Compression and Extension Spring Deflections<sup>a</sup>

| Spring Outside Dia. |       | Wire Size or Washburn and Moen Gauge, and Decimal Equivalent <sup>b</sup>   |       |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |      |
|---------------------|-------|---|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|------|
|                     |       | .10   | .12   | .14    | .16    | .18    | .20    | .22    | .24    | .26    | .28    | .30    | .32    | .34    | .36    | .38    | .41    | .475   | .54    | .625 |
| Nom.                | Dec.  | Deflection <i>f</i> (inch) per coil, at Load <i>P</i> (pounds) <sup>c</sup> |       |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |      |
| 7/64                | .1094 | .0277   | .0222 | .01824 | .01529 | .01302 | .01121 | .00974 | .00853 | .00751 | .00664 | .00589 | ...    | ...    | ...    | ...    | ...    | ...    | ...    |      |
|                     |       | .395  | .697  | 1.130  | 1.722  | 2.51   | 3.52   | 4.79   | 6.36   | 8.28   | 10.59  | 13.35  | ...    | ...    | ...    | ...    | ...    | ...    | ...    | ...  |
| 1/8                 | .125  | .0371   | .0299 | .0247  | .0208  | .01784 | .01548 | .01353 | .01192 | .01058 | .00943 | .00844 | .00758 | .00683 | .00617 | ...    | ...    | ...    | ...    |      |
|                     |       | .342  | .600  | .971   | 1.475  | 2.14   | 2.99   | 4.06   | 5.37   | 6.97   | 8.89   | 11.16  | 13.83  | 16.95  | 20.6   | ...    | ...    | ...    | ...    | ...  |
| 9/64                | .1406 | .0478   | .0387 | .0321  | .0272  | .0234  | .0204  | .01794 | .01590 | .01417 | .01271 | .01144 | .01034 | .00937 | .00852 | .00777 | ...    | ...    | ...    |      |
|                     |       | .301  | .528  | .852   | 1.291  | 1.868  | 2.61   | 3.53   | 4.65   | 6.02   | 7.66   | 9.58   | 11.84  | 14.47  | 17.51  | 21.0   | ...    | ...    | ...    | ...  |
| 5/32                | .1563 | .0600   | .0487 | .0406  | .0345  | .0298  | .0261  | .0230  | .0205  | .01832 | .01649 | .01491 | .01354 | .01234 | .01128 | .01033 | .00909 | ...    | ...    |      |
|                     |       | .268  | .470  | .758   | 1.146  | 1.656  | 2.31   | 3.11   | 4.10   | 5.30   | 6.72   | 8.39   | 10.35  | 12.62  | 15.23  | 18.22  | 23.5   | ...    | ...    | ...  |
| 11/64               | .1719 | .0735   | .0598 | .0500  | .0426  | .0369  | .0324  | .0287  | .0256  | .0230  | .0208  | .01883 | .01716 | .01569 | .01439 | .01324 | .01172 | .00914 | ...    |      |
|                     |       | .243  | .424  | .683   | 1.031  | 1.488  | 2.07   | 2.79   | 3.67   | 4.73   | 5.99   | 7.47   | 9.19   | 11.19  | 13.48  | 16.09  | 21.8   | 33.8   | ...    | ...  |
| 3/16                | .1875 | .0884   | .0720 | .0603  | .0516  | .0448  | .0394  | .0349  | .0313  | .0281  | .0255  | .0232  | .0212  | .01944 | .01788 | .01650 | .01468 | .01157 | .00926 |      |
|                     |       | .221  | .387  | .621   | .938   | 1.351  | 1.876  | 2.53   | 3.32   | 4.27   | 5.40   | 6.73   | 8.27   | 10.05  | 12.09  | 14.41  | 18.47  | 30.07  | 46.3   | ...  |
| 13/64               | .2031 | .1046   | .0854 | .0717  | .0614  | .0534  | .0470  | .0418  | .0375  | .0338  | .0307  | .0280  | .0257  | .0236  | .0218  | .0201  | .01798 | .01430 | .01155 |      |
|                     |       | .203  | .355  | .570   | .859   | 1.237  | 1.716  | 2.31   | 3.03   | 3.90   | 4.92   | 6.12   | 7.52   | 9.13   | 10.96  | 13.05  | 16.69  | 27.1   | 41.5   | ...  |
| 7/32                | .2188 | ...   | .1000 | .0841  | .0721  | .0628  | .0555  | .0494  | .0444  | .0401  | .0365  | .0333  | .0306  | .0282  | .0260  | .0241  | .0216  | .01733 | .01411 |      |
|                     |       | ...   | .328  | .526   | .793   | 1.140  | 1.580  | 2.13   | 2.79   | 3.58   | 4.52   | 5.61   | 6.88   | 8.35   | 10.02  | 11.92  | 15.22  | 24.6   | 37.5   | 61.3 |
| 15/64               | .2344 | ...   | .1156 | .0974  | .0836  | .0730  | .0645  | .0575  | .0518  | .0469  | .0427  | .0391  | .0359  | .0331  | .0307  | .0285  | .0256  | .0206  | .01690 |      |
|                     |       | ...   | .305  | .489   | .736   | 1.058  | 1.465  | 1.969  | 2.58   | 3.21   | 4.18   | 5.19   | 6.35   | 7.70   | 9.23   | 10.97  | 13.99  | 22.5   | 34.3   | 55.8 |
| 1/4                 | .250  | ...   | ...   | .1116  | .0960  | .0839  | .0742  | .0663  | .0597  | .0541  | .0494  | .0453  | .0417  | .0385  | .0357  | .0332  | .0299  | .0242  | .01996 |      |
|                     |       | ...   | ...   | .457   | .687   | .987   | 1.366  | 1.834  | 2.40   | 3.08   | 3.88   | 4.82   | 5.90   | 7.14   | 8.56   | 10.17  | 12.95  | 20.8   | 31.6   | 51.1 |
| 9/32                | .2813 | ...   | ...   | .1432  | .1234  | .1080  | .0958  | .0857  | .0774  | .0703  | .0643  | .0591  | .0545  | .0505  | .0469  | .0437  | .0395  | .0323  | .0268  |      |
|                     |       | ...   | ...   | .403   | .606   | .870   | 1.202  | 1.613  | 2.11   | 2.70   | 3.40   | 4.22   | 5.16   | 6.24   | 7.47   | 8.86   | 11.26  | 18.01  | 27.2   | 43.8 |
| 5/16                | .3125 | ...   | ...   | ...    | .1541  | .1351  | .1200  | .1076  | .0973  | .0886  | .0811  | .0746  | .0690  | .0640  | .0596  | .0556  | .0504  | .0415  | .0347  |      |
|                     |       | ...   | ...   | ...    | .542   | .778   | 1.074  | 1.440  | 1.881  | 2.41   | 3.03   | 3.75   | 4.58   | 5.54   | 6.63   | 7.85   | 9.97   | 15.89  | 23.9   | 38.3 |
| 11/32               | .3438 | ...   | ...   | ...    | ...    | .1633  | .1470  | .1321  | .1196  | .1090  | .0999  | .0921  | .0852  | .0792  | .0733  | .0690  | .0627  | .0518  | .0436  |      |
|                     |       | ...   | ...   | ...    | ...    | .703   | .970   | 1.300  | 1.697  | 2.17   | 2.73   | 3.38   | 4.12   | 4.98   | 5.95   | 7.05   | 8.94   | 14.21  | 21.3   | 34.1 |
| 3/8                 | .375  | ...   | ...   | ...    | ...    | ...    | .1768  | .1589  | .1440  | .1314  | .1206  | .1113  | .1031  | .0960  | .0895  | .0839  | .0764  | .0634  | .0535  |      |
|                     |       | ...   | ...   | ...    | ...    | .885   | 1.185  | 1.546  | 1.978  | 2.48   | 3.07   | 3.75   | 4.53   | 5.40   | 6.40   | 8.10   | 12.85  | 19.27  | 30.7   |      |

<sup>a</sup>This table is for ASTM A229 oil tempered spring steel with a torsional modulus  $G$  of 11,200,000 psi, and an uncorrected torsional stress of 100,000 psi. For other materials use the following factors: stainless steel, multiply  $f$  by 1.067; spring brass, multiply  $f$  by 2.24; phosphor bronze, multiply  $f$  by 1.867; Monel metal, multiply  $f$  by 1.244; beryllium copper, multiply  $f$  by 1.725; Inconel (non-magnetic), multiply  $f$  by 1.045.

<sup>b</sup>Round wire. For square wire, multiply  $f$  by 0.707, and  $p$ , by 1.2

<sup>c</sup>The upper figure is the deflection and the lower figure the load as read against each spring size. *Note:* Intermediate values can be obtained within reasonable accuracy by interpolation.

Table 5. (Continued) Compression and Extension Spring Deflections<sup>a</sup>

| Spring Outside Dia. |       | Wire Size or Washburn and Moen Gauge, and Decimal Equivalent   |       |       |       |       |       |       |       |       |       |       |       |       |       |                |       |       |               |
|---------------------|-------|--|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------------|-------|-------|---------------|
|                     |       | .026   | .028  | .030  | .032  | .034  | .036  | .038  | .041  | .0475 | .054  | .0625 | .072  | .080  | .0915 | $\frac{3}{32}$ | .12   | .11   | $\frac{1}{8}$ |
| Nom.                | Dec.  | Deflection <i>f</i> (inch) per coil, at Load <i>P</i> (pounds) |       |       |       |       |       |       |       |       |       |       |       |       |       |                |       |       |               |
| $\frac{1}{32}$      | .4063 | .1560  | .1434 | .1324 | .1228 | .1143 | .1068 | .1001 | .0913 | .0760 | .0645 | .0531 | .0436 | .0373 | .0304 | .0292          | .0241 | ...   | ...           |
|                     |       | 1.815  | 2.28  | 2.82  | 3.44  | 4.15  | 4.95  | 5.85  | 7.41  | 11.73 | 17.56 | 27.9  | 43.9  | 61.6  | 95.6  | 103.7          | 153.3 | ...   | ...           |
| $\frac{7}{16}$      | .4375 | .1827  | .1680 | .1553 | .1441 | .1343 | .1256 | .1178 | .1075 | .0898 | .0764 | .0631 | .0521 | .0448 | .0367 | .0353          | .0293 | .0234 | .0219         |
|                     |       | 1.678  | 2.11  | 2.60  | 3.17  | 3.82  | 4.56  | 5.39  | 6.82  | 10.79 | 16.13 | 25.6  | 40.1  | 56.3  | 86.9  | 94.3           | 138.9 | 217.  | 245.          |
| $\frac{1}{8}$       | .4688 | .212   | .1947 | .1800 | .1673 | .1560 | .1459 | .1370 | .1252 | .1048 | .0894 | .0741 | .0614 | .0530 | .0437 | .0420          | .0351 | .0282 | .0265         |
|                     |       | 1.559  | 1.956 | 2.42  | 2.94  | 3.55  | 4.23  | 5.00  | 6.33  | 9.99  | 14.91 | 23.6  | 37.0  | 51.7  | 79.7  | 86.4           | 126.9 | 197.3 | 223.          |
| $\frac{1}{2}$       | .500  | .243   | .223  | .207  | .1920 | .1792 | .1678 | .1575 | .1441 | .1209 | .1033 | .0859 | .0714 | .0619 | .0512 | .0494          | .0414 | .0335 | .0316         |
|                     |       | 1.456  | 1.826 | 2.26  | 2.75  | 3.31  | 3.95  | 4.67  | 5.90  | 9.30  | 13.87 | 21.9  | 34.3  | 47.9  | 73.6  | 80.0           | 116.9 | 181.1 | 205.          |
| $\frac{11}{32}$     | .5313 | .276   | .254  | .235  | .219  | .204  | .1911 | .1796 | .1645 | .1382 | .1183 | .0987 | .0822 | .0714 | .0593 | .0572          | .0482 | .0393 | .0371         |
|                     |       | 1.366  | 1.713 | 2.12  | 2.58  | 3.10  | 3.70  | 4.37  | 5.52  | 8.70  | 12.96 | 20.5  | 31.9  | 44.6  | 68.4  | 74.1           | 108.3 | 167.3 | 188.8         |
| $\frac{9}{16}$      | .5625 | ...  | .286  | .265  | .247  | .230  | .216  | .203  | .1861 | .1566 | .1343 | .1122 | .0937 | .0816 | .0680 | .0657          | .0555 | .0455 | .0430         |
|                     |       | ...  | 1.613 | 1.991 | 2.42  | 2.92  | 3.48  | 4.11  | 5.19  | 8.18  | 12.16 | 19.17 | 29.9  | 41.7  | 63.9  | 69.1           | 100.9 | 155.5 | 175.3         |
| $\frac{19}{32}$     | .5938 | ...  | ...   | .297  | .277  | .259  | .242  | .228  | .209  | .1762 | .1514 | .1267 | .1061 | .0926 | .0774 | .0748          | .0634 | .0522 | .0493         |
|                     |       | ...  | ...   | 1.880 | 2.29  | 2.76  | 3.28  | 3.88  | 4.90  | 7.71  | 11.46 | 18.04 | 28.1  | 39.1  | 60.0  | 64.8           | 94.4  | 145.2 | 163.6         |
| $\frac{5}{8}$       | .625  | ...  | ...   | .331  | .308  | .288  | .270  | .254  | .233  | .1969 | .1693 | .1420 | .1191 | .1041 | .0873 | .0844          | .0718 | .0593 | .0561         |
|                     |       | ...  | ...   | 1.782 | 2.17  | 2.61  | 3.11  | 3.67  | 4.63  | 7.29  | 10.83 | 17.04 | 26.5  | 36.9  | 56.4  | 61.0           | 88.7  | 136.2 | 153.4         |
| $\frac{21}{32}$     | .6563 | ...  | ...   | ...   | .342  | .320  | .300  | .282  | .259  | .219  | .1884 | .1582 | .1330 | .1164 | .0978 | .0946          | .0807 | .0668 | .0634         |
|                     |       | ...  | ...   | ...   | 2.06  | 2.48  | 2.95  | 3.49  | 4.40  | 6.92  | 10.27 | 16.14 | 25.1  | 34.9  | 53.3  | 57.6           | 83.7  | 128.3 | 144.3         |
| $\frac{11}{16}$     | .6875 | ...  | ...   | ...   | ...   | .352  | .331  | .311  | .286  | .242  | .208  | .1753 | .1476 | .1294 | .1089 | .1054          | .0901 | .0748 | .0710         |
|                     |       | ...  | ...   | ...   | ...   | 2.36  | 2.81  | 3.32  | 4.19  | 6.58  | 9.76  | 15.34 | 23.8  | 33.1  | 50.5  | 54.6           | 79.2  | 121.2 | 136.3         |
| $\frac{23}{32}$     | .7188 | ...  | ...   | ...   | ...   | ...   | .363  | .342  | .314  | .266  | .230  | .1933 | .1630 | .1431 | .1206 | .1168          | .1000 | .0833 | .0791         |
|                     |       | ...  | ...   | ...   | ...   | ...   | 2.68  | 3.17  | 3.99  | 6.27  | 9.31  | 14.61 | 22.7  | 31.5  | 48.0  | 51.9           | 75.2  | 114.9 | 129.2         |
| $\frac{3}{4}$       | .750  | ...  | ...   | ...   | ...   | ...   | ...   | .374  | .344  | .291  | .252  | .212  | .1791 | .1574 | .1329 | .1288          | .1105 | .0923 | .0877         |
|                     |       | ...  | ...   | ...   | ...   | ...   | ...   | 3.03  | 3.82  | 5.99  | 8.89  | 13.94 | 21.6  | 30.0  | 45.7  | 49.4           | 71.5  | 109.2 | 122.7         |
| $\frac{25}{32}$     | .7813 | ...  | ...   | ...   | ...   | ...   | ...   | ...   | .375  | .318  | .275  | .232  | .1960 | .1724 | .1459 | .1413          | .1214 | .1017 | .0967         |
|                     |       | ...  | ...   | ...   | ...   | ...   | ...   | ...   | 3.66  | 5.74  | 8.50  | 13.34 | 20.7  | 28.7  | 43.6  | 47.1           | 68.2  | 104.0 | 116.9         |
| $\frac{13}{16}$     | .8125 | ...  | ...   | ...   | ...   | ...   | ...   | ...   | .407  | .346  | .299  | .253  | .214  | .1881 | .1594 | .1545          | .1329 | .1115 | .1061         |
|                     |       | ...  | ...   | ...   | ...   | ...   | ...   | ...   | 3.51  | 5.50  | 8.15  | 12.78 | 19.80 | 27.5  | 41.7  | 45.1           | 65.2  | 99.3  | 111.5         |

<sup>a</sup>This table is for ASTM A229 oil tempered spring steel with a torsional modulus *G* of 11,200,000 psi, and an uncorrected torsional stress of 100,000 psi. For other materials, and other important footnotes, see page 325.

Table 5. (Continued) Compression and Extension Spring Deflections<sup>a</sup>

| Spring<br>Outside<br>Dia. |       | Wire Size or Washburn and Moen Gauge, and Decimal Equivalent |       |       |                |       |       |               |       |       |                |       |       |                |       |       |               |       |
|---------------------------|-------|--|-------|-------|----------------|-------|-------|---------------|-------|-------|----------------|-------|-------|----------------|-------|-------|---------------|-------|
|                           |       | 15   | 14    | 13    | $\frac{3}{32}$ | 12    | 11    | $\frac{1}{8}$ | 10    | 9     | $\frac{7}{32}$ | 8     | 7     | $\frac{3}{16}$ | 6     | 5     | $\frac{1}{2}$ | 4     |
|                           |       | .072   | .080  | .0915 | .0938          | .1055 | .1205 | .125          | .135  | .1483 | .1563          | .162  | .177  | .1875          | .192  | .207  | .2188         | .2253 |
| Nom.                      | Dec.  | Deflection $f$ (inch) per coil, at Load $P$ (pounds)         |       |       |                |       |       |               |       |       |                |       |       |                |       |       |               |       |
| $\frac{7}{8}$             | .875  | .251   | .222  | .1882 | .1825          | .1574 | .1325 | .1262         | .1138 | .0999 | .0928          | .0880 | .0772 | .0707          | .0682 | .0605 | .0552         | .0526 |
|                           |       | 18.26  | 25.3  | 39.4  | 41.5           | 59.9  | 91.1  | 102.3         | 130.5 | 176.3 | 209.           | 234.  | 312.  | 377.           | 407.  | 521.  | 626.          | 691.  |
| $\frac{29}{32}$           | .9063 | .271   | .239  | .204  | .1974          | .1705 | .1438 | .1370         | .1236 | .1087 | .1010          | .0959 | .0843 | .0772          | .0746 | .0663 | .0606         | .0577 |
|                           |       | 17.57  | 24.3  | 36.9  | 39.9           | 57.6  | 87.5  | 98.2          | 125.2 | 169.0 | 199.9          | 224.  | 299.  | 360.           | 389.  | 498.  | 598.          | 660.  |
| $\frac{15}{16}$           | .9375 | .292   | .258  | .219  | .213           | .1841 | .1554 | .1479         | .1338 | .1178 | .1096          | .1041 | .0917 | .0842          | .0812 | .0723 | .0662         | .0632 |
|                           |       | 16.94  | 23.5  | 35.6  | 38.4           | 55.4  | 84.1  | 94.4          | 120.4 | 162.3 | 191.9          | 215.  | 286.  | 345.           | 373.  | 477.  | 572.          | 631.  |
| $\frac{3}{32}$            | .9688 | .313   | .277  | .236  | .229           | .1982 | .1675 | .1598         | .1445 | .1273 | .1183          | .1127 | .0994 | .0913          | .0882 | .0786 | .0721         | .0688 |
|                           |       | 16.35  | 22.6  | 34.3  | 37.0           | 53.4  | 81.0  | 90.9          | 115.9 | 156.1 | 184.5          | 207.  | 275.  | 332.           | 358.  | 457.  | 548.          | 604.  |
| 1                         | 1.000 | .336   | .297  | .253  | .246           | .213  | .1801 | .1718         | .1555 | .1372 | .1278          | .1216 | .1074 | .0986          | .0954 | .0852 | .0783         | .0747 |
|                           |       | 15.80  | 21.9  | 33.1  | 35.8           | 51.5  | 78.1  | 87.6          | 111.7 | 150.4 | 177.6          | 198.8 | 264.  | 319.           | 344.  | 439.  | 526.          | 580.  |
| $1\frac{1}{32}$           | 1.031 | .359   | .317  | .271  | .263           | .228  | .1931 | .1843         | .1669 | .1474 | .1374          | .1308 | .1157 | .1065          | .1029 | .0921 | .0845         | .0809 |
|                           |       | 15.28  | 21.1  | 32.0  | 34.6           | 49.8  | 75.5  | 84.6          | 107.8 | 145.1 | 171.3          | 191.6 | 255.  | 307.           | 331.  | 423.  | 506.          | 557.  |
| $1\frac{1}{16}$           | 1.063 | .382   | .338  | .289  | .281           | .244  | .207  | .1972         | .1788 | .1580 | .1474          | .1404 | .1243 | .1145          | .1107 | .0993 | .0913         | .0873 |
|                           |       | 14.80  | 20.5  | 31.0  | 33.5           | 48.2  | 73.0  | 81.8          | 104.2 | 140.1 | 165.4          | 185.0 | 246.  | 296.           | 319.  | 407.  | 487.          | 537.  |
| $1\frac{1}{32}$           | 1.094 | .407   | .360  | .308  | .299           | .260  | .221  | .211          | .1910 | .1691 | .1578          | .1503 | .1332 | .1229          | .1188 | .1066 | .0982         | .0939 |
|                           |       | 14.34  | 19.83 | 30.0  | 32.4           | 46.7  | 70.6  | 79.2          | 100.8 | 135.5 | 159.9          | 178.8 | 238.  | 286.           | 308.  | 393.  | 470.          | 517.  |
| $1\frac{1}{8}$            | 1.125 | .432   | .383  | .328  | .318           | .277  | .235  | .224          | .204  | .1804 | .1685          | .1604 | .1424 | .1315          | .1272 | .1142 | .1053         | .1008 |
|                           |       | 13.92  | 19.24 | 29.1  | 31.4           | 45.2  | 68.4  | 76.7          | 97.6  | 131.2 | 154.7          | 173.0 | 230.  | 276.           | 298.  | 379.  | 454.          | 499.  |
| $1\frac{3}{16}$           | 1.188 | .485   | .431  | .368  | .358           | .311  | .265  | .254          | .231  | .204  | .1908          | .1812 | .1620 | .1496          | .1448 | .1303 | .1203         | .1153 |
|                           |       | 13.14  | 18.15 | 27.5  | 29.6           | 42.6  | 64.4  | 72.1          | 91.7  | 123.3 | 145.4          | 162.4 | 215.  | 259.           | 279.  | 355.  | 424.          | 467.  |
| $1\frac{1}{4}$            | 1.250 | .541   | .480  | .412  | .400           | .349  | .297  | .284          | .258  | .230  | .215           | .205  | .1824 | .1690          | .1635 | .1474 | .1363         | .1308 |
|                           |       | 12.44  | 17.19 | 26.0  | 28.0           | 40.3  | 60.8  | 68.2          | 86.6  | 116.2 | 137.0          | 153.1 | 203.  | 244.           | 263.  | 334.  | 399.          | 438.  |
| $1\frac{3}{16}$           | 1.313 | .600   | .533  | .457  | .444           | .387  | .331  | .317          | .288  | .256  | .240           | .229  | .205  | .1894          | .1836 | .1657 | .1535         | .1472 |
|                           |       | 11.81  | 16.31 | 24.6  | 26.6           | 38.2  | 57.7  | 64.6          | 82.0  | 110.1 | 129.7          | 144.7 | 191.6 | 230.           | 248.  | 315.  | 376.          | 413.  |
| $1\frac{3}{8}$            | 1.375 | .662   | .588  | .506  | .491           | .429  | .367  | .351          | .320  | .285  | .267           | .255  | .227  | .211           | .204  | .1848 | .1713         | .1650 |
|                           |       | 11.25  | 15.53 | 23.4  | 25.3           | 36.3  | 54.8  | 61.4          | 77.9  | 104.4 | 123.0          | 137.3 | 181.7 | 218.           | 235.  | 298.  | 356.          | 391   |
| $1\frac{7}{16}$           | 1.438 | .727   | .647  | .556  | .540           | .472  | .404  | .387          | .353  | .314  | .295           | .282  | .252  | .234           | .227  | .205  | .1905         | .1829 |
|                           |       | 10.73  | 14.81 | 22.3  | 24.1           | 34.6  | 52.2  | 58.4          | 74.1  | 99.4  | 117.0          | 130.6 | 172.6 | 207.           | 223.  | 283.  | 337.          | 371.  |

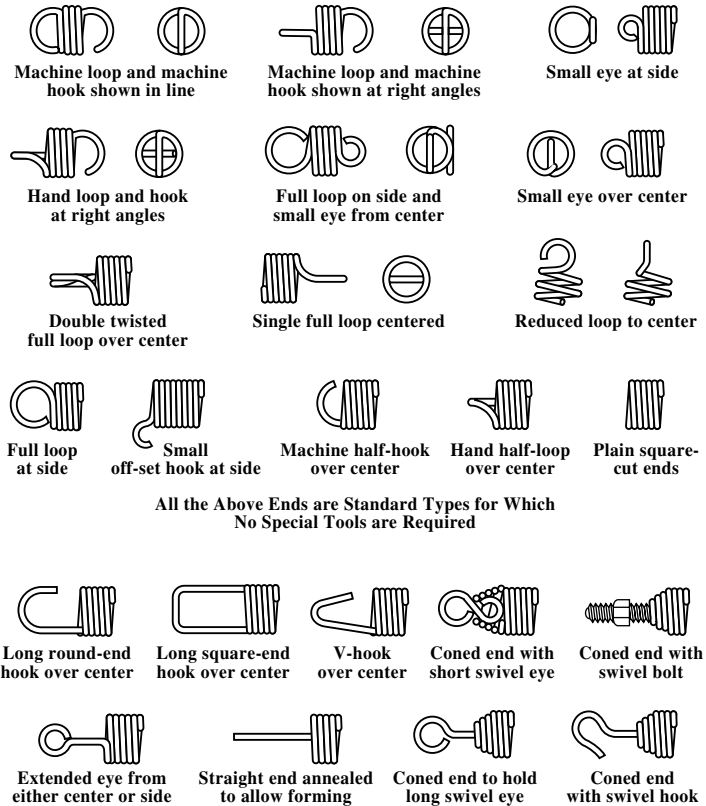
<sup>a</sup>This table is for ASTM A229 oil tempered spring steel with a torsional modulus  $G$  of 11,200,000 psi, and an uncorrected torsional stress of 100,000 psi. For other materials, and other important footnotes, see page 325.

Table 5. (Continued) Compression and Extension Spring Deflections<sup>a</sup>

| Spring<br>Outside<br>Dia.      |       | Wire Size or Washburn and Moen Gauge, and Decimal Equivalent |               |       |       |                |       |       |                |       |       |                |       |       |               |       |                |       |                |
|--------------------------------|-------|--|---------------|-------|-------|----------------|-------|-------|----------------|-------|-------|----------------|-------|-------|---------------|-------|----------------|-------|----------------|
|                                |       | 11   | $\frac{1}{8}$ | 10    | 9     | $\frac{7}{32}$ | 8     | 7     | $\frac{5}{16}$ | 6     | 5     | $\frac{3}{16}$ | 4     | 3     | $\frac{1}{4}$ | 2     | $\frac{5}{32}$ | 0     | $\frac{1}{16}$ |
|                                |       | .1205  | .125          | .135  | .1483 | .1563          | .162  | .177  | .1875          | .192  | .207  | .2188          | .2253 | .2437 | .250          | .2625 | .2813          | .3065 | .3125          |
| Nom.                           | Dec.  | Deflection $f$ (inch) per coil, at Load $P$ (pounds)         |               |       |       |                |       |       |                |       |       |                |       |       |               |       |                |       |                |
| 1½                             | 1.500 | .443   | .424          | .387  | .350  | .324           | .310  | .277  | .258           | .250  | .227  | .210           | .202  | .1815 | .1754         | .1612 | .1482          | .1305 | .1267          |
|                                |       | 49.8   | 55.8          | 70.8  | 94.8  | 111.5          | 124.5 | 164.6 | 197.1          | 213.  | 269.  | 321.           | 352.  | 452.  | 499.          | 574.  | 717.           | 947.  | 1008.          |
| 1⅝                             | 1.625 | .527   | .505          | .461  | .413  | .387           | .370  | .332  | .309           | .300  | .273  | .254           | .244  | .220  | .212          | .1986 | .1801          | .1592 | .1547          |
|                                |       | 45.7   | 51.1          | 64.8  | 86.7  | 102.0          | 113.9 | 150.3 | 180.0          | 193.9 | 246.  | 292.           | 321.  | 411.  | 446.          | 521.  | 650.           | 858.  | 912.           |
| 1¾                             | 1.750 | .619   | .593          | .542  | .485  | .456           | .437  | .392  | .366           | .355  | .323  | .301           | .290  | .261  | .253          | .237  | .215           | .1908 | .1856          |
|                                |       | 42.2   | 47.2          | 59.8  | 80.0  | 94.0           | 104.9 | 138.5 | 165.6          | 178.4 | 226.  | 269.           | 295.  | 377.  | 409.          | 477.  | 595.           | 783.  | 833.           |
| 1⅞                             | 1.875 | .717   | .687          | .629  | .564  | .530           | .508  | .457  | .426           | .414  | .377  | .351           | .339  | .306  | .296          | .278  | .253           | .225  | .219           |
|                                |       | 39.2   | 43.8          | 55.5  | 74.2  | 87.2           | 97.3  | 128.2 | 153.4          | 165.1 | 209.  | 248.           | 272.  | 348.  | 378.          | 440.  | 548.           | 721.  | 767.           |
| 1 <sup>5</sup> / <sub>16</sub> | 1.938 | .769   | .738          | .676  | .605  | .569           | .546  | .492  | .458           | .446  | .405  | .379           | .365  | .331  | .320          | .300  | .273           | .243  | .237           |
|                                |       | 37.8   | 42.3          | 53.6  | 71.6  | 84.2           | 93.8  | 123.6 | 147.9          | 159.2 | 201.  | 239.           | 262.  | 335.  | 364.          | 425.  | 528.           | 693.  | 737.           |
| 2                              | 2.000 | .823   | .789          | .723  | .649  | .610           | .585  | .527  | .492           | .478  | .436  | .407           | .392  | .355  | .344          | .323  | .295           | .263  | .256           |
|                                |       | 36.6   | 40.9          | 51.8  | 69.2  | 81.3           | 90.6  | 119.4 | 142.8          | 153.7 | 194.3 | 231.           | 253.  | 324.  | 351.          | 409.  | 509.           | 668.  | 710.           |
| 2 <sup>1</sup> / <sub>16</sub> | 2.063 | .878   | .843          | .768  | .693  | .652           | .626  | .564  | .526           | .512  | .467  | .436           | .421  | .381  | .369          | .346  | .316           | .282  | .275           |
|                                |       | 35.4   | 39.6          | 50.1  | 66.9  | 78.7           | 87.6  | 115.4 | 138.1          | 148.5 | 187.7 | 223.           | 245.  | 312.  | 339.          | 395.  | 491.           | 644.  | 685.           |
| 2 <sup>1</sup> / <sub>8</sub>  | 2.125 | .936   | .898          | .823  | .739  | .696           | .667  | .602  | .562           | .546  | .499  | .466           | .449  | .407  | .395          | .371  | .339           | .303  | .295           |
|                                |       | 34.3   | 38.3          | 48.5  | 64.8  | 76.1           | 84.9  | 111.8 | 133.6          | 143.8 | 181.6 | 216.           | 236.  | 302.  | 327.          | 381.  | 474.           | 622.  | 661.           |
| 2 <sup>3</sup> / <sub>16</sub> | 2.188 | .995   | .955          | .876  | .786  | .740           | .711  | .641  | .598           | .582  | .532  | .497           | .479  | .435  | .421          | .396  | .362           | .324  | .316           |
|                                |       | 33.3   | 37.2          | 47.1  | 62.8  | 73.8           | 82.2  | 108.3 | 129.5          | 139.2 | 175.8 | 209.           | 229.  | 292.  | 317.          | 369.  | 459.           | 601.  | 639.           |
| 2¼                             | 2.250 | 1.056  | 1.013         | .930  | .835  | .787           | .755  | .681  | .637           | .619  | .566  | .529           | .511  | .463  | .449          | .423  | .387           | .346  | .337           |
|                                |       | 32.3   | 36.1          | 45.7  | 60.9  | 71.6           | 79.8  | 105.7 | 125.5          | 135.0 | 170.5 | 202.           | 222.  | 283.  | 307.          | 357.  | 444.           | 582.  | 618.           |
| 2 <sup>5</sup> / <sub>16</sub> | 2.313 | 1.119  | 1.074         | .986  | .886  | .834           | .801  | .723  | .676           | .657  | .601  | .562           | .542  | .493  | .478          | .449  | .411           | .368  | .359           |
|                                |       | 31.4   | 35.1          | 44.4  | 59.2  | 69.5           | 77.5  | 101.9 | 121.8          | 131.0 | 165.4 | 196.3          | 215.  | 275.  | 298.          | 347.  | 430.           | 564.  | 599.           |
| 2⅝                             | 2.375 | 1.184  | 1.136         | 1.043 | .938  | .884           | .848  | .763  | .716           | .696  | .637  | .596           | .576  | .523  | .507          | .477  | .437           | .392  | .382           |
|                                |       | 30.5   | 34.1          | 43.1  | 57.5  | 67.6           | 75.3  | 99.1  | 118.3          | 127.3 | 160.7 | 190.7          | 209.  | 267.  | 289.          | 336.  | 417.           | 547.  | 581.           |
| 2 <sup>7</sup> / <sub>16</sub> | 2.438 | ...  | 1.201         | 1.102 | .991  | .934           | .897  | .810  | .757           | .737  | .674  | .631           | .609  | .554  | .537          | .506  | .464           | .416  | .405           |
|                                |       | ...  | 33.2          | 42.0  | 56.0  | 65.7           | 73.2  | 96.3  | 115.1          | 123.7 | 156.1 | 185.3          | 203.  | 259.  | 281.          | 327.  | 405.           | 531.  | 564.           |
| 2½                             | 2.500 | ...  | 1.266         | 1.162 | 1.046 | .986           | .946  | .855  | .800           | .778  | .713  | .667           | .644  | .586  | .568          | .536  | .491           | .441  | .430           |
|                                |       | ...  | 32.3          | 40.9  | 54.5  | 64.0           | 71.3  | 93.7  | 111.6          | 120.4 | 151.9 | 180.2          | 197.5 | 252.  | 273.          | 317.  | 394.           | 516.  | 548.           |

<sup>a</sup>This table is for ASTM A229 oil tempered spring steel with a torsional modulus  $G$  of 11,200,000 psi, and an uncorrected torsional stress of 100,000 psi. For other materials, and other important footnotes, see page 325.

**Extension Springs.**—About 10 per cent of all springs made by many companies are of this type, and they frequently cause trouble because insufficient consideration is given to stress due to initial tension, stress and deflection of hooks, special manufacturing methods, secondary operations and overstretching at assembly. Fig. 15 shows types of ends used on these springs.



**This Group of Special Ends Requires Special Tools**

Fig. 15. Types of Helical Extension Spring Ends

*Initial tension:* In the spring industry, the term "Initial tension" is used to define a force or load, measurable in pounds or ounces, which presses the coils of a close wound extension spring against one another. This force must be overcome before the coils of a spring begin to open up.

Initial tension is wound into extension springs by bending each coil as it is wound away from its normal plane, thereby producing a slight twist in the wire which causes the coil to spring back tightly against the adjacent coil. Initial tension can be wound into cold-coiled

## SPRING DESIGN

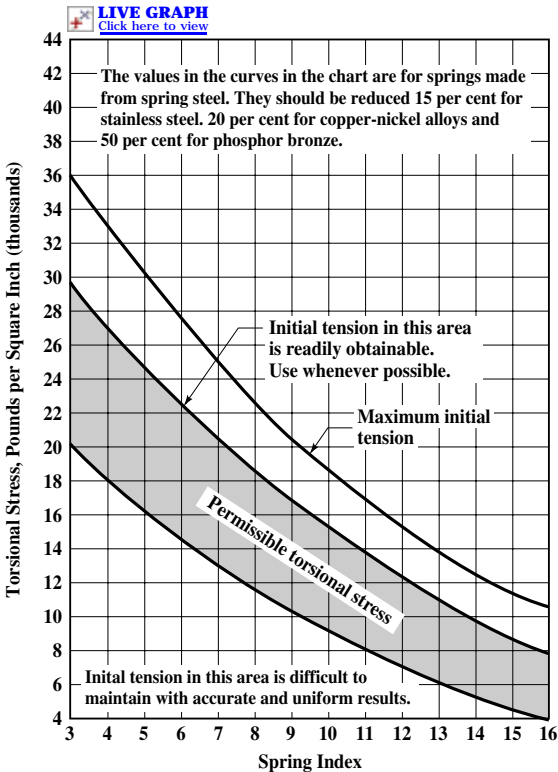


Fig. 16. Permissible Torsional Stress Caused by Initial Tension in Coiled Extension Springs for Different Spring Indexes

extension springs only. Hot-wound springs and springs made from annealed steel are hardened and tempered after coiling, and therefore initial tension cannot be produced. It is possible to make a spring having initial tension only when a high tensile strength, obtained by cold drawing or by heat-treatment, is possessed by the material as it is being wound into springs. Materials that possess the required characteristics for the manufacture of such springs include hard-drawn wire, music wire, pre-tempered wire, 18-8 stainless steel, phosphor-bronze, and many of the hard-drawn copper-nickel, and nonferrous alloys. Permissible torsional stresses resulting from initial tension for different spring indexes are shown in Fig. 16.

**Hook failure:** The great majority of breakages in extension springs occurs in the hooks. Hooks are subjected to both bending and torsional stresses and have higher stresses than the coils in the spring.

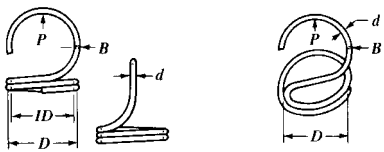
**Stresses in regular hooks:** The calculations for the stresses in hooks are quite complicated and lengthy. Also, the radii of the bends are difficult to determine and frequently vary between specifications and actual production samples. However, regular hooks are more

highly stressed than the coils in the body and are subjected to a bending stress at section B (see Table 6.) The bending stress  $S_b$  at section B should be compared with allowable stresses for torsion springs and with the elastic limit of the material in tension (See Figs. 7 through 10.)

*Stresses in cross over hooks:* Results of tests on springs having a normal average index show that the cross over hooks last longer than regular hooks. These results may not occur on springs of small index or if the cross over bend is made too sharply.

In as much as both types of hooks have the same bending stress, it would appear that the fatigue life would be the same. However, the large bend radius of the regular hooks causes some torsional stresses to coincide with the bending stresses, thus explaining the earlier breakages. If sharper bends were made on the regular hooks, the life should then be the same as for cross over hooks.

**Table 6. Formula for Bending Stress at Section B**

| Type of Hook   | Stress in Bending                    |
|--|--------------------------------------|
|  <p>Regular Hook</p> <p>Cross-over Hook</p> | $S_b = \frac{5PD^2}{I.D. \cdot d^3}$ |

*Stresses in half hooks:* The formulas for regular hooks can also be used for half hooks, because the smaller bend radius allows for the increase in stress. It will therefore be observed that half hooks have the same stress in bending as regular hooks.

Frequently overlooked facts by many designers are that one full hook deflects an amount equal to one half a coil and each half hook deflects an amount equal to one tenth of a coil. Allowances for these deflections should be made when designing springs. Thus, an extension spring, with regular full hooks and having 10 coils, will have a deflection equal to 11 coils, or 10 per cent more than the calculated deflection.

**Extension Spring Design.**—The available space in a product or assembly usually determines the limiting dimensions of a spring, but the wire size, number of coils, and initial tension are often unknown.

*Example:* An extension spring is to be made from spring steel ASTM A229, with regular hooks as shown in Fig. 17. Calculate the wire size, number of coils and initial tension.

*Note:* Allow about 20 to 25 per cent of the 9 pound load for initial tension, say 2 pounds, and then design for a 7 pound load (not 9 pounds) at  $\frac{5}{8}$  inch deflection. Also use lower stresses than for a compression spring to allow for overstretching during assembly and to obtain a safe stress on the hooks. Proceed as for compression springs, but locate a load in the tables somewhat higher than the 9 pound load.

*Method 1, using table:* From Table 5 locate  $\frac{3}{4}$  inch outside diameter in the left column and move to the right to locate a load  $P$  of 13.94 pounds. A deflection  $f$  of 0.212 inch appears above this figure. Moving vertically from this position to the top of the column a suitable wire diameter of 0.0625 inch is found.

The remaining design calculations are completed as follows:

*Step 1:* The stress with a load of 7 pounds is obtained as follows:  
The 7 pound load is 50.2 per cent of the 13.94 pound load. Therefore, the stress  $S$  at 7 pounds = 0.502 per cent  $\times$  100,000 = 50,200 pounds per square inch.



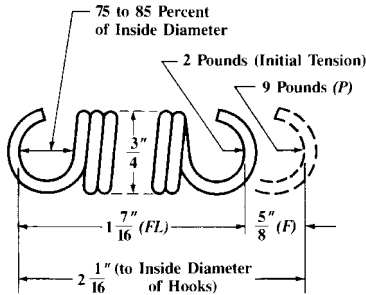


Fig. 17. Extension Spring Design Example

Step 2: The 50.2 per cent figure is also used to determine the deflection per coil  $f$ :  $0.502$  per cent  $\times 0.212 = 0.1062$  inch.

Step 3: The number of active coils. (say 6)

$$AC = \frac{F}{f} = \frac{0.625}{0.1062} = 5.86$$

This result should be reduced by 1 to allow for deflection of 2 hooks (see notes 1 and 2 that follow these calculations.) Therefore, a quick answer is: 5 coils of 0.0625 inch diameter wire. However, the design procedure should be completed by carrying out the following steps:

Step 4: The body length  $= (TC + 1) \times d = (5 + 1) \times 0.0625 = \frac{3}{8}$  inch.

Step 5: The length from the body to inside hook

$$= \frac{FL - \text{Body}}{2} = \frac{1.4375 - 0.375}{2} = 0.531 \text{ inch}$$

$$\text{Percentage of I.D.} = \frac{0.531}{\text{I.D.}} = \frac{0.531}{0.625} = 85 \text{ per cent}$$

This length is satisfactory, see Note 3 following this procedure.

Step 6:

$$\text{The spring index} = \frac{\text{O.D.}}{d} - 1 = \frac{0.75}{0.0625} - 1 = 11$$

Step 7: The initial tension stress is

$$S_{it} = \frac{S \times IT}{P} = \frac{50,200 \times 2}{7} = 14,340 \text{ pounds per square inch}$$

This stress is satisfactory, as checked against curve in Fig. 16.

Step 8: The curvature correction factor  $K = 1.12$  (Fig. 13).

Step 9: The total stress  $= (50,200 + 14,340) \times 1.12 = 72,285$  pounds per square inch

This result is less than 106,250 pounds per square inch permitted by the middle curve for 0.0625 inch wire in Fig. 3 and therefore is a safe working stress that permits some additional deflection that is usually necessary for assembly purposes.

*Step 10:* The large majority of hook breakage is due to high stress in bending and should be checked as follows:

From Table 6, stress on hook in bending is:

$$S_b = \frac{5PD^2}{\text{I.D.} \cdot d^3} = \frac{5 \times 9 \times 0.6875^2}{0.625 \times 0.0625^3} = 139,200 \text{ pounds per square inch}$$

This result is less than the top curve value, Fig. 8, for 0.0625 inch diameter wire, and is therefore safe. Also see Note 5 that follows.

*Notes:* The following points should be noted when designing extension springs:

- 1) All coils are active and thus  $AC = TC$ .
- 2) Each full hook deflection is approximately equal to  $\frac{1}{2}$  coil. Therefore for 2 hooks, reduce the total coils by 1. (Each half hook deflection is nearly equal to  $\frac{1}{10}$  of a coil.)
- 3) The distance from the body to the inside of a regular full hook equals 75 to 85 per cent (90 per cent maximum) of the I.D. For a cross over center hook, this distance equals the I.D.
- 4) Some initial tension should usually be used to hold the spring together. Try not to exceed the maximum curve shown on Fig. 16. Without initial tension, a long spring with many coils will have a different length in the horizontal position than it will when hung vertically.
- 5) The hooks are stressed in bending, therefore their stress should be less than the maximum bending stress as used for torsion springs — use top fatigue strength curves Figs. 7 through 10.

*Method 2, using formulas:* The sequence of steps for designing extension springs by formulas is similar to that for compression springs. The formulas for this method are given in Table 3.

**Tolerances for Compression and Extension Springs.**—Tolerances for coil diameter, free length, squareness, load, and the angle between loop planes for compression and extension springs are given in Tables 7 through 12. To meet the requirements of load, rate, free length, and solid height, it is necessary to vary the number of coils for compression springs by  $\pm 5$  per cent. For extension springs, the tolerances on the numbers of coils are: for 3 to 5 coils,  $\pm 20$  per cent; for 6 to 8 coils,  $\pm 30$  per cent; for 9 to 12 coils,  $\pm 40$  per cent. For each additional coil, a further  $1\frac{1}{2}$  per cent tolerance is added to the extension spring values. Closer tolerances on the number of coils for either type of spring lead to the need for trimming after coiling, and manufacturing time and cost are increased. Fig. 18 shows deviations allowed on the ends of extension springs, and variations in end alignments.

**Table 7. Compression and Extension Spring Coil Diameter Tolerances**

| Wire Diameter, Inch | Spring Index          |       |       |       |       |       |       |
|---------------------|-----------------------|-------|-------|-------|-------|-------|-------|
|                     | 4                     | 6     | 8     | 10    | 12    | 14    | 16    |
|                     | Tolerance, $\pm$ inch |       |       |       |       |       |       |
| 0.015               | 0.002                 | 0.002 | 0.003 | 0.004 | 0.005 | 0.006 | 0.007 |
| 0.023               | 0.002                 | 0.003 | 0.004 | 0.006 | 0.007 | 0.008 | 0.010 |
| 0.035               | 0.002                 | 0.004 | 0.006 | 0.007 | 0.009 | 0.011 | 0.013 |
| 0.051               | 0.003                 | 0.005 | 0.007 | 0.010 | 0.012 | 0.015 | 0.017 |
| 0.076               | 0.004                 | 0.007 | 0.010 | 0.013 | 0.016 | 0.019 | 0.022 |
| 0.114               | 0.006                 | 0.009 | 0.013 | 0.018 | 0.021 | 0.025 | 0.029 |
| 0.171               | 0.008                 | 0.012 | 0.017 | 0.023 | 0.028 | 0.033 | 0.038 |
| 0.250               | 0.011                 | 0.015 | 0.021 | 0.028 | 0.035 | 0.042 | 0.049 |
| 0.375               | 0.016                 | 0.020 | 0.026 | 0.037 | 0.046 | 0.054 | 0.064 |
| 0.500               | 0.021                 | 0.030 | 0.040 | 0.062 | 0.080 | 0.100 | 0.125 |

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SPRING DESIGN

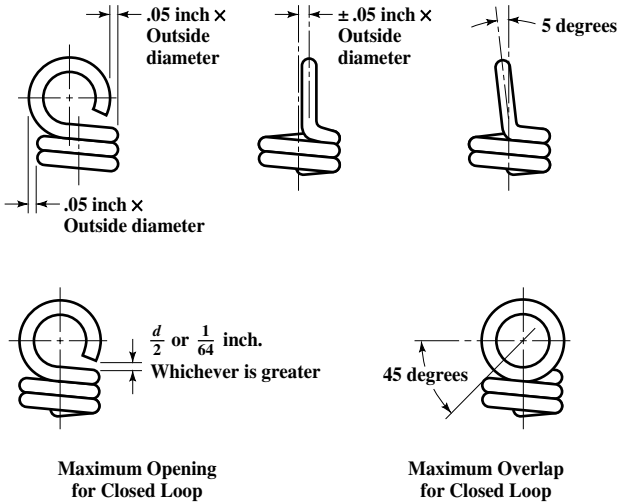


Fig. 18. Maximum Deviations Allowed on Ends and Variation in Alignment of Ends (Loops) for Extension Springs

**Table 8. Compression Spring Normal Free-Length Tolerances, Squared and Ground Ends**

| Number of Active Coils per Inch | Spring Index   |       |       |       |       |       |       |
|---------------------------------|--|-------|-------|-------|-------|-------|-------|
|                                 | 4  | 6     | 8     | 10    | 12    | 14    | 16    |
|                                 | Tolerance, ± Inch per Inch of Free Length <sup>a</sup> |       |       |       |       |       |       |
| 0.5                             | 0.010  | 0.011 | 0.012 | 0.013 | 0.015 | 0.016 | 0.016 |
| 1                               | 0.011  | 0.013 | 0.015 | 0.016 | 0.017 | 0.018 | 0.019 |
| 2                               | 0.013  | 0.015 | 0.017 | 0.019 | 0.020 | 0.022 | 0.023 |
| 4                               | 0.016  | 0.018 | 0.021 | 0.023 | 0.024 | 0.026 | 0.027 |
| 8                               | 0.019  | 0.022 | 0.024 | 0.026 | 0.028 | 0.030 | 0.032 |
| 12                              | 0.021  | 0.024 | 0.027 | 0.030 | 0.032 | 0.034 | 0.036 |
| 16                              | 0.022  | 0.026 | 0.029 | 0.032 | 0.034 | 0.036 | 0.038 |
| 20                              | 0.023  | 0.027 | 0.031 | 0.034 | 0.036 | 0.038 | 0.040 |

<sup>a</sup> For springs less than 0.5 inch long, use the tolerances for 0.5 inch long springs. For springs with unground closed ends, multiply the tolerances by 1.7.

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**Table 9. Extension Spring Normal Free-Length and End Tolerances**

| Free-Length Tolerances    |                  | End Tolerances        |                           | Free-Length Tolerances    |                  | End Tolerances        |                           |
|---------------------------|------------------|-----------------------|---------------------------|---------------------------|------------------|-----------------------|---------------------------|
| Spring Free Length (inch) | Tolerance (inch) | Total Number of Coils | Angle Between Loop Planes | Spring Free Length (inch) | Tolerance (inch) | Total Number of Coils | Angle Between Loop Planes |
| Up to 0.5                 | ±0.020           |                       |                           | Over 4.0 to 8.0           | ±0.093           | 13 to 16              | ±60°                      |
| Over 0.5 to 1.0           | ±0.030           | 3 to 6                | ±25°                      | Over 8.0 to 16.0          | ±0.156           | Over 16               | Random                    |
| Over 1.0 to 2.0           | ±0.040           | 7 to 9                | ±35°                      | Over 16.0 to 24.0         | ±0.218           |                       |                           |
| Over 2.0 to 4.0           | ±0.060           | 10 to 12              | ±45°                      |                           |                  |                       |                           |

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**Table 10. Compression Spring Squareness Tolerances**

| Slenderness Ratio<br>$FL/D^3$ <sup>a</sup> | Spring Index                           |     |     |     |     |     |     |
|--|--|-----|-----|-----|-----|-----|-----|
|  | 4                                      | 6   | 8   | 10  | 12  | 14  | 16  |
|  | Squareness Tolerances ( $\pm$ degrees) |     |     |     |     |     |     |
| 0.5  | 3.0                                    | 3.0 | 3.5 | 3.5 | 3.5 | 3.5 | 4.0 |
| 1.0  | 2.5                                    | 3.0 | 3.0 | 3.0 | 3.0 | 3.5 | 3.5 |
| 1.5  | 2.5                                    | 2.5 | 2.5 | 3.0 | 3.0 | 3.0 | 3.0 |
| 2.0  | 2.5                                    | 2.5 | 2.5 | 2.5 | 3.0 | 3.0 | 3.0 |
| 3.0  | 2.0                                    | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 3.0 |
| 4.0  | 2.0                                    | 2.0 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| 6.0  | 2.0                                    | 2.0 | 2.0 | 2.5 | 2.5 | 2.5 | 2.5 |
| 8.0  | 2.0                                    | 2.0 | 2.0 | 2.0 | 2.5 | 2.5 | 2.5 |
| 10.0                                       | 2.0                                    | 2.0 | 2.0 | 2.0 | 2.0 | 2.5 | 2.5 |
| 12.0                                       | 2.0                                    | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.5 |

<sup>a</sup> Slenderness Ratio =  $FL \div D$

Springs with closed and ground ends, in the free position. Squareness tolerances closer than those shown require special process techniques which increase cost. Springs made from fine wire sizes, and with high spring indices, irregular shapes or long free lengths, require special attention in determining appropriate tolerance and feasibility of grinding ends.

**Table 11. Compression Spring Normal Load Tolerances**

| Length Tolerance, $\pm$ inch | Deflection (inch) <sup>a</sup>    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|------------------------------|-----------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|                              | 0.05                              | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.40 | 0.50 | 0.75 | 1.00 | 1.50 | 2.00 | 3.00 | 4.00 | 6.00 |
|                              | Tolerance, $\pm$ Per Cent of Load |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 0.005                        | 12                                | 7    | 6    | 5    | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
| 0.010                        | ...                               | 12   | 8.5  | 7    | 6.5  | 5.5  | 5    | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
| 0.020                        | ...                               | 22   | 15.5 | 12   | 10   | 8.5  | 7    | 6    | 5    | ...  | ...  | ...  | ...  | ...  | ...  |
| 0.030                        | ...                               | ...  | 22   | 17   | 14   | 12   | 9.5  | 8    | 6    | 5    | ...  | ...  | ...  | ...  | ...  |
| 0.040                        | ...                               | ...  | ...  | 22   | 18   | 15.5 | 12   | 10   | 7.5  | 6    | 5    | ...  | ...  | ...  | ...  |
| 0.050                        | ...                               | ...  | ...  | ...  | 22   | 19   | 14.5 | 12   | 9    | 7    | 5.5  | ...  | ...  | ...  | ...  |
| 0.060                        | ...                               | ...  | ...  | ...  | 25   | 22   | 17   | 14   | 10   | 8    | 6    | 5    | ...  | ...  | ...  |
| 0.070                        | ...                               | ...  | ...  | ...  | ...  | 25   | 19.5 | 16   | 11   | 9    | 6.5  | 5.5  | ...  | ...  | ...  |
| 0.080                        | ...                               | ...  | ...  | ...  | ...  | ...  | 22   | 18   | 12.5 | 10   | 7.5  | 6    | 5    | ...  | ...  |
| 0.090                        | ...                               | ...  | ...  | ...  | ...  | ...  | 25   | 20   | 14   | 11   | 8    | 6    | 5    | ...  | ...  |
| 0.100                        | ...                               | ...  | ...  | ...  | ...  | ...  | ...  | 22   | 15.5 | 12   | 8.5  | 7    | 5.5  | ...  | ...  |
| 0.200                        | ...                               | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | 22   | 15.5 | 12   | 8.5  | 7    | 5.5  |
| 0.300                        | ...                               | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | 22   | 17   | 12   | 9.5  | 7    |
| 0.400                        | ...                               | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | 21   | 15   | 12   | 8.5  |
| 0.500                        | ...                               | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | 25   | 18.5 | 14.5 | 10.5 |

<sup>a</sup> From free length to loaded position.

**Torsion Spring Design.**—Fig. 19 shows the types of ends most commonly used on torsion springs. To produce them requires only limited tooling. The straight torsion end is the least expensive and should be used whenever possible. After determining the spring load or torque required and selecting the end formations, the designer usually estimates suitable space or size limitations. However, the space should be considered approximate until the wire size and number of coils have been determined. The wire size is dependent principally upon the torque. Design data can be developed with the aid of the tabular data, which is a simple method, or by calculation alone, as shown in the following sections. Many other factors affecting the design and operation of torsion springs are also covered in the section, *Torsion Spring Design Recommendations* on page 341. Design formulas are shown in Table 13.

*Curvature correction:* In addition to the stress obtained from the formulas for load or deflection, there is a direct shearing stress on the inside of the section due to curvature. Therefore, the stress obtained by the usual formulas should be multiplied by the factor  $K$

**Table 12. Extension Spring Normal Load Tolerances**

| Spring Index | $\frac{FL}{F}$ | Wire Diameter (inch)              |       |       |       |       |       |       |       |       |       |       |
|--------------|----------------|-----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|              |                | 0.015                             | 0.022 | 0.032 | 0.044 | 0.062 | 0.092 | 0.125 | 0.187 | 0.250 | 0.375 | 0.437 |
|              |                | Tolerance, $\pm$ Per Cent of Load |       |       |       |       |       |       |       |       |       |       |
| 4            | 12             | 20.0                              | 18.5  | 17.6  | 16.9  | 16.2  | 15.5  | 15.0  | 14.3  | 13.8  | 13.0  | 12.6  |
|              | 8              | 18.5                              | 17.5  | 16.7  | 15.8  | 15.0  | 14.5  | 14.0  | 13.2  | 12.5  | 11.5  | 11.0  |
|              | 6              | 16.8                              | 16.1  | 15.5  | 14.7  | 13.8  | 13.2  | 12.7  | 11.8  | 11.2  | 9.9   | 9.4   |
|              | 4.5            | 15.0                              | 14.7  | 14.1  | 13.5  | 12.6  | 12.0  | 11.5  | 10.3  | 9.7   | 8.4   | 7.9   |
|              | 2.5            | 13.1                              | 12.4  | 12.1  | 11.8  | 10.6  | 10.0  | 9.1   | 8.5   | 8.0   | 6.8   | 6.2   |
|              | 1.5            | 10.2                              | 9.9   | 9.3   | 8.9   | 8.0   | 7.5   | 7.0   | 6.5   | 6.1   | 5.3   | 4.8   |
|              | 0.5            | 6.2                               | 5.4   | 4.8   | 4.6   | 4.3   | 4.1   | 4.0   | 3.8   | 3.6   | 3.3   | 3.2   |
| 6            | 12             | 17.0                              | 15.5  | 14.6  | 14.1  | 13.5  | 13.1  | 12.7  | 12.0  | 11.5  | 11.2  | 10.7  |
|              | 8              | 16.2                              | 14.7  | 13.9  | 13.4  | 12.6  | 12.2  | 11.7  | 11.0  | 10.5  | 10.0  | 9.5   |
|              | 6              | 15.2                              | 14.0  | 12.9  | 12.3  | 11.6  | 10.9  | 10.7  | 10.0  | 9.4   | 8.8   | 8.3   |
|              | 4.5            | 13.7                              | 12.4  | 11.5  | 11.0  | 10.5  | 10.0  | 9.6   | 9.0   | 8.3   | 7.6   | 7.1   |
|              | 2.5            | 11.9                              | 10.8  | 10.2  | 9.8   | 9.4   | 9.0   | 8.5   | 7.9   | 7.2   | 6.2   | 6.0   |
|              | 1.5            | 9.9                               | 9.0   | 8.3   | 7.7   | 7.3   | 7.0   | 6.7   | 6.4   | 6.0   | 4.9   | 4.7   |
|              | 0.5            | 6.3                               | 5.5   | 4.9   | 4.7   | 4.5   | 4.3   | 4.1   | 4.0   | 3.7   | 3.5   | 3.4   |
| 8            | 12             | 15.8                              | 14.3  | 13.1  | 13.0  | 12.1  | 12.0  | 11.5  | 10.8  | 10.2  | 10.0  | 9.5   |
|              | 8              | 15.0                              | 13.7  | 12.5  | 12.1  | 11.4  | 11.0  | 10.6  | 10.1  | 9.4   | 9.0   | 8.6   |
|              | 6              | 14.2                              | 13.0  | 11.7  | 11.2  | 10.6  | 10.0  | 9.7   | 9.3   | 8.6   | 8.1   | 7.6   |
|              | 4.5            | 12.8                              | 11.7  | 10.7  | 10.1  | 9.7   | 9.0   | 8.7   | 8.3   | 7.8   | 7.2   | 6.6   |
|              | 2.5            | 11.2                              | 10.2  | 9.5   | 8.8   | 8.3   | 7.9   | 7.7   | 7.4   | 6.9   | 6.1   | 5.6   |
|              | 1.5            | 9.5                               | 8.6   | 7.8   | 7.1   | 6.9   | 6.7   | 6.5   | 6.2   | 5.8   | 4.9   | 4.5   |
|              | 0.5            | 6.3                               | 5.6   | 5.0   | 4.8   | 4.5   | 4.4   | 4.2   | 4.1   | 3.9   | 3.6   | 3.5   |
| 10           | 12             | 14.8                              | 13.3  | 12.0  | 11.9  | 11.1  | 10.9  | 10.5  | 9.9   | 9.3   | 9.2   | 8.8   |
|              | 8              | 14.2                              | 12.8  | 11.6  | 11.2  | 10.5  | 10.2  | 9.7   | 9.2   | 8.6   | 8.3   | 8.0   |
|              | 6              | 13.4                              | 12.1  | 10.8  | 10.5  | 9.8   | 9.3   | 8.9   | 8.6   | 8.0   | 7.6   | 7.2   |
|              | 4.5            | 12.3                              | 10.8  | 10.0  | 9.5   | 9.0   | 8.5   | 8.1   | 7.8   | 7.3   | 6.8   | 6.4   |
|              | 2.5            | 10.8                              | 9.6   | 9.0   | 8.4   | 8.0   | 7.7   | 7.3   | 7.0   | 6.5   | 5.9   | 5.5   |
|              | 1.5            | 9.2                               | 8.3   | 7.5   | 6.9   | 6.7   | 6.5   | 6.3   | 6.0   | 5.6   | 5.0   | 4.6   |
|              | 0.5            | 6.4                               | 5.7   | 5.1   | 4.9   | 4.7   | 4.5   | 4.3   | 4.2   | 4.0   | 3.8   | 3.7   |
| 12           | 12             | 14.0                              | 12.3  | 11.1  | 10.8  | 10.1  | 9.8   | 9.5   | 9.0   | 8.5   | 8.2   | 7.9   |
|              | 8              | 13.2                              | 11.8  | 10.7  | 10.2  | 9.6   | 9.3   | 8.9   | 8.4   | 7.9   | 7.5   | 7.2   |
|              | 6              | 12.6                              | 11.2  | 10.2  | 9.7   | 9.0   | 8.5   | 8.2   | 7.9   | 7.4   | 6.9   | 6.4   |
|              | 4.5            | 11.7                              | 10.2  | 9.4   | 9.0   | 8.4   | 8.0   | 7.6   | 7.2   | 6.8   | 6.3   | 5.8   |
|              | 2.5            | 10.5                              | 9.2   | 8.5   | 8.0   | 7.8   | 7.4   | 7.0   | 6.6   | 6.1   | 5.6   | 5.2   |
|              | 1.5            | 8.9                               | 8.0   | 7.2   | 6.8   | 6.5   | 6.3   | 6.1   | 5.7   | 5.4   | 4.8   | 4.5   |
|              | 0.5            | 6.5                               | 5.8   | 5.3   | 5.1   | 4.9   | 4.7   | 4.5   | 4.3   | 4.2   | 4.0   | 3.3   |
| 14           | 12             | 13.1                              | 11.3  | 10.2  | 9.7   | 9.1   | 8.8   | 8.4   | 8.1   | 7.6   | 7.2   | 7.0   |
|              | 8              | 12.4                              | 10.9  | 9.8   | 9.2   | 8.7   | 8.3   | 8.0   | 7.6   | 7.2   | 6.8   | 6.4   |
|              | 6              | 11.8                              | 10.4  | 9.3   | 8.8   | 8.3   | 7.7   | 7.5   | 7.2   | 6.8   | 6.3   | 5.9   |
|              | 4.5            | 11.1                              | 9.7   | 8.7   | 8.2   | 7.8   | 7.2   | 7.0   | 6.7   | 6.3   | 5.8   | 5.4   |
|              | 2.5            | 10.1                              | 8.8   | 8.1   | 7.6   | 7.1   | 6.7   | 6.5   | 6.2   | 5.7   | 5.2   | 5.0   |
|              | 1.5            | 8.6                               | 7.7   | 7.0   | 6.7   | 6.3   | 6.0   | 5.8   | 5.5   | 5.2   | 4.7   | 4.5   |
|              | 0.5            | 6.6                               | 5.9   | 5.4   | 5.2   | 5.0   | 4.8   | 4.6   | 4.4   | 4.3   | 4.2   | 4.0   |
| 16           | 12             | 12.3                              | 10.3  | 9.2   | 8.6   | 8.1   | 7.7   | 7.4   | 7.2   | 6.8   | 6.3   | 6.1   |
|              | 8              | 11.7                              | 10.0  | 8.9   | 8.3   | 7.8   | 7.4   | 7.2   | 6.8   | 6.5   | 6.0   | 5.7   |
|              | 6              | 11.0                              | 9.6   | 8.5   | 8.0   | 7.5   | 7.1   | 6.9   | 6.5   | 6.2   | 5.7   | 5.4   |
|              | 4.5            | 10.5                              | 9.1   | 8.1   | 7.5   | 7.2   | 6.8   | 6.5   | 6.2   | 5.8   | 5.3   | 5.1   |
|              | 2.5            | 9.7                               | 8.4   | 7.6   | 7.0   | 6.7   | 6.3   | 6.1   | 5.7   | 5.4   | 4.9   | 4.7   |
|              | 1.5            | 8.3                               | 7.4   | 6.6   | 6.2   | 6.0   | 5.8   | 5.6   | 5.3   | 5.1   | 4.6   | 4.4   |
|              | 0.5            | 6.7                               | 5.9   | 5.5   | 5.3   | 5.1   | 5.0   | 4.8   | 4.6   | 4.5   | 4.3   | 4.1   |

$FL/F$  = the ratio of the spring free length  $FL$  to the deflection  $F$ .

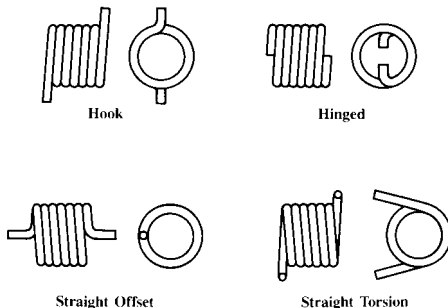


Fig. 19. The Most Commonly Used Types of Ends for Torsion Springs

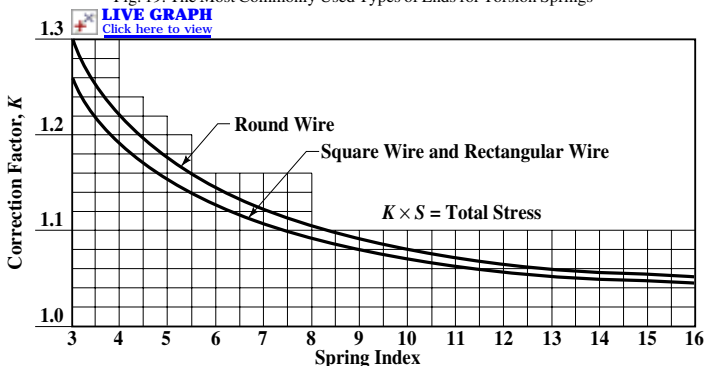


Fig. 20. Torsion Spring Stress Correction for Curvature

obtained from the curve in Fig. 20. The corrected stress thus obtained is used only for comparison with the allowable working stress (fatigue strength) curves to determine if it is a safe value, and should not be used in the formulas for deflection.

**Torque:** Torque is a force applied to a moment arm and tends to produce rotation. Torsion springs exert torque in a circular arc and the arms are rotated about the central axis. It should be noted that the stress produced is in bending, not in torsion. In the spring industry it is customary to specify torque in conjunction with the deflection or with the arms of a spring at a definite position. Formulas for torque are expressed in pound-inches. If ounce-inches are specified, it is necessary to divide this value by 16 in order to use the formulas.

When a load is specified at a distance from a centerline, the torque is, of course, equal to the load multiplied by the distance. The load can be in pounds or ounces with the distances in inches or the load can be in grams or kilograms with the distance in centimeters or millimeters, but to use the design formulas, all values must be converted to pounds and inches. Design formulas for torque are based on the tangent to the arc of rotation and presume that a rod is used to support the spring. The stress in bending caused by the moment  $P \times R$  is identical in magnitude to the torque  $T$ , provided a rod is used.

Theoretically, it makes no difference how or where the load is applied to the arms of torsion springs. Thus, in Fig. 21, the loads shown multiplied by their respective distances pro-

**Table 13. Formulas for Torsion Springs**

| Feature  | Springs made from round wire                         | Springs made from square wire                        |
|--|--|--|
|  | Formula <sup>a,b</sup>                               |  |
| $d =$<br>Wire diameter,<br>Inches                          | $\sqrt[3]{\frac{10.18T}{S_b}}$                       | $\sqrt[3]{\frac{6T}{S_b}}$                           |
|  | $\sqrt[4]{\frac{4000TND}{EF^\circ}}$                 | $\sqrt[4]{\frac{2375TND}{EF^\circ}}$                 |
| $S_b =$<br>Stress, bending<br>pounds per<br>square inch    | $\frac{10.18T}{d^3}$                                 | $\frac{6T}{d^3}$                                     |
|  | $\frac{EdF^\circ}{392ND}$                            | $\frac{EdF^\circ}{392ND}$                            |
| $N =$<br>Active Coils                                      | $\frac{EdF^\circ}{392S_bD}$                          | $\frac{EdF^\circ}{392S_bD}$                          |
|  | $\frac{Ed^4F^\circ}{4000TD}$                         | $\frac{Ed^4F^\circ}{2375TD}$                         |
| $F^\circ =$<br>Deflection                                  | $\frac{392S_bND}{Ed}$                                | $\frac{392S_bND}{Ed}$                                |
|  | $\frac{4000TND}{Ed^4}$                               | $\frac{2375TND}{Ed^4}$                               |
| $T =$<br>Torque<br>Inch lbs.<br>(Also = $P \times R$ )     | $0.0982S_b d^3$                                      | $0.1666S_b d^3$                                      |
|  | $\frac{Ed^4F^\circ}{4000ND}$                         | $\frac{Ed^4F^\circ}{2375ND}$                         |
| $ID_1 =$<br>Inside Diameter<br>After Deflection,<br>Inches | $\frac{N(ID \text{ free})}{N + \frac{F^\circ}{360}}$ | $\frac{N(ID \text{ free})}{N + \frac{F^\circ}{360}}$ |

<sup>a</sup> Where two formulas are given for one feature, the designer should use the one found to be appropriate for the given design. The end result from either of any two formulas is the same.

<sup>b</sup> The symbol notation is given on page 308.

duce the same torque; i.e.,  $20 \times 0.5 = 10$  pound-inches;  $10 \times 1 = 10$  pound-inches; and  $5 \times 2 = 10$  pound-inches. To further simplify the understanding of torsion spring torque, observe in both Fig. 22 and Fig. 23 that although the turning force is in a circular arc the torque is not equal to  $P$  times the radius. The torque in both designs equals  $P \times R$  because the spring rests against the support rod at point  $a$ .

*Design Procedure:* Torsion spring designs require more effort than other kinds because consideration has to be given to more details such as the proper size of a supporting rod, reduction of the inside diameter, increase in length, deflection of arms, allowance for friction, and method of testing.

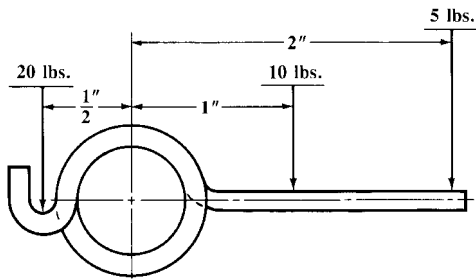


Fig. 21. Right-Hand Torsion Spring

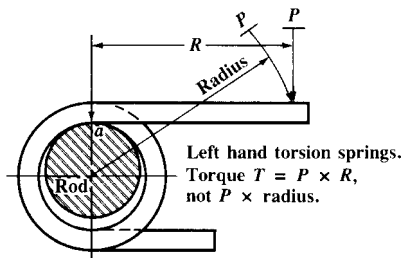


Fig. 22. Left-Hand Torsion Spring

The Torque is  $T = P \times R$ , Not  $P \times \text{Radius}$ , because the Spring is Resting Against the Support Rod at Point  $a$

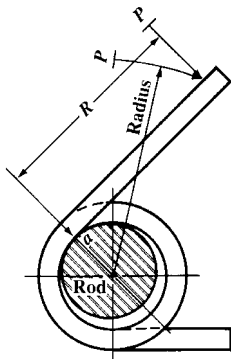


Fig. 23. Left-Hand Torsion Spring

As with the Spring in Fig. 22, the Torque is  $T = P \times R$ , Not  $P \times \text{Radius}$ , Because the Support Point Is at  $a$



*Example:* What music wire diameter and how many coils are required for the torsion spring shown in Fig. 24, which is to withstand at least 1000 cycles? Determine the corrected stress and the reduced inside diameter after deflection.

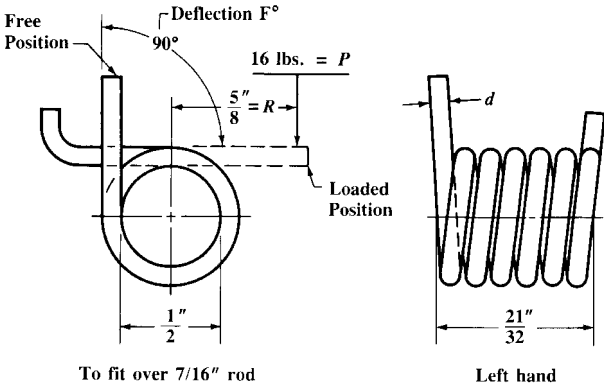


Fig. 24. Torsion Spring Design Example. The Spring Is to be Assembled on a  $\frac{7}{16}$ -Inch Support Rod

*Method 1, using table:* From Table 14, page 343, locate the  $\frac{1}{2}$  inch inside diameter for the spring in the left-hand column. Move to the right and then vertically to locate a torque value nearest to the required 10 pound-inches, which is 10.07 pound-inches. At the top of the same column, the music wire diameter is found, which is Number 31 gauge (0.085 inch). At the bottom of the same column the deflection for one coil is found, which is 15.81 degrees. As a 90-degree deflection is required, the number of coils needed is  $\frac{90}{15.81} = 5.69$  (say  $5\frac{3}{4}$  coils).

The spring index  $\frac{D}{d} = \frac{0.500 + 0.085}{0.085} = 6.88$  and thus the curvature correction factor

$K$  from Fig. 20 = 1.13. Therefore the corrected stress equals  $167,000 \times 1.13 = 188,700$  pounds per square inch which is below the Light Service curve (Fig. 7) and therefore should provide a fatigue life of over 1,000 cycles. The reduced inside diameter due to deflection is found from the formula in Table 13:

$$ID_1 = \frac{N(ID \text{ free})}{N + \frac{F}{360}} = \frac{5.75 \times 0.500}{5.75 + \frac{90}{360}} = 0.479 \text{ in.}$$

This reduced diameter easily clears a suggested  $\frac{7}{16}$  inch diameter supporting rod:  $0.479 - 0.4375 = 0.041$  inch clearance, and it also allows for the standard tolerance. The overall length of the spring equals the total number of coils plus one, times the wire diameter. Thus,  $6\frac{3}{4} \times 0.085 = 0.574$  inch. If a small space of about  $\frac{1}{64}$  in. is allowed between the coils to eliminate coil friction, an overall length of  $\frac{21}{32}$  inch results.

Although this completes the design calculations, other tolerances should be applied in accordance with the Torsion Spring Tolerance Tables 16 through 17 shown at the end of this section.

*Longer fatigue life:* If a longer fatigue life is desired, use a slightly larger wire diameter. Usually the next larger gage size is satisfactory. The larger wire will reduce the stress and still exert the same torque, but will require more coils and a longer overall length.

*Percentage method for calculating longer life:* The spring design can be easily adjusted for longer life as follows:

1) Select the next larger gage size, which is Number 32 (0.090 inch) from [Table 14](#). The torque is 11.88 pound-inches, the design stress is 166,000 pounds per square inch, and the deflection is 14.9 degrees per coil. As a percentage the torque is  $10/11.88 \times 100 = 84$  per cent.

2) The new stress is  $0.84 \times 166,000 = 139,440$  pounds per square inch. This value is under the bottom or Severe Service curve, [Fig. 7](#), and thus assures longer life.

3) The new deflection per coil is  $0.84 \times 14.97 = 12.57$  degrees. Therefore, the total number of coils required =  $90/12.57 = 7.16$  (say  $7 \frac{1}{8}$ ). The new overall length =  $8 \frac{1}{8} \times 0.090 = 0.73$  inch (say  $\frac{3}{4}$  inch). A slight increase in the overall length and new arm location are thus necessary.

*Method 2, using formulas:* When using this method, it is often necessary to solve the formulas several times because assumptions must be made initially either for the stress or for a wire size. The procedure for design using formulas is as follows (the design example is the same as in Method 1, and the spring is shown in [Fig. 24](#)):

*Step 1:* Note from [Table 13](#), page 338 that the wire diameter formula is:

$$d = \sqrt[3]{\frac{10.18T}{S_b}}$$

*Step 2:* Referring to [Fig. 7](#), select a trial stress, say 150,000 pounds per square inch.

*Step 3:* Apply the trial stress, and the 10 pound-inches torque value in the wire diameter formula:

$$d = \sqrt[3]{\frac{10.18T}{S_b}} = \sqrt[3]{\frac{10.18 \times 10}{150,000}} = \sqrt[3]{0.000679} = 0.0879 \text{ inch}$$

The nearest gauge sizes are 0.085 and 0.090 inch diameter. *Note:* [Table 21](#), page 351, can be used to avoid solving the cube root.

*Step 4:* Select 0.085 inch wire diameter and solve the equation for the actual stress:

$$S_b = \frac{10.18T}{d^3} = \frac{10.18 \times 10}{0.085^3} = 165,764 \text{ pounds per square inch}$$

*Step 5:* Calculate the number of coils from the equation, [Table 13](#):

$$N = \frac{EdF^{\circ}}{392S_bD} = \frac{28,500,000 \times 0.085 \times 90}{392 \times 165,764 \times 0.585} = 5.73 \text{ (say } 5 \frac{3}{4}\text{)}$$

*Step 6:* Calculate the total stress. The spring index is 6.88, and the correction factor  $K$  is 1.13, therefore total stress =  $165,764 \times 1.13 = 187,313$  pounds per square inch. *Note:* The corrected stress should not be used in any of the formulas as it does not determine the torque or the deflection.

**Torsion Spring Design Recommendations.**—The following recommendations should be taken into account when designing torsion springs:

*Hand:* The hand or direction of coiling should be specified and the spring designed so deflection causes the spring to wind up and to have more coils. This increase in coils and overall length should be allowed for during design. Deflecting the spring in an unwinding direction produces higher stresses and may cause early failure. When a spring is sighted down the longitudinal axis, it is "right hand" when the direction of the wire into the spring takes a clockwise direction or if the angle of the coils follows an angle similar to the threads

of a standard bolt or screw, otherwise it is "left hand." A spring must be coiled right-handed to engage the threads of a standard machine screw.

*Rods:* Torsion springs should be supported by a rod running through the center whenever possible. If unsupported, or if held by clamps or lugs, the spring will buckle and the torque will be reduced or unusual stresses may occur.

*Diameter Reduction:* The inside diameter reduces during deflection. This reduction should be computed and proper clearance provided over the supporting rod. Also, allowances should be considered for normal spring diameter tolerances.

*Winding:* The coils of a spring may be closely or loosely wound, but they seldom should be wound with the coils pressed tightly together. Tightly wound springs with initial tension on the coils do not deflect uniformly and are difficult to test accurately. A small space between the coils of about 20 to 25 per cent of the wire thickness is desirable. Square and rectangular wire sections should be avoided whenever possible as they are difficult to wind, expensive, and are not always readily available.

*Arm Length:* All the wire in a torsion spring is active between the points where the loads are applied. Deflection of long extended arms can be calculated by allowing one third of the arm length, from the point of load contact to the body of the spring, to be converted into coils. However, if the length of arm is equal to or less than one-half the length of one coil, it can be safely neglected in most applications.

*Total Coils:* Torsion springs having less than three coils frequently buckle and are difficult to test accurately. When thirty or more coils are used, light loads will not deflect all the coils simultaneously due to friction with the supporting rod. To facilitate manufacturing it is usually preferable to specify the total number of coils to the nearest fraction in eighths or quarters such as  $5 \frac{1}{8}$ ,  $5 \frac{1}{4}$ ,  $5 \frac{1}{2}$ , etc.

*Double Torsion:* This design consists of one left-hand-wound series of coils and one series of right-hand-wound coils connected at the center. These springs are difficult to manufacture and are expensive, so it often is better to use two separate springs. For torque and stress calculations, each series is calculated separately as individual springs; then the torque values are added together, but the deflections are not added.

*Bends:* Arms should be kept as straight as possible. Bends are difficult to produce and often are made by secondary operations, so they are therefore expensive. Sharp bends raise stresses that cause early failure. Bend radii should be as large as practicable. Hooks tend to open during deflection; their stresses can be calculated by the same procedure as that for tension springs.

*Spring Index:* The spring index must be used with caution. In design formulas it is  $D/d$ . For shop measurement it is  $O.D./d$ . For arbor design it is  $I.D./d$ . Conversions are easily performed by either adding or subtracting 1 from  $D/d$ .

*Proportions:* A spring index between 4 and 14 provides the best proportions. Larger ratios may require more than average tolerances. Ratios of 3 or less, often cannot be coiled on automatic spring coiling machines because of arbor breakage. Also, springs with smaller or larger spring indexes often do not give the same results as are obtained using the design formulas.

**Table of Torsion Spring Characteristics.**—Table 14 shows design characteristics for the most commonly used torsion springs made from wire of standard gauge sizes. The deflection for one coil at a specified torque and stress is shown in the body of the table. The figures are based on music wire (ASTM A228) and oil-tempered MB grade (ASTM A229), and can be used for several other materials which have similar values for the modulus of elasticity  $E$ . However, the design stress may be too high or too low, and the design stress, torque, and deflection per coil should each be multiplied by the appropriate correction factor in Table 15 when using any of the materials given in that table.

Table 14. Torsion Spring Deflections

|   |                              |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
|---|------------------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| AMW Wire Gauge<br>Decimal Equivalent <sup>a</sup> | 1<br>.010                    | 2<br>.011  | 3<br>.012  | 4<br>.013  | 5<br>.014  | 6<br>.016  | 7<br>.018  | 8<br>.020  | 9<br>.022  | 10<br>.024 | 11<br>.026 | 12<br>.029 | 13<br>.031 | 14<br>.033 | 15<br>.035 | 16<br>.037 |
| Design Stress, kpsi                               | 232                          | 229        | 226        | 224        | 221        | 217        | 214        | 210        | 207        | 205        | 202        | 199        | 197        | 196        | 194        | 192        |
| Torque, pound-inch                                | .0228                        | .0299      | .0383      | .0483      | .0596      | .0873      | .1226      | .1650      | .2164      | .2783      | .3486      | .4766      | .5763      | .6917      | .8168      | .9550      |
| Inside Diameter, inch                             | Deflection, degrees per coil |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| $\frac{1}{16}$                                    | 0.0625                       | 22.35      | 20.33      | 18.64      | 17.29      | 16.05      | 14.15      | 18.72      | 11.51      | 10.56      | 9.818      | 9.137      | 8.343      | 7.896      | ...        | ...        |
| $\frac{5}{64}$                                    | 0.078125                     | 27.17      | 24.66      | 22.55      | 20.86      | 19.32      | 16.96      | 15.19      | 13.69      | 12.52      | 11.59      | 10.75      | 9.768      | 9.215      | ...        | ...        |
| $\frac{3}{32}$                                    | 0.09375                      | 31.98      | 28.98      | 26.47      | 24.44      | 22.60      | 19.78      | 17.65      | 15.87      | 14.47      | 13.36      | 12.36      | 11.19      | 10.53      | 10.18      | 9.646      |
| $\frac{7}{64}$                                    | 0.109375                     | 36.80      | 33.30      | 30.38      | 28.02      | 25.88      | 22.60      | 20.12      | 18.05      | 16.43      | 15.14      | 13.98      | 12.62      | 11.85      | 11.43      | 10.82      |
| $\frac{1}{8}$                                     | 0.125                        | 41.62      | 37.62      | 34.29      | 31.60      | 29.16      | 25.41      | 22.59      | 20.23      | 18.38      | 16.91      | 15.59      | 14.04      | 13.17      | 12.68      | 11.99      |
| $\frac{5}{64}$                                    | 0.140625                     | 46.44      | 41.94      | 38.20      | 35.17      | 32.43      | 28.23      | 25.06      | 22.41      | 20.33      | 18.69      | 17.20      | 15.47      | 14.49      | 13.94      | 13.16      |
| $\frac{3}{32}$                                    | 0.15625                      | 51.25      | 46.27      | 42.11      | 38.75      | 35.71      | 31.04      | 27.53      | 24.59      | 22.29      | 20.46      | 18.82      | 16.89      | 15.81      | 15.19      | 14.33      |
| $\frac{3}{16}$                                    | 0.1875                       | 60.89      | 54.91      | 49.93      | 45.91      | 42.27      | 36.67      | 32.47      | 28.95      | 26.19      | 24.01      | 22.04      | 19.74      | 18.45      | 17.70      | 16.67      |
| $\frac{1}{32}$                                    | 0.21875                      | 70.52      | 63.56      | 57.75      | 53.06      | 48.82      | 42.31      | 37.40      | 33.31      | 30.10      | 27.55      | 25.27      | 22.59      | 21.09      | 20.21      | 19.01      |
| $\frac{1}{4}$                                     | 0.250                        | 80.15      | 72.20      | 65.57      | 60.22      | 55.38      | 47.94      | 42.34      | 37.67      | 34.01      | 31.10      | 28.49      | 25.44      | 23.73      | 22.72      | 21.35      |
| AMW Wire Gauge<br>Decimal Equivalent <sup>a</sup> | 17<br>.039                   | 18<br>.041 | 19<br>.043 | 20<br>.045 | 21<br>.047 | 22<br>.049 | 23<br>.051 | 24<br>.055 | 25<br>.059 | 26<br>.063 | 27<br>.067 | 28<br>.071 | 29<br>.075 | 30<br>.080 | 31<br>.085 |            |
| Design Stress, kpsi                               | 190                          | 188        | 187        | 185        | 184        | 183        | 182        | 180        | 178        | 176        | 174        | 173        | 171        | 169        | 167        |            |
| Torque, pound-inch                                | 1.107                        | 1.272      | 1.460      | 1.655      | 1.876      | 2.114      | 2.371      | 2.941      | 3.590      | 4.322      | 5.139      | 6.080      | 7.084      | 8.497      | 10.07      |            |
| Inside Diameter, inch                             | Deflection, degrees per coil |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| $\frac{1}{8}$                                     | 0.125                        | 10.80      | 10.29      | 9.876      | 9.447      | 9.102      | 8.784      | ...        | ...        | ...        | ...        | ...        | ...        | ...        | ...        |            |
| $\frac{5}{64}$                                    | 0.140625                     | 11.83      | 11.26      | 10.79      | 10.32      | 9.929      | 9.572      | 9.244      | 8.654      | 8.141      | ...        | ...        | ...        | ...        | ...        |            |
| $\frac{3}{32}$                                    | 0.15625                      | 12.86      | 12.23      | 11.71      | 11.18      | 10.76      | 10.36      | 9.997      | 9.345      | 8.778      | 8.279      | 7.975      | ...        | ...        | ...        |            |
| $\frac{3}{16}$                                    | 0.1875                       | 14.92      | 14.16      | 13.55      | 12.92      | 12.41      | 11.94      | 11.50      | 10.73      | 10.05      | 9.459      | 9.091      | 8.663      | 8.232      | 7.772      |            |
| $\frac{1}{32}$                                    | 0.21875                      | 16.97      | 16.10      | 15.39      | 14.66      | 14.06      | 13.52      | 13.01      | 12.11      | 11.33      | 10.64      | 10.21      | 9.711      | 9.212      | 8.680      |            |
| $\frac{1}{4}$                                     | 0.250                        | 19.03      | 18.04      | 17.22      | 16.39      | 15.72      | 15.09      | 14.52      | 13.49      | 12.60      | 11.82      | 11.32      | 10.76      | 10.19      | 9.588      |            |

<sup>a</sup>For sizes up to 13 gauge, the table values are for music wire with a modulus  $E$  of 29,000,000 psi; and for sizes from 27 to 31 gauge, the values are for oil-tempered MB with a modulus of 28,500,000 psi.

Table 14. (Continued) Torsion Spring Deflections

|   |                              |       |       |       |       |       |       |       |       |       |       |       |       |       |               |       |       |
|---|------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------------|-------|-------|
| AMW Wire Gauge<br>Decimal Equivalent <sup>a</sup> | 8                            | 9     | 10    | 11    | 12    | 13    | 14    | 15    | 16    | 17    | 18    | 19    | 20    | 21    | 22            | 23    |       |
| Design Stress, kpsi                               | 210                          | 207   | 205   | 202   | 199   | 197   | 196   | 194   | 192   | 190   | 188   | 187   | 185   | 184   | 183           | 182   |       |
| Torque, pound-inch                                | .1650                        | .2164 | .2783 | .3486 | .4766 | .5763 | .6917 | .8168 | .9550 | 1.107 | 1.272 | 1.460 | 1.655 | 1.876 | 2.114         | 2.371 |       |
| Inside Diameter, inch                             | Deflection, degrees per coil |       |       |       |       |       |       |       |       |       |       |       |       |       |               |       |       |
| $\frac{9}{32}$                                    | 0.28125                      | 42.03 | 37.92 | 34.65 | 31.72 | 28.29 | 26.37 | 25.23 | 23.69 | 22.32 | 21.09 | 19.97 | 19.06 | 18.13 | 17.37         | 16.67 | 16.03 |
| $\frac{5}{16}$                                    | 0.3125                       | 46.39 | 41.82 | 38.19 | 34.95 | 31.14 | 29.01 | 27.74 | 26.04 | 24.51 | 23.15 | 21.91 | 20.90 | 19.87 | 19.02         | 18.25 | 17.53 |
| $\frac{11}{32}$                                   | 0.34375                      | 50.75 | 45.73 | 41.74 | 38.17 | 33.99 | 31.65 | 30.25 | 28.38 | 26.71 | 25.21 | 23.85 | 22.73 | 21.60 | 20.68         | 19.83 | 19.04 |
| $\frac{3}{8}$                                     | 0.375                        | 55.11 | 49.64 | 45.29 | 41.40 | 36.84 | 34.28 | 32.76 | 30.72 | 28.90 | 27.26 | 25.78 | 24.57 | 23.34 | 22.33         | 21.40 | 20.55 |
| $\frac{13}{32}$                                   | 0.40625                      | 59.47 | 53.54 | 48.85 | 44.63 | 39.69 | 36.92 | 35.26 | 33.06 | 31.09 | 29.32 | 27.72 | 26.41 | 25.08 | 23.99         | 22.98 | 22.06 |
| $\frac{7}{16}$                                    | 0.4375                       | 63.83 | 57.45 | 52.38 | 47.85 | 42.54 | 39.56 | 37.77 | 35.40 | 33.28 | 31.38 | 29.66 | 28.25 | 26.81 | 25.64         | 24.56 | 23.56 |
| $\frac{15}{32}$                                   | 0.46875                      | 68.19 | 61.36 | 55.93 | 51.00 | 45.39 | 42.20 | 40.28 | 37.74 | 35.47 | 33.44 | 31.59 | 30.08 | 28.55 | 27.29         | 26.14 | 25.07 |
| $\frac{1}{2}$                                     | 0.500                        | 72.55 | 65.27 | 59.48 | 54.30 | 48.24 | 44.84 | 42.79 | 40.08 | 37.67 | 35.49 | 33.53 | 31.92 | 30.29 | 28.95         | 27.71 | 26.58 |
| AMW Wire Gauge<br>Decimal Equivalent <sup>a</sup> | 24                           | 25    | 26    | 27    | 28    | 29    | 30    | 31    | 32    | 33    | 34    | 35    | 36    | 37    | $\frac{1}{2}$ |       |       |
| Design Stress, kpsi                               | 180                          | 178   | 176   | 174   | 173   | 171   | 169   | 167   | 166   | 164   | 163   | 161   | 160   | 158   | 156           |       |       |
| Torque, pound-inch                                | 2.941                        | 3.590 | 4.322 | 5.139 | 6.080 | 7.084 | 8.497 | 10.07 | 11.88 | 13.81 | 16.00 | 18.83 | 22.07 | 25.49 | 29.92         |       |       |
| Inside Diameter, inch                             | Deflection, degrees per coil |       |       |       |       |       |       |       |       |       |       |       |       |       |               |       |       |
| $\frac{9}{32}$                                    | 0.28125                      | 14.88 | 13.88 | 13.00 | 12.44 | 11.81 | 11.17 | 10.50 | 9.897 | 9.418 | 8.934 | 8.547 | 8.090 | 7.727 | 7.353         | 6.973 |       |
| $\frac{5}{16}$                                    | 0.3125                       | 16.26 | 15.15 | 14.18 | 13.56 | 12.85 | 12.15 | 11.40 | 10.74 | 10.21 | 9.676 | 9.248 | 8.743 | 8.341 | 7.929         | 7.510 |       |
| $\frac{11}{32}$                                   | 0.34375                      | 17.64 | 16.42 | 15.36 | 14.67 | 13.90 | 13.13 | 12.31 | 11.59 | 11.00 | 10.42 | 9.948 | 9.396 | 8.955 | 8.504         | 8.046 |       |
| $\frac{3}{8}$                                     | 0.375                        | 19.02 | 17.70 | 16.54 | 15.79 | 14.95 | 14.11 | 13.22 | 12.43 | 11.80 | 11.16 | 10.65 | 10.05 | 9.569 | 9.080         | 8.583 |       |
| $\frac{13}{32}$                                   | 0.40625                      | 20.40 | 18.97 | 17.72 | 16.90 | 15.99 | 15.09 | 14.13 | 13.28 | 12.59 | 11.90 | 11.35 | 10.70 | 10.18 | 9.655         | 9.119 |       |
| $\frac{7}{16}$                                    | 0.4375                       | 21.79 | 20.25 | 18.90 | 18.02 | 17.04 | 16.07 | 15.04 | 14.12 | 13.38 | 12.64 | 12.05 | 11.35 | 10.80 | 10.23         | 9.655 |       |
| $\frac{15}{32}$                                   | 0.46875                      | 23.17 | 21.52 | 20.08 | 19.14 | 18.09 | 17.05 | 15.94 | 14.96 | 14.17 | 13.39 | 12.75 | 12.01 | 11.41 | 10.81         | 10.19 |       |
| $\frac{1}{2}$                                     | 0.500                        | 24.55 | 22.80 | 21.26 | 20.25 | 19.14 | 18.03 | 16.85 | 15.81 | 14.97 | 14.13 | 13.45 | 12.66 | 12.03 | 11.38         | 10.73 |       |

<sup>a</sup>For sizes up to 13 gauge, the table values are for music wire with a modulus  $E$  of 29,000,000 psi; and for sizes from 27 to 31 gauge, the values are for oil-tempered MB with a modulus of 28,500,000 psi.

Table 14. (Continued) Torsion Spring Deflections

|  |                              |            |            |            |            |            |            |                       |            |            |                         |            |            |                         |            |           |       |
|--|------------------------------|------------|------------|------------|------------|------------|------------|-----------------------|------------|------------|-------------------------|------------|------------|-------------------------|------------|-----------|-------|
| AMW Wire Gauge<br>Decimal Equivalent <sup>a</sup>          | 16<br>.037                   | 17<br>.039 | 18<br>.041 | 19<br>.043 | 20<br>.045 | 21<br>.047 | 22<br>.049 | 23<br>.051            | 24<br>.055 | 25<br>.059 | 26<br>.063              | 27<br>.067 | 28<br>.071 | 29<br>.075              | 30<br>.080 |           |       |
| Design Stress, kpsi  | 192                          | 190        | 188        | 187        | 185        | 184        | 183        | 182                   | 180        | 178        | 176                     | 174        | 173        | 171                     | 169        |           |       |
| Torque, pound-inch   | .9550                        | 1.107      | 1.272      | 1.460      | 1.655      | 1.876      | 2.114      | 2.371                 | 2.941      | 3.590      | 4.322                   | 5.139      | 6.080      | 7.084                   | 8.497      |           |       |
| Inside Diameter, inch                                      | Deflection, degrees per coil |            |            |            |            |            |            |                       |            |            |                         |            |            |                         |            |           |       |
| $\frac{17}{32}$  | 0.53125                      | 39.86      | 37.55      | 35.47      | 33.76      | 32.02      | 30.60      | 29.29                 | 28.09      | 25.93      | 24.07                   | 22.44      | 21.37      | 20.18                   | 19.01      | 17.76     |       |
| $\frac{9}{16}$   | 0.5625                       | 42.05      | 39.61      | 37.40      | 35.59      | 33.76      | 32.25      | 30.87                 | 29.59      | 27.32      | 25.35                   | 23.62      | 22.49      | 21.23                   | 19.99      | 18.67     |       |
| $\frac{19}{32}$  | 0.59375                      | 44.24      | 41.67      | 39.34      | 37.43      | 35.50      | 33.91      | 32.45                 | 31.10      | 28.70      | 26.62                   | 24.80      | 23.60      | 22.28                   | 20.97      | 19.58     |       |
| $\frac{5}{8}$  | 0.625                        | 46.43      | 43.73      | 41.28      | 39.27      | 37.23      | 35.56      | 34.02                 | 32.61      | 30.08      | 27.89                   | 25.98      | 24.72      | 23.33                   | 21.95      | 20.48     |       |
| $\frac{21}{32}$  | 0.65625                      | 48.63      | 45.78      | 43.22      | 41.10      | 38.97      | 37.22      | 35.60                 | 34.12      | 31.46      | 29.17                   | 27.16      | 25.83      | 24.37                   | 22.93      | 21.39     |       |
| $\frac{11}{16}$  | 0.6875                       | 50.82      | 47.84      | 45.15      | 42.94      | 40.71      | 38.87      | 37.18                 | 35.62      | 32.85      | 30.44                   | 28.34      | 26.95      | 25.42                   | 23.91      | 22.30     |       |
| $\frac{23}{32}$  | 0.71875                      | 53.01      | 49.90      | 47.09      | 44.78      | 42.44      | 40.52      | 38.76                 | 37.13      | 34.23      | 31.72                   | 29.52      | 28.07      | 26.47                   | 24.89      | 23.21     |       |
| $\frac{3}{4}$  | 0.750                        | 55.20      | 51.96      | 49.03      | 46.62      | 44.18      | 42.18      | 40.33                 | 38.64      | 35.61      | 32.99                   | 30.70      | 29.18      | 27.52                   | 25.87      | 24.12     |       |
| Wire Gauge <sup>ab</sup> or<br>Size and Decimal Equivalent | 31<br>.085                   | 32<br>.090 | 33<br>.095 | 34<br>.100 | 35<br>.106 | 36<br>.112 | 37<br>.118 | $\frac{1}{8}$<br>.125 | 10<br>.135 | 9<br>.1483 | $\frac{5}{32}$<br>.1563 | 8<br>.162  | 7<br>.177  | $\frac{3}{16}$<br>.1875 | 6<br>.192  | 5<br>.207 |       |
| Design Stress, kpsi  | 167                          | 166        | 164        | 163        | 161        | 160        | 158        | 156                   | 161        | 158        | 156                     | 154        | 150        | 149                     | 146        | 143       |       |
| Torque, pound-inch   | 10.07                        | 11.88      | 13.81      | 16.00      | 18.83      | 22.07      | 25.49      | 29.92                 | 38.90      | 50.60      | 58.44                   | 64.30      | 81.68      | 96.45                   | 101.5      | 124.6     |       |
| Inside Diameter, inch                                      | Deflection, degrees per coil |            |            |            |            |            |            |                       |            |            |                         |            |            |                         |            |           |       |
| $\frac{17}{32}$  | 0.53125                      | 16.65      | 15.76      | 14.87      | 14.15      | 13.31      | 12.64      | 11.96                 | 11.26      | 10.93      | 9.958                   | 9.441      | 9.064      | 8.256                   | 7.856      | 7.565     | 7.015 |
| $\frac{9}{16}$   | 0.5625                       | 17.50      | 16.55      | 15.61      | 14.85      | 13.97      | 13.25      | 12.53                 | 11.80      | 11.44      | 10.42                   | 9.870      | 9.473      | 8.620                   | 8.198      | 7.891     | 7.312 |
| $\frac{19}{32}$  | 0.59375                      | 18.34      | 17.35      | 16.35      | 15.55      | 14.62      | 13.87      | 13.11                 | 12.34      | 11.95      | 10.87                   | 10.30      | 9.882      | 8.984                   | 8.539      | 8.218     | 7.609 |
| $\frac{5}{8}$  | 0.625                        | 19.19      | 18.14      | 17.10      | 16.25      | 15.27      | 14.48      | 13.68                 | 12.87      | 12.47      | 11.33                   | 10.73      | 10.29      | 9.348                   | 8.881      | 8.545     | 7.906 |
| $\frac{21}{32}$  | 0.65625                      | 20.03      | 18.93      | 17.84      | 16.95      | 15.92      | 15.10      | 14.26                 | 13.41      | 12.98      | 11.79                   | 11.16      | 10.70      | 9.713                   | 9.222      | 8.872     | 8.202 |
| $\frac{11}{16}$  | 0.6875                       | 20.88      | 19.72      | 18.58      | 17.65      | 16.58      | 15.71      | 14.83                 | 13.95      | 13.49      | 12.25                   | 11.59      | 11.11      | 10.08                   | 9.564      | 9.199     | 8.499 |
| $\frac{23}{32}$  | 0.71875                      | 21.72      | 20.52      | 19.32      | 18.36      | 17.23      | 16.32      | 15.41                 | 14.48      | 14.00      | 12.71                   | 12.02      | 11.52      | 10.44                   | 9.905      | 9.526     | 8.796 |
| $\frac{3}{4}$  | 0.750                        | 22.56      | 21.31      | 20.06      | 19.06      | 17.88      | 16.94      | 15.99                 | 15.02      | 14.52      | 13.16                   | 12.44      | 11.92      | 10.81                   | 10.25      | 9.852     | 9.093 |

<sup>a</sup> For sizes up to 26 gauge, the table values are for music wire with a modulus  $E$  of 29,500,000 psi; for sizes from 27 to  $\frac{1}{8}$  inch diameter the table values are for music wire with a modulus of 28,500,000 psi; for sizes from 10 gauge to  $\frac{1}{8}$  inch diameter, the values are for oil-tempered MB with a modulus of 28,500,000 psi.

<sup>b</sup> Gauges 31 through 37 are AMW gauges. Gauges 10 through 5 are Washburn and Moen.

Table 14. (Continued) Torsion Spring Deflections

|  |                              |       |                |       |       |                |       |       |               |       |       |               |                |               |               |               |       |
|--|------------------------------|-------|----------------|-------|-------|----------------|-------|-------|---------------|-------|-------|---------------|----------------|---------------|---------------|---------------|-------|
| AMW Wire Gauge<br>Decimal Equivalent <sup>a</sup>                      | .24                          | .25   | .26            | .27   | .28   | .29            | .30   | .31   | .32           | .33   | .34   | .35           | .36            | .37           | $\frac{1}{8}$ |               |       |
| Design Stress, kpsi  | 180                          | 178   | 176            | 174   | 173   | 171            | 169   | 167   | 166           | 164   | 163   | 161           | 160            | 158           | 156           |               |       |
| Torque, pound-inch   | 2.941                        | 3.590 | 4.322          | 5.139 | 6.080 | 7.084          | 8.497 | 10.07 | 11.88         | 13.81 | 16.00 | 18.83         | 22.07          | 25.49         | 29.92         |               |       |
| Inside Diameter, inch  | Deflection, degrees per coil |       |                |       |       |                |       |       |               |       |       |               |                |               |               |               |       |
| $\frac{13}{16}$  | 0.8125                       | 38.38 | 35.54          | 33.06 | 31.42 | 29.61          | 27.83 | 25.93 | 24.25         | 22.90 | 21.55 | 20.46         | 19.19          | 18.17         | 17.14         | 16.09         |       |
| $\frac{7}{8}$  | 0.875                        | 41.14 | 38.09          | 35.42 | 33.65 | 31.70          | 29.79 | 27.75 | 25.94         | 24.58 | 23.03 | 21.86         | 20.49          | 19.39         | 18.29         | 17.17         |       |
| $\frac{15}{16}$  | 0.9375                       | 43.91 | 40.64          | 37.78 | 35.88 | 33.80          | 31.75 | 29.56 | 27.63         | 26.07 | 24.52 | 23.26         | 21.80          | 20.62         | 19.44         | 18.24         |       |
| 1  | 1.000                        | 46.67 | 43.19          | 40.14 | 38.11 | 35.89          | 33.71 | 31.38 | 29.32         | 27.65 | 26.00 | 24.66         | 23.11          | 21.85         | 20.59         | 19.31         |       |
| $1\frac{1}{16}$  | 1.0625                       | 49.44 | 45.74          | 42.50 | 40.35 | 37.99          | 35.67 | 33.20 | 31.01         | 29.24 | 27.48 | 26.06         | 24.41          | 23.08         | 21.74         | 20.38         |       |
| $1\frac{1}{8}$   | 1.125                        | 52.20 | 48.28          | 44.86 | 42.58 | 40.08          | 37.63 | 35.01 | 32.70         | 30.82 | 28.97 | 27.46         | 25.72          | 24.31         | 22.89         | 21.46         |       |
| $1\frac{3}{16}$  | 1.1875                       | 54.97 | 50.83          | 47.22 | 44.81 | 42.18          | 39.59 | 36.83 | 34.39         | 32.41 | 30.45 | 28.86         | 27.02          | 25.53         | 24.04         | 22.53         |       |
| $1\frac{1}{4}$   | 1.250                        | 57.73 | 53.38          | 49.58 | 47.04 | 44.27          | 41.55 | 38.64 | 36.08         | 33.99 | 31.94 | 30.27         | 28.33          | 26.76         | 25.19         | 23.60         |       |
| Washburn and Moen Gauge or<br>Size and Decimal Equivalent <sup>a</sup> | 10                           | 9     | $\frac{7}{16}$ | 8     | 7     | $\frac{3}{16}$ | 6     | 5     | $\frac{1}{2}$ | 4     | 3     | $\frac{1}{4}$ | $\frac{5}{16}$ | $\frac{3}{8}$ | $\frac{1}{2}$ | $\frac{3}{8}$ |       |
| Design Stress, kpsi  | .135                         | .1483 | .1563          | .162  | .177  | .1875          | .192  | .207  | .2188         | .2253 | .2437 | .250          | .2813          | .3125         | .3438         | .375          |       |
| Torque, pound-inch   | 38.90                        | 50.60 | 58.44          | 64.30 | 81.68 | 96.45          | 101.5 | 124.6 | 146.0         | 158.3 | 199.0 | 213.3         | 301.5          | 410.6         | 542.5         | 700.0         |       |
| Inside Diameter, inch  | Deflection, degrees per coil |       |                |       |       |                |       |       |               |       |       |               |                |               |               |               |       |
| $\frac{13}{16}$  | 0.8125                       | 15.54 | 14.08          | 13.30 | 12.74 | 11.53          | 10.93 | 10.51 | 9.687         | 9.208 | 8.933 | 8.346         | 8.125          | 7.382         | 6.784         | 6.292         | 5.880 |
| $\frac{7}{8}$  | 0.875                        | 16.57 | 15.00          | 14.16 | 13.56 | 12.26          | 11.61 | 11.16 | 10.28         | 9.766 | 9.471 | 8.840         | 8.603          | 7.803         | 7.161         | 6.632         | 6.189 |
| $\frac{15}{16}$  | 0.9375                       | 17.59 | 15.91          | 15.02 | 14.38 | 12.99          | 12.30 | 11.81 | 10.87         | 10.32 | 10.01 | 9.333         | 9.081          | 8.225         | 7.537         | 6.972         | 6.499 |
| 1  | 1.000                        | 18.62 | 16.83          | 15.88 | 15.19 | 13.72          | 12.98 | 12.47 | 11.47         | 10.88 | 10.55 | 9.827         | 9.559          | 8.647         | 7.914         | 7.312         | 6.808 |
| $1\frac{1}{16}$  | 1.0625                       | 19.64 | 17.74          | 16.74 | 16.01 | 14.45          | 13.66 | 13.12 | 12.06         | 11.44 | 11.09 | 10.32         | 10.04          | 9.069         | 8.291         | 7.652         | 7.118 |
| $1\frac{1}{8}$   | 1.125                        | 20.67 | 18.66          | 17.59 | 16.83 | 15.18          | 14.35 | 13.77 | 12.66         | 12.00 | 11.62 | 10.81         | 10.52          | 9.491         | 8.668         | 7.993         | 7.427 |
| $1\frac{3}{16}$  | 1.1875                       | 21.69 | 19.57          | 18.45 | 17.64 | 15.90          | 15.03 | 14.43 | 13.25         | 12.56 | 12.16 | 11.31         | 10.99          | 9.912         | 9.045         | 8.333         | 7.737 |
| $1\frac{1}{4}$   | 1.250                        | 22.72 | 20.49          | 19.31 | 18.46 | 16.63          | 15.71 | 15.08 | 13.84         | 13.11 | 12.70 | 11.80         | 11.47          | 10.33         | 9.422         | 8.673         | 8.046 |

<sup>a</sup>For sizes up to 26 gauge, the table values are for music wire with a modulus  $E$  of 29,500,000 psi; for sizes from 27 to  $\frac{1}{8}$  inch diameter the table values are for music wire with a modulus of 28,500,000 psi; for sizes from 10 gauge to  $\frac{1}{8}$  inch diameter, the values are for oil-tempered MB with a modulus of 28,500,000 psi.

For an example in the use of the table, see the example starting on page 340. Note: Intermediate values may be interpolated within reasonable accuracy.

**Table 15. Correction Factors for Other Materials**

| Material <sup>a</sup>         | Factor | Material <sup>a</sup>          | Factor |
|-------------------------------|--------|--------------------------------|--------|
| Hard Drawn MB                 | 0.75   | Stainless 316                  |        |
| Chrome-vanadium               | 1.10   | Up to 1/8 inch diameter        | 0.75   |
| Chrome-silicon                | 1.20   | Over 1/8 to 1/4 inch diameter  | 0.65   |
| Stainless 302 and 304         |        | Over 1/4 inch diameter         | 0.65   |
| Up to 1/8 inch diameter       | 0.85   | Stainless 17-7 PH              |        |
| Over 1/8 to 1/4 inch diameter | 0.75   | Up to 1/8 inch diameter        | 1.00   |
| Over 1/4 inch diameter        | 0.65   | Over 1/8 to 3/16 inch diameter | 1.07   |
| Stainless 431                 | 0.80   | Over 3/16 inch diameter        | 1.12   |
| Stainless 420                 | 0.85   | ...                            | ...    |

<sup>a</sup>For use with values in Table 14. *Note:* The figures in Table 14 are for music wire (ASTM A228) and oil-tempered MB grade (ASTM A229) and can be used for several other materials that have a similar modulus of elasticity  $E$ . However, the design stress may be too high or too low, and therefore the design stress, torque, and deflection per coil should each be multiplied by the appropriate correction factor when using any of the materials given in this table (Table 15).

**Torsion Spring Tolerances.**—Torsion springs are coiled in a different manner from other types of coiled springs and therefore different tolerances apply. The commercial tolerance on loads is  $\pm 10$  per cent and is specified with reference to the angular deflection. For example: 100 pound-inches  $\pm 10$  per cent at 45 degrees deflection. One load specified usually suffices. If two loads and two deflections are specified, the manufacturing and testing times are increased. Tolerances smaller than  $\pm 10$  per cent require each spring to be individually tested and adjusted, which adds considerably to manufacturing time and cost. Tables 16, 17, and 18 give, respectively, free angle tolerances, tolerances on the number of coils, and coil diameter tolerances.

**Table 16. Torsion Spring Tolerances for Angular Relationship of Ends**

| Number of Coils (N) | Spring Index                        |    |      |      |      |      |      |      |     |
|---------------------|-------------------------------------|----|------|------|------|------|------|------|-----|
|                     | 4                                   | 6  | 8    | 10   | 12   | 14   | 16   | 18   | 20  |
|                     | Free Angle Tolerance, $\pm$ degrees |    |      |      |      |      |      |      |     |
| 1                   | 2                                   | 3  | 3.5  | 4    | 4.5  | 5    | 5.5  | 5.5  | 6   |
| 2                   | 4                                   | 5  | 6    | 7    | 8    | 8.5  | 9    | 9.5  | 10  |
| 3                   | 5.5                                 | 7  | 8    | 9.5  | 10.5 | 11   | 12   | 13   | 14  |
| 4                   | 7                                   | 9  | 10   | 12   | 14   | 15   | 16   | 16.5 | 17  |
| 5                   | 8                                   | 10 | 12   | 14   | 16   | 18   | 20   | 20.5 | 21  |
| 6                   | 9.5                                 | 12 | 14.5 | 16   | 19   | 20.5 | 21   | 22.5 | 24  |
| 8                   | 12                                  | 15 | 18   | 20.5 | 23   | 25   | 27   | 28   | 29  |
| 10                  | 14                                  | 19 | 21   | 24   | 27   | 29   | 31.5 | 32.5 | 34  |
| 15                  | 20                                  | 25 | 28   | 31   | 34   | 36   | 38   | 40   | 42  |
| 20                  | 25                                  | 30 | 34   | 37   | 41   | 44   | 47   | 49   | 51  |
| 25                  | 29                                  | 35 | 40   | 44   | 48   | 52   | 56   | 60   | 63  |
| 30                  | 32                                  | 38 | 44   | 50   | 55   | 60   | 65   | 68   | 70  |
| 50                  | 45                                  | 55 | 63   | 70   | 77   | 84   | 90   | 95   | 100 |

**Table 17. Torsion Spring Tolerance on Number of Coils**

| Number of Coils | Tolerance      | Number of Coils | Tolerance      |
|-----------------|----------------|-----------------|----------------|
| up to 5         | $\pm 5^\circ$  | over 10 to 20   | $\pm 15^\circ$ |
| over 5 to 10    | $\pm 10^\circ$ | over 20 to 40   | $\pm 30^\circ$ |



**Table 18. Torsion Spring Coil Diameter Tolerances**

| Wire Diameter, Inch | Spring Index                    |       |       |       |       |       |       |
|---------------------|---------------------------------|-------|-------|-------|-------|-------|-------|
|                     | 4                               | 6     | 8     | 10    | 12    | 14    | 16    |
|                     | Coil Diameter Tolerance, ± inch |       |       |       |       |       |       |
| 0.015               | 0.002                           | 0.002 | 0.002 | 0.002 | 0.003 | 0.003 | 0.004 |
| 0.023               | 0.002                           | 0.002 | 0.002 | 0.003 | 0.004 | 0.005 | 0.006 |
| 0.035               | 0.002                           | 0.002 | 0.003 | 0.004 | 0.006 | 0.007 | 0.009 |
| 0.051               | 0.002                           | 0.003 | 0.005 | 0.007 | 0.008 | 0.010 | 0.012 |
| 0.076               | 0.003                           | 0.005 | 0.007 | 0.009 | 0.012 | 0.015 | 0.018 |
| 0.114               | 0.004                           | 0.007 | 0.010 | 0.013 | 0.018 | 0.022 | 0.028 |
| 0.172               | 0.006                           | 0.010 | 0.013 | 0.020 | 0.027 | 0.034 | 0.042 |
| 0.250               | 0.008                           | 0.014 | 0.022 | 0.030 | 0.040 | 0.050 | 0.060 |

**Miscellaneous Springs.**— This section provides information on various springs, some in common use, some less commonly used.

*Conical compression:* These springs taper from top to bottom and are useful where an increasing (instead of a constant) load rate is needed, where solid height must be small, and where vibration must be damped. Conical springs with a uniform pitch are easiest to coil. Load and deflection formulas for compression springs can be used – using the average mean coil diameter, and providing the deflection does not cause the largest active coil to lie against the bottom coil. When this happens, each coil must be calculated separately, using the standard formulas for compression springs.

*Constant force springs:* Those springs are made from flat spring steel and are finding more applications each year. Complicated design procedures can be eliminated by selecting a standard design from thousands now available from several spring manufacturers.

*Spiral, clock, and motor springs:* Although often used in wind-up type motors for toys and other products, these springs are difficult to design and results cannot be calculated with precise accuracy. However, many useful designs have been developed and are available from spring manufacturing companies.

*Flat springs:* These springs are often used to overcome operating space limitations in various products such as electric switches and relays. Table 19 lists formulas for designing flat springs. The formulas are based on standard beam formulas where the deflection is small.

**Table 19. Formulas for Flat Springs**

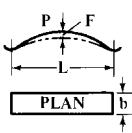
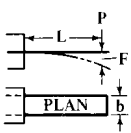
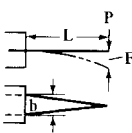
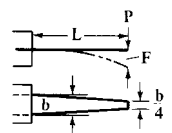
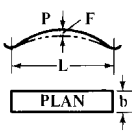
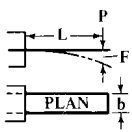
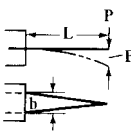
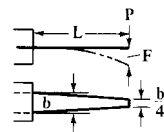
| Feature                      |  |  |  |  |
|------------------------------|---|---|---|---|
| Deflect., <i>f</i><br>Inches | $f = \frac{PL^3}{4Ebt^3}$<br>$= \frac{S_b L^2}{6Et}$                                | $f = \frac{4PL^3}{Ebt^3}$<br>$= \frac{2S_b L^2}{3Et}$                               | $f = \frac{6PL^3}{Ebt^3}$<br>$= \frac{S_b L^2}{Et}$                                 | $f = \frac{5.22PL^3}{Ebt^3}$<br>$= \frac{0.87S_b L^2}{Et}$                          |
| Load, <i>P</i><br>Pounds     | $P = \frac{2S_b bt^2}{3L}$<br>$= \frac{4Ebt^3 F}{L^3}$                              | $P = \frac{S_b bt^2}{6L}$<br>$= \frac{Ebt^3 F}{4L^3}$                               | $P = \frac{S_b bt^2}{6L}$<br>$= \frac{Ebt^3 F}{6L^3}$                               | $P = \frac{S_b bt^2}{6L}$<br>$= \frac{Ebt^3 F}{5.22L^3}$                            |

Table 19. (Continued) Formulas for Flat Springs

|                                 |   |   |   |   |
|---------------------------------|---|---|---|---|
| Feature                         |  |  |  |  |
| Stress, $S_b$<br>Bending<br>psi | $S_b = \frac{3PL}{2bt^2}$<br>$= \frac{6EtF}{L^2}$                                 | $S_b = \frac{6PL}{bt^2}$<br>$= \frac{3EtF}{2L^2}$                                 | $S_b = \frac{6PL}{bt^2}$<br>$= \frac{EtF}{L^2}$                                   | $S_b = \frac{6PL}{bt^2}$<br>$= \frac{EtF}{0.87L^2}$                               |
| Thickness, $t$<br>Inches        | $t = \frac{S_b L^2}{6EF}$<br>$= \sqrt[3]{\frac{PL^3}{4EbF}}$                      | $t = \frac{2S_b L^2}{3EF}$<br>$= \sqrt[3]{\frac{4PL^3}{EbF}}$                     | $t = \frac{S_b L^2}{EF}$<br>$= \sqrt[3]{\frac{6PL^3}{EbF}}$                       | $t = \frac{0.87S_b L^2}{EF}$<br>$= \sqrt[3]{\frac{5.22PL^3}{EbF}}$                |

Based on standard beam formulas where the deflection is small.

See page 308 for notation.

*Note:* Where two formulas are given for one feature, the designer should use the one found to be appropriate for the given design. The result from either of any two formulas is the same.

*Belleville washers or disc springs:* These washer type springs can sustain relatively large loads with small deflections, and the loads and deflections can be increased by stacking the springs.

Information on springs of this type is given in the section *DISC SPRINGS* starting on page 354.

*Volute springs:* These springs are often used on army tanks and heavy field artillery, and seldom find additional uses because of their high cost, long production time, difficulties in manufacture, and unavailability of a wide range of materials and sizes. Small volute springs are often replaced with standard compression springs.

*Torsion bars:* Although the more simple types are often used on motor cars, the more complicated types with specially forged ends are finding fewer applications as time goes.

**Moduli of Elasticity of Spring Materials.**—The modulus of elasticity in tension, denoted by the letter  $E$ , and the modulus of elasticity in torsion, denoted by the letter  $G$ , are used in formulas relating to spring design. Values of these moduli for various ferrous and nonferrous spring materials are given in Table 20.

**General Heat Treating Information for Springs.**—The following is general information on the heat treatment of springs, and is applicable to pre-tempered or hard-drawn spring materials only.

*Compression springs* are baked after coiling (before setting) to relieve residual stresses and thus permit larger deflections before taking a permanent set.

*Extension springs* also are baked, but heat removes some of the initial tension. Allowance should be made for this loss. Baking at 500 degrees F for 30 minutes removes approximately 50 per cent of the initial tension. The shrinkage in diameter however, will slightly increase the load and rate.

*Outside diameters shrink* when springs of music wire, pretempered MB, and other carbon or alloy steels are baked. Baking also slightly increases the free length and these changes produce a little stronger load and increase the rate.

*Outside diameters expand* when springs of stainless steel (18-8) are baked. The free length is also reduced slightly and these changes result in a little lighter load and a decrease the spring rate.

*Inconel, Monel, and nickel alloys* do not change much when baked.

*Beryllium-copper shrinks and deforms* when heated. Such springs usually are baked in fixtures or supported on arbors or rods during heating.

*Brass and phosphor bronze* springs should be given a light heat only. Baking above 450 degrees F will soften the material. Do not heat in salt pots.

*Torsion springs* do not require baking because coiling causes residual stresses in a direction that is helpful, but such springs frequently are baked so that jarring or handling will not cause them to lose the position of their ends.

**Table 20. Moduli of Elasticity in Torsion and Tension of Spring Materials**

| Ferrous Materials             |  |                         | Nonferrous Materials          |  |                         |
|-------------------------------|--|-------------------------|-------------------------------|--|-------------------------|
| Material<br>(Commercial Name) | Modulus of Elasticity <sup>a</sup> , psi |                         | Material<br>(Commercial Name) | Modulus of Elasticity <sup>a</sup> , psi |                         |
|                               | In Torsion, <i>G</i>                     | In Tension, <i>E</i>    |                               | In Torsion, <i>G</i>                     | In Tension, <i>E</i>    |
| Hard Drawn MB                 |  |                         | Spring Brass                  |  |                         |
| Up to 0.032 inch              | 11,700,000                               | 28,800,000              | Type 70-30                    | 5,000,000                                | 15,000,000              |
| 0.033 to 0.063 inch           | 11,600,000                               | 28,700,000              | Phosphor Bronze               |  |                         |
| 0.064 to 0.125 inch           | 11,500,000                               | 28,600,000              | 5 per cent tin                | 6,000,000                                | 15,000,000              |
| 0.126 to 0.625 inch           | 11,400,000                               | 28,500,000              | Beryllium-Copper              |  |                         |
| Music Wire                    |  |                         | Cold Drawn 4 Nos.             | 7,000,000                                | 17,000,000              |
| Up to 0.032 inch              | 12,000,000                               | 29,500,000              | Pretempered, fully hard       | 7,250,000                                | 19,000,000              |
| 0.033 to 0.063 inch           | 11,850,000                               | 29,000,000              | Inconel <sup>b</sup> 600      | 10,500,000                               | 31,000,000 <sup>c</sup> |
| 0.064 to 0.125 inch           | 11,750,000                               | 28,500,000              | Inconel <sup>b</sup> X 750    | 10,500,000                               | 31,000,000 <sup>c</sup> |
| 0.126 to 0.250 inch           | 11,600,000                               | 28,000,000              | Monel <sup>b</sup> 400        | 9,500,000                                | 26,000,000              |
| Oil-Tempered MB               | 11,200,000                               | 28,500,000              | Monel <sup>b</sup> K 500      | 9,500,000                                | 26,000,000              |
| Chrome-Vanadium               | 11,200,000                               | 28,500,000              | Duranickel <sup>b</sup> 300   | 11,000,000                               | 30,000,000              |
| Chrome-Silicon                | 11,200,000                               | 29,500,000              | Permanickel <sup>b</sup>      | 11,000,000                               | 30,000,000              |
| Silicon-Manganese             | 10,750,000                               | 29,000,000              | Ni Span <sup>b</sup> C 902    | 10,000,000                               | 27,500,000              |
| Stainless Steel               |  |                         | Elgiloy <sup>d</sup>          | 12,000,000                               | 29,500,000              |
| Types 302, 304, 316           | 10,000,000                               | 28,000,000 <sup>c</sup> | Iso-Elastic <sup>e</sup>      | 9,200,000                                | 26,000,000              |
| Type 17-7 PH                  | 10,500,000                               | 29,500,000              |                               |  |                         |
| Type 420                      | 11,000,000                               | 29,000,000              |                               |  |                         |
| Type 431                      | 11,400,000                               | 29,500,000              |                               |  |                         |

<sup>a</sup> Note: Modulus *G* (shear modulus) is used for compression and extension springs; modulus *E* (Young's modulus) is used for torsion, flat, and spiral springs.

<sup>b</sup> Trade name of International Nickel Company.

<sup>c</sup> May be 2,000,000 pounds per square inch less if material is not fully hard.

<sup>d</sup> Trade name of Hamilton Watch Company.

<sup>e</sup> Trade name of John Chatillon & Sons.

*Spring brass and phosphor bronze* springs that are not very highly stressed and are not subject to severe operating use may be stress relieved after coiling by immersing them in boiling water for a period of 1 hour.

*Positions of loops* will change with heat. Parallel hooks may change as much as 45 degrees during baking. Torsion spring arms will alter position considerably. These changes should be allowed for during looping or forming.

*Quick heating* after coiling either in a high-temperature salt pot or by passing a spring through a gas flame is not good practice. Samples heated in this way will not conform with production runs that are properly baked. A small, controlled-temperature oven should be used for samples and for small lot orders.

*Plated springs* should always be baked before plating to relieve coiling stresses and again after plating to relieve hydrogen embrittlement.

*Hardness* values fall with high heat—but music wire, hard drawn, and stainless steel will increase 2 to 4 points Rockwell C.

**Table 21. Squares, Cubes, and Fourth Powers of Wire Diameters**

| Steel Wire Gage (U.S.) | Music or Piano Wire Gage | Diameter |         | Section Area | Square    | Cube        | Fourth Power |
|------------------------|--------------------------|----------|---------|--------------|-----------|-------------|--------------|
|                        |                          | Inch     |         |              |           |             |              |
| 7-0                    | ...                      | 0.4900   | 0.1886  | 0.24010      | 0.11765   | 0.05765     |              |
| 6-0                    | ...                      | 0.4615   | 0.1673  | 0.21298      | 0.09829   | 0.04536     |              |
| 5-0                    | ...                      | 0.4305   | 0.1456  | 0.18533      | 0.07978   | 0.03435     |              |
| 4-0                    | ...                      | 0.3938   | 0.1218  | 0.15508      | 0.06107   | 0.02405     |              |
| 3-0                    | ...                      | 0.3625   | 0.1032  | 0.13141      | 0.04763   | 0.01727     |              |
| 2-0                    | ...                      | 0.331    | 0.0860  | 0.10956      | 0.03626   | 0.01200     |              |
| 1-0                    | ...                      | 0.3065   | 0.0738  | 0.09394      | 0.02879   | 0.008825    |              |
| 1                      | ...                      | 0.283    | 0.0629  | 0.08009      | 0.02267   | 0.006414    |              |
| 2                      | ...                      | 0.2625   | 0.0541  | 0.06891      | 0.01809   | 0.004748    |              |
| 3                      | ...                      | 0.2437   | 0.0466  | 0.05939      | 0.01447   | 0.003527    |              |
| 4                      | ...                      | 0.2253   | 0.0399  | 0.05076      | 0.01144   | 0.002577    |              |
| 5                      | ...                      | 0.207    | 0.0337  | 0.04285      | 0.00887   | 0.001836    |              |
| 6                      | ...                      | 0.192    | 0.0290  | 0.03686      | 0.00708   | 0.001359    |              |
| ...                    | 45                       | 0.180    | 0.0254  | 0.03240      | 0.00583   | 0.001050    |              |
| 7                      | ...                      | 0.177    | 0.0246  | 0.03133      | 0.00555   | 0.000982    |              |
| ...                    | 44                       | 0.170    | 0.0227  | 0.02890      | 0.00491   | 0.000835    |              |
| 8                      | ...                      | 0.162    | 0.0206  | 0.02624      | 0.00425   | 0.000689    |              |
| ...                    | 42                       | 0.154    | 0.0186  | 0.02372      | 0.00365   | 0.000563    |              |
| 9                      | ...                      | 0.1483   | 0.0173  | 0.02199      | 0.00326   | 0.000484    |              |
| ...                    | 41                       | 0.146    | 0.0167  | 0.02132      | 0.00311   | 0.000455    |              |
| ...                    | 40                       | 0.138    | 0.0150  | 0.01904      | 0.00263   | 0.000363    |              |
| 10                     | ...                      | 0.135    | 0.0143  | 0.01822      | 0.00246   | 0.000332    |              |
| ...                    | 39                       | 0.130    | 0.0133  | 0.01690      | 0.00220   | 0.000286    |              |
| ...                    | 38                       | 0.124    | 0.0121  | 0.01538      | 0.00191   | 0.000237    |              |
| 11                     | ...                      | 0.1205   | 0.0114  | 0.01452      | 0.00175   | 0.000211    |              |
| ...                    | 37                       | 0.118    | 0.0109  | 0.01392      | 0.00164   | 0.000194    |              |
| ...                    | 36                       | 0.112    | 0.0099  | 0.01254      | 0.00140   | 0.000157    |              |
| ...                    | 35                       | 0.106    | 0.0088  | 0.01124      | 0.00119   | 0.000126    |              |
| 12                     | ...                      | 0.1055   | 0.0087  | 0.01113      | 0.001174  | 0.0001239   |              |
| ...                    | 34                       | 0.100    | 0.0078  | 0.0100       | 0.001000  | 0.0001000   |              |
| ...                    | 33                       | 0.095    | 0.0071  | 0.00902      | 0.000857  | 0.0000815   |              |
| 13                     | ...                      | 0.0915   | 0.0066  | 0.00837      | 0.000766  | 0.0000701   |              |
| ...                    | 32                       | 0.090    | 0.0064  | 0.00810      | 0.000729  | 0.0000656   |              |
| ...                    | 31                       | 0.085    | 0.0057  | 0.00722      | 0.000614  | 0.0000522   |              |
| 14                     | ...                      | 0.080    | 0.0050  | 0.0064       | 0.000512  | 0.0000410   |              |
| ...                    | 29                       | 0.075    | 0.0044  | 0.00562      | 0.000422  | 0.0000316   |              |
| 15                     | ...                      | 0.072    | 0.0041  | 0.00518      | 0.000373  | 0.0000269   |              |
| ...                    | 28                       | 0.071    | 0.0040  | 0.00504      | 0.000358  | 0.0000254   |              |
| ...                    | 27                       | 0.067    | 0.0035  | 0.00449      | 0.000301  | 0.0000202   |              |
| ...                    | 26                       | 0.063    | 0.0031  | 0.00397      | 0.000250  | 0.0000158   |              |
| 16                     | ...                      | 0.0625   | 0.0031  | 0.00391      | 0.000244  | 0.0000153   |              |
| ...                    | 25                       | 0.059    | 0.0027  | 0.00348      | 0.000205  | 0.0000121   |              |
| ...                    | 24                       | 0.055    | 0.0024  | 0.00302      | 0.000166  | 0.00000915  |              |
| 17                     | ...                      | 0.054    | 0.0023  | 0.00292      | 0.000157  | 0.00000850  |              |
| ...                    | 23                       | 0.051    | 0.0020  | 0.00260      | 0.000133  | 0.00000677  |              |
| ...                    | 22                       | 0.049    | 0.00189 | 0.00240      | 0.000118  | 0.00000576  |              |
| 18                     | ...                      | 0.0475   | 0.00177 | 0.00226      | 0.000107  | 0.00000509  |              |
| ...                    | 21                       | 0.047    | 0.00173 | 0.00221      | 0.000104  | 0.00000488  |              |
| ...                    | 20                       | 0.045    | 0.00159 | 0.00202      | 0.000091  | 0.00000410  |              |
| ...                    | 19                       | 0.043    | 0.00145 | 0.00185      | 0.0000795 | 0.00000342  |              |
| 19                     | ...                      | 0.041    | 0.00132 | 0.00168      | 0.0000689 | 0.00000283  |              |
| ...                    | 17                       | 0.039    | 0.00119 | 0.00152      | 0.0000593 | 0.00000231  |              |
| ...                    | 16                       | 0.037    | 0.00108 | 0.00137      | 0.0000507 | 0.00000187  |              |
| ...                    | 15                       | 0.035    | 0.00096 | 0.00122      | 0.0000429 | 0.00000150  |              |
| 20                     | ...                      | 0.0348   | 0.00095 | 0.00121      | 0.0000421 | 0.00000147  |              |
| ...                    | 14                       | 0.033    | 0.00086 | 0.00109      | 0.0000359 | 0.00000119  |              |
| 21                     | ...                      | 0.0317   | 0.00079 | 0.00100      | 0.0000319 | 0.00000101  |              |
| ...                    | 13                       | 0.031    | 0.00075 | 0.00096      | 0.0000298 | 0.000000924 |              |
| ...                    | 12                       | 0.029    | 0.00066 | 0.00084      | 0.0000244 | 0.000000707 |              |
| 22                     | ...                      | 0.0286   | 0.00064 | 0.00082      | 0.0000234 | 0.000000669 |              |
| ...                    | 11                       | 0.026    | 0.00053 | 0.00068      | 0.0000176 | 0.000000457 |              |
| 23                     | ...                      | 0.0258   | 0.00052 | 0.00067      | 0.0000172 | 0.000000443 |              |
| ...                    | 10                       | 0.024    | 0.00045 | 0.00058      | 0.0000138 | 0.000000332 |              |
| 24                     | ...                      | 0.023    | 0.00042 | 0.00053      | 0.0000122 | 0.000000280 |              |
| ...                    | 9                        | 0.022    | 0.00038 | 0.00048      | 0.0000106 | 0.000000234 |              |

**Spring Failure.**—Spring failure may be breakage, high permanent set, or loss of load. The causes are listed in groups in [Table 22](#). Group 1 covers causes that occur most frequently; Group 2 covers causes that are less frequent; and Group 3 lists causes that occur occasionally.

**Table 22. Causes of Spring Failure**

|         | Cause                  | Comments and Recommendations  |
|---------|------------------------|---|
| Group 1 | High stress            | The majority of spring failures are due to high stresses caused by large deflections and high loads. High stresses should be used only for statically loaded springs. Low stresses lengthen fatigue life.   |
|         | Hydrogen embrittlement | Improper electroplating methods and acid cleaning of springs, without proper baking treatment, cause spring steels to become brittle, and are a frequent cause of failure. Nonferrous springs are immune.   |
|         | Sharp bends and holes  | Sharp bends on extension, torsion, and flat springs, and holes or notches in flat springs, cause high concentrations of stress, resulting in failure. Bend radii should be as large as possible, and tool marks avoided.  |
|         | Fatigue                | Repeated deflections of springs, especially above 1,000,000 cycles, even with medium stresses, may cause failure. Low stresses should be used if a spring is to be subjected to a very high number of operating cycles.   |
| Group 2 | Shock loading          | Impact, shock, and rapid loading cause far higher stresses than those computed by the regular spring formulas. High-carbon spring steels do not withstand shock loading as well as do alloy steels.   |
|         | Corrosion              | Slight rusting or pitting caused by acids, alkalis, galvanic corrosion, stress corrosion cracking, or corrosive atmosphere weakens the material and causes higher stresses in the corroded area.  |
|         | Faulty heat treatment  | Keeping spring materials at the hardening temperature for longer periods than necessary causes an undesirable growth in grain structure, resulting in brittleness, even though the hardness may be correct.   |
|         | Faulty material        | Poor material containing inclusions, seams, slivers, and flat material with rough, slit, or torn edges is a cause of early failure. Overdrawn wire, improper hardness, and poor grain structure also cause early failure.   |
| Group 3 | High temperature       | High operating temperatures reduce spring temper (or hardness) and lower the modulus of elasticity, thereby causing lower loads, reducing the elastic limit, and increasing corrosion. Corrosion-resisting or nickel alloys should be used.   |
|         | Low temperature        | Temperatures below $-40$ degrees F reduce the ability of carbon steels to withstand shock loads. Carbon steels become brittle at $-70$ degrees F. Corrosion-resisting, nickel, or nonferrous alloys should be used.   |
|         | Friction               | Close fits on rods or in holes result in a wearing away of material and occasional failure. The outside diameters of compression springs expand during deflection but they become smaller on torsion springs.   |
|         | Other causes           | Enlarged hooks on extension springs increase the stress at the bends. Carrying too much electrical current will cause failure. Welding and soldering frequently destroy the spring temper. Tool marks, nicks, and cuts often raise stresses. Deflecting torsion springs outwardly causes high stresses and winding them tightly causes binding on supporting rods. High speed of deflection, vibration, and surging due to operation near natural periods of vibration or their harmonics cause increased stresses. |

**Table 23. Arbor Diameters for Springs Made from Music Wire**

| Wire Dia. (inch) | Spring Outside Diameter (inch) |       |       |       |       |       |       |       |       |       |       |       |       |     |
|------------------|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-----|
|                  | 1/16                           | 3/32  | 1/8   | 5/32  | 3/16  | 7/32  | 1/4   | 9/32  | 5/16  | 11/32 | 3/8   | 7/16  | 1/2   |     |
|                  | Arbor Diameter (inch)          |       |       |       |       |       |       |       |       |       |       |       |       |     |
| 0.008            | 0.039                          | 0.060 | 0.078 | 0.093 | 0.107 | 0.119 | 0.129 | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.010            | 0.037                          | 0.060 | 0.080 | 0.099 | 0.115 | 0.129 | 0.142 | 0.154 | 0.164 | ...   | ...   | ...   | ...   | ... |
| 0.012            | 0.034                          | 0.059 | 0.081 | 0.101 | 0.119 | 0.135 | 0.150 | 0.163 | 0.177 | 0.189 | 0.200 | ...   | ...   | ... |
| 0.014            | 0.031                          | 0.057 | 0.081 | 0.102 | 0.121 | 0.140 | 0.156 | 0.172 | 0.187 | 0.200 | 0.213 | 0.234 | ...   | ... |
| 0.016            | 0.028                          | 0.055 | 0.079 | 0.102 | 0.123 | 0.142 | 0.161 | 0.178 | 0.194 | 0.209 | 0.224 | 0.250 | 0.271 | ... |
| 0.018            | ...                            | 0.053 | 0.077 | 0.101 | 0.124 | 0.144 | 0.161 | 0.182 | 0.200 | 0.215 | 0.231 | 0.259 | 0.284 | ... |
| 0.020            | ...                            | 0.049 | 0.075 | 0.096 | 0.123 | 0.144 | 0.165 | 0.184 | 0.203 | 0.220 | 0.237 | 0.268 | 0.296 | ... |
| 0.022            | ...                            | 0.046 | 0.072 | 0.097 | 0.122 | 0.145 | 0.165 | 0.186 | 0.206 | 0.224 | 0.242 | 0.275 | 0.305 | ... |
| 0.024            | ...                            | 0.043 | 0.070 | 0.095 | 0.120 | 0.144 | 0.166 | 0.187 | 0.207 | 0.226 | 0.245 | 0.280 | 0.312 | ... |
| 0.026            | ...                            | ...   | 0.067 | 0.093 | 0.118 | 0.143 | 0.166 | 0.187 | 0.208 | 0.228 | 0.248 | 0.285 | 0.318 | ... |
| 0.028            | ...                            | ...   | 0.064 | 0.091 | 0.115 | 0.141 | 0.165 | 0.187 | 0.208 | 0.229 | 0.250 | 0.288 | 0.323 | ... |
| 0.030            | ...                            | ...   | 0.061 | 0.088 | 0.113 | 0.138 | 0.163 | 0.187 | 0.209 | 0.229 | 0.251 | 0.291 | 0.328 | ... |
| 0.032            | ...                            | ...   | 0.057 | 0.085 | 0.111 | 0.136 | 0.161 | 0.185 | 0.209 | 0.229 | 0.251 | 0.292 | 0.331 | ... |
| 0.034            | ...                            | ...   | ...   | 0.082 | 0.109 | 0.134 | 0.159 | 0.184 | 0.208 | 0.229 | 0.251 | 0.292 | 0.333 | ... |
| 0.036            | ...                            | ...   | ...   | 0.078 | 0.106 | 0.131 | 0.156 | 0.182 | 0.206 | 0.229 | 0.250 | 0.294 | 0.333 | ... |
| 0.038            | ...                            | ...   | ...   | 0.075 | 0.103 | 0.129 | 0.154 | 0.179 | 0.205 | 0.227 | 0.251 | 0.293 | 0.335 | ... |
| 0.041            | ...                            | ...   | ...   | ...   | 0.098 | 0.125 | 0.151 | 0.176 | 0.201 | 0.226 | 0.250 | 0.294 | 0.336 | ... |
| 0.0475           | ...                            | ...   | ...   | ...   | 0.087 | 0.115 | 0.142 | 0.168 | 0.194 | 0.220 | 0.244 | 0.293 | 0.337 | ... |
| 0.054            | ...                            | ...   | ...   | ...   | ...   | 0.103 | 0.132 | 0.160 | 0.187 | 0.212 | 0.245 | 0.287 | 0.336 | ... |
| 0.0625           | ...                            | ...   | ...   | ...   | ...   | ...   | 0.108 | 0.146 | 0.169 | 0.201 | 0.228 | 0.280 | 0.330 | ... |
| 0.072            | ...                            | ...   | ...   | ...   | ...   | ...   | ...   | 0.129 | 0.158 | 0.186 | 0.214 | 0.268 | 0.319 | ... |
| 0.080            | ...                            | ...   | ...   | ...   | ...   | ...   | ...   | ...   | 0.144 | 0.173 | 0.201 | 0.256 | 0.308 | ... |
| 0.0915           | ...                            | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | 0.181 | 0.238 | 0.293 | ... |
| 0.1055           | ...                            | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | 0.215 | 0.271 | ... |
| 0.1205           | ...                            | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | 0.215 | ... |
| 0.125            | ...                            | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | 0.239 | ... |

| Wire Dia. (inch) | Spring Outside Diameter (inches) |       |        |       |       |       |       |       |       |       |       |       |       |      |
|------------------|----------------------------------|-------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|
|                  | 5/16                             | 5/8   | 1 1/16 | 3/4   | 13/16 | 7/8   | 15/16 | 1     | 1 1/8 | 1 1/4 | 1 3/8 | 1 1/2 | 1 3/4 | 2    |
|                  | Arbor Diameter (inches)          |       |        |       |       |       |       |       |       |       |       |       |       |      |
| 0.022            | 0.332                            | 0.357 | 0.380  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...  |
| 0.024            | 0.341                            | 0.367 | 0.393  | 0.415 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...  |
| 0.026            | 0.350                            | 0.380 | 0.406  | 0.430 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...  |
| 0.028            | 0.356                            | 0.387 | 0.416  | 0.442 | 0.467 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...  |
| 0.030            | 0.362                            | 0.395 | 0.426  | 0.453 | 0.481 | 0.506 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...  |
| 0.032            | 0.367                            | 0.400 | 0.432  | 0.462 | 0.490 | 0.516 | 0.540 | ...   | ...   | ...   | ...   | ...   | ...   | ...  |
| 0.034            | 0.370                            | 0.404 | 0.437  | 0.469 | 0.498 | 0.526 | 0.552 | 0.557 | ...   | ...   | ...   | ...   | ...   | ...  |
| 0.036            | 0.372                            | 0.407 | 0.442  | 0.474 | 0.506 | 0.536 | 0.562 | 0.589 | ...   | ...   | ...   | ...   | ...   | ...  |
| 0.038            | 0.375                            | 0.412 | 0.448  | 0.481 | 0.512 | 0.543 | 0.572 | 0.600 | 0.650 | ...   | ...   | ...   | ...   | ...  |
| 0.041            | 0.378                            | 0.416 | 0.456  | 0.489 | 0.522 | 0.554 | 0.586 | 0.615 | 0.670 | 0.718 | ...   | ...   | ...   | ...  |
| 0.0475           | 0.380                            | 0.422 | 0.464  | 0.504 | 0.541 | 0.576 | 0.610 | 0.643 | 0.706 | 0.763 | 0.812 | ...   | ...   | ...  |
| 0.054            | 0.381                            | 0.425 | 0.467  | 0.509 | 0.550 | 0.589 | 0.625 | 0.661 | 0.727 | 0.792 | 0.850 | 0.906 | ...   | ...  |
| 0.0625           | 0.379                            | 0.426 | 0.468  | 0.512 | 0.556 | 0.597 | 0.639 | 0.678 | 0.753 | 0.822 | 0.889 | 0.951 | 1.06  | 1.17 |
| 0.072            | 0.370                            | 0.418 | 0.466  | 0.512 | 0.555 | 0.599 | 0.641 | 0.682 | 0.765 | 0.840 | 0.911 | 0.980 | 1.11  | 1.22 |
| 0.080            | 0.360                            | 0.411 | 0.461  | 0.509 | 0.554 | 0.599 | 0.641 | 0.685 | 0.772 | 0.851 | 0.930 | 1.00  | 1.13  | 1.26 |
| 0.0915           | 0.347                            | 0.398 | 0.448  | 0.500 | 0.547 | 0.597 | 0.640 | 0.685 | 0.776 | 0.860 | 0.942 | 1.02  | 1.16  | 1.30 |
| 0.1055           | 0.327                            | 0.381 | 0.433  | 0.485 | 0.535 | 0.586 | 0.630 | 0.683 | 0.775 | 0.865 | 0.952 | 1.04  | 1.20  | 1.35 |
| 0.1205           | 0.303                            | 0.358 | 0.414  | 0.468 | 0.520 | 0.571 | 0.622 | 0.673 | 0.772 | 0.864 | 0.955 | 1.04  | 1.22  | 1.38 |
| 0.125            | 0.295                            | 0.351 | 0.406  | 0.461 | 0.515 | 0.567 | 0.617 | 0.671 | 0.770 | 0.864 | 0.955 | 1.05  | 1.23  | 1.39 |

## DISC SPRINGS

## Performance of Disc Springs

**Introduction.**—Disc springs, also known as Belleville springs, are conically formed from washers and have rectangular cross section. The disc spring concept was invented by a Frenchman Louis Belleville in 1865. His springs were relatively thick and had a small amount of cone height or “dish”, which determined axial deflection. At that time, these springs were used in the buffer parts of railway rolling stock, for recoil mechanisms of guns, and some other applications. The use of disc springs will be advantageous when space is limited and high force is required, as these conditions cannot be satisfied by using coil springs. Load-deflection characteristics of disc springs are linear and regressive depending on their dimensions and the type of stacking. A large number of standard sizes are available from disc spring manufacturers and distributors, so that custom sizes may not be required. Therefore, disc springs are widely used today in virtually all branches of engineering with possibilities of new applications.

**Disc Spring Nomenclature.**—Disc spring manufacturers assign their own part number for each disc spring, but the catalog numbers for disc springs are similar, so each item can often be identified regardless of the manufacturer. The disc spring identification number is a numerical code that provides basic dimensions in millimeters. Identification numbers representing the primary dimensions of the disc spring and consist of one, two, or three numbers separated from each other by dash marks or spaces. Disc spring manufacturers in the United States also provide dimensions in inches. Dimensions of several typical disc springs are shown in the following table. Basic nomenclature is illustrated in Fig. 1.

| Catalog Number (mm) | Outside Diameter $D$ (mm) | Inside Diameter $d$ (mm) | Thickness $t$ (mm) | Equivalent Catalog Number (inch) |
|---------------------|---------------------------|--------------------------|--------------------|----------------------------------|
| 8-4.2-0.4           | 8                         | 4.2                      | 0.4                | 0.315-0.165-0.0157               |
| 50-25.4-2           | 50                        | 25.4                     | 2                  | 1.97-1.00-0.0787                 |
| 200-102-12          | 200                       | 102                      | 12                 | 7.87-4.02-0.472                  |

Additional dimensions shown in catalogs are cone (dish) height  $h$  at unloaded condition, and overall height  $H = h + t$ , that combines the cone height and the thickness of a disc spring.

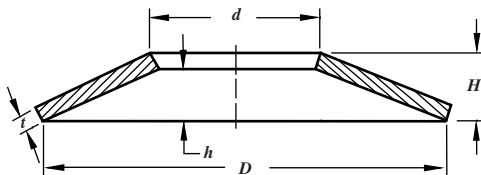


Fig. 1. Disc Spring Nomenclature

**Disc Spring Group Classification.**—Forces and stresses generated by compression depend on disc spring thickness much more than on any other dimensions. Standard DIN 2093 divides all disc springs into three groups in accordance with their thickness:

*Group 1* includes all disc springs with thickness less than 1.25 mm (0.0492 inch).

*Group 2* includes all disc springs with thickness between 1.25 mm and 6.0 mm (0.0492 inch and 0.2362 inch).

*Group 3* includes disc springs with thickness greater than 6.0 mm (0.2362 inch).

There are 87 standard disc spring items, which are manufactured in accordance with Standard DIN 2093 specifications for dimensions and quality requirements. There are 30 standard disc spring items in *Group 1*. The smallest and the largest disc springs in this

group are 8–4.2–0.2 and 40–20.4–1 respectively. *Group 2* has 45 standard disc spring items. The smallest and the largest disc springs are 22.5–11.2–1.25 and 200–102–5.5 respectfully. *Group 3* includes 12 standard disc spring items. The smallest and the largest disc springs of this group are 125–64–8 and 250–127–14 respectively.

#### Summary of Disc Spring Sizes Specified in DIN 2093

| Classification | OD                   |                      | ID                    |                       | Thickness             |                      |
|----------------|----------------------|----------------------|-----------------------|-----------------------|-----------------------|----------------------|
|                | Min.                 | Max.                 | Min.                  | Max.                  | Min.                  | Max.                 |
| <i>Group 1</i> | 6 mm<br>(0.236 in)   | 40 mm<br>(1.575 in)  | 3.2 mm<br>(0.126 in)  | 20.4 mm<br>(0.803 in) | 0.2 mm<br>(0.008 in)  | 1.2 mm<br>(0.047 in) |
| <i>Group 2</i> | 20 mm<br>(0.787 in)  | 225 mm<br>(8.858 in) | 10.2 mm<br>(0.402 in) | 112 mm<br>(4.409 in)  | 1.25 mm<br>(0.049 in) | 6 mm<br>(0.236 in)   |
| <i>Group 3</i> | 125 mm<br>(4.921 in) | 250 mm<br>(9.843 in) | 61 mm<br>(2.402 in)   | 127 mm<br>(5.000 in)  | 6.5 mm<br>(0.256 in)  | 16 mm<br>(0.630 in)  |

The number of catalog items by disc spring dimensions depends on the manufacturer. Currently, the smallest disc spring is 6–3.2–0.3 and the largest is 250–127–16. One of the U.S. disc spring manufacturers, Key Bellevilles, Inc. offers 190 catalog items. The greatest number of disc spring items can be found in Christian Bauer GmbH + Co. catalog. There are 291 disc spring catalog items in all three groups.

**Disc Spring Contact Surfaces.**—Disc springs are manufactured with and without contact (also called load-bearing) surfaces. Contact surfaces are small flats at points 1 and 3 in Fig. 2, adjacent to the corner radii of the spring. The width of the contact surfaces  $w$  depends on the outside diameter  $D$  of the spring, and its value is approximately  $w = D/150$ .

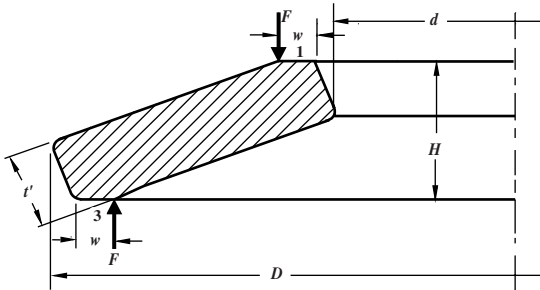


Fig. 2. Disc Spring with Contact Surfaces

Disc springs of *Group 1* and *Group 2*, that are contained in the DIN 2093 Standard, do not have contact surfaces, although some *Group 2* disc springs not included in DIN 2093 are manufactured with contact surfaces. All disc springs of *Group 3* (standard and nonstandard) are manufactured with contact surfaces. Almost all disc springs with contact surfaces are manufactured with reduced thickness.

Disc springs without contact surfaces have a corner radii  $r$  whose value depends on the spring thickness,  $t$ . One disc spring manufacturers recommends the following relationship:

$$r = t/6$$

**Disc Spring Materials.**—A wide variety of materials are available for disc springs, but selection of the material depends mainly on application. High-carbon steels are used only for *Group 1* disc springs. AISI 1070 and AISI 1095 carbon steels are used in the U.S. Similar high-carbon steels such as DIN 1.1231 and DIN 1.1238 (Germany), and BS 060 A67 and BS 060 A78 (Great Britain) are used in other countries. The most common materials for *Groups 2* and *3* springs operating under normal conditions are chromium-vanadium alloy steels such as AISI 6150 used in the U.S. Similar alloys such as DIN 1.8159 and DIN



1.7701 (Germany) and BS 735 A50 (Great Britain) are used in foreign countries. Some disc spring manufacturers in the U.S. also use chromium alloy steel AISI 5160. The hardness of disc springs in *Groups 2 and 3* should be 42 to 52 HRC. The hardness of disc springs in *Group 1* tested by the Vickers method should be 412 to 544 HV.

If disc springs must withstand corrosion and high temperatures, stainless steels and heat-resistant alloys are used. Most commonly used stainless steels in the United States are AISI types 301, 316, and 631, which are similar to foreign material numbers DIN 1.4310, DIN 1.4401, and DIN 1.4568, respectively. The operating temperature range for 631 stainless steel is  $-330$  to  $660^{\circ}\text{F}$  ( $-200$  to  $350^{\circ}\text{C}$ ). Among heat-resistant alloys, Inconel 718 and Inconel X750 (similar to DIN 2.4668 and DIN 2.4669, respectively) are the most popular. Operating temperature range for Inconel 718 is  $-440$  to  $1290^{\circ}\text{F}$  ( $-260$  to  $700^{\circ}\text{C}$ ).

When disc springs are stacked in large numbers and their total weight becomes a major concern, titanium  $\alpha$ - $\beta$  alloys can be used to reduce weight. In such cases, Ti-6Al-4V alloy is used.

If nonmagnetic and corrosion resistant properties are required and material strength is not an issue, phosphor bronzes and beryllium-coppers are the most popular copper alloys for disc springs. Phosphor bronze C52100, which is similar to DIN material number 2.1030, is used at the ordinary temperature range. Beryllium-coppers C17000 and C17200, similar to material numbers DIN 2.1245 and DIN 2.1247 respectively, works well at very low temperatures.

Strength properties of disc spring materials are characterized by moduli of elasticity and Poisson's ratios. These are summarized in [Table 1](#).

**Table 1. Strength Characteristics of Disc Spring Materials**

| Material                                       | Modulus of Elasticity |                   | Poisson's Ratio |
|--|-----------------------|-------------------|-----------------|
|  | $10^6$ psi            | N/mm <sup>2</sup> |                 |
| All Steels                                     | 28–31                 | 193,000–213,700   | 0.30            |
| Heat-resistant Alloys                          |                       |                   | 0.28–0.29       |
| $\alpha$ - $\beta$ Titanium Alloys (Ti-6Al-4V) | 17                    | 117,200           | 0.32            |
| Phosphor Bronze (C52100)                       | 16                    | 110,300           | 0.35            |
| Beryllium-copper (C17000)                      | 17                    | 117,200           | 0.30            |
| Beryllium-copper (C17200)                      | 18                    | 124,100           | 0.30            |

**Stacking of Disc Springs.**—Individual disc springs can be arranged in series and parallel stacks. Disc springs in series stacking, [Fig. 3](#), provide larger deflection  $S_{total}$  under the same load  $F$  as a single disc spring would generate. Disc springs in parallel stacking, [Fig. 4](#), generate higher loads  $F_{total}$  with the same deflection  $s$ , that a single disc spring would have.

$n$  = number of disc springs in stack

$s$  = deflection of single spring

$S_{total}$  = total deflection of stack of  $n$  springs

$F$  = load generated by a single spring

$F_{total}$  = total load generated by springs in stack

$L_0$  = length of unloaded spring stack

*Series:* For  $n$  disc springs arranged in series as in [Fig. 3](#), the following equations are applied:

$$F_{total} = F$$

$$S_{total} = s \times n$$

$$L_0 = H \times n = (t \div h) \times n \quad (1)$$

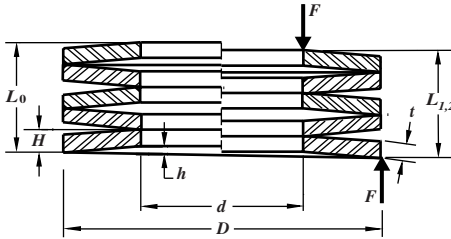


Fig. 3. Disc Springs in Series Stacking

$L_{1,2}$  indices indicate length of spring stack under minimum and maximum load

**Parallel:** Parallel stacking generates a force that is directly proportional to number of springs arranged in parallel. Two springs in parallel will double the force, three springs in parallel will triple the force, and so on. However, it is a common practice to use two springs in parallel in order to keep the frictional forces between the springs as low as possible. Otherwise, the actual spring force cannot be accurately determined due to deviation from its theoretical value.

For  $n$  disc springs arranged in parallel as in Fig. 4, the following equations are applied:

$$F_{total} = F \times n$$

$$S_{total} = s$$

$$L_0 = H + t(n - 1) = (h + t) + tn - t = h + tn \quad (2)$$

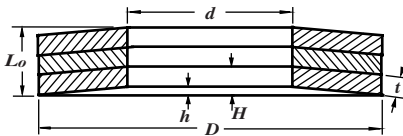


Fig. 4. Disc Springs in Parallel Stacking

**Parallel-Series:** When both higher force and greater deflection are required, disc springs must be arranged in a combined parallel-series stacking as illustrated in Fig. 5.

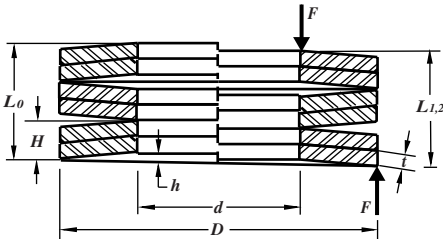


Fig. 5. Disc Springs in Parallel-Series Stacking

Normally, two springs in parallel are nested in series stacking. Two springs in parallel, called a pair, double the force, and the number of pairs,  $n_p$ , determines the total deflection,  $S_{total}$ .

For  $n_p$  disc spring pairs arranged in series, the following equations are applied:

$$\begin{aligned} F_{total} &= 2 \times F \\ S_{total} &= s \times n_p \\ L_0 &= H \times n_p = (2t + h) \times n_p \end{aligned} \quad (3)$$

### Disc Spring Forces and Stresses

Several methods of calculating forces and stresses for given disc spring configurations exist, some very complicated, others of limited accuracy. The theory which is widely used today for force and stress calculations was developed more than 65 years ago by Almen and Laszlo.

The theory is based on the following assumptions: cross sections are rectangular without radii, over the entire range of spring deflection; no stresses occur in the radial direction; disc springs are always under elastic deformation during deflection; and due to small cone angles of unloaded disc springs (between  $3.5^\circ$  and  $8.6^\circ$ ), mathematical simplifications are applied.

The theory provides accurate results for disc springs with the following ratios: outside-to-inside diameter,  $D/d = 1.3$  to  $2.5$ ; and cone height-to-thickness,  $h/t$  is up to  $1.5$ .

**Force Generated by Disc Springs Without Contact Surfaces.**—Disc springs in *Group 1* and most of disc springs in *Group 2* are manufactured without contact (load-bearing) surfaces, but have corner radii.

A single disc spring force applied to points 1 and 3 in Fig. 6 can be found from Equation (4) in which corner radii are not considered:

$$F = \frac{4 \cdot E \cdot s}{(1 - \mu^2) \cdot K_I \cdot D^2} \left[ \left( h - \frac{s}{2} \right) \cdot (h - s) \cdot t + t^3 \right] \quad (4)$$

where  $F$  = disc spring force;  $E$  = modulus of elasticity of spring material;  $\mu$  = Poisson's ratio of spring material;  $K_I$  = constant depending on outside-to-inside diameter ratio;  $D$  = disc spring nominal outside diameter;  $h$  = cone (dish) height;  $s$  = disc spring deflection; and,  $t$  = disc spring thickness.

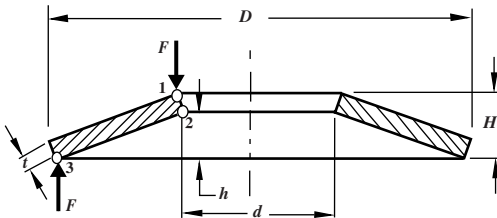


Fig. 6. Schematic of Applied Forces

It has been found that the theoretical forces calculated using Equation (4) are lower than the actual (measured) spring forces, as illustrated in Fig. 7. The difference between theoretical (trace 1) and measured force values (trace 3) was significantly reduced (trace 2) when the actual outside diameter of the spring in loaded condition was used in the calculations.

DISC SPRING FORCES AND STRESSES

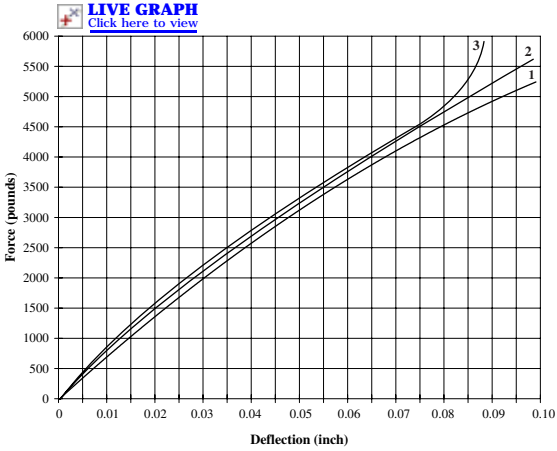


Fig. 7. Force–Deflection Relationships (80–36–3.6 Disc Springs)

- 1 – Theoretical Force Calculated by Equation (4)
- 2 – Theoretical Force Calculated by Equation (10)
- 3 – Measured Force

The actual outside diameter  $D_a$  of a disc spring contact circle is smaller than the nominal outside diameter  $D$  due to cone angle  $\alpha$  and corner radius  $r$ , as shown in Fig. 8. Diameter  $D_a$  cannot be measured, but can be calculated by Equation (9) developed by the author.

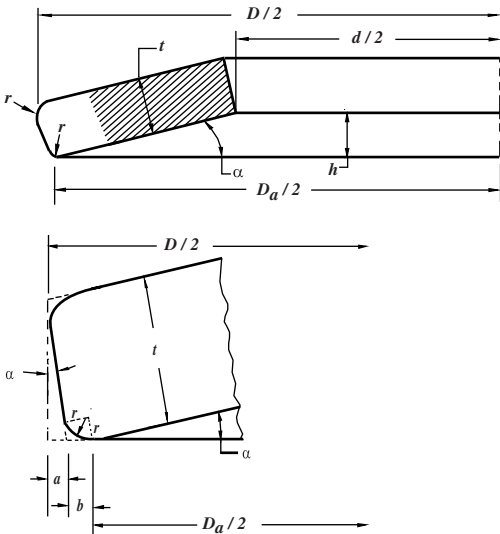


Fig. 8. Conventional Shape of Disc Spring

From Fig. 8,

$$\frac{D_a}{2} = \frac{D}{2} - (a + b) \tag{5}$$

where  $a = t \times \sin \alpha$  and  $b = r \times \cos \alpha$ . Substitution of  $a$  and  $b$  values into Equation (5) gives:

$$\frac{D_a}{2} = \frac{D}{2} - (t \sin \alpha + r \cos \alpha) \tag{6}$$

The cone angle  $\alpha$  is found from:

$$\tan \alpha = \frac{h}{\frac{D}{2} - \frac{d}{2}} = \frac{2h}{D - d} \quad \alpha = \text{atan}\left(\frac{2h}{D - d}\right) \tag{7}$$

Substituting  $\alpha$  from Equation (7) and  $r = t/6$  into Equation (6) gives:

$$\frac{D_a}{2} = \frac{D}{2} - t \left\{ \sin \left[ \text{atan}\left(\frac{2h}{D - d}\right) \right] + \frac{1}{6} \cos \left[ \text{atan}\left(\frac{2h}{D - d}\right) \right] \right\} \tag{8}$$

Finally,

$$D_a = D - 2t \left\{ \sin \left[ \text{atan}\left(\frac{2h}{D - d}\right) \right] + \frac{1}{6} \cos \left[ \text{atan}\left(\frac{2h}{D - d}\right) \right] \right\} \tag{9}$$

Substituting  $D_a$  from Equation (9) for  $D$  in Equation (4) yields Equation (10), that provides better accuracy for calculating disc spring forces.

$$F = \frac{4 \cdot E \cdot s}{(1 - \mu^2) \cdot K_1 \cdot D_a^2} \left[ \left( h - \frac{s}{2} \right) \cdot (h - s) \cdot t + t^3 \right] \tag{10}$$

The constant  $K_1$  depends on disc spring outside diameter  $D$ , inside diameter  $d$ , and their ratio  $\delta = D/d$ :

$$K_1 = \frac{\left( \frac{\delta - 1}{\delta} \right)^2}{\pi \cdot \left( \frac{\delta + 1}{\delta - 1} - \frac{2}{\ln \delta} \right)} \tag{11}$$

Table 2 compares the spring force of a series of disc springs deflected by 75% of their cone height, i.e.,  $s = 0.75h$ , as determined from manufacturers catalogs calculated in accordance with Equation (4), calculated forces by use of Equation (10), and measured forces.

**Table 2. Comparison Between Calculated and Measured Disc Spring Forces**

| Disc Spring Catalog Item         | Schnorr Handbook for Disc Springs | Christian Bauer Disc Spring Handbook | Key Bellevilles Disc Spring Catalog | Spring Force Calculated by Equation (10) | Measured Disc Spring Force |
|----------------------------------|-----------------------------------|--------------------------------------|-------------------------------------|--|----------------------------|
| 50 – 22.4 – 2.5<br>$S = 1.05$ mm | 8510 N<br>1913 lbf                | 8510 N<br>1913 lbf                   | 8616 N<br>1937 lbf                  | 9020 N<br>2028 lbf                       | 9563 N<br>2150 lbf         |
| 60 – 30.5 – 2.5<br>$S = 1.35$ mm | 8340 N<br>1875 lbf                | 8340 N<br>1875 lbf                   | 8465 N<br>1903 lbf                  | 8794 N<br>1977 lbf                       | 8896 N<br>2000 lbf         |
| 60 – 30.5 – 3<br>$S = 1.275$ mm  | 13200 N<br>2967 lbf               | 13270 N<br>2983 lbf                  | 13416 N<br>3016 lbf                 | 14052 N<br>3159 lbf                      | 13985 N<br>3144 lbf        |
| 70 – 35.5 – 3<br>$S = 1.575$ mm  | 12300 N<br>2765 lbf               | 12320 N<br>2770 lbf                  | 12397 N<br>2787 lbf                 | 12971 N<br>2916 lbf                      | 13287 N<br>2987 lbf        |
| 70 – 35.5 – 3.5<br>$S = 1.35$ mm |                                   | 16180 N<br>3637 lbf                  |                                     | 17170 N<br>3860 lbf                      | 17304 N<br>3890 lbf        |

Comparison made at 75% deflection, in Newtons (N) and pounds (lbf)

The difference between disc spring forces calculated by Equation (10) and the measured forces varies from  $-5.7\%$  (maximum) to  $+0.5\%$  (minimum). Disc spring forces calculated by Equation (4) and shown in manufacturers catalogs are less than measured forces by  $-11\%$  (maximum) to  $-6\%$  (minimum).

**Force Generated by Disc Spring with Contact Surfaces.**—Some of disc springs in Group 2 and all disc springs in Group 3 are manufactured with small contact (load-bearing) surfaces or flats in addition to the corner radii. These flats provide better contact between disc springs, but, at the same time, they reduce the springs outside diameter and generate higher spring force because in Equation (4) force  $F$  is inversely proportional to the square of outside diameter  $D^2$ . To compensate for the undesired force increase, the disc spring thickness is reduced from  $t$  to  $t'$ . Thickness reduction factors  $t'/t$  are approximately 0.94 for disc spring series A and B, and approximately 0.96 for series C springs. With such reduction factors, the disc spring force at 75% deflection is the same as for equivalent disc spring without contact surfaces. Equation (12), which is similar to Equation (10), has an additional constant  $K_4$  that correlates the increase in spring force due to contact surfaces. If disc springs do not have contact surfaces, then  $K_4^2 = K_4 = 1$ .

$$F = \frac{4 \cdot E \cdot K_4^2 \cdot s}{(1 - \mu^2) \cdot K_1 \cdot D_a^2} \left[ K_4^2 \cdot \left( h' - \frac{s}{2} \right) \cdot (h' - s) \cdot t' + (t')^3 \right] \quad (12)$$

where  $t'$  = reduced thickness of a disc spring

$h'$  = cone height adjusted to reduced thickness:  $h' = H - t'$  ( $h' > h$ )

$K_4$  = constant applied to disc springs with contact surfaces.

$K_4^2$  can be calculated as follows:

$$K_4^2 = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad (13)$$

where  $a = t'(H - 4t' + 3t)(5H - 8t' + 3t)$ ;  $b = 32(t')^3$ ; and,  $c = -t[5(H - t)^2 + 32t^2]$ .

**Disc Spring Functional Stresses.**—Disc springs are designed for both static and dynamic load applications. In static load applications, disc springs may be under constant or fluctuating load conditions that change up to 5,000 or 10,000 cycles over long time intervals. Dynamic loads occur when disc springs are under continuously changing deflection between pre-load (approximately 15% to 20% of the cone height) and the maximum deflection values over short time intervals. Both static and dynamic loads cause compressive and tensile stresses. The position of critical stress points on a disc spring cross section are shown in Fig. 9.

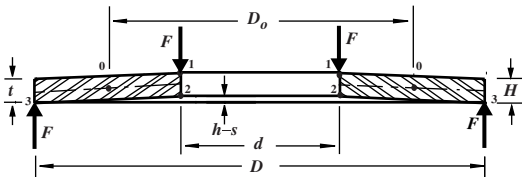


Fig. 9. Critical Stress Points

$s$  is deflection of spring by force  $F$ ;  $h - s$  is a cone height of loaded disc spring

Compressive stresses are acting at points 0 and 1, that are located on the top surface of the disc spring. Point 0 is located on the cross-sectional mid-point diameter, and point 1 is located on the top inside diameter. Tensile stresses are acting at points 2 and 3, which are located on the bottom surface of the disc spring. Point 2 is on the bottom inside diameter, and point 3 is on the bottom outside diameter. The following equations are used to calcu-

late stresses. The minus sign “-” indicates that compressive stresses are acting in a direction opposite to the tensile stresses.

$$\text{Point 0: } \sigma_0 = -\frac{3}{\pi} \cdot \frac{4E \cdot t \cdot s \cdot K_4}{(1 - \mu^2) \cdot K_1 \cdot D_a^2} \quad (14)$$

$$\text{Point 1: } \sigma_1 = -\frac{4E \cdot K_4 \cdot s \cdot \left[ K_4 \cdot K_2 \cdot \left( h - \frac{s}{2} \right) + K_3 \cdot t \right]}{(1 - \mu^2) \cdot K_1 \cdot D_a^2} \quad (15)$$

$$\text{Point 2: } \sigma_2 = \frac{4E \cdot K_4 \cdot s \cdot \left[ K_3 \cdot t - K_2 \cdot K_4 \cdot \left( h - \frac{s}{2} \right) \right]}{(1 - \mu^2) \cdot K_1 \cdot D_a^2} \quad (16)$$

$$\text{Point 3: } \sigma_3 = \frac{4E \cdot K_4 \cdot s \cdot \left[ K_4 \cdot (2K_3 - K_2) \cdot \left( h - \frac{s}{2} \right) + K_3 \cdot t \right]}{(1 - \mu^2) \cdot K_1 \cdot D_a^2 \cdot \delta} \quad (17)$$

$K_2$  and  $K_3$  are disc spring dimensional constants, defined as follows:

$$K_2 = \frac{6 \left( \frac{\delta - 1}{\ln \delta} - 1 \right)}{\pi \cdot \ln \delta} \quad (18) \quad K_3 = \frac{3 \cdot (\delta - 1)}{\pi \cdot \ln \delta} \quad (19)$$

where  $\delta = D/d$  is the outside-to-inside diameter ratio.

In static application, if disc springs are fully flattened (100% deflection), compressive stress at point 0 should not exceed the tensile strength of disc spring materials. For most spring steels, the permissible value is  $\sigma_0 \leq 1600 \text{ N/mm}^2$  or 232,000 psi.

In dynamic applications, certain limitations on tensile stress values are recommended to obtain controlled fatigue life of disc springs utilized in various stacking. Maximum tensile stresses at points 2 and 3 depend on the *Group* number of the disc springs. Stresses  $\sigma_2$  and  $\sigma_3$  should not exceed the following values:

|  | Group 1                                 | Group 2                                 | Group 3                                 |
|--|---|---|---|
| Maximum allowable tensile stresses at points 2 and 3 | 1300 N/mm <sup>2</sup><br>(188,000 psi) | 1250 N/mm <sup>2</sup><br>(181,000 psi) | 1200 N/mm <sup>2</sup><br>(174,000 psi) |

**Fatigue Life of Disc Springs.**—Fatigue life is measured in terms of the maximum number of cycles that dynamically loaded disc springs can sustain prior to failure. Dynamically loaded disc springs are divided into two groups: disc springs with unlimited fatigue life, which exceeds  $2 \times 10^6$  cycles without failure, and disc springs with limited fatigue life between  $10^4$  cycles and less than  $2 \times 10^6$  cycles.

Typically, fatigue life is estimated from three diagrams, each representing one of the three Groups of disc springs (Figs. 10, 11, and 12). Fatigue life is found at the intersection of the vertical line representing minimum tensile stress  $\sigma_{\min}$  with the horizontal line, which represents maximum tensile stress  $\sigma_{\max}$ . The point of intersection of these two lines defines fatigue life expressed in number of cycles  $N$  that can be sustained prior to failure.

*Example:* For *Group 2* springs in Fig. 11, the intersection point of the  $\sigma_{\min} = 500 \text{ N/mm}^2$  line with the  $\sigma_{\max} = 1200 \text{ N/mm}^2$  line, is located on the  $N = 10^5$  cycles line. The estimated fatigue life is  $10^5$  cycles.

DISC SPRING FATIGUE LIFE

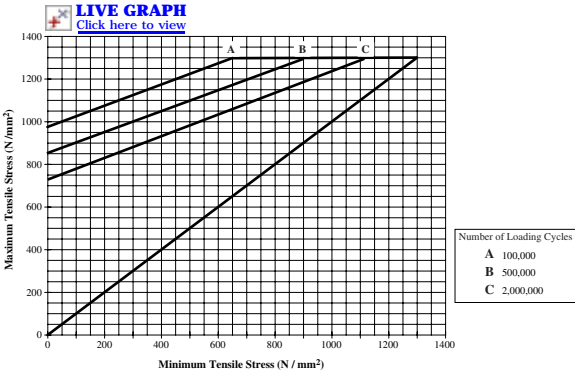


Fig. 10. Group 1 Diagram for Estimating Fatigue Life of Disc Springs ( $0.2 \leq t < 1.25$  mm)

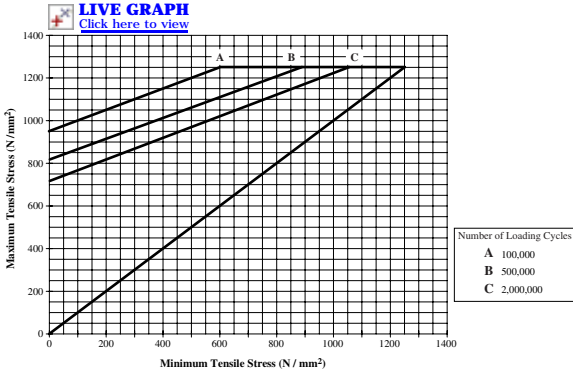


Fig. 11. Group 2 Diagram for Estimating Fatigue Life of Disc Springs ( $1.25 \leq t \leq 6$  mm)

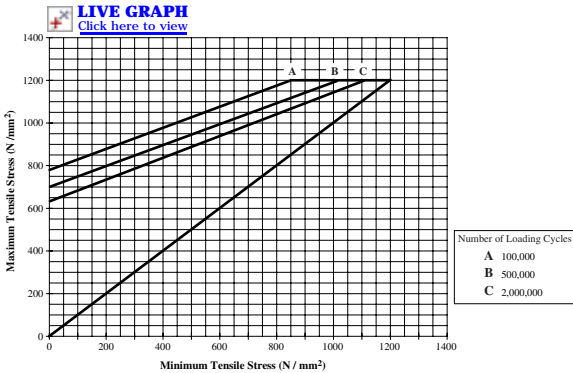


Fig. 12. Group 3 Diagram for Estimating Fatigue Life of Disc Springs ( $6 < t \leq 16$  mm)



When the intersection points of the minimum and maximum stress lines fall inside the areas of each cycle line, only the approximate fatigue life can be estimated by extrapolating the distance from the point of intersection to the nearest cycle line. The extrapolation cannot provide accurate values of fatigue life, because the distance between the cycle lines is expressed in logarithmic scale, and the distance between tensile strength values is expressed in linear scale (Figs. 10, 11, and 12), therefore linear-to-logarithmic scales ratio is not applicable.

When intersection points of minimum and maximum stress lines fall outside the cycle lines area, especially outside the  $N = 10^5$  cycles line, the fatigue life cannot be estimated.

Thus, the use of the fatigue life diagrams should be limited to such cases when the minimum and maximum tensile stress lines intersect exactly with each of the cycle lines.

To calculate fatigue life of disc springs without the diagrams, the following equations developed by the author can be used.

$$\text{Disc Springs in Group 1} \quad N = 10^{10.29085532 - 0.00542096(\sigma_{max} - 0.5\sigma_{min})} \quad (20)$$

$$\text{Disc Springs in Group 2} \quad N = 10^{10.10734911 - 0.00537616(\sigma_{max} - 0.5\sigma_{min})} \quad (21)$$

$$\text{Disc Springs in Group 3} \quad N = 10^{13.23985664 - 0.01084192(\sigma_{max} - 0.5\sigma_{min})} \quad (22)$$

As can be seen from Equations (20), (21), and (22), the maximum and minimum tensile stress range affects the fatigue life of disc springs. Since tensile stresses at Points 2 and 3 have different values, see Equations (16) and (17), it is necessary to determine at which critical point the minimum and maximum stresses should be used for calculating fatigue life. The general method is based on the diagram, Fig. 9, from which Point 2 or Point 3 can be found in relationship with disc spring outside-to-inside diameters ratio  $D_o/D_i$  and disc spring cone height-to-thickness ratio  $h/r$ . This method requires intermediate calculations of  $D_o/D_i$  and  $h/r$  ratios and is applicable only to disc springs without contact surfaces. The method is not valid for Group 3 disc springs or for disc springs in Group 2 that have contact surfaces and reduced thickness.

A simple and accurate method, that is valid for all disc springs, is based on the following statements:

if  $(\sigma_{2max} - 0.5\sigma_{2min}) > (\sigma_{3max} - 0.5\sigma_{3min})$ , then Point 2 is used, otherwise

if  $(\sigma_{3max} - 0.5\sigma_{3min}) > (\sigma_{2max} - 0.5\sigma_{2min})$ , then Point 3 is used

The maximum and minimum tensile stress range for disc springs in Groups 1, 2, and 3 is found from the following equations.

For disc springs in Group 1:

$$\sigma_{max} - 0.5\sigma_{min} = \frac{10.29085532 - \log N}{0.00542096} \quad (23)$$

For disc springs in Group 2:

$$\sigma_{max} - 0.5\sigma_{min} = \frac{10.10734911 - \log N}{0.00537616} \quad (24)$$

For disc springs in Group 3:

$$\sigma_{max} - 0.5\sigma_{min} = \frac{13.23985664 - \log N}{0.01084192} \quad (25)$$

Thus, Equations (23), (24), and (25) can be used to design any spring stack that provides required fatigue life. The following example illustrates how a maximum-minimum stress range is calculated in relationship with fatigue life of a given disc spring stack.

*Example:* A dynamically loaded stack, which utilizes disc springs in *Group 2*, must have the fatigue life of  $5 \times 10^5$  cycles. The maximum allowable tensile stress at Points 2 or 3 is  $1250 \text{ N/mm}^2$ . Find the minimum tensile stress value to sustain  $N = 5 \times 10^5$  cycles.

*Solution:* Substitution of  $\sigma_{\max} = 1250$  and  $N = 5 \times 10^5$  in Equation (24) gives:

$$1250 - 0.5\sigma_{\min} = \frac{10.10734911 - \log(5 \times 10^5)}{0.00537616} = \frac{10.10734911 - 5.69897}{0.00537616} = 820$$

from which  $\sigma_{\min} = \frac{1250 - 820}{0.5} = 860 \text{ N/mm}^2$  (124,700 psi)

**Recommended Dimensional Characteristics of Disc Springs.**—Dimensions of disc springs play a very important role in their performance. It is imperative to check selected disc springs for dimensional ratios, that should fall within the following ranges:

- 1) Diameters ratio,  $\delta = D_o/D_i = 1.7$  to  $2.5$ .
- 2) Cone height-to-thickness ratio,  $h_o/t = 0.4$  to  $1.3$ .
- 3) Outside diameter-to-thickness ratio,  $D_o/t = 18$  to  $40$ .

Small values of  $\delta$  correspond with small values of the other two ratios. The  $h_o/t$  ratio determines the shape of force-deflection characteristic graphs, that may be nearly linear or strongly curved. If  $h_o/t = 0.4$  the graph is almost linear during deflection of a disc spring up to its flat position. If  $h_o/t = 1.6$  the graph is strongly curved and its maximum point is at 75% deflection. Disc spring deflection from 75% to 100% slightly reduces spring force. Within the  $h_o/t = 0.4 - 1.3$  range, disc spring forces increase with the increase in deflection and reach maximum values at 100% deflection. In a stack of disc springs with a ratio  $h_o/t > 1.3$  deflection of individual springs may be unequal, and only one disc spring should be used if possible.

### Example Applications of Disc Springs

*Example 1, Disc Springs in Group 2 (no contact surfaces):* A mechanical device that works under dynamic loads must sustain a minimum of 1,000,000 cycles. The applied load varies from its minimum to maximum value every 30 seconds. The maximum load is approximately 20,000N (4,500 lbf). A 40-mm diameter guide rod is a receptacle for the disc springs. The rod is located inside a hollow cylinder. Deflection of the disc springs under minimum load should not exceed 5.5 mm (0.217 inch) including a 20 per cent pre-load deflection. Under maximum load, the deflection is limited to 8 mm (0.315 inch) maximum. Available space for the disc spring stack inside the cylinder is 35 to 40 mm (1.38 to 1.57 inch) in length and 80 to 85 mm (3.15 to 3.54 inch) in diameter.

Select the disc spring catalog item, determine the number of springs in the stack, the spring forces, the stresses at minimum and maximum deflection, and actual disc spring fatigue life.

*Solution:* 1) Disc spring standard inside diameter is 41 mm (1.61 inch) to fit the guide rod. The outside standard diameter is 80 mm (3.15 in) to fit the cylinder inside diameter. Disc springs with such diameters are available in various thickness: 2.25, 3.0, 4.0, and 5.0 mm (0.089, 0.118, 0.157, and 0.197 inch). The 2.25- and 3.0-mm thick springs do not fit the applied loads, since the maximum force values for disc springs with such thickness are 7,200N and 13,400N (1,600 lbf and 3,000 lbf) respectively. A 5.0-mm thick disc spring should not be used because its  $D_o/t$  ratio,  $80/5 = 16$ , is less than 18 and is considered as unfavorable. Disc spring selection is narrowed to an 80–41–4 catalog item.

2) Checking 80–41–4 disc spring for dimensional ratios:

$$\delta = D_o/D_i = 80/41 = 1.95 \quad h_o/t = 22/4 = 0.55 \quad D_o/t = 80/4 = 20$$

Because the dimensional ratios are favorable, the 80–41–4 disc springs are selected.

## DISC SPRING EXAMPLE

3) The number of springs in the stack is found from Equation (1):

$$n = L_o / (t + h) = 40 / (4 + 2.2) = \frac{40}{6.2} = 6.45.$$

Rounding  $n$  to the nearest integer gives  $n = 6$ . The actual length of unloaded spring stack is  $L_o = 6.2 \times 6 = 37.2$  mm (1.465 inch) and it satisfies the  $L_o < 40$  mm condition.

4) Calculating the cone angle  $\alpha$  from Equation (7) and actual outside diameter  $D_a$  from Equation (9) gives:

$$\alpha = \text{atan}\left(\frac{2 \times 2.2}{80 - 41}\right) = \text{atan}(0.11282) = 6.4^\circ$$

$$D_a = 80 - 2 \times 4 \left( \sin[\text{atan}(0.11282)] + \frac{1}{6} \cos[\text{atan}(0.11282)] \right)$$

$$D_a = 77.78 \text{ mm (3.062 in)}$$

5) Calculating constant  $K_1$  from Equation (11):

$$\delta = \frac{D}{d} = 1.95122$$

$$K_1 = \frac{\left(\frac{1.95122 - 1}{1.95122}\right)^2}{\pi \cdot \left[ \frac{1.95122 + 1}{1.95122 - 1} - \frac{2}{\ln(1.95122)} \right]} = 0.6841$$

6) Calculating minimum and maximum forces,  $F_{min}$  and  $F_{max}$  from Equation (10):

Based on the design requirements, the disc spring stack is deflecting by 5.5 mm (0.217 in) under minimum load, and each individual disc spring is deflecting by  $5.5/6 \cong 0.92$  mm (0.036 in). A single disc spring deflection  $s_{min} = 0.9$  mm (0.035 in) is used to calculate  $F_{min}$ . Under maximum load, the disc spring stack is permitted maximum deflection of 8 mm (0.315 in), and each individual disc spring deflects by  $8/6 \cong 1.33$  mm (0.0524 in). A disc spring deflection  $s_{max} = 1.32$  mm (0.052 in) will be used to calculate  $F_{max}$ . If disc springs are made of AISI 6150 alloy steel, then modulus of elasticity  $E = 206,000 \text{ N/mm}^2$  ( $30 \times 10^6$  psi) and Poisson's ratio  $\mu = 0.3$ .

$$F_{min} = \frac{4 \cdot 206000}{(1 - 0.3^2)(0.6841)(77.78)^2} \left[ \left(2.2 - \frac{0.9}{2}\right) \cdot (2.2 - 0.9) \cdot 4 + 4^3 \right] 0.9$$

$$F_{min} = 14390 \text{ N (3235 lbf)}$$

$$F_{max} = \frac{4 \cdot 206000}{(1 - 0.3^2)(0.6841)(77.78)^2} \left[ \left(2.2 - \frac{1.32}{2}\right) \cdot (2.2 - 1.32) \cdot 4 + 4^3 \right] 1.32$$

$$F_{max} = 20050 \text{ N (4510 lbf)}$$

7) Calculating constant  $K_2$ , Equation (18):

$$\delta = \frac{D}{d} = \frac{80}{41} = 1.95122$$

$$K_2 = \frac{6 \left( \frac{\delta - 1}{\ln \delta} - 1 \right)}{\pi \cdot \ln \delta} = \frac{6 \left( \frac{1.95122 - 1}{\ln(1.95122)} - 1 \right)}{\pi \cdot \ln(1.95122)} = 1.2086$$

8) Calculating constant  $K_3$  (Equation (19)):

$$K_3 = \frac{3 \cdot (\delta - 1)}{\pi \cdot \ln \delta} = \frac{3 \cdot (1.95122 - 1)}{\pi \cdot \ln(1.95122)} = 1.3589$$

9) Compressive stress  $\sigma_0$  at point 0 due to maximum deflection, Equation (14):

$$\sigma_0 = \frac{3}{\pi} \cdot \frac{4E \cdot t \cdot s \cdot K_4}{(1 - \mu^2) \cdot K_1 \cdot D_a^2} = \frac{3}{\pi} \cdot \frac{4 \cdot 206000 \cdot 4 \cdot 1.32 \cdot 1}{(1 - 0.3^2) \cdot 0.6841 \cdot 77.78^2}$$

$$\sigma_0 = 1103 \text{ N/mm}^2 = 160000 \text{ psi}$$

Because the compressive stress at point 0 does not exceed 1600 N/mm<sup>2</sup>, its current value satisfies the design requirement.

10) Tensile stress  $\sigma_2$  at point 2 due to minimum deflection  $s = 0.9$  mm, Equation (16):

$$\sigma_{2min} = \frac{4E \cdot K_4 \cdot s \cdot \left[ K_3 \cdot t - K_2 \cdot K_4 \cdot \left( h - \frac{s}{2} \right) \right]}{(1 - \mu^2) \cdot K_1 \cdot D_a^2} =$$

$$\frac{4 \cdot 206000 \cdot 1 \cdot 0.9 \cdot \left[ 1.3589 \cdot 4 - 1.2086 \cdot 1 \cdot \left( 2.2 - \frac{0.9}{2} \right) \right]}{(1 - 0.3^2) \cdot 0.6841 \cdot 77.78^2} = 654 \text{ N/mm}^2$$

11) Tensile stress  $\sigma_2$  at point 2 due to maximum deflection  $s = 1.32$  mm, Equation (16):

$$\sigma_{2max} = \frac{4E \cdot K_4 \cdot s \cdot \left[ K_3 \cdot t - K_2 \cdot K_4 \cdot \left( h - \frac{s}{2} \right) \right]}{(1 - \mu^2) \cdot K_1 \cdot D_a^2} =$$

$$\frac{4 \cdot 206000 \cdot 1 \cdot 1.32 \cdot \left[ 1.3589 \cdot 4 - 1.2086 \cdot 1 \cdot \left( 2.2 - \frac{1.32}{2} \right) \right]}{(1 - 0.3^2) \cdot 0.6841 \cdot 77.78^2} = 1032 \text{ N/mm}^2$$

Thus,  $\sigma_{2min} = 654 \text{ N/mm}^2$  (94,850 psi) and  $\sigma_{2max} = 1032 \text{ N/mm}^2$  (149,700 psi).

12) Tensile stress  $\sigma_3$  at point 3 due to minimum deflection  $s = 0.9$  mm, Equation (17):

$$\sigma_{3min} = \frac{4E \cdot K_4 \cdot s \cdot \left[ K_4 \cdot (2K_3 - K_2) \cdot \left( h - \frac{s}{2} \right) + K_3 \cdot t \right]}{(1 - \mu^2) \cdot K_1 \cdot D_a^2 \cdot \delta} =$$

$$\frac{4 \cdot 206000 \cdot 1 \cdot 0.9 \cdot \left[ 1 \cdot (2 \cdot 1.3589 - 1.2086) \cdot \left( 2.2 - \frac{0.9}{2} \right) + 1.3589 \cdot 4 \right]}{(1 - 0.3^2) \cdot 0.6841 \cdot 77.78^2 \cdot 1.95122} = 815 \text{ N/mm}^2$$

13) Tensile stress  $\sigma_3$  at point 3 due to maximum deflection  $s = 1.32$  mm, Equation (17):

$$\sigma_{3max} = \frac{4E \cdot K_4 \cdot s \cdot \left[ K_4 \cdot (2K_3 - K_2) \cdot \left( h - \frac{s}{2} \right) + K_3 \cdot t \right]}{(1 - \mu^2) \cdot K_1 \cdot D_a^2 \cdot \delta} =$$

$$\frac{4 \cdot 206000 \cdot 1 \cdot 1.32 \cdot \left[ 1 \cdot (2 \cdot 1.3589 - 1.2086) \cdot \left( 2.2 - \frac{1.32}{2} \right) + 1.3589 \cdot 4 \right]}{(1 - 0.3^2) \cdot 0.6841 \cdot 77.78^2 \cdot 1.95122} = 1149 \text{ N/mm}^2$$

Thus,  $\sigma_{3min} = 815 \text{ N/mm}^2$  (118,200 psi) and  $\sigma_{3max} = 1149 \text{ N/mm}^2$  (166,600 psi).

14) Functional tensile stress range at critical points 2 and 3.

Point 2:  $\sigma_{2max} - 0.5\sigma_{2min} = 1032 - 0.5 \times 654 = 705 \text{ N/mm}^2$

Point 3:  $\sigma_{3max} - 0.5\sigma_{3min} = 1149 - 0.5 \times 815 = 741.5 \text{ N/mm}^2$

Because  $\sigma_{3max} - 0.5\sigma_{3min} > \sigma_{2max} - 0.5\sigma_{2min}$ , the tensile stresses at point 3 are used for fatigue life calculations.

15) Fatigue life of selected disc springs, Equation (21):

$$N = 10^{[10.10734911 - 0.00537616(1149 - 0.5 \times 815)]} = 10^{10.10734911 - 3.98642264} = 10^{6.12092647}$$

$N = 1,321,000$  cycles. Thus, the calculated actual fatigue life exceeds required minimum number of cycles by 32%.

In conclusion, the six 80–41–4 disc springs arranged in series stacking, satisfy the requirements and will provide a 32 % longer fatigue life than required by the design criteria.

*Example 2:* A company wishes to use *Group 3* disc springs with contact surfaces on couplings to absorb bumping impacts between railway cars.

Given:

$D = 200$  mm, disc spring outside diameter

$d = 102$  mm, disc spring inside diameter

$t = 14$  mm, spring standard thickness

$t' = 13.1$  mm, spring reduced thickness

$h = 4.2$  mm, cone height of unloaded spring

$n = 22$ , number of springs in series stacking

$S_i = 33.9$  mm, initial deflection of the pack

$S_a = 36.0$  mm, additional deflection of the pack

Find the fatigue life in cycles and determine if the selected springs are suitable for the application.

The calculations are performed in the following sequence:

1) Determine the minimum  $s_{min}$  and maximum  $s_{max}$  deflections of a single disc spring:

$$s_{max} = \frac{(S_i + S_a)}{n} = \frac{(33.9 + 36)}{22} = 3.18 \text{ mm}$$

$$s_{min} = \frac{S_i}{n} = \frac{33.9}{22} = 1.54 \text{ mm}$$

2) Use Equations (16) and (17) to calculate tensile stresses  $\sigma_2$  and  $\sigma_3$  at  $s_{min}$  and  $s_{max}$  deflections:

$$\sigma_{2min} = 674 \text{ N/mm}^2, \sigma_{2max} = 1513 \text{ N/mm}^2, \sigma_{3min} = 707 \text{ N/mm}^2, \sigma_{3max} = 1379 \text{ N/mm}^2$$

3) Determine critical stress points:

$$\sigma_{2max} - 0.5\sigma_{2min} = 1513 - 0.5 \times 674 = 1176 \text{ N/mm}^2$$

$$\sigma_{3max} - 0.5\sigma_{3min} = 1379 - 0.5 \times 707 = 1025.5 \text{ N/mm}^2$$

Because  $(\sigma_{2max} - 0.5\sigma_{2min}) > (\sigma_{3max} - 0.5\sigma_{3min})$ , then tensile stresses at Point 2 are used to calculate fatigue life.

4) Fatigue life  $N$  is calculated using Equation (22):

$$N = 10^{[13.23985664 - (0.01084192 \times 1176)]} = 10^{0.49} = 3 \text{ cycles}$$

The selected disc springs at the above-mentioned minimum and maximum deflection values will not sustain any number of cycles. It is imperative to check the selected disc springs for dimensional ratios:

Outside-to-inside diameters ratio,  $200/102 = 1.96$ ; within recommended range.

Cone height-to-thickness ratio is  $4.2/13.1 = 0.3$ ; out of range, the minimum ratio is 0.4.

Outside diameter-to-thickness ratio is  $200/13.1 = 15$ ; out of range, the minimum ratio is 18. Thus, only one of the dimensional ratios satisfies the requirements for the best disc spring performance.

## WIRE ROPE, CHAIN, ROPE, AND HOOKS

### Strength and Properties of Wire Rope

**Wire Rope Construction.**—Essentially, a wire rope is made up of a number of strands laid helically about a metallic or non-metallic core. Each strand consists of a number of wires also laid helically about a metallic or non-metallic center. Various types of wire rope have been developed to meet a wide range of uses and operating conditions. These types are distinguished by the kind of core; the number of strands; the number, sizes, and arrangement of the wires in each strand; and the way in which the wires and strands are wound or laid about each other. The following descriptive material is based largely on information supplied by the Bethlehem Steel Co.

*Rope Wire Materials:* Materials used in the manufacture of rope wire are, in order of increasing strength: iron, phosphor bronze, traction steel, plow steel, improved plow steel, and bridge rope steel. Iron wire rope is largely used for low-strength applications such as elevator ropes not used for hoisting, and for stationary guy ropes.

Phosphor bronze wire rope is used occasionally for elevator governor-cable rope and for certain marine applications as life lines, clearing lines, wheel ropes and rigging.

Traction steel wire rope is used primarily as hoist rope for passenger and freight elevators of the traction drive type, an application for which it was specifically designed.

Ropes made of galvanized wire or wire coated with zinc by the electro-deposition process are used in certain applications where additional protection against rusting is required. As will be noted from the tables of wire-rope sizes and strengths, the breaking strength of galvanized wire rope is 10 per cent less than that of ungalvanized (bright) wire rope. Bethanized (zinc-coated) wire rope can be furnished to bright wire rope strength when so specified.

Galvanized carbon steel, tinned carbon steel, and stainless steel are used for small cords and strands ranging in diameter from  $\frac{1}{64}$  to  $\frac{3}{8}$  inch and larger.

Marline clad wire rope has each strand wrapped with a layer of tarred marline. The cladding provides hand protection for workers and wear protection for the rope.

*Rope Cores:* Wire-rope cores are made of fiber, cotton, asbestos, polyvinyl plastic, a small wire rope (independent wire-rope core), a multiple-wire strand (wire-strand core) or a cold-drawn wire-wound spring.

*Fiber* (manila or sisal) is the type of core most widely used when loads are not too great. It supports the strands in their relative positions and acts as a cushion to prevent nicking of the wires lying next to the core.

*Cotton* is used for small ropes such as sash cord and aircraft cord.

*Asbestos cores* can be furnished for certain special operations where the rope is used in oven operations.

*Polyvinyl plastics cores* are offered for use where exposure to moisture, acids, or caustics is excessive.

A *wire-strand core* often referred to as WSC, consists of a multiple-wire strand that may be the same as one of the strands of the rope. It is smoother and more solid than the independent wire rope core and provides a better support for the rope strands.

The *independent wire rope core*, often referred to as IWRC, is a small  $6 \times 7$  wire rope with a wire-strand core and is used to provide greater resistance to crushing and distortion of the wire rope. For certain applications it has the advantage over a wire-strand core in that it stretches at a rate closer to that of the rope itself.

Wire ropes with wire-strand cores are, in general, less flexible than wire ropes with independent wire-rope or non-metallic cores.

Ropes with metallic cores are rated  $7\frac{1}{2}$  per cent stronger than those with non-metallic cores.

*Wire-Rope Lay:* The lay of a wire rope is the direction of the helical path in which the strands are laid and, similarly, the lay of a strand is the direction of the helical path in which the wires are laid. If the wires in the strand or the strands in the rope form a helix similar to the threads of a right-hand screw, i.e., they wind around to the right, the lay is called right hand and, conversely, if they wind around to the left, the lay is called left hand. In the *regular lay*, the wires in the strands are laid in the opposite direction to the lay of the strands in the rope. In right-regular lay, the strands are laid to the right and the wires to the left. In left-regular lay, the strands are laid to the left, the wires to the right. In *Lang lay*, the wires and strands are laid in the same direction, i.e., in right Lang lay, both the wires and strands are laid to the right and in left Lang they are laid to the left.

Alternate lay ropes having alternate right and left laid strands are used to resist distortion and prevent clamp slippage, but because other advantages are missing, have limited use.

The regular lay wire rope is most widely used and right regular lay rope is customarily furnished. Regular lay rope has less tendency to spin or untwist when placed under load and is generally selected where long ropes are employed and the loads handled are frequently removed. Lang lay ropes have greater flexibility than regular lay ropes and are more resistant to abrasion and fatigue.

In preformed wire ropes the wires and strands are preshaped into a helical form so that when laid to form the rope they tend to remain in place. In a non-preformed rope, broken wires tend to "wicker out" or protrude from the rope and strands that are not seized tend to spring apart. Preforming also tends to remove locked-in stresses, lengthen service life, and make the rope easier to handle and to spool.

*Strand Construction:* Various arrangements of wire are used in the construction of wire rope strands. In the simplest arrangement six wires are grouped around a central wire thus making seven wires, all of the same size. Other types of construction known as "filler-wire," Warrington, Seale, etc. make use of wires of different sizes. Their respective patterns of arrangement are shown diagrammatically in the table of wire weights and strengths.

**Specifying Wire Rope.**—In specifying wire rope the following information will be required: length, diameter, number of strands, number of wires in each strand, type of rope construction, grade of steel used in rope, whether preformed or not preformed, type of center, and type of lay. The manufacturer should be consulted in selecting the best type of wire rope for a new application.

**Properties of Wire Rope.**—Important properties of wire rope are strength, wear resistance, flexibility, and resistance to crushing and distortion.

*Strength:* The strength of wire rope depends upon its size, kind of material of which the wires are made and their number, the type of core, and whether the wire is galvanized or not. Strengths of various types and sizes of wire ropes are given in the accompanying tables together with appropriate factors to apply for ropes with steel cores and for galvanized wire ropes.

*Wear Resistance:* When wire rope must pass back and forth over surfaces that subject it to unusual wear or abrasion, it must be specially constructed to give satisfactory service.

Such construction may make use of 1) relatively large outer wires; 2) Lang lay in which wires in each strand are laid in the same direction as the strand; and 3) flattened strands.

The object in each type is to provide a greater outside surface area to take the wear or abrasion. From the standpoint of material, improved plow steel has not only the highest tensile strength but also the greatest resistance to abrasion in regularly stocked wire rope.

**Flexibility:** Wire rope that undergoes repeated and severe bending, such as in passing around small sheaves and drums, must have a high degree of flexibility to prevent premature breakage and failure due to fatigue. Greater flexibility in wire rope is obtained by

1) using small wires in larger numbers; 2) using Lang lay; and 3) preforming, that is, the wires and strands of the rope are shaped during manufacture to fit the position they will assume in the finished rope.

**Resistance to Crushing and Distortion:** Where wire rope is to be subjected to transverse loads that may crush or distort it, care should be taken to select a type of construction that will stand up under such treatment.

Wire rope designed for such conditions may have 1) large outer wires to spread the load per wire over a greater area; and 2) an independent wire core or a high-carbon cold-drawn wound spring core.

**Standard Classes of Wire Rope.**—Wire rope is commonly designated by two figures, the first indicating the number of strands and the second, the number of wires per strand, as:  $6 \times 7$ , a six-strand rope having seven wires per strand, or  $8 \times 19$ , an eight-strand rope having 19 wires per strand. When such numbers are used as designations of standard wire rope classes, the second figure in the designation may be purely nominal in that the number of wires per strand for various ropes in the class may be slightly less or slightly more than the nominal as will be seen from the following brief descriptions. (For ropes with a wire strand core, a second group of two numbers may be used to indicate the construction of the wire core, as  $1 \times 21$ ,  $1 \times 43$ , and so on.)

**$6 \times 7$  Class (Standard Coarse Laid Rope):** Wire ropes in this class are for use where resistance to wear, as in dragging over the ground or across rollers, is an important requirement. Heavy hauling, rope transmissions, and well drilling are common applications. These wire ropes are furnished in right regular lay and occasionally in Lang lay. The cores may be of fiber, independent wire rope, or wire strand. Since this class is a relatively stiff type of construction, these ropes should be used with large sheaves and drums. Because of the small number of wires, a larger factor of safety may be called for.

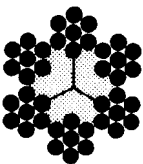


Fig. 1a.  
 $6 \times 7$  with fiber core

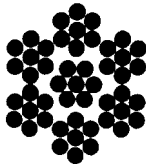


Fig. 1b.  
 $6 \times 7$  with  $1 \times 7$  WSC

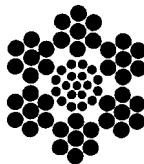


Fig. 1c.  
 $6 \times 7$  with  $1 \times 19$  WSC

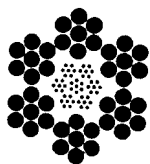


Fig. 1d.  
 $6 \times 7$  with IWRC

As shown in Figs. 1a through Figs. 1d, this class includes a  $6 \times 7$  construction with fiber core; a  $6 \times 7$  construction with  $1 \times 7$  wire strand core (sometimes called  $7 \times 7$ ); a  $6 \times 7$  construction with  $1 \times 19$  wire strand core; and a  $6 \times 7$  construction with independent wire rope core. Table 1 provides strength and weight data for this class.

Two special types of wire rope in this class are: aircraft cord, a  $6 \times 6$  or  $7 \times 7$  Bethanized wire rope of high tensile strength and sash cord, a  $6 \times 7$  iron rope used for a variety of purposes where strength is not an important factor.



**Table 1. Weights and Strengths of 6 × 7 (Standard Coarse Laid) Wire Ropes, Preformed and Not Preformed**

| Dia., Inches | Approx. Weight per Ft., Pounds | Breaking Strength, Tons of 2000 Lbs. |            |                 | Dia., Inches | Approx. Weight per Ft., Pounds | Breaking Strength, Tons of 2000 Lbs. |            |                 |
|--------------|--------------------------------|--------------------------------------|------------|-----------------|--------------|--------------------------------|--------------------------------------|------------|-----------------|
|              |                                | Impr. Plow Steel                     | Plow Steel | Mild Plow Steel |              |                                | Impr. Plow Steel                     | Plow Steel | Mild Plow Steel |
| ¼            | 0.094                          | 2.64                                 | 2.30       | 2.00            | ¾            | 0.84                           | 22.7                                 | 19.8       | 17.2            |
| ⅓            | 0.15                           | 4.10                                 | 3.56       | 3.10            | ⅞            | 1.15                           | 30.7                                 | 26.7       | 23.2            |
| ⅔            | 0.21                           | 5.86                                 | 5.10       | 4.43            | 1            | 1.50                           | 39.7                                 | 34.5       | 30.0            |
| ⅞            | 0.29                           | 7.93                                 | 6.90       | 6.00            | 1 ⅛          | 1.90                           | 49.8                                 | 43.3       | 37.7            |
| 1            | 0.38                           | 10.3                                 | 8.96       | 7.79            | 1 ¼          | 2.34                           | 61.0                                 | 53.0       | 46.1            |
| 1 ⅛          | 0.48                           | 13.0                                 | 11.3       | 9.82            | 1 ⅝          | 2.84                           | 73.1                                 | 63.6       | 55.3            |
| 1 ¼          | 0.59                           | 15.9                                 | 13.9       | 12.0            | 1 ¾          | 3.38                           | 86.2                                 | 75.0       | 65.2            |

For ropes with steel cores, add 7½ per cent to above strengths.

For galvanized ropes, deduct 10 per cent from above strengths.

Source: Rope diagrams, Bethlehem Steel Co. All data, U.S. Simplified Practice Recommendation 198-50.

**6 × 19 Class (Standard Hoisting Rope):** This rope is the most popular and widely used class. Ropes in this class are furnished in regular or Lang lay and may be obtained preformed or not preformed. Cores may be of fiber, independent wire rope, or wire strand. As can be seen from Table 2 and Figs. 2a through 2h, there are four common types: 6 × 25 filler wire construction with fiber core (not illustrated), independent wire core, or wire strand core (1 × 25 or 1 × 43); 6 × 19 Warrington construction with fiber core; 6 × 21 filler wire construction with fiber core; and 6 × 19, 6 × 21, and 6 × 17 Seale construction with fiber core.

**Table 2. Weights and Strengths of 6 × 19 (Standard Hoisting) Wire Ropes, Preformed and Not Preformed**

| Dia., Inches | Approx. Weight per Ft., Pounds | Breaking Strength, Tons of 2000 Lbs. |            |                 | Dia., Inches | Approx. Weight per Ft., Pounds | Breaking Strength, Tons of 2000 Lbs. |            |                 |
|--------------|--------------------------------|--------------------------------------|------------|-----------------|--------------|--------------------------------|--------------------------------------|------------|-----------------|
|              |                                | Impr. Plow Steel                     | Plow Steel | Mild Plow Steel |              |                                | Impr. Plow Steel                     | Plow Steel | Mild Plow Steel |
| ¼            | 0.10                           | 2.74                                 | 2.39       | 2.07            | 1 ¼          | 2.50                           | 64.6                                 | 56.2       | 48.8            |
| ⅓            | 0.16                           | 4.26                                 | 3.71       | 3.22            | 1 ⅝          | 3.03                           | 77.7                                 | 67.5       | 58.8            |
| ⅔            | 0.23                           | 6.10                                 | 5.31       | 4.62            | 1 ¾          | 3.60                           | 92.0                                 | 80.0       | 69.6            |
| ⅞            | 0.31                           | 8.27                                 | 7.19       | 6.25            | 1 ⅞          | 4.23                           | 107                                  | 93.4       | 81.2            |
| 1            | 0.40                           | 10.7                                 | 9.35       | 8.13            | 1 ¾          | 4.90                           | 124                                  | 108        | 93.6            |
| 1 ⅛          | 0.51                           | 13.5                                 | 11.8       | 10.2            | 1 ⅞          | 5.63                           | 141                                  | 123        | 107             |
| 1 ¼          | 0.63                           | 16.7                                 | 14.5       | 12.6            | 2            | 6.40                           | 160                                  | 139        | 121             |
| 1 ⅝          | 0.90                           | 23.8                                 | 20.7       | 18.0            | 2 ⅛          | 7.23                           | 179                                  | 156        | ...             |
| 1 ¾          | 1.23                           | 32.2                                 | 28.0       | 24.3            | 2 ¼          | 8.10                           | 200                                  | 174        | ...             |
| 1            | 1.60                           | 41.8                                 | 36.4       | 31.6            | 2 ½          | 10.00                          | 244                                  | 212        | ...             |
| 1 ⅞          | 2.03                           | 52.6                                 | 45.7       | 39.8            | 2 ¾          | 12.10                          | 292                                  | 254        | ...             |

The 6 × 25 filler wire with fiber core not illustrated.

For ropes with steel cores, add 7½ per cent to above strengths.

For galvanized ropes, deduct 10 per cent from above strengths.

Source: Rope diagrams, Bethlehem Steel Co. All data, U.S. Simplified Practice Recommendation 198-50.

**6 × 37 Class (Extra Flexible Hoisting Rope):** For a given size of rope, the component wires are of smaller diameter than those in the two classes previously described and hence have less resistance to abrasion. Ropes in this class are furnished in regular and Lang lay with fiber core or independent wire rope core, preformed or not preformed.

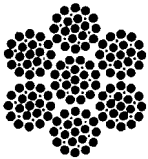


Fig. 2a.  
6 x 25 filler wire  
with WSC (1 x 25)

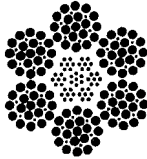


Fig. 2b.  
6 x 25 filler wire  
with IWRC

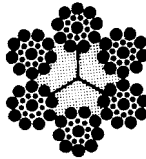


Fig. 2c.  
6 x 19 Seale  
with fiber core

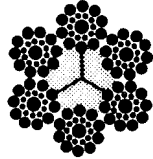


Fig. 2d.  
6 x 21 Seale  
with fiber core

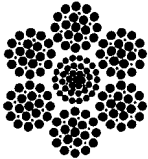


Fig. 2e.  
6 x 25 filler wire  
with WSC (1 x 43)

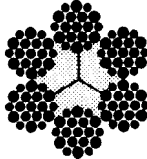


Fig. 2f.  
6 x 19 Warrington  
with fiber core

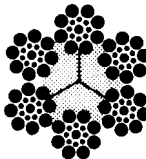


Fig. 2g.  
6 x 17 Seale  
with fiber core

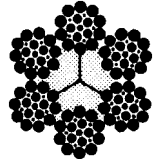


Fig. 2h.  
6 x 21 filler wire  
with fiber core

**Table 3. Weights and Strengths of 6 x 37 (Extra Flexible Hoisting) Wire Ropes, Preformed and Not Preformed**

| Dia.,<br>Inches | Approx.<br>Weight<br>per Ft.,<br>Pounds | Breaking Strength,<br>Tons of 2000 Lbs. |               | Dia.,<br>Inches | Approx.<br>Weight<br>per Ft.,<br>Pounds | Breaking Strength,<br>Tons of 2000 Lbs. |               |
|-----------------|---|---|---------------|-----------------|---|---|---------------|
|                 |   | Impr.<br>Plow<br>Steel                  | Plow<br>Steel |                 |   | Impr.<br>Plow<br>Steel                  | Plow<br>Steel |
| 1/4             | 0.10                                    | 2.59                                    | 2.25          | 1 1/2           | 3.49                                    | 87.9                                    | 76.4          |
| 5/16            | 0.16                                    | 4.03                                    | 3.50          | 1 5/8           | 4.09                                    | 103                                     | 89.3          |
| 3/8             | 0.22                                    | 5.77                                    | 5.02          | 1 3/4           | 4.75                                    | 119                                     | 103           |
| 7/16            | 0.30                                    | 7.82                                    | 6.80          | 1 7/8           | 5.45                                    | 136                                     | 118           |
| 1/2             | 0.39                                    | 10.2                                    | 8.85          | 2               | 6.20                                    | 154                                     | 134           |
| 9/16            | 0.49                                    | 12.9                                    | 11.2          | 2 1/8           | 7.00                                    | 173                                     | 150           |
| 5/8             | 0.61                                    | 15.8                                    | 13.7          | 2 1/4           | 7.85                                    | 193                                     | 168           |
| 3/4             | 0.87                                    | 22.6                                    | 19.6          | 2 1/2           | 9.69                                    | 236                                     | 205           |
| 7/8             | 1.19                                    | 30.6                                    | 26.6          | 2 3/4           | 11.72                                   | 284                                     | 247           |
| 1               | 1.55                                    | 39.8                                    | 34.6          | 3               | 14.0                                    | 335                                     | 291           |
| 1 1/8           | 1.96                                    | 50.1                                    | 43.5          | 3 1/4           | 16.4                                    | 390                                     | 339           |
| 1 1/4           | 2.42                                    | 61.5                                    | 53.5          | 3 1/2           | 19.0                                    | 449                                     | 390           |
| 1 3/8           | 2.93                                    | 74.1                                    | 64.5          | ...             | ...                                     | ...                                     | ...           |

For ropes with steel cores, add 7 1/2 per cent to above strengths.

For galvanized ropes, deduct 10 per cent from above strengths.

Source: Rope diagrams, Bethlehem Steel Co. All data, U. S. Simplified Practice Recommendation 198-50.

As shown in Table 3 and Figs. 3a through 3h, there are four common types: 6 x 29 filler wire construction with fiber core and 6 x 36 filler wire construction with independent wire rope core, a special rope for construction equipment; 6 x 35 (two operations) construction with fiber core and 6 x 41 Warrington Seale construction with fiber core, a standard crane rope in this class of rope construction; 6 x 41 filler wire construction with fiber core or independent wire core, a special large shovel rope usually furnished in Lang lay; and 6 x 46

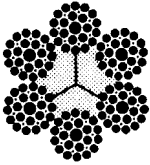


Fig. 3a.  
6 x 29 filler wire  
with fiber core

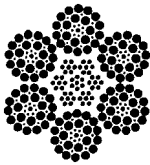


Fig. 3b.  
6 x 36 filler wire  
with IWRC

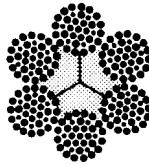


Fig. 3c.  
6 x 35 with  
fiber core

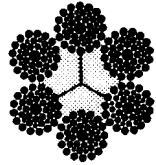


Fig. 3d.  
6 x 41 Warrington-Seale  
with fiber core

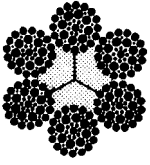


Fig. 3e.  
6 x 41 filler wire  
with fiber core

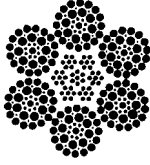


Fig. 3f.  
6 x 41 filler wire  
with IWRC

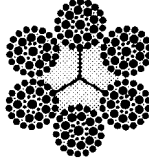


Fig. 3g.  
6 x 46 filler wire  
with fiber core

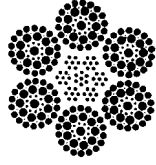


Fig. 3h.  
6 x 46 filler wire  
with IWRC

filler wire construction with fiber core or independent wire rope core, a special large shovel and dredge rope.

*8 x 19 Class (Special Flexible Hoisting Rope):* This rope is stable and smooth-running, and is especially suitable, because of its flexibility, for high speed operation with reverse bends. Ropes in this class are available in regular lay with fiber core.

As shown in Table 4 and Figs. 4a through 4d, there are four common types: 8 x 25 filler wire construction, the most flexible but the least wear resistant rope of the four types; Warrington type in 8 x 19 construction, less flexible than the 8 x 25; 8 x 21 filler wire construction, less flexible than the Warrington; and Seale type in 8 x 19 construction, which has the greatest wear resistance of the four types but is also the least flexible.

**Table 4. Weights and Strengths of 8 x 19 (Special Flexible Hoisting) Wire Ropes, Preformed and Not Preformed**

| Dia.,<br>Inches | Approx.<br>Weight<br>per Ft.,<br>Pounds | Breaking Strength,<br>Tons of 2000 Lbs. |               | Dia.,<br>Inches | Approx.<br>Weight<br>per Ft.,<br>Pounds | Breaking Strength,<br>Tons of 2000 Lbs. |               |
|-----------------|---|---|---------------|-----------------|---|---|---------------|
|                 |   | Impr.<br>Plow<br>Steel                  | Plow<br>Steel |                 |   | Impr.<br>Plow<br>Steel                  | Plow<br>Steel |
| 1/4             | 0.09                                    | 2.35                                    | 2.04          | 3/4             | 0.82                                    | 20.5                                    | 17.8          |
| 5/16            | 0.14                                    | 3.65                                    | 3.18          | 7/8             | 1.11                                    | 27.7                                    | 24.1          |
| 3/8             | 0.20                                    | 5.24                                    | 4.55          | 1               | 1.45                                    | 36.0                                    | 31.3          |
| 7/16            | 0.28                                    | 7.09                                    | 6.17          | 1 1/8           | 1.84                                    | 45.3                                    | 39.4          |
| 1/2             | 0.36                                    | 9.23                                    | 8.02          | 1 1/4           | 2.27                                    | 55.7                                    | 48.4          |
| 9/16            | 0.46                                    | 11.6                                    | 10.1          | 1 3/8           | 2.74                                    | 67.1                                    | 58.3          |
| 5/8             | 0.57                                    | 14.3                                    | 12.4          | 1 1/2           | 3.26                                    | 79.4                                    | 69.1          |

For ropes with steel cores, add 7 1/2 per cent to above strengths.

For galvanized ropes, deduct 10 per cent from above strengths.

Source: Rope diagrams, Bethlehem Steel Co. All data, U. S. Simplified Practice Recommendation 198-50.

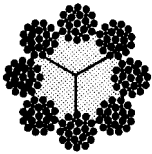


Fig. 4a.  
8 x 25 filler wire  
with fiber core

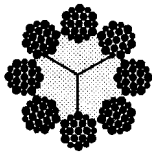


Fig. 4b.  
8 x 19 Warrington  
with fiber core

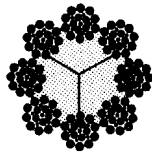


Fig. 4c.  
8 x 21 filler wire  
with fiber core

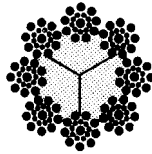


Fig. 4d.  
8 x 19 Seale  
with fiber core

Also in this class, but not shown in [Table 4](#) are elevator ropes made of traction steel and iron.

**18 x 7 Non-rotating Wire Rope:** This rope is specially designed for use where a minimum of rotating or spinning is called for, especially in the lifting or lowering of free loads with a single-part line. It has an inner layer composed of 6 strands of 7 wires each laid in left Lang lay over a fiber core and an outer layer of 12 strands of 7 wires each laid in right regular lay. The combination of opposing lays tends to prevent rotation when the rope is stretched. However, to avoid any tendency to rotate or spin, loads should be kept to at least one-eighth and preferably one-tenth of the breaking strength of the rope. Weights and strengths are shown in [Table 5](#).

**Table 5. Weights and Strengths of Standard 18 x 7 Nonrotating Wire Rope, Preformed and Not Preformed**

|                 |   |   |               | Recommended Sheave and Drum Diameters |   |   |               |
|-----------------|---|---|---------------|---------------------------------------|---|---|---------------|
|                 |   |   |               | Single layer on drum                  |   | Multiple layers on drum                 |               |
|                 |   | 36 rope diameters                       |               | 48 rope diameters                     |   | 60 rope diameters                       |               |
|                 |   |   |               |                                       |   |   |               |
| Fig. 5.         |   |   |               |                                       |   |   |               |
| Dia.,<br>Inches | Approx.<br>Weight<br>per Ft.,<br>Pounds | Breaking Strength,<br>Tons of 2000 Lbs. |               | Dia.,<br>Inches                       | Approx.<br>Weight<br>per Ft.,<br>Pounds | Breaking Strength,<br>Tons of 2000 Lbs. |               |
|                 |   | Impr.<br>Plow<br>Steel                  | Plow<br>Steel |                                       |   | Impr.<br>Plow<br>Steel                  | Plow<br>Steel |
| $\frac{3}{16}$  | 0.061                                   | 1.42                                    | 1.24          | $\frac{7}{8}$                         | 1.32                                    | 29.5                                    | 25.7          |
| $\frac{1}{4}$   | 0.108                                   | 2.51                                    | 2.18          | 1                                     | 1.73                                    | 38.3                                    | 33.3          |
| $\frac{5}{16}$  | 0.169                                   | 3.90                                    | 3.39          | $1\frac{1}{8}$                        | 2.19                                    | 48.2                                    | 41.9          |
| $\frac{3}{8}$   | 0.24                                    | 5.59                                    | 4.86          | $1\frac{1}{4}$                        | 2.70                                    | 59.2                                    | 51.5          |
| $\frac{7}{16}$  | 0.33                                    | 7.58                                    | 6.59          | $1\frac{3}{8}$                        | 3.27                                    | 71.3                                    | 62.0          |
| $\frac{1}{2}$   | 0.43                                    | 9.85                                    | 8.57          | $1\frac{1}{2}$                        | 3.89                                    | 84.4                                    | 73.4          |
| $\frac{9}{16}$  | 0.55                                    | 12.4                                    | 10.8          | $1\frac{5}{8}$                        | 4.57                                    | 98.4                                    | 85.6          |
| $\frac{5}{8}$   | 0.68                                    | 15.3                                    | 13.3          | $1\frac{3}{4}$                        | 5.30                                    | 114                                     | 98.8          |
| $\frac{3}{4}$   | 0.97                                    | 21.8                                    | 19.0          | ...                                   | ...                                     | ...                                     | ...           |

For galvanized ropes, deduct 10 per cent from above strengths.

Source: Rope diagrams, sheave and drum diameters, and data for  $\frac{3}{16}$ ,  $\frac{1}{4}$  and  $\frac{5}{16}$ -inch sizes, Bethlehem Steel Co. All other data, U. S. Simplified Practice Recommendation 198-50.

**Flattened Strand Wire Rope:** The wires forming the strands of this type of rope are wound around triangular centers so that a flattened outer surface is provided with a greater area than in the regular round rope to withstand severe conditions of abrasion. The triangu-

lar shape of the strands also provides superior resistance to crushing. Flattened strand wire rope is usually furnished in Lang lay and may be obtained with fiber core or independent wire rope core. The three types shown in Table 6 and Figs. 6a through 6c are flexible and are designed for hoisting work.

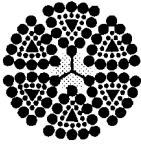


Fig. 6a.  
6 x 25 with fiber core

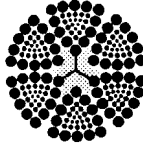


Fig. 6b.  
6 x 30 with fiber core

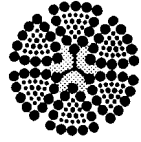


Fig. 6c.  
6 x 27 with fiber core

**Table 6. Weights and Strengths of Flattened Strand Wire Rope, Preformed and Not Preformed**

| Dia., Inches      | Approx. Weight per Ft., Pounds | Breaking Strength, Tons of 2000 Lbs. |                 | Dia., Inches | Approx. Weight per Ft., Pounds | Breaking Strength, Tons of 2000 Lbs. |                 |
|-------------------|--------------------------------|--------------------------------------|-----------------|--------------|--------------------------------|--------------------------------------|-----------------|
|                   |                                | Impr. Plow Steel                     | Mild Plow Steel |              |                                | Impr. Plow Steel                     | Mild Plow Steel |
| 3/8 <sup>a</sup>  | 0.25                           | 6.71                                 | ...             | 1 3/8        | 3.40                           | 85.5                                 | ...             |
| 1/2               | 0.45                           | 11.8                                 | 8.94            | 1 1/2        | 4.05                           | 101                                  | ...             |
| 5/16 <sup>a</sup> | 0.57                           | 14.9                                 | 11.2            | 1 5/8        | 4.75                           | 118                                  | ...             |
| 5/8               | 0.70                           | 18.3                                 | 13.9            | 1 3/4        | 5.51                           | 136                                  | ...             |
| 3/4               | 1.01                           | 26.2                                 | 19.8            | 2            | 7.20                           | 176                                  | ...             |
| 7/8               | 1.39                           | 35.4                                 | 26.8            | 2 1/4        | 9.10                           | 220                                  | ...             |
| 1                 | 1.80                           | 46.0                                 | 34.8            | 2 1/2        | 11.2                           | 269                                  | ...             |
| 1 1/8             | 2.28                           | 57.9                                 | 43.8            | 2 3/4        | 13.6                           | 321                                  | ...             |
| 1 1/4             | 2.81                           | 71.0                                 | 53.7            | ...          | ...                            | ...                                  | ...             |

<sup>a</sup>These sizes in Type B only.

Type H is not in U.S. Simplified Practice Recommendation.

Source: Rope diagrams, Bethlehem Steel Co. All other data, U.S. Simplified Practice Recommendation 198-50.

*Flat Wire Rope:* This type of wire rope is made up of a number of four-strand rope units placed side by side and stitched together with soft steel sewing wire. These four-strand units are alternately right and left lay to resist warping, curling, or rotating in service. Weights and strengths are shown in Table 7.

**Simplified Practice Recommendations.**—Because the total number of wire rope types is large, manufacturers and users have agreed upon and adopted a U.S. Simplified Practice Recommendation to provide a simplified listing of those kinds and sizes of wire rope which are most commonly used and stocked. These, then, are the types and sizes which are most generally available. Other types and sizes for special or limited uses also may be found in individual manufacturer's catalogs.


**Sizes and Strengths of Wire Rope.**—The data shown in Tables 1 through 7 have been taken from U.S. Simplified Practice Recommendation 198-50 but do not include those wire ropes shown in that Simplified Practice Recommendation which are intended primarily for marine use.

*Wire Rope Diameter:* The diameter of a wire rope is the diameter of the circle that will just enclose it, hence when measuring the diameter with calipers, care must be taken to obtain the largest outside dimension, taken across the opposite strands, rather than the smallest dimension across opposite "valleys" or "flats." It is standard practice for the nominal diameter to be the minimum with all tolerances taken on the plus side. Limits for diam-

eter as well as for minimum breaking strength and maximum pitch are given in Federal Specification for Wire Rope, RR-R—571a.

*Wire Rope Strengths:* The strength figures shown in the accompanying tables have been obtained by a mathematical derivation based on actual breakage tests of wire rope and represent from 80 to 95 per cent of the total strengths of the individual wires, depending upon the type of rope construction.

**Table 7. Weights and Strengths of Standard Flat Wire Rope, Not Preformed**

| <br>Flat Wire Rope |              |                                |                                      | This rope consists of a number of 4-strand rope units placed side by side and stitched together with soft steel sewing wire. |                                   |              |                                |                                      |                 |
|---|--------------|--------------------------------|--------------------------------------|--|-----------------------------------|--------------|--------------------------------|--------------------------------------|-----------------|
| Width and Thickness, Inches   | No. of Ropes | Approx. Weight per Ft., Pounds | Breaking Strength, Tons of 2000 Lbs. |  | Width and Thickness, Inches       | No. of Ropes | Approx. Weight per Ft., Pounds | Breaking Strength, Tons of 2000 Lbs. |                 |
|   |              |                                | Plow Steel                           | Mild Plow-Steel  |                                   |              |                                | Plow Steel                           | Mild Plow Steel |
| $\frac{1}{4} \times 1\frac{1}{2}$   | 7            | 0.69                           | 16.8                                 | 14.6   | $\frac{1}{2} \times 4$            | 9            | 3.16                           | 81.8                                 | 71.2            |
| $\frac{1}{4} \times 2$  | 9            | 0.88                           | 21.7                                 | 18.8   | $\frac{1}{2} \times 4\frac{1}{2}$ | 10           | 3.82                           | 90.9                                 | 79.1            |
| $\frac{1}{4} \times 2\frac{1}{2}$   | 11           | 1.15                           | 26.5                                 | 23.0   | $\frac{1}{2} \times 5$            | 12           | 4.16                           | 109                                  | 94.9            |
| $\frac{1}{4} \times 3$  | 13           | 1.34                           | 31.3                                 | 27.2   | $\frac{1}{2} \times 5\frac{1}{2}$ | 13           | 4.50                           | 118                                  | 103             |
|   |              |                                |                                      |  | $\frac{1}{2} \times 6$            | 14           | 4.85                           | 127                                  | 111             |
| $\frac{5}{16} \times 1\frac{1}{2}$  | 5            | 0.77                           | 18.5                                 | 16.0   | $\frac{1}{2} \times 7$            | 16           | 5.85                           | 145                                  | 126             |
| $\frac{5}{16} \times 2$   | 7            | 1.05                           | 25.8                                 | 22.4   |                                   |              |                                |                                      |                 |
| $\frac{5}{16} \times 2\frac{1}{2}$  | 9            | 1.33                           | 33.2                                 | 28.8   | $\frac{3}{8} \times 3\frac{1}{2}$ | 6            | 3.40                           | 85.8                                 | 74.6            |
| $\frac{5}{16} \times 3$   | 11           | 1.61                           | 40.5                                 | 35.3   | $\frac{3}{8} \times 4$            | 7            | 3.95                           | 100                                  | 87.1            |
| $\frac{5}{16} \times 3\frac{1}{2}$  | 13           | 1.89                           | 47.9                                 | 41.7   | $\frac{3}{8} \times 4\frac{1}{2}$ | 8            | 4.50                           | 114                                  | 99.5            |
| $\frac{5}{16} \times 4$   | 15           | 2.17                           | 55.3                                 | 48.1   | $\frac{3}{8} \times 5$            | 9            | 5.04                           | 129                                  | 112             |
|   |              |                                |                                      |  | $\frac{3}{8} \times 5\frac{1}{2}$ | 10           | 5.59                           | 143                                  | 124             |
| $\frac{3}{8} \times 2$  | 6            | 1.25                           | 31.4                                 | 27.3   | $\frac{3}{8} \times 6$            | 11           | 6.14                           | 157                                  | 137             |
| $\frac{3}{8} \times 2\frac{1}{2}$   | 8            | 1.64                           | 41.8                                 | 36.4   | $\frac{3}{8} \times 7$            | 13           | 7.23                           | 186                                  | 162             |
| $\frac{3}{8} \times 3$  | 9            | 1.84                           | 47.1                                 | 40.9   | $\frac{3}{8} \times 8$            | 15           | 8.32                           | 214                                  | 186             |
| $\frac{3}{8} \times 3\frac{1}{2}$   | 11           | 2.23                           | 57.5                                 | 50.0   |                                   |              |                                |                                      |                 |
| $\frac{3}{8} \times 4$  | 12           | 2.44                           | 62.7                                 | 54.6   | $\frac{3}{4} \times 5$            | 8            | 6.50                           | 165                                  | 143             |
| $\frac{3}{8} \times 4\frac{1}{2}$   | 14           | 2.83                           | 73.2                                 | 63.7   | $\frac{3}{4} \times 6$            | 9            | 7.31                           | 185                                  | 161             |
| $\frac{3}{8} \times 5$  | 15           | 3.03                           | 78.4                                 | 68.2   | $\frac{3}{4} \times 7$            | 10           | 8.13                           | 206                                  | 179             |
| $\frac{3}{8} \times 5\frac{1}{2}$   | 17           | 3.42                           | 88.9                                 | 77.3   | $\frac{3}{4} \times 8$            | 11           | 9.70                           | 227                                  | 197             |
| $\frac{3}{8} \times 6$  | 18           | 3.63                           | 94.1                                 | 81.9   |                                   |              |                                |                                      |                 |
|   |              |                                |                                      |  | $\frac{7}{8} \times 5$            | 7            | 7.50                           | 190                                  | 165             |
| $\frac{1}{2} \times 2\frac{1}{2}$   | 6            | 2.13                           | 54.5                                 | 47.4   | $\frac{7}{8} \times 6$            | 8            | 8.56                           | 217                                  | 188             |
| $\frac{1}{2} \times 3$  | 7            | 2.47                           | 63.6                                 | 55.4   | $\frac{7}{8} \times 7$            | 9            | 9.63                           | 244                                  | 212             |
| $\frac{1}{2} \times 3\frac{1}{2}$   | 8            | 2.82                           | 72.7                                 | 63.3   | $\frac{7}{8} \times 8$            | 10           | 10.7                           | 271                                  | 236             |

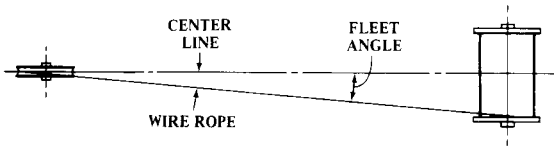
Source: Rope diagram, Bethlehem Steel Co.; all data, U.S. Simplified Practice Recommendation 198-50.

**Safe Working Loads and Factors of Safety.**—The maximum load for which a wire rope is to be used should take into account such associated factors as friction, load caused by bending around each sheave, acceleration and deceleration, and, if a long length of rope is to be used for hoisting, the weight of the rope at its maximum extension. The condition of the rope — whether new or old, worn or corroded — and type of attachments should also be considered.

Factors of safety for standing rope usually range from 3 to 4; for operating rope, from 5 to 12. Where there is the element of hazard to life or property, higher values are used.

**Installing Wire Rope.**—The main precaution to be taken in removing and installing wire rope is to avoid kinking which greatly lessens the strength and useful life. Thus, it is preferable when removing wire rope from the reel to have the reel with its axis in a horizontal position and, if possible, mounted so that it will revolve and the wire rope can be taken off straight. If the rope is in a coil, it should be unwound with the coil in a vertical position as by rolling the coil along the ground. Where a drum is to be used, the rope should be run directly onto it from the reel, taking care to see that it is not bent around the drum in a direction opposite to that on the reel, thus causing it to be subject to reverse bending. On flat or smooth-faced drums it is important that the rope be started from the proper end of the drum. A right lay rope that is being overwound on the drum, that is, it passes over the top of the drum as it is wound on, should be started from the right flange of the drum (looking at the drum from the side that the rope is to come) and a left lay rope from the left flange.

When the rope is under wound on the drum, a right lay rope should be started from the left flange and a left lay rope from the right flange, so that the rope will spool evenly and the turns will lie snugly together.



Sheaves and drums should be properly aligned to prevent undue wear. The proper position of the main or lead sheave for the rope as it comes off the drum is governed by what is called the fleet angle or angle between the rope as it stretches from drum to sheave and an imaginary center-line passing through the center of the sheave groove and a point halfway between the ends of the drum. When the rope is at one end of the drum, this angle should not exceed one and a half to two degrees. With the lead sheave mounted with its groove on this center-line, a safe fleet angle is obtained by allowing 30 feet of lead for each two feet of drum width.

*Sheave and Drum Dimensions:* Sheaves and drums should be as large as possible to obtain maximum rope life. However, factors such as the need for lightweight equipment for easy transport and use at high speeds, may call for relatively small sheaves with consequent sacrifice in rope life in the interest of overall economy. No hard and fast rules can be laid down for any particular rope if the utmost in economical performance is to be obtained. Where maximum rope life is of prime importance, the following recommendations of Federal Specification RR-R-571a for minimum sheave or drum diameters  $D$  in terms of rope diameter  $d$  will be of interest. For  $6 \times 7$  rope (six strands of 7 wires each)  $D = 72d$ ; for  $6 \times 19$  rope,  $D = 45d$ ; for  $6 \times 25$  rope,  $D = 45d$ ; for  $6 \times 29$  rope,  $D = 30d$ ; for  $6 \times 37$  rope,  $D = 27d$ ; and for  $8 \times 19$  rope,  $D = 31d$ .

Too small a groove for the rope it is to carry will prevent proper seating of the rope in the bottom of the groove and result in uneven distribution of load on the rope. Too large a groove will not give the rope sufficient side support. Federal Specification RR-R-571a recommends that sheave groove diameters be larger than the nominal rope diameters by the following minimum amounts: For ropes of  $\frac{1}{4}$ - to  $\frac{5}{16}$ -inch diameters,  $\frac{1}{64}$  inch larger; for  $\frac{3}{8}$ - to  $\frac{3}{4}$ -inch diameter ropes,  $\frac{1}{32}$  inch larger; for  $\frac{13}{16}$ - to  $1\frac{1}{8}$ -inch diameter ropes,  $\frac{3}{64}$  inch larger; for  $1\frac{3}{16}$ - to  $1\frac{1}{2}$ -inch ropes,  $\frac{1}{16}$  inch larger; for  $1\frac{9}{16}$ - to  $2\frac{1}{4}$ -inch ropes,  $\frac{3}{32}$  inch larger; and for  $2\frac{5}{16}$  and larger diameter ropes,  $\frac{1}{8}$  inch larger. For new or regrooved sheaves these values should be doubled; in other words for  $\frac{1}{4}$ - to  $\frac{5}{16}$ -inch diameter ropes, the groove diameter should be  $\frac{1}{32}$  inch larger, and so on.

*Drum or Reel Capacity:* The length of wire rope, in feet, that can be spooled onto a drum or reel, is computed by the following formula, where

$$A = \text{depth of rope space on drum, inches: } A = (H - D - 2Y) \div 2$$

$$B = \text{width between drum flanges, inches}$$

$$D = \text{diameter of drum barrel, inches}$$

$$H = \text{diameter of drum flanges, inches}$$

$$K = \text{factor from Table 8 for size of line selected}$$

$$Y = \text{depth not filled on drum or reel where winding is to be less than full capacity}$$

$$L = \text{length of wire rope on drum or reel, feet: } L = (A + D) \times A \times B \times K$$

**Table 8. Factors  $K$  Used in Calculating Wire Rope Drum and Reel Capacities**

| Rope Dia., In. | Factor $K$ | Rope Dia., In.  | Factor $K$ | Rope Dia., In. | Factor $K$ |
|----------------|------------|-----------------|------------|----------------|------------|
| $\frac{3}{32}$ | 23.4       | $\frac{1}{2}$   | 0.925      | $1\frac{3}{8}$ | 0.127      |
| $\frac{1}{8}$  | 13.6       | $\frac{9}{16}$  | 0.741      | $1\frac{1}{2}$ | 0.107      |
| $\frac{3}{64}$ | 10.8       | $\frac{5}{8}$   | 0.607      | $1\frac{5}{8}$ | 0.0886     |
| $\frac{5}{32}$ | 8.72       | $1\frac{1}{16}$ | 0.506      | $1\frac{3}{4}$ | 0.0770     |
| $\frac{3}{16}$ | 6.14       | $\frac{3}{4}$   | 0.428      | $1\frac{7}{8}$ | 0.0675     |
| $\frac{7}{32}$ | 4.59       | $1\frac{3}{16}$ | 0.354      | 2              | 0.0597     |
| $\frac{1}{4}$  | 3.29       | $\frac{7}{8}$   | 0.308      | $2\frac{1}{8}$ | 0.0532     |
| $\frac{5}{16}$ | 2.21       | 1               | 0.239      | $2\frac{1}{4}$ | 0.0476     |
| $\frac{3}{8}$  | 1.58       | $1\frac{1}{8}$  | 0.191      | $2\frac{3}{8}$ | 0.0419     |
| $\frac{7}{16}$ | 1.19       | $1\frac{1}{4}$  | 0.152      | $2\frac{1}{2}$ | 0.0380     |

*Note:* The values of “ $K$ ” allow for normal oversize of ropes, and the fact that it is practically impossible to “thread-wind” ropes of small diameter. However, the formula is based on uniform rope winding and will not give correct figures if rope is wound non-uniformly on the reel. The amount of tension applied when spooling the rope will also affect the length. The formula is based on the same number of wraps of rope in each layer, which is not strictly correct, but does not result in appreciable error unless the width ( $B$ ) of the reel is quite small compared with the flange diameter ( $H$ ).

*Example:* Find the length in feet of  $\frac{9}{16}$ -inch diameter rope required to fill a drum having the following dimensions:  $B = 24$  inches,  $D = 18$  inches,  $H = 30$  inches,

$$A = (30 - 18 - 0) \div 2 = 6 \text{ inches}$$

$$L = (6 + 18) \times 6 \times 24 \times 0.741 = 2560.0 \text{ or } 2560 \text{ feet}$$

The above formula and factors  $K$  allow for normal oversize of ropes but will not give correct figures if rope is wound non-uniformly on the reel.

*Load Capacity of Sheave or Drum:* To avoid excessive wear and groove corrugation, the radial pressure exerted by the wire rope on the sheave or drum must be kept within certain maximum limits. The radial pressure of the rope is a function of rope tension, rope diameter, and tread diameter of the sheave and can be determined by the following equation:

$$P = \frac{2T}{D \times d}$$

where  $P$  = Radial pressure in pounds per square inch (see Table 9)

$T$  = Rope tension in pounds

$D$  = Tread diameter of sheave or drum in inches

$d$  = Rope diameter in inches

According to the Bethlehem Steel Co. the radial pressures shown in Table 9 are recommended as maximums according to the material of which the sheave or drum is made.



**Table 9. Maximum Radial Pressures for Drums and Sheaves**

| Type of Wire Rope | Drum or Sheave Material                   |                  |                              | Type of Wire Rope       | Drum or Sheave Material                   |            |                              |
|-------------------|---|------------------|------------------------------|-------------------------|---|------------|------------------------------|
|                   | Cast Iron                                 | Cast Steel       | Manganese Steel <sup>a</sup> |                         | Cast Iron                                 | Cast Steel | Manganese Steel <sup>a</sup> |
|                   | Recommended Maximum Radial Pressures, psi |                  |                              |                         | Recommended Maximum Radial Pressures, psi |            |                              |
| 6 × 7             | 300 <sup>b</sup>                          | 550 <sup>b</sup> | 1500 <sup>b</sup>            | 6 × 8 Flattened Strand  | 450                                       | 850        | 2200                         |
| 6 × 19            | 500 <sup>b</sup>                          | 900 <sup>b</sup> | 2500 <sup>b</sup>            | 6 × 25 Flattened Strand | 800                                       | 1450       | 4000                         |
| 6 × 37            | 600                                       | 1075             | 3000                         | 6 × 30 Flattened Strand | 800                                       | 1450       | 4000                         |

<sup>a</sup> 11 to 13 per cent manganese.

<sup>b</sup> These values are for regular lay rope. Lang lay rope values may be increased by 15 per cent.

**Minimum Sheave- and Drum-Groove Dimensions for Wire Rope Applications**

| Nominal Rope Diameter | Groove Radius |       | Nominal Rope Diameter | Groove Radius |       | Nominal Rope Diameter | Groove Radius |       |
|-----------------------|---------------|-------|-----------------------|---------------|-------|-----------------------|---------------|-------|
|                       | New           | Worn  |                       | New           | Worn  |                       | New           | Worn  |
| 1/4                   | 0.135         | 0.129 | 1 3/8                 | 0.876         | 0.833 | 3 3/8                 | 1.807         | 1.730 |
| 5/16                  | 0.167         | 0.160 | 1 3/4                 | 0.939         | 0.897 | 3 1/2                 | 1.869         | 1.794 |
| 3/8                   | 0.201         | 0.190 | 1 7/8                 | 1.003         | 0.959 | 3 3/4                 | 1.997         | 1.918 |
| 7/16                  | 0.234         | 0.220 | 2                     | 1.085         | 1.025 | 4                     | 2.139         | 2.050 |
| 1/2                   | 0.271         | 0.256 | 2 1/8                 | 1.137         | 1.079 | 4 1/4                 | 2.264         | 2.178 |
| 5/16                  | 0.303         | 0.288 | 2 1/4                 | 1.210         | 1.153 | 4 1/2                 | 2.396         | 2.298 |
| 5/8                   | 0.334         | 0.320 | 2 3/8                 | 1.271         | 1.199 | 4 3/4                 | 2.534         | 2.434 |
| 3/4                   | 0.401         | 0.380 | 2 1/2                 | 1.338         | 1.279 | 5                     | 2.663         | 2.557 |
| 7/8                   | 0.468         | 0.440 | 2 5/8                 | 1.404         | 1.339 | 5 1/4                 | 2.804         | 2.691 |
| 1                     | 0.543         | 0.513 | 2 3/4                 | 1.481         | 1.409 | 5 1/2                 | 2.929         | 2.817 |
| 1 1/8                 | 0.605         | 0.577 | 2 7/8                 | 1.544         | 1.473 | 5 3/4                 | 3.074         | 2.947 |
| 1 1/4                 | 0.669         | 0.639 | 3                     | 1.607         | 1.538 | 6                     | 3.198         | 3.075 |
| 1 3/8                 | 0.736         | 0.699 | 3 1/8                 | 1.664         | 1.598 |                       |               |       |
| 1 1/2                 | 0.803         | 0.759 | 3 1/4                 | 1.731         | 1.658 |                       |               |       |

All dimensions in inches. Data taken from *Wire Rope Users Manual*, 2nd ed., American Iron and Steel Institute, Washington, D. C. The values given in this table are applicable to grooves in sheaves and drums but are not generally suitable for pitch design, since other factors may be involved.

**Rope Loads due to Bending:** When a wire rope is bent around a sheave, the resulting bending stress  $s_b$  in the outer wire, and equivalent bending load  $P_b$  (amount that direct tension load on rope is increased by bending) may be computed by the following formulas:

$s_b = Ed_w \div D$ ;  $P_b = s_b A$ , where  $A = d^2 Q$ .  $E$  is the modulus of elasticity of the wire rope (varies with the type and condition of rope from 10,000,000 to 14,000,000. An average value of 12,000,000 is frequently used),  $d$  is the diameter of the wire rope,  $d_w$  is the diameter of the component wire (for 6 × 7 rope,  $d_w = 0.106d$ ; for 6 × 19 rope,  $0.063d$ ; for 6 × 37 rope,  $0.045d$ ; and for 8 × 19 rope,  $d_w = 0.050d$ ).  $D$  is the pitch diameter of the sheave in inches,  $A$  is the metal cross-sectional area of the rope, and  $Q$  is a constant, values for which are: 6 × 7 (Fiber Core) rope, 0.380; 6 × 7 (IWRC or WSC), 0.437; 6 × 19 (Fiber Core), 0.405; 6 × 19 (IWRC or WSC), 0.475; 6 × 37 (Fiber Core), 0.400; 6 × 37 (IWRC), 0.470; 8 × 19 (Fiber Core), 0.370; and Flattened Strand Rope, 0.440.

**Example:** Find the bending stress and equivalent bending load due to the bending of a 6 × 19 (Fiber Core) wire rope of 1/2-inch diameter around a 24-inch pitch diameter sheave.

$$d_w = 0.063 \times 0.5 = 0.0315 \text{ in.} \quad A = 0.5^2 \times 0.405 = 0.101 \text{ sq. in.}$$

$$s_b = 12,000,000 \times 0.0315 \div 24 = 15,750 \text{ lbs. per sq. in.}$$

$$P_b = 15,750 \times 0.101 = 1590 \text{ lbs.}$$

**Cutting and Seizing of Wire Rope.**—Wire rope can be cut with mechanical wire rope shears, an abrasive wheel, an electric resistance cutter (used for ropes of smaller diameter only), or an acetylene torch. This last method fuses the ends of the wires in the strands. It is important that the rope be seized on either side of where the cut is to be made. Any annealed low carbon steel wire may be used for seizing, the recommended sizes being as follows: For a wire rope of  $\frac{1}{4}$ - to  $\frac{15}{16}$ -inch diameter, use a seizing wire of 0.054-inch (No. 17 Steel Wire Gage); for a rope of 1- to  $1\frac{1}{8}$ -inch diameter, use a 0.105-inch wire (No. 12); and for rope of  $1\frac{3}{4}$ - to  $3\frac{1}{2}$ -inch diameter, use a 0.135-inch wire (No. 10). Except for preformed wire ropes, a minimum of two seizings on either side of a cut is recommended. Four seizings should be used on either side of a cut for Lang lay rope, a rope with a steel core, or a non-spinning type of rope.

The following method of seizing is given in Federal Specification for wire rope, RR-R-571a. Lay one end of the seizing wire in the groove between two strands of wire rope and wrap the other end tightly in a close helix over the portion in the groove. A seizing iron (round bar  $\frac{1}{2}$  to  $\frac{5}{8}$  inch diameter by 18 inches long) should be used to wrap the seizing tightly. This bar is placed at right angles to the rope next to the first turn or two of the seizing wire. The seizing wire is brought around the back of the seizing iron and wrapped loosely around the wire rope in the opposite direction to that of the seizing coil. As the seizing iron is now rotated around the rope it will carry the seizing wire snugly and tightly into place. When completed, both ends of the seizing should be twisted together tightly.

**Maintenance of Wire Rope.**—Heavy abrasion, overloading, and bending around sheaves or drums that are too small in diameter are the principal reasons for the rapid deterioration of wire rope. Wire rope in use should be inspected periodically for evidence of wear and damage by corrosion. Such inspections should take place at progressively shorter intervals over the useful life of the rope as wear tends to accelerate with use. Where wear is rapid, the outside of a wire rope will show flattened surfaces in a short time.

If there is any hazard involved in the use of the rope, it may be prudent to estimate the remaining strength and service life. This assessment should be done for the weakest point where the most wear or largest number of broken wires are in evidence. One way to arrive at a conclusion is to set an arbitrary number of broken wires in a given strand as an indication that the rope should be removed from service and an ultimate strength test run on the worn sample. The arbitrary figure can then be revised and rechecked until a practical working formula is arrived at. A piece of waste rubbed along the wire rope will help to reveal broken wires. The effects of corrosion are not easy to detect because the exterior wires may appear to be only slightly rusty, and the damaging effects of corrosion may be confined to the hidden inner wires where it cannot be seen. To prevent damage by corrosion, the rope should be kept well lubricated. Use of zinc coated wire rope may be indicated for some applications.

Periodic cleaning of wire rope by using a stiff brush and kerosene or with compressed air or live steam and relubricating will help to lengthen rope life and reduce abrasion and wear on sheaves and drums. Before storing after use, wire rope should be cleaned and lubricated.

**Lubrication of Wire Rope.**—Although wire rope is thoroughly lubricated during manufacture to protect it against corrosion and to reduce friction and wear, this lubrication should be supplemented from time to time. Special lubricants are supplied by wire rope manufacturers. These lubricants vary somewhat with the type of rope application and operating condition. Where the preferred lubricant can not be obtained from the wire rope manufacturer, an adhesive type of lubricant similar to that used for open gearing will often be found suitable. At normal temperatures, some wire rope lubricants may be practically solid and will require thinning before application. Thinning may be done by heating to 160 to 200 degrees F. or by diluting with gasoline or some other fluid that will allow the lubricant to penetrate the rope. The lubricant may be painted on the rope or the rope may be passed through a box or tank filled with the lubricant.

**Replacement of Wire Rope.**—When an old wire rope is to be replaced, all drums and sheaves should be examined for wear. All evidence of scoring or imprinting of grooves from previous use should be removed and sheaves with flat spots, defective bearings, and broken flanges, should be repaired or replaced. It will frequently be found that the area of maximum wear is located relatively near one end of the rope. By cutting off that portion, the remainder of the rope may be salvaged for continued use. Sometimes the life of a rope can be increased by simply changing it end for end at about one-half the estimated normal life. The worn sections will then no longer come at the points that cause the greatest wear.

### Wire Rope Slings and Fittings

**Slings.**—A few of the simpler sling arrangements or hitches as they are called, are shown in the accompanying illustration. Normally  $6 \times 19$  Class wire rope is recommended where a diameter in the  $\frac{1}{4}$ -inch to  $1\frac{1}{8}$ -inch range is to be used and  $6 \times 37$  Class wire rope where a diameter in the  $1\frac{1}{4}$ -inch and larger range is to be used. However, the  $6 \times 19$  Class may be used even in the larger sizes if resistance to abrasion is of primary importance and the  $6 \times 37$  Class in the smaller sizes if greater flexibility is desired.

The *straight lift hitch*, Fig. 7a, is a straight connector between crane hook and load.

The *basket hitch* may be used with two hooks so that the sides are vertical as shown at Fig. 7b or with a single hook with sides at various angles with the vertical as shown at Fig. 7c, Fig. 7d, and Fig. 7e. As the angle with the vertical increases, a greater tension is placed on the rope so that for any given load, a sling of greater lifting capacity must be used.

The *choker hitch*, shown at Fig. 7f, is widely used for lifting bundles of items such as bars, poles, pipe, and similar objects. The choker hitch holds these items firmly, but the load must be balanced so that it rides safely. Since additional stress is imposed on the rope due to the choking action, the capacity of this type of hitch is 25 per cent less than that of the comparable straight lift. If two choker hitches are used at an angle, these angles must also be taken into consideration as with the basket hitches.

**Wire Rope Fittings.**—Many varieties of swaged fittings are available for use with wire rope and several industrial and aircraft types are shown in the accompanying illustration. Swaged fittings on wire rope have an efficiency (ability to hold the wire rope) of approximately 100 per cent of the catalogue rope strength. These fittings are attached to the end or body of the wire rope by the application of high pressure through special dies that cause the material of the fitting to “flow” around the wires and strands of the rope to form a union that is as strong as the rope itself. The more commonly used types, of swaged fittings range from  $\frac{1}{8}$ - to  $\frac{5}{8}$ -inch diameter sizes in industrial types and from the  $\frac{1}{16}$ - to  $\frac{5}{8}$ -inch sizes in aircraft types. These fittings are furnished attached to the wire strand, rope, or cable.

**Applying Clips and Attaching Sockets.**—In attaching U-bolt clips for fastening the end of a wire rope to form a loop, it is essential that the saddle or base of the clip bears against the longer or “live” end of the rope loop and the U-bolt against the shorter or “dead” end. The “U” of the clips should never bear against the live end of the rope because the rope may be cut or kinked. A wire-rope thimble should be used in the loop eye of the rope to prevent kinking when rope clips are used. The strength of a clip fastening is usually less than 80 per cent of the strength of the rope. Table 10 gives the proper size, number, and spacing for each size of wire rope.

In attaching commercial sockets of forged steel to wire rope ends, the following procedure is recommended. The wire rope is seized at the end and another seizing is applied at a distance from the end equal to the length of the basket of the socket. As explained in a previous section, soft iron wire is used and particularly for the larger sizes of wire rope, it is important to use a seizing iron to secure a tight winding. For large ropes, the seizing should be several inches long.

Wire Rope Slings and Fittings

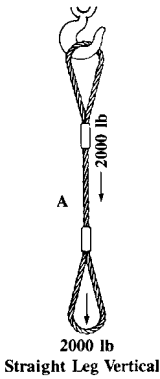


Fig. 7a. Straight Lift  
One leg vertical  
Load capacity is 100% of a single rope.

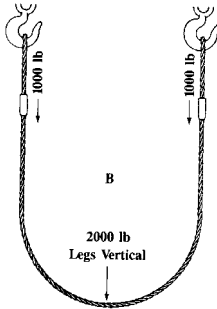


Fig. 7b. Basket Hitch  
Two legs vertical  
Load capacity is 200% of the single rope in Fig. 7a.

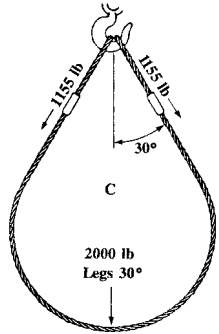


Fig. 7c. Basket Hitch  
Two legs at 30° with the vertical  
Load capacity is 174% of the single rope in Fig. 7a.

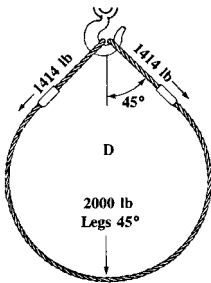


Fig. 7d. Basket Hitch  
Two legs at 45° with the vertical  
Load capacity is 141% of the single rope in Fig. 7a.

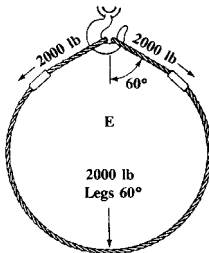


Fig. 7e. Basket Hitch  
Two legs at 60° with the vertical  
Load capacity is 100% of the single rope in Fig. 7a.



Fig. 7f. Choker Hitch  
One leg vertical, with slip-through loop  
Rated capacity is 75% of the single rope in Fig. 7a.

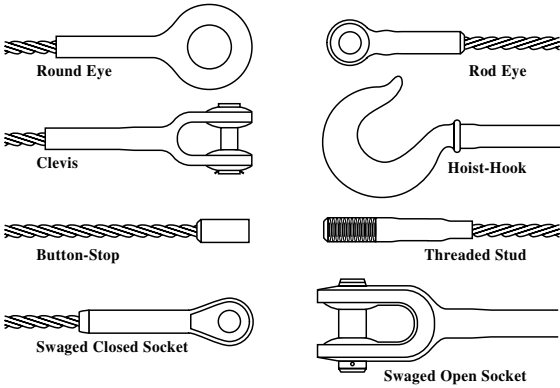
The end seizing is now removed and the strands are separated so that the fiber core can be cut back to the next seizing. The individual wires are then untwisted and "broomed out" and for the distance they are to be inserted in the socket are carefully cleaned with benzine, naphtha, or unleaded gasoline. The wires are then dipped into commercial muriatic (hydrochloric) acid and left (usually one to three minutes) until the wires are bright and clean or, if zinc coated, until the zinc is removed. After cleaning, the wires are dipped into a hot soda solution (1 pound of soda to 4 gallons of water at 175 degrees F. minimum) to neutralize the acid. The rope is now placed in a vise. A temporary seizing is used to hold the wire ends

## Rated Capacities for Improved Plow Steel Wire Rope and Wire Rope Slings (in tons of 2,000 lbs)

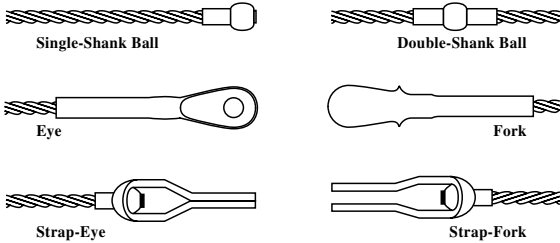
| Dia.<br>(in.)  | Independent Wire Rope Core |      |      |        |      |      |            |      |      |            |      |      | Fiber Core |      |      |          |      |      |        |      |      |            |      |      |            |      |      |            |      |      |     |     |     |     |
|--|----------------------------|------|------|--------|------|------|------------|------|------|------------|------|------|------------|------|------|----------|------|------|--------|------|------|------------|------|------|------------|------|------|------------|------|------|-----|-----|-----|-----|
|  | Vertical                   |      |      | Choker |      |      | 60° Bridle |      |      | 45° Bridle |      |      | 30° Bridle |      |      | Vertical |      |      | Choker |      |      | 60° Bridle |      |      | 45° Bridle |      |      | 30° Bridle |      |      |     |     |     |     |
|  | A                          | B    | C    | A      | B    | C    | A          | B    | C    | A          | B    | C    | A          | B    | C    | A        | B    | C    | A      | B    | C    | A          | B    | C    | A          | B    | C    | A          | B    | C    | A   | B   | C   |     |
| Single Leg, 6 × 19 Wire Rope                           |                            |      |      |        |      |      |            |      |      |            |      |      |            |      |      |          |      |      |        |      |      |            |      |      |            |      |      |            |      |      |     |     |     |     |
| ¼  | 0.59                       | 0.56 | 0.53 | 0.44   | 0.42 | 0.40 | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 0.55     | 0.51 | 0.49 | 0.41   | 0.38 | 0.37 | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... |     |
| ⅜  | 1.3                        | 1.2  | 1.1  | 0.98   | 0.93 | 0.86 | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 1.2      | 1.1  | 1.1  | 0.91   | 0.85 | 0.80 | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... |     |
| ½  | 2.3                        | 2.2  | 2.0  | 1.7    | 1.6  | 1.5  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 2.1      | 2.0  | 1.8  | 1.6    | 1.5  | 1.4  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... |     |
| ⅝  | 3.6                        | 3.4  | 3.0  | 2.7    | 2.5  | 2.2  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 3.3      | 3.1  | 2.8  | 2.5    | 2.3  | 2.1  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... |     |
| ¾  | 5.1                        | 4.9  | 4.2  | 3.8    | 3.6  | 3.1  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 4.8      | 4.4  | 3.9  | 3.6    | 3.3  | 2.9  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... |     |
| ⅞  | 6.9                        | 6.6  | 5.5  | 5.2    | 4.9  | 4.1  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 6.4      | 5.9  | 5.1  | 4.8    | 4.5  | 3.9  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... |     |
| 1  | 9.0                        | 8.5  | 7.2  | 6.7    | 6.4  | 5.4  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 8.4      | 7.7  | 6.7  | 6.3    | 5.8  | 5.0  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... |     |
| 1⅛   | 11                         | 10   | 9.0  | 8.5    | 7.8  | 6.8  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 10       | 9.5  | 8.4  | 7.9    | 7.1  | 6.3  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... |     |
| Single Leg, 6 × 37 Wire Rope                           |                            |      |      |        |      |      |            |      |      |            |      |      |            |      |      |          |      |      |        |      |      |            |      |      |            |      |      |            |      |      |     |     |     |     |
| 1¼   | 13                         | 12   | 10   | 9.9    | 9.2  | 7.9  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 12       | 11   | 9.8  | 9.2    | 8.3  | 7.4  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... |     |
| 1⅝   | 16                         | 15   | 13   | 12     | 11   | 9.6  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 15       | 13   | 12   | 11     | 10   | 8.9  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... |     |
| 1½   | 19                         | 17   | 15   | 14     | 13   | 11   | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 17       | 16   | 14   | 13     | 12   | 10   | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... | ... |
| 1¾   | 26                         | 24   | 20   | 19     | 18   | 15   | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 24       | 21   | 19   | 18     | 16   | 14   | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... | ... |
| 2  | 33                         | 30   | 26   | 25     | 23   | 20   | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | 31       | 28   | 25   | 23     | 21   | 18   | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... | ... |
| 2¼   | 41                         | 38   | 33   | 31     | 29   | 25   | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ...      | ...  | ...  | ...    | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... | ... |
| Two-Leg Bridle or Basket Hitch, 6 × 19 Wire Rope Sling |                            |      |      |        |      |      |            |      |      |            |      |      |            |      |      |          |      |      |        |      |      |            |      |      |            |      |      |            |      |      |     |     |     |     |
| ¼  | 1.2                        | 1.1  | 1.0  | ...    | ...  | ...  | 1.0        | 0.97 | 0.92 | 0.83       | 0.79 | 0.75 | 0.59       | 0.56 | 0.53 | 1.1      | 1.0  | 0.99 | ...    | ...  | ...  | 0.95       | 0.88 | 0.85 | 0.77       | 0.72 | 0.70 | 0.55       | 0.51 | 0.49 | ... | ... |     |     |
| ⅜  | 2.0                        | 2.5  | 2.3  | ...    | ...  | ...  | 2.3        | 2.1  | 2.0  | 1.8        | 1.8  | 1.8  | 1.3        | 1.2  | 1.1  | 2.4      | 2.2  | 2.1  | ...    | ...  | ...  | 2.1        | 1.9  | 1.8  | 1.7        | 1.6  | 1.5  | 1.2        | 1.1  | 1.1  | ... | ... |     |     |
| ½  | 4.0                        | 4.4  | 3.9  | ...    | ...  | ...  | 4.0        | 3.6  | 3.4  | 3.2        | 3.1  | 2.8  | 2.3        | 2.2  | 2.0  | 4.3      | 3.9  | 3.7  | ...    | ...  | ...  | 3.7        | 3.4  | 3.2  | 3.0        | 2.8  | 2.6  | 2.1        | 2.0  | 1.8  | ... | ... |     |     |
| ⅝  | 7.2                        | 6.6  | 6.0  | ...    | ...  | ...  | 6.2        | 5.9  | 5.2  | 5.1        | 4.8  | 4.2  | 3.6        | 3.4  | 3.0  | 6.7      | 6.2  | 5.6  | ...    | ...  | ...  | 6.2        | 5.3  | 4.8  | 4.7        | 4.4  | 4.0  | 3.3        | 3.1  | 2.8  | ... | ... |     |     |
| ¾  | 10                         | 9.7  | 8.4  | ...    | ...  | ...  | 8.9        | 8.4  | 7.3  | 7.2        | 6.9  | 5.9  | 5.1        | 4.9  | 4.2  | 9.5      | 8.8  | 7.8  | ...    | ...  | ...  | 8.2        | 7.6  | 6.8  | 6.7        | 6.2  | 5.5  | 4.8        | 4.4  | 3.9  | ... | ... |     |     |
| ⅞  | 14                         | 13   | 11   | ...    | ...  | ...  | 12         | 11   | 9.6  | 9.8        | 9.3  | 7.8  | 6.9        | 6.6  | 5.5  | 13       | 12   | 10   | ...    | ...  | ...  | 11         | 10   | 8.9  | 9.1        | 8.4  | 7.3  | 6.4        | 5.9  | 5.1  | ... | ... |     |     |
| 1  | 18                         | 17   | 14   | ...    | ...  | ...  | 15         | 15   | 12   | 13         | 12   | 10   | 9.0        | 8.5  | 7.2  | 17       | 15   | 13   | ...    | ...  | ...  | 14         | 13   | 11   | 12         | 11   | 9.4  | 8.4        | 7.7  | 6.7  | ... | ... |     |     |
| 1⅛   | 23                         | 21   | 18   | ...    | ...  | ...  | 19         | 18   | 16   | 16         | 15   | 13   | 11         | 10   | 9.0  | 21       | 19   | 17   | ...    | ...  | ...  | 18         | 16   | 14   | 15         | 13   | 12   | 10         | 9.5  | 8.4  | ... | ... |     |     |
| Two-Leg Bridle or Basket Hitch, 6 × 37 Wire Rope Sling |                            |      |      |        |      |      |            |      |      |            |      |      |            |      |      |          |      |      |        |      |      |            |      |      |            |      |      |            |      |      |     |     |     |     |
| 1¼   | 26                         | 24   | 21   | ...    | ...  | ...  | 23         | 21   | 18   | 19         | 17   | 15   | 13         | 12   | 10   | 25       | 22   | 20   | ...    | ...  | ...  | 21         | 19   | 17   | 17         | 16   | 14   | 12         | 11   | 9.8  | ... | ... |     |     |
| 1⅝   | 32                         | 29   | 25   | ...    | ...  | ...  | 28         | 25   | 22   | 22         | 21   | 18   | 16         | 15   | 13   | 30       | 27   | 24   | ...    | ...  | ...  | 26         | 23   | 20   | 21         | 19   | 17   | 15         | 13   | 12   | ... | ... |     |     |
| 1½   | 38                         | 35   | 30   | ...    | ...  | ...  | 33         | 30   | 26   | 27         | 25   | 21   | 19         | 17   | 15   | 35       | 32   | 28   | ...    | ...  | ...  | 30         | 27   | 24   | 25         | 22   | 20   | 17         | 16   | 14   | ... | ... |     |     |
| 1¾   | 51                         | 47   | 41   | ...    | ...  | ...  | 44         | 41   | 35   | 36         | 33   | 29   | 26         | 24   | 20   | 46       | 43   | 39   | ...    | ...  | ...  | 41         | 37   | 33   | 34         | 30   | 27   | 24         | 21   | 19   | ... | ... |     |     |
| 2  | 66                         | 61   | 53   | ...    | ...  | ...  | 57         | 53   | 46   | 47         | 43   | 37   | 33         | 30   | 26   | 62       | 55   | 49   | ...    | ...  | ...  | 53         | 43   | 43   | 43         | 39   | 35   | 31         | 26   | 25   | ... | ... |     |     |
| 2¼   | 83                         | 76   | 66   | ...    | ...  | ...  | 72         | 66   | 67   | 58         | 54   | 47   | 41         | 38   | 33   | ...      | ...  | ...  | ...    | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ...        | ...  | ...  | ... | ... | ... |     |

A—socket or swaged terminal attachment; B—mechanical sleeve attachment; C—hand-tucked splice attachment. Data from *Longshoring Industry*, OSHA Safety and Health Standards Digest, OSHA 2232, 1985.

Industrial Types



Aircraft Types



Wire Rope Fittings

together until the socket is placed over the rope end. The temporary seizing is then removed and the socket located so that the ends of the wires are about even with the upper end of the basket. The opening around the rope at the bottom of the socket is now sealed with putty.

**Table 10. Clips Required for Fastening Wire Rope End**

| Rope Dia., In. | U-Bolt Dia., In. | Min. No. of Clips | Clip Spacing, In. | Rope Dia., In. | U-Bolt Dia., In. | Min. No. of Clips | Clip Spacing, In. | Rope Dia., In. | U-Bolt Dia., In. | Min. No. of Clips | Clip Spacing, In. |
|----------------|------------------|-------------------|-------------------|----------------|------------------|-------------------|-------------------|----------------|------------------|-------------------|-------------------|
| $\frac{3}{16}$ | $\frac{11}{32}$  | 2                 | 3                 | $\frac{3}{4}$  | $\frac{7}{8}$    | 4                 | $6\frac{3}{4}$    | $1\frac{5}{8}$ | $1\frac{3}{4}$   | 6                 | $13\frac{1}{4}$   |
| $\frac{1}{4}$  | $\frac{7}{16}$   | 2                 | $3\frac{1}{4}$    | $\frac{7}{8}$  | 1                | 4                 | 8                 | $1\frac{3}{4}$ | $1\frac{5}{16}$  | 7                 | $14\frac{1}{2}$   |
| $\frac{5}{16}$ | $\frac{1}{2}$    | 2                 | $3\frac{1}{4}$    | 1              | $1\frac{1}{8}$   | 4                 | $8\frac{3}{4}$    | 2              | $2\frac{1}{8}$   | 8                 | $16\frac{1}{2}$   |
| $\frac{3}{8}$  | $\frac{9}{16}$   | 2                 | 4                 | $1\frac{1}{8}$ | $1\frac{1}{4}$   | 5                 | $9\frac{3}{4}$    | $2\frac{1}{4}$ | $2\frac{5}{8}$   | 8                 | $16\frac{1}{2}$   |
| $\frac{7}{16}$ | $\frac{5}{8}$    | 2                 | $4\frac{1}{2}$    | $1\frac{1}{4}$ | $1\frac{7}{16}$  | 5                 | $10\frac{3}{4}$   | $2\frac{1}{2}$ | $2\frac{7}{8}$   | 8                 | $17\frac{3}{4}$   |
| $\frac{1}{2}$  | $\frac{11}{16}$  | 3                 | 5                 | $1\frac{3}{8}$ | $1\frac{1}{2}$   | 6                 | $11\frac{1}{2}$   | ...            | ...              | ...               | ...               |
| $\frac{5}{8}$  | $\frac{3}{4}$    | 3                 | $5\frac{3}{4}$    | $1\frac{1}{2}$ | $1\frac{23}{32}$ | 6                 | $12\frac{1}{2}$   | ...            | ...              | ...               | ...               |

A special high grade pure zinc is used to fill the socket. Babbit metal should not be used as it will not hold properly. For proper fluidity and penetration, the zinc is heated to a tem-

perature in the 830- to 900-degree F. range. If a pyrometer is not available to measure the temperature of the molten zinc, a dry soft pine stick dipped into the zinc and quickly withdrawn will show only a slight discoloration and no zinc will adhere to it. If the wood chars, the zinc is too hot. The socket is now permitted to cool and the resulting joint is ready for use. When properly prepared, the strength of the joint should be approximately equal to that of the rope itself.

### Crane Chain and Hooks

**Material for Crane Chains.**—The best material for crane and hoisting chains is a good grade of wrought iron, in which the percentage of phosphorus, sulfur, silicon, and other impurities is comparatively low. The tensile strength of the best grades of wrought iron does not exceed 46,000 pounds per square inch, whereas mild steel with about 0.15 per cent carbon has a tensile strength nearly double this amount. The ductility and toughness of wrought iron, however, is greater than that of ordinary commercial steel, and for this reason it is preferable for chains subjected to heavy intermittent strains, because wrought iron will always give warning by bending or stretching, before breaking. Another important reason for using wrought iron in preference to steel is that a perfect weld can be effected more easily. Heat-treated alloy steel is also widely used for chains. This steel contains carbon, 0.30 per cent, max; phosphorus, 0.045 per cent, max; and sulfur, 0.045 per cent, max. The selection and amounts of alloying elements are left to the individual manufacturers.

**Strength of Chains.**—When calculating the strength of chains it should be observed that the strength of a link subjected to tensile stresses is not equal to twice the strength of an iron bar of the same diameter as the link stock, but is a certain amount less, owing to the bending action caused by the manner in which the load is applied to the link. The strength is also reduced somewhat by the weld. The following empirical formula is commonly used for calculating the breaking load, in pounds, of wrought-iron crane chains:  $W = 54,000D^2$  in which  $W$  = breaking load in pounds and  $D$  = diameter of bar (in inches) from which links are made. The working load for chains should not exceed one-third the value of  $W$ , and, it is often one-fourth or one-fifth of the breaking load. When a chain is wound around a casting and severe bending stresses are introduced, a greater factor of safety should be used.

**Care of Hoisting and Crane Chains.**—Chains used for hoisting heavy loads are subject to deterioration, both apparent and invisible. The links wear, and repeated loading causes localized deformations to form cracks that spread until the links fail. Chain wear can be reduced by occasional lubrication. The life of a wrought-iron chain can be prolonged by frequent annealing or normalizing unless it has been so highly or frequently stressed that small cracks have formed. If this condition is present, annealing or normalizing will not "heal" the material, and the links will eventually fracture. To anneal a wrought-iron chain, heat it to cherry-red and allow it to cool slowly. Annealing should be done every six months, and oftener if the chain is subjected to unusually severe service.

**Maximum Allowable Wear at Any Point of Link**

| Chain Size (in.)                 | Maximum Allowable Wear (in.) | Chain Size (in.) | Maximum Allowable Wear (in.) | Chain Size (in.) | Maximum Allowable Wear (in.) |
|----------------------------------|------------------------------|------------------|------------------------------|------------------|------------------------------|
| $\frac{1}{4}$ ( $\frac{9}{32}$ ) | $\frac{3}{64}$               | $\frac{3}{4}$    | $\frac{5}{32}$               | $1\frac{1}{4}$   | $\frac{1}{4}$                |
| $\frac{3}{8}$                    | $\frac{5}{64}$               | $\frac{7}{8}$    | $\frac{11}{64}$              | $1\frac{3}{8}$   | $\frac{3}{32}$               |
| $\frac{1}{2}$                    | $\frac{7}{64}$               | 1                | $\frac{3}{16}$               | $1\frac{1}{2}$   | $\frac{5}{16}$               |
| $\frac{5}{8}$                    | $\frac{9}{64}$               | $1\frac{1}{8}$   | $\frac{7}{32}$               | $1\frac{3}{4}$   | $\frac{11}{32}$              |





Source: Longshoring Industry, OSHA 2232, 1985.

Chains should be examined periodically for twists, as a twisted chain will wear rapidly. Any links that have worn excessively should be replaced with new ones, so that every link will do its full share of work during the life of the chain, without exceeding the limit of

safety. Chains for hoisting purposes should be made with short links, so that they will wrap closely around the sheaves or drums without bending. The diameter of the winding drums should be not less than 25 or 30 times the diameter of the iron used for the links. The accompanying table lists the maximum allowable wear for various sizes of chains.

**Safe Loads for Ropes and Chains.**—Safe loads recommended for wire rope or chain slings depend not only upon the strength of the sling but also upon the method of applying it to the load, as shown by the accompanying table giving safe loads as prepared by OSHA. The loads recommended in this table are more conservative than those usually specified, in order to provide ample allowance for some unobserved weakness in the sling, or the possibility of excessive strains due to misjudgment or accident.

**Safe Working Loads in Pounds for Manila Rope and Chains**

| Diameter of Rope, or Chain Link, Inch | <br>Rope or Chain Vertical |              |             | <br>Sling at 60° |              |             | <br>Sling at 45° |              |             | <br>Sling at 30° |              |             |
|---------------------------------------|---|--------------|-------------|---|--------------|-------------|---|--------------|-------------|---|--------------|-------------|
|                                       | Manila Rope   | Crane Chain  |             | Manila Rope   | Crane Chain  |             | Manila Rope   | Crane Chain  |             | Manila Rope   | Crane Chain  |             |
|                                       |   | Wrought Iron | Alloy Steel |   | Wrought Iron | Alloy Steel |   | Wrought Iron | Alloy Steel |   | Wrought Iron | Alloy Steel |
| 1/4 <sup>a</sup>                      | 120   | 1060         | 3240        | 204   | 1835         | 5640        | 170   | 1500         | 4540        | 120   | 1060         | 3240        |
| 5/16 <sup>a</sup>                     | 200   | 1655         | ...         | 346   | 2865         | ...         | 282   | 2340         | ...         | 200   | 1655         | ...         |
| 3/8                                   | 270   | 2385         | 6600        | 467   | 4200         | 11,400      | 380   | 3370         | 9300        | 270   | 2385         | 6600        |
| 7/16 <sup>a</sup>                     | 350   | 3250         | ...         | 605   | 5600         | ...         | 493   | 4600         | ...         | 350   | 3250         | ...         |
| 15/32                                 | 450   | ...          | ...         | 775   | ...          | ...         | 635   | ...          | ...         | 450   | ...          | ...         |
| 1/2                                   | 530   | 4200         | 11,240      | 915   | 7400         | 19,500      | 798   | 6000         | 15,800      | 530   | 4200         | 11,240      |
| 9/16 <sup>a</sup>                     | 690   | 5400         | ...         | 1190  | 9200         | ...         | 973   | 7600         | ...         | 690   | 5400         | ...         |
| 5/8                                   | 880   | 6600         | 16,500      | 1520  | 11,400       | 28,500      | 1240  | 9400         | 23,300      | 880   | 6600         | 16,500      |
| 3/4                                   | 1080  | 9600         | 23,000      | 1870  | 16,600       | 39,800      | 1520  | 13,400       | 32,400      | 1080  | 9600         | 23,000      |
| 13/16                                 | 1300  | ...          | ...         | 2250  | ...          | ...         | 1830  | ...          | ...         | 1300  | ...          | ...         |
| 7/8                                   | 1540  | 13,000       | 28,600      | 2660  | 22,400       | 49,800      | 2170  | 18,400       | 40,600      | 1540  | 13,000       | 28,600      |
| 1                                     | 1800  | 17,000       | 38,600      | 3120  | 29,400       | 67,000      | 2540  | 24,000       | 54,600      | 1800  | 17,000       | 38,600      |
| 1 1/16                                | 2000  | ...          | ...         | 3400  | ...          | ...         | 2800  | ...          | ...         | 2000  | ...          | ...         |
| 1 1/8                                 | 2400  | 20,000       | 44,400      | 4200  | 34,600       | 77,000      | 3400  | 28,400       | 63,000      | 2400  | 20,000       | 44,400      |
| 1 1/4                                 | 2700  | 24,800       | 57,400      | 4600  | 42,600       | 99,400      | 3800  | 35,000       | 81,000      | 2700  | 24,800       | 57,400      |
| 1 3/16                                | 3000  | ...          | ...         | 5200  | ...          | ...         | 4200  | ...          | ...         | 3000  | ...          | ...         |
| 1 3/8                                 | ...   | 30,000       | 67,000      | ...   | 51,800       | 116,000     | ...   | 42,200       | 94,000      | ...   | 30,000       | 67,000      |
| 1 1/2                                 | 3600  | 35,600       | 79,400      | 6200  | 61,600       | 137,000     | 5000  | 50,400       | 112,000     | 3600  | 35,600       | 79,400      |
| 1 5/8                                 | 4500  | 41,800       | 85,000      | 7800  | 72,400       | 147,000     | 6400  | 59,000       | 119,000     | 4500  | 41,800       | 85,000      |
| 1 3/4                                 | 5200  | 48,400       | 95,800      | 9000  | 84,000       | 163,000     | 7400  | 68,600       | 124,000     | 5200  | 48,400       | 95,800      |
| 1 7/8                                 | ...   | 55,200       | ...         | ...   | 95,800       | ...         | ...   | 78,200       | ...         | ...   | 55,200       | ...         |
| 2                                     | 6200  | 63,200       | ...         | 10,800  | 109,600      | ...         | 8800  | 89,600       | ...         | 6200  | 63,200       | ...         |
| 2 1/8                                 | 7200  | ...          | ...         | 12,400  | ...          | ...         | 10,200  | ...          | ...         | 7200  | ...          | ...         |








<sup>a</sup> These sizes of wrought chain are no longer manufactured in the United States.

Data from *Longshoring Industry*, OSHA Safety and Health Standards Digest, OSHA 2232, 1985.

The working load limit is defined as the maximum load in pounds that should ever be applied to chain, when the chain is new or in "as new" condition, and when the load is uniformly applied in direct tension to a straight length of chain. This limit is also affected by the number of chains used and their configuration. The accompanying table shows the working load limit for various configurations of heat-treated alloy steel chain using a 4 to 1 design factor, which conforms to ISO practice.



**Working Load Limit for Heat-Treated Alloy Steel Chain, pounds**

| Chain Size (in.) | Single Leg   | Double Leg   |  |  |  | Triple and Quad Leg  |  |  |
|------------------|--|--|--|--|--|--|--|--|
|                  | 90°<br> | 60°<br> | 45°<br> | 30°<br> | 60°<br> | 45°<br> | 30°<br> |  |
| 1/4              | 3,600  | 6,200  | 5,050  | 3,600  | 9,300  | 7,600  | 5,400  |  |
| 3/8              | 6,400  | 11,000   | 9,000  | 6,400  | 16,550   | 13,500   | 9,500  |  |
| 1/2              | 11,400   | 19,700   | 16,100   | 11,400   | 29,600   | 24,200   | 17,100   |  |
| 5/8              | 17,800   | 30,800   | 25,150   | 17,800   | 46,250   | 37,750   | 26,700   |  |
| 3/4              | 25,650   | 44,400   | 36,250   | 25,650   | 66,650   | 54,400   | 38,450   |  |
| 7/8              | 34,900   | 60,400   | 49,300   | 34,900   | 90,650   | 74,000   | 52,350   |  |

Source: The Crosby Group.

**Protection from Sharp Corners:** When the load to be lifted has sharp corners or edges, as are often encountered with castings, and with structural steel and other similar objects, pads or wooden protective pieces should be applied at the corners, to prevent the slings from being abraded or otherwise damaged where they come in contact with the load. These precautions are especially important when the slings consist of wire cable or fiber rope, although they should also be used even when slings are made of chain. Wooden corner-pieces are often provided for use in hoisting loads with sharp angles. If pads of burlap or other soft material are used, they should be thick and heavy enough to sustain the pressure, and distribute it over a considerable area, instead of allowing it to be concentrated directly at the edges of the part to be lifted.

**Strength of Manila Rope**

| Dia. (in.) | Circumference (in.) | Weight of 100 feet of Rope <sup>a</sup> (lb) | New Rope Tensile Strength <sup>b</sup> (lb) | Working Load <sup>c</sup> (lb) | Dia. (in.) | Circumference (in.) | Weight of 100 feet of Rope <sup>a</sup> (lb) | New Rope Tensile Strength <sup>b</sup> (lb) | Working Load <sup>c</sup> (lb) |
|------------|---------------------|--|---|--------------------------------|------------|---------------------|--|---|--------------------------------|
| 3/16       | 5/8                 | 1.50   | 406   | 41                             | 1 5/16     | 4                   | 47.8   | 13,500                                      | 1930                           |
| 1/4        | 3/4                 | 2.00   | 540   | 54                             | 1 1/2      | 4 1/2               | 60.0   | 16,700                                      | 2380                           |
| 5/16       | 1                   | 2.90   | 900   | 90                             | 1 5/8      | 5                   | 74.5   | 20,200                                      | 2880                           |
| 3/8        | 1 1/8               | 4.10   | 1220  | 122                            | 1 3/4      | 5 1/2               | 89.5   | 23,800                                      | 3400                           |
| 7/16       | 1 1/4               | 5.25   | 1580  | 176                            | 2          | 6                   | 108  | 28,000                                      | 4000                           |
| 1/2        | 1 1/2               | 7.50   | 2380  | 264                            | 2 1/8      | 6 1/2               | 125  | 32,400                                      | 4620                           |
| 9/16       | 1 3/4               | 10.4   | 3100  | 388                            | 2 1/4      | 7                   | 146  | 37,000                                      | 5300                           |
| 5/8        | 2                   | 13.3   | 3960  | 496                            | 2 1/2      | 7 1/2               | 167  | 41,800                                      | 5950                           |
| 3/4        | 2 1/4               | 16.7   | 4860  | 695                            | 2 5/8      | 8                   | 191  | 46,800                                      | 6700                           |
| 13/16      | 2 1/2               | 19.5   | 5850  | 835                            | 2 7/8      | 8 1/2               | 215  | 52,000                                      | 7450                           |
| 7/8        | 2 3/4               | 22.4   | 6950  | 995                            | 3          | 9                   | 242  | 57,500                                      | 8200                           |
| 1          | 3                   | 27.0   | 8100  | 1160                           | 3 1/4      | 10                  | 298  | 69,500                                      | 9950                           |
| 1 1/16     | 3 1/4               | 31.2   | 9450  | 1350                           | 3 1/2      | 11                  | 366  | 82,000                                      | 11,700                         |
| 1 1/8      | 3 1/2               | 36.0   | 10,800                                      | 1540                           | 4          | 12                  | 434  | 94,500                                      | 13,500                         |
| 1 1/4      | 3 3/4               | 41.6   | 12,200                                      | 1740                           | ...        | ...                 | ...  | ...   | ...                            |

<sup>a</sup> Average value is shown; maximum is 5 per cent higher.

<sup>b</sup> Based on tests of new and unused rope of standard construction in accordance with Cordage Institute Standard Test Methods.

<sup>c</sup> These values are for rope in good condition with appropriate splices, in noncritical applications, and under normal service conditions. These values should be reduced where life, limb, or valuable property are involved, or for exceptional service conditions such as shock loads or sustained loads.

Data from Cordage Institute Rope Specifications for three-strand laid and eight-strand plaited manila rope (standard construction).

## Strength of Nylon and Double Braided Nylon Rope

| Dia. (in.)   | Circumference (in.) | Weight of 100 feet of Rope <sup>a</sup> (lb) | New Rope Tensile Strength <sup>b</sup> (lb) | Working Load <sup>c</sup> (lb) | Dia. (in.)      | Circumference (in.) | Weight of 100 feet of Rope <sup>a</sup> (lb) | New Rope Tensile Strength <sup>b</sup> (lb) | Working Load <sup>c</sup> (lb) |
|--|---------------------|--|---|--------------------------------|-----------------|---------------------|--|---|--------------------------------|
| Nylon Rope   |                     |  |   |                                |                 |                     |  |   |                                |
| $\frac{3}{16}$                                     | $\frac{5}{8}$       | 1.00   | 900   | 75                             | $1\frac{1}{16}$ | 4                   | 45.0   | 38,800                                      | 4,320                          |
| $\frac{1}{4}$                                      | $\frac{3}{4}$       | 1.50   | 1,490                                       | 124                            | $1\frac{1}{2}$  | $4\frac{1}{2}$      | 55.0   | 47,800                                      | 5,320                          |
| $\frac{5}{16}$                                     | 1                   | 2.50   | 2,300                                       | 192                            | $1\frac{5}{8}$  | 5                   | 66.5   | 58,500                                      | 6,500                          |
| $\frac{3}{8}$                                      | $1\frac{1}{8}$      | 3.50   | 3,340                                       | 278                            | $1\frac{3}{4}$  | $5\frac{1}{2}$      | 83.0   | 70,000                                      | 7,800                          |
| $\frac{7}{16}$                                     | $1\frac{1}{4}$      | 5.00   | 4,500                                       | 410                            | 2               | 6                   | 95.0   | 83,000                                      | 9,200                          |
| $\frac{1}{2}$                                      | $1\frac{1}{2}$      | 6.50   | 5,750                                       | 525                            | $2\frac{1}{8}$  | $6\frac{1}{2}$      | 109  | 95,500                                      | 10,600                         |
| $\frac{9}{16}$                                     | $1\frac{3}{4}$      | 8.15   | 7,200                                       | 720                            | $2\frac{1}{4}$  | 7                   | 129  | 113,000                                     | 12,600                         |
| $\frac{5}{8}$                                      | 2                   | 10.5   | 9,350                                       | 935                            | $2\frac{1}{2}$  | $7\frac{1}{2}$      | 149  | 126,000                                     | 14,000                         |
| $\frac{3}{4}$                                      | $2\frac{1}{4}$      | 14.5   | 12,800                                      | 1,420                          | $2\frac{3}{8}$  | 8                   | 168  | 146,000                                     | 16,200                         |
| $\frac{13}{16}$                                    | $2\frac{1}{2}$      | 17.0   | 15,300                                      | 1,700                          | $2\frac{7}{8}$  | $8\frac{1}{2}$      | 189  | 162,000                                     | 18,000                         |
| $\frac{7}{8}$                                      | $2\frac{3}{4}$      | 20.0   | 18,000                                      | 2,000                          | 3               | 9                   | 210  | 180,000                                     | 20,000                         |
| 1  | 3                   | 26.4   | 22,600                                      | 2,520                          | $3\frac{1}{4}$  | 10                  | 264  | 226,000                                     | 25,200                         |
| $1\frac{1}{16}$                                    | $3\frac{1}{4}$      | 29.0   | 26,000                                      | 2,880                          | $3\frac{1}{2}$  | 11                  | 312  | 270,000                                     | 30,000                         |
| $1\frac{1}{8}$                                     | $3\frac{1}{2}$      | 34.0   | 29,800                                      | 3,320                          | 4               | 12                  | 380  | 324,000                                     | 36,000                         |
| $1\frac{1}{4}$                                     | $3\frac{3}{4}$      | 40.0   | 33,800                                      | 3,760                          | ...             | ...                 | ...  | ...   | ...                            |
| Double Braided Nylon Rope (Nylon Cover—Nylon Core) |                     |  |   |                                |                 |                     |  |   |                                |
| $\frac{1}{4}$                                      | $\frac{3}{4}$       | 1.56   | 1,650                                       | 150                            | $1\frac{1}{16}$ | 4                   | 43.1   | 44,700                                      | 5,590                          |
| $\frac{5}{16}$                                     | 1                   | 2.44   | 2,570                                       | 234                            | $1\frac{1}{8}$  | $4\frac{1}{4}$      | 47.3   | 49,000                                      | 6,130                          |
| $\frac{3}{8}$                                      | $1\frac{1}{8}$      | 3.52   | 3,700                                       | 336                            | $1\frac{1}{2}$  | $4\frac{1}{2}$      | 56.3   | 58,300                                      | 7,290                          |
| $\frac{7}{16}$                                     | $1\frac{1}{4}$      | 4.79   | 5,020                                       | 502                            | $1\frac{3}{8}$  | 5                   | 66.0   | 68,300                                      | 8,540                          |
| $\frac{1}{2}$                                      | $1\frac{1}{2}$      | 6.25   | 6,550                                       | 655                            | $1\frac{3}{4}$  | $5\frac{1}{2}$      | 76.6   | 79,200                                      | 9,900                          |
| $\frac{9}{16}$                                     | $1\frac{3}{4}$      | 7.91   | 8,270                                       | 919                            | 2               | 6                   | 100  | 103,000                                     | 12,900                         |
| $\frac{5}{8}$                                      | 2                   | 9.77   | 10,200                                      | 1,130                          | $2\frac{1}{8}$  | $6\frac{1}{2}$      | 113  | 117,000                                     | 14,600                         |
| $\frac{3}{4}$                                      | $2\frac{1}{4}$      | 14.1   | 14,700                                      | 1,840                          | $2\frac{1}{4}$  | 7                   | 127  | 131,000                                     | 18,700                         |
| $\frac{13}{16}$                                    | $2\frac{1}{2}$      | 16.5   | 17,200                                      | 2,150                          | $2\frac{1}{2}$  | $7\frac{1}{2}$      | 156  | 161,000                                     | 23,000                         |
| $\frac{7}{8}$                                      | $2\frac{3}{4}$      | 19.1   | 19,900                                      | 2,490                          | $2\frac{5}{8}$  | 8                   | 172  | 177,000                                     | 25,300                         |
| 1  | 3                   | 25.0   | 26,000                                      | 3,250                          | 3               | 9                   | 225  | 231,000                                     | 33,000                         |
| $1\frac{1}{16}$                                    | $3\frac{1}{4}$      | 28.2   | 29,300                                      | 3,660                          | $3\frac{1}{4}$  | 10                  | 264  | 271,000                                     | 38,700                         |
| $1\frac{1}{8}$                                     | $3\frac{1}{2}$      | 31.6   | 32,800                                      | 4,100                          | $3\frac{1}{2}$  | 11                  | 329  | 338,000                                     | 48,300                         |
| $1\frac{1}{4}$                                     | $3\frac{3}{4}$      | 39.1   | 40,600                                      | 5,080                          | 4               | 12                  | 400  | 410,000                                     | 58,600                         |

<sup>a</sup> Average value is shown. Maximum for nylon rope is 5 per cent higher; tolerance for double braided nylon rope is  $\pm 5$  per cent.

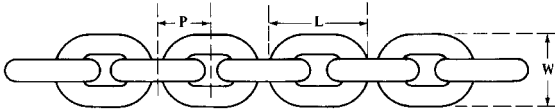
<sup>b</sup> Based on tests of new and unused rope of standard construction in accordance with Cordage Institute Standard Test Methods. For double braided nylon rope these values are minimums and are based on a large number of tests by various manufacturers; these values represent results two standard deviations below the mean. The minimum tensile strength is determined by the formula  $1057 \times (\text{linear density})^{0.995}$ .

<sup>c</sup> These values are for rope in good condition with appropriate splices, in noncritical applications, and under normal service conditions. These values should be reduced where life, limb, or valuable property are involved, or for exceptional service conditions such as shock loads or sustained loads.

Data from Cordage Institute Specifications for nylon rope (three-strand laid and eight-strand plaited, standard construction) and double braided nylon rope.

**Loads Lifted by Crane Chains.**—To find the approximate weight a chain will lift when rove as a tackle, multiply the safe load given in the table *Close-link Hoisting, Sling and Crane Chain* by the number of parts or chains at the movable block, and subtract one-quarter for frictional resistance.

To find the size of chain required for lifting a given weight, divide the weight by the number of chains at the movable block, and add one-third for friction; next find in the column headed "Average Safe Working Load" the corresponding load, and then the corresponding size of chain in the column headed "Size." With the heavy chain or where the chain is unusually long, the weight of the chain itself should also be considered.



**Close-link Hoisting, Sling and Crane Chain**

| Size    | Standard Pitch, <i>P</i><br>Inches | Average Weight per Foot, Pounds | Outside Length, <i>L</i><br>Inches | Outside Width, <i>W</i><br>Inches | Average Safe Working Load, Pounds | Proof Test, Pounds <sup>a</sup> | Approximate Breaking Load, Pounds |
|---------|------------------------------------|---------------------------------|------------------------------------|-----------------------------------|-----------------------------------|---------------------------------|-----------------------------------|
| 1/4     | 25/32                              | 3/4                             | 13/16                              | 7/8                               | 1,200                             | 2,500                           | 5,000                             |
| 5/16    | 27/32                              | 1                               | 1 1/2                              | 1 1/16                            | 1,700                             | 3,500                           | 7,000                             |
| 3/8     | 31/32                              | 1 1/2                           | 1 3/4                              | 1 1/4                             | 2,500                             | 5,000                           | 10,000                            |
| 7/16    | 1 1/32                             | 2                               | 2 1/16                             | 1 3/8                             | 3,500                             | 7,000                           | 14,000                            |
| 1/2     | 1 1/16                             | 2 1/2                           | 2 3/8                              | 1 11/16                           | 4,500                             | 9,000                           | 18,000                            |
| 9/16    | 1 1/8                              | 3 1/4                           | 2 7/8                              | 1 7/8                             | 5,500                             | 11,000                          | 22,000                            |
| 5/8     | 1 1/4                              | 4                               | 3                                  | 2 1/16                            | 6,700                             | 14,000                          | 27,000                            |
| 11/16   | 1 1/2                              | 5                               | 3 1/4                              | 2 1/4                             | 8,100                             | 17,000                          | 32,500                            |
| 3/4     | 1 5/8                              | 6 1/4                           | 3 3/4                              | 2 1/2                             | 10,000                            | 20,000                          | 40,000                            |
| 13/16   | 2 1/16                             | 7                               | 3 3/4                              | 2 11/16                           | 10,500                            | 23,000                          | 42,000                            |
| 7/8     | 2 1/8                              | 8                               | 4                                  | 2 7/8                             | 12,000                            | 26,000                          | 48,000                            |
| 15/16   | 2 1/4                              | 9                               | 4 3/8                              | 3 1/16                            | 13,500                            | 29,000                          | 54,000                            |
| 1       | 2 1/2                              | 10                              | 4 3/8                              | 3 1/4                             | 15,200                            | 32,000                          | 61,000                            |
| 1 1/16  | 2 5/8                              | 12                              | 4 7/8                              | 3 7/16                            | 17,200                            | 35,000                          | 69,000                            |
| 1 1/8   | 2 3/4                              | 13                              | 5 1/8                              | 3 3/4                             | 19,500                            | 40,000                          | 78,000                            |
| 1 1/4   | 3 1/16                             | 14 1/2                          | 5 9/16                             | 3 7/8                             | 22,000                            | 46,000                          | 88,000                            |
| 1 1/2   | 3 1/2                              | 16                              | 5 3/4                              | 4 1/8                             | 23,700                            | 51,000                          | 95,000                            |
| 1 3/8   | 3 3/8                              | 17 1/2                          | 6 1/8                              | 4 1/4                             | 26,000                            | 54,000                          | 104,000                           |
| 1 3/4   | 3 5/8                              | 19                              | 6 7/16                             | 4 9/16                            | 28,500                            | 58,000                          | 114,000                           |
| 1 7/8   | 3 11/16                            | 21 1/2                          | 6 11/16                            | 4 3/4                             | 30,500                            | 62,000                          | 122,000                           |
| 2       | 3 7/8                              | 23                              | 7                                  | 5                                 | 33,500                            | 67,000                          | 134,000                           |
| 1 9/16  | 4                                  | 25                              | 7 3/8                              | 5 5/16                            | 35,500                            | 70,500                          | 142,000                           |
| 1 5/8   | 4 1/4                              | 28                              | 7 3/4                              | 5 1/2                             | 38,500                            | 77,000                          | 154,000                           |
| 1 11/16 | 4 1/2                              | 30                              | 8 1/8                              | 5 11/16                           | 39,500                            | 79,000                          | 158,000                           |
| 1 3/4   | 4 3/4                              | 31                              | 8 1/2                              | 5 7/8                             | 41,500                            | 83,000                          | 166,000                           |
| 1 15/16 | 5                                  | 33                              | 8 7/8                              | 6 1/16                            | 44,500                            | 89,000                          | 178,000                           |
| 1 7/8   | 5 1/4                              | 35                              | 9 1/4                              | 6 3/8                             | 47,500                            | 95,000                          | 190,000                           |
| 1 15/16 | 5 1/2                              | 38                              | 9 5/8                              | 6 9/16                            | 50,500                            | 101,000                         | 202,000                           |
| 2       | 5 3/4                              | 40                              | 10                                 | 6 3/4                             | 54,000                            | 108,000                         | 216,000                           |
| 2 1/16  | 6                                  | 43                              | 10 3/8                             | 6 11/16                           | 57,500                            | 115,000                         | 230,000                           |
| 2 1/8   | 6 1/4                              | 47                              | 10 3/4                             | 7 1/8                             | 61,000                            | 122,000                         | 244,000                           |
| 2 1/4   | 6 1/2                              | 50                              | 11 1/8                             | 7 1/16                            | 64,500                            | 129,000                         | 258,000                           |
| 2 1/2   | 6 3/4                              | 53                              | 11 1/2                             | 7 3/8                             | 68,200                            | 136,500                         | 273,000                           |
| 2 3/8   | 6 7/8                              | 58 1/2                          | 11 7/8                             | 8                                 | 76,000                            | 152,000                         | 304,000                           |
| 2 1/2   | 7                                  | 65                              | 12 1/4                             | 8 3/8                             | 84,200                            | 168,500                         | 337,000                           |
| 2 5/8   | 7 1/8                              | 70                              | 12 5/8                             | 8 3/4                             | 90,500                            | 181,000                         | 362,000                           |
| 2 3/4   | 7 1/4                              | 73                              | 13                                 | 9 1/8                             | 96,700                            | 193,500                         | 387,000                           |
| 2 7/8   | 7 1/2                              | 76                              | 13 1/2                             | 9 1/2                             | 103,000                           | 206,000                         | 412,000                           |
| 3       | 7 3/4                              | 86                              | 14                                 | 9 7/8                             | 109,000                           | 218,000                         | 436,000                           |

<sup>a</sup>Chains tested to U.S. Government and American Bureau of Shipping requirements.

Winding Drum Scores for Chain

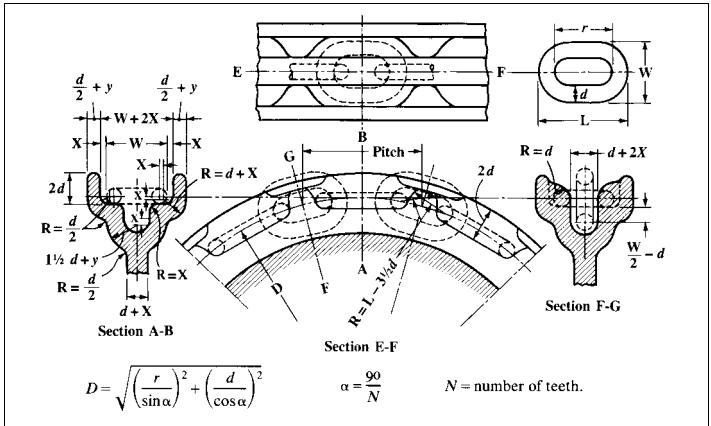
| Chain Size | A       | B     | C      | D     | Chain Size | A       | B      | C     | D     |
|------------|---------|-------|--------|-------|------------|---------|--------|-------|-------|
| 3/8        | 1 1/2   | 3/16  | 9/16   | 3/16  | 3/8        | 1 1/4   | 1 1/32 | 3/16  | 1     |
| 7/16       | 1 11/16 | 7/32  | 5/8    | 9/32  | 7/16       | 1 7/16  | 3/8    | 7/32  | 1 1/8 |
| 1/2        | 1 7/8   | 1/4   | 11/16  | 5/16  | 1/2        | 1 9/16  | 7/16   | 1/4   | 1 1/4 |
| 9/16       | 2 1/16  | 9/32  | 3/4    | 11/32 | 9/16       | 1 3/4   | 15/32  | 9/32  | 1 3/8 |
| 5/8        | 2 5/16  | 5/16  | 13/16  | 3/8   | 5/8        | 1 7/8   | 17/32  | 5/16  | 1 1/2 |
| 11/16      | 2 1/2   | 11/32 | 7/8    | 13/32 | 11/16      | 2 1/16  | 9/16   | 11/32 | 1 5/8 |
| 3/4        | 2 11/16 | 3/8   | 15/16  | 7/16  | 3/4        | 2 3/16  | 5/8    | 3/8   | 1 3/4 |
| 13/16      | 2 7/8   | 13/32 | 1      | 15/32 | 13/16      | 2 3/8   | 21/32  | 13/32 | 1 7/8 |
| 7/8        | 3 1/8   | 7/16  | 1 1/16 | 1/2   | 7/8        | 2 1/2   | 23/32  | 7/16  | 2     |
| 15/16      | 3 5/16  | 15/32 | 1 1/8  | 17/32 | 15/16      | 2 11/16 | 3/4    | 15/32 | 2 1/8 |
| 1          | 3 1/2   | 1/2   | 1 3/16 | 9/16  | 1          | 2 13/16 | 13/16  | 1/2   | 2 1/4 |

All dimensions are in inches.

Sprocket Wheels for Ordinary Link Chains

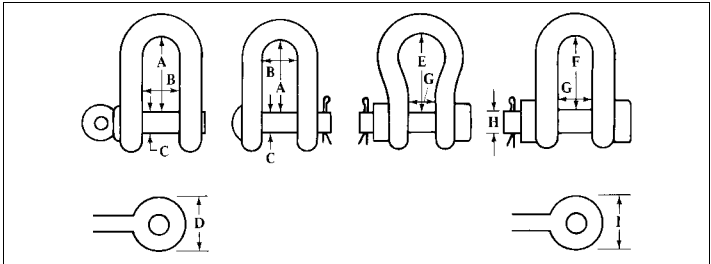
| Size of Chain  | 3/16    | 1/4    | 5/16                         | 3/8   | 7/16   | 1/2   | 9/16    | 5/8   | 11/16  | 3/4   | 13/16   | 7/8   | 15/16 | 1     |       |
|----------------|---------|--------|------------------------------|-------|--------|-------|---------|-------|--------|-------|---------|-------|-------|-------|-------|
| Length of Link | 1 3/8   | 1 1/2  | 1 3/4                        | 2     | 2 1/4  | 2 1/2 | 2 7/8   | 3 1/4 | 3 1/2  | 3 3/4 | 4       | 4 1/4 | 4 1/2 | 4 3/4 |       |
| Width of Link  | 1 3/16  | 1      | 1 3/16                       | 1 3/8 | 1 1/16 | 1 3/4 | 1 15/16 | 2 1/8 | 2 5/16 | 2 1/2 | 2 11/16 | 3     | 3 1/4 | 3 1/2 |       |
| X              | 1/16    | 3/32   | 3/32                         | 3/32  | 3/32   | 3/32  | 1/16    | 1/16  | 1/16   | 1/16  | 1/16    | 1/16  | 1/16  | 1/16  |       |
|                | 3/32    | 3/32   | 3/32                         | 3/32  | 3/32   | 1/16  | 1/16    | 1/16  | 1/16   | 1/16  | 1/16    | 1/16  | 1/16  | ...   |       |
| No. of Teeth   | Angle α |        | D = Pitch Diameter in Inches |       |        |       |         |       |        |       |         |       |       |       |       |
|                | 7       | 12°51' | 4.50                         | 4.50  | 5.06   | 5.63  | 6.18    | 6.76  | 7.88   | 9.01  | 9.58    | 10.14 | 10.71 | 11.27 | 11.84 |
| 8              | 11°15'  | 5.13   | 5.13                         | 5.77  | 6.42   | 7.06  | 7.71    | 8.97  | 10.27  | 10.91 | 11.56   | 12.20 | 12.85 | 13.50 | 14.13 |
| 9              | 10°0'   | 5.76   | 5.76                         | 6.48  | 7.21   | 7.74  | 8.65    | 10.08 | 11.53  | 12.26 | 12.98   | 13.72 | 14.43 | 15.15 | 15.87 |
| 10             | 9°0'    | 6.40   | 6.40                         | 7.18  | 8.00   | 8.79  | 9.61    | 11.19 | 12.80  | 13.61 | 14.40   | 15.21 | 16.01 | 16.81 | 17.61 |
| 11             | 8°11'   | 7.03   | 7.03                         | 7.91  | 8.79   | 9.67  | 10.55   | 12.30 | 14.07  | 14.95 | 15.83   | 16.71 | 17.55 | 18.47 | 19.35 |
| 12             | 7°30'   | 7.66   | 7.66                         | 8.62  | 9.59   | 10.53 | 11.49   | 13.41 | 15.33  | 16.29 | 17.26   | 18.20 | 19.17 | 20.13 | 21.09 |
| 13             | 6°55'   | 8.29   | 8.29                         | 9.33  | 10.38  | 11.41 | 12.45   | 14.52 | 16.60  | 17.65 | 18.68   | 19.72 | 20.76 | 21.80 | 22.84 |
| 14             | 6°25'   | 8.93   | 8.93                         | 10.05 | 11.17  | 12.28 | 13.40   | 15.63 | 17.90  | 18.99 | 20.06   | 21.23 | 22.35 | 23.46 | 24.58 |
| 15             | 6°0'    | 9.57   | 9.57                         | 10.76 | 11.96  | 13.16 | 14.35   | 16.74 | 19.14  | 20.34 | 21.54   | 22.74 | 23.93 | 25.13 | 26.33 |
| 16             | 5°37'   | 10.20  | 10.20                        | 11.47 | 12.76  | 14.03 | 15.30   | 17.85 | 20.41  | 21.69 | 22.97   | 24.24 | 25.52 | 26.80 | 28.08 |
| 17             | 5°17'   | 10.84  | 10.84                        | 12.19 | 13.56  | 14.90 | 16.26   | 18.97 | 21.68  | 23.04 | 24.40   | 25.75 | 27.11 | 28.47 | 29.83 |
| 18             | 5°0'    | 11.47  | 11.47                        | 12.91 | 14.36  | 15.78 | 17.21   | 20.08 | 22.95  | 24.34 | 25.83   | 27.26 | 28.70 | 30.14 | 31.57 |
| 19             | 4°44'   | 12.11  | 12.11                        | 13.62 | 15.16  | 16.65 | 18.16   | 21.19 | 24.22  | 25.73 | 27.26   | 28.77 | 30.29 | 31.80 | 33.31 |
| 20             | 4°30'   | 12.75  | 12.75                        | 14.34 | 15.96  | 17.53 | 19.12   | 22.30 | 25.50  | 27.09 | 28.69   | 30.28 | 31.88 | 33.46 | 35.06 |
| 21             | 4°17'   | 13.38  | 13.38                        | 15.05 | 16.74  | 18.40 | 20.07   | 23.42 | 26.77  | 28.44 | 30.12   | 31.79 | 33.46 | 35.13 | 36.81 |
| 22             | 4°6'    | 14.02  | 14.02                        | 15.77 | 17.53  | 19.27 | 21.03   | 24.53 | 28.03  | 29.79 | 31.55   | 33.30 | 35.04 | 36.83 | 38.56 |
| 23             | 3°55'   | 14.66  | 14.66                        | 16.49 | 18.32  | 20.15 | 21.98   | 25.64 | 29.31  | 31.14 | 32.97   | 34.81 | 36.63 | 38.48 | 40.30 |
| 24             | 3°45'   | 15.29  | 15.29                        | 17.20 | 19.11  | 21.02 | 22.94   | 26.76 | 30.58  | 32.49 | 34.41   | 36.32 | 38.23 | 40.15 | ...   |
| 25             | 3°36'   | 15.93  | 15.93                        | 17.92 | 19.90  | 21.90 | 23.89   | 27.87 | 31.85  | 33.84 | 35.84   | 37.83 | 39.82 | ...   | ...   |
| 26             | 3°28'   | 16.56  | 16.56                        | 18.62 | 20.70  | 22.77 | 24.85   | 28.98 | 33.13  | 35.20 | 37.27   | 39.34 | 41.41 | ...   | ...   |
| 27             | 3°20'   | 17.20  | 17.20                        | 19.34 | 21.50  | 23.65 | 25.80   | 30.10 | 34.40  | 36.55 | 38.70   | 40.85 | ...   | ...   | ...   |
| 28             | 3°13'   | 17.84  | 17.84                        | 20.06 | 22.29  | 24.52 | 26.75   | 31.21 | 35.67  | 37.90 | 40.04   | ...   | ...   | ...   | ...   |

Sprocket Wheels for Ordinary Link Chains (Continued)



Additional Tables

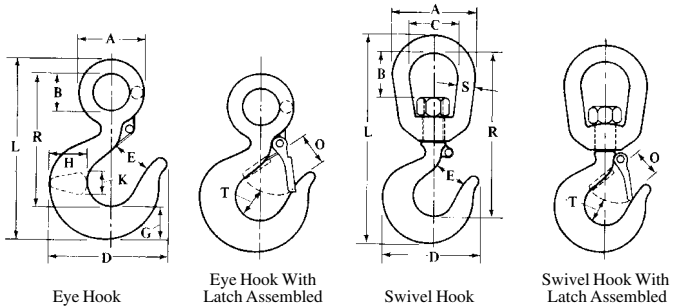
Dimensions of Forged Round Pin, Screw Pin, and Bolt Type Chain Shackles and Bolt Type Anchor Shackles



| Working Load Limit (tons) | Nominal Shackle Size | A       | B       | C     | D      | E       | F       | G       | H     | I      |
|---------------------------|----------------------|---------|---------|-------|--------|---------|---------|---------|-------|--------|
| 1/2                       | 1/4                  | 7/8     | 15/16   | 5/16  | 11/16  | ...     | ...     | ...     | ...   | ...    |
| 3/4                       | 5/16                 | 1 1/32  | 17/32   | 3/8   | 13/16  | ...     | ...     | ...     | ...   | ...    |
| 1                         | 3/8                  | 1 1/4   | 21/32   | 7/16  | 31/32  | ...     | ...     | ...     | ...   | ...    |
| 1 1/2                     | 7/16                 | 1 7/16  | 23/32   | 1/2   | 1 1/16 | ...     | ...     | ...     | ...   | ...    |
| 2                         | 1/2                  | 1 5/8   | 13/16   | 5/8   | 1 3/16 | 1 1/8   | 1 5/8   | 1 3/16  | 5/8   | 1 3/16 |
| 3 1/4                     | 5/8                  | 2       | 1 1/4   | 3/4   | 1 1/16 | 2 3/8   | 2       | 1 1/16  | 3/4   | 1 9/16 |
| 4 3/4                     | 3/4                  | 2 3/8   | 1 1/4   | 7/8   | 1 7/8  | 2 13/16 | 2 3/8   | 1 1/4   | 7/8   | 1 7/8  |
| 6 1/2                     | 7/8                  | 2 13/16 | 1 7/16  | 1     | 2 1/8  | 3 5/16  | 2 13/16 | 1 7/16  | 1     | 2 1/8  |
| 8 1/2                     | 1                    | 3 7/16  | 1 11/16 | 1 1/8 | 2 3/8  | 3 3/4   | 3 3/16  | 1 11/16 | 1 1/2 | 2 3/8  |
| 9 1/2                     | 1 1/8                | 3 1/16  | 1 13/16 | 1 1/4 | 2 5/8  | 4 1/4   | 3 3/16  | 1 13/16 | 1 1/4 | 2 5/8  |
| 12                        | 1 1/4                | 3 5/16  | 2 1/2   | 1 3/8 | 3      | 4 11/16 | 3 15/16 | 2 1/2   | 1 3/8 | 3      |
| 13 1/2                    | 1 3/8                | 4 3/8   | 2 1/4   | 1 1/2 | 3 5/16 | 5 3/16  | 4 3/8   | 2 1/4   | 1 1/2 | 3 5/16 |
| 17                        | 1 1/2                | 4 13/16 | 2 3/8   | 1 5/8 | 3 3/8  | 5 3/4   | 4 13/16 | 2 3/8   | 1 5/8 | 3 3/8  |
| 25                        | 1 3/4                | 5 1/4   | 2 5/8   | 2     | 4 3/8  | 7       | 5 3/4   | 2 5/8   | 2     | 4 3/8  |
| 35                        | 2                    | 6 3/4   | 3 1/4   | 2 1/4 | 5      | 7 3/4   | 6 3/4   | 3 1/4   | 2 1/4 | 5      |

All dimensions are in inches. Load limits are in tons of 2000 pounds.

Source: The Crosby Group.



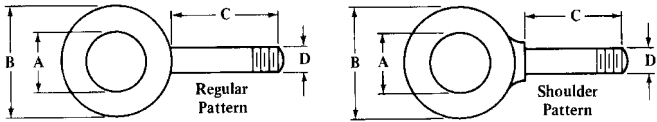
**Dimensions of Crane Hooks**

| Feature                     | Capacity of Hook in Tons (tons of 2000 lbs) |      |      |      |      |       |       |       |       |       |       |       |  |
|-----------------------------|---|------|------|------|------|-------|-------|-------|-------|-------|-------|-------|--|
|                             | 1.1   | 1.65 | 2.2  | 3.3  | 4.95 | 7.7   | 12.1  | 16.5  | 24.2  | 33    | 40.7  | 49.5  |  |
|                             | Dimensions for Eye Hooks                    |      |      |      |      |       |       |       |       |       |       |       |  |
| A                           | 1.47  | 1.75 | 2.03 | 2.41 | 2.94 | 3.81  | 4.69  | 5.38  | 6.62  | 7.00  | 8.50  | 9.31  |  |
| B                           | 0.75  | 0.91 | 1.12 | 1.25 | 1.56 | 2.00  | 2.44  | 2.84  | 3.50  | 3.50  | 4.50  | 4.94  |  |
| D                           | 2.88  | 3.19 | 3.62 | 4.09 | 4.94 | 6.50  | 7.56  | 8.69  | 11.00 | 13.62 | 14.06 | 15.44 |  |
| E                           | 0.94  | 1.03 | 1.06 | 1.22 | 1.50 | 1.88  | 2.25  | 2.50  | 3.38  | 4.00  | 4.25  | 4.75  |  |
| G                           | 0.75  | 0.84 | 1.00 | 1.12 | 1.44 | 1.81  | 2.25  | 2.59  | 3.00  | 3.66  | 4.56  | 5.06  |  |
| H                           | 0.81  | 0.94 | 1.16 | 1.31 | 1.62 | 2.06  | 2.62  | 2.94  | 3.50  | 4.62  | 5.00  | 5.50  |  |
| K                           | 0.56  | 0.62 | 0.75 | 0.84 | 1.12 | 1.38  | 1.62  | 1.94  | 2.38  | 3.00  | 3.75  | 4.12  |  |
| L                           | 4.34  | 4.94 | 5.56 | 6.40 | 7.91 | 10.09 | 12.44 | 13.94 | 17.09 | 19.47 | 24.75 | 27.38 |  |
| R                           | 3.22  | 3.66 | 4.09 | 4.69 | 5.75 | 7.38  | 9.06  | 10.06 | 12.50 | 14.06 | 18.19 | 20.12 |  |
| T                           | 0.81  | 0.81 | 0.84 | 1.19 | 1.38 | 1.78  | 2.12  | 2.56  | 2.88  | 3.44  | 3.88  | 4.75  |  |
| O                           | 0.88  | 0.97 | 1.00 | 1.12 | 1.34 | 1.69  | 2.06  | 2.25  | 3.00  | 3.62  | 3.75  | 4.25  |  |
| Dimensions for Swivel Hooks |   |      |      |      |      |       |       |       |       |       |       |       |  |
| A                           | 2   | 2.50 | 3    | 3    | 3.50 | 4.50  | 5     | 5.63  | 7     | 7     | ...   | ...   |  |
| B                           | 0.94  | 1.31 | 1.63 | 1.56 | 1.75 | 2.31  | 2.38  | 2.69  | 4.19  | 4.19  | ...   | ...   |  |
| C                           | 1.25  | 1.50 | 1.75 | 1.75 | 2    | 2.50  | 2.75  | 3.13  | 4     | 4     | ...   | ...   |  |
| D                           | 2.88  | 3.19 | 3.63 | 4.09 | 4.94 | 6.5   | 7.56  | 8.69  | 11    | 13.63 | ...   | ...   |  |
| E                           | 0.94  | 1.03 | 1.06 | 1.22 | 1.5  | 1.88  | 2.25  | 2.5   | 3.38  | 4     | ...   | ...   |  |
| L                           | 5.56  | 6.63 | 7.63 | 8.13 | 9.59 | 12.41 | 14.50 | 15.88 | 21.06 | 23.22 | ...   | ...   |  |
| R                           | 4.47  | 5.28 | 6.02 | 6.38 | 7.41 | 9.59  | 11.13 | 12.03 | 16.56 | 18.06 | ...   | ...   |  |
| S                           | 0.38  | 0.50 | 0.63 | 0.63 | 0.75 | 1     | 1.13  | 1.25  | 1.5   | 1.5   | ...   | ...   |  |
| T                           | 0.81  | 0.81 | 0.84 | 1.19 | 1.38 | 1.78  | 2.13  | 2.56  | 2.88  | 3.44  | ...   | ...   |  |
| O                           | 0.88  | 0.97 | 1    | 1.13 | 1.34 | 1.69  | 2.06  | 2.25  | 3     | 3.63  | ...   | ...   |  |

Source: The Crosby Group. All dimensions are in inches. Hooks are made of alloy steel, quenched and tempered. For swivel hooks, the data are for a bail of carbon steel. The ultimate load is four times the working load limit (capacity). The swivel hook is a positioning device and is not intended to rotate under load; special load swiveling hooks must be used in such applications.

**Method of Making an Eye-splice.**—When a loop is formed at the end of a rope by splicing the free end to the main or standing part of the rope, this is known as an *eye-splice*. The end of the rope is first unlaidd about as far as it would be for making a short splice. After bending the end around to form a loop of the required size, the middle strand *a*, Fig. 8a, is tucked under a strand on the main part of the rope. The strand *b* is next inserted from the rear side under the strand on the main part which is just above the strand under which *a* was inserted. Since strand *b* is pushed under the strand on the main part from the rear side, it will come out at the point where strand *a* went in, as Fig. 8b. The third strand *c* is now passed over the strand under which strand *a* was inserted, and then under the next successive one, as Fig. 8c. These three strands are next pulled taut and then about one-third of the fiber should be cut from them; they are next tucked away by passing a strand over its adjoining one and under the next successive strand. The reason for cutting away part of the fiber or yarns is to reduce the size of the splice and give it a neater appearance. By gradually thinning out the fiber, the over-lapping strands may be given a gradual taper, as Fig. 8d which shows the completed eye-splice.

HOOKS, SHACKLES, AND EYES



Hot Dip Galvanized, Forged Steel Eye-bolts

| Shank            |       | Eye Dia. |       | Safe Load <sup>a</sup><br>(tons) | Shank |       | Eye Dia. |       | Safe Load <sup>a</sup><br>(tons) |
|------------------|-------|----------|-------|----------------------------------|-------|-------|----------|-------|----------------------------------|
| D                | C     | A        | B     |                                  | D     | C     | A        | B     |                                  |
| Regular Pattern  |       |          |       |                                  |       |       |          |       |                                  |
| 1/4              | 2     | 1/2      | 1     | 0.25                             | 3/4   | 4 1/2 | 1 1/2    | 3     | 2.6                              |
| 1/4              | 4     | 1/2      | 1     | 0.25                             | 3/4   | 6     | 1 1/2    | 3     | 2.6                              |
| 5/16             | 2 1/4 | 5/8      | 1 1/4 | 0.4                              | 3/4   | 8     | 1 1/2    | 3     | 2.6                              |
| 5/16             | 4 1/4 | 5/8      | 1 1/4 | 0.4                              | 3/4   | 10    | 1 1/2    | 3     | 2.6                              |
| 3/8              | 2 1/2 | 3/4      | 1 1/2 | 0.6                              | 3/4   | 10    | 1 1/2    | 3     | 2.6                              |
| 3/8              | 4 1/2 | 3/4      | 1 1/2 | 0.6                              | 3/4   | 10    | 1 1/2    | 3     | 2.6                              |
| 3/8              | 6     | 3/4      | 1 1/2 | 0.6                              | 7/8   | 5     | 1 3/4    | 3 1/2 | 3.6                              |
| 1/2              | 3 3/4 | 1        | 2     | 1.1                              | 7/8   | 8     | 1 3/4    | 3 1/2 | 3.6                              |
| 1/2              | 6     | 1        | 2     | 1.1                              | 7/8   | 10    | 1 3/4    | 3 1/2 | 3.6                              |
| 1/2              | 8     | 1        | 2     | 1.1                              | 1     | 6     | 2        | 4     | 5                                |
| 1/2              | 10    | 1        | 2     | 1.1                              | 1     | 9     | 2        | 4     | 5                                |
| 1/2              | 12    | 1        | 2     | 1.1                              | 1     | 10    | 2        | 4     | 5                                |
| 5/8              | 4     | 1 1/4    | 2 1/2 | 1.75                             | 1     | 10    | 2        | 4     | 5                                |
| 5/8              | 6     | 1 1/4    | 2 1/2 | 1.75                             | 1 1/4 | 8     | 2 1/2    | 5     | 7.6                              |
| 5/8              | 8     | 1 1/4    | 2 1/2 | 1.75                             | 1 1/4 | 10    | 2 1/2    | 5     | 7.6                              |
| 5/8              | 10    | 1 1/4    | 2 1/2 | 1.75                             | 1 1/4 | 10    | 2 1/2    | 5     | 7.6                              |
| 5/8              | 12    | 1 1/4    | 2 1/2 | 1.75                             | ...   | ...   | ...      | ...   | ...                              |
| Shoulder Pattern |       |          |       |                                  |       |       |          |       |                                  |
| 1/4              | 2     | 1/2      | 7/8   | 0.25                             | 5/8   | 6     | 1 1/4    | 2 1/4 | 1.75                             |
| 1/4              | 4     | 1/2      | 7/8   | 0.25                             | 3/4   | 4 1/2 | 1 1/2    | 2 3/4 | 2.6                              |
| 5/16             | 2 1/4 | 5/8      | 1 1/8 | 0.4                              | 3/4   | 6     | 1 1/2    | 2 3/4 | 2.6                              |
| 5/16             | 4 1/4 | 5/8      | 1 1/8 | 0.4                              | 7/8   | 5     | 1 3/4    | 3 1/4 | 3.6                              |
| 3/8              | 2 1/2 | 3/4      | 1 3/8 | 0.6                              | 1     | 6     | 2        | 3 3/4 | 5                                |
| 3/8              | 4 1/2 | 3/4      | 1 3/8 | 0.6                              | 1     | 9     | 2        | 3 3/4 | 5                                |
| 1/2              | 3 3/4 | 1        | 1 3/4 | 1.1                              | 1 1/4 | 8     | 2 1/2    | 4 1/2 | 7.6                              |
| 1/2              | 6     | 1        | 1 3/4 | 1.1                              | 1 1/4 | 12    | 2 1/2    | 4 1/2 | 7.6                              |
| 5/8              | 4     | 1 1/4    | 2 1/4 | 1.75                             | 1 1/2 | 15    | 3        | 5 1/2 | 10.7                             |

<sup>a</sup>The ultimate or breaking load is 5 times the safe working load.  
 All dimensions are in inches. Safe loads are in tons of 2000 pounds.  
 Source: The Crosby Group.



Fig. 8a. Eye-Splice



Fig. 8b. Eye-Splice

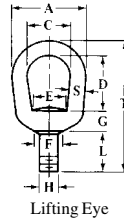
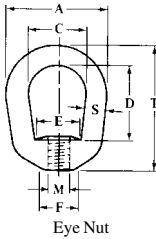


Fig. 8c. Eye-Splice



Fig. 8d. Eye-Splice

Eye Nuts and Lift Eyes



Eye Nuts

The general function of eye nuts is similar to that of eye-bolts. Eye nuts are utilized for a variety of applications in either the swivel or tapped design.

| M     | A     | C     | D      | E       | F      | S     | T       | Working Load Limit (lbs) <sup>a</sup> |
|-------|-------|-------|--------|---------|--------|-------|---------|---------------------------------------|
| 1/4   | 1 1/4 | 3/4   | 1 1/16 | 2 1/32  | 1/2    | 1/4   | 1 11/16 | 520                                   |
| 5/16  | 1 3/4 | 3/4   | 1 1/16 | 2 1/32  | 1/2    | 1/4   | 1 11/16 | 850                                   |
| 3/8   | 1 5/8 | 1     | 1 1/4  | 3/4     | 5/8    | 5/16  | 2 1/16  | 1,250                                 |
| 7/16  | 2     | 1 1/4 | 1 1/2  | 1       | 13/16  | 3/8   | 2 1/2   | 1,700                                 |
| 1/2   | 2     | 1 1/4 | 1 1/2  | 1       | 13/16  | 3/8   | 2 1/2   | 2,250                                 |
| 5/8   | 2 1/2 | 1 1/2 | 2      | 1 3/16  | 1      | 1/2   | 3 3/16  | 3,600                                 |
| 3/4   | 3     | 1 3/4 | 2 3/8  | 1 3/8   | 1 1/8  | 5/8   | 3 3/8   | 5,200                                 |
| 7/8   | 3 1/2 | 2     | 2 5/8  | 1 5/8   | 1 5/8  | 3/4   | 4 5/16  | 7,200                                 |
| 1     | 4     | 2 1/4 | 3 1/16 | 1 7/8   | 1 9/16 | 7/8   | 5       | 10,000                                |
| 1 1/8 | 4     | 2 1/4 | 3 1/16 | 1 7/8   | 1 9/16 | 7/8   | 5       | 12,300                                |
| 1 1/4 | 4 1/2 | 2 1/2 | 3 1/2  | 1 15/16 | 1 7/8  | 1     | 5 3/4   | 15,500                                |
| 1 3/8 | 5     | 2 3/4 | 3 3/4  | 2       | 2      | 1 1/8 | 6 1/4   | 18,500                                |
| 1 1/2 | 5 5/8 | 3 3/8 | 4      | 2 3/8   | 2 1/4  | 1 1/4 | 6 3/4   | 22,500                                |
| 2     | 7     | 4     | 6 1/4  | 4       | 3 3/8  | 1 1/2 | 10      | 40,000                                |

<sup>a</sup>Data for eye nuts are for hot dip galvanized, quenched, and tempered forged steel.

Lifting Eyes

| A     | C     | D      | E       | F      | G      | H     | L       | S     | T        | Working Load Limit Threaded (lbs) <sup>a</sup> |
|-------|-------|--------|---------|--------|--------|-------|---------|-------|----------|--|
| 1 1/4 | 3/4   | 1 1/16 | 1 9/32  | 1/2    | 3/8    | 5/16  | 1 1/16  | 1/4   | 2 3/8    | 850  |
| 1 5/8 | 1     | 1 1/4  | 3/4     | 9/16   | 1/2    | 3/8   | 1 5/16  | 5/16  | 3        | 1,250  |
| 2     | 1 1/4 | 1 1/2  | 1       | 13/16  | 5/8    | 1/2   | 1 1/4   | 3/8   | 3 3/4    | 2,250  |
| 2 1/2 | 1 1/2 | 2      | 1 3/16  | 1      | 1 1/16 | 5/8   | 1 1/2   | 1/2   | 4 1 1/16 | 3,600  |
| 3     | 1 3/4 | 2 3/8  | 1 3/8   | 1 1/8  | 7/8    | 3/4   | 1 3/4   | 5/8   | 5 5/8    | 5,200  |
| 3 1/2 | 2     | 2 5/8  | 1 5/8   | 1 5/16 | 1 5/16 | 7/8   | 2       | 3/4   | 6 5/16   | 7,200  |
| 4     | 2 1/4 | 3 1/16 | 1 7/8   | 1 9/16 | 1 1/16 | 1     | 2 1/16  | 7/8   | 7 1/16   | 10,000   |
| 4 1/2 | 2 1/2 | 3 1/2  | 1 15/16 | 1 7/8  | 1 1/4  | 1 1/8 | 2 1/2   | 1     | 8 1/4    | 12,500   |
| 5 5/8 | 3 3/8 | 4      | 2 3/8   | 2 3/8  | 1 1/2  | 1 3/8 | 2 15/16 | 1 1/4 | 9 1 1/16 | 18,000   |

<sup>a</sup>Data for lifting eyes are for quenched and tempered forged steel.

All dimensions are in inches. Source: The Crosby Group.



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## THE ELEMENTS, HEAT, MASS, AND WEIGHT

Table 1. The Elements — Symbols, Atomic Numbers and Weights, Melting Points

| Name of Element | Sym bol | Atomic |          | Melting Point, °C   | Name of Element | Sym bol | Atomic |          | Melting Point, °C |
|-----------------|---------|--------|----------|---------------------|-----------------|---------|--------|----------|-------------------|
|                 |         | Num.   | Weight   |                     |                 |         | Num.   | Weight   |                   |
| Actinium        | Ac      | 89     | 227.028  | 1050                | Neon            | Ne      | 10     | 20.1179  | -248.67           |
| Aluminum        | Al      | 13     | 26.9815  | 660.37              | Neptunium       | Np      | 93     | 237.048  | 640 ± 1           |
| Americium       | Am      | 95     | (243)    | 994 ± 4             | Nickel          | Ni      | 28     | 58.69    | 1453              |
| Antimony        | Sb      | 51     | 121.75   | 630.74              | Niobium         | Nb      | 41     | 92.9064  | 2468 ± 10         |
| Argon           | A       | 18     | 39.948   | -189.2              | Nitrogen        | N       | 7      | 14.0067  | -209.86           |
| Arsenic         | As      | 33     | 74.9216  | 817 <sup>a</sup>    | Nobelium        | No      | 102    | (259)    | ...               |
| Astatine        | At      | 85     | (210)    | 302                 | Osmium          | Os      | 76     | 190.2    | 3045 ± 30         |
| Barium          | Ba      | 56     | 137.33   | 725                 | Oxygen          | O       | 8      | 15.9994  | -218.4            |
| Berkelium       | Bk      | 97     | (247)    | ...                 | Palladium       | Pd      | 46     | 106.42   | 1554              |
| Beryllium       | Be      | 4      | 9.01218  | 1278 ± 5            | Phosphorus      | P       | 15     | 30.9738  | 44.1              |
| Bismuth         | Bi      | 83     | 208.980  | 271.3               | Platinum        | Pt      | 78     | 195.08   | 1772              |
| Boron           | B       | 5      | 10.81    | 2079                | Plutonium       | Pu      | 94     | (244)    | 641               |
| Bromine         | Br      | 35     | 79.904   | -7.2                | Polonium        | Po      | 84     | (209)    | 254               |
| Cadmium         | Cd      | 48     | 112.41   | 320.9               | Potassium       | K       | 19     | 39.0938  | 63.25             |
| Calcium         | Ca      | 20     | 40.08    | 839 ± 2             | Praseodymium    | Pr      | 59     | 140.908  | 931 ± 4           |
| Californium     | Cf      | 98     | (251)    | ...                 | Promethium      | Pm      | 61     | (145)    | 1080 <sup>b</sup> |
| Carbon          | C       | 6      | 12.011   | 3652 <sup>c</sup>   | Protactinium    | Pa      | 91     | 231.0359 | 1600              |
| Cerium          | Ce      | 58     | 140.12   | 798 ± 2             | Radium          | Ra      | 88     | 226.025  | 700               |
| Cesium          | Cs      | 55     | 132.9054 | 28.4 ± 0.01         | Radon           | Rn      | 86     | (222)    | -71               |
| Chlorine        | Cl      | 17     | 35.453   | -100.98             | Rhenium         | Re      | 75     | 186.207  | 3180              |
| Chromium        | Cr      | 24     | 51.996   | 1857 ± 20           | Rhodium         | Rh      | 45     | 102.906  | 1965 ± 3          |
| Cobalt          | Co      | 27     | 58.9332  | 1495                | Rubidium        | Rb      | 37     | 85.4678  | 38.89             |
| Copper          | Cu      | 29     | 63.546   | 1083.4 ± 0.2        | Ruthenium       | Ru      | 44     | 101.07   | 2310              |
| Curium          | Cm      | 96     | (247)    | 1340 ± 40           | Samarium        | Sm      | 62     | 150.36   | 1072 ± 5          |
| Dysprosium      | Dy      | 66     | 162.5    | 1409                | Scandium        | Sc      | 21     | 44.9559  | 1539              |
| Einsteinium     | Es      | 99     | (252)    | ...                 | Selenium        | Se      | 34     | 78.96    | 217               |
| Erbium          | Er      | 68     | 167.26   | 1522                | Silicon         | Si      | 14     | 28.0855  | 1410              |
| Europium        | Eu      | 63     | 151.96   | 822 ± 5             | Silver          | Ag      | 47     | 107.868  | 961.93            |
| Fermium         | Fm      | 100    | (257)    | ...                 | Sodium          | Na      | 11     | 22.9898  | 97.81 ± 0.03      |
| Fluorine        | F       | 9      | 18.9984  | -219.62             | Strontium       | Sr      | 38     | 87.62    | 769               |
| Francium        | Fr      | 87     | (223)    | 27 <sup>b</sup>     | Sulfur          | S       | 16     | 32.06    | 112.8             |
| Gadolinium      | Gd      | 64     | 157.25   | 1311 ± 1            | Tantalum        | Ta      | 73     | 180.9479 | 2996              |
| Gallium         | Ga      | 31     | 69.72    | 29.78               | Technetium      | Tc      | 43     | (98)     | 2172              |
| Germanium       | Ge      | 32     | 72.59    | 937.4               | Tellurium       | Te      | 52     | 127.60   | 449.5 ± 0.3       |
| Gold            | Au      | 79     | 196.967  | 1064.434            | Terbium         | Tb      | 65     | 158.925  | 1360 ± 4          |
| Hafnium         | Hf      | 72     | 178.49   | 2227 ± 20           | Thallium        | Tl      | 81     | 204.383  | 303.5             |
| Helium          | He      | 2      | 4.00260  | -272.2 <sup>d</sup> | Thorium         | Th      | 90     | 232.038  | 1750              |
| Holmium         | Ho      | 67     | 164.930  | 1470                | Thulium         | Tm      | 69     | 168.934  | 1545 ± 15         |
| Hydrogen        | H       | 1      | 1.00794  | -259.14             | Tin             | Sn      | 50     | 118.71   | 231.9681          |
| Indium          | In      | 49     | 114.82   | 156.61              | Titanium        | Ti      | 22     | 47.88    | 1660 ± 10         |
| Iodine          | I       | 53     | 126.905  | 113.5               | Tungsten        | W       | 74     | 183.85   | 3410 ± 20         |
| Iridium         | Ir      | 77     | 192.22   | 2410                | Unnilhexium     | Unh     | 106    | (266)    | ...               |
| Iron            | Fe      | 26     | 55.847   | 1535                | Unnilnonium     | Unn     | 109    | (266)    | ...               |
| Krypton         | Kr      | 36     | 83.80    | -156.6              | Unniloctium     | Uno     | 108    | (265)    | ...               |
| Lanthanum       | La      | 57     | 138.906  | 920 ± 5             | Unnilpentium    | Unp     | 105    | (262)    | ...               |
| Lawrencium      | Lw      | 103    | (260)    | ...                 | Unnilquadium    | Unq     | 104    | (261)    | ...               |
| Lead            | Pb      | 82     | 207.2    | 327.502             | Unnilseptium    | Uns     | 107    | (261)    | ...               |
| Lithium         | Li      | 3      | 6.941    | 180.54              | Uranium         | U       | 92     | 238.029  | 1132 ± 0.8        |
| Lutetium        | Lu      | 71     | 174.967  | 1656 ± 5            | Vanadium        | V       | 23     | 50.9415  | 1890 ± 10         |
| Magnesium       | Mg      | 12     | 24.305   | 648.8 ± 0.5         | Xenon           | Xe      | 54     | 131.29   | -111.9            |
| Manganese       | Mn      | 25     | 54.9380  | 1244 ± 2            | Ytterbium       | Yb      | 70     | 173.04   | 824 ± 5           |
| Mendelevium     | Md      | 101    | (258)    | ...                 | Yttrium         | Y       | 39     | 88.9059  | 1523 ± 8          |
| Mercury         | Hg      | 80     | 200.59   | -38.87              | Zinc            | Zn      | 30     | 65.39    | 419.58            |
| Molybdenum      | Mo      | 42     | 95.94    | 2617                | Zirconium       | Zr      | 40     | 91.224   | 1852 ± 2          |
| Neodymium       | Nd      | 60     | 144.24   | 1010                |                 |         |        |          |                   |

<sup>a</sup> At 28 atm.<sup>b</sup> Approximate.<sup>c</sup> Sublimates.<sup>d</sup> At 26 atm.

Notes: Values in parentheses are atomic weights of the most stable known isotopes. Melting points at standard pressure except as noted.

### Heat and Combustion Related Properties

**Latent Heat.**—When a body changes from the solid to the liquid state or from the liquid to the gaseous state, a certain amount of heat is used to accomplish this change. This heat does not raise the temperature of the body and is called latent heat. When the body changes again from the gaseous to the liquid, or from the liquid to the solid state, it gives out this quantity of heat. The *latent heat of fusion* is the heat supplied to a solid body at the melting point; this heat is absorbed by the body although its temperature remains nearly stationary during the whole operation of melting. The *latent heat of evaporation* is the heat that must be supplied to a liquid at the boiling point to transform the liquid into a vapor. The latent heat is generally given in British thermal units per pound. When it is said that the latent heat of evaporation of water is 966.6, this means that it takes 966.6 heat units to evaporate 1 pound of water after it has been raised to the boiling point, 212°F.

When a body changes from the solid to the gaseous state without passing through the liquid stage, as solid carbon dioxide does, the process is called *sublimation*.

**Table 2. Latent Heat of Fusion**

| Substance        | Btu per Pound | Substance  | Btu per Pound | Substance | Btu per Pound |
|------------------|---------------|------------|---------------|-----------|---------------|
| Bismuth          | 22.75         | Paraffine  | 63.27         | Sulfur    | 16.86         |
| Beeswax          | 76.14         | Phosphorus | 9.06          | Tin       | 25.65         |
| Cast iron, gray  | 41.40         | Lead       | 10.00         | Zinc      | 50.63         |
| Cast iron, white | 59.40         | Silver     | 37.92         | Ice       | 144.00        |

**Table 3. Latent Heat of Evaporation**

| Liquid          | Btu per Pound | Liquid           | Btu per Pound | Liquid     | Btu per Pound |
|-----------------|---------------|------------------|---------------|------------|---------------|
| Alcohol, ethyl  | 371.0         | Carbon bisulfide | 160.0         | Turpentine | 133.0         |
| Alcohol, methyl | 481.0         | Ether            | 162.8         | Water      | 966.6         |
| Ammonia         | 529.0         | Sulfur dioxide   | 164.0         |            |               |

**Table 4. Boiling Points of Various Substances at Atmospheric Pressure**

| Substance        | Boiling Point, °F | Substance         | Boiling Point, °F | Substance       | Boiling Point, °F |
|------------------|-------------------|-------------------|-------------------|-----------------|-------------------|
| Aniline          | 363               | Chloroform        | 140               | Saturated brine | 226               |
| Alcohol          | 173               | Ether             | 100               | Sulfur          | 833               |
| Ammonia          | -28               | Linseed oil       | 597               | Sulfuric acid   | 590               |
| Benzine          | 176               | Mercury           | 676               | Water, pure     | 212               |
| Bromine          | 145               | Napthaline        | 428               | Water, sea      | 213.2             |
| Carbon bisulfide | 118               | Nitric acid       | 248               | Wood alcohol    | 150               |
|                  |                   | Oil of turpentine | 315               |                 |                   |

**Specific Heat.**—The specific heat of a substance is the ratio of the heat required to raise the temperature of a certain weight of the given substance 1°F, to the heat required to raise the temperature of the same weight of water 1°F. As the specific heat is not constant at all temperatures, it is generally assumed that it is determined by raising the temperature from 62 to 63°F. For most substances, however, specific heat is practically constant for temperatures up to 212°F.

In metric units, specific heat is defined as the ratio of the heat needed to raise the temperature of a mass by 1°C, to the heat needed to raise the temperature of the same mass of water by 1°C. In the metric system, heat is measured in calories (cal), mass is in grams (g), and measurements usually taken at 15°C.

Because specific heat is a dimensionless ratio, the values given in the table that follows are valid in both the US system and the metric system.

**Table 5. Average Specific Heats (Btu/lb-°F) of Various Substances**

| Substance                    | Specific Heat | Substance          | Specific Heat |
|------------------------------|---------------|--------------------|---------------|
| Alcohol (absolute)           | 0.700         | Lead               | 0.031         |
| Alcohol (density 0.8)        | 0.622         | Lead (fluid)       | 0.037         |
| Aluminum                     | 0.214         | Limestone          | 0.217         |
| Antimony                     | 0.051         | Magnesia           | 0.222         |
| Benzine                      | 0.450         | Marble             | 0.210         |
| Brass                        | 0.094         | Masonry, brick     | 0.200         |
| Brickwork                    | 0.200         | Mercury            | 0.033         |
| Cadmium                      | 0.057         | Naphtha            | 0.310         |
| Carbon                       | 0.204         | Nickel             | 0.109         |
| Charcoal                     | 0.200         | Oil, machine       | 0.400         |
| Chalk                        | 0.215         | Oil, olive         | 0.350         |
| Coal                         | 0.240         | Paper              | 0.32          |
| Coke                         | 0.203         | Phosphorus         | 0.189         |
| Copper, 32° to 212° F        | 0.094         | Platinum           | 0.032         |
| Copper, 32° to 572° F        | 0.101         | Quartz             | 0.188         |
| Corundum                     | 0.198         | Sand               | 0.195         |
| Ether                        | 0.503         | Silica             | 0.191         |
| Fusel oil                    | 0.564         | Silver             | 0.056         |
| Glass                        | 0.194         | Soda               | 0.231         |
| Gold                         | 0.031         | Steel, high carbon | 0.117         |
| Graphite                     | 0.201         | Steel, mild        | 0.116         |
| Ice                          | 0.504         | Stone (generally)  | 0.200         |
| Iron, cast                   | 0.130         | Sulfur             | 0.178         |
| Iron, wrought, 32° to 212° F | 0.110         | Sulfuric acid      | 0.330         |
| 32° to 392° F                | 0.115         | Tin (solid)        | 0.056         |
| 32° to 572° F                | 0.122         | Tin (fluid)        | 0.064         |
| 32° to 662° F                | 0.126         | Turpentine         | 0.472         |
| Iron, at high temperatures:  |               | Water              | 1.000         |
| 1382° to 1832° F             | 0.213         | Wood, fir          | 0.650         |
| 1750° to 1840° F             | 0.218         | Wood, oak          | 0.570         |
| 1920° to 2190° F             | 0.199         | Wood, pine         | 0.467         |
| Kerosene                     | 0.500         | Zinc               | 0.095         |

**Table 6. Specific Heat of Gases (Btu/lb-°F)**

| Gas            | Constant Pressure | Constant Volume | Gas        | Constant Pressure | Constant Volume |
|----------------|-------------------|-----------------|------------|-------------------|-----------------|
| Acetic acid    | 0.412             | ...             | Chloroform | 0.157             | ...             |
| Air            | 0.238             | 0.168           | Ethylene   | 0.404             | 0.332           |
| Alcohol        | 0.453             | 0.399           | Hydrogen   | 3.409             | 2.412           |
| Ammonia        | 0.508             | 0.399           | Nitrogen   | 0.244             | 0.173           |
| Carbonic acid  | 0.217             | 0.171           | Oxygen     | 0.217             | 0.155           |
| Carbonic oxide | 0.245             | 0.176           | Steam      | 0.480             | 0.346           |
| Chlorine       | 0.121             | ...             |            |                   |                 |

**Heat Loss from Uncovered Steam Pipes.**—The loss of heat from a bare steam or hot-water pipe varies with the temperature difference of the inside the pipe and that of the surrounding air. The loss is 2.15 Btu per hour, per square foot of pipe surface, per degree F of temperature difference when the latter is 100 degrees; for a difference of 200 degrees, the loss is 2.66 Btu; for 300 degrees, 3.26 Btu; for 400 degrees, 4.03 Btu; for 500 degrees, 5.18 Btu. Thus, if the pipe area is 1.18 square feet per foot of length, and the temperature difference 300°F, the loss per hour per foot of length =  $1.18 \times 300 \times 3.26 = 1154$  Btu.

**Table 7. Values of Thermal Conductivity ( $k$ ) and of Conductance ( $C$ ) of Common Building and Insulating Materials**

| Type of Material   | Thick-ness, in.                  | $k$ or $C^a$ | Type of Material            | Thick-ness, in. | $k$ or $C^a$ | Max. Temp., °F | Density, lb per cu. ft. | $k^a$             |
|--------------------|----------------------------------|--------------|-----------------------------|-----------------|--------------|----------------|-------------------------|-------------------|
| <b>BUILDING</b>    |                                  |              | <b>BUILDING (Continued)</b> |                 |              |                |                         |                   |
| <b>Batt:</b>       | ...                              | ...          | <b>Siding:</b>              | ...             | ...          | ...            | ...                     | ...               |
| Mineral Fiber      | 2-2 $\frac{3}{4}$                | 0.14         | Metal <sup>b</sup>          | Avg.            | 1.61         | ...            | ...                     | ...               |
| Mineral Fiber      | 3-3 $\frac{1}{2}$                | 0.09         | Wood, Med. Density          | $\frac{7}{16}$  | 1.49         | ...            | ...                     | ...               |
| Mineral Fiber      | 3 $\frac{1}{2}$ -6 $\frac{1}{2}$ | 0.05         | Stone:                      | ...             | ...          | ...            | ...                     | ...               |
| Mineral Fiber      | 6-7                              | 0.04         | Lime or Sand                | 1               | 12.50        | ...            | ...                     | ...               |
| Mineral Fiber      | 8 $\frac{1}{2}$                  | 0.03         | Wall Tile:                  | ...             | ...          | ...            | ...                     | ...               |
| <b>Block:</b>      | ...                              | ...          | Hollow Clay, 1-Cell         | 4               | 0.9          | ...            | ...                     | ...               |
| Cinder             | 4                                | 0.90         | Hollow Clay, 2-Cell         | 8               | 0.54         | ...            | ...                     | ...               |
| Cinder             | 8                                | 0.58         | Hollow Clay, 3-Cell         | 12              | 0.40         | ...            | ...                     | ...               |
| Cinder             | 12                               | 0.53         | Hollow Gypsum               | Avg.            | 0.7          | ...            | ...                     | ...               |
| <b>Block:</b>      | ...                              | ...          | <b>INSULATING</b>           |                 |              |                |                         |                   |
| Concrete           | 4                                | 1.40         | Blanket, Mineral Fiber:     | ...             | ...          | ...            | ...                     | ...               |
| Concrete           | 8                                | 0.90         | Felt                        | ...             | ...          | 400            | 3 to 8                  | 0.26              |
| Concrete           | 12                               | 0.78         | Rock or Slag                | ...             | ...          | 1200           | 6 to 12                 | 0.26 <sup>c</sup> |
| <b>Board:</b>      | ...                              | ...          | Glass                       | ...             | ...          | 350            | 0.65                    | 0.33              |
| Asbestos Cement    | $\frac{1}{4}$                    | 16.5         | Textile                     | ...             | ...          | 350            | 0.65                    | 0.31              |
| Plaster            | $\frac{1}{2}$                    | 2.22         | Blanket, Hairfelt           | ...             | ...          | 180            | 10                      | 0.29              |
| Plywood            | $\frac{3}{4}$                    | 1.07         | Board, Block and Pipe       | ...             | ...          | ...            | ...                     | ...               |
| <b>Brick:</b>      | ...                              | ...          | <b>Insulation:</b>          | ...             | ...          | ...            | ...                     | ...               |
| Common             | 1                                | 5.0          | Amosite                     | ...             | ...          | 1500           | 15 to 18                | 0.32 <sup>c</sup> |
| Face               | 1                                | 9.0          | Asbestos Paper              | ...             | ...          | 700            | 30                      | 0.40 <sup>c</sup> |
| Concrete (poured)  | 1                                | 12.0         | Glass or Slag (for Pipe)    | ...             | ...          | 350            | 3 to 4                  | 0.23              |
| <b>Floor:</b>      | ...                              | ...          | Glass or Slag (for Pipe)    | ...             | ...          | 1000           | 10 to 15                | 0.33 <sup>c</sup> |
| Wood Subfloor      | $\frac{3}{4}$                    | 1.06         | Glass, Cellular             | ...             | ...          | 800            | 9                       | 0.40              |
| Hardwood Finish    | $\frac{3}{4}$                    | 1.47         | Magnesia (85%)              | ...             | ...          | 600            | 11 to 12                | 0.35 <sup>c</sup> |
| Tile               | Avg.                             | 20.0         | Mineral Fiber               | ...             | ...          | 100            | 15                      | 0.29              |
| <b>Glass:</b>      | ...                              | ...          | Polystyrene, Beaded         | ...             | ...          | 170            | 1                       | 0.28              |
| Architectural      | ...                              | 10.00        | Polystyrene, Rigid          | ...             | ...          | 170            | 1.8                     | 0.25              |
| <b>Mortar:</b>     | ...                              | ...          | Rubber, Rigid Foam          | ...             | ...          | 150            | 4.5                     | 0.22              |
| Cement             | 1                                | 5.0          | Wood Felt                   | ...             | ...          | 180            | 20                      | 0.31              |
| <b>Plaster:</b>    | ...                              | ...          | <b>Loose Fill:</b>          | ...             | ...          | ...            | ...                     | ...               |
| Sand               | $\frac{3}{8}$                    | 13.30        | Cellulose                   | ...             | ...          | ...            | 2.5 to 3                | 0.27              |
| Sand and Gypsum    | $\frac{1}{2}$                    | 11.10        | Mineral Fiber               | ...             | ...          | ...            | 2 to 5                  | 0.28              |
| Stucco             | 1                                | 5.0          | Perlite                     | ...             | ...          | ...            | 5 to 8                  | 0.37              |
| <b>Roofing:</b>    | ...                              | ...          | Silica Aerogel              | ...             | ...          | ...            | 7.6                     | 0.17              |
| Asphalt Roll       | Avg.                             | 6.50         | Vermiculite                 | ...             | ...          | ...            | 7 to 8.2                | 0.47              |
| Shingle, asb. cem. | Avg.                             | 4.76         | Mineral Fiber Cement:       | ...             | ...          | ...            | ...                     | ...               |
| Shingle, asphalt   | Avg.                             | 2.27         | Clay Binder                 | ...             | ...          | 1800           | 24 to 30                | 0.49 <sup>c</sup> |
| Shingle, wood      | Avg.                             | 1.06         | Hydraulic Binder            | ...             | ...          | 1200           | 30 to 40                | 0.75 <sup>c</sup> |

<sup>a</sup> Units are in Btu/hr-ft<sup>2</sup>-°F. Where thickness is given as 1 inch, the value given is thermal conductivity ( $k$ ); for other thicknesses the value given is thermal conductance ( $C$ ). All values are for a test mean temperature of 75°F, except those designated with <sup>c</sup>, which are for 100°F.

<sup>b</sup> Over hollowback sheathing.

<sup>c</sup> Test mean temperature 100°F, see footnote <sup>a</sup>.

Source: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.: *Handbook of Fundamentals*.

**Table 8. Typical Values of Coefficient of Linear Thermal Expansion for Thermoplastics and Other Commonly Used Materials**

| Material <sup>a</sup> | in/in/deg F × 10 <sup>-5</sup> | cm/cm/deg C × 10 <sup>-5</sup> | Material <sup>a</sup>    | in/in/deg F × 10 <sup>-5</sup> | cm/cm/deg C × 10 <sup>-5</sup> |
|-----------------------|--------------------------------|--------------------------------|--------------------------|--------------------------------|--------------------------------|
| Liquid Crystal—GR     | 0.3                            | 0.6                            | ABS—GR                   | 1.7                            | 3.1                            |
| Glass                 | 0.4                            | 0.7                            | Polypropylene—GR         | 1.8                            | 3.2                            |
| Steel                 | 0.6                            | 1.1                            | Epoxy—GR                 | 2.0                            | 3.6                            |
| Concrete              | 0.8                            | 1.4                            | Polyphenylene sulfide—GR | 2.0                            | 3.6                            |
| Copper                | 0.9                            | 1.6                            | Acetal—GR                | 2.2                            | 4.0                            |
| Bronze                | 1.0                            | 1.8                            | Epoxy                    | 3.0                            | 5.4                            |
| Brass                 | 1.0                            | 1.8                            | Polycarbonate            | 3.6                            | 6.5                            |
| Aluminum              | 1.2                            | 2.2                            | Acrylic                  | 3.8                            | 6.8                            |
| Polycarbonate—GR      | 1.2                            | 2.2                            | ABS                      | 4.0                            | 7.2                            |
| Nylon—GR              | 1.3                            | 2.3                            | Nylon                    | 4.5                            | 8.1                            |
| TP polyester—GR       | 1.4                            | 2.5                            | Acetal                   | 4.8                            | 8.5                            |
| Magnesium             | 1.4                            | 2.5                            | Polypropylene            | 4.8                            | 8.6                            |
| Zinc                  | 1.7                            | 3.1                            | TP Polyester             | 6.9                            | 12.4                           |
| ABS—GR                | 1.7                            | 3.1                            | Polyethylene             | 7.2                            | 13.0                           |

<sup>a</sup> GR = Typical glass fiber-reinforced material. Other plastics materials shown are unfilled.

**Table 9. Linear Expansion of Various Substances between 32 and 212°F**  
Expansion of Volume = 3 × Linear Expansion

| Substance          | Linear Expansion for 1°F | Substance           | Linear Expansion for 1°F |
|--------------------|--------------------------|---------------------|--------------------------|
| Brick              | 0.000030                 | Masonry, brick from | 0.000026                 |
| Cement, Portland   | 0.000060                 | to                  | 0.000050                 |
| Concrete           | 0.000080                 | Plaster             | 0.000092                 |
| Ebonite            | 0.0000428                | Porcelain           | 0.000020                 |
| Glass, thermometer | 0.000050                 | Quartz, from        | 0.000043                 |
| Glass, hard        | 0.000040                 | to                  | 0.000079                 |
| Granite            | 0.000044                 | Slate               | 0.000058                 |
| Marble, from       | 0.000031                 | Sandstone           | 0.000065                 |
| to                 | 0.000079                 | Wood, pine          | 0.000028                 |

**Table 10. Coefficients of Heat Transmission**

| Metal         | Btu per Second | Metal         | Btu per Second | Metal       | Btu per Second |
|---------------|----------------|---------------|----------------|-------------|----------------|
| Aluminum      | 0.00203        | German silver | 0.00050        | Steel, soft | 0.00062        |
| Antimony      | 0.00022        | Iron          | 0.00089        | Silver      | 0.00610        |
| Brass, yellow | 0.00142        | Lead          | 0.00045        | Tin         | 0.00084        |
| Brass, red    | 0.00157        | Mercury       | 0.00011        | Zinc        | 0.00170        |
| Copper        | 0.00404        | Steel, hard   | 0.00034        | ...         | ...            |

Heat transmitted, in British thermal units, per second, through metal 1 inch thick, per square inch of surface, for a temperature difference of 1°F

**Table 11. Coefficients of Heat Radiation**

| Surface                | Btu per Hour | Surface               | Btu per Hour |
|------------------------|--------------|-----------------------|--------------|
| Cast-iron, new         | 0.6480       | Sawdust               | 0.7215       |
| Cast-iron, rusted      | 0.6868       | Sand, fine            | 0.7400       |
| Copper, polished       | 0.0327       | Silver, polished      | 0.0266       |
| Glass                  | 0.5948       | Tin, polished         | 0.0439       |
| Iron, ordinary         | 0.5662       | Tinned iron, polished | 0.0858       |
| Iron, sheet-, polished | 0.0920       | Water                 | 1.0853       |
| Oil                    | 1.4800       | ...                   | ...          |

Heat radiated, in British thermal units, per square foot of surface per hour, for a temperature difference of 1°F

**Table 12. Freezing Mixtures**

| Mixture   | Temperature Change, °F |      |
|---|------------------------|------|
|   | From                   | To   |
| Common salt (NaCl), 1 part; snow, 3 parts   | 32                     | ±0   |
| Common salt (NaCl), 1 part; snow, 1 part  | 32                     | -0.4 |
| Calcium chloride (CaCl <sub>2</sub> ), 3 parts; snow, 2 parts                                       | 32                     | -27  |
| Calcium chloride (CaCl <sub>2</sub> ), 2 parts; snow, 1 part  | 32                     | -44  |
| Sal ammoniac (NH <sub>4</sub> Cl), 5 parts; saltpeter (KNO <sub>3</sub> ), 5 parts; water, 16 parts | 50                     | +10  |
| Sal ammoniac (NH <sub>4</sub> Cl), 1 part; saltpeter (KNO <sub>3</sub> ), 1 part; water, 1 part     | 46                     | -11  |
| Ammonium nitrate (NH <sub>4</sub> NO <sub>3</sub> ), 1 part; water, 1 part                          | 50                     | +3   |
| Potassium hydrate (KOH), 4 parts; snow, 3 parts   | 32                     | -35  |

**Ignition Temperatures.**—The following temperatures are required to ignite the different substances specified: Phosphorus, transparent, 120°F; bisulfide of carbon, 300°F; gun cotton, 430°F; nitro-glycerine, 490°F; phosphorus, amorphous, 500°F; rifle powder, 550°F; charcoal, 660°F; dry pine wood, 800°F; dry oak wood, 900°F.

**Table 13. Typical Thermal Properties of Various Metals**

| Material and Alloy Designation <sup>a</sup> | Density,<br>ρ<br>lb/in <sup>3</sup> | Melting Point, °F |          | Conductivity, <i>k</i> ,<br>Btu/hr-ft-°F | Specific Heat, <i>C</i> ,<br>Btu/lb-°F | Coeff. of Expansion, α<br>μin/in-°F |
|---|-------------------------------------|-------------------|----------|--|--|-------------------------------------|
|   |                                     | solidus           | liquidus |  |  |                                     |
| Aluminum Alloys                             |                                     |                   |          |  |  |                                     |
| 2011  | 0.102                               | 995               | 1190     | 82.5                                     | 0.23                                   | 12.8                                |
| 2017  | 0.101                               | 995               | 1185     | 99.4                                     | 0.22                                   | 13.1                                |
| 2024  | 0.100                               | 995               | 1180     | 109.2                                    | 0.22                                   | 12.9                                |
| 3003  | 0.099                               | 1190              | 1210     | 111                                      | 0.22                                   | 12.9                                |
| 5052  | 0.097                               | 1100              | 1200     | 80                                       | 0.22                                   | 13.2                                |
| 5086  | 0.096                               | 1085              | 1185     | 73                                       | 0.23                                   | 13.2                                |
| 6061  | 0.098                               | 1080              | 1200     | 104                                      | 0.23                                   | 13.0                                |
| 7075  | 0.101                               | 890               | 1180     | 70                                       | 0.23                                   | 13.1                                |
| Copper-Base Alloys                          |                                     |                   |          |  |  |                                     |
| Manganese Bronze                            | 0.302                               | 1590              | 1630     | 61                                       | 0.09                                   | 11.8                                |
| C11000 (Electrolytic tough pitch)           | 0.321                               | 1941              | 1981     | 226                                      | 0.09                                   | 9.8                                 |
| C14500 (Free machining Cu)                  | 0.323                               | 1924              | 1967     | 205                                      | 0.09                                   | 9.9                                 |
| C17200, C17300 (Beryllium Cu)               | 0.298                               | 1590              | 1800     | 62                                       | 0.10                                   | 9.9                                 |
| C18200 (Chromium Cu)                        | 0.321                               | 1958              | 1967     | 187                                      | 0.09                                   | 9.8                                 |
| C18700 (Leaded Cu)                          | 0.323                               | 1750              | 1975     | 218                                      | 0.09                                   | 9.8                                 |
| C22000 (Commercial bronze, 90%)             | 0.318                               | 1870              | 1910     | 109                                      | 0.09                                   | 10.2                                |
| C23000 (Red brass, 85%)                     | 0.316                               | 1810              | 1880     | 92                                       | 0.09                                   | 10.4                                |
| C26000 (Cartridge brass, 70%)               | 0.313                               | 1680              | 1750     | 70                                       | 0.09                                   | 11.1                                |
| C27000 (Yellow brass)                       | 0.306                               | 1660              | 1710     | 67                                       | 0.09                                   | 11.3                                |
| C28000 (Muntz metal, 60%)                   | 0.303                               | 1650              | 1660     | 71                                       | 0.09                                   | 11.6                                |
| C33000 (Low-leaded brass tube)              | 0.310                               | 1660              | 1720     | 67                                       | 0.09                                   | 11.2                                |
| C35300 (High-leaded brass)                  | 0.306                               | 1630              | 1670     | 67                                       | 0.09                                   | 11.3                                |
| C35600 (Extra-high-leaded brass)            | 0.307                               | 1630              | 1660     | 67                                       | 0.09                                   | 11.4                                |
| C36000 (Free machining brass)               | 0.307                               | 1630              | 1650     | 67                                       | 0.09                                   | 11.4                                |
| C36500 (Leaded Muntz metal)                 | 0.304                               | 1630              | 1650     | 71                                       | 0.09                                   | 11.6                                |
| C46400 (Naval brass)                        | 0.304                               | 1630              | 1650     | 67                                       | 0.09                                   | 11.8                                |
| C51000 (Phosphor bronze, 5% A)              | 0.320                               | 1750              | 1920     | 40                                       | 0.09                                   | 9.9                                 |
| C54400 (Free cutting phos. bronze)          | 0.321                               | 1700              | 1830     | 50                                       | 0.09                                   | 9.6                                 |
| C62300 (Aluminum bronze, 9%)                | 0.276                               | 1905              | 1915     | 31.4                                     | 0.09                                   | 9.0                                 |
| C62400 (Aluminum bronze, 11%)               | 0.269                               | 1880              | 1900     | 33.9                                     | 0.09                                   | 9.2                                 |
| C63000 (Ni-Al bronze)                       | 0.274                               | 1895              | 1930     | 21.8                                     | 0.09                                   | 9.0                                 |
| Nickel-Silver                               | 0.314                               | 1870              | 2030     | 17                                       | 0.09                                   | 9.0                                 |



**Table 13. Typical Thermal Properties of Various Metals (Continued)**

| Material and Alloy Designation <sup>a</sup> | Density,<br>$\rho$<br>lb/in <sup>3</sup> | Melting Point, °F |          | Conductivity, $k$ ,<br>Btu/hr-ft-°F | Specific Heat, $C$ ,<br>Btu/lb-°F | Coeff. of Expansion, $\alpha$<br>$\mu\text{in/in-}^\circ\text{F}$ |
|---|--|-------------------|----------|-------------------------------------|-----------------------------------|---|
|   |  | solidus           | liquidus |                                     |                                   |   |
| Nickel-Base Alloys                          |  |                   |          |                                     |                                   |   |
| Nickel 200, 201, 205                        | 0.321                                    | 2615              | 2635     | 43.3                                | 0.11                              | 8.5   |
| Hastelloy C-22                              | 0.314                                    | 2475              | 2550     | 7.5                                 | 0.10                              | 6.9   |
| Hastelloy C-276                             | 0.321                                    | 2415              | 2500     | 7.5                                 | 0.10                              | 6.2   |
| Inconel 718                                 | 0.296                                    | 2300              | 2437     | 6.5                                 | 0.10                              | 7.2   |
| Monel                                       | 0.305                                    | 2370              | 2460     | 10                                  | 0.10                              | 8.7   |
| Monel 400                                   | 0.319                                    | 2370              | 2460     | 12.6                                | 0.10                              | 7.7   |
| Monel K500                                  | 0.306                                    | 2400              | 2460     | 10.1                                | 0.10                              | 7.6   |
| Monel R405                                  | 0.319                                    | 2370              | 2460     | 10.1                                | 0.10                              | 7.6   |
| Stainless Steels                            |  |                   |          |                                     |                                   |   |
| S30100                                      | 0.290                                    | 2550              | 2590     | 9.4                                 | 0.12                              | 9.4   |
| S30200, S30300, S30323                      | 0.290                                    | 2550              | 2590     | 9.4                                 | 0.12                              | 9.6   |
| S30215                                      | 0.290                                    | 2500              | 2550     | 9.2                                 | 0.12                              | 9.0   |
| S30400, S30500                              | 0.290                                    | 2550              | 2650     | 9.4                                 | 0.12                              | 9.6   |
| S30430                                      | 0.290                                    | 2550              | 2650     | 6.5                                 | 0.12                              | 9.6   |
| S30800                                      | 0.290                                    | 2550              | 2650     | 8.8                                 | 0.12                              | 9.6   |
| S30900, S30908                              | 0.290                                    | 2550              | 2650     | 9.0                                 | 0.12                              | 8.3   |
| S31000, S31008                              | 0.290                                    | 2550              | 2650     | 8.2                                 | 0.12                              | 8.8   |
| S31600, S31700                              | 0.290                                    | 2500              | 2550     | 9.4                                 | 0.12                              | 8.8   |
| S31703                                      | 0.290                                    | 2500              | 2550     | 8.3                                 | 0.12                              | 9.2   |
| S32100                                      | 0.290                                    | 2550              | 2600     | 9.3                                 | 0.12                              | 9.2   |
| S34700                                      | 0.290                                    | 2550              | 2650     | 9.3                                 | 0.12                              | 9.2   |
| S34800                                      | 0.290                                    | 2550              | 2650     | 9.3                                 | 0.12                              | 9.3   |
| S38400                                      | 0.290                                    | 2550              | 2650     | 9.4                                 | 0.12                              | 9.6   |
| S40300, S41000, S41600, S41623              | 0.280                                    | 2700              | 2790     | 14.4                                | 0.11                              | 5.5   |
| S40500                                      | 0.280                                    | 2700              | 2790     | 15.6                                | 0.12                              | 6.0   |
| S41400                                      | 0.280                                    | 2600              | 2700     | 14.4                                | 0.11                              | 5.8   |
| S42000, S42020                              | 0.280                                    | 2650              | 2750     | 14.4                                | 0.11                              | 5.7   |
| S42200                                      | 0.280                                    | 2675              | 2700     | 13.8                                | 0.11                              | 6.2   |
| S42900                                      | 0.280                                    | 2650              | 2750     | 14.8                                | 0.11                              | 5.7   |
| S43000, S43020, S43023                      | 0.280                                    | 2600              | 2750     | 15.1                                | 0.11                              | 5.8   |
| S43600                                      | 0.280                                    | 2600              | 2750     | 13.8                                | 0.11                              | 5.2   |
| S44002, S44004                              | 0.280                                    | 2500              | 2700     | 14.0                                | 0.11                              | 5.7   |
| S44003                                      | 0.280                                    | 2500              | 2750     | 14.0                                | 0.11                              | 5.6   |
| S44600                                      | 0.270                                    | 2600              | 2750     | 12.1                                | 0.12                              | 5.8   |
| S50100, S50200                              | 0.280                                    | 2700              | 2800     | 21.2                                | 0.11                              | 6.2   |
| Cast Iron and Steel                         |  |                   |          |                                     |                                   |   |
| Malleable Iron, A220 (50005, 60004, 80002)  | 0.265                                    |                   |          | 29.5                                | 0.12                              | 7.5   |
| Grey Cast Iron                              | 0.25                                     |                   |          | 28.0                                | 0.25                              | 5.8   |
| Ductile Iron, A536 (120-90-02)              | 0.25                                     |                   |          |                                     | 0.16                              | 5.9-6.2   |
| Ductile Iron, A536 (100-70-03)              | 0.25                                     |                   |          | 20.0                                | 0.16                              | 5.9-6.2   |
| Ductile Iron, A536 (80-55-06)               | 0.25                                     |                   |          | 18.0                                | 0.15                              | 5.9-6.2   |
| Ductile Iron, A536 (65-45-120)              | 0.25                                     |                   |          | 20.8                                | 0.15                              | 5.9-6.2   |
| Ductile Iron, A536 (60-40-18)               | 0.25                                     |                   |          |                                     | 0.12                              | 5.9-6.2   |
| Cast Steel, 3%C                             | 0.25                                     |                   |          | 28.0                                | 0.12                              | 7.0   |
| Titanium Alloys                             |  |                   |          |                                     |                                   |   |
| Commercially Pure                           | 0.163                                    | 3000              | 3040     | 9.0                                 | 0.12                              | 5.1   |
| Ti-5Al-2.5Sn                                | 0.162                                    | 2820              | 3000     | 4.5                                 | 0.13                              | 5.3   |
| Ti-8Mn                                      | 0.171                                    | 2730              | 2970     | 6.3                                 | 0.19                              | 6.0   |

<sup>a</sup> Alloy designations correspond to the Aluminum Association numbers for aluminum alloys and to the unified numbering system (UNS) for copper and stainless steel alloys. A220 and A536 are ASTM specified irons.

**Adjusting Lengths for Reference Temperature.**—The standard reference temperature for industrial length measurements is 20 degrees Celsius (68 degrees Fahrenheit). For other temperatures, corrections should be made in accordance with the difference in thermal expansion for the two parts, especially when the gage is made of a different material than the part to be inspected.

*Example:* An aluminum part is to be measured with a steel gage when the room temperature is 30 °C. The aluminum part has a coefficient of linear thermal expansion,  $\alpha_{part} = 24.7 \times 10^{-6}$  mm/mm-°C, and for the steel gage,  $\alpha_{Gage} = 10.8 \times 10^{-6}$  mm/mm-°C.

At the reference temperature, the specified length of the aluminum part is 20.021 mm. What is the length of the part at the measuring (room) temperature?

$\Delta L$ , the change in the measured length due to temperature, is given by:

$$\begin{aligned}\Delta L &= L(T_R - T_0)(\alpha_{part} - \alpha_{Gage}) \\ &= 20.021(30 - 20)(24.7 - 10.8) \times 10^{-6} \text{ mm} \\ &= 2782.919 \times 10^{-6} \approx 0.003 \text{ mm}\end{aligned}$$

where  $L$  = length of part at reference temperature;  $T_R$  = room temperature (temperature of part and gage); and,  $T_0$  = reference temperature.

Thus, the temperature corrected length at 30°C is  $L + \Delta L = 20.021 + 0.003 = 20.024$  mm.

**Length Change Due to Temperature.**—Table 14 gives changes in length for variations from the standard reference temperature of 68°F (20°C) for materials of known coefficients of expansion,  $\alpha$ . Coefficients of expansion are given in tables on pages 402, 403, 415, 416, 427, and elsewhere.

*Example:* In Table 14, for coefficients between those listed, add appropriate listed values. For example, a length change for a coefficient of 7 is the sum of values in the 5 and 2 columns. Fractional interpolation also is possible. Thus, in a steel bar with a coefficient of thermal expansion of  $6.3 \times 10^{-6} = 0.0000063$  in/in = 6.3  $\mu\text{m/in}$  of length/°F, the increase in length at 73°F is  $25 + 5 + 1.5 = 31.5$   $\mu\text{m/in}$  of length. For a steel with the same coefficient of expansion, the change in length, measured in degrees C, is expressed in microns (micrometers)/meter ( $\mu\text{m/m}$ ) of length.

Alternatively, and for temperatures beyond the scope of the table, the length difference due to a temperature change is equal to the coefficient of expansion multiplied by the change in temperature, i.e.,  $\Delta L = \alpha \Delta T$ . Thus, for the previous example,  $\Delta L = 6.3 \times (73 - 68) = 6.3 \times 5 = 31.5$   $\mu\text{m/in}$ .

**Change in Radius of Thin Circular Ring with Temperature.**—Consider a circular ring of initial radius  $r$ , that undergoes a temperature change  $\Delta T$ . Initially, the circumference of the ring is  $c = 2\pi r$ . If the coefficient of expansion of the ring material is  $\alpha$ , the change in circumference due to the temperature change is  $\Delta c = 2\pi r \alpha \Delta T$

The new circumference of the ring will be:  $c_n = c + \Delta c = 2\pi r + 2\pi r \alpha \Delta T = 2\pi r(1 + \alpha \Delta T)$

*Note:* An increase in temperature causes  $\Delta c$  to be positive, and a decrease in temperature causes  $\Delta c$  to be negative.

As the circumference increases, the radius of the circle also increases. If the new radius is  $R$ , the new circumference  $2\pi R$ . For a given change in temperature,  $\Delta T$ , the change in radius of the ring is found as follows:

$$c_n = 2\pi R = 2\pi r(1 + \alpha \Delta T) \quad R = r + r\alpha \Delta T \quad \Delta r = R - r = r\alpha \Delta T$$

LENGTH/TEMPERATURE CHANGES

**Table 14. Differences in Length in Inches/Inch (Microns/Meter) for Changes from the Standard Temperature of 68°F (20°C)**

| Temperature<br>Deg.<br>F C |     | Coefficient of Thermal Expansion of Material per Degree F (C) × 10 <sup>6</sup> |     |     |      |      |   |      |      |      |      |
|----------------------------|-----|---|-----|-----|------|------|---|------|------|------|------|
|                            |     | 1   | 2   | 3   | 4    | 5    | 10  | 15   | 20   | 25   | 30   |
|                            |     | Total Change in Length from Standard Temperature {                              |     |     |      |      | for °F in microinches/inch of length (μin/in)<br>for °C or °K in microns/meter of length (μm/m) |      |      |      |      |
| 38                         | -10 | -30   | -60 | -90 | -120 | -150 | -300  | -450 | -600 | -750 | -900 |
| 39                         | -9  | -29   | -58 | -87 | -116 | -145 | -290  | -435 | -580 | -725 | -870 |
| 40                         | -8  | -28   | -56 | -84 | -112 | -140 | -280  | -420 | -560 | -700 | -840 |
| 41                         | -7  | -27   | -54 | -81 | -108 | -135 | -270  | -405 | -540 | -675 | -810 |
| 42                         | -6  | -26   | -52 | -78 | -104 | -130 | -260  | -390 | -520 | -650 | -780 |
| 43                         | -5  | -25   | -50 | -75 | -100 | -125 | -250  | -375 | -500 | -625 | -750 |
| 44                         | -4  | -24   | -48 | -72 | -96  | -120 | -240  | -360 | -480 | -600 | -720 |
| 45                         | -3  | -23   | -46 | -69 | -92  | -115 | -230  | -345 | -460 | -575 | -690 |
| 46                         | -2  | -22   | -44 | -66 | -88  | -110 | -220  | -330 | -440 | -550 | -660 |
| 47                         | -1  | -21   | -42 | -63 | -84  | -105 | -210  | -315 | -420 | -525 | -630 |
| 48                         | 0   | -20   | -40 | -60 | -80  | -100 | -200  | -300 | -400 | -500 | -600 |
| 49                         | 1   | -19   | -38 | -57 | -76  | -95  | -190  | -285 | -380 | -475 | -570 |
| 50                         | 2   | -18   | -36 | -54 | -72  | -90  | -180  | -270 | -360 | -450 | -540 |
| 51                         | 3   | -17   | -34 | -51 | -68  | -85  | -170  | -255 | -340 | -425 | -510 |
| 52                         | 4   | -16   | -32 | -48 | -64  | -80  | -160  | -240 | -320 | -400 | -480 |
| 53                         | 5   | -15   | -30 | -45 | -60  | -75  | -150  | -225 | -300 | -375 | -450 |
| 54                         | 6   | -14   | -28 | -42 | -56  | -70  | -140  | -210 | -280 | -350 | -420 |
| 55                         | 7   | -13   | -26 | -39 | -52  | -65  | -130  | -195 | -260 | -325 | -390 |
| 56                         | 8   | -12   | -24 | -36 | -48  | -60  | -120  | -180 | -240 | -300 | -360 |
| 57                         | 9   | -11   | -22 | -33 | -44  | -55  | -110  | -165 | -220 | -275 | -330 |
| 58                         | 10  | -10   | -20 | -30 | -40  | -50  | -100  | -150 | -200 | -250 | -300 |
| 59                         | 11  | -9  | -18 | -27 | -36  | -45  | -90   | -135 | -180 | -225 | -270 |
| 60                         | 12  | -8  | -16 | -24 | -32  | -40  | -80   | -120 | -160 | -200 | -240 |
| 61                         | 13  | -7  | -14 | -21 | -28  | -35  | -70   | -105 | -140 | -175 | -210 |
| 62                         | 14  | -6  | -12 | -18 | -24  | -30  | -60   | -90  | -120 | -150 | -180 |
| 63                         | 15  | -5  | -10 | -15 | -20  | -25  | -50   | -75  | -100 | -125 | -150 |
| 64                         | 16  | -4  | -8  | -12 | -16  | -20  | -40   | -60  | -80  | -100 | -120 |
| 65                         | 17  | -3  | -6  | -9  | -12  | -15  | -30   | -45  | -60  | -75  | -90  |
| 66                         | 18  | -2  | -4  | -6  | -8   | -10  | -20   | -30  | -40  | -50  | -60  |
| 67                         | 19  | -1  | -2  | -3  | -4   | -5   | -10   | -15  | -20  | -25  | -30  |
| 68                         | 20  | 0   | 0   | 0   | 0    | 0    | 0   | 0    | 0    | 0    | 0    |
| 69                         | 21  | 1   | 2   | 3   | 4    | 5    | 10  | 15   | 20   | 25   | 30   |
| 70                         | 22  | 2   | 4   | 6   | 8    | 10   | 20  | 30   | 40   | 50   | 60   |
| 71                         | 23  | 3   | 6   | 9   | 12   | 15   | 30  | 45   | 60   | 75   | 90   |
| 72                         | 24  | 4   | 8   | 12  | 16   | 20   | 40  | 60   | 80   | 100  | 120  |
| 73                         | 25  | 5   | 10  | 15  | 20   | 25   | 50  | 75   | 100  | 125  | 150  |
| 74                         | 26  | 6   | 12  | 18  | 24   | 30   | 60  | 90   | 120  | 150  | 180  |
| 75                         | 27  | 7   | 14  | 21  | 28   | 35   | 70  | 105  | 140  | 175  | 210  |
| 76                         | 28  | 8   | 16  | 24  | 32   | 40   | 80  | 120  | 160  | 200  | 240  |
| 77                         | 29  | 9   | 18  | 27  | 36   | 45   | 90  | 135  | 180  | 225  | 270  |
| 78                         | 30  | 10  | 20  | 30  | 40   | 50   | 100   | 150  | 200  | 250  | 300  |
| 79                         | 31  | 11  | 22  | 33  | 44   | 55   | 110   | 165  | 220  | 275  | 330  |
| 80                         | 32  | 12  | 24  | 36  | 48   | 60   | 120   | 180  | 240  | 300  | 360  |
| 81                         | 33  | 13  | 26  | 39  | 52   | 65   | 130   | 195  | 260  | 325  | 390  |
| 82                         | 34  | 14  | 28  | 42  | 56   | 70   | 140   | 210  | 280  | 350  | 420  |
| 83                         | 35  | 15  | 30  | 45  | 60   | 75   | 150   | 225  | 300  | 375  | 450  |
| 84                         | 36  | 16  | 32  | 48  | 64   | 80   | 160   | 240  | 320  | 400  | 480  |
| 85                         | 37  | 17  | 34  | 51  | 68   | 85   | 170   | 255  | 340  | 425  | 510  |
| 86                         | 38  | 18  | 36  | 54  | 72   | 90   | 180   | 270  | 360  | 450  | 540  |
| 87                         | 39  | 19  | 38  | 57  | 76   | 95   | 190   | 285  | 380  | 475  | 570  |
| 88                         | 40  | 20  | 40  | 60  | 80   | 100  | 200   | 300  | 400  | 500  | 600  |
| 89                         | 41  | 21  | 42  | 63  | 84   | 105  | 210   | 315  | 420  | 525  | 630  |
| 90                         | 42  | 22  | 44  | 66  | 88   | 110  | 220   | 330  | 440  | 550  | 660  |
| 91                         | 43  | 23  | 46  | 69  | 92   | 115  | 230   | 345  | 460  | 575  | 690  |
| 92                         | 44  | 24  | 48  | 72  | 96   | 120  | 240   | 360  | 480  | 600  | 720  |
| 93                         | 45  | 25  | 50  | 75  | 100  | 125  | 250   | 375  | 500  | 625  | 750  |
| 94                         | 46  | 26  | 52  | 78  | 104  | 130  | 260   | 390  | 520  | 650  | 780  |
| 95                         | 47  | 27  | 54  | 81  | 108  | 135  | 270   | 405  | 540  | 675  | 810  |
| 96                         | 48  | 28  | 56  | 84  | 112  | 140  | 280   | 420  | 560  | 700  | 840  |
| 97                         | 49  | 29  | 58  | 87  | 116  | 145  | 290   | 435  | 580  | 725  | 870  |
| 98                         | 50  | 30  | 60  | 90  | 120  | 150  | 300   | 450  | 600  | 750  | 900  |

## Properties of Mass and Weight

**Specific Gravity.**—Specific gravity is a number indicating how many times a certain volume of a material is heavier than an equal volume of water. The density of water differs slightly at different temperatures, so the usual custom is to make comparisons on the basis that the water has a temperature of 62°F. The weight of 1 cubic inch of pure water at 62°F is 0.0361 pound. If the specific gravity of any material is known, the weight of a cubic inch of the material, therefore, can be found by multiplying its specific gravity by 0.0361. To find the weight per cubic foot of a material, multiply the specific gravity by 62.355. If the weight of a cubic inch of a material is known, the specific gravity is found by dividing the weight per cubic inch by 0.0361.

*Example:* Given the specific gravity of cast iron is 7.2. Then, the weight of 5 cubic inches of cast iron =  $7.2 \times 0.0361 \times 5 = 1.2996$  pounds.

*Example:* Given the weight of a cubic inch of gold is 0.697 pound. Then, the specific gravity of gold =  $0.697 \div 0.0361 = 19.31$

If the weight per cubic foot of a material is known, the specific gravity is found by multiplying this weight by 0.01604.

Table 15. Average Specific Gravity of Various Substances

| Substance              | Specific Gravity | <sup>a</sup> Weight lb/ft <sup>3</sup> | Substance           | Specific Gravity | <sup>a</sup> Weight lb/ft <sup>3</sup> | Substance       | Specific Gravity | <sup>a</sup> Weight lb/ft <sup>3</sup> |
|------------------------|------------------|--|---------------------|------------------|--|-----------------|------------------|--|
| ABS                    | 1.05             | 66                                     | Glass               | 2.6              | 162                                    | Platinum        | 21.5             | 1342                                   |
| Acrylic                | 1.19             | 74                                     | Glass, crushed      | ...              | 74                                     | Polycarbonate   | 1.19             | 74                                     |
| Aluminum bronze        | 7.8              | 486                                    | Gold, 22 carat fine | 17.5             | 1091                                   | Polyethylene    | 0.97             | 60                                     |
| Aluminum, cast         | 2.6              | 160                                    | Gold, pure          | 19.3             | 1204                                   | Polypropylene   | 0.91             | 57                                     |
| Aluminum, wrought      | 2.7              | 167                                    | Granite             | 2.7              | 168                                    | Polyurethane    | 1.05             | 66                                     |
| Asbestos               | 2.4              | 150                                    | Gravel              | ...              | 109                                    | Quartz          | 2.6              | 162                                    |
| Asphaltum              | 1.4              | 87                                     | Gypsum              | 2.4              | 150                                    | Salt, common    | ...              | 48                                     |
| Borax                  | 1.8              | 112                                    | Ice                 | 0.9              | 56                                     | Sand, dry       | ...              | 100                                    |
| Brick, common          | 1.8              | 112                                    | Iron, cast          | 7.2              | 447                                    | Sand, wet       | ...              | 125                                    |
| Brick, fire            | 2.3              | 143                                    | Iron, wrought       | 7.7              | 479                                    | Sandstone       | 2.3              | 143                                    |
| Brick, hard            | 2.0              | 125                                    | Iron slag           | 2.7              | 168                                    | Silver          | 10.5             | 656                                    |
| Brick, pressed         | 2.2              | 137                                    | Lead                | 11.4             | 711                                    | Slate           | 2.8              | 175                                    |
| Brickwork, in cement   | 1.8              | 112                                    | Limestone           | 2.6              | 162                                    | Soapstone       | 2.7              | 168                                    |
| Brickwork, in mortar   | 1.6              | 100                                    | Marble              | 2.7              | 168                                    | Steel           | 7.9              | 491                                    |
| CPVC                   | 1.55             | 97                                     | Masonry             | 2.4              | 150                                    | Sulfur          | 2.0              | 125                                    |
| Cement, Portland (set) | 3.1              | 193                                    | Mercury             | 13.56            | 845.3                                  | Tar, bituminous | 1.2              | 75                                     |
| Chalk                  | 2.3              | 143                                    | Mica                | 2.8              | 175                                    | Tile            | 1.8              | 112                                    |
| Charcoal               | 0.4              | 25                                     | Mortar              | 1.5              | 94                                     | Trap rock       | 3.0              | 187                                    |
| Coal, anthracite       | 1.5              | 94                                     | Nickel, cast        | 8.3              | 517                                    | Water at 62°F   | 1.0              | 62.355                                 |
| Coal, bituminous       | 1.3              | 81                                     | Nickel, rolled      | 8.7              | 542                                    | White metal     | 7.3              | 457                                    |
| Concrete               | 2.2              | 137                                    | Nylon 6, Cast       | 1.16             | 73                                     | Zinc, cast      | 6.9              | 429                                    |
| Earth, loose           | ...              | 75                                     | PTFE                | 2.19             | 137                                    | Zinc, sheet     | 7.2              | 450                                    |
| Earth, rammed          | ...              | 100                                    | Phosphorus          | 1.8              | 112                                    | ...             | ...              | ...                                    |
| Emery                  | 4.0              | 249                                    | Plaster of Paris    | 1.8              | 112                                    | ...             | ...              | ...                                    |

<sup>a</sup> The weight per cubic foot is calculated on the basis of the specific gravity except for those substances that occur in bulk, heaped, or loose form. In these instances, only the weights per cubic foot are given because the voids present in representative samples make the values of the specific gravities inaccurate.

**Specific Gravity of Gases.**—The specific gravity of gases is the number that indicates their weight in comparison with that of an equal volume of air. The specific gravity of air is 1, and the comparison is made at 32°F. Values are given in Table 16.

**Specific Gravity of Liquids.**—The specific gravity of liquids is the number that indicates how much a certain volume of the liquid weighs compared with an equal volume of water, the same as with solid bodies. Specific gravity of various liquids is given in Table 17.

The density of liquid is often expressed in degrees on the hydrometer, an instrument for determining the density of liquids, provided with graduations made to an arbitrary scale. The hydrometer consists of a glass tube with a bulb at one end containing air, and arranged with a weight at the bottom so as to float in an upright position in the liquid, the density of

**Table 16. Specific Gravity of Gases At 32°F**

| Gas              | Sp. Gr. | Gas               | Sp. Gr. | Gas            | Sp. Gr. |
|------------------|---------|-------------------|---------|----------------|---------|
| Air <sup>a</sup> | 1.000   | Ether vapor       | 2.586   | Marsh gas      | 0.555   |
| Acetylene        | 0.920   | Ethylene          | 0.967   | Nitrogen       | 0.971   |
| Alcohol vapor    | 1.601   | Hydrofluoric acid | 2.370   | Nitric oxide   | 1.039   |
| Ammonia          | 0.592   | Hydrochloric acid | 1.261   | Nitrous oxide  | 1.527   |
| Carbon dioxide   | 1.520   | Hydrogen          | 0.069   | Oxygen         | 1.106   |
| Carbon monoxide  | 0.967   | Illuminating gas  | 0.400   | Sulfur dioxide | 2.250   |
| Chlorine         | 2.423   | Mercury vapor     | 6.940   | Water vapor    | 0.623   |

<sup>a</sup> 1 cubic foot of air at 32°F and atmospheric pressure weighs 0.0807 pound.

which is to be measured. The depth to which the hydrometer sinks in the liquid is read off on the graduated scale. The most commonly used hydrometer is the Baumé, see [Table 18](#). The value of the degrees of the Baumé scale differs according to whether the liquid is heavier or lighter than water. The specific gravity for liquids heavier than water equals  $145 \div (145 - \text{degrees Baumé})$ . For liquids lighter than water, the specific gravity equals  $140 \div (130 + \text{degrees Baumé})$ .

**Table 17. Specific Gravity of Liquids**

| Liquid              | Sp. Gr. | Liquid        | Sp. Gr. | Liquid          | Sp. Gr. |
|---------------------|---------|---------------|---------|-----------------|---------|
| Acetic acid         | 1.06    | Fluoric acid  | 1.50    | Petroleum oil   | 0.82    |
| Alcohol, commercial | 0.83    | Gasoline      | 0.70    | Phosphoric acid | 1.78    |
| Alcohol, pure       | 0.79    | Kerosene      | 0.80    | Rape oil        | 0.92    |
| Ammonia             | 0.89    | Linseed oil   | 0.94    | Sulfuric acid   | 1.84    |
| Benzene             | 0.69    | Mineral oil   | 0.92    | Tar             | 1.00    |
| Bromine             | 2.97    | Muriatic acid | 1.20    | Turpentine oil  | 0.87    |
| Carbolic acid       | 0.96    | Naphtha       | 0.76    | Vinegar         | 1.08    |
| Carbon disulfide    | 1.26    | Nitric acid   | 1.50    | Water           | 1.00    |
| Cotton-seed oil     | 0.93    | Olive oil     | 0.92    | Water, sea      | 1.03    |
| Ether, sulfuric     | 0.72    | Palm oil      | 0.97    | Whale oil       | 0.92    |

**Table 18. Degrees on Baumé's Hydrometer Converted to Specific Gravity**

| Deg. Baumé | Specific Gravity for Liquids |                    | Deg. Baumé | Specific Gravity for Liquids |                    | Deg. Baumé | Specific Gravity for Liquids |                    |
|------------|------------------------------|--------------------|------------|------------------------------|--------------------|------------|------------------------------|--------------------|
|            | Heavier than Water           | Lighter than Water |            | Heavier than Water           | Lighter than Water |            | Heavier than Water           | Lighter than Water |
| 0          | 1.000                        | ...                | 27         | 1.229                        | 0.892              | 54         | 1.593                        | 0.761              |
| 1          | 1.007                        | ...                | 28         | 1.239                        | 0.886              | 55         | 1.611                        | 0.757              |
| 2          | 1.014                        | ...                | 29         | 1.250                        | 0.881              | 56         | 1.629                        | 0.753              |
| 3          | 1.021                        | ...                | 30         | 1.261                        | 0.875              | 57         | 1.648                        | 0.749              |
| 4          | 1.028                        | ...                | 31         | 1.272                        | 0.870              | 58         | 1.667                        | 0.745              |
| 5          | 1.036                        | ...                | 32         | 1.283                        | 0.864              | 59         | 1.686                        | 0.741              |
| 6          | 1.043                        | ...                | 33         | 1.295                        | 0.859              | 60         | 1.706                        | 0.737              |
| 7          | 1.051                        | ...                | 34         | 1.306                        | 0.854              | 61         | 1.726                        | 0.733              |
| 8          | 1.058                        | ...                | 35         | 1.318                        | 0.849              | 62         | 1.747                        | 0.729              |
| 9          | 1.066                        | ...                | 36         | 1.330                        | 0.843              | 63         | 1.768                        | 0.725              |
| 10         | 1.074                        | 1.000              | 37         | 1.343                        | 0.838              | 64         | 1.790                        | 0.721              |
| 11         | 1.082                        | 0.993              | 38         | 1.355                        | 0.833              | 65         | 1.813                        | 0.718              |
| 12         | 1.090                        | 0.986              | 39         | 1.368                        | 0.828              | 66         | 1.836                        | 0.714              |
| 13         | 1.099                        | 0.979              | 40         | 1.381                        | 0.824              | 67         | 1.859                        | 0.710              |
| 14         | 1.107                        | 0.972              | 41         | 1.394                        | 0.819              | 68         | 1.883                        | 0.707              |
| 15         | 1.115                        | 0.966              | 42         | 1.408                        | 0.814              | 69         | 1.908                        | 0.704              |
| 16         | 1.124                        | 0.959              | 43         | 1.422                        | 0.809              | 70         | 1.933                        | 0.700              |
| 17         | 1.133                        | 0.952              | 44         | 1.436                        | 0.805              | 71         | 1.959                        | 0.696              |
| 18         | 1.142                        | 0.946              | 45         | 1.450                        | 0.800              | 72         | 1.986                        | 0.693              |
| 19         | 1.151                        | 0.940              | 46         | 1.465                        | 0.796              | 73         | 2.014                        | 0.689              |
| 20         | 1.160                        | 0.933              | 47         | 1.480                        | 0.791              | 74         | 2.042                        | 0.686              |
| 21         | 1.169                        | 0.927              | 48         | 1.495                        | 0.787              | 75         | 2.071                        | 0.683              |
| 22         | 1.179                        | 0.921              | 49         | 1.510                        | 0.782              | 76         | 2.101                        | 0.679              |
| 23         | 1.189                        | 0.915              | 50         | 1.526                        | 0.778              | 77         | 2.132                        | 0.676              |
| 24         | 1.198                        | 0.909              | 51         | 1.542                        | 0.773              | 78         | 2.164                        | 0.673              |
| 25         | 1.208                        | 0.903              | 52         | 1.559                        | 0.769              | 79         | 2.197                        | 0.669              |
| 26         | 1.219                        | 0.897              | 53         | 1.576                        | 0.765              | 80         | 2.230                        | 0.666              |

**Average Weights and Volumes of Solid Fuels.**—Anthracite coal, 55–65 lb/ft<sup>3</sup>; 34–41 ft<sup>3</sup>/ton (2240 lb); 67 lb/bushel. Bituminous coal, 50–55 lb/ft<sup>3</sup>; 41–45 ft<sup>3</sup>/ton (2240 lb); 60 lb/bushel. Charcoal, 8–18.5 lb/ft<sup>3</sup>; 120–124 ft<sup>3</sup>/ton (2240 lb); 20 lb/bushel. Coke, 28 lb/ft<sup>3</sup>; 80 ft<sup>3</sup>/ton (2240 lb); 40 lb/bushel.

**How to Estimate the Weight of Natural Piles.**—To calculate the upper and lower limits of the weight of a substance piled naturally on a circular plate, so as to form a cone of material, use the equation:

$$W = MD^3 \tag{1}$$

where  $W$  = weight, lb;  $D$  = diameter of plate, ft. (Fig. 1a); and,  $M$  = materials factor, whose upper and lower limits are given in Table 19b.

For a rectangular plate, calculate the weight of material piled naturally by means of the following equation:

$$W = MRA^3 \tag{2}$$

where  $A$  and  $B$  = the length and width in ft., respectively, of the rectangular plate in Fig. 1b, with  $B \leq A$ ; and,  $R$  = is a factor given in Table 19a as a function of the ratio  $B/A$ .

*Example:* Find the upper and lower limits of the weight of dry ashes piled naturally on a plate 10 ft. in diameter.

Using Equation (1),  $M = 4.58$  from Table 19b, the lower limit  $W = 4.58 \times 10^3 = 4,580$  lb. For  $M = 5.89$ , the upper limit  $W = 5.89 \times 10^3 = 5,890$  lb.

*Example:* What weight of dry ashes rests on a rectangular plate 10 ft. by 5 ft.?

For  $B/A = 5/10 = 0.5$ ,  $R = 0.39789$  from Table 19a. Using Equation (2), for  $M = 4.58$ , the lower limit  $W = 4.58 \times 0.39789 \times 10^3 = 1,822$  lb. For  $M = 5.89$ , the upper limit  $W = 5.89 \times 0.39789 \times 10^3 = 2,344$  lb.

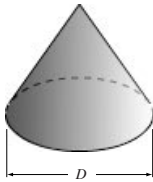


Fig. 1a. Conical Pile

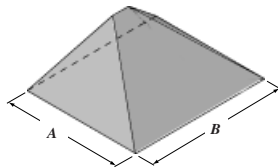


Fig. 1b. Rectangular Pile

**Table 19a. Factor  $R$  as a function of  $B/A$  ( $B \leq A$ )**

| $B/A$ | $R$     | $B/A$ | $R$     | $B/A$ | $R$     | $B/A$ | $R$     | $B/A$ | $R$     |
|-------|---------|-------|---------|-------|---------|-------|---------|-------|---------|
| 0.01  | 0.00019 | 0.18  | 0.05817 | 0.35  | 0.20666 | 0.52  | 0.42691 | 0.69  | 0.70015 |
| 0.02  | 0.00076 | 0.19  | 0.06458 | 0.36  | 0.21782 | 0.53  | 0.44170 | 0.70  | 0.71747 |
| 0.03  | 0.00170 | 0.20  | 0.07130 | 0.37  | 0.22921 | 0.54  | 0.45667 | 0.71  | 0.73491 |
| 0.04  | 0.00302 | 0.21  | 0.07833 | 0.38  | 0.24085 | 0.55  | 0.47182 | 0.72  | 0.75245 |
| 0.05  | 0.00470 | 0.22  | 0.08566 | 0.39  | 0.25273 | 0.56  | 0.48713 | 0.73  | 0.77011 |
| 0.06  | 0.00674 | 0.23  | 0.09329 | 0.40  | 0.26483 | 0.57  | 0.50262 | 0.74  | 0.78787 |
| 0.07  | 0.00914 | 0.24  | 0.10121 | 0.41  | 0.27717 | 0.58  | 0.51826 | 0.75  | 0.80572 |
| 0.08  | 0.01190 | 0.25  | 0.10942 | 0.42  | 0.28973 | 0.59  | 0.53407 | 0.76  | 0.82367 |
| 0.09  | 0.01501 | 0.26  | 0.11792 | 0.43  | 0.30252 | 0.60  | 0.55004 | 0.77  | 0.84172 |
| 0.10  | 0.01846 | 0.27  | 0.12670 | 0.44  | 0.31552 | 0.61  | 0.56616 | 0.78  | 0.85985 |
| 0.11  | 0.02226 | 0.28  | 0.13576 | 0.45  | 0.32873 | 0.62  | 0.58243 | 0.79  | 0.87807 |
| 0.12  | 0.02640 | 0.29  | 0.14509 | 0.46  | 0.34216 | 0.63  | 0.59884 | 0.80  | 0.89636 |
| 0.13  | 0.03088 | 0.30  | 0.15470 | 0.47  | 0.35579 | 0.64  | 0.61539 | 0.81  | 0.91473 |
| 0.14  | 0.03569 | 0.31  | 0.16457 | 0.48  | 0.36963 | 0.65  | 0.63208 | 0.82  | 0.93318 |
| 0.15  | 0.04082 | 0.32  | 0.17471 | 0.49  | 0.38366 | 0.66  | 0.64891 | 0.83  | 0.95169 |
| 0.16  | 0.04628 | 0.33  | 0.18511 | 0.50  | 0.39789 | 0.67  | 0.66586 | 0.84  | 0.97027 |
| 0.17  | 0.05207 | 0.34  | 0.19576 | 0.51  | 0.41231 | 0.68  | 0.68295 | 0.85  | 0.98891 |
|       |         |       |         |       |         |       |         |       | ...     |
|       |         |       |         |       |         |       |         |       | ...     |

Table 19b. Limits of Factor *M* for Various Materials

| Material                   | Factor <i>M</i> | Material                   | Factor <i>M</i> | Material                | Factor <i>M</i> |
|----------------------------|-----------------|----------------------------|-----------------|-------------------------|-----------------|
| Almonds, whole             | 2.12-3.93       | Coffee, ground             | 1.89-3.27       | Peanuts, unshelled      | 1.13-3.14       |
| Aluminum chips             | 0.92-1.96       | Coke, pulverized           | 2.21            | Peanuts, shelled        | 2.65-5.89       |
| Aluminum silicate          | 3.7-6.41        | Copper oxide, powdered     | 20.87           | Peas, dry               | 2.75-3.05       |
| Ammonium chloride          | 3.93-6.81       | Cork, granulated           | 1.57-1.96       | Potassium carbonate     | 3.85-6.68       |
| Asbestos, shred            | 2.62-3.27       | Corn on cob                | 1.29-1.33       | Potassium sulphate      | 5.5-6.28        |
| Ashes, dry                 | 4.58-5.89       | Corn sugar                 | 2.34-4.06       | Pumice                  | 5.24-5.89       |
| Ashes, damp                | 6.24-7.80       | Cottonseed, dry, de-linted | 1.66-5.24       | Rice, bran              | 1.51-2.75       |
| Asphalt, crushed           | 3.4-5.89        | Diatomaceous earth         | 0.83-1.23       | Rubber, scrap, ground   | 2.11-4.58       |
| Bakelite, powdered         | 3.93-5.24       | Dicalcium phosphate        | 5.63            | Salt, dry, coarse       | 3.02-8.38       |
| Baking powder              | 3.1-5.37        | Ebonite, crushed           | 4.91-9.16       | Salt, dry, fine         | 5.29-10.47      |
| Barium carbonate           | 9.42            | Epsoin salts               | 3.02-6.54       | Saltpeter               | 6.05-10.47      |
| Bauxite, mine run          | 5.9-6.69        | Feldspar, ground           | 8.51-9.16       | Salt rock, crushed      | 4.58            |
| Beans, navy, dry           | 3.63            | Fish scrap                 | 5.24-6.54       | Sand, very fine         | 7.36-9          |
| Beets, sugar, shredded     | 0.47-0.55       | Flour                      | 5.61-10.43      | Sawdust, dry            | 0.95-2.85       |
| Bicarbonate of soda        | 3.10            | Flue dust                  | 2.65-3.40       | Sesame seed             | 2.04-4.84       |
| Borax                      | 3.78-9.16       | Flourspar (Flourite)       | 10.73-14.40     | Shellac, powdered       | 2.34-4.06       |
| Boric acid                 | 4.16-7.20       | Graphite, flake            | 3.02-5.24       | Slag, furnace, granular | 4.53-8.51       |
| Bronze chips               | 3.93-6.54       | Gravel                     | 6.8-13.18       | Soap powder             | 1.51-3.27       |
| Buckwheat                  | 2.8-3.17        | Gypsum, calcined           | 6.04-6.59       | Sodium nitrate          | 3.96-4.66       |
| Calcium lactate            | 3.4-3.8         | Hominy                     | 2.8-6.54        | Sodium sulphite         | 10.54           |
| Calcium oxide (lime)       | 3.30            | Hops, dry                  | 4.58            | Sodium sulphate         | 6.92            |
| Carbon, ground             | 2.51            | Kaolin clay                | 12.32-21.34     | Soybeans                | 3.48-6.28       |
| Casein                     | 2.72-4.71       | Lead silicate, granulated  | 25.26           | Steel chips, crushed    | 7.56-19.63      |
| Cashew nuts                | 4.19-4.84       | Lead sulphate, pulverized  | 24.09           | Sugar, refined          | 3.78-7.2        |
| Cast iron chips            | 17.02-26.18     | Lime ground                | 7.85            | Sulphur                 | 4.5-6.95        |
| Cement, Portland           | 6.8-13.09       | Limestone, crushed         | 6.42-11.78      | Talcum powder           | 4.37-5.9        |
| Cinders, coal              | 3.02-5.24       | Magnesium chloride         | 4.32            | Tin oxide, ground       | 9.17            |
| Clay, blended for tile     | 5.89            | Malt, dry, ground          | 1.66-2.88       | Tobacco stems           | 1.96-3.27       |
| Coal, anthracite, chestnut | 2.43            | Manganese sulphate         | 5.29-9.16       | Trisodium phosphate     | 4.53-7.85       |
| Coal, bituminous, sized    | 2.64-4.48       | Marble, crushed            | 6.8-12.44       | Walnut shells, crushed  | 2.65-5.24       |
| Coal, ground               | 2.90            | Mica, ground               | 1.24-1.43       | Wood chips, fir         | 2.49-2.88       |
| Cocoa, powdered            | 3.93-4.58       | Milk, whole, powdered      | 2.62            | Zinc sulphate           | 8.85-11.12      |
| Coconut, shredded          | 2.62-2.88       | Oats                       | 1.74-2.86       | ...                     | ...             |
| Coffee beans               | 2.42-5.89       | Orange peel, dry           | 1.96            | ...                     | ...             |

**Earth or Soil Weight.**—Loose earth has a weight of approximately 75 pounds per cubic foot and rammed earth, 100 pounds per cubic foot. The solid crust of the earth, according to an estimate, is composed approximately of the following elements:

Oxygen, 44.0 to 48.7 per cent; silicon, 22.8 to 36.2 per cent; aluminum, 6.1 to 9.9 per cent; iron, 2.4 to 9.9 per cent; calcium, 0.9 to 6.6 per cent; magnesium, 0.1 to 2.7 per cent; sodium, 2.4 to 2.5 per cent; potassium, 1.7 to 3.1 per cent.

**Molecular Weight.**—The smallest mass of a chemical combination which can be conceived of as existing and yet preserving its chemical properties is known as a *molecule*. The molecular weight of a chemical compound is equal to the sum of the atomic weights of the atoms contained in the molecule, and are calculated from the atomic weights, when the symbol of the compound is known. The atomic weight of silver is 107.88; of nitrogen, 14.01; and of oxygen, 16; hence, the molecular weight of silver-nitrate, the chemical formula of which is  $\text{AgNO}_3$  equals  $107.88 + 14.01 + (3 \times 16) = 169.89$ .

**Mol.**—The term “mol” is used as a designation of quantity in electro-chemistry, and indicates the number of grams of a substance equal to its molecular weight. For example, one mol of silver-nitrate equals 169.89 grams, the molecular weight of silver-nitrate being 169.89.

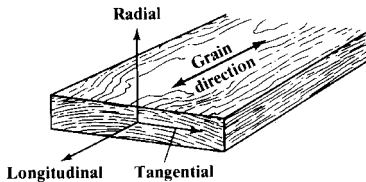
## PROPERTIES OF WOOD, CERAMICS, PLASTICS, METALS, WATER, AND AIR

### Properties of Wood

**Mechanical Properties of Wood.**—Wood is composed of cellulose, lignin, ash-forming minerals, and extractives formed into a cellular structure. (Extractives are substances that can be removed from wood by extraction with such solvents as water, alcohol, acetone, benzene, and ether.) Variations in the characteristics and volumes of the four components and differences in the cellular structure result in some woods being heavy and some light, some stiff and some flexible, and some hard and some soft. For a single species, the properties are relatively constant within limits; therefore, selection of wood by species alone may sometimes be adequate. However, to use wood most effectively in engineering applications, the effects of physical properties or specific characteristics must be considered.

The mechanical properties listed in the accompanying [Table 1](#) were obtained from tests on small pieces of wood termed “clear” and “straight grained” because they did not contain such characteristics as knots, cross grain, checks, and splits. However, these test pieces did contain such characteristics as growth rings that occur in consistent patterns within the piece. Since wood products may contain knots, cross grain, etc., these characteristics must be taken into account when assessing actual properties or when estimating actual performance. In addition, the methods of data collection and analysis have changed over the years during which the data in [Table 1](#) have been collected; therefore, the appropriateness of the data should be reviewed when used for critical applications such as stress grades of lumber.

Wood is an orthotropic material; that is, its mechanical properties are unique and independent in three mutually perpendicular directions—longitudinal, radial, and tangential. These directions are illustrated in the following figure.



**Modulus of Rupture:** The modulus of rupture in bending reflects the maximum load-carrying capacity of a member and is proportional to the maximum moment borne by the member. The modulus is an accepted criterion of strength, although it is not a true stress because the formula used to calculate it is valid only to the proportional limit.

**Work to Maximum Load in Bending:** The work to maximum load in bending represents the ability to absorb shock with some permanent deformation and more or less injury to a specimen; it is a measure of the combined strength and toughness of the wood under bending stress.

**Maximum Crushing Strength:** The maximum crushing strength is the maximum stress sustained by a compression parallel-to-grain specimen having a ratio of length to least diameter of less than 11.

**Compression Perpendicular to Grain:** Strength in compression perpendicular to grain is reported as the stress at the proportional limit because there is no clearly defined ultimate stress for this property.



**Shear Strength Parallel to Grain:** Shear strength is a measure of the ability to resist internal slipping of one part upon another along the grain. The values listed in the table are averages of the radial and tangential shears.

**Tensile Strength Perpendicular to Grain:** The tensile strength perpendicular to the grain is a measure of the resistance of wood to forces acting across the grain that tend to split the material. Averages of radial and tangential measurements are listed.

**Table 1. Mechanical Properties of Commercially Important U.S. Grown Woods**

| Use the first number in each column for GREEN wood; use the second number for DRY wood. | Static Bending                           |   |      |      | Maximum Crushing Strength (10 <sup>3</sup> psi) | Compression Strength Perpendicular to Grain (psi) | Shear Strength Parallel to Grain (psi) | Tensile Strength Perp. to Grain (psi) |     |       |     |     |
|---|--|---|------|------|---|---|--|---------------------------------------|-----|-------|-----|-----|
|   | Modulus of Rupture (10 <sup>3</sup> psi) | Work to Max Load (in.-lb/in. <sup>3</sup> ) |      |      |   |   |  |                                       |     |       |     |     |
| Basswood, American  | 5.0                                      | 8.7   | 5.3  | 7.2  | 2.22  | 4.73  | 170                                    | 370                                   | 600 | 990   | 280 | 350 |
| Cedar, N. white   | 4.2                                      | 6.5   | 5.7  | 4.8  | 1.90  | 3.96  | 230                                    | 310                                   | 620 | 850   | 240 | 240 |
| Cedar, W. red   | 5.2                                      | 7.5   | 5.0  | 5.8  | 2.77  | 4.56  | 240                                    | 460                                   | 770 | 990   | 230 | 220 |
| Douglas Fir, coast <sup>a</sup>   | 7.7                                      | 12.4  | 7.6  | 9.9  | 3.78  | 7.23  | 380                                    | 800                                   | 900 | 1,130 | 300 | 340 |
| Douglas Fir, interior W.  | 7.7                                      | 12.6  | 7.2  | 10.6 | 3.87  | 7.43  | 420                                    | 760                                   | 940 | 1,290 | 290 | 350 |
| Douglas Fir, interior N.  | 7.4                                      | 13.1  | 8.1  | 10.5 | 3.47  | 6.90  | 360                                    | 770                                   | 950 | 1,400 | 340 | 390 |
| Douglas Fir, interior S.  | 6.8                                      | 11.9  | 8.0  | 9.0  | 3.11  | 6.23  | 340                                    | 740                                   | 950 | 1,510 | 250 | 330 |
| Fir, balsam   | 5.5                                      | 9.2   | 4.7  | 5.1  | 2.63  | 5.28  | 190                                    | 404                                   | 662 | 944   | 180 | 180 |
| Hemlock, Eastern  | 6.4                                      | 8.9   | 6.7  | 6.8  | 3.08  | 5.41  | 360                                    | 650                                   | 850 | 1,060 | 230 | ... |
| Hemlock, Mountain   | 6.3                                      | 11.5  | 11.0 | 10.4 | 2.88  | 6.44  | 370                                    | 860                                   | 930 | 1,540 | 330 | ... |
| Hemlock, Western  | 6.6                                      | 11.3  | 6.9  | 8.3  | 3.36  | 7.20  | 280                                    | 550                                   | 860 | 1,290 | 290 | 340 |
| Pine, E. white  | 4.9                                      | 9.9   | 5.2  | 8.3  | 2.44  | 5.66  | 220                                    | 580                                   | 680 | 1,170 | 250 | 420 |
| Pine, Virginia  | 7.3                                      | 13.0  | 10.9 | 13.7 | 3.42  | 6.71  | 390                                    | 910                                   | 890 | 1,350 | 400 | 380 |
| Pine, W. white  | 4.7                                      | 9.7   | 5.0  | 8.8  | 2.43  | 5.04  | 190                                    | 470                                   | 680 | 1,040 | 260 | ... |
| Redwood, old-growth   | 7.5                                      | 10.0  | 7.4  | 6.9  | 4.20  | 6.15  | 420                                    | 700                                   | 800 | 940   | 260 | 240 |
| Redwood, young-growth   | 5.9                                      | 7.9   | 5.7  | 5.2  | 3.11  | 5.22  | 270                                    | 520                                   | 890 | 1,110 | 300 | 250 |
| Spruce, Engelmann   | 4.7                                      | 9.3   | 5.1  | 6.4  | 2.18  | 4.48  | 200                                    | 410                                   | 640 | 1,200 | 240 | 350 |
| Spruce, red   | 6.0                                      | 10.8  | 6.9  | 8.4  | 2.72  | 5.54  | 260                                    | 550                                   | 750 | 1,290 | 220 | 350 |
| Spruce, white   | 5.0                                      | 9.4   | 6.0  | 7.7  | 2.35  | 5.18  | 210                                    | 430                                   | 640 | 970   | 220 | 360 |

<sup>a</sup> Coast: grows west of the summit of the Cascade Mountains in OR and WA. Interior west: grows in CA and all counties in OR and WA east of but adjacent to the Cascade summit. Interior north: grows in remainder of OR and WA and ID, MT, and WY. Interior south: grows in UT, CO, AZ, and NM.

Results of tests on small, clear, straight-grained specimens. Data for dry specimens are from tests of seasoned material adjusted to a moisture content of 12%.


Source: U.S. Department of Agriculture: *Wood Handbook*.

**Weight of Wood.**—The weight of seasoned wood per cord is approximately as follows, assuming about 70 cubic feet of *solid wood* per cord: beech, 3300 pounds; chestnut, 2600 pounds; elm, 2900 pounds; maple, 3100 pounds; poplar, 2200 pounds; white pine, 2200 pounds; red oak, 3300 pounds; white oak, 3500 pounds. For additional weights of green and dry woods, see [Table 2](#).

**Weight per Foot of Wood, Board Measure.**—The following is the weight in pounds of various kinds of woods, commercially known as dry timber, per foot board measure: white oak, 4.16; white pine, 1.98; Douglas fir, 2.65; short leaf yellow pine, 2.65; red pine, 2.60; hemlock, 2.08; spruce, 2.08; cypress, 2.39; cedar, 1.93; chestnut, 3.43; Georgia yellow pine, 3.17; California spruce, 2.08. For other woods, divide the weight/ft<sup>3</sup> from [Table 2](#) by 12 to obtain the approximate weight per board foot.

**Effect of Pressure Treatment on Mechanical Properties of Wood.**—The strength of wood preserved with creosote, coal-tar, creosote-coal-tar mixtures, creosote-petroleum mixtures, or pentachlorophenol dissolved in petroleum oil is not reduced. However, water-borne salt preservatives contain chemicals such as copper, arsenic, chromium, and ammonia, which have the potential of affecting mechanical properties of treated wood and

causing mechanical fasteners to corrode. Preservative salt-retention levels required for marine protection may reduce bending strength by 10 per cent or more.

**Density of Wood.**—The following formula can be used to find the density of wood in lb/ft<sup>3</sup> as a function of its moisture content. 

$$\rho = 62.4 \left( \frac{G}{1 + G \times 0.009 \times M} \right) \left( 1 + \frac{M}{100} \right)$$

where  $\rho$  is the density,  $G$  is the specific gravity of wood, and  $M$  is the moisture content expressed in per cent.

**Table 2. Weights of American Woods, in Pounds per Cubic Foot**

| Species                    | Green | Airdry | Species                       | Green | Airdry | Species                 | Green | Airdry |
|----------------------------|-------|--------|-------------------------------|-------|--------|-------------------------|-------|--------|
|                            |       |        |                               |       |        |                         |       |        |
| Alder, red                 | 46    | 28     | Douglas fir, Rocky Mt. region | 35    | 30     | Oak, red                | 64    | 44     |
| Ash, black                 | 52    | 34     | Elm, American                 | 54    | 35     | Oak, white              | 63    | 47     |
| Ash, commercial white      | 48    | 41     | Elm, rock                     | 53    | 44     | Pine, lodgepole         | 39    | 29     |
| Ash, Oregon                | 46    | 38     | Elm, slippery                 | 56    | 37     | Pine, northern white    | 36    | 25     |
| Aspen                      | 43    | 26     | Fir, balsam                   | 45    | 25     | Pine, Norway            | 42    | 34     |
| Basswood                   | 42    | 26     | Fir, commercial white         | 46    | 27     | Pine, ponderosa         | 45    | 28     |
| Beech                      | 54    | 45     | Gum, black                    | 45    | 35     | Pines, southern yellow: |       |        |
| Birch                      | 57    | 44     | Gum, red                      | 50    | 34     | Pine, loblolly          | 53    | 36     |
| Birch, paper               | 50    | 38     | Hemlock, eastern              | 50    | 28     | Pine, longleaf          | 55    | 41     |
| Cedar, Alaska              | 36    | 31     | Hemlock, western              | 41    | 29     | Pine, shortleaf         | 52    | 36     |
| Cedar, eastern red         | 37    | 33     | Hickory, pecan                | 62    | 45     | Pine, sugar             | 52    | 25     |
| Cedar, northern white      | 28    | 22     | Hickory, true                 | 63    | 51     | Pine, western white     | 35    | 27     |
| Cedar, southern white      | 26    | 23     | Honeylocust                   | 61    | ...    | Poplar, yellow          | 38    | 28     |
| Cedar, western red         | 27    | 23     | Larch, western                | 48    | 36     | Redwood                 | 50    | 28     |
| Cherry, black              | 45    | 35     | Locust, black                 | 58    | 48     | Spruce, eastern         | 34    | 28     |
| Chestnut                   | 55    | 30     | Maple, bigleaf                | 47    | 34     | Spruce, Engelmann       | 39    | 23     |
| Cottonwood, eastern        | 49    | 28     | Maple, black                  | 54    | 40     | Spruce, Sitka           | 33    | 28     |
| Cottonwood, northern black | 46    | 24     | Maple, red                    | 50    | 38     | Sycamore                | 52    | 34     |
| Cypress, southern          | 51    | 32     | Maple, silver                 | 45    | 33     | Tamarack                | 47    | 37     |
| Douglas fir, coast region  | 38    | 34     | Maple, sugar                  | 56    | 44     | Walnut, black           | 58    | 38     |

Source: United States Department of Agriculture

**Machinability of Wood.**—The ease of working wood with hand tools generally varies directly with the specific gravity of the wood; the lower the specific gravity, the easier the wood is to cut with a sharp tool. A rough idea of the specific gravity of various woods can be obtained from the preceding table by dividing the weight of wood in lb/ft<sup>3</sup> by 62.355.

A wood species that is easy to cut does not necessarily develop a smooth surface when it is machined. Three major factors, other than specific gravity, influence the smoothness of the surface obtained by machining: interlocked and variable grain, hard deposits in the grain, and reaction wood. Interlocked and variable grain is a characteristic of many tropical and some domestic species; this type of grain structure causes difficulty in planing quarter sawn boards unless careful attention is paid to feed rates, cutting angles, and sharpness of the knives. Hard deposits of calcium carbonate, silica, and other minerals in the grain tend to dull cutting edges quickly, especially in wood that has been dried to the usual in service moisture content. Reaction wood results from growth under some physical stress such as occurs in leaning trunks and crooked branches. Generally, reaction wood occurs as tension wood in hardwoods and as compression wood in softwoods. Tension wood is particularly troublesome, often resulting in fibrous and fuzzy surfaces, especially in woods of lower density. Reaction wood may also be responsible for pinching saw blades, resulting in burning and dulling of teeth.

The Table 3 rates the suitability of various domestic hardwoods for machining. The data for each species represent the percentage of pieces machined that successfully met the listed quality requirement for the processes. For example, 62 per cent of the black walnut

pieces planed came out perfect, but only 34 per cent of the pieces run on the shaper achieved good to excellent results.

**Table 3. Machinability and Related Properties of Various Domestic Hardwoods**

| Type of Wood   | Planing          | Shaping           | Turning           | Boring            | Mortising         | Sanding           |
|----------------|------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
|                | Quality Required |                   |                   |                   |                   |                   |
|                | Perfect          | Good to Excellent | Fair to Excellent | Good to Excellent | Fair to Excellent | Good to Excellent |
| Alder, red     | 61               | 20                | 88                | 64                | 52                | ...               |
| Ash            | 75               | 55                | 79                | 94                | 58                | 75                |
| Aspen          | 26               | 7                 | 65                | 78                | 60                | ...               |
| Basswood       | 64               | 10                | 68                | 76                | 51                | 17                |
| Beech          | 83               | 24                | 90                | 99                | 92                | 49                |
| Birch          | 63               | 57                | 80                | 97                | 97                | 34                |
| Birch, paper   | 47               | 22                | ...               | ...               | ...               | ...               |
| Cherry, black  | 80               | 80                | 88                | 100               | 100               | ...               |
| Chestnut       | 74               | 28                | 87                | 91                | 70                | 64                |
| Cottonwood     | 21               | 3                 | 70                | 70                | 52                | 19                |
| Elm, soft      | 33               | 13                | 65                | 94                | 75                | 66                |
| Hackberry      | 74               | 10                | 77                | 99                | 72                | ...               |
| Hickory        | 76               | 20                | 84                | 100               | 98                | 80                |
| Magnolia       | 65               | 27                | 79                | 71                | 32                | 37                |
| Maple, bigleaf | 52               | 56                | 8                 | 100               | 80                | ...               |
| Maple, hard    | 54               | 72                | 82                | 99                | 95                | 38                |
| Maple, soft    | 41               | 25                | 76                | 80                | 34                | 37                |
| Oak, red       | 91               | 28                | 84                | 99                | 95                | 81                |
| Oak, white     | 87               | 35                | 85                | 95                | 99                | 83                |
| Pecan          | 88               | 40                | 89                | 100               | 98                | ...               |
| Sweetgum       | 51               | 28                | 86                | 92                | 53                | 23                |
| Sycamore       | 22               | 12                | 85                | 98                | 96                | 21                |
| Tanoak         | 80               | 39                | 81                | 100               | 100               | ...               |
| Tupelo, black  | 48               | 32                | 75                | 82                | 24                | 21                |
| Tupelo, water  | 55               | 52                | 79                | 62                | 33                | 34                |
| Walnut, black  | 62               | 34                | 91                | 100               | 98                | ...               |
| Willow         | 52               | 5                 | 58                | 71                | 24                | 24                |
| Yellow-poplar  | 70               | 13                | 81                | 87                | 63                | 19                |

The data above represent the percentage of pieces attempted that meet the quality requirement listed.

### Nominal and Minimum Sizes of Sawn Lumber

| Type of Lumber   | Thickness (inches) |                |                     | Face Widths (inches) |                     |                      |
|------------------|--------------------|----------------|---------------------|----------------------|---------------------|----------------------|
|                  | Nominal, $T_n$     | Dry            | Green               | Nominal, $W_n$       | Dry                 | Green                |
| Boards           | 1                  | $\frac{3}{4}$  | $\frac{25}{32}$     | 2 to 4               | $W_n - \frac{1}{2}$ | $W_n - \frac{7}{16}$ |
|                  | $1\frac{1}{4}$     | 1              | $1\frac{1}{32}$     | 5 to 7               | $W_n - \frac{1}{2}$ | $W_n - \frac{3}{8}$  |
|                  | $1\frac{1}{2}$     | $1\frac{1}{4}$ | $1\frac{9}{32}$     | 8 to 16              | $W_n - \frac{3}{4}$ | $W_n - \frac{1}{2}$  |
| Dimension Lumber | 2                  | $1\frac{1}{2}$ | $1\frac{9}{16}$     | 2 to 4               | $W_n - \frac{1}{2}$ | $W_n - \frac{7}{16}$ |
|                  | $2\frac{1}{2}$     | 2              | $2\frac{1}{16}$     | 5 to 6               | $W_n - \frac{1}{2}$ | $W_n - \frac{3}{8}$  |
|                  | 3                  | $2\frac{1}{2}$ | $2\frac{9}{16}$     | 8 to 16              | $W_n - \frac{3}{4}$ | $W_n - \frac{1}{2}$  |
|                  | $3\frac{1}{2}$     | 3              | $3\frac{1}{16}$     | ...                  | ...                 | ...                  |
|                  | 4                  | $3\frac{1}{2}$ | $3\frac{9}{16}$     | ...                  | ...                 | ...                  |
| Timbers          | $4\frac{1}{2}$     | 4              | $4\frac{1}{16}$     | ...                  | ...                 | ...                  |
|                  | 5 and up           | ...            | $T_n - \frac{1}{2}$ | 5 and up             | ...                 | $W_n - \frac{1}{2}$  |

Source: National Forest Products Association: *Design Values for Wood Construction*. Moisture content: dry lumber  $\leq 19\%$ ; green lumber  $> 19\%$ . Dimension lumber refers to lumber 2 to 4 inches thick (nominal) and 2 inches or greater in width. Timbers refers to lumber of approximately square cross-section,  $5 \times 5$  inches or larger, and a width no more than 2 inches greater than the thickness.

## Tabulated Properties of Ceramics, Plastics, and Metals

## Typical Properties of Ceramics Materials

| Material  | Density <sup>a</sup><br>(lb/in. <sup>3</sup> ) | Dielectric<br>Strength<br>(V/mil) | Coeff. of<br>Expansion <sup>b</sup><br>(10 <sup>-6</sup> in./in.-°F) | Flexural<br>Strength<br>(10 <sup>3</sup> psi) | Mohs's<br>Hardness <sup>c</sup> | Operating<br>Temperature<br>(°F) | Tensile<br>Strength<br>(10 <sup>3</sup> psi) | Compressive<br>Strength<br>(10 <sup>3</sup> psi) | Thermal<br>Conductivity <sup>d</sup><br>(Btu-ft-hr-ft <sup>-2</sup> -°F) |           |
|---|--|-----------------------------------|--|---|---------------------------------|----------------------------------|--|--|--|-----------|
| Machinable Glass Ceramic  | 0.09   | 1000                              | 4.1-7.0  |   | 48 Ra                           | 1472                             | ...  | 50   | 0.85   |           |
|   | 0.11   | 400                               | 6  | 15  | 5.5                             | 700                              | ...  | 40   | 0.24   |           |
|   | 0.10   | 380                               | 5.2  | 14  | 5.0                             | 1100                             | ...  | 32   | 0.34   |           |
| Glass-Mica  | 0.09-0.10                                      | 400                               | 10.5-11.2  | 12.5-13                                       | 90 Rh                           | 750                              | 6  | 40-45  | 0.24-0.29  |           |
|   | 0.10   | 380                               | 9.4  | 11  | 90 Rh                           | 1100                             | 5  | 32   | 0.34   |           |
|   | 0.13-0.17                                      | 300-325                           | 11-11.5  | 9-10  | 90 Rh                           | 700-750                          | 6-6.5  | 33-35  | 0.29-0.31  |           |
| Aluminum Silicate   | 0.14   | 350                               | 10.3   | 9   | 90 Rh                           | 1300                             | 6  | 30   | 0.3  |           |
|   | 0.10   | 80                                | 2.5  | 4.5   | 1-2                             | 1000                             | ...  | 12   | 0.92   |           |
| Alumina Silicate  | 0.08   | 100                               | 2.9  | 10  | 6.0                             | 2100                             | ...  | 25   | 0.75   |           |
|   | 0.08   | 70                                | ...  | ...   | ...                             | 2370                             | ...  | ...  | 0.38   |           |
| Silica Foam   | 0.03   | 80                                | 0.3  | 0.4   | NA                              | 2000                             | ...  | 1.4  | 0.10   |           |
| TiO <sub>2</sub> (Titania)  | 0.14   | 100                               | 4.61   | 20  | 8                               | 1800                             | 7.5  | 100  | ...  |           |
| Lava (Grade A)  | 0.08   | 80                                | 1.83   | 9   | 6                               | 2000                             | 2.5  | 40   | 0.92   |           |
| Zirconium Phosphate   | 0.11   | NA                                | 0.5  | 7.5   | NA                              | 2800                             | ...  | 30   | 0.4 (approx.)  |           |
| ZrO <sub>2</sub>  | 0.21   | ...                               | 6.1  | 102   | 1300 V                          | ...                              | ...  | 261  | 1.69   |           |
| ZrO <sub>2</sub> -SiO <sub>2</sub> (Zircon)                             | 0.11   | 220                               | 1.94   | 16  | 7.5                             | 1825                             | 10   | 90   | ...  |           |
| 2MgO-SiO <sub>2</sub> (Forsterite)                                      | 0.11   | 240                               | 5.56   | 20  | 7.5                             | 1825                             | 10   | 85   | 4.58   |           |
| MgO-SiO <sub>2</sub> (Steatite)   | 0.09-0.10                                      | 210-240                           | 3.83-5.44  | 18-21   | 7.5                             | 1825                             | 8.5-10                                       | 80-90  | 3.17-3.42  |           |
| 2MgO-2Al <sub>2</sub> O <sub>3</sub> -5SiO <sub>2</sub><br>(Cordierite) | 0.06   | 60                                | 0.33   | 3.4   | 6.5                             | 2000                             | 2.5  | 18.5   | 1.00   |           |
|   | 0.08   | 100-172                           | 1.22-1.28  | 8-12  | 7-7.5                           | 2000                             | 3.5-3.7                                      | 30-40  | 1.00   |           |
|   | 0.09   | 200                               | 1.33   | 15  | 8                               | 2000                             | 4  | 50   | 1.83   |           |
| Al <sub>2</sub> O <sub>3</sub><br>(Alumina)                             | 94%  | 0.13                              | 210  | 3.33  | 44                              | 9                                | 2700   | 20   | 315  | 16.00     |
|   | 96%  | 0.13-0.14                         | 210  | 3.5-3.7                                       | 48-60                           | 9                                | 2600-2800                                    | 25   | 375  | 20.3-20.7 |
|   | 99.5%  | 0.14                              | 200  | 3.72  | 70                              | 9                                | 2700   | 28   | 380  | 21.25     |
|   | 99.9%  | 0.14                              | ...  | 3.75  | 72                              | 9                                | 2900   | ...  | 400  | ...       |

<sup>a</sup>Obtain specific gravity by dividing density in lb/in.<sup>3</sup> by 0.0361; for density in lb/ft<sup>3</sup>, multiply lb/in.<sup>3</sup> by 1728; for g/cm<sup>3</sup>, multiply density in lb/in.<sup>3</sup> by 27.68; for kg/m<sup>3</sup>, multiply density in lb/in.<sup>3</sup> by 27,679.9.

<sup>b</sup>To convert coefficient of expansion to 10<sup>-6</sup> in./in.-°C, multiply table value by 1.8.

<sup>c</sup>Mohs's Hardness scale is used unless otherwise indicated as follows: Ra and Rh for Rockwell A and H scales, respectively; V for Vickers hardness.

<sup>d</sup>To convert conductivity from Btu-ft/hr-ft<sup>2</sup>-°F to cal-cm/sec-cm<sup>2</sup>-°C, divide by 241.9.

## Typical Properties of Plastics Materials

| Material              | Density <sup>a</sup><br>(lb/in <sup>3</sup> ) | Specific Gravity | Dielectric Strength<br>(V/mil) | Coeff. of Expansion <sup>b</sup><br>(10 <sup>-6</sup> in/in-°F) | Tensile Modulus<br>(10 <sup>3</sup> psi) | Izod Impact<br>(ft-lb/in of notch) | Flexural Modulus<br>(ksi at 73°F) | % Elongation | Hardness <sup>c</sup> | Max. Operating Temp. (°F) |
|-----------------------|---|------------------|--------------------------------|---|--|------------------------------------|-----------------------------------|--------------|-----------------------|---------------------------|
| ABS, Extrusion Grade  | 0.038   | 1.05             | ...                            | 53.0  | 275                                      | 7                                  | 300                               | ...          | 105 Rr                | 200                       |
| ABS, High Impact      | 0.037   | 1.03             | ...                            | ...   | 200                                      | ...                                | 330                               | ...          | 105 Rr                | ...                       |
| Acetal, 20% Glass     | 0.056   | 1.55             | ...                            | ...   | 1000                                     | 0.9                                | 715                               | ...          | 94 Rm                 | ...                       |
| Acetal, Copolymer     | 0.051   | 1.41             | 380                            | 47.0  | 437                                      | 2                                  | 400                               | 13           | 94 Rm                 | ...                       |
| Acetyl, Homopolymer   | 0.051   | 1.41             | ...                            | 58.0  | 310                                      | ...                                | 320                               | ...          | 94 Rm                 | 200                       |
| Acrylic               | 0.043   | 1.19             | 500                            | 35.0  | 400                                      | 0.5                                | 400                               | 2.7          | 94 Rm                 | 180                       |
| Azdel                 | 0.043   | 1.19             | 500                            | 15.0  | 750                                      | 14                                 | 800                               | 2.1          | 94 Rm                 | 311                       |
| CPVC                  | 0.056   | 1.55             | ...                            | 34.0  | 400                                      | 3                                  | 400                               | 4            | ...                   | 212                       |
| Fiber Glass Sheet     | 0.067   | 1.87             | ...                            | 11.1  | ...                                      | 8                                  | 1                                 | ...          | 101 Rm                | 260                       |
| Nylon 6, 30% Glass    | 0.050   | 1.39             | ...                            | ...   | 1350                                     | 2.8                                | 1400                              | ...          | 119 Rr                | ...                       |
| Nylon 6, Cast         | 0.042   | 1.16             | 295                            | 45.0  | 380                                      | 1.4                                | 450                               | 20           | 100 Rr                | 210                       |
| Nylon 6/6, Cast       | 0.047   | 1.30             | ...                            | ...   | ...                                      | ...                                | ...                               | ...          | ...                   | ...                       |
| Nylon 6/6, Extruded   | 0.041   | 1.14             | 600                            | 45.0  | 390                                      | 1                                  | ...                               | 240          | 118 Rr                | 230                       |
| Nylon 60L, Cast       | 0.042   | 1.16             | ...                            | ...   | ...                                      | 2.2                                | ...                               | ...          | ...                   | ...                       |
| PET, unfilled         | 0.049   | 1.36             | 1300                           | 39.0  | 500                                      | 0.5                                | 400                               | 70           | ...                   | 230                       |
| PTFE (Teflon)         | 0.079   | 2.19             | 480                            | 50.0  | 225                                      | 3                                  | 80                                | 350          | ...                   | ...                       |
| PVC                   | 0.050   | 1.39             | 500                            | 29.5  | 550                                      | 0.8                                | 400                               | 31-40        | 110 Rr                | 170                       |
| PVDF                  | 0.064   | 1.77             | 260                            | 60.0  | 320                                      | 3                                  | 200                               | 80           | 100 Rr                | 180                       |
| Phenolics             | 0.050   | 1.38             | ...                            | 11.1  | ...                                      | 2.4                                | 1000                              | ...          | 100 Rm                | 248                       |
| Polycarbonate         | 0.043   | 1.19             | 380                            | 37.5  | 345                                      | 14                                 | 340                               | 110          | 74 Rm                 | 290                       |
| Polyetherimide        | 0.046   | 1.27             | 480                            | ...   | 430                                      | 1.1                                | 480                               | ...          | ...                   | ...                       |
| Polyethylene, HD      | 0.035   | 0.97             | 475                            | 20.0  | 156                                      | 6                                  | 160                               | 900          | ...                   | 180                       |
| Polyethylene, UHMW    | 0.034   | 0.94             | 710                            | 19.0  | 110                                      | No Break                           | 130                               | 450          | 64 Rr                 | 176                       |
| Polymethylpentene     | 0.030   | 0.83             | ...                            | ...   | 220                                      | ...                                | 2.5                               | ...          | ...                   | ...                       |
| Polymid, unfilled     | 0.051   | 1.41             | 560                            | ...   | 300                                      | 1.5                                | ...                               | ...          | ...                   | ...                       |
| Polyphenylene Sulfide | 0.047   | 1.30             | 380                            | ...   | ...                                      | 0.5                                | 550                               | ...          | ...                   | ...                       |
| Polypropylene         | 0.033   | 0.91             | 600                            | 96.0  | 155                                      | 0.75                               | 200                               | 120          | 92 Rr                 | 150                       |
| Polysulfone           | 0.045   | 1.25             | 425                            | 31.0  | 360                                      | 1.2                                | 390                               | 50           | 120 Rr                | 325                       |
| Polyurethane          | 0.038   | 1.05             | ...                            | ...   | ...                                      | ...                                | ...                               | 465-520      | ...                   | ...                       |

<sup>a</sup> To obtain specific gravity, divide density in lb/in<sup>3</sup> by 0.0361; for density in lb/ft<sup>3</sup>, multiply lb/in<sup>3</sup> by 1728; for g/cm<sup>3</sup>, multiply density in lb/in<sup>3</sup> by 27.68; for kg/m<sup>3</sup>, multiply density in lb/in<sup>3</sup> by 27,679.9.

<sup>b</sup> To convert coefficient of expansion to 10<sup>-6</sup> in/in-°C, multiply table value by 1.8.

<sup>c</sup> Hardness value scales are as follows: Rm for Rockwell M scale; Rr for Rockwell R scale.

## Mechanical Properties of Various Investment Casting Alloys

| Alloy Designation                    | Material Condition | Tensile Strength (10 <sup>3</sup> psi) | 0.2% Yield Strength <sup>a</sup> (10 <sup>3</sup> psi) | % Elongation | Hardness    |
|--------------------------------------|--------------------|--|--|--------------|-------------|
| Aluminum                             |                    |  |  |              |             |
| 356                                  | As Cast            | 32-40                                  | 22-30  | 3-7          | ...         |
| A356                                 | As Cast            | 38-40                                  | 28-36  | 3-10         | ...         |
| A357                                 | As Cast            | 33-50                                  | 27-40  | 3-9          | ...         |
| 355, C355                            | As Cast            | 35-50                                  | 28-39  | 1-8          | ...         |
| D712 (40E)                           | As Cast            | 34-40                                  | 25-32  | 4-8          | ...         |
| A354                                 | As Cast            | 47-55                                  | 36-45  | 2-5          | ...         |
| RR-350                               | As Cast            | 32-45                                  | 24-38  | 1.5-5        | ...         |
| Precedent 71                         | As Cast            | 35-55                                  | 25-45  | 2-5          | ...         |
| KO-1                                 | As Cast            | 56-60                                  | 48-55  | 3-5          | ...         |
| Copper-Base Alloys <sup>a</sup>      |                    |  |  |              |             |
| Al Bronze C (954)                    | As Cast            | 75-85                                  | 30-40  | 10-20        | 80-85 Rb    |
|                                      | Heat-Treated       | 90-105                                 | 45-55  | 6-10         | 91-96 Rb    |
| Al Bronze D (955)                    | As Cast            | 90-100                                 | 40-50  | 6-10         | 91-96 Rb    |
|                                      | Heat-Treated       | 110-120                                | 60-70  | 5-8          | 93-98 Rb    |
| Manganese Bronze, A                  | ...                | 65-75                                  | 25-40  | 16-24        | 60-65 Rb    |
| Manganese Bronze, C                  | ...                | 110-120                                | 60-70  | 8-16         | 95-100 Rb   |
| Silicon Bronze                       | ...                | 45                                     | 18   | 20           | ...         |
| Tin Bronze                           | ...                | 40-50                                  | 18-30  | 20-35        | 40-50 Rb    |
| Lead. Yellow Brass (854)             | ...                | 30-50                                  | 11-20  | 15-25        | ...         |
| Red Brass                            | ...                | 30-40                                  | 14-25  | 20-30        | 30-35 Rb    |
| Silicon Brass                        | ...                | 70                                     | 32   | 24           | ...         |
| Pure Copper                          | ...                | 20-30                                  | ...  | 4-50         | 35-42 Rb    |
| Beryllium Cu 10C (820)               | As Cast            | 45-50                                  | 40-45  | 15-20        | 50-55 Rb    |
|                                      | Hardened           | 90-100                                 | 90-130   | 3-8          | 90-95 Rb    |
| Beryllium Cu 165C (824)              | ...                | 70-155                                 | 40-140   | 1-15         | 60 Rb-38 Rc |
| Beryllium Cu 20C (825)               | As Cast            | 70-80                                  | 50-55  | 18-23        | 75-80 Rb    |
|                                      | Hardened           | 110-160                                | ...  | 1-4          | 25-44 Rc    |
| Beryllium Cu 275C (828)              | As Cast            | 80-90                                  | ...  | 15-20        | 80-85 Rb    |
| Chrome Copper                        | ...                | 33-50                                  | 20-40  | 20-30        | 70-78 Rb    |
| Carbon and Low-Alloy Steels and Iron |                    |  |  |              |             |
| IC 1010                              | Annealed           | 50-60                                  | 30-35  | 30-35        | 50-55 Rb    |
| IC 1020                              | Annealed           | 60-70                                  | 40-45  | 25-40        | 80 Rb       |
| IC 1030                              | Annealed           | 65-75                                  | 45-50  | 20-30        | 75 Rb       |
|                                      | Hardened           | 85-150                                 | 60-150   | 0-15         | 20-50 Rc    |
| IC 1035                              | Annealed           | 70-80                                  | 45-55  | 20-30        | 80 Rb       |
|                                      | Hardened           | 90-150                                 | 85-150   | 0-15         | 25-52 Rc    |
| IC 1045                              | Annealed           | 80-90                                  | 50-60  | 20-25        | 100 Rb      |
|                                      | Hardened           | 100-180                                | 90-180   | 0-10         | 25-57 Rc    |
| IC 1050                              | Annealed           | 90-110                                 | 50-65  | 20-25        | 100 Rb      |
|                                      | Hardened           | 125-180                                | 100-180  | 0-10         | 30-60 Rc    |
| IC 1060                              | Annealed           | 100-120                                | 55-70  | 5-10         | 25 Rc       |
|                                      | Hardened           | 120-200                                | 100-180  | 0-3          | 30-60 Rc    |
| IC 1090                              | Annealed           | 110-150                                | 70-80  | 12-20        | 30 Rc       |
|                                      | Hardened           | 130-180                                | 130-180  | 0-3          | 37-50 Rc    |
|                                      | Hardened           | 130-200                                | 110-180  | 5-10         | 30-58 Rc    |
| IC 2345                              | Hardened           | 130-200                                | 100-130  | 5-20         | 23-49 Rc    |
| IC 4130                              | Hardened           | 130-200                                | 100-155  | 5-20         | 29-57 Rc    |
| IC 4140                              | Hardened           | 140-200                                | 120-180  | 5-10         | 25-58 Rc    |
| IC 4330                              | Hardened           | 130-190                                | 100-175  | 5-20         | 25-48 Rc    |
| IC 4340                              | Hardened           | 130-200                                | 100-180  | 5-20         | 20-55 Rc    |
| IC 4620                              | Hardened           | 110-150                                | 90-130   | 10-20        | 20-32 Rc    |
| IC 6150, IC 8740                     | Hardened           | 140-200                                | 120-180  | 5-10         | 30-60 Rc    |
| IC 8620                              | Hardened           | 100-130                                | 80-110   | 10-20        | 20-45 Rc    |
| IC 8630                              | Hardened           | 120-170                                | 100-130  | 7-20         | 25-50 Rc    |
| IC 8640                              | Hardened           | 130-200                                | 100-180  | 5-20         | 30-60 Rc    |

## Mechanical Properties of Various Investment Casting Alloys (Continued)

| Alloy Designation                                | Material Condition | Tensile Strength (10 <sup>3</sup> psi) | 0.2% Yield Strength <sup>a</sup> (10 <sup>3</sup> psi) | % Elongation | Hardness    |
|--|--------------------|--|--|--------------|-------------|
| Carbon and Low-Alloy Steels and Iron (Continued) |                    |  |  |              |             |
| IC 8665  | Hardened           | 170-220                                | 140-200  | 0-10         | ...         |
| IC 8730  | Hardened           | 120-170                                | 110-150  | 7-20         | ...         |
| IC 52100   | Hardened           | 180-230                                | 140-180  | 1-7          | 30-65 Rc    |
| IC 1722AS  | Hardened           | 130-170                                | 100-140  | 6-12         | 25-48 Rc    |
| 1.2% Si Iron                                     | ...                | 50-60                                  | 37-43  | 30-35        | 55 Rb       |
| Ductile Iron, Ferritic                           | Annealed           | 60-80                                  | 40-50  | 18-24        | 143-200 Bhn |
| Ductile Iron, Pearlitic                          | Normalized         | 100-120                                | 70-80  | 3-10         | 243-303 Bhn |
| Hardenable Stainless Steel                       |                    |  |  |              |             |
| CA-15  | Hardened           | 95-200                                 | 75-160   | 5-12         | 94 Rb-45 Rc |
| IC 416   | Hardened           | 95-200                                 | 75-160   | 3-8          | 94 Rb-45 Rc |
| CA-40  | Hardened           | 200-225                                | 130-210  | 0-5          | 30-52 Rc    |
| IC 431   | Hardened           | 110-160                                | 75-105   | 5-20         | 20-40 Rc    |
| IC 17-4  | Hardened           | 150-190                                | 140-160  | 6-20         | 34-44 Rc    |
| Am-355   | Hardened           | 200-220                                | 150-165  | 6-12         | ...         |
| IC 15-5  | Hardened           | 135-170                                | 110-145  | 5-15         | 26-38 Rc    |
| CD-4M Cu   | Annealed           | 100-115                                | 75-85  | 20-30        | 94-100 Rb   |
|  | Hardened           | 135-145                                | 100-120  | 10-25        | 28-32 Rc    |
| Austenitic Stainless Steels                      |                    |  |  |              |             |
| CF-3, CF-3M, CF-8, CF-8M, IC 316F                | Annealed           | 70-85                                  | 40-50  | 35-50        | 90 Rb (max) |
| CF-8C  | Annealed           | 70-85                                  | 32-36  | 30-40        | 90 Rb (max) |
| CF-16F   | Annealed           | 65-75                                  | 30-35  | 35-45        | 90 Rb (max) |
| CF-20  | Annealed           | 65-75                                  | 30-45  | 35-60        | 90 Rb (max) |
| CH-20  | Annealed           | 70-80                                  | 30-40  | 30-45        | 90 Rb (max) |
| CN-7M  | Annealed           | 65-75                                  | 25-35  | 35-45        | 90 Rb (max) |
| IC 321, CK-20                                    | Annealed           | 65-75                                  | 30-40  | 35-45        | 90 Rb (max) |
| Nickel-Base Alloys                               |                    |  |  |              |             |
| Alloy B  | Annealed           | 75-85                                  | 50-60  | 8-12         | 90-100 Rb   |
| Alloy C  | As Cast            | 80-95                                  | 45-55  | 8-12         | 90-100 Rb   |
|  | Annealed           | 75-95                                  | 45-55  | 8-12         | 90 Rb-25 Rc |
| Alloy X <sup>b</sup>                             | AC to 24°C         | 63-70                                  | 41-45  | 10-15        | 85-96 Rb    |
|  | AC to 816°C        | 35-45                                  | ...  | 12-20        | ...         |
| Invar (Fe-Ni alloy)                              | As Cast            | 50-60                                  | 25-30  | 30-40        | 50-60 Rb    |
| In 600 (Inconel)                                 | As Cast            | 65-75                                  | 35-40  | 10-20        | 80-90 Rb    |
| In 625 (Inconel)                                 | Annealed           | 80-100                                 | 40-55  | 15-30        | 10-20 Rc    |
| Monel 410  | As Cast            | 65-75                                  | 32-38  | 25-35        | 65-75 Rb    |
| S Monel  | Annealed           | 100-110                                | 55-65  | 5-10         | 20-28 Rc    |
|  | Hardened           | 120-140                                | 85-100   | 0            | 32-38 Rc    |
| RH Monel   | As Cast            | 100-110                                | 60-80  | 10-20        | 20-30 Rc    |
| Monel E  | As Cast            | 65-80                                  | 33-40  | 25-35        | 67-78 Rb    |
| M-35 Monel                                       | As Cast            | 65-80                                  | 25-35  | 25-40        | 65-85 Rb    |
| Cobalt-Base Alloys                               |                    |  |  |              |             |
| Cobalt 21  | As Cast            | 95-130                                 | 65-95  | 8-20         | 24-32 Rc    |
| Cobalt 25  | As Cast            | 90-120                                 | 60-75  | 15-25        | 20-25 Rc    |
| Cobalt 31  | As Cast            | 105-130                                | 75-90  | 6-10         | 20-30 Rc    |
| Cobalt 36  | As Cast            | 90-105                                 | 60-70  | 15-20        | 30-36 Rc    |
| F75  | As Cast            | 95-110                                 | 70-80  | 8-15         | 25-34 Rc    |
| N-155  | Sol. Anneal        | 90-100                                 | 50-60  | 15-30        | 90-100 Rb   |

<sup>a</sup> For copper alloys, yield strength is determined by 0.5% extension under load or 0.2% offset method. A number in parentheses following a copper alloy indicates the UNS designation of that alloy (for example, Al Bronze C (954) identifies the alloy as UNS C95400).

<sup>b</sup> AC = air cooled to temperature indicated.

Source: Investment Casting Institute. Mechanical properties are average values of separately cast test bars, and are for reference only. Items marked ... indicates data are not available. Alloys identified by IC followed by an SAE designation number (IC 1010 steel, for example) are generally similar to the SAE material although properties and chemical composition may be different.

## Typical Properties of Compressed and Sintered Powdered Metal Alloys

| Alloy Number <sup>a</sup> and Nominal Composition (%) |                                   | Density (g/cc) | Hardness | Strength (10 <sup>3</sup> psi) |                  |       | % Elongation |
|---|-----------------------------------|----------------|----------|--------------------------------|------------------|-------|--------------|
|   |                                   |                |          | Transverse Rupture             | Ultimate Tensile | Yield |              |
| Copper Base   |                                   |                |          |                                |                  |       |              |
| ...   | 100Cu                             | 7.7-7.9        | 81-82 Rh | 54-68                          | 24-34            | ...   | 10-26        |
| CZP-3002  | 70Cu, 1.5Pb, Bal. Zn              | 8              | 75 Rh    | ...                            | 33.9             | ...   | 24           |
| CNZ-1818  | 63Cu, 17.5Ni, Bal. Zn             | 7.9            | 90 Rh    | 73                             | 34               | 20    | 11           |
| CTG-1004  | 10Sn, 4.4C, Bal. Cu               | 7              | 67 Rh    | 20                             | 9.4              | 6.5   | 6            |
| CTG-1001  | 10Sn, 1C, Bal. Cu                 | 6.5            | 45 Rh    | 25.8                           | 15.1             | 9.6   | 9.7          |
| Iron Base (Balance of composition, Fe)                |                                   |                |          |                                |                  |       |              |
| FC-2015   | 23.5Cu, 1.5C                      | 6.5            | 65 Rb    | 80                             | 52.4             | 48.5  | 0            |
| FC-0800   | 8Cu, 0.4C                         | 6.3-6.8        | 39-55 Rb | 75-100                         | 38-54            | 32-47 | 1 or less    |
| FX-2008   | 20Cu, 1C                          | 7.3            | 93 Rb    | 164.2                          | 72.3             | 57.7  | 2            |
| FN-0408   | 4Ni, 1-2Cu, 0.75C                 | 6.3-7          | 64-84 Rb | 70-107                         | 37-63            | 30-47 | 1-1.6        |
| F-0000  | 100Fe                             | 6.5            | 26 Rf    | 37.7                           | 15.7             | 11    | 5.7          |
| FN-0005   | 0.45C, 0.50 MnS                   | 6.4-6.8        | 66-78 Rf | 44-61                          | ...              | ...   | ...          |
| F-0000  | 0.02C, 0.45P                      | 6.6-7.2        | 35-50 Rb | 90-125                         | ...              | 29-38 | 3.9-5.5      |
| F-0008  | 0.6-0.9C                          | 6.2-7          | 50-70 Rb | 61-100                         | 35-57            | 30-40 | <0.5 to 1    |
| FC-0508   | 0.6-0.9C, 4-6Cu                   | 5.9-6.8        | 60-80 Rb | 100-145                        | 58-82            | 50-70 | <0.5 to 1    |
| FN-0405   | 4Ni, 0.5C                         | 6.6-7.0        | 73-82 Rb | 90-100                         | 47-50            | 38-40 | <1           |
| FN-0208   | 2Ni, 0.8C                         | 6.6-7.0        | 50-70 Rb | 70-108                         | 47-58            | 35-51 | <1           |
| FN-0205   | 2Ni, 0.5C                         | 6.6-7.0        | 51-61 Rb | 72-93                          | 35-45            | 27-31 | 2.0-2.5      |
| FN-0200   | 2Ni, 0.25C                        | 6.6            | 29 Rb    | 57.5                           | 25.8             | 19.0  | 1.3          |
| FC-0208   | 2Cu, 0.75C                        | 6.5-6.7        | 68-72 Rb | 95-107                         | 56-61            | 51-54 | up to 1      |
| FC-2008   | 20Cu, 1C                          | 6.2            | 45 Rb    | 79.5                           | 47.8             | 40.0  | 1.3          |
| ...   | 4Ni, 0.6C, 1.6Cu, 0.55Mo          | 7.0            | 92 Rb    | 190.0                          | 100.0            | 65.0  | 2.5          |
| FL-4605   | 1.8Ni, 0.6C, 1.6Cu, 0.55Mo        | 7.0            | 87 Rb    | 170.0                          | 80.0             | 55.0  | 2.5          |
| FL-4605   | 1.8Ni, 0.6C, 0.55Mo               | 7.0            | 80 Rb    | 150.0                          | ...              | ...   | ...          |
| SS-316L   | 17Cr, 13Ni, 2.2Mo, 0.9Si          | 6.5            | 65 Rb    | 94.0                           | 45.0             | 30.0  | 6.0          |
| ...   | 17Cr, 13Ni, 2.2Mo, 0.9Si, 15-20Cu | 7.3            | 66 Rb    | 108.6                          | 59.2             | 49.7  | 4.3          |
| SS-410  | 13Cr, 0.8Si, 0.8Mn                | 6.2            | 15 Rc    | 85.0                           | 66.7             | 56.9  | 0            |
| FL-4608   | 2Cu, 3.8Ni, 0.9C, 0.75Mo          | 6.8            | 24 Rc    | 107.3                          | 55.8             | 46.5  | 1.5          |
| SS-303N1  | 18Cr, 11Ni, 1Mn                   | 6.4            | 62 Rb    | 86.0                           | 39.0             | 32.0  | 0.5          |
| SS-304N1  | 19Cr, 10Ni, 1Mn                   | 6.4            | 61 Rb    | 112.0                          | 43.0             | 38.0  | 0.5          |
| Tungsten Base   |                                   |                |          |                                |                  |       |              |
| 90W, 6Ni, 4Cu   |                                   | 17.0           | 24 Rc    | ...                            | 110              | 80    | 6            |
| 90W, 7Ni, 3Cu   |                                   | 17.0           | 25 Rc    | ...                            | 120              | 88    | 10           |
| 92.5W, 5.25Ni, 2.25Cu                                 |                                   | 17.5           | 26 Rc    | ...                            | 114              | 84    | 7            |
| 92.5W, Bal. Ni, Fe, and Mo                            |                                   | 17.6           | 30 Rc    | ...                            | 120              | 90    | 4            |
| 93W, Bal. Ni, Fe, and Mo                              |                                   | 17.7           | 32 Rc    | ...                            | 125              | 95    | 4            |
| 95W, 3.5Ni, 1.5Cu                                     |                                   | 18.0           | 27 Rc    | ...                            | 110              | 85    | 7            |
| 95W, 3.5Ni, 1.5Fe                                     |                                   | 18.0           | 27 Rc    | ...                            | 120              | 90    | 7            |
| 97W, 2.1Ni, 0.9Fe                                     |                                   | 18.5           | 28 Rc    | ...                            | 123              | 85    | 5            |

<sup>a</sup> Copper- and iron-base alloy designations are Metal Powder Industries Federation (MPIF) alloy numbers.



**Typical Elastic Properties of Materials**

| Material                   | Modulus of Elasticity (10 <sup>6</sup> psi) | Shear Modulus (10 <sup>6</sup> psi) | Bulk Modulus (10 <sup>6</sup> psi) | Poisson's Ratio |
|----------------------------|---|-------------------------------------|------------------------------------|-----------------|
| Aluminum, var. alloys      | 9.9–10.3                                    | 3.7–3.9                             | 9.9–10.2                           | 0.330–0.334     |
| Aluminum, 6061-T6          | 10.2  | 3.8                                 | ...                                | 0.35            |
| Aluminum, 2024-T4          | 10.6  | 4.0                                 | ...                                | 0.32            |
| Beryllium copper           | 18  | 7                                   | ...                                | 0.29            |
| Brass, 70–30               | 15.9  | 6                                   | 15.7                               | 0.331           |
| Brass, cast                | 14.5  | 5.3                                 | 16.8                               | 0.357           |
| Bronze                     | 14.9  | 6.5                                 | ...                                | 0.14            |
| Copper                     | 15.6  | 5.8                                 | 17.9                               | 0.355           |
| Glass                      | 6.7   | 2.7                                 | ...                                | 0.24            |
| Glass ceramic (machinable) | 9.7   | 3.7                                 | ...                                | 0.29            |
| Inconel                    | 31  | 11                                  | ...                                | 0.27–0.38       |
| Iron, cast                 | 13.5–21.0                                   | 5.2–8.2                             | 8.4–15.5                           | 0.221–0.299     |
| Iron, ductile              | 23.8–25.2                                   | 9.1–9.6                             | ...                                | 0.26–0.31       |
| Iron, grey cast            | 14.5  | 6                                   | ...                                | 0.211           |
| Iron, malleable            | 23.6  | 9.3                                 | 17.2                               | 0.271           |
| Lead                       | 5.3   | 1.9                                 | ...                                | 0.43            |
| Magnesium                  | 6.5   | 2.4                                 | ...                                | 0.35            |
| Magnesium alloy            | 6.3   | 2.5                                 | 4.8                                | 0.281           |
| Molybdenum                 | 48  | 17                                  | ...                                | 0.307           |
| Monel metal                | 25  | 9.5                                 | 22.5                               | 0.315           |
| Nickel silver              | 18.5  | 7                                   | ...                                | 0.322           |
| Nickel steel               | 30  | 11.5                                | ...                                | 0.291           |
| Phosphor bronze            | 13.8  | 5.1                                 | 16.3                               | 0.359           |
| Stainless steel 18–8       | 27.6  | 10.6                                | 23.6                               | 0.305           |
| Steel, cast                | 28.5  | 11.3                                | 20.2                               | 0.265           |
| Steel, cold-rolled         | 29.5  | 11.5                                | 23.1                               | 0.287           |
| Steel, all others          | 28.6–30.0                                   | 11.0–11.9                           | 22.6–24.0                          | 0.283–0.292     |
| Titanium (99.0 Ti)         | 15–16                                       | 6.5                                 | ...                                | 0.24            |
| Titanium (Ti-8Al-1Mo-1V)   | 18  | 6.8                                 | ...                                | 0.32            |
| Zinc, cast alloys          | 10.9–12.4                                   | ...                                 | ...                                | 0.33            |
| Zinc, wrought alloys       | 6.2–14                                      | ...                                 | ...                                | 0.33            |
| Z-nickel                   | 30  | 11                                  | ...                                | 0.36            |

Data represent typical values, but material properties may vary widely, depending on exact composition, material condition, and processing. Symbol ... indicates no data available.

**Average Ultimate Strength of Common Materials other than Metals**  
(pounds per square inch)

| Material                      | Compression | Tension | Material                       | Compression | Tension |
|-------------------------------|-------------|---------|--------------------------------|-------------|---------|
| Bricks, best hard             | 12,000      | 400     | Concrete, Portland             | 1,000       | 200     |
| Bricks, light red             | 1,000       | 40      | Concrete, Portland, 1 year old | 2,000       | 400     |
| Brickwork, common             | 1,000       | 50      | Granite                        | 19,000      | 700     |
| Brickwork, best               | 2,000       | 300     | Limestone and sandstone        | 9,000       | 300     |
| Cement, Portland, 1 month old | 2,000       | 400     | Trap rock                      | 20,000      | 800     |
| Cement, Portland, 1 year old  | 3,000       | 500     | Slate                          | 14,000      | 500     |
|                               |             |         | Vulcanized fiber               | 39,000      | 13,000  |

## Minimum Tensile Strength of Spring Wire by Diameter

| Wire Dia. (in.) | Wire Type                                      |               |              |                      |            |                 |                |
|-----------------|--|---------------|--------------|----------------------|------------|-----------------|----------------|
|                 | Music Wire                                     | Hard-Drawn MB | Oil Temp. MB | Stainless Steel 18-8 | Cr-V Alloy | Phosphor Bronze | Chrome Silicon |
|                 | Minimum Tensile Strength (10 <sup>3</sup> psi) |               |              |                      |            |                 |                |
| 0.004           | 439  | ...           | ...          | 325                  | ...        | 140             | ...            |
| 0.008           | 399  | ...           | ...          | 325                  | ...        | 140             | ...            |
| 0.012           | 377  | ...           | ...          | 316                  | ...        | ...             | ...            |
| 0.020           | 350  | 283           | 288          | 300                  | ...        | ...             | ...            |
| 0.028           | 333  | 271           | 281          | 284                  | ...        | ...             | ...            |
| 0.032           | 327  | 265           | 275          | 278                  | 281        | ...             | 300            |
| 0.035           | 322  | 261           | 268          | 274                  | 276        | ...             | 298            |
| 0.041           | 314  | 255           | 261          | 270                  | 270        | 135             | 298            |
| 0.047           | 307  | 248           | 254          | 262                  | 263        | ...             | 292            |
| 0.054           | 301  | 243           | 248          | 258                  | 257        | ...             | 292            |
| 0.063           | 293  | 237           | 242          | 251                  | 251        | 130             | 290            |
| 0.072           | 287  | 232           | 236          | 245                  | 245        | ...             | 288            |
| 0.080           | 282  | 227           | 230          | 240                  | 240        | ...             | 285            |
| 0.092           | 275  | 220           | 225          | 233                  | 235        | ...             | 280            |
| 0.105           | 269  | 216           | 220          | 227                  | 229        | 125             | 275            |
| 0.120           | 263  | 210           | 215          | 221                  | 222        | ...             | 275            |
| 0.135           | 258  | 206           | 210          | 213                  | 219        | ...             | 270            |
| 0.148           | 253  | 203           | 205          | 207                  | 215        | ...             | 268            |
| 0.162           | 249  | 200           | 200          | 200                  | 212        | ...             | 162            |
| 0.177           | 245  | 195           | 195          | 195                  | 210        | ...             | 260            |
| 0.192           | 241  | 192           | 190          | 189                  | 206        | ...             | 260            |
| 0.207           | 238  | 190           | 185          | 185                  | 204        | ...             | 260            |
| 0.225           | 225  | 186           | 183          | 180                  | 200        | 120             | 255            |
| 0.250           | 220  | 182           | 180          | 174                  | 196        | ...             | 250            |
| 0.312           | ...  | 174           | 178          | 160                  | 189        | 110             | 245            |
| 0.375           | ...  | 167           | 175          | ...                  | 187        | ...             | 240            |
| 0.437           | ...  | 165           | 170          | ...                  | 186        | ...             | 235            |
| 0.500           | ...  | 156           | 165          | ...                  | 185        | 100             | 230            |

For allowable working stresses and recommended design stresses in bending, related to severity of service, refer to Fig. 1 through Fig. 10 on pages 314 through 317, and for endurance limits for compression springs made from these materials refer to Fig. 11 on page 319 in the section on spring stresses.

**Effect of Temperature on Strength and Elasticity of Metals.**—Most ferrous metals have a maximum strength at approximately 400 degrees F, whereas the strength of nonferrous alloys is a maximum at about room temperature. The table on page 421 gives general data for variation in metal strength with temperature.

The modulus of elasticity of metals decreases regularly with increasing temperatures above room temperature until at some elevated temperature it falls off rapidly and reaches zero at the melting point.

## Influence of Temperature on the Strength of Metals

| Material         | Degrees Fahrenheit                               |     |     |     |     |      |      |      |
|------------------|--|-----|-----|-----|-----|------|------|------|
|                  | 210  | 400 | 570 | 750 | 930 | 1100 | 1300 | 1475 |
|                  | Strength in Per Cent of Strength at 70 Degrees F |     |     |     |     |      |      |      |
| Wrought iron     | 104  | 112 | 116 | 96  | 76  | 42   | 25   | 15   |
| Cast iron        | ...  | 100 | 99  | 92  | 76  | 42   | ...  | ...  |
| Steel castings   | 109  | 125 | 121 | 97  | 57  | ...  | ...  | ...  |
| Structural steel | 103  | 132 | 122 | 86  | 49  | 28   | ...  | ...  |
| Copper           | 95   | 85  | 73  | 59  | 42  | ...  | ...  | ...  |
| Bronze           | 101  | 94  | 57  | 26  | 18  | ...  | ...  | ...  |

**Pressure and Flow of Water**

**Water Pressure.**—Water is composed of two elements, hydrogen and oxygen, in the ratio of two volumes of hydrogen to one of oxygen. In the common system of measure, water boils under atmospheric pressure at 212 degrees F and freezes at 32 degrees F. Water's greatest density is 62.425 pounds per cubic foot, at 39.1 degrees F. In metric (SI) measure, water boils under atmospheric pressure at 100°C (Celsius) and freezes at 0°C. Its density is equal to 1 kilogram per liter, where 1 liter is 1 cubic decimeter. Also in metric SI, pressure is given in pascals (Pa) or the equivalent newtons per square meter. See page 2544 for additional information on the metric (SI) system of units.

For higher temperatures, the pressure slightly decreases in the proportion indicated by the table *Density of Water at Different Temperatures*. The pressure per square inch is equal in all directions, downwards, upwards, and sideways. Water can be compressed only to a very slight degree, the compressibility being so slight that even at the depth of a mile, a cubic foot of water weighs only about one-half pound more than at the surface.

**Pressure in Pounds per Square Inch for Different Heads of Water**

| Head, ft | 0     | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     |
|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0        | ...   | 0.43  | 0.87  | 1.30  | 1.73  | 2.16  | 2.60  | 3.03  | 3.46  | 3.90  |
| 10       | 4.33  | 4.76  | 5.20  | 5.63  | 6.06  | 6.49  | 6.93  | 7.36  | 7.79  | 8.23  |
| 20       | 8.66  | 9.09  | 9.53  | 9.96  | 10.39 | 10.82 | 11.26 | 11.69 | 12.12 | 12.56 |
| 30       | 12.99 | 13.42 | 13.86 | 14.29 | 14.72 | 15.15 | 15.59 | 16.02 | 16.45 | 16.89 |
| 40       | 17.32 | 17.75 | 18.19 | 18.62 | 19.05 | 19.48 | 19.92 | 20.35 | 20.78 | 21.22 |
| 50       | 21.65 | 22.08 | 22.52 | 22.95 | 23.38 | 23.81 | 24.25 | 24.68 | 25.11 | 25.55 |
| 60       | 25.98 | 26.41 | 26.85 | 27.28 | 27.71 | 28.14 | 28.58 | 29.01 | 29.44 | 29.88 |
| 70       | 30.31 | 30.74 | 31.18 | 31.61 | 32.04 | 32.47 | 32.91 | 33.34 | 33.77 | 34.21 |
| 80       | 34.64 | 35.07 | 35.51 | 35.94 | 36.37 | 36.80 | 37.24 | 37.67 | 38.10 | 38.54 |
| 90       | 38.97 | 39.40 | 39.84 | 40.27 | 40.70 | 41.13 | 41.57 | 42.00 | 42.43 | 42.87 |

**Heads of Water in Feet Corresponding to Certain Pressures in Pounds per Square Inch**

| Pressure, lb/in <sup>2</sup> | 0     | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     |
|------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0                            | ...   | 2.3   | 4.6   | 6.9   | 9.2   | 11.5  | 13.9  | 16.2  | 18.5  | 20.8  |
| 10                           | 23.1  | 25.4  | 27.7  | 30.0  | 32.3  | 34.6  | 36.9  | 39.3  | 41.6  | 43.9  |
| 20                           | 46.2  | 48.5  | 50.8  | 53.1  | 55.4  | 57.7  | 60.0  | 62.4  | 64.7  | 67.0  |
| 30                           | 69.3  | 71.6  | 73.9  | 76.2  | 78.5  | 80.8  | 83.1  | 85.4  | 87.8  | 90.1  |
| 40                           | 92.4  | 94.7  | 97.0  | 99.3  | 101.6 | 103.9 | 106.2 | 108.5 | 110.8 | 113.2 |
| 50                           | 115.5 | 117.8 | 120.1 | 122.4 | 124.7 | 127.0 | 129.3 | 131.6 | 133.9 | 136.3 |
| 60                           | 138.6 | 140.9 | 143.2 | 145.5 | 147.8 | 150.1 | 152.4 | 154.7 | 157.0 | 159.3 |
| 70                           | 161.7 | 164.0 | 166.3 | 168.6 | 170.9 | 173.2 | 175.5 | 177.8 | 180.1 | 182.4 |
| 80                           | 184.8 | 187.1 | 189.4 | 191.7 | 194.0 | 196.3 | 198.6 | 200.9 | 203.2 | 205.5 |
| 90                           | 207.9 | 210.2 | 212.5 | 214.8 | 217.1 | 219.4 | 221.7 | 224.0 | 226.3 | 228.6 |

**Volumes of Water at Different Temperatures**

| Degrees F | Volume  | Degrees F | Volume  | Degrees F | Volume  | Degrees F | Volume  |
|-----------|---------|-----------|---------|-----------|---------|-----------|---------|
| 39.1      | 1.00000 | 86        | 1.00425 | 131       | 1.01423 | 176       | 1.02872 |
| 50        | 1.00025 | 95        | 1.00586 | 140       | 1.01678 | 185       | 1.03213 |
| 59        | 1.00083 | 104       | 1.00767 | 149       | 1.01951 | 194       | 1.03570 |
| 68        | 1.00171 | 113       | 1.00967 | 158       | 1.02241 | 203       | 1.03943 |
| 77        | 1.00286 | 122       | 1.01186 | 167       | 1.02548 | 212       | 1.04332 |

## Density of Water at Different Temperatures

| Temp. (°F) | Wt. per Cu Ft (lb/ft <sup>3</sup> ) | Temp. (°F) | Wt. per Cu Ft (lb/ft <sup>3</sup> ) | Temp. (°F) | Wt. per Cu Ft (lb/ft <sup>3</sup> ) | Temp. (°F) | Wt. per Cu Ft (lb/ft <sup>3</sup> ) | Temp. (°F) | Wt. per Cu Ft (lb/ft <sup>3</sup> ) | Temp. (°F) | Wt. per Cu Ft (lb/ft <sup>3</sup> ) |
|------------|-------------------------------------|------------|-------------------------------------|------------|-------------------------------------|------------|-------------------------------------|------------|-------------------------------------|------------|-------------------------------------|
| 32         | 62.42                               | 130        | 61.56                               | 220        | 59.63                               | 320        | 56.66                               | 420        | 52.6                                | 520        | 47.6                                |
| 40         | 62.42                               | 140        | 61.37                               | 230        | 59.37                               | 330        | 56.30                               | 430        | 52.2                                | 530        | 47.0                                |
| 50         | 62.41                               | 150        | 61.18                               | 240        | 59.11                               | 340        | 55.94                               | 440        | 51.7                                | 540        | 46.3                                |
| 60         | 62.37                               | 160        | 60.98                               | 250        | 58.83                               | 350        | 55.57                               | 450        | 51.2                                | 550        | 45.6                                |
| 70         | 62.31                               | 170        | 60.77                               | 260        | 58.55                               | 360        | 55.18                               | 460        | 50.7                                | 560        | 44.9                                |
| 80         | 62.23                               | 180        | 60.55                               | 270        | 58.26                               | 370        | 54.78                               | 470        | 50.2                                | 570        | 44.1                                |
| 90         | 62.13                               | 190        | 60.32                               | 280        | 57.96                               | 380        | 54.36                               | 480        | 49.7                                | 580        | 43.3                                |
| 100        | 62.02                               | 200        | 60.12                               | 290        | 57.65                               | 390        | 53.94                               | 490        | 49.2                                | 590        | 42.6                                |
| 110        | 61.89                               | 210        | 59.88                               | 300        | 57.33                               | 400        | 53.50                               | 500        | 48.7                                | 600        | 41.8                                |
| 120        | 61.74                               | 212        | 59.83                               | 310        | 57.00                               | 410        | 53.00                               | 510        | 48.1                                | ...        | ...                                 |

## Table of Horsepower due to Certain Head of Water

| Head in Feet | Horsepower | Head in Feet | Horsepower | Head in Feet | Horsepower | Head in Feet | Horsepower | Head in Feet | Horsepower |
|--------------|------------|--------------|------------|--------------|------------|--------------|------------|--------------|------------|
| 1            | 0.0016     | 170          | 0.274      | 340          | 0.547      | 520          | 0.837      | 1250         | 2.012      |
| 10           | 0.0161     | 180          | 0.290      | 350          | 0.563      | 540          | 0.869      | 1300         | 2.093      |
| 20           | 0.0322     | 190          | 0.306      | 360          | 0.580      | 560          | 0.901      | 1350         | 2.173      |
| 30           | 0.0483     | 200          | 0.322      | 370          | 0.596      | 580          | 0.934      | 1400         | 2.254      |
| 40           | 0.0644     | 210          | 0.338      | 380          | 0.612      | 600          | 0.966      | 1450         | 2.334      |
| 50           | 0.0805     | 220          | 0.354      | 390          | 0.628      | 650          | 1.046      | 1500         | 2.415      |
| 60           | 0.0966     | 230          | 0.370      | 400          | 0.644      | 700          | 1.127      | 1550         | 2.495      |
| 70           | 0.1127     | 240          | 0.386      | 410          | 0.660      | 750          | 1.207      | 1600         | 2.576      |
| 80           | 0.1288     | 250          | 0.402      | 420          | 0.676      | 800          | 1.288      | 1650         | 2.656      |
| 90           | 0.1449     | 260          | 0.418      | 430          | 0.692      | 850          | 1.368      | 1700         | 2.737      |
| 100          | 0.1610     | 270          | 0.435      | 440          | 0.708      | 900          | 1.449      | 1750         | 2.818      |
| 110          | 0.1771     | 280          | 0.451      | 450          | 0.724      | 950          | 1.529      | 1800         | 2.898      |
| 120          | 0.1932     | 290          | 0.467      | 460          | 0.740      | 1000         | 1.610      | 1850         | 2.978      |
| 130          | 0.2093     | 300          | 0.483      | 470          | 0.757      | 1050         | 1.690      | 1900         | 3.059      |
| 140          | 0.2254     | 310          | 0.499      | 480          | 0.773      | 1100         | 1.771      | 1950         | 3.139      |
| 150          | 0.2415     | 320          | 0.515      | 490          | 0.789      | 1150         | 1.851      | 2000         | 3.220      |
| 160          | 0.2576     | 330          | 0.531      | 500          | 0.805      | 1200         | 1.932      | 2100         | 3.381      |

The table gives the horsepower of 1 cubic foot of water per minute, and is based on an efficiency of 85 per cent.

**Flow of Water in Pipes.**—The quantity of water that will flow through a pipe depends primarily on the head but also on the diameter of the pipe, the character of the interior surface, and the number and shape of the bends. The head may be either the distance between the levels of the surface of water in a reservoir and the point of discharge, or it may be caused by mechanically applied pressure, as by pumping, when the head is calculated as the vertical distance corresponding to the pressure.

One pound per square inch is equal to 2.309 feet head, and a 1-foot head is equal to a pressure of 0.433 pound per square inch.

All formulas for finding the amount of water that will flow through a pipe in a given time are approximate. The formula that follows will give results within 5 or 10 per cent of actual flows, if applied to pipe lines carefully laid and in fair condition.

## FLOW OF WATER

$$V = C \sqrt{\frac{hD}{L + 54D}}$$

where  $V$  = approximate mean velocity in feet per second;  $C$  = coefficient from the accompanying table;  $D$  = diameter of pipe in feet;  $h$  = total head in feet; and,  $L$  = total length of pipe line in feet.

Values of Coefficient  $C$ 

| Dia. of Pipe |        | C  | Dia. of Pipe |        | C  | Dia. of Pipe |        | C  |
|--------------|--------|----|--------------|--------|----|--------------|--------|----|
| Feet         | Inches |    | Feet         | Inches |    | Feet         | Inches |    |
| 0.1          | 1.2    | 23 | 0.8          | 9.6    | 46 | 3.5          | 42     | 64 |
| 0.2          | 2.4    | 30 | 0.9          | 10.8   | 47 | 4.0          | 48     | 66 |
| 0.3          | 3.6    | 34 | 1.0          | 12.0   | 48 | 5.0          | 60     | 68 |
| 0.4          | 4.8    | 37 | 1.5          | 18.0   | 53 | 6.0          | 72     | 70 |
| 0.5          | 6.0    | 39 | 2.0          | 24.0   | 57 | 7.0          | 84     | 72 |
| 0.6          | 7.2    | 42 | 2.5          | 30.0   | 60 | 8.0          | 96     | 74 |
| 0.7          | 8.4    | 44 | 3.0          | 36.0   | 62 | 10.0         | 120    | 77 |

*Example:* A pipe line, 1 mile long, 12 inches in diameter, discharges water under a head of 100 feet. Find the velocity and quantity of discharge.

From the table, the coefficient  $C$  is found to be 48 for a pipe 1 foot in diameter, hence:

$$V = 48 \sqrt{\frac{100 \times 1}{5280 + 54 \times 1}} = 6.57 \text{ feet per second}$$

To find the discharge in cubic feet per second, multiply the velocity found by the area of cross-section of the pipe in square feet:

$$6.57 \times 0.7854 = 5.16 \text{ cubic feet per second}$$

The loss of head due to a bend in the pipe is most frequently given as the equivalent length of straight pipe, which would cause the same loss in head as the bend. Experiments show that a right-angle bend should have a radius of about three times the diameter of the pipe. Assuming this curvature, then, if  $d$  is the diameter of the pipe in inches and  $L$  is the length of straight pipe in feet that causes the same loss of head as the bend in the pipe, the following formula gives the equivalent length of straight pipe that should be added to simulate a right-angle bend:

$$L = 4d \div 3$$

Thus, the loss of head due to a right-angle bend in a 6-inch pipe would be equal to that in 8 feet of straight pipe. Experiments undertaken to determine the losses due to valves in pipe lines indicate that a fully open gate valve in a pipe causes a loss of head corresponding to the loss in a length of pipe equal to six diameters.

**Buoyancy.**—A body submerged in water or other fluid will lose in weight an amount equal to the weight of the fluid displaced by the body. This is known as the principle of Archimedes.

*Example, Weight of a Submerged Body:* To illustrate, suppose the upper surface of a 10-inch cube is 20 inches below the surface of the water. The total downward pressure on the upper side of this cube will equal the area of the top surface of the cube, in square inches, multiplied by the product of the depth, in inches, to which the surface is submerged and the weight of 1 cubic inch of water.

Thus, the

weight of 1 cubic inch of water: 0.03617 pounds

downward pressure:  $10 \times 10 \times 20 \times 0.03617 = 72.34$  pounds

upward pressure on the under side:  $10 \times 10 \times 30 \times 0.03617 = 108.51$  pounds

weight of the water displaced by the body:  $10 \times 10 \times 10 \times 0.03617 = 36.17$  pounds

upward pressure – downward pressure:  $108.51 - 72.34 = 36.17$  pounds

This excess of upward pressure explains why it is comparatively easy to lift a submerged stone or other body.

## Flow of Water Through Nozzles in Cubic Feet per Second

| Head in Feet, at Nozzle | Pressure, lb/in <sup>2</sup> | Theoretical Velocity, ft/s | Diameter of Nozzle, Inches |      |      |      |      |       |       |       |
|-------------------------|------------------------------|----------------------------|----------------------------|------|------|------|------|-------|-------|-------|
|                         |                              |                            | 1                          | 1.5  | 2    | 2.5  | 3    | 3.5   | 4     | 4.5   |
| 5                       | 2.17                         | 17.93                      | 0.10                       | 0.22 | 0.39 | 0.61 | 0.88 | 1.20  | 1.56  | 1.98  |
| 10                      | 4.33                         | 25.36                      | 0.14                       | 0.31 | 0.55 | 0.86 | 1.24 | 1.69  | 2.21  | 2.80  |
| 20                      | 8.66                         | 35.87                      | 0.20                       | 0.44 | 0.78 | 1.22 | 1.76 | 2.40  | 3.13  | 3.96  |
| 30                      | 12.99                        | 43.93                      | 0.24                       | 0.54 | 0.96 | 1.50 | 2.16 | 2.93  | 3.83  | 4.85  |
| 40                      | 17.32                        | 50.72                      | 0.28                       | 0.62 | 1.11 | 1.73 | 2.49 | 3.39  | 4.43  | 5.60  |
| 50                      | 21.65                        | 56.71                      | 0.31                       | 0.70 | 1.24 | 1.93 | 2.78 | 3.79  | 4.95  | 6.26  |
| 60                      | 25.99                        | 62.12                      | 0.34                       | 0.76 | 1.36 | 2.12 | 3.05 | 4.15  | 5.42  | 6.86  |
| 70                      | 30.32                        | 67.10                      | 0.37                       | 0.82 | 1.46 | 2.29 | 3.29 | 4.48  | 5.86  | 7.41  |
| 80                      | 34.65                        | 71.73                      | 0.39                       | 0.88 | 1.56 | 2.45 | 3.52 | 4.79  | 6.26  | 7.92  |
| 90                      | 38.98                        | 76.08                      | 0.41                       | 0.93 | 1.66 | 2.59 | 3.73 | 5.08  | 6.64  | 8.40  |
| 100                     | 43.31                        | 80.20                      | 0.44                       | 0.98 | 1.75 | 2.73 | 3.94 | 5.36  | 7.00  | 8.86  |
| 120                     | 51.97                        | 87.85                      | 0.48                       | 1.08 | 1.92 | 2.99 | 4.31 | 5.87  | 7.67  | 9.70  |
| 140                     | 60.63                        | 94.89                      | 0.52                       | 1.16 | 2.07 | 3.23 | 4.66 | 6.34  | 8.28  | 10.48 |
| 160                     | 69.29                        | 101.45                     | 0.55                       | 1.24 | 2.21 | 3.46 | 4.98 | 6.78  | 8.85  | 11.20 |
| 180                     | 77.96                        | 107.60                     | 0.59                       | 1.32 | 2.35 | 3.67 | 5.28 | 7.19  | 9.39  | 11.88 |
| 200                     | 86.62                        | 113.42                     | 0.62                       | 1.39 | 2.47 | 3.87 | 5.57 | 7.58  | 9.90  | 12.53 |
| 250                     | 108.27                       | 126.81                     | 0.69                       | 1.56 | 2.77 | 4.32 | 6.22 | 8.47  | 11.07 | 14.01 |
| 300                     | 129.93                       | 138.91                     | 0.76                       | 1.70 | 3.03 | 4.74 | 6.82 | 9.28  | 12.12 | 15.34 |
| 350                     | 151.58                       | 150.04                     | 0.82                       | 1.84 | 3.27 | 5.11 | 7.37 | 10.02 | 13.09 | 16.57 |
| 400                     | 173.24                       | 160.40                     | 0.87                       | 1.97 | 3.50 | 5.47 | 7.87 | 10.72 | 14.00 | 17.72 |
| 450                     | 194.89                       | 170.13                     | 0.93                       | 2.09 | 3.71 | 5.80 | 8.35 | 11.37 | 14.85 | 18.79 |
| 500                     | 216.54                       | 179.33                     | 0.98                       | 2.20 | 3.91 | 6.11 | 8.80 | 11.98 | 15.65 | 19.81 |

| Head in Feet, at Nozzle | Pressure, lb/in <sup>2</sup> | Theoretical Velocity, ft/s | Diameter of Nozzle, Inches |       |       |      |      |      |       |       |
|-------------------------|------------------------------|----------------------------|----------------------------|-------|-------|------|------|------|-------|-------|
|                         |                              |                            | 5                          | 6     | 7     | 8    | 9    | 10   | 11    | 12    |
| 5                       | 2.17                         | 17.93                      | 2.45                       | 3.52  | 4.79  | 6.3  | 7.9  | 9.8  | 11.8  | 14.1  |
| 10                      | 4.33                         | 25.36                      | 3.46                       | 4.98  | 6.78  | 8.9  | 11.2 | 13.8 | 16.7  | 19.9  |
| 20                      | 8.66                         | 35.87                      | 4.89                       | 7.04  | 9.59  | 12.5 | 15.8 | 19.6 | 23.7  | 28.2  |
| 30                      | 12.99                        | 43.93                      | 5.99                       | 8.63  | 11.74 | 15.3 | 19.4 | 24.0 | 29.0  | 34.5  |
| 40                      | 17.32                        | 50.72                      | 6.92                       | 9.96  | 13.56 | 17.7 | 22.4 | 27.7 | 33.5  | 39.8  |
| 50                      | 21.65                        | 56.71                      | 7.73                       | 11.13 | 15.16 | 19.8 | 25.1 | 30.9 | 37.4  | 44.5  |
| 60                      | 25.99                        | 62.12                      | 8.47                       | 12.20 | 16.60 | 21.7 | 27.4 | 33.9 | 41.0  | 48.8  |
| 70                      | 30.32                        | 67.10                      | 9.15                       | 13.18 | 17.93 | 23.4 | 29.6 | 36.6 | 44.3  | 52.7  |
| 80                      | 34.65                        | 71.73                      | 9.78                       | 14.08 | 19.17 | 25.0 | 31.7 | 39.1 | 47.3  | 56.3  |
| 90                      | 38.98                        | 76.08                      | 10.37                      | 14.94 | 20.33 | 26.6 | 33.6 | 41.5 | 50.2  | 59.8  |
| 100                     | 43.31                        | 80.20                      | 10.94                      | 15.75 | 21.43 | 28.0 | 35.4 | 43.7 | 52.9  | 63.0  |
| 120                     | 51.97                        | 87.85                      | 11.98                      | 17.25 | 23.48 | 30.7 | 38.8 | 47.9 | 58.0  | 69.0  |
| 140                     | 60.63                        | 94.89                      | 12.94                      | 18.63 | 25.36 | 33.1 | 41.9 | 51.8 | 62.6  | 74.5  |
| 160                     | 69.29                        | 101.45                     | 13.83                      | 19.92 | 27.11 | 35.4 | 44.8 | 55.3 | 66.9  | 79.7  |
| 180                     | 77.96                        | 107.60                     | 14.67                      | 21.13 | 28.76 | 37.6 | 47.5 | 58.7 | 71.0  | 84.5  |
| 200                     | 86.62                        | 113.42                     | 15.47                      | 22.27 | 30.31 | 39.6 | 50.1 | 61.9 | 74.9  | 89.1  |
| 250                     | 108.27                       | 126.81                     | 17.29                      | 24.90 | 33.89 | 44.3 | 56.0 | 69.2 | 83.7  | 99.6  |
| 300                     | 129.93                       | 138.91                     | 18.94                      | 27.27 | 37.12 | 48.5 | 61.4 | 75.8 | 91.7  | 109.1 |
| 350                     | 151.58                       | 150.04                     | 20.46                      | 29.46 | 40.10 | 52.4 | 66.3 | 81.8 | 99.0  | 117.8 |
| 400                     | 173.24                       | 160.40                     | 21.87                      | 31.49 | 42.87 | 56.0 | 70.9 | 87.5 | 105.9 | 126.0 |
| 450                     | 194.89                       | 170.13                     | 23.20                      | 33.40 | 45.47 | 59.4 | 75.2 | 92.8 | 112.3 | 133.6 |
| 500                     | 216.54                       | 179.33                     | 24.45                      | 35.21 | 47.93 | 62.6 | 79.2 | 97.8 | 118.4 | 140.8 |

FLOW OF WATER

**Theoretical Velocity of Water Due to Head in Feet**

| Head in Feet | Theoretical Velocity |        | Head in Feet | Theoretical Velocity |        | Head in Feet | Theoretical Velocity |        |
|--------------|----------------------|--------|--------------|----------------------|--------|--------------|----------------------|--------|
|              | ft/s                 | ft/min |              | ft/s                 | ft/min |              | ft/s                 | ft/min |
| 1            | 8.01                 | 481    | 48           | 55.56                | 3334   | 95           | 78.16                | 4690   |
| 2            | 11.34                | 681    | 49           | 56.13                | 3368   | 96           | 78.57                | 4715   |
| 3            | 13.89                | 833    | 50           | 56.70                | 3403   | 97           | 78.98                | 4739   |
| 4            | 16.04                | 962    | 51           | 57.27                | 3436   | 98           | 79.39                | 4764   |
| 5            | 17.93                | 1076   | 52           | 57.83                | 3470   | 99           | 79.79                | 4788   |
| 6            | 19.64                | 1179   | 53           | 58.38                | 3503   | 100          | 80.19                | 4812   |
| 7            | 21.21                | 1273   | 54           | 58.93                | 3536   | 105          | 82.18                | 4931   |
| 8            | 22.68                | 1361   | 55           | 59.47                | 3569   | 110          | 84.11                | 5047   |
| 9            | 24.05                | 1444   | 56           | 60.01                | 3601   | 115          | 86.00                | 5160   |
| 10           | 25.36                | 1522   | 57           | 60.54                | 3633   | 120          | 87.85                | 5271   |
| 11           | 26.59                | 1596   | 58           | 61.07                | 3665   | 125          | 89.66                | 5380   |
| 12           | 27.78                | 1667   | 59           | 61.60                | 3696   | 130          | 91.44                | 5487   |
| 13           | 28.91                | 1735   | 60           | 62.12                | 3727   | 135          | 93.18                | 5591   |
| 14           | 30.00                | 1800   | 61           | 62.63                | 3758   | 140          | 94.89                | 5694   |
| 15           | 31.06                | 1864   | 62           | 63.14                | 3789   | 145          | 96.57                | 5794   |
| 16           | 32.07                | 1925   | 63           | 63.65                | 3819   | 150          | 98.22                | 5893   |
| 17           | 33.06                | 1984   | 64           | 64.15                | 3850   | 155          | 99.84                | 5991   |
| 18           | 34.02                | 2042   | 65           | 64.65                | 3880   | 160          | 101.44               | 6087   |
| 19           | 34.95                | 2097   | 66           | 65.15                | 3909   | 165          | 103.01               | 6181   |
| 20           | 35.86                | 2152   | 67           | 65.64                | 3939   | 170          | 104.56               | 6274   |
| 21           | 36.75                | 2205   | 68           | 66.13                | 3968   | 175          | 106.09               | 6366   |
| 22           | 37.61                | 2257   | 69           | 66.61                | 3997   | 180          | 107.59               | 6456   |
| 23           | 38.46                | 2308   | 70           | 67.09                | 4026   | 185          | 109.08               | 6545   |
| 24           | 39.28                | 2357   | 71           | 67.57                | 4055   | 190          | 110.54               | 6633   |
| 25           | 40.09                | 2406   | 72           | 68.05                | 4083   | 195          | 111.99               | 6720   |
| 26           | 40.89                | 2454   | 73           | 68.52                | 4111   | 200          | 113.42               | 6805   |
| 27           | 41.67                | 2500   | 74           | 68.99                | 4139   | 205          | 114.82               | 6890   |
| 28           | 42.43                | 2546   | 75           | 69.45                | 4167   | 210          | 116.22               | 6973   |
| 29           | 43.18                | 2591   | 76           | 69.91                | 4195   | 215          | 117.59               | 7056   |
| 30           | 43.92                | 2636   | 77           | 70.37                | 4222   | 220          | 118.95               | 7137   |
| 31           | 44.65                | 2679   | 78           | 70.83                | 4250   | 225          | 120.30               | 7218   |
| 32           | 45.36                | 2722   | 79           | 71.28                | 4277   | 230          | 121.62               | 7298   |
| 33           | 46.07                | 2764   | 80           | 71.73                | 4304   | 235          | 122.94               | 7377   |
| 34           | 46.76                | 2806   | 81           | 72.17                | 4331   | 240          | 124.24               | 7455   |
| 35           | 47.44                | 2847   | 82           | 72.62                | 4357   | 245          | 125.53               | 7532   |
| 36           | 48.11                | 2887   | 83           | 73.06                | 4384   | 250          | 126.80               | 7608   |
| 37           | 48.78                | 2927   | 84           | 73.50                | 4410   | 255          | 128.06               | 7684   |
| 38           | 49.43                | 2966   | 85           | 73.94                | 4436   | 260          | 129.31               | 7759   |
| 39           | 50.08                | 3005   | 86           | 74.37                | 4462   | 270          | 131.78               | 7907   |
| 40           | 50.72                | 3043   | 87           | 74.80                | 4488   | 280          | 134.20               | 8052   |
| 41           | 51.35                | 3081   | 88           | 75.23                | 4514   | 290          | 136.57               | 8195   |
| 42           | 51.97                | 3119   | 89           | 75.66                | 4540   | 300          | 138.91               | 8335   |
| 43           | 52.59                | 3155   | 90           | 76.08                | 4565   | 310          | 141.20               | 8472   |
| 44           | 53.19                | 3192   | 91           | 76.50                | 4590   | 320          | 143.46               | 8608   |
| 45           | 53.79                | 3228   | 92           | 76.92                | 4615   | 330          | 145.69               | 8741   |
| 46           | 54.39                | 3264   | 93           | 77.34                | 4641   | 340          | 147.88               | 8873   |
| 47           | 54.98                | 3299   | 94           | 77.75                | 4665   | 350          | 150.04               | 9002   |

## Gallons of Water per Foot of Pipe

| Nominal Pipe Size (in.) | Iron or Steel |           | Copper |        |        |
|-------------------------|---------------|-----------|--------|--------|--------|
|                         | Sched. 40     | Sched. 80 | Type K | Type L | Type M |
| 1/8                     | 0.0030        | 0.0019    | 0.0014 | 0.0016 | 0.0016 |
| 1/4                     | 0.0054        | 0.0037    | 0.0039 | 0.0040 | 0.0043 |
| 3/8                     | 0.0099        | 0.0073    | 0.0066 | 0.0075 | 0.0083 |
| 1/2                     | 0.0158        | 0.0122    | 0.0113 | 0.0121 | 0.0132 |
| 5/8                     | ...           | ...       | 0.0173 | 0.0181 | 0.0194 |
| 3/4                     | 0.0277        | 0.0225    | 0.0226 | 0.0251 | 0.0268 |
| 1                       | 0.0449        | 0.0374    | 0.0404 | 0.0429 | 0.0454 |

Multiply the length of pipe in feet by the factor from the table to find the volume contained in gallons.

## Friction Loss in Fittings—Equivalent Length of Pipe in Feet

| Nominal Pipe Size (in.) | Elbows   |          |                 |            |            |               | Standard Tee  |                  |
|-------------------------|----------|----------|-----------------|------------|------------|---------------|---------------|------------------|
|                         | 90° Std. | 45° Std. | 90° Long Radius | 90° Street | 45° Street | Square Corner | Flow thru Run | Flow thru Branch |
| 1/4                     | 0.9      | 0.5      | 0.6             | 1.5        | 0.8        | 1.7           | 0.6           | 1.8              |
| 1/2                     | 1.6      | 0.8      | 1.0             | 2.6        | 1.3        | 3.0           | 1.0           | 4.0              |
| 3/4                     | 2.1      | 1.1      | 1.4             | 3.4        | 1.8        | 3.9           | 1.4           | 5.1              |
| 1                       | 2.6      | 1.4      | 1.7             | 4.4        | 2.3        | 5.0           | 1.7           | 6.0              |
| 1 1/4                   | 3.5      | 1.8      | 2.3             | 5.8        | 3.0        | 6.5           | 2.3           | 6.9              |
| 1 1/2                   | 4.0      | 2.1      | 2.7             | 6.7        | 3.5        | 7.6           | 2.7           | 8.1              |
| 2                       | 5.5      | 2.8      | 4.3             | 8.6        | 4.5        | 9.8           | 4.3           | 12.0             |
| 2 1/2                   | 6.2      | 3.3      | 5.1             | 10.3       | 5.4        | 11.7          | 5.1           | 14.3             |
| 3                       | 7.7      | 4.1      | 6.3             | 12.8       | 6.6        | 14.6          | 6.3           | 16.3             |
| 4                       | 10.1     | 5.4      | 8.3             | 16.8       | 8.7        | 19.1          | 8.3           | 22.1             |
| 6                       | 15.2     | 8.1      | 12.5            | 25.3       | 13.1       | 28.8          | 12.5          | 32.2             |
| 8                       | 20.0     | 10.6     | 16.5            | 33.3       | 17.3       | 37.9          | 16.5          | 39.9             |
| 10                      | 25.1     | 13.4     | 20.7            | 41.8       | 21.7       | 47.6          | 20.7          | 50.1             |
| 12                      | 29.8     | 15.9     | 24.7            | 49.7       | 25.9       | 56.7          | 24.7          | 59.7             |

**Pipe Expansion Due to Temperature Changes.**—The expansion for any length of pipe caused by a given temperature change can be determined from the following table. Find the expansion factor corresponding to the expected difference in the minimum and maximum pipe temperatures and divide by 100 to obtain the increase in length per foot of pipe. Multiply the increase per foot result by the length of the pipe run to get the total change in pipe length.

## Linear Expansion and Contraction Factors per 100 Feet of Pipe

| Temperature Change, °F | Pipe Material |        |      |      |           |
|------------------------|---------------|--------|------|------|-----------|
|                        | Steel         | Copper | PVC  | FRP  | PP & PVDF |
| 0                      | 0             | 0      | 0    | 0    | 0         |
| 20                     | 0.15          | 0.25   | 0.62 | 0.26 | 2.00      |
| 40                     | 0.30          | 0.45   | 1.30 | 0.52 | 4.00      |
| 60                     | 0.46          | 0.65   | 2.20 | 0.78 | 6.00      |
| 80                     | 0.61          | 0.87   | 2.80 | 1.05 | 8.00      |
| 100                    | 0.77          | 1.10   | 3.50 | 1.31 | 10.00     |
| 120                    | 0.92          | 1.35   | 4.25 | 1.57 | 12.00     |
| 140                    | 1.08          | 1.57   | 4.80 | 1.83 | 14.00     |
| 160                    | 1.24          | 1.77   | 5.50 | 2.09 | 16.00     |
| 180                    | 1.40          | 2.00   | 6.30 | 2.35 | 18.00     |
| 200                    | 1.57          | 2.25   | 7.12 | 2.62 | 20.00     |

Multiply the length of pipe by the table factor and divide by 100 for the increase or decrease in length.



## Properties, Compression, and Flow of Air

**Properties of Air.**—Air is a mechanical mixture composed of 78 per cent of nitrogen, 21 per cent of oxygen, and 1 per cent of argon, by volume. The density of dry air at 32 degrees F and atmospheric pressure (29.92 inches of mercury or 14.70 pounds per square inch) is 0.08073 pound per cubic foot. The density of air at any other temperature or pressure is

$$\rho = \frac{1.325 \times B}{T}$$

in which  $\rho$  = density in pounds per cubic foot;  $B$  = height of barometric pressure in inches of mercury;  $T$  = absolute temperature in degrees Rankine. (When using pounds as a unit, here and elsewhere, care must be exercised to differentiate between pounds mass and pounds force. See *Acceleration of Gravity  $g$  Used in Mechanics Formulas* on page 142 and *The Use of the Metric SI System in Mechanics Calculations* on page 142.)

## Volumes and Weights of Air at Different Temperatures, at Atmospheric Pressure

| Temperature, °F | Volume of 1 lb of Air in Cubic Feet | Density, Pounds per Cubic Foot | Temperature, °F | Volume of 1 lb of Air in Cubic Feet | Density, Pounds per Cubic Foot | Temperature, °F | Volume of 1 lb of Air in Cubic Feet | Density, Pounds per Cubic Foot |
|-----------------|-------------------------------------|--------------------------------|-----------------|-------------------------------------|--------------------------------|-----------------|-------------------------------------|--------------------------------|
| 0               | 11.57                               | 0.0864                         | 172             | 15.92                               | 0.0628                         | 800             | 31.75                               | 0.0315                         |
| 12              | 11.88                               | 0.0842                         | 182             | 16.18                               | 0.0618                         | 900             | 34.25                               | 0.0292                         |
| 22              | 12.14                               | 0.0824                         | 192             | 16.42                               | 0.0609                         | 1000            | 37.31                               | 0.0268                         |
| 32              | 12.39                               | 0.0807                         | 202             | 16.67                               | 0.0600                         | 1100            | 39.37                               | 0.0254                         |
| 42              | 12.64                               | 0.0791                         | 212             | 16.92                               | 0.0591                         | 1200            | 41.84                               | 0.0239                         |
| 52              | 12.89                               | 0.0776                         | 230             | 17.39                               | 0.0575                         | 1300            | 44.44                               | 0.0225                         |
| 62              | 13.14                               | 0.0761                         | 250             | 17.89                               | 0.0559                         | 1400            | 46.95                               | 0.0213                         |
| 72              | 13.39                               | 0.0747                         | 275             | 18.52                               | 0.0540                         | 1500            | 49.51                               | 0.0202                         |
| 82              | 13.64                               | 0.0733                         | 300             | 19.16                               | 0.0522                         | 1600            | 52.08                               | 0.0192                         |
| 92              | 13.89                               | 0.0720                         | 325             | 19.76                               | 0.0506                         | 1700            | 54.64                               | 0.0183                         |
| 102             | 14.14                               | 0.0707                         | 350             | 20.41                               | 0.0490                         | 1800            | 57.14                               | 0.0175                         |
| 112             | 14.41                               | 0.0694                         | 375             | 20.96                               | 0.0477                         | 2000            | 62.11                               | 0.0161                         |
| 122             | 14.66                               | 0.0682                         | 400             | 21.69                               | 0.0461                         | 2200            | 67.11                               | 0.0149                         |
| 132             | 14.90                               | 0.0671                         | 450             | 22.94                               | 0.0436                         | 2400            | 72.46                               | 0.0138                         |
| 142             | 15.17                               | 0.0659                         | 500             | 24.21                               | 0.0413                         | 2600            | 76.92                               | 0.0130                         |
| 152             | 15.41                               | 0.0649                         | 600             | 26.60                               | 0.0376                         | 2800            | 82.64                               | 0.0121                         |
| 162             | 15.67                               | 0.0638                         | 700             | 29.59                               | 0.0338                         | 3000            | 87.72                               | 0.0114                         |

The absolute zero from which all temperatures must be counted when dealing with the weight and volume of gases is assumed to be  $-459.7$  degrees F. Hence, to obtain the absolute temperature  $T$  used in preceding formula, add the value 459.7 to the temperature observed on a regular Fahrenheit thermometer.

In obtaining the value of  $B$ , 1 inch of mercury at 32 degrees F may be taken as equal to a pressure of 0.491 pound per square inch.

*Example 1:* What would be the weight of a cubic foot of air at atmospheric pressure (29.92 inches of mercury) at 100 degrees F? The weight,  $W$ , is given by  $W = \rho V$ .

$$W = \rho V = \frac{1.325 \times 29.92}{100 + 459.7} \times 1 = 0.0708 \text{ pound}$$

## Density of Air at Different Pressures and Temperatures

| Temp.<br>of Air,<br>°F | Gage Pressure, Pounds            |        |        |        |       |       |       |       |       |       |       |       |       |       |       |
|------------------------|----------------------------------|--------|--------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                        | 0                                | 5      | 10     | 20     | 30    | 40    | 50    | 60    | 80    | 100   | 120   | 150   | 200   | 250   | 300   |
|                        | Density in Pounds per Cubic Foot |        |        |        |       |       |       |       |       |       |       |       |       |       |       |
| -20                    | 0.0900                           | 0.1205 | 0.1515 | 0.2125 | 0.274 | 0.336 | 0.397 | 0.458 | 0.580 | 0.702 | 0.825 | 1.010 | 1.318 | 1.625 | 1.930 |
| -10                    | 0.0882                           | 0.1184 | 0.1485 | 0.2090 | 0.268 | 0.328 | 0.388 | 0.448 | 0.567 | 0.687 | 0.807 | 0.989 | 1.288 | 1.588 | 1.890 |
| 0                      | 0.0864                           | 0.1160 | 0.1455 | 0.2040 | 0.263 | 0.321 | 0.380 | 0.438 | 0.555 | 0.672 | 0.790 | 0.968 | 1.260 | 1.553 | 1.850 |
| 10                     | 0.0846                           | 0.1136 | 0.1425 | 0.1995 | 0.257 | 0.314 | 0.372 | 0.429 | 0.543 | 0.658 | 0.774 | 0.947 | 1.233 | 1.520 | 1.810 |
| 20                     | 0.0828                           | 0.1112 | 0.1395 | 0.1955 | 0.252 | 0.307 | 0.364 | 0.420 | 0.533 | 0.645 | 0.757 | 0.927 | 1.208 | 1.489 | 1.770 |
| 30                     | 0.0811                           | 0.1088 | 0.1366 | 0.1916 | 0.246 | 0.301 | 0.357 | 0.412 | 0.522 | 0.632 | 0.742 | 0.908 | 1.184 | 1.460 | 1.735 |
| 40                     | 0.0795                           | 0.1067 | 0.1338 | 0.1876 | 0.241 | 0.295 | 0.350 | 0.404 | 0.511 | 0.619 | 0.727 | 0.890 | 1.161 | 1.431 | 1.701 |
| 50                     | 0.0780                           | 0.1045 | 0.1310 | 0.1839 | 0.237 | 0.290 | 0.343 | 0.396 | 0.501 | 0.607 | 0.713 | 0.873 | 1.139 | 1.403 | 1.668 |
| 60                     | 0.0764                           | 0.1025 | 0.1283 | 0.1803 | 0.232 | 0.284 | 0.336 | 0.388 | 0.493 | 0.596 | 0.700 | 0.856 | 1.116 | 1.376 | 1.636 |
| 80                     | 0.0736                           | 0.0988 | 0.1239 | 0.1738 | 0.224 | 0.274 | 0.324 | 0.374 | 0.473 | 0.572 | 0.673 | 0.824 | 1.074 | 1.325 | 1.573 |
| 100                    | 0.0710                           | 0.0954 | 0.1197 | 0.1676 | 0.215 | 0.264 | 0.312 | 0.360 | 0.455 | 0.551 | 0.648 | 0.794 | 1.035 | 1.276 | 1.517 |
| 120                    | 0.0680                           | 0.0921 | 0.1155 | 0.1618 | 0.208 | 0.255 | 0.302 | 0.348 | 0.440 | 0.533 | 0.626 | 0.767 | 1.001 | 1.234 | 1.465 |
| 140                    | 0.0663                           | 0.0889 | 0.1115 | 0.1565 | 0.201 | 0.246 | 0.291 | 0.336 | 0.426 | 0.516 | 0.606 | 0.742 | 0.968 | 1.194 | 1.416 |
| 150                    | 0.0652                           | 0.0874 | 0.1096 | 0.1541 | 0.198 | 0.242 | 0.286 | 0.331 | 0.419 | 0.508 | 0.596 | 0.730 | 0.953 | 1.175 | 1.392 |
| 175                    | 0.0626                           | 0.0840 | 0.1054 | 0.1482 | 0.191 | 0.233 | 0.275 | 0.318 | 0.403 | 0.488 | 0.573 | 0.701 | 0.914 | 1.128 | 1.337 |
| 200                    | 0.0603                           | 0.0809 | 0.1014 | 0.1427 | 0.184 | 0.225 | 0.265 | 0.305 | 0.388 | 0.470 | 0.552 | 0.674 | 0.879 | 1.084 | 1.287 |
| 225                    | 0.0581                           | 0.0779 | 0.0976 | 0.1373 | 0.177 | 0.216 | 0.255 | 0.295 | 0.374 | 0.452 | 0.531 | 0.649 | 0.846 | 1.043 | 1.240 |
| 250                    | 0.0560                           | 0.0751 | 0.0941 | 0.1323 | 0.170 | 0.208 | 0.247 | 0.284 | 0.360 | 0.436 | 0.513 | 0.627 | 0.817 | 1.007 | 1.197 |
| 275                    | 0.0541                           | 0.0726 | 0.0910 | 0.1278 | 0.164 | 0.201 | 0.238 | 0.274 | 0.348 | 0.421 | 0.494 | 0.605 | 0.789 | 0.972 | 1.155 |
| 300                    | 0.0523                           | 0.0707 | 0.0881 | 0.1237 | 0.159 | 0.194 | 0.230 | 0.265 | 0.336 | 0.407 | 0.478 | 0.585 | 0.762 | 0.940 | 1.118 |
| 350                    | 0.0491                           | 0.0658 | 0.0825 | 0.1160 | 0.149 | 0.183 | 0.216 | 0.249 | 0.316 | 0.382 | 0.449 | 0.549 | 0.715 | 0.883 | 1.048 |
| 400                    | 0.0463                           | 0.0621 | 0.0779 | 0.1090 | 0.140 | 0.172 | 0.203 | 0.235 | 0.297 | 0.360 | 0.423 | 0.517 | 0.674 | 0.831 | 0.987 |
| 450                    | 0.0437                           | 0.0586 | 0.0735 | 0.1033 | 0.133 | 0.163 | 0.192 | 0.222 | 0.281 | 0.340 | 0.399 | 0.488 | 0.637 | 0.786 | 0.934 |
| 500                    | 0.0414                           | 0.0555 | 0.0696 | 0.978  | 0.126 | 0.154 | 0.182 | 0.210 | 0.266 | 0.322 | 0.379 | 0.463 | 0.604 | 0.746 | 0.885 |
| 550                    | 0.0394                           | 0.0528 | 0.0661 | 0.930  | 0.120 | 0.146 | 0.173 | 0.200 | 0.253 | 0.306 | 0.359 | 0.440 | 0.573 | 0.749 | 0.841 |
| 600                    | 0.0376                           | 0.0504 | 0.0631 | 0.885  | 0.114 | 0.139 | 0.165 | 0.190 | 0.241 | 0.292 | 0.343 | 0.419 | 0.547 | 0.675 | 0.801 |

**Relation Between Pressure, Temperature, and Volume of Air.**—This relationship is expressed by the following formulas:

$$PV = 53.3mT \quad \text{For fps units}$$

$$PV = 1545.3nT \quad \text{For fps units}$$

$$PV = 8314nT \quad \text{For SI units}$$

in which  $P$  = absolute pressure in pounds per square foot or Pa ( $N/m^2$ );  $V$  = volume in cubic feet or cubic meter;  $T$  = absolute temperature in degrees R or degrees K;  $m$  = the mass of substance; and  $n$  = number of pound moles or kg moles. A mole is the mass of substance, in appropriate units, divided by its molecular weight. The first equation above is for air only; the second and third are general formulas that apply to any gas that behaves the ideal gas law.

*Example 2:* What is the volume of one pound of air at a pressure of 24.7 pounds per square inch and at a temperature of 210 degrees F?

$$PV = 53.3mT \quad V = \frac{53.3mT}{P} \quad V = \frac{53.3 \times 1 \times (210 + 459.6)}{24.7 \times 144}$$

$$= 10.04 \text{ cubic ft}$$

**Relation Between Barometric Pressure, and Pressures in Pounds per Square Inch and Square Foot**

| Barometer, Inches | Pressure in Psi <sup>a</sup> | Pressure in Psf <sup>a</sup> | Barometer, Inches | Pressure in Psi <sup>a</sup> | Pressure in Psf <sup>a</sup> | Barometer, Inches | Pressure in Psi <sup>a</sup> | Pressure in Psf <sup>a</sup> |
|-------------------|------------------------------|------------------------------|-------------------|------------------------------|------------------------------|-------------------|------------------------------|------------------------------|
| 28.00             | 13.75                        | 1980                         | 29.25             | 14.36                        | 2068                         | 30.50             | 14.98                        | 2156                         |
| 28.25             | 13.87                        | 1997                         | 29.50             | 14.48                        | 2086                         | 30.75             | 15.10                        | 2174                         |
| 28.50             | 13.99                        | 2015                         | 29.75             | 14.61                        | 2103                         | 31.00             | 15.22                        | 2192                         |
| 28.75             | 14.12                        | 2033                         | 30.00             | 14.73                        | 2121                         | 31.25             | 15.34                        | 2210                         |
| 29.00             | 14.24                        | 2050                         | 30.25             | 14.85                        | 2139                         | ...               | ...                          | ...                          |

<sup>a</sup> Psi is pounds per square inch; Psf is pounds per square foot

**Expansion and Compression of Air.**—The formula for the relationship between pressure, temperature, and volume of air just given indicates that when the pressure remains constant the volume is directly proportional to the absolute temperature. If the temperature remains constant, the volume is inversely proportional to the absolute pressure. Theoretically, air (as well as other gases) can be expanded or compressed according to different laws.

*Adiabatic Expansion or Compression* takes place when the air is expanded or compressed without transmission of heat to or from it, as, for example, if the air could be expanded or compressed in a cylinder of an absolutely nonconducting material.

- Let:  $P_1$  = initial absolute pressure in pounds per square foot  
 $V_1$  = initial volume in cubic feet  
 $T_1$  = initial absolute temperature in degrees R  
 $P_2$  = absolute pressure in pounds per square foot, after compression  
 $V_2$  = volume in cubic feet, after compression  
 $T_2$  = absolute temperature in degrees R, after compression

Then:

$$\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{0.71} \quad \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{1.41} \quad \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{0.41}$$

$$\frac{V_2}{V_1} = \left(\frac{T_1}{T_2}\right)^{2.46} \quad \frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{3.46} \quad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{0.29}$$

These formulas are also applicable if all pressures are in pounds per square inch; if all volumes are in cubic inches; or if any other consistent set of units is used for pressure or volume.

*Example 3:* A volume of 165 cubic feet of air, at a pressure of 15 pounds per square inch, is compressed adiabatically to a pressure of 80 pounds per square inch. What will be the volume at this pressure?

$$V_2 = V_1 \left( \frac{P_1}{P_2} \right)^{0.71} = 165 \left( \frac{15}{80} \right)^{0.71} = 50 \text{ cubic feet, approx.}$$

*Isothermal Expansion or Compression* takes place when a gas is expanded or compressed with an addition or transmission of sufficient heat to maintain a constant temperature.

Let:  $P_1$  = initial absolute pressure in pounds per square foot

$V_1$  = initial volume in cubic feet

$P_2$  = absolute pressure in pounds per square foot, after compression

$V_2$  = volume in cubic feet, after compression

$R = 53.3$

$T$  = temperature in degrees Rankine maintained during isothermal expansion or contraction

Then:

$$P_1 \times V_1 = P_2 \times V_2 = RT$$

*Example 4:* The same volume of air as in [Example 3](#) is compressed isothermally from 15 to 80 pounds per square inch. What will be the volume after compression?

$$V_2 = \frac{P_1 \times V_1}{P_2} = \frac{15 \times 165}{80} = 31 \text{ cubic feet}$$

### Foot-pounds of Work Required in Compression of Air Initial Pressure = 1 atmosphere = 14.7 pounds per square inch

| Gage Pressure in Pounds per Square Inch | Isothermal Compression   | Adiabatic Compression | Actual Compression | Gage Pressure in Pounds per Square Inch | Isothermal Compression   | Adiabatic Compression | Actual Compression |
|---|--|-----------------------|--------------------|---|--|-----------------------|--------------------|
|   | Foot-pounds Required per Cubic Foot of Air at Initial Pressure |                       |                    |   | Foot-pounds Required per Cubic Foot of Air at Initial Pressure |                       |                    |
| 5                                       | 619.6  | 649.5                 | 637.5              | 55                                      | 3393.7   | 4188.9                | 3870.8             |
| 10                                      | 1098.2   | 1192.0                | 1154.6             | 60                                      | 3440.4   | 4422.8                | 4029.8             |
| 15                                      | 1488.3   | 1661.2                | 1592.0             | 65                                      | 3577.6   | 4645.4                | 4218.2             |
| 20                                      | 1817.7   | 2074.0                | 1971.4             | 70                                      | 3706.3   | 4859.6                | 4398.1             |
| 25                                      | 2102.6   | 2451.6                | 2312.0             | 75                                      | 3828.0   | 5063.9                | 4569.5             |
| 30                                      | 2353.6   | 2794.0                | 2617.8             | 80                                      | 3942.9   | 5259.7                | 4732.9             |
| 35                                      | 2578.0   | 3111.0                | 2897.8             | 85                                      | 4051.5   | 5450.0                | 4890.1             |
| 40                                      | 2780.8   | 3405.5                | 3155.6             | 90                                      | 4155.7   | 5633.1                | 5042.1             |
| 45                                      | 2966.0   | 3681.7                | 3395.4             | 95                                      | 4254.3   | 5819.3                | 5187.3             |
| 50                                      | 3136.2   | 3942.3                | 3619.8             | 100                                     | 4348.1   | 5981.2                | 5327.9             |

**Work Required in Compression of Air.**—The total work required for compression and expulsion of air, adiabatically compressed, is:

$$\text{Total work in foot-pounds} = 3.46 P_1 V_1 \left[ \left( \frac{P_2}{P_1} \right)^{0.29} - 1 \right]$$

where  $P_1$  = initial absolute pressure in pounds per square foot;  $P_2$  = absolute pressure in pounds per square foot, after compression; and,  $V_1$  = initial volume in cubic feet.

The total work required for isothermal compression is:

$$\text{Total work in foot-pounds} = P_1 V_1 \log_e \frac{V_1}{V_2}$$

in which  $P_1$ ,  $P_2$ , and  $V_1$  denote the same quantities as in the previous equation, and  $V_2$  = volume of air in cubic feet, after compression.

The work required to compress air isothermally, that is, when the heat of compression is removed as rapidly as produced, is considerably less than the work required for compressing air adiabatically, or when all the heat is retained. In practice, neither of these two theoretical extremes is obtainable, but the power required for air compression is about the median between the powers that would be required for each. The accompanying table gives the average number of foot-pounds of work required to compress air.

**Horsepower Required to Compress Air.**—In the accompanying tables is given the horsepower required to compress one cubic foot of free air per minute (isothermally and adiabatically) from atmospheric pressure (14.7 pounds per square inch) to various gage pressures, for one-, two-, and three-stage compression. The formula for calculating the horsepower required to compress, adiabatically, a given volume of free air to a given pressure is:

$$\text{HP} = \frac{144NPVn}{33,000(n-1)} \left[ \left( \frac{P_2}{P} \right)^{\frac{n-1}{n}} - 1 \right]$$

where  $N$  = number of stages in which compression is accomplished

$P$  = atmospheric pressure in pounds per square inch

$P_2$  = absolute terminal pressure in pounds per square inch

$V$  = volume of air, in cubic feet, compressed per minute, at atmospheric pressure

$n$  = exponent of the compression curve = 1.41 for adiabatic compression

For different methods of compression and for one cubic foot of air per minute, this formula may be simplified as follows:

For one-stage compression:  $\text{HP} = 0.015P(R^{0.29} - 1)$

For two-stage compression:  $\text{HP} = 0.030P(R^{0.145} - 1)$

For three-stage compression:  $\text{HP} = 0.045P(R^{0.0975} - 1)$

For four-stage compression:  $\text{HP} = 0.060P(R^{0.0725} - 1)$

In these latter formulas  $R = \frac{P_2}{P}$  = number of atmospheres to be compressed

The formula for calculating the horsepower required to compress isothermally a given volume of free air to a given pressure is:

$$\text{HP} = \frac{144PV}{33000} \left( \log_e \frac{P_2}{P} \right)$$

Natural logarithms are obtained by multiplying common logarithms by 2.30259 or by using a handheld calculator.

**Continuity Equation.**—The net rate of mass inflow to the control volume is equal to the rate of increase of mass within the control volume.

For steady flow,  $\rho_1 A_1 V_1 = \rho_2 A_2 V_2 = M$  where  $\rho$  = density,  $A$  = area,  $V$  = velocity, and  $M$  = mass flow rate.

If the flow is steady and incompressible, then  $A_1 V_1 = A_2 V_2 = Q$  where  $Q$  is flow.

**Horsepower Required to Compress Air, Single-Stage Compression**

Horsepower required to compress one cubic foot of free air per minute (isothermally and adiabatically) from atmospheric pressure (14.7 pounds per square inch) to various gage pressures.

Single-Stage Compression, initial temperature of air, 60°F, jacket cooling not considered.

| Gage Pressure,<br>Pounds | Absolute Pressure,<br>Pounds | Number of Atmospheres | Isothermal Compression               |            | Adiabatic Compression                                |                                      |                         |                              |
|--------------------------|------------------------------|-----------------------|--------------------------------------|------------|--|--------------------------------------|-------------------------|------------------------------|
|                          |                              |                       | Mean Effective Pressure <sup>a</sup> | Horsepower | Mean Effective Pressure, <sup>a</sup><br>Theoretical | Mean Eff. Pressure plus 15% Friction | Horsepower, Theoretical | Horsepower plus 15% Friction |
| 5                        | 19.7                         | 1.34                  | 4.13                                 | 0.018      | 4.46   | 5.12                                 | 0.019                   | 0.022                        |
| 10                       | 24.7                         | 1.68                  | 7.57                                 | 0.033      | 8.21   | 9.44                                 | 0.036                   | 0.041                        |
| 15                       | 29.7                         | 2.02                  | 11.02                                | 0.048      | 11.46  | 13.17                                | 0.050                   | 0.057                        |
| 20                       | 34.7                         | 2.36                  | 12.62                                | 0.055      | 14.30  | 16.44                                | 0.062                   | 0.071                        |
| 25                       | 39.7                         | 2.70                  | 14.68                                | 0.064      | 16.94  | 19.47                                | 0.074                   | 0.085                        |
| 30                       | 44.7                         | 3.04                  | 16.30                                | 0.071      | 19.32  | 22.21                                | 0.084                   | 0.096                        |
| 35                       | 49.7                         | 3.38                  | 17.90                                | 0.078      | 21.50  | 24.72                                | 0.094                   | 0.108                        |
| 40                       | 54.7                         | 3.72                  | 19.28                                | 0.084      | 25.53  | 27.05                                | 0.103                   | 0.118                        |
| 45                       | 59.7                         | 4.06                  | 20.65                                | 0.090      | 25.40  | 29.21                                | 0.111                   | 0.127                        |
| 50                       | 64.7                         | 4.40                  | 21.80                                | 0.095      | 27.23  | 31.31                                | 0.119                   | 0.136                        |
| 55                       | 69.7                         | 4.74                  | 22.95                                | 0.100      | 28.90  | 33.23                                | 0.126                   | 0.145                        |
| 60                       | 74.7                         | 5.08                  | 23.90                                | 0.104      | 30.53  | 35.10                                | 0.133                   | 0.153                        |
| 65                       | 79.7                         | 5.42                  | 24.80                                | 0.108      | 32.10  | 36.91                                | 0.140                   | 0.161                        |
| 70                       | 84.7                         | 5.76                  | 25.70                                | 0.112      | 33.57  | 38.59                                | 0.146                   | 0.168                        |
| 75                       | 89.7                         | 6.10                  | 26.62                                | 0.116      | 35.00  | 40.25                                | 0.153                   | 0.175                        |
| 80                       | 94.7                         | 6.44                  | 27.52                                | 0.120      | 36.36  | 41.80                                | 0.159                   | 0.182                        |
| 85                       | 99.7                         | 6.78                  | 28.21                                | 0.123      | 37.63  | 43.27                                | 0.164                   | 0.189                        |
| 90                       | 104.7                        | 7.12                  | 28.93                                | 0.126      | 38.89  | 44.71                                | 0.169                   | 0.195                        |
| 95                       | 109.7                        | 7.46                  | 29.60                                | 0.129      | 40.11  | 46.12                                | 0.175                   | 0.201                        |
| 100                      | 114.7                        | 7.80                  | 30.30                                | 0.132      | 41.28  | 47.46                                | 0.180                   | 0.207                        |
| 110                      | 124.7                        | 8.48                  | 31.42                                | 0.137      | 43.56  | 50.09                                | 0.190                   | 0.218                        |
| 120                      | 134.7                        | 9.16                  | 32.60                                | 0.142      | 45.69  | 52.53                                | 0.199                   | 0.229                        |
| 130                      | 144.7                        | 9.84                  | 33.75                                | 0.147      | 47.72  | 54.87                                | 0.208                   | 0.239                        |
| 140                      | 154.7                        | 10.52                 | 34.67                                | 0.151      | 49.64  | 57.08                                | 0.216                   | 0.249                        |
| 150                      | 164.7                        | 11.20                 | 35.59                                | 0.155      | 51.47  | 59.18                                | 0.224                   | 0.258                        |
| 160                      | 174.7                        | 11.88                 | 36.30                                | 0.158      | 53.70  | 61.80                                | 0.234                   | 0.269                        |
| 170                      | 184.7                        | 12.56                 | 37.20                                | 0.162      | 55.60  | 64.00                                | 0.242                   | 0.278                        |
| 180                      | 194.7                        | 13.24                 | 38.10                                | 0.166      | 57.20  | 65.80                                | 0.249                   | 0.286                        |
| 190                      | 204.7                        | 13.92                 | 38.80                                | 0.169      | 58.80  | 67.70                                | 0.256                   | 0.294                        |
| 200                      | 214.7                        | 14.60                 | 39.50                                | 0.172      | 60.40  | 69.50                                | 0.263                   | 0.303                        |

<sup>a</sup> Mean Effective Pressure (MEP) is defined as that single pressure rise, above atmospheric, which would require the same horsepower as the actual varying pressures during compression.

## Horsepower Required to Compress Air, Two-Stage Compression

Horsepower required to compress one cubic foot of free air per minute (isothermally and adiabatically) from atmospheric pressure (14.7 pounds per square inch) to various gage pressures.  
Two-Stage Compression, initial temperature of air, 60°F, jacket cooling not considered.

| Gage Pressure,<br>Pounds | Absolute Pressure,<br>Pounds | Number of<br>Atmospheres | Correct Ratio of<br>Cylinder Volumes | Intercooler Gage<br>Pressure | Isothermal<br>Compression                  |            | Adiabatic Compression                              |  |                            |                                     | Percentage of Saving<br>over One-stage<br>Compression |
|--------------------------|------------------------------|--------------------------|--------------------------------------|------------------------------|--|------------|--|--|----------------------------|-------------------------------------|---|
|                          |                              |                          |                                      |                              | Mean<br>Effective<br>Pressure <sup>a</sup> | Horsepower | Mean Eff.<br>Pressure, <sup>a</sup><br>Theoretical | Mean Eff.<br>Pressure plus<br>1.5 per cent<br>Friction | Horsepower,<br>Theoretical | HP plus<br>1.5 per cent<br>Friction |   |
| 50                       | 64.7                         | 4.40                     | 2.10                                 | 16.2                         | 21.80                                      | 0.095      | 24.30  | 27.90  | 0.106                      | 0.123                               | 10.9  |
| 60                       | 74.7                         | 5.08                     | 2.25                                 | 18.4                         | 23.90                                      | 0.104      | 27.20  | 31.30  | 0.118                      | 0.136                               | 11.3  |
| 70                       | 84.7                         | 5.76                     | 2.40                                 | 20.6                         | 25.70                                      | 0.112      | 29.31  | 33.71  | 0.128                      | 0.147                               | 12.3  |
| 80                       | 94.7                         | 6.44                     | 2.54                                 | 22.7                         | 27.52                                      | 0.120      | 31.44  | 36.15  | 0.137                      | 0.158                               | 13.8  |
| 90                       | 104.7                        | 7.12                     | 2.67                                 | 24.5                         | 28.93                                      | 0.126      | 33.37  | 38.36  | 0.145                      | 0.167                               | 14.2  |
| 100                      | 114.7                        | 7.80                     | 2.79                                 | 26.3                         | 30.30                                      | 0.132      | 35.20  | 40.48  | 0.153                      | 0.176                               | 15.0  |
| 110                      | 124.7                        | 8.48                     | 2.91                                 | 28.1                         | 31.42                                      | 0.137      | 36.82  | 42.34  | 0.161                      | 0.185                               | 15.2  |
| 120                      | 134.7                        | 9.16                     | 3.03                                 | 29.8                         | 32.60                                      | 0.142      | 38.44  | 44.20  | 0.168                      | 0.193                               | 15.6  |
| 130                      | 144.7                        | 9.84                     | 3.14                                 | 31.5                         | 33.75                                      | 0.147      | 39.86  | 45.83  | 0.174                      | 0.200                               | 16.3  |
| 140                      | 154.7                        | 10.52                    | 3.24                                 | 32.9                         | 34.67                                      | 0.151      | 41.28  | 47.47  | 0.180                      | 0.207                               | 16.7  |
| 150                      | 164.7                        | 11.20                    | 3.35                                 | 34.5                         | 35.59                                      | 0.155      | 42.60  | 48.99  | 0.186                      | 0.214                               | 16.9  |
| 160                      | 174.7                        | 11.88                    | 3.45                                 | 36.1                         | 36.30                                      | 0.158      | 43.82  | 50.39  | 0.191                      | 0.219                               | 18.4  |
| 170                      | 184.7                        | 12.56                    | 3.54                                 | 37.3                         | 37.20                                      | 0.162      | 44.93  | 51.66  | 0.196                      | 0.225                               | 19.0  |
| 180                      | 194.7                        | 13.24                    | 3.64                                 | 38.8                         | 38.10                                      | 0.166      | 46.05  | 52.95  | 0.201                      | 0.231                               | 19.3  |
| 190                      | 204.7                        | 13.92                    | 3.73                                 | 40.1                         | 38.80                                      | 0.169      | 47.16  | 54.22  | 0.206                      | 0.236                               | 19.5  |
| 200                      | 214.7                        | 14.60                    | 3.82                                 | 41.4                         | 39.50                                      | 0.172      | 48.18  | 55.39  | 0.210                      | 0.241                               | 20.1  |
| 210                      | 224.7                        | 15.28                    | 3.91                                 | 42.8                         | 40.10                                      | 0.174      | 49.35  | 56.70  | 0.216                      | 0.247                               | ...   |
| 220                      | 234.7                        | 15.96                    | 3.99                                 | 44.0                         | 40.70                                      | 0.177      | 50.30  | 57.70  | 0.220                      | 0.252                               | ...   |
| 230                      | 244.7                        | 16.64                    | 4.08                                 | 45.3                         | 41.30                                      | 0.180      | 51.30  | 59.10  | 0.224                      | 0.257                               | ...   |
| 240                      | 254.7                        | 17.32                    | 4.17                                 | 46.6                         | 41.90                                      | 0.183      | 52.25  | 60.10  | 0.228                      | 0.262                               | ...   |
| 250                      | 264.7                        | 18.00                    | 4.24                                 | 47.6                         | 42.70                                      | 0.186      | 52.84  | 60.76  | 0.230                      | 0.264                               | ...   |
| 260                      | 274.7                        | 18.68                    | 4.32                                 | 48.8                         | 43.00                                      | 0.188      | 53.85  | 62.05  | 0.235                      | 0.270                               | ...   |
| 270                      | 284.7                        | 19.36                    | 4.40                                 | 50.0                         | 43.50                                      | 0.190      | 54.60  | 62.90  | 0.238                      | 0.274                               | ...   |
| 280                      | 294.7                        | 20.04                    | 4.48                                 | 51.1                         | 44.00                                      | 0.192      | 55.50  | 63.85  | 0.242                      | 0.278                               | ...   |
| 290                      | 304.7                        | 20.72                    | 4.55                                 | 52.2                         | 44.50                                      | 0.194      | 56.20  | 64.75  | 0.246                      | 0.282                               | ...   |
| 300                      | 314.7                        | 21.40                    | 4.63                                 | 53.4                         | 45.80                                      | 0.197      | 56.70  | 65.20  | 0.247                      | 0.283                               | ...   |
| 350                      | 364.7                        | 24.80                    | 4.98                                 | 58.5                         | 47.30                                      | 0.206      | 60.15  | 69.16  | 0.262                      | 0.301                               | ...   |
| 400                      | 414.7                        | 28.20                    | 5.31                                 | 63.3                         | 49.20                                      | 0.214      | 63.19  | 72.65  | 0.276                      | 0.317                               | ...   |
| 450                      | 464.7                        | 31.60                    | 5.61                                 | 67.8                         | 51.20                                      | 0.223      | 65.93  | 75.81  | 0.287                      | 0.329                               | ...   |
| 500                      | 514.7                        | 35.01                    | 5.91                                 | 72.1                         | 52.70                                      | 0.229      | 68.46  | 78.72  | 0.298                      | 0.342                               | ...   |

<sup>a</sup> Mean Effective Pressure (MEP) is defined as that single pressure rise, above atmospheric, which would require the same horsepower as the actual varying pressures during compression.

**Horsepower Required to Compress Air, Three-stage Compression**

Horsepower required for compressing one cubic foot of free air per minute (isothermally and adiabatically) from atmospheric pressure (14.7 pounds per square inch) to various gage pressures.

Three-stage Compression, initial temperature of air, 60°F, jacket-cooling not considered.

| Gage Pressure,<br>Pounds | Absolute Pressure,<br>Pounds | Number of<br>Atmospheres | Correct Ratio of<br>Cylinder Volumes | Intercooler<br>Gage Pressure,<br>First and<br>Second Stages | Isothermal<br>Compression                  |            | Adiabatic Compression                              |   |                           |                                 | Percentage of Saving<br>over Two-stage<br>Compression |
|--------------------------|------------------------------|--------------------------|--------------------------------------|---|--|------------|--|---|---------------------------|---------------------------------|---|
|                          |                              |                          |                                      |   | Mean<br>Effective<br>Pressure <sup>a</sup> | Horsepower | Mean Eff.<br>Pressure, <sup>a</sup><br>Theoretical | Mean Eff.<br>Pressure plus<br>15 per cent<br>Friction | Horsepower<br>Theoretical | HP plus 15 per<br>cent Friction |   |
| 100                      | 114.7                        | 7.8                      | 1.98                                 | 14.4-42.9   | 30.30                                      | 0.132      | 33.30  | 38.30   | 0.145                     | 0.167                           | 5.23  |
| 150                      | 164.7                        | 11.2                     | 2.24                                 | 18.2-59.0   | 35.59                                      | 0.155      | 40.30  | 46.50   | 0.175                     | 0.202                           | 5.92  |
| 200                      | 214.7                        | 14.6                     | 2.44                                 | 21.2-73.0   | 39.50                                      | 0.172      | 45.20  | 52.00   | 0.196                     | 0.226                           | 6.67  |
| 250                      | 264.7                        | 18.0                     | 2.62                                 | 23.8-86.1   | 42.70                                      | 0.186      | 49.20  | 56.60   | 0.214                     | 0.246                           | 6.96  |
| 300                      | 314.7                        | 21.4                     | 2.78                                 | 26.1-98.7   | 45.30                                      | 0.197      | 52.70  | 60.70   | 0.229                     | 0.264                           | 7.28  |
| 350                      | 364.7                        | 24.8                     | 2.92                                 | 28.2-110.5  | 47.30                                      | 0.206      | 55.45  | 63.80   | 0.242                     | 0.277                           | 7.64  |
| 400                      | 414.7                        | 28.2                     | 3.04                                 | 30.0-121.0  | 49.20                                      | 0.214      | 58.25  | 66.90   | 0.253                     | 0.292                           | 8.33  |
| 450                      | 464.7                        | 31.6                     | 3.16                                 | 31.8-132.3  | 51.20                                      | 0.223      | 60.40  | 69.40   | 0.263                     | 0.302                           | 8.36  |
| 500                      | 514.7                        | 35.0                     | 3.27                                 | 33.4-142.4  | 52.70                                      | 0.229      | 62.30  | 71.70   | 0.273                     | 0.314                           | 8.38  |
| 550                      | 564.7                        | 38.4                     | 3.38                                 | 35.0-153.1  | 53.75                                      | 0.234      | 65.00  | 74.75   | 0.283                     | 0.326                           | 8.80  |
| 600                      | 614.7                        | 41.8                     | 3.47                                 | 36.3-162.3  | 54.85                                      | 0.239      | 66.85  | 76.90   | 0.291                     | 0.334                           | 8.86  |
| 650                      | 664.7                        | 45.2                     | 3.56                                 | 37.6-171.5  | 56.00                                      | 0.244      | 67.90  | 78.15   | 0.296                     | 0.340                           | 9.02  |
| 700                      | 714.7                        | 48.6                     | 3.65                                 | 38.9-180.8  | 57.15                                      | 0.249      | 69.40  | 79.85   | 0.303                     | 0.348                           | 9.18  |
| 750                      | 764.7                        | 52.0                     | 3.73                                 | 40.1-189.8  | 58.10                                      | 0.253      | 70.75  | 81.40   | 0.309                     | 0.355                           | ...   |
| 800                      | 814.7                        | 55.4                     | 3.82                                 | 41.4-199.5  | 59.00                                      | 0.257      | 72.45  | 83.25   | 0.315                     | 0.362                           | ...   |
| 850                      | 864.7                        | 58.8                     | 3.89                                 | 42.5-207.8  | 60.20                                      | 0.262      | 73.75  | 84.90   | 0.321                     | 0.369                           | ...   |
| 900                      | 914.7                        | 62.2                     | 3.95                                 | 43.4-214.6  | 60.80                                      | 0.265      | 74.80  | 86.00   | 0.326                     | 0.375                           | ...   |
| 950                      | 964.7                        | 65.6                     | 4.03                                 | 44.6-224.5  | 61.72                                      | 0.269      | 76.10  | 87.50   | 0.331                     | 0.381                           | ...   |
| 1000                     | 1014.7                       | 69.0                     | 4.11                                 | 45.7-233.3  | 62.40                                      | 0.272      | 77.20  | 88.80   | 0.336                     | 0.383                           | ...   |
| 1050                     | 1064.7                       | 72.4                     | 4.15                                 | 46.3-238.3  | 63.10                                      | 0.275      | 78.10  | 90.10   | 0.340                     | 0.391                           | ...   |
| 1100                     | 1114.7                       | 75.8                     | 4.23                                 | 47.5-248.3  | 63.80                                      | 0.278      | 79.10  | 91.10   | 0.344                     | 0.396                           | ...   |
| 1150                     | 1164.7                       | 79.2                     | 4.30                                 | 48.5-256.8  | 64.40                                      | 0.281      | 80.15  | 92.20   | 0.349                     | 0.401                           | ...   |
| 1200                     | 1214.7                       | 82.6                     | 4.33                                 | 49.0-261.3  | 65.00                                      | 0.283      | 81.00  | 93.15   | 0.353                     | 0.405                           | ...   |
| 1250                     | 1264.7                       | 86.0                     | 4.42                                 | 50.3-272.3  | 65.60                                      | 0.286      | 82.00  | 94.30   | 0.357                     | 0.411                           | ...   |
| 1300                     | 1314.7                       | 89.4                     | 4.48                                 | 51.3-280.8  | 66.30                                      | 0.289      | 82.90  | 95.30   | 0.362                     | 0.416                           | ...   |
| 1350                     | 1364.7                       | 92.8                     | 4.53                                 | 52.0-287.3  | 66.70                                      | 0.291      | 84.00  | 96.60   | 0.366                     | 0.421                           | ...   |
| 1400                     | 1414.7                       | 96.2                     | 4.58                                 | 52.6-293.5  | 67.00                                      | 0.292      | 84.60  | 97.30   | 0.368                     | 0.423                           | ...   |
| 1450                     | 1464.7                       | 99.6                     | 4.64                                 | 53.5-301.5  | 67.70                                      | 0.295      | 85.30  | 98.20   | 0.371                     | 0.426                           | ...   |
| 1500                     | 1514.7                       | 103.0                    | 4.69                                 | 54.3-309.3  | 68.30                                      | 0.298      | 85.80  | 98.80   | 0.374                     | 0.430                           | ...   |
| 1550                     | 1564.7                       | 106.4                    | 4.74                                 | 55.0-317.3  | 68.80                                      | 0.300      | 86.80  | 99.85   | 0.378                     | 0.434                           | ...   |
| 1600                     | 1614.7                       | 109.8                    | 4.79                                 | 55.8-323.3  | 69.10                                      | 0.302      | 87.60  | 100.80  | 0.382                     | 0.438                           | ...   |

<sup>a</sup> Mean Effective Pressure (MEP) is defined as that single pressure rise, above atmospheric, which would require the same horsepower as the actual varying pressures during compression.



**Flow of Air in Pipes.**—The following formulas are used:

$$v = \sqrt{\frac{25,000 dp}{L}} \quad p = \frac{Lv^2}{25,000 d}$$

where  $v$  = velocity of air in feet per second

$p$  = loss of pressure due to flow through the pipes in ounces per square inch

$d$  = inside diameter of pipe in inches

$L$  = length of pipe in feet

The quantity of air discharged in cubic feet per second is the product of the velocity as obtained from the preceding formula and the area of the pipe in square feet. The horsepower required to drive air through a pipe equals the volume of air in cubic feet per second multiplied by the pressure in pounds per square foot, and this product divided by 550.

### Volume of Air Transmitted Through Pipes, in Cubic Feet per Minute

| Velocity of Air in Feet per Second | Actual Inside Diameter of Pipe, Inches |       |       |       |       |       |       |        |        |      |
|------------------------------------|--|-------|-------|-------|-------|-------|-------|--------|--------|------|
|                                    | 1                                      | 2     | 3     | 4     | 6     | 8     | 10    | 12     | 16     | 24   |
| 1                                  | 0.33                                   | 1.31  | 2.95  | 5.2   | 11.8  | 20.9  | 32.7  | 47.1   | 83.8   | 188  |
| 2                                  | 0.65                                   | 2.62  | 5.89  | 10.5  | 23.6  | 41.9  | 65.4  | 94.2   | 167.5  | 377  |
| 3                                  | 0.98                                   | 3.93  | 8.84  | 15.7  | 35.3  | 62.8  | 98.2  | 141.4  | 251.3  | 565  |
| 4                                  | 1.31                                   | 5.24  | 11.78 | 20.9  | 47.1  | 83.8  | 131.0 | 188.0  | 335.0  | 754  |
| 5                                  | 1.64                                   | 6.55  | 14.7  | 26.2  | 59.0  | 104.0 | 163.0 | 235.0  | 419.0  | 942  |
| 6                                  | 1.96                                   | 7.85  | 17.7  | 31.4  | 70.7  | 125.0 | 196.0 | 283.0  | 502.0  | 1131 |
| 7                                  | 2.29                                   | 9.16  | 20.6  | 36.6  | 82.4  | 146.0 | 229.0 | 330.0  | 586.0  | 1319 |
| 8                                  | 2.62                                   | 10.50 | 23.5  | 41.9  | 94.0  | 167.0 | 262.0 | 377.0  | 670.0  | 1508 |
| 9                                  | 2.95                                   | 11.78 | 26.5  | 47.0  | 106.0 | 188.0 | 294.0 | 424.0  | 754.0  | 1696 |
| 10                                 | 3.27                                   | 13.1  | 29.4  | 52.0  | 118.0 | 209.0 | 327.0 | 471.0  | 838.0  | 1885 |
| 12                                 | 3.93                                   | 15.7  | 35.3  | 63.0  | 141.0 | 251.0 | 393.0 | 565.0  | 1005.0 | 2262 |
| 15                                 | 4.91                                   | 19.6  | 44.2  | 78.0  | 177.0 | 314.0 | 491.0 | 707.0  | 1256.0 | 2827 |
| 18                                 | 5.89                                   | 23.5  | 53.0  | 94.0  | 212.0 | 377.0 | 589.0 | 848.0  | 1508.0 | 3393 |
| 20                                 | 6.55                                   | 26.2  | 59.0  | 105.0 | 235.0 | 419.0 | 654.0 | 942.0  | 1675.0 | 3770 |
| 24                                 | 7.86                                   | 31.4  | 71.0  | 125.0 | 283.0 | 502.0 | 785.0 | 1131.0 | 2010.0 | 4524 |
| 25                                 | 8.18                                   | 32.7  | 73.0  | 131.0 | 294.0 | 523.0 | 818.0 | 1178.0 | 2094.0 | 4712 |
| 28                                 | 9.16                                   | 36.6  | 82.0  | 146.0 | 330.0 | 586.0 | 916.0 | 1319.0 | 2346.0 | 5278 |
| 30                                 | 9.80                                   | 39.3  | 88.0  | 157.0 | 353.0 | 628.0 | 982.0 | 1414.0 | 2513.0 | 5655 |

**Flow of Compressed Air in Pipes.**—When there is a comparatively small difference of pressure at the two ends of the pipe, the volume of flow in cubic feet per minute is found by the formula:

$$V = 58 \sqrt{\frac{pd^5}{WL}}$$

where  $V$  = volume of air in cubic feet per minute

$p$  = difference in pressure at the two ends of the pipe in pounds per square inch

$d$  = inside diameter of pipe in inches

$W$  = weight in pounds of one cubic foot of entering air

$L$  = length of pipe in feet

**Velocity of Escaping Compressed Air.**—If air, or gas, flows from one chamber to another, as from a chamber or tank through an orifice or nozzle into the open air, large changes in velocity may take place owing to the difference in pressures. Since the change takes place almost instantly, little heat can escape from the fluid and the flow may be assumed to be adiabatic.

For a large container with a small orifice or hole from which the air escapes, the velocity of escape (theoretical) may be calculated from the formula:

$$v_2 = \sqrt{2g \cdot \frac{k}{k-1} \cdot 53.3(459.7 + F) \left[ 1 - \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} \right]}$$

In this formula,  $v_2$  = velocity of escaping air in feet per second;  $g$  = acceleration due to gravity, 32.16 feet per second squared;  $k = 1.41$  for adiabatic expansion or compression of air;  $F$  = temperature, degrees F;  $p_2$  = atmospheric pressure = 14.7 pounds per square inch; and  $p_1$  = pressure of air in container, pounds per square inch. In applying the preceding formula, when the ratio  $p_2/p_1$  approximately equals 0.53, under normal temperature conditions at sea level, the escape velocity  $v_2$  will be equal to the velocity of sound. Increasing the pressure  $p_1$  will not increase the velocity of escaping air beyond this limiting velocity unless a special converging diverging nozzle design is used rather than an orifice.

The accompanying table provides velocity of escaping air for various values of  $p_1$ . These values were calculated from the preceding formula simplified by substituting the appropriate constants:

$$v_2 = 108.58 \sqrt{(459.7 + F) \left[ 1 - \left( \frac{14.7}{p_1} \right)^{0.29} \right]}$$

### Velocity of Escaping Air at 70-Degrees F

| Pressure Above Atmospheric Pressure |                   |                    | Theoretical Velocity, Feet per Second | Pressure Above Atmospheric Pressure |                   |                    | Theoretical Velocity, Feet per Second |
|-------------------------------------|-------------------|--------------------|---------------------------------------|-------------------------------------|-------------------|--------------------|---------------------------------------|
| In Atmospheres                      | In Inches Mercury | In lbs per sq. in. |                                       | In Atmospheres                      | In Inches Mercury | In lbs per sq. in. |                                       |
| 0.010                               | 0.30              | 0.147              | 134                                   | 0.408                               | 12.24             | 6.00               | 769                                   |
| 0.068                               | 2.04              | 1.00               | 344                                   | 0.500                               | 15.00             | 7.35               | 833                                   |
| 0.100                               | 3.00              | 1.47               | 413                                   | 0.544                               | 16.33             | 8.00               | 861                                   |
| 0.136                               | 4.08              | 2.00               | 477                                   | 0.612                               | 18.37             | 9.00               | 900                                   |
| 0.204                               | 6.12              | 3.00               | 573                                   | 0.680                               | 20.41             | 10.0               | 935                                   |
| 0.272                               | 8.16              | 4.00               | 650                                   | 0.816                               | 24.49             | 12.0               | 997                                   |
| 0.340                               | 10.20             | 5.00               | 714                                   | 0.884                               | 26.53             | 13.0               | 1025                                  |

The theoretical velocities in the preceding table must be reduced by multiplying by a "coefficient of discharge," which varies with the orifice and the pressure. The following coefficients are used for orifices in thin plates and short tubes.

| Type of Orifice       | Pressures in Atmospheres Above Atmospheric Pressure |      |      |      |
|-----------------------|---|------|------|------|
|                       | 0.01  | 0.1  | 0.5  | 1    |
| Orifice in thin plate | 0.65  | 0.64 | 0.57 | 0.54 |
| Orifice in short tube | 0.83  | 0.82 | 0.71 | 0.67 |

## STANDARD STEELS

### Properties, Compositions, and Applications

Steel is the generic term for a large family of iron-carbon alloys, which are malleable, within some temperature range, immediately after solidification from the molten state. The principal raw materials used in steelmaking are iron ore, coal, and limestone. These materials are converted in a blast furnace into a product known as "pig iron," which contains considerable amounts of carbon, manganese, sulfur, phosphorus, and silicon. Pig iron is hard, brittle, and unsuitable for direct processing into wrought forms. Steelmaking is the process of refining pig iron as well as iron and steel scrap by removing undesirable elements from the melt and then adding desirable elements in predetermined amounts. A primary reaction in most steelmaking is the combination of carbon with oxygen to form a gas. If dissolved oxygen is not removed from the melt prior to or during pouring, the gaseous products continue to evolve during solidification. If the steel is strongly deoxidized by the addition of deoxidizing elements, no gas is evolved, and the steel is called "killed" because it lies quietly in the molds. Increasing degrees of gas evolution (decreased deoxidation) characterize steels called "semikilled," "capped," or "rimmed." The degree of deoxidation affects some of the properties of the steel. In addition to oxygen, liquid steel contains measurable amounts of dissolved hydrogen and nitrogen. For some critical steel applications, special deoxidation practices as well as vacuum treatments may be used to reduce and control dissolved gases.

The carbon content of common steel grades ranges from a few hundredths of a per cent to about 1 per cent. All steels also contain varying amounts of other elements, principally manganese, which acts as a deoxidizer and facilitates hot working. Silicon, phosphorus, and sulfur are also always present, if only in trace amounts. Other elements may be present, either as residuals that are not intentionally added, but result from the raw materials or steelmaking practice, or as alloying elements added to effect changes in the properties of the steel.

Steels can be cast to shape, or the cast ingot or strand can be reheated and hot worked by rolling, forging, extrusion, or other processes into a wrought mill shape. Wrought steels are the most widely used of engineering materials, offering a multitude of forms, finishes, strengths, and usable temperature ranges. No other material offers comparable versatility for product design.

**Standard Steel Classification.**—Wrought steels may be classified systematically into groups based on some common characteristic, such as chemical composition, deoxidation practice, finishing method, or product form. Chemical composition is the most often used basis for identifying and assigning standard designations to wrought steels. Although carbon is the principal hardening and strengthening element in steel, no single element controls the steel's characteristics. The combined effect of several elements influences response to heat treatment, hardness, strength, microstructure, corrosion resistance, and formability. The standard steels can be divided broadly into three main groups: carbon steels, alloy steels, and stainless steels.

*Carbon Steels:* A steel qualifies as a carbon steel when its manganese content is limited to 1.65 per cent (max), silicon to 0.60 per cent (max), and copper to 0.60 per cent (max). With the exception of deoxidizers and boron when specified, no other alloying elements are added intentionally, but they may be present as residuals. If any of these incidental elements are considered detrimental for special applications, maximum acceptable limits may be specified. In contrast to most alloy steels, carbon steels are most often used without a final heat treatment; however, they may be annealed, normalized, case hardened, or quenched and tempered to enhance fabrication or mechanical properties. Carbon steels may be killed, semikilled, capped, or rimmed, and, when necessary, the method of deoxidation may be specified.

*Alloy Steels:* Alloy steels comprise not only those grades that exceed the element content limits for carbon steel, but also any grade to which different elements than used for carbon steel are added, within specific ranges or specific minimums, to enhance mechanical properties, fabricating characteristics, or any other attribute of the steel. By this definition, alloy steels encompass all steels other than carbon steels; however, by convention, steels containing over 3.99 per cent chromium are considered "special types" of alloy steel, which include the stainless steels and many of the tool steels.

In a technical sense, the term alloy steel is reserved for those steels that contain a modest amount of alloying elements (about 1–4 per cent) and generally depend on thermal treatments to develop specific mechanical properties. Alloy steels are always killed, but special deoxidation or melting practices, including vacuum, may be specified for special critical applications. Alloy steels generally require additional care throughout their manufacture, because they are more sensitive to thermal and mechanical operations.

*Stainless Steels:* Stainless steels are high-alloy steels and have superior corrosion resistance to the carbon and conventional low-alloy steels because they contain relatively large amounts of chromium. Although other elements may also increase corrosion resistance, their usefulness in this respect is limited.

Stainless steels generally contain at least 10 per cent chromium, with or without other elements. It has been customary in the United States, however, to include in the stainless steel classification those steels that contain as little as 4 per cent chromium. Together, these steels form a family known as the stainless and heat-resisting steels, some of which possess very high strength and oxidation resistance. Few, however, contain more than 30 per cent chromium or less than 50 per cent iron.

In the broadest sense, the standard stainless steels can be divided into three groups based on their structures: austenitic, ferritic, and martensitic. In each of the three groups, there is one composition that represents the basic, general-purpose alloy. All other compositions are derived from the basic alloy, with specific variations in composition being made to obtain very specific properties.

The *austenitic grades* are nonmagnetic in the annealed condition, although some may become slightly magnetic after cold working. They can be hardened only by cold working, and not by heat treatment, and combine outstanding corrosion and heat resistance with good mechanical properties over a wide temperature range. The austenitic grades are further classified into two subgroups: the chromium–nickel types and the less frequently used chromium–manganese–low–nickel types. The basic composition in the chromium–nickel group is widely known as 18–8 (Cr–Ni) and is the general-purpose austenitic grade. This grade is the basis for over 20 modifications that can be characterized as follows: the chromium–nickel ratio has been modified to change the forming characteristics; the carbon content has been decreased to prevent intergranular corrosion; the elements niobium or titanium have been added to stabilize the structure; or molybdenum has been added or the chromium and nickel contents have been increased to improve corrosion or oxidation resistance.

The standard *ferritic grades* are always magnetic and contain chromium but no nickel. They can be hardened to some extent by cold working, but not by heat treatment, and they combine corrosion and heat resistance with moderate mechanical properties and decorative appeal. The ferritic grades generally are restricted to a narrower range of corrosive conditions than the austenitic grades. The basic ferritic grade contains 17 per cent chromium. In this series, there are free-machining modifications and grades with increased chromium content to improve scaling resistance. Also in this ferritic group is a 12 per cent chromium steel (the basic composition of the martensitic group) with other elements, such as aluminum or titanium, added to prevent hardening.

The standard *martensitic grades* are magnetic and can be hardened by quenching and tempering. They contain chromium and, with two exceptions, no nickel. The basic martensitic grade normally contains 12 per cent chromium. There are more than 10 standard com-

positions in the martensitic series; some are modified to improve machinability and others have small additions of nickel or other elements to improve the mechanical properties or their response to heat treatment. Still others have greatly increased carbon content, in the tool steel range, and are hardenable to the highest levels of all the stainless steels. The martensitic grades are excellent for service in mild environments such as the atmosphere, freshwater, steam, and weak acids, but are not resistant to severely corrosive solutions.

**Numbering Systems for Metals and Alloys.**—Several different numbering systems have been developed for metals and alloys by various trade associations, professional engineering societies, standards organizations, and by private industries for their own use. The numerical code used to identify the metal or alloy may or may not be related to a specification, which is a statement of the technical and commercial requirements that the product must meet. Numbering systems in use include those developed by the American Iron and Steel Institute (AISI), Society of Automotive Engineers (SAE), American Society for Testing and Materials (ASTM), American National Standards Institute (ANSI), Steel Founders Society of America, American Society of Mechanical Engineers (ASME), American Welding Society (AWS), Aluminum Association, Copper Development Association, U.S. Department of Defense (Military Specifications), and the General Accounting Office (Federal Specifications).

The Unified Numbering System (UNS) was developed through a joint effort of the ASTM and the SAE to provide a means of correlating the different numbering systems for metals and alloys that have a commercial standing. This system avoids the confusion caused when more than one identification number is used to specify the same material, or when the same number is assigned to two entirely different materials. It is important to understand that a UNS number is not a specification; it is an identification number for metals and alloys for which detailed specifications are provided elsewhere. UNS numbers are shown in [Table 1](#); each number consists of a letter prefix followed by five digits. In some, the letter is suggestive of the family of metals identified by the series, such as A for aluminum and C for copper. Whenever possible, the numbers in the UNS groups contain numbering sequences taken directly from other systems to facilitate identification of the material; e.g., the corresponding UNS number for AISI 1020 steel is G10200. The UNS numbers corresponding to the commonly used AISI-SAE numbers that are used to identify plain carbon, alloy, and tool steels are given in [Table 2](#).

**Table 1. Unified Numbering System (UNS) for Metals and Alloys**

| UNS Series       | Metal   |
|------------------|---|
| A00001 to A99999 | Aluminum and aluminum alloys                              |
| C00001 to C99999 | Copper and copper alloys                                  |
| D00001 to D99999 | Specified mechanical property steels                      |
| E00001 to E99999 | Rare earth and rare earthlike metals and alloys           |
| F00001 to F99999 | Cast irons  |
| G00001 to G99999 | AISI and SAE carbon and alloy steels (except tool steels) |
| H00001 to H99999 | AISI and SAE H-steels                                     |
| J00001 to J99999 | Cast steels (except tool steels)                          |
| K00001 to K99999 | Miscellaneous steels and ferrous alloys                   |
| L00001 to L99999 | Low-melting metals and alloys                             |
| M00001 to M99999 | Miscellaneous nonferrous metals and alloys                |
| N00001 to N99999 | Nickel and nickel alloys                                  |
| P00001 to P99999 | Precious metals and alloys                                |
| R00001 to R99999 | Reactive and refractory metals and alloys                 |
| S00001 to S99999 | Heat and corrosion resistant (stainless) steels           |
| T00001 to T99999 | Tool steels, wrought and cast                             |
| W00001 to W99999 | Welding filler metals                                     |
| Z00001 to Z99999 | Zinc and zinc alloys                                      |

**Identifying Metals.**—When it is necessary to sort materials, several rough methods may be used without elaborate chemical analysis. The most obvious of these is by using a magnet to pick out those materials that contain magnetic elements. To differentiate various levels of carbon and other elements in a steel bar, hold the bar in contact with a grinding wheel and observe the sparks. With high levels of carbon, for instance, sparks are produced that appear to split into several bright tracers. Patterns produced by several other elements, including small amounts of aluminum and titanium, for instance, can be identified with the aid of Data Sheet 13, issued by the American Society for Metals (ASM), Metals Park, OH.

**Standard Steel Numbering System.**—The most widely used systems for identifying wrought carbon, low-alloy, and stainless steels are based on chemical composition, and are those of the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE). These systems are almost identical, but they are carefully coordinated. The standard steels so designated have been developed cooperatively by producers and users and have been found through long experience to cover most of the wrought ferrous metals used in automotive vehicles and related equipment. These designations, however, are not specifications, and should not be used for purchasing unless accompanied by supplementary information necessary to describe commercially the product desired. Engineering societies, associations, and institutes whose members make, specify, or purchase steel products publish standard specifications, many of which have become well known and respected. The most comprehensive and widely used specifications are those published by the American Society for Testing and Materials (ASTM). The U.S. government and various companies also publish their own specification for steel products to serve their own special procurement needs. The Unified Numbering System (UNS) for metals and alloys is also used to designate steels (see pages 440 and 442).

The numerical designation system used by both AISI and SAE for wrought carbon, alloy, and stainless steels is summarized in Table 3. In Table 4 is given the compositions of the standard carbon steels; Table 5 lists the standard low-alloy steel compositions; and Table 6 includes the typical compositions of the standard stainless steels.

**Binary Alloy.**—An alloy containing two elements. When the term is used in regard to iron or steel, it refers to a material that has one alloying element in addition to iron. Since carbon is always present in steel, plain carbon steel is the typical binary iron alloy.

**Ternary Alloy.**—This is an alloy consisting of three elements. When the term refers to steel, it denotes a steel which contains two alloying elements in addition to iron; since carbon is always present, it is one of these elements. The third element may be nickel, chromium, manganese, tungsten, molybdenum, titanium, or any other element that is alloyed to give the steel some special property.

**Quarternary Alloy.**—A quarternary alloy is an alloy consisting of four elements. When applied to steel, such an alloy contains, in addition to iron, three alloying elements. Carbon is one of these, and the other two may be chromium and nickel, silicon and manganese, etc.

**Damascus Steel.**—A characteristic feature of Damascus steel is its surface patterns which vary with the carbon content and are either in the form of wavy parallel stripes or mottled patterns. This steel represents an early development in steel making, as it was imported during the Middle Ages to Western Europe through Syria and Palestine, and is known also as Indian steel and bulat. The old Indian method of producing real damascene steel consists in using a pure ore and the best grade of charcoal. The Persian practice is to use soft iron bars and charcoal and plumbago (black lead or graphite) to supply the carbon; and a third method consists of a certain heat-treatment which resembles a prolonged tempering. One investigator has concluded that the carbon, irregularly dispersed in the metal and forming two distinct combinations, is what causes the damask or characteristic pattern and that the slower the cooling the larger the veins will be.

An imitation of Damascus steel can be obtained by etching the surface of the steel blade with acids, the parts which are not to be attacked by the acid being protected by a "resist."

## NUMBERING SYSTEMS

**Table 2. AISI and SAE Numbers and Their Corresponding UNS Numbers for Plain Carbon, Alloy, and Tool Steels**

| AISI-SAE Numbers                | UNS Numbers | AISI-SAE Numbers | UNS Numbers | AISI-SAE Numbers | UNS Numbers | AISI-SAE Numbers | UNS Numbers |
|---------------------------------|-------------|------------------|-------------|------------------|-------------|------------------|-------------|
| Plain Carbon Steels             |             |                  |             |                  |             |                  |             |
| 1005                            | G10050      | 1030             | G10300      | 1070             | G10700      | 1566             | G15660      |
| 1006                            | G10060      | 1035             | G10350      | 1078             | G10780      | 1110             | G11100      |
| 1008                            | G10080      | 1037             | G10370      | 1080             | G10800      | 1117             | G11170      |
| 1010                            | G10100      | 1038             | G10380      | 1084             | G10840      | 1118             | G11180      |
| 1012                            | G10120      | 1039             | G10390      | 1086             | G10860      | 1137             | G11370      |
| 1015                            | G10150      | 1040             | G10400      | 1090             | G10900      | 1139             | G11390      |
| 1016                            | G10160      | 1042             | G10420      | 1095             | G10950      | 1140             | G11400      |
| 1017                            | G10170      | 1043             | G10430      | 1513             | G15130      | 1141             | G11410      |
| 1018                            | G10180      | 1044             | G10440      | 1522             | G15220      | 1144             | G11440      |
| 1019                            | G10190      | 1045             | G10450      | 1524             | G15240      | 1146             | G11460      |
| 1020                            | G10200      | 1046             | G10460      | 1526             | G15260      | 1151             | G11510      |
| 1021                            | G10210      | 1049             | G10490      | 1527             | G15270      | 1211             | G12110      |
| 1022                            | G10220      | 1050             | G10500      | 1541             | G15410      | 1212             | G12120      |
| 1023                            | G10230      | 1053             | G10530      | 1548             | G15480      | 1213             | G12130      |
| 1025                            | G10250      | 1055             | G10550      | 1551             | G15510      | 1215             | G12150      |
| 1026                            | G10260      | 1059             | G10590      | 1552             | G15520      | 12L14            | G12144      |
| 1029                            | G10290      | 1060             | G10600      | 1561             | G15610      | ...              | ...         |
| Alloy Steels                    |             |                  |             |                  |             |                  |             |
| 1330                            | G13300      | 4150             | G41500      | 5140             | G51400      | 8642             | G86420      |
| 1335                            | G13350      | 4161             | G41610      | 5150             | G51500      | 8645             | G86450      |
| 1340                            | G13400      | 4320             | G43200      | 5155             | G51550      | 8655             | G86550      |
| 1345                            | G13450      | 4340             | G43400      | 5160             | G51600      | 8720             | G87200      |
| 4023                            | G40230      | E4340            | G43406      | E51100           | G51986      | 8740             | G87400      |
| 4024                            | G40240      | 4615             | G46150      | E52100           | G52986      | 8822             | G88220      |
| 4027                            | G40270      | 4620             | G46200      | 6118             | G61180      | 9260             | G92600      |
| 4028                            | G40280      | 4626             | G46260      | 6150             | G61500      | 50B44            | G50441      |
| 4037                            | G40370      | 4720             | G47200      | 8615             | G86150      | 50B46            | G50461      |
| 4047                            | G40470      | 4815             | G48150      | 8617             | G86170      | 50B50            | G50501      |
| 4118                            | G41180      | 4817             | G48170      | 8620             | G86200      | 50B60            | G50601      |
| 4130                            | G41300      | 4820             | G48200      | 8622             | G86220      | 51B60            | G51601      |
| 4137                            | G41370      | 5117             | G51170      | 8625             | G86250      | 81B45            | G81451      |
| 4140                            | G41400      | 5120             | G51200      | 8627             | G86270      | 94B17            | G94171      |
| 4142                            | G41420      | 5130             | G51300      | 8630             | G86300      | 94B30            | G94301      |
| 4145                            | G41450      | 5132             | G51320      | 8637             | G86370      | ...              | ...         |
| 4147                            | G41470      | 5135             | G51350      | 8640             | G86400      | ...              | ...         |
| Tool Steels (AISI and UNS Only) |             |                  |             |                  |             |                  |             |
| M1                              | T11301      | T6               | T12006      | A6               | T30106      | P4               | T51604      |
| M2                              | T11302      | T8               | T12008      | A7               | T30107      | P5               | T51605      |
| M4                              | T11304      | T15              | T12015      | A8               | T30108      | P6               | T51606      |
| M6                              | T11306      | H10              | T20810      | A9               | T30109      | P20              | T51620      |
| M7                              | T11307      | H11              | T20811      | A10              | T30110      | P21              | T51621      |
| M10                             | T11310      | H12              | T20812      | D2               | T30402      | F1               | T60601      |
| M3-1                            | T11313      | H13              | T20813      | D3               | T30403      | F2               | T60602      |
| M3-2                            | T11323      | H14              | T20814      | D4               | T30404      | L2               | T61202      |
| M30                             | T11330      | H19              | T20819      | D5               | T30405      | L3               | T61203      |
| M33                             | T11333      | H21              | T20821      | D7               | T30407      | L6               | T61206      |
| M34                             | T11334      | H22              | T20822      | O1               | T31501      | W1               | T72301      |
| M36                             | T11336      | H23              | T20823      | O2               | T31502      | W2               | T72302      |
| M41                             | T11341      | H24              | T20824      | O6               | T31506      | W5               | T72305      |
| M42                             | T11342      | H25              | T20825      | O7               | T31507      | CA2              | T90102      |
| M43                             | T11343      | H26              | T20826      | S1               | T41901      | CD2              | T90402      |
| M44                             | T11344      | H41              | T20841      | S2               | T41902      | CD5              | T90405      |
| M46                             | T11346      | H42              | T20842      | S4               | T41904      | CH12             | T90812      |
| M47                             | T11347      | H43              | T20843      | S5               | T41905      | CH13             | T90813      |
| T1                              | T12001      | A2               | T30102      | S6               | T41906      | CO1              | T91501      |
| T2                              | T12002      | A3               | T30103      | S7               | T41907      | CS5              | T91905      |
| T4                              | T12004      | A4               | T30104      | P2               | T51602      | ...              | ...         |
| T5                              | T12005      | A5               | T30105      | P3               | T51603      | ...              | ...         |

**Table 3. AISI-SAE System of Designating Carbon and Alloy Steels**

| AISI-SAE Designation <sup>a</sup> |       | Type of Steel and Nominal Alloy Content (%)                 |
|-----------------------------------|-------|---|
|                                   |       | Carbon Steels   |
| 10xx                              |       | Plain Carbon (Mn 1.00% max.)                                |
| 11xx                              |       | Resulturized  |
| 12xx                              |       | Resulturized and Rephosphorized                             |
| 15xx                              |       | Plain Carbon (Max. Mn range 1.00 to 1.65%)                  |
|                                   |       | Manganese Steels  |
| 13xx                              |       | Mn 1.75   |
|                                   |       | Nickel Steels   |
| 23xx                              |       | Ni 3.50   |
| 25xx                              |       | Ni 5.00   |
|                                   |       | Nickel-Chromium Steels                                      |
| 31xx                              |       | Ni 1.25; Cr 0.65 and 0.80                                   |
| 32xx                              |       | Ni 1.75; Cr 1.07  |
| 33xx                              |       | Ni 3.50; Cr 1.50 and 1.57                                   |
| 34xx                              |       | Ni 3.00; Cr 0.77  |
|                                   |       | Molybdenum Steels   |
| 40xx                              |       | Mo 0.20 and 0.25  |
| 44xx                              |       | Mo 0.40 and 0.52  |
|                                   |       | Chromium-Molybdenum Steels                                  |
| 41xx                              |       | Cr 0.50, 0.80, and 0.95; Mo 0.12, 0.20, 0.25, and 0.30      |
|                                   |       | Nickel-Chromium-Molybdenum Steels                           |
| 43xx                              |       | Ni 1.82; Cr 0.50 and 0.80; Mo 0.25                          |
| 43BVxx                            |       | Ni 1.82; Cr 0.50; Mo 0.12 and 0.35; V 0.03 min.             |
| 47xx                              |       | Ni 1.05; Cr 0.45; Mo 0.20 and 0.35                          |
| 81xx                              |       | Ni 0.30; Cr 0.40; Mo 0.12                                   |
| 86xx                              |       | Ni 0.55; Cr 0.50; Mo 0.20                                   |
| 87xx                              |       | Ni 0.55; Cr 0.50; Mo 0.25                                   |
| 88xx                              |       | Ni 0.55; Cr 0.50; Mo 0.35                                   |
| 93xx                              |       | Ni 3.25; Cr 1.20; Mo 0.12                                   |
| 94xx                              |       | Ni 0.45; Cr 0.40; Mo 0.12                                   |
| 97xx                              |       | Ni 0.55; Cr 0.20; Mo 0.20                                   |
| 98xx                              |       | Ni 1.00; Cr 0.80; Mo 0.25                                   |
|                                   |       | Nickel-Molybdenum Steels                                    |
| 46xx                              |       | Ni 0.85 and 1.82; Mo 0.20 and 0.25                          |
| 48xx                              |       | Ni 3.50; Mo 0.25  |
|                                   |       | Chromium Steels   |
| 50xx                              |       | Cr 0.27, 0.40, 0.50, and 0.65                               |
| 51xx                              |       | Cr 0.80, 0.87, 0.92, 0.95, 1.00, and 1.05                   |
| 50xxx                             |       | Cr 0.50; C 1.00 min.  |
| 51xxx                             |       | Cr 1.02; C 1.00 min.  |
| 52xxx                             |       | Cr 1.45; C 1.00 min.  |
|                                   |       | Chromium-Vanadium Steels                                    |
| 61xx                              |       | Cr 0.60, 0.80, and 0.95; V 0.10 and 0.15 min                |
|                                   |       | Tungsten-Chromium Steels                                    |
| 72xx                              |       | W 1.75; Cr 0.75   |
|                                   |       | Silicon-Manganese Steels                                    |
| 92xx                              |       | Si 1.40 and 2.00; Mn 0.65, 0.82, and 0.85; Cr 0.00 and 0.65 |
|                                   |       | High-Strength Low-Alloy Steels                              |
| 9xx                               |       | Various SAE grades  |
| xxBxx                             |       | B denotes boron steels                                      |
| xxLxx                             |       | L denotes leaded steels                                     |
| AISI                              | SAE   | Stainless Steels  |
| 2xx                               | 302xx | Chromium-Manganese-Nickel Steels                            |
| 3xx                               | 303xx | Chromium-Nickel Steels                                      |
| 4xx                               | 514xx | Chromium Steels   |
| 5xx                               | 515xx | Chromium Steels   |

<sup>a</sup> xx in the last two digits of the carbon and low-alloy designations (but not the stainless steels) indicates that the carbon content (in hundredths of a per cent) is to be inserted.



## CHEMICAL COMPOSITIONS

**Table 4. Composition of AISI-SAE Standard Carbon Steels**

| AISI-SAE No.                                 | UNS No. | Composition(%) <sup>a</sup> |           |                     |                     |
|--|---------|-----------------------------|-----------|---------------------|---------------------|
|  |         | C                           | Mn        | P(max) <sup>b</sup> | S(max) <sup>b</sup> |
| Nonresulfurized Grades — 1 per cent Mn (max) |         |                             |           |                     |                     |
| 1005 <sup>c</sup>                            | G10050  | 0.06 max                    | 0.35 max  | 0.040               | 0.050               |
| 1006 <sup>c</sup>                            | G10060  | 0.08 max                    | 0.25–0.40 | 0.040               | 0.050               |
| 1008   | G10080  | 0.10 max                    | 0.30–0.50 | 0.040               | 0.050               |
| 1010   | G10100  | 0.08–0.13                   | 0.30–0.60 | 0.040               | 0.050               |
| 1012   | G10120  | 0.10–0.15                   | 0.30–0.60 | 0.040               | 0.050               |
| 1015   | G10150  | 0.13–0.18                   | 0.30–0.60 | 0.040               | 0.050               |
| 1016   | G10160  | 0.13–0.18                   | 0.60–0.90 | 0.040               | 0.050               |
| 1017   | G10170  | 0.15–0.20                   | 0.30–0.60 | 0.040               | 0.050               |
| 1018   | G10180  | 0.15–0.20                   | 0.60–0.90 | 0.040               | 0.050               |
| 1019   | G10190  | 0.15–0.20                   | 0.70–1.00 | 0.040               | 0.050               |
| 1020   | G10200  | 0.18–0.23                   | 0.30–0.60 | 0.040               | 0.050               |
| 1021   | G10210  | 0.18–0.23                   | 0.60–0.90 | 0.040               | 0.050               |
| 1022   | G10220  | 0.18–0.23                   | 0.70–1.00 | 0.040               | 0.050               |
| 1023   | G10230  | 0.20–0.25                   | 0.30–0.60 | 0.040               | 0.050               |
| 1025   | G10250  | 0.22–0.28                   | 0.30–0.60 | 0.040               | 0.050               |
| 1026   | G10260  | 0.22–0.28                   | 0.60–0.90 | 0.040               | 0.050               |
| 1029   | G10290  | 0.25–0.31                   | 0.60–0.90 | 0.040               | 0.050               |
| 1030   | G10300  | 0.28–0.34                   | 0.60–0.90 | 0.040               | 0.050               |
| 1035   | G10350  | 0.32–0.38                   | 0.60–0.90 | 0.040               | 0.050               |
| 1037   | G10370  | 0.32–0.38                   | 0.70–1.00 | 0.040               | 0.050               |
| 1038   | G10380  | 0.35–0.42                   | 0.60–0.90 | 0.040               | 0.050               |
| 1039   | G10390  | 0.37–0.44                   | 0.70–1.00 | 0.040               | 0.050               |
| 1040   | G10400  | 0.37–0.44                   | 0.60–0.90 | 0.040               | 0.050               |
| 1042   | G10420  | 0.40–0.47                   | 0.60–0.90 | 0.040               | 0.050               |
| 1043   | G10430  | 0.40–0.47                   | 0.70–1.00 | 0.040               | 0.050               |
| 1044   | G10440  | 0.43–0.50                   | 0.30–0.60 | 0.040               | 0.050               |
| 1045   | G10450  | 0.43–0.50                   | 0.60–0.90 | 0.040               | 0.050               |
| 1046   | G10460  | 0.43–0.50                   | 0.70–1.00 | 0.040               | 0.050               |
| 1049   | G10490  | 0.46–0.53                   | 0.60–0.90 | 0.040               | 0.050               |
| 1050   | G10500  | 0.48–0.55                   | 0.60–0.90 | 0.040               | 0.050               |
| 1053   | G10530  | 0.48–0.55                   | 0.70–1.00 | 0.040               | 0.050               |
| 1055   | G10550  | 0.50–0.60                   | 0.60–0.90 | 0.040               | 0.050               |
| 1059 <sup>c</sup>                            | G10590  | 0.55–0.65                   | 0.50–0.80 | 0.040               | 0.050               |
| 1060   | G10600  | 0.55–0.65                   | 0.60–0.90 | 0.040               | 0.050               |
| 1064 <sup>c</sup>                            | G10640  | 0.60–0.70                   | 0.50–0.80 | 0.040               | 0.050               |
| 1065 <sup>c</sup>                            | G10650  | 0.60–0.70                   | 0.60–0.90 | 0.040               | 0.050               |
| 1069 <sup>c</sup>                            | G10690  | 0.65–0.75                   | 0.40–0.70 | 0.040               | 0.050               |
| 1070   | G10700  | 0.65–0.75                   | 0.60–0.90 | 0.040               | 0.050               |
| 1078   | G10780  | 0.72–0.85                   | 0.30–0.60 | 0.040               | 0.050               |
| 1080   | G10800  | 0.75–0.88                   | 0.60–0.90 | 0.040               | 0.050               |
| 1084   | G10840  | 0.80–0.93                   | 0.60–0.90 | 0.040               | 0.050               |
| 1086 <sup>c</sup>                            | G10860  | 0.80–0.93                   | 0.30–0.50 | 0.040               | 0.050               |
| 1090   | G10900  | 0.85–0.98                   | 0.60–0.90 | 0.040               | 0.050               |
| 1095   | G10950  | 0.90–1.03                   | 0.30–0.50 | 0.040               | 0.050               |

**Table 4. (Continued) Composition of AISI-SAE Standard Carbon Steels**

| AISI-SAE No.  | UNS No. | Composition(%) <sup>a</sup> |           |                     |                     |
|---|---------|-----------------------------|-----------|---------------------|---------------------|
|   |         | C                           | Mn        | P(max) <sup>b</sup> | S(max) <sup>b</sup> |
| Nonresulfurized Grades — Over 1 per cent Mn             |         |                             |           |                     |                     |
| 1513  | G15130  | 0.10–0.16                   | 1.10–1.40 | 0.040               | 0.050               |
| 1522  | G15220  | 0.18–0.24                   | 1.10–1.40 | 0.040               | 0.050               |
| 1524  | G15240  | 0.19–0.25                   | 1.35–1.65 | 0.040               | 0.050               |
| 1526  | G15260  | 0.22–0.29                   | 1.10–1.40 | 0.040               | 0.050               |
| 1527  | G15270  | 0.22–0.29                   | 1.20–1.50 | 0.040               | 0.050               |
| 1541  | G15410  | 0.36–0.44                   | 1.35–1.65 | 0.040               | 0.050               |
| 1548  | G15480  | 0.44–0.52                   | 1.10–1.40 | 0.040               | 0.050               |
| 1551  | G15510  | 0.45–0.56                   | 0.85–1.15 | 0.040               | 0.050               |
| 1552  | G15520  | 0.47–0.55                   | 1.20–1.50 | 0.040               | 0.050               |
| 1561  | G15610  | 0.55–0.65                   | 0.75–1.05 | 0.040               | 0.050               |
| 1566  | G15660  | 0.60–0.71                   | 0.85–1.15 | 0.040               | 0.050               |
| Free-Machining Grades — Resulfurized                    |         |                             |           |                     |                     |
| 1110  | G11100  | 0.08–0.13                   | 0.30–0.60 | 0.040               | 0.08–0.13           |
| 1117  | G11170  | 0.14–0.20                   | 1.00–1.30 | 0.040               | 0.08–0.13           |
| 1118  | G11180  | 0.14–0.20                   | 1.30–1.60 | 0.040               | 0.08–0.13           |
| 1137  | G11370  | 0.32–0.39                   | 1.35–1.65 | 0.040               | 0.08–0.13           |
| 1139  | G11390  | 0.35–0.43                   | 1.35–1.65 | 0.040               | 0.13–0.20           |
| 1140  | G11400  | 0.37–0.44                   | 0.70–1.00 | 0.040               | 0.08–0.13           |
| 1141  | G11410  | 0.37–0.45                   | 1.35–1.65 | 0.040               | 0.08–0.13           |
| 1144  | G11440  | 0.40–0.48                   | 1.35–1.65 | 0.040               | 0.24–0.33           |
| 1146  | G11460  | 0.42–0.49                   | 0.70–1.00 | 0.040               | 0.08–0.13           |
| 1151  | G11510  | 0.48–0.55                   | 0.70–1.00 | 0.040               | 0.08–0.13           |
| Free-Machining Grades — Resulfurized and Rephosphorized |         |                             |           |                     |                     |
| 1211  | G12110  | 0.13 max                    | 0.60–0.90 | 0.07–0.12           | 0.10–0.15           |
| 1212  | G12120  | 0.13 max                    | 0.70–1.00 | 0.07–0.12           | 0.16–0.23           |
| 1213  | G12130  | 0.13 max                    | 0.70–1.00 | 0.07–0.12           | 0.24–0.33           |
| 1215  | G12150  | 0.09 max                    | 0.75–1.05 | 0.04–0.09           | 0.26–0.35           |
| 12L14 <sup>d</sup>                                      | G12144  | 0.15 max                    | 0.85–1.15 | 0.04–0.09           | 0.26–0.35           |

<sup>a</sup>The following notes refer to boron, copper, lead, and silicon additions: Boron: Standard killed carbon steels, which are generally fine grain, may be produced with a boron treatment addition to improve hardenability. Such steels are produced to a range of 0.0005–0.003 per cent B. These steels are identified by inserting the letter "B" between the second and third numerals of the AISI or SAE number, e.g., 10B46. Copper: When copper is required, 0.20 per cent (min) is generally specified. Lead: Standard carbon steels can be produced with a lead range of 0.15–0.35 per cent to improve machinability. Such steels are identified by inserting the letter "L" between the second and third numerals of the AISI or SAE number, e.g., 12L15 and 10L45. Silicon: It is not common practice to produce the 12XX series of resulfurized and rephosphorized steels to specified limits for silicon because of its adverse effect on machinability. When silicon ranges or limits are required for resulfurized or nonresulfurized steels, however, these values apply: a range of 0.08 per cent Si for Si max up to 0.15 per cent inclusive, a range of 0.10 per cent Si for Si max over 0.15 to 0.20 per cent inclusive, a range of 0.15 per cent Si for Si max over 0.20 to 0.30 per cent inclusive, and a range of 0.20 per cent Si for Si max over 0.30 to 0.60 per cent inclusive. Example: Si max is 0.25 per cent, range is 0.10–0.25 per cent.

<sup>b</sup> Values given are maximum percentages, except where a range of values is given.

<sup>c</sup> Standard grades for wire rods and wire only.

<sup>d</sup> 0.15–0.35 per cent Pb.

Table 5. Compositions of AISI-SAE Standard Alloy Steels

| AISI-SAE No.       | UNS No. | Composition (%) <sup>a,b</sup> |           |         |             |           |           |           |           |
|--------------------|---------|--------------------------------|-----------|---------|-------------|-----------|-----------|-----------|-----------|
|                    |         | C                              | Mn        | P (max) | S (max)     | Si        | Ni        | Cr        | Mo        |
| 1330               | G13300  | 0.28-0.33                      | 1.60-1.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | ...       | ...       |
| 1335               | G13350  | 0.33-0.38                      | 1.60-1.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | ...       | ...       |
| 1340               | G13400  | 0.38-0.43                      | 1.60-1.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | ...       | ...       |
| 1345               | G13450  | 0.43-0.48                      | 1.60-1.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | ...       | ...       |
| 4023               | G40230  | 0.20-0.25                      | 0.70-0.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | ...       | 0.20-0.30 |
| 4024               | G40240  | 0.20-0.25                      | 0.70-0.90 | 0.035   | 0.035-0.050 | 0.15-0.35 | ...       | ...       | 0.20-0.30 |
| 4027               | G40270  | 0.25-0.30                      | 0.70-0.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | ...       | 0.20-0.30 |
| 4028               | G40280  | 0.25-0.30                      | 0.70-0.90 | 0.035   | 0.035-0.050 | 0.15-0.35 | ...       | ...       | 0.20-0.30 |
| 4037               | G40370  | 0.35-0.40                      | 0.70-0.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | ...       | 0.20-0.30 |
| 4047               | G40470  | 0.45-0.50                      | 0.70-0.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | ...       | 0.20-0.30 |
| 4118               | G41180  | 0.18-0.23                      | 0.70-0.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.40-0.60 | 0.08-0.15 |
| 4130               | G41300  | 0.28-0.33                      | 0.40-0.60 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.80-1.10 | 0.15-0.25 |
| 4137               | G41370  | 0.35-0.40                      | 0.70-0.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.80-1.10 | 0.15-0.25 |
| 4140               | G41400  | 0.38-0.43                      | 0.75-1.00 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.80-1.10 | 0.15-0.25 |
| 4142               | G41420  | 0.40-0.45                      | 0.75-1.00 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.80-1.10 | 0.15-0.25 |
| 4145               | G41450  | 0.43-0.48                      | 0.75-1.00 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.80-1.10 | 0.15-0.25 |
| 4147               | G41470  | 0.45-0.50                      | 0.75-1.00 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.80-1.10 | 0.15-0.25 |
| 4150               | G41500  | 0.48-0.53                      | 0.75-1.00 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.80-1.10 | 0.15-0.25 |
| 4161               | G41610  | 0.56-0.64                      | 0.75-1.00 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.70-0.90 | 0.25-0.35 |
| 4320               | G43200  | 0.17-0.22                      | 0.45-0.65 | 0.035   | 0.040       | 0.15-0.35 | 1.65-2.00 | 0.40-0.60 | 0.20-0.30 |
| 4340               | G43400  | 0.38-0.43                      | 0.60-0.80 | 0.035   | 0.040       | 0.15-0.35 | 1.65-2.00 | 0.70-0.90 | 0.20-0.30 |
| E4340 <sup>c</sup> | G43406  | 0.38-0.43                      | 0.65-0.85 | 0.025   | 0.025       | 0.15-0.35 | 1.65-2.00 | 0.70-0.90 | 0.20-0.30 |
| 4615               | G46150  | 0.13-0.18                      | 0.45-0.65 | 0.035   | 0.040       | 0.15-0.35 | 1.65-2.00 | ...       | 0.20-0.30 |
| 4620               | G46200  | 0.17-0.22                      | 0.45-0.65 | 0.035   | 0.040       | 0.15-0.35 | 1.65-2.00 | ...       | 0.20-0.30 |
| 4626               | G46260  | 0.24-0.29                      | 0.45-0.65 | 0.035   | 0.040       | 0.15-0.35 | 0.70-1.00 | ...       | 0.15-0.25 |
| 4720               | G47200  | 0.17-0.22                      | 0.50-0.70 | 0.035   | 0.040       | 0.15-0.35 | 0.90-1.20 | 0.35-0.55 | 0.15-0.25 |
| 4815               | G48150  | 0.13-0.18                      | 0.40-0.60 | 0.035   | 0.040       | 0.15-0.35 | 3.25-3.75 | ...       | 0.20-0.30 |
| 4817               | G48170  | 0.15-0.20                      | 0.40-0.60 | 0.035   | 0.040       | 0.15-0.35 | 3.25-3.75 | ...       | 0.20-0.30 |
| 4820               | G48200  | 0.18-0.23                      | 0.50-0.70 | 0.035   | 0.040       | 0.15-0.35 | 3.25-3.75 | ...       | 0.20-0.30 |
| 5117               | G51170  | 0.15-0.20                      | 0.70-0.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.70-0.90 | ...       |
| 5120               | G51200  | 0.17-0.22                      | 0.70-0.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.70-0.90 | ...       |
| 5130               | G51300  | 0.28-0.33                      | 0.70-0.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.80-1.10 | ...       |
| 5132               | G51320  | 0.30-0.35                      | 0.60-0.80 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.75-1.00 | ...       |
| 5135               | G51350  | 0.33-0.38                      | 0.60-0.80 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.80-1.05 | ...       |
| 5140               | G51400  | 0.38-0.43                      | 0.70-0.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.70-0.90 | ...       |
| 5150               | G51500  | 0.48-0.53                      | 0.70-0.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.70-0.90 | ...       |
| 5155               | G51550  | 0.51-0.59                      | 0.70-0.90 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.70-0.90 | ...       |
| 5160               | G51600  | 0.56-0.64                      | 0.75-1.00 | 0.035   | 0.040       | 0.15-0.35 | ...       | 0.70-0.90 | ...       |

Table 5. (Continued) Compositions of AISI-SAE Standard Alloy Steels

| AISI-SAE No.                       | UNS No. | Composition (%) <sup>a,b</sup> |           |         |         |           |           |           |             |
|------------------------------------|---------|--------------------------------|-----------|---------|---------|-----------|-----------|-----------|-------------|
|                                    |         | C                              | Mn        | P (max) | S (max) | Si        | Ni        | Cr        | Mo          |
| E51100 <sup>c</sup>                | G51986  | 0.98-1.10                      | 0.25-0.45 | 0.025   | 0.025   | 0.15-0.35 | ...       | 0.90-1.15 | ...         |
| E52100 <sup>c</sup>                | G52986  | 0.98-1.10                      | 0.25-0.45 | 0.025   | 0.025   | 0.15-0.35 | ...       | 1.30-1.60 | ...         |
| 6118                               | G61180  | 0.16-0.21                      | 0.50-0.70 | 0.035   | 0.040   | 0.15-0.35 | ...       | 0.50-0.70 | 0.10-0.15 V |
| 6150                               | G61500  | 0.48-0.53                      | 0.70-0.90 | 0.035   | 0.040   | 0.15-0.35 | ...       | 0.80-1.10 | 0.15 V min  |
| 8615                               | G86150  | 0.13-0.18                      | 0.70-0.90 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.15-0.25   |
| 8617                               | G86170  | 0.15-0.20                      | 0.70-0.90 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.15-0.25   |
| 8620                               | G86200  | 0.18-0.23                      | 0.70-0.90 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.15-0.25   |
| 8622                               | G86220  | 0.20-0.25                      | 0.70-0.90 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.15-0.25   |
| 8625                               | G86250  | 0.23-0.28                      | 0.70-0.90 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.15-0.25   |
| 8627                               | G86270  | 0.25-0.30                      | 0.70-0.90 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.15-0.25   |
| 8630                               | G86300  | 0.28-0.33                      | 0.70-0.90 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.15-0.25   |
| 8637                               | G86370  | 0.35-0.40                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.15-0.25   |
| 8640                               | G86400  | 0.38-0.43                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.15-0.25   |
| 8642                               | G86420  | 0.40-0.45                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.15-0.25   |
| 8645                               | G86450  | 0.43-0.48                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.15-0.25   |
| 8655                               | G86550  | 0.51-0.59                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.15-0.25   |
| 8720                               | G87200  | 0.18-0.23                      | 0.70-0.90 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.20-0.30   |
| 8740                               | G87400  | 0.38-0.43                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.20-0.30   |
| 8822                               | G88220  | 0.20-0.25                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | 0.40-0.70 | 0.40-0.60 | 0.30-0.40   |
| 9260                               | G92600  | 0.56-0.64                      | 0.75-1.00 | 0.035   | 0.040   | 1.80-2.20 | ...       | ...       | ...         |
| Standard Boron Grades <sup>d</sup> |         |                                |           |         |         |           |           |           |             |
| 50B44                              | G50441  | 0.43-0.48                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | ...       | 0.40-0.60 | ...         |
| 50B46                              | G50461  | 0.44-0.49                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | ...       | 0.20-0.35 | ...         |
| 50B50                              | G50501  | 0.48-0.53                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | ...       | 0.40-0.60 | ...         |
| 50B60                              | G50601  | 0.56-0.64                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | ...       | 0.40-0.60 | ...         |
| 51B60                              | G51601  | 0.56-0.64                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | ...       | 0.70-0.90 | ...         |
| 81B45                              | G81451  | 0.43-0.48                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | 0.20-0.40 | 0.35-0.55 | 0.08-0.15   |
| 94B17                              | G94171  | 0.15-0.20                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | 0.30-0.60 | 0.30-0.50 | 0.08-0.15   |
| 94B30                              | G94301  | 0.28-0.33                      | 0.75-1.00 | 0.035   | 0.040   | 0.15-0.35 | 0.30-0.60 | 0.30-0.50 | 0.08-0.15   |

<sup>a</sup> Small quantities of certain elements are present that are not specified or required. These incidental elements may be present to the following maximum amounts: Cu, 0.35 per cent; Ni, 0.25 per cent; Cr, 0.20 per cent; and Mo, 0.06 per cent.

<sup>b</sup> Standard alloy steels can also be produced with a lead range of 0.15-0.35 per cent. Such steels are identified by inserting the letter "L" between the second and third numerals of the AISI or SAE number, e.g., 41L40.

<sup>c</sup> Electric furnace steel.

<sup>d</sup> 0.0005-0.003 per cent B.

Source: American Iron and Steel Institute: *Steel Products Manual*.

**Table 6. Standard Stainless Steels — Typical Compositions**

| AISI Type (UNS) | Typical Composition (%)  | AISI Type (UNS) | Typical Composition (%)   |
|-----------------|--|-----------------|---|
| Austenitic      |  |                 |   |
| 201 (S20100)    | 16–18 Cr, 3.5–5.5 Ni, 0.15 C, 5.5–7.5 Mn, 0.75 Si, 0.060 P, 0.030 S, 0.25 N                    | 310 (S31000)    | 24–26 Cr, 19–22 Ni, 0.25 C, 2.0 Mn, 1.5 Si, 0.045 P, 0.030 S  |
| 202 (S20200)    | 17–19 Cr, 4–6 Ni, 0.15 C, 7.5–10.0 Mn, 0.75 Si, 0.060 P, 0.030 S, 0.25 N                       | 310S (S31008)   | 24–26 Cr, 19–22 Ni, 0.08 C, 2.0 Mn, 1.5 Si, 0.045 P, 0.30 S   |
| 205 (S20500)    | 16.5–18 Cr, 1–1.75 Ni, 0.12–0.25 C, 14–15.5 Mn, 0.75 Si, 0.060 P, 0.030 S, 0.32–0.40 N         | 314 (S31400)    | 23–26 Cr, 19–22 Ni, 0.25 C, 2.0 Mn, 1.5–3.0 Si, 0.045 P, 0.030 S  |
| 301 (S30100)    | 16–18 Cr, 6–8 Ni, 0.15 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S                                    | 316 (S31600)    | 16–18 Cr, 10–14 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 2.0–3.0 Mo, 0.10 N                                   |
| 302 (S30200)    | 17–19 Cr, 8–10 Ni, 0.15 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 0.10 N                           | 316L (S31603)   | 16–18 Cr, 10–14 Ni, 0.03 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 2.0–3.0 Mo, 0.10 N                                   |
| 302B (S30215)   | 17–19 Cr, 8–10 Ni, 0.15 C, 2.0 Mn, 2.0–3.0 Si, 0.045 P, 0.030 S                                | 316F (S31620)   | 16–18 Cr, 10–14 Ni, 0.08 C, 2.0 Mn, 1.0 Si, 0.20 P, 0.10 S min, 1.75–2.50 Mo  |
| 303 (S30300)    | 17–19 Cr, 8–10 Ni, 0.15 C, 2.0 Mn, 1.0 Si, 0.20 P, 0.015 S min, 0.60 Mo (optional)             | 316N (S31651)   | 16–18 Cr, 10–14 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 2–3 Mo, 0.10–0.16 N                                  |
| 303Se (S30323)  | 17–19 Cr, 8–10 Ni, 0.15 C, 2.0 Mn, 1.0 Si, 0.20 P, 0.060 S, 0.15 Se min                        | 317 (S31700)    | 18–20 Cr, 11–15 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 3.0–4.0 Mo, 0.10 N max                               |
| 304 (S30400)    | 18–20 Cr, 8–10.5 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 0.10 N                         | 317L (S31703)   | 18–20 Cr, 11–15 Ni, 0.03 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 3–4 Mo, 0.10 N max                                   |
| 304L (S30403)   | 18–20 Cr, 8–12 Ni, 0.03 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 0.10 N                           | 321 (S32100)    | 17–19 Cr, 9–12 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S [Ti, 5(C+N) min, 0.70 max], 0.10 max                   |
| 304 Cu (S30430) | 17–19 Cr, 8–10 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 3–4 Cu                           | 329 (S32900)    | 23–28 Cr, 2.5–5 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.040 P, 0.030 S, 1–2 Mo   |
| 304N (S30451)   | 18–20 Cr, 8–10.5 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 0.10–0.16 N                    | 330 (N08330)    | 17–20 Cr, 34–37 Ni, 0.08 C, 2.0 Mn, 0.75–1.50 Si, 0.040 P, 0.030 S  |
| 305 (S30500)    | 17–19 Cr, 10.5–13 Ni, 0.12 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S                                | 347 (S34700)    | 17–19 Cr, 9–13 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S (Nb + Ta, 10 × C min, 1 max)                           |
| 308 (S30800)    | 19–21 Cr, 10–12 Ni, 0.08 C, 2.0 Mn, 1.0 Si, 0.045 P, 0.030 S                                   | 348 (S34800)    | 17–19 Cr, 9–13 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S (Nb + Ta, 10 × C min, 1 max, but 0.10 Ta max), 0.20 Ca |
| 309 (S30900)    | 22–24 Cr, 12–15 Ni, 0.20 C, 2.0 Mn, 1.0 Si, 0.045 P, 0.030 S                                   | 384 (S38400)    | 15–17 Cr, 17–19 Ni, 0.08 C, 2.0 Mn, 1.0 Si, 0.045 P, 0.030 S  |
| 309S (S30908)   | 22–24 Cr, 12–15 Ni, 0.08 C, 2.0 Mn, 1.0 Si, 0.045 P, 0.030 S                                   | ...             | ...   |
| Ferritic        |  |                 |   |
| 405 (S40500)    | 11.5–14.5 Cr, 0.08 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.1–0.3 Al, 0.60 max                   | 430FSe (S43023) | 16–18 Cr, 0.12 C, 1.25 Mn, 1.0 Si, 0.060 P, 0.060 S, 0.15 Se min  |
| 409 (S40900)    | 10.5–11.75 Cr, 0.08 C, 1.0 Mn, 1.0 Si, 0.045 P, 0.030 S, 0.05 Ni (Ti 6 × C, but with 0.75 max) | 434 (S43400)    | 16–18 Cr, 0.12 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.75–1.25 Mo  |
| 429 (S42900)    | 14–16 Cr, 0.12 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.30 S, 0.75 Ni                                     | 436 (S43600)    | 16–18 Cr, 0.12 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.75–1.25 Mo (Nb + Ta 5 × C min, 0.70 max)                      |
| 430 (S43000)    | 16–18 Cr, 0.12 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.30 S, 0.75 Ni                                     | 442 (S44200)    | 18–23 Cr, 0.20 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S  |
| 430F (S43020)   | 16–18 Cr, 0.12 C, 1.25 Mn, 1.0 Si, 0.060 P, 0.15 S min, 0.60 Mo (optional)                     | 446 (S44600)    | 23–27 Cr, 0.20 C, 1.5 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.025 N   |

**Table 6. (Continued) Standard Stainless Steels — Typical Compositions**

| AISI Type (UNS)   | Typical Composition (%)  | AISI Type (UNS)  | Typical Composition (%)   |
|-------------------|--|------------------|---|
| Martensitic       |  |                  |   |
| 403<br>(S40300)   | 11.5–13.0 Cr, 1.15 C, 1.0 Mn, 0.5 Si, 0.040 P, 0.030 S, 0.60 Ni                    | 420F<br>(S42020) | 12–14 Cr, over 0.15 C, 1.25 Mn, 1.0 Si, 0.060 P, 0.15 S min, 0.60 Mo max (optional)                                   |
| 410<br>(S41000)   | 11.5–13.5 Cr, 0.15 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.75 Ni                    | 422<br>(S42200)  | 11–12.50 Cr, 0.50–1.0 Ni, 0.20–0.25 C, 0.50–1.0 Mn, 0.50 Si, 0.025 P, 0.025 S, 0.90–1.25 Mo, 0.20–0.30 V, 0.90–1.25 W |
| 414<br>(S41400)   | 11.5–13.5 Cr, 1.25–2.50 Ni, 0.15 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 1.25–2.50 Ni | 431<br>(S41623)  | 15–17 Cr, 1.25–2.50 Ni, 0.20 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S  |
| 416<br>(S41600)   | 12–14 Cr, 0.15 C, 1.25 Mn, 1.0 Si, 0.060 P, 0.15 S min, 0.060 Mo (optional)        | 440A<br>(S44002) | 16–18 Cr, 0.60–0.75 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.75 Mo  |
| 416Se<br>(S41623) | 12–14 Cr, 0.15 C, 1.25 Mn, 1.0 Si, 0.060 P, 0.060 S, 0.15 Se min                   | 440B<br>(S44003) | 16–18 Cr, 0.75–0.95 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.75 Mo  |
| 420<br>(S42000)   | 12–14 Cr, 0.15 C min, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S                             | 440C<br>(S44004) | 16–18 Cr, 0.95–1.20 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.75 Mo  |
| Heat-Resisting    |  |                  |   |
| 501<br>(S50100)   | 4–6 Cr, 0.10 C min, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.40–0.65 Mo                 | 502<br>(S50200)  | 4–6 Cr, 0.10 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.40–0.65 Mo  |

**Thermal Treatments of Steel.**—Steel's versatility is due to its response to thermal treatment. Although most steel products are used in the as-rolled or un-heat-treated condition, thermal treatment greatly increases the number of properties that can be obtained, because at certain "critical temperatures" iron changes from one type of crystal structure to another. This structural change, known as an allotropic transformation, is spontaneous and reversible and can be made to occur by simply changing the temperature of the metal.

In steel, the transformation in crystal structure occurs over a range of temperatures, bounded by lower and upper critical points. When heated, most carbon and low-alloy steels have a critical temperature range between 1300 and 1600 degrees F. Steel above this temperature, but below the melting range, has a crystalline structure known as austenite, in which the carbon and alloying elements are dissolved in a solid solution. Below this critical range, the crystal structure changes to a phase known as ferrite, which is capable of maintaining only a very small percentage of carbon in solid solution. The remaining carbon exists in the form of carbides, which are compounds of carbon and iron and certain of the other alloying elements. Depending primarily on cooling rate, the carbides may be present as thin plates alternating with the ferrite (pearlite); as spheroidal globular particles at ferrite grain boundaries or dispersed throughout the ferrite; or as a uniform distribution of extremely fine particles throughout a "ferritelike" phase, which has an acicular (needle-like) appearance, named martensite. In some of the highly alloyed stainless steels the addition of certain elements stabilizes the austenite structure so that it persists even at very low temperatures (austenitic grades). Other alloying elements can prevent the formation of austenite entirely up to the melting point (ferritic grades).

Fundamentally, all steel heat treatments are intended to either harden or soften the metal. They involve one or a series of operations in which the solid metal is heated and cooled under specified conditions to develop a required structure and properties. In general, there are five major forms of heat treatment for the standard steels that modify properties to suit either fabrication or end use.

*Quenching and Tempering:* The primary hardening treatment for steel, quenching and tempering, usually consists of three successive operations: heating the steel above the critical range and holding it at these temperatures for a sufficient time to approach a uniform

solid solution (austenitizing); cooling the steel rapidly by quenching in oil, water, brine, salt or air to form a hard, usually brittle, metastable structure known as untempered or white martensite; tempering the steel by reheating it to a temperature below the critical range in order to obtain the required combination of hardness, strength, ductility, toughness, and structural stability (tempered martensite).

Two well-known modifications of conventional quenching and tempering are "austempering" and "martempering." They involve interrupted quenching techniques (two or more quenching media) that can be utilized for some steels to obtain desired structures and properties while minimizing distortion and cracking problems that may occur in conventional hardening.

*Normalizing:* The steel is heated to a temperature above the critical range, after which it is cooled in still air to produce a generally fine pearlite structure. The purpose is to promote uniformity of structure and properties after a hot-working operation such as forging or extrusion. Steels may be placed in service in the normalized condition, or they may be subjected to additional thermal treatment after subsequent machining or other operations.

*Annealing:* The steel is heated to a temperature above or within the critical range, then cooled at a predetermined slow rate (usually in a furnace) to produce a coarse pearlite structure. This treatment is used to soften the steel for improved machinability; to improve or restore ductility for subsequent forming operations; or to eliminate the residual stresses and microstructural effects of cold working.

*Spheroidize Annealing:* This is a special form of annealing that requires prolonged heating at an appropriate temperature followed by slow cooling in order to produce globular carbides, a structure desirable for machining, cold forming, or cold drawing, or for the effect it will have on subsequent heat treatment.

*Stress Relieving:* This process reduces internal stresses, caused by machining, cold working, or welding, by heating the steel to a temperature below the critical range and holding it there long enough to equalize the temperature throughout the piece.

See the sections *HARDENING, TEMPERING, AND ANNEALING* on page 503 and *Heat Treating High-Speed Steels* on page 538 for more information about the heat treatment of steels.

**Applications.**—Many factors enter into the selection of a steel for a particular application. These factors include the mechanical and physical properties needed to satisfy the design requirements and service environment; the cost and availability of the material; the cost of processing (machining, heat treatment, welding, etc.); and the suitability of available processing equipment or the cost of any new equipment required.

These steel selection considerations require input from designers, metallurgists, manufacturing engineers, service engineers, and procurement specialists, and can be considered proper or optimum when the part is made from the lowest cost material consistent with satisfying engineering and service requirements. The factors in selection can vary widely among different organizations, so that several different steels may be used successfully for similar applications. The best choice of a steel for any application most often results from a balance or trade-offs among the various selection considerations.

The AISI/SAE designated "standard steels" provide a convenient way for engineers and metallurgists to state briefly but clearly the chemical composition and, in some instances, some of the properties desired, and they are widely recognized and used in the United States and in many other countries. There are, however, numerous nonstandard carbon, alloy, and stainless steel grades that are widely used for special applications.

The following sections and tables illustrate the general characteristics and typical applications of most of the standard carbon, alloy, and stainless steel grades.

*General Application of SAE Steels:* These applications are intended as a general guide only since the selection may depend on the exact character of the service, cost of material,

machinability when machining is required, or other factors. When more than one steel is recommended for a given application, information on the characteristics of each steel listed will be found in the section beginning on page 452.

- Adapters, 1145
- Agricultural steel, 1070, 1080
- Aircraft forgings, 4140
- Axles front or rear, 1040, 4140
- Axle shafts, 1045, 2340, 2345, 3135, 3140, 3141, 4063, 4340
- Ball-bearing races, 52100
- Balls for ball bearings, 52100
- Body stock for cars, rimmed\*
- Bolts and screws, 1035
- Bolts
  - anchor, 1040
  - cold-headed, 4042
  - connecting-rod, 3130
  - heat-treated, 2330
  - heavy-duty, 4815, 4820
  - steering-arm, 3130
- Brake levers, 1030, 1040
- Bumper bars, 1085
- Cams free-wheeling, 4615, 4620
- Camshafts, 1020, 1040
- Carburized parts, 1020, 1022, 1024, 1117, 1118, 1320, 2317, 2515, 3310, 3115, 3120, 4023, 4032
- Chain pins transmission, 4320, 4815, 4820
- Chains transmission, 3135, 3140
- Clutch disks, 1060, 1070, 1085
- Clutch springs, 1060
- Coil springs, 4063
- Cold-headed bolts, 4042
- Cold-heading
  - steel, 30905, 1070
  - wire or rod, rimmed\*, 1035
- Cold-rolled steel, 1070
- Connecting-rods, 1040, 3141
- Connecting-rod bolts, 3130
- Corrosion resisting, 51710, 30805
- Covers transmission, rimmed\*
- Crankshafts, 1045, 1145, 3135, 3140, 3141
- Crankshafts Diesel engine, 4340
- Cushion springs, 1060
- Cutlery stainless, 51335
- Cylinder studs, 3130
- Deep-drawing steel, rimmed\*, 30905
- Differential gears, 4023
- Disks clutch, 1070, 1060
- Ductile steel, 30905
- Fan blades, 1020
- Fatigue resisting 4340, 4640
- Fender stock for cars, rimmed\*
- Forgings
  - aircraft, 4140
  - carbon steel, 1040, 1045
  - heat-treated, 3240, 5140, 6150
  - high-duty, 6150
  - small or medium, 1035
  - large, 1036
- Free-cutting steel
  - carbon, 1111, 1113
  - chromium-nickel steel, 30615
  - manganese steel, 1132, 1137
- Gears
  - carburized, 1320, 2317, 3115, 3120, 3310, 4119, 4125, 4320, 4615, 4620, 4815, 4820
  - heat-treated, 2345
  - car and truck, 4027, 4032
  - cyanide-hardening, 5140
  - differential, 4023
  - high duty, 4640, 6150
  - oil-hardening, 3145, 3150, 4340, 5150
  - ring, 1045, 3115, 3120, 4119
  - transmission, 3115, 3120, 4119
  - truck and bus, 3310, 4320
- Gear shift levers, 1030
- Harrow disks, 1080
- Hay-rake teeth, 1095
- Key stock, 1030, 2330, 3130
- Leaf springs, 1085, 9260
- Levers
  - brake, 1030, 1040
  - gear shift, 1030
  - heat-treated, 2330
- Lock washers, 1060
- Mower knives, 1085
- Mower sections, 1070
- Music wire, 1085
- Nuts, 3130
  - heat-treated, 2330
- Oil pans automobile, rimmed\*
- Pinions carburized, 3115, 3120, 4320
- Piston pins, 3115, 3120
- Plow
  - beams, 1070

\* The "rimmed" and "killed" steels listed are in the SAE 1008, 1010, and 1015 group. See general description of these steels.



- disks, 1080
- shares, 1080
- Propeller shafts, 2340, 2345, 4140
- Races ball-bearing, 52100
- Ring gears, 3115, 3120, 4119
- Rings snap, 1060, 1070, 1090
- Rivets, rimmed\*
- Rod and wire, killed\*
- Rod cold-heading, 1035
- Roller bearings, 4815
- Rollers for bearings, 52100
- Screws and bolts, 1035
- Screw stock
  - Bessemer, 1111, 1112, 1113
  - open-hearth, 1115
- Screws heat-treated, 2330
- Seat springs, 10956
- Shafts
  - axle, 1045
  - cyanide-hardening, 5140
  - heavy-duty, 4340, 6150, 4615, 4620
  - oil-hardening, 5150
  - propeller, 2340, 2345, 4140
  - transmission, 4140
- Sheets and strips, rimmed\*
- Snap rings, 1060, 1070, 1090
- Spline shafts, 1045, 1320, 2340, 2345, 3115, 3120, 3135, 3140, 4023
- Spring clips, 1060
- Springs
  - coil, 1095, 4063, 6150
  - clutch, 1060
  - cushion, 1060
  - hard-drawn coiled, 1066
  - leaf, 1085, 1095, 4063, 4068, 9260, 6150
  - oil-hardening, 5150
  - oil-tempered wire, 1066
  - seat, 1095
  - valve, 1060
- Spring wire, 1045
  - hard-drawn, 1055
  - oil-tempered, 1055
- Stainless irons, 51210, 51710
- Steel
  - cold-rolled, 1070
  - cold-heading, 30905
  - free-cutting carbon, 1111, 1113
  - free-cutting chrome-nickel, 30615
  - free-cutting manganese, 1132
  - minimum distortion, 4615, 4620, 4640
  - soft ductile, 30905
- Steering arms, 4042
- Steering-arm bolts, 3130
- Steering knuckles, 3141
- Steering-knuckle pins, 4815, 4820
- Tacks, rimmed\*
- Thrust washers, 1060
  - oil-hardened, 5150
- Transmission shafts, 4140
- Tubing, 1040
  - front axle, 4140
  - seamless, 1030
  - welded, 1020
- Universal joints, 1145
- Valve springs, 1060
- Washers lock, 1060
- Welded structures, 30705
- Wire and rod, killed\*
- Wire
  - cold-heading, rimmed\*
  - hard-drawn spring, 1045, 1055
  - music, 1085
  - oil-tempered spring, 1055
- Wrist-pins automobile, 1020
- Yokes, 1145

**Carbon Steels.**—*SAE Steels 1006, 1008, 1010, 1015*: These steels are the lowest carbon steels of the plain carbon type, and are selected where cold formability is the primary requisite of the user. They are produced both as rimmed and killed steels. Rimmed steel is used for sheet, strip, rod, and wire where excellent surface finish or good drawing qualities are required, such as body and fender stock, hoods, lamps, oil pans, and other deep-drawn and -formed products. This steel is also used for cold-heading wire for tacks, and rivets and low carbon wire products. Killed steel (usually aluminum killed or special killed) is used for difficult stampings, or where nonaging properties are needed. Killed steels (usually silicon killed) should be used in preference to rimmed steel for forging or heat-treating applications.

These steels have relatively low tensile values and should not be selected where much strength is desired. Within the carbon range of the group, strength and hardness will rise with increases in carbon and/or with cold work, but such increases in strength are at the sacrifice of ductility or the ability to withstand cold deformation. Where cold rolled strip is used, the proper temper designation should be specified to obtain the desired properties.

With less than 0.15 carbon, the steels are susceptible to serious grain growth, causing brittleness, which may occur as the result of a combination of critical strain (from cold work) followed by heating to certain elevated temperatures. If cold-worked parts formed from these steels are to be later heated to temperatures in excess of 1100 degrees F, the user should exercise care to avoid or reduce cold working. When this condition develops, it can be overcome by heating the parts to a temperature well in excess of the upper critical point, or at least 1750 degrees F.

Steels in this group, being nearly pure iron or ferritic in structure, do not machine freely and should be avoided for cut screws and operations requiring broaching or smooth finish on turning. The machinability of bar, rod, and wire products is improved by cold drawing. Steels in this group are readily welded.

*SAE 1016, 1017, 1018, 1019, 1020, 1021, 1022, 1023, 1024, 1025, 1026, 1027, 1030:*

Steels in this group, due to the carbon range covered, have increased strength and hardness, and reduced cold formability compared to the lowest carbon group. For heat-treating purposes, they are known as carburizing or case hardening grades. When uniform response to heat treatment is required, or for forgings, killed steel is preferred; for other uses, semi-killed or rimmed steel may be indicated, depending on the combination of properties desired. Rimmed steels can ordinarily be supplied up to 0.25 carbon.

Selection of one of these steels for carburizing applications depends on the nature of the part, the properties desired, and the processing practice preferred. Increases in carbon give greater core hardness with a given quench, or permit the use of thicker sections. Increases in manganese improve the hardenability of both the core and case; in carbon steels this is the only change in composition that will increase case hardenability. The higher manganese variants also machine much better. For carburizing applications, SAE 1016, 1018, and 1019 are widely used for thin sections or water-quenched parts. SAE 1022 and 1024 are used for heavier sections or where oil quenching is desired, and SAE 1024 is sometimes used for such parts as transmission and rear axle gears. SAE 1027 is used for parts given a light case to obtain satisfactory core properties without drastic quenching. SAE 1025 and 1030, although not usually regarded as carburizing types, are sometimes used in this manner for larger sections or where greater core hardness is needed.

For cold-formed or -headed parts, the lowest manganese grades (SAE 1017, 1020, and 1025) offer the best formability at their carbon level. SAE 1020 is used for fan blades and some frame members, and SAE 1020 and 1025 are widely used for low-strength bolts. The next higher manganese types (SAE 1018, 1021, and 1026) provide increased strength.

All steels listed may be readily welded or brazed by the common commercial methods. SAE 1020 is frequently used for welded tubing. These steels are used for numerous forged parts, the lower-carbon grades where high strength is not essential. Forgings from the lower-carbon steels usually machine better in the as-forged condition without annealing, or after normalizing.

*SAE 1030, 1033, 1034, 1035, 1036, 1038, 1039, 1040, 1041, 1042, 1043, 1045, 1046, 1049, 1050, 1052:* These steels, of the medium-carbon type, are selected for uses where higher mechanical properties are needed and are frequently further hardened and strengthened by heat treatment or by cold work. These grades are ordinarily produced as killed steels.

Steels in this group are suitable for a wide variety of automotive-type applications. The particular carbon and manganese level selected is affected by a number of factors. Increases in the mechanical properties required in section thickness, or in depth of hardening, ordinarily indicate either higher carbon or manganese or both. The heat-treating practice preferred, particularly the quenching medium, has a great effect on the steel selected. In general, any of the grades over 0.30 carbon may be selectively hardened by induction or flame methods.

The lower-carbon and manganese steels in this group find usage for certain types of cold-formed parts. SAE 1030 is used for shift and brake levers. SAE 1034 and 1035 are used in the form of wire and rod for cold upsetting such as bolts, and SAE 1038 for bolts and studs. The parts cold-formed from these steels are usually heat-treated prior to use. Stampings are generally limited to flat parts or simple bends. The higher-carbon SAE 1038, 1040, and 1042 are frequently cold drawn to specified physical properties for use without heat treatment for some applications such as cylinder head studs.

Any of this group of steels may be used for forgings, the selection being governed by the section size and the physical properties desired after heat treatment. Thus, SAE 1030 and 1035 are used for shifter forks and many small forgings where moderate properties are desired, but the deeper-hardening SAE 1036 is used for more critical parts where a higher strength level and more uniformity are essential, such as some front suspension parts. Forgings such as connecting rods, steering arms, truck front axles, axle shafts, and tractor wheels are commonly made from the SAE 1038 to 1045 group. Larger forgings at similar strength levels need more carbon and perhaps more manganese. Examples are crankshafts made from SAE 1046 and 1052. These steels are also used for small forgings where high hardness after oil quenching is desired. Suitable heat treatment is necessary on forgings from this group to provide machinability. These steels are also widely used for parts machined from bar stock, the selection following an identical pattern to that described for forgings. They are used both with and without heat treatment, depending on the application and the level of properties needed. As a class, they are considered good for normal machining operations. It is also possible to weld these steels by most commercial methods, but precautions should be taken to avoid cracking from too rapid cooling.

*SAE 1055, 1060, 1062, 1064, 1065, 1066, 1070, 1074, 1078, 1080, 1085, 1086, 1090, 1095:* Steels in this group are of the high-carbon type, having more carbon than is required to achieve maximum as quenched hardness. They are used for applications where the higher carbon is needed to improve wear characteristics for cutting edges, to make springs, and for special purposes. Selection of a particular grade is affected by the nature of the part, its end use, and the manufacturing methods available.

In general, cold-forming methods are not practical on this group of steels, being limited to flat stampings and springs coiled from small-diameter wire. Practically all parts from these steels are heat treated before use, with some variations in heat-treating methods to obtain optimum properties for the particular use to which the steel is to be put.

Uses in the spring industry include SAE 1065 for pretempered wire and SAE 1066 for cushion springs of hard-drawn wire, SAE 1064 may be used for small washers and thin stamped parts, SAE 1074 for light flat springs formed from annealed stock, and SAE 1080 and 1085 for thicker flat springs. SAE 1085 is also used for heavier coil springs. Valve spring wire and music wire are special products.

Due to good wear properties when properly heat-treated, the high-carbon steels find wide usage in the farm implement industry. SAE 1070 has been used for plow beams, SAE 1074 for plow shares, and SAE 1078 for such parts as rake teeth, scrapers, cultivator shovels, and plow shares. SAE 1085 has been used for scraper blades, disks, and for spring tooth harrows. SAE 1086 and 1090 find use as mower and binder sections, twine holders, and knottor disks.

*SAE 1111, 1112, 1113:* This class of steels is intended for those uses where easy machining is the primary requirement. They are characterized by a higher sulfur content than comparable carbon steels. This composition results in some sacrifice of cold-forming properties, weldability, and forging characteristics. In general, the uses are similar to those for carbon steels of similar carbon and manganese content.

These steels are commonly known as Bessemer screw stock, and are considered the best machining steels available, machinability improving within the group as sulfur increases. They are used for a wide variety of machined parts. Although of excellent strength in the

cold-drawn condition, they have an unfavorable property of cold shortness and are not commonly used for vital parts. These steels may be cyanided or carburized, but when uniform response to heat-treating is necessary, open-hearth steels are recommended.

*SAE 1109, 1114, 1115, 1116, 1117, 1118, 1119, 1120, 1126:* Steels in this group are used where a combination of good machinability and more uniform response to heat treatment is needed. The lower-carbon varieties are used for small parts that are to be cyanided or carbonitrided. SAE 1116, 1117, 1118, and 1119 carry more manganese for better hardenability, permitting oil quenching after case-hardening heat treatments in many instances. The higher-carbon SAE 1120 and 1126 provide more core hardness when this is needed.

*SAE 1132, 1137, 1138, 1140, 1141, 1144, 1145, 1146, 1151:* This group of steels has characteristics comparable to carbon steels of the same carbon level, except for changes due to higher sulfur as noted previously. They are widely used for parts where large amounts of machining are necessary, or where threads, splines, or other contours present special problems with tooling. SAE 1137, for example, is widely used for nuts and bolts and studs with machined threads. The higher-manganese SAE 1132, 1137, 1141, and 1144 offer greater hardenability, the higher-carbon types being suitable for oil quenching for many parts. All these steels may be selectively hardened by induction or flame heating if desired.

**Carburizing Grades of Alloy Steels.**—*Properties of the Case:* The properties of carburized and hardened cases (surface layers) depend on the carbon and alloy content, the structure of the case, and the degree and distribution of residual stresses. The carbon content of the case depends on the details of the carburizing process, and the response of iron and the alloying elements present, to carburization. The original carbon content of the steel has little or no effect on the carbon content produced in the case. The hardenability of the case, therefore, depends on the alloy content of the steel and the final carbon content produced by carburizing, but not on the initial carbon content of the steel.

With complete carbide solution, the effect of alloying elements on the hardenability of the case is about the same as the effect of these elements on the hardenability of the core. As an exception to this statement, any element that inhibits carburizing may reduce the hardenability of the case. Some elements that raise the hardenability of the core may tend to produce more retained austenite and consequently somewhat lower hardness in the case.

Alloy steels are frequently used for case hardening because the required surface hardness can be obtained by moderate speeds of quenching. Slower quenching may mean less distortion than would be encountered with water quenching. It is usually desirable to select a steel that will attain a minimum surface hardness of 58 or 60 Rockwell C after carburizing and oil quenching. Where section sizes are large, a high-hardenability alloy steel may be necessary, whereas for medium and light sections, low-hardenability steels will suffice.

In general, the case-hardening alloy steels may be divided into two classes as far as the hardenability of the case is concerned. Only the general type of steel (SAE 3300–4100, etc.) is discussed. The original carbon content of the steel has no effect on the carbon content of the case, so the last two digits in the specification numbers are not meaningful as far as the case is concerned.

a) High-Hardenability Case: SAE 2500, 3300, 4300, 4800, 9300

As these are high-alloy steels, both the case and the core have high hardenability. They are used particularly for carburized parts having thick sections, such as bevel drive pinions and heavy gears. Good case properties can be obtained by oil quenching. These steels are likely to have retained austenite in the case after carburizing and quenching; consequently, special precautions or treatments, such as refrigeration, may be required.

b) Medium-Hardenability Case: SAE 1300, 2300, 4000, 4100, 4600, 5100, 8600, 8700

Carburized cases of these steels have medium hardenability, which means that their hardenability is intermediate between that of plain carbon steel and the higher-alloy car-

burizing steels discussed earlier. In general, these steels can be used for average-size case-hardened automotive parts such as gears, pinions, piston pins, ball studs, universal joint crosses, crankshafts, etc. Satisfactory case hardness is usually produced by oil quenching.

**Core Properties:** The core properties of case-hardened steels depend on both carbon and alloy content of the steel. Each of the general types of alloy case-hardening steel is usually made with two or more carbon contents to permit different hardenability in the core.

The most desirable hardness for the core depends on the design and functioning of the individual part. In general, where high compressive loads are encountered, relatively high core hardness is beneficial in supporting the case. Low core hardnesses may be desirable where great toughness is essential.

The case-hardening steels may be divided into three general classes, depending on hardenability of the core.

a) Low-Hardenability Core: SAE 4017, 4023, 4024, 4027,\* 4028,\* 4608, 4615, 4617,\* 8615,\* 8617\*

b) Medium-Hardenability Core: SAE 1320, 2317, 2512, 2515,\* 3115, 3120, 4032, 4119, 4317, 4620, 4621, 4812, 4815,\* 5115, 5120, 8620, 8622, 8720, 9420

c) High-Hardenability Core: SAE 2517, 3310, 3316, 4320, 4817, 4820, 9310, 9315, 9317

**Heat Treatments:** In general, all the alloy carburizing steels are made with fine grain and most are suitable for direct quenching from the carburizing temperature. Several other types of heat treatment involving single and double quenching are also used for most of these steels. (See on page 532 and on page 533)

**Directly Hardenable Grades of Alloy Steels.**—These steels may be considered in five groups on the basis of approximate mean carbon content of the SAE specification. In general, the last two figures of the specification agree with the mean carbon content. Consequently the heading “0.30–0.37 Mean Carbon Content of SAE Specification” includes steels such as SAE 1330, 3135, and 4137.

It is necessary to deviate from the above plan in the classification of the carbon molybdenum steels. When carbon molybdenum steels are used, it is customary to specify higher carbon content for any given application than would be specified for other alloy steels, due to the low alloy content of these steels. For example, SAE 4063 is used for the same applications as SAE 4140, 4145, and 5150. Consequently, in the following discussion, the carbon molybdenum steels have been shown in the groups where they belong on the basis of applications rather than carbon content.

| Mean Carbon Content<br>of SAE Specification | Common Applications   |
|---|---|
| (a) 0.30–0.37 per cent                      | Heat-treated parts requiring moderate strength and great toughness.                     |
| (b) 0.40–0.42 per cent                      | Heat-treated parts requiring higher strength and good toughness.                        |
| (c) 0.45–0.50 per cent                      | Heat-treated parts requiring fairly high hardness and strength with moderate toughness. |
| (d) 0.50–0.62 per cent                      | Springs and hand tools.   |
| (e) 1.02 per cent                           | Ball and roller bearings.   |

For the present discussion, steels of each carbon content are divided into two or three groups on the basis of hardenability. Transformation ranges and consequently heat-treating practices vary somewhat with different alloying elements even though the hardenability is not changed.

**0.30–0.37 Mean Carbon Content of SAE Specification:** These steels are frequently used for water-quenched parts of moderate section size and for oil-quenched parts of small section size. Typical applications of these steels are connecting rods, steering arms and steering knuckles, axle shafts, bolts, studs, screws, and other parts requiring strength and

\* Borderline classifications might be considered in the next higher hardenability group.

toughness where section size is small enough to permit the desired physical properties to be obtained with the customary heat treatment.

Steels falling in this classification may be subdivided into two groups on the basis of hardenability:

- a) Low Hardenability: SAE 1330, 1335, 4037, 4042, 4130, 5130, 5132, 8630
- b) Medium Hardenability: SAE 2330, 3130, 3135, 4137, 5135, 8632, 8635, 8637, 8735, 9437

*0.40–0.42 Mean Carbon Content of SAE Specification:* In general, these steels are used for medium and large size parts requiring high degree of strength and toughness. The choice of the proper steel depends on the section size and the mechanical properties that must be produced. The low and medium hardenability steels are used for average size automotive parts such as steering knuckles, axle shafts, propeller shafts, etc. The high hardenability steels are used particularly for large axles and shafts for large aircraft parts.

These steels are usually considered as oil quenching steels, although some large parts made of the low and medium hardenability classifications may be quenched in water under properly controlled conditions.

These steels may be divided into three groups on the basis of hardenability:

- a) Low Hardenability: SAE 1340, 4047, 5140, 9440
- b) Medium Hardenability: SAE 2340, 3140, 3141, 4053, 4063, 4140, 4640, 8640, 8641, 8642, 8740, 8742, 9442
- c) High Hardenability: SAE 4340, 9840

*0.45–0.50 Mean Carbon Content of SAE Specification:* These steels are used primarily for gears and other parts requiring fairly high hardness as well as strength and toughness. Such parts are usually oil-quenched and a minimum of 90 per cent martensite in the as-quenched condition is desirable.

- a) Low Hardenability: SAE 5045, 5046, 5145, 9747, 9763
- b) Medium Hardenability: SAE 2345, 3145, 3150, 4145, 5147, 5150, 8645, 8647, 8650, 8745, 8747, 8750, 9445, 9845
- c) High Hardenability: SAE 4150, 9850

*0.50–0.63 Mean Carbon Content of SAE Specification:* These steels are used primarily for springs and hand tools. The hardenability necessary depends on the thickness of the material and the quenching practice.

- a) Medium hardenability: SAE 4068, 5150, 5152, 6150, 8650, 9254, 9255, 9260, 9261
- b) High Hardenability: SAE 8653, 8655, 8660, 9262

*1.02 Mean Carbon Content of SAE Specification—SAE 50100, 51100, 52100:* These straight chromium electric furnace steels are used primarily for the races and balls or rollers of antifriction bearings. They are also used for other parts requiring high hardness and wear resistance. The compositions of the three steels are identical, except for a variation in chromium, with a corresponding variation in hardenability.

- a) Low Hardenability: SAE 50100
- b) Medium Hardenability: SAE 51100, 52100

*Resulfurized Steel:* Some of the alloy steels, SAE 4024, 4028, and 8641, are made resulfurized so as to give better machinability at a relatively high hardness. In general, increased sulfur results in decreased transverse ductility, notched impact toughness, and weldability.

**Characteristics and Typical Applications of Standard Stainless Steels.**—Typical applications of various stainless steel alloys are given in the following. The first number given is the AISI designation followed by the UNS number in parenthesis. (See also *Numbering Systems for Metals and Alloys* on page 440)

*201 (S20100):* High work-hardening rate; low-nickel equivalent of type 301. Flatware; automobile wheel covers, trim.

*202 (S20200)*: General-purpose low-nickel equivalent of type 302. Kitchen equipment; hub caps; milk handling.

*205 (S20500)*: Lower work-hardening rate than type 202; used for spinning and special drawing operations. Nonmagnetic and cryogenic parts.

*301 (S30100)*: High work-hardening rate; used for structural applications where high strength plus high ductility are required. Railroad cars; trailer bodies; aircraft structurals; fasteners; automobile wheel covers, trim; pole line hardware.

*302 (S30200)*: General-purpose austenitic stainless steel. Trim; food-handling equipment; aircraft cowlings; antennas; springs; cookware; building exteriors; tanks; hospital, household appliances; jewelry; oil refining equipment; signs.

*302B (S30215)*: More resistant to scale than type 302. Furnace parts; still liners; heating elements; annealing covers; burner sections.

*303 (S30300)*: Free-machining modification of type 302, for heavier cuts. Screw machine products; shafts; valves; bolts; bushings; nuts.

*303Se (S30323)*: Free-machining modification of type 302, for lighter cuts; used where hot working or cold heading may be involved. Aircraft fittings; bolts; nuts; rivets; screws; studs.

*304 (S30400)*: Low-carbon modification of type 302 for restriction of carbide precipitation during welding. Chemical and food processing equipment; brewing equipment; cryogenic vessels; gutters; downspouts; flashings.

*304L (S30403)*: Extra-low-carbon modification of type 304 for further restriction of carbide precipitation during welding. Coal hopper linings; tanks for liquid fertilizer and tomato paste.

*304Cu (S30430)*: Lower work-hardening rate than type 304. Severe cold-heading applications.

*304N (S30451)*: Higher nitrogen than type 304 to increase strength with minimum effect on ductility and corrosion resistance, more resistant to increased magnetic permeability. Type 304 applications requiring higher strength.

*305 (S30500)*: Low work-hardening rate; used for spin forming, severe drawing, cold heading, and forming. Coffee urn tops; mixing bowls; reflectors.

*308 (S30800)*: Higher-alloy steel having high corrosion and heat resistance. Welding filler metals to compensate for alloy loss in welding; industrial furnaces.

*309 (S30900)*: High-temperature strength and scale resistance. Aircraft heaters; heat-treating equipment; annealing covers; furnace parts; heat exchangers; heat-treating trays; oven linings; pump parts.

*309S (S30908)*: Low-carbon modification of type 309. Welded constructions; assemblies subject to moist corrosion conditions.

*310 (S31000)*: Higher elevated temperature strength and scale resistance than type 309. Heat exchangers; furnace parts; combustion chambers; welding filler metals; gas-turbine parts; incinerators; recuperators; rolls for roller hearth furnaces.

*310S (S31008)*: Low-carbon modification of type 310. Welded constructions; jet engine rings.

*314 (S31400)*: More resistant to scale than type 310. Severe cold-heading or -forming applications. Annealing and carburizing boxes; heat-treating fixtures; radiant tubes.

*316 (S31600)*: Higher corrosion resistance than types 302 and 304; high creep strength. Chemical and pulp handling equipment; photographic equipment; brandy vats; fertilizer parts; ketchup cooking kettles; yeast tubs.

*316L (S31603)*: Extra-low-carbon modification of type 316. Welded construction where intergranular carbide precipitation must be avoided. Type 316 applications requiring extensive welding.

*316F (S31620)*: Higher phosphorus and sulfur than type 316 to improve machining and nonseizing characteristics. Automatic screw machine parts.

*316N (S31651)*: Higher nitrogen than type 316 to increase strength with minimum effect on ductility and corrosion resistance. Type 316 applications requiring extra strength.

317 (S31700): Higher corrosion and creep resistance than type 316. Dyeing and ink manufacturing equipment.

317L (S31703): Extra-low-carbon modification of type 317 for restriction of carbide precipitation during welding. Welded assemblies.

321 (S32100): Stabilized for weldments subject to severe corrosive conditions, and for service from 800 to 1650°F Aircraft exhaust manifolds; boiler shells; process equipment; expansion joints; cabin heaters; fire walls; flexible couplings; pressure vessels.

329 (S32900): Austenitic-ferritic type with general corrosion resistance similar to type 316 but with better resistance to stress-corrosion cracking; capable of age hardening. Valves; valve fittings; piping; pump parts.

330 (N08330): Good resistance to carburization and oxidation and to thermal shock. Heat-treating fixtures.

347 (S34700): Similar to type 321 with higher creep strength. Airplane exhaust stacks; welded tank cars for chemicals; jet engine parts.

348 (S34800): Similar to type 321; low retentivity. Tubes and pipes for radioactive systems; nuclear energy uses.

384 (S38400): Suitable for severe cold heading or cold forming; lower cold-work-hardening rate than type 305. Bolts; rivets; screws; instrument parts.

403 (S40300): "Turbine quality" grade. Steam turbine blading and other highly stressed parts including jet engine rings.

405 (S40500): Nonhardenable grade for assemblies where air-hardening types such as 410 or 403 are objectionable. Annealing boxes; quenching racks; oxidation-resistant partitions.

409 (S40900): General-purpose construction stainless. Automotive exhaust systems; transformer and capacitor cases; dry fertilizer spreaders; tanks for agricultural sprays.

410 (S41000): General-purpose heat-treatable type. Machine parts; pump shafts; bolts; bushings; coal chutes; cutlery; hardware; jet engine parts; mining machinery; rifle barrels; screws; valves.

414 (41400): High hardenability steel. Springs; tempered rules; machine parts, bolts; mining machinery; scissors; ships' bells; spindles; valve seats.

416 (S41600): Free-machining modification of type 410, for heavier cuts. Aircraft fittings; bolts; nuts; fire extinguisher inserts; rivets; screws.

416Se (S41623): Free-machining modification of type 410, for lighter cuts. Machined parts requiring hot working or cold heading.

420 (S42000): Higher carbon modification of type 410. Cutlery; surgical instruments; valves; wear-resisting parts; glass molds; hand tools; vegetable choppers.

420F (S42020): Free-machining modification of type 420. Applications similar to those for type 420 requiring better machinability.

422 (S42200): High strength and toughness at service temperatures up to 1200 degrees F. Steam turbine blades; fasteners.

429 (S42900): Improved weldability as compared to type 430. Nitric acid and nitrogen-fixation equipment.

430 (S43000): General-purpose nonhardenable chromium type. Decorative trim; nitric acid tanks; annealing baskets; combustion chambers; dishwashers; heaters; mufflers; range hoods; recuperators; restaurant equipment.

430F (S43020): Free-machining modification of type 430, for heavier cuts. Screw machine parts.

430FSe (S43023): Free-machining modification of type 430, for lighter cuts. Machined parts requiring light cold heading or forming.

431 (S43100): Special-purpose hardenable steel used where particularly high mechanical properties are required. Aircraft fittings; beater bars; paper machinery; bolts.

434 (S43400): Modification of type 430 designed to resist atmospheric corrosion in the presence of winter road conditioning and dust-laying compounds. Automotive trim and fasteners.



*436 (S43600)*: Similar to types 430 and 434. Used where low "roping" or "ridging" required. General corrosion and heat-resistant applications such as automobile trim.

*440A (S44002)*: Hardenable to higher hardness than type 420 with good corrosion resistance. Cutlery; bearings; surgical tools.

*440B (S44003)*: Cutlery grade. Cutlery, valve parts; instrument bearings.

*440C (S44004)*: Yields highest hardnesses of hardenable stainless steels. Balls; bearings; races; nozzles; balls and seats for oil well pumps; valve parts.

*442 (S44200)*: High-chromium steel, principally for parts that must resist high service temperatures without scaling. Furnace parts; nozzles; combustion chambers.

*446 (S44600)*: High-resistance to corrosion and scaling at high temperatures, especially for intermittent service; often used in sulfur-bearing atmosphere. Annealing boxes; combustion chambers; glass molds; heaters; pyrometer tubes; recuperators; stirring rods; valves.

*501 (S50100)*: Heat resistance; good mechanical properties at moderately elevated temperatures. Heat exchangers; petroleum refining equipment.

*502 (S50200)*: More ductility and less strength than type 501. Heat exchangers; petroleum refining equipment; gaskets.

**Chromium-Nickel Austenitic Steels** (Not capable of heat treatment).—*SAE 30201*:

This steel is an austenitic chromium–nickel–manganese stainless steel usually required in flat products. In the annealed condition, it exhibits higher strength values than the corresponding chromium–nickel stainless steel (SAE 30301). It is nonmagnetic in the annealed condition, but may be magnetic when cold-worked. SAE 30201 is used to obtain high strength by work-hardening and is well suited for corrosion-resistant structural members requiring high strength with low weight. It has excellent resistance to a wide variety of corrosive media, showing behavior comparable to stainless grade SAE 30301. It has high ductility and excellent forming properties. Owing to this steel's work-hardening rate and yield strength, tools for forming must be designed to allow for a higher springback or recovery rate. It is used for automotive trim, automotive wheel covers, railroad passenger car bodies and structural members, and truck trailer bodies.

*SAE 30202*: Like chromium–nickel stainless steel SAE 30302, this is a general-purpose stainless steel. It has excellent corrosion resistance and deep drawing qualities. It is nonhardenable by thermal treatments, but may be cold worked to high tensile strengths. In the annealed condition, it is nonmagnetic but slightly magnetic when cold-worked. Applications for this stainless steel are hub cap, railcar and truck trailer bodies, and spring wire.

*SAE 30301*: Capable of attaining high tensile strength and ductility by moderate or severe cold working. It is used largely in the cold-rolled or cold-drawn condition in the form of sheet, strip, and wire. Its corrosion resistance is good but not equal to SAE 30302.

*SAE 30302*: The most widely used of the general-purpose austenitic chromium–nickel stainless steels. It is used for deep drawing largely in the annealed condition. It can be worked to high tensile strengths but with slightly lower ductility than SAE 30301.

*SAE 30303F*: A free-machining steel recommended for the manufacture of parts produced on automatic screw machines. Caution must be used in forging this steel.

*SAE 30304*: Similar to SAE 30302 but somewhat superior in corrosion resistance and having superior welding properties for certain types of equipment.

*SAE 30305*: Similar to SAE 30304 but capable of lower hardness. Has greater ductility with slower work-hardening tendency.

*SAE 30309*: A steel with high heat-resisting qualities which is resistant to oxidation at temperatures up to about 1800 degrees F.

*SAE 30310*: This steel has the highest heat-resisting properties of the chromium nickel steels listed here and will resist oxidation at temperatures up to about 1900 degrees F.

*SAE 30316*: Recommended for use in parts where unusual resistance to chemical or salt water corrosion is necessary. It has superior creep strength at elevated temperatures.

*SAE 30317*: Similar to SAE 30316 but has the highest corrosion resistance of all these alloys in many environments.

*SAE 30321*: Recommended for use in the manufacture of welded structures where heat treatment after welding is not feasible. It is also recommended for use where temperatures up to 1600 degrees F are encountered in service.

*SAE 30325*: Used for such parts as heat control shafts.

*SAE 30347*: This steel is similar to SAE 30321. This niobium alloy is sometimes preferred to titanium because niobium is less likely to be lost in welding operations.

**Stainless Chromium Irons and Steels.**—*SAE 51409*: An 11 per cent chromium alloy developed, especially for automotive mufflers and tailpipes. Resistance to corrosion and oxidation is very similar to SAE 51410. It is nonhardenable and has good forming and welding characteristics. This alloy is recommended for mildly corrosive applications where surface appearance is not critical.

*SAE 51410*: A general-purpose stainless steel capable of heat treatment to show good physical properties. It is used for general stainless applications, both in the heat-treated and annealed condition but is not as resistant to corrosion as SAE 51430 in either the annealed or heat-treated condition.

*SAE 51414*: A corrosion and heat-resisting nickel-bearing chromium steel with somewhat better corrosion resistance than SAE 51410. It will attain slightly higher mechanical properties when heat-treated than SAE 51410. It is used in the form of tempered strip or wire, and in bars and forgings for heat-treated parts.

*SAE 51416F*: A free-machining grade for the manufacture of parts produced in automatic screw machines.

*SAE 51420*: This steel heat-treatable to a relatively high hardness. It will harden to a maximum of approximately 500 Brinell. Maximum corrosion resisting qualities exist only in the fully hardened condition. It is used for cutlery, hardened pump shafts, etc.

*SAE 51420F*: This is similar to SAE 51420 except for its free-machining properties.

*SAE 51430*: This high-chromium steel is not capable of heat treatment and is recommended for use in shallow parts requiring moderate draw. Corrosion and heat resistance are superior to SAE 51410.

*SAE 51430F*: This steel is similar to SAE 51430 except for its free-machining properties.

*SAE 51431*: This nickel-bearing chromium steel is designed for heat treatment to high mechanical properties. Its corrosion resistance is superior to other hardenable steels.

*SAE 51440A*: A hardenable chromium steel with greater quenched hardness than SAE 51420 and greater toughness than SAE 51440B and 51440C. Maximum corrosion resistance is obtained in the fully hardened and polished condition.

*SAE 51440B*: A hardenable chromium steel with greater quenched hardness than SAE 51440A. Maximum corrosion resistance is obtained in the fully hardened and polished condition. Capable of hardening to 50–60 Rockwell C depending on carbon content.

*SAE 51440C*: This steel has the greatest quenched hardness and wear resistance on heat treatment of any corrosion- or heat-resistant steel.

*SAE 51440F*: The same as SAE 51440C, except for its free-machining characteristics.

*SAE 51442*: A corrosion- and heat-resisting chromium steel with corrosion-resisting properties slightly better than SAE 51430 and with good scale resistance up to 1600 degrees F.

*SAE 51446*: A corrosion- and heat-resisting steel with maximum amount of chromium consistent with commercial malleability. Used principally for parts that must resist high temperatures in service without scaling. Resists oxidation up to 2000 degrees F.

*SAE 51501*: Used for its heat and corrosion resistance and good mechanical properties at temperatures up to approximately 1000 degrees F.

**High-Strength, Low-Alloy Steels.**—High-strength, low-alloy (HSLA) steel represents a specific group of steels in which enhanced mechanical properties and, sometimes, resistance to atmospheric corrosion are obtained by the addition of moderate amounts of one or more alloying elements other than carbon. Different types are available, some of which are carbon–manganese steels and others contain further alloy additions, governed by special requirements for weldability, formability, toughness, strength, and economics. These steels may be obtained in the form of sheet, strip, plates, structural shapes, bars, and bar size sections.

HSLA steels are especially characterized by their mechanical properties, obtained in the as-rolled condition. They are not intended for quenching and tempering. For certain applications, they are sometimes annealed, normalized, or stress relieved with some influence on mechanical properties.

Where these steels are used for fabrication by welding, care must be exercised in selection of grade and in the details of the welding process. Certain grades may be welded without preheat or postheat.

Because of their high strength-to-weight ratio, abrasion resistance, and, in certain compositions, improved atmospheric corrosion resistance, these steels are adapted particularly for use in mobile equipment and other structures where substantial weight savings are generally desirable. Typical applications are truck bodies, frames, structural members, scrapers, truck wheels, cranes, shovels, booms, chutes, and conveyors.

*Grade 942X:* A niobium- or vanadium-treated carbon–manganese high-strength steel similar to 945X and 945C except for somewhat improved welding and forming properties.

*Grade 945A:* A HSLA steel with excellent welding characteristics, both arc and resistance, and the best formability, weldability, and low-temperature notch toughness of the high-strength steels. It is generally used in sheets, strip, and light plate thicknesses.

*Grade 945C:* A carbon–manganese high-strength steel with satisfactory arc welding properties if adequate precautions are observed. It is similar to grade 950C, except that lower carbon and manganese improve arc welding characteristics, formability, and low-temperature notch toughness at some sacrifice in strength.

*Grade 945X:* A niobium- or vanadium-treated carbon–manganese high-strength steel similar to 945C, except for somewhat improved welding and forming properties.

*Grade 950A:* A HSLA steel with good weldability, both arc and resistance, with good low-temperature notch toughness, and good formability. It is generally used in sheet, strip, and light plate thicknesses.

*Grade 950B:* A HSLA steel with satisfactory arc welding properties and fairly good low-temperature notch toughness and formability.

*Grade 950C:* A carbon–manganese high-strength steel that can be arc welded with special precautions, but is unsuitable for resistance welding. The formability and toughness are fair.

*Grade 950D:* A HSLA steel with good weldability, both arc and resistance, and fairly good formability. Where low-temperature properties are important, the effect of phosphorus in conjunction with other elements present should be considered.

*Grade 950X:* A niobium- or vanadium-treated carbon–manganese high-strength steel similar to 950C, except for somewhat improved welding and forming properties.

*Grades 955X, 960X, 965X, 970X, 980X:* These are steels similar to 945X and 950X with higher strength obtained by increased amounts of strengthening elements, such as carbon or manganese, or by the addition of nitrogen up to about 0.015 per cent. This increased strength involves reduced formability and usually decreased weldability. Toughness will vary considerably with composition and mill practice.

The formability, composition, and minimum mechanical properties of the HSLA steel grades are shown in [Tables 7](#) through [Table 9](#) on page [463](#).

**Table 7. HSLA Steel Grades in Approximate Order of Increasing Excellence**

| Weldability      | Formability      | Toughness        |
|------------------|------------------|------------------|
| 980X             | 980X             | 980X             |
| 970X             | 970X             | 970X             |
| 965X             | 965X             | 965X             |
| 960X             | 960X             | 960X             |
| 955X, 950C, 942X | 955X             | 955X             |
| 945C             | 950C             | 945C, 950C, 942X |
| 950B, 950X       | 950D             | 945X, 950X       |
| 945X             | 950B, 950X, 942X | 950D             |
| 950D             | 945C, 945X       | 950B             |
| 950A             | 950A             | 950A             |
| 945A             | 945A             | 945A             |

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**Table 8. Chemical Composition Ladle Analysis of HSLA Steels (max. per cent)**

| Grade | C    | Mn   | P    | Grade | C    | Mn   | P    |
|-------|------|------|------|-------|------|------|------|
| 942X  | 0.21 | 1.35 | 0.04 | 950D  | 0.15 | 1.00 | 0.15 |
| 945A  | 0.15 | 1.00 | 0.04 | 950X  | 0.23 | 1.35 | 0.04 |
| 945C  | 0.23 | 1.40 | 0.04 | 955X  | 0.25 | 1.35 | 0.04 |
| 945X  | 0.22 | 1.35 | 0.04 | 960X  | 0.26 | 1.45 | 0.04 |
| 950A  | 0.15 | 1.30 | 0.04 | 965X  | 0.26 | 1.45 | 0.04 |
| 950B  | 0.22 | 1.30 | 0.04 | 970X  | 0.26 | 1.65 | 0.04 |
| 950C  | 0.25 | 1.60 | 0.04 | 980X  | 0.26 | 1.65 | 0.04 |

Sulfur, 0.05 per cent max; silicon, 0.90 per cent max.

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**Table 9. Minimum Mechanical Properties of High-strength Low-alloy Steels**

| Grade         | Form                                 | Strength <sup>a</sup> (psi) |         | % Elongation |       | Grade                 | Form                                 | Strength <sup>a</sup> (psi) |         | % Elongation |       |
|---------------|--------------------------------------|-----------------------------|---------|--------------|-------|-----------------------|--------------------------------------|-----------------------------|---------|--------------|-------|
|               |                                      | Yield                       | Tensile | 2 in.        | 8 in. |                       |                                      | Yield                       | Tensile | 2 in.        | 8 in. |
| 942X          | Plates, shapes, bars to 4 in. incl.  | 42,000                      | 60,000  | 24           | 20    | 955X                  | Sheet and strip                      | 55,000                      | 70,000  | 20           | ...   |
| 945A, C       | Sheet and strip                      | 45,000                      | 60,000  | 22           | ...   | 960X                  | Plates, shapes, bars To 1½ in. incl. | 55,000                      | 70,000  | ...          | 17    |
|               | Plates, shapes, bars To ½ in. incl.  | 45,000                      | 65,000  | 22           | 18    |                       | Sheet and strip                      | 60,000                      | 75,000  | 18           | ...   |
| 945X          | ½-1½ in. incl.                       | 42,000                      | 62,000  | 24           | 19    | 965X                  | Plates, shapes, bars To 1½ in. incl. | 60,000                      | 75,000  | ...          | 16    |
|               | 1½-3 in. incl.                       | 40,000                      | 62,000  | 24           | 19    |                       | Sheet and strip                      | 65,000                      | 80,000  | 16           | ...   |
|               | Sheet and strip                      | 45,000                      | 60,000  | 25           | ...   | 970X                  | Plates, shapes, bars To ¾ in. incl.  | 65,000                      | 80,000  | ...          | 15    |
|               | Plates, shapes, bars To 1½ in. incl. | 45,000                      | 60,000  | 22           | 19    |                       | Sheet and strip                      | 70,000                      | 85,000  | 14           | ...   |
| 950A, B, C, D | Sheet and strip                      | 50,000                      | 70,000  | 22           | ...   | 980X                  | Plates, shapes, bars To ¾ in. incl.  | 70,000                      | 85,000  | ...          | 14    |
|               | Plates, shapes, bars To ½ in. incl.  | 50,000                      | 70,000  | 22           | 18    |                       | Sheet and strip                      | 80,000                      | 95,000  | 12           | ...   |
|               | ½-1½ in. incl.                       | 45,000                      | 67,000  | 24           | 19    | Plates to ¾ in. incl. | 80,000                               | 95,000                      | ...     | 10           |       |
| 950X          | 1½-3 in. incl.                       | 42,000                      | 63,000  | 24           | 19    |                       |                                      |                             |         |              |       |
|               | Sheet and strip                      | 50,000                      | 65,000  | 22           | ...   |                       |                                      |                             |         |              |       |
|               | Plates, shapes, bars To 1½ in. incl. | 50,000                      | 65,000  | ...          | 18    |                       |                                      |                             |         |              |       |

<sup>a</sup>Yield strength to be measured at 0.2 per cent offset. Mechanical properties to be determined in accordance with ASTM A 370.

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**Typical Mechanical Properties of Steel.**—Tables 10 through 13 provide expected minimum and/or typical mechanical properties of selected standard carbon and alloy steels and stainless steels.

**Table 10. Expected Minimum Mechanical Properties of Cold-Drawn Carbon-Steel Rounds, Squares, and Hexagons**

| Size,<br>in.                        | As Cold-Drawn            |       |  |  |                          | Cold-Drawn Followed by<br>Low-Temperature Stress Relief |       |  |  |                       | Cold-Drawn Followed by<br>High-Temperature Stress Relief |       |  |  |                    |
|-------------------------------------|--------------------------|-------|--|--|--------------------------|---|-------|--|--|-----------------------|--|-------|--|--|--------------------|
|                                     | Strength                 |       | Elonga-<br>tion in<br>2 in.,<br>Per cent | Reduc-<br>tion in<br>Area,<br>Per cent | Hard-<br>ness,<br>Bhn    | Strength  |       | Elonga-<br>tion in<br>2 in.,<br>Per cent | Reduc-<br>tion in<br>Area,<br>Per cent | Hard-<br>ness,<br>Bhn | Strength   |       | Elonga-<br>tion in<br>2 in.,<br>Per cent | Reduc-<br>tion in<br>Area,<br>Per cent | Hard-<br>ness, Bhn |
|                                     | Tensile                  | Yield |  |  |                          | Tensile   | Yield |  |  |                       | Tensile  | Yield |  |  |                    |
|                                     | 1000 lb/in. <sup>2</sup> |       | 1000 lb/in. <sup>2</sup>                 |  | 1000 lb/in. <sup>2</sup> |   |       |  |  |                       |  |       |  |  |                    |
| AISI 1018 and 1025 Steels           |                          |       |  |  |                          |   |       |  |  |                       |  |       |  |  |                    |
| $\frac{5}{8}$ – $\frac{7}{8}$       | 70                       | 60    | 18                                       | 40                                     | 143                      | ....  | ....  | ....                                     | ....                                   | ...                   | 65   | 45    | 20                                       | 45                                     | 131                |
| Over $\frac{7}{8}$ – $1\frac{1}{4}$ | 65                       | 55    | 16                                       | 40                                     | 131                      | ....  | ....  | ....                                     | ....                                   | ...                   | 60   | 45    | 20                                       | 45                                     | 121                |
| Over $1\frac{1}{4}$ –2              | 60                       | 50    | 15                                       | 35                                     | 121                      | ....  | ....  | ....                                     | ....                                   | ...                   | 55   | 45    | 16                                       | 40                                     | 111                |
| Over 2–3                            | 55                       | 45    | 15                                       | 35                                     | 111                      | ....  | ....  | ....                                     | ....                                   | ...                   | 50   | 40    | 15                                       | 40                                     | 101                |
| AISI 1117 and 1118 Steels           |                          |       |  |  |                          |   |       |  |  |                       |  |       |  |  |                    |
| $\frac{5}{8}$ – $\frac{7}{8}$       | 75                       | 65    | 15                                       | 40                                     | 149                      | 80  | 70    | 15                                       | 40                                     | 163                   | 70   | 50    | 18                                       | 45                                     | 143                |
| Over $\frac{7}{8}$ – $1\frac{1}{4}$ | 70                       | 60    | 15                                       | 40                                     | 143                      | 75  | 65    | 15                                       | 40                                     | 149                   | 65   | 50    | 16                                       | 45                                     | 131                |
| Over $1\frac{1}{4}$ –2              | 65                       | 55    | 13                                       | 35                                     | 131                      | 70  | 60    | 13                                       | 35                                     | 143                   | 60   | 50    | 15                                       | 40                                     | 121                |
| Over 2–3                            | 60                       | 50    | 12                                       | 30                                     | 121                      | 65  | 55    | 12                                       | 35                                     | 131                   | 55   | 45    | 15                                       | 40                                     | 111                |
| AISI 1035 Steel                     |                          |       |  |  |                          |   |       |  |  |                       |  |       |  |  |                    |
| $\frac{5}{8}$ – $\frac{7}{8}$       | 85                       | 75    | 13                                       | 35                                     | 170                      | 90  | 80    | 13                                       | 35                                     | 179                   | 80   | 60    | 16                                       | 45                                     | 163                |
| Over $\frac{7}{8}$ – $1\frac{1}{4}$ | 80                       | 70    | 12                                       | 35                                     | 163                      | 85  | 75    | 12                                       | 35                                     | 170                   | 75   | 60    | 15                                       | 45                                     | 149                |
| Over $1\frac{1}{4}$ –2              | 75                       | 65    | 12                                       | 35                                     | 149                      | 80  | 70    | 12                                       | 35                                     | 163                   | 70   | 60    | 15                                       | 40                                     | 143                |
| Over 2–3                            | 70                       | 60    | 10                                       | 30                                     | 143                      | 75  | 65    | 10                                       | 30                                     | 149                   | 65   | 55    | 12                                       | 35                                     | 131                |
| AISI 1040 and 1140 Steels           |                          |       |  |  |                          |   |       |  |  |                       |  |       |  |  |                    |
| $\frac{5}{8}$ – $\frac{7}{8}$       | 90                       | 80    | 12                                       | 35                                     | 179                      | 95  | 85    | 12                                       | 35                                     | 187                   | 85   | 65    | 15                                       | 45                                     | 170                |
| Over $\frac{7}{8}$ – $1\frac{1}{4}$ | 85                       | 75    | 12                                       | 35                                     | 170                      | 90  | 80    | 12                                       | 35                                     | 179                   | 80   | 65    | 15                                       | 45                                     | 163                |
| Over $1\frac{1}{4}$ –2              | 80                       | 70    | 10                                       | 30                                     | 163                      | 85  | 75    | 10                                       | 30                                     | 170                   | 75   | 60    | 15                                       | 40                                     | 149                |
| Over 2–3                            | 75                       | 65    | 10                                       | 30                                     | 149                      | 80  | 70    | 10                                       | 30                                     | 163                   | 70   | 55    | 12                                       | 35                                     | 143                |

**Table 10. (Continued) Expected Minimum Mechanical Properties of Cold-Drawn Carbon-Steel Rounds, Squares, and Hexagons**

| Size,<br>in.                        | As Cold-Drawn            |       |  |  |                          | Cold-Drawn Followed by<br>Low-Temperature Stress Relief |       |  |  |                       | Cold-Drawn Followed by<br>High-Temperature Stress Relief |       |  |  |                    |
|-------------------------------------|--------------------------|-------|--|--|--------------------------|---|-------|--|--|-----------------------|--|-------|--|--|--------------------|
|                                     | Strength                 |       | Elonga-<br>tion in<br>2 in.,<br>Per cent | Reduc-<br>tion in<br>Area,<br>Per cent | Hard-<br>ness,<br>Bhn    | Strength  |       | Elonga-<br>tion in<br>2 in.,<br>Per cent | Reduc-<br>tion in<br>Area,<br>Per cent | Hard-<br>ness,<br>Bhn | Strength   |       | Elonga-<br>tion in<br>2 in.,<br>Per cent | Reduc-<br>tion in<br>Area,<br>Per cent | Hard-<br>ness, Bhn |
|                                     | Tensile                  | Yield |  |  |                          | Tensile   | Yield |  |  |                       | Tensile  | Yield |  |  |                    |
|                                     | 1000 lb/in. <sup>2</sup> |       | 1000 lb/in. <sup>2</sup>                 |  | 1000 lb/in. <sup>2</sup> |   |       |  |  |                       |  |       |  |  |                    |
| AISI 1045, 1145, and 1146 Steels    |                          |       |  |  |                          |   |       |  |  |                       |  |       |  |  |                    |
| $\frac{5}{8}$ - $\frac{7}{8}$       | 95                       | 85    | 12                                       | 35                                     | 187                      | 100   | 90    | 12                                       | 35                                     | 197                   | 90   | 70    | 15                                       | 45                                     | 179                |
| Over $\frac{7}{8}$ -1 $\frac{1}{4}$ | 90                       | 80    | 11                                       | 30                                     | 179                      | 95  | 85    | 11                                       | 30                                     | 187                   | 85   | 70    | 15                                       | 45                                     | 170                |
| Over 1 $\frac{1}{4}$ -2             | 85                       | 75    | 10                                       | 30                                     | 170                      | 90  | 80    | 10                                       | 30                                     | 179                   | 80   | 65    | 15                                       | 40                                     | 163                |
| Over 2-3                            | 80                       | 70    | 10                                       | 30                                     | 163                      | 85  | 75    | 10                                       | 25                                     | 170                   | 75   | 60    | 12                                       | 35                                     | 149                |
| AISI 1050, 1137, and 1151 Steels    |                          |       |  |  |                          |   |       |  |  |                       |  |       |  |  |                    |
| $\frac{5}{8}$ - $\frac{7}{8}$       | 100                      | 90    | 11                                       | 35                                     | 197                      | 105   | 95    | 11                                       | 35                                     | 212                   | 95   | 75    | 15                                       | 45                                     | 187                |
| Over $\frac{7}{8}$ -1 $\frac{1}{4}$ | 95                       | 85    | 11                                       | 30                                     | 187                      | 100   | 90    | 11                                       | 30                                     | 197                   | 90   | 75    | 15                                       | 40                                     | 179                |
| Over 1 $\frac{1}{4}$ -2             | 90                       | 80    | 10                                       | 30                                     | 179                      | 95  | 85    | 10                                       | 30                                     | 187                   | 85   | 70    | 15                                       | 40                                     | 170                |
| Over 2-3                            | 85                       | 75    | 10                                       | 30                                     | 170                      | 90  | 80    | 10                                       | 25                                     | 179                   | 80   | 65    | 12                                       | 35                                     | 163                |
| AISI 1141 Steel                     |                          |       |  |  |                          |   |       |  |  |                       |  |       |  |  |                    |
| $\frac{5}{8}$ - $\frac{7}{8}$       | 105                      | 95    | 11                                       | 30                                     | 212                      | 110   | 100   | 11                                       | 30                                     | 223                   | 100  | 80    | 15                                       | 40                                     | 197                |
| Over $\frac{7}{8}$ -1 $\frac{1}{4}$ | 100                      | 90    | 10                                       | 30                                     | 197                      | 105   | 95    | 10                                       | 30                                     | 212                   | 95   | 80    | 15                                       | 40                                     | 187                |
| Over 1 $\frac{1}{4}$ -2             | 95                       | 85    | 10                                       | 30                                     | 187                      | 100   | 90    | 10                                       | 25                                     | 197                   | 90   | 75    | 15                                       | 40                                     | 179                |
| Over 2-3                            | 90                       | 80    | 10                                       | 20                                     | 179                      | 95  | 85    | 10                                       | 20                                     | 187                   | 85   | 70    | 12                                       | 30                                     | 170                |
| AISI 1144 Steel                     |                          |       |  |  |                          |   |       |  |  |                       |  |       |  |  |                    |
| $\frac{5}{8}$ - $\frac{7}{8}$       | 110                      | 100   | 10                                       | 30                                     | 223                      | 115   | 105   | 10                                       | 30                                     | 229                   | 105  | 85    | 15                                       | 40                                     | 212                |
| Over $\frac{7}{8}$ -1 $\frac{1}{4}$ | 105                      | 95    | 10                                       | 30                                     | 212                      | 110   | 100   | 10                                       | 30                                     | 223                   | 100  | 85    | 15                                       | 40                                     | 197                |
| Over 1 $\frac{1}{4}$ -2             | 100                      | 90    | 10                                       | 25                                     | 197                      | 105   | 95    | 10                                       | 25                                     | 212                   | 95   | 80    | 15                                       | 35                                     | 187                |
| Over 2-3                            | 95                       | 85    | 10                                       | 20                                     | 187                      | 100   | 90    | 10                                       | 20                                     | 197                   | 90   | 75    | 12                                       | 30                                     | 179                |

Source: AISI Committee of Hot-Rolled and Cold-Finished Bar Producers and published in 1974 DATABOOK issue of the American Society for Metals' *METAL PROGRESS* magazine and used with its permission.

**Table 11a. Typical Mechanical Properties of Selected Carbon and Alloy Steels (Hot Rolled, Normalized, and Annealed)**

| AISI No. <sup>a</sup> | Treatment           | Strength            |        | Elongation, Per cent | Reduction in Area, Per cent | Hardness, Bhn | Impact Strength (Izod), ft-lb |
|-----------------------|---------------------|---------------------|--------|----------------------|-----------------------------|---------------|-------------------------------|
|                       |                     | Tensile             | Yield  |                      |                             |               |                               |
|                       |                     | lb/in. <sup>2</sup> |        |                      |                             |               |                               |
| 1015                  | As-rolled           | 61,000              | 45,500 | 39.0                 | 61.0                        | 126           | 81.5                          |
|                       | Normalized (1700 F) | 61,500              | 47,000 | 37.0                 | 69.6                        | 121           | 85.2                          |
|                       | Annealed (1600 F)   | 56,000              | 41,250 | 37.0                 | 69.7                        | 111           | 84.8                          |
| 1020                  | As-rolled           | 65,000              | 48,000 | 36.0                 | 59.0                        | 143           | 64.0                          |
|                       | Normalized (1600 F) | 64,000              | 50,250 | 35.8                 | 67.9                        | 131           | 86.8                          |
|                       | Annealed (1600 F)   | 57,250              | 42,750 | 36.5                 | 66.0                        | 111           | 91.0                          |
| 1022                  | As-rolled           | 73,000              | 52,000 | 35.0                 | 67.0                        | 149           | 60.0                          |
|                       | Normalized (1700 F) | 70,000              | 52,000 | 34.0                 | 67.5                        | 143           | 86.5                          |
|                       | Annealed (1600 F)   | 65,250              | 46,000 | 35.0                 | 63.6                        | 137           | 89.0                          |
| 1030                  | As-rolled           | 80,000              | 50,000 | 32.0                 | 57.0                        | 179           | 55.0                          |
|                       | Normalized (1700 F) | 75,000              | 50,000 | 32.0                 | 60.8                        | 149           | 69.0                          |
|                       | Annealed (1550 F)   | 67,250              | 49,500 | 31.2                 | 57.9                        | 126           | 51.2                          |
| 1040                  | As-rolled           | 90,000              | 60,000 | 25.0                 | 50.0                        | 201           | 36.0                          |
|                       | Normalized (1650 F) | 85,500              | 54,250 | 28.0                 | 54.9                        | 170           | 48.0                          |
|                       | Annealed (1450 F)   | 75,250              | 51,250 | 30.2                 | 57.2                        | 149           | 32.7                          |
| 1050                  | As-rolled           | 105,000             | 60,000 | 20.0                 | 40.0                        | 229           | 23.0                          |
|                       | Normalized (1650 F) | 108,500             | 62,000 | 20.0                 | 39.4                        | 217           | 20.0                          |
|                       | Annealed (1450 F)   | 92,250              | 53,000 | 23.7                 | 39.9                        | 187           | 12.5                          |
| 1060                  | As-rolled           | 118,000             | 70,000 | 17.0                 | 34.0                        | 241           | 13.0                          |
|                       | Normalized (1650 F) | 112,500             | 61,000 | 18.0                 | 37.2                        | 229           | 9.7                           |
|                       | Annealed (1450 F)   | 90,750              | 54,000 | 22.5                 | 38.2                        | 179           | 8.3                           |
| 1080                  | As-rolled           | 140,000             | 85,000 | 12.0                 | 17.0                        | 293           | 5.0                           |
|                       | Normalized (1650 F) | 146,500             | 76,000 | 11.0                 | 20.6                        | 293           | 5.0                           |
|                       | Annealed (1450 F)   | 89,250              | 54,500 | 24.7                 | 45.0                        | 174           | 4.5                           |
| 1095                  | As-rolled           | 140,000             | 83,000 | 9.0                  | 18.0                        | 293           | 3.0                           |
|                       | Normalized (1650 F) | 147,000             | 72,500 | 9.5                  | 13.5                        | 293           | 4.0                           |
|                       | Annealed (1450 F)   | 95,250              | 55,000 | 13.0                 | 20.6                        | 192           | 2.0                           |
| 1117                  | As-rolled           | 70,600              | 44,300 | 33.0                 | 63.0                        | 143           | 60.0                          |
|                       | Normalized (1650 F) | 67,750              | 44,000 | 33.5                 | 63.8                        | 137           | 62.8                          |
|                       | Annealed (1575 F)   | 62,250              | 40,500 | 32.8                 | 58.0                        | 121           | 69.0                          |
| 1118                  | As-rolled           | 75,600              | 45,900 | 32.0                 | 70.0                        | 149           | 80.0                          |
|                       | Normalized (1700 F) | 69,250              | 46,250 | 33.5                 | 65.9                        | 143           | 76.3                          |
|                       | Annealed (1450 F)   | 65,250              | 41,250 | 34.5                 | 66.8                        | 131           | 78.5                          |
| 1137                  | As-rolled           | 91,000              | 55,000 | 28.0                 | 61.0                        | 192           | 61.0                          |
|                       | Normalized (1650 F) | 97,000              | 57,500 | 22.5                 | 48.5                        | 197           | 47.0                          |
|                       | Annealed (1450 F)   | 84,750              | 50,000 | 26.8                 | 53.9                        | 174           | 36.8                          |
| 1141                  | As-rolled           | 98,000              | 52,000 | 22.0                 | 38.0                        | 192           | 8.2                           |
|                       | Normalized (1650 F) | 102,500             | 58,750 | 22.7                 | 55.5                        | 201           | 38.8                          |
|                       | Annealed (1500 F)   | 86,800              | 51,200 | 25.5                 | 49.3                        | 163           | 25.3                          |
| 1144                  | As-rolled           | 102,000             | 61,000 | 21.0                 | 41.0                        | 212           | 39.0                          |
|                       | Normalized (1650 F) | 96,750              | 58,000 | 21.0                 | 40.4                        | 197           | 32.0                          |
|                       | Annealed (1450 F)   | 84,750              | 50,250 | 24.8                 | 41.3                        | 167           | 48.0                          |

**Table 11a. (Continued) Typical Mechanical Properties of Selected Carbon and Alloy Steels (Hot Rolled, Normalized, and Annealed)**

| AISI No. <sup>a</sup> | Treatment           | Strength            |         | Elongation, Per cent | Reduction in Area, Per cent | Hardness, Bhn | Impact Strength (Izod), ft-lb |
|-----------------------|---------------------|---------------------|---------|----------------------|-----------------------------|---------------|-------------------------------|
|                       |                     | Tensile             | Yield   |                      |                             |               |                               |
|                       |                     | lb/in. <sup>2</sup> |         |                      |                             |               |                               |
| 1340                  | Normalized (1600 F) | 121,250             | 81,000  | 22.0                 | 62.9                        | 248           | 68.2                          |
|                       | Annealed (1475 F)   | 102,000             | 63,250  | 25.5                 | 57.3                        | 207           | 52.0                          |
| 3140                  | Normalized (1600 F) | 129,250             | 87,000  | 19.7                 | 57.3                        | 262           | 39.5                          |
|                       | Annealed (1500 F)   | 100,000             | 61,250  | 24.5                 | 50.8                        | 197           | 34.2                          |
| 4130                  | Normalized (1600 F) | 97,000              | 63,250  | 25.5                 | 59.5                        | 197           | 63.7                          |
|                       | Annealed (1585 F)   | 81,250              | 52,250  | 28.2                 | 55.6                        | 156           | 45.5                          |
| 4140                  | Normalized (1600 F) | 148,000             | 95,000  | 17.7                 | 46.8                        | 302           | 16.7                          |
|                       | Annealed (1500 F)   | 95,000              | 60,500  | 25.7                 | 56.9                        | 197           | 40.2                          |
| 4150                  | Normalized (1600 F) | 167,500             | 106,500 | 11.7                 | 30.8                        | 321           | 8.5                           |
|                       | Annealed (1500 F)   | 105,750             | 55,000  | 20.2                 | 40.2                        | 197           | 18.2                          |
| 4320                  | Normalized (1640 F) | 115,000             | 67,250  | 20.8                 | 50.7                        | 235           | 53.8                          |
|                       | Annealed (1560 F)   | 84,000              | 61,625  | 29.0                 | 58.4                        | 163           | 81.0                          |
| 4340                  | Normalized (1600 F) | 185,500             | 125,000 | 12.2                 | 36.3                        | 363           | 11.7                          |
|                       | Annealed (1490 F)   | 108,000             | 68,500  | 22.0                 | 49.9                        | 217           | 37.7                          |
| 4620                  | Normalized (1650 F) | 83,250              | 53,125  | 29.0                 | 66.7                        | 174           | 98.0                          |
|                       | Annealed (1575 F)   | 74,250              | 54,000  | 31.3                 | 60.3                        | 149           | 69.0                          |
| 4820                  | Normalized (1580 F) | 109,500             | 70,250  | 24.0                 | 59.2                        | 229           | 81.0                          |
|                       | Annealed (1500 F)   | 98,750              | 67,250  | 22.3                 | 58.8                        | 197           | 68.5                          |
| 5140                  | Normalized (1600 F) | 115,000             | 68,500  | 22.7                 | 59.2                        | 229           | 28.0                          |
|                       | Annealed (1525 F)   | 83,000              | 42,500  | 28.6                 | 57.3                        | 167           | 30.0                          |
| 5150                  | Normalized (1600 F) | 126,250             | 76,750  | 20.7                 | 58.7                        | 255           | 23.2                          |
|                       | Annealed (1520 F)   | 98,000              | 51,750  | 22.0                 | 43.7                        | 197           | 18.5                          |
| 5160                  | Normalized (1575 F) | 138,750             | 77,000  | 17.5                 | 44.8                        | 269           | 8.0                           |
|                       | Annealed (1495 F)   | 104,750             | 40,000  | 17.2                 | 30.6                        | 197           | 7.4                           |
| 6150                  | Normalized (1600 F) | 136,250             | 89,250  | 21.8                 | 61.0                        | 269           | 26.2                          |
|                       | Annealed (1500 F)   | 96,750              | 59,750  | 23.0                 | 48.4                        | 197           | 20.2                          |
| 8620                  | Normalized (1675 F) | 91,750              | 51,750  | 26.3                 | 59.7                        | 183           | 73.5                          |
|                       | Annealed (1600 F)   | 77,750              | 55,875  | 31.3                 | 62.1                        | 149           | 82.8                          |
| 8630                  | Normalized (1600 F) | 94,250              | 62,250  | 23.5                 | 53.5                        | 187           | 69.8                          |
|                       | Annealed (1550 F)   | 81,750              | 54,000  | 29.0                 | 58.9                        | 156           | 70.2                          |
| 8650                  | Normalized (1600 F) | 148,500             | 99,750  | 14.0                 | 40.4                        | 302           | 10.0                          |
|                       | Annealed (1465 F)   | 103,750             | 56,000  | 22.5                 | 46.4                        | 212           | 21.7                          |
| 8740                  | Normalized (1600 F) | 134,750             | 88,000  | 16.0                 | 47.9                        | 269           | 13.0                          |
|                       | Annealed (1500 F)   | 100,750             | 60,250  | 22.2                 | 46.4                        | 201           | 29.5                          |
| 9255                  | Normalized (1650 F) | 135,250             | 84,000  | 19.7                 | 43.4                        | 269           | 10.0                          |
|                       | Annealed (1550 F)   | 112,250             | 70,500  | 21.7                 | 41.1                        | 229           | 6.5                           |
| 9310                  | Normalized (1630 F) | 131,500             | 82,750  | 18.8                 | 58.1                        | 269           | 88.0                          |
|                       | Annealed (1550 F)   | 119,000             | 63,750  | 17.3                 | 42.1                        | 241           | 58.0                          |

<sup>a</sup> All grades are fine-grained except those in the 1100 series that are coarse-grained. Austenitizing temperatures are given in parentheses. Heat-treated specimens were oil-quenched unless otherwise indicated.

Source: Bethlehem Steel Corp. and Republic Steel Corp. as published in 1974 DATABOOK issue of the American Society for Metals' METAL PROGRESS magazine and used with its permission.



**Table 11b. Typical Mechanical Properties of Selected Carbon and Alloy Steels (Hot Rolled, Normalized, and Annealed)**

| AISI No. <sup>a</sup> | Tempering Temperature, °F | Strength                 |       | Elongation, Per cent | Reduction in Area, Per cent | Hardness, Bhn |
|-----------------------|---------------------------|--------------------------|-------|----------------------|-----------------------------|---------------|
|                       |                           | Tensile                  | Yield |                      |                             |               |
|                       |                           | 1000 lb/in. <sup>2</sup> |       |                      |                             |               |
| 1030 <sup>b</sup>     | 400                       | 123                      | 94    | 17                   | 47                          | 495           |
|                       | 600                       | 116                      | 90    | 19                   | 53                          | 401           |
|                       | 800                       | 106                      | 84    | 23                   | 60                          | 302           |
|                       | 1000                      | 97                       | 75    | 28                   | 65                          | 255           |
|                       | 1200                      | 85                       | 64    | 32                   | 70                          | 207           |
| 1040 <sup>b</sup>     | 400                       | 130                      | 96    | 16                   | 45                          | 514           |
|                       | 600                       | 129                      | 94    | 18                   | 52                          | 444           |
|                       | 800                       | 122                      | 92    | 21                   | 57                          | 352           |
|                       | 1000                      | 113                      | 86    | 23                   | 61                          | 269           |
|                       | 1200                      | 97                       | 72    | 28                   | 68                          | 201           |
| 1040                  | 400                       | 113                      | 86    | 19                   | 48                          | 262           |
|                       | 600                       | 113                      | 86    | 20                   | 53                          | 255           |
|                       | 800                       | 110                      | 80    | 21                   | 54                          | 241           |
|                       | 1000                      | 104                      | 71    | 26                   | 57                          | 212           |
|                       | 1200                      | 92                       | 63    | 29                   | 65                          | 192           |
| 1050 <sup>b</sup>     | 400                       | 163                      | 117   | 9                    | 27                          | 514           |
|                       | 600                       | 158                      | 115   | 13                   | 36                          | 444           |
|                       | 800                       | 145                      | 110   | 19                   | 48                          | 375           |
|                       | 1000                      | 125                      | 95    | 23                   | 58                          | 293           |
|                       | 1200                      | 104                      | 78    | 28                   | 65                          | 235           |
| 1050                  | 400                       | ...                      | ...   | ...                  | ...                         | ...           |
|                       | 600                       | 142                      | 105   | 14                   | 47                          | 321           |
|                       | 800                       | 136                      | 95    | 20                   | 50                          | 277           |
|                       | 1000                      | 127                      | 84    | 23                   | 53                          | 262           |
|                       | 1200                      | 107                      | 68    | 29                   | 60                          | 223           |
| 1060                  | 400                       | 160                      | 113   | 13                   | 40                          | 321           |
|                       | 600                       | 160                      | 113   | 13                   | 40                          | 321           |
|                       | 800                       | 156                      | 111   | 14                   | 41                          | 311           |
|                       | 1000                      | 140                      | 97    | 17                   | 45                          | 277           |
|                       | 1200                      | 116                      | 76    | 23                   | 54                          | 229           |
| 1080                  | 400                       | 190                      | 142   | 12                   | 35                          | 388           |
|                       | 600                       | 189                      | 142   | 12                   | 35                          | 388           |
|                       | 800                       | 187                      | 138   | 13                   | 36                          | 375           |
|                       | 1000                      | 164                      | 117   | 16                   | 40                          | 321           |
|                       | 1200                      | 129                      | 87    | 21                   | 50                          | 255           |
| 1095 <sup>b</sup>     | 400                       | 216                      | 152   | 10                   | 31                          | 601           |
|                       | 600                       | 212                      | 150   | 11                   | 33                          | 534           |
|                       | 800                       | 199                      | 139   | 13                   | 35                          | 388           |
|                       | 1000                      | 165                      | 110   | 15                   | 40                          | 293           |
|                       | 1200                      | 122                      | 85    | 20                   | 47                          | 235           |
| 1095                  | 400                       | 187                      | 120   | 10                   | 30                          | 401           |
|                       | 600                       | 183                      | 118   | 10                   | 30                          | 375           |
|                       | 800                       | 176                      | 112   | 12                   | 32                          | 363           |
|                       | 1000                      | 158                      | 98    | 15                   | 37                          | 321           |
|                       | 1200                      | 130                      | 80    | 21                   | 47                          | 269           |
| 1137                  | 400                       | 157                      | 136   | 5                    | 22                          | 352           |
|                       | 600                       | 143                      | 122   | 10                   | 33                          | 285           |
|                       | 800                       | 127                      | 106   | 15                   | 48                          | 262           |
|                       | 1000                      | 110                      | 88    | 24                   | 62                          | 229           |
|                       | 1200                      | 95                       | 70    | 28                   | 69                          | 197           |

**Table 11b. (Continued) Typical Mechanical Properties of Selected Carbon and Alloy Steels (Hot Rolled, Normalized, and Annealed)**

| AISI No. <sup>a</sup> | Tempering Temperature, °F | Strength                 |       | Elongation, Per cent | Reduction in Area, Per cent | Hardness, Bhn |
|-----------------------|---------------------------|--------------------------|-------|----------------------|-----------------------------|---------------|
|                       |                           | Tensile                  | Yield |                      |                             |               |
|                       |                           | 1000 lb/in. <sup>2</sup> |       |                      |                             |               |
| 1137 <sup>b</sup>     | 400                       | 217                      | 169   | 5                    | 17                          | 415           |
|                       | 600                       | 199                      | 163   | 9                    | 25                          | 375           |
|                       | 800                       | 160                      | 143   | 14                   | 40                          | 311           |
|                       | 1000                      | 120                      | 105   | 19                   | 60                          | 262           |
|                       | 1200                      | 94                       | 77    | 25                   | 69                          | 187           |
| 1141                  | 400                       | 237                      | 176   | 6                    | 17                          | 461           |
|                       | 600                       | 212                      | 186   | 9                    | 32                          | 415           |
|                       | 800                       | 169                      | 150   | 12                   | 47                          | 331           |
|                       | 1000                      | 130                      | 111   | 18                   | 57                          | 262           |
| 1144                  | 400                       | 103                      | 86    | 23                   | 62                          | 217           |
|                       | 600                       | 127                      | 91    | 17                   | 36                          | 277           |
|                       | 800                       | 126                      | 90    | 17                   | 40                          | 262           |
|                       | 1000                      | 123                      | 88    | 18                   | 42                          | 248           |
|                       | 1200                      | 117                      | 83    | 20                   | 46                          | 235           |
| 1330 <sup>b</sup>     | 400                       | 105                      | 73    | 23                   | 55                          | 217           |
|                       | 600                       | 232                      | 211   | 9                    | 39                          | 459           |
|                       | 800                       | 207                      | 186   | 9                    | 44                          | 402           |
|                       | 1000                      | 168                      | 150   | 15                   | 53                          | 335           |
|                       | 1200                      | 127                      | 112   | 18                   | 60                          | 263           |
| 1340                  | 400                       | 106                      | 83    | 23                   | 63                          | 216           |
|                       | 600                       | 262                      | 231   | 11                   | 35                          | 505           |
|                       | 800                       | 230                      | 206   | 12                   | 43                          | 453           |
|                       | 1000                      | 183                      | 167   | 14                   | 51                          | 375           |
|                       | 1200                      | 140                      | 120   | 17                   | 58                          | 295           |
| 4037                  | 400                       | 116                      | 90    | 22                   | 66                          | 252           |
|                       | 600                       | 149                      | 110   | 6                    | 38                          | 310           |
|                       | 800                       | 138                      | 111   | 14                   | 53                          | 295           |
|                       | 1000                      | 127                      | 106   | 20                   | 60                          | 270           |
|                       | 1200                      | 115                      | 95    | 23                   | 63                          | 247           |
| 4042                  | 400                       | 101                      | 61    | 29                   | 60                          | 220           |
|                       | 600                       | 261                      | 241   | 12                   | 37                          | 516           |
|                       | 800                       | 234                      | 211   | 13                   | 42                          | 455           |
|                       | 1000                      | 187                      | 170   | 15                   | 51                          | 380           |
|                       | 1200                      | 143                      | 128   | 20                   | 59                          | 300           |
| 4130 <sup>b</sup>     | 400                       | 115                      | 100   | 28                   | 66                          | 238           |
|                       | 600                       | 236                      | 212   | 10                   | 41                          | 467           |
|                       | 800                       | 217                      | 200   | 11                   | 43                          | 435           |
|                       | 1000                      | 186                      | 173   | 13                   | 49                          | 380           |
|                       | 1200                      | 150                      | 132   | 17                   | 57                          | 315           |
| 4140                  | 400                       | 118                      | 102   | 22                   | 64                          | 245           |
|                       | 600                       | 257                      | 238   | 8                    | 38                          | 510           |
|                       | 800                       | 225                      | 208   | 9                    | 43                          | 445           |
|                       | 1000                      | 181                      | 165   | 13                   | 49                          | 370           |
|                       | 1200                      | 138                      | 121   | 18                   | 58                          | 285           |
| 4150                  | 400                       | 110                      | 95    | 22                   | 63                          | 230           |
|                       | 600                       | 280                      | 250   | 10                   | 39                          | 530           |
|                       | 800                       | 256                      | 231   | 10                   | 40                          | 495           |
|                       | 1000                      | 220                      | 200   | 12                   | 45                          | 440           |
|                       | 1200                      | 175                      | 160   | 15                   | 52                          | 370           |
| 4340                  | 400                       | 139                      | 122   | 19                   | 60                          | 290           |
|                       | 600                       | 272                      | 243   | 10                   | 38                          | 520           |
|                       | 800                       | 250                      | 230   | 10                   | 40                          | 486           |
|                       | 1000                      | 213                      | 198   | 10                   | 44                          | 430           |
|                       | 1200                      | 170                      | 156   | 13                   | 51                          | 360           |
|                       |                           | 140                      | 124   | 19                   | 60                          | 280           |

**Table 11b. (Continued) Typical Mechanical Properties of Selected Carbon and Alloy Steels (Hot Rolled, Normalized, and Annealed)**

| AISI No. <sup>a</sup> | Tempering Temperature, °F | Strength                 |       | Elongation, Per cent | Reduction in Area, Per cent | Hardness, Bhn |
|-----------------------|---------------------------|--------------------------|-------|----------------------|-----------------------------|---------------|
|                       |                           | Tensile                  | Yield |                      |                             |               |
|                       |                           | 1000 lb/in. <sup>2</sup> |       |                      |                             |               |
| 5046                  | 400                       | 253                      | 204   | 9                    | 25                          | 482           |
|                       | 600                       | 205                      | 168   | 10                   | 37                          | 401           |
|                       | 800                       | 165                      | 135   | 13                   | 50                          | 336           |
|                       | 1000                      | 136                      | 111   | 18                   | 61                          | 282           |
|                       | 1200                      | 114                      | 95    | 24                   | 66                          | 235           |
| 50B46                 | 400                       | ...                      | ...   | ...                  | ...                         | 560           |
|                       | 600                       | 258                      | 235   | 10                   | 37                          | 505           |
|                       | 800                       | 202                      | 181   | 13                   | 47                          | 405           |
|                       | 1000                      | 157                      | 142   | 17                   | 51                          | 322           |
|                       | 1200                      | 128                      | 115   | 22                   | 60                          | 273           |
| 50B60                 | 400                       | ...                      | ...   | ...                  | ...                         | 600           |
|                       | 600                       | 273                      | 257   | 8                    | 32                          | 525           |
|                       | 800                       | 219                      | 201   | 11                   | 34                          | 435           |
|                       | 1000                      | 163                      | 145   | 15                   | 38                          | 350           |
|                       | 1200                      | 130                      | 113   | 19                   | 50                          | 290           |
| 5130                  | 400                       | 234                      | 220   | 10                   | 40                          | 475           |
|                       | 600                       | 217                      | 204   | 10                   | 46                          | 440           |
|                       | 800                       | 185                      | 175   | 12                   | 51                          | 379           |
|                       | 1000                      | 150                      | 136   | 15                   | 56                          | 305           |
|                       | 1200                      | 115                      | 100   | 20                   | 63                          | 245           |
| 5140                  | 400                       | 260                      | 238   | 9                    | 38                          | 490           |
|                       | 600                       | 229                      | 210   | 10                   | 43                          | 450           |
|                       | 800                       | 190                      | 170   | 13                   | 50                          | 365           |
|                       | 1000                      | 145                      | 125   | 17                   | 58                          | 280           |
|                       | 1200                      | 110                      | 96    | 25                   | 66                          | 235           |
| 5150                  | 400                       | 282                      | 251   | 5                    | 37                          | 525           |
|                       | 600                       | 252                      | 230   | 6                    | 40                          | 475           |
|                       | 800                       | 210                      | 190   | 9                    | 47                          | 410           |
|                       | 1000                      | 163                      | 150   | 15                   | 54                          | 340           |
|                       | 1200                      | 117                      | 118   | 20                   | 60                          | 270           |
| 5160                  | 400                       | 322                      | 260   | 4                    | 10                          | 627           |
|                       | 600                       | 290                      | 257   | 9                    | 30                          | 555           |
|                       | 800                       | 233                      | 212   | 10                   | 37                          | 461           |
|                       | 1000                      | 169                      | 151   | 12                   | 47                          | 341           |
|                       | 1200                      | 130                      | 116   | 20                   | 56                          | 269           |
| 51B60                 | 400                       | ...                      | ...   | ...                  | ...                         | 600           |
|                       | 600                       | ...                      | ...   | ...                  | ...                         | 540           |
|                       | 800                       | 237                      | 216   | 11                   | 36                          | 460           |
|                       | 1000                      | 175                      | 160   | 15                   | 44                          | 355           |
|                       | 1200                      | 140                      | 126   | 20                   | 47                          | 290           |
| 6150                  | 400                       | 280                      | 245   | 8                    | 38                          | 538           |
|                       | 600                       | 250                      | 228   | 8                    | 39                          | 483           |
|                       | 800                       | 208                      | 193   | 10                   | 43                          | 420           |
|                       | 1000                      | 168                      | 155   | 13                   | 50                          | 345           |
|                       | 1200                      | 137                      | 122   | 17                   | 58                          | 282           |
| 81B45                 | 400                       | 295                      | 250   | 10                   | 33                          | 550           |
|                       | 600                       | 256                      | 228   | 8                    | 42                          | 475           |
|                       | 800                       | 204                      | 190   | 11                   | 48                          | 405           |
|                       | 1000                      | 160                      | 149   | 16                   | 53                          | 338           |
|                       | 1200                      | 130                      | 115   | 20                   | 55                          | 280           |

**Table 11b. (Continued) Typical Mechanical Properties of Selected Carbon and Alloy Steels (Hot Rolled, Normalized, and Annealed)**

| AISI No. <sup>a</sup> | Tempering Temperature, °F | Strength                 |       | Elongation, Per cent | Reduction in Area, Per cent | Hardness, Bhn |
|-----------------------|---------------------------|--------------------------|-------|----------------------|-----------------------------|---------------|
|                       |                           | Tensile                  | Yield |                      |                             |               |
|                       |                           | 1000 lb/in. <sup>2</sup> |       |                      |                             |               |
| 8630                  | 400                       | 238                      | 218   | 9                    | 38                          | 465           |
|                       | 600                       | 215                      | 202   | 10                   | 42                          | 430           |
|                       | 800                       | 185                      | 170   | 13                   | 47                          | 375           |
|                       | 1000                      | 150                      | 130   | 17                   | 54                          | 310           |
|                       | 1200                      | 112                      | 100   | 23                   | 63                          | 240           |
| 8640                  | 400                       | 270                      | 242   | 10                   | 40                          | 505           |
|                       | 600                       | 240                      | 220   | 10                   | 41                          | 460           |
|                       | 800                       | 200                      | 188   | 12                   | 45                          | 400           |
|                       | 1000                      | 160                      | 150   | 16                   | 54                          | 340           |
| 86B45                 | 1200                      | 130                      | 116   | 20                   | 62                          | 280           |
|                       | 400                       | 287                      | 238   | 9                    | 31                          | 525           |
|                       | 600                       | 246                      | 225   | 9                    | 40                          | 475           |
| 86B45                 | 800                       | 200                      | 191   | 11                   | 41                          | 395           |
|                       | 1000                      | 160                      | 150   | 15                   | 49                          | 335           |
|                       | 1200                      | 131                      | 127   | 19                   | 58                          | 280           |
|                       | 400                       | 281                      | 243   | 10                   | 38                          | 525           |
| 8650                  | 600                       | 250                      | 225   | 10                   | 40                          | 490           |
|                       | 800                       | 210                      | 192   | 12                   | 45                          | 420           |
|                       | 1000                      | 170                      | 153   | 15                   | 51                          | 340           |
|                       | 1200                      | 140                      | 120   | 20                   | 58                          | 280           |
| 8660                  | 400                       | ...                      | ...   | ...                  | ...                         | 580           |
|                       | 600                       | ...                      | ...   | ...                  | ...                         | 535           |
|                       | 800                       | 237                      | 225   | 13                   | 37                          | 460           |
|                       | 1000                      | 190                      | 176   | 17                   | 46                          | 370           |
|                       | 1200                      | 155                      | 138   | 20                   | 53                          | 315           |
| 8740                  | 400                       | 290                      | 240   | 10                   | 41                          | 578           |
|                       | 600                       | 249                      | 225   | 11                   | 46                          | 495           |
|                       | 800                       | 208                      | 197   | 13                   | 50                          | 415           |
|                       | 1000                      | 175                      | 165   | 15                   | 55                          | 363           |
|                       | 1200                      | 143                      | 131   | 20                   | 60                          | 302           |
| 9255                  | 400                       | 305                      | 297   | 1                    | 3                           | 601           |
|                       | 600                       | 281                      | 260   | 4                    | 10                          | 578           |
|                       | 800                       | 233                      | 216   | 8                    | 22                          | 477           |
|                       | 1000                      | 182                      | 160   | 15                   | 32                          | 352           |
|                       | 1200                      | 144                      | 118   | 20                   | 42                          | 285           |
| 9260                  | 400                       | ...                      | ...   | ...                  | ...                         | 600           |
|                       | 600                       | ...                      | ...   | ...                  | ...                         | 540           |
|                       | 800                       | 255                      | 218   | 8                    | 24                          | 470           |
|                       | 1000                      | 192                      | 164   | 12                   | 30                          | 390           |
|                       | 1200                      | 142                      | 118   | 20                   | 43                          | 295           |
| 94B30                 | 400                       | 250                      | 225   | 12                   | 46                          | 475           |
|                       | 600                       | 232                      | 206   | 12                   | 49                          | 445           |
|                       | 800                       | 195                      | 175   | 13                   | 57                          | 382           |
|                       | 1000                      | 145                      | 135   | 16                   | 65                          | 307           |
|                       | 1200                      | 120                      | 105   | 21                   | 69                          | 250           |

<sup>a</sup> All grades are fine-grained except those in the 1100 series that are coarse-grained. Austenitizing temperatures are given in parentheses. Heat-treated specimens were oil-quenched unless otherwise indicated.

<sup>b</sup> Water quenched.

Source: Bethlehem Steel Corp. and Republic Steel Corp. as published in 1974 DATABOOK issue of the American Society for Metals' *METAL PROGRESS* magazine and used with its permission.

**Table 12. Nominal Mechanical Properties of Standard Stainless Steels**

| Grade                | Condition                           | Tensile Strength (psi) | 0.2 Per Cent Yield Strength (psi) | Elongation in 2 in. (%) | Reduction of Area (%) | Hardness |     |
|----------------------|-------------------------------------|------------------------|-----------------------------------|-------------------------|-----------------------|----------|-----|
|                      |                                     |                        |                                   |                         |                       | Rockwell | Bhn |
| Austenitic Steels    |                                     |                        |                                   |                         |                       |          |     |
| 201                  | Annealed                            | 115,000                | 55,000                            | 55                      | ...                   | B90      | ... |
|                      | 1/4-hard                            | 125,000 <sup>a</sup>   | 75,000 <sup>a</sup>               | 20 <sup>a</sup>         | ...                   | C25      | ... |
|                      | 1/2-hard                            | 150,000 <sup>a</sup>   | 110,000 <sup>a</sup>              | 10 <sup>a</sup>         | ...                   | C32      | ... |
|                      | 3/4-hard                            | 175,000 <sup>a</sup>   | 135,000 <sup>a</sup>              | 5 <sup>a</sup>          | ...                   | C37      | ... |
|                      | Full-hard                           | 185,000 <sup>a</sup>   | 140,000 <sup>a</sup>              | 4 <sup>a</sup>          | ...                   | C41      | ... |
| 202                  | Annealed                            | 105,000                | 55,000                            | 55                      | ...                   | B90      | ... |
|                      | 1/4-hard                            | 125,000 <sup>a</sup>   | 75,000 <sup>a</sup>               | 12 <sup>a</sup>         | ...                   | C27      | ... |
| 301                  | Annealed                            | 110,000                | 40,000                            | 60                      | ...                   | B85      | 165 |
|                      | 1/4-hard                            | 125,000 <sup>a</sup>   | 75,000 <sup>a</sup>               | 25 <sup>a</sup>         | ...                   | C25      | ... |
|                      | 1/2-hard                            | 150,000 <sup>a</sup>   | 110,000 <sup>a</sup>              | 15 <sup>a</sup>         | ...                   | C32      | ... |
|                      | 3/4-hard                            | 175,000 <sup>a</sup>   | 135,000 <sup>a</sup>              | 12 <sup>a</sup>         | ...                   | C37      | ... |
|                      | Full-hard                           | 185,000                | 140,000 <sup>a</sup>              | 8 <sup>a</sup>          | ...                   | C41      | ... |
| 302                  | Annealed                            | 90,000                 | 37,000                            | 55                      | 65                    | B82      | 155 |
|                      | 1/4-hard (sheet, strip)             | 125,000 <sup>a</sup>   | 75,000 <sup>a</sup>               | 12 <sup>a</sup>         | ...                   | C25      | ... |
|                      | Cold-drawn (bar, wire) <sup>b</sup> | To 350,000             | ...                               | ...                     | ...                   | ...      | ... |
| 302B                 | Annealed                            | 95,000                 | 40,000                            | 50                      | 65                    | B85      | 165 |
| 303, 303Se           | Annealed                            | 90,000                 | 35,000                            | 50                      | 55                    | B84      | 160 |
| 304                  | Annealed                            | 85,000                 | 35,000                            | 55                      | 65                    | B80      | 150 |
| 304L                 | Annealed                            | 80,000                 | 30,000                            | 55                      | 65                    | B76      | 140 |
| 305                  | Annealed                            | 85,000                 | 37,000                            | 55                      | 70                    | B82      | 156 |
| 308                  | Annealed                            | 85,000                 | 35,000                            | 55                      | 65                    | B80      | 150 |
| 309, 309S            | Annealed                            | 90,000                 | 40,000                            | 45                      | 65                    | B85      | 165 |
| 310, 310S            | Annealed                            | 95,000                 | 40,000                            | 45                      | 65                    | B87      | 170 |
| 314                  | Annealed                            | 100,000                | 50,000                            | 45                      | 60                    | B87      | 170 |
| 316                  | Annealed                            | 85,000                 | 35,000                            | 55                      | 70                    | B80      | 150 |
|                      | Cold-drawn (bar, wire) <sup>b</sup> | To 300,000             | ...                               | ...                     | ...                   | ...      | ... |
| 316L                 | Annealed                            | 78,000                 | 30,000                            | 55                      | 65                    | B76      | 145 |
| 317                  | Annealed                            | 90,000                 | 40,000                            | 50                      | 55                    | B85      | 160 |
| 321                  | Annealed                            | 87,000                 | 35,000                            | 55                      | 65                    | B80      | 150 |
| 347, 348             | Annealed                            | 92,000                 | 35,000                            | 50                      | 65                    | B84      | 160 |
| Martensitic Steels   |                                     |                        |                                   |                         |                       |          |     |
| 403, 410, 416, 416Se | Annealed                            | 75,000                 | 40,000                            | 30                      | 65                    | B82      | 155 |
|                      | Hardened <sup>c</sup>               | ...                    | ...                               | ...                     | ...                   | C43      | 410 |
|                      | Tempered at                         |                        |                                   |                         |                       |          |     |
|                      | 400°F                               | 190,000                | 145,000                           | 15                      | 55                    | C41      | 390 |
|                      | 600°F                               | 180,000                | 140,000                           | 15                      | 55                    | C39      | 375 |
|                      | 800°F                               | 195,000                | 150,000                           | 17                      | 55                    | C41      | 390 |
|                      | 1000°F                              | 145,000                | 115,000                           | 20                      | 65                    | C31      | 300 |
|                      | 1200°F                              | 110,000                | 85,000                            | 23                      | 65                    | B97      | 225 |
|                      | 1400°F                              | 90,000                 | 60,000                            | 30                      | 70                    | B89      | 180 |

**Table 12. (Continued) Nominal Mechanical Properties of Standard Stainless Steels**

| Grade                          | Condition             | Tensile Strength (psi) | 0.2 Per Cent Yield Strength (psi) | Elongation in 2 in. (%) | Reduction of Area (%) | Hardness |     |     |
|--------------------------------|-----------------------|------------------------|-----------------------------------|-------------------------|-----------------------|----------|-----|-----|
|                                |                       |                        |                                   |                         |                       | Rockwell | Bhn |     |
| Martensitic Steels (Continued) |                       |                        |                                   |                         |                       |          |     |     |
| 414                            | Annealed              | 120,000                | 95,000                            | 17                      | 55                    | C22      | 235 |     |
|                                | Hardened <sup>c</sup> | ...                    | ...                               | ...                     | ...                   | C44      | 426 |     |
|                                | Tempered at           |                        |                                   |                         |                       |          |     |     |
|                                | 400°F                 | 200,000                | 150,000                           | 15                      | 55                    | C43      | 415 |     |
|                                | 600°F                 | 190,000                | 145,000                           | 15                      | 55                    | C41      | 400 |     |
|                                | 800°F                 | 200,000                | 150,000                           | 16                      | 58                    | C43      | 415 |     |
|                                | 1000°F                | 145,000                | 120,000                           | 20                      | 60                    | C34      | 325 |     |
| 420, 420F                      | 1200°F                | 120,000                | 105,000                           | 20                      | 65                    | C24      | 260 |     |
|                                | Annealed              | 95,000                 | 50,000                            | 25                      | 55                    | B92      | 195 |     |
|                                | Hardened <sup>d</sup> | ...                    | ...                               | ...                     | ...                   | C54      | 540 |     |
|                                | Tempered at           |                        |                                   |                         |                       |          |     |     |
|                                | 600°F                 | 230,000                | 195,000                           | 8                       | 25                    | C50      | 500 |     |
|                                | 431                   | Annealed               | 125,000                           | 95,000                  | 20                    | 60       | C24 | 260 |
|                                |                       | Hardened <sup>d</sup>  | ...                               | ...                     | ...                   | ...      | C45 | 440 |
| Tempered at                    |                       |                        |                                   |                         |                       |          |     |     |
| 400°F                          |                       | 205,000                | 155,000                           | 15                      | 55                    | C43      | 415 |     |
| 600°F                          |                       | 195,000                | 150,000                           | 15                      | 55                    | C41      | 400 |     |
| 800°F                          |                       | 205,000                | 155,000                           | 15                      | 60                    | C43      | 415 |     |
| 1000°F                         |                       | 150,000                | 130,000                           | 18                      | 60                    | C34      | 325 |     |
| 440A                           | 1200°F                | 125,000                | 95,000                            | 20                      | 60                    | C24      | 260 |     |
|                                | Annealed              | 105,000                | 60,000                            | 20                      | 45                    | B95      | 215 |     |
|                                | Hardened <sup>d</sup> | ...                    | ...                               | ...                     | ...                   | C56      | 570 |     |
|                                | Tempered              |                        |                                   |                         |                       |          |     |     |
|                                | 600°F                 | 260,000                | 240,000                           | 5                       | 20                    | C51      | 510 |     |
|                                | 440B                  | Annealed               | 107,000                           | 62,000                  | 18                    | 35       | B96 | 220 |
|                                |                       | Hardened <sup>d</sup>  | ...                               | ...                     | ...                   | ...      | C58 | 590 |
| Tempered                       |                       |                        |                                   |                         |                       |          |     |     |
| 440C, 440F                     | 600°F                 | 280,000                | 270,000                           | 3                       | 15                    | C55      | 555 |     |
|                                | Annealed              | 110,000                | 65,000                            | 13                      | 25                    | B97      | 230 |     |
|                                | Hardened <sup>d</sup> | ...                    | ...                               | ...                     | ...                   | C60      | 610 |     |
|                                | Tempered              |                        |                                   |                         |                       |          |     |     |
|                                | 600°F                 | 285,000                | 275,000                           | 2                       | 10                    | C57      | 580 |     |
|                                | 501                   | Annealed               | 70,000                            | 30,000                  | 28                    | 65       | ... | 160 |
|                                | 502                   | Annealed               | 70,000                            | 30,000                  | 30                    | 75       | B80 | 150 |
| Ferritic Steels                |                       |                        |                                   |                         |                       |          |     |     |
| 405                            | Annealed              | 70,000                 | 40,000                            | 30                      | 60                    | B80      | 150 |     |
| 430                            | Annealed              | 75,000                 | 45,000                            | 30                      | 60                    | B82      | 155 |     |
| 430F, 430FSe                   | Annealed              | 80,000                 | 55,000                            | 25                      | 60                    | B86      | 170 |     |
| 446                            | Annealed              | 80,000                 | 50,000                            | 23                      | 50                    | B86      | 170 |     |

<sup>a</sup> Minimum.<sup>b</sup> Depending on size and amount of cold reduction.<sup>c</sup> Hardening temperature 1800 degrees F, 1-in.-diam. bars.<sup>d</sup> Hardening temperature 1900 degrees F, 1-in.-diam. bars.Source: *Metals Handbook*, 8th edition, Volume 1.

Table 13. Strength Data for Iron and Steel

| Material                   | Ultimate Strength   |   |                                      | Yield Point,<br>Thousands of<br>Pounds per<br>Square Inch | Modulus of Elasticity                       |   |
|----------------------------|---|---|--------------------------------------|---|---|---|
|                            | Tension,<br>Thousands<br>of Pounds per<br>Square Inch, <i>T</i> | Compression,<br>in terms<br>of <i>T</i> | Shear,<br>in<br>terms<br>of <i>T</i> |   | Tension,<br>Millions<br>of psi,<br><i>E</i> | Shear, <sup>a</sup><br>in<br>terms<br>of <i>E</i> |
| Cast iron, gray, class 20  | 20 <sup>b</sup>   | 3.6 <i>T</i> to 4.4 <i>T</i>            | 1.6 <i>T</i>                         | ...   | 11.6  | 0.40 <i>E</i>                                     |
| class 25                   | 25 <sup>b</sup>   | 3.6 <i>T</i> to 4.4 <i>T</i>            | 1.4 <i>T</i>                         | ...   | 14.2  | 0.40 <i>E</i>                                     |
| class 30                   | 30 <sup>b</sup>   | 3.7 <i>T</i>                            | 1.4 <i>T</i>                         | ...   | 14.5  | 0.40 <i>E</i>                                     |
| class 35                   | 35 <sup>b</sup>   | 3.2 <i>T</i> to 3.9 <i>T</i>            | 1.4 <i>T</i>                         | ...   | 16.0  | 0.40 <i>E</i>                                     |
| class 40                   | 40 <sup>b</sup>   | 3.1 <i>T</i> to 3.4 <i>T</i>            | 1.3 <i>T</i>                         | ...   | 17  | 0.40 <i>E</i>                                     |
| class 50                   | 50 <sup>b</sup>   | 3.0 <i>T</i> to 3.4 <i>T</i>            | 1.3 <i>T</i>                         | ...   | 18  | 0.40 <i>E</i>                                     |
| class 60                   | 60 <sup>b</sup>   | 2.8 <i>T</i>                            | 1.0 <i>T</i>                         | ...   | 19.9  | 0.40 <i>E</i>                                     |
| malleable                  | 40 to 100 <sup>c</sup>  | ...                                     | ...                                  | 30 to 80 <sup>c</sup>                                     | 25  | 0.43 <i>E</i>                                     |
| nodular (ductile iron)     | 60 to 120 <sup>d</sup>  | ...                                     | ...                                  | 40 to 90 <sup>d</sup>                                     | 23  | ...   |
| Cast steel, carbon         | 60 to 100   | <i>T</i>                                | 0.75 <i>T</i>                        | 30 to 70  | 30  | 0.38 <i>E</i>                                     |
| low-alloy                  | 70 to 200   | <i>T</i>                                | 0.75 <i>T</i>                        | 45 to 170   | 30  | 0.38 <i>E</i>                                     |
| Steel, SAE 950 (low-alloy) | 65 to 70  | <i>T</i>                                | 0.75 <i>T</i>                        | 45 to 50  | 30  | 0.38 <i>E</i>                                     |
| 1025 (low-carbon)          | 60 to 103   | <i>T</i>                                | 0.75 <i>T</i>                        | 40 to 90  | 30  | 0.38 <i>E</i>                                     |
| 1045 (medium-carbon)       | 80 to 182   | <i>T</i>                                | 0.75 <i>T</i>                        | 50 to 162   | 30  | 0.38 <i>E</i>                                     |
| 1095 (high-carbon)         | 90 to 213   | <i>T</i>                                | 0.75 <i>T</i>                        | 20 to 150   | 30  | 0.39 <i>E</i>                                     |
| 1112 (free-cutting)*       | 60 to 100   | <i>T</i>                                | 0.75 <i>T</i>                        | 30 to 95  | 30  | 0.38 <i>E</i>                                     |
| 1212 (free-cutting)        | 57 to 80  | <i>T</i>                                | 0.75 <i>T</i>                        | 25 to 72  | 30  | 0.38 <i>E</i>                                     |
| 1330 (alloy)               | 90 to 162   | <i>T</i>                                | 0.75 <i>T</i>                        | 27 to 149   | 30  | 0.38 <i>E</i>                                     |
| 2517 (alloy) <sup>e</sup>  | 88 to 190   | <i>T</i>                                | 0.75 <i>T</i>                        | 60 to 155   | 30  | 0.38 <i>E</i>                                     |
| 3140 (alloy)               | 93 to 188   | <i>T</i>                                | 0.75 <i>T</i>                        | 62 to 162   | 30  | 0.38 <i>E</i>                                     |
| 3310 (alloy) <sup>e</sup>  | 104 to 172  | <i>T</i>                                | 0.75 <i>T</i>                        | 56 to 142   | 30  | 0.38 <i>E</i>                                     |
| 4023 (alloy) <sup>e</sup>  | 105 to 170  | <i>T</i>                                | 0.75 <i>T</i>                        | 60 to 114   | 30  | 0.38 <i>E</i>                                     |
| 4130 (alloy)               | 81 to 179   | <i>T</i>                                | 0.75 <i>T</i>                        | 46 to 161   | 30  | 0.38 <i>E</i>                                     |
| 4340 (alloy)               | 109 to 220  | <i>T</i>                                | 0.75 <i>T</i>                        | 68 to 200   | 30  | 0.38 <i>E</i>                                     |
| 4640 (alloy)               | 98 to 192   | <i>T</i>                                | 0.75 <i>T</i>                        | 62 to 169   | 30  | 0.38 <i>E</i>                                     |
| 4820 (alloy) <sup>e</sup>  | 98 to 209   | <i>T</i>                                | 0.75 <i>T</i>                        | 68 to 184   | 30  | 0.38 <i>E</i>                                     |
| 5150 (alloy)               | 98 to 210   | <i>T</i>                                | 0.75 <i>T</i>                        | 51 to 190   | 30  | 0.38 <i>E</i>                                     |
| 52100 (alloy)              | 100 to 238  | <i>T</i>                                | 0.75 <i>T</i>                        | 81 to 228   | 30  | 0.38 <i>E</i>                                     |
| 6150 (alloy)               | 96 to 228   | <i>T</i>                                | 0.75 <i>T</i>                        | 59 to 210   | 30  | 0.38 <i>E</i>                                     |
| 8650 (alloy)               | 110 to 228  | <i>T</i>                                | 0.75 <i>T</i>                        | 69 to 206   | 30  | 0.38 <i>E</i>                                     |
| 8740 (alloy)               | 100 to 179  | <i>T</i>                                | 0.75 <i>T</i>                        | 60 to 165   | 30  | 0.38 <i>E</i>                                     |
| 9310 (alloy) <sup>e</sup>  | 117 to 187  | <i>T</i>                                | 0.75 <i>T</i>                        | 63 to 162   | 30  | 0.38 <i>E</i>                                     |
| 9840 (alloy)               | 120 to 285  | <i>T</i>                                | 0.75 <i>T</i>                        | 45 to 50  | 30  | 0.38 <i>E</i>                                     |
| Steel, stainless, SAE      |   |   |                                      |   |   |   |
| 30302 <sup>f</sup>         | 85 to 125   | <i>T</i>                                | ...                                  | 35 to 95  | 28  | 0.45 <i>E</i>                                     |
| 30321 <sup>f</sup>         | 85 to 95  | <i>T</i>                                | ...                                  | 30 to 60  | 28  | ...   |
| 30347 <sup>f</sup>         | 90 to 100   | <i>T</i>                                | ...                                  | 35 to 65  | 28  | ...   |
| 51420 <sup>g</sup>         | 95 to 230   | <i>T</i>                                | ...                                  | 50 to 195   | 29  | 0.40 <i>E</i>                                     |
| 51430 <sup>h</sup>         | 75 to 85  | <i>T</i>                                | ...                                  | 40 to 70  | 29  | ...   |
| 51446 <sup>h</sup>         | 80 to 85  | <i>T</i>                                | ...                                  | 50 to 70  | 29  | ...   |
| 51501 <sup>g</sup>         | 70 to 175   | <i>T</i>                                | ...                                  | 30 to 135   | 29  | ...   |
| Steel, structural          |   |   |                                      |   |   |   |
| common                     | 60 to 75  | <i>T</i>                                | 0.75 <i>T</i>                        | 33 <sup>b</sup>   | 29  | 0.41 <i>E</i>                                     |
| rivet                      | 52 to 62  | <i>T</i>                                | 0.75 <i>T</i>                        | 28 <sup>b</sup>   | 29  | ...   |
| rivet, high-strength       | 68 to 82  | <i>T</i>                                | 0.75 <i>T</i>                        | 38 <sup>b</sup>   | 29  | ...   |
| Wrought iron               | 34 to 54  | <i>T</i>                                | 0.83 <i>T</i>                        | 23 to 32  | 28  | ...   |

<sup>a</sup> Synonymous in other literature to the modulus of elasticity in torsion and the modulus of rigidity, *G*.

<sup>b</sup> Minimum specified value of the American Society for Testing and Materials. The specifications for the various materials are as follows: Cast iron, ASTM A48; structural steel for bridges and structures, ASTM A7; structural rivet steel, ASTM A141; high-strength structural rivet steel, ASTM A195.

<sup>c</sup> Range of minimum specified values of the ASTM (ASTM A47, A197, and A220).

<sup>d</sup> Range of minimum specified values of the ASTM (ASTM A339) and the Munitions Board Standards Agency (MIL-I-17166A and MIL-I-11466).

<sup>e</sup> Carburizing grades of steel.

<sup>f</sup> Nonhardenable nickel-chromium and Chromium-nickel-manganese steel (austenitic).

<sup>g</sup> Hardenable chromium steel (martensitic).

<sup>h</sup> Nonhardenable chromium steel (ferritic).

**TOOL STEELS****Overview**

As the designation implies, tool steels serve primarily for making tools used in manufacturing and in the trades for the working and forming of metals, wood, plastics, and other industrial materials. Tools must withstand high specific loads, often concentrated at exposed areas, may have to operate at elevated or rapidly changing temperatures and in continual contact with abrasive types of work materials, and are often subjected to shocks, or may have to perform under other varieties of adverse conditions. Nevertheless, when employed under circumstances that are regarded as normal operating conditions, the tool should not suffer major damage, untimely wear resulting in the dulling of the edges, or be susceptible to detrimental metallurgical changes.

Tools for less demanding uses, such as ordinary handtools, including hammers, chisels, files, mining bits, etc., are often made of standard AISI steels that are not considered as belonging to any of the tool steel categories.

The steel for most types of tools must be used in a heat-treated state, generally hardened and tempered, to provide the properties needed for the particular application. The adaptability to heat treatment with a minimum of harmful effects, which dependably results in the intended beneficial changes in material properties, is still another requirement that tool steels must satisfy.

To meet such varied requirements, steel types of different chemical composition, often produced by special metallurgical processes, have been developed. Due to the large number of tool steel types produced by the steel mills, which generally are made available with proprietary designations, it is rather difficult for the user to select those types that are most suitable for any specific application, unless the recommendations of a particular steel producer or producers are obtained.

Substantial clarification has resulted from the development of a classification system that is now widely accepted throughout the industry, on the part of both the producers and the users of tool steels. That system is used in the following as a base for providing concise information on tool steel types, their properties, and methods of tool steel selection.

The tool steel classification system establishes seven basic categories of tool and die steels. These categories are associated with the predominant applicational characteristics of the tool steel types they comprise. A few of these categories are composed of several groups to distinguish between families of steel types that, while serving the same general purpose, differ with regard to one or more dominant characteristics.

To provide an easily applicable guide for the selection of tool steel types best suited for a particular application, the subsequent discussions and tables are based on the previously mentioned application-related categories. As an introduction to the detailed surveys, a concise discussion is presented of the principal tool steel characteristics that govern the suitability for varying service purposes and operational conditions. A brief review of the major steel alloying elements and of the effect of these constituents on the significant characteristics of tool steels is also given in the following sections.

**The Properties of Tool Steels.**—Tool steels must possess certain properties to a higher than ordinary degree to make them adaptable for uses that require the ability to sustain heavy loads and perform dependably even under adverse conditions.

The extent and the types of loads, the characteristics of the operating conditions, and the expected performance with regard to both the duration and the level of consistency are the principal considerations, in combination with the aspects of cost, that govern the selection of tool steels for specific applications.

Although it is not possible to define and apply exact parameters for measuring significant tool steel characteristics, certain properties can be determined that may greatly assist in appraising the suitability of various types of tool steels for specific uses.



Because tool steels are generally heat-treated to make them adaptable to the intended use by enhancing the desirable properties, *the behavior of the steel during heat treatment* is of prime importance. The behavior of the steel comprises, in this respect, both the resistance to harmful effects and the attainment of the desirable properties. The following are considered the major properties related to heat treatment:

**Safety in Hardening:** This designation expresses the ability of the steel to withstand the harmful effects of exposure to very high heat and particularly to the sudden temperature changes during quenching, without harmful effects. One way of obtaining this property is by adding alloying elements to reduce the critical speed at which quenching must be carried out, thus permitting the use of milder quenching media such as oil, salt, or just still air.

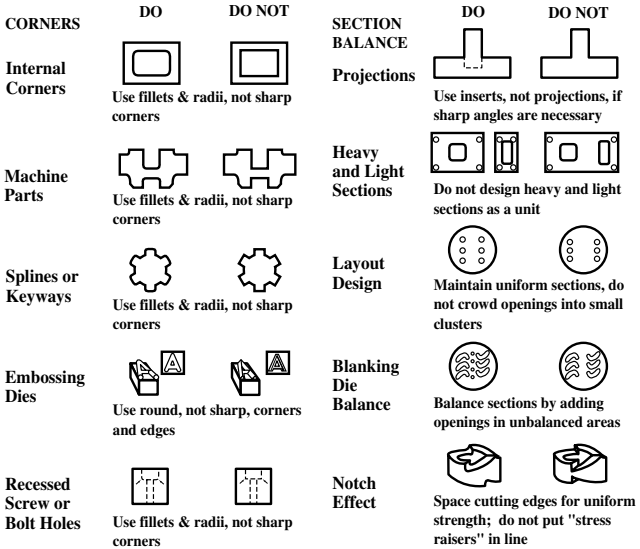


Fig. 1. Tool and die design tips to reduce breakage in heat treatment.

*Courtesy of Society of Automotive Engineers, Inc.*

The most common harm parts made of tool steel suffer from during heat treatment is the development of cracks. In addition to the composition of the steel and the applied heat-treating process, the configuration of the part can also affect the sensitivity to cracking. The preceding figure illustrates a few design characteristics related to cracking and warpage in heat treatment; the observation of these design tips, which call for generous filleting, avoidance of sharp angles, and major changes without transition in the cross-section, is particularly advisable when using tool steel types with a low index value for safety in hardening.

In current practice, the previously mentioned property of tool steels is rated in the order of decreasing safety (i.e., increasing sensitivity) as Highest, Very High, High, Medium, and Low safety, expressed in Tables 6 through 11 by the letters A, B, C, D, and E.

**Distortions in Heat Treating:** In parts made from tool steels, distortions are often a consequence of inadequate design (See Fig. 1.) or improper heat treatment (e.g., lack of stress relieving). However, certain types of tool steels display different degrees of sensitivity to

distortion. Steels that are less stable require safer design of the parts for which they are used, more careful heat treatment, including the proper support for long and slender parts, or thin sections, and possibly greater grinding allowance to permit subsequent correction of the distorted shape. Some parts made of a type of steel generally sensitive to distortions can be heat-treated with very little damage when the requirements of the part call for a relatively shallow hardened layer over a soft core. However, for intricate shapes and large tools, steel types should be selected that possess superior nondeforming properties. The ratings used in Tables 6 through 11 express the nondeforming properties (stability of shape in heat treatment) of the steel types and start with the lowest distortion (the best stability) designated as A; the greatest susceptibility to distortion is designated as E.

*Depth of Hardening:* Hardening depth is indicated by a relative rating based on how deep the phase transformation penetrates from the surface and thus produces a hardened layer. Because of the effect of the heat-treating process, and particularly of the applied quenching medium, on the depth of hardness, reference is made in Tables 6 through 11 to the quench that results in the listed relative hardenability values. These values are designated by letters A, B, and C, expressing deep, medium, and shallow depth, respectively.

*Resistance to Decarburization:* Higher or lower sensitivity to losing a part of the carbon content of the surface exposed to heat depends on the chemistry of the steel. The sensitivity can be balanced partially by appropriate heat-treating equipment and processes. Also, the amount of material to be removed from the surface after heat treatment, usually by grinding, should be specified in such a manner as to avoid the retention of a decarburized layer on functional surfaces. The relative resistance of individual tool steel types to decarburization during heat treatment is rated in Tables 6 through 11 from High to Low, expressed by the letters A, B, and C.

Tool steels must be workable with generally available means, without requiring highly specialized processes. The tools made from these steels must, of course, perform adequately, often under adverse environmental and burdensome operational conditions. The ability of the individual types of tool steels to satisfy, to different degrees, such application requirements can also be appraised on the basis of significant properties, such as the following.

*Machinability:* Tools are precision products whose final shape and dimensions must be produced by machining, a process to which not all tool steel types lend themselves equally well. The difference in machinability is particularly evident in tool steels that, depending on their chemical composition, may contain substantial amounts of metallic carbides, beneficial to increased wear resistance, yet detrimental to the service life of tools with which the steel has to be worked. The microstructure of the steel type can also affect the ease of machining and, in some types, certain phase conditions, such as those due to low carbon content, may cause difficulties in achieving a fine surface finish. Certain types of tool steels have their machinability improved by the addition of small amounts of sulfur or lead.

Machinability affects the cost of making the tool, particularly for intricate tool shapes, and must be considered in selection of the steel to be used. The ratings in Tables 6 through 11, starting with A for the greatest ease of machining to E for the lowest machinability, refer to working of the steel in an unhardened condition. Machinability is not necessarily identical with grindability, which expresses how well the steel is adapted to grinding after heat treating. The ease of grinding, however, may become an important consideration in tool steel selection, particularly for cutting tools and dies, which require regular sharpening involving extensive grinding. AVCO Bay State Abrasives Company compiled information on the relative grindability of frequently used types of tool steels. A simplified version of that information is presented in Table 1, which assigns the listed tool steel types to one of the following grindability grades: High (A), Medium (B), Low (C), and Very Low (D), expressing decreasing ratios of volume of metal removed to wheel wear.

**Table 1. Relative Grindability of Selected Types of Frequently Used Tool Steels**

| AISI Tool Steel Type        | H41 |    |        | H42    |    | H43 |    | Other H |     | D2  |     | D3 |    | D5 |    | D7 |     | A Types |  | O Types |  | L Types |  | F Types |  |
|-----------------------------|-----|----|--------|--------|----|-----|----|---------|-----|-----|-----|----|----|----|----|----|-----|---------|--|---------|--|---------|--|---------|--|
| Relative Grindability Index | B   |    |        | B      |    | B   |    | A       |     | B   |     | B  |    | B  |    | C  |     | A       |  | A       |  | A       |  | B       |  |
| High-Speed Tool Steel Type  | M1  | M2 | M3 (1) | M3 (2) | M4 | M7  | M8 | M10     | M15 | M36 | M43 | T1 | T2 | T3 | T5 | T6 | T15 |         |  |         |  |         |  |         |  |
| Relative Grindability Index | A   | B  | C      | C      | D  | B   | A  | B       | D   | B   | B   | A  | B  | C  | B  | B  | D   |         |  |         |  |         |  |         |  |

**Hot Hardness:** This property designates the steel's resistance to the softening effect of elevated temperature. This characteristic is related to the tempering temperature of the type of steel, which is controlled by various alloying elements such as tungsten, molybdenum, vanadium, cobalt, and chromium.

Hot hardness is a necessary property of tools used for hot work, like forging, casting, and hot extrusion. Hot hardness is also important in cutting tools operated at high-speed, which generate sufficient heat to raise their temperature well above the level where ordinary steels lose their hardness; hence the designation *high-speed steels*, which refers to a family of tool steels developed for use at high cutting speeds. Frequently it is the degree of the tool steel's resistance to softening at elevated temperature that governs important process data, such as the applicable cutting speed. In the ratings of Tables 6 through 11, tool steel types having the highest hot hardness are marked with A, subsequent letters expressing gradually decreasing capacity to endure elevated temperature without losing hardness.

**Wear Resistance:** The gradual erosion of the tool's operating surface, most conspicuously occurring at the exposed edges, is known as wear. Resistance to wear prolongs the useful life of the tool by delaying the degradation of its surface through abrasive contact with the work at regular operating temperatures; these temperatures vary according to the type of process. Wear resistance is observable experimentally and measurable by comparison. Certain types of metallic carbides embedded into the steel matrix are considered to be the prime contributing factors to wear resistance, besides the hardness of the heat-treated steel material. The ratings of Tables 6 through 11, starting with A for the best to E for poor, are based on conditions thought to be normal in operations for which various types of tool materials are primarily used.

**Toughness:** In tool steels, this property expresses ability to sustain shocks, suddenly applied and relieved loads, or major impacts, without breaking. Steels used for making tools must also be able to absorb such forces with only a minimum of elastic deformation and without permanent deformation to any extent that would interfere with the proper functioning of the tool. Certain types of tool steels, particularly those with high carbon content and without the presence of beneficial alloying constituents, tend to be the most sensitive to shocks, although they can also be made to act tougher when used for tools that permit a hardened case to be supported by a soft core. Tempering improves toughness, while generally reducing hardness. The rating indexes in Tables 6 through 11, A for the highest toughness through E for the types most sensitive to shocks, apply to tools heat treated to hardness values normally used for the particular type of tool steel.

**Common Tool Faults and Failures.**—The proper selection of the steel grade used for any particular type of tool is of great importance, but it should be recognized that many of the failures experienced in common practice originate from causes other than those related to the tool material.

To permit a better appraisal of the actual causes of failure and possible corrective action, a general, although not complete, list of common tool faults, resulting failures, and corrective actions is shown in Tables 2a through 2d. In this list, the potential failure causes are grouped into four categories. The possibility of more than a single cause being responsible for the experienced failure should not be excluded.

*Note:* Examples of tool failures from causes such as listed above may be found in “The Tool Steel Trouble Shooter” handbook, published by Bethlehem Steel Corporation.

Finally, it must be remembered that the proper usage of tools is indispensable for obtaining satisfactory performance and tool life. Using the tools properly involves, for example, the avoidance of damage to the tool; overloading; excessive speeds and feeds; the application of adequate coolant when called for; a rigid setup; proper alignment; and firm tool and work holding.

**Table 2a. Common Tool Faults, Failures, and Cures**  
Improper Tool Design

| Fault Description   | Probable Failure   | Possible Cure   |
|---|--|---|
| Drastic section changes—widely different thicknesses of adjacent wall sections or protruding elements | In liquid quenching, the thin section will cool and then harden more rapidly than the adjacent thicker section, setting up stresses that may exceed the strength of the steel. | Make such parts of two pieces or use an air-hardening tool steel that avoids the harsh action of a liquid quench.   |
| Sharp corners on shoulders or in square holes   | Cracking can occur, particularly in liquid quenching, due to stress concentrations.  | Apply fillets to the corners and/or use an air-hardening tool steel.  |
| Sharp cornered keyways  | Failure may arise during service, and is usually considered to be caused by fatigue.   | The use of round keyways should be preferred when the general configuration of the part makes it prone to failure due to square keyways.                                  |
| Abrupt section changes in battering tools   | Due to impact in service, pneumatic tools are particularly sensitive to stress concentrations that lead to fatigue failures.   | Use taper transitions, which are better than even generous fillets.   |
| Functional inadequacy of tool design—e.g., insufficient guidance for a punch                          | Excessive wear or breakage in service may occur.   | Assure solid support, avoid unnecessary play, adapt travel length to operational conditions (e.g., punch to penetrate to four-fifths of thickness in hard work material). |
| Improper tool clearance, such as in blanking and punching tools                                       | Deformed and burred parts may be produced, excessive tool wear or breakage can result.   | Adapt clearances to material conditions and dimensions to reduce tool load and to obtain clean sheared surfaces.  |

**The Effect of Alloying Elements on Tool Steel Properties.**—*Carbon (C):* The presence of carbon, usually in excess of 0.60 per cent for nonalloyed types, is essential for raising the hardenability of steels to the levels needed for tools. Raising the carbon content by different amounts up to a maximum of about 1.3 per cent increases the hardness slightly and the wear resistance considerably. The amount of carbon in tool steels is designed to attain certain properties (such as in the water-hardening category where higher carbon content may be chosen to improve wear resistance, although to the detriment of toughness) or, in the alloyed types of tool steels, in conformance with the other constituents to produce well-balanced metallurgical and performance properties.

*Manganese (Mn):* In small amounts, to about 0.60 per cent, manganese is added to reduce brittleness and to improve forgeability. Larger amounts of manganese improve hardenability, permitting oil quenching for nonalloyed carbon steels, thus reducing deformation, although with regard to several other properties, manganese is not an equivalent replacement for the regular alloying elements.

*Silicon (Si):* In itself, silicon may not be considered an alloying element of tool steels, but it is needed as a deoxidizer and improves the hot-forming properties of the steel. In combination with certain alloying elements, the silicon content is sometimes raised to about 2 per cent to increase the strength and toughness of steels used for tools that have to sustain shock loads.

**Table 2b. Common Tool Faults, Failures, and Cures**  
Faulty Condition or Inadequate Grade of Tool Steel

| Fault Description  | Probable Failure  | Possible Cure  |
|--|---|--|
| Improper tool steel grade selection  | Typical failures:<br>Chipping—insufficient toughness.<br>Wear—poor abrasion resistance.<br>Softening—inadequate “red hardness.” | Choose the tool steel grade by following recommendations and improve selection when needed, guided by property ratings.  |
| Material defects—voids, streaks, tears, flakes, surface cooling cracks, etc. | When not recognized during material inspection, tools made of defective steel often prove to be useless.                        | Obtain tool steels from reliable sources and inspect tool material for detectable defects.   |
| Decarburized surface layer (“bark”) in rolled tool steel bars                | Cracking may originate from the decarburized layer or it will not harden (“soft skin”).   | Provide allowance for stock to be removed from all surfaces of hot-rolled tool steel. Recommended amounts are listed in tool steel catalogs and vary according to section size, generally about 10 per cent for smaller and 5 per cent for larger diameters. |
| Brittleness caused by poor carbide distribution in high-alloy tool steels    | Excessive brittleness can cause chipping or breakage during service.  | Bars with large diameter (above about 4 inches) tend to be prone to nonuniform carbide distribution. Choose upset forged discs instead of large-diameter bars.   |
| Unfavorable grain flow   | Improper grain flow of the steel used for milling cutters and similar tools can cause teeth to break out.                       | Upset forged discs made with an upset ratio of about 2 to 1 (starting to upset thickness) display radial grain flow. Highly stressed tools, such as gear-shaper cutters, may require the cross forging of blanks.  |

**Tungsten (W):** Tungsten is one of the important alloying elements of tool steels, particularly because of two valuable properties: it improves “hot hardness,” that is, the resistance of the steel to the softening effect of elevated temperature, and it forms hard, abrasion-resistant carbides, thus improving the wear properties of tool steels.

**Vanadium (V):** Vanadium contributes to the refinement of the carbide structure and thus improves the forgeability of alloy tool steels. Vanadium has a very strong tendency to form a hard carbide, which improves both the hardness and the wear properties of tool steels. However, a large amount of vanadium carbide makes the grinding of the tool very difficult (causing low grindability).

**Molybdenum (Mo):** In small amounts, molybdenum improves certain metallurgical properties of alloy steels such as deep hardening and toughness. It is used often in larger amounts in certain high-speed tool steels to replace tungsten, primarily for economic reasons, often with nearly equivalent results.

**Cobalt (Co):** As an alloying element of tool steels, cobalt increases hot hardness and is used in applications where that property is needed. Substantial addition of cobalt, however, raises the critical quenching temperature of the steel with a tendency to increase the decarburization of the surface, and reduces toughness.

**Chromium (Cr):** This element is added in amounts of several per cent to high-alloy tool steels, and up to 12 per cent to types in which chromium is the major alloying element. Chromium improves hardenability and, together with high carbon, provides both wear resistance and toughness, a combination valuable in certain tool applications. However, high chromium raises the hardening temperature of the tool steel, and thus can make it prone to hardening deformations. A high percentage of chromium also affects the grindability of the tool steel.

**Nickel (Ni):** Generally in combination with other alloying elements, particularly chromium, nickel is used to improve the toughness and, to some extent, the wear resistance of tool steels.

**Table 2c. Common Tool Faults, Failures, and Cures**  
Heat-Treatment Faults

| Fault Description   | Probable Failure  | Possible Cure  |
|---|---|--|
| Improper preparation for heat treatment. Certain tools may require stress relieving or annealing, and often preheating, too | Tools highly stressed during machining or forming, unless stress relieved, may aggravate the thermal stresses of heat treatment, thus causing cracks. Excessive temperature gradients developed in nonpreheated tools with different section thicknesses can cause warpage. | Stress relieve, when needed, before hardening. Anneal prior to heavy machining or cold forming (e.g., hobbing). Preheat tools (a) having substantial section thickness variations or (b) requiring high quenching temperatures, as those made of high-speed tool steels.       |
| Overheating during hardening; quenching from too high a temperature   | Causes grain coarsening and a sensitivity to cracking that is more pronounced in tools with drastic section changes.  | Overheated tools have a characteristic microstructure that aids recognition of the cause of failure and indicates the need for improved temperature control.   |
| Low hardening temperature   | The tool may not harden at all, or in its outer portion only, thereby setting up stresses that can lead to cracks.  | Controlling both the temperature of the furnace and the time of holding the tool at quenching temperature will prevent this not too frequent deficiency.   |
| Inadequate composition or condition of the quenching media  | Water-hardening tool steels are particularly sensitive to inadequate quenching media, which can cause soft spots or even violent cracking.  | For water-hardening tool steels, use water free of dissolved air and contaminants, also assure sufficient quantity and proper agitation of the quench.   |
| Improper handling during and after quenching  | Cracking, particularly of tools with sharp corners, during the heat treatment can result from holding the part too long in the quench or incorrectly applied tempering.   | Following the steel producer's specifications is a safe way to assure proper heat-treatment handling. In general, the tool should be left in the quench until it reaches a temperature of 150 to 200°F, and should then be transferred promptly into a warm tempering furnace. |
| Insufficient tempering  | Omission of double tempering for steel types that require it may cause early failure by heat checking in hot-work steels or make the tool abnormally sensitive to grinding checks.  | Double temper highly alloyed tool steel of the high-speed, hot-work, and high-chromium categories, to remove stresses caused by martensite formed during the first tempering phase. Second temper also increases hardness of most high-speed steels.                           |
| Decarburization and carburization   | Unless hardened in a neutral atmosphere the original carbon content of the tool surface may be changed: Reduced carbon (decarburization) causes a soft layer that wears rapidly. Increased carbon (carburization) when excessive may cause brittleness.                     | Heating in neutral atmosphere or well-maintained salt bath and controlling the furnace temperature and the time during which the tool is subjected to heating can usually keep the carbon imbalance within acceptable limits.  |

The addition of more than one element to a steel often produces what is called a synergistic effect. Thus, the combined effects of two or more alloy elements may be greater than the sum of the individual effects of each element.

**Classification of Tool Steels.**—Steels for tools must satisfy a number of different, often conflicting requirements. The need for specific steel properties arising from widely varying applications has led to the development of many compositions of tool steels, each intended to meet a particular combination of applicational requirements. The diversity of tool steels, their number being continually expanded by the addition of new developments, makes it extremely difficult for the user to select the type best suited to his needs, or to find equivalent alternatives for specific types available from particular sources.

As a cooperative industrial effort under the sponsorship of AISI and SAE, a tool classification system has been developed in which the commonly used tool steels are grouped into seven major categories. These categories, several of which contain more than a single group, are listed in [Table 3](#) with the letter symbols used for their identification. The individual types of tool steels within each category are identified by suffix numbers following the letter symbols.

**Table 2d. Common Tool Faults, Failures, and Cures**  
Grinding Damages

| Fault Description   | Probable Failure   | Possible Cure   |
|---|--|---|
| Grinding Damages  |  |   |
| Excessive stock removal rate causing heating of the part surface beyond the applied tempering temperature | Scorched tool surface displaying temper colors varying from yellow to purple, depending on the degree of heat, causes softening of the ground surface. When coolant is used, a local rehardening can take place, often resulting in cracks.  | Prevention: by reducing speed and feed, or using coarser, softer, more open-structured grinding wheel, with ample coolant. Correction: eliminate the discolored layer by subsequent light stock removal. Not always a cure, because the effects of abusive grinding may not be corrected.                     |
| Improper grinding wheel specifications; grain too fine or bond too hard                                   | Intense localized heating during grinding may set up surface stresses causing grinding cracks. These cracks are either parallel but at right angles to the direction of grinding or, when more advanced, form a network. May need cold etch or magnetic particle testing to become recognizable. | Prevention: by correcting the grinding wheel specifications. Correction: in shallow (0.002- to 0.004-inch) cracks, by removing the damaged layer, when permitted by the design of the tool, using very light grinding passes.   |
| Incorrectly dressed or loaded grinding wheel  | Heating of the work surface can cause scorching or cracking. Incorrect dressing can also cause a poor finish of the ground work surface.   | Dress wheel with sharper diamond and faster diamond advance to produce coarser wheel surface. Alternate dressing methods, like crush-dressing, can improve wheel surface conditions. Dress wheel regularly to avoid loading or glazing of the wheel surface.  |
| Inadequate coolant, with regard to composition, amount, distribution, and cleanliness                     | Introducing into the tool surface heat that is not adequately dissipated or absorbed by the coolant can cause softening, or even the development of cracks.  | Improve coolant supply and quality, or reduce stock removal rate to reduce generation of heat in grinding.  |
| Damage caused by abusive abrasive cutoff  | The intensive heat developed during this process can cause a hardening of the steel surface, or may even result in cracks.   | Reduce rate of advance; adopt wheel specifications better suited for the job. Use ample coolant or, when harmful effect not eliminated, replace abrasive cutoff by some cooler-acting stock separation method (e.g., sawing or lathe cutoff) unless damaged surface is being removed by subsequent machining. |

**Table 3. Classification of Tool Steels**

| Category Designation        | Letter Symbol | Group Designation                 |
|-----------------------------|---------------|-----------------------------------|
| High-Speed Tool Steels      | M             | Molybdenum types                  |
|                             | T             | Tungsten types                    |
| Hot-Work Tool Steels        | H1-H19        | Chromium types                    |
|                             | H20-H39       | Tungsten types                    |
|                             | H40-H59       | Molybdenum types                  |
| Cold-Work Tool Steels       | D             | High-carbon, high-chromium types  |
|                             | A             | Medium-alloy, air-hardening types |
|                             | O             | Oil-hardening types               |
| Shock-Resisting Tool Steels | S             | ...                               |
| Mold Steels                 | P             | ...                               |
| Special-Purpose Tool Steels | L             | Low-alloy types                   |
|                             | F             | Carbon-tungsten types             |
| Water-Hardening Tool Steels | W             | ...                               |

The following detailed discussion of tool steels will be in agreement with these categories, showing for each type the percentages of the major alloying elements. However, these values are for identification only; elements in tool steels of different producers in the mean analysis of the individual types may deviate from the listed percentages.

**Table 4. Classification, Approximate Compositions, and Properties Affecting Selection of Tool and Die Steels**  
(From SAE Recommended Practice)

| Type of Tool Steel                      | Chemical Composition <sup>a</sup> |      |      |                   |                   |      |                   |                   | Non-warping Prop. | Safety in Hardening | Toughness         | Depth of Hardening | Wear Resistance |
|---|-----------------------------------|------|------|-------------------|-------------------|------|-------------------|-------------------|-------------------|---------------------|-------------------|--------------------|-----------------|
|   | C                                 | Mn   | Si   | Cr                | V                 | W    | Mo                | Co                |                   |                     |                   |                    |                 |
| <b>Water Hardening</b>                  |                                   |      |      |                   |                   |      |                   |                   |                   |                     |                   |                    |                 |
| 0.80 Carbon                             | 70–85                             | b    | b    | b                 | ...               | ...  | ...               | ...               | Poor              | Fair                | Good <sup>c</sup> | Shallow            | Fair            |
| 0.90 Carbon                             | 85–95                             | b    | b    | b                 | ...               | ...  | ...               | ...               | Poor              | Fair                | Good <sup>c</sup> | Shallow            | Fair            |
| 1.00 Carbon                             | 95–1.10                           | b    | b    | b                 | ...               | ...  | ...               | ...               | Poor              | Fair                | Good <sup>c</sup> | Shallow            | Good            |
| 1.20 Carbon                             | 1.10–1.30                         | b    | b    | b                 | ...               | ...  | ...               | ...               | Poor              | Fair                | Good <sup>c</sup> | Shallow            | Good            |
| 0.90 Carbon–V                           | 0.85–0.95                         | b    | b    | b                 | 0.15–0.35         | ...  | ...               | ...               | Poor              | Fair                | Good              | Shallow            | Fair            |
| 1.00 Carbon–V                           | 0.95–1.10                         | b    | b    | b                 | 0.15–0.35         | ...  | ...               | ...               | Poor              | Fair                | Good              | Shallow            | Good            |
| 1.00 Carbon–VV                          | 0.90–1.10                         | b    | b    | b                 | 0.35–0.50         | ...  | ...               | ...               | Poor              | Fair                | Good              | Shallow            | Good            |
| <b>Oil Hardening</b>                    |                                   |      |      |                   |                   |      |                   |                   |                   |                     |                   |                    |                 |
| Low Manganese                           | 0.90                              | 1.20 | 0.25 | 0.50              | 0.20 <sup>d</sup> | 0.50 | ...               | ...               | Good              | Good                | Fair              | Deep               | Good            |
| High Manganese                          | 0.90                              | 1.60 | 0.25 | 0.35 <sup>d</sup> | 0.20 <sup>d</sup> | ...  | 0.30 <sup>d</sup> | ...               | Good              | Good                | Fair              | Deep               | Good            |
| High-Carbon, High-Chromium <sup>e</sup> | 2.15                              | 0.35 | 0.35 | 12.00             | 0.80 <sup>d</sup> | ...  | 0.75 <sup>d</sup> | 0.80 <sup>d</sup> | Good              | Good                | Poor              | Through            | Best            |
| Chromium                                | 1.00                              | 0.35 | 0.25 | 1.40              | ...               | ...  | 0.40              | ...               | Fair              | Good                | Fair              | Deep               | Good            |
| Molybdenum Graphitic                    | 1.45                              | 0.75 | 1.00 | ...               | ...               | ...  | 0.25              | ...               | Fair              | Good                | Fair              | Deep               | Good            |
| Nickel–Chromium <sup>f</sup>            | 0.75                              | 0.70 | 0.25 | 0.85              | 0.25 <sup>d</sup> | ...  | 0.50 <sup>d</sup> | ...               | Fair              | Good                | Fair              | Deep               | Fair            |
| <b>Air Hardening</b>                    |                                   |      |      |                   |                   |      |                   |                   |                   |                     |                   |                    |                 |
| High-Carbon, High-Chromium              | 1.50                              | 0.40 | 0.40 | 12.00             | 0.80 <sup>d</sup> | ...  | 0.90              | 0.60 <sup>d</sup> | Best              | Best                | Fair              | Through            | Best            |
| 5 Per Cent Chromium                     | 1.00                              | 0.60 | 0.25 | 5.25              | 0.40 <sup>d</sup> | ...  | 1.10              | ...               | Best              | Best                | Fair              | Through            | Good            |
| High-Carbon, High-Chromium–Cobalt       | 1.50                              | 0.40 | 0.40 | 12.00             | 0.80 <sup>d</sup> | ...  | 0.90              | 3.10              | Best              | Best                | Fair              | Through            | Best            |
| <b>Shock-Resisting</b>                  |                                   |      |      |                   |                   |      |                   |                   |                   |                     |                   |                    |                 |
| Chromium–Tungsten                       | 0.50                              | 0.25 | 0.35 | 1.40              | 0.20              | 2.25 | 0.40 <sup>d</sup> | ...               | Fair              | Good                | Good              | Deep               | Fair            |
| Silicon–Molybdenum                      | 0.50                              | 0.40 | 1.00 | ...               | 0.25 <sup>d</sup> | ...  | 0.50              | ...               | Poor <sup>g</sup> | Poor <sup>h</sup>   | Best              | Deep               | Fair            |
| Silicon–Manganese                       | 0.55                              | 0.80 | 2.00 | 0.30 <sup>d</sup> | 0.25 <sup>d</sup> | ...  | 0.40 <sup>d</sup> | ...               | Poor <sup>g</sup> | Poor <sup>h</sup>   | Best              | Deep               | Fair            |
| <b>Hot Work</b>                         |                                   |      |      |                   |                   |      |                   |                   |                   |                     |                   |                    |                 |
| Chromium–Molybdenum–Tungsten            | 0.35                              | 0.30 | 1.00 | 5.00              | 0.25 <sup>d</sup> | 1.25 | 1.50              | ...               | Good              | Good                | Good              | Through            | Fair            |
| Chromium–Molybdenum–V                   | 0.35                              | 0.30 | 1.00 | 5.00              | 0.40              | ...  | 1.50              | ...               | Good              | Good                | Good              | Through            | Fair            |
| Chromium–Molybdenum–VV                  | 0.35                              | 0.30 | 1.00 | 5.00              | 0.90              | ...  | 1.50              | ...               | Good              | Good                | Good              | Through            | Fair            |
| Tungsten                                | 0.32                              | 0.30 | 0.20 | 3.25              | 0.40              | 9.00 | ...               | ...               | Good              | Good                | Good              | Through            | Fair            |



**Table 4. (Continued) Classification, Approximate Compositions, and Properties Affecting Selection of Tool and Die Steels**  
(From SAE Recommended Practice)

| Type of Tool Steel                  | Chemical Composition <sup>a</sup> |      |      |      |      |       |      |       | Non-warping Prop. | Safety in Hardening | Toughness | Depth of Hardening | Wear Resistance |
|-------------------------------------|-----------------------------------|------|------|------|------|-------|------|-------|-------------------|---------------------|-----------|--------------------|-----------------|
|                                     | C                                 | Mn   | Si   | Cr   | V    | W     | Mo   | Co    |                   |                     |           |                    |                 |
| High Speed                          |                                   |      |      |      |      |       |      |       |                   |                     |           |                    |                 |
| Tungsten, 18-4-1                    | 0.70                              | 0.30 | 0.30 | 4.10 | 1.10 | 18.00 | ...  | ...   | Good              | Good                | Poor      | Through            | Good            |
| Tungsten, 18-4-2                    | 0.80                              | 0.30 | 0.30 | 4.10 | 2.10 | 18.50 | 0.80 | ...   | Good              | Good                | Poor      | Through            | Good            |
| Tungsten, 18-4-3                    | 1.05                              | 0.30 | 0.30 | 4.10 | 3.25 | 18.50 | 0.70 | ...   | Good              | Good                | Poor      | Through            | Best            |
| Cobalt-Tungsten, 14-4-2-5           | 0.80                              | 0.30 | 0.30 | 4.10 | 2.00 | 14.00 | 0.80 | 5.00  | Good              | Fair                | Poor      | Through            | Good            |
| Cobalt-Tungsten, 18-4-1-5           | 0.75                              | 0.30 | 0.30 | 4.10 | 1.00 | 18.00 | 0.80 | 5.00  | Good              | Fair                | Poor      | Through            | Good            |
| Cobalt-Tungsten, 18-4-2-8           | 0.80                              | 0.30 | 0.30 | 4.10 | 1.75 | 18.50 | 0.80 | 8.00  | Good              | Fair                | Poor      | Through            | Good            |
| Cobalt-Tungsten, 18-4-2-12          | 0.80                              | 0.30 | 0.30 | 4.10 | 1.75 | 20.00 | 0.80 | 12.00 | Good              | Fair                | Poor      | Through            | Good            |
| Molybdenum, 8-2-1                   | 0.80                              | 0.30 | 0.30 | 4.00 | 1.15 | 1.50  | 8.50 | ...   | Good              | Fair                | Poor      | Through            | Good            |
| Molybdenum-Tungsten, 6-6-2          | 0.83                              | 0.30 | 0.30 | 4.10 | 1.90 | 6.25  | 5.00 | ...   | Good              | Fair                | Poor      | Through            | Good            |
| Molybdenum-Tungsten, 6-6-3          | 1.15                              | 0.30 | 0.30 | 4.10 | 3.25 | 5.75  | 5.25 | ...   | Good              | Fair                | Poor      | Through            | Best            |
| Molybdenum-Tungsten, 6-6-4          | 1.30                              | 0.30 | 0.30 | 4.25 | 4.25 | 5.75  | 5.25 | ...   | Good              | Fair                | Poor      | Through            | Best            |
| Cobalt-Molybdenum-Tungsten, 6-6-2-8 | 0.85                              | 0.30 | 0.30 | 4.10 | 2.00 | 6.00  | 5.00 | 8.00  | Good              | Fair                | Poor      | Through            | Good            |

<sup>a</sup> C = carbon; Mn = manganese; Si = silicon; Cr = chromium; V = vanadium; W = tungsten; Mo = molybdenum; Co = cobalt.

<sup>b</sup> Carbon tool steels are usually available in four grades or qualities: *Special (Grade 1)*—The highest quality water-hardening carbon tool steel, controlled for hardenability, chemistry held to closest limits, and subject to rigid tests to ensure maximum uniformity in performance; *Extra (Grade 2)*—A high-quality water-hardening carbon tool steel, controlled for hardenability, subject to tests to ensure good service; *Standard (Grade 3)*—A good-quality water-hardening carbon tool steel, not controlled for hardenability, recommended for application where some latitude with respect to uniformity is permissible; *Commercial (Grade 4)*—A commercial-quality water-hardening carbon tool steel, not controlled for hardenability, not subject to special tests. On *special* and *extra* grades, limits on manganese, silicon, and chromium are not generally required if Shepherd hardenability limits are specified. For *standard* and *commercial* grades, limits are 0.35 max. each for Mn and Si; 0.15 max. Cr for standard; 0.20 max. Cr for commercial.

<sup>c</sup> Toughness decreases somewhat when increasing depth of hardening.

<sup>d</sup> Optional element. Steels have found satisfactory application either with or without the element present. In silicon-manganese steel listed under Shock-Resisting Steels, if chromium, vanadium, and molybdenum are not present, then hardenability will be affected.

<sup>e</sup> This steel may have 0.50 per cent nickel as an optional element. The steel has been found to give satisfactory application either with or without the element present.

<sup>f</sup> Approximate nickel content of this steel is 1.50 per cent.

<sup>g</sup> Poor when water quenched, fair when oil quenched.

<sup>h</sup> Poor when water quenched, good when oil quenched.

**Table 5. Quick Reference Guide for Tool Steel Selection**

| Application Areas   | Tool Steel Categories and AISI Letter Symbol   |   |  |   |                |                                      |   |
|---|--|---|--|---|----------------|--------------------------------------|---|
|   | High-Speed Tool Steels, M and T  | Hot-Work Tool Steels, H   | Cold-Work Tool Steels, D, A, and O   | Shock-Resisting Tool Steels, S                            | Mold Steels, P | Special-Purpose Tool Steels, L and F | Water-Hardening Tool Steels, W  |
| Examples of Typical Applications  |  |   |  |   |                |                                      |   |
| Cutting Tools<br>Single-point types (lathe, planer, boring)<br>Milling cutters<br>Drills<br>Reamers<br>Taps<br>Threading dies<br>Form cutters | General-purpose production tools: M2, T1<br>For increased abrasion resistance: M3, M4, and M10<br>Heavy-duty work calling for high hot hardness: T5, T15<br>Heavy-duty work calling for high abrasion resistance: M42, M44 |   | Tools with keen edges (knives, razors)<br>Tools for operations where no high-speed is involved, yet stability in heat treatment and substantial abrasion resistance are needed | Pipe cutter wheels  |                |                                      | Uses that do not require hot hardness or high abrasion resistance.<br>Examples with carbon content of applicable group:<br>Taps (1.05/1.10% C)<br>Reamers (1.10/1.15% C)<br>Twist drills (1.20/1.25% C)<br>Files (1.35/1.40% C) |
| Hot Forging<br>Tools and Dies<br>Dies and inserts<br>Forging machine plungers and pierces   | For combining hot hardness with high abrasion resistance: M2, T1   | Dies for presses and hammers: H20, H21<br>For severe conditions over extended service periods: H22 to H26, also H43 | Hot trimming dies: D2  | Hot trimming dies<br>Blacksmith tools<br>Hot swaging dies |                |                                      | Smith's tools (1.65/0.70% C)<br>Hot chisels (0.70/0.75% C)<br>Drop forging dies (0.90/1.00% C)<br>Applications limited to short-run production  |
| Hot Extrusion<br>Tools and Dies<br>Extrusion dies and mandrels,<br>Dummy blocks<br>Valve extrusion tools                                      | Brass extrusion dies: T1   | Extrusion dies and dummy blocks: H20 to H26<br>For tools that are exposed to less heat: H10 to H19                  |  | Compression molding: S1                                   |                |                                      |   |

**Table 5. (Continued) Quick Reference Guide for Tool Steel Selection**

| Application Areas   | Tool Steel Categories and AISI Letter Symbol  |   |  |   |                                   |  |   |
|---|---|---|--|---|-----------------------------------|--|---|
|   | High-Speed Tool Steels, M and T   | Hot-Work Tool Steels, H   | Cold-Work Tool Steels, D, A, and O   | Shock-Resisting Tool Steels, S  | Mold Steels, P                    | Special-Purpose Tool Steels, L and F   | Water-Hardening Tool Steels, W  |
| Examples of Typical Applications  |   |   |  |   |                                   |  |   |
| Cold-Forming Dies<br>Bending, forming, drawing, and deep drawing dies and punches | Burnishing tools: M1, T1  | Cold heading: die casting dies: H13   | Drawing dies: O1<br>Coining tools: O1, D2<br>Forming and bending dies: A2<br>Thread rolling dies: D2                   | Hobbing and short-run applications: S1, S7<br>Rivet sets and rivet busters          |                                   | Blanking, forming, and trimmer dies when toughness has precedence over abrasion resistance: L6 | Cold-heading dies: W1 or W2 (C $\cong$ 1.00%)<br>Bending dies: W1 (C $\cong$ 1.00%) |
| Shearing Tools<br>Dies for piercing, punching, and trimming<br>Shear blades       | Special dies for cold and hot work: T1<br>For work requiring high abrasion resistance: M2, M3 | For shearing knives: H11, H12<br>For severe hot shearing applications: M21, M25 | Dies for medium runs: A2, A6 also O1 and O4<br>Dies for long runs: D2, D3<br>Trimming dies (also for hot trimming): A2 | Cold and hot shear blades<br>Hot punching and piercing tools<br>Boilermaker's tools |                                   | Knives for work requiring high toughness: L6   | Trimming dies (0.90/0.95% C)<br>Cold blanking and punching dies (1.00% C)           |
| Die Casting Dies and Plastics Molds   |   | For zinc and lead: H11<br>For aluminum: H13<br>For brass: H21                   | A2 and A6<br><br>O1  |   | Plastics molds: P2 to P4, and P20 |  |   |
| Structural Parts for Severe Service Conditions                                    | Roller bearings for high-temperature environment: T1<br>Lathe centers: M2 and T1              | For aircraft components (landing gear, arrester hooks, rocket cases): H11       | Lathe centers: D2, D3<br>Arbors: O1<br>Bushings: A4<br>Gages: D2   | Pawls<br>Clutch parts   |                                   | Spindles, clutch parts (where high toughness is needed): L6                                    | Spring steel (1.10/1.15% C)   |
| Battering Tools for Hand and Power Tool Use                                       |   |   |  | Pneumatic chisels for cold work: S5<br>For higher performance: S7                   |                                   |  | For intermittent use: W1 (0.80% C)  |

**The Selection of Tool Steels for Particular Applications.**—Although the advice of the specialized steel producer is often sought as a reliable source of information, the engineer is still faced with the task of selecting the tool steel. It must be realized that frequently the designation of the tool or of the process will not define the particular tool steel type best suited for the job. For that reason, tool steel selection tables naming a single type for each listed application cannot take into consideration such often conflicting work factors as ease of tool fabrication and maintenance (resharpening), productivity, product quality, and tooling cost.

When data related to past experience with tool steels for identical or similar applications are not available, a tool steel selection procedure may be followed, based on information in this Handbook section as follows:

1) Identify the AISI category that contains the sought type of steel by consulting the Quick Reference Table, [Table 5](#), starting on page [485](#).

Within the defined category

- a) find from the listed applications of the most frequently used types of tool steels the particular type that corresponds to the job on hand; or
- b) evaluate from the table of property ratings the best compromise between any conflicting properties (e.g., compromising on wear resistance to obtain better toughness).

For those willing to refine even further the first choice or to improve on it when there is not entirely satisfactory experience in one or more meaningful respects, the identifying analyses of the different types of tool steels within each general category may provide additional guidance. In this procedure, the general discussion of the effects of different alloying elements on the properties of tool steels, in a previous section, will probably be found useful.

The following two examples illustrate the procedure for refining an original choice with the purpose of adopting a tool steel grade best suited to a particular set of conditions:

*Example 1, Workpiece—Trimming Dies:* For the manufacture of a type of trimming die, the first choice was grade A2, because for the planned medium rate of production, the lower material cost was considered an advantage.

A subsequent rise in the production rate indicated the use of a higher-alloy tool steel, such as D2, whose increased abrasion resistance would permit longer runs between regrinds.

A still further increase in the abrasion-resistant properties was then sought, which led to the use of D7, the high carbon and high chromium content of which provided excellent edge retainment, although at the cost of greatly reduced grindability. Finally, it became a matter of economic appraisal, whether the somewhat shorter tool regrind intervals (for D2) or the more expensive tool sharpening (for D7) constituted the lesser burden.

*Example 2, Workpiece—Circular form cutter made of high-speed tool steel for use on multiple-spindle automatic turning machines:* The first choice from the [Table 5](#) may be the classical tungsten-base high-speed tool steel T1, because of its good performance and ease of heat treatment, or its alternate in the molybdenum high-speed tool steel category, the type M2.

In practice, neither of these grades provided a tool that could hold its edge and profile over the economical tool change time, because of the abrasive properties of the work material and the high cutting speeds applied in the cycle. An overrating of the problem resulted in reaching for the top of the scale, making the tool from T15, a high-alloy high-speed tool steel (high vanadium and high cobalt).

Although the performance of the tools made of T15 was excellent, the cost of this steel type was rather high, and the grinding of the tool, both for making it and in the regularly needed resharpening, proved to be very time-consuming and expensive. Therefore, an intermediate tool steel type was tried, the M3 that provided added abrasion resistance (due to increased carbon and vanadium content), and was less expensive and much easier to grind than the T15.

### High-Speed Tool Steels

The primary application of high-speed steels is to tools used for the working of metals at high cutting speeds. Cutting metal at high speed generates heat, the penetration of the cutting tool edge into the work material requires great hardness and strength, and the continued frictional contact of the tool with both the parent material and the detached chips can only be sustained by an abrasion-resistant tool edge.

Accordingly, the dominant properties of high-speed steel are a) resistance to the softening effect of elevated temperature; b) great hardness penetrating to substantial depth from the surface; and c) excellent abrasion resistance.

High-speed tool steels are listed in the AISI specifications in two groups: molybdenum types and tungsten types, these designations expressing the dominant alloying element of the respective group.

**Molybdenum-Type High-Speed Tool Steels.**—Unlike the traditional tungsten-base high-speed steels, the tool steels listed in this category are considered to have molybdenum as the principal alloying constituent, this element also being used in the designation of the group. Other significant elements like tungsten and cobalt might be present in equal, or even greater amounts in several types listed in this category. The available range of types also includes high-speed tool steels with higher than usual carbon and vanadium content. Amounts of these alloying elements have been increased to obtain better abrasion resistance although such a change in composition may adversely affect the machinability and the grindability of the steel. The series in whose AISI identification numbers the number 4 is the first digit was developed to attain exceptionally high hardness in heat treatment that, for these types, usually requires triple tempering rather than the double tempering generally applied for high-speed tool steels.

*Frequently Used Molybdenum Types: AISI M1:* This alloy was developed as a substitute for the classical T1 to save on the alloying element tungsten by replacing most of it with molybdenum. In most uses, this steel is an acceptable substitute, although it requires greater care or more advanced equipment for its heat treatment than the tungsten alloyed type it replaces. The steel is often selected for cutting tools like drills, taps, milling cutters, reamers, lathe tools used for lighter cuts, and for shearing dies.

*AISI M2:* Similar to M1, yet with substantial tungsten content replacing a part of the molybdenum. This is one of the general-purpose high-speed tool steels, combining the economic advantages of the molybdenum-type steels with greater ease of hardening, excellent wear resistance, and improved toughness. It is a preferred steel type for the manufacture of general-purpose lathe tools; of most categories of multiple-edge cutting tools, like milling cutters, taps, dies, reamers, and for form tools in lathe operations.

*AISI M3:* A high-speed tool steel with increased vanadium content for improved wear resistance, yet still below the level where vanadium would interfere with the ease of grinding. This steel is preferred for cutting tools requiring improved wear resistance, like broaches, form tools, milling cutters, chasers, and reamers.

*AISI M7:* The chemical composition of this type is similar to that of M1, except for the higher carbon and vanadium content that raises the cutting efficiency without materially reducing the toughness. Because of sensitivity to decarburization, heat treatment in a salt bath or a controlled atmosphere is advisable. Used for blanking and trimming dies, shear blades, lathe tools, and thread rolling dies.

*AISI M10:* Although the relatively high vanadium content assures excellent wear and cutting properties, the only slightly increased carbon does not cause brittleness to an extent that is harmful in many applications. Form cutters and single-point lathe tools, broaches, planer tools, punches, blanking dies, and shear blades are examples of typical uses.

*AISI M42:* In applications where high hardness both at regular and at elevated temperatures is needed, this type of high-speed steel with high cobalt content can provide excellent service. Typical applications are tool bits, form tools, shaving tools, fly cutters, roll turning

Table 6. Molybdenum High-Speed Steels

| Identifying Chemical Composition and Typical Heat-Treatment Data |                                      |                  |             |           |           |           |           |           |            |           |           |           |           |           |           |           |           |           |           |
|--|--------------------------------------|------------------|-------------|-----------|-----------|-----------|-----------|-----------|------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Identifying Chemical Elements in Per Cent                        | AISI Type                            | M1               | M2          | M3 Cl. 1  | M3 Cl. 2  | M4        | M6        | M7        | M10        | M30       | M33       | M34       | M36       | M41       | M42       | M43       | M44       | M46       | M47       |
|  | C                                    | 0.80             | 0.85; 1.00  | 1.05      | 1.20      | 1.30      | 0.80      | 1.00      | 0.85; 1.00 | 0.80      | 0.90      | 0.90      | 0.80      | 1.10      | 1.10      | 1.20      | 1.15      | 1.25      | 1.10      |
|  | W                                    | 1.50             | 6.00        | 6.00      | 6.00      | 5.50      | 4.00      | 1.75      | ...        | 2.00      | 1.50      | 2.00      | 6.00      | 6.75      | 1.50      | 2.75      | 5.25      | 2.00      | 1.50      |
|  | Mo                                   | 8.00             | 5.00        | 5.00      | 5.00      | 4.50      | 5.00      | 8.75      | 8.00       | 8.00      | 9.50      | 8.00      | 5.00      | 3.75      | 9.50      | 8.00      | 6.25      | 8.25      | 9.50      |
|  | Cr                                   | 4.00             | 4.00        | 4.00      | 4.00      | 4.00      | 4.00      | 4.00      | 4.00       | 4.00      | 4.00      | 4.00      | 4.00      | 4.25      | 3.75      | 3.75      | 4.25      | 4.00      | 3.75      |
|  | V                                    | 1.00             | 2.00        | 2.40      | 3.00      | 4.00      | 1.50      | 2.00      | 2.00       | 1.25      | 1.15      | 2.00      | 2.00      | 2.00      | 1.15      | 1.60      | 2.25      | 3.20      | 1.25      |
| Co   | ...                                  | ...              | ...         | ...       | ...       | 12.00     | ...       | ...       | 5.00       | 8.00      | 8.00      | 8.00      | 5.00      | 8.00      | 8.25      | 12.00     | 8.25      | 5.00      |           |
| Heat-Treat. Data   | Hardening Temperature Range, °F      | 2150–2225        | 2175–2225   | 2200–2250 | 2200–2250 | 2250      | 2150–2200 | 2150–2225 | 2150–2225  | 2200–2250 | 2200–2250 | 2200–2250 | 2225–2275 | 2175–2220 | 2170–2210 | 2175–2220 | 2190–2240 | 2175–2225 | 2150–2200 |
|  | Tempering Temperature Range, °F      | 1000–1100        | 1000–1160   | 1000–1100 | 1000–1100 | 1000–1100 | 1000–1100 | 1000–1100 | 1000–1100  | 1000–1100 | 1000–1100 | 1000–1100 | 1000–1100 | 1000–1100 | 950–1100  | 950–1100  | 1000–1160 | 975–1050  | 975–1100  |
|  | Approx. Tempered Hardness, Rc        | 65–60            | 65–60       | 66–61     | 66–61     | 66–61     | 66–61     | 66–61     | 65–60      | 65–60     | 65–60     | 65–60     | 65–60     | 70–65     | 70–65     | 70–65     | 70–62     | 69–67     | 70–65     |
| Relative Ratings of Properties (A = greatest to E = least)       |                                      |                  |             |           |           |           |           |           |            |           |           |           |           |           |           |           |           |           |           |
| Characteristics in Heat Treatment                                | Safety in Hardening                  | D                | D           | D         | D         | D         | D         | D         | D          | D         | D         | D         | D         | D         | D         | D         | D         | D         |           |
|  | Depth of Hardening                   | A                | A           | A         | A         | A         | A         | A         | A          | A         | A         | A         | A         | A         | A         | A         | A         | A         |           |
|  | Resistance to Decarburization        | C                | B           | B         | B         | B         | C         | C         | C          | C         | C         | C         | C         | C         | C         | C         | C         | C         |           |
|  | Stability of Shape in Heat Treatment | Quenching Medium | Air or Salt | C         | C         | C         | C         | C         | C          | C         | C         | C         | C         | C         | C         | C         | C         | C         |           |
| Oil  | D                                    |                  | D           | D         | D         | D         | D         | D         | D          | D         | D         | D         | D         | D         | D         | D         | D         |           |           |
| Service Properties   | Machinability                        | D                | D           | D         | D/E       | D         | D         | D         | D          | D         | D         | D         | D         | D         | D         | D         | D         | D         |           |
|  | Hot Hardness                         | B                | B           | B         | B         | B         | A         | B         | B          | A         | A         | A         | A         | A         | A         | A         | A         | A         |           |
|  | Wear Resistance                      | B                | B           | B         | B         | A         | B         | B         | B          | B         | B         | B         | B         | B         | B         | B         | B         | B         |           |
|  | Toughness                            | E                | E           | E         | E         | E         | E         | E         | E          | E         | E         | E         | E         | E         | E         | E         | E         | E         |           |

tools, and thread rolling dies. Important uses are found for M42, and for other types of the "M40" group in the working of "difficult-to-machine" alloys.

**Tungsten-Type High-Speed Tool Steels.**—For several decades following their introduction, the tungsten-base high-speed steels were the only types available for cutting operations involving the generation of substantial heat, and are still preferred by users who do not have the kind of advanced heat-treating equipment that efficient hardening of the molybdenum-type high-speed tool steels requires. Most tungsten high-speed steels display excellent resistance to decarburization and can be brought to good hardness by simple heat treatment. However, even with tungsten-type high-speed steels, heat treatment using modern methods and furnaces can appreciably improve the metallurgical qualities of the hardened material and the performance of the cutting tools made from these steels.

**Table 7. Tungsten High-Speed Tool Steels—Identifying Chemical Composition and Typical Heat-Treatment Data**

| AISI Type                                      |                  | T1          | T2        | T4        | T5        | T6        | T8        | T15       |
|--|------------------|-------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Identifying Chemical Elements in Per Cent      |                  |             |           |           |           |           |           |           |
| C  |                  | 0.75        | 0.80      | 0.75      | 0.80      | 0.80      | 0.75      | 1.50      |
| W  |                  | 18.00       | 18.00     | 18.00     | 18.00     | 20.00     | 14.00     | 12.00     |
| Cr   |                  | 4.00        | 4.00      | 4.00      | 4.00      | 4.50      | 4.00      | 4.00      |
| V  |                  | 1.00        | 2.00      | 1.00      | 2.00      | 1.50      | 2.00      | 5.00      |
| Co   |                  | ...         | ...       | 5.00      | ...       | ...       | 5.00      | 5.00      |
| Heat-Treatment Data                            |                  |             |           |           |           |           |           |           |
| Hardening Temperature Range, °F                |                  | 2300–2375   | 2300–2375 | 2300–2375 | 2325–2375 | 2325–2375 | 2300–2375 | 2200–2300 |
| Tempering Temperature Range, °F                |                  | 1000–1100   | 1000–1100 | 1000–1100 | 1000–1100 | 1000–1100 | 1000–1100 | 1000–1200 |
| Approx. Tempered Hardness, R <sub>c</sub>      |                  | 65–60       | 66–61     | 66–62     | 65–60     | 65–60     | 65–60     | 68–63     |
| Characteristics in Heat Treatment <sup>a</sup> |                  |             |           |           |           |           |           |           |
| Safety in Hardening                            |                  | C           | C         | D         | D         | D         | D         | D         |
| Depth of Hardening                             |                  | A           | A         | A         | A         | A         | A         | A         |
| Resistance to Decarburization                  |                  | A           | A         | B         | C         | C         | B         | B         |
| Stability of Shape in Heat Treatment           | Quenching Medium | Air or Salt | C         | C         | C         | C         | C         | C         |
|  |                  | Oil         | D         | D         | D         | D         | D         | D         |
| Service Properties                             |                  |             |           |           |           |           |           |           |
| Machinability                                  |                  | D           | D         | D         | D         | D/E       | D         | D/E       |
| Hot Hardness                                   |                  | B           | B         | A         | A         | A         | A         | A         |
| Wear Resistance                                |                  | B           | B         | B         | B         | B         | B         | A         |
| Toughness                                      |                  | E           | E         | E         | E         | E         | E         | E         |

<sup>a</sup>Relative Ratings of Properties (A = greatest to E = least)

*Frequently Used Tungsten Types: AISI T1:* Also mentioned as the 18–4–1 type with reference to the nominal percentage of its principal alloying elements (W–Cr–V), it is considered to be the classical type of high-speed tool steel. The chemical composition of T1 was developed in the early 1900s, and has changed very little since. T1 is still considered to be perhaps the best general-purpose high-speed tool steel because of the comparative ease of its machining and heat treatment. It combines a high degree of cutting ability with relative toughness. T1 steel is used for all types of multiple-edge cutting tools like drills, reamers, milling cutters, threading taps and dies, light- and medium-duty lathe tools, and is also used for punches, dies, and machine knives, as well as for structural parts that are subjected to elevated temperatures, like lathe centers, and certain types of antifriction bearings.

*AISI T2:* Similar to T1 except for somewhat higher carbon content and twice the vanadium contained in the former grade. Its handling ease, both in machining and heat treating, is comparable to that of T1, although it should be held at the quenching temperature slightly longer, particularly when the heating is carried out in a controlled atmosphere furnace. The applications are similar to that of T1, however, because of its increased wear

resistance T2 is preferred for tools required for finer cuts, and where the form or size retention of the tool is particularly important, such as for form and finishing tools.

**AISI T5:** The essential characteristic of this type of high-speed steel, its superior red hardness, stems from its substantial cobalt content that, combined with the relatively high amount of vanadium, provides this steel with excellent wear resistance. In heat treatment, the tendency for decarburization must be considered, and heating in a controlled, slightly reducing atmosphere is recommended. This type of high-speed tool steel is mainly used for single-point tools and inserts; it is well adapted for working at high-speeds and feeds, for cutting hard materials and those that produce discontinuous chips, also for nonferrous metals and, for all kinds of tools needed for hogging (removing great bulks of material).

**AISI T15:** The performance qualities of this high-alloy tool steel surpass most of those found in other grades of high-speed tool steels. The high vanadium content, supported by uncommonly high carbon assures superior cutting ability and wear resistance. The addition of high cobalt increases the "hot hardness," and therefore tools made of T15 can sustain cutting speeds in excess of those commonly applicable to tools made of steel. The machining and heat treatment of T15 does not cause extraordinary problems, although for best results, heating to high temperature is often applied in its heat treatment, and double or even triple tempering is recommended. On the other hand, T15 is rather difficult to grind because of the presence of large amounts of very hard metallic carbides; therefore, it is considered to have a very low "grindability" index. The main uses are in the field of high-speed cutting and the working of hard metallic materials, T15 being often considered to represent in its application a transition from the regular high-speed tool steels to cemented carbides. Lathe tool bits, form cutters, and solid and inserted blade milling cutters are examples of uses of this steel type for cutting tools; excellent results may also be obtained with such tools as cold-work dies, punches, blanking, and forming dies, etc. The low toughness rating of the T15 steel excludes its application for operations that involve shock or sudden variations in load.

### Hot-Work Tool Steels

A family of special tool steels has been developed for tools that in their regular service are in contact with hot metals over a shorter or longer period of time, with or without cooling being applied, and are known as hot-work steels. The essential property of these steels is their capability to sustain elevated temperature without seriously affecting the usefulness of the tools made from them. Depending on the purpose of the tools for which they were developed, the particular types of hot-work tool steels have different dominant properties and are assigned to one of three groups, based primarily on their principal alloying elements.

**Hot-Work Tool Steels, Chromium Types.**—As referred to in the group designation, the chromium content is considered the characteristic element of these tool steels. Their predominant properties are high hardenability, excellent toughness, and great ductility, even at the cost of wear resistance. Some members of this family are made with the addition of tungsten, and in one type, cobalt as well. These alloying elements improve the resistance to the softening effect of elevated temperatures, but reduce ductility.

**Frequently Used Chromium Types:** *AISI H11:* This hot-work tool steel of the Chromium-molybdenum-vanadium type has excellent ductility, can be machined easily, and retains its strength at temperatures up to 1000 degrees F.

These properties, combined with relatively good abrasion and shock resistance, account for the varied fields of application of H11, which include the following typical uses: a) structural applications where high strength is needed at elevated operating temperatures, as for gas turbine engine components; and b) hot-work tools, particularly of the kind whose service involves shocks and drastic cooling of the tool, such as in extrusion tools, pierce and draw punches, bolt header dies, etc.



**Table 8. Hot-Work Tool Steels**

| Identifying Chemical Composition and Typical Heat-Treatment Data |                                      |                  |             |           |           |           |           |                |           |           |           |           |           |                  |           |           |      |   |
|--|--------------------------------------|------------------|-------------|-----------|-----------|-----------|-----------|----------------|-----------|-----------|-----------|-----------|-----------|------------------|-----------|-----------|------|---|
| AISI   | Group                                | Chromium Types   |             |           |           |           |           | Tungsten Types |           |           |           |           |           | Molybdenum Types |           |           |      |   |
|  | Type                                 | H10              | H11         | H12       | H13       | H14       | H19       | H21            | H22       | H23       | H24       | H25       | H26       | H41              | H42       | H43       |      |   |
| Identifying Chemical Elements in Per Cent                        | C                                    | 0.40             | 0.35        | 0.35      | 0.35      | 0.40      | 0.40      | 0.35           | 0.35      | 0.35      | 0.45      | 0.25      | 0.50      | 0.65             | 0.60      | 0.55      |      |   |
|  | W                                    | ...              | ...         | 1.50      | ...       | 5.00      | 4.25      | 9.00           | 11.00     | 12.00     | 15.00     | 15.00     | 18.00     | 1.50             | 6.00      | ...       |      |   |
|  | Mo                                   | 2.50             | 1.50        | 1.50      | 1.50      | ...       | ...       | ...            | ...       | ...       | ...       | ...       | ...       | 8.00             | 5.00      | 8.00      |      |   |
|  | Cr                                   | 3.25             | 5.00        | 5.00      | 5.00      | 5.00      | 4.25      | 3.50           | 2.00      | 12.00     | 3.00      | 4.00      | 4.00      | 4.00             | 4.00      | 4.00      |      |   |
|  | V                                    | 0.40             | 0.40        | 0.40      | 1.00      | ...       | 2.00      | ...            | ...       | ...       | ...       | ...       | ...       | 1.00             | 1.00      | 2.00      | 2.00 |   |
|  | Co                                   | ...              | ...         | ...       | ...       | ...       | 4.25      | ...            | ...       | ...       | ...       | ...       | ...       | ...              | ...       | ...       | ...  |   |
| Heat-Treat. Data   | Hardening Temperature Range, °F      | 1850–1900        | 1825–1875   | 1825–1875 | 1825–1900 | 1850–1950 | 2000–2200 | 2000–2200      | 2000–2200 | 2000–2300 | 2000–2250 | 2100–2300 | 2150–2300 | 2000–2175        | 2050–2225 | 2000–2175 |      |   |
|  | Tempering Temperature Range, °F      | 1000–1200        | 1000–1200   | 1000–1200 | 1000–1200 | 1100–1200 | 1000–1300 | 1100–1250      | 1100–1250 | 1200–1500 | 1050–1200 | 1050–1250 | 1050–1250 | 1050–1200        | 1050–1200 | 1050–1200 |      |   |
|  | Approx. Tempered Hardness, Rc        | 56–39            | 54–38       | 55–38     | 53–38     | 47–40     | 59–40     | 54–36          | 52–39     | 47–30     | 55–45     | 44–35     | 58–43     | 60–50            | 60–50     | 58–45     |      |   |
| Relative Ratings of Properties (A = greatest to D = least)       |                                      |                  |             |           |           |           |           |                |           |           |           |           |           |                  |           |           |      |   |
| Characteristics in Heat Treatment                                | Safety in Hardening                  |                  | A           | A         | A         | A         | A         | B              | B         | B         | B         | B         | B         | B                | C         | C         | C    |   |
|  | Depth of Hardening                   |                  | A           | A         | A         | A         | A         | A              | A         | A         | A         | A         | A         | A                | A         | A         | A    | A |
|  | Resistance to Decarburization        |                  | B           | B         | B         | B         | B         | B              | B         | B         | B         | B         | B         | B                | C         | B         | C    |   |
|  | Stability of Shape in Heat Treatment | Quenching Medium | Air or Salt | B         | B         | B         | B         | C              | C         | C         | C         | ...       | C         | C                | C         | C         | C    | C |
|  |                                      |                  | Oil         | ...       | ...       | ...       | ...       | ...            | D         | D         | D         | D         | D         | D                | D         | D         | D    | D |
| Service Properties   | Machinability                        |                  | C/D         | C/D       | C/D       | C/D       | D         | D              | D         | D         | D         | D         | D         | D                | D         | D         | D    |   |
|  | Hot Hardness                         |                  | C           | C         | C         | C         | C         | C              | C         | C         | B         | B         | B         | B                | B         | B         | B    |   |
|  | Wear Resistance                      |                  | D           | D         | D         | D         | D         | C/D            | C/D       | C/D       | C/D       | C         | D         | C                | C         | C         | C    |   |
|  | Toughness                            |                  | C           | B         | B         | B         | C         | C              | C         | C         | D         | D         | C         | D                | D         | D         | D    |   |

*AISI H12:* The properties of this type of steel are comparable to those of H11, with increased abrasion resistance and hot hardness, resulting from the addition of tungsten, yet in an amount that does not affect the good toughness of this steel type. The applications, based on these properties, are hot-work tools that often have to withstand severe impact, such as various punches, bolt header dies, trimmer dies, and hot shear blades. H12 is also used to make aluminum extrusion dies and die-casting dies.

*AISI H13:* This type of tool steel differs from the preceding ones particularly in properties related to the addition of about 1 per cent vanadium, which contributes to increased hot hardness, abrasion resistance, and reduced sensitivity to heat checking. Such properties are needed in die casting, particularly of aluminum, where the tools are subjected to drastic heating and cooling at high operating temperatures. Besides die-casting dies, H13 is also widely used for extrusion dies, trimmer dies, hot gripper and header dies, and hot shear blades.

*AISI H19:* This high-alloyed hot-work tool steel, containing chromium, tungsten, cobalt, and vanadium, has excellent resistance to abrasion and shocks at elevated temperatures. It is particularly well adapted to severe hot-work uses where the tool, to retain its size and shape, must withstand wear and the washing-out effect of molten work material. Typical applications include brass extrusion dies and dummy blocks, inserts for forging and valve extrusion dies, press forging dies, and hot punches.

**Hot-Work Tool Steels, Tungsten Types.**—Substantial amounts of tungsten, yet very low-carbon content characterize the hot-work tool steels of this group. These tool steels have been developed for applications where the tool is in contact with the hot-work material over extended periods of time; therefore, the resistance of the steel to the softening effect of elevated temperatures is of prime importance, even to the extent of accepting a lower degree of toughness.

*Frequently Used Tungsten Types:* *AISI H21:* This medium-tungsten alloyed hot-work tool steel has substantially increased abrasion resistance over the chromium alloyed types, yet possesses a degree of toughness that represents a transition between the chromium and the higher-alloyed tungsten-steel types. The principal applications are for tools subjected to continued abrasion, yet to only a limited amount of shock loads, like tools for the extrusion of brass, both dies and dummy blocks, pierces for forging machines, inserts for forging tools, and hot nut tools. Another typical application is dies for the hot extrusion of automobile valves.

*AISI H24:* The comparatively high tungsten content (about 14 per cent) of this steel results in good hardness, great compression strength, and excellent abrasion resistance, but makes it sensitive to shock loads. By taking these properties into account, the principal applications include extrusion dies for brass in long-run operations, hot-forming and gripper dies with shallow impressions, punches that are subjected to great wear yet only to moderate shocks, and hot shear blades.

*AISI H20:* The composition of this high-alloyed tungsten-type hot-work steel resembles the tungsten-type high-speed steel AISI T1, except for the somewhat lower carbon content for improved toughness. The high amount of tungsten provides the maximum resistance to the softening effect of elevated temperature and assures excellent wear-resistant properties, including withstanding the washing-out effect of certain processes. However, this steel is less resistant to thermal shocks than the chromium hot-work steels. Typical applications comprise extrusion dies for long production runs, extrusion mandrels operated without cooling, hot piercing punches, hot forging dies and inserts. It is also used as special structural steel for springs operating at elevated temperatures.

**Hot-Work Tool Steels, Molybdenum Types.**—These steels are closely related to certain types of molybdenum high-speed steels and possess excellent resistance to the softening effect of elevated temperature but their ductility is rather low. These steel types are generally available on special orders only.

*Frequently Used Molybdenum Types: AISI H43:* The principal constituents of this hot-work steel, chromium, molybdenum, and vanadium, provide excellent abrasion- and wear-resistant properties at elevated temperatures. H43 has a good resistance to the development of heat checks and a toughness adequate for many different purposes. Applications include tools and operations that tend to cause surface wear in high-temperature work, like hot headers, punch and die inserts, hot heading and hot nut dies, as well as different kinds of punches operating at high temperature in service involving considerable wear.

### Cold-Work Tool Steels

Tool steels of the cold-working category are primarily intended for die work, although their use is by no means restricted to that general field. Cold-work tool steels are extensively used for tools whose regular service does not involve elevated temperatures. They are available in chemical compositions adjusted to the varying requirements of a wide range of different applications. According to their predominant properties, characterized either by the chemical composition or by the quenching medium in heat treatment, the cold-work tool steels are assigned to three different groups, as discussed in what follows.

**Cold-Work Tool Steels, High-Carbon, High-Chromium Types.**—The chemical composition of tool steels of this family is characterized by the very high chromium content, to the order of 12 to 13 per cent, and the uncommonly high carbon content, in the range of about 1.50 to 2.30 per cent. Additional alloying elements that are present in different amounts in some of the steel types of this group are vanadium, molybdenum, and cobalt, each of which contributes desirable properties.

The predominant properties of the whole group are: 1) excellent dimensional stability in heat treatment, where, with one exception, air quench is used; 2) great wear resistance, particularly in the types with the highest carbon content; and 3) rather good machinability.

*Frequently Used High-Carbon, High-Chromium Types: AISI D2:* An air-hardening die steel with high-carbon, high-chromium content having several desirable tool steel properties, such as abrasion resistance, high hardness, and nondeforming characteristics. The carbon content of this type, although relatively high, is not particularly detrimental to its machining. The ease of working can be further improved by selecting the same basic type with the addition of sulfur. Several steel producers supply the sulfurized version of D2, in which the uniformly distributed sulfide particles substantially improve the machinability and the resulting surface finish. The applications comprise primarily cold-working press tools for shearing (blanking and stamping dies, punches, shear blades), for forming (bending, seaming), also for thread rolling dies, solid gages, and wear-resistant structural parts. Dies for hot trimming of forgings are also made of D2 which is then heated treated to a lower hardness for the purpose of increasing toughness.

*AISI D3:* The high carbon content of this high-chromium tool steel type results in excellent resistance to wear and abrasion and provides superior compressive strength as long as the pressure is applied gradually, without exerting sudden shocks. In hardening, an oil quench is used, without affecting the excellent nondeforming properties of this type. Its deep-hardening properties make it particularly suitable for tools that require repeated regrinding during their service life, such as different types of dies and punches. The more important applications comprise blanking, stamping, and trimming dies and punches for long production runs; forming, bending and drawing tools; and structural elements like plug and ring gages, and lathe centers, in applications where high wear resistance is important.

**Cold-Work Tool Steels, Oil-Hardening Types.**—With a relatively low percentage of alloying elements, yet with a substantial amount of manganese, these less expensive types of tool steels attain good depth of hardness in an oil quench, although at the cost of reduced resistance to deformation. Their good machinability supports general-purpose applica-

tions, yet because of relatively low wear resistance, they are mostly selected for comparatively short-run work.

*Frequently Used Oil-Hardening Types: AISI O1:* A low-alloy tool steel that is hardened in oil and exhibits only a low tendency to shrinking or warping. It is used for cutting tools, the operation of which does not generate high heat, such as taps and threading dies, reamers, and broaches, and for press tools like blanking, trimming, and forming dies in short- or medium-run operations.

*AISI O2:* Manganese is the dominant alloying element in this type of oil-hardening tool steel that has good nondeforming properties, can be machined easily, and performs satisfactorily in low-volume production. The low hardening temperature results in good safety in hardening, both with regard to form stability and freedom from cracking. The combination of handling ease, including free-machining properties, with good wear resistance, makes this type of tool steel adaptable to a wide range of common applications such as cutting tools for low- and medium-speed operations; forming tools including thread rolling dies; structural parts such as bushings and fixed gages, and for plastics molds.

*AISI O6:* This oil-hardening type of tool steel belongs to a group often designated as graphitic because of the presence of small particles of graphitic carbon that are uniformly dispersed throughout the steel. Usually, about one-third of the total carbon is present as free graphite in nodular form, which contributes to the uncommon ease of machining. In the service of parts made of this type of steel, the free graphite acts like a lubricant, reducing wear and galling. The ease of hardening is also excellent, requiring only a comparatively low quenching temperature. Deep hardness penetration is produced and the oil quench causes very little dimensional change. The principal applications of the O6 tool steel are in the field of structural parts, like arbors, bushings, bodies for inserted tool cutters, and shanks for cutting tools, jigs, and machine parts, and fixed gages like plugs, rings, and snap gages. It is also used for blanking, forming, and trimming dies and punches, in applications where the stability of the tool material is more important than high wear resistance.

**Cold-Work Tool Steels, Medium-Alloy, Air-Hardening Types.**—The desirable nondeforming properties of the high-chromium types are approached by the members of this family, with substantially lower alloy content that, however, is sufficient to permit hardening by air quenching. The machinability is good, and the comparatively low wear resistance is balanced by relatively high toughness, a property that, in certain applications, may be considered of prime importance.

*Frequently Used Medium-Alloy, Air-Hardening Types: AISI A2:* The lower chromium content, about 5 per cent, makes this air-hardening tool steel less expensive than the high-chromium types, without affecting its nondeforming properties. The somewhat reduced wear resistance is balanced by greater toughness, making this type suitable for press work where the process calls for tough tool materials. The machinability is improved by the addition of about 0.12 percent sulfur, offered as a variety of the basic composition by several steel producers. The prime uses of this tool steel type are punches for blanking and forming, cold and hot trimming dies (the latter heat treated to a lower hardness), thread rolling dies, and plastics molds.

*AISI A6:* The composition of this type of tool steel makes it adaptable to air hardening from a relatively low temperature, comparable to that of oil-hardening types, yet offering improved stability in heat treating. Its reduced tendency to heat-treatment distortions makes this tool steel type well adapted for die work, forming tools, and gages, which do not require the highest degree of wear resistance.

### **Shock-Resisting, Mold, and Special-Purpose Tool Steels**

There are fields of tool application in which specific properties of the tool steels have dominant significance, determining to a great extent the performance and the service life of tools made of these materials. To meet these requirements, special types of tool steels

Table 9. Cold-Work Tool Steels

| Identifying Chemical Composition and Typical Heat-Treatment Data |                                      |                                  |           |           |           |           |                                   |           |           |           |           |           |           |                     |           |           |           |           |
|--|--------------------------------------|----------------------------------|-----------|-----------|-----------|-----------|-----------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|---------------------|-----------|-----------|-----------|-----------|
| AISI   | Group                                | High-Carbon, High-Chromium Types |           |           |           |           | Medium-Alloy, Air-Hardening Types |           |           |           |           |           |           | Oil-Hardening Types |           |           |           |           |
|  |                                      | D2                               | D3        | D4        | D5        | D7        | A2                                | A3        | A4        | A6        | A7        | A8        | A9        | A10                 | O1        | O2        | O6        | O7        |
| Identifying Chemical Elements in Per Cent                        | C                                    | 1.50                             | 2.25      | 2.25      | 1.50      | 2.35      | 1.00                              | 1.25      | 1.00      | 0.70      | 2.25      | 0.55      | 0.50      | 1.35                | 0.90      | 0.90      | 1.45      | 1.20      |
|  | Mn                                   | ...                              | ...       | ...       | ...       | ...       | ...                               | ...       | 2.00      | 2.00      | ...       | ...       | ...       | 1.80                | 1.00      | 1.60      | ...       | ...       |
|  | Si                                   | ...                              | ...       | ...       | ...       | ...       | ...                               | ...       | ...       | ...       | ...       | ...       | ...       | 1.25                | ...       | ...       | 1.00      | ...       |
|  | W                                    | ...                              | ...       | ...       | ...       | ...       | ...                               | ...       | ...       | ...       | 1.00      | 1.25      | ...       | ...                 | 0.50      | ...       | ...       | 1.75      |
|  | Mo                                   | 1.00                             | ...       | 1.00      | 1.00      | 1.00      | 1.00                              | 1.00      | 1.00      | 1.25      | 1.00      | 1.25      | 1.40      | 1.50                | ...       | ...       | 0.25      | ...       |
|  | Cr                                   | 12.00                            | 12.00     | 12.00     | 12.00     | 12.00     | 5.00                              | 5.00      | 1.00      | 1.00      | 5.25      | 5.00      | 5.00      | ...                 | 0.50      | ...       | ...       | 0.75      |
|  | V                                    | 1.00                             | ...       | ...       | ...       | 4.00      | ...                               | 1.00      | ...       | ...       | 4.75      | ...       | 1.00      | ...                 | ...       | ...       | ...       | ...       |
| Co   | ...                                  | ...                              | ...       | 3.00      | ...       | ...       | ...                               | ...       | ...       | ...       | ...       | ...       | ...       | ...                 | ...       | ...       | ...       |           |
| Heat-Treatment Data  | Ni                                   | ...                              | ...       | ...       | ...       | ...       | ...                               | ...       | ...       | ...       | ...       | 1.50      | 1.80      | ...                 | ...       | ...       | ...       |           |
|  | Hardening Temperature Range, °F      | 1800–1875                        | 1700–1800 | 1775–1850 | 1800–1875 | 1850–1950 | 1700–1800                         | 1750–1850 | 1500–1600 | 1525–1600 | 1750–1800 | 1800–1850 | 1800–1875 | 1450–1500           | 1450–1500 | 1400–1475 | 1450–1500 | 1550–1525 |
|  | Quenching Medium                     | Air                              | Oil       | Air       | Air       | Air       | Air                               | Air       | Air       | Air       | Air       | Air       | Air       | Air                 | Oil       | Oil       | Oil       | Oil       |
|  | Tempering Temperature Range, °F      | 400–1000                         | 400–1000  | 400–1000  | 400–1000  | 300–1000  | 350–1000                          | 350–1000  | 350–800   | 300–800   | 300–1000  | 350–1100  | 950–1150  | 350–800             | 350–500   | 350–500   | 350–600   | 350–550   |
| Approx. Tempered Hardness, Rc                                    | 61–54                                | 61–54                            | 61–54     | 61–54     | 65–58     | 62–57     | 65–57                             | 62–54     | 60–54     | 67–57     | 60–50     | 56–35     | 62–55     | 62–57               | 62–57     | 63–58     | 64–58     |           |
| Relative Ratings of Properties (A = greatest to E = least)       |                                      |                                  |           |           |           |           |                                   |           |           |           |           |           |           |                     |           |           |           |           |
| Characteristics in Heat Treatment                                | Safety in Hardening                  | A                                | C         | A         | A         | A         | A                                 | A         | A         | A         | A         | A         | A         | A                   | B         | B         | B         | B         |
|  | Depth of Hardening                   | A                                | A         | A         | A         | A         | A                                 | A         | A         | A         | A         | A         | A         | A                   | B         | B         | B         | B         |
|  | Resistance to Decarburization        | B                                | B         | B         | B         | B         | B                                 | B         | A/B       | A/B       | B         | B         | B         | A/B                 | A         | A         | A         | A         |
|  | Stability of Shape in Heat Treatment | A                                | B         | A         | A         | A         | A                                 | A         | A         | A         | A         | A         | A         | A                   | B         | B         | B         | B         |
| Service Properties   | Machinability                        | E                                | E         | E         | E         | E         | D                                 | D         | D/E       | D/E       | E         | D         | D         | C/D                 | C         | C         | B         | C         |
|  | Hot Hardness                         | C                                | C         | C         | C         | C         | C                                 | C         | D         | D         | C         | C         | C         | D                   | E         | E         | E         | E         |
|  | Wear Resistance                      | B/C                              | B         | B         | B/C       | A         | C                                 | B         | C/D       | C/D       | A         | C/D       | C/D       | C                   | D         | D         | D         | D         |
|  | Toughness                            | E                                | E         | E         | E         | E         | D                                 | D         | D         | D         | E         | C         | C         | D                   | D         | D         | D         | C         |

have been developed. These individual types grew into families with members that, while similar in their major characteristics, provide related properties to different degrees. Originally developed for a specific use, the resulting particular properties of some of these tool steels made them desirable for other uses as well. In the tool steel classification system, they are shown in three groups, as discussed in what follows.

**Shock-Resisting Tool Steels.**—These steels are made with low-carbon content for increased toughness, even at the expense of wear resistance, which is generally low. Each member of this group also contains alloying elements, different in composition and amount, selected to provide properties particularly adjusted to specific applications. Such varying properties are the degree of toughness (generally, high in all members), hot hardness, abrasion resistance, and machinability.

*Properties and Applications of Frequently Used Shock-Resisting Types: AISI S1:* This Chromium–tungsten alloyed tool steel combines, in its hardened state, great toughness with high hardness and strength. Although it has a low-carbon content for reasons of good toughness, the carbon-forming alloys contribute to deep hardenability and abrasion resistance. When high wear resistance is also required, this property can be improved by carburizing the surface of the tool while still retaining its shock-resistant characteristics. Primary uses are for battering tools, including hand and pneumatic chisels. The chemical composition, particularly the silicon and tungsten content, provides good hot hardness, too, up to operating temperatures of about 1050 °F, making this tool steel type also adaptable for such hot-work tool applications involving shock loads, as headers, pierces, forming tools, drop forge die inserts, and heavy shear blades.

*AISI S2:* This steel type serves primarily for hand chisels and pneumatic tools, although it also has limited applications for hot work. Although its wear-resistance properties are only moderate, S2 is sometimes used for forming and thread rolling applications, when the resistance to rupturing is more important than extended service life. For hot-work applications, this steel requires heat treatment in a neutral atmosphere to avoid either carburization or decarburization of the surface. Such conditions make this tool steel type particularly susceptible to failure in hot-work uses.

*AISI S5:* This composition is essentially a Silicon–manganese type tool steel with small additions of chromium, molybdenum, and vanadium for the purpose of improved deep hardening and refinement of the grain structure. The most important properties of this steel are its high elastic limit and good ductility, resulting in excellent shock-resisting characteristics, when used at atmospheric temperatures. Its recommended quenching medium is oil, although a water quench may also be applied as long as the design of the tools avoids sharp corners or drastic sectional changes. Typical applications include pneumatic tools in severe service, like chipping chisels, also shear blades, heavy-duty punches, and bending rolls. Occasionally, this steel is also used for structural applications, like shanks for carbide tools and machine parts subject to shocks.

**Mold Steels.**—These materials differ from all other types of tool steels by their very low-carbon content, generally requiring carburizing to obtain a hard operating surface. A special property of most steel types in this group is the adaptability to shaping by impression (hobbing) instead of by conventional machining. They also have high resistance to decarburization in heat treatment and dimensional stability, characteristics that obviate the need for grinding following heat treatment. Molding dies for plastics materials require an excellent surface finish, even to the degree of high luster; the generally high-chromium content of these types of tool steels greatly aids in meeting this requirement.

*Properties and Applications of Frequently Used Mold Steel Types: AISI P3 and P4:*

Essentially, both types of tool steels were developed for the same special purpose, that is, the making of plastics molds. The application conditions of plastics molds require high core strength, good wear resistance at elevated temperature, and excellent surface finish. Both types are carburizing steels that possess good dimensional stability. Because hob-

**Table 10. Shock-Resisting, Mold, and Special-Purpose Tool Steels**

| Identifying Chemical Composition and Typical Heat-Treatment Data |                                      |                             |           |           |           |                        |                        |                        |                        |                        |                        |                  |                             |                 |           |           |           |     |
|--|--------------------------------------|-----------------------------|-----------|-----------|-----------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------|-----------------------------|-----------------|-----------|-----------|-----------|-----|
| AISI   | Category                             | Shock-Resisting Tool Steels |           |           |           | Mold Steels            |                        |                        |                        |                        |                        |                  | Special-Purpose Tool Steels |                 |           |           |           |     |
|  | Types                                | S1                          | S2        | S5        | S7        | P2                     | P3                     | P4                     | P5                     | P6                     | P20                    | P21 <sup>a</sup> | L2 <sup>b</sup>             | L3 <sup>b</sup> | L6        | F1        | F2        |     |
| Identifying Elements in Per Cent                                 | C                                    | 0.50                        | 0.50      | 0.55      | 0.50      | 0.07                   | 0.10                   | 0.07                   | 0.10                   | 0.10                   | 0.35                   | 0.20             | 0.50/1.10                   | 1.00            | 0.70      | 1.00      | 1.25      |     |
|  | Mn                                   | ...                         | ...       | 0.80      | ...       | ...                    | ...                    | ...                    | ...                    | ...                    | ...                    | ...              | ...                         | ...             | ...       | ...       | ...       |     |
|  | Si                                   | ...                         | 1.00      | 2.00      | ...       | ...                    | ...                    | ...                    | ...                    | ...                    | ...                    | ...              | ...                         | ...             | ...       | ...       | ...       |     |
|  | W                                    | 2.50                        | ...       | ...       | ...       | ...                    | ...                    | ...                    | ...                    | ...                    | ...                    | ...              | ...                         | ...             | ...       | 1.25      | 3.50      |     |
|  | Mo                                   | ...                         | 0.50      | 0.40      | 1.40      | 0.20                   | ...                    | 0.75                   | ...                    | ...                    | 0.40                   | ...              | ...                         | ...             | 0.25      | ...       | ...       |     |
|  | Cr                                   | 1.50                        | ...       | ...       | 3.25      | 2.00                   | 0.60                   | 5.00                   | 2.25                   | 1.50                   | 1.25                   | ...              | 1.00                        | 1.50            | 0.75      | ...       | ...       |     |
|  | V                                    | ...                         | ...       | ...       | ...       | ...                    | ...                    | ...                    | ...                    | ...                    | ...                    | ...              | 0.20                        | 0.20            | ...       | ...       | ...       |     |
| Ni   | ...                                  | ...                         | ...       | ...       | 0.50      | 1.25                   | ...                    | ...                    | 3.50                   | ...                    | 4.00                   | ...              | ...                         | 1.50            | ...       | ...       |           |     |
| Heat-Treat. Data   | Hardening Temperature, °F            | 1650–1750                   | 1550–1650 | 1600–1700 | 1700–1750 | 1525–1550 <sup>c</sup> | 1475–1525 <sup>c</sup> | 1775–1825 <sup>c</sup> | 1550–1600 <sup>c</sup> | 1450–1500 <sup>c</sup> | 1500–1600 <sup>c</sup> | Soln. treat.     | 1550–1700                   | 1500–1600       | 1450–1550 | 1450–1600 | 1450–1600 |     |
|  | Tempering Temp. Range, °F            | 400–1200                    | 350–800   | 350–800   | 400–1150  | 350–500                | 350–500                | 350–900                | 350–500                | 350–450                | 900–1100               | Aged             | 350–1000                    | 350–600         | 350–1000  | 350–500   | 350–500   |     |
|  | Approx. Tempered Hardness, Rc        | 58–40                       | 60–50     | 60–50     | 57–45     | 64–58 <sup>d</sup>     | 64–58 <sup>d</sup>     | 64–58 <sup>d</sup>     | 64–58 <sup>d</sup>     | 61–58 <sup>d</sup>     | 37–28 <sup>d</sup>     | 40–30            | 63–45                       | 63–56           | 62–45     | 64–60     | 65–62     |     |
| Relative Ratings of Properties (A = greatest to E = least)       |                                      |                             |           |           |           |                        |                        |                        |                        |                        |                        |                  |                             |                 |           |           |           |     |
| Characteristics in Heat Treatment                                | Safety in Hardening                  |                             | C         | E         | C         | B/C                    | C                      | C                      | C                      | C                      | C                      | A                | D                           | D               | C         | E         | E         |     |
|  | Depth of Hardening                   |                             | B         | B         | B         | A                      | B <sup>e</sup>         | B <sup>e</sup>         | B <sup>e</sup>         | B <sup>e</sup>         | A <sup>e</sup>         | B                | A                           | B               | B         | B         | C         | C   |
|  | Resist. to Decarb.                   |                             | B         | C         | C         | B                      | A                      | A                      | A                      | A                      | A                      | A                | A                           | A               | A         | A         | A         | A   |
|  | Stability of Shape in Heat Treatment | Quench. Med.                | Air       | ...       | ...       | ...                    | A                      | ...                    | ...                    | B                      | ...                    | B                | C                           | A               | ...       | ...       | ...       | ... |
|  |                                      |                             | Oil       | D         | ...       | D                      | C                      | C                      | C                      | ...                    | C                      | C                | ...                         | A               | D         | D         | C         | ... |
| Water <sup>f</sup>   |                                      | ...                         | E         | ...       | ...       | ...                    | ...                    | ...                    | E                      | ...                    | ...                    | ...              | E                           | E               | ...       | E         | E         |     |
| Service Properties   | Machinability                        |                             | D         | C/D       | C/D       | D                      | C/D                    | D                      | D/E                    | D                      | D                      | C/D              | D                           | C               | C         | D         | C         | D   |
|  | Hot Hardness                         |                             | D         | E         | E         | C                      | E                      | E                      | D                      | E                      | E                      | D                | E                           | D               | E         | E         | E         | E   |
|  | Wear Resistance                      |                             | D/E       | D/E       | D/E       | D/E                    | D                      | D                      | C                      | D                      | D                      | D/E              | D                           | D/E             | D         | D         | D         | B/C |
|  | Toughness                            |                             | B         | A         | A         | B                      | C                      | C                      | C                      | C                      | C                      | C                | D                           | B               | D         | B         | E         | E   |

<sup>a</sup> Contains also about 1.20 per cent Al. Solution treated in hardening.<sup>b</sup> Quenched in oil.<sup>c</sup> After carburizing.<sup>d</sup> Carburized case.<sup>e</sup> Core hardenability.<sup>f</sup> Sometimes brine is used.

bing, that is, sinking the cavity by pressing a punch representing the inverse replica of the cavity into the tool material, is the process by which many plastics mold cavities are produced, good "hobbability" of the tool steels used for this purpose is an important requirement. The different chemistry of these two types of mold steels is responsible for the high core hardness of the P4, which makes it better suited for applications requiring high strength at elevated temperature.

*AISI P6:* This nickel–chromium-type plastics mold steel has exceptional core strength and develops a deep carburized case. Due to the high nickel–chromium content, the cavities of molds made of this steel type are produced by machining rather than by hobbing. An outstanding characteristic of this steel type is the high luster that is produced by polishing of the hard case surface.

*AISI P20:* This general-type mold steel is adaptable to both through hardening and carburized case hardening. In through hardening, an oil quench is used and a relatively lower, yet deeply penetrating hardness is obtained, such as is needed for zinc die-casting dies and injection molds for plastics. After the direct quenching and tempering, carburizing produces a very hard case and comparatively high core hardness. When thus heat treated, this steel is particularly well adapted for making compression, transfer, and plunger-type plastics molds.

**Special-Purpose Tool Steels.**—These steels include several low-alloy types of tool steels that were developed to provide transitional types between the more commonly used basic types of tool steels, and thereby contribute to the balancing of certain conflicting properties such as wear resistance and toughness; to offer intermediate depth of hardening; and to be less expensive than the higher-alloyed types of tool steels.

*Properties and Applications of Frequently Used Special-Purpose Types:* *AISI L6:* This material is a low-alloy-type special-purpose tool steel. The comparatively safe hardening and the fair nondeforming properties, combined with the service advantage of good toughness in comparison to most other oil-hardening types, explains the acceptance of this steel with a rather special chemical composition. The uses of L6 are for tools whose toughness requirements prevail over abrasion-resistant properties, such as forming rolls and forming and trimmer dies in applications where combinations of moderate shock- and wear-resistant properties are sought. The areas of use also include structural parts, like clutch members, pawls, and knuckle pins, that must withstand shock loads and still display good wear properties.

*AISI F2:* This carbon–tungsten type is one of the most abrasion-resistant of all water-hardening tool steels. However, it is sensitive to thermal changes, such as are involved in heat treatment and it is also susceptible to distortions. Consequently, its use is limited to tools of simple shape in order to avoid cracking in hardening. The shallow hardening characteristics of F2 result in a tough core and are desirable properties for certain tool types that, at the same time, require excellent wear-resistant properties.

**Water-Hardening Tool Steels.**—Steel types in this category are made without, or with only a minimum amount of alloying elements and, their heat treatment needs the harsh quenching action of water or brine, hence the general designation of the category.

Water-hardening steels are usually available with different percentages of carbon, to provide properties required for different applications; the classification system lists a carbon range of 0.60 to 1.40 per cent. In practice, however, the steel mills produce these steels in a few varieties of differing carbon content, often giving proprietary designations to each particular group. Typical carbon content limits of frequently used water-hardening tool steels are 0.70–0.90, 0.90–1.10, 1.05–1.20, and 1.20–1.30 per cent. The appropriate group should be chosen according to the intended use, as indicated in the steel selection guide for this category, keeping in mind that whereas higher carbon content results in deeper hardness penetration, it also reduces toughness.

The general system distinguishes the following four grades, listed in the order of decreasing quality: 1) special; 2) extra; 3) standard; and 4) commercial.



The differences between these grades, which are not offered by all steel mills, are defined in principle only. The distinguishing characteristics are purity and consistency, resulting from different degrees of process refinement and inspection steps applied in making the steel. Higher qualities are selected for assuring dependable uniformity and performance of the tools made from the steel.

The groups with higher carbon content are more sensitive to heat-treatment defects and are generally used for the more demanding applications, so the better grades are usually chosen for the high-carbon types and the lower grades for applications where steels with lower carbon content only are needed.

Water-hardening tool steels, although the least expensive, have several drawbacks, but these are quite acceptable in many types of applications. Some limiting properties are the tendency to deformation in heat treatment due to harsh effects of the applied quenching medium, the sensitivity to heat during the use of the tools made of these steels, the only fair degree of toughness, and the shallow penetration of hardness. However, this last-mentioned property may prove a desirable characteristic in certain applications, such as cold-heading dies, because the relatively shallow hard case is supported by the tough, although softer core.

The AISI designation for water-hardening tool steels is W, followed by a numeral indicating the type, primarily defined by the chemical composition, as shown in Table 11.

**Table 11. Water-Hardening Tool Steels—Identifying Chemical Composition and Heat-Treatment Data**

| Chemical Composition in Per Cent                                |   | AISI Types                    |                                      |                    |              |                 |           |
|---|---|-------------------------------|--------------------------------------|--------------------|--------------|-----------------|-----------|
|   |   | W1                            | W2                                   | W5                 |              |                 |           |
| C   | 0.60–1.40   | 0.60–1.40                     | 1.10                                 |                    |              |                 |           |
| V   | Varying carbon content may be available                           |                               |                                      |                    |              |                 |           |
| Cr  | ...   | 0.25                          | ...                                  |                    |              |                 |           |
| Mn  | These elements are adjusted to satisfy the hardening requirements |                               |                                      |                    |              |                 |           |
| Si  |   |                               |                                      |                    |              |                 |           |
| Heat-Treatment Data   |   |                               |                                      |                    |              |                 |           |
| Hardening Temperature Ranges, °F<br>Varying with Carbon Content | 0.60–0.80%  | 1450–1500                     |                                      |                    |              |                 |           |
|   | 0.85–1.05%  | 1425–1550                     |                                      |                    |              |                 |           |
|   | 1.10–1.40%  | 1400–1525                     |                                      |                    |              |                 |           |
| Quenching Medium  |   | Brine or Water                |                                      |                    |              |                 |           |
| Tempering Temperature Range, °F                                 |   | 350–650                       |                                      |                    |              |                 |           |
| Approx. Tempered Hardness, Rc                                   |   | 64–50                         |                                      |                    |              |                 |           |
| Relative Ratings of Properties (A = greatest to E = least)      |   |                               |                                      |                    |              |                 |           |
| Characteristics in Heat Treatment                               |   |                               |                                      | Service Properties |              |                 |           |
| Safety in Hardening   | Depth of Hardening  | Resistance to Decarburization | Stability of Shape in Heat Treatment | Machinability      | Hot Hardness | Wear Resistance | Toughness |
| D   | C   | A                             | E                                    | A                  | E            | D/E             | C/D       |

*Water-Hardening Type W1 (Plain Carbon) Tool Steels, Recommended Applications:*

*Group I (C-0.70 to 0.90%):* This group is relatively tough and therefore preferred for tools that are subjected to shocks or abusive treatment. Used for such applications as: hand tools, chisels, screwdriver blades, cold punches, and nail sets, and fixture elements, vise jaws, anvil faces, and chuck jaws.

*Group II (C-0.90 to 1.10%):* This group combines greater hardness with fair toughness, resulting in improved cutting capacity and moderate ability to sustain shock loads. Used for such applications as: hand tools, knives, center punches, pneumatic chisels, cutting tools, reamers, hand taps, and threading dies, wood augers; die parts, drawing and heading dies, shear knives, cutting and forming dies; and fixture elements, drill bushings, lathe centers, collets, and fixed gages.

*Group III (C-1.05 to 1.20%):* The higher carbon content of this group increases the depth of hardness penetrations, yet reduces toughness, thus the resistance to shock loads. Preferred for applications where wear resistance and cutting ability are the prime considerations. Used for such applications as: hand tools, woodworking chisels, paper knives, cutting tools (for low-speed applications), milling cutters, reamers, planer tools, thread chasers, center drills, die parts, cold blanking, coining, bending dies.

*Group IV (C-1.20 to 1–30%):* The high carbon content of this group produces a hard case of considerable depth with improved wear resistance yet sensitive to shock and concentrated stresses. Selected for applications where the capacity to withstand abrasive wear is needed, and where the retention of a keen edge or the original shape of the tool is important. Used for such applications as: cutting tools for finishing work, like cutters and reamers, and for cutting chilled cast iron and forming tools, for ferrous and nonferrous metals, and burnishing tools.

By adding small amounts of alloying elements to W-steel types 2 and 5, certain characteristics that are desirable for specific applications are improved. The vanadium in type 2 contributes to retaining a greater degree of fine-grain structure after heat treating. Chromium in type 5 improves the deep-hardening characteristics of the steel, a property needed for large sections, and assists in maintaining the keen cutting edge that is desirable in cutting tools like broaches, reamers, threading taps, and dies.

### Mill Production Forms of Tool Steels

Tool steels are produced in many different forms, but not all those listed in the following are always readily available; certain forms and shapes are made for special orders only.

*Hot-Finished Bars and Cold-Finished Bars:* These bars are the most commonly produced forms of tool steels. Bars can be furnished in many different cross-sections, the round shape being the most common. Sizes can vary over a wide range, with a more limited number of standard stock sizes. Various conditions may also be available, however, technological limitations prevent all conditions applying to every size, shape, or type of steel. Tool steel bars may be supplied in one of the following conditions and surface finishes:

*Conditions:* Hot-rolled or forged (natural); hot-rolled or forged and annealed; hot-rolled or forged and heat-treated; cold- or hot-drawn (as drawn); and cold- or hot-drawn and annealed.

*Finishes:* Hot-rolled finish (scale not removed); pickled or blast-cleaned; cold-drawn; turned or machined; rough ground; centerless ground or precision flat ground; and polished (rounds only).

Other forms in which tool steels are supplied are the following:

*Rolled or Forged Special Shapes:* These shapes are usually produced on special orders only, for the purpose of reducing material loss and machining time in the large-volume manufacture of certain frequently used types of tools.

*Forgings:* All types of tool steels may be supplied in the form of forgings, that are usually specified for special shapes and for dimensions that are beyond the range covered by bars.

*Wires:* Tool steel wires are produced either by hot or cold drawing and are specified when special shapes, controlled dimensional accuracy, improved surface finish, or special mechanical properties are required. Round wire is commonly produced within an approximate size range of 0.015 to 0.500 inch, and these dimensions also indicate the limits within which other shapes of tool steel wires, like oval, square, or rectangular, may be produced.

*Drill Rods:* Rods are produced in round, rectangular, square, hexagonal, and octagonal shapes, usually with tight dimensional tolerances to eliminate subsequent machining, thereby offering manufacturing economies for the users.

*Hot-Rolled Plates and Sheets, and Cold-Rolled Strips:* Such forms of tool steel are generally specified for the high-volume production of specific tool types.

**Tool Bits:** These pieces are semifinished tools and are used by clamping in a tool holder or shank in a manner permitting ready replacement. Tool bits are commonly made of high-speed types of tool steels, mostly in square, but also in round, rectangular, and other shapes. Tool bits are made of hot rolled bars and are commonly, yet not exclusively, supplied in hardened and ground form, ready for use after the appropriate cutting edges are ground, usually in the user's plant.

**Hollow Bars:** These bars are generally produced by trepanning, boring, or drilling of solid round rods and are used for making tools or structural parts of annular shapes, like rolls, ring gages, bushings, etc.

**Tolerances of Dimensions.**—Such tolerances have been developed and published by the American Iron and Steel Institute (AISI) as a compilation of available industry experience that, however, does not exclude the establishment of closer tolerances, particularly for hot rolled products manufactured in large quantities. The tolerances differ for various categories of production processes (e.g., forged, hot-rolled, cold-drawn, centerless ground) and of general shapes.

**Allowances for Machining.**—These allowances provide freedom from soft spots and defects of the tool surface, thereby preventing failures in heat treatment or in service. After a layer of specific thickness, known as the allowance, has been removed, the bar or other form of tool steel material should have a surface without decarburization and other surface defects, such as scale marks or seams. The industry wide accepted machining allowance values for tool steels in different conditions, shapes, and size ranges are spelled out in AISI specifications and are generally also listed in the tool steel catalogs of the producer companies.

**Decarburization Limits.**—Heating of steel for production operation causes the oxidation of the exposed surfaces resulting in the loss of carbon. That condition, called decarburization, penetrates to a certain depth from the surface, depending on the applied process, the shape and the dimensions of the product. Values of tolerance for decarburization must be considered as one of the factors for defining the machining allowances, which must also compensate for expected variations of size and shape, the dimensional effects of heat treatment, and so forth. Decarburization can be present not only in hot-rolled and forged, but also in rough turned and cold-drawn conditions.

**Advances in Tool Steel Making Technology.**—Significant advances in processes for tool steel production have been made that offer more homogeneous materials of greater density and higher purity for applications where such extremely high quality is required. Two of these methods of tool steel production are of particular interest.

**Vacuum-melted tool steels:** These steels are produced by the consumable electrode method, which involves remelting of the steel originally produced by conventional processes. Inside a vacuum-tight shell that has been evacuated, the electrode cast of tool steel of the desired chemical analysis is lowered into a water-cooled copper mold where it strikes a low-voltage, high-amperage arc causing the electrode to be consumed by gradual melting. The undesirable gases and volatiles are drawn off by the vacuum, and the inclusions float on the surface of the pool, accumulating on the top of the produced ingot, to be removed later by cropping. In the field of tool steels, the consumable-electrode vacuum-melting (CVM) process is applied primarily to the production of special grades of hot-work and high-speed tool steels.

**High-speed tool steels produced by powder metallurgy:** The steel produced by conventional methods is reduced to a fine powder by a gas atomization process. The powder is compacted by a hot isostatic method with pressures in the range of 15,000 to 17,000 psi. The compacted billets are hot-rolled to the final bar size, yielding a tool-steel material which has 100 per cent theoretical density. High-speed tool steels produced by the P/M method offer a tool material providing increased tool wear life and high impact strength, of particular advantage in interrupted cuts.

## HARDENING, TEMPERING, AND ANNEALING

### Heat Treatment Of Standard Steels

**Heat-Treating Definitions.**—This glossary of heat-treating terms has been adopted by the American Foundrymen's Association, the American Society for Metals, the American Society for Testing and Materials, and the Society of Automotive Engineers. Since it is not intended to be a specification but is strictly a set of definitions, temperatures have purposely been omitted.

**Aging:** Describes a time–temperature-dependent change in the properties of certain alloys. Except for strain aging and age softening, it is the result of precipitation from a solid solution of one or more compounds whose solubility decreases with decreasing temperature. For each alloy susceptible to aging, there is a unique range of time–temperature combinations to which it will respond.

**Annealing:** A term denoting a treatment, consisting of heating to and holding at a suitable temperature followed by cooling at a suitable rate, used primarily to soften but also to simultaneously produce desired changes in other properties or in microstructure. The purpose of such changes may be, but is not confined to, improvement of machinability; facilitation of cold working; improvement of mechanical or electrical properties; or increase in stability of dimensions. The time–temperature cycles used vary widely both in maximum temperature attained and in cooling rate employed, depending on the composition of the material, its condition, and the results desired. When applicable, the following more specific process names should be used: Black Annealing, Blue Annealing, Box Annealing, Bright Annealing, Cycle Annealing, Flame Annealing, Full Annealing, Graphitizing, Intermediate Annealing, Isothermal Annealing, Process Annealing, Quench Annealing, and Spheroidizing. When the term is used without qualification, full annealing is implied. When applied only for the relief of stress, the process is properly called stress relieving.

**Black Annealing:** Box annealing or pot annealing, used mainly for sheet, strip, or wire.

**Blue Annealing:** Heating hot-rolled sheet in an open furnace to a temperature within the transformation range and then cooling in air, to soften the metal. The formation of a bluish oxide on the surface is incidental.

**Box Annealing:** Annealing in a sealed container under conditions that minimize oxidation. In box annealing, the charge is usually heated slowly to a temperature below the transformation range, but sometimes above or within it, and is then cooled slowly; this process is also called “close annealing” or “pot annealing.”

**Bright Annealing:** Annealing in a protective medium to prevent discoloration of the bright surface.

**Cycle Annealing:** An annealing process employing a predetermined and closely controlled time–temperature cycle to produce specific properties or microstructure.

**Flame Annealing:** Annealing in which the heat is applied directly by a flame.

**Full Annealing:** Austenitizing and then cooling at a rate such that the hardness of the product approaches a minimum.

**Graphitizing:** Annealing in such a way that some or all of the carbon is precipitated as graphite.

**Intermediate Annealing:** Annealing at one or more stages during manufacture and before final thermal treatment.

**Isothermal Annealing:** Austenitizing and then cooling to and holding at a temperature at which austenite transforms to a relatively soft ferrite-carbide aggregate.

**Process Annealing:** An imprecise term used to denote various treatments that improve workability. For the term to be meaningful, the condition of the material and the time–temperature cycle used must be stated.

**Quench Annealing:** Annealing an austenitic alloy by *Solution Heat Treatment*.

**Spheroidizing:** Heating and cooling in a cycle designed to produce a spheroidal or globular form of carbide.

*Austempering:* Quenching from a temperature above the transformation range, in a medium having a rate of heat abstraction high enough to prevent the formation of high-temperature transformation products, and then holding the alloy, until transformation is complete, at a temperature below that of pearlite formation and above that of martensite formation.

*Austenitizing:* Forming austenite by heating into the transformation range (partial austenitizing) or above the transformation range (complete austenitizing). When used without qualification, the term implies complete austenitizing.

*Baking:* Heating to a low temperature in order to remove entrained gases.

*Bluing:* A treatment of the surface of iron-base alloys, usually in the form of sheet or strip, on which, by the action of air or steam at a suitable temperature, a thin blue oxide film is formed on the initially scale-free surface, as a means of improving appearance and resistance to corrosion. This term is also used to denote a heat treatment of springs after fabrication, to reduce the internal stress created by coiling and forming.

*Carbon Potential:* A measure of the ability of an environment containing active carbon to alter or maintain, under prescribed conditions, the carbon content of the steel exposed to it. In any particular environment, the carbon level attained will depend on such factors as temperature, time, and steel composition.

*Carbon Restoration:* Replacing the carbon lost in the surface layer from previous processing by carburizing this layer to substantially the original carbon level.

*Carbonitriding:* A case-hardening process in which a suitable ferrous material is heated above the lower transformation temperature in a gaseous atmosphere of such composition as to cause simultaneous absorption of carbon and nitrogen by the surface and, by diffusion, create a concentration gradient. The process is completed by cooling at a rate that produces the desired properties in the workpiece.

*Carburizing:* A process in which carbon is introduced into a solid iron-base alloy by heating above the transformation temperature range while in contact with a carbonaceous material that may be a solid, liquid, or gas. Carburizing is frequently followed by quenching to produce a hardened case.

*Case:* 1) The surface layer of an iron-base alloy that has been suitably altered in composition and can be made substantially harder than the interior or core by a process of case hardening; and 2) the term case is also used to designate the hardened surface layer of a piece of steel that is large enough to have a distinctly softer core or center.

*Cementation:* The process of introducing elements into the outer layer of metal objects by means of high-temperature diffusion.

*Cold Treatment:* Exposing to suitable subzero temperatures for the purpose of obtaining desired conditions or properties, such as dimensional or microstructural stability. When the treatment involves the transformation of retained austenite, it is usually followed by a tempering treatment.

*Conditioning Heat Treatment:* A preliminary heat treatment used to prepare a material for a desired reaction to a subsequent heat treatment. For the term to be meaningful, the treatment used must be specified.

*Controlled Cooling:* A term used to describe a process by which a steel object is cooled from an elevated temperature, usually from the final hot-forming operation in a predetermined manner of cooling to avoid hardening, cracking, or internal damage.

*Core:* 1) The interior portion of an iron-base alloy that after case hardening is substantially softer than the surface layer or case; and 2) the term core is also used to designate the relatively soft central portion of certain hardened tool steels.

*Critical Range or Critical Temperature Range:* Synonymous with *Transformation Range*, which is preferred.

*Cyaniding:* A process of case hardening an iron-base alloy by the simultaneous absorption of carbon and nitrogen by heating in a cyanide salt. Cyaniding is usually followed by quenching to produce a hard case.

*Decarburization:* The loss of carbon from the surface of an iron-base alloy as the result of heating in a medium that reacts with the carbon.

*Drawing:* Drawing, or drawing the temper, is synonymous with *Tempering*, which is preferable.

*Eutectic Alloy:* The alloy composition that freezes at constant temperature similar to a pure metal. The lowest melting (or freezing) combination of two or more metals. The alloy structure (homogeneous) of two or more solid phases formed from the liquid eutectically.

*Hardenability:* In a ferrous alloy, the property that determines the depth and distribution of hardness induced by quenching.

*Hardening:* Any process of increasing hardness of metal by suitable treatment, usually involving heating and cooling. See also *Aging*.

*Hardening, Case:* A process of surface hardening involving a change in the composition of the outer layer of an iron-base alloy followed by appropriate thermal treatment. Typical case-hardening processes are *Carburizing*, *Cyaniding*, *Carbonitriding*, and *Nitriding*.

*Hardening, Flame:* A process of heating the surface layer of an iron-base alloy above the transformation temperature range by means of a high-temperature flame, followed by quenching.

*Hardening, Precipitation:* A process of hardening an alloy in which a constituent precipitates from a supersaturated solid solution. See also *Aging*.

*Hardening, Secondary:* An increase in hardness following the normal softening that occurs during the tempering of certain alloy steels.

*Heating, Differential:* A heating process by which the temperature is made to vary throughout the object being heated so that on cooling, different portions may have such different physical properties as may be desired.

*Heating, Induction:* A process of local heating by electrical induction.

*Heat Treatment:* A combination of heating and cooling operations applied to a metal or alloy in the solid state to obtain desired conditions or properties. Heating for the sole purpose of hot working is excluded from the meaning of this definition.

*Heat Treatment, Solution:* A treatment in which an alloy is heated to a suitable temperature and held at this temperature for a sufficient length of time to allow a desired constituent to enter into solid solution, followed by rapid cooling to hold the constituent in solution. The material is then in a supersaturated, unstable state, and may subsequently exhibit *Age Hardening*.

*Homogenizing:* A high-temperature heat-treatment process intended to eliminate or to decrease chemical segregation by diffusion.

*Isothermal Transformation:* A change in phase at constant temperature.

*Malleablizing:* A process of annealing white cast iron in which the combined carbon is wholly or in part transformed to graphitic or free carbon and, in some cases, part of the carbon is removed completely. See *Temper Carbon*.

*Maraging:* A precipitation hardening treatment applied to a special group of iron-base alloys to precipitate one or more intermetallic compounds in a matrix of essentially carbon-free martensite.

*Martempering:* A hardening procedure in which an austenitized ferrous workpiece is quenched into an appropriate medium whose temperature is maintained substantially at the  $M_s$  of the workpiece, held in the medium until its temperature is uniform throughout but not long enough to permit bainite to form, and then cooled in air. The treatment is followed by tempering.

*Nitriding:* A process of case hardening in which an iron-base alloy of special composition is heated in an atmosphere of ammonia or in contact with nitrogenous material. Surface hardening is produced by the absorption of nitrogen without quenching.

*Normalizing:* A process in which an iron-base alloy is heated to a temperature above the transformation range and subsequently cooled in still air at room temperature.

*Overheated:* A metal is said to have been overheated if, after exposure to an unduly high temperature, it develops an undesirably coarse grain structure but is not permanently damaged. The structure damaged by overheating can be corrected by suitable heat treatment or by mechanical work or by a combination of the two. In this respect it differs from a Burnt structure.

*Patenting:* A process of heat treatment applied to medium- or high-carbon steel in wire making prior to the wire drawing or between drafts. It consists in heating to a temperature above the transformation range, followed by cooling to a temperature below that range in air or in a bath of molten lead or salt maintained at a temperature appropriate to the carbon content of the steel and the properties required of the finished product.

*Preheating:* Heating to an appropriate temperature immediately prior to austenitizing when hardening high-hardenability constructional steels, many of the tool steels, and heavy sections.

*Quenching:* Rapid cooling. When applicable, the following more specific terms should be used: Direct Quenching, Fog Quenching, Hot Quenching, Interrupted Quenching, Selective Quenching, Slack Quenching, Spray Quenching, and Time Quenching.

*Direct Quenching:* Quenching carburized parts directly from the carburizing operation.

*Fog Quenching:* Quenching in a mist.

*Hot Quenching:* An imprecise term used to cover a variety of quenching procedures in which a quenching medium is maintained at a prescribed temperature above 160 degrees F (71 degrees C).

*Interrupted Quenching:* A quenching procedure in which the workpiece is removed from the first quench at a temperature substantially higher than that of the quenchant and is then subjected to a second quenching system having a different cooling rate than the first.

*Selective Quenching:* Quenching only certain portions of a workpiece.

*Slack Quenching:* The incomplete hardening of steel due to quenching from the austenitizing temperature at a rate slower than the critical cooling rate for the particular steel, resulting in the formation of one or more transformation products in addition to martensite.

*Spray Quenching:* Quenching in a spray of liquid.

*Time Quenching:* Interrupted quenching in which the duration of holding in the quenching medium is controlled.

*Soaking:* Prolonged heating of a metal at a selected temperature.

*Stabilizing Treatment:* A treatment applied to stabilize the dimensions of a workpiece or the structure of a material such as 1) before finishing to final dimensions, heating a workpiece to or somewhat beyond its operating temperature and then cooling to room temperature a sufficient number of times to ensure stability of dimensions in service; 2) transforming retained austenite in those materials that retain substantial amounts when quench hardened (see cold treatment); and 3) heating a solution-treated austenitic stainless steel that contains controlled amounts of titanium or niobium plus tantalum to a temperature below the solution heat-treating temperature to cause precipitation of finely divided, uniformly distributed carbides of those elements, thereby substantially reducing the amount of carbon available for the formation of chromium carbides in the grain boundaries on subsequent exposure to temperatures in the sensitizing range.

*Stress Relieving:* A process to reduce internal residual stresses in a metal object by heating the object to a suitable temperature and holding for a proper time at that temperature. This treatment may be applied to relieve stresses induced by casting, quenching, normalizing, machining, cold working, or welding.

*Temper Carbon:* The free or graphitic carbon that comes out of solution usually in the form of rounded nodules in the structure during *Graphitizing* or *Malleablizing*.

*Tempering:* Heating a quench-hardened or normalized ferrous alloy to a temperature below the transformation range to produce desired changes in properties.

*Double Tempering:* A treatment in which quench hardened steel is given two complete tempering cycles at substantially the same temperature for the purpose of ensuring completion of the tempering reaction and promoting stability of the resulting microstructure.

*Snap Temper:* A precautionary interim stress-relieving treatment applied to high hardenability steels immediately after quenching to prevent cracking because of delay in tempering them at the prescribed higher temperature.

*Temper Brittleness:* Brittleness that results when certain steels are held within, or are cooled slowly through, a certain range of temperatures below the transformation range. The brittleness is revealed by notched-bar impact tests at or below room temperature.

*Transformation Ranges or Transformation Temperature Ranges:* Those ranges of temperature within which austenite forms during heating and transforms during cooling. The two ranges are distinct, sometimes overlapping but never coinciding. The limiting temperatures of the ranges depend on the composition of the alloy and on the rate of change of temperature, particularly during cooling.

*Transformation Temperature:* The temperature at which a change in phase occurs. The term is sometimes used to denote the limiting temperature of a transformation range. The following symbols are used for iron and steels:

$Ac_{cm}$  = In hypereutectoid steel, the temperature at which the solution of cementite in austenite is completed during heating

$Ac_1$  = The temperature at which austenite begins to form during heating

$Ac_3$  = The temperature at which transformation of ferrite to austenite is completed during heating

$Ac_4$  = The temperature at which austenite transforms to delta ferrite during heating

$Ae_1, Ae_3, Ae_{cm}, Ae_4$  = The temperatures of phase changes at equilibrium

$Ar_{cm}$  = In hypereutectoid steel, the temperature at which precipitation of cementite starts during cooling

$Ar_1$  = The temperature at which transformation of austenite to ferrite or to ferrite plus cementite is completed during cooling

$Ar_3$  = The temperature at which austenite begins to transform to ferrite during cooling

$Ar_4$  = The temperature at which delta ferrite transforms to austenite during cooling

$M_s$  = The temperature at which transformation of austenite to martensite starts during cooling

$M_f$  = The temperature, during cooling, at which transformation of austenite to martensite is substantially completed

All these changes except the formation of martensite occur at lower temperatures during cooling than during heating, and depend on the rate of change of temperature.

**Hardness and Hardenability.**—Hardenability is the property of steel that determines the *depth and distribution of hardness* induced by quenching from the austenitizing temperature. Hardenability should not be confused with hardness as such or with maximum hardness. Hardness is a measure of the ability of a metal to resist penetration as determined by any one of a number of standard tests (Brinell, Rockwell, Vickers, etc). The maximum attainable hardness of any steel depends solely on carbon content and is not significantly affected by alloy content. Maximum hardness is realized only when the cooling rate in quenching is rapid enough to ensure full transformation to martensite.

The as-quenched surface hardness of a steel part is dependent on carbon content and cooling rate, but the *depth* to which a certain hardness level is maintained with given quenching conditions is a function of its hardenability. Hardenability is largely determined by the percentage of alloying elements in the steel; however, austenite grain size, time and temperature during austenitizing, and prior microstructure also significantly affect the hardness depth. The hardenability required for a particular part depends on size, design, and service stresses. For highly stressed parts, the best combination of strength and toughness is obtained by through hardening to a martensitic structure followed by adequate tempering. There are applications, however, where through hardening is not necessary or even



desirable. For parts that are stressed principally at or near the surface, or in which wear resistance or resistance to shock loading is anticipated, a shallow hardening steel with a moderately soft core may be appropriate.

For through hardening of thin sections, carbon steels may be adequate; but as section size increases, alloy steels of increasing hardenability are required. The usual practice is to select the most economical grade that can meet the desired properties consistently. It is not good practice to utilize a higher alloy grade than necessary, because excessive use of alloying elements adds little to the properties and can sometimes induce susceptibility to quenching cracks.

*Quenching Media:* The choice of quenching media is often a critical factor in the selection of steel of the proper hardenability for a particular application. Quenching severity can be varied by selection of quenching medium, agitation control, and additives that improve the cooling capability of the quenchant. Increasing the quenching severity permits the use of less expensive steels of lower hardenability; however, consideration must also be given to the amount of distortion that can be tolerated and the susceptibility to quench cracking. In general, the more severe the quenchant and the less symmetrical the part being quenched, the greater are the size and shape changes that result from quenching and the greater is the risk of quench cracking. Consequently, although water quenching is less costly than oil quenching, and water quenching steels are less expensive than those requiring oil quenching, it is important to know that the parts being hardened can withstand the resulting distortion and the possibility of cracking.

Oil, salt, and synthetic water-polymer quenchant are also used, but they often require steels of higher alloy content and hardenability. A general rule for the selection of steel and quenchant for a particular part is that the steel should have a hardenability not exceeding that required by the severity of the quenchant selected. The carbon content of the steel should also not exceed that required to meet specified hardness and strength, because quench cracking susceptibility increases with carbon content.

The choice of quenching media is important in hardening, but another factor is agitation of the quenching bath. The more rapidly the bath is agitated, the more rapidly heat is removed from the steel and the more effective is the quench.

*Hardenability Test Methods:* The most commonly used method for determining hardenability is the end-quench test developed by Jominy and Boegehold, and described in detail in both SAE J406 and ASTM A255. In this test a normalized 1-inch-round, approximately 4-inch-long specimen of the steel to be evaluated is heated uniformly to its austenitizing temperature. The specimen is then removed from the furnace, placed in a jig, and immediately end quenched by a jet of room-temperature water. The water is played on the end face of the specimen, without touching the sides, until the entire specimen has cooled. Longitudinal flat surfaces are ground on opposite sides of the piece and Rockwell C scale hardness readings are taken at  $\frac{1}{16}$ -inch intervals from the quenched end. The resulting data are plotted on graph paper with the hardness values as ordinates ( $y$ -axis) and distances from the quenched end as abscissas ( $x$ -axis). Representative data have been accumulated for a variety of standard steel grades and are published by SAE and AISI as "H-bands." These data show graphically and in tabular form the high and low limits applicable to each grade. The suffix H following the standard AISI/SAE numerical designation indicates that the steel has been produced to specific hardenability limits.

Experiments have confirmed that the cooling rate at a given point along the Jominy bar corresponds closely to the cooling rate at various locations in round bars of various sizes. In general, when end-quench curves for different steels coincide approximately, similar treatments will produce similar properties in sections of the same size. On occasion it is necessary to predict the end-quench hardenability of a steel not available for testing, and reasonably accurate means of calculating hardness for any Jominy location on a section of steel of known analysis and grain size have been developed.

**Tempering:** As-quenched steels are in a highly stressed condition and are seldom used without tempering. Tempering imparts plasticity or toughness to the steel, and is inevitably accompanied by a loss in hardness and strength. The loss in strength, however, is only incidental to the very important increase in toughness, which is due to the relief of residual stresses induced during quenching and to precipitation, coalescence, and spheroidization of iron and alloy carbides resulting in a microstructure of greater plasticity.

Alloying slows the tempering rate, so that alloy steel requires a higher tempering temperature to obtain a given hardness than carbon steel of the same carbon content. The higher tempering temperature for a given hardness permits a greater relaxation of residual stress and thereby improves the steel's mechanical properties. Tempering is done in furnaces or in oil or salt baths at temperatures varying from 300 to 1200 degrees F. With most grades of alloy steel, the range between 500 and 700 degrees F is avoided because of a phenomenon known as "blue brittleness," which reduces impact properties. Tempering the martensitic stainless steels in the range of 800-1100 degrees F is not recommended because of the low and erratic impact properties and reduced corrosion resistance that result. Maximum toughness is achieved at higher temperatures. It is important to temper parts as soon as possible after quenching, because any delay greatly increases the risk of cracking resulting from the high-stress condition in the as-quenched part.

**Surface Hardening Treatment (Case Hardening).**—Many applications require high hardness or strength primarily at the surface, and complex service stresses frequently require not only a hard, wear-resistant surface, but also core strength and toughness to withstand impact stress.

To achieve these different properties, two general processes are used: 1) The chemical composition of the surface is altered, prior to or after quenching and tempering; the processes used include carburizing, nitriding, cyaniding, and carbonitriding; and 2) Only the surface layer is hardened by the heating and quenching process; the most common processes used for surface hardening are flame hardening and induction hardening.

**Carburizing:** Carbon is diffused into the part's surface to a controlled depth by heating the part in a carbonaceous medium. The resulting depth of carburization, commonly referred to as case depth, depends on the carbon potential of the medium used and the time and temperature of the carburizing treatment. The steels most suitable for carburizing to enhance toughness are those with sufficiently low carbon contents, usually below 0.03 per cent. Carburizing temperatures range from 1550 to 1750 degrees F, with the temperature and time at temperature adjusted to obtain various case depths. Steel selection, hardenability, and type of quench are determined by section size, desired core hardness, and service requirements.

Three types of carburizing are most often used: 1) *Liquid carburizing* involves heating the steel in molten barium cyanide or sodium cyanide. The case absorbs some nitrogen in addition to carbon, thus enhancing surface hardness; 2) *Gas carburizing* involves heating the steel in a gas of controlled carbon content. When used, the carbon level in the case can be closely controlled; and 3) *Pack carburizing*, which involves sealing both the steel and solid carbonaceous material in a gas-tight container, then heating this combination.

With any of these methods, the part may be either quenched after the carburizing cycle without reheating or air cooled followed by reheating to the austenitizing temperature prior to quenching. The case depth may be varied to suit the conditions of loading in service. However, service characteristics frequently require that only selective areas of a part have to be case hardened. Covering the areas not to be cased, with copper plating or a layer of commercial paste, allows the carbon to penetrate only the exposed areas. Another method involves carburizing the entire part, then removing the case in selected areas by machining, prior to quench hardening.

**Nitriding:** The steel part is heated to a temperature of 900-1150 degrees F in an atmosphere of ammonia gas and dissociated ammonia for an extended period of time that

depends on the case depth desired. A thin, very hard case results from the formation of nitrides. Strong nitride-forming elements (chromium and molybdenum) are required to be present in the steel, and often special nonstandard grades containing aluminum (a strong nitride former) are used. The major advantage of this process is that parts can be quenched and tempered, then machined, prior to nitriding, because only a little distortion occurs during nitriding.

**Cyaniding:** This process involves heating the part in a bath of sodium cyanide to a temperature slightly above the transformation range, followed by quenching, to obtain a thin case of high hardness.


**Carbonitriding:** This process is similar to cyaniding except that the absorption of carbon and nitrogen is accomplished by heating the part in a gaseous atmosphere containing hydrocarbons and ammonia. Temperatures of 1425–1625 degrees F are used for parts to be quenched, and lower temperatures, 1200–1450 degrees F, may be used where a liquid quench is not required.

**Flame Hardening:** This process involves rapid heating with a direct high-temperature gas flame, such that the surface layer of the part is heated above the transformation range, followed by cooling at a rate that causes the desired hardening. Steels for flame hardening are usually in the range of 0.30–0.60 per cent carbon, with hardenability appropriate for the case depth desired and the quenchant used. The quenchant is usually sprayed on the surface a short distance behind the heating flame. Immediate tempering is required and may be done in a conventional furnace or by a flame-tempering process, depending on part size and costs.

**Induction Hardening:** This process is similar in many respects to flame hardening except that the heating is caused by a high-frequency electric current sent through a coil or inductor surrounding the part. The depth of heating depends on the frequency, the rate of heat conduction from the surface, and the length of the heating cycle. Quenching is usually accomplished with a water spray introduced at the proper time through jets in or near the inductor block or coil. In some instances, however, parts are oil-quenched by immersing them in a bath of oil after they reach the hardening temperature.

**Structure of Fully Annealed Carbon Steel.**—In carbon steel that has been fully annealed, there are normally present, apart from such impurities as phosphorus and sulfur, two constituents: the element iron in a form metallurgically known as *ferrite* and the chemical compound iron carbide in the form metallurgically known as *cementite*. This latter constituent consists of 6.67 per cent carbon and 93.33 per cent iron. A certain proportion of these two constituents will be present as a mechanical mixture. This mechanical mixture, the amount of which depends on the carbon content of the steel, consists of alternate bands or layers of ferrite and cementite. Under the microscope, the matrix frequently has the appearance of mother-of-pearl and hence has been named *pearlite*. Pearlite contains about 0.85 per cent carbon and 99.15 per cent iron, neglecting impurities. A fully annealed steel containing 0.85 per cent carbon would consist entirely of pearlite. Such a steel is known as *eutectoid* steel and has a laminated structure characteristic of a eutectic alloy. Steel that has less than 0.85 per cent carbon (*hypoeutectoid* steel) has an excess of ferrite above that required to mix with the cementite present to form pearlite; hence, both ferrite and pearlite are present in the fully annealed state. Steel having a carbon content greater than 0.85 per cent (*hypereutectoid* steel) has an excess of cementite over that required to mix with the ferrite to form pearlite; hence, both cementite and pearlite are present in the fully annealed state. The structural constitution of carbon steel in terms of ferrite, cementite, pearlite and austenite for different carbon contents and at different temperatures is shown by the accompanying figure, *Phase Diagram of Carbon Steel*.

**Effect of Heating Fully Annealed Carbon Steel.**—When carbon steel in the fully annealed state is heated above the lower critical point, which is some temperature in the range of 1335 to 1355 degrees F (depending on the carbon content), the alternate bands or

layers of ferrite and cementite that make up the pearlite begin to merge into each other. This process continues until the pearlite is thoroughly "dissolved," forming what is known as *austenite*. If the temperature of the steel continues to rise and there is present, in addition to the pearlite, any excess ferrite or cementite, this also will begin to dissolve into the austenite until finally only austenite will be present. The temperature at which the excess ferrite or cementite is completely dissolved in the austenite is called the *upper critical point*. This temperature varies with the carbon content of the steel much more widely than the lower critical point (see Fig. 1).  [LIVE GRAPH](#)  
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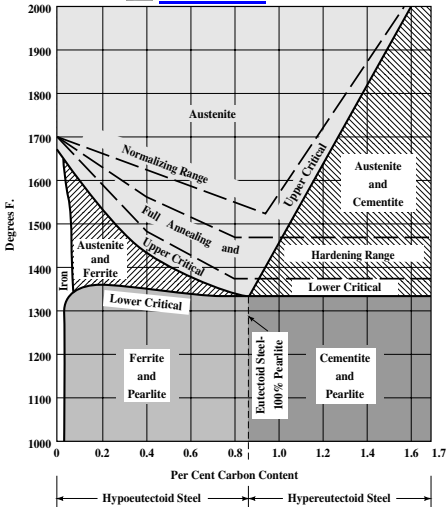


Fig. 1. Phase Diagram of Carbon Steel

**Effect of Slow Cooling on Carbon Steel.**—If carbon steel that has been heated to the point where it consists entirely of austenite is slowly cooled, the process of transformation that took place during the heating will be reversed, but the upper and lower critical points will occur at somewhat lower temperatures than they do on heating. Assuming that the steel was originally fully annealed, its structure on returning to atmospheric temperature after slow cooling will be the same as before in terms of the proportions of ferrite or cementite and pearlite present. The austenite will have entirely disappeared.

**Effect of Rapid Cooling or Quenching on Carbon Steel.**—Observations have shown that as the rate at which carbon steel is cooled from an austenitic state is increased, the temperature at which the austenite begins to change into pearlite drops more and more below the slow cooling transformation temperature of about 1300 degrees F. (For example, a 0.80 per cent carbon steel that is cooled at such a rate that the temperature drops 500 degrees in one second will show transformation of austenite beginning at 930 degrees F.) As the cooling rate is increased, the laminations of the pearlite formed by the transformation of the austenite become finer and finer up to the point where they cannot be detected under a high-power microscope, while the steel itself increases in hardness and tensile strength. As the rate of cooling is still further increased, this transformation temperature suddenly drops to around 500 degrees F or lower, depending on the carbon content of the steel. The cooling rate at which this sudden drop in transformation temperature takes place is called the *critical cooling rate*. When a piece of carbon steel is quenched at this rate or faster, a new struc-

ture is formed. The austenite is transformed into *martensite*, which is characterized by an angular needlelike structure and a very high hardness.

If carbon steel is subjected to a severe quench or to extremely rapid cooling, a small percentage of the austenite, instead of being transformed into martensite during the quenching operation, may be retained. Over a period of time, however, this remaining austenite tends to be gradually transformed into martensite even though the steel is not subjected to further heating or cooling. Martensite has a lower density than austenite, and such a change, or "aging" as it is called, often results in an appreciable increase in volume or "growth" and the setting up of new internal stresses in the steel.

**Steel Heat-Treating Furnaces.**—Various types of furnaces heated by gas, oil, or electricity are used for the heat treatment of steel. These furnaces include the oven or box type in various modifications for "in-and-out" or for continuous loading and unloading; the retort type; the pit type; the pot type; and the salt-bath electrode type.

*Oven or Box Furnaces:* This type of furnace has a box or oven-shaped heating chamber. The "in-and-out" oven furnaces are loaded by hand or by a track-mounted car that, when rolled into the furnace, forms the bottom of the heating chamber. The car type is used where heavy or bulky pieces must be handled. Some oven-type furnaces are provided with a full muffle or a semimuffle, which is an enclosed refractory chamber into which the parts to be heated are placed. The full-muffle, being fully enclosed, prevents any flames or burning gases from coming in contact with the work and permits a special atmosphere to be used to protect or condition the work. The semimuffle, which is open at the top, protects the work from direct impingement of the flame although it does not shut off the work from the hot gases. In the direct-heat-type oven furnace, the work is open to the flame. In the electric oven furnace, a retort is provided when gas atmospheres are to be employed to confine the gas and prevent it from attacking the heating elements. Where muffles are used, they must be replaced periodically, and a greater amount of fuel is required than in a direct-heat type of oven furnace.

For continuous loading and unloading, there are several types of furnaces such as rotary hearth car; roller-, furnace belt-, walking-beam, or pusher-conveyor; and a continuous-kiln-type through which track-mounted cars are run. In the continuous type of furnace, the work may pass through several zones that are maintained at different temperatures for preheating, heating, soaking, and cooling.

*Retort Furnace:* This is a vertical type of furnace provided with a cylindrical metal retort into which the parts to be heat-treated are suspended either individually, if large enough, or in a container of some sort. The use of a retort permits special gas atmospheres to be employed for carburizing, nitriding, etc.

*Pit-Type Furnace:* This is a vertical furnace arranged for the loading of parts in a metal basket. The parts within the basket are heated by convection, and when the basket is lowered into place, it fits into the furnace chamber in such a way as to provide a dead-air space to prevent direct heating.

*Pot-Type Furnace:* This furnace is used for the immersion method of heat treating small parts. A cast-alloy pot is employed to hold a bath of molten lead or salt in which the parts are placed for heating.

*Salt Bath Electrode Furnace:* In this type of electric furnace, heating is accomplished by means of electrodes suspended directly in the salt bath. The patented grouping and design of electrodes provide an electromagnetic action that results in an automatic stirring action. This stirring tends to produce an even temperature throughout the bath.

*Vacuum Furnace:* Vacuum heat treatment is a relatively new development in metallurgical processing, with a vacuum substituting for the more commonly used protective gas atmospheres. The most often used furnace is the "cold wall" type, consisting of a water-cooled vessel that is maintained near ambient temperature during operation. During quenching, the chamber is backfilled up to or above atmospheric pressure with an inert gas,

which is circulated by an internal fan. When even faster cooling rates are needed, furnaces are available with capability for liquid quenching, performed in an isolated chamber.

**Fluidized-Bed Furnace:** Fluidized-bed techniques are not new; however, new furnace designs have extended the technology into the temperature ranges required for most common heat treatments. In fluidization, a bed of dry, finely divided particles, typically aluminum oxide, is made to behave like a liquid by feeding gas upward through the bed. An important characteristic of the bed is high-efficiency heat transfer. Applications include continuous or batch-type units for all general heat treatments.

**Physical Properties of Heat-Treated Steels.**—Steels that have been “fully hardened” to the same hardness when quenched will have about the same tensile and yield strengths regardless of composition and alloying elements. When the hardness of such a steel is known, it is also possible to predict its reduction of area and tempering temperature. The accompanying figures illustrating these relationships have been prepared by the Society of Automotive Engineers.

Fig. 1 gives the range of Brinell hardnesses that could be expected for any particular tensile strength or it may be used to determine the range of tensile strengths that would correspond to any particular hardness. Fig. 2 shows the relationship between the tensile strength or hardness and the yield point. The solid line is the normal-expectancy curve. The dotted-line curves give the range of the variation of scatter of the plotted data. Fig. 3 shows the relationship that exists between the tensile strength (or hardness) and the reduction of area. The curve to the left represents the alloy steels and that on the right the carbon steels. Both are normal-expectancy curves and the extremities of the perpendicular lines that intersect them represent the variations from the normal-expectancy curves that may be caused by quality differences and by the magnitude of parasitic stresses induced by quenching. Fig. 4 shows the relationship between the hardness (or approximately equivalent tensile strength) and the tempering temperature. Three curves are given, one for fully hardened steels with a carbon content between 0.40 and 0.55 per cent, one for fully hardened steels with a carbon content between 0.30 and 0.40 per cent, and one for steels that are not fully hardened.

From Fig. 1, it can be seen that for a tensile strength of, say, 200,000 pounds per square inch, the Brinell hardness could range between 375 and 425. By taking 400 as the mean hardness value and using Fig. 4, it can be seen that the tempering temperature of fully hardened steels of 0.40 to 0.55 per cent carbon content would be 990 degrees F and that of fully hardened steels of 0.30 to 0.40 per cent carbon would be 870 degrees F. This chart also shows that the tempering temperature for a steel not fully hardened would approach 520 degrees F. A yield point of  $0.9 \times 200,000$ , or 180,000, pounds per square inch is indicated (Fig. 2) for the fully hardened steel with a tensile strength of 200,000 pounds per square inch. Most alloy steels of 200,000 pounds per square inch tensile strength would probably have a reduction in area of close to 44 per cent (Fig. 3) but some would have values in the range of 35 to 53 per cent. Carbon steels of the same tensile strength would probably have a reduction in area of close to 24 per cent but could possibly range from 17 to 31 per cent.

Figs. 2 and 3 represent steel in the quenched and tempered condition and Fig. 1 represents steel in the hardened and tempered, as-rolled, annealed, and normalized conditions. These charts give a good general indication of mechanical properties; however, more exact information when required should be obtained from tests on samples of the individual heats of steel under consideration.

### Hardening

**Basic Steps in Hardening.**—The operation of hardening steel consists fundamentally of two steps. The first step is to heat the steel to some temperature above (usually at least 100 degrees F above) its transformation point so that it becomes entirely austenitic in structure. The second step is to quench the steel at some rate faster than the critical rate (which

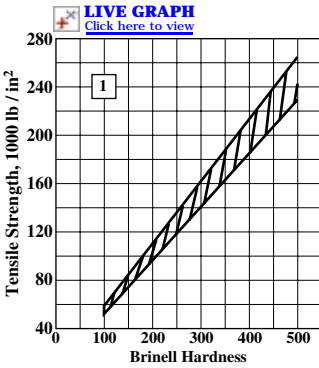


Fig. 1.

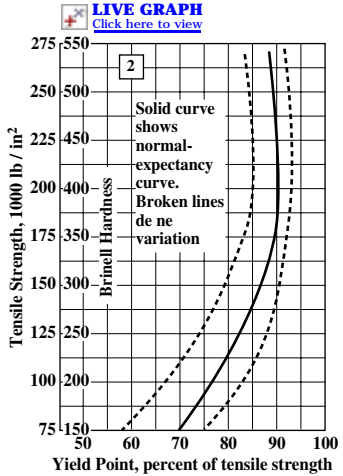


Fig. 2.

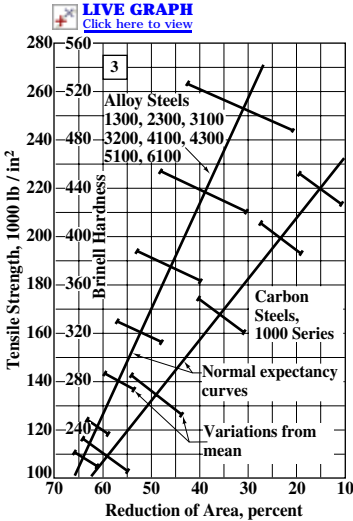


Fig. 3.

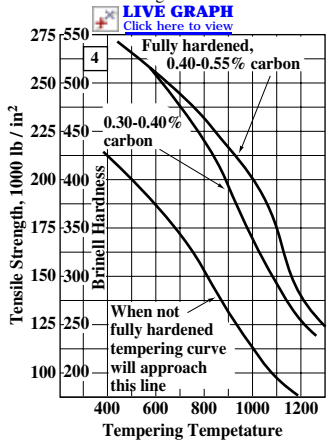


Fig. 4.

depends on the carbon content, the amounts of alloying elements present other than carbon, and the grain size of the austenite) to produce a martensitic structure. The hardness of a martensitic steel depends on its carbon content and ranges from about 460 Brinell at 0.20 per cent carbon to about 710 Brinell above 0.50 carbon. In comparison, ferrite has a hardness of about 90 Brinell, pearlite about 240 Brinell, and cementite around 550 Brinell.

**Critical Points of Decalescence and Recalescence.**—The critical or transformation point at which pearlite is transformed into austenite as it is being heated is also called the *decalescence point*. If the temperature of the steel was observed as it passed through the

decalescence point, it would be noted that it would continue to absorb heat without appreciably rising in temperature, although the immediate surroundings were hotter than the steel. Similarly, the critical or transformation point at which austenite is transformed back into pearlite on cooling is called the *recalescence point*. When this point is reached, the steel will give out heat so that its temperature instead of continuing to fall, will momentarily increase.

The recalescence point is lower than the decalescence point by anywhere from 85 to 215 degrees F, and the lower of these points does not manifest itself unless the higher one has first been fully passed. These critical points have a direct relation to the hardening of steel. Unless a temperature sufficient to reach the decalescence point is obtained, so that the pearlite is changed into austenite, no hardening action can take place; and unless the steel is cooled suddenly before it reaches the recalescence point, thus preventing the changing back again from austenite to pearlite, no hardening can take place. The critical points vary for different kinds of steel and must be determined by tests. The variation in the critical points makes it necessary to heat different steels to different temperatures when hardening.

**Hardening Temperatures.**—The maximum temperature to which a steel is heated before quenching to harden it is called the hardening temperature. Hardening temperatures vary for different steels and different classes of service, although, in general, it may be said that the hardening temperature for any given steel is above the lower critical point of that steel.

Just how far above this point the hardening temperature lies for any particular steel depends on three factors: 1) the chemical composition of the steel; 2) the amount of excess ferrite (if the steel has less than 0.85 per cent carbon content) or the amount of excess cementite (if the steel has more than 0.85 per cent carbon content) that is to be dissolved in the austenite; and 3) the maximum grain size permitted, if desired.

The general range of full-hardening temperatures for carbon steels is shown by the diagram. This range is merely indicative of general practice and is not intended to represent absolute hardening temperature limits. It can be seen that for steels of less than 0.85 per cent carbon content, the hardening range is above the upper critical point — that is, above the temperature at which all the excess ferrite has been dissolved in the austenite. On the other hand, for steels of more than 0.85 per cent carbon content, the hardening range lies somewhat below the upper critical point. This indicates that in this hardening range, some of the excess cementite still remains undissolved in the austenite. If steel of more than 0.85 per cent carbon content were heated above the upper critical point and then quenched, the resulting grain size would be excessively large.

At one time, it was considered desirable to heat steel only to the minimum temperature at which it would fully harden, one of the reasons being to avoid grain growth that takes place at higher temperature. It is now realized that no such rule as this can be applied generally since there are factors other than hardness that must be taken into consideration. For example, in many cases, toughness can be impaired by too low a temperature just as much as by too high a temperature. It is true, however, that too high hardening temperatures result in warpage, distortion, increased scale, and decarburization.

**Hardening Temperatures for Carbon Tool Steels.**—The best hardening temperatures for any given tool steel are dependent on the type of tool and the intended class of service. Wherever possible, the specific recommendations of the tool steel manufacturer should be followed. General recommendations for hardening temperatures of carbon tool steels based on carbon content are as follows: For steel of 0.65 to 0.80 per cent carbon content, 1450 to 1550 degrees F; for steel of 0.80 to 0.95 per cent carbon content, 1410 to 1460 degrees F; for steel of 0.95 to 1.10 per cent carbon content, 1390 to 1430 degrees F; and for steels of 1.10 per cent and over carbon content, 1380 to 1420 degrees F. For a given hardening temperature range, the higher temperatures tend to produce deeper hardness penetration and increased compressional strength, whereas the lower temperatures tend to result in shallower hardness penetration but increased resistance to splitting or bursting stresses.



**Determining Hardening Temperatures.**—A hardening temperature can be specified directly or it may be specified indirectly as a certain temperature rise above the lower critical point of the steel. Where the temperature is specified directly, a pyrometer of the type that indicates the furnace temperature or a pyrometer of the type that indicates the work temperature may be employed. If the pyrometer shows furnace temperature, care must be taken to allow sufficient time for the work to reach the furnace temperature after the pyrometer indicates that the required hardening temperature has been attained. If the pyrometer indicates work temperature, then, where the workpiece is large, time must be allowed for the interior of the work to reach the temperature of the surface, which is the temperature indicated by the pyrometer.

Where the hardening temperature is specified as a given temperature rise above the critical point of the steel, a pyrometer that indicates the temperature of the work should be used. The critical point, as well as the given temperature rise, can be more accurately determined with this type of pyrometer. As the work is heated, its temperature, as indicated by the pyrometer, rises steadily until the lower critical or decalescence point of the steel is reached. At this point, the temperature of the work ceases to rise and the pyrometer indicating or recording pointer remains stationary or fluctuates slightly. After a certain elapsed period, depending on the heat input rate, the internal changes in structure of the steel that take place at the lower critical point are completed and the temperature of the work again begins to rise. A small fluctuations in temperature may occur in the interval during which structural changes are taking place, so for uniform practice, the critical point may be considered as the temperature at which the pointer first becomes stationary.

**Heating Steel in Liquid Baths.**—The liquid bath commonly used for heating steel tools preparatory to hardening are molten lead, sodium cyanide, barium chloride, a mixture of barium and potassium chloride, and other metallic salts. The molten substance is retained in a crucible or pot and the heat required may be obtained from gas, oil, or electricity. The principal advantages of heating baths are as follows: No part of the work can be heated to a temperature above that of the bath; the temperature can be easily maintained at whatever degree has proved, in practice, to give the best results; the submerged steel can be heated uniformly, and the finished surfaces are protected against oxidation.

**Salt Baths.**—Molten baths of various salt mixtures or compounds are used extensively for heat-treating operations such as hardening and tempering; they are also utilized for annealing ferrous and nonferrous metals. Commercial salt-bath mixtures are available that meet a wide range of temperature and other metallurgical requirements. For example, there are neutral baths for heating tool and die steels without carburizing the surfaces; baths for carburizing the surfaces of low-carbon steel parts; baths adapted for the usual tempering temperatures of, say, 300 to 1100 degrees F; and baths that may be heated to temperatures up to approximately 2400 degrees F for hardening high-speed steels. Salt baths are also adapted for local or selective hardening, the type of bath being selected to suit the requirements. For example, a neutral bath may be used for annealing the ends of tubing or other parts, or an activated cyanide bath for carburizing the ends of shafts or other parts. Surfaces that are not to be carburized are protected by copper plating. When the work is immersed, the unplated surfaces are subjected to the carburizing action.

Baths may consist of a mixture of sodium, potassium, barium, and calcium chlorides or nitrates of sodium, potassium, barium, and calcium in varying proportions, to which sodium carbonate and sodium cyanide are sometimes added to prevent decarburization. Various proportions of these salts provide baths of different properties. Potassium cyanide is seldom used as sodium cyanide costs less. The specific gravity of a salt bath is not as high as that of a lead bath; consequently, the work may be suspended in a salt bath and does not have to be held below the surface as in a lead bath.

**The Lead Bath.**—The lead bath is extensively used, but is not adapted to the high temperatures required for hardening high-speed steel, as it begins to vaporize at about 1190 degrees F. As the temperature increases, the lead volatilizes and gives off poisonous

vapors; hence, lead furnaces should be equipped with hoods to carry away the fumes. Lead baths are generally used for temperatures below 1500 or 1600 degrees F. They are often employed for heating small pieces that must be hardened in quantities. It is important to use pure lead that is free from sulfur. The work should be preheated before plunging it into the molten lead.

**Defects in Hardening.**—Uneven heating is the cause of most of the defects in hardening. Cracks of a circular form, from the corners or edges of a tool, indicate uneven heating in hardening. Cracks of a vertical nature and dark-colored fissures indicate that the steel has been burned and should be put on the scrap heap. Tools that have hard and soft places have been either unevenly heated, unevenly cooled, or “soaked,” a term used to indicate prolonged heating. A tool not thoroughly moved about in the hardening fluid will show hard and soft places, and have a tendency to crack. Tools that are hardened by dropping them to the bottom of the tank sometimes have soft places, owing to contact with the floor or sides.

**Scale on Hardened Steel.**—The formation of scale on the surface of hardened steel is due to the contact of oxygen with the heated steel; hence, to prevent scale, the heated steel must not be exposed to the action of the air. When using an oven heating furnace, the flame should be so regulated that it is not visible in the heating chamber. The heated steel should be exposed to the air as little as possible, when transferring it from the furnace to the quenching bath. An old method of preventing scale and retaining a fine finish on dies used in jewelry manufacture, small taps, etc., is as follows: Fill the die impression with powdered boracic acid and place near the fire until the acid melts; then add a little more acid to ensure covering all the surfaces. The die is then hardened in the usual way. If the boracic acid does not come off entirely in the quenching bath, immerse the work in boiling water. Dies hardened by this method are said to be as durable as those heated without the acid.

**Hardening or Quenching Baths.**—The purpose of a quenching bath is to remove heat from the steel being hardened at a rate that is faster than the critical cooling rate. Generally speaking, the more rapid the rate of heat extraction above the cooling rate, the higher will be the resulting hardness. To obtain the different rates of cooling required by different classes of work, baths of various kinds are used. These include plain or fresh water, brine, caustic soda solutions, oils of various classes, oil-water emulsions, baths of molten salt or lead for high-speed steels, and air cooling for some high-speed steel tools when a slow rate of cooling is required. To minimize distortion and cracking where such tendencies are present, without sacrificing depth-of-hardness penetration, a quenching medium should be selected that will cool rapidly at the higher temperatures and more slowly at the lower temperatures, that is below 750 degrees F. Oil quenches in general meet this requirement.

*Oil Quenching Baths:* Oil is used very extensively as a quenching medium as it results in a good proportion of hardness, toughness, and freedom from warpage when used with standard steels. Oil baths are used extensively for alloy steels. Various kinds of oils are employed, such as prepared mineral oils and vegetable, animal, and fish oils, either singly or in combination. Prepared mineral quenching oils are widely used because they have good quenching characteristics, are chemically stable, do not have an objectionable odor, and are relatively inexpensive. Special compounded oils of the soluble type are used in many plants instead of such oils as fish oil, linseed oil, cottonseed oil, etc. The soluble properties enable the oil to form an emulsion with water.

Oil cools steel at a slower rate than water, but the rate is fast enough for alloy steel. Oils have different cooling rates, however, and this rate may vary through the initial and final stages of the quenching operation. Faster cooling in the initial stage and slower cooling at lower temperatures are preferable because there is less danger of cracking the steel. The temperature of quenching oil baths should range ordinarily between 90 and 130 degrees F. A fairly constant temperature may be maintained either by circulating the oil through cooling coils or by using a tank provided with a cold-water jacket.

A good quenching oil should possess a flash and fire point sufficiently high to be safe under the conditions used and 350 degrees F should be about the minimum point. The specific heat of the oil regulates the hardness and toughness of the quenched steel; and the greater the specific heat, the higher will be the hardness produced. Specific heats of quenching oils vary from 0.20 to 0.75, the specific heats of fish, animal, and vegetable oils usually being from 0.2 to 0.4, and of soluble and mineral oils from 0.5 to 0.7. The efficient temperature range for quenching oil is from 90 to 140 degrees F.

**Quenching in Water.**—Many carbon tool steels are hardened by immersing them in a bath of fresh water, but water is not an ideal quenching medium. Contact between the water and work and the cooling of the hot steel are impaired by the formation of gas bubbles or an insulating vapor film especially in holes, cavities, or pockets. The result is uneven cooling and sometimes excessive strains which may cause the tool to crack; in fact, there is greater danger of cracking in a fresh-water bath than in one containing salt water or brine.

In order to secure more even cooling and reduce danger of cracking, either rock salt (8 or 9 per cent) or caustic soda (3 to 5 per cent) may be added to the bath to eliminate or prevent the formation of a vapor film or gas pockets, thus promoting rapid early cooling. Brine is commonly used and  $\frac{3}{4}$  pound of rock salt per gallon of water is equivalent to about 8 per cent of salt. Brine is not inherently a more severe or drastic quenching medium than plain water, although it may seem to be because the brine makes better contact with the heated steel and, consequently, cooling is more effective. In still-bath quenching, a slow up-and-down movement of the tool is preferable to a violent swishing around.

The temperature of water-base quenching baths should preferably be kept around 70 degrees F, but 70 to 90 or 100 degrees F is a safe range. The temperature of the hardening bath has a great deal to do with the hardness obtained. The higher the temperature of the quenching water, the more nearly does its effect approach that of oil; and if boiling water is used for quenching, it will have an effect even more gentle than that of oil — in fact, it would leave the steel nearly soft. Parts of irregular shape are sometimes quenched in a water bath that has been warmed somewhat to prevent sudden cooling and cracking.

When water is used, it should be “soft” because unsatisfactory results will be obtained with “hard” water. Any contamination of water-base quenching liquids by soap tends to decrease their rate of cooling. A water bath having 1 or 2 inches of oil on the top is sometimes employed to advantage for quenching tools made of high-carbon steel as the oil through which the work first passes reduces the sudden quenching action of the water.

The bath should be amply large to dissipate the heat rapidly and the temperature should be kept about constant so that successive pieces will be cooled at the same rate. Irregularly shaped parts should be immersed so that the heaviest or thickest section enters the bath first. After immersion, the part to be hardened should be agitated in the bath; the agitation reduces the tendency of the formation of a vapor coating on certain surfaces, and a more uniform rate of cooling is obtained. The work should never be dropped to the bottom of the bath until quite cool.

*Flush or Local Quenching by Pressure-Spraying:* When dies for cold heading, drawing, extruding, etc., or other tools, require a hard working surface and a relatively soft but tough body, the quenching may be done by spraying water under pressure against the interior or other surfaces to be hardened. Special spraying fixtures are used to hold the tool and apply the spray where the hardening is required. The pressure spray prevents the formation of gas pockets previously referred to in connection with the fresh-water quenching bath; hence, fresh water is effective for flush quenching and there is no advantage in using brine.

**Quenching in Molten Salt Bath.**—A molten salt bath may be used in preference to oil for quenching high-speed steel. The object in using a liquid salt bath for quenching (instead of an oil bath) is to obtain maximum hardness with minimum cooling stresses and distortion that might result in cracking expensive tools, especially if there are irregular sections. The temperature of the quenching bath may be around 1100 or 1200 degrees F. Quenching is

followed by cooling to room temperature and then the tool is tempered or drawn in a bath having a temperature range of 950 to 1100 degrees F. In many cases, the tempering temperature is about 1050 degrees F.

**Tanks for Quenching Baths.**—The main point to be considered in a quenching bath is to keep it at a uniform temperature, so that successive pieces quenched will be subjected to the same heat treatment. The next consideration is to keep the bath agitated, so that it will not be of different temperatures in different places; if thoroughly agitated and kept in motion, as the case with the bath shown in Fig. 1, it is not even necessary to keep the pieces in motion in the bath, as steam will not be likely to form around the pieces quenched. Experience has proved that if a piece is held still in a thoroughly agitated bath, it will come out much straighter than if it has been moved around in an unagitated bath, an important consideration, especially when hardening long pieces. It is, besides, no easy matter to keep heavy and long pieces in motion unless it be done by mechanical means.

In Fig. 1 is shown a water or brine tank for quenching baths. Water is forced by a pump or other means through the supply pipe into the intermediate space between the outer and inner tank. From the intermediate space, it is forced into the inner tank through holes as indicated. The water returns to the storage tank by overflowing from the inner tank into the outer one and then through the overflow pipe as indicated. In Fig. 3 is shown another water or brine tank of a more common type. In this case, the water or brine is pumped from the storage tank and continuously returned to it. If the storage tank contains a large volume of water, there is no need for a special means for cooling. Otherwise, arrangements must be made for cooling the water after it has passed through the tank. The bath is agitated by the force with which the water is pumped into it. The holes at A are drilled at an angle, so as to throw the water toward the center of the tank. In Fig. 2 is shown an oil-quenching tank in which water is circulated in an outer surrounding tank to keep the oil bath cool. Air is forced into the oil bath to keep it agitated. Fig. 4 shows the ordinary type of quenching tank cooled by water forced through a coil of pipe. This arrangement can be used for oil, water, or brine. Fig. 5 shows a similar type of quenching tank, but with two coils of pipe. Water flows through one of these and steam through the other. By these means, it is possible to keep the bath at a constant temperature.

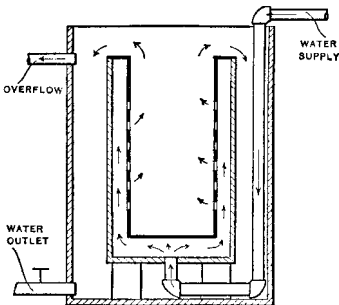


Fig. 1.

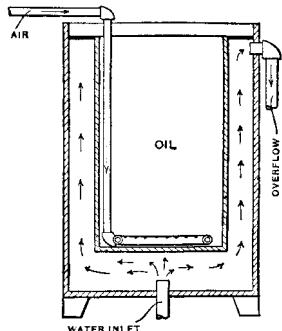


Fig. 2.

**Interrupted Quenching.**—*Austempering, martempering, and isothermal quenching* are three methods of interrupted quenching that have been developed to obtain greater toughness and ductility for given hardnesses and to avoid the difficulties of quench cracks, internal stresses, and warpage, frequently experienced when the conventional method of

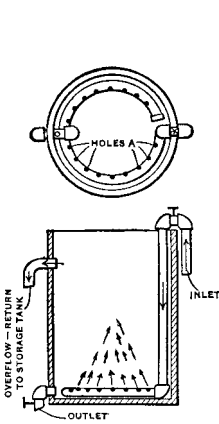


Fig. 3.

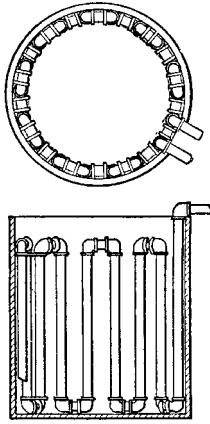


Fig. 4.

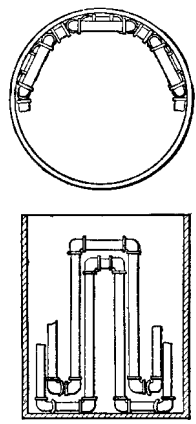


Fig. 5.

quenching steel directly and rapidly from above the transformation point to atmospheric temperature is employed. In each of these three methods, quenching is begun when the work has reached some temperature above the transformation point and is conducted at a rate faster than the critical rate. The rapid cooling of the steel is interrupted, however, at some temperature above that at which martensite begins to form. The three methods differ in the temperature range at which interruption of the rapid quench takes place, the length of time that the steel is held at this temperature, and whether the subsequent cooling to atmospheric temperature is rapid or slow, and is or is not preceded by a tempering operation.

One of the reasons for maintaining the steel at a constant temperature for a definite period of time is to permit the inside sections of the piece to reach the same temperature as the outer sections so that when transformation of the structure does take place, it will occur at about the same rate and period of time throughout the piece. In order to maintain the constant temperature required in interrupted quenching, a quenching arrangement for absorbing and dissipating a large quantity of heat without increase in temperature is needed. Molten salt baths equipped for water spray or air cooling around the exterior of the bath container have been used for this purpose.

*Austempering:* This is a heat-treating process in which steels are quenched in a bath maintained at some constant temperature in the range of 350 to 800 degrees F, depending on the analysis of the steel and the characteristics to be obtained. On immersion in the quenching bath, the steel is cooled more rapidly than the critical quenching rate. When the temperature of the steel reaches that of the bath, however, the quenching action is interrupted. If the steel is now held at this temperature for a predetermined length of time, say, from 10 to 60 minutes, the austenitic structure of the steel is gradually changed into a new structure, called *bainite*. The structure of bainite is acicular (needlelike) and resembles that of tempered martensite such as is usually obtained by quenching in the usual manner to atmospheric temperature and tempering at 400 degrees F or higher.

Hardnesses ranging up to 60 Rockwell C, depending on the carbon and alloy content of the steel, are obtainable and compare favorably with those obtained for the respective steels by a conventional quench and tempering to above 400 degrees F. Much greater

toughness and ductility are obtained in an austempered piece, however, as compared with a similar piece quenched and tempered in the usual manner.

Two factors are important in austempering. First, the steel must be quenched rapidly enough to the specified subtransformation temperature to avoid any formation of pearlite, and, second, it must be held at this temperature until the transformation from austenite to bainite is completed. Time and temperature transformation curves (called S-curves because of their shape) have been developed for different steels and these curves provide important data governing the conduct of austempering, as well as the other interrupted quenching methods.

Austempering has been applied chiefly to steels having 0.60 per cent or more carbon content with or without additional low-alloy content, and to pieces of small diameter or section, usually under 1 inch, but varying with the composition of the steel. Case-hardened parts may also be austempered.

*Martempering:* In this process the steel is first rapidly quenched from some temperature above the transformation point down to some temperature (usually about 400 degrees F) just above that at which martensite begins to form. It is then held at this temperature for a length of time sufficient to equalize the temperature throughout the part, after which it is removed and cooled in air. As the temperature of the steel drops below the transformation point, martensite begins to form in a matrix of austenite at a fairly uniform rate throughout the piece. The soft austenite acts as a cushion to absorb some of the stresses which develop as the martensite is formed. The difficulties presented by quench cracks, internal stresses, and dimensional changes are largely avoided, thus a structure of high hardness can be obtained. If greater toughness and ductility are required, conventional tempering may follow. In general, heavier sections can be hardened more easily by the martempering process than by the austempering process. The martempering process is especially suited to the higher-alloyed steels.

*Isothermal Quenching:* This process resembles austempering in that the steel is first rapidly quenched from above the transformation point down to a temperature that is above that at which martensite begins to form and is held at this temperature until the austenite is completely transformed into bainite. The constant temperature to which the piece is quenched and then maintained is usually 450 degrees F or above. The process differs from austempering in that after transformation to a bainite structure has been completed, the steel is immersed in another bath and is brought up to some higher temperature, depending on the characteristics desired, and is maintained at this temperature for a definite period of time, followed by cooling in air. Thus, tempering to obtain the desired toughness or ductility takes place immediately after the structure of the steel has changed to bainite and before it is cooled to atmospheric temperature.

**Laser and Electron-Beam Surface Hardening.**—Industrial lasers and electron-beam equipment are now available for surface hardening of steels. The laser and electron beams can generate very intense energy fluxes and steep temperature profiles in the workpiece, so that external quench media are not needed. This self-quenching is due to a cold interior with sufficient mass acting as a large heat sink to rapidly cool the hot surface by conducting heat to the interior of a part. The laser beam is a beam of light and does not require a vacuum for operation. The electron beam is a stream of electrons and processing usually takes place in a vacuum chamber or envelope. Both processes may normally be applied to finished machined or ground surfaces, because little distortion results.

### Tempering

The object of *tempering* or *drawing* is to reduce the brittleness in hardened steel and to remove the internal strains caused by the sudden cooling in the quenching bath. The tempering process consists in heating the steel by various means to a certain temperature and then cooling it. When steel is in a fully hardened condition, its structure consists largely of

*martensite*. On reheating to a temperature of from about 300 to 750 degrees F, a softer and tougher structure known as *troostite* is formed. If the steel is reheated to a temperature of from 750 to 1290 degrees F, a structure known as *sorbite* is formed that has somewhat less strength than troostite but much greater ductility.

**Tempering Temperatures.**—If steel is heated in an oxidizing atmosphere, a film of oxide forms on the surface that changes color as the temperature increases. These oxide colors (see [Table 1](#)) have been used extensively in the past as a means of gaging the correct amount of temper; but since these colors are affected to some extent by the composition of the metal, the method is not dependable.

**Table 1. Temperatures as Indicated by the Color of Plain Carbon Steel**

| Degrees Centigrade | Degrees Fahrenheit | Color of Steel    | Degrees Centigrade | Degrees Fahrenheit | Color of Steel    |
|--------------------|--------------------|-------------------|--------------------|--------------------|-------------------|
| 221.1              | 430                | Very pale yellow  | 265.6              | 510                | Spotted red-brown |
| 226.7              | 440                | Light yellow      | 271.1              | 520                | Brown-purple      |
| 232.2              | 450                | Pale straw-yellow | 276.7              | 530                | Light purple      |
| 237.8              | 460                | Straw-yellow      | 282.2              | 540                | Full purple       |
| 243.3              | 470                | Deep straw-yellow | 287.8              | 550                | Dark purple       |
| 248.9              | 480                | Dark yellow       | 293.3              | 560                | Full blue         |
| 254.4              | 490                | Yellow-brown      | 298.9              | 570                | Dark blue         |
| 260.0              | 500                | Brown-yellow      | 337.8              | 640                | Light blue        |

The availability of reliable pyrometers in combination with tempering baths of oil, salt, or lead make it possible to heat the work uniformly and to a given temperature within close limits.

Suggested temperatures for tempering various tools are given in [Table 2](#).

**Tempering in Oil.**—Oil baths are extensively used for tempering tools (especially in quantity), the work being immersed in oil heated to the required temperature, which is indicated by a thermometer. It is important that the oil have a uniform temperature throughout and that the work be immersed long enough to acquire this temperature. Cold steel should not be plunged into a bath heated for tempering, owing to the danger of cracking. The steel should either be preheated to about 300 degrees F, before placing it in the bath, or the latter should be at a comparatively low temperature before immersing the steel, and then be heated to the required degree. A temperature of from 650 to 700 degrees F can be obtained with heavy tempering oils; for higher temperatures, either a bath of nitrate salts or a lead bath may be used.

In tempering, the best method is to immerse the pieces to be tempered before starting to heat the oil, so that they are heated with the oil. After the pieces tempered are taken out of the oil bath, they should be immediately dipped in a tank of caustic soda, and after that in a tank of hot water. This will remove all oil that might adhere to the tools. The following tempering oil has given satisfactory results: mineral oil, 94 per cent; saponifiable oil, 6 per cent; specific gravity, 0.920; flash point, 550 degrees F; fire test, 625 degrees F.

**Tempering in Salt Baths.**—Molten salt baths may be used for tempering or drawing operations. Nitrate baths are particularly adapted for the usual drawing temperature range of, say, 300 to 1100 degrees F. Tempering in an oil bath usually is limited to temperatures of 500 to 600 degrees F, and some heat-treating specialists recommend the use of a salt bath for temperatures above 350 or 400 degrees F, as it is considered more efficient and economical. Tempering in a bath (salt or oil) has several advantages, such as ease in controlling the temperature range and maintenance of a uniform temperature. The work is also heated much more rapidly in a molten bath. A gas- or oil-fired muffle or semimuffle furnace may be used for tempering, but a salt bath or oil bath is preferable. A salt bath is rec-

**Table 2. Tempering Temperatures for Various Plain Carbon Steel Tools**

| Degrees F  | Class of Tool  |
|------------|--|
| 495 to 500 | Taps $\frac{1}{2}$ inch or over, for use on automatic screw machines                                     |
| 495 to 500 | Nut taps $\frac{1}{2}$ inch and under  |
| 515 to 520 | Taps $\frac{1}{4}$ inch and under, for use on automatic screw machines                                   |
| 525 to 530 | Thread dies to cut thread close to shoulder  |
| 500 to 510 | Thread dies for general work   |
| 495        | Thread dies for tool steel or steel tube   |
| 525 to 540 | Dies for bolt threader threading to shoulder   |
| 460 to 470 | Thread rolling dies  |
| 430 to 435 | Hollow mills (solid type) for roughing on automatic screw machines                                       |
| 485        | Knurls   |
| 450        | Twist drills for hard service  |
| 450        | Centering tools for automatic screw machines   |
| 430        | Forming tools for automatic screw machines   |
| 430 to 435 | Cut-off tools for automatic screw machines   |
| 440 to 450 | Profile cutters for milling machines   |
| 430        | Formed milling cutters   |
| 435 to 440 | Milling cutters  |
| 430 to 440 | Reamers  |
| 460        | Counterbores and countersinks  |
| 480        | Cutters for tube- or pipe-cutting machines   |
| 460 to 520 | Snaps for pneumatic hammers — harden full length, temper to 460 degrees, then bring point to 520 degrees |

ommended for tempering high-speed steel, although furnaces may also be used. The bath or furnace temperature should be increased gradually, say, from 300 to 400 degrees F up to the tempering temperature, which may range from 1050 to 1150 degrees F for high-speed steel.

**Tempering in a Lead Bath.**—The lead bath is commonly used for heating steel in connection with tempering, as well as for hardening. The bath is first heated to the temperature at which the steel should be tempered; the preheated work is then placed in the bath long enough to acquire this temperature, after which it is removed and cooled. As the melting temperature of pure lead is about 620 degrees F, tin is commonly added to it to lower the temperature sufficiently for tempering. Reductions in temperature can be obtained by varying the proportions of lead and tin, as shown in [Table 3](#).

**Table 3. Temperatures of Lead Bath Alloys**

| Parts Lead | Parts Tin | Melting Temp., Deg. F | Parts Lead | Parts Tin | Melting Temp., Deg. F | Parts Lead | Parts Tin | Melting Temp., Deg. F |
|------------|-----------|-----------------------|------------|-----------|-----------------------|------------|-----------|-----------------------|
| 200        | 8         | 560                   | 39         | 8         | 510                   | 19         | 8         | 460                   |
| 100        | 8         | 550                   | 33         | 8         | 500                   | 17         | 8         | 450                   |
| 75         | 8         | 540                   | 28         | 8         | 490                   | 16         | 8         | 440                   |
| 60         | 8         | 530                   | 24         | 8         | 480                   | 15         | 8         | 430                   |
| 48         | 8         | 520                   | 21         | 8         | 470                   | 14         | 8         | 420                   |

**To Prevent Lead from Sticking to Steel.**—To prevent hot lead from sticking to parts heated in it, mix common whiting with wood alcohol, and paint the part that is to be heated. Water can be used instead of alcohol, but in that case, the paint must be thoroughly dry, as



otherwise the moisture will cause the lead to "fly." Another method is to make a thick paste according to the following formula: Pulverized charred leather, 1 pound; fine wheat flour, 1½ pounds; fine table salt, 2 pounds. Coat the tool with this paste and heat slowly until dry, then proceed to harden. Still another method is to heat the work to a blue color, or about 600 degrees F, and then dip it in a strong solution of salt water, prior to heating in the lead bath. The lead is sometimes removed from parts having fine projections or teeth, by using a stiff brush just before immersing in the cooling bath. Removal of lead is necessary to prevent the formation of soft spots.

**Tempering in Sand.**—The sand bath is used for tempering certain classes of work. One method is to deposit the sand on an iron plate or in a shallow box that has burners beneath it. With this method of tempering, tools such as boiler punches, etc., can be given a varying temper by placing them endwise in the sand. As the temperature of the sand bath is higher toward the bottom, a tool can be so placed that the color of the lower end will become a deep dark blue when the middle portion is a very dark straw, and the working end or top a light straw color, the hardness gradually increasing from the bottom up.

**Double Tempering.**—In tempering high-speed steel tools, it is common practice to repeat the tempering operation or "double temper" the steel. Double tempering is done by heating the steel to the tempering temperature (say, 1050 degrees F) and holding it at that temperature for two hours. It is then cooled to room temperature, reheated to 1050 degrees F for another two-hour period, and again cooled to room temperature. After the first tempering operation, some untempered martensite remains in the steel. This martensite is not only tempered by a second tempering operation but is relieved of internal stresses, thus improving the steel for service conditions. The hardening temperature for the higher-alloy steels may affect the hardness after tempering. For example, molybdenum high-speed steel when heated to 2100 degrees F had a hardness of 61 Rockwell C after tempering, whereas a temperature of 2250 degrees F resulted in a hardness of 64.5 Rockwell C after tempering.

### Annealing, Spheroidizing, and Normalizing

Annealing of steel is a heat-treating process in which the steel is heated to some elevated temperature, usually in or near the critical range, is held at this temperature for some period of time, and is then cooled, usually at a slow rate. Spheroidizing and normalizing may be considered as special cases of annealing.

The *full annealing* of carbon steel consists in heating it slightly above the *upper* critical point for hypoeutectoid steels (steels of less than 0.85 per cent carbon content) and slightly above the *lower* critical point for hypereutectoid steels (steels of more than 0.85 per cent carbon content), holding it at this temperature until it is uniformly heated and then slowly cooling it to 1000 degrees F or below. The resulting structure is layerlike, or lamellar, in character due to the pearlite that is formed during the slow cooling.

Annealing is employed 1) to soften steel for machining, cutting, stamping, etc., or for some particular service; 2) to alter ductility, toughness, electrical or magnetic characteristics or other physical properties; 3) to refine the crystal structure; 4) to produce grain reorientation; and 5) to relieve stresses and hardness resulting from cold working.

The *spheroidizing* of steel, according to the American Society of Metals, is "any process of heating and cooling that produces a rounded or globular form of carbide." High-carbon steels are spheroidized to improve their machinability especially in continuous cutting operations such as are performed by lathes and screw machines. In low-carbon steels, spheroidizing may be employed to meet certain strength requirements before subsequent heat treatment. Spheroidizing also tends to increase resistance to abrasion.

The *normalizing* of steel consists in heating it to some temperature above that used for annealing, usually about 100 degrees F above the upper critical range, and then cooling it in still air at room temperature. Normalizing is intended to put the steel into a uniform, unstressed condition of proper grain size and refinement so that it will properly respond to

further heat treatments. It is particularly important in the case of forgings that are to be later heat treated. Normalizing may or may not (depending on the composition) leave steel in a sufficiently soft state for machining with available tools. Annealing for machinability is often preceded by normalizing and the combined treatment — frequently called a *double anneal* — produces a better result than a simple anneal.

**Annealing Practice.**—For carbon steels, the following annealing temperatures are recommended by the American Society for Testing and Materials: Steels of less than 0.12 per cent carbon content, 1600 to 1700 degrees F; steels of 0.12 to 0.29 per cent carbon content, 1550 to 1600 degrees F, steels of 0.30 to 0.49 per cent carbon content, 1500 to 1550 degrees F; and for 0.50 to 1.00 per cent carbon steels, from 1450 to 1500 degrees F. Slightly lower temperatures are satisfactory for steels having more than 0.75 per cent manganese content. Heating should be uniform to avoid the formation of additional stresses. In the case of large workpieces, the heating should be slow enough so that the temperature of the interior does not lag too far behind that of the surface.

It has been found that in annealing steel, the higher the temperature to which it is heated to produce an austenitic structure, the greater the tendency of the structure to become lamellar (pearlitic) in cooling. On the other hand, the closer the austenitizing temperature to the critical temperature, the greater is the tendency of the annealed steel to become spheroidal.

*Rate of Cooling:* After heating the steel to some temperature within the annealing range, it should be cooled slowly enough to permit the development of the desired softness and ductility. In general, the slower the cooling rate, the greater the resulting softness and ductility. Steel of a high-carbon content should be cooled more slowly than steel of a low-carbon content; and the higher the alloy content, the slower is the cooling rate usually required. Where extreme softness and ductility are not required, the steel may be cooled in the annealing furnace to some temperature well below the critical point, say, to about 1000 degrees F and then removed and cooled in air.

**Annealing by Constant-Temperature Transformation.**—It has been found that steel that has been heated above the critical point so that it has an austenitic structure can be transformed into a lamellar (pearlitic) or a spheroidal structure by holding it for a definite period of time at some constant subcritical temperature. In other words, it is feasible to anneal steel by means of a constant-temperature transformation as well as by the conventional continuous cooling method. When the constant-temperature transformation method is employed, the steel, after being heated to some temperature above the critical and held at this temperature until it is austenitized, is cooled as rapidly as feasible to some relatively high subcritical transformation temperature. The selection of this temperature is governed by the desired microstructure and hardness required and is taken from a transformation time and temperature curve (often called a TTT curve). As drawn for a particular steel, such a curve shows the length of time required to transform that steel from an austenitic state at various subcritical temperatures. After being held at the selected sub-critical temperature for the required length of time, the steel is cooled to room temperature — again, as rapidly as feasible. This rapid cooling down to the selected transformation temperature and then down to room temperature has a negligible effect on the structure of the steel and often produces a considerable saving in time over the conventional slow cooling method of annealing.

The softest condition in steel can be developed by heating it to a temperature usually less than 100 degrees F above the lower critical point and then cooling it to some temperature, usually less than 100 degrees, below the critical point, where it is held until the transformation is completed. Certain steels require a very lengthy period of time for transformation of the austenite when held at a constant temperature within this range. For such steels, a practical procedure is to allow most of the transformation to take place in this temperature range where a soft product is formed and then to finish the transformation at a lower temperature where the time for the completion of the transformation is short.

**Spheroidizing Practice.**—A common method of spheroidizing steel consists in heating it to or slightly below the lower critical point, holding it at this temperature for a period of time, and then cooling it slowly to about 1000 degrees F or below. The length of time for which the steel is held at the spheroidizing temperature largely governs the degree of spheroidization. High-carbon steel may be spheroidized by subjecting it to a temperature that alternately rises and falls between a point within and a point without the critical range. Tool steel may be spheroidized by heating to a temperature slightly above the critical range and then, after being held at this temperature for a period of time, cooling without removal from the furnace.

**Normalizing Practice.**—When using the lower-carbon steels, simple normalizing is often sufficient to place the steel in its best condition for machining and will lessen distortion in carburizing or hardening. In the medium- and higher-carbon steels, combined normalizing and annealing constitutes the best practice. For unimportant parts, the normalizing may be omitted entirely or annealing may be practiced only when the steel is otherwise difficult to machine. Both processes are recommended in the following heat treatments (for SAE steels) as representing the best metallurgical practice. The temperatures recommended for normalizing and annealing have been made indefinite in many instances because of the many different types of furnaces used in various plants and the difference in results desired.

### Case Hardening

In order to harden low-carbon steel, it is necessary to increase the carbon content of the surface of the steel so that a thin outer "case" can be hardened by heating the steel to the hardening temperature and then quenching it. The process, therefore, involves two separate operations. The first is the *carburizing* operation for impregnating the outer surface with sufficient carbon, and the second operation is that of heat treating the carburized parts so as to obtain a hard outer case and, at the same time, give the "core" the required physical properties. The term "case hardening" is ordinarily used to indicate the complete process of carburizing and hardening.

**Carburization.**—Carburization is the result of heating iron or steel to a temperature below its melting point in the presence of a solid, liquid, or gaseous material that decomposes so as to liberate carbon when heated to the temperature used. In this way, it is possible to obtain by the gradual penetration, diffusion, or absorption of the carbon by the steel, a "zone" or "case" of higher-carbon content at the outer surfaces than that of the original object. When a carburized object is rapidly cooled or quenched in water, oil, brine, etc., from the proper temperature, this case becomes hard, leaving the inside of the piece soft, but of great toughness.

**Use of Carbonaceous Mixtures.**—When carburizing materials of the solid class are used, the case-hardening process consists in packing steel articles in metal boxes or pots, with a carbonaceous compound surrounding the steel objects. The boxes or pots are sealed and placed in a carburizing oven or furnace maintained usually at a temperature of from about 1650 to 1700 degrees F for a length of time depending on the extent of the carburizing action desired. The carbon from the carburizing compound will then be absorbed by the steel on the surfaces desired, and the low-carbon steel is converted into high-carbon steel at these portions. The internal sections and the insulated parts of the object retain practically their original low-carbon content. The result is a steel of a dual structure, a high-carbon and a low-carbon steel in the same piece. The carburized steel may now be heat treated by heating and quenching, in much the same way as high-carbon steel is hardened, in order to develop the properties of hardness and toughness; but as the steel is, in reality, two steels in one, one high-carbon and one low-carbon, the correct heat treatment after carburizing includes two distinct processes, one suitable for the high-carbon portion or the "case," as it is generally called, and one suitable for the low-carbon portion or core. The method of heat treatment varies according to the kind of steel used. Usually, an initial heating and slow

cooling is followed by reheating to 1400–1450 degrees F, quenching in oil or water, and a final tempering. More definite information is given in the following section on S.A.E. steels.

**Carburizers:** There are many commercial carburizers on the market in which the materials used as the generator may be hard and soft wood charcoal, animal charcoal, coke, coal, beans and nuts, bone and leather, or various combinations of these. The energizers may be barium, cyanogen, and ammonium compounds, various salts, soda ash, or lime and oil hydrocarbons.

**Pack-Hardening.**—When cutting tools, gages, and other parts made from high-carbon steels are heated for hardening while packed in some carbonaceous material in order to protect delicate edges, corners, or finished surfaces, the process usually is known as pack-hardening. Thus, the purpose is to protect the work, prevent scale formation, ensure uniform heating, and minimize the danger of cracking and warpage. The work is packed, as in carburizing, and in the same type of receptacle. Common hardwood charcoal often is used, especially if it has had an initial heating to eliminate shrinkage and discharge its more impure gases. The lowest temperature required for hardening should be employed for pack-hardening — usually 1400 to 1450 degrees F for carbon steels. Pack-hardening has also been applied to high-speed steels, but modern developments in heat-treating salts have made it possible to harden high-speed steel without decarburization, injury to sharp edges, or marring the finished surfaces. See *Salt Baths* on page 516.

**Cyanide Hardening.**—When low-carbon steel requires a very hard outer surface but does not need high shock-resisting qualities, the cyanide-hardening process may be employed to produce what is known as superficial hardness. This superficial hardening is the result of carburizing a very thin outer skin (which may be only a few thousandths inch thick) by immersing the steel in a bath containing sodium cyanide. The temperatures usually vary from 1450 to 1650 degrees F and the percentage of sodium cyanide in the bath extends over a wide range, depending on the steel used and properties required.

**Nitriding Process.**—Nitriding is a process for surface hardening certain alloy steels by heating the steel in an atmosphere of nitrogen (ammonia gas) at approximately 950 degrees F. The steel is then cooled slowly. Finish machined surfaces hardened by nitriding are subject to minimum distortion. The physical properties, such as toughness, high impact strength, etc., can be imparted to the core by previous heat treatments and are unaffected by drawing temperatures up to 950 degrees F. The “Nitralloy” steels suitable for this process may be readily machined in the heat-treated as well as in the annealed state, and they forge as easily as alloy steels of the same carbon content. Certain heat treatments must be applied prior to nitriding, the first being annealing to relieve rolling, forging, or machining strains. Parts or sections not requiring heat treating should be machined or ground to the exact dimensions required. Close tolerances must be maintained in finish machining, but allowances for growth due to adsorption of nitrogen should be made, and this usually amounts to about 0.0005 inch for a case depth of 0.02 inch. Parts requiring heat treatment for definite physical properties are forged or cut from annealed stock, heat treated for the desired physical properties, rough machined, normalized, and finish machined. If quenched and drawn parts are normalized afterwards, the drawing and normalizing temperatures should be alike. The normalizing temperature may be below but should never be above the drawing temperature.

**Ion Nitriding.**—Ion nitriding, also referred to as glow discharge nitriding, is a process for case hardening of steel parts such as tool spindles, cutting tools, extrusion equipment, forging dies, gears, and crankshafts. An electrical potential ionizes low-pressure nitrogen gas, and the ions produced are accelerated to and impinge on the workpiece, heating it to the appropriate temperature for diffusion to take place. Therefore, there is no requirement for a supplemental heat source. The inward diffusion of the nitrogen ions forms the iron and

alloy nitrides in the case. White layer formation, familiar in conventional gas nitriding, is readily controlled by this process.

**Liquid Carburizing.**—Activated liquid salt baths are now used extensively for carburizing. Sodium cyanide and other salt baths are used. The salt bath is heated by electrodes immersed in it, the bath itself acting as the conductor and resistor. One or more groups of electrodes, with two or more electrodes per group, may be used. The heating is accompanied by a stirring action to ensure uniform temperature and carburizing activity throughout the bath. The temperature may be controlled by a thermocouple immersed in the bath and connecting with a pyrometer designed to provide automatic regulation. The advantages of liquid baths include rapid action; uniform carburization; minimum distortion; and elimination of the packing and unpacking required when carbonaceous mixtures are used. In selective carburizing, the portions of the work that are not to be carburized are copper-plated and the entire piece is then immersed in an activated cyanide bath. The copper inhibits any carburizing action on the plated parts, and this method offers a practical solution for selectively carburizing any portion of a steel part.

**Gas Carburizing.**—When carburizing gases are used, the mixture varies with the type of case and quality of product desired. The gaseous hydrocarbons most widely used are methane (natural gas), propane, and butane. These carbon-bearing gases are mixed with air, with manufactured gases of several types, with flue gas, or with other specially prepared “diluent” gases. It is necessary to maintain a continuous fresh stream of carburizing gases to the carburizing retort or muffle, as well as to remove the spent gases from the muffle continuously, in order to obtain the correct mixture of gases inside the muffle. A slight pressure is maintained on the muffle to exclude unwanted gases.

The horizontal rotary type of gas carburizing furnace has a retort or muffle that revolves slowly. This type of furnace is adapted to small parts such as ball and roller bearings, chain links, small axles, bolts, etc. With this type of furnace, very large pieces such as gears, for example, may be injured by successive shocks due to tumbling within the rotor.

The vertical pit type of gas carburizer has a stationary workholder that is placed vertically in a pit. The work, instead of circulating in the gases as with the rotary type, is stationary and the gases circulate around it. This type is applicable to long large shafts or other parts or shapes that cannot be rolled in a rotary type of furnace.

There are three types of continuous gas furnaces that may be designated as

- 1) direct quench and manually operated
- 2) direct quench and mechanically operated
- 3) cooling-zone type

Where production does not warrant using a large continuous-type furnace, a horizontal muffle furnace of the batch type may be used, especially if the quantities of work are varied and the production not continuous.

**Vacuum Carburizing.**—Vacuum carburizing is a high-temperature gas carburizing process that is performed at pressures below atmospheric. The furnace atmosphere usually consists solely of an enriching gas, such as natural gas, pure methane, or propane; nitrogen is sometimes used as a carrier gas. Vacuum carburizing offers several advantages such as combining of processing operations and reduced total processing time.

**Carburizing Steels.**—A low-carbon steel containing, say, from 0.10 to 0.20 per cent of carbon is suitable for carburized case hardening. In addition to straight-carbon steels, the low-carbon alloy steels are employed. The alloys add to case-hardened parts the same advantageous properties that they give to other classes of steel. Various steels suitable for case hardening will be found in the section on SAE steels.

**To Clean Work after Case Hardening.**—To clean work, especially if knurled, or if dirt is likely to stick into crevices after case hardening, wash it in caustic soda (1 part soda to 10 parts water). In making the solution, the soda should be put into hot water gradually, and the mixture stirred until the soda is thoroughly dissolved. A still more effective method of

cleaning is to dip the work into a mixture of 1 part sulfuric acid and 2 parts water. Leave the pieces in this mixture about three minutes; then wash them immediately in a soda solution.

**Flame Hardening.**—This method of hardening is especially applicable to the selective hardening of large steel forgings or castings that must be finish-machined prior to heat-treatment, or that because of size or shape cannot be heat treated by using a furnace or bath. An oxyacetylene torch is used to heat quickly the surface to be hardened; this surface is then quenched to secure a hardened layer that may vary in depth from a mere skin to  $\frac{1}{4}$  inch and with hardness ranging from 400 to 700 Brinell. A multiflame torchhead may be equipped with quenching holes or a spray nozzle back of the flame. This is not a carburizing or a case-hardening process as the torch is only a heating medium. Most authorities recommend tempering or drawing of the hardened surface at temperatures between 200 and 350 degrees F. This treatment may be done in a standard furnace, an oil bath, or with a gas flame. It should follow the hardening process as closely as possible. Medium-carbon and many low-alloy steels are suitable for flame hardening. Plain carbon steels ranging from 0.35 to 0.60 per cent carbon will give hardnesses of from 400 to 700 Brinell. Steels in the 0.40 to 0.45 per cent carbon range are preferred, as they have excellent core properties and produce hardnesses of from 400 to 500 Brinell without checking or cracking. Higher-carbon steels will give greater hardnesses, but extreme care must be taken to prevent cracking. Careful control of the quenching operation is required.

*Spinning Method of Flame Hardening:* This method is employed on circular objects that can be rotated or spun past a stationary flame. It may be subdivided according to the speed of rotation, as where the part is rotated slowly in front of a stationary flame and the quench is applied immediately after the flame. This method is used on large circular pieces such as track wheels and bearing surfaces. There will be a narrow band of material with lower hardness between adjacent torches if more than one path of the flame is required to harden the surface. There will also be an area of lower hardness where the flame is extinguished. A second method is applicable to small rollers or pinions. The work is spun at a speed of 50 to 150 rpm in front of the flame until the entire piece has reached the proper temperature; then it is quenched as a unit by a cooling spray or by ejecting it into a cooling bath.

*The Progressive Method:* In this method the torch travels along the face of the work and the work remains stationary. It is used to harden lathe ways, gear teeth, and track rails.

*The Stationary or Spot-hardening Method:* When this method is employed, the work and torch are both stationary. When the spot to be hardened reaches the quenching temperature, the flame is removed and the quench applied.

*The Combination Method:* This approach is a combination of the spinning and progressive methods, and is used for long bearing surfaces. The work rotates slowly past the torch as the torch travels longitudinally across the face of the work at the rate of the torch width per revolution of the work.

Equipment for the stationary method of flame hardening consists merely of an acetylene torch, an oxyacetylene supply, and a suitable means of quenching; but when the other methods are employed, work-handling tools are essential and specialty designed torches are desirable. A lathe is ideally suited for the spinning or combination hardening method, whereas a planer is easily adapted for progressive hardening. Production jobs, such as the hardening of gears, require specially designed machines. These machines reduce handling and hardening time, as well as assuring consistent results.

**Induction Hardening.**—The hardening of steel by means of induction heating and subsequent quenching in either liquid or air is particularly applicable to parts that require localized hardening or controlled depth of hardening and to irregularly shaped parts, such as cams that require uniform surface hardening around their contour.

Advantages offered by induction hardening are: 1) a short heating cycle that may range from a fraction of a second to several seconds (heat energy can be induced in a piece of steel at the rate of 100 to 250 Btu per square inch per minute by induction heating, as com-

pared with a rate of 3 Btu per square inch per minute for the same material at room temperature when placed in a furnace with a wall temperature of 2000 degrees F); 2) absence of tendency to produce oxidation or decarburization; 3) exact control of depth and area of hardening; 4) close regulation of degree of hardness obtained by automatic timing of heating and quenching cycles; 5) minimum amount of warpage or distortion; and 6) possibility of substituting carbon steels for higher-cost alloy steels.

The principal advantage of induction hardening to the designer lies in its application to localized zones. Thus, specific areas in a given part can be heat treated separately to the respective hardnesses required. Parts can be designed so that the stresses at any given point in the finished piece can be relieved by local heating. Parts can be designed in which welded or brazed assemblies are built up prior to heat treating with only internal surfaces or projections requiring hardening.

**Types of Induction Heating Equipment.**—Induction heating is secured by placing the metal part inside or close to an “applicator” coil of one or more turns, through which alternating current is passed. The coil, formed to suit the general class of work to be heated, is usually made of copper tubing through which water is passed to prevent overheating of the coil itself. The workpiece is held either in a fixed position or is rotated slowly within or close to the applicator coil. Where the length of work is too great to permit heating in a fixed position, progressive heating may be employed. Thus, a rod or tube of steel may be fed through an applicator coil of one or more turns so that the heating zone travels progressively along the entire length of the workpiece.

The frequency of the alternating current used and the type of generator employed to supply this current to the applicator coil depend on the character of the work to be done.

There are three types of commercial equipment used to produce high-frequency current for induction heating: 1) motor generator sets that deliver current at frequencies of approximately 1000, 2000, 3000, and 10,000 cycles; 2) spark gap oscillator units that produce frequencies ranging from 80,000 to 300,000 cycles; and 3) vacuum tube oscillator sets, which produce currents at frequencies ranging from 350,000 to 15,000,000 cycles or more.

**Depth of Heat Penetration.**—Generally speaking, the higher the frequency used, the shallower the depth of heat penetration. For heating clear through, for deep hardening, and for large workpieces, low power concentrations and low frequencies are usually used. For very shallow and closely controlled depths of heating, as in surface hardening, and in localized heat treating of small workpieces, currents at high frequencies are used.

For example, a  $\frac{1}{2}$ -inch round bar of hardenable steel will be heated through its entire structure quite rapidly by an induced current of 2000 cycles. After quenching, the bar would show through hardness with a decrease in hardness from surface to center. The same piece of steel could be readily heated and surface hardened to a depth of 0.100 inch with current at 9600 cycles, and to an even shallower depth with current at 100,000 cycles. A  $\frac{1}{4}$ -inch bar, however, would not reach a sufficiently high temperature at 2000 cycles to permit hardening, but at 9600 cycles through hardening would be accomplished. Current at over 100,000 cycles would be needed for surface hardening such a bar.

**Types of Steel for Induction Hardening.**—Most of the standard types of steels can be hardened by induction heating, providing the carbon content is sufficient to produce the desired degree of hardness by quenching. Thus, low-carbon steels with a carburized case, medium- and high-carbon steels (both plain and alloy), and cast iron with a portion of the carbon in combined form, may be used for this purpose. Induction heating of alloy steels should be limited primarily to the shallow hardening type, that is those of low alloy content, otherwise the severe quench usually required may result in a highly stressed surface with consequent reduced load-carrying capacity and danger of cracking.

**Through Hardening, Annealing, and Normalizing by Induction.**—For through hardening, annealing, and normalizing by induction, low power concentrations are desirable to prevent too great a temperature differential between the surface and the interior of the

work. A satisfactory rate of heating is obtained when the total power input to the work is slightly greater than the radiation losses at the desired temperature. If possible, as low a frequency should be used as is consistent with good electrical coupling. A number of applicator coils may be connected in a series so that several workpieces can be heated simultaneously, thus reducing the power input to each. Widening the spacing between work and applicator coil also will reduce the amount of power delivered to the work.

**Induction Surface Hardening.**—As indicated earlier in “Depth of Heat Penetration,” currents at much higher frequencies are required in induction surface hardening than in through hardening by induction. In general, the smaller the workpiece, the thinner the section, or the shallower the depth to be hardened, the higher will be the frequency required. High power concentrations are also needed to make possible a short heating period so that an undue amount of heat will not be conducted to adjacent or interior areas, where a change in hardness is not desired. Generators of large capacity and applicator coils of but a few turns, or even a single turn, provide the necessary concentration of power in the localized area to be hardened.

Induction heating of internal surfaces, such as the interior of a hollow cylindrical part or the inside of a hole, can be accomplished readily with applicator coils shaped to match the cross-section of the opening, which may be round, square, elliptical or other form. If the internal surface is of short length, a multiturn applicator coil extending along its entire length may be employed. Where the power available is insufficient to heat the entire internal surface at once, progressive heating is used. For this purpose, an applicator coil of few turns — often but a single turn — is employed, and either coil or work is moved so that the heated zone passes progressively from one end of the hole or opening to the other. For bores of small diameter, a hairpin-shaped applicator, extending the entire length of the hole, may be used and the work rotated about the axis of the hole to ensure even heating.

**Quenching After Induction Heating.**—After induction heating, quenching may be by immersion in a liquid bath (usually oil), by liquid spray (usually water), or by self-quenching. (The term “self-quenching” is used when there is no quenching medium and hardening of the heated section is due chiefly to rapid absorption of heat by the mass of cool metal adjacent to it.) Quenching by immersion offers the advantage of even cooling and is particularly satisfactory for through heated parts. Spray quenching may be arranged so that the quenching ring and applicator coil are in the same or adjacent units, permitting the quenching cycle to follow the heating cycle immediately without removal of the work from the holding fixture. Automatic timing to a fraction of a second may also be employed for both heating and quenching with this arrangement to secure the exact degree of hardness desired. Self-quenching is applicable only in thin-surface hardening where the mass of adjacent cool metal in the part is great enough to conduct the heat rapidly out of the surface layer that is being hardened. It has been recommended that for adequate self-quenching, the mass of the unheated section should be at least ten times that of the heated shell. It has been found difficult to use the self-quenching technique to produce hardened shells of much more than about 0.060 inch thickness. Close to this limit, self-quenching can only be accomplished with the easily hardenable steels. By using a combination of self-quench and liquid quench, however, it is possible to produce hardened shells on work too thin to self-quench completely. In general, self-quenching is confined chiefly to relatively small parts and simple shapes.

**Induction Hardening of Gear Teeth.**—Several advantages are claimed for the induction hardening of gear teeth. One advantage is that the gear teeth can be completely machined, including shaving, when in the soft-annealed or normalized condition, and then hardened, because when induction heating is used, distortion is held to a minimum. Another advantage claimed is that bushings and inserts can be assembled in the gears before hardening. A wide latitude in choice of built-up webs and easily machined hubs is afforded because the hardness of neither web nor hub is affected by the induction-hardening operation although slight dimensional changes may occur in certain designs. Regular carbon steels can be



used in place of alloy steels for a wide variety of gears, and a steel with a higher carbon content can frequently be substituted for a carburizing steel so that the carburizing operation can be eliminated. Another saving in time is the elimination of cleaning after hardening.

In heating spur gear teeth by induction, the gear is usually placed inside a circular unit that combines the applicator coil and quenching ring. An automatic timing device controls both the heating and quenching cycles. During the heating cycle, the gear is rotated at 25 to 35 rpm to ensure uniform heating.

In hardening bevel gears, the applicator coil is wound to conform to the face angle of the gear. In some spiral-bevel gears, there is a tendency to obtain more heat on one side of the tooth than on the other. In some sizes of spiral-bevel gears, this tendency can be overcome by applying slightly more heat to ensure hardening of the concave side. In some forms of spiral-bevel gears, it has been the practice to carburize that part of the gear surface which is to be hardened, after the teeth have been rough-cut. Carburizing is followed by the finish-cutting operation, after which the teeth can be induction heated, using a long enough period to heat the entire tooth. When the gear is quenched, only the carburized surface will become hardened.

**Table 4a. Typical Heat Treatments for SAE Carbon Steels (Carburizing Grades)**

| SAE No.      | Normalize, Deg. F        | Carburize, Deg. F        | Cool <sup>a</sup> | Reheat, Deg. F | Cool <sup>a</sup> | 2nd Reheat, Deg. F | Cool <sup>a</sup> | Temper, <sup>b</sup> Deg. F |
|--------------|--------------------------|--------------------------|-------------------|----------------|-------------------|--------------------|-------------------|-----------------------------|
| 1010 to 1022 | ...                      | 1650-1700                | A                 | ...            | ...               | ...                | ...               | 250-400                     |
|              | ...                      | 1650-1700                | B                 | 1400-1450      | A                 | ...                | ...               | 250-400                     |
|              | ...                      | 1650-1700                | C                 | 1400-1450      | A                 | ...                | ...               | 250-400                     |
|              | ...                      | 1650-1700                | C                 | 1650-1700      | B                 | 1400-1450          | A                 | 250-400                     |
|              | ...                      | 1500-1650 <sup>c,d</sup> | B                 | ...            | ...               | ...                | ...               | Optional                    |
| ...          | 1350-1575 <sup>e,d</sup> | D                        | ...               | ...            | ...               | ...                | Optional          |                             |
| 1024         | 1650-1750 <sup>f</sup>   | 1650-1700                | E                 | .....          | ...               | ...                | ...               | 250-400                     |
|              | ...                      | 1350-1575 <sup>e,d</sup> | D                 | ...            | ...               | ...                | ...               | Optional                    |
| 1025 to 1026 | ...                      | 1650-1700                | A                 | ...            | ...               | ...                | ...               | 250-400                     |
|              | ...                      | 1500-1650 <sup>c,d</sup> | B                 | ...            | ...               | ...                | ...               | Optional                    |
| 1027         | ...                      | 1350-1575 <sup>e,d</sup> | D                 | ...            | ...               | ...                | ...               | Optional                    |
| 1030         | ...                      | 1500-1650 <sup>c,d</sup> | B                 | ...            | ...               | ...                | ...               | Optional                    |
|              | ...                      | 1350-1575 <sup>e,d</sup> | D                 | ...            | ...               | ...                | ...               | Optional                    |
| 1111 to 1113 | ...                      | 1500-1650 <sup>c,d</sup> | B                 | ...            | ...               | ...                | ...               | Optional                    |
|              | ...                      | 1350-1575 <sup>e,d</sup> | D                 | ...            | ...               | ...                | ...               | Optional                    |
| 1109 to 1120 | ...                      | 1650-1700                | A                 | ...            | ...               | ...                | ...               | 250-400                     |
|              | ...                      | 1650-1700                | B                 | 1400-1450      | A                 | ...                | ...               | 250-400                     |
|              | ...                      | 1650-1700                | C                 | 1400-1450      | A                 | ...                | ...               | 250-400                     |
|              | ...                      | 1650-1700                | C                 | 1650-1700      | B                 | 1400-1450          | A                 | 250-400                     |
|              | ...                      | 1500-1650 <sup>c,d</sup> | B                 | ...            | ...               | ...                | ...               | Optional                    |
| ...          | 1350-1575 <sup>e,d</sup> | D                        | ...               | ...            | ...               | ...                | Optional          |                             |
| 1126         | ...                      | 1500-1650 <sup>c,d</sup> | B                 | ...            | ...               | ...                | ...               | Optional                    |
|              | ...                      | 1350-1575 <sup>e,d</sup> | D                 | ...            | ...               | ...                | ...               | Optional                    |

<sup>a</sup> Symbols: A = water or brine; B = water or oil; C = cool slowly; D = air or oil; E = oil; F = water, brine, or oil.

<sup>b</sup> Even where tempering temperatures are shown, tempering is not mandatory in many applications. Tempering is usually employed for partial stress relief and improves resistance to grinding cracks.

<sup>c</sup> Activated or cyanide baths.

<sup>d</sup> May be given refining heat as in other processes.

<sup>e</sup> Carbonitriding atmospheres

<sup>f</sup> Normalizing temperatures at least 50 deg. F above the carburizing temperature are sometimes recommended where minimum heat-treatment distortion is of vital importance.

**Table 4b. Typical Heat Treatments for SAE Carbon Steels (Heat-Treating Grades)**

| SAE Number   | Normalize,<br>Deg. F | Anneal,<br>Deg. F             | Harden,<br>Deg. F | Quench <sup>a</sup> | Temper,<br>Deg. F         |
|--------------|----------------------|-------------------------------|-------------------|---------------------|---------------------------|
| 1025 & 1030  | ...                  | ...                           | 1575-1650         | A                   | To<br>Desired<br>Hardness |
| 1033 to 1035 | ...                  | ...                           | 1525-1575         | B                   |                           |
| 1036         | { 1600-1700          | ...                           | 1525-1575         | B                   |                           |
|              | { ...                | ...                           | 1525-1575         | B                   |                           |
| 1038 to 1040 | { 1600-1700          | ...                           | 1525-1575         | B                   |                           |
|              | { ...                | ...                           | 1525-1575         | B                   |                           |
| 1041         | 1600-1700            | and/or 1400-1500              | 1475-1550         | E                   |                           |
| 1042 to 1050 | 1600-1700            | ...                           | 1475-1550         | B                   |                           |
| 1052 & 1055  | 1550-1650            | and/or 1400-1500              | 1475-1550         | E                   |                           |
| 1060 to 1074 | 1550-1650            | and/or 1400-1500              | 1475-1550         | E                   |                           |
| 1078         | ...                  | 1400-1500 <sup>a</sup>        | 1450-1500         | A                   |                           |
| 1080 to 1090 | 1550-1650            | and/or 1400-1500 <sup>a</sup> | 1450-1500         | E <sup>b</sup>      |                           |
| 1095         | { ...                | 1400-1500 <sup>a</sup>        | 1450-1500         | F                   |                           |
|              | { ...                | 1400-1500 <sup>a</sup>        | 1500-1600         | E                   |                           |
| 1132 & 1137  | 1600-1700            | and/or 1400-1500              | 1525-1575         | B                   |                           |
| 1138 & 1140  | { ...                | ...                           | 1500-1550         | B                   |                           |
|              | { 1600-1700          | ...                           | 1500-1550         | B                   |                           |
| 1141 & 1144  | { ...                | 1400-1500                     | 1475-1550         | E                   |                           |
|              | { 1600-1700          | 1400-1500                     | 1475-1550         | E                   |                           |
| 1145 to 1151 | { ...                | ...                           | 1475-1550         | B                   |                           |
|              | { 1600-1700          | ...                           | 1475-1550         | B                   |                           |

<sup>a</sup> Slow cooling produces a spheroidal structure in these high-carbon steels that is sometimes required for machining purposes.

<sup>b</sup> May be water- or brine-quenched by special techniques such as partial immersion or time quenched; otherwise they are subject to quench cracking.

**Table 5a. Typical Heat Treatments for SAE Alloy Steels (Carburizing Grades)**

| SAE No.      | Normal-ize <sup>a</sup> | Cycle Anneal <sup>b</sup> | Carburized,<br>Deg. F  | Cool <sup>c</sup> | Reheat,<br>Deg. F      | Cool <sup>c</sup> | Temper, <sup>d</sup><br>Deg. F |
|--------------|-------------------------|---------------------------|------------------------|-------------------|------------------------|-------------------|--------------------------------|
| 1320         | { yes                   | ...                       | 1650-1700              | E                 | 1400-1450 <sup>e</sup> | E                 | 250-350                        |
|              | { yes                   | ...                       | 1650-1700              | E                 | 1475-1525 <sup>f</sup> | E                 | 250-350                        |
|              | { yes                   | ...                       | 1650-1700              | C                 | 1400-1450 <sup>e</sup> | E                 | 250-350                        |
|              | { yes                   | ...                       | 1650-1700              | C                 | 1500-1550 <sup>f</sup> | E                 | 250-350                        |
|              | { yes                   | ...                       | 1650-1700              | E <sup>g</sup>    | ...                    | ...               | 250-350                        |
|              | { yes                   | ...                       | 1500-1650 <sup>h</sup> | E                 | ...                    | ...               | 250-350                        |
| 2317         | { yes                   | yes                       | 1650-1700              | E                 | 1375-1425 <sup>e</sup> | E                 | 250-350                        |
|              | { yes                   | yes                       | 1650-1700              | E                 | 1450-1500 <sup>f</sup> | E                 | 250-350                        |
|              | { yes                   | yes                       | 1650-1700              | C                 | 1375-1425 <sup>e</sup> | E                 | 250-350                        |
|              | { yes                   | yes                       | 1650-1700              | C                 | 1475-1525 <sup>f</sup> | E                 | 250-350                        |
|              | { yes                   | yes                       | 1650-1700              | E <sup>g</sup>    | ...                    | ...               | 250-350                        |
|              | { yes                   | yes                       | 1450-1650 <sup>h</sup> | E                 | ...                    | ...               | 250-350                        |
| 2512 to 2517 | { yes <sup>i</sup>      | ...                       | 1650-1700              | C                 | 1325-1375 <sup>e</sup> | E                 | 250-350                        |
|              | { yes <sup>i</sup>      | ...                       | 1650-1700              | C                 | 1425-1475 <sup>f</sup> | E                 | 250-350                        |
| 3115 & 3120  | { yes                   | ...                       | 1650-1700              | E                 | 1400-1450 <sup>e</sup> | E                 | 250-350                        |
|              | { yes                   | ...                       | 1650-1700              | E                 | 1475-1525 <sup>f</sup> | E                 | 250-350                        |
|              | { yes                   | ...                       | 1650-1700              | C                 | 1400-1450 <sup>e</sup> | E                 | 250-350                        |
|              | { yes                   | ...                       | 1650-1700              | C                 | 1500-1550 <sup>f</sup> | E                 | 250-350                        |
|              | { yes                   | ...                       | 1650-1700              | E <sup>g</sup>    | ...                    | ...               | 250-350                        |
|              | { yes                   | .....                     | 1500-1650 <sup>h</sup> | E                 | ...                    | ...               | 250-350                        |
| 3310 & 3316  | { yes <sup>i</sup>      | ...                       | 1650-1700              | E                 | 1400-1450 <sup>e</sup> | E                 | 250-350                        |
|              | { yes <sup>i</sup>      | ...                       | 1650-1700              | C                 | 1475-1500 <sup>f</sup> | E                 | 250-350                        |
| 4017 to 4032 | yes                     | yes                       | 1650-1700              | E <sup>g</sup>    | ...                    | ...               | 250-350                        |

**Table 5a. (Continued) Typical Heat Treatments for SAE Alloy Steels (Carburizing Grades)**

| SAE No.                     | Normal-ize <sup>a</sup> | Cycle Anneal <sup>b</sup> | Carburized, Deg. F | Cool <sup>c</sup> | Reheat, Deg. F         | Cool <sup>c</sup> | Temper, <sup>d</sup> Deg. F |     |         |
|-----------------------------|-------------------------|---------------------------|--------------------|-------------------|------------------------|-------------------|-----------------------------|-----|---------|
| 4119 & 4125                 | yes                     | ...                       | 1650-1700          | E <sup>g</sup>    | ...                    | ...               | 250-350                     |     |         |
| 4317 & 4320<br>4608 to 4621 | }                       | {                         | yes                | yes               | 1650-1700              | E                 | 1425-1475 <sup>e</sup>      | E   | 250-350 |
|                             |                         |                           | yes                | yes               | 1650-1700              | E                 | 1475-1527 <sup>f</sup>      | E   | 250-350 |
|                             |                         |                           | yes                | yes               | 1650-1700              | C                 | 1425-1475 <sup>e</sup>      | E   | 250-350 |
|                             |                         |                           | yes                | yes               | 1650-1700              | C                 | 1475-1525 <sup>f</sup>      | E   | 250-350 |
|                             |                         |                           | yes                | yes               | 1650-1700              | E <sup>g</sup>    | ...                         | ... | 250-350 |
|                             |                         |                           | yes                | yes               | 1650-1700              | E <sup>g</sup>    | ...                         | ... | 250-350 |
|                             |                         |                           | yes                | ...               | 1500-1650 <sup>h</sup> | E                 | ...                         | ... | 250-350 |
| 4812 to 4820                | {                       | }                         | yes <sup>i</sup>   | yes               | 1650-1700              | E                 | 1375-1425 <sup>e</sup>      | E   | 250-350 |
|                             |                         |                           | yes <sup>i</sup>   | yes               | 1650-1700              | E                 | 1450-1500 <sup>f</sup>      | E   | 250-350 |
|                             |                         |                           | yes <sup>i</sup>   | yes               | 1650-1700              | C                 | 1375-1425 <sup>e</sup>      | E   | 250-350 |
|                             |                         |                           | yes <sup>i</sup>   | yes               | 1650-1700              | C                 | 1450-1500 <sup>f</sup>      | E   | 250-350 |
|                             |                         |                           | ...                | ...               | 1650-1700              | E <sup>g</sup>    | ...                         | ... | 250-350 |
| 5115 & 5120                 | {                       | }                         | yes                | ...               | 1650-1700              | E                 | 1425-1475 <sup>e</sup>      | E   | 250-350 |
|                             |                         |                           | yes                | ...               | 1650-1700              | E                 | 1500-1550 <sup>f</sup>      | E   | 250-350 |
|                             |                         |                           | yes                | ...               | 1650-1700              | C                 | 1425-1475 <sup>e</sup>      | E   | 250-350 |
|                             |                         |                           | yes                | ...               | 1650-1700              | C                 | 1500-1550 <sup>f</sup>      | E   | 250-350 |
|                             |                         |                           | yes                | ...               | 1500-1650 <sup>h</sup> | E                 | ...                         | ... | 250-350 |
| 8615 to 8625<br>8720        | }                       | {                         | yes                | yes               | 1650-1700              | E                 | 1475-1525 <sup>e</sup>      | E   | 250-350 |
|                             |                         |                           | yes                | yes               | 1650-1700              | E                 | 1525-1575 <sup>f</sup>      | E   | 250-350 |
|                             |                         |                           | yes                | yes               | 1650-1700              | C                 | 1475-1525 <sup>e</sup>      | E   | 250-350 |
|                             |                         |                           | yes                | yes               | 1650-1700              | C                 | 1525-1575 <sup>f</sup>      | E   | 250-350 |
|                             |                         |                           | yes                | yes               | 1650-1700              | E <sup>g</sup>    | ...                         | ... | 250-350 |
|                             |                         |                           | yes                | yes               | 1500-1650 <sup>h</sup> | E                 | ...                         | ... | 250-350 |
| 9310 to 9317                | {                       | }                         | yes <sup>i</sup>   | ...               | 1650-1700              | E                 | 1400-1450 <sup>e</sup>      | E   | 250-350 |
|                             |                         |                           | yes <sup>i</sup>   | ...               | 1650-1700              | C                 | 1500-1525                   | E   | 250-350 |

<sup>a</sup> Normalizing temperatures should be not less than 50 deg. F higher than the carburizing temperature. Follow by air cooling.

<sup>b</sup> For cycle annealing, heat to normalizing temperature—hold for uniformity—cool rapidly to 1000-1250 deg. F; hold 1 to 3 hours, then air or furnace cool to obtain a structure suitable for machining and finishing.

<sup>c</sup> Symbols: C = cool slowly; E = oil.

<sup>d</sup> Tempering treatment is optional and is generally employed for partial stress relief and improved resistance to cracking from grinding operations.

<sup>e</sup> For use when case hardness only is paramount.

<sup>f</sup> For use when higher core hardness is desired.

<sup>g</sup> Treatment is for fine-grained steels only, when a second reheat is often unnecessary.

<sup>h</sup> Treatment is for activated or cyanide baths. Parts may be given refining heats as indicated for other heat-treating processes.

<sup>i</sup> After normalizing, reheat to temperatures of 1000-1200 deg. F and hold approximately 4 hours.

**Metallography.**—The science or study of the microstructure of metal is known by most metallurgists as “metallography” or sometimes “crystallography”. The examination of metals and metal alloys by the aid of the microscope is one of the most effective methods of studying their properties, and is also a valuable means of controlling the quality of manufactured metallic articles and of testing the finished product. In preparing the specimen, a flat surface is first formed by filing or grinding, and then given a high polish, which is later etched in order to reveal clearly the internal structure under the microscope. This process shows clearly to an experienced observer the effect of variation in composition, heat-treatment, etc., and in many cases it has proved a correct means of determining certain properties of industrial products that a chemical analysis has failed to reveal.

**Table 5b. Typical Heat Treatments for SAE Alloy Steels (Directly Hardenable Grades)**

| SAE No.  | Normalize, Deg. F   |  | Anneal, Deg. F   | Harden, Deg. F  | Quench <sup>a</sup>                                      | Temper, Deg. F                          |   |
|--|---|--|--|---|--|---|---|
| 1330   | { ...<br>1600–1700  | and/or   | ...<br>1500–1600   | 1525–1575<br>1525–1575  | B<br>B   | { To desired hardness                   |   |
| 1335 & 1340  | { ...<br>1600–1700  | and/or   | ...<br>1500–1600   | 1500–1550<br>1525–1575  | E<br>E   |   |   |
| 2330   | { ...<br>1600–1700  | and/or   | ...<br>1400–1500   | 1450–1500<br>1450–1500  | E<br>E   |   |   |
| 2340 & 2345  | { ...<br>1600–1700  | and/or   | ...<br>1400–1500   | 1425–1475<br>1425–1475  | E<br>E   |   |   |
| 3130   | { ...<br>1600–1700  |  | ...  | 1500–1550   | B  |   |   |
| 3135 to 3141   | { ...<br>1600–1700  | and/or   | ...<br>1450–1550   | 1500–1550<br>1500–1550  | E<br>E   |   |   |
| 3145 & 3150  | { ...<br>1600–1700  | and/or   | ...<br>1400–1500   | 1500–1550<br>1500–1550  | E<br>E   |   |   |
| 4037 & 4042  | ...   |  | 1525–1575  | 1500–1575   | E  |   | { Gears, 350–450<br>To desired hardness |
| 4047 & 4053<br>4063 & 4068<br>4130<br>4137 & 4140<br>4145 & 4150<br>4340   | ...<br>...<br>1600–1700<br>1600–1700<br>1600–1700<br>1600–1700  | and/or<br>and/or<br>and/or<br>and/or<br>and draw   | 1450–1550<br>1450–1550<br>1450–1550<br>1450–1550<br>1100–1225  | 1500–1575<br>1475–1550<br>1600–1650<br>1550–1600<br>1500–1600<br>1475–1525  | E<br>E<br>B<br>E<br>E<br>E                               |   | { To desired hardness                   |
| 4640   | { 1600–1700<br>1600–1700  | and/or<br>and/or   | 1450–1550<br>1450–1500   | 1450–1500<br>1450–1500  | E<br>E   |   | To desired hardness<br>Gears, 350–450   |
| 5045 & 5046<br>5130 & 5132   | 1600–1700<br>1650–1750  | and/or<br>and/or   | 1450–1550<br>1450–1550   | 1475–1500<br>1500–1550  | E<br>G   | 250–300<br>To desired hardness          |   |
| 5135 to 5145   | 1650–1750   | and/or   | 1450–1550  | 1500–1550   | E  | { To desired hardness<br>Gears, 350–400 |   |
| 5147 to 5152   | 1650–1750   | and/or   | 1450–1550  | 1475–1550   | E  | { To desired hardness<br>Gears, 350–400 |   |
| 50100<br>51100<br>52100  | { ...<br>...  |  | 1350–1450<br>1350–1450   | 1425–1475<br>1500–1600  | H<br>E   | To desired hardness                     |   |
| 6150<br>9254 & 9262<br>8627 to 8632<br>8635 to 8641<br>8642 to 8653<br>8655 & 8660<br>8735 & 8740<br>8745 & 8750<br>9437 & 9440<br>9442 to 9747<br>9840<br>9845 & 9850 | 1650–1750<br>...<br>1600–1700<br>1600–1700<br>1600–1700<br>1650–1750<br>1600–1700<br>1600–1700<br>1600–1700<br>1600–1700<br>1600–1700<br>1600–1700<br>1600–1700 | and/or<br>and/or<br>and/or<br>and/or<br>and/or<br>and/or<br>and/or<br>and/or<br>and/or<br>and/or<br>and/or<br>and/or | 1550–1650<br>...<br>1450–1550<br>1450–1550<br>1450–1550<br>1450–1550<br>1450–1550<br>1450–1550<br>1450–1550<br>1450–1550<br>1450–1550<br>1450–1550 | 1600–1650<br>1500–1650<br>1550–1650<br>1525–1575<br>1500–1550<br>1475–1550<br>1525–1575<br>1500–1550<br>1550–1600<br>1500–1600<br>1500–1550 | E<br>E<br>B<br>E<br>E<br>E<br>E<br>E<br>E<br>E<br>E<br>E | { To desired hardness                   |   |

<sup>a</sup> Symbols: B = water or oil; E = oil; G = water, caustic solution, or oil; H = water.

**Table 5c. Typical Heat Treatments for SAE Alloy Steels (Heat-Treating Grades—Chromium–Nickel Austenitic Steels)**

| SAE No.        | Normalize | Anneal, <sup>a</sup> Deg. F | Harden, Deg. F | Quenching Medium | Temper |
|----------------|-----------|-----------------------------|----------------|------------------|--------|
| 30301 to 30347 | ...       | 1800–2100                   | ...            | Water or Air     | ...    |

<sup>a</sup> Quench to produce full austenitic structure using water or air in accordance with thickness of section. Annealing temperatures given cover process and full annealing as used by industry, the lower end of the range being used for process annealing.

**Table 5d. Typical Heat Treatments for SAE Alloy Steels**  
(Heat-Treating Grades—Stainless Chromium Irons and Steels)

| SAE No. <sup>a</sup>                 | Normalize      | Sub-critical Anneal, Deg. F   | Full Anneal Deg. F            | Harden Deg. F    | Quenching Medium | Temper Deg. F       |
|--------------------------------------|----------------|-------------------------------|-------------------------------|------------------|------------------|---------------------|
| 51410                                | { ...<br>... } | 1300–1350 <sup>b</sup><br>... | 1550–1650 <sup>c</sup><br>... | ...<br>1750–1850 | } Oil or air     | To desired hardness |
| 51414                                | { ...<br>... } | 1200–1250 <sup>b</sup><br>... | ...                           | ...<br>1750–1850 | } Oil or air     | To desired hardness |
| 51416                                | { ...<br>... } | 1300–1350 <sup>b</sup><br>... | 1550–1650 <sup>c</sup><br>... | ...<br>1750–1850 | } Oil or air     | To desired hardness |
| 51420<br>51420F                      | { ...<br>... } | 1350–1450 <sup>b</sup><br>... | 1550–1650 <sup>c</sup><br>... | ...<br>1800–1850 | } Oil or air     | To desired hardness |
| 51430                                | ...            | 1400–1500 <sup>d</sup>        | ...                           | ...              | ...              | ...                 |
| 51430F                               | ...            | 1250–1500 <sup>d</sup>        | ...                           | ...              | ...              | ...                 |
| 51431                                | ...            | 1150–1225 <sup>b</sup>        | ...                           | 1800–1900        | Oil or air       | To desired hardness |
| 51440A<br>51440B<br>51440C<br>51440F | } ...          | 1350–1440 <sup>b</sup>        | 1550–1650 <sup>c</sup>        | 1850–1950        | Oil or air       | To desired hardness |
| 51442                                | ...            | 1400–1500 <sup>d</sup>        | ...                           | ...              | ...              | ...                 |
| 51446                                | ...            | 1500–1650 <sup>d</sup>        | ...                           | ...              | ...              | ...                 |
| 51501                                | ...            | 1325–1375 <sup>b</sup>        | 1525–1600 <sup>c</sup>        | 1600–1700        | Oil or air       | To desired hardness |

<sup>a</sup> Suffixes A, B, and C denote steels differing in carbon content only. Suffix F denotes a free-machining steel.

<sup>b</sup> Usually air cooled, but may be furnace cooled.

<sup>c</sup> Cool slowly in furnace.

<sup>d</sup> Cool rapidly in air.

**Table 6. Typical SAE Heat Treatments for Grades of Chromium–Nickel Austenitic Steels Not Hardenable by Thermal Treatment**

| SAE Steels | AISI No. | Annealing <sup>a</sup> Temperature (degrees F) | Annealing Temperature (deg. C) | Quenching Medium |
|------------|----------|--|--------------------------------|------------------|
| 30201      | 201      | 1850–2050                                      | 1010–1120                      | Air              |
| 30202      | 202      | 1850–2050                                      | 1010–1120                      | Air              |
| 30301      | 301      | 1850–2050                                      | 1010–1120                      | Air              |
| 30302      | 302      | 1850–2050                                      | 1010–1120                      | Air              |
| 30303      | 303      | 1850–2050                                      | 1010–1120                      | Air              |
| 30304      | 304      | 1850–2050                                      | 1010–1120                      | Air              |
| 30305      | 305      | 1850–2050                                      | 1010–1120                      | Air              |
| 30309      | 309      | 1900–2050                                      | 1040–1120                      | Air              |
| 30310      | 310      | 1900–2100                                      | 1040–1150                      | Air              |
| 30316      | 316      | 1850–2050                                      | 1010–1120                      | Air              |
| 30317      | 317      | 1850–2050                                      | 1010–1120                      | Air              |
| 30321      | 321      | 1750–2050                                      | 955–1120                       | Air              |
| 30325      | 325      | 1800–2100                                      | 980–1150                       | Air              |
| 30330      | ...      | 1950–2150                                      | 1065–1175                      | Air              |
| 30347      | 347      | 1850–2050                                      | 1010–1120                      | Air              |

<sup>a</sup> Quench to produce full austenitic structure in accordance with the thickness of the section. Annealing temperatures given cover process and full annealing as already established and used by industry, the lower end of the range being used for process annealing.

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Table 7. Typical SAE Heat Treatments for Stainless Chromium Steels

| SAE Steels          | AISI No.          | Normalizing Temperature (degrees F) | Subcritical Annealing Temperature (degrees F) | Full Annealing <sup>a</sup> Temperature (degrees F) | Hardening Temperature (degrees F) | Quenching Medium | Temper              |
|---------------------|-------------------|-------------------------------------|---|---|-----------------------------------|------------------|---------------------|
| 51409               | ...               | ...                                 | ...   | 1625  | ...                               | Air              | ...                 |
| 51410               | 410               | ...                                 | 1300–1350 <sup>b</sup>                        | 1500–1650   | ...                               | } Oil or air     | To desired hardness |
|                     |                   | ...                                 | ...   | ...   | 1700–1850                         |                  |                     |
| 51414               | 414               | ...                                 | 1200–1250 <sup>b</sup>                        | ...   | ...                               | } Oil or air     | To desired hardness |
|                     |                   | ...                                 | ...   | ...   | 1800–1900                         |                  |                     |
| 51416               | 416               | ...                                 | 1300–1350 <sup>c</sup>                        | 1500–1650   | ...                               | } Oil or air     | To desired hardness |
|                     |                   | ...                                 | ...   | ...   | 1700–1850                         |                  |                     |
| 51420               | 420               | ...                                 | 1350–1450 <sup>b</sup>                        | 1550–1650   | ...                               | } Oil or air     | To desired hardness |
|                     |                   | ...                                 | ...   | ...   | 1800–1900                         |                  |                     |
| 51420F <sup>d</sup> | ...               | ...                                 | 1350–1450 <sup>b</sup>                        | 1550–1650   | ...                               | } Oil or air     | To desired hardness |
|                     |                   | ...                                 | ...   | ...   | 1800–1900                         |                  |                     |
| 51430               | 430               | ...                                 | 1400–1500 <sup>c</sup>                        | ...   | ...                               | ...              | ...                 |
| 51430F <sup>d</sup> | ...               | ...                                 | 1250–1400 <sup>c</sup>                        | ...   | ...                               | ...              | ...                 |
| 51431               | 431               | ...                                 | 1150–1225 <sup>b</sup>                        | ...   | 1800–1950                         | Oil or air       | To desired hardness |
| 51434               | ...               | }                                   | 1400–1600 <sup>c</sup>                        | ...   | ...                               | ...              | ...                 |
| 51436               | ...               |                                     |   |   |                                   |                  |                     |
| 51440A <sup>d</sup> | 440A <sup>d</sup> | }                                   | 1350–1440 <sup>b</sup>                        | 1550–1650   | 1850–1950                         | Oil or air       | To desired hardness |
| 51440B <sup>d</sup> | 440B <sup>d</sup> |                                     |   |   |                                   |                  |                     |
| 51440C <sup>d</sup> | 440C <sup>d</sup> |                                     |   |   |                                   |                  |                     |
| 51440F <sup>d</sup> | ...               |                                     |   |   |                                   |                  |                     |
| 51442               | 442               | ...                                 | 1350–1500 <sup>c</sup>                        | ...   | ...                               | ...              | ...                 |
| 51446               | 446               | ...                                 | 1450–1600 <sup>b</sup>                        | ...   | ...                               | ...              | ...                 |
| 51501               | 501               | ...                                 | 1325–1375 <sup>c</sup>                        | 1525–1600   | 1600–1700                         | Oil or air       | To desired hardness |

<sup>a</sup>Cool slowly in furnace.

<sup>b</sup>Usually air cooled but may be furnace cooled.

<sup>c</sup>Cool rapidly in air.

<sup>d</sup>Suffixes A, B, and C denote three types of steel differing only in carbon content. Suffix F denotes a free-machining steel.

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### Heat Treating High-Speed Steels

**Cobaltcrom Steel.**—A tungstenless alloy steel or high-speed steel that contains approximately 1.5 per cent carbon, 12.5 per cent chromium, and 3.5 per cent cobalt. Tools such as dies and milling cutters, made from cobaltcrom steel can be cast to shape in suitable molds, the teeth of cutters being formed so that it is necessary only to grind them.

Before the blanks can be machined, they must be annealed; this operation is performed by pack annealing at the temperature of 1800 degrees F, for a period of from three to six hours, according to the size of the castings being annealed. The following directions are given for the hardening of blanking and trimming dies, milling cutters, and similar tools made from cobaltcrom steel: Heat slowly in a hardening furnace to about 1830 degrees F, and hold at this temperature until the tools are thoroughly soaked. Reduce the temperature about 50 degrees, withdraw the tools from the furnace, and allow them to cool in the atmosphere. As soon as the red color disappears from the cooling tool, place it in quenching oil until cold. The slight drop of 50 degrees in temperature while the tool is still in the hardening furnace is highly important to obtain proper results. The steel will be injured if the tool is heated above 1860 degrees F. In cooling milling cutters or other rotary tools, it is suggested that they be suspended on a wire to ensure a uniform rate of cooling.

Tools that are to be subjected to shocks or vibration, such as pneumatic rivet sets, shear blades, etc., should be heated slowly to 1650 degrees F, after which the temperature should be reduced to about 1610 degrees F, at which point the tool should be removed from the furnace and permitted to cool in the atmosphere. No appreciable scaling occurs in the hardening of cobaltcrom steel tools.

**Preheating Tungsten High-Speed Steel.**—Tungsten high-speed steel must be hardened at a very high temperature; consequently, tools made from such steel are seldom hardened without at least one preheating stage to avoid internal strain. This requirement applies especially to milling cutters, taps, and other tools having thin teeth and thick bodies and to forming tools of irregular shape and section. The tools should be heated slowly and carefully to a temperature somewhat below the critical point of the steel, usually in the range of 1500 to 1600 degrees F. Limiting the preheating temperature prevents the operation from being unduly sensitive, and the tool may be safely left in the furnace until it reaches a uniform temperature throughout its length and cross-section.

A single stage of preheating is customary for tools of simple form that are not more than from 1 to 1½ inches in thickness. For large, intricate tools, two stages of preheating are frequently used. The first brings the tool up to a temperature of about 1100 to 1200 degrees F, and the second raises its temperature to 1550 to 1600 degrees F. A preheating time of 5 minutes for each ¼ inch in tool thickness has been recommended for a furnace temperature of 1600 degrees F. This is where a single stage of preheating is used and the furnace capacity should be sufficient to maintain practically constant temperature when the tools are changed. To prevent undue chilling, it is common practice to insert a single tool or a small lot in the hardening furnace whenever a tool or lot is removed, rather than to insert a full charge of cold metal at one time.

Preheating is usually done in a simple type of oven furnace heated by gas, electricity, or oil. Atmospheric control is seldom used, although for 18–4–1 steel a slightly reducing atmosphere (2 to 6 per cent carbon monoxide) has been found to produce the least amount of scale and will result in a better surface after final hardening.

**Hardening of Tungsten High-Speed Steel.**—All tungsten high-speed steels must be heated to a temperature close to their fusion point to develop their maximum efficiency as metal-cutting tools. Hardening temperatures ranging from 2200 to 2500 deg. F may be needed. The effects of changes in the hardening temperature on the cutting efficiency of several of the more common high-speed steels are shown in [Table 1](#). The figures given are ratios, the value 1.00 for each steel being assigned to the highest observed cutting speed for

that steel. The figures for different steels, therefore, cannot be directly compared with each other, except to note changes in the point of maximum cutting efficiency.

**Table 1. Relation of Hardening Temperature to Cutting Efficiency**

| Hardening Temperature, Deg. F | Typical Analyses of High-Speed Steels |            |                   |                   |
|-------------------------------|---------------------------------------|------------|-------------------|-------------------|
|                               | 18 - 4 - 1                            | 14 - 4 - 2 | 18 - 4 - 1 Cobalt | 14 - 4 - 2 Cobalt |
| 2200                          | 0.86                                  | 0.83       | 0.84              | 0.85              |
| 2250                          | 0.88                                  | 0.88       | 0.86              | 0.88              |
| 2300                          | 0.90                                  | 0.93       | 0.90              | 0.91              |
| 2350                          | 0.95                                  | 0.98       | 0.94              | 0.94              |
| 2400                          | 0.99                                  | 0.98       | 0.98              | 0.98              |
| 2450                          | 1.00                                  | ...        | 0.99              | 1.00              |
| 2500                          | 0.98                                  | ...        | 1.00              | 0.97              |

The figures in the table refer to tools heated in an oven-type furnace in which a neutral atmosphere is maintained. The available data indicate that a steel reaches its best cutting qualities at a temperature approximately 50 deg. F lower than the figures in the table if it is hardened in a bath-type furnace. It is, however, desirable to use a hardening temperature approximately 50 deg. F lower than that giving maximum cutting qualities, to avoid the possibility of overheating the tool.

*Length of Time for Heating:* The cutting efficiency of a tool is affected by the time that it is kept at the hardening temperature, almost as much as by the hardening temperature itself. It has been common practice to heat a tool for hardening until a "sweat" appeared on its surface. This sweat is presumably a melting of the oxide film on the surface of a tool heated in an oxidizing atmosphere. It does not appear when the tool is heated in an inert atmosphere. This method of determining the proper heating time is at best an approximation and indicates only the temperature on the outside of the tool rather than the condition of the interior. As such, it cannot be relied upon to give consistent results.

The only safe method is to heat the tool for a definite predetermined time, based on the size and the thickness of metal that the heat must penetrate to reach the interior. The values given in [Table 2](#) are based on a series of experiments to determine the relative cutting efficiency of a group of tools hardened in an identical manner, except for variations in the time the tools were kept at the hardening temperature. The time given is based on that required to harden throughout a tool resting on a conducting hearth; the tool receives heat freely from three sides, on its large top surface and its smaller side surfaces. (The table does not apply to a disk lying flat on the hearth.) For a tool having a projecting cutting edge, such as a tap, the thickness or depth of the projecting portion on which the cutting edge is formed should be used when referring to the table.

**Table 2. Length of Heating Time for Through Hardening**

| High-Speed Steel Tool Thickness, in Inches | Time in Furnace at High Heat, in Minutes | High-Speed Steel Tool Thickness, in Inches | Time in Furnace at High Heat, in Minutes | High-Speed Steel Tool Thickness, in Inches | Time in Furnace at High Heat, in Minutes |
|--|--|--|--|--|--|
| 1/4  | 2  | 1 1/2                                      | 7  | 5  | 18                                       |
| 1/2  | 3  | 2  | 8  | 6  | 20                                       |
| 3/4  | 4  | 3  | 12                                       | 8  | 25                                       |
| 1  | 5  | 4  | 15                                       | 10   | 30                                       |

The time periods given in [Table 2](#) are based on complete penetration of the hardening effect. For very thick tools, the practical procedure is to harden to a depth sufficient to produce an adequate cutting edge, leaving the interior of the tool relatively soft.



Where atmosphere control is not provided, it often will be found impracticable to use both the temperature for maximum cutting efficiency, given in [Table 1](#), and the heating time, given in [Table 2](#), because abnormal scaling, grain growth, and surface decarburization of the tool will result. The principal value of an accurate control of the furnace atmosphere appears to lie in the fact that its use makes possible the particular heat treatment that produces the best structure in the tool without destruction of the tool surface or grain.

**Quenching Tungsten High-Speed Steel.**—High-speed steel is usually quenched in oil. The oil bath offers a convenient quench; it calls for no unusual care in handling and brings about a uniform and satisfactory rate of cooling, which does not vary appreciably with the temperature of the oil. Some authorities believe it desirable to withdraw the tool from the oil bath for a few seconds after it has reached a dull red. It is also believed desirable to move the tool around in the quenching oil, particularly immediately after it has been placed in it, to prevent the formation of a gas film on the tool. Such a film is usually a poor conductor of heat and slows the rate of cooling.

*Salt Bath:* Quenching in a lead or salt bath at from 1000 to 1200 deg. F has the advantage that cooling of the tool from hardening to room temperature is accomplished in two stages, thus reducing the possibility of setting up internal strains that may tend to crack the tool. The quenching temperature is sufficiently below the lower critical point for a tool so quenched to be allowed to cool to room temperature in still air. This type of quench is particularly advantageous for tools of complicated section that would easily develop hardening cracks. The salt quench has the advantage that the tool sinks and requires only a support, whereas the same tool will float in the lead bath and must be held under the surface. It is believed that the lead quench gives a somewhat higher matrix hardness, and is of advantage for tools that tend to fail by nose abrasion. Tools treated as described are brittle unless given a regular tempering treatment, because the 1000-deg. F quenching temperature is not a substitute for later tempering at the same temperature, after the tool has cooled to room temperature.

*Air Cooling:* Many high-speed steel tools are quenched in air, either in a stream of dry compressed air or in still air. Small sections harden satisfactorily in still air, but heavier sections should be subjected to air under pressure. One advantage of air cooling is that the tool can be kept straight and free from distortion, although it is likely that there will be more scale on a tool thus quenched than when oil, lead, or salt is used. Cooling between steel plates may help to keep thin flat tools straight and flat.

**Straightening High-Speed Tools when Quenching.**—The final straightness required in a tool must be considered when it is quenched. When several similar tools are to be hardened, a jig can be used to advantage for holding the tools while quenching. When long slender tools are quenched without holders, they frequently warp and must be straightened later. The best time for this straightening is during the first few minutes after the tools have been quenched, as the steel is then quite pliable and may be straightened without difficulty. The straightening must be done at once, as the tools become hard in a few minutes.

**Anneal Before Rehardening.**—Tools that are too soft after hardening must be annealed before rehardening. A quick anneal, such as previously described, is all that is required to put such a tool into the proper condition for rehardening. This treatment is absolutely essential. For milling cutters and forming tools of irregular section, a full anneal should be used.

**Tempering or Drawing Tungsten High-Speed Steel.**—The tempering or drawing temperature for high-speed steel tools usually varies from 900 to 1200 deg. F. This temperature is higher for turning and planing tools than for such tools as milling cutters, forming tools, etc. If the temperature is below 800 deg. F, the tool is likely to be too brittle. The general idea is to temper tools at the highest temperature likely to occur in service. Because this temperature ordinarily would not be known, the general practice is to temper at whatever temperature experience with that particular steel and tool has proved to be the best.

The furnace used for tempering usually is kept at a temperature of from 1000 to 1100 deg. F for ordinary high-speed steels and from 1200 to 1300 deg. F for steels of the cobalt type. These furnace temperatures apply to tools of the class used on lathes and planers. Such tools, in service, frequently heat to the point of visible redness. Milling cutters, forming tools, or any other tools for lighter duty may be tempered as low as 850 or 900 deg. F. When the tool has reached the temperature of the furnace, it should be held at this temperature for from one to several hours until it has been heated evenly throughout. It should then be allowed to cool gradually in the air and in a place that is dry and free from air drafts. In tempering, the tool should not be quenched, because quenching tends to produce strains that may result later in cracks.

**Annealing Tungsten High-Speed Steel.**—The following method of annealing high-speed steel has been used extensively. Use an iron box or pipe of sufficient size to allow at least  $\frac{1}{2}$  inch of packing between the pieces of steel to be annealed and the sides of the box or pipe. It is not necessary that each piece of steel be kept separate from every other piece, but only that the steel be prevented from touching the sides of the annealing pipe or box. Pack carefully with powdered charcoal, fine dry lime, or mica (preferably charcoal), and cover with an airtight cap or lute with fire clay; heat slowly to 1600 to 1650 deg. F and keep at this heat from 2 to 8 hours, depending on the size of the pieces to be annealed. A piece measuring 2 by 1 by 8 inches requires about 3 hours. Cool as slowly as possible, and do not expose to the air until cold, because cooling in air is likely to cause partial hardening. A good method is to allow the box or pipe to remain in the furnace until cold.

**Hardening Molybdenum High-Speed Steels.**—Table 3 gives the compositions of several molybdenum high-speed steels that are widely used for general commercial tool applications. The general method of hardening molybdenum high-speed steels resembles that used for 18–4–1 tungsten high-speed steel except that the hardening temperatures are lower and more precautions must be taken to avoid decarburization, especially on tools made from Type I or Type II steels, when the surface is not ground after hardening. Either salt baths or atmosphere-controlled furnaces are recommended for hardening molybdenum high-speed steels.

**Table 3. Compositions of Molybdenum High-Speed Steels**

| Element    | Molybdenum–Tungsten   |                                    | Molybdenum–Vanadium   | Tungsten–Molybdenum    |
|------------|-----------------------|------------------------------------|-----------------------|------------------------|
|            | Type Ia<br>(Per Cent) | Type Ib <sup>a</sup><br>(Per Cent) | Type II<br>(Per Cent) | Type III<br>(Per Cent) |
| Carbon     | 0.70–0.85             | 0.76–0.82                          | 0.70–0.90             | 0.75–0.90              |
| Tungsten   | 1.25–2.00             | 1.60–2.30                          | ...                   | 5.00–6.00              |
| Chromium   | 3.00–5.00             | 3.70–4.20                          | 3.00–5.00             | 3.50–5.00              |
| Vanadium   | 0.90–1.50             | 1.05–1.35                          | 1.50–2.25             | 1.25–1.75              |
| Molybdenum | 8.00–9.50             | 8.00–9.00                          | 7.50–9.50             | 3.50–5.50              |
| Cobalt     | See footnote          | 4.50–5.50                          | See footnote          | See footnote           |

<sup>a</sup> Cobalt may be used in any of these steels in varying amounts up to 9 per cent, and the vanadium content may be as high as 2.25 percent. When cobalt is used in Type III steel, the vanadium content may be as high as 2.25 per cent. When cobalt is used in Type III steel, this steel becomes susceptible to decarburization. As an illustration of the use of cobalt, Type Ib steel is included. This is steel T10 in the U.S. Navy Specification 46S37, dated November 1, 1939.

The usual method is to preheat uniformly in a separate furnace to 1250 to 1550 deg. F then transfer to a high-heat furnace maintained within the hardening temperature range given in Table 4. Single-point cutting tools, in general, should be hardened at the upper end of the temperature range indicated by Table 4. Slight grain coarsening is not objectionable in such tools when they are properly supported in service and are not subjected to chattering; however, when these tools are used for intermittent cuts, it is better to use the middle of the temperature range. All other cutting tools, such as drills, countersinks, taps, milling

cutters, reamers, broaches, and form tools, should be hardened in the middle of the range shown. For certain tools, such as slender taps, cold punches, and blanking and trimming dies, where greater toughness to resist shocks is required, the lower end of the hardening temperature range should be used.

**Table 4. Heat Treatment of Molybdenum High-Speed Steels**

| Heat-Treating Operation | Molybdenum–Tungsten                                | Molybdenum–Vanadium           | Tungsten–Molybdenum            |
|-------------------------|--|-------------------------------|--------------------------------|
|                         | Types Ia and Ib <sup>a</sup><br>(Temp., in Deg. F) | Type II<br>(Temp., in Deg. F) | Type III<br>(Temp., in Deg. F) |
| Forging                 | 1850–2000  | 1850–2000                     | 1900–2050                      |
| Not below               | 1600   | 1600                          | 1600                           |
| Annealing               | 1450–1550  | 1450–1550                     | 1450–1550                      |
| Strain relief           | 1150–1350  | 1150–1350                     | 1150–1350                      |
| Preheating              | 1250–1500  | 1250–1500                     | 1250–1550                      |
| Hardening <sup>b</sup>  | 2150–2250 <sup>a</sup>                             | 2150–2250                     | 2175–2275                      |
| Salt                    | 2150–2225  | 2150–2225                     | 2150–2250                      |
| Tempering               | 950–1100   | 950–1100                      | 950–1100                       |

<sup>a</sup> For similar working conditions, Type Ib steel requires a slightly higher hardening heat than Type Ia.

<sup>b</sup> The higher side of the hardening range should be used for large sections, and the lower side for small sections.

Molybdenum high-speed steels can be pack-hardened following the same practice as is used for tungsten high-speed steels, but keeping on the lower side of the hardening range (approximately 1850 degrees F). Special surface treatments such as nitriding by immersion in molten cyanide that are used for tungsten high-speed steels are also applicable to molybdenum high-speed tools.

When heated in an open fire or in furnaces without atmosphere control, these steels do not sweat like 18–4–1 steels; consequently, determining the proper time in the high-heat chamber is a matter of experience. This time approximates that used with 18–4–1 steels, although it may be slightly longer when the lower part of the hardening range is used. Much can be learned by preliminary hardening of test pieces and checking on the hardness fracture and structure. It is difficult to give the exact heating time, because it is affected by temperature, type of furnace, size and shape, and furnace atmosphere. Rate of heat transfer is most rapid in salt baths, and slowest in controlled-atmosphere furnaces with high carbon monoxide content.

**Quenching and Tempering of Molybdenum High-Speed Tools.**—Quenching may be done in oil, air, or molten bath. To reduce the possibility of breakage and undue distortion of intricately shaped tools, it is advisable to quench in a molten bath at approximately 1100 degrees F. The tool also may be quenched in oil and removed while still red, or at approximately 1100 degrees F. The tool is then cooled in air to room temperature, and tempered immediately to avoid cracking.

When straightening is necessary, it should be done after quenching and before cooling to room temperature prior to tempering.

To temper, the tools should be reheated slowly and uniformly to 950 to 1100 degrees F. For general work, 1050 degrees F is most common. The tools should be held at this temperature at least 1 hour. Two hours is a safer minimum, and 4 hours is maximum. The time and temperature depend on the hardness and toughness required. Where tools are subjected to more or less shock, multiple temperings are suggested.

**Protective Coatings for Molybdenum Steels.**—To protect the surface from oxidation during heat treatment, borax may be applied by sprinkling it lightly over the steel when the latter is heated in a furnace to a low temperature (1200 to 1400 deg. F). Small tools may be rolled in a box of borax before heating. Another method more suitable for finished tools is

to apply the borax or boric acid in the form of a supersaturated water solution. The tools are then immersed in the solution at 180 to 212 deg. F, or the solution may be applied with a brush or spray. Pieces so treated are heated as usual, taking care in handling to ensure good adherence of the coating. Special protective coatings or paints, when properly applied, have been found extremely useful. These materials do not fuse or run at the temperatures used, and therefore do not affect the furnace hearth. When applying these coatings, it is necessary to have a surface free from scale or grease to ensure good adherence. Coatings may be sprayed or brushed on, and usually one thin coat is sufficient. Heavy coats tend to pit the surface of the tool and are difficult to remove. Tools covered with these coatings should be allowed to dry before they are charged into the preheat furnace. After hardening and tempering, the coating can be easily removed by light blasting with sand or steel shot. When tools are lightly ground, these coatings come off immediately. Protection may also be obtained by wrapping pieces in stainless steel foil.

**Nitriding High-Speed Steel Tools.**—Nitriding is applied to high-speed steel for the purpose of increasing tool life by producing a very hard skin or case, the thickness of which ordinarily is from 0.001 to 0.002 inch. Nitriding is done after the tool has been fully heat treated and finish-ground. (The process differs entirely from that which is applied to surface harden certain alloy steels by heating in an atmosphere of nitrogen or ammonia gas.) The temperature of the high-speed steel nitriding bath, which is a mixture of sodium and potassium cyanides, is equal to or slightly lower than the tempering temperature. For ordinary tools, this temperature usually varies from about 1025 to 1050 deg. F; but if the tools are exceptionally fragile, the range may be reduced to 950 or 1000 deg. F. Accurate temperature control is essential to prevent exceeding the final tempering temperature. The nitriding time may vary from 10 or 15 minutes to 30 minutes or longer, and should be determined by experiment. The shorter periods are applied to tools for iron or steel, or any shock-resisting tools, and the longer periods are for tools used in machining nonferrous metals and plastics. This nitriding process is applied to tools such as hobs, reamers, taps, box tools, form tools, and milling cutters. Nitriding may increase tool life 50 to 200 per cent, or more, but it should always be preceded by correct heat treatment.

*Nitriding Bath Mixtures and Temperatures:* A mixture of 60 per cent sodium cyanide and 40 per cent potassium cyanide is commonly used for nitriding. This mixture has a melting point of 925 deg. F, which is gradually reduced to 800 deg. F as the cyanate content of the bath increases. A more economical mixture of 70 per cent sodium cyanide and 30 per cent potassium cyanide may be used if the operating temperature of the bath is only 1050 deg. F. Nitriding bath temperatures should not exceed 1100 deg. F because higher temperatures accelerate the formation of carbonate at the expense of the essential cyanide. A third mixture suitable for nitriding consists of 55 per cent sodium cyanide, 25 per cent potassium chloride, and 20 per cent sodium carbonate. This mixture melts at 930 deg. F.

**Equipment for Hardening High-Speed Steel.**—Equipment for hardening high-speed steel consists of a hardening furnace capable of maintaining a temperature of 2350 to 2450 deg. F; a preheating furnace capable of maintaining a temperature of 1700 to 1800 deg. F, and of sufficient size to hold a number of pieces of the work; a tempering (drawing) furnace capable of maintaining a temperature of 1000 to 1200 deg. F as a general rule; and a water-cooled tank of quenching oil.

High-speed steels usually are heated for hardening either in some type of electric furnace or in a gas-fired furnace of the muffle type. The small furnaces used for high-speed steel seldom are oil-fired. It is desirable to use automatic temperature control and, where an oven type of furnace is employed, a controlled atmosphere is advisable because of the variations in cutting qualities caused by hardening under uncontrolled conditions. Some furnaces of both electric and fuel-fired types are equipped with a salt bath suitable for high-speed steel hardening temperatures. Salt baths have the advantage of providing protection against the atmosphere during the heating period. A type of salt developed for commercial use is water-soluble, so that all deposits from the hardening bath may be removed by

immersion in water after quenching in oil or salt, or after air cooling. One type of electric furnace heats the salt bath internally by electrodes immersed in it. The same type of furnace is also applied to various heat-treating operations, such as cyanide hardening, liquid carburizing, tempering, and annealing.

An open-forge fire has many disadvantages, especially in hardening cutters or other tools that cannot be ground all over after hardening. The air blast decarburizes the steel and lack of temperature control makes it impossible to obtain uniform results. Electric and gas furnaces provide continuous uniform heat, and the temperature may be regulated accurately, especially when pyrometers are used. In shops equipped with only one furnace for carbon steel and one for high-speed steel, the tempering can be done in the furnace used for hardening carbon steel after the preheating is finished and the steel has been removed for hardening.

**Heating High-Speed Steel for Forging.**—Care should be taken not to heat high-speed steel for forging too abruptly. In winter, the steel may be extremely cold when brought into the forge shop. If the steel is put directly into the hot forge fire, it is likely to develop cracks that will show up later in the finished tool. The steel, therefore, should be warmed gradually before heating for forging.

### Subzero Treatment of Steel

Subzero treatment consists of subjecting the steel, after hardening and either before or after tempering, to a subzero temperature (that usually ranges from  $-100$  to  $-120$  deg. F) and for a period of time varying with the size or volume of the tool, gage, or other part. Commercial equipment is available for obtaining these low temperatures.

The subzero treatment is employed by most gage manufacturers to stabilize precision gages and prevent subsequent changes in size or form. Subzero treatment is also applied to some high-speed steel cutting tools. The object here is to increase the durability or life of the tools; however, up to the present time, the results of tests by metallurgists and tool engineers often differ considerably and in some instances are contradictory. Methods of procedure also vary, especially with regard to the order and number of operations in the complete heat-treating and cooling cycle.

**Changes Resulting From Subzero Treatment.**—When steel is at the hardening temperature it contains a solid solution of carbon and iron known as *austenite*. When the steel is hardened by sudden cooling, most of the austenite, which is relatively soft, tough, and ductile even at room temperatures, is transformed into martensite, a hard and strong constituent. If all the austenite were changed to martensite upon reaching room temperature, this process would be an ideal hardening operation, but many steels retain some austenite. In general, the higher the carbon and alloy contents and the higher the hardening temperature, the greater the tendency to retain austenite. When steel is cooled to subzero temperatures, the stability of the retained austenite is reduced so that it is more readily transformed. To obtain more complete transformation, the subzero treatment may be repeated. The ultimate transformation of austenite to martensite may take place in carbon steel without the aid of subzero treatment, but this natural transformation might require 6 months or longer, whereas by refrigeration this change occurs in a few hours.

The thorough, uniform heating that is always recommended in heat-treating operations should be accompanied by thorough, uniform cooling when the subzero treatment is applied. To ensure uniform cooling, the subzero cooling period should be increased for the larger tools and it may range from 2 to 6 hours. The tool or other part is sometimes surrounded by one or more layers of heavy wrapping or asbestos paper to delay the cooling somewhat and ensure uniformity. After the cooling cycle is started, it should continue without interruption.

Subzero treatment may sometimes cause cracking. Normally, the austenite in steel provides a cushioning effect that may prevent cracking or breakage resulting from treatments

involving temperature and dimensional changes; but if this cushioning effect is removed, particularly at very low temperatures as in subzero treatments, there may be danger of cracking, especially with tools having large or irregular sections and sharp corners offering relatively low resistance to stresses. This effect is one reason why subzero treatments may differ in regard to the cooling and tempering cycle.

**Stabilizing Dimensions of Gages or Precision Parts by Subzero Cooling.**—Transformation of austenite into martensite is accompanied by an increase in volume; consequently, the transformation of austenite, that may occur naturally over a period of months or years, tends to change the dimensions and form of steel parts, and such changes may be serious in the case of precision gages, close-fitting machine parts, etc. To prevent such changes, the subzero treatment has proved effective. Gage-blocks, for example, may be stabilized by hardening followed by repeated cycles of chilling and tempering, to transform a large percentage of the austenite into martensite.

*Order of Operations for Stabilizing Precision Gages:* If precision gages and sine-bars, are heat-treated in the ordinary manner and then are finished without some stabilizing treatment, dimensional changes and warpage are liable to occur. Sub-zero cooling provides a practical and fairly rapid method of obtaining the necessary stabilization by transforming the austenite into martensite. In stabilization treatments of this kind, tempering is the final operation. One series of treatments that has been recommended after hardening and rough-grinding is as follows:

a) Cool to  $-120$  degrees F. (This cooling period may require from one to six hours, depending on the size and form of the gage.)

b) Place gage in boiling water for two hours (oil or salt bath may also be used).

Note: Steps (a) and (b) may be repeated from two to six times, depending on the size and form of the gage. These repeated cycles will eventually transform practically all the austenite into martensite. Two or three cooling and drawing operations usually are sufficient for such work as thread gages and gage-blocks.

c) Follow with regular tempering or drawing operation and finish gage by lapping.

*Series of Stabilizing Treatments for Chromium Steel:* The following series of treatments has proved successful in stabilizing precision gage-blocks made from SAE 52100 chromium steel.

a) Preheat to 600 degrees F and then heat to 1575 degrees F for a period of four minutes.

b) Quench in oil at 85 degrees F. (Uniform quenching is essential.)

c) Temper at 275 degrees F for one hour.

d) Cool in tempering furnace to room temperature.

e) Continue cooling in atmosphere of industrial refrigerator for six hours with temperature of atmosphere at  $-120$  degrees F.

f) Allow gage-blocks to return to room temperature and again temper.

Note: The complete treatment consists of six subzero cooling periods, each followed by a tempering operation. The transformation to martensite is believed to be complete even after the fifth cooling period. The hardness is about 66 Rockwell C. Transformation is checked by magnetic tests based upon the magnetism of martensite and the nonmagnetic qualities of austenite.

**Stabilizing Dimensions of Close-Fitting Machine Parts.**—Subzero treatment will always cause an increase in size. Machine parts subjected to repeated and perhaps drastic changes in temperature, as in aircraft, may eventually cause trouble due to growth or warpage as the austenite gradually changes to martensite. In some instances, the sizes of close-fitting moving parts have increased sufficiently to cause seizure. Such treatment, for example, may be applied to precision bearings made from SAE 52100 or alloy carburizing steels for stabilizing or aging them. *Time* aging of 52100 steels after hardening has been found to cause changes as large as 0.0025 inch in medium size sections. A practical remedy is to apply the subzero treatment before the final grinding or other machining operation.

**Subzero Treatment of Carburized Parts to Improve Physical Properties.**—The subzero treatment has been applied to carburized machine parts. For example, the amount of retained austenite in carburized gears may be sufficient to reduce the life of the gears. In one component, the Rockwell hardness was increased from 55 C to 65 C without loss of impact resistance qualities; in fact, impact and fatigue resistance may be increased in some examples.

**Application of Subzero Treatments to High-Speed Steel.**—The subzero treatment has been applied to such tools as milling cutters, hobs, taps, broaches, and drills. It is applicable to different classes of high-speed steels, such as the 18–4–1 tungsten, 18–4–14 cobalt, and the molybdenum high-speed steels. This *cold* treatment is applied preferably in conjunction with the heat treatment, both being combined in a continuous cycle of operations. The general procedure is either to harden the steel, cool it to a subzero temperature, and then temper; or, especially if there is more than one tempering operation, the first one may *precede* subzero cooling. The cooling and tempering cycle may be repeated two or more times. The number and order of the operations, or the complete cycle, may be varied to suit the class of work and, to minimize the danger of cracking, particularly if the tool has large or irregular sections, sharp corners or edges, or a high cobalt content. A subzero treatment of some kind with a final tempering operation for stress relief, is intended to increase strength and toughness without much loss in hardness; consequently, if there is greater strength at a given hardness, tools subjected to subzero treatment can operate with a higher degree of hardness than those heat treated in the ordinary manner, or, if greater toughness is preferred, it can be obtained by tempering to the original degree of hardness.

**Order of Cooling and Tempering Periods for High-speed Steel.**—The order or cycle for the cooling and tempering periods has not been standardized. The methods that follow have been applied to high-speed steel tools. They are given as examples of procedure and are subject to possible changes due to subsequent developments. The usual ranges of preheating and hardening temperatures are given; but for a particular steel, the recommended temperatures should be obtained from the manufacturer.

- 1) *Double Subzero Treatment:* (For rugged simple tool forms without irregular sections, sharp corners or edges where cracks might develop during the subzero treatment).
  - a) Preheat between 1400 and 1600 degrees F (double preheating is preferable, the first preheating ranging from 700 to 1000 degrees F).
  - b) Heat to the hardening temperature. (*Note:* Tests indicate that the effect of subzero treatment on high-speed steel may be influenced decidedly by the hardening temperature. If this temperature is near the lower part of the range, the results are unsatisfactory. Effective temperatures for ordinary high-speed steels appear to range from 2300 to 2350 degrees F).
  - c) Quench in oil, salt, lead, or air, down to a workpiece temperature of 150–200 degrees F. (*Note:* One method is to quench in oil; a second method is to quench in oil to about 200–225 degrees F and then air cool; a third method is to quench in salt bath at 1050–1100 degrees F and then air cool.)
  - d) Cool in refrigerating unit to temperature of –100 to –120 degrees F *right after quenching.* (*Note:* Tests have shown that a delay of one hour has a detrimental effect, and in ten hours the efficiency of the subzero treatment is reduced 50 per cent. This is because the austenite becomes more and more stabilized when the subzero treatment is delayed; consequently, the austenite is more difficult to transform into martensite.) The refrigerating period usually varies from two to six hours, depending on the size of the tool. Remove the tool from the refrigerating unit and allow it to return to room temperature.
  - e) Temper to required hardness for a period of two and one-half to three hours. The tempering temperature usually varies from a minimum of 1000 to 1100 degrees F for ordinary high-speed steels. Tests indicate that if this first tempering is less than two and one-half hours at 1050 degrees F, there will not be sufficient precipitation of car-

bides at the tempering temperature to allow complete transformation of the retained austenite on cooling, whereas more than three hours causes some loss in room temperature hardness, hot hardness, strength, and toughness.

- f) Repeat subzero treatment, step (d).
  - g) Repeat the tempering operation, step (e). (*Note:* The time for the second tempering operation is sometimes reduced to about one-half the time required for the first tempering.)
- 2) *Single Subzero Treatment:* This treatment is the same as procedure (1) except that a second subzero cooling is omitted; hence, the cycle consists of hardening, subzero cooling, and double tempering. Procedure (3), which follows, also has one subzero cooling period in the cycle, but this *follows* the first tempering operation.
- 3) *Tempering Followed by Subzero Treatment:* This treatment is for tools having irregular sections, sharp corners, or edges where cracks might develop if the hardening operation were followed immediately by subzero cooling.
- a) Preheat and heat for hardening.
  - b) Preheat and heat for hardening.
  - c) Quench as described under procedure (1).
  - d) Temper to required hardness.
  - e) Cool to subzero temperature  $-100$  to  $-120$  degrees F and then allow the tool to return to room temperature.
  - f) Repeat tempering operation.

### Testing the Hardness of Metals

**Brinell Hardness Test.**—The Brinell test for determining the hardness of metallic materials consists in applying a known load to the surface of the material to be tested through a hardened steel ball of known diameter. The diameter of the resulting permanent impression in the metal is measured and the Brinell Hardness Number (BHN) is then calculated from the following formula in which  $D$  = diameter of ball in millimeters,  $d$  = measured diameter at the rim of the impression in millimeters, and  $P$  = applied load in kilograms.

$$\text{BHN} = \frac{\text{load on indenting tool in kilograms}}{\text{surface area of indentation in sq. mm.}} = \frac{P}{\frac{\pi D}{2}(D - \sqrt{D^2 - d^2})}$$

If the steel ball were not deformed under the applied load and if the impression were truly spherical, then the preceding formula would be a general one, and any combination of applied load and size of ball could be used. The impression, however, is not quite a spherical surface because there must always be some deformation of the steel ball and some recovery of form of the metal in the impression; hence, for a standard Brinell test, the size and characteristics of the ball and the magnitude of the applied load must be standardized. In the standard Brinell test, a ball 10 millimeters in diameter and a load of 3000, 1500, or 500 kilograms is used. It is desirable, although not mandatory, that the test load be of such magnitude that the diameter of the impression be in the range of 2.50 to 4.75 millimeters. The following test loads and approximate Brinell numbers for this range of impression diameters are: 3000 kg, 160 to 600 BHN; 1500 kg, 80 to 300 BHN; 500 kg, 26 to 100 BHN. In making a Brinell test, the load should be applied steadily and without a jerk for at least 15 seconds for iron and steel, and at least 30 seconds in testing other metals. A minimum period of 2 minutes, for example, has been recommended for magnesium and magnesium alloys. (For the softer metals, loads of 250, 125, or 100 kg are sometimes used.)

According to the American Society for Testing and Materials Standard E10-66, a steel ball may be used on material having a BHN not over 450, a Hultgren ball on material not over 500, or a carbide ball on material not over 630. The Brinell hardness test is not recommended for material having a BHN over 630.



**Rockwell Hardness Test.**—The Rockwell hardness tester is essentially a machine that measures hardness by determining the depth of penetration of a penetrator into the specimen under certain fixed conditions of test. The penetrator may be either a steel ball or a diamond spheroconical penetrator. The hardness number is related to the depth of indentation and the number is higher the harder the material. A minor load of 10 kg is first applied, causing an initial penetration; the dial is set at zero on the black-figure scale, and the major load is applied. This major load is customarily 60 or 100 kg when a steel ball is used as a penetrator, but other loads may be used when necessary. The ball penetrator is  $\frac{1}{16}$  inch in diameter normally, but other penetrators of larger diameter, such as  $\frac{1}{8}$  inch, may be employed for soft metals. When a diamond spheroconical penetrator is employed, the load usually is 150 kg. Experience decides the best combination of load and penetrator for use. After the major load is applied and removed, according to standard procedure, the reading is taken while the minor load is still applied.

**The Rockwell Hardness Scales.**—The various Rockwell scales and their applications are shown in the following table. The type of penetrator and load used with each are shown in Tables 1 and 2, which give comparative hardness values for different hardness scales.

| Scale               | Testing Application   |
|---------------------|---|
| A                   | For tungsten carbide and other extremely hard materials. Also for thin, hard sheets.              |
| B                   | For materials of medium hardness such as low- and medium-carbon steels in the annealed condition. |
| C                   | For materials harder than Rockwell B-100.   |
| D                   | Where a somewhat lighter load is desired than on the C scale, as on case-hardened pieces.         |
| E                   | For very soft materials such as bearing metals.   |
| F                   | Same as the E scale but using a $\frac{1}{16}$ -inch ball.  |
| G                   | For metals harder than tested on the B scale.   |
| H & K               | For softer metals.  |
| 15-N; 30-N;<br>45-N | Where a shallow impression or a small area is desired. For hardened steel and hard alloys.        |
| 15-T; 30-T;<br>45-T | Where a shallow impression or a small area is desired for materials softer than hardened steel.   |

**Shore's Scleroscope.**—The scleroscope is an instrument that measures the hardness of the work in terms of elasticity. A diamond-tipped hammer is allowed to drop from a known height on the metal to be tested. As this hammer strikes the metal, it rebounds, and the harder the metal, the greater the rebound. The extreme height of the rebound is recorded, and an average of a number of readings taken on a single piece will give a good indication of the hardness of the work. The surface smoothness of the work affects the reading of the instrument. The readings are also affected by the contour and mass of the work and the depth of the case, in carburized work, the soft core of light-depth carburizing, pack-hardening, or cyanide hardening, absorbing the force of the hammer fall and decreasing the rebound. The hammer weighs about 40 grains, the height of the rebound of hardened steel is in the neighborhood of 100 on the scale, or about  $6\frac{1}{4}$  inches, and the total fall is about 10 inches or 255 millimeters.

**Vickers Hardness Test.**—The Vickers test is similar in principle to the Brinell test. The standard Vickers penetrator is a square-based diamond pyramid having an included point angle of 136 degrees. The numerical value of the hardness number equals the applied load in kilograms divided by the area of the pyramidal impression: A smooth, firmly supported, flat surface is required. The load, which usually is applied for 30 seconds, may be 5, 10, 20, 30, 50, or 120 kilograms. The 50-kilogram load is the most usual. The hardness number is based upon the diagonal length of the square impression. The Vickers test is considered to

be very accurate, and may be applied to thin sheets as well as to larger sections with proper load regulation.

**Knoop Hardness Numbers.**—The Knoop hardness test is applicable to extremely thin metal, plated surfaces, exceptionally hard and brittle materials, very shallow carburized or nitrided surfaces, or whenever the applied load must be kept below 3600 grams. The Knoop indenter is a diamond ground to an elongated pyramidal form and it produces an indentation having long and short diagonals with a ratio of approximately 7 to 1. The longitudinal angle of the indenter is 172 degrees, 30 minutes, and the transverse angle 130 degrees. The Tukon Tester in which the Knoop indenter is used is fully automatic under electronic control. The Knoop hardness number equals the load in kilograms divided by the projected area of indentation in square millimeters. The indentation number corresponding to the long diagonal and for a given load may be determined from a table computed for a theoretically perfect indenter. The load, which may be varied from 25 to 3600 grams, is applied for a definite period and always normal to the surface tested. Lapped plane surfaces free from scratches are required.

**Monotron Hardness Indicator.**—With this instrument, a diamond-ball impressor point  $\frac{3}{4}$  mm in diameter is forced into the material to a depth of  $\frac{1}{500}$  inch and the pressure required to produce this constant impression indicates the hardness. One of two dials shows the pressure in kilograms and pounds, and the other shows the depth of the impression in millimeters and inches. Readings in Brinell numbers may be obtained by means of a scale designated as *M-1*.

**Keep's Test.**—With this apparatus, a standard steel drill is caused to make a definite number of revolutions while it is pressed with standard force against the specimen to be tested. The hardness is automatically recorded on a diagram on which a dead soft material gives a horizontal line, and a material as hard as the drill itself gives a vertical line, intermediate hardness being represented by the corresponding angle between 0 and 90 degrees.

**Comparison of Hardness Scales.**—Tables 1 and 2 show comparisons of various hardness scales. All such tables are based on the assumption that the metal tested is homogeneous to a depth several times that of the indentation. To the extent that the metal being tested is not homogeneous, errors are introduced because different loads and different shapes of penetrators meet the resistance of metal of varying hardness, depending on the depth of indentation. Another source of error is introduced in comparing the hardness of different materials as measured on different hardness scales. This error arises from the fact that in any hardness test, metal that is severely cold-worked actually supports the penetrator, and different metals, different alloys, and different analyses of the same type of alloy have different cold-working properties. In spite of the possible inaccuracies introduced by such factors, it is of considerable value to be able to compare hardness values in a general way.

The data shown in Table 1 are based on extensive tests on carbon and alloy steels mostly in the heat-treated condition, but have been found to be reliable on constructional alloy steels and tool steels in the as-forged, annealed, normalized, quenched, and tempered conditions, providing they are homogeneous. These hardness comparisons are not as accurate for special alloys such as high manganese steel, 18-8 stainless steel and other austenitic steels, nickel-base alloys, constructional alloy steels, and nickel-base alloys in the cold-worked condition.

The data shown in Table 2 are for hardness measurements of unhardened steel, steel of soft temper, grey and malleable cast iron, and most nonferrous metals. Again these hardness comparisons are not as accurate for annealed metals of high Rockwell B hardness such as austenitic stainless steel, nickel and high nickel alloys, and cold-worked metals of low B-scale hardness such as aluminum and the softer alloys.

HARDNESS TESTING

**Table 1. Comparative Hardness Scales for Steel**

| Rockwell C-Scale Hardness Number | Diamond Pyramid Hardness Number Vickers | Brinell Hardness Number 10-mm Ball, 3000-kgf Load |               |                       | Rockwell Hardness Number             |                                       | Rockwell Superficial Hardness Number Superficial Diamond Indenter |                        |                        | Shore Scleroscope Hardness Number |
|----------------------------------|---|---|---------------|-----------------------|--------------------------------------|---------------------------------------|---|------------------------|------------------------|-----------------------------------|
|                                  |   | Standard Ball                                     | Hultgren Ball | Tungsten Carbide Ball | A-Scale 60-kgf Load Diamond Indenter | D-Scale 100-kgf Load Diamond Indenter | 15-N Scale 15-kgf Load  | 30-N Scale 30-kgf Load | 45-N Scale 45-kgf Load |                                   |
| 68                               | 940                                     | ...   | ...           | ...                   | 85.6                                 | 76.9                                  | 93.2  | 84.4                   | 75.4                   | 97                                |
| 67                               | 900                                     | ...   | ...           | ...                   | 85.0                                 | 76.1                                  | 92.9  | 83.6                   | 74.2                   | 95                                |
| 66                               | 865                                     | ...   | ...           | ...                   | 84.5                                 | 75.4                                  | 92.5  | 82.8                   | 73.3                   | 92                                |
| 65                               | 832                                     | ...   | ...           | (739)                 | 83.9                                 | 74.5                                  | 92.2  | 81.9                   | 72.0                   | 91                                |
| 64                               | 800                                     | ...   | ...           | (722)                 | 83.4                                 | 73.8                                  | 91.8  | 81.1                   | 71.0                   | 88                                |
| 63                               | 772                                     | ...   | ...           | (705)                 | 82.8                                 | 73.0                                  | 91.4  | 80.1                   | 69.9                   | 87                                |
| 62                               | 746                                     | ...   | ...           | (688)                 | 82.3                                 | 72.2                                  | 91.1  | 79.3                   | 68.8                   | 85                                |
| 61                               | 720                                     | ...   | ...           | (670)                 | 81.8                                 | 71.5                                  | 90.7  | 78.4                   | 67.7                   | 83                                |
| 60                               | 697                                     | ...   | (613)         | (654)                 | 81.2                                 | 70.7                                  | 90.2  | 77.5                   | 66.6                   | 81                                |
| 59                               | 674                                     | ...   | (599)         | (634)                 | 80.7                                 | 69.9                                  | 89.8  | 76.6                   | 65.5                   | 80                                |
| 58                               | 653                                     | ...   | (587)         | 615                   | 80.1                                 | 69.2                                  | 89.3  | 75.7                   | 64.3                   | 78                                |
| 57                               | 633                                     | ...   | (575)         | 595                   | 79.6                                 | 68.5                                  | 88.9  | 74.8                   | 63.2                   | 76                                |
| 56                               | 613                                     | ...   | (561)         | 577                   | 79.0                                 | 67.7                                  | 88.3  | 73.9                   | 62.0                   | 75                                |
| 55                               | 595                                     | ...   | (546)         | 560                   | 78.5                                 | 66.9                                  | 87.9  | 73.0                   | 60.9                   | 74                                |
| 54                               | 577                                     | ...   | (534)         | 543                   | 78.0                                 | 66.1                                  | 87.4  | 72.0                   | 59.8                   | 72                                |
| 53                               | 560                                     | ...   | (519)         | 525                   | 77.4                                 | 65.4                                  | 86.9  | 71.2                   | 58.6                   | 71                                |
| 52                               | 544                                     | (500)   | (508)         | 512                   | 76.8                                 | 64.6                                  | 86.4  | 70.2                   | 57.4                   | 69                                |
| 51                               | 528                                     | (487)   | (494)         | 496                   | 76.3                                 | 63.8                                  | 85.9  | 69.4                   | 56.1                   | 68                                |
| 50                               | 513                                     | (475)   | (481)         | 481                   | 75.9                                 | 63.1                                  | 85.5  | 68.5                   | 55.0                   | 67                                |
| 49                               | 498                                     | (464)   | (469)         | 469                   | 75.2                                 | 62.1                                  | 85.0  | 67.6                   | 53.8                   | 66                                |
| 48                               | 484                                     | (451)   | (455)         | 455                   | 74.7                                 | 61.4                                  | 84.5  | 66.7                   | 52.5                   | 64                                |
| 47                               | 471                                     | 442   | 443           | 443                   | 74.1                                 | 60.8                                  | 83.9  | 65.8                   | 51.4                   | 63                                |
| 46                               | 458                                     | 432   | 432           | 432                   | 73.6                                 | 60.0                                  | 83.5  | 64.8                   | 50.3                   | 62                                |
| 45                               | 446                                     | 421   | 421           | 421                   | 73.1                                 | 59.2                                  | 83.0  | 64.0                   | 49.0                   | 60                                |
| 44                               | 434                                     | 409   | 409           | 409                   | 72.5                                 | 58.5                                  | 82.5  | 63.1                   | 47.8                   | 58                                |
| 43                               | 423                                     | 400   | 400           | 400                   | 72.0                                 | 57.7                                  | 82.0  | 62.2                   | 46.7                   | 57                                |
| 42                               | 412                                     | 390   | 390           | 390                   | 71.5                                 | 56.9                                  | 81.5  | 61.3                   | 45.5                   | 56                                |
| 41                               | 402                                     | 381   | 381           | 381                   | 70.9                                 | 56.2                                  | 80.9  | 60.4                   | 44.3                   | 55                                |
| 40                               | 392                                     | 371   | 371           | 371                   | 70.4                                 | 55.4                                  | 80.4  | 59.5                   | 43.1                   | 54                                |
| 39                               | 382                                     | 362   | 362           | 362                   | 69.9                                 | 54.6                                  | 79.9  | 58.6                   | 41.9                   | 52                                |
| 38                               | 372                                     | 353   | 353           | 353                   | 69.4                                 | 53.8                                  | 79.4  | 57.7                   | 40.8                   | 51                                |
| 37                               | 363                                     | 344   | 344           | 344                   | 68.9                                 | 53.1                                  | 78.8  | 56.8                   | 39.6                   | 50                                |
| 36                               | 354                                     | 336   | 336           | 336                   | 68.4                                 | 52.3                                  | 78.3  | 55.9                   | 38.4                   | 49                                |
| 35                               | 345                                     | 327   | 327           | 327                   | 67.9                                 | 51.5                                  | 77.7  | 55.0                   | 37.2                   | 48                                |
| 34                               | 336                                     | 319   | 319           | 319                   | 67.4                                 | 50.8                                  | 77.2  | 54.2                   | 36.1                   | 47                                |
| 33                               | 327                                     | 311   | 311           | 311                   | 66.8                                 | 50.0                                  | 76.6  | 53.3                   | 34.9                   | 46                                |
| 32                               | 318                                     | 301   | 301           | 301                   | 66.3                                 | 49.2                                  | 76.1  | 52.1                   | 33.7                   | 44                                |
| 31                               | 310                                     | 294   | 294           | 294                   | 65.8                                 | 48.4                                  | 75.6  | 51.3                   | 32.5                   | 43                                |
| 30                               | 302                                     | 286   | 286           | 286                   | 65.3                                 | 47.7                                  | 75.0  | 50.4                   | 31.3                   | 42                                |
| 29                               | 294                                     | 279   | 279           | 279                   | 64.7                                 | 47.0                                  | 74.5  | 49.5                   | 30.1                   | 41                                |
| 28                               | 286                                     | 271   | 271           | 271                   | 64.3                                 | 46.1                                  | 73.9  | 48.6                   | 28.9                   | 41                                |
| 27                               | 279                                     | 264   | 264           | 264                   | 63.8                                 | 45.2                                  | 73.3  | 47.7                   | 27.8                   | 40                                |
| 26                               | 272                                     | 258   | 258           | 258                   | 63.3                                 | 44.6                                  | 72.8  | 46.8                   | 26.7                   | 38                                |
| 25                               | 266                                     | 253   | 253           | 253                   | 62.8                                 | 43.8                                  | 72.2  | 45.9                   | 25.5                   | 38                                |
| 24                               | 260                                     | 247   | 247           | 247                   | 62.4                                 | 43.1                                  | 71.6  | 45.0                   | 24.3                   | 37                                |
| 23                               | 254                                     | 243   | 243           | 243                   | 62.0                                 | 42.1                                  | 71.0  | 44.0                   | 23.1                   | 36                                |
| 22                               | 248                                     | 237   | 237           | 237                   | 61.5                                 | 41.6                                  | 70.5  | 43.2                   | 22.0                   | 35                                |

**Table 1. (Continued) Comparative Hardness Scales for Steel**

| Rockwell C-Scale Hardness Number | Diamond Pyramid Hardness Number Vickers | Brinell Hardness Number 10-mm Ball, 3000-kgf Load |               |                       | Rockwell Hardness Number             |                                       | Rockwell Superficial Hardness Number Superficial Diamond Indenter |                        |                        | Shore Scleroscope Hardness Number |
|----------------------------------|---|---|---------------|-----------------------|--------------------------------------|---------------------------------------|---|------------------------|------------------------|-----------------------------------|
|                                  |   | Standard Ball                                     | Hultgren Ball | Tungsten Carbide Ball | A-Scale 60-kgf Load Diamond Indenter | D-Scale 100-kgf Load Diamond Indenter | 15-N Scale 15-kgf Load  | 30-N Scale 30-kgf Load | 45-N Scale 45-kgf Load |                                   |
| <b>21</b>                        | <b>243</b>                              | <b>231</b>  | <b>231</b>    | <b>231</b>            | <b>61.0</b>                          | <b>40.9</b>                           | <b>69.9</b>   | <b>42.3</b>            | <b>20.7</b>            | 35                                |
| <b>20</b>                        | <b>238</b>                              | <b>226</b>  | <b>226</b>    | <b>226</b>            | <b>60.5</b>                          | <b>40.1</b>                           | <b>69.4</b>   | <b>41.5</b>            | <b>19.6</b>            | 34                                |
| (18)                             | 230                                     | 219   | 219           | 219                   | ...                                  | ...                                   | ...   | ...                    | ...                    | 33                                |
| (16)                             | 222                                     | 212   | 212           | 212                   | ...                                  | ...                                   | ...   | ...                    | ...                    | 32                                |
| (14)                             | 213                                     | 203   | 203           | 203                   | ...                                  | ...                                   | ...   | ...                    | ...                    | 31                                |
| (12)                             | 204                                     | 194   | 194           | 194                   | ...                                  | ...                                   | ...   | ...                    | ...                    | 29                                |
| (10)                             | 196                                     | 187   | 187           | 187                   | ...                                  | ...                                   | ...   | ...                    | ...                    | 28                                |
| (8)                              | 188                                     | 179   | 179           | 179                   | ...                                  | ...                                   | ...   | ...                    | ...                    | 27                                |
| (6)                              | 180                                     | 171   | 171           | 171                   | ...                                  | ...                                   | ...   | ...                    | ...                    | 26                                |
| (4)                              | 173                                     | 165   | 165           | 165                   | ...                                  | ...                                   | ...   | ...                    | ...                    | 25                                |
| (2)                              | 166                                     | 158   | 158           | 158                   | ...                                  | ...                                   | ...   | ...                    | ...                    | 24                                |
| (0)                              | 160                                     | 152   | 152           | 152                   | ...                                  | ...                                   | ...   | ...                    | ...                    | 24                                |

Note: The values in this table shown in **boldface** type correspond to those shown in American Society for Testing and Materials Specification E140-67.

Values in ( ) are beyond the normal range and are given for information only.

**Turner's Sclerometer.**—In making this test a weighted diamond point is drawn, once forward and once backward, over the smooth surface of the material to be tested. The hardness number is the weight in grams required to produce a standard scratch.

**Mohs's Hardness Scale.**—Hardness, in general, is determined by what is known as Mohs's scale, a standard for hardness that is applied mainly to nonmetallic elements and minerals. In this hardness scale, there are ten degrees or steps, each designated by a mineral, the difference in hardness of the different steps being determined by the fact that any member in the series will scratch any of the preceding members. This scale is as follows:

- 1) talc; 2) gypsum; 3) calcite; 4) fluor spar; 5) apatite; 6) orthoclase; 7) quartz;  
8) topaz; 9) sapphire or corundum; and 10) diamond.

These minerals, arbitrarily selected as standards, are successively harder, from talc, the softest of all minerals, to diamond, the hardest. This scale, which is now universally used for nonmetallic minerals, is not applied to metals.

**Relation Between Hardness and Tensile Strength.**—The approximate relationship between the hardness and tensile strength is shown by the following formula:

Tensile strength =  $Bhn \times 515$  (for Brinell numbers up to 175).

Tensile strength =  $Bhn \times 490$  (for Brinell numbers larger than 175).

The above formulas give the tensile strength in pounds per square inch for steels. These approximate relationships between hardness and tensile strength do not apply to nonferrous metals with the possible exception of certain aluminum alloys.

**Durometer Tests.**—The durometer is a portable hardness tester for measuring hardness of rubber, plastics, and some soft metals. The instrument is designed to apply pressure to the specimen and the hardness is read from a scale while the pressure is maintained. Various scales can be used by changing the indenter and the load applied.

**Table 2. Comparative Hardness Scales for Unhardened Steel, Soft-Temper Steel, Grey and Malleable Cast Iron, and Nonferrous Alloys**

| Rockwell Hardness Number       |                          |                           | Rockwell Superficial Hardness Number |                             |                             | Rockwell Hardness Number      |                           |                           | Brinell Hardness Number  |                     |                 |
|--------------------------------|--------------------------|---------------------------|--------------------------------------|-----------------------------|-----------------------------|-------------------------------|---------------------------|---------------------------|--------------------------|---------------------|-----------------|
| $\frac{1}{16}$ " Ball Indenter |                          |                           | $\frac{1}{16}$ " Ball Indenter       |                             |                             | $\frac{1}{8}$ " Ball Indenter |                           |                           | "Brale" Indenter         | 10-mm Standard Ball |                 |
| B scale<br>100-kg<br>Load      | F scale<br>60-kg<br>Load | G scale<br>150-kg<br>Load | 15-T scale<br>15-kg<br>Load          | 30-T scale<br>30-kg<br>Load | 45-T scale<br>45-kg<br>Load | E scale<br>100-kg<br>Load     | H scale<br>100-kg<br>Load | K scale<br>150-kg<br>Load | A scale<br>60-kg<br>Load | 500-kg<br>Load      | 3000-kg<br>Load |
| 100                            | ...                      | 82.5                      | 93.0                                 | 82.0                        | 72.0                        | ...                           | ...                       | ...                       | 61.5                     | 201                 | 240             |
| 99                             | ...                      | 81.0                      | 92.5                                 | 81.5                        | 71.0                        | ...                           | ...                       | ...                       | 61.0                     | 195                 | 234             |
| 98                             | ...                      | 79.0                      | ...                                  | 81.0                        | 70.0                        | ...                           | ...                       | ...                       | 60.0                     | 189                 | 228             |
| 97                             | ...                      | 77.5                      | 92.0                                 | 80.5                        | 69.0                        | ...                           | ...                       | ...                       | 59.5                     | 184                 | 222             |
| 96                             | ...                      | 76.0                      | ...                                  | 80.0                        | 68.0                        | ...                           | ...                       | ...                       | 59.0                     | 179                 | 216             |
| 95                             | ...                      | 74.0                      | 91.5                                 | 79.0                        | 67.0                        | ...                           | ...                       | ...                       | 58.0                     | 175                 | 210             |
| 94                             | ...                      | 72.5                      | ...                                  | 78.5                        | 66.0                        | ...                           | ...                       | ...                       | 57.5                     | 171                 | 205             |
| 93                             | ...                      | 71.0                      | 91.0                                 | 78.0                        | 65.5                        | ...                           | ...                       | ...                       | 57.0                     | 167                 | 200             |
| 92                             | ...                      | 69.0                      | 90.5                                 | 77.5                        | 64.5                        | ...                           | ...                       | 100                       | 56.5                     | 163                 | 195             |
| 91                             | ...                      | 67.5                      | ...                                  | 77.0                        | 63.5                        | ...                           | ...                       | 99.5                      | 56.0                     | 160                 | 190             |
| 90                             | ...                      | 66.0                      | 90.0                                 | 76.0                        | 62.5                        | ...                           | ...                       | 98.5                      | 55.5                     | 157                 | 185             |
| 89                             | ...                      | 64.0                      | 89.5                                 | 75.5                        | 61.5                        | ...                           | ...                       | 98.0                      | 55.0                     | 154                 | 180             |
| 88                             | ...                      | 62.5                      | ...                                  | 75.0                        | 60.5                        | ...                           | ...                       | 97.0                      | 54.0                     | 151                 | 176             |
| 87                             | ...                      | 61.0                      | 89.0                                 | 74.5                        | 59.5                        | ...                           | ...                       | 96.5                      | 53.5                     | 148                 | 172             |
| 86                             | ...                      | 59.0                      | 88.5                                 | 74.0                        | 58.5                        | ...                           | ...                       | 95.5                      | 53.0                     | 145                 | 169             |
| 85                             | ...                      | 57.5                      | ...                                  | 73.5                        | 58.0                        | ...                           | ...                       | 94.5                      | 52.5                     | 142                 | 165             |
| 84                             | ...                      | 56.0                      | 88.0                                 | 73.0                        | 57.0                        | ...                           | ...                       | 94.0                      | 52.0                     | 140                 | 162             |
| 83                             | ...                      | 54.0                      | 87.5                                 | 72.0                        | 56.0                        | ...                           | ...                       | 93.0                      | 51.0                     | 137                 | 159             |
| 82                             | ...                      | 52.5                      | ...                                  | 71.5                        | 55.0                        | ...                           | ...                       | 92.0                      | 50.5                     | 135                 | 156             |
| 81                             | ...                      | 51.0                      | 87.0                                 | 71.0                        | 54.0                        | ...                           | ...                       | 91.0                      | 50.0                     | 133                 | 153             |
| 80                             | ...                      | 49.0                      | 86.5                                 | 70.0                        | 53.0                        | ...                           | ...                       | 90.5                      | 49.5                     | 130                 | 150             |
| 79                             | ...                      | 47.5                      | ...                                  | 69.5                        | 52.0                        | ...                           | ...                       | 89.5                      | 49.0                     | 128                 | 147             |
| 78                             | ...                      | 46.0                      | 86.0                                 | 69.0                        | 51.0                        | ...                           | ...                       | 88.5                      | 48.5                     | 126                 | 144             |
| 77                             | ...                      | 44.0                      | 85.5                                 | 68.0                        | 50.0                        | ...                           | ...                       | 88.0                      | 48.0                     | 124                 | 141             |
| 76                             | ...                      | 42.5                      | ...                                  | 67.5                        | 49.0                        | ...                           | ...                       | 87.0                      | 47.0                     | 122                 | 139             |
| 75                             | 99.5                     | 41.0                      | 85.0                                 | 67.0                        | 48.5                        | ...                           | ...                       | 86.0                      | 46.5                     | 120                 | 137             |
| 74                             | 99.0                     | 39.0                      | ...                                  | 66.0                        | 47.5                        | ...                           | ...                       | 85.0                      | 46.0                     | 118                 | 135             |
| 73                             | 98.5                     | 37.5                      | 84.5                                 | 65.5                        | 46.5                        | ...                           | ...                       | 84.5                      | 45.5                     | 116                 | 132             |
| 72                             | 98.0                     | 36.0                      | 84.0                                 | 65.0                        | 45.5                        | ...                           | ...                       | 83.5                      | 45.0                     | 114                 | 130             |
| 71                             | 97.5                     | 34.5                      | ...                                  | 64.0                        | 44.5                        | 100                           | ...                       | 82.5                      | 44.5                     | 112                 | 127             |
| 70                             | 97.0                     | 32.5                      | 83.5                                 | 63.5                        | 43.5                        | 99.5                          | ...                       | 81.5                      | 44.0                     | 110                 | 125             |
| 69                             | 96.0                     | 31.0                      | 83.0                                 | 62.5                        | 42.5                        | 99.0                          | ...                       | 81.0                      | 43.5                     | 109                 | 123             |
| 68                             | 95.5                     | 29.5                      | ...                                  | 62.0                        | 41.5                        | 98.0                          | ...                       | 80.0                      | 43.0                     | 107                 | 121             |
| 67                             | 95.0                     | 28.0                      | 82.5                                 | 61.5                        | 40.5                        | 97.5                          | ...                       | 79.0                      | 42.5                     | 106                 | 119             |
| 66                             | 94.5                     | 26.5                      | 82.0                                 | 60.5                        | 39.5                        | 97.0                          | ...                       | 78.0                      | 42.0                     | 104                 | 117             |
| 65                             | 94.0                     | 25.0                      | ...                                  | 60.0                        | 38.5                        | 96.0                          | ...                       | 77.5                      | ...                      | 102                 | 116             |
| 64                             | 93.5                     | 23.5                      | 81.5                                 | 59.5                        | 37.5                        | 95.5                          | ...                       | 76.5                      | 41.5                     | 101                 | 114             |
| 63                             | 93.0                     | 22.0                      | 81.0                                 | 58.5                        | 36.5                        | 95.0                          | ...                       | 75.5                      | 41.0                     | 99                  | 112             |
| 62                             | 92.0                     | 20.5                      | ...                                  | 58.0                        | 35.5                        | 94.5                          | ...                       | 74.5                      | 40.5                     | 98                  | 110             |
| 61                             | 91.5                     | 19.0                      | 80.5                                 | 57.0                        | 34.5                        | 93.5                          | ...                       | 74.0                      | 40.0                     | 96                  | 108             |
| 60                             | 91.0                     | 17.5                      | ...                                  | 56.5                        | 33.5                        | 93.0                          | ...                       | 73.0                      | 39.5                     | 95                  | 107             |
| 59                             | 90.5                     | 16.0                      | 80.0                                 | 56.0                        | 32.0                        | 92.5                          | ...                       | 72.0                      | 39.0                     | 94                  | 106             |
| 58                             | 90.0                     | 14.5                      | 79.5                                 | 55.0                        | 31.0                        | 92.0                          | ...                       | 71.0                      | 38.5                     | 92                  | ...             |
| 57                             | 89.5                     | 13.0                      | ...                                  | 54.5                        | 30.0                        | 91.0                          | ...                       | 70.5                      | 38.0                     | 91                  | ...             |
| 56                             | 89.0                     | 11.5                      | 79.0                                 | 54.0                        | 29.0                        | 90.5                          | ...                       | 69.5                      | ...                      | 90                  | ...             |
| 55                             | 88.0                     | 10.0                      | 78.5                                 | 53.0                        | 28.0                        | 90.0                          | ...                       | 68.5                      | 37.5                     | 89                  | ...             |
| 54                             | 87.5                     | 8.5                       | ...                                  | 52.5                        | 27.0                        | 89.5                          | ...                       | 68.0                      | 37.0                     | 87                  | ...             |
| 53                             | 87.0                     | 7.0                       | 78.0                                 | 51.5                        | 26.0                        | 89.0                          | ...                       | 67.0                      | 36.5                     | 86                  | ...             |
| 52                             | 86.5                     | 5.5                       | 77.5                                 | 51.0                        | 25.0                        | 88.0                          | ...                       | 66.0                      | 36.0                     | 85                  | ...             |
| 51                             | 86.0                     | 4.0                       | ...                                  | 50.5                        | 24.0                        | 87.5                          | ...                       | 65.0                      | 35.5                     | 84                  | ...             |
| 50                             | 85.5                     | 2.5                       | 77.0                                 | 49.5                        | 23.0                        | 87.0                          | ...                       | 64.5                      | 35.0                     | 83                  | ...             |
| 49                             | 85.0                     | 1.0                       | 76.5                                 | 49.0                        | 22.0                        | 86.5                          | ...                       | 63.5                      | ...                      | 82                  | ...             |

**Table 2. (Continued) Comparative Hardness Scales for Unhardened Steel, Soft-Temper Steel, Grey and Malleable Cast Iron, and Nonferrous Alloys**

| Rockwell Hardness Number       |                          |                           | Rockwell Superficial Hardness Number |                             |                             | Rockwell Hardness Number      |                           |                           | Brinell Hardness Number  |                     |                 |
|--------------------------------|--------------------------|---------------------------|--------------------------------------|-----------------------------|-----------------------------|-------------------------------|---------------------------|---------------------------|--------------------------|---------------------|-----------------|
| $\frac{1}{16}$ " Ball Indenter |                          |                           | $\frac{1}{16}$ " Ball Indenter       |                             |                             | $\frac{1}{8}$ " Ball Indenter |                           |                           | "Brale" Indenter         | 10-mm Standard Ball |                 |
| B scale<br>100-kg<br>Load      | F scale<br>60-kg<br>Load | G scale<br>150-kg<br>Load | 15-T scale<br>15-kg<br>Load          | 30-T scale<br>30-kg<br>Load | 45-T scale<br>45-kg<br>Load | E scale<br>100-kg<br>Load     | H scale<br>100-kg<br>Load | K scale<br>150-kg<br>Load | A scale<br>60-kg<br>Load | 500-kg<br>Load      | 3000-kg<br>Load |
| 48                             | 84.5                     | ...                       | ...                                  | 48.5                        | 20.5                        | 85.5                          | ...                       | 62.5                      | 34.5                     | 81                  | ...             |
| 47                             | 84.0                     | ...                       | 76.0                                 | 47.5                        | 19.5                        | 85.0                          | ...                       | 61.5                      | 34.0                     | 80                  | ...             |
| 46                             | 83.0                     | ...                       | 75.5                                 | 47.0                        | 18.5                        | 84.5                          | ...                       | 61.0                      | 33.5                     | ...                 | ...             |
| 45                             | 82.5                     | ...                       | ...                                  | 46.0                        | 17.5                        | 84.0                          | ...                       | 60.0                      | 33.0                     | 79                  | ...             |
| 44                             | 82.0                     | ...                       | 75.0                                 | 45.5                        | 16.5                        | 83.5                          | ...                       | 59.0                      | 32.5                     | 78                  | ...             |
| 43                             | 81.5                     | ...                       | 74.5                                 | 45.0                        | 15.5                        | 82.5                          | ...                       | 58.0                      | 32.0                     | 77                  | ...             |
| 42                             | 81.0                     | ...                       | ...                                  | 44.0                        | 14.5                        | 82.0                          | ...                       | 57.5                      | 31.5                     | 76                  | ...             |
| 41                             | 80.5                     | ...                       | 74.0                                 | 43.5                        | 13.5                        | 81.5                          | ...                       | 56.5                      | 31.0                     | 75                  | ...             |
| 40                             | 79.5                     | ...                       | 73.5                                 | 43.0                        | 12.5                        | 81.0                          | ...                       | 55.5                      | ...                      | ...                 | ...             |
| 39                             | 79.0                     | ...                       | ...                                  | 42.0                        | 11.0                        | 80.0                          | ...                       | 54.5                      | 30.5                     | 74                  | ...             |
| 38                             | 78.5                     | ...                       | 73.0                                 | 41.5                        | 10.0                        | 79.5                          | ...                       | 54.0                      | 30.0                     | 73                  | ...             |
| 37                             | 78.0                     | ...                       | 72.5                                 | 40.5                        | 9.0                         | 79.0                          | ...                       | 53.0                      | 29.5                     | 72                  | ...             |
| 36                             | 77.5                     | ...                       | ...                                  | 40.0                        | 8.0                         | 78.5                          | 100                       | 52.0                      | 29.0                     | ...                 | ...             |
| 35                             | 77.0                     | ...                       | 72.0                                 | 39.5                        | 7.0                         | 78.0                          | 99.5                      | 51.5                      | 28.5                     | 71                  | ...             |
| 34                             | 76.5                     | ...                       | 71.5                                 | 38.5                        | 6.0                         | 77.0                          | 99.0                      | 50.5                      | 28.0                     | 70                  | ...             |
| 33                             | 75.5                     | ...                       | ...                                  | 38.0                        | 5.0                         | 76.5                          | ...                       | 49.5                      | ...                      | 69                  | ...             |
| 32                             | 75.0                     | ...                       | 71.0                                 | 37.5                        | 4.0                         | 76.0                          | 98.5                      | 48.5                      | 27.5                     | ...                 | ...             |
| 31                             | 74.5                     | ...                       | ...                                  | 36.5                        | 3.0                         | 75.5                          | 98.0                      | 48.0                      | 27.0                     | 68                  | ...             |
| 30                             | 74.0                     | ...                       | 70.5                                 | 36.0                        | 2.0                         | 75.0                          | ...                       | 47.0                      | 26.5                     | 67                  | ...             |
| 29                             | 73.5                     | ...                       | 70.0                                 | 35.5                        | 1.0                         | 74.0                          | 97.5                      | 46.0                      | 26.0                     | ...                 | ...             |
| 28                             | 73.0                     | ...                       | ...                                  | 34.5                        | ...                         | 73.5                          | 97.0                      | 45.0                      | 25.5                     | 66                  | ...             |
| 27                             | 72.5                     | ...                       | 69.5                                 | 34.0                        | ...                         | 73.0                          | 96.5                      | 44.5                      | 25.0                     | ...                 | ...             |
| 26                             | 72.0                     | ...                       | 69.0                                 | 33.0                        | ...                         | 72.5                          | ...                       | 43.5                      | 24.5                     | 65                  | ...             |
| 25                             | 71.0                     | ...                       | ...                                  | 32.5                        | ...                         | 72.0                          | 96.0                      | 42.5                      | ...                      | 64                  | ...             |
| 24                             | 70.5                     | ...                       | 68.5                                 | 32.0                        | ...                         | 71.0                          | 95.5                      | 41.5                      | 24.0                     | ...                 | ...             |
| 23                             | 70.0                     | ...                       | 68.0                                 | 31.0                        | ...                         | 70.5                          | ...                       | 41.0                      | 23.5                     | 63                  | ...             |
| 22                             | 69.5                     | ...                       | ...                                  | 30.5                        | ...                         | 70.0                          | 95.0                      | 40.0                      | 23.0                     | ...                 | ...             |
| 21                             | 69.0                     | ...                       | 67.5                                 | 29.5                        | ...                         | 69.5                          | 94.5                      | 39.0                      | 22.5                     | 62                  | ...             |
| 20                             | 68.5                     | ...                       | ...                                  | 29.0                        | ...                         | 68.5                          | ...                       | 38.0                      | 22.0                     | ...                 | ...             |
| 19                             | 68.0                     | ...                       | 67.0                                 | 28.5                        | ...                         | 68.0                          | 94.0                      | 37.5                      | 21.5                     | 61                  | ...             |
| 18                             | 67.0                     | ...                       | 66.5                                 | 27.5                        | ...                         | 67.5                          | 93.5                      | 36.5                      | ...                      | ...                 | ...             |
| 17                             | 66.5                     | ...                       | ...                                  | 27.0                        | ...                         | 67.0                          | 93.0                      | 35.5                      | 21.0                     | 60                  | ...             |
| 16                             | 66.0                     | ...                       | 66.0                                 | 26.0                        | ...                         | 66.5                          | ...                       | 35.0                      | 20.5                     | ...                 | ...             |
| 15                             | 65.5                     | ...                       | 65.5                                 | 25.5                        | ...                         | 65.5                          | 92.5                      | 34.0                      | 20.0                     | 59                  | ...             |
| 14                             | 65.0                     | ...                       | ...                                  | 25.0                        | ...                         | 65.0                          | 92.0                      | 33.0                      | ...                      | ...                 | ...             |
| 13                             | 64.5                     | ...                       | 65.0                                 | 24.0                        | ...                         | 64.5                          | ...                       | 32.0                      | ...                      | 58                  | ...             |
| 12                             | 64.0                     | ...                       | 64.5                                 | 23.5                        | ...                         | 64.0                          | 91.5                      | 31.5                      | ...                      | ...                 | ...             |
| 11                             | 63.5                     | ...                       | ...                                  | 23.0                        | ...                         | 63.5                          | 91.0                      | 30.5                      | ...                      | ...                 | ...             |
| 10                             | 63.0                     | ...                       | 64.0                                 | 22.0                        | ...                         | 62.5                          | 90.5                      | 29.5                      | ...                      | 57                  | ...             |
| 9                              | 62.0                     | ...                       | ...                                  | 21.5                        | ...                         | 62.0                          | ...                       | 29.0                      | ...                      | ...                 | ...             |
| 8                              | 61.5                     | ...                       | 63.5                                 | 20.5                        | ...                         | 61.5                          | 90.0                      | 28.0                      | ...                      | ...                 | ...             |
| 7                              | 61.0                     | ...                       | 63.0                                 | 20.0                        | ...                         | 61.0                          | 89.5                      | 27.0                      | ...                      | 56                  | ...             |
| 6                              | 60.5                     | ...                       | ...                                  | 19.5                        | ...                         | 60.5                          | ...                       | 26.0                      | ...                      | ...                 | ...             |
| 5                              | 60.0                     | ...                       | 62.5                                 | 18.5                        | ...                         | 60.0                          | 89.0                      | 25.5                      | ...                      | 55                  | ...             |
| 4                              | 59.5                     | ...                       | 62.0                                 | 18.0                        | ...                         | 59.0                          | 88.5                      | 24.5                      | ...                      | ...                 | ...             |
| 3                              | 59.0                     | ...                       | ...                                  | 17.0                        | ...                         | 58.5                          | 88.0                      | 23.5                      | ...                      | ...                 | ...             |
| 2                              | 58.0                     | ...                       | 61.5                                 | 16.5                        | ...                         | 58.0                          | ...                       | 23.0                      | ...                      | 54                  | ...             |
| 1                              | 57.5                     | ...                       | 61.0                                 | 16.0                        | ...                         | 57.5                          | 87.5                      | 22.0                      | ...                      | ...                 | ...             |
| 0                              | 57.0                     | ...                       | ...                                  | 15.0                        | ...                         | 57.0                          | 87.0                      | 21.0                      | ...                      | 53                  | ...             |

Not applicable to annealed metals of high B-scale hardness such as austenitic stainless steels, nickel and high-nickel alloys nor to cold-worked metals of low B-scale hardness such as aluminum and the softer alloys. (Compiled by Wilson Mechanical Instrument Co.)

## NONFERROUS ALLOYS

## Strength Data for Nonferrous Metals

The ultimate tensile, shear, and yield strengths and moduli of elasticity of many nonferrous metals are given in Table 1. Values for the most part are given in ranges rather than as single values because of differences in composition, forms, sizes, and shapes for the aluminum alloys plus differences in heat treatments undergone for the other nonferrous metals. The values in the table are meant to serve as a guide, not as specifications. More specific data should be obtained from the supplier.

Table 1. Strength Data for Nonferrous Metals

| Material                  | Ultimate Strength, kpsi |          | Yield Strength, kpsi<br>(0.2% offset) | Modulus of Elasticity, 10 <sup>6</sup> psi |                    |
|---------------------------|-------------------------|----------|---------------------------------------|--|--------------------|
|                           | in Tension              | in Shear |                                       | in Tension, <i>E</i>                       | in Shear, <i>G</i> |
| Aluminum alloys, cast,    |                         |          |                                       |  |                    |
| sand-cast                 | 19 to 35                | 14 to 26 | 8 to 25                               | 10.3                                       | ...                |
| heat-treated              | 20 to 48                | 20 to 34 | 16 to 40                              | 10.3                                       | ...                |
| permanent-mold-cast,      | 23 to 35                | 16 to 27 | 9 to 24                               | 10.3                                       | ...                |
| heat-treated              | 23 to 48                | 15 to 36 | 8.5 to 43                             | 10.3                                       | ...                |
| die-cast                  | 30 to 46                | 19 to 29 | 16 to 27                              | 10.3                                       | ...                |
| Aluminum alloys, wrought, |                         |          |                                       |  |                    |
| annealed                  | 10 to 42                | 7 to 26  | 4 to 22                               | 10.0 to 10.6                               | ...                |
| cold-worked               | 12 to 63                | 8 to 34  | 11 to 59                              | 10.0 to 10.3                               | ...                |
| heat-treated              | 22 to 83                | 14 to 48 | 13 to 73                              | 10.0 to 11.4                               | ...                |
| Aluminum bronze, cast,    | 62 to 90                | ...      | 25 to 37                              | 15 to 18                                   | ...                |
| heat-treated              | 80 to 110               | ...      | 32 to 65                              | 15 to 18                                   | ...                |
| Aluminum bronze, wrought, |                         |          |                                       |  |                    |
| annealed                  | 55 to 80                | ...      | 20 to 40                              | 16 to 19                                   | ...                |
| cold-worked               | 71 to 110               | ...      | 62 to 66                              | 16 to 19                                   | ...                |
| heat-treated              | 101 to 151              | ...      | 48 to 94                              | 16 to 19                                   | ...                |
| Brasses, leaded, cast     | 32 to 40                | 29 to 31 | 12 to 15                              | 12 to 14                                   | ...                |
| flat products, wrought    | 46 to 85                | 31 to 45 | 14 to 62                              | 14 to 17                                   | 5.3 to 6.4         |
| wire, wrought             | 50 to 88                | 34 to 46 | ...                                   | 15   | 5.6                |
| Brasses, nonleaded,       |                         |          |                                       |  |                    |
| flat products, wrought    | 34 to 99                | 28 to 48 | 10 to 65                              | 15 to 17                                   | 5.6 to 6.4         |
| wire, wrought             | 40 to 130               | 29 to 60 | ...                                   | 15 to 17                                   | 5.6 to 6.4         |
| Copper, wrought,          |                         |          |                                       |  |                    |
| flat products             | 32 to 57                | 22 to 29 | 10 to 53                              | 17   | 6.4                |
| wire                      | 35 to 66                | 24 to 33 | ...                                   | 17   | 6.4                |
| Inconel, cast             | 70 to 95                | ...      | 30 to 45                              | 23   | ...                |
| flat products, wrought    | 80 to 170               | ...      | 30 to 160                             | 31   | 11                 |
| wire, wrought             | 80 to 185               | ...      | 25 to 175                             | 31   | 11                 |
| Lead                      | 2.2 to 4.9              | ...      | ...                                   | 0.8 to 2.0                                 | ...                |
| Magnesium, cast,          |                         |          |                                       |  |                    |
| sand & permanent mold     | 22 to 40                | 17 to 22 | 12 to 23                              | 6.5  | 2.4                |
| die-cast                  | 33                      | 20       | 22                                    | 6.5  | 2.4                |
| Magnesium, wrought        |                         |          |                                       |  |                    |
| sheet and plate           | 35 to 42                | 21 to 23 | 20 to 32                              | 6.5  | 2.4                |
| bars, rods, and shapes    | 37 to 55                | 19 to 27 | 26 to 44                              | 6.5  | 2.4                |
| Monel, cast               | 65 to 90                | ...      | 32 to 40                              | 19   | ...                |
| flat products, wrought    | 70 to 140               | ...      | 25 to 130                             | 26   | 9.5                |
| wire, wrought             | 70 to 170               | ...      | 25 to 160                             | 26   | 9.5                |
| Nickel, cast,             | 45 to 60                | ...      | 20 to 30                              | 21.5                                       | ...                |
| flat products, wrought    | 55 to 130               | ...      | 15 to 115                             | 30   | 11                 |
| wire, wrought             | 50 to 165               | ...      | 10 to 155                             | 30   | 11                 |
| Nickel silver, cast       | 40 to 50                | ...      | 24 to 25                              | ...  | ...                |
| flat products, wrought    | 49 to 115               | 41 to 59 | 18 to 90                              | 17.5 to 18                                 | 6.6 to 6.8         |
| wire, wrought             | 50 to 145               | ...      | 25 to 90                              | 17.5 to 18                                 | 6.6 to 6.8         |
| Phosphor bronze, wrought  |                         |          |                                       |  |                    |
| flat products             | 40 to 128               | ...      | 14 to 80                              | 15 to 17                                   | 5.6 to 6.4         |
| wire                      | 50 to 147               | ...      | 20 to 80                              | 16 to 17                                   | 6 to 6.4           |
| Silicon bronze, wrought,  |                         |          |                                       |  |                    |
| flat products             | 56 to 110               | 42 to 63 | 21 to 62                              | 15   | 5.6                |
| wire                      | 50 to 145               | 36 to 70 | 25 to 70                              | 15 to 17                                   | 5.6 to 6.4         |
| Tin bronze, leaded, cast  | 21 to 38                | 23 to 43 | 15 to 18                              | 10 to 14.5                                 | ...                |
| Titanium                  | 50 to 135               | ...      | 40 to 120                             | 15.0 to 16.5                               | ...                |
| Zinc, commercial rolled   | 19.5 to 31              | ...      | ...                                   | ...  | ...                |
| Zirconium                 | 22 to 83                | ...      | ...                                   | 9 to 14.5                                  | 4.8                |

Consult the index for data on metals not listed and for more data on metals listed.

### Copper and Copper Alloys

Pure copper is a reddish, highly malleable metal, and was one of the first to be found and utilized. Copper and its alloys are widely used because of their excellent electrical and thermal conductivities, outstanding resistance to corrosion, ease of fabrication, and broad ranges of obtainable strengths and special properties. Almost 400 commercial copper and copper-alloy compositions are available from mills as wrought products (rod, plate, sheet, strip, tube, pipe, extrusions, foil, forgings, and wire) and from foundries as castings.

Copper alloys are grouped into several general categories according to composition:

- coppers and high-copper alloys
- brasses
- bronzes
- copper nickels
- copper–nickel–zinc alloys (nickel silvers)
- leaded coppers
- special alloys

The designation system originally developed by the U.S. copper and brass industry for identifying copper alloys used a three-digit number preceded by the letters CA. These designations have now been made part of the Unified Numbering System (UNS) simply by expanding the numbers to five digits preceded by the letter C. Because the old numbers are embedded in the new UNS numbers, no confusion results. UNS C10000 to C79999 are assigned to wrought compositions, and UNS C80000 to C99999 are assigned to castings. The designation system is not a specification, but a method for identifying the composition of mill and foundry products. The precise technical and quality assurance requirements to be satisfied are defined in relevant standard specifications issued by the federal government, the military, and the ASTM.

#### Classification of Copper and Copper Alloys

| Family                         | Principal Alloying Element | UNS Numbers <sup>a</sup>                    |
|--------------------------------|----------------------------|---|
| Coppers, high-copper alloys    |                            | C1xxxx                                      |
| Brasses                        | Zn                         | C2xxxx, C3xxxx, C4xxxx,<br>C66400 to C69800 |
| Phosphor bronzes               | Sn                         | C5xxxx                                      |
| Aluminum bronzes               | Al                         | C60600 to C64200                            |
| Silicon bronzes                | Si                         | C64700 to C66100                            |
| Copper nickels, nickel silvers | Ni                         | C7xxxx                                      |

<sup>a</sup> Wrought alloys.

**Cast Copper Alloys.**—Generally, casting permits greater latitude in the use of alloying elements than in the fabrication of wrought products, which requires either hot or cold working. The cast compositions of coppers and high-copper alloys have a designated minimum copper content and may include other elements to impart special properties. The cast brasses comprise copper–zinc–tin alloys (red, semired, and yellow brasses); manganese bronze alloys (high-strength yellow brasses); leaded manganese bronze alloys (leaded high-strength yellow brasses); and copper–zinc–silicon alloys (silicon brasses and bronzes).

The cast bronze alloys have four main families: copper–tin alloys (tin bronzes); copper–tin–lead alloys (leaded and high leaded tin bronzes); copper–tin–nickel alloys (nickel–tin bronzes); and copper–aluminum alloys (aluminum bronzes).

The cast copper–nickel alloys contain nickel as the principal alloying element. The leaded coppers are cast alloys containing 20 per cent or more lead.

Table 2 lists the properties and applications of common cast copper alloys.



**Table 2. Properties and Applications of Cast Coppers and Copper Alloys**

| UNS Designation    | Nominal Composition (%)                                      | Typical Mechanical Properties, as Cast or Heat Treated <sup>a</sup> |                      |                         |                                   | Typical Applications   |
|--------------------|--|---|----------------------|-------------------------|-----------------------------------|--|
|                    |  | Tensile Strength (ksi)  | Yield Strength (ksi) | Elongation in 2 in. (%) | Machinability Rating <sup>b</sup> |  |
| Copper Alloys      |  |   |                      |                         |                                   |  |
| C80100             | 99.95 Cu + Ag min, 0.05 others max                           | 25  | 9                    | 40                      | 10                                | Electrical and thermal conductors; corrosion and oxidation-resistant applications.   |
| C80300             | 99.95 Cu + Ag min, 0.034 Ag min, 0.05 others max             | 25  | 9                    | 40                      | 10                                | Electrical and thermal conductors; corrosion and oxidation-resistant applications.   |
| C80500             | 99.75 Cu + Ag min, 0.034 Ag min, 0.02 B max, 0.23 others max | 25  | 9                    | 40                      | 10                                | Electrical and thermal conductors; corrosion and oxidation-resistant applications.   |
| C80700             | 99.75 Cu + Ag min, 0.02 B max, 0.23 others max               | 25  | 9                    | 40                      | 10                                | Electrical and thermal conductors; corrosion and oxidation-resistant applications.   |
| C80900             | 99.70 Cu + Ag min, 0.034 Ag min, 0.30 others max             | 25  | 9                    | 40                      | 10                                | Electrical and thermal conductors; corrosion and oxidation-resistant applications.   |
| C81100             | 99.70 Cu + Ag min, 0.30 others max                           | 25  | 9                    | 40                      | 10                                | Electrical and thermal conductors; corrosion and oxidation resistant applications.   |
| High-Copper Alloys |  |   |                      |                         |                                   |  |
| C81300             | 98.5 Cu min, 0.06 Be, 0.80 Co, 0.40 others max               | (53)  | (36)                 | (11)                    | 20                                | Higher hardness electrical and thermal conductors.   |
| C81400             | 98.5 Cu min, 0.06 Be, 0.80 Cr, 0.40 others max               | (53)  | (36)                 | (11)                    | 20                                | Higher hardness electrical and thermal conductors.   |
| C81500             | 98.0 Cu min, 1.0 Cr, 0.50 others max                         | (51)  | (40)                 | (17)                    | 20                                | Electrical and/or thermal conductors used as structural members where strength and hardness greater than that of C80100-81100 are required.  |
| C81700             | 94.2 Cu min, 1.0 Ag, 0.4 Be, 0.9 Co, 0.9 Ni                  | (92)  | (68)                 | (8)                     | 30                                | Electrical and/or thermal conductors used as structural members where strength and hardness greater than that of C80100-81100 are required. Also used in place of C81500 where electrical and/or thermal conductivities can be sacrificed for hardness and strength. |
| C81800             | 95.6 Cu min, 1.0 Ag, 0.4 Be, 1.6 Co                          | 50 (102)  | 25 (75)              | 20 (8)                  | 20                                | Resistance-welding electrodes, dies.   |
| C82000             | 96.8 Cu, 0.6 Be, 2.6 Co                                      | 50 (100)  | 20 (75)              | 20 (8)                  | 20                                | Current-carrying parts, contact and switch blades, bushings and bearings, and soldering iron and resistance-welding tips.  |
| C82100             | 97.7 Cu, 0.5 Be, 0.9 Co, 0.9 Ni                              | (92)  | (68)                 | (8)                     | 30                                | Electrical and/or thermal conductors used as structural members where strength and hardness greater than that of C80100-81100 are required. Also used in place of C81500 where electrical and/or thermal conductivities can be sacrificed for hardness and strength. |
| C82200             | 96.5 Cu min, 0.6 Be, 1.5 Ni                                  | 57 (95)   | 30 (75)              | 20 (8)                  | 20                                | Clutch rings, brake drums, seam-welder electrodes, projection welding dies, spot-welding tips, beam-welder shapes, bushings, water-cooled holders.   |
| C82400             | 96.4 Cu min, 1.70 Be, 0.25 Co                                | 72 (150)  | 37 (140)             | 20 (1)                  | 20                                | Safety tools, molds for plastic parts, cams, bushings, bearings, valves, pump parts, gears.  |
| C82500             | 97.2 Cu, 2.0 Be, 0.5 Co, 0.25 Si                             | 80 (160)  | 45                   | 20 (1)                  | 20                                | Safety tools, molds for plastic parts, cams, bushings, bearings, valves, pump parts.   |
| C82600             | 95.2 Cu min, 2.3 Be, 0.5 Co, 0.25 Si                         | 82 (165)  | 47 (155)             | 20 (1)                  | 20                                | Bearings and molds for plastic parts.  |
| C82700             | 96.3 Cu, 2.45 Be, 1.25 Ni                                    | (155)   | (130)                | (0)                     | 20                                | Bearings and molds for plastic parts.  |
| C82800             | 96.6 Cu, 2.6 Be, 0.5 Co, 0.25 Si                             | 97 (165)  | 55 (145)             | 20 (1)                  | 10                                | Molds for plastic parts, cams, bushings, bearings, valves, pump parts, sleeves.  |

**Table 2. (Continued) Properties and Applications of Cast Coppers and Copper Alloys**

| UNS Designation                                     | Nominal Composition (%)            | Typical Mechanical Properties, as Cast or Heat Treated <sup>a</sup> |                      |                         |                                   | Typical Applications  |
|---|------------------------------------|---|----------------------|-------------------------|-----------------------------------|---|
|   |                                    | Tensile Strength (ksi)  | Yield Strength (ksi) | Elongation in 2 in. (%) | Machinability Rating <sup>b</sup> |   |
| <b>Red Brasses and Leaded Red Brasses</b>           |                                    |   |                      |                         |                                   |   |
| C83300  | 93 Cu, 1.5 Sn, 1.5 Pb, 4 Zn        | 32  | 10                   | 35                      | 35                                | Terminal ends for electrical cables.  |
| C83400  | 90 Cu, 10 Zn                       | 35  | 10                   | 30                      | 60                                | Moderate strength, moderate conductivity castings; rotating bands.  |
| C83600  | 85 Cu, 5 Sn, 5 Pb, 5 Zn            | 37  | 17                   | 30                      | 84                                | Valves, flanges, pipe fittings, plumbing goods, pump castings, water pump impellers and housings, ornamental fixtures, small gears.   |
| C83800  | 83 Cu, 4 Sn, 6 Pb, 7 Zn            | 35  | 16                   | 25                      | 90                                | Low-pressure valves and fittings, plumbing supplies and fittings, general hardware, air-gas-water fittings, pump components, railroad catenary fittings.                                      |
| <b>Semired Brasses and Leaded Semired Brasses</b>   |                                    |   |                      |                         |                                   |   |
| C84200  | 80 Cu, 5 Sn, 2.5 Pb, 12.5 Zn       | 35  | 14                   | 27                      | 80                                | Pipe fittings, elbows, T's, couplings, bushings, locknuts, plugs, unions.   |
| C84400  | 81 Cu, 3 Sn, 7 Pb, 9 Zn            | 34  | 15                   | 26                      | 90                                | General hardware, ornamental castings, plumbing supplies and fixtures, low-pressure valves and fittings.  |
| C84500  | 78 Cu, 3 Sn, 7 Pb, 12 Zn           | 35  | 14                   | 28                      | 90                                | Plumbing fixtures, cocks, faucets, stops, waste, air and gas fittings, low-pressure valve fittings.   |
| C84800  | 76 Cu, 3 Sn, 6 Pb, 15 Zn           | 36  | 14                   | 30                      | 90                                | Plumbing fixtures, cocks, faucets, stops, waste, air, and gas, general hardware, and low-pressure valve fittings.   |
| <b>Yellow Brasses and Leaded Yellow Brasses</b>     |                                    |   |                      |                         |                                   |   |
| C85200  | 72 Cu, 1 Sn, 3 Pb, 24 Zn           | 38  | 13                   | 35                      | 80                                | Plumbing fittings and fixtures, ferrules, valves, hardware, ornamental brass, chandeliers, and irons.   |
| C85400  | 67 Cu, 1 Sn, 3 Pb, 29 Zn           | 34  | 12                   | 35                      | 80                                | General-purpose yellow casting alloy not subject to high internal pressure. Furniture hardware, ornamental castings, radiator fittings, ship trimmings, battery clamps, valves, and fittings. |
| C85500  | 61 Cu, 0.8 Al, bal Zn              | 60  | 23                   | 40                      | 80                                | Ornamental castings.  |
| C85700  | 63 Cu, 1 Sn, 1 Pb, 34.7 Zn, 0.3 Al | 50  | 18                   | 40                      | 80                                | Bushings, hardware fittings, ornamental castings.   |
| C85800  | 58 Cu, 1 Sn, 1 Pb, 40 Zn           | 55  | 30                   | 15                      | 80                                | General-purpose die-casting alloy having moderate strength.   |
| <b>Manganese and Leaded Manganese Bronze Alloys</b> |                                    |   |                      |                         |                                   |   |
| C86100  | 67 Cu, 21 Zn, 3 Fe, 5 Al, 4 Mn     | 95  | 50                   | 20                      | 30                                | Marine castings, gears, gun mounts, bushings and bearings, marine racing propellers.  |
| C86200  | 64 Cu, 26 Zn, 3 Fe, 4 Al, 3 Mn     | 95  | 48                   | 20                      | 30                                | Marine castings, gears, gun mounts, bushings and bearings.  |
| C86300  | 63 Cu, 25 Zn, 3 Fe, 6 Al, 3 Mn     | 115   | 83                   | 15                      | 8                                 | Extra-heavy duty, high-strength alloy. Large valve stems, gears, cams, slow-speed heavy-load bearings, screwdown nuts, hydraulic cylinder-parts.  |
| C86400  | 59 Cu, 1 Pb, 40 Zn                 | 65  | 25                   | 20                      | 65                                | Free-machining manganese bronze. Valve stems, marine fittings, lever arms, brackets, light-duty gears.  |
| C86500  | 58 Cu, 0.5 Sn, 39.5 Zn, 1 Fe, 1 Al | 71  | 28                   | 30                      | 26                                | Machinery parts requiring strength and toughness, lever arms, valve stems, gears.   |
| C86700  | 58 Cu, 1 Pb, 41 Zn                 | 85  | 42                   | 20                      | 55                                | High strength, free-machining manganese bronze. Valve stems.  |
| C86800  | 55 Cu, 37 Zn, 3 Ni, 2 Fe, 3 Mn     | 82  | 38                   | 22                      | 30                                | Marine fittings, marine propellers.   |
| <b>Silicon Bronzes and Silicon Brasses</b>          |                                    |   |                      |                         |                                   |   |
| C87200  | 89 Cu min, 4 Si                    | 55  | 25                   | 30                      | 40                                | Bearings, bells, impellers, pump and valve components, marine fittings, corrosion-resistant castings.   |
| C87400  | 83 Cu, 14 Zn, 3 Si                 | 55  | 24                   | 30                      | 50                                | Bearings, gears, impellers, rocker arms, valve stems, clamps.   |

**Table 2. (Continued) Properties and Applications of Cast Coppers and Copper Alloys**

| UNS Designation         | Nominal Composition (%)                   | Typical Mechanical Properties, as Cast or Heat Treated <sup>a</sup> |                      |                         |                                   | Typical Applications   |
|-------------------------|---|---|----------------------|-------------------------|-----------------------------------|--|
|                         |   | Tensile Strength (ksi)  | Yield Strength (ksi) | Elongation in 2 in. (%) | Machinability Rating <sup>b</sup> |  |
| C87500                  | 82 Cu, 14 Zn, 4 Si                        | 67  | 30                   | 21                      | 50                                | Bearings, gears, impellers, rocker arms, valve stems, small boat proellers.  |
| C87600                  | 90 Cu, 5.5 Zn, 4.5 Si                     | 66  | 32                   | 20                      | 40                                | Valve stems.   |
| C87800                  | 82 Cu, 14 Zn, 4 Si                        | 85  | 50                   | 25                      | 40                                | High-strength, thin-wall die castings; brush holders, lever arms, brackets, clamps, hexagonal nuts.                              |
| C87900                  | 65 Cu, 34 Zn, 1 Si                        | 70  | 35                   | 25                      | 80                                | General-purpose die-casting alloy having moderate strength.  |
| Tin Bronzes             |   |   |                      |                         |                                   |  |
| C90200                  | 93 Cu, 7 Sn                               | 38  | 16                   | 30                      | 20                                | Bearings and bushings.   |
| C90300                  | 88 Cu, 8 Sn, 4 Zn                         | 45  | 21                   | 30                      | 30                                | Bearings, bushings, pump impellers, piston rings, valve components, seal rings, steam fittings, gears.                           |
| C90500                  | 88 Cu, 10 Sn, 2 Zn                        | 45  | 22                   | 25                      | 30                                | Bearings, bushings, pump impellers, piston rings, valve components, steam fittings, gears.                                       |
| C90700                  | 89 Cu, 11 Sn                              | 44 (55)   | 22 (30)              | 20 (16)                 | 20                                | Gears, bearings, bushings.   |
| C90900                  | 87 Cu, 13 Sn                              | 40  | 20                   | 15                      | 20                                | Bearings and bushings.   |
| C91000                  | 85 Cu, 14 Sn, 1 Zn                        | 32  | 25                   | 2                       | 20                                | Piston rings and bearings.   |
| C91100                  | 84 Cu, 16 Sn                              | 35  | 25                   | 2                       | 10                                | Piston rings, bearings, bushings, bridge plates.   |
| C91300                  | 81 Cu, 19 Sn                              | 35  | 30                   | 0.5                     | 10                                | Piston rings, bearings, bushings, bridge plates, bells.  |
| C91600                  | 88 Cu, 10.5 Sn, 1.5 Ni                    | 44 (60)   | 22 (32)              | 16 (16)                 | 20                                | Gears.   |
| C91700                  | 86.5 Cu, 12 Sn, 1.5 Ni                    | 44 (60)   | 22 (32)              | 16 (16)                 | 20                                | Gears.   |
| Leaded Tin Bronzes      |   |   |                      |                         |                                   |  |
| C92200                  | 88 Cu, 6 Sn, 1.5 Pb, 4.5 Zn               | 40  | 20                   | 30                      | 42                                | Valves, fittings, and pressure-containing parts for use up to 550°F.   |
| C92300                  | 87 Cu, 8 Sn, 4 Zn                         | 40  | 20                   | 25                      | 42                                | Valves, pipe fittings, and high-pressure steam castings. Superior machinability to C90300.                                       |
| C92500                  | 87 Cu, 11 Sn, 1 Pb, 1 Ni                  | 44  | 20                   | 20                      | 30                                | Gears, automotive synchronizer rings.  |
| C92600                  | 87 Cu, 10 Sn, 1 Pb, 2 Zn                  | 44  | 20                   | 30                      | 40                                | Bearings, bushings, pump impellers, piston rings, valve components, steam fittings, and gears. Superior machinability to C90500. |
| C92700                  | 88 Cu, 10 Sn, 2 Pb                        | 42  | 21                   | 20                      | 45                                | Bearings, bushings, pump impellers, piston rings, and gears. Superior machinability to C90500.                                   |
| C92800                  | 79 Cu, 16 Sn, 5 Pb                        | 40  | 30                   | 1                       | 70                                | Piston rings.  |
| C92900                  | 82 Cu min, 9 Sn min, 2 Pb min, 2.8 Ni min | 47 (47)   | 26 (26)              | 20 (20)                 | 40                                | Gears, wear plates, guides, cams, parts requiring machinability superior to that of C91600 or 91700.                             |
| High-Leaded Tin Bronzes |   |   |                      |                         |                                   |  |
| C93200                  | 83 Cu, 6.3 Sn min, 7 Pb, 3 Zn             | 35  | 18                   | 20                      | 70                                | General-utility bearings and bushings.   |
| C93400                  | 84 Cu, 8 Sn, 8 Pb                         | 32  | 16                   | 20                      | 70                                | Bearings and bushings.   |
| C93500                  | 85 Cu, 5 Sn, 9 Pb                         | 32  | 16                   | 20                      | 70                                | Small bearings and bushings, bronze backing for rabbit-lined automotive bearings.  |
| C93700                  | 80 Cu, 10 Sn, 10 Pb                       | 35  | 18                   | 20                      | 80                                | Bearings for high speed and heavy pressures, pumps, impellers, corrosion-resistant applications, pressure tight castings.        |
| C93800                  | 78 Cu, 7 Sn, 15 Pb                        | 30  | 16                   | 18                      | 80                                | Bearings for general service and moderate pressure, pump impellers, and bodies for use in acid mine water.                       |
| C93900                  | 79 Cu, 6 Sn, 15 Pb                        | 32  | 22                   | 7                       | 80                                | Continuous castings only. Bearings for general service, pump bodies, and impellers for mine waters.                              |
| C94300                  | 70 Cu, 5 Sn, 25 Pb                        | 27  | 13                   | 15                      | 80                                | High-speed bearings for light loads.   |
| C94400                  | 81 Cu, 8 Sn, 11 Pb, 0.35 P                | 32  | 16                   | 18                      | 80                                | General-utility alloy for bushings and bearings.   |
| C94500                  | 73 Cu, 7 Sn, 20 Pb                        | 25  | 12                   | 12                      | 80                                | Locomotive wearing parts; high-low, low-speed bearings.  |

**Table 2. (Continued) Properties and Applications of Cast Coppers and Copper Alloys**

| UNS Designation    | Nominal Composition (%)                         | Typical Mechanical Properties, as Cast or Heat Treated <sup>a</sup> |                      |                         |                                   | Typical Applications  |
|--------------------|---|---|----------------------|-------------------------|-----------------------------------|---|
|                    |   | Tensile Strength (ksi)  | Yield Strength (ksi) | Elongation in 2 in. (%) | Machinability Rating <sup>b</sup> |   |
| Nickel-Tin Bronzes |   |   |                      |                         |                                   |   |
| C94700             | 88 Cu, 5 Sn, 2 Zn, 5 Ni                         | 50 (85)   | 23 (60)              | 35 (10)                 | 30 (20)                           | Valve stems and bodies, bearings, wear guides, shift forks, feeding mechanisms, circuit breaker parts, gears, piston cylinders, nozzles.                      |
| C94800             | 87 Cu, 5 Sn, 5 Ni                               | 45 (60)   | 23 (30)              | 35 (8)                  | 50 (40)                           | Structural castings, gear components, motion-translation devices, machinery parts, bearings.  |
| Aluminum Bronzes   |   |   |                      |                         |                                   |   |
| C95200             | 88 Cu, 3 Fe, 9 Al                               | 80  | 27                   | 35                      | 50                                | Acid-resisting pumps, bearing, gears, valve seats, guides, plungers, pump rods, bushings.   |
| C95300             | 89 Cu, 1 Fe, 10 Al                              | 75 (85)   | 27 (42)              | 25 (15)                 | 55                                | Pickling baskets, nuts, gears, steel mill slippers, marine equipment, welding jaws.   |
| C95400             | 85 Cu, 4 Fe, 11 Al                              | 85 (105)  | 35 (54)              | 18 (8)                  | 60                                | Bearings, gears, worms, bushings, valve seats and guides, pickling hooks.   |
| C95500             | 81 Cu, 4 Ni, 4 Fe, 11 Al                        | 100 (120)   | 44 (68)              | 12 (10)                 | 50                                | Valve guides and seats in aircraft engines, corrosion-resistant parts, bushings, gears, worms, pickling hooks and baskets, agitators.                         |
| C95600             | 91 Cu, 7 Al, 2 Si                               | 75  | 34                   | 18                      | 60                                | Cable connectors, terminals, valve stems, marine hardware, gears, worms, pole-line hardware.  |
| C95700             | 75 Cu, 2 Ni, 3 Fe, 8 Al, 12 Mn                  | 95  | 45                   | 26                      | 50                                | Propellers, impellers, stator clamp segments, safety tools, welding rods, valves, pump casings.   |
| C95800             | 81 Cu, 5 Ni, 4 Fe, 9 Al, 1 Mn                   | 95  | 38                   | 25                      | 50                                | Propeller hubs, blades, and other parts in contact with salt water.   |
| Copper-Nickels     |   |   |                      |                         |                                   |   |
| C96200             | 88.6 Cu, 10 Ni, 1.4 Fe                          | 45 min  | 25 min               | 20 min                  | 10                                | Components of items being used for seawater corrosion resistance.   |
| C96300             | 79.3 Cu, 20 Ni, 0.7 Fe                          | 75 min  | 55 min               | 10 min                  | 15                                | Centrifugally cast tailshaft sleeves.   |
| C96400             | 69.1 Cu, 30 Ni, 0.9 Fe                          | 68  | 37                   | 28                      | 20                                | Valves, pump bodies, flanges, elbows used for seawater corrosion resistance.  |
| C96600             | 68.5 Cu, 30 Ni, 1 Fe, 0.5 Be                    | (110)   | (70)                 | (7)                     | 20                                | High-strength constructional parts for seawater corrosion resistance.   |
| Nickel Silvers     |   |   |                      |                         |                                   |   |
| C97300             | 56 Cu, 2 Sn, 10 Pb, 12 Ni, 20 Zn                | 35  | 17                   | 20                      | 70                                | Hardware fittings, valves and valve trim, statuary, ornamental castings.  |
| C97400             | 59 Cu, 3 Sn, 5 Pb, 17 Ni, 16 Zn                 | 38  | 17                   | 20                      | 60                                | Valves, hardware, fittings, ornamental castings.  |
| C97600             | 64 Cu, 4 Sn, 4 Pb, 20 Ni, 8 Zn                  | 45  | 24                   | 20                      | 70                                | Marine castings, sanitary fittings, ornamental hardware, valves, pumps.   |
| C97800             | 66 Cu, 5 Sn, 2 Pb, 25 Ni, 2 Zn                  | 55  | 30                   | 15                      | 60                                | Ornamental and sanitary castings, valves and valve seats, musical instrument components.  |
| Special Alloys     |   |   |                      |                         |                                   |   |
| C99300             | 71.8 Cu, 15 Ni, 0.7 Fe, 11 Al, 1.5 Co           | 95  | 55                   | 2                       | 20                                | Glass-making molds, plate glass rolls, marine hardware.   |
| C99400             | 90.4 Cu, 2.2 Ni, 2.0 Fe, 1.2 Al, 1.2 Si, 3.0 Zn | 66 (79)   | 34 (54)              | 25                      | 50                                | Valve stems, marine and other uses requiring resistance to dezincification and dealuminification, propeller wheels, electrical parts, mining equipment gears. |
| C99500             | 87.9 Cu, 4.5 Ni, 4.0 Fe, 1.2 Al, 1.2 Si, 1.2 Zn | 70 min  | 40 min               | 12 min                  | 50                                | Same as C99400, but where higher yield strength is required.  |
| C99700             | 56.5 Cu, Al, 1.5 Pb, 12 Mn, 5 Ni, 24 Zn         | 55  | 25                   | 25                      | 80                                | ...   |
| C99750             | 58 Cu, 1 Al, 1 Pb, 20 Mn, 20 Zn                 | 65 (75)   | 32 (40)              | 30 (20)                 | ...                               | ...   |

<sup>a</sup> Values in parentheses are for heat-treated condition.<sup>b</sup> Free cutting brass = 100.

Source: Copper Development Association, New York.

**Wrought Copper Alloys.**—Wrought copper alloys can be utilized in the annealed, cold-worked, stress-relieved, or hardened-by-heat-treatment conditions, depending on composition and end use. The “temper designation” for copper alloys is defined in ASTM Standard Recommended Practice B601, which is applicable to all product forms.

Wrought copper and high-copper alloys, like cast alloys, have a designated minimum copper content and may include other elements to impart special properties. Wrought brasses have zinc as the principal alloying element and may have other designated elements. They comprise the copper–zinc alloys; copper–zinc–lead alloys (leaded brasses); and copper–zinc–tin alloys (tin brasses).

Wrought bronzes comprise four main groups; copper–tin–phosphorus alloys (phosphor bronze); copper–tin–lead–phosphorus alloys (leaded phosphor bronze); copper–aluminum alloys (aluminum bronzes); and copper–silicon alloys (silicon bronze).

Wrought copper–nickel alloys, like the cast alloys, have nickel as the principal alloying element. The wrought copper–nickel–zinc alloys are known as “nickel silvers” because of their color.

Table 3 lists the nominal composition, properties, and applications of common wrought copper alloys.

**Table 3. Properties and Applications of Wrought Coppers and Copper Alloys**

| Name and Number  | Nominal Composition (%)         | Strength (ksi) |       | Elongation in 2 in. (%) | Machinability Rating <sup>a</sup> | Fabricating Characteristics and Typical Applications   |
|--|---------------------------------|----------------|-------|-------------------------|-----------------------------------|--|
|  |                                 | Tensile        | Yield |                         |                                   |  |
| C10100<br>Oxygen-free electronic                                       | 99.99 Cu                        | 32–66          | 10–53 | 55                      | 20                                | Excellent hot and cold workability; good forgeability. Fabricated by blanking, coining, copper-smithing, drawing and upsetting, hot forging and pressing, spinning, swaging, stamping. Uses: busbars, bus conductors, waveguides, hollow conductors, lead-in wires and anodes for vacuum tubes, vacuum seals, transistor components, glass to metal seals, coaxial cables and tubes, klystrons, microwave tubes, rectifiers. |
| C10200<br>Oxygen-free copper   | 99.95 Cu                        | 32–66          | 10–53 | 55                      | 20                                | Fabricating characteristics same as C10100. Uses: busbars, waveguides.   |
| C10300<br>Oxygen-free, extra-low phosphorus                            | 99.95 Cu,<br>0.003 P            | 32–55          | 10–50 | 50                      | 20                                | Fabricating characteristics same as C10100. Uses: busbars, electrical conductors, tubular bus, and applications requiring good conductivity and welding or brazing properties.   |
| C10400, C10500,<br>C10700<br>Oxygen-free, silver-bearing               | 99.95 Cu                        | 32–66          | 10–53 | 55                      | 20                                | Fabricating characteristics same as C10100. Uses: auto gaskets, radiators, busbars, conductivity wire, contacts, radio parts, winding, switches, terminals, commutator segments; chemical process equipment, printing rolls, clad metals, printed-circuit foil.  |
| C10800<br>Oxygen-free, low phosphorus                                  | 99.95 Cu,<br>0.009 P            | 32–55          | 10–50 | 50                      | 20                                | Fabricating characteristics same as C10100. Uses: refrigerators, air conditioners, gas and heater lines, oil burner tubes, plumbing pipe and tube, brewery tubes, condenser and heat-exchanger tubes, dairy and distiller tubes, pulp and paper lines, tanks; air, gasoline, and hydraulic lines.  |
| C11000<br>Electrolytic tough pitch copper                              | 99.90 Cu,<br>0.04 O             | 32–66          | 10–53 | 55                      | 20                                | Fabricating characteristics same as C10100. Uses: downspouts, gutters, roofing, gaskets, auto radiators, busbars, nails, printing rolls, rivets, radio parts.  |
| C11000<br>Electrolytic tough pitch, anneal-resistant                   | 99.90 Cu,<br>0.04 O,<br>0.01 Cd | 66             | ...   | ...                     | 20                                | Fabricated by drawing and stranding, stamping. Uses: electrical power transmission where resistance to softening under overloads is desired.   |
| C11300,<br>C11400, C11500,<br>C11600 Silver-bearing tough pitch copper | 99.90 Cu,<br>0.04 O,<br>Ag      | 32–66          | 10–53 | 55                      | 20                                | Fabricating characteristics same as C10100. Uses: gaskets, radiators, busbars, windings, switches, chemical process equipment, clad metals, printed-circuit foil.  |

**Table 3. (Continued) Properties and Applications of Wrought Coppers and Copper Alloys**

| Name and Number   | Nominal Composition (%)                         | Strength (ksi) |       | Elongation in 2 in. (%) | Machinability Rating <sup>a</sup> | Fabricating Characteristics and Typical Applications   |
|---|---|----------------|-------|-------------------------|-----------------------------------|--|
|   |   | Tensile        | Yield |                         |                                   |  |
| C12000, C12100<br>Phosphorus deoxidized, low residual phosphorus                  | 99.9 Cu   | 32-57          | 10-53 | 55                      | 20                                | Fabricating characteristics same as C10100. Uses: busbars, electrical conductors, tubular bus, and applications requiring welding or brazing.  |
| C12200, C12210<br>Phosphorus deoxidized copper, high residual phosphorus          | 99.90 Cu,<br>0.02 P                             | 32-55          | 10-53 | 55                      | 20                                | Fabricating characteristics same as C10100. Uses: gas and heater lines; oil burner tubing; plumbing pipe and tubing; condenser, evaporator, heat exchanger, dairy, and distiller tubing; steam and water lines; air, gasoline, and hydraulic lines.  |
| C12500, C12700,<br>C12800, C12900,<br>C13000 Fire-refined tough pitch with silver | 99.88 Cu  | 32-66          | 10-53 | 55                      | 20                                | Fabricating characteristics same as C10100. Uses: same as C11000, Electrolytic tough pitch copper.   |
| C14200<br>Phosphorus deoxidized, arsenical  | 99.68 Cu,<br>0.3 As,<br>0.02 P                  | 32-55          | 10-50 | 45                      | 20                                | Fabricating characteristics same as C10100. Uses: staybolts, heat-exchanger and condenser tubes.   |
| C14300, C14310<br>Cadmium copper, deoxidized                                      | 99.9 Cu,<br>0.1 Cd                              | 32-58          | 11-56 | 42                      | 20                                | Fabricating characteristics same as C10100. Uses: anneal-resistant electrical applications requiring thermal softening and embrittlement resistance, lead frames, contacts, terminals, solder-coated and solder-fabricated parts, furnace-brazed assemblies and welded components, cable wrap.   |
| C14500, C14510,<br>C14520<br>Tellurium bearing                                    | 99.5 Cu,<br>0.50 Te,<br>0.008 P                 | 32-56          | 10-51 | 50                      | 85                                | Fabricating characteristics same as C10100. Uses: Forgings and screw-machine products, and parts requiring high conductivity, extensive machining, corrosion resistance, copper color, or a combination of these; electrical connectors, motor and switch parts, plumbing fittings, soldering coppers, welding torch tips, transistor bases, and furnace-brazed articles.                                    |
| C14700, C14710,<br>C14720<br>Sulfur bearing                                       | 99.6 Cu,<br>0.40 S                              | 32-57          | 10-55 | 52                      | 85                                | Fabricating characteristics same as C10100. Uses: screw-machine products and parts requiring high conductivity, extensive machining, corrosion resistance, copper color, or a combination of these; electrical connectors, motor and switch components, plumbing fittings, cold-headed and machined parts, cold forgings, furnace-brazed articles, screws, soldering coppers, rivets and welding torch tips. |
| C15000<br>Zirconium copper  | 99.8 Cu,<br>0.15 Zr                             | 29-76          | 6-72  | 54                      | 20                                | Fabricating characteristics same as C10100. Uses: switches, high-temperature circuit breakers, commutators, stud bases for power transmitters, rectifiers, soldering welding tips.   |
| C15500  | 99.75 Cu,<br>0.06 P,<br>0.11 Mg,<br>Ag          | 40-80          | 18-72 | 40                      | 20                                | Fabricating characteristics same as C10100. Uses: high-conductivity light-duty springs, electrical contacts, fittings, clamps, connectors, diaphragms, electronic components, resistance-welding electrodes.   |
| C15715  | 99.6 Cu,<br>0.13 Al <sub>2</sub> O <sub>3</sub> | 52-88          | 44-84 | 27                      | 20                                | Excellent cold workability. Fabricated by extrusion, drawing, rolling, heading, swaging, machining, blanking, roll threading. Uses: integrated-circuit lead frames, diode leads; vacuum, microwave, and x-ray tube components; electrical components; brush springs; commutators, electric generator and motor components.   |
| C15720  | 99.5 Cu,<br>0.18 Al <sub>2</sub> O <sub>3</sub> | 64-98          | 54-96 | 25                      | ...                               | Excellent cold workability. Fabricated by extrusion, drawing, rolling, heading, swaging, machining, blanking. Uses: relay and switch springs, lead frames, contact supports, heat sinks, circuit breaker parts, rotor bars, resistance-welding electrodes and wheels, connectors, soldering gun tips.  |

**Table 3. (Continued) Properties and Applications of Wrought Coppers and Copper Alloys**

| Name and Number                                    | Nominal Composition (%)                         | Strength (ksi) |        | Elongation in 2 in. (%) | Machinability Rating <sup>a</sup> | Fabricating Characteristics and Typical Applications  |
|--|---|----------------|--------|-------------------------|-----------------------------------|---|
|  |   | Tensile        | Yield  |                         |                                   |   |
| C15760   | 98.8 Cu,<br>0.58 Al <sub>2</sub> O <sub>3</sub> | 70-90          | 65-87  | 22                      | ...                               | Excellent cold workability. Fabricated by extrusion and drawing. Uses: resistance-welding electrodes, soldering gun tips, MIG welding contact tips, continuous-casting molds.   |
| C16200, C16210<br>Cadmium copper                   | 99.0 Cu,<br>1.0 Cd                              | 35-100         | 7-69   | 57                      | 20                                | Excellent cold workability; good hot formability. Uses: trolley wires, heating pads, electric-blanket elements, spring contacts, railbands, high-strength transmission lines, connectors, cable wrap, switch-gear components, and waveguide cavities.   |
| C16500   | 98.6 Cu,<br>0.8 Cd,<br>0.6 Sn                   | 40-95          | 14-71  | 53                      | 20                                | Fabricating characteristics same as C16200. Uses: electrical springs and contacts, trolley wire, clips, flat cable, resistance-welding electrodes.  |
| C17000<br>Beryllium copper                         | 98.3 Cu,<br>1.7 Be,<br>0.20 Co                  | 70-190         | 32-170 | 45                      | 20                                | Fabricating characteristics same as C16200. Commonly fabricated by blanking, forming and bending, turning, drilling, tapping. Uses: bellows, Bourdon tubing, diaphragms, fuse clips, fasteners, lock-washers, springs, switch parts, roll pins, valves, welding equipment.  |
| C17200<br>Beryllium copper                         | 98.1 Cu,<br>1.9 Be,<br>0.20 Co                  | 68-212         | 25-195 | 48                      | 20                                | Similar to C17000, particularly for its nonsparking characteristics.  |
| C17300<br>Beryllium copper                         | 98.1 Cu,<br>1.9 Be,<br>0.40 Pb                  | 68-212         | 25-195 | 48                      | 50                                | Combines superior machinability with good fabricating characteristics of C17200.  |
| C17500, C17510<br>Beryllium copper                 | 96.9 Cu,<br>2.5 Co,<br>0.6 Be                   | 45-115         | 25-110 | 28                      | ...                               | Fabricating characteristics same as C16200. Uses: fuse clips, fasteners, springs, switches and relay parts, electrical conductors, welding equipment.   |
| C18200, C18400,<br>C18500<br>Chromium copper       | 99.2 Cu   | 34-86          | 14-77  | 40                      | 20                                | Excellent cold workability, good hot workability. Uses: resistance-welding electrodes, seam-welding wheels, switch gear, electrode holder jaws, cable connectors, current-carrying arms and shafts, circuit-breaker parts, molds, spot-welding tips, flash-welding electrodes, electrical and thermal conductors requiring strength, switch contacts.                 |
| C18700<br>Leaded copper                            | 99.0 Cu,<br>1.0 Pb                              | 32-55          | 10-50  | 45                      | 85                                | Good cold workability; poor hot formability. Uses: connectors, motor and switch parts, screw-machine parts requiring high conductivity.   |
| C18900   | 98.7 Cu,<br>0.8 Sn,<br>0.3 Si,<br>0.20 Mn       | 38-95          | 9-52   | 48                      | 20                                | Fabricating characteristics same as C10100. Uses: welding rod and wire for inert gas tungsten arc and metal arc welding and oxyacetylene welding of copper.   |
| C19000<br>Copper-nickel-phosphorus alloy           | 98.6 Cu,<br>1.1 Ni,<br>0.3 P                    | 38-115         | 20-81  | 50                      | 30                                | Fabricating characteristics same as C10100. Uses: springs, clips, electrical connectors, power tube and electron tube components, high-strength electrical conductors, bolts, nails, screws, cotter pins, and parts requiring some combination of high strength, high electrical or thermal conductivity, high resistance to fatigue and creep, and good workability. |
| C19100<br>Copper-nickel-phosphorus-tellurium alloy | 98.2 Cu,<br>1.1 Ni,<br>0.5 Te,<br>0.2 P         | 36-104         | 10-92  | 27                      | 75                                | Good hot and cold workability. Uses: forgings and screw-machine parts requiring high strength, hardenability, extensive machining, corrosion resistance, copper color, good conductivity, or a combination of these; bolts, bushings, electrical connectors, gears, marine hardware, nuts, pinions, tie rods, turnbuckle barrels, welding torch tips.                 |
| C19200   | 99 Cu,<br>1.0 Fe,<br>0.03 P                     | 37-77          | 11-74  | 40                      | 20                                | Excellent hot and cold workability. Uses: automotive hydraulic brake lines, flexible hose, electrical terminals, fuse clips, gaskets, gift hollow ware, applications requiring resistance to softening and stress corrosion, air-conditioning and heat-exchanger tubing.  |

**Table 3. (Continued) Properties and Applications of Wrought Coppers and Copper Alloys**

| Name and Number   | Nominal Composition (%)                              | Strength (ksi) |       | Elongation in 2 in. (%) | Machinability Rating <sup>a</sup> | Fabricating Characteristics and Typical Applications  |
|---|--|----------------|-------|-------------------------|-----------------------------------|---|
|   |  | Tensile        | Yield |                         |                                   |   |
| C19400  | 97.4 Cu,<br>2.4 Fe,<br>0.13 Zn,<br>0.04 P            | 45–76          | 24–73 | 32                      | 20                                | Excellent hot and cold workability. Uses: circuit-breaker components, contact springs, electrical clamps, electrical springs, electrical terminals, flexible hose, fuse clips, gaskets, gift hollow ware, plug contacts, rivets, and welded condenser tubes.              |
| C19500  | 97.0 Cu,<br>1.5 Fe,<br>0.6 Sn,<br>0.10 P,<br>0.80 Co | 80–97          | 65–95 | 15                      | 20                                | Excellent hot and cold workability. Uses: electrical springs, sockets, terminals, connectors, clips, and other current-carrying parts requiring strength.   |
| C21000<br>Gilding, 95%                                    | 95.0 Cu,<br>5.0 Zn                                   | 34–64          | 10–58 | 45                      | 20                                | Excellent cold workability, good hot workability for blanking, coining, drawing, piercing and punching, shearing, spinning, squeezing and swaging, stamping. Uses: coins, medals, bullet jackets, fuse caps, primers, plaques, jewelry base for gold plate.               |
| C22000<br>Commercial bronze,<br>90%                       | 90.0 Cu,<br>10.0 Zn                                  | 37–72          | 10–62 | 50                      | 20                                | Fabricating characteristics same as C21000, plus heading and up-setting, roll threading and knurling, hot forging and pressing. Uses: etching bronze, grillwork, screen cloth, weatherstripping, lipstick cases, compacts, marine hardware, screws, rivets.               |
| C22600<br>Jewelry bronze, 87.5%                           | 87.5 Cu,<br>12.5 Zn                                  | 39–97          | 11–62 | 46                      | 30                                | Fabricating characteristics same as C21000, plus heading and up-setting, roll threading and knurling. Uses: angles, channels, chain, fasteners, costume jewelry, lipstick cases, powder compacts, base for gold plate.  |
| C23000<br>Red brass, 85%                                  | 85.0 Cu,<br>15.0 Zn                                  | 39–105         | 10–63 | 55                      | 30                                | Excellent cold workability; good hot formability. Uses: weather-stripping, conduit, sockets, fasteners, fire extinguishers, condenser and heat-exchanger tubing, plumbing pipe, radiator cores.   |
| C24000<br>Low brass, 80%                                  | 80.0 Cu,<br>20.0 Zn                                  | 42–125         | 12–65 | 55                      | 30                                | Excellent cold workability. Fabricating characteristics same as C23000. Uses: battery caps, bellows, musical instruments, clock dials, pump lines, flexible hose.   |
| C26000, C26100,<br>C26130, C26200<br>Cartridge brass, 70% | 70.0 Cu,<br>30.0 Zn                                  | 44 –<br>130    | 11–65 | 66                      | ...                               | Excellent cold workability. Uses: radiator cores and tanks, flashlight shells, lamp fixtures, fasteners, screws, springs, grillwork, stencils, plumbing accessories, plumbing brass goods, locks, hinges, ammunition components, plumbing accessories, pins, rivets.      |
| C26800, C27000<br>Yellow brass                            | 65.0 Cu,<br>35.0 Zn                                  | 46–128         | 14–62 | 65                      | 30                                | Excellent cold workability. Fabricating characteristics same as C23000. Uses: same as C26000 except not used for ammunition.  |
| C28000<br>Muntz metal, 60%                                | 60.0 Cu,<br>40.0 Zn                                  | 54–74          | 21–55 | 52                      | 40                                | Excellent hot formability and forgeability for blanking, forming and bending, hot forging and pressing, hot heading and upsetting, shearing. Uses: architectural, large nuts and bolts, brazing rod, condenser plates, heat-exchanger and condenser tubing, hot forgings. |
| C31400<br>Leaded commercial<br>bronze                     | 89.0 Cu,<br>1.9 Pb,<br>0.1 Zn                        | 37–60          | 12–55 | 45                      | 80                                | Excellent machinability. Uses: screws, machine parts, pickling crates.  |
| C31600<br>Leaded commercial<br>bronze, nickel-bearing     | 89.0 Cu,<br>1.9 Pb,<br>1.0 Ni,<br>8.1 Zn             | 37–67          | 12–59 | 45                      | 80                                | Good cold workability; poor hot formability. Uses: electrical connectors, fasteners, hardware, nuts, screws, screw-machine parts.   |
| C33000<br>Low-leaded brass tube                           | 66.0 Cu,<br>0.5 Pb,<br>33.5 Zn                       | 47–75          | 15–60 | 60                      | 60                                | Combines good machinability and excellent cold workability. Fabricated by forming and bending, machining, piercing and punching. Uses: pump and power cylinders and liners, ammunition primers, plumbing accessories.   |



**Table 3. (Continued) Properties and Applications of Wrought Coppers and Copper Alloys**

| Name and Number                        | Nominal Composition (%)        | Strength (ksi)     |       | Elongation in 2 in. (%) | Machinability Rating <sup>a</sup> | Fabricating Characteristics and Typical Applications   |
|--|--------------------------------|--------------------|-------|-------------------------|-----------------------------------|--|
|  |                                | Tensile            | Yield |                         |                                   |  |
| C33200<br>High-leaded brass tube       | 66.0 Cu,<br>2.0 Pb,<br>32.0 Zn | 47–75              | 15–60 | 50                      | 80                                | Excellent machinability. Fabricated by piercing, punching, and machining. Uses: general-purpose screw-machine parts.   |
| C33500<br>Low-leaded brass             | 63.5 Cu,<br>0.5 Pb,<br>36 Zn   | 46–74              | 14–60 | 65                      | 60                                | Similar to C33200. Commonly fabricated by blanking, drawing, machining, piercing and punching, stamping. Uses: butts, hinges, watch backs.   |
| C34000<br>Medium-leaded brass          | 63.5 Cu,<br>1.0 Pb,<br>35.5 Zn | 47–88              | 15–60 | 60                      | 70                                | Similar to C33200. Fabricated by blanking, heading and upsetting, machining, piercing and punching, roll threading and knurling, stamping. Uses: butts, gears, nuts, rivets, screws, dials, engravings, instrument plates.                                     |
| C34200<br>High-leaded brass            | 63.5 Cu,<br>2.0 Pb,<br>34.5 Zn | 49–85              | 17–62 | 52                      | 90                                | Combines excellent machinability with moderate cold workability. Uses: clock plates and nuts, clock and watch backs, gears, wheels and channel plate.  |
| C35000<br>Medium-leaded brass          | 62.5 Cu,<br>1.1 Pb,<br>36.4 Zn | 45–95              | 13–70 | 66                      | 70                                | Fair cold workability; poor hot formability. Uses: bearing cages, book dies, clock plates, gears, hinges, hose couplings, keys, lock parts, lock tumblers, meter parts, nuts, sink strainers, strike plates, templates, type characters, washers, wear plates. |
| C35300<br>High-leaded brass            | 61.5 Cu,<br>2.8 Pb,<br>36.5 Zn | 49–85              | 17–62 | 52                      | 90                                | Similar to C34200.   |
| C35600<br>Extra-high-leaded brass      | 61.5 Cu,<br>2.5 Pb,<br>36 Zn   | 47–97              | 17–87 | 60                      | 100                               | Excellent machinability. Fabricated by blanking, machining, piercing and punching, stamping. Uses: clock plates and nuts, clock and watch backs, gears, wheels, and channel plate.   |
| C36000<br>Free-cutting brass           | 61.5 Cu,<br>3.1 Pb,<br>35.4 Zn | 49–68              | 18–45 | 53                      | 100                               | Excellent machinability. Fabricated by machining, roll threading, and knurling. Uses: gears, pinions, automatic high-speed screw-machine parts.  |
| C36500 to C36800<br>Leaded Muntz metal | 59.5 Cu,<br>0.5 Pb,<br>40.0 Zn | 54 (As hot rolled) | 20    | 45                      | 60                                | Combines good machinability with excellent hot formability. Uses: condenser-tube plates.   |
| C37000<br>Free-cutting Muntz metal     | 60.0 Cu,<br>1.0 Pb,<br>39.0 Zn | 54–80              | 20–60 | 40                      | 70                                | Fabricating characteristics similar to C36500 to 36800. Uses: automatic screw-machine parts.   |
| C37700<br>Forging brass                | 59.5 Cu,<br>2.0 Pb,<br>38.0 Zn | 52 (As extruded)   | 20    | 45                      | 80                                | Excellent hot workability. Fabricated by heading and upsetting, hot forging and pressing, hot heading and upsetting, machining. Uses: forgings and pressings of all kinds.   |
| C38500<br>Architectural bronze         | 57.0 Cu,<br>3.0 Pb,<br>40.0 Zn | 60 (As extruded)   | 20    | 30                      | 90                                | Excellent machinability and hot workability. Fabricated by hot forging and pressing, forming, bending, and machining. Uses: architectural extrusions, store fronts, thresholds, trim, butts, hinges, lock bodies, and forgings.                                |
| C40500                                 | 95 Cu,<br>1 Sn,<br>4 Zn        | 39–78              | 12–70 | 49                      | 20                                | Excellent cold workability. Fabricated by blanking, forming, and drawing. Uses: meter clips, terminals, fuse clips, contact and relay springs, washers.  |
| C40800                                 | 95 Cu,<br>2 Sn,<br>3 Zn        | 42–79              | 13–75 | 43                      | 20                                | Excellent cold workability. Fabricated by blanking, stamping, and shearing. Uses: electrical connectors.   |
| C41100                                 | 91 Cu,<br>0.5 Sn,<br>8.5 Zn    | 39–106             | 11–72 | 43                      | 20                                | Excellent cold workability, good hot formability. Fabricated by blanking, forming and bending, drawing, piercing and punching, shearing, spinning, and stamping. Uses: bushings, bearing sleeves, thrust washers, flexible metal hose.                         |
| C41300                                 | 90.0 Cu,<br>1.0 Sn,<br>9.0 Zn  | 41–105             | 12–82 | 45                      | 20                                | Excellent cold workability; good hot formability. Uses: plater bar for jewelry products, flat springs for electrical switchgear.   |

**Table 3. (Continued) Properties and Applications of Wrought Coppers and Copper Alloys**

| Name and Number                                  | Nominal Composition (%)                   | Strength (ksi) |       | Elongation in 2 in. (%) | Machinability Rating <sup>a</sup> | Fabricating Characteristics and Typical Applications  |
|--|---|----------------|-------|-------------------------|-----------------------------------|---|
|  |   | Tensile        | Yield |                         |                                   |   |
| C41500   | 91 Cu,<br>1.8 Sn,<br>7.2 Zn               | 46–81          | 17–75 | 44                      | 30                                | Excellent cold workability. Fabricated by blanking, drawing, bending, forming, shearing, and stamping. Uses: spring applications for electrical switches.   |
| C42200   | 87.5 Cu,<br>1.1 Sn,<br>11.4 Zn            | 43–88          | 15–75 | 46                      | 30                                | Excellent cold workability; good hot formability. Fabricated by blanking, piercing, forming, and drawing. Uses: sash chains, fuse clips, terminals, spring washers, contact springs, electrical connectors.   |
| C42500   | 88.5 Cu,<br>2.0 Sn,<br>9.5 Zn             | 45–92          | 18–76 | 49                      | 30                                | Excellent cold workability. Fabricated by blanking, piercing, forming, and drawing. Uses: electrical switches, springs, terminals, connectors, fuse clips, pen clips, weather stripping.  |
| C43000   | 87.0 Cu,<br>2.2 Sn,<br>10.8 Zn            | 46–94          | 18–73 | 55                      | 30                                | Excellent cold workability; good hot formability. Fabricated by blanking, coining, drawing, forming, bending, heading, and upsetting. Uses: same as C42500.   |
| C43400   | 85.0 Cu,<br>0.7 Sn,<br>14.3 Zn            | 45–90          | 15–75 | 49                      | 30                                | Excellent cold workability. Fabricated by blanking, drawing, bonding, forming, stamping, and shearing. Uses: electrical switch parts, blades, relay springs, contacts.  |
| C43500   | 81.0 Cu,<br>0.9 Sn,<br>18.1 Zn            | 46–80          | 16–68 | 46                      | 30                                | Excellent cold workability for fabrication by forming and bending. Uses: Bourdon tubing and musical instruments.  |
| C44300, C44400,<br>C44500<br>Inhibited admiralty | 71.0 Cu,<br>28.0 Zn,<br>1.0 Sn            | 48–55          | 18–22 | 65                      | 30                                | Excellent cold workability for forming and bending. Uses: condenser, evaporator and heat-exchanger tubing, condenser tubing plates, distiller tubing, ferrules.   |
| C46400 to C46700<br>Naval brass                  | 60.0 Cu,<br>39.2 Zn,<br>0.8 Sn            | 55–88          | 25–66 | 50                      | 30                                | Excellent hot workability and hot forgeability. Fabricated by blanking, drawing, bending, heading and upsetting, hot forging, pressing. Uses: aircraft turnbuckle barrels, balls, bolts, marine hardware, nuts, propeller shafts, rivets, valve stems, condenser plates, welding rod.                         |
| C48200<br>Naval brass, medium-leaded             | 60.5 Cu,<br>0.7 Pb,<br>0.8 Sn,<br>38.0 Zn | 56–75          | 25–53 | 43                      | 50                                | Good hot workability for hot forging, pressing, and machining operations. Uses: marine hardware, screw-machine products, valve stems.   |
| C48500<br>Leaded naval brass                     | 60.0 Cu,<br>1.8 Pb,<br>37.5 Zn,<br>0.7 Sn | 57–75          | 25–53 | 40                      | 70                                | Combines good hot forgeability and machinability. Fabricated by hot forging and pressing, machining. Uses: marine hardware, screw-machine parts, valve stems.   |
| C50500<br>Phosphor bronze,<br>1.25% E            | 98.7 Cu,<br>1.3 Sn,<br>trace P            | 40–79          | 14–50 | 48                      | 20                                | Excellent cold workability; good hot formability. Fabricated by blanking, bending, heading and upsetting, shearing and swaging. Uses: electrical contacts, flexible hose, pole-line hardware.   |
| C51000<br>Phosphor bronze,<br>5% A               | 94.8 Cu,<br>5.0 Sn,<br>trace P            | 47–140         | 19–80 | 64                      | 20                                | Excellent cold workability. Fabricated by blanking, drawing, bending, heading and upsetting, roll threading and knurling, shearing, stamping. Uses: bellows, Bourdon tubing, clutch discs, cotter pins, diaphragms, fasteners, lock washers, wire brushes, chemical hardware, textile machinery, welding rod. |
| C51100   | 95.6 Cu,<br>4.2 Sn,<br>0.2 P              | 46–103         | 50–80 | 48                      | 20                                | Excellent cold workability. Uses: bridge bearing plates, locator bars, fuse clips, sleeve bushings, springs, switch parts, truss wire, wire brushes, chemical hardware, perforated sheets, textile machinery.   |

**Table 3. (Continued) Properties and Applications of Wrought Coppers and Copper Alloys**

| Name and Number                     | Nominal Composition (%)                    | Strength (ksi)       |         | Elongation in 2 in. (%) | Machinability Rating <sup>a</sup> | Fabricating Characteristics and Typical Applications   |
|-------------------------------------|--|----------------------|---------|-------------------------|-----------------------------------|--|
|                                     |  | Tensile              | Yield   |                         |                                   |  |
| C52100<br>Phosphor bronze,<br>8% C  | 92.0 Cu,<br>8.0 Sn,<br>trace P             | 55-140               | 24-80   | 70                      | 20                                | Good cold workability for blanking, drawing, forming and bending, shearing, stamping. Uses: generally for more severe service conditions than C51000.  |
| C52400<br>Phosphor bronze,<br>10% D | 90.0 Cu,<br>10.0 Sn,<br>trace P            | 66-147               | 28      | 70                      | 20                                | Good cold workability for blanking, forming and bending, shearing. Uses: heavy bars and plates for severe compression, bridge and expansion plates and fittings, articles requiring good spring qualities, resilience, fatigue resistance, good wear and corrosion resistance. |
| C54400                              | 88.0 Cu,<br>4.0 Pb,<br>4.0 Zn,<br>4.0 Sn   | 44-75                | 19-63   | 50                      | 80                                | Excellent machinability; good cold workability. Fabricated by blanking, drawing, bending, machining, shearing, stamping. Uses: bearings, bushings, gears, pinions, shafts, thrust washers, valve parts.  |
| C60800                              | 95.0 Cu,<br>5.0 Al                         | 60                   | 27      | 55                      | 20                                | Good cold workability; fair hot formability. Uses: condenser, evaporator and heat-exchanger tubes, distiller tubes, ferrules.  |
| C61000                              | 92.0 Cu,<br>8.0 Al                         | 52-60                | 17-27   | 45                      | 20                                | Good hot and cold workability. Uses: bolts, pump parts, shafts, tie rods, overlay on steel for wearing surfaces.   |
| C61300                              | 90.3 Cu,<br>0.35 Sn,<br>6.8 Al,<br>0.35 Sn | 70-85                | 30-58   | 42                      | 30                                | Good hot and cold formability. Uses: nuts, bolts, corrosion resistant vessels and tanks, structural components, machine parts, condenser tube and piping systems, marine protective sheathing and fasteners, munitions mixing troughs and blending chambers.                   |
| C61400<br>Aluminum bronze, D        | 91.0 Cu,<br>7.0 Al,<br>2.0 Fe              | 76-89                | 33-60   | 45                      | 20                                | Similar to C61300.   |
| C61500                              | 90.0 Cu,<br>8.0 Al,<br>2.0 Ni              | 70-145               | 22-140  | 55                      | 30                                | Good hot and cold workability. Fabricating characteristics similar to C52100. Uses: hardware, decorative metal trim, interior furnishings and other articles requiring high tarnish resistance.  |
| C61800                              | 89.0 Cu,<br>1.0 Fe,<br>10.0 Al             | 80-85                | 39-42.5 | 28                      | 40                                | Fabricated by hot forging and hot pressing. Uses: bushings, bearings, corrosion-resistant applications, welding rods.  |
| C61900                              | 86.5 Cu,<br>4.0 Fe,<br>9.5 Al              | 92-152               | 49-145  | 30                      | ...                               | Excellent hot formability for fabricating by blanking, forming, bending, shearing, and stamping. Uses: springs, contacts, and switch components.   |
| C62300                              | 87.0 Cu,<br>3.0 Fe,<br>10.0 Al             | 75-98                | 35-52   | 35                      | 50                                | Good hot and cold formability. Fabricated by bending, hot forging, hot pressing, forming, and welding. Uses: bearings, bushings, valve guides, gears, valve seats, nuts, bolts, pump rods, worm gears, and cams.   |
| C62400                              | 86.0 Cu,<br>3.0 Fe,<br>11.0 Al             | 90-105               | 40-52   | 18                      | 50                                | Excellent hot formability for fabrication by hot forging and hot bending. Uses: bushings, gears, cams, wear strips, nuts, drift pins, tie rods.  |
| C62500                              | 82.7 Cu,<br>4.3 Fe,<br>13.0 Al             | 100<br>(As extruded) | 55      | 1                       | 20                                | Excellent hot formability for fabrication by hot forging and machining. Uses: guide bushings, wear strips, cams, dies, forming rolls.  |
| C63000                              | 82.0 Cu,<br>3.0 Fe,<br>10.0 Al,<br>5.0 Ni  | 90-118               | 50-75   | 20                      | 30                                | Good hot formability. Fabricated by hot forging and forging. Uses: nuts, bolts, valve seats, plunger tips, marine shafts, valve guides, aircraft parts, pump shafts, structural members.   |
| C63200                              | 82.0 Cu,<br>4.0 Fe,<br>9.0 Al,<br>5.0 Ni   | 90-105               | 45-53   | 25                      | 30                                | Good hot formability. Fabricated by hot forming and welding. Uses: nuts, bolts, structural pump parts, shafting requiring corrosion resistance.  |

**Table 3. (Continued) Properties and Applications of Wrought Coppers and Copper Alloys**

| Name and Number                     | Nominal Composition (%)                              | Strength (ksi) |         | Elongation in 2 in. (%) | Machinability Rating <sup>a</sup> | Fabricating Characteristics and Typical Applications   |
|-------------------------------------|--|----------------|---------|-------------------------|-----------------------------------|--|
|                                     |  | Tensile        | Yield   |                         |                                   |  |
| C63600                              | 95.5 Cu,<br>3.5 Al,<br>1.0 Si                        | 60–84          | ...     | 64                      | 40                                | Excellent cold workability; fair hot formability. Fabricated by cold heading. Uses: components for pole-line hardware, cold-headed nuts for wire and cable connectors, bolts and screw products.   |
| C63800                              | 95.0 Cu,<br>2.8 Al,<br>1.8 Si,<br>0.40 Co            | 82–130         | 54–114  | 36                      | ...                               | Excellent cold workability and hot formability. Uses: springs, switch parts, contacts, relay springs, glass sealing, and porcelain enameling.  |
| C64200                              | 91.2 Cu,<br>7.0 Al,<br>1.8 Si                        | 75–102         | 35–68   | 32                      | 60                                | Excellent hot formability. Fabricated by hot forming, forging, machining. Uses: valve stems, gears, marine hardware, pole-line hardware, bolts, nuts, valve bodies, and components.  |
| C65100<br>Low-silicon bronze, B     | 98.5 Cu,<br>1.5 Si                                   | 40–105         | 15–71   | 55                      | 30                                | Excellent hot and cold workability. Fabricated by forming and bending, heading and upsetting, hot forging and pressing, roll threading and knurling, squeezing and swaging. Uses: hydraulic pressure lines, anchor screws, bolts, cable clamps, cap screws, machine screws, marine hardware, nuts, pole-line hardware, rivets, U-bolts, electrical conduits, heat-exchanger tubing, welding rod. |
| C65500<br>High-silicon bronze, A    | 97.0 Cu,<br>3.0 Si                                   | 56–145         | 21–71   | 63                      | 30                                | Excellent hot and cold workability. Fabricated by blanking, drawing, forming and bending, heading and upsetting, hot forging and pressing, roll threading and knurling, shearing, squeezing and swaging. Uses: similar to C65100 including propeller shafts.   |
| C66700<br>Manganese brass           | 70.0 Cu,<br>28.8 Zn,<br>1.2 Mn                       | 45.8–100       | 12–92.5 | 60                      | 30                                | Excellent cold formability. Fabricated by blanking, bending, forming, stamping, welding. Uses: brass products resistance welded by spot, seam, and butt welding.   |
| C67400                              | 58.5 Cu,<br>36.5 Zn,<br>1.2 Al,<br>2.8 Mn,<br>1.0 Sn | 70–92          | 34–55   | 28                      | 25                                | Excellent hot formability. Fabricated by hot forging and pressing, machining. Uses: bushings, gears, connecting rods, shafts, wear plates.   |
| C67500<br>Manganese bronze, A       | 58.5 Cu,<br>1.4 Fe,<br>39.0 Zn,<br>1.0 Sn,<br>0.1 Mn | 65–84          | 30–60   | 33                      | 30                                | Excellent hot workability. Fabricated by hot forging and pressing, hot heading and upsetting. Uses: clutch discs, pump rods, shafting, balls, valve stems and bodies.  |
| C68700<br>Aluminum brass, arsenical | 77.5 Cu,<br>20.5 Zn,<br>2.0 Al,<br>trace As          | 60             | 27      | 55                      | 30                                | Excellent cold workability for forming and bending. Uses: condenser, evaporator- and heat-exchanger tubing, condenser tubing plates, distiller tubing, ferrules.   |
| C68800                              | 73.5 Cu,<br>22.7 Zn,<br>3.4 Al,<br>0.40 Co           | 82–129         | 55–114  | 36                      | ...                               | Excellent hot and cold formability. Fabricated by blanking, drawing, forming and bending, shearing and stamping. Uses: springs, switches, contacts, relays, drawn parts.   |
| C69000                              | 73.3 Cu,<br>3.4 Al,<br>0.6 Ni,<br>22.7 Zn            | 82–130         | 52–117  | 35                      | ...                               | Fabricating characteristics same as C68800. Uses: contacts, relays, switches, springs, drawn parts.  |
| C69400<br>Silicon red brass         | 81.5 Cu,<br>14.5 Zn,<br>4.0 Si                       | 80–100         | 40–57   | 25                      | 30                                | Excellent hot formability for fabrication by forging, screw-machine operations. Uses: valve stems where corrosion resistance and high strength are critical.   |
| C70400<br>Copper nickel, 5%         | 92.4 Cu,<br>1.5 Fe,<br>5.5 Ni,<br>0.6 Mn             | 38–77          | 40–76   | 46                      | 20                                | Excellent cold workability; good hot formability. Fabricated by forming, bending, and welding. Uses: condensers, evaporators, heat exchangers, ferrules, salt water piping, lithium bromide absorption tubing, shipboard condenser intake systems.   |

**Table 3. (Continued) Properties and Applications of Wrought Coppers and Copper Alloys**

| Name and Number                | Nominal Composition (%)                         | Strength (ksi) |        | Elongation in 2 in. (%) | Machinability Rating <sup>a</sup> | Fabricating Characteristics and Typical Applications  |
|--------------------------------|---|----------------|--------|-------------------------|-----------------------------------|---|
|                                |   | Tensile        | Yield  |                         |                                   |   |
| C70600<br>Copper nickel, 10%   | 88.6 Cu,<br>1.4 Fe,<br>10.0 Ni                  | 44–60          | 16–57  | 42                      | 20                                | Good hot and cold workability. Fabricated by forming and bending, welding. Uses: condensers, condenser plates, distiller tubing, evaporator and heat-exchanger tubing, ferrules.  |
| C71000<br>Copper nickel, 20%   | 79.0 Cu,<br>21.0 Ni                             | 49–95          | 13–85  | 40                      | 20                                | Good hot and cold formability. Fabricated by blanking, forming and bending, welding. Uses: communication relays, condensers, condenser plates, electrical springs, evaporator and heat-exchanger tubes, ferrules, resistors.  |
| C71500<br>Copper nickel, 30%   | 69.5 Cu,<br>30.0 Ni,<br>0.5 Fe                  | 54–75          | 20–70  | 45                      | 20                                | Similar to C70600.  |
| C72200                         | 82.2 Cu,<br>16.5 Ni,<br>0.8 Fe,<br>0.5 Cr       | 46–70          | 18–66  | 46                      | ...                               | Good hot and cold formability. Fabricated by forming, bending, and welding. Uses: condenser tubing, heat-exchanger tubing, salt water piping.   |
| C72500                         | 88.2 Cu,<br>9.5 Ni,<br>2.3 Sn                   | 55–120         | 22–108 | 35                      | 20                                | Excellent cold and hot formability. Fabricated by blanking, brazing, coining, drawing, etching, forming and bending, heading and upsetting, roll threading and knurling, shearing, spinning, squeezing, stamping, and swaging. Uses: relay and switch springs, connectors, brazing alloy, lead frames, control and sensing bellows. |
| C73500                         | 72.0 Cu,<br>10.0 Zn,<br>18.0 Ni                 | 50–100         | 15–84  | 37                      | 20                                | Fabricating characteristics same as C74500. Uses: hollow ware, medallions, jewelry, base for silver plate, cosmetic cases, musical instruments, name plates, contacts.  |
| C74500<br>Nickel silver, 65–10 | 65.0 Cu,<br>25.0 Zn,<br>10.0 Ni                 | 49–130         | 18–76  | 50                      | 20                                | Excellent cold workability. Fabricated by blanking, drawing, etching, forming and bending, heading and upsetting, roll threading and knurling, shearing, spinning, squeezing, and swaging. Uses: rivets, screws, slide fasteners, optical parts, etching stock, hollow ware, nameplates, platers' bars.                             |
| C75200<br>Nickel silver, 65–18 | 65.0 Cu,<br>17.0 Zn,<br>18.0 Ni                 | 56–103         | 25–90  | 45                      | 20                                | Fabricating characteristics similar to C74500. Uses: rivets, screws, table flatware, truss wire, zip-pers, bows, camera parts, core bars, temples, base for silver plate, costume jewelry, etching stock, hollow ware, nameplates, radio dials.   |
| C75400<br>Nickel silver, 65–15 | 65.0 Cu,<br>20.0 Zn,<br>15.0 Ni                 | 53–92          | 18–79  | 43                      | 20                                | Fabricating characteristics similar to C74500. Uses: camera parts, optical equipment, etching stock, jewelry.   |
| C75700<br>Nickel silver, 65–12 | 65.0 Cu,<br>23.0 Zn,<br>12.0 Ni                 | 52–93          | 18–79  | 48                      | 20                                | Fabricating characteristics similar to C74500. Uses: slide fasteners, camera parts, optical parts, etching stock, name plates.  |
| C76390                         | 61 Cu,<br>13 Zn,<br>24.5 Ni,<br>1 Pb,<br>0.5 Sn | 90             | 85     | 6                       | 40                                | Fabricated by machining, roll threading, and knurling. Uses: hardware, fasteners, connectors for electronic applications.   |
| C77000<br>Nickel silver, 55–18 | 55.0 Cu,<br>27.0 Zn,<br>18.0 Ni                 | 60–145         | 27–90  | 40                      | 30                                | Good cold workability. Fabricated by blanking, forming and bending, and shearing. Uses: optical goods, springs, and resistance wire.  |
| C78200                         | 65.0 Cu,<br>2.0 Pb,<br>25.0 Zn,<br>8.0 Ni       | 53–91          | 23–76  | 40                      | 60                                | Good cold formability. Fabricated by blanking, milling, and drilling. Uses: key blanks, watch plates, watch parts.  |

<sup>a</sup>Free-cutting brass = 100.

Source: Copper Development Association, New York.

**Strength of Copper-Zinc-Tin Alloys (U.S. Government Tests)**

| Percentage of |      |     | Tensile Strength, lb/in <sup>2</sup> | Percentage of |      |     | Tensile Strength, lb/in <sup>2</sup> | Percentage of |      |     | Tensile Strength, lb/in <sup>2</sup> |
|---------------|------|-----|--------------------------------------|---------------|------|-----|--------------------------------------|---------------|------|-----|--------------------------------------|
| Copper        | Zinc | Tin |                                      | Copper        | Zinc | Tin |                                      | Copper        | Zinc | Tin |                                      |
| 45            | 50   | 5   | 15,000                               | 60            | 20   | 20  | 10,000                               | 75            | 20   | 5   | 45,000                               |
| 50            | 45   | 5   | 50,000                               | 65            | 30   | 5   | 50,000                               | 75            | 15   | 10  | 45,000                               |
| 50            | 40   | 10  | 15,000                               | 65            | 25   | 10  | 42,000                               | 75            | 10   | 15  | 43,000                               |
| 55            | 43   | 2   | 65,000                               | 65            | 20   | 15  | 30,000                               | 75            | 5    | 20  | 41,000                               |
| 55            | 40   | 5   | 62,000                               | 65            | 15   | 20  | 18,000                               | 80            | 15   | 5   | 45,000                               |
| 55            | 35   | 10  | 32,500                               | 65            | 10   | 25  | 12,000                               | 80            | 10   | 10  | 45,000                               |
| 55            | 30   | 15  | 15,000                               | 70            | 25   | 5   | 45,000                               | 80            | 5    | 15  | 47,500                               |
| 60            | 37   | 3   | 60,000                               | 70            | 20   | 10  | 44,000                               | 85            | 10   | 5   | 43,500                               |
| 60            | 35   | 5   | 52,500                               | 70            | 15   | 15  | 37,000                               | 85            | 5    | 10  | 46,500                               |
| 60            | 30   | 10  | 40,000                               | 70            | 10   | 20  | 30,000                               | 90            | 5    | 5   | 42,000                               |

**Copper-Silicon and Copper-Beryllium Alloys**

**Everdur.**—This copper-silicon alloy is available in five slightly different nominal compositions for applications that require high strength, good fabricating and fusing qualities, immunity to rust, free-machining and a corrosion resistance equivalent to copper. The following table gives the nominal compositions and tensile strengths, yield strengths, and per cent elongations for various tempers and forms.

**Table 4. Nominal Composition and Properties of Everdur**

| Desig. No. | Nominal Composition |      |      |      |      | Temper <sup>a</sup> | Strength      |             | Elongation (%)       |
|------------|---------------------|------|------|------|------|---------------------|---------------|-------------|----------------------|
|            | Cu                  | Si   | Mn   | Pb   | Al   |                     | Tensile (ksi) | Yield (ksi) |                      |
| 655        | 95.80               | 3.10 | 1.10 | ...  | ...  | A                   | 52            | 15          | 35 <sup>b</sup>      |
|            |                     |      |      |      |      | HRA                 | 50            | 18          | 40                   |
|            |                     |      |      |      |      | CRA                 | 52            | 18          | 35                   |
|            |                     |      |      |      |      | CRHH                | 71            | 40          | 10                   |
|            |                     |      |      |      |      | CRH                 | 87            | 60          | 3                    |
| 651        | 98.25               | 1.50 | 0.25 | ...  | ...  | H                   | 70 to 85      | 38 to 50    | 17 to 8 <sup>b</sup> |
|            |                     |      |      |      |      | AP                  | 38            | 10          | 35                   |
|            |                     |      |      |      |      | HP                  | 50            | 40          | 7                    |
| 661        | 95.60               | 3.00 | 1.00 | 0.40 | ...  | XHB                 | 75 to 85      | 45 to 55    | 8 to 6 <sup>b</sup>  |
|            |                     |      |      |      |      | A                   | 52            | 15          | 35 <sup>b</sup>      |
| 6552       | 94.90               | 4.00 | 1.10 | ...  | ...  | H                   | 85            | 50          | 13 to 8 <sup>b</sup> |
| 637        | 90.75               | 2.00 | ...  | ...  | 7.25 | AC                  | 45            | ...         | 15                   |
|            |                     |      |      |      |      | A                   | 75 to 90      | 37.5 to 45  | 12 to 9 <sup>b</sup> |

<sup>a</sup> Symbols used are: HRA for hot-rolled and annealed tank plates; CRA for cold-rolled sheets and strips; CRHH for cold-rolled half hard strips; abd CRH for cold-rolled hard strips. For round, square, hexagonal, and octagonal rods: A for annealed; H for hard; and XHB for extra-hard bolt temper (in coils for cold-heading). For pipe and tube: AP for annealed; and HP for hard. For castings: AC for as cast.

<sup>b</sup> Per cent elongation in 4 times the diameter or thickness of the specimen. All other values are per cent elongation in 2 inches.

Designation numbers are those of the American Brass Co.

The values given for the tensile strength, yield strength, and elongation are all minimum values. Where ranges are shown, the first values given are for the largest diameter or largest size specimens. Yield strength values were determined at 0.50 per cent elongation under load.

**Copper-Beryllium Alloys.**—Alloys of copper and beryllium present health hazards. Particles produced by machining may be absorbed into the body through the skin, the mouth, the nose, or an open wound, resulting in a condition requiring immediate medical attention. Working of these alloys requires protective clothing or other shielding in a monitored environment. Copper-beryllium alloys involved in a fire give off profuse toxic fumes that must not be inhaled.

These alloys contain copper, beryllium, cobalt, and silver, and fall into two groups. One group whose beryllium content is greater than one per cent is characterized by its high strength and hardness and the other, whose beryllium content is less than one per cent, by its high electrical and thermal conductivity. The alloys have many applications in the electrical and aircraft industries or wherever strength, corrosion resistance, conductivity, non-magnetic and nonsparking properties are essential. Beryllium copper is obtainable in the form of strips, rods and bars, wire, platers, bars, billets, tubes, and casting ingots.

*Composition and Properties:* Table 5 lists some of the more common wrought alloys and gives some of their mechanical properties.

**Table 5. Wrought Copper-Beryllium Properties**

| Alloy <sup>a</sup> | Form                               | Temper <sup>b</sup> | Heat Treatment                     | Tensile Strength (ksi) | Yield Strength 0.2% Offset (ksi) | Elongation in 2 in. (%) |
|--------------------|------------------------------------|---------------------|------------------------------------|------------------------|----------------------------------|-------------------------|
| 25                 | Rod, Bar, and Plate                | A                   | ...                                | 60-85                  | 20-30                            | 35-60                   |
|                    |                                    | ½ H or H            | ...                                | 85-130                 | 75-105                           | 10-20                   |
|                    |                                    | AT                  | 3 hr at 600°F or mill heat treated | 165-190                | 145-175                          | 3-10                    |
|                    |                                    | ½ HT or HT          | 2 hr at 600°F or mill heat treated | 175-215                | 150-200                          | 2-5                     |
|                    | Wire                               | A                   | ...                                | 58-78                  | 20-35                            | 35-55                   |
|                    |                                    | ¼ H                 | ...                                | 90-115                 | 70-95                            | 10-35                   |
|                    |                                    | ½ H                 | ...                                | 110-135                | 90-110                           | 5-10                    |
|                    |                                    | ¾ H                 | ...                                | 130-155                | 110-135                          | 2-8                     |
|                    |                                    | AT                  | 3 hr at 600°F                      | 165-190                | 145-175                          | 3-8                     |
|                    |                                    | ¼ HT                | 2 hr at 600°F                      | 175-205                | 160-190                          | 2-5                     |
|                    |                                    | ½ HT                | 2 hr at 600°F                      | 190-215                | 175-200                          | 1-3                     |
|                    |                                    | ¾ HT                | 2 hr at 600°F                      | 195-220                | 180-205                          | 1-3                     |
|                    |                                    | XHT                 | Mill heat treated                  | 115-165                | 95-145                           | 2-8                     |
|                    |                                    | 165                 | Rod, Bar, and Plate                | A                      | ...                              | 60-85                   |
| ½ H or H           | ...                                |                     |                                    | 85-130                 | 75-105                           | 10-20                   |
| AT                 | 3 hr at 650°F or mill heat treated |                     |                                    | 150-180                | 125-155                          | 4-10                    |
| ½ HT or HT         | 2 hr at 650°F or mill heat treated |                     |                                    | 165-200                | 135-165                          | 2-5                     |
| 10                 | Rod, Bar, and Plate                | A                   | ...                                | 35-55                  | 20-30                            | 20-35                   |
|                    |                                    | ½ H or H            | ...                                | 65-80                  | 55-75                            | 10-15                   |
|                    |                                    | AT                  | 3 hr at 900°F or mill heat treated | 100-120                | 80-100                           | 10-25                   |
|                    |                                    | ½ HT or HT          | 2 hr at 900°F or mill heat treated | 110-130                | 100-120                          | 8-20                    |
| 50                 | Rod, Bar, and Plate                | A                   | ...                                | 35-55                  | 20-30                            | 20-35                   |
|                    |                                    | ½ H or H            | ...                                | 65-80                  | 55-75                            | 10-15                   |
|                    |                                    | AT                  | 3 hr at 900°F or mill heat treated | 100-120                | 80-100                           | 10-25                   |
|                    |                                    | ½ HT or HT          | 2 hr at 900°F or mill heat treated | 110-130                | 100-120                          | 8-20                    |
| 35                 | Rod, Bar, and Plate                | A                   | ...                                | 35-55                  | 20-30                            | 20-35                   |
|                    |                                    | ½ H or H            | ...                                | 65-80                  | 55-75                            | 10-15                   |
|                    |                                    | AT                  | 3 hr at 900°F or mill heat treated | 100-120                | 80-100                           | 10-25                   |
|                    |                                    | ½ HT or HT          | 2 hr at 900°F or mill heat treated | 110-130                | 100-120                          | 8-20                    |

<sup>a</sup> Composition (in per cent) of alloys is as follows: alloy 25: 1.80-2.05 Be, 0.20-0.35 Co, balance Cu; alloy 165: 1.6-1.8 Be, 0.20-0.35 Co, balance Cu; alloy 10: 0.4-0.7 Be, 2.35-2.70 Co, balance Cu; alloy 50, 0.25-0.50 Be, 1.4-1.7 Co, 0.9-1.1 Ag, balance Cu; alloy 35, 0.25-0.50 Be, 1.4-1.6 Ni, balance Cu.

<sup>b</sup> Temper symbol designations: A, solution annealed; H, hard; HT, heat-treated from hard; At, heat-treated from solution annealed.

**Aluminum and Aluminum Alloys**

Pure aluminum is a silver-white metal characterized by a slightly bluish cast. It has a specific gravity of 2.70, resists the corrosive effects of many chemicals, and has a malleability approaching that of gold. When alloyed with other metals, numerous properties are obtained that make these alloys useful over a wide range of applications.

Aluminum alloys are light in weight compared with steel, brass, nickel, or copper; can be fabricated by all common processes; are available in a wide range of sizes, shapes, and forms; resist corrosion; readily accept a wide range of surface finishes; have good electrical and thermal conductivities; and are highly reflective to both heat and light.

**Characteristics of Aluminum and Aluminum Alloys.**—Aluminum and its alloys lose part of their strength at elevated temperatures, although some alloys retain good strength at temperatures from 400 to 500 degrees F. At subzero temperatures, however, their strength increases without loss of ductility so that aluminum is a particularly useful metal for low-temperature applications.

When aluminum surfaces are exposed to the atmosphere, a thin invisible oxide skin forms immediately that protects the metal from further oxidation. This self-protecting characteristic gives aluminum its high resistance to corrosion. Unless exposed to some substance or condition that destroys this protective oxide coating, the metal remains protected against corrosion. Aluminum is highly resistant to weathering, even in industrial atmospheres. It is also corrosion resistant to many acids. Alkalis are among the few substances that attack the oxide skin and therefore are corrosive to aluminum. Although the metal can safely be used in the presence of certain mild alkalis with the aid of inhibitors, in general, direct contact with alkaline substances should be avoided. Direct contact with certain other metals should be avoided in the presence of an electrolyte; otherwise, galvanic corrosion of the aluminum may take place in the contact area. Where other metals must be fastened to aluminum, the use of a bituminous paint coating or insulating tape is recommended.

Aluminum is one of the two common metals having an electrical conductivity high enough for use as an electric conductor. The conductivity of electric-conductor (EC) grade is about 62 per cent that of the International Annealed Copper Standard. Because aluminum has less than one-third the specific gravity of copper, however, a pound of aluminum will go almost twice as far as a pound of copper when used as a conductor. Alloying lowers the conductivity somewhat so that wherever possible the EC grade is used in electric conductor applications. However, aluminum takes a set, which often results in loosening of screwed connectors, leading to arcing and fires. Special clamping designs are therefore required when aluminum is used for electrical wiring, especially in buildings.

Aluminum has nonsparking and nonmagnetic characteristics that make the metal useful for electrical shielding purposes such as in bus bar housings or enclosures for other electrical equipment and for use around inflammable or explosive substances.

Aluminum can be cast by any method known. It can be rolled to any desired thickness down to foil thinner than paper and in sheet form can be stamped, drawn, spun, or roll-formed. The metal also may be hammered or forged. Aluminum wire, drawn from rolled rod, may be stranded into cable of any desired size and type. The metal may be extruded into a variety of shapes. It may be turned, milled, bored, or otherwise machined in equipment often operating at their maximum speeds. Aluminum rod and bar may readily be employed in the high-speed manufacture of parts made on automatic screw-machine.

Almost any method of joining is applicable to aluminum—riveting, welding, or brazing. A wide variety of mechanical aluminum fasteners simplifies the assembly of many products. Resin bonding of aluminum parts has been successfully employed, particularly in aircraft components.

For the majority of applications, aluminum needs no protective coating. Mechanical finishes such as polishing, sandblasting, or wire brushing meet the majority of needs. When



additional protection is desired, chemical, electrochemical, and paint finishes are all used. Vitreous enamels have been developed for aluminum, and the metal may also be electroplated.

**Temper Designations for Aluminum Alloys.**—The temper designation system adopted by the Aluminum Association and used in industry pertains to all forms of wrought and cast aluminum and aluminum alloys except ingot. It is based on the sequences of basic treatments used to produce the various tempers. The temper designation follows the alloy designation, being separated by a dash.

Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter. These digits designate specific sequences of basic treatments, but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added.

The basic temper designations and subdivisions are as follows:

–*F*, as fabricated: Applies to products that acquire some temper from shaping processes not having special control over the amount of strain-hardening or thermal treatment. For wrought products, there are no mechanical property limits.

–*O*, annealed, recrystallized (*wrought products only*): Applies to the softest temper of wrought products.

–*H*, strain-hardened (*wrought products only*): Applies to products that have their strength increased by strain-hardening with or without supplementary thermal treatments to produce partial softening.

The –*H* is always followed by two or more digits. The first digit indicates the specific combination of basic operations, as follows:

–*H1*, strain-hardened only: Applies to products that are strain-hardened to obtain the desired mechanical properties without supplementary thermal treatment. The number following this designation indicates the degree of strain-hardening.

–*H2*, strain-hardened and then partially annealed: Applies to products that are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. For alloys that age-soften at room temperature, the –*H2* tempers have approximately the same ultimate strength as the corresponding –*H3* tempers. For other alloys, the –*H2* tempers have approximately the same ultimate strengths as the corresponding –*H1* tempers and slightly higher elongations. The number following this designation indicates the degree of strain-hardening remaining after the product has been partially annealed.

–*H3*, strain-hardened and then stabilized: Applies to products which are strain-hardened and then stabilized by a low-temperature heating to slightly lower their strength and increase ductility. This designation applies only to the magnesium-containing alloys that, unless stabilized, gradually age-soften at room temperature. The number following this designation indicates the degree of strain-hardening remaining after the product has been strain-hardened a specific amount and then stabilized.

The second digit following the designations –*H1*, –*H2*, and –*H3* indicates the final degree of strain-hardening. Numeral 8 has been assigned to indicate tempers having a final degree of strain-hardening equivalent to that resulting from approximately 75 per cent reduction of area. Tempers between –*O* (annealed) and 8 (full hard) are designated by numerals 1 through 7. Material having an ultimate strength about midway between that of the –*O* temper and that of the 8 temper is designated by the numeral 4 (half hard); between –*O* and 4 by the numeral 2 (quarter hard); and between 4 and 8 by the numeral 6 (three-quarter hard). (*Note:* For two-digit –*H* tempers whose second figure is odd, the standard limits for ultimate strength are exactly midway between those for the adjacent two-digit –*H* tempers whose second figures are even.) Numeral 9 designates extra-hard tempers.

The third digit, when used, indicates a variation of a two-digit -H temper, and is used when the degree of control of temper or the mechanical properties are different from but close to those for the two-digit -H temper designation to which it is added. (*Note:* The minimum ultimate strength of a three-digit -H temper is at least as close to that of the corresponding two-digit -H temper as it is to the adjacent two-digit -H tempers.) Numerals 1 through 9 may be arbitrarily assigned and registered with the Aluminum Association for an alloy and product to indicate a specific degree of control of temper or specific mechanical property limits. Zero has been assigned to indicate degrees of control of temper or mechanical property limits negotiated between the manufacturer and purchaser that are not used widely enough to justify registration with the Aluminum Association.

The following three-digit -H temper designations have been assigned for wrought products in all alloys:

-H111: Applies to products that are strain-hardened less than the amount required for a controlled H11 temper.

-H112: Applies to products that acquire some temper from shaping processes not having special control over the amount of strain-hardening or thermal treatment, but for which there are mechanical property limits, or mechanical property testing is required.

The following three-digit H temper designations have been assigned for wrought products in alloys containing more than a normal 4 per cent magnesium.

-H311: Applies to products that are strain-hardened less than the amount required for a controlled H31 temper.

-H321: Applies to products that are strain-hardened less than the amount required for a controlled H32 temper.

-H323: Applies to products that are specially fabricated to have acceptable resistance to stress-corrosion cracking.

-H343: Applies to products that are specially fabricated to have acceptable resistance to stress-corrosion cracking.

The following three-digit -H temper designations have been assigned for

| Patterned or Embossed Sheet | Fabricated Form                       |
|-----------------------------|---------------------------------------|
| -H114                       | -O temper                             |
| -H124, -H224, -H324         | -H11, -H21, -H31 temper, respectively |
| -H134, -H234, -H334         | -H12, -H22, -H32 temper, respectively |
| -H144, -H244, -H344         | -H13, -H23, -H33 temper, respectively |
| -H154, -H254, -H354         | -H14, -H24, -H34 temper, respectively |
| -H164, -H264, -H364         | -H15, -H25, -H35 temper, respectively |
| -H174, -H274, -H374         | -H16, -H26, -H36 temper, respectively |
| -H184, -H284, -H384         | -H17, -H27, -H37 temper, respectively |
| -H194, -H294, -H394         | -H18, -H28, -H38 temper, respectively |
| -H195, -H395                | -H19, -H39 temper, respectively       |

-W, *solution heat-treated*: An unstable temper applicable only to alloys that spontaneously age at room temperature after solution heat treatment. This designation is specific only when the period of natural aging is indicated.

-T, *thermally treated to produce stable tempers other than -F, -O, or -H*: Applies to products that are thermally treated, with or without supplementary strain-hardening, to produce stable tempers. The -T is always followed by one or more digits. Numerals 2 through 10 have been assigned to indicate specific sequences of basic treatments, as follows:

-T1, *naturally aged to a substantially stable condition*: Applies to products for which the rate of cooling from an elevated temperature-shaping process, such as casting or extrusion, is such that their strength is increased by room-temperature aging.

–T2, *annealed (cast products only)*: Designates a type of annealing treatment used to improve ductility and increase dimensional stability of castings.

–T3, *solution heat-treated and then cold-worked*: Applies to products that are cold-worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in applicable specifications.

–T4, *solution heat-treated and naturally aged to a substantially stable condition*: Applies to products that are not cold-worked after solution heat treatment, or in which the effect of cold work in flattening or straightening may not be recognized in applicable specifications.

–T5, *artificially aged only*: Applies to products that are artificially aged after an elevated-temperature rapid-cool fabrication process, such as casting or extrusion, to improve mechanical properties or dimensional stability, or both.

–T6, *solution heat-treated and then artificially aged*: Applies to products that are not cold-worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in applicable specifications.

–T7, *solution heat-treated and then stabilized*: Applies to products that are stabilized to carry them beyond the point of maximum hardness, providing control of growth or residual stress or both.

–T8, *solution heat-treated, cold-worked, and then artificially aged*: Applies to products that are cold-worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in applicable specifications.

–T9, *solution heat-treated, artificially aged, and then cold-worked*: Applies to products that are cold-worked to improve strength.

–T10, *artificially aged and then cold-worked*: Applies to products that are artificially aged after an elevated-temperature rapid-cool fabrication process, such as casting or extrusion, and then cold-worked to improve strength.

Additional digits may be added to designations –T1 through –T10 to indicate a variation in treatment that significantly alters the characteristics of the product. These may be arbitrarily assigned and registered with The Aluminum Association for an alloy and product to indicate a specific treatment or specific mechanical property limits.

These additional digits have been assigned for wrought products in all alloys:

–T\_\_51, *stress-relieved by stretching*: Applies to products that are stress-relieved by stretching the following amounts after solution heat-treatment:

|                     |                                 |
|---------------------|---------------------------------|
| Plate               | 1½ to 3 per cent permanent set  |
| Rod, Bar and Shapes | 1 to 3 per cent permanent set   |
| Drawn tube          | 0.5 to 3 per cent permanent set |

Applies directly to plate and rolled or cold-finished rod and bar.

These products receive no further straightening after stretching.

Applies to extruded rod and bar shapes and tube when designated as follows:

–T\_\_510 : Products that receive no further straightening after stretching.

–T\_\_511: Products that receive minor straightening after stretching to comply with standard tolerances.

–T\_\_52, *stress-relieved by compressing*: Applies to products that are stress-relieved by compressing after solution heat-treatment, to produce a nominal permanent set of 2½ per cent.

–T\_\_54, *stress-relieved by combined stretching and compressing*: Applies to die forgings that are stress relieved by restriking cold in the finish die.

The following two-digit –T temper designations have been assigned for wrought products in all alloys:

–T42: Applies to products solution heat-treated and naturally aged that attain mechanical properties different from those of the –T4 temper.

–T62: Applies to products solution heat-treated and artificially aged that attain mechanical properties different from those of the –T6 temper.

**Aluminum Alloy Designation Systems.**—Aluminum casting alloys are listed in many specifications of various standardizing agencies. The numbering systems used by each differ and are not always correlatable. Casting alloys are available from producers who use a commercial numbering system and this numbering system is the one used in the tables of aluminum casting alloys given in this section.

Table 6a lists the nominal composition of commonly used aluminum casting alloys, and Tables 6b and 6c list the typical tensile properties of separately cast bars.

**Table 6a. Nominal Compositions (in per cent) of Common Aluminum Casting Alloys (AA/ANSI)**

| Alloy  | Producer <sup>a</sup> | Si        | Fe               | Cu        | Mn                | Mg        | Cr        | Ni      | Zn      | Ti        | Others            |       |
|--------|-----------------------|-----------|------------------|-----------|-------------------|-----------|-----------|---------|---------|-----------|-------------------|-------|
|        |                       |           |                  |           |                   |           |           |         |         |           | Each              | Total |
| 201.0  | S                     | 0.10      | 0.15             | 4.0–5.2   | 0.20–0.50         | 0.15–0.55 | ...       | ...     | ...     | 0.15–0.35 | 0.05 <sup>b</sup> | 0.10  |
| 204.0  | S&P                   | 0.20      | 0.35             | 4.2–5.0   | 0.10              | 0.15–0.35 | ...       | 0.05    | 0.10    | 0.15–0.30 | 0.05 <sup>c</sup> | 0.15  |
| 208.0  | S&P                   | 2.5–3.5   | 1.2              | 3.5–4.5   | 0.50              | 0.10      | ...       | 0.35    | 1.0     | 0.25      | ...               | 0.50  |
| 222.0  | S&P                   | 2.0       | 1.5              | 9.2–10.7  | 0.50              | 0.15–0.35 | ...       | 0.50    | 0.8     | 0.25      | ...               | 0.35  |
| 242.0  | S&P                   | 0.7       | 1.0              | 3.5–4.5   | 0.35              | 1.2–1.8   | 0.25      | 1.7–2.3 | 0.35    | 0.25      | 0.05              | 0.15  |
| 295.0  | S                     | 0.7–1.5   | 1.0              | 4.0–5.0   | 0.35              | 0.03      | ...       | ...     | 0.35    | 0.25      | 0.05              | 0.15  |
| 308.0  | P                     | 5.0–6.0   | 1.0              | 4.0–5.0   | 0.50              | 0.10      | ...       | ...     | 1.0     | 0.25      | ...               | 0.50  |
| 319.0  | S&P                   | 5.5–6.5   | 1.0              | 3.0–4.0   | 0.50              | 0.10      | ...       | 0.35    | 1.0     | 0.25      | ...               | 0.50  |
| 328.0  | S                     | 7.5–8.5   | 1.0              | 1.0–2.0   | 0.20–0.6          | 0.20–0.6  | 0.35      | 0.25    | 1.5     | 0.25      | ...               | 0.50  |
| 332.0  | P                     | 8.5–10.5  | 1.2              | 2.0–4.0   | 0.50              | 0.50–1.5  | ...       | 0.50    | 1.0     | 0.25      | ...               | 0.50  |
| 333.0  | P                     | 8.0–10.0  | 1.0              | 3.0–4.0   | 0.50              | 0.05–0.50 | ...       | 0.50    | 1.0     | 0.25      | ...               | 0.50  |
| 336.0  | P                     | 11.0–13.0 | 1.2              | 0.50–1.5  | 0.35              | 0.7–1.3   | ...       | 2.0–3.0 | 0.35    | 0.25      | 0.05              | ...   |
| 355.0  | S&P                   | 4.5–5.5   | 0.6 <sup>d</sup> | 1.0–1.5   | 0.50 <sup>d</sup> | 0.40–0.6  | 0.25      | ...     | 0.35    | 0.25      | 0.05              | 0.15  |
| C355.0 | S&P                   | 4.5–5.5   | 0.20             | 1.0–1.5   | 0.10              | 0.40–0.6  | ...       | ...     | 0.10    | 0.20      | 0.05              | 0.15  |
| 356.0  | S&P                   | 6.5–7.5   | 0.6 <sup>d</sup> | 0.25      | 0.35 <sup>d</sup> | 0.20–0.45 | ...       | ...     | 0.35    | 0.25      | 0.05              | 0.15  |
| 356.0  | S&P                   | 6.5–7.5   | 0.20             | 0.20      | 0.10              | 0.25–0.45 | ...       | ...     | 0.10    | 0.20      | 0.05              | 0.15  |
| 357.0  | S&P                   | 6.5–7.5   | 0.15             | 0.05      | 0.03              | 0.45–0.6  | ...       | ...     | 0.05    | 0.20      | 0.05              | 0.15  |
| A357.0 | S&P                   | 6.5–7.5   | 0.20             | 0.20      | 0.10              | 0.40–0.7  | ...       | ...     | 0.10    | 0.04–0.20 | 0.05 <sup>e</sup> | 0.15  |
| 443.0  | S&P                   | 4.5–6.0   | 0.8              | 0.6       | 0.50              | 0.05      | 0.25      | ...     | 0.50    | 0.25      | ...               | 0.35  |
| B443.0 | S&P                   | 4.5–6.0   | 0.8              | 0.15      | 0.35              | 0.05      | ...       | ...     | 0.35    | 0.25      | 0.05              | 0.15  |
| A444.0 | P                     | 6.5–7.5   | 0.20             | 0.10      | 0.10              | 0.05      | ...       | ...     | 0.10    | 0.20      | 0.05              | 0.15  |
| 512.0  | S                     | 1.4–2.2   | 0.6              | 0.35      | 0.8               | 3.5–4.5   | 0.25      | ...     | 0.35    | 0.25      | 0.05              | 0.15  |
| 513.0  | P                     | 0.30      | 0.40             | 0.10      | 0.30              | 3.5–4.5   | ...       | ...     | 1.4–2.2 | 0.20      | 0.05              | 0.15  |
| 514.0  | S                     | 0.35      | 0.50             | 0.15      | 0.35              | 3.5–4.5   | ...       | ...     | 0.15    | 0.25      | 0.05              | 0.15  |
| 520.0  | S                     | 0.25      | 0.30             | 0.25      | 0.15              | 9.5–10.6  | ...       | ...     | 0.15    | 0.25      | 0.05              | 0.15  |
| 705.0  | S&P                   | 0.20      | 0.8              | 0.20      | 0.40–0.6          | 1.4–1.8   | 0.20–0.40 | ...     | 2.7–3.3 | 0.25      | 0.05              | 0.15  |
| 707.0  | S&P                   | 0.20      | 0.8              | 0.20      | 0.40–0.6          | 1.8–2.4   | 0.20–0.40 | ...     | 4.0–4.5 | 0.25      | 0.05              | 0.15  |
| 710.0  | S                     | 0.15      | 0.50             | 0.35–0.65 | 0.05              | 0.6–0.8   | ...       | ...     | 6.0–7.0 | 0.25      | 0.05              | 0.15  |
| 711.0  | P                     | 0.30      | 0.7–1.4          | 0.35–0.65 | 0.05              | 0.25–0.45 | ...       | ...     | 6.0–7.0 | 0.20      | 0.05              | 0.15  |
| 712.0  | S                     | 0.30      | 0.50             | 0.25      | 0.10              | 0.50–0.65 | 0.40–0.6  | ...     | 5.0–6.5 | 0.15–0.25 | 0.05              | 0.20  |
| 850.0  | S&P                   | 0.7       | 0.7              | 0.7–1.3   | 0.10              | 0.10      | ...       | 0.7–1.3 | ...     | 0.20      | — <sup>f</sup>    | 0.30  |
| 851.0  | S&P                   | 2.0–3.0   | 0.7              | 0.7–1.3   | 0.10              | 0.10      | ...       | 0.3–0.7 | ...     | 0.20      | — <sup>f</sup>    | 0.30  |

<sup>a</sup> S = sand cast; P = permanent mold cast. The sum of those "Others" metallic elements 0.010 per cent or more each, expressed to the second decimal before determining the sum. Source: *Standards for Aluminum Sand and Permanent Mold Castings*, courtesy of the Aluminum Association.

<sup>b</sup> Also contains 0.40–1.0 per cent silver.

<sup>c</sup> Also contains 0.05 max. per cent tin.

<sup>d</sup> If iron exceeds 0.45 per cent, manganese content should not be less than one-half the iron content.

<sup>e</sup> Also contains 0.04–0.07 per cent beryllium.

<sup>f</sup> Also contains 5.5–7.0 per cent tin.

**Table 6b. Mechanical Property Limits for Separately Cast Test Bars of Commonly Used Aluminum Sand Casting Alloys**

| Alloy  | Temper <sup>a</sup> | Minimum Properties     |       |                            | Typical Brinell Hardness (500 kgf load, 10-mm ball) |
|--------|---------------------|------------------------|-------|----------------------------|---|
|        |                     | Tensile Strength (ksi) |       | Elongation In 2 inches (%) |   |
|        |                     | Ultimate               | Yield |                            |   |
| 201.0  | T7                  | 60.0                   | 50.0  | 3.0                        | 110-140   |
| 204.0  | T4                  | 45.0                   | 28.0  | 6.0                        | ...   |
| 208.0  | F                   | 19.0                   | 12.0  | 1.5                        | 40-70   |
| 222.0  | O                   | 23.0                   | ...   | ...                        | 65-95   |
| 222.0  | T61                 | 30.0                   | ...   | ...                        | 100-130   |
| 242.0  | O                   | 23.0                   | ...   | ...                        | 55-85   |
| 242.0  | T571                | 29.0                   | ...   | ...                        | 70-100  |
| 242.0  | T61                 | 32.0                   | 20.0  | ...                        | 90-120  |
| 242.0  | T77                 | 24.0                   | 13.0  | 1.0                        | 60-90   |
| 295.0  | T4                  | 29.0                   | 13.0  | 6.0                        | 45-75   |
| 295.0  | T6                  | 32.0                   | 20.0  | 3.0                        | 60-90   |
| 295.0  | T62                 | 36.0                   | 28.0  | ...                        | 80-110  |
| 295.0  | T7                  | 29.0                   | 16.0  | 3.0                        | 55-85   |
| 319.0  | F                   | 23.0                   | 13.0  | 1.5                        | 55-85   |
| 319.0  | T5                  | 25.0                   | ...   | ...                        | 65-95   |
| 319.0  | T6                  | 31.0                   | 20.0  | 1.5                        | 65-95   |
| 328.0  | F                   | 25.0                   | 14.0  | 1.0                        | 45-75   |
| 328.0  | T6                  | 34.0                   | 21.0  | 1.0                        | 65-95   |
| 354.0  | b                   | ...                    | ...   | ...                        | ...   |
| 355.0  | T51                 | 25.0                   | 18.0  | ...                        | 50-80   |
| 355.0  | T6                  | 32.0                   | 20.0  | 2.0                        | 70-105  |
| 355.0  | T7                  | 35.0                   | ...   | ...                        | 70-100  |
| 355.0  | T71                 | 30.0                   | 22.0  | ...                        | 60-95   |
| C355.0 | T6                  | 36.0                   | 25.0  | 2.5                        | 75-105  |
| 356.0  | F                   | 19.0                   | ...   | 2.0                        | 40-70   |
| 356.0  | T51                 | 23.0                   | 16.0  | ...                        | 45-75   |
| 356.0  | T6                  | 30.0                   | 20.0  | 3.0                        | 55-90   |
| 356.0  | T7                  | 31.0                   | 29.0  | ...                        | 60-90   |
| 356.0  | T71                 | 25.0                   | 18.0  | 3.0                        | 45-75   |
| A356.0 | T6                  | 34.0                   | 24.0  | 3.5                        | 70-105  |
| 443.0  | F                   | 17.0                   | 7.0   | 3.0                        | 25-55   |
| B443.0 | F                   | 17.0                   | 6.0   | 3.0                        | 25-55   |
| 512.0  | F                   | 17.0                   | 10.0  | ...                        | 35-65   |
| 514.0  | F                   | 22.0                   | 9.0   | 6.0                        | 35-65   |
| 520.0  | T4 <sup>c</sup>     | 42.0                   | 22.0  | 12.0                       | 60-90   |
| 535.0  | F or T5             | 35.0                   | 18.0  | 9.0                        | 60-90   |
| 705.0  | F or T5             | 30.0                   | 17.0  | 5.0                        | 50-80   |
| 707.0  | T5                  | 33.0                   | 22.0  | 2.0                        | 70-100  |
| 707.0  | T7                  | 37.0                   | 30.0  | 1.0                        | 65-95   |
| 710.0  | F or T5             | 32.0                   | 20.0  | 2.0                        | 60-90   |
| 712.0  | F or T5             | 34.0                   | 25.0  | 4.0                        | 60-90   |
| 713.0  | F or T5             | 32.0                   | 22.0  | 3.0                        | 60-90   |
| 771.0  | T5                  | 42.0                   | 38.0  | 1.5                        | 85-115  |
| 771.0  | T51                 | 32.0                   | 27.0  | 3.0                        | 70-100  |
| 771.0  | T52                 | 36.0                   | 30.0  | 1.5                        | 70-100  |
| 771.0  | T53                 | 36.0                   | 27.0  | 1.5                        | ...   |
| 771.0  | T6                  | 42.0                   | 35.0  | 5.0                        | 75-105  |
| 771.0  | T71                 | 48.0                   | 45.0  | 2.0                        | 105-135   |
| 850.0  | T5                  | 16.0                   | ...   | 5.0                        | 30-60   |
| 851.0  | T5                  | 17.0                   | ...   | 3.0                        | 30-60   |
| 852.0  | T5                  | 24.0                   | 18.0  | ...                        | 45-75   |

Source: Standards for Aluminum Sand and Permanent Mold Castings, courtesy of the Aluminum Association.

<sup>a</sup>F indicates "as cast" condition.

<sup>b</sup>Mechanical properties for these alloys depend on the casting process. For further information consult the individual foundries.

<sup>c</sup>The T4 temper of Alloy 520.0 is unstable; significant room temperature aging occurs within life expectancy of most castings. Elongation may decrease by as much as 80 percent.

**Table 6c. Mechanical Property Limits for Separately Cast Test Bars of Commonly Used Aluminum Permanent Mold Casting Alloys**

| Alloy  | Temper <sup>a</sup> | Minimum Properties     |       |                            | Typical Brinell Hardness (500 kgf load, 10-mm ball) |
|--------|---------------------|------------------------|-------|----------------------------|---|
|        |                     | Tensile Strength (ksi) |       | Elongation In 2 inches (%) |   |
|        |                     | Ultimate               | Yield |                            |   |
| 204.0  | T4                  | 48.0                   | 29.0  | 8.0                        | ...   |
| 208.0  | T4                  | 33.0                   | 15.0  | 4.5                        | 60-90   |
| 208.0  | T6                  | 35.0                   | 22.0  | 2.0                        | 75-105  |
| 208.0  | T7                  | 33.0                   | 16.0  | 3.0                        | 65-95   |
| 222.0  | T551                | 30.0                   | ...   | ...                        | 100-130   |
| 222.0  | T65                 | 40.0                   | ...   | ...                        | 125-155   |
| 242.0  | T571                | 34.0                   | ...   | ...                        | 90-120  |
| 242.0  | T61                 | 40.0                   | ...   | ...                        | 95-125  |
| 296.0  | T6                  | 35.0                   | ...   | 2.0                        | 75-105  |
| 308.0  | F                   | 24.0                   | ...   | ...                        | 55-85   |
| 319.0  | F                   | 28.0                   | 14.0  | 1.5                        | 70-100  |
| 319.0  | T6                  | 34.0                   | ...   | 2.0                        | 75-105  |
| 332.0  | T5                  | 31.0                   | ...   | ...                        | 90-120  |
| 333.0  | F                   | 28.0                   | ...   | ...                        | 65-100  |
| 333.0  | T5                  | 30.0                   | ...   | ...                        | 70-105  |
| 333.0  | T6                  | 35.0                   | ...   | ...                        | 85-115  |
| 333.0  | T7                  | 31.0                   | ...   | ...                        | 75-105  |
| 336.0  | T551                | 31.0                   | ...   | ...                        | 90-120  |
| 336.0  | T65                 | 40.0                   | ...   | ...                        | 110-140   |
| 354.0  | T61                 | 48.0                   | 37.0  | 3.0                        | ...   |
| 354.0  | T62                 | 52.0                   | 42.0  | 2.0                        | ...   |
| 355.0  | T51                 | 27.0                   | ...   | ...                        | 60-90   |
| 355.0  | T6                  | 37.0                   | ...   | 1.5                        | 75-105  |
| 355.0  | T62                 | 42.0                   | ...   | ...                        | 90-120  |
| 355.0  | T7                  | 36.0                   | ...   | ...                        | 70-100  |
| 355.0  | T71                 | 34.0                   | 27.0  | ...                        | 65-95   |
| C355.0 | T61                 | 40.0                   | 30.0  | 3.0                        | 75-105  |
| 356.0  | F                   | 21.0                   | ...   | 3.0                        | 40-70   |
| 356.0  | T51                 | 25.0                   | ...   | ...                        | 55-85   |
| 356.0  | T6                  | 33.0                   | 22.0  | 3.0                        | 65-95   |
| 356.0  | T7                  | 25.0                   | ...   | 3.0                        | 60-90   |
| 356.0  | T71                 | 25.0                   | ...   | 3.0                        | 60-90   |
| A356.0 | T61                 | 37.0                   | 26.0  | 5.0                        | 70-100  |
| 357.0  | T6                  | 45.0                   | ...   | 3.0                        | 75-105  |
| A357.0 | T61                 | 45.0                   | 36.0  | 3.0                        | 85-115  |
| 359.0  | T61                 | 45.0                   | 34.0  | 4.0                        | 75-105  |
| 359.0  | T62                 | 47.0                   | 38.0  | 3.0                        | 85-115  |
| 443.0  | F                   | 21.0                   | 7.0   | 2.0                        | 30-60   |
| B443.0 | F                   | 21.0                   | 6.0   | 2.5                        | 30-60   |
| A444.0 | T4                  | 20.0                   | ...   | 20.0                       | ...   |
| 513.0  | F                   | 22.0                   | 12.0  | 2.5                        | 45-75   |
| 535.0  | F                   | 35.0                   | 18.0  | 8.0                        | 60-90   |
| 705.0  | T5                  | 37.0                   | 17.0  | 10.0                       | 55-85   |
| 707.0  | T7                  | 45.0                   | 35.0  | 3.0                        | 80-110  |
| 711.0  | T1                  | 28.0                   | 18.0  | 7.0                        | 55-85   |
| 713.0  | T5                  | 32.0                   | 22.0  | 4.0                        | 60-90   |
| 850.0  | T5                  | 18.0                   | ...   | 8.0                        | 30-60   |
| 851.0  | T5                  | 17.0                   | ...   | 3.0                        | 30-60   |
| 851.0  | T6                  | 18.0                   | ...   | 8.0                        | ...   |
| 852.0  | T5                  | 27.0                   | ...   | 3.0                        | 55-85   |

Source: Standards for Aluminum Sand and Permanent Mold Castings. Courtesy of the Aluminum Association.

<sup>a</sup>F indicates "as cast" condition.

A system of four-digit numerical designations for wrought aluminum and wrought aluminum alloys was adopted by the Aluminum Association in 1954. This system is used by the commercial producers and is similar to the one used by the SAE; the difference being the addition of two prefix letters.

The first digit of the designation identifies the alloy type: 1) indicating an aluminum of 99.00 per cent or greater purity; 2) copper; 3) manganese; 4) silicon; 5) magnesium; 6) magnesium and silicon; 7) zinc; 8) some element other than those aforementioned; and 9) unused (not assigned at present).

If the second digit in the designation is zero, it indicates that there is no special control on individual impurities; integers 1 through 9 indicate special control on one or more individual impurities.

In the 1000 series group for aluminum of 99.00 per cent or greater purity, the last two of the four digits indicate to the nearest hundredth the amount of aluminum above 99.00 per cent. Thus designation 1030 indicates 99.30 per cent minimum aluminum. In the 2000 to 8000 series groups the last two of the four digits have no significance but are used to identify different alloys in the group. At the time of adoption of this designation system most of the existing commercial designation numbers were used for these last two digits, as for example, 14S became 2014, 3S became 3003, and 75S became 7075. When new alloys are developed and are commercially used these last two digits are assigned consecutively beginning with -01, skipping any numbers previously assigned at the time of initial adoption.

Experimental alloys are also designated in accordance with this system but they are indicated by the prefix X. The prefix is dropped upon standardization.

Table 7a shows the product forms and nominal compositions of common wrought aluminum alloys, and Table 7b lists typical mechanical properties of wrought aluminum alloys.

**Table 7a. Nominal Compositions of Common Wrought Aluminum Alloys**

| Alloy             | Alloying Elements — Aluminum and Normal Impurities Constitute Remainder |      |                                 |      |     |     |     |      |     |     |      |      |     |
|-------------------|---|------|---------------------------------|------|-----|-----|-----|------|-----|-----|------|------|-----|
|                   | Si  | Cu   | Mn                              | Mg   | Cr  | Ni  | Zn  | Ti   | Pb  | Bi  | V    | Z    | Fe  |
| 1050              | ...   | ...  | 99.50 per cent minimum aluminum |      |     |     | ... | ...  | ... | ... | ...  | ...  | ... |
| 1060              | ...   | ...  | 99.60 per cent minimum aluminum |      |     |     | ... | ...  | ... | ... | ...  | ...  | ... |
| 1100              | ...   | 0.12 | 99.00 per cent minimum aluminum |      |     |     | ... | ...  | ... | ... | ...  | ...  | ... |
| 1145              | ...   | ...  | 99.45 per cent minimum aluminum |      |     |     | ... | ...  | ... | ... | ...  | ...  | ... |
| 1175              | ...   | ...  | 99.75 per cent minimum aluminum |      |     |     | ... | ...  | ... | ... | ...  | ...  | ... |
| 1200              | ...   | ...  | 99.00 per cent minimum aluminum |      |     |     | ... | ...  | ... | ... | ...  | ...  | ... |
| 1230              | ...   | ...  | 99.30 per cent minimum aluminum |      |     |     | ... | ...  | ... | ... | ...  | ...  | ... |
| 1235              | ...   | ...  | 99.35 per cent minimum aluminum |      |     |     | ... | ...  | ... | ... | ...  | ...  | ... |
| 1345              | ...   | ...  | 99.45 per cent minimum aluminum |      |     |     | ... | ...  | ... | ... | ...  | ...  | ... |
| 1350 <sup>a</sup> | ...   | ...  | 99.50 per cent minimum aluminum |      |     |     | ... | ...  | ... | ... | ...  | ...  | ... |
| 2011              | ...   | 5.5  | ...                             | ...  | ... | ... | ... | ...  | 0.4 | 0.4 | ...  | ...  | ... |
| 2014              | 0.8   | 4.4  | 0.8                             | 0.50 | ... | ... | ... | ...  | ... | ... | ...  | ...  | ... |
| 2017              | 0.50  | 4.0  | 0.7                             | 0.6  | ... | ... | ... | ...  | ... | ... | ...  | ...  | ... |
| 2018              | ...   | 4.0  | ...                             | 0.7  | ... | 2.0 | ... | ...  | ... | ... | ...  | ...  | ... |
| 2024              | ...   | 4.4  | 0.6                             | 1.5  | ... | ... | ... | ...  | ... | ... | ...  | ...  | ... |
| 2025              | 0.8   | 4.4  | 0.8                             | ...  | ... | ... | ... | ...  | ... | ... | ...  | ...  | ... |
| 2036              | ...   | 2.6  | 0.25                            | 0.45 | ... | ... | ... | ...  | ... | ... | ...  | ...  | ... |
| 2117              | ...   | 2.6  | ...                             | 0.35 | ... | ... | ... | ...  | ... | ... | ...  | ...  | ... |
| 2124              | ...   | 4.4  | 0.6                             | 1.5  | ... | ... | ... | ...  | ... | ... | ...  | ...  | ... |
| 2218              | ...   | 4.0  | ...                             | 1.5  | ... | 2.0 | ... | ...  | ... | ... | ...  | ...  | ... |
| 2219              | ...   | 6.3  | 0.30                            | ...  | ... | ... | ... | 0.06 | ... | ... | 0.10 | 0.18 | ... |
| 2319              | ...   | 6.3  | 0.30                            | ...  | ... | ... | ... | 0.15 | ... | ... | 0.10 | 0.18 | ... |
| 2618              | 0.18  | 2.3  | ...                             | 1.6  | ... | 1.0 | ... | 0.07 | ... | ... | ...  | ...  | 1.1 |

**Table 7a. (Continued) Nominal Compositions of Common Wrought Aluminum Alloys**

| Alloy             | Alloying Elements — Aluminum and Normal Impurities Constitute Remainder |      |      |      |      |     |     |      |     |     |     |      |      |
|-------------------|---|------|------|------|------|-----|-----|------|-----|-----|-----|------|------|
|                   | Si  | Cu   | Mn   | Mg   | Cr   | Ni  | Zn  | Ti   | Pb  | Bi  | V   | Z    | Fe   |
| 3003              | ...   | 0.12 | 1.2  | ...  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 3004              | ...   | ...  | 1.2  | 1.0  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 3005              | ...   | ...  | 1.2  | 0.40 | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 4032              | 12.2  | 0.9  | ...  | 1.0  | ...  | 0.9 | ... | ...  | ... | ... | ... | ...  | ...  |
| 4043              | 5.2   | ...  | ...  | ...  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 4045              | 10.0  | ...  | ...  | ...  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 4047              | 12.0  | ...  | ...  | ...  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 4145              | 10.0  | 4.0  | ...  | ...  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5005              | ...   | ...  | ...  | 0.8  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5050              | ...   | ...  | ...  | 1.4  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5052              | ...   | ...  | ...  | 2.5  | 0.25 | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5056              | ...   | ...  | 0.12 | 5.0  | 0.12 | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5083              | ...   | ...  | 0.7  | 4.4  | 0.15 | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5086              | ...   | ...  | 0.45 | 4.0  | 0.15 | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5183              | ...   | ...  | 0.8  | 4.8  | 0.15 | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5252              | ...   | ...  | ...  | 2.5  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5254              | ...   | ...  | ...  | 3.5  | 0.25 | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5356              | ...   | ...  | 0.12 | 5.0  | 0.12 | ... | ... | 0.13 | ... | ... | ... | ...  | ...  |
| 5456              | ...   | ...  | 0.8  | 5.1  | 0.12 | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5457              | ...   | ...  | 0.30 | 1.0  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5554              | ...   | ...  | 0.8  | 2.7  | 0.12 | ... | ... | 0.12 | ... | ... | ... | ...  | ...  |
| 5556              | ...   | ...  | 0.8  | 5.1  | 0.12 | ... | ... | 0.12 | ... | ... | ... | ...  | ...  |
| 5652              | ...   | ...  | ...  | 2.5  | 0.25 | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 5654              | ...   | ...  | ...  | 3.5  | 0.25 | ... | ... | 0.10 | ... | ... | ... | ...  | ...  |
| 6003              | 0.7   | ...  | ...  | 1.2  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 6005              | 0.8   | ...  | ...  | 0.50 | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 6053              | 0.7   | ...  | ...  | 1.2  | 0.25 | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 6061              | 0.6   | 0.28 | ...  | 1.0  | 0.20 | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 6066              | 1.4   | 1.0  | 0.8  | 1.1  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 6070              | 1.4   | 0.28 | 0.7  | 0.8  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 6101              | 0.50  | ...  | ...  | 0.6  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 6105              | 0.8   | ...  | ...  | 0.62 | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 6151              | 0.9   | ...  | ...  | 0.6  | 0.25 | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 6201              | 0.7   | ...  | ...  | 0.8  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 6253              | 0.7   | ...  | ...  | 1.2  | 0.25 | ... | ... | 2.0  | ... | ... | ... | ...  | ...  |
| 6262              | 0.6   | 0.28 | ...  | 1.0  | 0.09 | ... | ... | ...  | 0.6 | 0.6 | ... | ...  | ...  |
| 6351              | 1.0   | ...  | 0.6  | 0.6  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 6463              | 0.40  | ...  | ...  | 0.7  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 7005              | ...   | ...  | 0.45 | 1.4  | 0.13 | ... | 4.5 | 0.04 | ... | ... | ... | 0.14 | ...  |
| 7008              | ...   | ...  | ...  | 1.0  | 0.18 | ... | 5.0 | ...  | ... | ... | ... | ...  | ...  |
| 7049              | ...   | 1.6  | ...  | 2.4  | 0.16 | ... | 7.7 | ...  | ... | ... | ... | ...  | ...  |
| 7050              | ...   | 2.3  | ...  | 2.2  | 6.2  | ... | ... | ...  | ... | ... | ... | 0.12 | ...  |
| 7072              | ...   | ...  | ...  | ...  | ...  | ... | 1.0 | ...  | ... | ... | ... | ...  | ...  |
| 7075              | ...   | 1.6  | ...  | 2.5  | 0.23 | ... | 5.6 | ...  | ... | ... | ... | ...  | ...  |
| 7108              | ...   | ...  | ...  | 1.0  | ...  | ... | 5.0 | ...  | ... | ... | ... | 0.18 | ...  |
| 7178              | ...   | 2.0  | ...  | 2.8  | 0.23 | ... | 6.8 | ...  | ... | ... | ... | ...  | ...  |
| 8017              | ...   | 0.15 | ...  | 0.03 | ...  | ... | ... | ...  | ... | ... | ... | ...  | 0.7  |
| 8030 <sup>b</sup> | ...   | 0.22 | ...  | ...  | ...  | ... | ... | ...  | ... | ... | ... | ...  | ...  |
| 8177              | ...   | ...  | ...  | 0.08 | ...  | ... | ... | ...  | ... | ... | ... | ...  | 0.35 |

<sup>a</sup> Formerly designated EC.<sup>b</sup> Boron 0.02 per cent.

Source: Aluminum Standards and Data. Courtesy of the Aluminum Association.



**Table 7b. Typical Mechanical Properties of Wrought Aluminum Alloys**

| Alloy and Temper              | Tension        |       |                            |                            | Brinell Hardness Number<br>500 kg load,<br>10-mm ball | Ultimate Shearing Strength (ksi) | Endurance Limit <sup>a</sup> (ksi) |
|-------------------------------|----------------|-------|----------------------------|----------------------------|---|----------------------------------|------------------------------------|
|                               | Strength (ksi) |       | Elongation in 2 inches (%) |                            |   |                                  |                                    |
|                               | Ultimate       | Yield | 1/16-inch Thick Specimen   | 1/2-inch Diameter Specimen |   |                                  |                                    |
| 1060-O                        | 10             | 4     | 43                         | ...                        | 19  | 7                                | 3                                  |
| 1060-H12                      | 12             | 11    | 16                         | ...                        | 23  | 8                                | 4                                  |
| 1060-H14                      | 14             | 13    | 12                         | ...                        | 26  | 9                                | 5                                  |
| 1060-H16                      | 16             | 15    | 8                          | ...                        | 30  | 10                               | 6.5                                |
| 1060-H18                      | 19             | 18    | 6                          | ...                        | 35  | 11                               | 6.5                                |
| 1100-O                        | 13             | 5     | 35                         | 45                         | 23  | 9                                | 5                                  |
| 1100-H12                      | 16             | 15    | 12                         | 25                         | 28  | 10                               | 6                                  |
| 1100-H14                      | 18             | 17    | 9                          | 20                         | 32  | 11                               | 7                                  |
| 1100-H16                      | 21             | 20    | 6                          | 17                         | 38  | 12                               | 9                                  |
| 1100-H18                      | 24             | 22    | 5                          | 15                         | 44  | 13                               | 9                                  |
| 1350-O                        | 12             | 4     | ...                        | ... <sup>b</sup>           | ...   | 8                                | ...                                |
| 1350-H12                      | 14             | 12    | ...                        | ...                        | ...   | 9                                | ...                                |
| 1350-H14                      | 16             | 14    | ...                        | ...                        | ...   | 10                               | ...                                |
| 1350-H16                      | 18             | 16    | ...                        | ...                        | ...   | 11                               | ...                                |
| 1350-H19                      | 27             | 24    | ...                        | ... <sup>c</sup>           | ...   | 15                               | 7                                  |
| 2011-T3                       | 55             | 43    | ...                        | 15                         | 95  | 32                               | 18                                 |
| 2011-T8                       | 59             | 45    | ...                        | 12                         | 100   | 35                               | 18                                 |
| 2014-O                        | 27             | 14    | ...                        | 18                         | 45  | 18                               | 13                                 |
| 2014-T4, T451                 | 62             | 42    | ...                        | 20                         | 105   | 38                               | 20                                 |
| 2014-T6, T651                 | 70             | 60    | ...                        | 13                         | 135   | 42                               | 18                                 |
| Alclad 2014-O                 | 25             | 10    | 21                         | ...                        | ...   | 18                               | ...                                |
| Alclad 2014-T3                | 63             | 40    | 20                         | ...                        | ...   | 37                               | ...                                |
| Alclad 2014-T4, T451          | 61             | 37    | 22                         | ...                        | ...   | 37                               | ...                                |
| Alclad 2014-T6, T651          | 68             | 60    | 10                         | ...                        | ...   | 41                               | ...                                |
| 2017-O                        | 26             | 10    | ...                        | 22                         | 45  | 18                               | 13                                 |
| 2017-T4, T451                 | 62             | 40    | ...                        | 22                         | 105   | 38                               | 18                                 |
| 2018-T61                      | 61             | 46    | ...                        | 12                         | 120   | 39                               | 17                                 |
| 2024-O                        | 27             | 11    | 20                         | 22                         | 47  | 18                               | 13                                 |
| 2024-T3                       | 70             | 50    | 18                         | ...                        | 120   | 41                               | 20                                 |
| 2024-T4, T351                 | 68             | 47    | 20                         | 19                         | 120   | 41                               | 20                                 |
| 2024-T361 <sup>d</sup>        | 72             | 57    | 13                         | ...                        | 130   | 42                               | 18                                 |
| Alclad 2024-O                 | 26             | 11    | 20                         | ...                        | ...   | 18                               | ...                                |
| Alclad 2024-T3                | 65             | 45    | 18                         | ...                        | ...   | 40                               | ...                                |
| Alclad 2024-T4, T351          | 64             | 42    | 19                         | ...                        | ...   | 40                               | ...                                |
| Alclad 2024-T361 <sup>d</sup> | 67             | 53    | 11                         | ...                        | ...   | 41                               | ...                                |
| Alclad 2024-T81, T851         | 65             | 60    | 6                          | ...                        | ...   | 40                               | ...                                |
| Alclad 2024-T861 <sup>d</sup> | 70             | 66    | 6                          | ...                        | ...   | 42                               | ...                                |
| 2025-T6                       | 58             | 37    | ...                        | 19                         | 110   | 35                               | 18                                 |
| 2036-T4                       | 49             | 28    | 24                         | ...                        | ...   | ...                              | 18 <sup>e</sup>                    |
| 2117-T4                       | 43             | 24    | ...                        | 27                         | 70  | 28                               | 14                                 |
| 2218-T72                      | 48             | 37    | ...                        | 11                         | 95  | 30                               | ...                                |
| 2219-O                        | 25             | 11    | 18                         | ...                        | ...   | ...                              | ...                                |
| 2219-T42                      | 52             | 27    | 20                         | ...                        | ...   | ...                              | ...                                |
| 2219-T31, T351                | 52             | 36    | 17                         | ...                        | ...   | ...                              | ...                                |
| 2219-T37                      | 57             | 46    | 11                         | ...                        | ...   | ...                              | ...                                |
| 2219-T62                      | 60             | 42    | 10                         | ...                        | ...   | ...                              | 15                                 |
| 2219-T81, T851                | 66             | 51    | 10                         | ...                        | ...   | ...                              | 15                                 |
| 2219-T87                      | 69             | 57    | 10                         | ...                        | ...   | ...                              | 15                                 |
| 3003-O                        | 16             | 6     | 30                         | 40                         | 28  | 11                               | 7                                  |

**Table 7b. (Continued) Typical Mechanical Properties of Wrought Aluminum Alloys**

| Alloy and Temper | Tension        |       |                            |                            | Brinell Hardness Number<br>500 kg load,<br>10-mm ball | Ultimate Shearing Strength (ksi) | Endurance Limit <sup>a</sup> (ksi) |
|------------------|----------------|-------|----------------------------|----------------------------|---|----------------------------------|------------------------------------|
|                  | Strength (ksi) |       | Elongation in 2 inches (%) |                            |   |                                  |                                    |
|                  | Ultimate       | Yield | 1/16-inch Thick Specimen   | 1/2-inch Diameter Specimen |   |                                  |                                    |
| 3003-H12         | 19             | 18    | 10                         | 20                         | 35  | 12                               | 8                                  |
| 3003-H14         | 22             | 21    | 8                          | 16                         | 40  | 14                               | 9                                  |
| 3003-H16         | 26             | 25    | 5                          | 14                         | 47  | 15                               | 10                                 |
| 3003-H18         | 29             | 27    | 4                          | 10                         | 55  | 16                               | 10                                 |
| Alclad 3003-O    | 16             | 6     | 30                         | 40                         | ...   | 11                               | ...                                |
| Alclad 3003-H12  | 19             | 18    | 10                         | 20                         | ...   | 12                               | ...                                |
| Alclad 3003-H14  | 22             | 21    | 8                          | 16                         | ...   | 14                               | ...                                |
| Alclad 3003-H16  | 26             | 25    | 5                          | 14                         | ...   | 15                               | ...                                |
| Alclad 3003-H18  | 29             | 27    | 4                          | 10                         | ...   | 16                               | ...                                |
| 3004-O           | 26             | 10    | 20                         | 25                         | 45  | 16                               | 14                                 |
| 3004-H32         | 31             | 25    | 10                         | 17                         | 52  | 17                               | 15                                 |
| 3004-H34         | 35             | 29    | 9                          | 12                         | 63  | 18                               | 15                                 |
| 3004-H36         | 38             | 33    | 5                          | 9                          | 70  | 20                               | 16                                 |
| 3004-H38         | 41             | 36    | 5                          | 6                          | 77  | 21                               | 16                                 |
| Alclad 3004-O    | 26             | 10    | 20                         | 25                         | ...   | 16                               | ...                                |
| Alclad 3004-H32  | 31             | 25    | 10                         | 17                         | ...   | 17                               | ...                                |
| Alclad 3004-H34  | 35             | 29    | 9                          | 12                         | ...   | 18                               | ...                                |
| Alclad 3004-H36  | 38             | 33    | 5                          | 9                          | ...   | 20                               | ...                                |
| Alclad 3004-H38  | 41             | 36    | 5                          | 6                          | ...   | 21                               | ...                                |
| 3105-O           | 17             | 8     | 24                         | ...                        | ...   | 12                               | ...                                |
| 3105-H12         | 22             | 19    | 7                          | ...                        | ...   | 14                               | ...                                |
| 3105-H14         | 25             | 22    | 5                          | ...                        | ...   | 15                               | ...                                |
| 3105-H16         | 28             | 25    | 4                          | ...                        | ...   | 16                               | ...                                |
| 3105-H18         | 31             | 28    | 3                          | ...                        | ...   | 17                               | ...                                |
| 3105-H25         | 26             | 23    | 8                          | ...                        | ...   | 15                               | ...                                |
| 4032-T6          | 55             | 46    | ...                        | 9                          | 120   | 38                               | 16                                 |
| 5005-O           | 18             | 6     | 25                         | ...                        | 28  | 11                               | ...                                |
| 5005-H12         | 20             | 19    | 10                         | ...                        | ...   | 14                               | ...                                |
| 5005-H14         | 23             | 22    | 6                          | ...                        | ...   | 14                               | ...                                |
| 5005-H16         | 26             | 25    | 5                          | ...                        | ...   | 15                               | ...                                |
| 5005-H18         | 29             | 28    | 4                          | ...                        | ...   | 16                               | ...                                |
| 5005-H32         | 20             | 17    | 11                         | ...                        | 36  | 14                               | ...                                |
| 5005-H34         | 23             | 20    | 8                          | ...                        | 41  | 14                               | ...                                |
| 5005-H36         | 26             | 24    | 6                          | ...                        | 46  | 15                               | ...                                |
| 5005-H38         | 29             | 27    | 5                          | ...                        | 51  | 16                               | ...                                |
| 5050-O           | 21             | 8     | 24                         | ...                        | 36  | 15                               | 12                                 |
| 5050-H32         | 25             | 21    | 9                          | ...                        | 46  | 17                               | 13                                 |
| 5050-H34         | 28             | 24    | 8                          | ...                        | 53  | 18                               | 13                                 |
| 5050-H36         | 30             | 26    | 7                          | ...                        | 58  | 19                               | 14                                 |
| 5050-H38         | 32             | 29    | 6                          | ...                        | 63  | 20                               | 14                                 |
| 5052-O           | 28             | 13    | 25                         | 30                         | 47  | 18                               | 16                                 |
| 5052-H32         | 33             | 28    | 12                         | 18                         | 60  | 20                               | 17                                 |
| 5052-H34         | 38             | 31    | 10                         | 14                         | 68  | 21                               | 18                                 |
| 5052-H36         | 40             | 35    | 8                          | 10                         | 73  | 23                               | 19                                 |
| 5052-H38         | 42             | 37    | 7                          | 8                          | 77  | 24                               | 20                                 |
| 5056-O           | 42             | 22    | ...                        | 35                         | 65  | 26                               | 20                                 |
| 5056-H18         | 63             | 59    | ...                        | 10                         | 105   | 34                               | 22                                 |
| 5056-H38         | 60             | 50    | ...                        | 15                         | 100   | 32                               | 22                                 |
| 5083-O           | 42             | 21    | ...                        | 22                         | ...   | 25                               | ...                                |
| 5083-H321, H116  | 46             | 33    | ...                        | 16                         | ...   | ...                              | 23                                 |

**Table 7b. (Continued) Typical Mechanical Properties of Wrought Aluminum Alloys**

| Alloy and Temper     | Tension        |       |                            |                            | Brinell Hardness Number<br>500 kg load,<br>10-mm ball | Ultimate Shearing Strength (ksi) | Endurance Limit <sup>a</sup> (ksi) |
|----------------------|----------------|-------|----------------------------|----------------------------|---|----------------------------------|------------------------------------|
|                      | Strength (ksi) |       | Elongation in 2 inches (%) |                            |   |                                  |                                    |
|                      | Ultimate       | Yield | 1/16-inch Thick Specimen   | 1/2-inch Diameter Specimen |   |                                  |                                    |
| 5086-O               | 38             | 17    | 22                         | ...                        | ...   | 23                               | ...                                |
| 5086-H32, H116       | 42             | 30    | 12                         | ...                        | ...   | ...                              | ...                                |
| 5086-H34             | 47             | 37    | 10                         | ...                        | ...   | 27                               | ...                                |
| 5086-H112            | 39             | 19    | 14                         | ...                        | ...   | ...                              | ...                                |
| 5154-O               | 35             | 17    | 27                         | ...                        | 58  | 22                               | 17                                 |
| 5154-H32             | 39             | 30    | 15                         | ...                        | 67  | 22                               | 18                                 |
| 5154-H34             | 42             | 33    | 13                         | ...                        | 73  | 24                               | 19                                 |
| 5154-H36             | 45             | 36    | 12                         | ...                        | 78  | 26                               | 20                                 |
| 5154-H38             | 48             | 39    | 10                         | ...                        | 80  | 28                               | 21                                 |
| 5154-H112            | 35             | 17    | 25                         | ...                        | 63  | ...                              | 17                                 |
| 5252-H25             | 34             | 25    | 11                         | ...                        | 68  | 21                               | ...                                |
| 5252-H38, H28        | 41             | 35    | 5                          | ...                        | 75  | 23                               | ...                                |
| 5254-O               | 35             | 17    | 27                         | ...                        | 58  | 22                               | 17                                 |
| 5254-H32             | 39             | 30    | 15                         | ...                        | 67  | 22                               | 18                                 |
| 5254-H34             | 42             | 33    | 13                         | ...                        | 73  | 24                               | 19                                 |
| 5254-H36             | 45             | 36    | 12                         | ...                        | 78  | 26                               | 20                                 |
| 5254-H38             | 48             | 39    | 10                         | ...                        | 80  | 28                               | 21                                 |
| 5254-H112            | 35             | 17    | 25                         | ...                        | 63  | ...                              | 17                                 |
| 5454-O               | 36             | 17    | 22                         | ...                        | 62  | 23                               | ...                                |
| 5454-H32             | 40             | 30    | 10                         | ...                        | 73  | 24                               | ...                                |
| 5454-H34             | 44             | 35    | 10                         | ...                        | 81  | 26                               | ...                                |
| 5454-H111            | 38             | 26    | 14                         | ...                        | 70  | 23                               | ...                                |
| 5454-H112            | 36             | 18    | 18                         | ...                        | 62  | 23                               | ...                                |
| 5456-O               | 45             | 23    | ...                        | 24                         | ...   | ...                              | ...                                |
| 5456-H112            | 45             | 24    | ...                        | 22                         | ...   | ...                              | ...                                |
| 5456-H321, H116      | 51             | 37    | ...                        | 16                         | 90  | 30                               | ...                                |
| 5457-O               | 19             | 7     | 22                         | ...                        | 32  | 12                               | ...                                |
| 5457-H25             | 26             | 23    | 12                         | ...                        | 48  | 16                               | ...                                |
| 5457-H38, H28        | 30             | 27    | 6                          | ...                        | 55  | 18                               | ...                                |
| 5652-O               | 28             | 13    | 25                         | 30                         | 47  | 18                               | 16                                 |
| 5652-H32             | 33             | 28    | 12                         | 18                         | 60  | 20                               | 17                                 |
| 5652-H34             | 38             | 31    | 10                         | 14                         | 68  | 21                               | 18                                 |
| 5652-H36             | 40             | 35    | 8                          | 10                         | 73  | 23                               | 19                                 |
| 5652-H38             | 42             | 37    | 7                          | 8                          | 77  | 24                               | 20                                 |
| 5657-H25             | 23             | 20    | 12                         | ...                        | 40  | 14                               | ...                                |
| 5657-H38, H28        | 28             | 24    | 7                          | ...                        | 50  | 15                               | ...                                |
| 6061-O               | 18             | 8     | 25                         | 30                         | 30  | 12                               | 9                                  |
| 6061-T4, T451        | 35             | 21    | 22                         | 25                         | 65  | 24                               | 14                                 |
| 6061-T6, T651        | 45             | 40    | 12                         | 17                         | 95  | 30                               | 14                                 |
| Alclad 6061-O        | 17             | 7     | 25                         | ...                        | ...   | 11                               | ...                                |
| Alclad 6061-T4, T451 | 33             | 19    | 22                         | ...                        | ...   | 22                               | ...                                |
| Alclad 6061-T6, T651 | 42             | 37    | 12                         | ...                        | ...   | 27                               | ...                                |
| 6063-O               | 13             | 7     | ...                        | ...                        | 25  | 10                               | 8                                  |
| 6063-T1              | 22             | 13    | 20                         | ...                        | 42  | 14                               | 9                                  |
| 6063-T4              | 25             | 13    | 22                         | ...                        | ...   | ...                              | ...                                |
| 6063-T5              | 27             | 21    | 12                         | ...                        | 60  | 17                               | 10                                 |
| 6063-T6              | 35             | 31    | 12                         | ...                        | 73  | 22                               | 10                                 |
| 6063-T83             | 37             | 35    | 9                          | ...                        | 82  | 22                               | ...                                |
| 6063-T831            | 30             | 27    | 10                         | ...                        | 70  | 18                               | ...                                |
| 6063-T832            | 42             | 39    | 12                         | ...                        | 95  | 27                               | ...                                |

**Table 7b. (Continued) Typical Mechanical Properties of Wrought Aluminum Alloys**

| Alloy and Temper        | Tension        |       |                            |                            | Brinell Hardness Number<br>500 kg load,<br>10-mm ball | Ultimate Shearing Strength (ksi) | Endurance Limit <sup>a</sup> (ksi) |
|-------------------------|----------------|-------|----------------------------|----------------------------|---|----------------------------------|------------------------------------|
|                         | Strength (ksi) |       | Elongation in 2 inches (%) |                            |   |                                  |                                    |
|                         | Ultimate       | Yield | 1/16-inch Thick Specimen   | 1/2-inch Diameter Specimen |   |                                  |                                    |
| 6066-O                  | 22             | 12    | ...                        | 18                         | 43  | 14                               | ...                                |
| 6066-T4, T451           | 52             | 30    | ...                        | 18                         | 90  | 29                               | ...                                |
| 6066-T6, T651           | 57             | 52    | ...                        | 12                         | 120   | 34                               | 16                                 |
| 6070-T6                 | 55             | 51    | 10                         | ...                        | ...   | 34                               | 14                                 |
| 6101-H111               | 14             | 11    | ...                        | ...                        | ...   | ...                              | ...                                |
| 6101-T6                 | 32             | 28    | 15                         | ...                        | 71  | 20                               | ...                                |
| 6262-T9                 | 58             | 55    | ...                        | 10                         | 120   | 35                               | 13                                 |
| 6351-T4                 | 36             | 22    | 20                         | ...                        | ...   | ...                              | ...                                |
| 6351-T6                 | 45             | 41    | 14                         | ...                        | 95  | 29                               | 13                                 |
| 6463-T1                 | 22             | 13    | 20                         | ...                        | 42  | 14                               | 10                                 |
| 6463-T5                 | 27             | 21    | 12                         | ...                        | 60  | 17                               | 10                                 |
| 6463-T6                 | 35             | 31    | 12                         | ...                        | 74  | 22                               | 10                                 |
| 7049-T73                | 75             | 65    | ...                        | 12                         | 135   | 44                               | ...                                |
| 7049-T7352              | 75             | 63    | ...                        | 11                         | 135   | 43                               | ...                                |
| 7050-T73510,<br>T73511  | 72             | 63    | ...                        | 12                         | ...   | ...                              | ...                                |
| 7050-T7451 <sup>f</sup> | 76             | 68    | ...                        | 11                         | ...   | 44                               | ...                                |
| 7050-T7651              | 80             | 71    | ...                        | 11                         | ...   | 47                               | ...                                |
| 7075-O                  | 33             | 15    | 17                         | 16                         | 60  | 22                               | ...                                |
| 7075-T6, T651           | 83             | 73    | 11                         | 11                         | 150   | 48                               | 23                                 |
| Alclad 7075-O           | 32             | 14    | 17                         | ...                        | ...   | 22                               | ...                                |
| Alclad 7075-T6, T651    | 76             | 67    | 11                         | ...                        | ...   | 46                               | ...                                |
| 7178-O                  | 33             | 15    | 15                         | 16                         | ...   | ...                              | ...                                |
| 7178-T6, T651           | 88             | 78    | 10                         | 11                         | ...   | ...                              | ...                                |
| 7178-T76, T7651         | 83             | 73    | ...                        | 11                         | ...   | ...                              | ...                                |
| Alclad 7178-O           | 32             | 14    | 16                         | ...                        | ...   | ...                              | ...                                |
| Alclad 7178-T6, T651    | 81             | 71    | 10                         | ...                        | ...   | ...                              | ...                                |
| 8176-H24                | 17             | 14    | 15                         | ...                        | ...   | 10                               | ...                                |

<sup>a</sup> Based on 500,000,000 cycles of completely reversed stress using the R. R. Moore type of machine and specimen.

<sup>b</sup> 1350-O wire should have an elongation of approximately 23 per cent in 10 inches.

<sup>c</sup> 1350-H19 wire should have an elongation of approximately 1.5 per cent in 10 inches.

<sup>d</sup> Tempers T361 and T861 were formerly designated T36 and T86, respectively.

<sup>e</sup> Based on  $10^7$  cycles using flexural type testing of sheet specimens.

<sup>f</sup> T7451, although not previously registered, has appeared in the literature and in some specifications as T73651.

The data given in this table are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes. The indicated typical mechanical properties for all except O temper material are higher than the specified minimum properties. For O temper products, typical ultimate and yield values are slightly lower than specified (maximum) values.

Source: Aluminum Standards and Data. Courtesy of the Aluminum Association.

**Heat-treatability of Wrought Aluminum Alloys.**—In high-purity form, aluminum is soft and ductile. Most commercial uses, however, require greater strength than pure aluminum affords. This extra strength is achieved in aluminum first by the addition of other elements to produce various alloys, which singly or in combination impart strength to the metal. Further strengthening is possible by means that classify the alloys roughly into two categories, non-heat-treatable and heat-treatable.

*Non-heat-treatable alloys:* The initial strength of alloys in this group depends upon the hardening effect of elements such as manganese, silicon, iron and magnesium, singly or in

various combinations. The non-heat-treatable alloys are usually designated, therefore, in the 1000, 3000, 4000, or 5000 series. These alloys are work-hardenable, so further strengthening is made possible by various degrees of cold working, denoted by the "H" series of tempers. Alloys containing appreciable amounts of magnesium when supplied in strain-hardened tempers are usually given a final elevated-temperature treatment called *stabilizing* for property stability.

*Heat-treatable alloys:* The initial strength of alloys in this group is enhanced by the addition of alloying elements such as copper, magnesium, zinc, and silicon. These elements singly or in various combinations show increasing solid solubility in aluminum with increasing temperature, so it is possible to subject them to thermal treatments that will impart pronounced strengthening.

The first step, called *heat-treatment* or *solution heat-treatment*, is an elevated-temperature process designed to put the soluble element in solid solution. This step is followed by rapid quenching, usually in water, which momentarily "freezes" the structure and for a short time renders the alloy very workable. Some fabricators retain this more workable structure by storing the alloys at below freezing temperatures until they can be formed. At room or elevated temperatures the alloys are not stable after quenching, however, and precipitation of the constituents from the supersaturated solution begins. After a period of several days at room temperature, termed *aging* or *room-temperature precipitation*, the alloy is considerably stronger. Many alloys approach a stable condition at room temperature, but some alloys, particularly those containing magnesium and silicon or magnesium and zinc, continue to age-harden for long periods of time at room temperature.

Heating for a controlled time at slightly elevated temperatures provides even further strengthening and properties are stabilized. This process is called *artificial aging* or *precipitation hardening*. By application of the proper combination of solution heat-treatment, quenching, cold working and artificial aging, the highest strengths are obtained.

**Clad Aluminum Alloys.**—The heat-treatable alloys in which copper or zinc are major alloying constituents are less resistant to corrosive attack than the majority of non-heat-treatable alloys. To increase the corrosion resistance of these alloys in sheet and plate form they are often clad with high-purity aluminum, a low magnesium-silicon alloy, or an alloy containing 1 per cent zinc. The cladding, usually from 2½ to 5 per cent of the total thickness on each side, not only protects the composite due to its own inherently excellent corrosion resistance but also exerts a galvanic effect that further protects the core material.

Special composites may be obtained such as clad non-heat-treatable alloys for extra corrosion protection, for brazing purposes, or for special surface finishes. Some alloys in wire and tubular form are clad for similar reasons and on an experimental basis extrusions also have been clad.

**Aluminum Alloys, Wrought, Sheet.**—*Physical Properties:* In the form of sheets, the tensile strength varies from 35,000 for soft temper to 62,000 pounds per square inch for heat-treated sheets, and the elongation in 2 inches from 12 to 18 per cent. The yield strength of a heat-treated sheet is about 40,000 pounds per square inch minimum.

**Characteristics of Principal Aluminum Alloy Series Groups.**—*1000 series:* These alloys are characterized by high corrosion resistance, high thermal and electrical conductivity, low mechanical properties and good workability. Moderate increases in strength may be obtained by strain-hardening. Iron and silicon are the major impurities.

*2000 series:* Copper is the principal alloying element in this group. These alloys require solution heat-treatment to obtain optimum properties; in the heat-treated condition mechanical properties are similar to, and sometimes exceed, those of mild steel. In some instances artificial aging is employed to further increase the mechanical properties. This treatment materially increases yield strength, with attendant loss in elongation; its effect on tensile (ultimate) strength is not as great. The alloys in the 2000 series do not have as good corrosion resistance as most other aluminum alloys and under certain conditions they

may be subject to intergranular corrosion. Therefore, these alloys in the form of sheet are usually clad with a high-purity alloy or a magnesium-silicon alloy of the 6000 series which provides galvanic protection to the core material and thus greatly increases resistance to corrosion. Alloy 2024 is perhaps the best known and most widely used aircraft alloy.

*3000 series:* Manganese is the major alloying element of alloys in this group, which are generally non-heat-treatable. Because only a limited percentage of manganese, up to about 1.5 per cent, can be effectively added to aluminum, it is used as a major element in only a few instances. One of these, however, is the popular 3003, used for moderate-strength applications requiring good workability.

*4000 series:* The major alloying element of this group is silicon, which can be added in sufficient quantities to cause substantial lowering of the melting point without producing brittleness in the resulting alloys. For these reasons aluminum-silicon alloys are used in welding wire and as brazing alloys where a lower melting point than that of the parent metal is required. Most alloys in this series are non-heat-treatable, but when used in welding heat-treatable alloys they will pick up some of the alloying constituents of the latter and so respond to heat-treatment to a limited extent. The alloys containing appreciable amounts of silicon become dark gray when anodic oxide finishes are applied, and hence are in demand for architectural applications.

*5000 series:* Magnesium is one of the most effective and widely used alloying elements for aluminum. When it is used as the major alloying element or with manganese, the result is a moderate to high strength non-heat-treatable alloy. Magnesium is considerably more effective than manganese as a hardener, about 0.8 per cent magnesium being equal to 1.25 per cent manganese, and it can be added in considerably higher quantities. Alloys in this series possess good welding characteristics and good resistance to corrosion in marine atmospheres. However, certain limitations should be placed on the amount of cold work and the safe operating temperatures permissible for the higher magnesium content alloys (over about 3½ per cent for operating temperatures over about 150 deg. F) to avoid susceptibility to stress corrosion.

*6000 series:* Alloys in this group contain silicon and magnesium in approximate proportions to form magnesium silicide, thus making them capable of being heat-treated. The major alloy in this series is 6061, one of the most versatile of the heat-treatable alloys. Though less strong than most of the 2000 or 7000 alloys, the magnesium-silicon (or magnesium-silicide) alloys possess good formability and corrosion resistance, with medium strength. Alloys in this heat-treatable group may be formed in the -T4 temper (solution heat-treated but not artificially aged) and then reach full -T6 properties by artificial aging.

*7000 series:* Zinc is the major alloying element in this group, and when coupled with a smaller percentage of magnesium, results in heat-treatable alloys of very high strength. Other elements such as copper and chromium are usually added in small quantities. A notable member of this group is 7075, which is among the highest strength aluminum alloys available and is used in air-frame structures and for highly stressed parts.

**Type Metal.**—Antimony gives to metals the property of expansion on solidification, and hence, is used in type metal for casting type for the printing trades to insure completely filling the molds. Type metals are generally made with from 5 to 25 per cent of antimony, and with lead, tin and sometimes a small percentage of copper as the other alloying metals.

The compositions of a number of type metal alloys are as follows (figures given are per-centages): lead 77.5, tin 6.5, antimony 16; lead 70, tin, 10, antimony 18, copper, 2; lead 63.2, tin 12, antimony 24, copper 0.8; lead 60.5, tin 14.5, antimony 24–25, copper 0.75; lead 60, tin 35, antimony 5; and lead 55.5, tin 40, antimony 4.5.

A high grade of type metal is composed of the following percentages: lead 50; tin 25; and antimony 25.

### Magnesium Alloys

**Magnesium Alloys.**—Magnesium is the lightest of all structural metals. Silver-white in color, pure magnesium is relatively soft, so is rarely used for structural purposes in the pure state. Principal metallurgical uses for pure magnesium are as an alloying element for aluminum and other metals; as a reducing agent in the extraction of such metals as titanium, zirconium, hafnium, and uranium; as a nodularizing agent in the manufacture of ductile iron; and as a sulfur removal agent in steel manufacture. Magnesium alloys are made by alloying up to about 10 per cent of other metals and have low density and an excellent combination of mechanical properties, as shown in [Table 8a](#), resulting in high strength-to-weight ratios.

Magnesium alloys are the easiest of all the structural metals to machine, and these alloys have very high weld efficiencies. Magnesium is readily processed by all the standard casting and fabrication techniques used in metalworking, especially by pressure die casting. Because the metal work hardens rapidly, cold forming is limited to mild deformation, but magnesium alloys have excellent working characteristics at temperatures between 300 and 500 degrees F.

These alloys have relatively low elastic moduli, so they will absorb energy with good resistance to dents and high damping capacities. Fatigue strength also is good, particularly in the low-stress, high-cycle range. The alloys can be precipitation hardened, so mechanical properties can be improved by solution heat treatment and aging. Corrosion resistance was greatly improved recently, when methods were found to limit heavy metal impurities to "parts per million."

**Applications of Magnesium Alloys.**—Magnesium alloys are used in a wide variety of structural applications including industrial, materials handling, automotive, consumer-durable, and aerospace equipment. In industrial machinery, the alloys are used for parts that operate at high speeds, which must have light weight to allow rapid acceleration and minimize inertial forces. Materials handling equipment applications include hand trucks, dockboards, grain shovels, and gravity conveyors. Automotive applications include wheels, gearboxes, clutch housings, valve covers, and brake pedal and other brackets. Consumer durables include luggage, softball bats, tennis rackets, and housings for cameras and projectors. Their high strength-to-weight ratio suits magnesium alloys to use in a variety of aircraft structures, particularly helicopters. Very intricate shapes that are uneconomical to produce in other materials are often cast in magnesium, sometimes without draft. Wrought magnesium alloys are made in the form of bars, forgings, extrusions, wire, sheet, and plate.

**Alloy and Temper Designation.**—Magnesium alloys are designated by a standard four-part system established by the ASTM, and now also used by the SAE, that indicates both chemical composition and temper. Designations begin with two letters representing the two alloying elements that are specified in the greatest amount; these letters are arranged in order of decreasing percentage of alloying elements or alphabetically if they are present in equal amounts. The letters are followed by digits representing the respective composition percentages, rounded off to whole numbers, and then by a serial letter indicating some variation in composition of minor constituents. The final part, separated by a hyphen, consists of a letter followed by a number, indicating the temper condition. The letters that designate the more common alloying elements are A, aluminum; E, rare earths; H, thorium; K, zirconium; M, manganese; Q, silver; S, silicon; T, tin; Z, zinc.

The letters and numbers that indicate the temper designation are: F, as fabricated; O, annealed; H10, H11, strain hardened; H23, H24, H26, strain hardened and annealed; T4, solution heat treated; T5, artificially aged; T6, solution heat treated and artificially aged; and T8, solution heat treated, cold-worked, and artificially aged.

The nominal composition and typical properties of magnesium alloys are listed in [Tables 8a](#) and [8b](#).

**Table 8a. Nominal Compositions of Magnesium Alloys**

| Alloy  | Al   | Zn  | Mn <sup>a</sup> | Si  | Zr   | Ag  | Th  | Y   | Rare Earth |
|--|------|-----|-----------------|-----|------|-----|-----|-----|------------|
| Sand and Permanent Mold (Gravity Die) Castings |      |     |                 |     |      |     |     |     |            |
| AM100A-T61                                     | 10.0 | ... | 0.10            | ... | ...  | ... | ... | ... | ...        |
| AZ63A-T6                                       | 6.0  | 3.0 | 0.15            | ... | ...  | ... | ... | ... | ...        |
| AZ81A-T4                                       | 7.6  | 0.7 | 0.13            | ... | ...  | ... | ... | ... | ...        |
| AZ91C-T6                                       | 8.7  | 0.7 | 0.13            | ... | ...  | ... | ... | ... | ...        |
| AZ91E-T6 <sup>b</sup>                          | 8.7  | 0.7 | 0.17            | ... | ...  | ... | ... | ... | ...        |
| AZ92A-T6                                       | 9.0  | 2.0 | 0.10            | ... | ...  | ... | ... | ... | ...        |
| EZ33A-T5                                       | ...  | 2.6 | ...             | ... | 0.8  | ... | ... | ... | 3.3        |
| HK31A-T6                                       | ...  | 0.3 | ...             | ... | 0.7  | ... | 3.3 | ... | ...        |
| HZ32A-T6                                       | ...  | 2.1 | ...             | ... | 0.8  | ... | 3.3 | ... | 0.1        |
| K1A-F  | ...  | ... | ...             | ... | 0.7  | ... | ... | ... | ...        |
| QE22A-T6                                       | ...  | ... | ...             | ... | 0.7  | 2.5 | ... | ... | 2.2        |
| QH21A-T6                                       | ...  | 0.2 | ...             | ... | 0.7  | ... | 1.1 | ... | 1.1        |
| ZE41A-T5                                       | ...  | 4.3 | 0.15            | ... | 0.7  | ... | ... | ... | 1.3        |
| ZE63A-T6                                       | ...  | 5.8 | ...             | ... | 0.7  | ... | ... | ... | 2.6        |
| ZH62A-T5                                       | ...  | 5.7 | ...             | ... | 0.8  | ... | 1.8 | ... | ...        |
| ZK51A-T5                                       | ...  | 4.6 | ...             | ... | 0.8  | ... | ... | ... | ...        |
| ZK61A-T6                                       | ...  | 6.0 | ...             | ... | 0.8  | ... | ... | ... | ...        |
| WE54A-F  | ...  | ... | ...             | ... | 0.5  | ... | ... | 5.3 | 3.5        |
| Pressure Die Castings                          |      |     |                 |     |      |     |     |     |            |
| AZ91A-F  | 9.0  | 0.7 | 0.13            | ... | ...  | ... | ... | ... | ...        |
| AZ91B-F <sup>c</sup>                           | 9.0  | 0.7 | 0.13            | ... | ...  | ... | ... | ... | ...        |
| AZ91D-F <sup>b</sup>                           | 9.0  | 0.7 | 0.15            | ... | ...  | ... | ... | ... | ...        |
| AM60A-F  | 6.0  | ... | 0.13            | ... | ...  | ... | ... | ... | ...        |
| AM60B-F <sup>b</sup>                           | 6.0  | ... | 0.25            | ... | ...  | ... | ... | ... | ...        |
| AS41A-F <sup>d</sup>                           | 4.3  | ... | 0.35            | 1.0 | ...  | ... | ... | ... | ...        |
| Extruded Bars and Shapes                       |      |     |                 |     |      |     |     |     |            |
| AZ10A-F  | 1.3  | 0.4 | 0.20            | ... | ...  | ... | ... | ... | ...        |
| AZ31B-F  | 3.0  | 1.0 | 0.20            | ... | ...  | ... | ... | ... | ...        |
| AZ31C-F  | 3.0  | 1.0 | 0.15            | ... | ...  | ... | ... | ... | ...        |
| AZ61A-F  | 6.5  | 1.0 | 0.15            | ... | ...  | ... | ... | ... | ...        |
| AZ80A-T5                                       | 8.5  | 0.5 | 0.12            | ... | ...  | ... | ... | ... | ...        |
| HM31A-F  | ...  | ... | 1.20            | ... | ...  | ... | 3.0 | ... | ...        |
| M1A-F  | ...  | ... | 1.20            | ... | ...  | ... | ... | ... | ...        |
| ZK40A-T5                                       | ...  | 4.0 | ...             | ... | 0.45 | ... | ... | ... | ...        |
| ZK60A-F  | ...  | 5.5 | ...             | ... | 0.45 | ... | ... | ... | ...        |
| Sheet and Plate                                |      |     |                 |     |      |     |     |     |            |
| AZ31B-H24                                      | 3.0  | 1.0 | 0.20            | ... | ...  | ... | ... | ... | ...        |
| AZ31C-H24                                      | 3.0  | 1.0 | 0.15            | ... | ...  | ... | ... | ... | ...        |
| HK31A-H24                                      | ...  | ... | ...             | ... | 0.7  | ... | 3.3 | ... | ...        |
| HM21A-T8                                       | ...  | ... | 0.80            | ... | ...  | ... | 2.0 | ... | ...        |

<sup>a</sup> All manganese values are minimum.<sup>b</sup> High-purity alloy, Ni, Fe, and Cu severely restricted.<sup>c</sup> 0.30 per cent maximum residual copper is allowed.<sup>d</sup> For battery applications.Source: *Metals Handbook*, 9th edition, Vol. 2, American Society for Metals.



**Table 8b. Typical Room-Temperature Mechanical Properties of Magnesium Alloys**

| Alloy  | Tensile Strength (ksi) | Yield Strength |                   |               | Elongation in 2 in. (%) | Shear Strength (ksi) | Hardness Rockwell B <sup>a</sup> |
|--|------------------------|----------------|-------------------|---------------|-------------------------|----------------------|----------------------------------|
|  |                        | Tensile (ksi)  | Compressive (ksi) | Bearing (ksi) |                         |                      |                                  |
| Sand and Permanent Mold (Gravity Die) Castings |                        |                |                   |               |                         |                      |                                  |
| AM100A-T61                                     | 40                     | 22             | 22                | 68            | 1                       | ...                  | 69                               |
| AZ63A-T6                                       | 40                     | 14             | 14                | 44            | 12                      | 18                   | 55                               |
| AZ81A-T4                                       | 40                     | 12             | 12                | 35            | 15                      | 21                   | 55                               |
| AZ91C-T6                                       | 40                     | 21             | 21                | 52            | 6                       | 21                   | 70                               |
| AZ91E-T6 <sup>b</sup>                          | 40                     | 21             | 21                | 52            | 6                       | 21                   | 70                               |
| AZ92A-T6                                       | 40                     | 22             | 22                | 65            | 3                       | 21                   | 81                               |
| EZ33A-T5                                       | 23                     | 16             | 16                | 40            | 3                       | 20                   | 50                               |
| HK31A-T6                                       | 32                     | 15             | 15                | 40            | 8                       | 21                   | 55                               |
| HZ32A-T6                                       | 27                     | 13             | 13                | 37            | 4                       | 20                   | 55                               |
| K1A-F  | 26                     | 8              | 8                 | 18            | 19                      | 8                    | ...                              |
| QE22A-T6                                       | 38                     | 28             | 28                | ...           | 3                       | ...                  | 80                               |
| QH21A-T6                                       | 40                     | 30             | 30                | ...           | 4                       | 22                   | ...                              |
| ZE41A-T5                                       | 30                     | 20             | 20                | 51            | 4                       | 23                   | 62                               |
| ZE63A-T6                                       | 44                     | 28             | 28                | ...           | 10                      | ...                  | 60-85                            |
| ZH62A-T5                                       | 35                     | 22             | 22                | 49            | 4                       | 23                   | 70                               |
| ZK51A-T5                                       | 30                     | 20             | 20                | 51            | 4                       | 22                   | 62                               |
| ZK61A-T6                                       | 45                     | 28             | 28                | ...           | 10                      | ...                  | ...                              |
| WE54A-F  | 40                     | 29             | 29                | ...           | 4                       | ...                  | ...                              |
| Pressure Die Castings                          |                        |                |                   |               |                         |                      |                                  |
| AZ91A-F  | 34                     | 23             | 23                | ...           | 3                       | 20                   | 63                               |
| AZ91B-FAZ91B-F <sup>c</sup>                    | 34                     | 23             | 23                | ...           | 3                       | 20                   | 63                               |
| AZ91D-F <sup>b</sup>                           | 34                     | 23             | 23                | ...           | 3                       | 20                   | 63                               |
| AM60A-F  | 32                     | 19             | 19                | ...           | 8                       | ...                  | ...                              |
| AM60B-F <sup>b</sup>                           | 32                     | 19             | 19                | ...           | 8                       | ...                  | ...                              |
| AS41A-F <sup>d</sup>                           | 31                     | 20             | 20                | ...           | 6                       | ...                  | ...                              |
| Extruded Bars and Shapes                       |                        |                |                   |               |                         |                      |                                  |
| AZ10A-F  | 35                     | 21             | 10                | ...           | 10                      | ...                  | ...                              |
| AZ31B-F  | 38                     | 29             | 14                | 33            | 15                      | 19                   | 49                               |
| AZ31C-F  | 38                     | 29             | 14                | 33            | 15                      | 19                   | 49                               |
| AZ61A-F  | 45                     | 33             | 19                | 41            | 16                      | 20                   | 60                               |
| AZ80A-T5                                       | 55                     | 40             | 35                | ...           | 7                       | 24                   | 82                               |
| HM31A-F  | 42                     | 33             | 27                | 50            | 10                      | 22                   | ...                              |
| M1A-F  | 37                     | 26             | 12                | 28            | 12                      | 18                   | 44                               |
| ZK40A-T5                                       | 40                     | 37             | 20                | ...           | 4                       | ...                  | ...                              |
| ZK60A-F  | 51                     | 41             | 36                | 59            | 11                      | 26                   | 88                               |
| Sheet and Plate                                |                        |                |                   |               |                         |                      |                                  |
| AZ31B-H24                                      | 42                     | 32             | 26                | 47            | 15                      | 23                   | 73                               |
| AZ31C-H24                                      | 42                     | 32             | 26                | 47            | 15                      | 23                   | 73                               |
| HK31A-H24                                      | 38                     | 30             | 23                | 41            | 9                       | ...                  | 68                               |
| HM21A-T8                                       | 34                     | 25             | 19                | 39            | 11                      | 18                   | ...                              |

<sup>a</sup> 500 kg load, 10-mm ball.<sup>b</sup> High-purity alloy, Ni, Fe, and Cu severely restricted.<sup>c</sup> 0.30 per cent maximum residual copper is allowed.<sup>d</sup> For battery applications.Source: *Metals Handbook*, 9th edition, Vol. 2, American Society for Metals.

### Nickel and Nickel Alloys

**Characteristics of Nickel and Nickel Alloys.**—Nickel is a white metal, similar in some respects to iron but with good oxidation and corrosion resistances. Nickel and its alloys are used in a variety of applications, usually requiring specific corrosion resistance or high strength at high temperature. Some nickel alloys exhibit very high toughness; others have very high strength, high proportional limits, and high moduli compared with steel. Commercially, pure nickel has good electrical, magnetic, and magnetostrictive properties. Nickel alloys are strong, tough, and ductile at cryogenic temperatures, and several of the so-called nickel-based superalloys have good strength at temperatures up to 2000 degrees F.

Most wrought nickel alloys can be hot and cold-worked, machined, and welded successfully; an exception is the most highly alloyed nickel compound—forged nickel-based superalloys—in which these operations are more difficult. The casting alloys can be machined or ground, and many can be welded and brazed.

There are five categories into which the common nickel-based metals and alloys can be separated: the pure nickel and high nickel (over 94 per cent Ni) alloys; the nickel–molybdenum and nickel–molybdenum–chromium superalloys, which are specifically for corrosive or high-temperature, high-strength service; the nickel–molybdenum–chromium–copper alloys, which are also specified for corrosion applications; the nickel–copper (Monel) alloys, which are used in actively corrosive environments; and the nickel–chromium and nickel–chromium–iron superalloys, which are noted for their strength and corrosion resistance at high temperatures.

Descriptions and compositions of some commonly used nickel and high nickel alloys are shown in [Table 9](#).

### Titanium and Titanium Alloys

Titanium is a gray, light metal with a better strength-to-weight ratio than any other metal at room temperature, and is used in corrosive environments or in applications that take advantage of its light weight, good strength, and nonmagnetic properties. Titanium is available commercially in many alloys, but multiple requirements can be met by a single grade of the commercially pure metal. The alloys of titanium are of three metallurgical types: alpha, alpha–beta, and beta, with these designations referring to the predominant phases present in the microstructure.

Titanium has a strong affinity for hydrogen, oxygen, and nitrogen gases, which tend to embrittle the material; carbon is another embrittling agent. Titanium is outstanding in its resistance to strongly oxidizing acids, aqueous chloride solutions, moist chlorine gas, sodium hypochlorite, and seawater and brine solutions. Nearly all nonaircraft applications take advantage of this corrosion resistance. Its uses in aircraft engine compressors and in airframe structures are based on both its high corrosion resistance and high strength-to-weight ratio.

Procedures for forming titanium are similar to those for forming stainless steel. Titanium and its alloys can be machined and abrasive ground; however, sharp tools and continuous feed are required to prevent work hardening. Tapping is difficult because the metal galls.

Titanium castings can be produced by investment or graphite mold methods; however, because of the highly reactive nature of the metal in the presence of oxygen, casting must be done in a vacuum.

Generally, titanium is welded by gas-tungsten arc or plasma arc techniques, and the key to successful welding lies in proper cleaning and shielding. The alpha–beta titanium alloys can be heat treated for higher strength, but they are not easily welded. Beta and alpha–beta alloys are designed for formability; they are formed in the soft state, and then heat treated for high strength.

The properties of some wrought titanium alloys are shown in [Table 10](#).

**Table 9. Common Cast and Wrought Nickel and High Nickel Alloys — Designations, Compositions, Typical Properties, and Uses**

| UNS Designation | Description and Common Name               | Nominal Composition (Weight %)                      | Typical Room-Temperature Properties |                  |            | Form           | Typical Uses   |
|-----------------|---|---|-------------------------------------|------------------|------------|----------------|--|
|                 |   |   | Tensile (ksi)                       | 0.2% Yield (ksi) | Elong. (%) |                |  |
| N02200          | Commercially pure Ni (Nickel 200)         | 99.5 Ni   | 67                                  | 22               | 47         | Wrought        | Food processing and chemical equipment.  |
| N04400          | Nickel-copper alloy (Monel 400)           | 65 Ni, 32 Cu, 2 Fe                                  | 79                                  | 30               | 48         | Wrought        | Valves, pumps, shafts, marine fixtures and fasteners, electrical and petroleum refining equipment. |
| N05500          | Age-hardened Ni-Cu alloy (Monel K 500)    | 65 Ni, 30 Cu, 2 Fe, 3 Al + Ti                       | 160                                 | 111              | 24         | Wrought        | Pump shafts, impellers, springs, fasteners, and electronic and oil well components.                |
| N06002          | Ni-Cr Alloy (Hastelloy X)                 | 60 Ni, 22 Cr, 19 Fe, 9 Mo, 0.6 W                    | 114                                 | 52               | 43         | Wrought        | Turbine and furnace parts, petrochemical equipment.  |
| N06003          | Ni-Cr alloy (Nichrome V)                  | 80 Ni, 20 Cr  | 100                                 | 60               | 30         | Wrought        | Heating elements, resistors, electronic parts.   |
| N06333          | Ni-Cr alloy (RA 333)                      | 48 Ni, 25 Cr, 18 Fe, 3 Mo, 3 W, 3 Co                | 100                                 | 50               | 50         | Wrought        | Turbine and furnace parts.   |
| N06600          | Ni-Cr alloy (Inconel 600)                 | 75 Ni, 15 Cr, 10 Fe                                 | 90                                  | 36               | 47         | Wrought        | Chemical, electronic, food processing and heat treating equipment; nuclear steam generator tubing. |
| N06625          | Ni-Cr alloy (Inconel 625)                 | 61 Ni, 21 Cr, 2 Fe, 9 Mo, 4 Nb                      | 142                                 | 86               | 42         | Wrought        | Turbine parts, marine and chemical equipment.  |
| N07001          | Age-hardened Ni-Cr alloy (Waspalloy)      | 58 Ni, 20 Cr, 14 Co, 4 Mo, 3 Al, 1.3 Ti, B, Zr      | 185                                 | 115              | 25         | Wrought        | Turbine parts.   |
| N07500          | Age-hardened Ni-Cr alloy (Udimet 500)     | 52 Ni, 18 Cr, 19 Co, 4 Mo, 3 Al, 3 Ti, B, Zr        | 176                                 | 110              | 16         | Wrought & Cast | Turbine parts.   |
| N07750          | Age-hardened Ni-Cr alloy (Inconel X-750)  | 73 Ni, 16 Cr, 7 Fe, 2.5 Ti, 1 Al, 1 Nb              | 185                                 | 130              | 20         | Wrought        | Turbine parts, nuclear reactor springs, bolts, extrusion dies, forming tools.                      |
| N08800          | Ni-Cr-Fe alloy (Incoloy 800)              | 32 Ni, 21 Cr, 46 Fe, 0.4 Ti, 0.4 Al                 | 87                                  | 42               | 44         | Wrought        | Heat exchangers, furnace parts, chemical and power plant piping.                                   |
| N08825          | Ni-Cr-Fe alloy (Incoloy 825)              | 42 Ni, 22 Cr, 30 Fe, 3 Mo, 2 Cu, 1 Ti, Al           | 91                                  | 35               | 50         | Wrought        | Heat treating and chemical handling equipment.   |
| N09901          | Age-hardened Ni-Cr-Fe alloy (Incoloy 901) | 43 Ni, 12 Cr, 36 Fe, 6 Mo, 3 Ti + Al, B             | 175                                 | 130              | 14         | Wrought        | Turbine parts.   |
| N10001          | Ni-Mo alloy (Hastelloy B)                 | 67 Ni, 28 Mo, 5 Fe                                  | 121                                 | 57               | 63         | Wrought        | Chemical handling equipment.   |
| N10004          | Ni-Cr-Mo alloy (Hastelloy W)              | 59 Ni, 5 Cr, 25 Mo, 5 Fe, 0.6 V                     | 123                                 | 53               | 55         | Wrought        | Weld wire for joining dissimilar metals, engine repair and maintenance.                            |
| N10276          | Ni-Cr-Mo alloy (Hastelloy C-276)          | 57 Ni, 15 Cr, 16 Mo, 5 Fe, 4 W, 2 Co                | 116                                 | 52               | 60         | Wrought        | Chemical handling equipment.   |
| N13100          | Ni-Co alloy (IN 100)                      | 60 Ni, 10 Cr, 15 Co, 3 Mo, 5.5 Al, 5 Ti, 1 V, B, Zr | 147                                 | 123              | 9          | Cast           | Turbine parts.   |

**Table 10. Mechanical Properties of Wrought Titanium Alloys**

| Nominal Composition (%)                    | Condition  | Tensile Strength (ksi) | Room Temperature     |                | Reduction in Area (%) |
|--|--|------------------------|----------------------|----------------|-----------------------|
|  |  |                        | Yield Strength (ksi) | Elongation (%) |                       |
| Commercially Pure                          |  |                        |                      |                |                       |
| 99.5 Ti                                    | Annealed   | 48                     | 35                   | 30             | 55                    |
| 99.2 Ti                                    | Annealed   | 63                     | 50                   | 28             | 50                    |
| 99.1 Ti                                    | Annealed   | 75                     | 65                   | 25             | 45                    |
| 99.0 Ti                                    | Annealed   | 96                     | 85                   | 20             | 40                    |
| 99.2 Ti <sup>a</sup>                       | Annealed   | 63                     | 50                   | 28             | 50                    |
| 98.9 Ti <sup>b</sup>                       | Annealed   | 75                     | 65                   | 25             | 42                    |
| Alpha Alloys                               |  |                        |                      |                |                       |
| 5 Al, 2.5 Sn                               | Annealed   | 125                    | 117                  | 16             | 40                    |
| 5 Al, 2.5 Sn (low O <sub>2</sub> )         | Annealed   | 117                    | 108                  | 16             | ...                   |
| Near Alpha Alloys                          |  |                        |                      |                |                       |
| 8 Al, 1 Mo, 1 V                            | Duplex annealed                                  | 145                    | 138                  | 15             | 28                    |
| 11 Sn, 1 Mo, 2.25 Al, 5.0 Zr, 1 Mo, 0.2 Si | Duplex annealed                                  | 160                    | 144                  | 15             | 35                    |
| 6 Al, 2 Sn, 4 Zr, 2 Mo                     | Duplex annealed                                  | 142                    | 130                  | 15             | 35                    |
| 5 Al, 5 Sn, 2 Zr, 2 Mo, 0.25 Si            | 975°C (1785°F) (½ h), AC 595°C (1100°F)(2 h), AC | 152                    | 140                  | 13             | ...                   |
| 6 Al, 2 Nb, 1 Ta, 1 Mo                     | As rolled 2.5 cm (1 in.) plate                   | 124                    | 110                  | 13             | 34                    |
| 6 Al, 2 Sn, 1.5 Zr, 1 Mo, 0.35 Bi, 0.1 Si  | Beta forge + duplex anneal                       | 147                    | 137                  | 11             | ...                   |
| Alpha-Beta Alloys                          |  |                        |                      |                |                       |
| 8 Mn                                       | Annealed   | 137                    | 125                  | 15             | 32                    |
| 3 Al, 2.5 V                                | Annealed   | 100                    | 85                   | 20             | ...                   |
| 6 Al, 4 V                                  | Annealed   | 144                    | 134                  | 14             | 30                    |
|  | Solution + age                                   | 170                    | 160                  | 10             | 25                    |
| 6 Al, 4 V (low O <sub>2</sub> )            | Annealed   | 130                    | 120                  | 15             | 35                    |
| 6 Al, 6 V, 2 Sn                            | Annealed   | 155                    | 145                  | 14             | 30                    |
|  | Solution + age                                   | 185                    | 170                  | 10             | 20                    |
| 7 Al, 4 Mo                                 | Solution + age                                   | 160                    | 150                  | 16             | 22                    |
| 6 Al, 2 Sn, 4 Zr, 6 Mo                     | Solution + age                                   | 184                    | 170                  | 10             | 23                    |
| 6 Al, 2 Sn, 2 Zr, 2 Mo, 2 Cr, 0.25 Si      | Solution + age                                   | 185                    | 165                  | 11             | 33                    |
| 10 V, 2 Fe, 3 Al                           | Solution + age                                   | 185                    | 174                  | 10             | 19                    |
| Beta Alloys                                |  |                        |                      |                |                       |
| 13 V, 11 Cr, 3 Al                          | Solution + age                                   | 177                    | 170                  | 8              | ...                   |
|  | Solution + age                                   | 185                    | 175                  | 8              | ...                   |
| 8 Mo, 8 V, 2 Fe, 3 Al                      | Solution + age                                   | 190                    | 180                  | 8              | ...                   |
| 3 Al, 8 V, 6 Cr, 4 Mo, 4 Zr                | Solution + age                                   | 210                    | 200                  | 7              | ...                   |
|  | Annealed   | 128                    | 121                  | 15             | ...                   |
| 11.5 Mo, 6 Zr, 4.5 Sn                      | Solution + age                                   | 201                    | 191                  | 11             | ...                   |

<sup>a</sup> Also contains 0.2 Pd.<sup>b</sup> Also contains 0.8 Ni and 0.3 Mo.

Source: Titanium Metals Corp. of America and RMI Co.

## PLASTICS

## PLASTICS

## Properties of Plastics

## Characteristics of Important Plastics Families

|  |  |
|--|--|
| ABS<br>(acrylonitrile-butadiene-styrene) | Rigid, low-cost thermoplastic, easily machined and thermo-formed.  |
| Acetal                                   | Engineering thermoplastic with good strength, wear resistance, and dimensional stability. More dimensionally stable than nylon under wet and humid conditions.   |
| Acrylic                                  | Clear, transparent, strong, break-resistant thermoplastic with excellent chemical resistance and weatherability.   |
| CPVC<br>(chlorinated PVC)                | Thermoplastic with properties similar to PVC, but operates to a 40-60°F higher temperature.  |
| Fiberglass                               | Thermosetting composite with high strength-to-weight ratio, excellent dielectric properties, and unaffected by corrosion.  |
| Nylon                                    | Thermoplastic with excellent impact resistance, ideal for wear applications such as bearings and gears, self-lubricating under some circumstances.   |
| PEEK<br>(polyetheretherketone)           | Engineering thermoplastic, excellent temperature resistance, suitable for continuous use above 500°F, excellent flexural and tensile properties.   |
| PET<br>(polyethylene-terephthalate)      | Dimensionally stable thermoplastic with superior machining characteristics compared to acetal.   |
| Phenolic                                 | Thermosetting family of plastics with minimal thermal expansion, high compressive strength, excellent wear and abrasion resistance, and a low coefficient of friction. Used for bearing applications and molded parts. |
| Polycarbonate                            | Transparent tough thermoplastic with high impact strength, excellent chemical resistance and electrical properties, and good dimensional stability.  |
| Polypropylene                            | Good chemical resistance combined with low moisture absorption and excellent electrical properties, retains strength up to 250°F.  |
| Polysulfone                              | Durable thermoplastic, good electrical properties, operates at temperatures in excess of 300°F.  |
| Polyurethane                             | Thermoplastic, excellent impact and abrasion resistance, resists sunlight and weathering.  |
| PTFE<br>(polytetrafluoroethylene)        | Thermoplastic, low coefficient of friction, withstands up to 500°F, inert to chemicals and solvents, self-lubricating with a low thermal-expansion rate.   |
| PVC<br>(polyvinyl chloride)              | Thermoplastic, resists corrosive solutions and gases both acid and alkaline, good stiffness.   |
| PVDF<br>(polyvinylidene-fluoride)        | Thermoplastic, outstanding chemical resistance, excellent substitute for PVC or polypropylene. Good mechanical strength and dielectric properties.   |

**Plastics Materials.**—Plastics materials, often called resins, are made up of many repeating groups of atoms or molecules linked in long chains (called polymers) that combine such elements as oxygen, hydrogen, nitrogen, carbon, silicon, fluorine, and sulfur. Both the lengths of the chains and the mechanisms that bond the links of the chains together are related directly to the mechanical and physical properties of the materials. There are two main groups: thermoplastics and thermosets.

*Thermoplastic materials* become soft and moldable when heated, and change back to solids when allowed to cool. Examples of thermoplastics are acetal, acrylic, cellulose acetate, nylon, polyethylene, polystyrene, vinyl, and nylon. Thermoplastic materials that are flexible even when cool are known as thermoplastic elastomers or TPEs. When thermoplastic materials are heated, the linked chains of molecules can move relative to each other, allowing the mass to flow into a different shape. Cooling prevents further flow. Although the heating/cooling cycle can be repeated, recycling reduces mechanical properties and appearance.

*Thermoset plastics* such as amino, epoxy, phenolic, and unsaturated polyesters, are so named because they are changed chemically during processing and become hard solids. Although the structures of thermoset materials are similar to those of thermoplastic materials, processing develops cross-links between adjacent molecules, forming complex networks that prevent relative movement between the chains at any temperature. Many rubbers that are processed by vulcanizing, such as butyl, latex, neoprene, nitrile, polyurethane, and silicone, also are classified as thermosets. Heating a thermoset degrades the material so that it cannot be reprocessed satisfactorily.

*Elastomers* are flexible materials that can be stretched up to about double their length at room temperature and can return to their original length when released. Thermoplastic elastomers are often used in place of rubber, and may also be used as additives to improve the impact strength of rigid thermoplastics.

**Structures.**—Thermoplastics can be classified by their structures into categories such as amorphous (noncrystalline), crystalline, and liquid crystalline polymers (LCP). Amorphous thermoplastics include polycarbonate, polystyrene, ABS (acrylonitrile-butadiene-styrene), SAN (styrene-acrylonitrile), and PVC (polyvinylchloride). Crystalline thermoplastics have polymer chains that are packed together in an organized way, as distinct from the unorganized structures of amorphous plastics, and include acetal, nylon, polyethylene, polypropylene, and polyester. The organized regions in crystalline thermoplastics are joined by noncrystalline (amorphous) zones, and the structures are such that the materials are stronger and stiffer, though less resistant to impact, than completely noncrystalline materials. Crystalline thermoplastics have higher melting temperatures and higher shrinkage and warpage factors than amorphous plastics. Liquid crystalline plastics are polymers with highly ordered rod-like structures and have high mechanical property values, good dimensional stability and chemical resistance, and are easy to process, with melting temperatures similar to those of crystalline plastics. Unlike amorphous and crystalline plastics, liquid crystalline plastics retain significant order in the melt phase. As a result, they have the lowest shrinkage and warpage of the three types of thermoplastics.

**Mixtures.**—Characteristics of plastics materials can be changed by mixing or combining different types of polymers and by adding nonplastics materials. Particulate fillers such as wood flour, silica, sand, ceramic and carbon powder, tiny glass balls, and powdered metal are added to increase modulus and electrical conductivity, to improve resistance to heat or ultraviolet light, and to reduce cost, for example. Plasticizers may be added to decrease modulus and increase flexibility. Other additives may be used to increase resistance to effects of ultraviolet light and heat or to prevent oxidation, and for a variety of other purposes.

*Reinforcing fibers* of glass, carbon, or Aramid (aromatic polyamide fibers having high tensile strength, a range of moduli, good toughness, and stress-strain behavior similar to

that of metals) are added to improve mechanical properties. Careful design and process selection must be used to position the fibers so that they will provide the required strength where it is needed. Continuous fiber may be positioned carefully in either a thermoplastics or thermoset matrix to produce basic parts generally called composites, which have the highest mechanical properties and cost of the reinforced plastics.

*Copolymers* embody two or more different polymers and may have properties that are completely different from those of the individual polymers (homopolymers) from which they are made. An approach known as alloying consists of pure mechanical blending of two or more different polymers, often with special additives to make them compatible. These "alloys" are compounded so as to retain the most desirable characteristics of each constituent, especially in impact strength and flame resistance. However, properties usually are intermediate between those of the constituent materials.

**Physical Properties.**—Almost all proposed uses of plastics require some knowledge of the physical properties of the materials, and this information is generally readily available from manufacturers. Properties such as density, ductility, elasticity and plasticity, homogeneity, uniformity of composition, shrinkage during cooling from the molding temperature, transmittal of light, toughness (resistance to impact), brittleness, notch sensitivity, isotropy (properties that are the same when measured in any direction) and anisotropy (properties that vary when measured in different directions), and lubricity (load-bearing characteristics under relative motion) may all need consideration when a material suitable for a specific application is to be specified.

Most of the terms used to describe the physical characteristics of metals, such as density, ductility, brittleness, elasticity, notch sensitivity, specific gravity, and toughness, have similar meanings when they are applied to plastics, but different measures are often used with plastics. Like cast metals, many plastics are isotropic so that their characteristics are the same measured in any direction. Properties of rolled metals and extruded plastics vary when measured in the longitudinal and transverse directions, so these materials are anisotropic.

*Density* is a measure of the mass per unit volume, usually expressed in lb/in.<sup>3</sup> or g/cm<sup>3</sup> at a temperature of 73.4 degrees F (23 degrees C). Density information is used mainly to calculate the amount of material required to make a part of a given volume, the volume being calculated from drawing dimensions.

*Specific gravity* is the ratio of the mass of a given volume of a material to the mass of the same volume of water, both measured at 73.4 degrees F (23 degrees C). The ratio is dimensionless so is useful for comparing different materials, and is used in cost estimating and quality control.

*Shrinkage* is the ratio of the dimension of the plastics molding to the corresponding dimension of the mold, expressed in in./in. or cm/cm, both at room temperature. As with a die casting die, the moldmaker uses this ratio to determine mold cavity measurements that will produce a part of the required dimensions. Shrinkage in a given material can vary with wall thickness, direction of flow of the plastics in the mold, and molding conditions. Amorphous and liquid crystalline thermoplastics have lower shrinkage ratios than crystalline thermoplastics. Glass-reinforced and filled materials have lower shrinkage than unfilled materials.

*Water absorption* is the amount of increase in weight of a material due to absorption of water, expressed as a percentage of the original weight. Standard test specimens are first dried for 24 hr, then weighed before and after immersion in water at 73.4 degrees F (23 degrees C) for various lengths of time. Water absorption affects both mechanical and electrical properties and part dimensions. Parts made from materials with low water absorption rates tend to have greater dimensional stability.

*Opacity (or transparency)* is a measure of the amount of light transmitted through a given material under specific conditions. Measures are expressed in terms of haze and

luminous transmittance. Haze measurements indicate the percentage of light transmitted through a test specimen that is scattered more than 2.5 degrees from the incident beam. Luminous transmittance is the ratio of transmitted light to incident light.

*Elasticity* is the ability of a material to return to its original size and shape after being deformed. Most plastics have limited elasticity, although rubber and materials classified as thermoplastic elastomers (TPEs) have excellent elasticity.

*Plasticity* is the inverse of elasticity, and a material that tends to stay in the shape or size to which it has been deformed has high plasticity. Some plastics can be formed cold by being stressed beyond the yield point and such plastics then exhibit plasticity. When thermoplastics are heated to their softening temperature, they have almost perfect plasticity.

*Ductility* is the ability of a material to be stretched, pulled, or rolled into shape without destroying the integrity of the material.

*Toughness* is a measure of the ability of a material to absorb mechanical energy without cracking or breaking. Tough material can absorb mechanical energy with either elastic or plastic deformation. High-impact unfilled plastics generally have excellent toughness, and low- or moderate-impact materials may also be tough if their ultimate strength is high enough (see *Typical Stress–Strain Curves* on page 598). The area under the stress–strain curve is often used as the measure of toughness for a particular plastics material.

*Brittleness* is the lack of toughness. Brittle plastics frequently have low impact and high stiffness properties. Many glass-reinforced and mineral-filled materials are brittle.

*Notch sensitivity* is a measure of the ease with which a crack progresses through a material from an existing notch, crack, or sharp corner.

*Lubricity* describes the load-bearing characteristics of a material under relative motion. Plastics with good lubricity have low coefficients of friction with other materials (or sometimes with themselves) and no tendency to gall.

*Homogeneous* means uniform. The degree of homogeneity indicates the uniformity of composition of a material throughout its mass. In a completely homogeneous body, the smallest sample has the same physical properties as the body. An unfilled thermoplastics is a reasonably homogeneous material.

*Heterogeneous* means varying. In a heterogeneous body, for example, a glass-reinforced material, the composition varies from point to point. Many heterogeneous materials are treated as homogeneous for design purposes because a small sample of the material has the same properties as the body.

*Isotropy* means that the properties at any point in a body are the same, regardless of the direction in which they are measured.

*Anisotropy* means that the physical properties of a material depend on the direction of measurement. Various degrees of anisotropy exist, depending on the amount of symmetry of the material or component shape. For example, cast metals and plastics tend to be isotropic so that samples cut in any direction within a cast body tend to have the same physical properties. However, rolled metals tend to develop crystal orientation in the direction of rolling so that they have different mechanical properties in the rolling and transverse-to-rolling directions.

Extruded plastics film also may have different properties in the extruding and transverse directions so that these materials are oriented biaxially and are anisotropic. Composite materials that have fiber reinforcements carefully oriented in the direction of applied loads, surrounded by a plastics matrix, have a high degree of property orientation with direction at various points in the structure and are anisotropic.

As another example, wood, page 411, is an anisotropic material with distinct properties in three directions and is very stiff and strong in the direction of growth. Fair properties are also found in one direction perpendicular to the growth direction, but in a third direction at right angles to the other two directions, the mechanical properties are much lower.



The preceding examples involve mechanical properties, but anisotropy is also used in referring to the way a material shrinks in the mold. Anisotropic shrinkage is important in molding crystalline and glass-fiber-reinforced materials for which shrinkage values are usually listed for the flow direction and the cross-flow direction. These values are of most concern to the tool designer and molder, but the existence of anisotropy and its severity must be considered when a material is chosen for a part having tight tolerances.

*Significance of Elasticity, Homogeneity, and Isotropy:* Structural analysis during design of components uses two independent constants, Young's modulus ( $E$ ) and Poisson's ratio ( $\nu$ ), but two constants are sufficient only for elastic, isotropic materials that respond linearly to loads (when load is proportional to deformation). Designers often use the same values for these constants everywhere in the structure, which is correct only if the structure is homogeneous.

Assumptions of linear elasticity, isotropy, and homogeneity are reasonable for many analyses and are a good starting point, but use of these assumptions can lead to significant design errors with plastics, particularly with glass-reinforced and liquid crystalline polymers, which are highly anisotropic. In the following, plastics are assumed to be linearly elastic, homogeneous, and isotropic to allow a simpler presentation of mechanical properties in line with the data provided in plastics manufacturers' marketing data sheets. The standard equations of structural analysis (bending, torsion, pressure in a pipe, etc.) also require these assumptions.

As the degree of anisotropy increases, the number of constants or moduli required to describe the material also increases, up to a maximum of 21. Uncertainty about material properties and the questionable applicability of the simple analysis techniques employed point to the need for extensive end-use testing of plastics parts before approval of a particular application. A partial solution to this problem lies in the use of finite-element-analysis (FEA) methods. The applicability of FEA methods requires good understanding of the anisotropic nature of plastics materials.

**Mechanical Properties.**—Almost all end-use applications involve some degree of loading, so mechanical properties are of prime importance in designing with plastics. Material selection is usually based on manufacturers' marketing data sheets listing tensile strength, modulus of elasticity ( $E$ ), elongation, impact strength, stress and strain behavior, and shear strength. Suppliers' data often are generated under standard test conditions so may not be directly transferable to the components produced. Because of the somewhat lower modulus of elasticity of plastics materials ( $10^5$  for plastics compared with  $10^6$  lb<sub>f</sub>/in<sup>2</sup> for metals), different units of measure are used to express the results.

Determination of the true meaning of mechanical properties and their relation to end-use requirements is of vital importance in design. In practical applications, materials are seldom subjected to steady deformation without the influence of other factors such as environment and temperature. A thorough understanding of mechanical properties and tests used to determine such properties, and the effects of adverse or beneficial conditions on mechanical properties over long time periods, is extremely important. Some manufacturers offer design and technical advice to customers who do not possess this understanding.

*Stress:* A three-dimensional body having a balanced system of external forces  $F_1$  through  $F_5$  acting on it, such that the body is at rest, is shown in Fig. 1. Such a body develops internal forces to transfer and distribute the external loads. If the body is cut at an arbitrary cross-section and one part is removed, as shown at the right in Fig. 1, a new system of

forces acting on the cut surface is developed to balance the remaining external forces. Similar forces (stresses) exist within the uncut body.

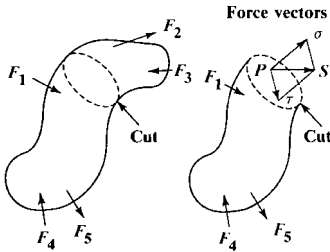


Fig. 1. Internal Forces and Stresses in a Body

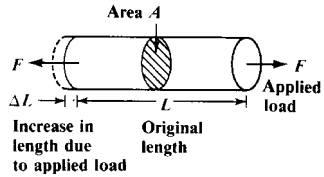


Fig. 2. Simple Tension Load

Stresses must be defined with both magnitude and direction. The stress  $S$  acting in the direction shown in Fig. 1, on the point  $P$  of the cut surface, has two stress components. One of these components,  $\sigma$ , acts perpendicular to the surface and is called a normal or direct stress. The other stress,  $\tau$ , acts parallel to the surface and is called a shear stress.

*Normal stress* is illustrated by the simple tension test shown in Fig. 2, where the direct stress is the ratio of applied load to the original cross-sectional area in lb<sub>f</sub>/in<sup>2</sup>. In the Système International (SI or metric system, see pages 2544, and starting on page 2576) the stress,  $\sigma$ , is expressed in newtons/meter<sup>2</sup> (N/m<sup>2</sup>).

$$\text{Stress} = \frac{\text{Load}}{\text{Area}} \text{ or } \sigma = \frac{F}{A} \quad (1)$$

If the load is applied as shown in Fig. 2, the test piece is in tension, and if reversed, it is in compression.

*Normal strain* is also illustrated by the diagram in Fig. 2, where the load or stress applied to the test piece causes it to change its length. If the bar has an original length  $L$ , and changes its length by  $\Delta L$ , the strain,  $\epsilon$ , is defined as

$$\text{Strain} = \frac{\text{Change of Length}}{\text{Original Length}} \text{ or } \epsilon = \frac{\Delta L}{L} \quad (2)$$

Strain is the ratio between the amount of deformation of the material and its original length and is a dimensionless quantity. Extensions of most materials under load are generally very small. Strain ( $\mu\epsilon$  or microstrain in most metals) is measured and expressed in microinches (millionths of an inch) per inch, or  $10^{-6}$  in./in. ( $10^{-6}$  cm/cm). Alternatively, strain is expressed as a percentage. The three methods compare as follows:

$$1000\mu\epsilon = 0.001 = 0.1 \text{ per cent strain}$$

$$10000\mu\epsilon = 0.010 = 1 \text{ per cent strain}$$

*Modulus of Elasticity:* Most metals and plastics have deformations that are proportional to the imposed loads over a range of loads. Stress is proportional to load and strain is proportional to deformation, so stress is proportional to strain and is expressed by Hooke's law:

$$\frac{\text{Stress}}{\text{Strain}} = \text{Constant} = E \quad (3)$$

The constant  $E$  is called the modulus of elasticity, Young's modulus, or, in the plastics industry, tensile modulus. Referring to Fig. 2, tensile modulus is given by the formula:

$$E = \frac{\sigma}{\epsilon} = \frac{F/A}{\Delta L/L} = \frac{FL}{A\Delta L} \quad (4)$$

Thus, the modulus is the slope of the initial portion of the stress-strain curve. An elastic material does not necessarily obey Hooke's law, since it is possible for a material to return to its original shape without the stress being proportional to the strain. If a material does obey Hooke's law, however, it is elastic.

The straight portion of the stress-strain curve for many plastics is difficult to locate, and it is necessary to construct a straight line tangent to the initial portion of the curve to use as a modulus. The shape of a line so obtained is called the initial modulus. In some plastics, the initial modulus can be misleading, owing to the nonlinear elasticity of the material. Some suppliers therefore provide the so-called 1 per cent secant modulus, which is the ratio of stress to strain at 1 per cent strain on the stress-strain curve. In the illustration of typical stress-strain curves in Fig. 3, the secant modulus at the point *E* is the slope of the line *OE*.

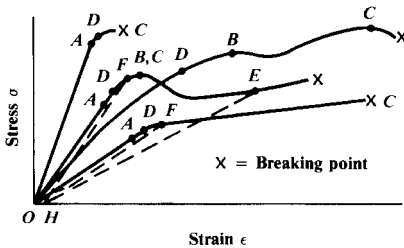


Fig. 3. Typical Stress-Strain Curves

For metals, Young's modulus is expressed in terms of  $10^6$  lb<sub>f</sub>/in.<sup>2</sup>, N/m<sup>2</sup>, or Pa, as convenient (see starting on page 2576). For plastics, tensile modulus is expressed as  $10^5$  lb<sub>f</sub>/in.<sup>2</sup> or in GPa (1 GPa = 145,000 lb<sub>f</sub>/in.<sup>2</sup>).

*Secant modulus* is the ratio of stress to corresponding strain at any point on the stress-strain curve (see *Modulus of Elasticity*).

*Proportional limit* is the greatest stress at which a material is capable of sustaining the applied load without losing the proportionality of stress to strain. This limit is the point on the stress-strain curve where the slope begins to change, as shown at *A* on each of the curves in Fig. 3. Proportional limit is expressed in lb<sub>f</sub>/in.<sup>2</sup> (MPa or GPa).

*Yield point* is the first point on the stress-strain curve where an increase in strain occurs without an increase in stress, and is indicated by *B* on some of the curves in Fig. 3. The slope of the curve is zero at this point; however, some materials do not have a yield point.

*Ultimate strength* is the maximum stress a material withstands when subjected to a load, and is indicated by *C* in Fig. 3. Ultimate strength is expressed in lb<sub>f</sub>/in.<sup>2</sup> (MPa or GPa).

*Elastic limit* is indicated by the point *D* on the stress-strain curve in Fig. 3, and is the level beyond which the material is permanently deformed when the load is removed. Although many materials can be loaded beyond their proportional limit and still return to zero strain when the load is removed, some plastics have no proportional limit in that no region exists where the stress is proportional to strain (i.e., where the material obeys Hooke's law).

*Yield strength* is the stress at which a material shows a specified deviation from stress to strain proportionality. Some materials do not show a yield strength clearly, and it may be desirable to choose an arbitrary stress level beyond the elastic limit, especially with plas-

tics that have a very high strain at the yield point, to establish a realistic yield strength. Such a point is seen at  $F$  on some of the curves in Fig. 3, and is defined by constructing a line parallel to  $OA$  at a specified offset strain,  $H$ . The stress at the intersection of the line with the stress-strain curve at  $F$  would be the yield strength at  $H$  offset. If  $H$  were at 2 per cent strain,  $F$  would be described as the yield strength at a 2 per cent strain offset.

*Poisson's ratio* is defined on page 204. Under a tensile load, a rectangular bar of length  $L$ , with sides of widths  $b$  and  $d$ , lengthens by an amount  $\Delta L$ , producing a longitudinal strain of

$$\epsilon = \frac{\Delta L}{L} \quad (5)$$

The bar is reduced in its lateral dimensions and the associated lateral strains will be opposite in sign, resulting in

$$\epsilon = -\frac{\Delta b}{b} = -\frac{\Delta d}{d} \quad (6)$$

If the deformation is within the elastic range, the ratio (Poisson's ratio  $\nu$ ) of the lateral to the longitudinal strains will be constant. The formula is:

$$\nu = \frac{\text{Lateral Strain}}{\text{Longitudinal Strain}} = \frac{\Delta d/d}{\Delta L/L} \quad (7)$$

Values of  $\nu$  for most engineering materials lie between 0.20 and 0.40, and these values hold for unfilled rigid thermoplastics. Values of  $\nu$  for filled or reinforced rigid thermoplastics fall between 0.10 and 0.40 and for structural foam between 0.30 and 0.40. Rigid thermoset plastics have Poisson's ratios between 0.20 and 0.40, whether filled or unfilled, and elastomers can approach 0.5.

*Shear stress* is treated on page 215. Any block of material is subject to a set of equal and opposite shearing forces  $Q$ . If the block is envisaged as an infinite number of infinitesimally thin layers as shown diagrammatically in Fig. 4, it is easy to imagine a tendency for one layer subject to a force to slide over the next layer, producing a shear form of deformation or failure. The shear stress  $\tau$  is defined as

$$\tau = \frac{\text{Shear Load}}{\text{Area Resisting Load}} = \frac{Q}{A} \quad (8)$$

Shear stress is always tangential to the area on which it acts. Shearing strain is the angle of deformation  $\gamma$  and is measured in radians.

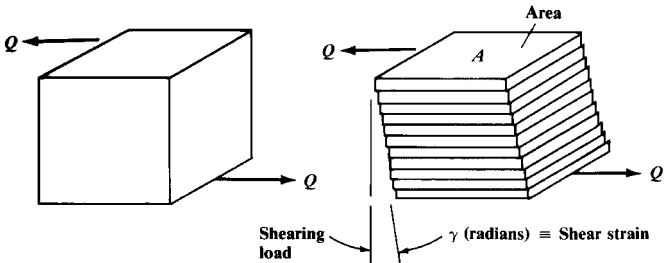


Fig. 4. Shear Stress is Visualized as a Force  $Q$  Causing Infinitely Thin Layers of a Component to Slide Past Each Other, Producing a Shear Form of Failure

*Shear modulus* is a constant  $G$ , otherwise called the modulus of rigidity, and, for materials that behave according to Hooke's law, is directly comparable to the modulus of elasticity used in direct stress calculations. The constant is derived from

$$G = \frac{\text{Shear Stress}}{\text{Shear Strain}} = \frac{\tau}{\gamma} \quad (9)$$

*Relating Material Constants:* Although only two material constants are required to characterize a material that is linearly elastic, homogeneous, and isotropic, three such constants have been introduced here. These three constants are tensile modulus  $E$ , Poisson's ratio  $\nu$ , and shear modulus  $G$ , and they are related by the following equation, based on elasticity principles:

$$\frac{E}{G} = 2(1 + \nu) \quad (10)$$

This relationship holds for most metals and is generally applicable to injection-moldable thermoplastics. It must be remembered, however, that most plastics, and particularly fiber-reinforced and liquid crystalline materials, are inherently either nonlinear, or anisotropic, or both.

*Direct shear* refers to a shear strength test much used in the plastics industry with a setup similar to that shown in Fig. 5, and the results of such tests are often described in manufacturers' marketing data sheets as the shear strength of the material. The shear strength reported from such a test is not a pure shear strength because a considerable part of the load is transferred by bending or compressing, or both, rather than by pure shear, and results can be affected by the susceptibility of the material to the sharpness of the load faces in the test apparatus. Thus, the test cannot be used to develop shear stress–strain curves or to determine the shear modulus.

When analyzing plastics in a pure shear situation or when the maximum shear stress is calculated in a complex stress environment, designers often use a shear strength value of about half the tensile strength, or the direct shear strength obtained from the test referred to above, whichever is least.

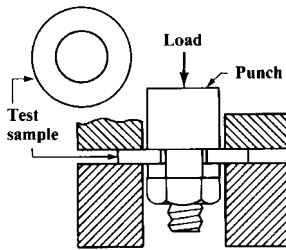


Fig. 5. Direct Shear Test Used in the Plastics Industry

*True stress and true strain* are terms not in frequent use. In Fig. 2, the stress, sometimes called the engineering stress, is calculated from an increasing load  $F$ , acting over a constant area  $A$ . Because the cross-sectional area is reduced with most materials, use of that smaller cross-sectional area in the calculation yields what is called the "true stress." In addition, the direct strain referred to earlier, that is, the total change in length divided by the original length, is often called the "engineering strain." The true strain would be the instantaneous deformation divided by the instantaneous length. Therefore, the shape of such a stress–strain curve would not be the same as a simple stress–strain curve. Modulus values and stress–strain curves are almost universally based on engineering stress and strain.

**Other Measures of Strength and Modulus.**—Tensile and compression properties of many engineering materials, which are treated as linearly elastic, homogeneous, and isotropic, are often considered to be identical, so as to eliminate the need to measure properties in compression. Also, if tension and compression properties are identical, under standard beam bending theory, there is no need to measure the properties in bending. In a concession to the nonlinear, anisotropic nature of most plastics, these properties, particularly flexural properties, are often reported on manufacturers' marketing data sheets.

*Compression Strength and Modulus:* Because of the relative simplicity of testing in tension the elastic modulus of a material is usually measured and reported as a tension value. For design purposes it often is necessary to know the stress-strain relationship for compression loading. With most elastic materials at low stress levels, the tensile and compressive stress-strain curves are nearly equivalent. At higher stress levels, the compressive strain is less than the tensile strain. Unlike tensile loading, which usually results in a clear-cut failure, stressing in compression produces a slow and indefinite yielding that seldom leads to failure. Because of this phenomenon, compressive strength is customarily expressed as the stress in lb/in.<sup>2</sup> (Pa) required to deform a standard plastics test specimen to a certain strain. Compression modulus is not always reported, because defining a stress at a given strain is equivalent to reporting a secant modulus. If a compression modulus is given, it is usually an initial modulus.

*Bending Strength and Modulus:* When material of rectangular cross-section is bent, it is apparent that one surface is stretched in tension and the other side is compressed. Within the material is a line or plane of zero stress called the neutral axis. Simple beam bending theory makes the following assumptions: that the beam is initially straight, unstressed, and symmetric; the material is linearly elastic, homogeneous, and isotropic; the proportional limit is not exceeded; Young's modulus for the material is the same in tension and compression; and all deflections are small so that planar cross-sections remain planar before and after bending.

In these conditions, the formula for bending stress  $\sigma$  is

$$\sigma = \frac{3FL}{2bh^2} \quad (11)$$

the formula for bending or flexural modulus  $E$  is

$$E = \frac{FL^3}{4bh^3Y} \quad (12)$$

and the formula for deflection  $Y$  is

$$Y = \frac{FL^3}{4Ebh^3} \quad (13)$$

where  $F$ , the force in pounds, is centered between the specimen support points,  $L$  is the distance in inches between the support points,  $b$  and  $h$  are the width and thickness of the test specimen in inches, and  $Y$  is the deflection in inches at the central load point.

Using the preceding relationships, the flexural strength and flexural modulus (of elasticity) for any material can be determined in the laboratory. The flexural modulus reported is usually the initial modulus from the load deflection curve. Most plastics parts must be analyzed in bending, so use of flexural values should give more accurate results than corresponding tensile values.

*Rate Dependence of Mechanical Properties:* Tensile and flexural data in manufacturers' literature are measured at specific displacement rates. These rates are usually not consistent with the loading environment encountered in use of the product. The same plastics material, under differing rates or in other environmental conditions, can produce different stress-strain curves. Designers should be aware of the loading rates in specific applica-

tions and request the appropriate data. End-use testing must always be considered, but particularly when adequate data are not available.

**Time-Related Mechanical Properties.**—Mechanical properties discussed previously were related to loads applied gradually and applied for short periods. Long-term and very short-term loading may give somewhat different results. With high-performance thermoplastics it is important to consider creep, impact, fatigue, and related issues. Even the best laboratory test methods do not always predict structural response of production parts accurately, and other factors may also affect results.

*Creep* is defined as increasing strain over time in the presence of a constant stress when deformation continues without increases in load or stress. The rate of creep for a given material depends on applied stress, temperature, and time.

Creep behavior of a material is important, and a crucial issue with plastics, where parts are to be subjected to loads for extended periods and where the maximum deflection is critical. To determine the creep behavior, test samples may be loaded in tension, compression, or flexure in a constant-temperature environment. Under constant loads, deflection is recorded at regular intervals over suitable periods. Results are generally obtained for four or more stress levels and recorded as creep curves of strain versus time on a logarithmic scale. In general, crystalline materials have lower creep rates than amorphous plastics. Glass reinforcement generally improves the creep resistance.

*Apparent or Creep Modulus:* If the deflection of a part subjected to continuous loading is calculated by using the modulus of elasticity  $E$ , results are likely to be inaccurate because the effects of creep have not been considered. If the stress level and temperature are known and creep curves are available for the temperature in question, an apparent or creep modulus  $E_{app}$  can be calculated from the creep curves by the formula:  $E_{app} = \sigma / \epsilon_c$ , where  $\sigma$  is the calculated stress level and  $\epsilon_c$  is the strain from the creep curve at the expected time and temperature.

This value  $E_{app}$  can be used instead of  $E$  in predicting the maximum deflection, using the methods described subsequently (page 602).

Manufacturers' data often include curves of creep modulus (or log creep modulus) versus log time at either constant stress or constant strain, derived from creep data. This information may also be provided as tables of values at constant stress and temperature for various time periods. Some manufacturers provide creep data in the form of creep modulus figures rather than curves.

*Creep rupture* data are obtained in the same manner as creep data except that higher stresses are used and time is measured to failure. Such failures may be brittle or ductile with some degree of necking. Results are generally plotted as log stress versus log time to failure.

*Stress relaxation* occurs when plastics parts are assembled into a permanent deflected condition, as in a press fit, a bolted assembly, or some plastics springs. Under constant strain over a period of time, the stress level decreases due to the same internal molecular movement that produces creep. Stress relaxation is important with such applications as bolt preloading and springs, where loading must be maintained. The relaxation can be assessed by applying a fixed strain to a sample and measuring the load over time. A relaxation modulus similar to the creep modulus can be derived from the relaxation data. Relaxation data are not as readily available as creep data, but the decrease in load due to stress relaxation can be approximated by using the creep modulus  $E_{app}$  calculated from the creep curves.

Plastics parts often fail due to imposition of excessive fixed strains over extended periods of time, for example, a plastics tube that is a press fit over a steel shaft. No relaxation rupture equivalent to creep rupture exists, so for initial design purposes a strain limit of 20 percent of the strain at the yield point or yield strength is suggested for high-elongation plas-

tics. For low-elongation brittle plastics that have no yield point, 20 per cent of the elongation at break is also recommended. These figures should be regarded only as guidelines for development of initial design concepts; prototype parts should be thoroughly tested under end-use conditions to confirm the suitability of the design. Higher or lower property limits may also be indicated in manufacturers' data on specific materials.

*Extrapolating creep and relaxation data* must be done with caution. When creep and relaxation data are plotted as log property against log time, the curves are generally less pronounced, facilitating extrapolation. This procedure is common practice, particularly with creep modulus and creep rupture data. Extrapolation should not exceed one unit of log time, and the strain limit of 20 per cent of the yield or ultimate strength mentioned above should not be exceeded.

*Impact loading* describes a situation in which a load is imposed rapidly. Any moving body has kinetic energy and when the motion is stopped by a collision, the energy is dissipated. Ability of a plastics part to absorb energy is determined by the shape, size, thickness, and type of material. Impact testing methods now available do not provide designers with information that can be used analytically. The tests can be used for comparing relative notch sensitivity or relative impact resistance, so can be useful in choosing a series of materials to be evaluated for an application or in grading materials within a series.

*Impact testing* by the Izod and Charpy methods, in which a pendulum arm is swung from a certain height to impact a notched test specimen, is the most widely used for measuring impact strength. Impact with the test specimen reduces the energy remaining in the arm, and this energy loss is recorded in ft-lb (J). The value of such tests is that they permit comparison of the relative notch toughness of two or more materials under specific conditions.

*Tensile impact* tests mount the test specimen on the swinging arm. Attached to the test specimen is a cross piece that is arrested by a notched anvil as the bar swings down, allowing the energy stored in the arm to break the specimen under tension as it passes through the notch. Another impact test used for plastics allows a weighted, round-ended cylindrical "dart" to fall on a flat disk of the plastics to be tested. This test is good for ranking materials because it represents conditions that are encountered by actual parts in certain applications.

*Fatigue tests* are designed to measure the relative ability of plastics materials to withstand repeated stresses or other cyclic phenomena. For example, a snap-action, or snap-fit latch that is continually opened and closed, a gear tooth, a bearing, a structural component subject to vibration or to repeated impacts. Cyclic loading can cause mechanical deterioration and progressive fracture, leading to failure in service. Typical fatigue tests are carried out on machines designed to subject a cantilever test piece to reversing flexural loading cycles at different stress levels. Numbers of cycles before failure are recorded for each stress level. Data are normally presented in plots of log stress versus log cycles called *S-N* curves for specific cycle rates and environmental temperatures. With thermoplastics materials there is the added complication that heat built up by the frequency of the cyclic stress may contribute to failure. Significantly different *S-N* curves can be produced for the same materials by testing at different frequencies, mean stresses, waveforms, and methods, such as testing in tension rather than in bending. Testing usually cannot reproduce the conditions under which components will work. Only tests on the end product can determine whether the design is suitable for the purpose to be served.

**Thermal Properties.**—Melting temperatures of crystalline thermoplastics are sharp and clearly defined, but amorphous and liquid crystalline materials soften and become more fluid over wider temperature ranges. Melting points have greater significance in molding and assembly operations than in product design, which usually deals with the product's temperatures.



*Glass transition temperature* is a level at which a plastics material undergoes a significant change in properties. Below this temperature  $T_g$ , the material has a stiff, glassy, brittle response to loads. Above  $T_g$  the material has a more ductile, rubbery response.

*Vicat softening point* is the temperature at which a small, circular, lightly gravity-loaded, heated probe penetrates a specific distance into a thermoplastics test specimen. This test measures the ability of a thermoplastics material to withstand a short-term contact with a heated surface, and is most useful for crystalline plastics. Amorphous thermoplastics materials tend to creep during the test, which reduces its usefulness for such materials.

*Deflection temperature under load* (DTUL) is the temperature at which a test bar of 0.5 in. thickness, loaded to a specified bending stress, will deflect by 0.010 in. This test is run at bending stresses of 66 lb<sub>f</sub>/in.<sup>2</sup> or 264 lb<sub>f</sub>/in.<sup>2</sup> or both. The value obtained is sometimes referred to as the heat distortion temperature (HDT), and is an indication of the ability of the material to perform at elevated temperatures under load. Both stress and deflection for a specific design of test bar are given so the test may be regarded as establishing the temperature at which the flexural modulus is reduced to particular values, 35,200 lb<sub>f</sub>/in.<sup>2</sup> at 66 lb<sub>f</sub>/in.<sup>2</sup> stress, and 140,000 lb<sub>f</sub>/in.<sup>2</sup> at 264 lb<sub>f</sub>/in.<sup>2</sup> stress.

*Linear thermal expansion:* Like metals, thermoplastic materials expand when heated and contract when cooled. For a given temperature range, most plastics change dimensions much more than metals. The coefficient of linear thermal expansion (CLTE) is the ratio of the change in a linear dimension to the original dimension for a unit change of temperature and is expressed as in/in/degree F, or cm/cm/degree C. Typical average values for common materials are shown in the table on page 402. These values do not take account of grades, molding conditions, wall thickness, or direction of flow in molding.

*Thermal conductivity* is the rate at which a material conducts heat energy along its length or through its thickness.

*Aging at elevated temperatures* may affect physical, mechanical, electrical, or thermal properties of plastics materials. Data from tests on specimens stored at specific temperatures for suitable periods are presented as plots of properties versus aging time at various temperatures, and may be used as an indication of thermal stability of the material.

*Temperature index* is a rating by Underwriters Laboratories (UL) of electrical and mechanical properties (with and without effects of impacts) of plastics materials used in electrical equipment for certain continuous operating conditions.

*Flammability ratings* also are produced by Underwriters Laboratories. UL tests measure the ability to continue burning after a flame is removed, and the percentage of oxygen needed for the material to continue burning. Other tests measure combustibility, ignition temperatures, and smoke generation.

**Effect of Temperature on Mechanical Properties.**—The inverse relationship between strain rate and temperature must be kept in mind when designing with plastics materials. Stress/strain curves for tests performed with one strain rate at several temperatures are similar to those for tests with one temperature and several strain rates. Therefore, very high strain rates and very low temperatures produce similar responses in materials. Conversely, the effects of very low strain rates, that is, creep effects, can be determined more quickly by testing at elevated temperatures. Testing at temperatures near or above the highest values expected in everyday use of a product helps the designer estimate long-term performance of components.

Strength, modulus, and elongation behavior are similar for tensile, compressive, flexural, and shear properties. Generally, strength and modulus decrease with increasing temperature. The effect of temperature increases is shown by the curves in Fig. 6 for crystalline and amorphous materials, where a gradual drop in modulus is seen as the glass transition temperature  $T_g$  is approached. Above the glass transition temperature, amorphous materi-

als have a rapid loss of modulus, and even with glass-fiber reinforcement they display a rapid drop in modulus above the glass transition temperature. Crystalline materials maintain a significant usable modulus at temperatures approaching the crystalline melting point, and glass-fiber reinforcement can significantly improve the modulus of crystalline materials between the glass transition and melting temperatures. Generally, strength versus temperature curves are similar to modulus curves and elongation increases with rising temperatures.

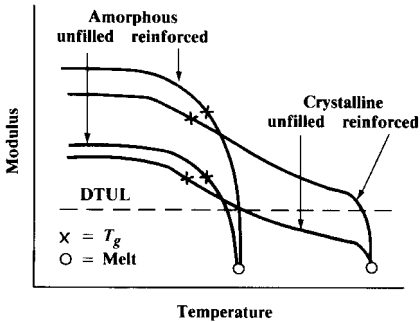


Fig. 6. Modulus Behavior of Crystalline and Amorphous Plastics Showing  $T_g$  and Melt Temperatures and the Effect of Reinforcement on Deflection Temperature Under Load (DTUL)

Isochronous stress and isometric stress curves are taken from measurements made at fixed temperatures, although sometimes curves are available for other-than-ambient temperatures. Creep rupture and apparent modulus curves also are often plotted against the log of time, with temperature as a parameter. Refer to sections on creep, creep modulus, and creep rupture beginning on page 602.

As temperatures drop significantly below ambient, most plastics materials lose much of their room temperature impact strength, although a few materials show only a gradual decrease. Plastics reinforced with long glass fibers have relatively high Izod impact values at room temperature, and retain these values at  $-40$  degrees F ( $-40$  degrees C).

**Electrical Properties.**—The most notable electrical property of plastics is that they are good insulators, but there are many other electrical properties that must be considered in plastics part design.

*Conductivity* in solids depends on the availability and mobility of movable charge carriers within the material. Metals are good conductors because the metal atom has a loosely held, outermost electron, and the close proximity of the atoms allows these outer electrons to break free and move within the lattice structure. These free electrons give metals the ability to conduct large currents, even at low voltages. Outer electrons in materials such as glass, porcelain, and plastics are tightly bound to the atoms or molecules so there are no free electrons. Electrical current cannot be conducted and the materials act as insulators.

*Volume resistivity* is the electrical resistance of a material when a current is applied to it. The resistance is measured in ohm-cm. Materials having values above  $10^8$  ohm-cm are considered to be insulators, and materials with values between  $10^8$  and  $10^3$  ohm-cm are considered to be partial conductors. Most plastics have volume resistivity in the range of  $10^{12}$  to  $10^{18}$  ohm-cm.

*Surface resistivity* is a measure of the susceptibility of a material to surface contamination, particularly moisture. The tests use electrodes that are placed on the same side of the material.

*Dielectric strength* is a measure of the voltage required to cause an insulator to break down and allow an electric current to pass and is expressed in volts per 0.001 in. of thickness. Variables that may affect test results include temperature, sample thickness and condition, rate of voltage increase and duration of test, sample contamination, and internal voids.

*Dielectric constant or permittivity* is a dimensionless constant that indicates how easily a material can become polarized by imposition of an electrical field on an insulator. Reversal of the direction of flow of the current results in reversal of the polarization. The dielectric constant is the ratio of the permittivity of the material in normal ambient conditions to the permittivity of a vacuum. Permittivity is important when plastics are used as insulating materials in high-frequency electrical apparatus. Changes in temperature, moisture levels, electrical frequency, and part thickness may affect the dielectric constant.

*Heat dissipation factor* is a measure of heat energy dissipated by rapidly repeated reversals of polarization, as with an alternating current. The dissipation factor may also be thought of as the ratio of heat energy lost compared to that transmitted at a given frequency, often 1 MHz ( $10^6$  cycles/sec). Some dielectric constants and heat dissipation factor values are shown in Table 1.

Arc resistance is the length of time required for an electric arc imposed on the surface of an insulating material to develop a conductive path. Materials that resist such a development are preferred for parts of switchgear and other high-voltage apparatus. Tests are used mostly for thermosetting materials because conductive paths can be formed on such materials from the decomposition products resulting from heating by an electric arc.

**Table 1. Typical Values of Dielectric Constants and Heat Dissipation Factors for Various Thermoplastics at Room Temperature**

| Material      | Dielectric Constant | Heat Dissipation Factor | Material              | Dielectric Constant | Heat Dissipation Factor |
|---------------|---------------------|-------------------------|-----------------------|---------------------|-------------------------|
| Acetal        | 3.7–3.9             | 0.001–0.007             | Polypropylene         | 2.3–2.9             | 0.003–0.014             |
| Acrylic       | 2.1–3.9             | 0.001–0.060             | Polysulfone           | 2.7–3.8             | 0.0008–0.009            |
| ABS           | 2.9–3.4             | 0.006–0.021             | Modified PPO          | 2.4–3.1             | 0.0002–0.005            |
| Nylon 6/6     | 3.1–8.3             | 0.006–0.190             | Polyphenylene sulfide | 2.9–4.5             | 0.001–0.002             |
| Polycarbonate | 2.9–3.8             | 0.0006–0.026            | Polyarylate           | 2.6–3.1             | 0.001–0.022             |
| TP Polyester  | 3.0–4.5             | 0.0012–0.022            | Liquid crystal        | 3.7–10              | 0.010–0.060             |

*Comparative tracking index (CTI)* is another UL test that is similar to the arc resistance test except that the surface to be tested is precoated with an ammonium chloride electrolyte. The test measures the voltage required to cause a conductive path to form between the electrodes, and indicates the arc resistance of a contaminated surface, often found in electrical and electronic equipment.

**End-Use Environmental Considerations.**—The environment that will be encountered by the product is a prime consideration at the design stage. Problems with cracking, crazing, discoloration, loss of properties, melting, or dissolving can be encountered in the presence of high or low temperatures, chemical substances, energy sources, and radiation. Plastics components also are often subjected to processing, assembly, finishing, and cleaning operations before reaching their ultimate environment.

The stress level in the plastics product greatly affects performance. Generally, increased stress levels resulting from injection molding, forming, assembly work, and end-use forces reduce resistance to environmental factors. Although many plastics are hygroscopic and absorption of water results in dimensional and property changes, plastics are widely accepted because of their relative compatibility with the environment compared with metals. Some chemicals attack the polymer chain directly by reaction, resulting in a progres-

sive lowering of the molecular weight of the polymer and changes in the short-term mechanical properties. Others dissolve the material, although high-molecular-weight plastics dissolve very slowly. Swelling, changes in weight and dimensions, and loss of properties are evidence of solvation.

Plasticization may result if the chemical is miscible with the polymer, resulting in loss of strength, stiffness, and creep resistance, and increased impact resistance. The material may swell and warp due to relaxation of molded-in stresses. Environmental stress cracking may cause catastrophic failure when plastics are stressed, even when the product appears to be unaffected by exposure to a chemical.

Chemical compatibility data are obtained from standard test bars exposed to or placed in the chemical of study and tested as previously described for such properties as tensile strength, flexural modulus, dimensional change, weight, and discoloration. Chemical resistance from some commonly used thermoplastics materials are shown in [Table 2](#), but are only general guidelines and cannot substitute for tests on the end product. More extensive tests expose samples to a chemical in the presence of fixed stress or fixed strain distribution along its length, followed by examination for the stress or strain location at which damage begins.

The preceding tests may provide data about chemical compatibility but do not generate reliable information on performance properties for design purposes. The only test that provides such information is the creep rupture test, conducted at appropriate temperatures in the environment that will be encountered by the product, preferably on prototype parts. Plastics are degraded to varying degrees by ultraviolet light, which causes fading, chalking, and embrittlement. Plastics that will resist the action of ultraviolet rays are available on the market.

### Design Analysis

**Structural Analysis.**—Even the simplest plastics parts may be subjected to stresses caused by assembly, handling, temperature variations, and other environmental effects. Simple analysis using information in *Moment of Inertia* starting on page [236](#) and *Beam Calculations* on page [260](#) can be used to make sure that newly designed parts can withstand these stresses. These methods may also be used for product improvement, cost reduction, and failure analysis of existing parts.

**Safety Factors:** In setting safety factors for plastics parts there are no hard and fast rules. The most important consideration is the consequence of failure. For example, a little extra deflection in an outside wall or a crack in one of six internal screw bosses may not cause much concern, but the failure of a pressure vessel or water valve might have serious safety or product liability implications. Tests should be run on actual parts at the most extreme operating conditions that could possibly be encountered before any product is marketed. For example, maximum working load should be applied at the maximum temperature and in the presence of any chemicals that might be encountered in service. Loads, temperatures, and chemicals to which a product may be exposed prior to its end use also should be investigated. Impact loading tests should be performed at the lowest temperature expected, including during assembly and shipping. Effects of variations in resin lots and molding conditions must also be considered.

Failures in testing of preproduction lots often can be corrected by increasing the wall thickness, using ribs or gussets, and eliminating stress concentrations. Changing the material to another grade of the same resin or to a different plastics with more suitable mechanical properties is another possible solution. Reviews of product data and discussions with experienced engineers suggest the design stresses shown in [Table 3](#) are suitable for use with the structural analysis information indicated above and the equations presented here, for preliminary design analysis and evaluating general product dimensions. Products designed under these guidelines must be thoroughly tested before being marketed.

**Table 2. Chemical Resistance of Various Materials by Chemical Classes**

|                                     | Polyarylate                   |   |   |   |   |   |   |   |   |   | Polycarbonate                |   |   |   |   |   |   |   |   |  |
|-------------------------------------|-------------------------------|---|---|---|---|---|---|---|---|---|------------------------------|---|---|---|---|---|---|---|---|--|
|                                     | Polyphenylene Sulfide*        |   |   |   |   |   |   |   |   |   | Polysulfone*                 |   |   |   |   |   |   |   |   |  |
|                                     | Liquid Crystal Polymer*       |   |   |   |   |   |   |   |   |   | Modified Polyphenylene Oxide |   |   |   |   |   |   |   |   |  |
|                                     | Polyester Elastomer           |   |   |   |   |   |   |   |   |   | Polypropylene                |   |   |   |   |   |   |   |   |  |
|                                     | Thermoplastic Polyester (PET) |   |   |   |   |   |   |   |   |   | ABS                          |   |   |   |   |   |   |   |   |  |
|                                     | Thermoplastic Polyester (PBT) |   |   |   |   |   |   |   |   |   | 316 Stainless Steel          |   |   |   |   |   |   |   |   |  |
|                                     | Nylon 6/6                     |   |   |   |   |   |   |   |   |   | Carbon Steel                 |   |   |   |   |   |   |   |   |  |
|                                     | Acetal Homopolymer            |   |   |   |   |   |   |   |   |   | Aluminum                     |   |   |   |   |   |   |   |   |  |
|                                     | Acetal Copolymer              |   |   |   |   |   |   |   |   |   |                              |   |   |   |   |   |   |   |   |  |
| ACIDS AND BASES                     |                               |   |   |   |   |   |   |   |   |   |                              |   |   |   |   |   |   |   |   |  |
| Acids, weak                         | A                             | B | C | A | A | A | A | A | A | A | A                            | A | B | A | A | A | A | C | Dilute mineral acids                      |  |
| Acids, strong                       | C                             | C | C | B | — | C | B | A | — | C | C                            | — | A | A | B | C | C | C | Concentrated mineral acids                |  |
| Bases, weak                         | A                             | C | A | B | B | A | B | A | — | C | A                            | A | A | A | A | B | C | C | Dilute sodium hydroxide                   |  |
| Bases, strong                       | A                             | C | C | — | — | B | C | A | — | C | A                            | — | A | A | B | B | C | C | Concentrated sodium hydroxide             |  |
| Acids, organic, weak                | A                             | B | C | A | A | A | A | A | A | A | B                            | A | A | A | A | C | C | C | Acetic acid, vinegar                      |  |
| Acids, organic, strong              | C                             | C | C | B | — | C | B | A | — | C | C                            | A | A | A | B | C | C | C | Trichloroacetic acid                      |  |
| AUTOMOTIVE                          |                               |   |   |   |   |   |   |   |   |   |                              |   |   |   |   |   |   |   |   |  |
| Automotive, fuel                    | A                             | A | A | A | A | A | A | A | A | C | C                            | A | C | C | A | A | A | A |   |  |
| Automotive, lubricants              | A                             | A | A | A | A | A | A | A | A | C | C                            | A | A | A | A | A | B | A |   |  |
| Automotive, hydraulic               | A                             | A | — | A | A | — | A | A | C | C | C                            | A | A | A | — | — | — | — |   |  |
| SOLVENTS                            |                               |   |   |   |   |   |   |   |   |   |                              |   |   |   |   |   |   |   |   |  |
| Aliphatic hydrocarbons              | A                             | A | A | A | A | A | A | A | A | A | A                            | B | C | A | A | A | A | A | Heptane, hexane                           |  |
| Aliphatic hydrocarbons, halogenated | A                             | B | C | B | B | A | A | A | C | C | —                            | — | — | B | B | B | B | B | Ethylene chloride, chloroform             |  |
| Alcohols                            | A                             | A | B | A | A | A | A | A | A | A | A                            | A | A | A | A | A | B | B | Ethanol, cyclohexanol                     |  |
| Aldehydes                           | A                             | A | A | A | B | B | A | A | — | C | B                            | — | A | — | A | B | A | A | Acetaldehyde, formaldehyde                |  |
| Amines                              | —                             | — | — | — | — | — | C | B | — | C | C                            | — | A | — | A | B | B | B | Aniline, triethanolamine                  |  |
| Aromatic hydrocarbons               | A                             | B | A | A | B | B | A | A | C | C | C                            | C | C | C | A | A | A | A | Toluene, xylene, naphtha                  |  |
| Aromatic hydrocarbons, halogenated  | —                             | — | — | — | — | C | — | A | C | C | C                            | — | — | — | A | A | A | A | Chlorobenzene                             |  |
| Aromatic, hydroxy                   | C                             | C | C | C | — | C | A | A | — | C | C                            | — | A | — | B | C | A | A | Phenol                                    |  |
| Esters                              | B                             | B | A | B | B | B | A | A | C | C | C                            | — | C | — | B | B | B | B | Ethyl acetate, dioctyl phthalate          |  |
| Ethers                              | B                             | — | A | A | — | — | A | — | A | B | —                            | C | — | A | A | A | A | A | Butyl ether, diethyl ether                |  |
| Ketones                             | B                             | B | A | B | B | B | A | A | C | C | C                            | — | B | C | A | A | A | A | Methyl ethyl ketone, acetone              |  |
| MISCELLANEOUS                       |                               |   |   |   |   |   |   |   |   |   |                              |   |   |   |   |   |   |   |   |  |
| Detergents                          | A                             | — | A | — | B | — | — | A | A | A | —                            | B | A | — | A | A | B | B | Laundry and dishwashing detergents, soaps |  |
| Inorganic salts                     | B                             | B | B | — | A | — | — | A | — | A | —                            | — | A | A | B | B | B | B | Zinc chloride, cupric sulfate             |  |
| Oxidizing agents, strong            | C                             | C | C | — | C | — | B | B | — | C | —                            | — | A | — | C | C | C | C | 30% hydrogen peroxide, bromine (wet)      |  |
| Oxidizing agents, weak              | C                             | C | C | A | — | A | A | A | — | A | A                            | A | A | B | C | A | A | A | Sodium hypochlorite solution              |  |
| Water, ambient                      | A                             | A | B | A | A | A | A | A | A | A | A                            | A | A | A | A | C | A | B |   |  |
| Water, hot                          | B                             | C | B | C | C | B | A | A | — | C | —                            | A | C | — | A | C | B | B |   |  |
| Water, steam                        | C                             | C | C | C | C | C | B | A | — | C | —                            | — | C | — | A | C | — | — |   |  |

This information is presented for instructional purposes and is not intended for design. The data were extracted from numerous sources making consistent rating assignments difficult. Furthermore, the response of any given material to specific chemicals in any one class can vary significantly. Indeed, during the preparation of the table, the effect on one plastics of various chemicals in the same category ranged from essentially no effect to total dissolution. Therefore, an "A" rating for a particular plastics exposed to a particular class of chemicals should not be interpreted as applying to all chemicals in that class. The rating simply means that for the chemicals in that class found in the literature reviewed, the rating was generally an "A." There may be other chemicals in the same class for which the rating would be "C." Finally, the typical chemicals listed do not necessarily correspond to the ones on which the individual ratings are based.

A—minimal effect; B—some effect; C—generally not recommended.  
 Room temperature except for hot water, steam, and materials marked with a \* = 200°. Generally, extended exposure (more than a week) data were used.

**Table 3. Design Stresses for Preliminary Part Designs Expressed as a Percentage of Manufacturers' Data Sheet Strength Values**

|                                   | Failure Not Critical | Failure Critical |
|-----------------------------------|----------------------|------------------|
| Intermittent (Nonfatigue) loading | 25–50                | 10–25            |
| Continuous loading                | 10–25                | 5–10             |

*Failure Criteria:* Setting of failure criteria is beyond the scope of this section, which is intended to give only basic general information on plastics. Designers who wish to rationalize complex stress states and analyses might investigate the maximum shear theory of failure (otherwise known as Coulomb or Tresca theory). It is further suggested that the shear strength be taken as the manufacturer's published shear strength, or half the tensile strength, whichever is lower. Better still, use half the stress at the elastic limit, if known.

*Pressure Vessels:* The most common plastics pressure vessel takes the form of a tube with internal pressure. In selecting a wall thickness for the tube, it is convenient to use the thin-wall hoop stress equation:

$$\text{hoop stress } \sigma = \frac{Pd}{2t} \quad (14)$$

where  $P$  = the uniform internal pressure in the tube,  $d$  = inside diameter of the tube, and  $t$  = the tube wall thickness. This equation is reasonably accurate for tubes where the wall thickness is less than 0.1 of the inside diameter of the tube. As the wall thickness increases, the error becomes quite large.

For thick-walled tubes the maximum hoop stress on the wall surface inside the tube can be calculated from

$$\text{hoop stress } \sigma = P \frac{1+R}{1-R} \quad (15)$$

where  $R = (d_i/d_o)^2$ , and  $d_i$  and  $d_o$  are the inside and outside diameters of the tube, respectively.

*Press Fits:* Press fits are used widely in assembly work for speed and convenience, although they sometimes are unsatisfactory with thermoplastics parts. Common applications are to a plastics hub or boss accepting a plastics or metal shaft or pin. Forcing the pin into the hole expands the hub, creating a tensile or hoop stress.

If the interference is too great, very high strain and stress develop and the plastics part will: a) fail immediately by developing a crack parallel to the hub axis to relieve the stress, a typical hoop stress failure; b) survive assembly but fail prematurely due to creep rupture caused by the high induced-stress levels; and c) undergo stress relaxation sufficient to reduce the stress to a level that can be sustained.

For a typical press fit, the allowable design stress depends on the particular plastics material, temperature, and other environmental considerations. Hoop stress equations for such a design make use of a geometry factor  $\gamma$ :

$$\gamma = \frac{1 + (d_s/d_o)^2}{1 - (d_s/d_o)^2} \quad (16)$$

where  $d_s$  = diameter of the pin to be inserted and  $d_o$  = outside diameter of the boss.

When both the shaft and the hub are of the same, or essentially the same, materials, the hoop stress  $\sigma$ , given the diametral interference,  $i = d_s - d_i$ , is

$$\sigma = \frac{i}{d_s} E_p \frac{\gamma}{\gamma + 1} \quad (17)$$

and the allowable interference  $i_a$ , given the permissible design stress  $\sigma_a$ , is

$$i_a = d_s \frac{\sigma_a}{E_p} \frac{\gamma + 1}{\gamma} \quad (18)$$

When the shaft is metal and the hub is plastics, the hoop stress, given  $i$ , is obtained from

$$\sigma = \frac{i}{d_s} E_p \frac{\gamma}{\gamma + \nu_p} \quad (19)$$

and the allowable interference  $i_a$ , given the permissible design stress for plastics  $\sigma_a$ , is

$$i_a = d_s \frac{\sigma_a}{E_p} \frac{\gamma + \nu_p}{\gamma} \quad (20)$$

where  $E_p$  = modulus of elasticity of plastics and  $\nu_p$  = Poisson's ratio for plastics.

**Pipe Threads:** Pipe threads on plastics pipes and other parts used in plastics plumbing and pneumatic assemblies require only hand tight assembly to effect a good seat, especially if a compatible sealant tape or compound is used. Assembling a tapered male pipe thread into a mating female thread in a plastics part is analogous to driving a cone into a round hole and may result in a split boss. Sometimes straight threads and an O-ring seal can avoid the need for pipe threads. When pipe threads must be used, torque control is essential.

When mating metal to plastics pipe threads, the threaded plastics component should be the male member, so that the plastics are in compression. If torque can be controlled during assembly, use fluoroplastics tape on female plastics pipe threads. If torque cannot be controlled, consider using an external hoop ring, either pressed on or molded in. Do not design flats into plastics parts for assembly purposes, because they will encourage overtightening. If some provision for improved gripping must be made, use wings or a textured surface. An approximate formula for the hoop stress  $\sigma$  produced in a plastics boss with internal pipe threads is

$$\sigma = \frac{3T}{tdL} \quad (21)$$

where  $T$  = torque in in.-lb,  $t$  = wall thickness of the plastics boss in in.,  $d$  = pipe outside diameter in in., and  $L$  = length of thread engagement in in.

This equation assumes certain geometric relationships and a coefficient of friction of 0.15. If compatible thread lubricants are used during assembly, the torque must be reduced. To ensure safety and reliability, all threaded assemblies must be subjected to long-term testing under operating pressures, temperatures, and stresses caused by installation procedures exceeding those likely to be encountered in service.

**Thermal Stresses.**—When materials with different coefficients of thermal expansion are bolted, riveted, bonded, crimped, pressed, welded, or fastened by any method that prevents relative movement between the parts, there is potential for thermal stress to exist. Typical examples are joining of nonreinforced thermoplastics parts with materials such as metals, glass, or ceramics that usually have much lower coefficients of thermal expansion. The basic relationship for thermal expansion is

$$\Delta L = \alpha L \Delta T \quad (22)$$

where  $\Delta L$  = change in length,  $\alpha$  = coefficient of thermal expansion (see page 402),  $L$  = linear dimension under consideration (including hole diameters), and  $\Delta T$  = temperature change.

If the plastics component is constrained so that it cannot expand or contract, the strain  $\epsilon_T$ , induced by a temperature change, is calculated by

$$\epsilon_T = \frac{\Delta L}{L} = \alpha \Delta T \tag{23}$$

The stress can then be calculated by multiplying the strain  $\epsilon_T$  by the tensile modulus of the material at the temperature involved. A typical example is of a plastics part to be mounted to a metal part, such as a window in a housing. Both components expand with changes in temperature. The plastics imposes insignificant load to the metal but considerable stress is generated in the plastics. For such an example, the approximate thermal stress  $\sigma_T$  in the plastics is given by

$$\sigma_T = (\alpha_m - \alpha_p) E_p \Delta T \tag{24}$$

where  $\alpha_m$  = coefficient of thermal expansion of the metal,  $\alpha_p$  = coefficient of thermal expansion of the plastics, and  $E_p$  = tensile modulus of the plastics at the temperature involved.

Other equations for thermal expansion in various situations are shown in Fig. 7.

Most plastics expand more than metals with temperature increases and their modulus drops. The result is a compressive load in the plastics that often results in buckling. Conversely, as the temperature drops, the plastics shrinks more than the metal and develops an increased tensile modulus. These conditions can cause tensile rupture of the plastics part. Clearances around fasteners, warpage, creep, or failure, or yield of adhesives tend to relieve the thermal stress. Allowances must be made for temperature changes, especially with large parts subjected to wide variations. Provision is often made for relative motion  $\Delta L_{rel}$ , between two materials, as illustrated in Fig. 7:

$$\Delta L_{rel} = (\alpha_p - \alpha_m) L \Delta T \tag{25}$$

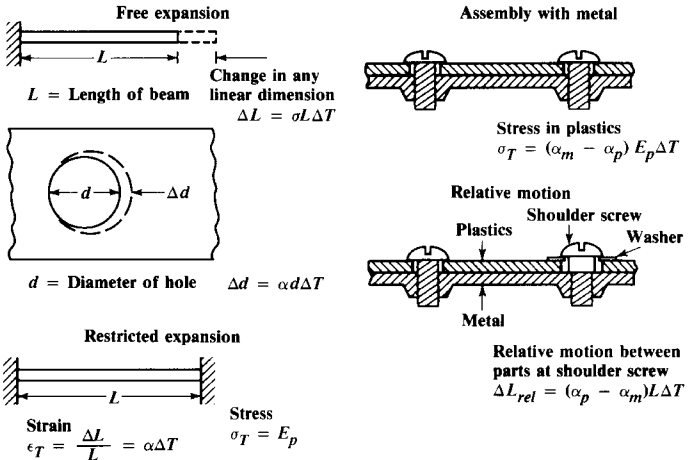


Fig. 7. Thermal Expansion Equations for Various Combinations of Materials and Situations

**Design for Injection Moldings.**—Injection molding uses equipment similar to that for die casting, in that a precision steel mold is clamped shut, and melted material (here, plasticized plastics) is forced into the cavity between the mold components. The pelletized plastics material is fed into a heated chamber, or barrel, by a large, slowly rotating screw,



and is melted. When a sufficient quantity to fill the cavity has been prepared, the screw is moved axially under high pressure to force the material into the cavity. The mold has channels through which coolant is circulated to remove heat and to chill the plastics. When the plastics has cooled sufficiently, the mold is unclamped and opened, and the molding is forced out by strategically located ejectors. During cooling and removal, material for the next part is plasticized within the barrel, ready for the cycle to be repeated.

Product analysis provides a good approach to design for plastics molding. A basic principle of plastics molding design, when moldings are being substituted for parts made by other means, is to incorporate as many functions into the molding as possible, especially those requiring nuts, bolts, and washers, for instance. Material should be selected that fulfills the maximum requirements, such as the functions mentioned, as well as insulation from the passage of heat or electricity, and allows use of the minimum amount of material.

Important material selection criteria include ability to withstand the heat of assembly, finishing, shipping, operating, and heat from internal sources. Effects of chemicals in the environment and approvals of government and other agencies also should be checked. Many such approvals specify wall thicknesses, color additives, fillers, and operating temperatures. Plans for assembly by bonding may dictate use of certain materials, and the question of painting, plating, or other surface coatings must be considered. Cost of candidate materials compared with the alternatives must be weighed, using the formula for cost per in.<sup>3</sup> = 0.0361 × specific gravity × material cost per lb. Material cost required for a part is obtained by multiplying the cost per in.<sup>3</sup> by the part volume. A rough estimate of likely part cost is double the cost of material for the part.

**Wall Thicknesses:** The thickness of material used in a plastics molding is of the greatest importance, and should be settled before the mold is made, since modifications are costly. In general, wall thicknesses should be kept as thin as practical and as uniform as possible. Ideally, the flow of molding material should be so arranged that it moves through thicker sections into thinner ones rather than the reverse. Geometric, structural, or functional needs may prevent ideal design, but examination of alternatives can often prevent problems from arising. Most injection-molded plastics parts range in thickness from  $\frac{1}{32}$  to  $\frac{3}{16}$  in. (0.8 to 4.8 mm) with the dimensions within that range related to the total size of the part.

**Impact Resistance:** The impact resistance of a plastics part is directly related to its ability to absorb mechanical energy without fracture or deformation, and this ability depends on the material properties and the part geometry. Increasing wall thickness may improve the impact resistance but may also hurt impact resistance by making the part too stiff so that it is unable to deflect and distribute the force.

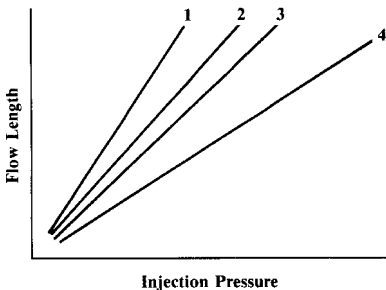


Fig. 8. Typical Spiral-Flow Curves for (1) Nylon 6/6, (2) Polyester Thermoplastics PBT, Liquid-Crystal-Glass-Reinforced, and Polyphenylene-Sulfide-Glass-Reinforced, (3) Acetal Copolymer, and (4) PBT-Glass-Reinforced Plastics Materials

Design engineers must also have some knowledge of mold design and, in determining wall thickness, should consider the ability of plastics to flow into the narrow mold channels. This flowability depends on temperature and pressure to some extent, but varies for different materials, as shown in Fig. 8.

Table 4 shows typical nominal wall thicknesses for various types of thermoplastics.

**Table 4. Typical Nominal Wall Thicknesses for Various Classes of Thermoplastics**

| Thermoplastics Group                  | Typical Working Range (in.) | Thermoplastics Group        | Typical Working Range (in.) |
|---------------------------------------|-----------------------------|-----------------------------|-----------------------------|
| Acrylonitrile-butadiene-styrene (ABS) | 0.045–0.140                 | Polyester elastomer         | 0.025–0.125                 |
| Acetal                                | 0.030–0.120                 | Polyethylene                | 0.030–0.200                 |
| Acrylic                               | 0.025–0.150                 | Polyphenylene sulfide       | 0.020–0.180                 |
| Liquid-crystal polymer                | 0.008–0.120                 | Polypropylene               | 0.025–0.150                 |
| Long-fiber-reinforced plastics        | 0.075–1.000                 | Polystyrene                 | 0.035–0.150                 |
| Modified polyphenylene ether          | 0.045–0.140                 | Polysulfone                 | 0.050–0.150                 |
| Nylon                                 | 0.010–0.115                 | Polyurethane                | 0.080–0.750                 |
| Polyarylate                           | 0.045–0.150                 | Polyvinyl chloride (PVC)    | 0.040–0.150                 |
| Polycarbonate                         | 0.040–0.150                 | Styrene-acrylonitrile (SAN) | 0.035–0.150                 |
| Polyester                             | 0.025–0.125                 | ...                         | ...                         |

If the plastics part is to carry loads, load-bearing areas should be analyzed for stress and deflection. When stress or deflection is too high, solutions are to use ribs or contours to increase section modulus; to use a higher-strength, higher-modulus (fiber-reinforced) material; or to increase the wall thickness if it is not already too thick. Where space allows, adding or thickening ribs can increase structural integrity without thickening walls.

Equations (11), (12), and (13) can be related to formulas using the section modulus and moment of inertia on page 261, where Case 2, for (i), stress at the beam center is given by  $\sigma = -W/4Z$ .

On page 260, note that  $Z = I \div$  distance from neutral axis to extreme fiber ( $h \div 2$  in the plastics example). The rectangular beam section diagrammed on page 239 gives the equivalent of  $I = bh^3/12$  for the rectangular section in the plastics example. Therefore,

$$Z = \frac{I}{h/2} = \frac{bh^3}{12} \times \frac{2}{h} = \frac{bh^2}{6}$$

In  $\sigma = -W/4Z$ , the (–) sign indicates that the beam is supported at the ends, so that the upper fibers are in compression and the lower fibers are in tension. Also,  $W = F$  and  $l = L$  in the respective equations, so that stress,  $\sigma = FL/4(bh^2)/6$ , and  $\sigma = 3FL/2bh^2$ .

To calculate (ii) maximum deflection  $Y$  at load, use  $Y = Wl^3/48EI$  from page 261, where  $W = F$ ,  $l = L$ ,  $E = E$ , from Equation (12) and  $I = bh^3/12$ . Therefore,

$$Y = \frac{FL^3}{48E(bh^2/12)} = \frac{FL^3}{4Ebh^3}$$

As an example, assume that a beam as described in connection with Equations (11), (12), and (13) is 0.75 in. wide, with a constant wall thickness of 0.080 in., so that the cross-sectional area is 0.060 in.<sup>2</sup>, and there is a central load  $W$  of 5 lb. Based on a bending or flexural modulus of 300,000 lb/in.<sup>2</sup>, the maximum stress is calculated at 6250 lb/in.<sup>2</sup> and the maximum deflection at 0.694 in. Both the stress and the deflection are too high, so a decision is made to add a rib measuring 0.040 in. thick by 0.400 in. deep, with a small draft of  $\frac{1}{2}$  degree per side, to reinforce the structure.

The equations on page 261, the drawing page 245 representing the ribbed section (neglecting radii), and the accompanying formulas, permit calculation of the maximum stress and deflection for the ribbed section.

With the new cross-sectional area only slightly larger at 0.0746 in.<sup>2</sup>, the calculated stress is reduced to 2270 lb/in.<sup>2</sup>, and the deflection goes down to 0.026 in., which is acceptable for both the material and the application. To achieve the same result from a heavier beam would require a thickness of 0.239 in., tripling the weight of the beam and increasing molding difficulties. The rib adds only 25 percent to the total section weight.

Use of ribs allows the structural characteristics of a part to be tailored to suit its function, but ribs can cause warping and appearance problems, so are best avoided if they are not structurally necessary. If the first parts produced require strengthening, ribs can be added or thickened without high cost after the tool is finished because the work consists only of removing steel from the mold. In general, ribs should have a base thickness of about half the thickness of the adjacent wall, and be kept as thin as possible where they are positioned near faces that need to have a good appearance.

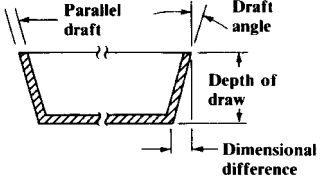
Where structural strength is more important than appearance, or when using materials that have low shrinkage, ribs can be made 75 or 100 per cent of the wall thickness. However, where the rib base joins the main molding there is an increase in thickness forming a heavy mass of material. Shrinkage of this mass can produce a cavity or void, a hollow area or sink, or can distort the molding. If the mass is very large, cooling time may be prolonged, leading to low output from the machine. Large masses of material in other parts of a molding are also best avoided. These problems can usually be addressed by good mold design.

Ribs need not be of constant height or width, and are often varied in proportions to suit the stress distribution in the part. All ribs should have a minimum of  $\frac{1}{2}$  degree of draft per side for ease of removal from the mold, and a minimum radius of 0.005 in. at the base to avoid stress-raising corners. Draft and thickness requirements will usually limit the height of the rib, which can be from 1.5 to 5 times the base thickness, and several evenly spaced ribs are generally preferred to a single large one. Smooth transitions should be made to other structural features such as bosses, walls, and pads.

Other ways to improve section properties include use of top-hat and corrugated sections, crowning or doming of some areas, and reinforcement with metal or other inserts that are placed in the mold before it is closed. To keep molded parts uniform in wall thickness, cores or projections may be provided in the mold to prevent a space being filled with molding material. Blind holes can be cored by pins that are supported on only one side of the mold and through holes by pins that pass through both sides. The length to width ratio should be kept as low as possible to prevent bending or breakage under the high pressures used in the injection molding process.

Agency approvals for resistance to flammability or heat, electrical properties, or other characteristics are usually based on specific wall thicknesses. These restrictions sometimes necessitate thicker walls than are required for structural strength purposes.

**Draft:** Most molded parts have features that must be cut into the mold perpendicular to the parting line. Removal of these parts from the mold is easier if they are tapered in the direction of mold opening. This taper is called draft in the line of draw or mold movement, and it allows the part to break free of the mold by creating a clearance as soon as the mold starts to open. Plastics materials shrink as they cool, so they grip mold projections very tightly and ejection can be difficult without sufficient draft. A draft of  $\frac{1}{2}$  degree on each side of a projection on the part is generally considered as a minimum, although up to 3 degrees per side is often used. Draft angles in degrees for various draw depths, and the resulting dimensional changes per side in inches (rounded to three decimal places), between the dimensions at the base and at the top of a projection are shown in [Table 5](#). A rule of thumb is that 1 degree of draft yields 0.017 in. of difference in dimension per inch of draw length. Where a minimum of variation in wall thickness is needed to produce walls that are perpendicular to the direction of draw, the mold sometimes can be designed to produce parallel draft, as seen at the left in [Table 5](#). The amount of draft required also depends

**Table 5. Dimensional Changes for Various Combinations of Draft Angles and Draw Depths (Values to Nearest 0.001 in.)**


The diagram illustrates a tapered cylindrical part. The top surface is labeled 'Parallel draft'. The angle between the vertical axis and the slanted side is labeled 'Draft angle'. The vertical height of the part is labeled 'Depth of draw'. The horizontal distance between the top and bottom edges of the part is labeled 'Dimensional difference'.

| Draw Depth (in) | Draft Angle (degrees) |               |               |       |       |       |       |       |
|-----------------|-----------------------|---------------|---------------|-------|-------|-------|-------|-------|
|                 | $\frac{1}{8}$         | $\frac{1}{4}$ | $\frac{1}{2}$ | 1     | 2     | 3     | 4     | 5     |
| 1               | 0.002                 | 0.004         | 0.009         | 0.017 | 0.035 | 0.052 | 0.070 | 0.080 |
| 2               | 0.004                 | 0.009         | 0.017         | 0.035 | 0.070 | 0.105 | 0.140 | 0.175 |
| 3               | 0.007                 | 0.013         | 0.026         | 0.053 | 0.105 | 0.157 | 0.210 | 0.263 |
| 4               | 0.009                 | 0.018         | 0.035         | 0.070 | 0.140 | 0.210 | 0.280 | 0.350 |
| 5               | 0.011                 | 0.022         | 0.044         | 0.088 | 0.175 | 0.262 | 0.350 | 0.437 |
| 6               | 0.013                 | 0.026         | 0.052         | 0.105 | 0.209 | 0.314 | 0.420 | 0.525 |
| 7               | 0.015                 | 0.031         | 0.061         | 0.123 | 0.244 | 0.367 | 0.490 | 0.612 |
| 8               | 0.018                 | 0.035         | 0.070         | 0.140 | 0.279 | 0.419 | 0.559 | 0.700 |
| 9               | 0.020                 | 0.040         | 0.078         | 0.158 | 0.314 | 0.472 | 0.629 | 0.787 |
| 10              | 0.022                 | 0.044         | 0.087         | 0.175 | 0.349 | 0.524 | 0.699 | 0.875 |

on the surface finish of the mold walls. Any surface texture will increase the draft requirement by at least 1 degree per side for every 0.001 in. of texture depth.

**Fillets, Radii, and Undercuts:** Sharp corners are always to be avoided in injection-molded part designs because they represent points of stress concentration. Sharp corners in metal parts often are less important because the stresses are low compared with the strength of the material or because local yielding redistributes the loads. Sharp inside corners are particularly to be avoided in moldings because severe molded-in stresses are generated as the material shrinks onto the mold corner. Sharp corners also cause poor material flow patterns, reduced mechanical properties, and increased tool wear. Therefore, inside corner radii should be made equal to half the nominal wall thickness, with a minimum of 0.020 in. for parts subject to stress and 0.005 in. radius for stress-free parts. Outside corners should have a radius equal to the inside corner radius plus the wall thickness.

With an inside radius of half the wall thickness, a stress concentration of 1.5 is a reasonable assumption, and for radii down to 0.1 times the wall thickness, a stress concentration of 3 is likely. More information on stress concentrations is found in *Working Stress* on page 208, *Stress Concentration Factors* on page 209, and in the charts pages 209 through 212. A suitable value for  $q$  in Equation (8) on page 209, for plastics materials, is 1. Most plastics parts are so designed that they can be ejected parallel with the direction of mold parting. Complex parts with undercuts may require mold designs with cavity-forming projections that must move at an angle to the direction of opening. Between these two extremes lie such items as "windows," or simple openings in the side of a molding, which can be produced by the normal interaction of the two main parts of the mold.

**Design for Assembly.**—An advantage of the flexibility of plastics parts is that they can often be designed for assembly by means of molded-in snap-fit, press-fit, pop-on, and thread fasteners, so that no additional fasteners, adhesives, solvents, or special equipment is required. Improper assembly can be minimized, but tooling is often made more complex and disassembly may be difficult with these methods.

*Chemical bonding* involves fixtures, substances, and safety equipment, is suited to applications that must be leak-tight, and does not create stresses. However, adhesives and solvents can be dangerous and preparation and cure times can be prolonged.

*Thermal welding* methods include ultrasonic, hot-plate, spin, induction, and radio-frequency energy and require special equipment. Thermal methods are also used for staking, swaging, and other heat deformation procedures. Materials must be compatible and have similar melting temperatures.

*Mechanical fasteners* designed for metals are generally usable with plastics, and there are many other fasteners designed specifically for plastics. Typical are bolts, self-tapping and thread-forming screws, rivets, threaded inserts, and spring clips. Care must be taken to avoid overstressing the parts. Creep can result in loss of preload in poorly designed systems.

*Snap-fit* designs are widely used, a typical application being to battery compartment covers. All snap-fit designs have a molded part that must flex like a spring, usually past a designed-in interference, then return to its unflexed position to hold the parts together. There must be sufficient holding power without exceeding the elastic or fatigue limits of the material. With the typical snap-fit designs in Fig. 9, beam equations can be used to calculate the maximum strain during assembly. If the stress is kept below the yield point of the material, the flexing finger returns to its original position.

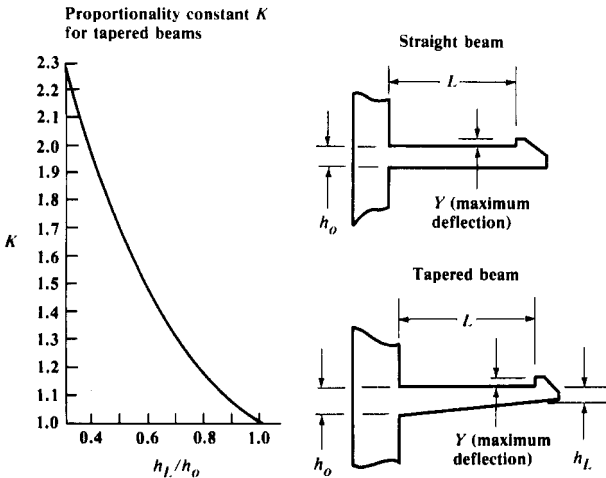


Fig. 9. Snap-fit Designs for Cantilever Beams with Rectangular Cross Sections

With some materials the calculated bending stress can exceed the yield point stress considerably if the movement is done rapidly. In other words, the flexing finger passes through its maximum deflection or strain and the material does not respond as it should if the yield stress has been greatly exceeded. It is common to evaluate snap-ins by calculating strain instead of stress.

Dynamic strain  $\epsilon$ , for the straight beam, is calculated from

$$\epsilon = \frac{3Yh_0}{2L^2} \quad (26)$$

and for the tapered beam, from

$$\epsilon = \frac{3Yh_o}{2L^2K} \quad (27)$$

The derived values should be compared with the permissible dynamic strain limits for the material in question, if known. A tapered finger provides more-uniform stress distribution and is recommended where possible. Sharp corners or structural discontinuities that will cause stress concentrations on fingers such as those shown must be avoided.

Snap-in arrangements usually require undercuts produced by a sliding core in the mold as shown in Fig. 10a. Sometimes the snap finger can be simply popped off when the mold is opened. An alternative to the sliding core is shown in Fig. 10b, which requires an opening in the molding at the base of the flexing finger. Other snap-in assembly techniques that take advantage of the flexibility of plastics are shown in Fig. 11.

Molded-in threads in holes usually are formed by cores that require some type of unscrewing or collapsing mechanism leading to tooling complications. External threads can often be molded by positioning them across the parting plane of the mold. Molding of threads finer than 28 to the inch is generally not practical.

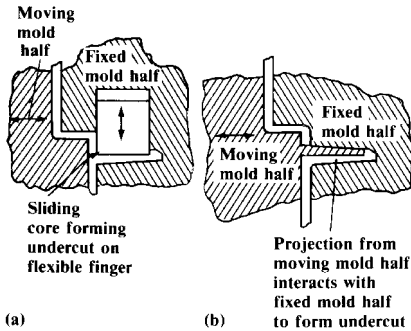


Fig. 10. (left) (a) Arrangement for Molding an Undercut on the End of a Flexible Finger Using a Sliding Core; (b) With the Undercut Formed by a Mold Projection, the Sliding Core is Eliminated.

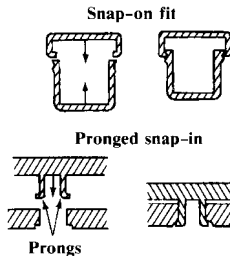


Fig. 11. (right) Examples of Snap-In and Snap-On Arrangements

Chemical bonding may use solvents or adhesives. Use of solvents is limited to compatible materials that can be dissolved by the same solvent. Chemical resistance of many plastics, especially crystalline materials, limits the use of this method. Safety precautions must also be considered in handling the solvents to protect workers and for solvent recovery.

With adhesive bonding, a third adhesive substance is introduced at the interface between the parts to be joined. Adhesives can join plastics, metals, ceramics, glass, wood, or other bondable substances.

Typical adhesives used for thermoplastics are epoxies, acrylics, polyurethanes, phenolics, rubbers, polyesters, and vinyls. Cyanoacrylates are often used because of their rapid adhesion to many materials. Manufacturers' recommendations should be sought because many adhesives contain solvents that partially dissolve the plastics surfaces, giving improved adhesion. However, some adhesives can attack certain plastics, leading to deterioration and failure. The main disadvantages of adhesives are that they are slow, use long clamp times, require fixtures, and may involve special ovens or curing conditions. Surface preparation also may be difficult because the presence of grease, oil, mold-release material, or even a fingerprint can spoil a bond. Some materials may need surface preparation such as chemical etching or mechanical roughening to improve joint strength.

Ultrasonic welding is frequently used for joining parts of similar material, of small and medium size, is rapid, and can be automated. High-frequency (20–40 kHz) vibrational energy is directed to the interfaces to be joined, creating localized molecular excitation that causes the plastics to melt. With proper joint designs, welds can be made in only 2 seconds that are as strong as the base materials. When the energy is switched off, the plastics solidifies immediately. Parts to be welded ultrasonically must be so designed that the energy is concentrated in an initially small contact area, creating rapid melting and melt flow that progresses along the joint as the parts are pressed together. The lower part of the assembly is supported in a rigid nest fixture and the upper part is aligned, usually by the joint design. This upper part has freedom to couple acoustically when it is in contact with the horn through which the ultrasonic energy is transmitted.

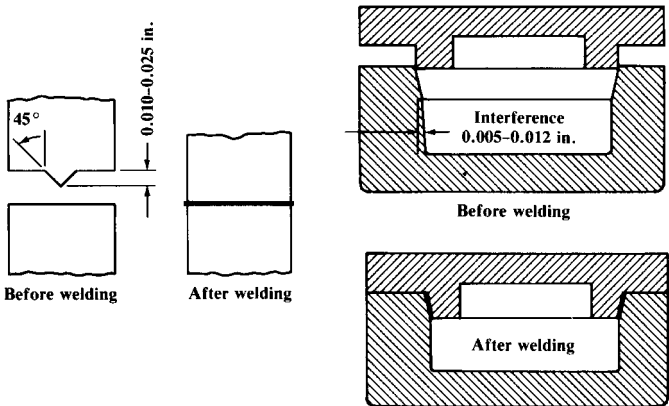


Fig. 12. (left) Energy Director Types of Ultrasonic Weld Joint Designs for Assembly of Plastics Moldings, and (right) Typical Shear Interference

Typical joint designs are shown in Fig. 12, where the example at the left is of a simple butt-type energy director design that works well with amorphous materials. The inverted V-projection, known as an energy director, concentrates the energy in a small area on both sides of the joint. This area melts quickly and the material flows as the parts are pressed together. A basic shear interference joint is seen at the right in Fig. 12. Melting of both components starts at the small initial contact area and flow continues along the near-verti-

cal wall as the parts are pressed together, creating a continuous, leakproof joint with a strength that often exceeds that of the parts joined.

This design is preferred with liquid crystal polymers and crystalline materials such as nylon, acetal, and thermoplastics polyester, and for any application of these materials where high strength and a hermetic seal are required. Many variations of these basic designs are possible and manufacturers of materials and ultrasonic equipment offer literature and design assistance. Ultrasonic vibrations may also be used for staking, swaging, and spot-welding in assembly of plastics parts.

With hygroscopic materials, welding should be completed as soon as possible after molding because moisture can cause weaker bonds. Drying may be advisable immediately before welding. Drawbacks with ultrasonic welding are that design, quality control, equipment maintenance, and settings are of critical importance for consistent, high-strength welds; the equipment is costly; the process uses large amounts of electric power especially with large parts; and parts to be joined must be of the same or similar materials. Filled and reinforced materials also present difficulties with compatibility.

Operating frequencies used in ultrasonic welding are in the range of 20–40 kHz, above the range detectable by the ear. However, discomforting sounds may be generated when plastics parts vibrate at lower frequencies, and may make sound-proofing necessary.

Vibration welding resembles ultrasonic welding except that the parts to be joined are rubbed together to produce heat to melt the joint faces by friction. The energy is transferred in the form of high-amplitude, low-frequency, reciprocating motion. When the vibration stops, the weld area cools and the parts remain joined in the alignment provided by the welding fixture. Typical frequencies used are 120–240 Hz and amplitudes range between 0.10 and 0.20 in. of linear displacement. When the geometry or assembly design prevents linear movement, vibration-welding equipment can be designed to produce angular displacement of parts.

Like ultrasonic welding, vibration welding produces high-strength joints and is better suited to large parts and irregular joint faces. Moisture in hygroscopic materials such as nylon has less effect on the joint strength than it does with ultrasonic methods.

Spin welding is a rapid and economical method of joining parts that have circular joint interfaces. The process usually is completed in about 3 seconds and can be automated easily. Frictional heat for welding is generated by rotating one part against the other (usually fixed) with a controlled pressure. When the rotation is stopped, pressure is maintained during cooling and solidification of the melted material. Simple equipment such as a drill press is often sufficient for this process.

Radio-frequency welding, often called heat sealing, is widely used with flexible thermoplastics films and sheets of materials such as vinyl (plasticized PVC) and polyurethane, and for joining injection-molded parts, usually to film. Heat for welding is generated by a strong radio-frequency field to the joint region through a metal die formed to suit the joint shape. The die also applies the pressure required to complete the weld. Some plastics are transparent to radio frequency, so cannot be welded by this method.

Electromagnetic or induction welding uses inductive heating to generate fusion temperatures in thermoplastics materials as shown at the top in Fig. 13. Fine, magnetizable particles embedded in a gasket, preform, filament, ribbon, adhesive, coextruded film, or molded part are excited by the radio frequency and are thus heated to welding temperatures. The heated parts are pressed together, and as the temperature rises, the material of the particle carrier flows under pressure through the joint interface, filling voids and cavities and becoming an integral part of the weld. Ideally, the melted material should be contained and subjected to an internal pressure by the surrounding component surfaces. Proper joint design is essential to successful welding and some basic designs are also shown in Fig. 13.

Requirements of the preform often add cost to this welding method but the cost is offset by low reject rates resulting from good reliability of the welds. Structural, hermetic welds



can be produced in most thermoplastics materials and automation can be used for large-volume production. The process also offers great latitude in joint size, configuration, tolerance requirements, and ability to bond some dissimilar materials. A disadvantage is that no metal can be near the joint line during energization of the inductor coil. All components of an assembly to be induction-welded must therefore be nonmetallic, or metallic components must be placed where they will not be subjected to the radio-frequency field from the inductor.

**Assembly with Fasteners.**—Metal fasteners of high strength can overstress plastics parts, so torque-controlled tightening or special design provisions are needed. Examples of poor and preferred designs are shown in Fig. 14. Where torque cannot be controlled, even with a shoulder screw, various types of washers can be used to spread the compression force over wider areas.

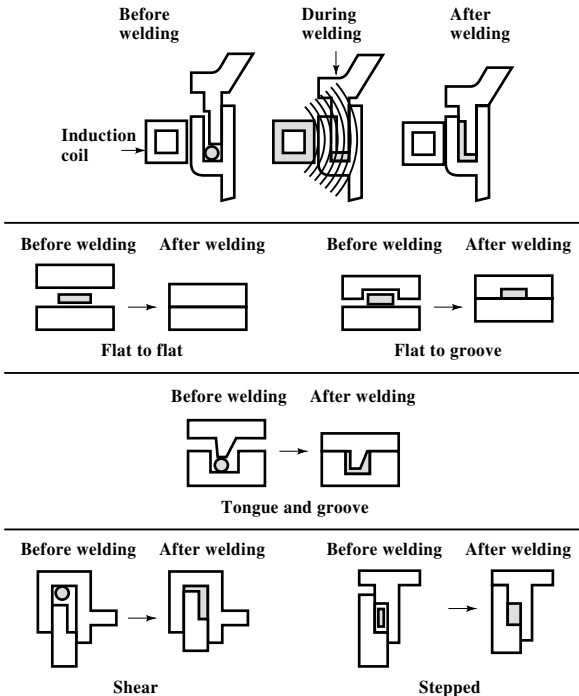


Fig. 13. Typical Joint Designs Used in Induction Welding of Plastics Materials

Metal inserts are available in a wide range of shapes and sizes for permanent installation of metal threads or bushings in plastics parts. Inserts are typically installed in molded bosses, designed with holes to suit the insert to be used. Some inserts are pressed into place and others are installed by methods designed to limit stress and increase strength. Generally, the outside of the insert is provided with projections of various configurations that penetrate the plastics and prevent movement under normal forces exerted during assem-

bly. Inserts can also be installed with equipment similar to that used for ultrasonic welding, the plastics being melted to enhance contact with the metal and reduce insertion stresses.

Thread-cutting and -forming screws are widely used with plastics parts. Information on standard self-threading screws is found in *SELF-THREADING SCREWS* starting on page 1639. Thread-forming screws must be used carefully with high-modulus, low-creep materials, as high hoop stresses can be generated during insertion. Screws with multiple lobes and screws with alternating low and high threads have excellent holding power in plastics. Molded holes must have sufficient depth to prevent bottoming, and boss walls must be thick enough to resist stresses. A rule of thumb is that the outside diameter of the boss should be double the major diameter of the screw.

Hollow aluminum or other metal rivets are often used in plastics assembly, as are stamped sheet metal components, especially push-on or -in designs. Molded plastics fasteners also are frequently used.

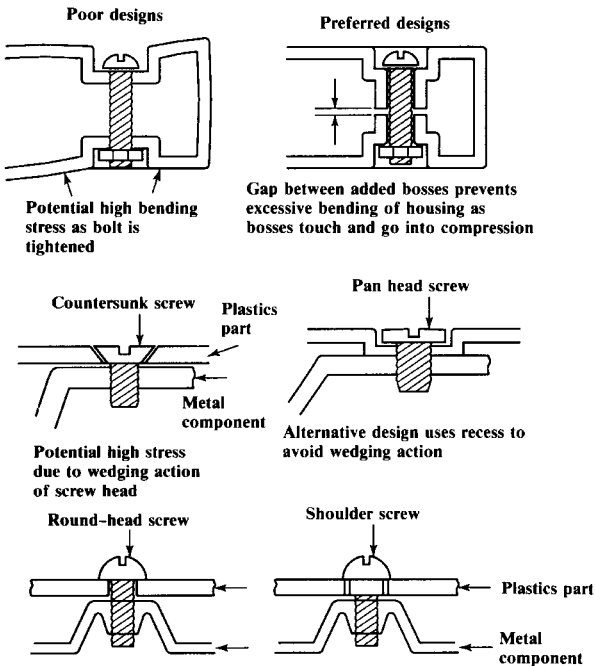


Fig. 14. Examples of Poor and Good Designs Used for Assembly of Plastics Parts with Metal Fasteners

**Machining Plastics.**—Plastics can be molded into complex shapes so do not usually need to be machined. However, machining is sometimes more cost-effective than making a complex tool, especially when requirements are for prototype development, low-volume production, undercuts, angular holes, or other openings that are difficult to produce in a mold. Specialized methods for development of prototypes are discussed later. All machin-

ing of plastics requires dust control, adequate ventilation, safety guards, and eye protection.

Like some metals, plastics may need to be annealed before machining to avoid warpage. Specific annealing instructions can be obtained from plastics suppliers. The modulus of elasticity of plastics is 10–60 times smaller than for metals, and this resilience permits much greater deflection of the work material during cutting. Thermoplastics materials must be held and supported firmly to prevent distortion, and sharp tools are essential to keep cutting forces to a minimum.

Plastics recover elastically during and after machining so that drilled or tapped holes often end up tapered or of smaller diameter than the tool. Turned diameters also can end up larger than the dimensions measured immediately after the finishing cut. The low thermal conductivity of plastics causes most of the heat generated in cutting to be absorbed by the tool. Heat in the plastics tends to stay at the surface. The heat must be removed by an air blast or a liquid coolant for good results in machining.

Plastics have thermal expansion coefficients some 10 times higher than those of metals, so that more heat is generated during machining than with metals. Adequate tool clearances must be provided to minimize heating. Compared with metals, temperatures at which plastics soften, deform and degrade are quite low. Allowing frictional heat to build up causes gumming, discoloration, poor tolerance control, and rough finishes. These effects are more pronounced with plastics such as polystyrene and polyvinyl chloride, having low melting points, than with plastics having higher melting points such as nylon, fluoroplastics, and polyphenylene sulfide. Sufficient clearances must be provided on cutting tools to prevent rubbing contact between the tool and the work. Tool surfaces that will come into contact with plastics during machining must be polished to reduce frictional drag and resulting temperature increases. Proper rake angles depend on depth of cut, cutting speed, and type of plastics being cut. Large rake angles should be used to produce continuous-type cuttings, but they should not be so large as to cause brittle fracture of the work, and resulting discontinuous chips. A discussion of machining techniques follows.

*Turning and Cutting Off:* High speed steel and carbide tools are commonly used with cutting speeds of 200–500 and 500–800 ft/min, respectively. Water-soluble coolants can be used to keep down temperatures at the shear zone and improve the finish, except when they react with the work material. Chatter may result from the low modulus of elasticity and can be reduced by close chucking and follow rests. Box tools are good for long, thin parts. Tools for cutting off plastics require greater front and side clearances than are needed for metal. Cutting speeds should be about half those used for turning operations.

*Drilling:* Chip flow in drilling is poor, the rake angles are insufficient and cutting speeds vary from the center to the periphery of the drill, so that drilling imposes severe loading on the workpiece. Drills of high speed steel or premium high speed steel (T15, M33, or M41–M47) are recommended, with low helix angles, point angles of 70–120 deg, and wide, highly polished flutes to ease chip exit. Normal feed rates are in the range of 0.001–0.012 in./rev for holes of  $\frac{1}{16}$  to 2 in. diameter, with speeds of 100–250 ft/min, using lower speeds for deep and blind holes. Point angles of 60–90 deg (included) are used for many plastics, but an angle of 120 deg should be used for rigid polyvinyl chloride and acrylic (polymethyl methacrylate).

Clearance angles of 9–15 deg are usually sufficient to prevent the drill flanks from rubbing in the bottom of the hole, but acrylic materials require angles of 12–20 deg. Tests may be needed to determine the drill diameter for accurately sized holes, taking thermal expansion and elastic recovery into account. Reaming may be used to size holes accurately, but diameters produced may also be affected by thermal expansion of the plastics. Close-fitting bushings in drill jigs may increase friction on the drill and cause chips to plug up the drill flutes. For positioning accuracy, removable templates may be used to spot the hole position, then removed for the drilling to be completed. Pilot holes are not necessary,

except when the hole is to be reamed or counterbored. Peck feeds to remove chips and compressed air cooling may be needed, especially for deep holes.

Drilling and reaming speed and feed recommendations for various materials are shown in Table 6.

These speeds and feeds can be increased where there is no melting, burning, discoloration, or poor surface finish. Drilling is best done with commercially available drills designed for plastics, usually having large helix angles, narrow lands, and highly polished or chromium-plated flutes to expel chips rapidly and minimize frictional heating. Circle cutters are often preferred for holes in thin materials. Deep holes may require peck feeds. Drills must be kept sharp and cool, and carbide tools may be needed in high production, especially with glass-reinforced materials. Cool with clean compressed air to avoid contamination. Use aqueous solutions for deep drilling because metalcutting fluids and oils may degrade or attack the plastics and may cause a cleaning problem. Hold plastics parts firmly during drilling to counter the tendency for the tooling to grab and spin the work.

**Table 6. Speeds and Feeds for Drilling Holes of 0.25 to 0.375 in. Diameter in Various Thermoplastics**

| Material                | Speed (rpm) | Feed <sup>a</sup> | Comments                     |
|-------------------------|-------------|-------------------|------------------------------|
| Polyethylene            | 1,000–2,000 | H                 | Easy to machine              |
| Polyvinyl chloride      | 1,000–2,000 | M                 | Tends to become gummy        |
| Acrylic                 | 500–1,500   | M–H               | Easy to drill with lubricant |
| Polystyrene             | 500–1,500   | H                 | Must have coolant            |
| ABS                     | 500–1,000   | M–H               |                              |
| Polytetrafluoroethylene | 1,000       | L–M               | Easy to drill                |
| Nylon 6/6               | 1,000       | H                 | Easy to drill                |
| Polycarbonate           | 500–1,500   | M–H               | Easy to drill, some gumming  |
| Acetal                  | 1,000–2,000 | H                 | Easy to drill                |
| Polypropylene           | 1,000–2,000 | H                 | Easy to drill                |
| Polyester               | 1,000–1,500 | H                 | Easy to drill                |

<sup>a</sup> H = high; M = medium; L = low.

*Tapping and Threading of Plastics:* Many different threaded fasteners can be used with plastics, including thread-tapping and -forming screws, threaded metal inserts, and molded-in threads, but threads must sometimes be machined after molding. For tapping of through-holes in thin cast, molded, or extruded thermoplastics and thermosets, a speed of 50 ft/min is appropriate. Tapping of filled materials is done at 25 ft/min. These speeds should be reduced for deep or blind holes, and when the percentage of thread is greater than 65–75 per cent. Taps should be of M10, M7, or M1, molybdenum high-speed steel, with finish-ground and -polished flutes. Two-flute taps are recommended for holes up to 0.125 in. diameter. Oversize taps may be required to make up for elastic recovery of the plastics. The danger of retapping on the return stroke can be reduced by blunting the withdrawal edges of the tool.

*Sawing Thermoset Cast or Molded Plastics:* Circular or band saws may be used for sawing. Circular saws provide smoother cut faces than band saws, but band saws run cooler so are often preferred even for straight cuts. Projection of the circular saw above the table should be minimized. Saws should have skip teeth or buttress teeth with zero front rake and a raker set. Precision-tooth saw blades should be used for thicknesses up to 1 in., and saws with buttress teeth are recommended for thicknesses above 1 in. Dull edges to the teeth cause chipping of the plastics and may cause breakage of the saw. Sawing speeds and other recommendations for using blades of high-carbon steel are shown in the accompanying table.

### Speeds and Numbers of Teeth for Sawing Plastics Materials with High-Carbon Steel Saw Blades

| Material Thickness (in.) | Number of Teeth on Blade | Peripheral Speed (ft/min)         |   |
|--------------------------|--------------------------|-----------------------------------|---|
|                          |                          | Thermoset Cast or Molded Plastics | Thermoplastics (and Epoxy, Melamine, Phenolic and Allyl Thermosets) |
| 0–0.5                    | 8–14                     | 2000–3000                         | 4000–5000   |
| 0.5–1                    | 6–8                      | 1800–2200                         | 3500–4300   |
| 1–3                      | 3                        | 1500–2200                         | 3000–3500   |
| >3                       | >3                       | 1200–1800                         | 2500–3000   |

*Milling of Plastics:* Peripheral cutting with end mills is used for edge preparation, slotting and similar milling operations, and end cutting can also be used for facing operations. Speeds for milling range from 800 to 1400 ft/min for peripheral end milling of many thermoplastics and from 400 to 800 ft/min for many thermosets. However, slower speeds are generally used for other milling operations, with some thermoplastics being machined at 300–500 ft/min, and some thermosets at 150–300 ft/min. Adequate support and suitable feed rates are very important. A table feed that is too low will generate excessive heat and cause surface cracks, loss of dimensional accuracy, and poor surface finish. Too high a feed rate will produce a rough surface. High-speed steel tools (M2, M3, M7, or T15) are generally used, but for glass-reinforced nylon, silicone, polyimide, and allyl, carbide (C2) is recommended.

*New Techniques:* Lasers can be used for machining plastics, especially sheet laminates, although their use may generate internal stresses. Ultrasonic machining has no thermal, chemical, or electrical reaction with the workpiece and can produce holes down to 0.003 in. diameter, tight tolerances (0.0005 in.), and very smooth finishes (0.15  $\mu$ m. with No. 600 boron carbide abrasive powder). Water-jet cutting using pressures up to 60,000 lb/in.<sup>2</sup> is widely used for plastics and does not introduce stresses into the material. Tolerances of  $\pm$  0.004 in. can be held, depending on the equipment available. Process variables, pressures, feed rates, and the nozzle diameter depend on the material being cut. This method does not work with hollow parts unless they can be filled with a solid core.

**Development of Prototypes.**—Prototypes are made for testing of properties such as stress and fatigue resistance, to find ways to improve quality and reliability, to improve tooling, and to reduce time to market. Prototyping may answer questions about finish, sink marks that result from contraction, witness lines from mold joints, ejector pin marks, knit or weld lines, texturing, moldability, shrinkage, mechanical strength, pull-out resistance of inserts, electrical properties, and problems of mating with other parts.

Prototypes of moldings are made in five major steps including design; refining the design; making a model (physical or computer); making a mold; and producing parts. The model may be made from wood, plaster, plastics (by machining), or a metal. Some 90 per cent of prototypes are made by modern CAD/CAM methods that allow holding of dimensional tolerances of 2–3 per cent of drawing specifications.

Prototypes can also be made by a process called stereo lithography that uses a tank of photosensitive liquid polymer, an x-y scanning, ultraviolet laser with a beam diameter of 0.010 in., a z-axis elevator platform, and a controlling computer. The platform height is adjusted so that a suitable thickness of liquid polymer covers its surface. The laser beam is focused on the liquid surface and hardens the polymer at this point by heating.

The CAD representation of the prototype is described by a model in which thin (0.005–0.020 in.) cross sections can be isolated. Data representing the lowest level of the prototype are used to move the platform so that a layer of the polymer corresponding to the lowest “slice” is hardened. The platform is then lowered, the liquid polymer flows over the hard-

ened layer, and the platform is again raised, less an amount equal to the next "slice." The process is repeated for successive "slices" of the prototype, which is thus built up gradually to form a hollow, three-dimensional shape corresponding to the model in the CAD program. The part thus produced is fairly brittle but can be used for visual examination, design verification, and marketing evaluation, and can be replicated from other materials such as plastics or metals by casting or other methods.

Finishing and decorating methods used for plastics parts include spray painting, vacuum metallizing, hot stamping, silk screening, and plating. Conductive coatings may be applied to inside surfaces, usually by flame- or arc-spraying, to dissipate static electricity and provide electromagnetic shielding. Thorough cleaning is essential. Materials such as polyethylene, polypropylene, and acetal have waxlike surfaces that may not be painted easily or may need pretreatment or special primers. Many amorphous plastics are easy to paint. Suitable coatings include polyurethane-, epoxy-, acrylic-, alkyd-, and vinyl-based paints. Oven curing may distort parts made from non-heat-resistant materials.

Vacuum metallizing and sputter-plating require application of a special base coat and a protective clear top coat before and after treatment. Resistance heating or an electron beam can be used to melt the metallizing materials such as aluminum, silver, copper, and gold, which usually are pure elements. Sputter plating uses a plasma to produce the metallic vapor and can use brass as well as the metals mentioned. Chromium plating requires etched surfaces to ensure good adhesion.

Plastics may be polished by buffing methods similar to those used on metals, but experiments to determine the effect of frictional heat are recommended. Surfaces can be heated to 300–400 deg. F by buffing, and some plastics soften and melt at these temperatures. Heating sometimes causes plastics to give off toxic gases, so masks should be worn to filter out such gases and dust. Parting lines, imperfections, scratches, saw lines, and scars resulting from fabrication can be treated with abrasives prior to buffing. Wet or dry abrasives such as silicon carbide or aluminum oxide are generally used, in grain sizes of 60 to as fine as 320. Some buffing compounds are ineffective on plastics. Scratch lines should be presented at a slight angle to the buff surface for best results. Light, tallow-free grease will help keep the abrasive surface free from buildup, and speeds of 5,000 to 6,000 surface feet per minute are recommended.

For low-melting point plastics, soft cotton buffs are best, with surface speeds of 4,000 to 5,000 feet per minute, using a wet or greasy tripoli or silica compound. For finishing, only rouge may be needed for a satisfactory finish. If a cleaning solvent is used it should be checked to see that it does not dissolve the plastics, and it should be used only in a well-ventilated area. Acrylics such as Acrylite or Plexiglass may also be 'flame polished,' under advice from the materials supplier.

**Plastics Gearing.**—Plastics gears may be cut from blanks, as with metal gears, or molded to shape in an injection-molding machine, for lower production costs, though tooling may cost more. Cut plastics gears may be of similar design to their metal counterparts, but molded gears are usually of modified form to suit the material characteristics. Plastics materials also may be preferred for gears because of superior sliding properties with reduced noise and need for lubrication, chemical or electrical properties, or resistance to wear. However, plastics gear teeth slide more smoothly and easily against metal teeth than do plastics against plastics, and wear is less. For power transmission, plastics gear teeth are usually of involute form. See also *Non-metallic Gearing* on page 2149.

Most plastics gears are made from nylons and acetals, although acrylonitrile-butadiene-styrenes (ABS), polycarbonates, polysulfones, phenylene oxides, poly-urethanes, and thermoplastic polyesters can also be used. Additives used in plastics gears include glass fiber for added strength, and fibers, beads, and powders for reduced thermal expansion and improved dimensional stability. Other materials, such as molybdenum disulfide, tetrafluoroethylene (TFE), and silicones, may be added as lubricants to improve wear resistance.

Choice of plastics gear material depends on requirements for size and nature of loads to be transmitted, speeds, required life, working environment, type of cooling, lubrication, and operating precision. Because of cost, plastics gears are sometimes not enclosed in sealed housings, so are often given only a single coating of lubricant grease. Overloading of lubricated plastics gear teeth will usually cause tooth fracture, and unlubricated teeth often suffer excessive wear. Thermoplastics strength varies with temperature, with higher temperatures reducing root stress and permitting tooth deformation. In calculating power to be transmitted by spur, helical, and straight bevel gearing, the following formulas should be used with the factors given in Tables 7, 8, and 9.

For internal and external spur gears,

$$HP = \frac{S_s FYV}{55(600 + V)PC_s} \quad (28)$$

For internal and external helical gears,

$$HP = \frac{S_s FYV}{423(78 + \sqrt{V})P_n C_s} \quad (29)$$

For straight bevel gears,

$$HP = \frac{S_s FYV(C - F)}{55(600 + V)PCC_s} \quad (30)$$

where  $S_s$  = safe stress in bending (from Table 8);  $F$  = face width in inches;  $Y$  = tooth form factor (from Table 7);  $C$  = pitch cone distance in inches;  $C_s$  = service factor (from Table 9);  $P$  = diametral pitch;  $P_n$  = normal diametral pitch; and  $V$  = velocity at pitch circle diameter in ft/min.

**Table 7. Tooth Form Factors  $Y$  for Plastics Gears**

| Number of Teeth | 14½-deg Involute or Cycloidal | 20-deg Full Depth Involute | 20-deg Stub Tooth Involute | 20-deg Internal Full Depth |       |
|-----------------|-------------------------------|----------------------------|----------------------------|----------------------------|-------|
|                 |                               |                            |                            | Pinion                     | Gear  |
| 12              | 0.210                         | 0.245                      | 0.311                      | 0.327                      | ...   |
| 13              | 0.220                         | 0.261                      | 0.324                      | 0.327                      | ...   |
| 14              | 0.226                         | 0.276                      | 0.339                      | 0.330                      | ...   |
| 15              | 0.236                         | 0.289                      | 0.348                      | 0.330                      | ...   |
| 16              | 0.242                         | 0.259                      | 0.361                      | 0.333                      | ...   |
| 17              | 0.251                         | 0.302                      | 0.367                      | 0.342                      | ...   |
| 18              | 0.261                         | 0.308                      | 0.377                      | 0.349                      | ...   |
| 19              | 0.273                         | 0.314                      | 0.386                      | 0.358                      | ...   |
| 20              | 0.283                         | 0.320                      | 0.393                      | 0.364                      | ...   |
| 21              | 0.289                         | 0.327                      | 0.399                      | 0.371                      | ...   |
| 22              | 0.292                         | 0.330                      | 0.405                      | 0.374                      | ...   |
| 24              | 0.298                         | 0.336                      | 0.415                      | 0.383                      | ...   |
| 26              | 0.307                         | 0.346                      | 0.424                      | 0.393                      | ...   |
| 28              | 0.314                         | 0.352                      | 0.430                      | 0.399                      | 0.691 |
| 30              | 0.320                         | 0.358                      | 0.437                      | 0.405                      | 0.679 |
| 34              | 0.327                         | 0.371                      | 0.446                      | 0.415                      | 0.660 |
| 38              | 0.336                         | 0.383                      | 0.456                      | 0.424                      | 0.644 |
| 43              | 0.346                         | 0.396                      | 0.462                      | 0.430                      | 0.628 |

**Table 7. (Continued) Tooth Form Factors  $Y$  for Plastics Gears**

| Number of Teeth | 14½-deg Involute or Cycloidal | 20-deg Full Depth Involute | 20-deg Stub Tooth Involute | 20-deg Internal Full Depth |       |
|-----------------|-------------------------------|----------------------------|----------------------------|----------------------------|-------|
|                 |                               |                            |                            | Pinion                     | Gear  |
| 50              | 0.352                         | 0.480                      | 0.474                      | 0.437                      | 0.613 |
| 60              | 0.358                         | 0.421                      | 0.484                      | 0.446                      | 0.597 |
| 75              | 0.364                         | 0.434                      | 0.496                      | 0.452                      | 0.581 |
| 100             | 0.371                         | 0.446                      | 0.506                      | 0.462                      | 0.565 |
| 150             | 0.377                         | 0.459                      | 0.518                      | 0.468                      | 0.550 |
| 300             | 0.383                         | 0.471                      | 0.534                      | 0.478                      | 0.534 |
| Rack            | 0.390                         | 0.484                      | 0.550                      | ...                        | ...   |

These values assume a moderate temperature increase and some initial lubrication. With bevel gearing, divide the number of teeth by the cosine of the pitch angle and use the data in the table. For example, if a 20-deg PA bevel gear has 40 teeth and a pitch angle of 58 deg, 40 divided by the cosine of 58 deg =  $40 \div 0.529919 \sim 75$ , and  $Y = 0.434$ .

**Table 8. Safe Bending Stress (lb/in<sup>2</sup>) Values for Plastics Gears**

| Plastics Type | Safe Stress |              |
|---------------|-------------|--------------|
|               | Unfilled    | Glass-filled |
| ABS           | 3,000       | 6,000        |
| Acetal        | 5,000       | 7,000        |
| Nylon         | 6,000       | 12,000       |
| Polycarbonate | 6,000       | 9,000        |
| Polyester     | 3,500       | 8,000        |
| Polyurethane  | 2,500       | ...          |

**Table 9. Service Factors for Plastics Gears**

| Type of Load | 8–10 Hr/Day | 24 Hr/Day | Intermittent, 3 Hr/Day | Occasional, ½ Hr/Day |
|--------------|-------------|-----------|------------------------|----------------------|
| Steady       | 1.00        | 1.25      | 0.80                   | 0.50                 |
| Light shock  | 1.25        | 1.5       | 1.00                   | 0.80                 |
| Medium shock | 1.5         | 1.75      | 1.25                   | 1.00                 |
| Heavy shock  | 1.75        | 2.00      | 1.5                    | 1.25                 |

*Example:* As an example, assume that a material is to be selected for a spur gear that must transmit  $\frac{1}{8}$  hp at 350 rpm, for 8 hrs/day under a steady load. The gear is to have 75 teeth, 32 diametral pitch, 20 deg pressure angle, 0.375 in. face width, and a pitch diameter of 2.3438 in. Using Equation (28),

$$HP = \frac{S_s FYV}{55(600 + V)PC_s} \quad \text{or} \quad S_s = \frac{55(600 + V)PC_s HP}{FYV}$$

$$\text{hp} = 0.125, \quad Y = 0.434 \quad \text{and}$$

$$V = \frac{\text{rpm} \times \pi \times D}{12} = \frac{350 \times 3.1416 \times 2.3438}{12} = 215 \text{ ft/min}$$



therefore,

$$S_s = \frac{55(600 + 215)32 \times 1.00 \times 0.125}{0.375 \times 0.434 \times 215} = 5,124 \text{ lb/in.}^2$$

From Table 8 it is apparent that the gear could be molded from several materials. Available physical and chemical characteristics must now be considered in relation to the operating environment for the gear. Strengths of plastics materials decrease with increasing temperatures and not all plastics resist the effects of some liquids, including some lubricants. Some plastics deteriorate when in sunlight for long periods; some are more dimensionally stable than others; and wear resistance varies from one to another. Manufacturers' data sheets will answer some of these questions.

**Backlash:** Plastics gears should be so dimensioned that they will provide sufficient backlash at the highest temperatures likely to be encountered in service. Dimensional allowances must also be made for gears made of hygroscopic plastics that may be exposed to damp service conditions. Teeth of heavily loaded gears usually have tip relief to reduce effects of deflection, and have full fillet radii to reduce stress concentrations. Such modifications to tooth form are also desirable in plastics gears. If the pinion in a pair of gears has a small number of teeth, undercutting may result. Undercutting weakens teeth, causes undue wear, and may affect continuity of action. The undercutting can be reduced by using the long-short addendum system, which involves increasing the addendum of the pinion teeth and reducing that of the gear teeth. The modified addendum method will also reduce the amount of initial wear that takes place during the initial stages of contact between the teeth.

**Accuracy:** The Gear Handbook, AGMA 390-03a-1980, Part 2, Gear Classification, provides a system whereby results of gear accuracy measurements are expressed in terms of maximum tooth-to-tooth and composite tolerances. This system uses AGMA quality numbers related to maximum tolerances, by pitch and diameter, and is equally applicable to plastics gears as to metal gears. AGMA quality numbers must be chosen for a pair of mating gears early in the design process, and the finished gears must be inspected by being run in close mesh with a master gear in a center-distance measuring instrument to make sure that the errors do not exceed the specified tolerances.

To prevent failure from fatigue and wear caused by excessive flexing of the teeth, plastics gears must be made to the same standards of accuracy as metal gears. Solidification shrinkage of plastics requires that dimensions of molds for gears be larger than the dimensions of the parts to be produced from them. The amount of the shrinkage is usually added to the mold dimension (with the mold at operating temperature). However, this procedure cannot be followed for the tooth profile as it would introduce large errors in the pressure angle. Increases in pressure angle cause gear teeth to become wider at the root and more pointed. Sliding conditions are improved and the teeth are stronger, so that higher loading values can be used.

Shrinkage allowances have the greatest effect on the accuracy of the molded gears, so tooth profiles must be calculated extremely carefully in terms of mold profile. If a tooth is merely made larger by using a standard hobbing cutter to cut the tool whereby the teeth in the mold are electroeroded, differential shrinkage caused by the molded tooth being thicker at the root than at the tip will distort the shape of the molded tooth, making it thinner at the tip and thicker at the root. With two mating gears, these faulty shapes will affect the pressure angle resulting in binding, wear, and general malfunction. If the tooth thickness limits for a molded gear are to be held to +0.000 in., -0.001 in., the outside diameter must be permitted to vary up to 0.0027 in. for 20-deg, and 0.0039 in. for 14½-deg pressure angle gears. All high-accuracy gears should be specified with AGMA quality numbers and inspected with center-distance measuring machines if the required accuracy is to be achieved.

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## DRAFTING PRACTICES

## American National Standard Drafting Practices

Several American National Standards for use in preparing engineering drawings and related documents are referred to for use.

**Sizes of Drawing Sheets.**—Recommended trimmed sheet sizes, based on ANSI Y14.1-1980 (R1987), are shown in the following table.

| Size, inches |         |   |         | Metric Size, mm |            |    |           |
|--------------|---------|---|---------|-----------------|------------|----|-----------|
| A            | 8½ × 11 | D | 22 × 34 | A0              | 841 × 1189 | A3 | 297 × 420 |
| B            | 11 × 17 | E | 34 × 44 | A1              | 594 × 841  | A4 | 210 × 297 |
| C            | 17 × 22 | F | 28 × 40 | A2              | 420 × 594  |    |           |

The standard sizes shown by the left-hand section of the table are based on the dimensions of the commercial letter head, 8½ × 11 inches, in general use in the United States. The use of the basic sheet size 8½ × 11 inches and its multiples permits filing of small tracings and folded blueprints in commercial standard letter files with or without correspondence. These sheet sizes also cut without unnecessary waste from the present 36-inch rolls of paper and cloth.

For drawings made in the metric system of units or for foreign correspondence, it is recommended that the metric standard trimmed sheet sizes be used. (Right-hand section of table.) These sizes are based on the width-to-length ratio of 1 to  $\sqrt{2}$ .

**Line Conventions and Drawings.**—American National Standard Y14.2M-1979 (R1987) establishes line and lettering practices for engineering drawings. The line conventions and the symbols for section lining are as shown on [Tables 1](#) and [2](#).

Approximate width of THICK lines for metric drawings are 0.6 mm, and for inch drawings, 0.032 inch. Approximate width of THIN lines for metric drawings are 0.3 mm, and for inch drawings, 0.016 inch. These approximate line widths are intended to differentiate between THICK and THIN lines and are not values for control of acceptance or rejection of the drawings.






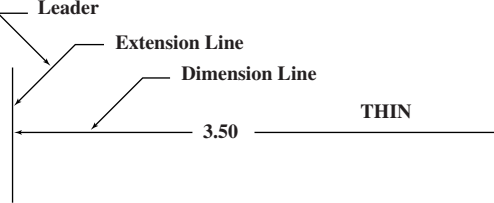








**Surface-Texture Symbols.**—A detailed explanation of the use of surface-texture symbols from American National Standard Y14.36M-1996 begins on page [731](#).

**Geometric Dimensioning and Tolerancing.**—ANSI/ASME Y14.5M-1994, “Dimensioning and Tolerancing,” covers dimensioning, tolerancing, and similar practices for engineering drawings and related documentation. The mathematical definitions of dimensioning and tolerancing principles are given in the standard ANSI/ASME Y14.5.1M-1994. ISO standards ISO 8015 and ISO 26921 contain a detailed explanation of ISO geometric dimensioning and tolerancing practices.

Geometric dimensioning and tolerancing provides a comprehensive system for symbolically defining the geometrical tolerance zone within which features must be contained. It provides an accurate transmission of design specifications among the three primary users of engineering drawings; design, manufacturing and quality assurance.

Some techniques introduced in ANSI/ASME Y14.5M-1994 have been accepted by ISO. These techniques include projected tolerance zone, three-plane datum concept, total runout tolerance, multiple datums, and datum targets. Although this Standard follows ISO practice closely, there are still differences between ISO and U.S. practice. (A comparison of the symbols used in ISO standards and Y14.5M is given on page [633](#).)

**Table 1. American National Standard for Engineering Drawings**  
ANSI/ASME Y14.2M-1992

|  |  |              |
|--|--|--------------|
| Visible Line                                   |                 | <b>THICK</b> |
| Hidden Line                                    |                 | <b>THIN</b>  |
| Section Line                                   |                 | <b>THIN</b>  |
| Center Line                                    |                 | <b>THIN</b>  |
| Symmetry Line                                  |                 | <b>THIN</b>  |
| Dimension Line<br>Extension Line<br>And Leader |                 | <b>THIN</b>  |
| Cutting-Plane Line or Viewing-Plane Line       |                 | <b>THICK</b> |
|  |                | <b>THICK</b> |
| Break Line                                     |  Short Breaks | <b>THICK</b> |
|  |  Long Breaks  | <b>THIN</b>  |
| Phantom Line                                   |               | <b>THIN</b>  |
|  |               | <b>THIN</b>  |
| Stitch Line                                    |               | <b>THIN</b>  |
| Chain Line                                     |               | <b>THICK</b> |

**Table 2. American National Standard Symbols for Section Lining**  
ANSI Y14.2M-1979 (R1987)


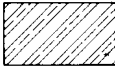
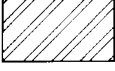

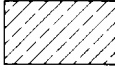

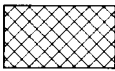
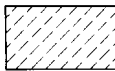


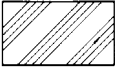


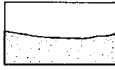
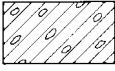
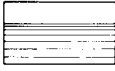
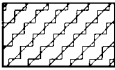

|   |   |   |  |
|---|---|---|--|
|    | Cast and Malleable iron (Also for general use of all materials) |    | Titanium and refractory material                     |
|    | Steel   |    | Electric windings, electro magnets, resistance, etc. |
|    | Bronze, brass, copper, and compositions                         |    | Concrete   |
|    | White metal, zinc, lead, babbitt, and alloys                    |    | Marble, slate, glass, porcelain, etc.                |
|    | Magnesium, aluminum, and aluminum alloys                        |    | Earth  |
|   | Rubber, plastic electrical insulation                           |   | Rock   |
|  | Cork, felt, fabric, leather, fiber                              |  | Sand   |
|  | Sound insulation  |  | Water and other liquids                              |
|  | Thermal insulation  |  | Wood-across grain<br>Wood-with grain                 |

Table 3. Comparison of ANSI and ISO Geometric Symbols ASME Y14.5M-1994

| Symbol for               | ANSI Y14.5M | ISO  | Symbol for                    | ANSI Y14.5 | ISO  | Symbol for                 | ANSI Y14.5M | ISO  |
|--------------------------|-------------|------|-------------------------------|------------|------|----------------------------|-------------|------|
| Straightness             |             |      | Circular Runout <sup>a</sup>  |            |      | Feature Control Frame      |             |      |
| Flatness                 |             |      | Total Runout <sup>a</sup>     |            |      | Datum Feature <sup>a</sup> |             |      |
| Circularity              |             |      | At Maximum Material Condition |            |      | All Around - Profile       |             |      |
| Cylindricity             |             |      | At Least Material Condition   |            |      | Conical Taper              |             |      |
| Profile of a Line        |             |      | Regardless of Feature Size    | NONE       | NONE | Slope                      |             |      |
| Profile of a Surface     |             |      | Projected Tolerance Zone      |            |      | Counterbore/Spotface       |             |      |
| Angularity               |             |      | Diameter                      |            |      | Countersink                |             |      |
| Perpendicularity         |             |      | Basic Dimension               |            |      | Depth/Deep                 |             |      |
| Parallelism              |             |      | Reference Dimension           | (50)       | (50) | Square (Shape)             |             |      |
| Position                 |             |      | Datum Target                  |            |      | Dimension Not to Scale     |             |      |
| Concentricity/Coaxiality |             |      | Target Point                  |            |      | Number of Times/Places     |             |      |
| Symmetry                 |             |      | Dimension Origin              |            |      | Arc Length                 |             |      |
| Radius                   |             |      | Spherical Radius              |            |      | Spherical Diameter         |             |      |
| Between <sup>a</sup>     |             | None | Controlled Radius             |            | None | Statistical Tolerance      |             | None |

<sup>a</sup> Arrowheads may be filled in.

One major area of disagreement is the ISO "principle of independency" versus the "Taylor principle." Y14.5M and standard U.S. practice both follow the Taylor principle, in which a geometric tolerancing zone may not extend beyond the boundary (or envelope) of perfect form at MMC (maximum material condition). This boundary is prescribed to control variations as well as the size of individual features. The U.S. definition of independency further defines features of size as being independent and not required to maintain a perfect relationship with other features. The envelope principle is optional in treatment of these principles. A summary of the application of ANSI/ASME geometric control symbols and their use with basic dimensions and modifiers is given in Table 1.

**Table 1. Application of Geometric Control Symbols**

| Type        | Geometric Characteristics | Pertains To       | Basic Dimensions          | Feature Modifier                        | Datum Modifier                          |
|-------------|---------------------------|-------------------|---------------------------|---|---|
| Form        |                           | Straightness      |                           | Modifier not applicable                 | NO datum                                |
|             |                           | Circularity       |                           |   |   |
|             |                           | Flatness          |                           |   |   |
|             |                           | Cylindricity      |                           |   |   |
| Profile     |                           | Profile (Line)    | Individual or related     | Yes if related                          | RFS implied unless MMC or LMC is stated |
|             |                           | Profile (Surface) |                           |   |   |
| Orientation |                           | Angularity        | ALWAYS related feature(s) | Yes                                     |   |
|             |                           | Perpendicularity  |                           | RFS implied unless MMC or LMC is stated |   |
|             |                           | Parallelism       |                           |   |   |
| Location    |                           | Position          |                           | Yes                                     |   |
|             |                           | Concentricity     |                           | Only RFS                                |   |
|             |                           | Symmetry          |                           |   |   |
| Runout      |                           | Circular Runout   |                           | Only RFS                                | Only RFS                                |
|             |                           | Total Runout      |                           |   |   |

Five types of geometric control, when datums are indicated, when basic dimensions are required, and when MMC and LMC modifiers may be used.

ANSI/ASME Y14.5M features metric SI units (the International System of Units), but customary units may be used without violating any principles. On drawings where all dimensions are either in millimeters or in inches, individual identification of linear units is not required. However, the drawing should contain a note stating UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN MILLIMETERS (or IN INCHES, as applicable). According to this Standard, all dimensions are applicable at a temperature of 20 C (68 F) unless otherwise specified. Compensation may be made for measurements taken at other temperatures.

Angular units are expressed in degrees and decimals of a degree (35.4) or in degrees ( $^{\circ}$ ), minutes ( $'$ ), and seconds ( $''$ ), as in  $35^{\circ} 25' 10''$ . A 90-degree angle is implied where center lines and depicting features are shown on a drawing at right angles and no angle is specified. A 90-degree BASIC angle applies where center lines of features in a pattern or surface shown at right angles on a drawing are located or defined by basic dimensions and no angle is specified.

**Definitions.**—The following terms are defined as their use applies to ANSI/ASME Y14.5M.

*Datum Feature:* The feature of a part that is used to establish a datum.

*Datum Identifier:* The graphic symbol on a drawing used to indicate the datum feature.

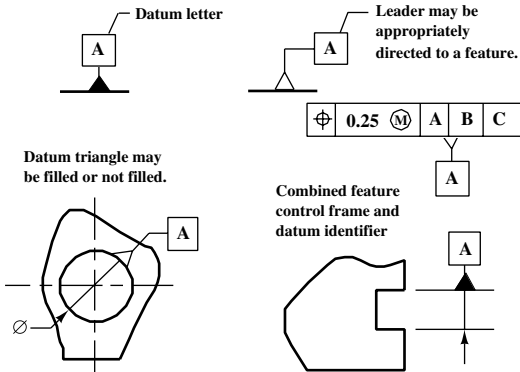


Fig. 1. Datum Feature Symbol

**Datum Plane:** The individual theoretical planes of the reference frame derived from a specified datum feature. A datum is the origin from which the location or other geometric characteristics of features of a part are established.

**Datum Reference Frame:** Sufficient features on a part are chosen to position the part in relationship to three planes. The three planes are mutually perpendicular and together called the datum reference frame. The planes follow an order of precedence and allow the part to be immobilized. This immobilization in turn creates measurable relationships among features.

**Datum Simulator:** Formed by the datum feature contacting a precision surface such as a surface plate, gage surface or by a mandrel contacting the datum. Thus, the plane formed by contact restricts motion and constitutes the specific reference surface from which measurements are taken and dimensions verified. The datum simulator is the practical embodiment of the datum feature during manufacturing and quality assurance.

**Datum Target:** A specified point, line, or area on a part, used to establish a datum.

**Degrees of Freedom:** The three directions of movement or translation are called degrees of freedom in a three-dimensional environment. They are up-down, left-right, fore-aft, roll, pitch and yaw.

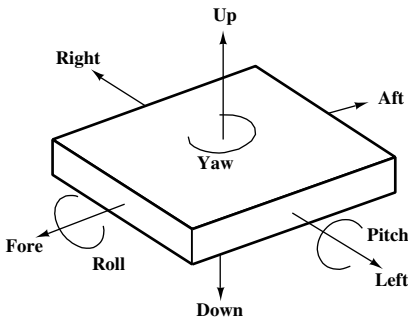


Fig. 2. Degrees of Freedom (Movement) That Must be Controlled, Depending on the Design Requirements.



**Dimension, Basic:** A numerical value used to describe the theoretically exact size, orientation, location, or optionally, profile, of a feature or datum or datum target. Basic dimensions are indicated by a rectangle around the dimension and are not tolerated directly or by default. The specific dimensional limits are determined by the permissible variations as established by the tolerance zone specified in the feature control frame. A dimension is only considered basic for the geometric control to which it is related.

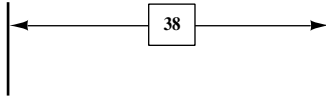


Fig. 3. Basic Dimensions

**Dimension Origin:** Symbol used to indicate the origin and direction of a dimension between two features. The dimension originates from the symbol with the dimension tolerance zone being applied at the other feature.

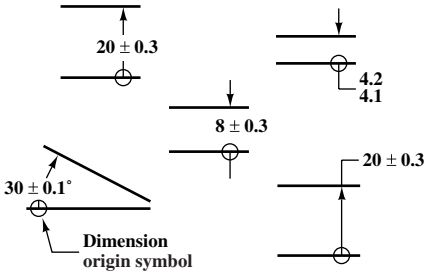


Fig. 4. Dimension Origin Symbol

**Dimension, Reference:** A dimension, usually without tolerance, used for information purposes only. Considered to be auxiliary information and not governing production or inspection operations. A reference dimension is a repeat of a dimension or is derived from a calculation or combination of other values shown on the drawing or on related drawings.

**Feature Control Frame:** Specification on a drawing that indicates the type of geometric control for the feature, the tolerance for the control, and the related datums, if applicable.

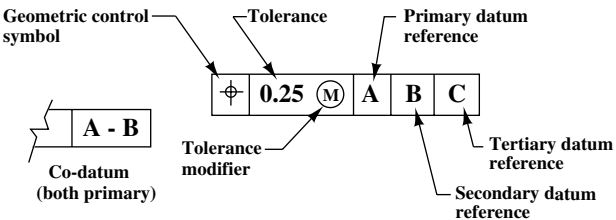


Fig. 5. Feature Control Frame and Datum Order of Precedence

**Feature:** The general term applied to a physical portion of a part, such as a surface, hole, pin, tab, or slot.

**Least Material Condition (LMC):** The condition in which a feature of size contains the least amount of material within the stated limits of size, for example, upper limit or maximum hole diameter and lower limit or minimum shaft diameter.

**Limits, Upper and Lower (UL and LL):** The arithmetic values representing the maximum and minimum size allowable for a dimension or tolerance. The upper limit represents the maximum size allowable. The lower limit represents the minimum size allowable.

**Maximum Material Condition (MMC):** The condition in which a feature of size contains the maximum amount of material within the stated limits of size. For example, the lower limit of a hole is the minimum hole diameter. The upper limit of a shaft is the maximum shaft diameter.

**Position:** Formerly called true position, position is the theoretically exact location of a feature established by basic dimensions.

**Regardless of Feature Size (RFS):** The term used to indicate that a geometric tolerance or datum reference applies at any increment of size of the feature within its tolerance limits. RFS is the default condition unless MMC or LMC is specified. The concept is now the default in ANSI/ASME Y14.5M-1994, unless specifically stated otherwise. Thus the symbol for RFS is no longer supported in ANSI/ASME Y14.5M-1994.

**Size, Actual:** The term indicating the size of a feature as produced.

**Size, Feature of:** A feature that can be described dimensionally. May include a cylindrical or spherical surface, or a set of two opposed parallel surfaces associated with a size dimension.

**Tolerance Zone Symmetry:** In geometric tolerancing, the tolerance value stated in the feature control frame is always a single value. Unless otherwise specified, it is assumed that the boundaries created by the stated tolerance are bilateral and equidistant about the perfect form control specified. However, if desired, the tolerance may be specified as unilateral or unequally bilateral. (See Figs. 6 through 8)

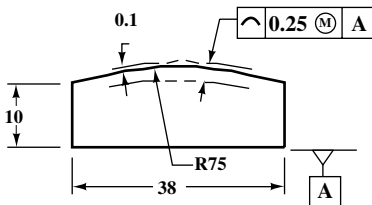
**Tolerance, Bilateral:** A tolerance where variation is permitted in both directions from the specified dimension. Bilateral tolerances may be equal or unequal.

**Tolerance, Geometric:** The general term applied to the category of tolerances used to control form, profile, orientation, location, and runout.

**Tolerance, Unilateral:** A tolerance where variation is permitted in only one direction from the specified dimension.

**True Geometric Counterpart:** The theoretically perfect plane of a specified datum feature.

**Virtual Condition:** A constant boundary generated by the collective effects of the feature size, its specified MMC or LMC material condition, and the geometric tolerance for that condition.



**Bilateral zone with 0.1 of the 0.25 tolerance outside perfect form.**

Fig. 6. Application of a bilateral geometric tolerance

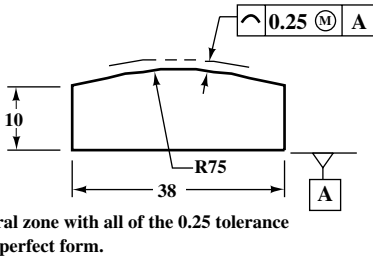


Fig. 7. Application of a unilateral geometric tolerance zone outside perfect form

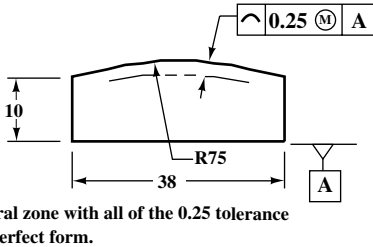


Fig. 8. Application of a unilateral geometric tolerance zone inside a perfect form

**Datum Referencing.**—A datum indicates the origin of a dimensional relationship between a toleranced feature and a designated feature or features on a part. The designated feature serves as a datum feature, whereas its true geometric counterpart establishes the datum plane. Because measurements cannot be made from a true geometric counterpart, which is theoretical, a datum is assumed to exist in, and be simulated by the associated processing equipment.

For example, machine tables and surface plates, although not true planes, are of such quality that they are used to simulate the datums from which measurements are taken and dimensions are verified. When magnified, flat surfaces of manufactured parts are seen to have irregularities, so that contact is made with a datum plane formed at a number of surface extremities or high points.

Sufficient datum features, those most important to the design of the part, are chosen to position the part in relation to a set of three mutually perpendicular planes, the datum reference frame. This reference frame exists only in theory and not on the part. Therefore, it is necessary to establish a method for simulating the theoretical reference frame from existing features of the part. This simulation is accomplished by positioning the part on appropriate datum features to adequately relate the part to the reference frame and to restrict the degrees of freedom of the part in relation to it.

These reference frame planes are simulated in a mutually perpendicular relationship to provide direction as well as the origin for related dimensions and measurements. Thus, when the part is positioned on the datum reference frame (by physical contact between each datum feature and its counterpart in the associated processing equipment), dimensions related to the datum reference frame by a feature control frame are thereby mutually perpendicular. This theoretical reference frame constitutes the three-plane dimensioning system used for datum referencing.

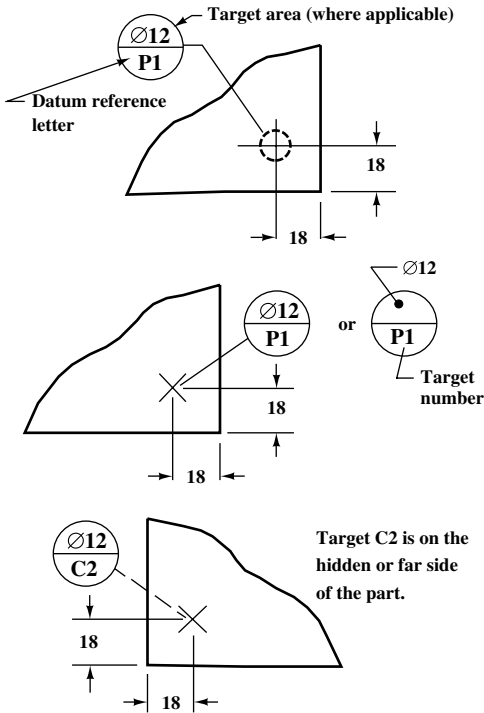


Fig. 9. Datum target symbols

Depending on the degrees of freedom that must be controlled, a simple reference frame may suffice. At other times, additional datum reference frames may be necessary where physical separation occurs or the functional relationship. Depending on the degrees of freedom that must be controlled, a single datum of features require that datum reference frames be applied at specific locations on the part. Each feature control frame must contain the datum feature references that are applicable.

**Datum Targets:** Datum targets are used to establish a datum plane. They may be points, lines or surface areas. Datum targets are used when the datum feature contains irregularities, the surface is blocked by other features or the entire surface cannot be used. Examples where datum targets may be indicated include uneven surfaces, forgings and castings, weldments, non-planar surfaces or surfaces subject to warping or distortion. The datum target symbol is located outside the part outline with a leader directed to the target point, area or line. The targets are dimensionally located on the part using basic or toleranced dimensions. If basic dimensions are used, established tooling or gaging tolerances apply. A solid leader line from the symbol to the target is used for visible or near side locations with a dashed leader line used for hidden or far side locations. The datum target symbol is divided horizontally into two halves. The top half contains the target point area if applicable; the bottom half contains a datum feature identifying letter and target number. Target

numbers indicate the quantity required to define a primary, secondary, or tertiary datum. If indicating a target point or target line, the top half is left blank. Datum targets and datum features may be combined to form the datum reference frame, Fig. 9.

**Datum Target points:** A datum target point is indicated by the symbol "X," which is dimensionally located on a direct view of the surface. Where there is no direct view, the point location is dimensioned on multiple views.

**Datum Target Lines:** A datum target line is dimensionally located on an edge view of the surface using a phantom line on the direct view. Where there is no direct view, the location is dimensioned on multiple views. Where the length of the datum target line must be controlled, its length and location are dimensioned.

**Datum Target Areas:** Where it is determined that an area or areas of flat contact are necessary to ensure establishment of the datum, and where spherical or pointed pins would be inadequate, a target area of the desired shape is specified. Examples include the need to span holes, finishing irregularities, or rough surface conditions. The datum target area may be indicated with the "X" symbol as with a datum point, but the area of contact is specified in the upper half of the datum target symbol. Datum target areas may additionally be specified by defining controlling dimensions and drawing the contact area on the feature with section lines inside a phantom outline of the desired shape.

**Positional Tolerance.**—A positional tolerance defines a zone within which the center, axis, or center plane of a feature of size is permitted to vary from true (theoretically exact) position. Basic dimensions establish the true position from specified datum features and between interrelated features. A positional tolerance is indicated by the position symbol, a tolerance, and appropriate datum references placed in a feature control frame.

**Modifiers:** In certain geometric tolerances, modifiers in the form of additional symbols may be used to further refine the level of control. The use of the MMC and LMC modifiers has been common practice for many years. However, several new modifiers were introduced with the 1994 U.S. national standard. Some of the new modifiers include free state, tangent plane and statistical tolerancing, Fig. 10.

|            |     |     |               |                          |                       |
|------------|-----|-----|---------------|--------------------------|-----------------------|
| ⓕ          | Ⓜ   | Ⓛ   | Ⓣ             | Ⓟ                        | ⓈⓉ                    |
| Free State | MMC | LMC | Tangent Plane | Projected Tolerance Zone | Statistical Tolerance |

Fig. 10. Tolerance modifiers

**Projected Tolerance Zone:** Application of this concept is recommended where any variation in perpendicularity of the threaded or press-fit holes could cause fasteners such as screws, studs, or pins to interfere with mating parts. An interference with subsequent parts can occur even though the hole axes are inclined within allowable limits. This interference occurs because, without a projected tolerance zone, a positional tolerance is applied only to the depth of threaded or press-fit holes. Unlike the floating fastener application involving clearance holes only, the attitude of a fixed fastener is restrained by the inclination of the produced hole into which it assembles.

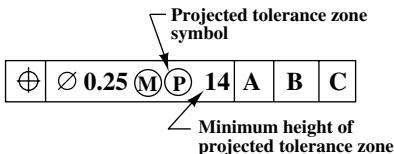


Fig. 11. Projected tolerance zone callout

With a projected tolerance zone equal to the thickness of the mating part, the inclinational error is accounted for in both parts. The minimum extent and direction of the projected tolerance zone is shown as a value in the feature control frame. The zone may be shown in a drawing view as a dimensioned value with a heavy chain line drawn closely adjacent to an extension of the center line of the hole.

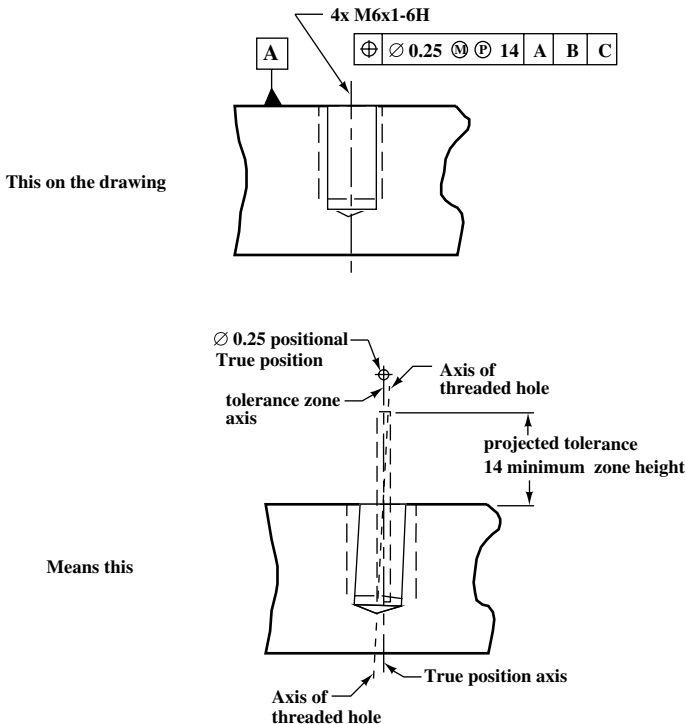


Fig. 12. Projected tolerance zone application

**Statistical Tolerance:** The statistical tolerancing symbol is a modifier that may be used to indicate that a tolerance is controlled statistically as opposed to being controlled arithmetically. With arithmetic control, assembly tolerances are typically divided arithmetically among the individual components of the assembly. This division results in the assumption that assemblies based on “worst case” conditions would be guaranteed to fit because the worst case set of parts fit — so that anything better would fit as well.

When this technique is restrictive, statistical tolerancing, via the symbol, may be specified in the feature control frame as a method of increasing tolerances for individual parts. This procedure may reduce manufacturing costs because its use changes the assumption that statistical process control may make a statistically significant quantity of parts fit, but not absolutely all. The technique should only be used when sound statistical methods are employed.

**Tangent Plane:** When it is desirable to control the surface of a feature by the contacting or high points of the surface, a tangent plane symbol is added as a modifier to the tolerance in the feature control frame, Fig. 13.

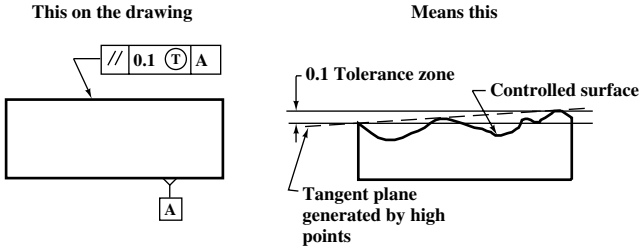


Fig. 13. Tangent plane modifier

**Free State:** The free state modifier symbol is used when the geometric tolerance applies to the feature in its "free state," or after removal of any forces used in the manufacturing process. With removal of forces the part may distort due to gravity, flexibility, spring back, or other release of internal stresses developed during fabrication. Typical applications include parts with extremely thin walls and non-rigid parts made of rubber or plastics. The modifier is placed in the tolerance portion of the feature control frame and follows any other modifier.

The above examples are just a few of the numerous concepts and related symbols covered by ANSI/ASME Y14.5M-1994. Refer to the standard for a complete discussion with further examples of the application of geometric dimensioning and tolerancing principles.

**Checking Drawings.**—In order that the drawings may have a high standard of excellence, a set of instructions, as given in the following, has been issued to the checkers, and also to the draftsmen and tracers in the engineering department of a well-known machine-building company.

**Inspecting a New Design:** When a new design is involved, first inspect the layouts carefully to see that the parts function correctly under all conditions, that they have the proper relative proportions, that the general design is correct in the matters of strength, rigidity, bearing areas, appearance, convenience of assembly, and direction of motion of the parts, and that there are no interferences. Consider the design as a whole to see if any improvements can be made. If the design appears to be unsatisfactory in any particular, or improvements appear to be possible, call the matter to the attention of the chief engineer.

**Checking for Strength:** Inspect the design of the part being checked for strength, rigidity, and appearance by comparing it with other parts for similar service whenever possible, giving preference to the later designs in such comparison, unless the later designs are known to be unsatisfactory. If there is any question regarding the matter, compute the stresses and deformations or find out whether the chief engineer has approved the stresses or deformations that will result from the forces applied to the part in service. In checking parts that are to go on a machine of increased size, be sure that standard parts used in similar machines and proposed for use on the larger machine, have ample strength and rigidity under the new and more severe service to which they will be put.

**Materials Specified:** Consider the kind of material required for the part and the various possibilities of molding, forging, welding, or otherwise forming the rough part from this material. Then consider the machining operations to see whether changes in form or design will reduce the number of operations or the cost of machining.

See that parts are designed with reference to the economical use of material, and whenever possible, utilize standard sizes of stock and material readily obtainable from local

dealers. In the case of alloy steel, special bronze, and similar materials, be sure that the material can be obtained in the size required.

*Method of Making Drawing:* Inspect the drawing to see that the projections and sections are made in such a way as to show most clearly the form of the piece and the work to be done on it. Make sure that any worker looking at the drawing will understand what the shape of the piece is and how it is to be molded or machined. Make sure that the delineation is correct in every particular, and that the information conveyed by the drawing as to the form of the piece is complete.

*Checking Dimensions:* Check all dimensions to see that they are correct. Scale all dimensions and see that the drawing is to scale. See that the dimensions on the drawing agree with the dimensions scaled from the lay-out. Wherever any dimension is out of scale, see that the dimension is so marked. Investigate any case where the dimension, the scale of the drawing, and the scale of the lay-out do not agree. All dimensions not to scale must be underlined on the tracing. In checking dimensions, note particularly the following points:

See that all figures are correctly formed and that they will print clearly, so that the workers can easily read them correctly.

See that the overall dimensions are given.

See that all witness lines go to the correct part of the drawing.

See that all arrow points go to the correct witness lines.

See that proper allowance is made for all fits.

See that the tolerances are correctly given where necessary.

See that all dimensions given agree with the corresponding dimensions of adjacent parts.

Be sure that the dimensions given on a drawing are those that the machinist will use, and that the worker will not be obliged to do addition or subtraction to obtain the necessary measurements for machining or checking his work.

Avoid strings of dimensions where errors can accumulate. It is generally better to give a number of dimensions from the same reference surface or center line.

When holes are to be located by boring on a horizontal spindle boring machine or other similar machine, give dimensions to centers of bored holes in rectangular coordinates and from the center lines of the first hole to be bored, so that the operator will not be obliged to add measurements or transfer gages.

*Checking Assembly:* See that the part can readily be assembled with the adjacent parts. If necessary, provide tapped holes for eyebolts and cored holes for tongs, lugs, or other methods of handling.

Make sure that, in being assembled, the piece will not interfere with other pieces already in place and that the assembly can be taken apart without difficulty.

Check the sum of a number of tolerances; this sum must not be great enough to permit two pieces that should not be in contact to come together.

*Checking Castings:* In checking castings, study the form of the pattern, the methods of molding, the method of supporting and venting the cores, and the effect of draft and rough molding on clearances.

Avoid undue metal thickness, and especially avoid thick and thin sections in the same casting.

Indicate all metal thicknesses, so that the molder will know what chaplets to use for supporting the cores.

See that ample fillets are provided, and that they are properly dimensioned.

See that the cores can be assembled in the mold without crushing or interference.

See that swelling, shrinkage, or misalignment of cores will not make trouble in machining.

See that the amount of extra material allowed for finishing is indicated.



See that there is sufficient extra material for finishing on large castings to permit them to be "cleaned up," even though they warp. In such castings, make sure that the metal thickness will be sufficient after finishing, even though the castings do warp.

Make sure that sufficient sections are shown so that the pattern makers and molders will not be compelled to make assumptions about the form of any part of the casting. These details are particularly important when a number of sections of the casting are similar in form, while others differ slightly.

*Checking Machined Parts:* Study the sequences of operations in machining and see that all finish marks are indicated.

See that the finish marks are placed on the lines to which dimensions are given.

See that methods of machining are indicated where necessary.

Give all drill, reamer, tap, and rose bit sizes.

See that jig and gage numbers are indicated at the proper places.

See that all necessary bosses, lugs, and openings are provided for lifting, handling, clamping, and machining the piece.

See that adequate wrench room is provided for all nuts and bolt heads.

Avoid special tools, such as taps, drills, reamers, etc., unless such tools are specifically authorized.

Where parts are right- and left-hand, be sure that the hand is correctly designated. When possible, mark parts as symmetrical, so as to avoid having them right- and left-hand, but do not sacrifice correct design or satisfactory operation on this account.

When heat-treatment is required, the heat-treatment should be specified.

Check the title, size of machine, the scale, and the drawing number on both the drawing and the drawing record card.

**Tapers for Machine Tool Spindles.**—Various standard tapers have been used for the taper holes in the spindles of machine tools, such as drilling machines, lathes, milling machines, or other types requiring a taper hole for receiving either the shank of a cutter, an arbor, a center, or any tool or accessory requiring a tapering seat. The Morse taper represents a generally accepted standard for drilling machines.

#### Morse Tapers

| Morse Taper | Taper per Foot | Morse Taper | Taper per Foot | Morse Taper | Taper per Foot |
|-------------|----------------|-------------|----------------|-------------|----------------|
| 0           | 0.62460        | 2           | 0.59941        | 4           | 0.62326        |
| 1           | 0.59858        | 3           | 0.60235        | 5           | 0.63151        |

The headstock and tailstock spindles of lathes also have the Morse taper in most cases; but the Jarno, the Reed (which is the short Jarno), and the Brown & Sharpe have also been used. Milling machine spindles formerly had Brown & Sharpe tapers in most cases.

In 1927, the milling machine manufacturers of the National Machine Tool Builders' Association adopted a standard taper of  $3\frac{1}{2}$  inches per foot. This comparatively steep taper has the advantage of insuring instant release of arbors or adapters.

#### National Machine Tool Builders' Association Tapers

| Taper Number <sup>a</sup> | Large End Diameter | Taper Number <sup>a</sup> | Large End Diameter |
|---------------------------|--------------------|---------------------------|--------------------|
| 30                        | $1\frac{1}{4}$     | 50                        | $2\frac{3}{4}$     |
| 40                        | $1\frac{3}{4}$     | 60                        | $4\frac{1}{4}$     |

<sup>a</sup>Standard taper of  $3\frac{1}{2}$  inches per foot

The British Standard for milling machine spindles is also  $3\frac{1}{2}$  inches taper per foot and includes these large end diameters:  $1\frac{3}{8}$  inches,  $1\frac{3}{4}$  inches,  $2\frac{3}{4}$  inches, and  $3\frac{1}{4}$  inches.

## ALLOWANCES AND TOLERANCES FOR FITS

### Limits and Fits

Fits between cylindrical parts, i.e., cylindrical fits, govern the proper assembly and performance of many mechanisms. Clearance fits permit relative freedom of motion between a shaft and a hole—axially, radially, or both. Interference fits secure a certain amount of tightness between parts, whether these are meant to remain permanently assembled or to be taken apart from time to time. Or again, two parts may be required to fit together snugly—without apparent tightness or looseness. The designer's problem is to specify these different types of fits in such a way that the shop can produce them. Establishing the specifications requires the adoption of two manufacturing limits for the hole and two for the shaft, and, hence, the adoption of a manufacturing tolerance on each part.

In selecting and specifying limits and fits for various applications, it is essential in the interests of interchangeable manufacturing that 1) standard definitions of terms relating to limits and fits be used; 2) preferred basic sizes be selected wherever possible to reduce material and tooling costs; 3) limits be based upon a series of preferred tolerances and allowances; and 4) a uniform system of applying tolerances (preferably unilateral) be used. These principles have been incorporated in both the American and British standards for limits and fits. Information about these standards is given beginning on page 651.

**Basic Dimensions.**—The basic size of a screw thread or machine part is the theoretical or nominal standard size from which variations are made. For example, a shaft may have a *basic* diameter of 2 inches, but a maximum variation of minus 0.010 inch may be permitted. The minimum hole should be of basic size wherever the use of standard tools represents the greatest economy. The maximum shaft should be of basic size wherever the use of standard purchased material, without further machining, represents the greatest economy, even though special tools are required to machine the mating part.

**Tolerances.**—Tolerance is the amount of variation permitted on dimensions or surfaces of machine parts. The tolerance is equal to the difference between the maximum and minimum limits of any specified dimension. For example, if the maximum limit for the diameter of a shaft is 2.000 inches and its minimum limit 1.990 inches, the tolerance for this diameter is 0.010 inch. The extent of these tolerances is established by determining the maximum and minimum clearances required on operating surfaces. As applied to the fitting of machine parts, the word tolerance means the amount that duplicate parts are allowed to vary in size in connection with manufacturing operations, owing to unavoidable imperfections of workmanship. Tolerance may also be defined as the amount that duplicate parts are permitted to vary in size to secure sufficient accuracy without unnecessary refinement. The terms “tolerance” and “allowance” are often used interchangeably, but, according to common usage, *allowance* is a difference in dimensions prescribed to secure various classes of fits between different parts.

**Unilateral and Bilateral Tolerances.**—The term “unilateral tolerance” means that the total tolerance, as related to a basic dimension, is in *one* direction only. For example, if the basic dimension were 1 inch and the tolerance were expressed as 1.000–0.002, or as 1.000 + 0.002, these would be unilateral tolerances because the total tolerance in each is in one direction. On the contrary, if the tolerance were divided, so as to be partly plus and partly minus, it would be classed as “bilateral.”

Thus,  $1.000 \begin{matrix} +0.001 \\ -0.001 \end{matrix}$

is an example of bilateral tolerance, because the total tolerance of 0.002 is given in two directions—plus and minus.

When unilateral tolerances are used, one of the three following methods should be used to express them:

- 1) Specify, limiting dimensions only as  
Diameter of hole: 2.250, 2.252  
Diameter of shaft: 2.249, 2.247
  - 2) One limiting size may be specified with its tolerances as  
Diameter of hole: 2.250 + 0.002, -0.000  
Diameter of shaft: 2.249 + 0.000, -0.002
  - 3) The nominal size may be specified for both parts, with a notation showing both allowance and tolerance, as  
Diameter of hole:  $2\frac{1}{4} + 0.002, -0.000$   
Diameter of shaft:  $2\frac{1}{4} - 0.001, -0.003$
- Bilateral tolerances should be specified as such, usually with plus and minus tolerances of equal amount. An example of the expression of bilateral tolerances is

$$2 \pm 0.001 \quad \text{or} \quad 2 \begin{array}{l} +0.001 \\ -0.001 \end{array}$$

**Application of Tolerances.**—According to common practice, tolerances are applied in such a way as to show the permissible amount of dimensional variation in the direction that is less dangerous. When a variation in either direction is equally dangerous, a bilateral tolerance should be given. When a variation in one direction is more dangerous than a variation in another, a unilateral tolerance should be given in the less dangerous direction.

For nonmating surfaces, or atmospheric fits, the tolerances may be bilateral, or unilateral, depending entirely upon the nature of the variations that develop in manufacture. On mating surfaces, with few exceptions, the tolerances should be unilateral.

Where tolerances are required on the distances between holes, usually they should be bilateral, as variation in either direction is normally equally dangerous. The variation in the distance between shafts carrying gears, however, should always be unilateral and plus; otherwise, the gears might run too tight. A slight increase in the backlash between gears is seldom of much importance.

One exception to the use of unilateral tolerances on mating surfaces occurs when tapers are involved; either bilateral or unilateral tolerances may then prove advisable, depending upon conditions. These tolerances should be determined in the same manner as the tolerances on the distances between holes. When a variation either in or out of the position of the mating taper surfaces is equally dangerous, the tolerances should be bilateral. When a variation in one direction is of less danger than a variation in the opposite direction, the tolerance should be unilateral and in the less dangerous direction.

**Locating Tolerance Dimensions.**—Only one dimension in the same straight line can be controlled within fixed limits. That dimension is the distance between the cutting surface of the tool and the locating or registering surface of the part being machined. Therefore, it is incorrect to locate any point or surface with tolerances from more than one point in the same straight line.

Every part of a mechanism must be located in each plane. Every operating part must be located with proper operating allowances. After such requirements of location are met, all other surfaces should have liberal clearances. Dimensions should be given between those points or surfaces that it is essential to hold in a specific relation to each other. This restriction applies particularly to those surfaces in each plane that control the location of other component parts. Many dimensions are relatively unimportant in this respect. It is good practice to establish a common locating point in each plane and give, as far as possible, all such dimensions from these common locating points. The locating points on the drawing, the locating or registering points used for machining the surfaces and the locating points for measuring should all be identical.

The initial dimensions placed on component drawings should be the exact dimensions that would be used if it were possible to work without tolerances. Tolerances should be

given in that direction in which variations will cause the least harm or danger. When a variation in either direction is equally dangerous, the tolerances should be of equal amount in both directions, or bilateral. The initial clearance, or allowance, between operating parts should be as small as the operation of the mechanism will permit. The maximum clearance should be as great as the proper functioning of the mechanism will permit.

**Direction of Tolerances on Gages.**—The extreme sizes for all plain limit gages shall not exceed the extreme limits of the part to be gaged. All variations in the gages, whatever their cause or purpose, shall bring these gages within these extreme limits.

The data for gage tolerances on page 678 cover gages to inspect workpieces held to tolerances in the American National Standard ANSI B4.4M-1981.

**Allowance for Forced Fits.**—The allowance per inch of diameter usually ranges from 0.001 inch to 0.0025 inch, 0.0015 being a fair average. Ordinarily the allowance per inch decreases as the diameter increases; thus the total allowance for a diameter of 2 inches might be 0.004 inch, whereas for a diameter of 8 inches the total allowance might not be over 0.009 or 0.010 inch. The parts to be assembled by forced fits are usually made cylindrical, although sometimes they are slightly tapered. The advantages of the taper form are that the possibility of abrasion of the fitted surfaces is reduced; that less pressure is required in assembling; and that the parts are more readily separated when renewal is required. On the other hand, the taper fit is less reliable, because if it loosens, the entire fit is free with but little axial movement. Some lubricant, such as white lead and lard oil mixed to the consistency of paint, should be applied to the pin and bore before assembling, to reduce the tendency toward abrasion.

**Pressure for Forced Fits.**—The pressure required for assembling cylindrical parts depends not only upon the allowance for the fit, but also upon the area of the fitted surfaces, the pressure increasing in proportion to the distance that the inner member is forced in. The approximate ultimate pressure in tons can be determined by the use of the following formula in conjunction with the accompanying table of *Pressure Factors for Forced Fits*. Assuming that  $A$  = area of surface in contact in "fit";  $a$  = total allowance in inches;  $P$  = ultimate pressure required, in tons;  $F$  = pressure factor based upon assumption that the diameter of the hub is twice the diameter of the bore, that the shaft is of machine steel, and that the hub is of cast iron:

$$P = \frac{A \times a \times F}{2}$$

**Pressure Factors for Forced Fits**

| Diameter, Inches | Pressure Factor | Diameter, Inches | Pressure Factor | Diameter, Inches | Pressure Factor | Diameter, Inches | Pressure Factor | Diameter, Inches | Pressure Factor |
|------------------|-----------------|------------------|-----------------|------------------|-----------------|------------------|-----------------|------------------|-----------------|
| 1                | 500             | 3½               | 132             | 6                | 75              | 9                | 48.7            | 14               | 30.5            |
| 1¼               | 395             | 3¾               | 123             | 6¼               | 72              | 9½               | 46.0            | 14½              | 29.4            |
| 1½               | 325             | 4                | 115             | 6½               | 69              | 10               | 43.5            | 15               | 28.3            |
| 1¾               | 276             | 4¼               | 108             | 6¾               | 66              | 10½              | 41.3            | 15½              | 27.4            |
| 2                | 240             | 4½               | 101             | 7                | 64              | 11               | 39.3            | 16               | 26.5            |
| 2¼               | 212             | 4¾               | 96              | 7¼               | 61              | 11½              | 37.5            | 16½              | 25.6            |
| 2½               | 189             | 5                | 91              | 7½               | 59              | 12               | 35.9            | 17               | 24.8            |
| 2¾               | 171             | 5¼               | 86              | 7¾               | 57              | 12½              | 34.4            | 17½              | 24.1            |
| 3                | 156             | 5½               | 82              | 8                | 55              | 13               | 33.0            | 18               | 23.4            |
| 3¼               | 143             | 5¾               | 78              | 8½               | 52              | 13½              | 31.7            | ...              | ...             |

**Allowance for Given Pressure.**—By transposing the preceding formula, the approximate allowance for a required ultimate tonnage can be determined. Thus,  $a = \frac{2P}{AF}$ . The

average ultimate pressure in tons commonly used ranges from 7 to 10 times the diameter in inches.

**Expansion Fits.**—In assembling certain classes of work requiring a very tight fit, the inner member is contracted by sub-zero cooling to permit insertion into the outer member and a tight fit is obtained as the temperature rises and the inner part expands. To obtain the sub-zero temperature, solid carbon dioxide or “dry ice” has been used but its temperature of about 109 degrees F. below zero will not contract some parts sufficiently to permit insertion in holes or recesses. Greater contraction may be obtained by using high purity liquid nitrogen which has a temperature of about 320 degrees F. below zero. During a temperature reduction from 75 degrees F. to -321 degrees F., the shrinkage per inch of diameter varies from about 0.002 to 0.003 inch for steel; 0.0042 inch for aluminum alloys; 0.0046 inch for magnesium alloys; 0.0033 inch for copper alloys; 0.0023 inch for monel metal; and 0.0017 inch for cast iron (not alloyed). The cooling equipment may vary from an insulated bucket to a special automatic unit, depending upon the kind and quantity of work. One type of unit is so arranged that parts are precooled by vapors from the liquid nitrogen before immersion. With another type, cooling is entirely by the vapor method.

**Shrinkage Fits.**—General practice seems to favor a smaller allowance for shrinkage fits than for forced fits, although in many shops the allowances are practically the same for each, and for some classes of work, shrinkage allowances exceed those for forced fits. The shrinkage allowance also varies to a great extent with the form and construction of the part that has to be shrunk into place. The thickness or amount of metal around the hole is the most important factor. The way in which the metal is distributed also has an influence on the results. Shrinkage allowances for locomotive driving wheel tires adopted by the American Railway Master Mechanics Association are as follows:

|                         |       |       |       |       |       |       |
|-------------------------|-------|-------|-------|-------|-------|-------|
| Center diameter, inches | 38    | 44    | 50    | 56    | 62    | 66    |
| Allowances, inches      | 0.040 | 0.047 | 0.053 | 0.060 | 0.066 | 0.070 |

Whether parts are to be assembled by forced or shrinkage fits depends upon conditions. For example, to press a tire over its wheel center, without heating, would ordinarily be a rather awkward and difficult job. On the other hand, pins, etc., are easily and quickly forced into place with a hydraulic press and there is the additional advantage of knowing the exact pressure required in assembling, whereas there is more or less uncertainty connected with a shrinkage fit, unless the stresses are calculated. Tests to determine the difference in the quality of shrinkage and forced fits showed that the resistance of a shrinkage fit to slippage for an axial pull was 3.66 times greater than that of a forced fit, and in rotation or torsion, 3.2 times greater. In each comparative test, the dimensions and allowances were the same.

**Allowances for Shrinkage Fits.**—The most important point to consider when calculating shrinkage fits is the stress in the hub at the bore, which depends chiefly upon the shrinkage allowance. If the allowance is excessive, the elastic limit of the material will be exceeded and permanent set will occur, or, in extreme conditions, the ultimate strength of the metal will be exceeded and the hub will burst. The intensity of the grip of the fit and the resistance to slippage depends mainly upon the thickness of the hub; the greater the thickness, the stronger the grip, and *vice versa*. Assuming the modulus of elasticity for steel to be 30,000,000, and for cast iron, 15,000,000, the shrinkage allowance per inch of nominal diameter can be determined by the following formula, in which  $A$  = allowance per inch of diameter;  $T$  = true tangential tensile stress at inner surface of outer member;  $C$  = factor taken from one of the accompanying Tables 1, 2, and 3.

For a cast-iron hub and steel shaft:

$$A = \frac{T(2 + C)}{30,000,000} \quad (1)$$

When both hub and shaft are of steel:

$$A = \frac{T(1 + C)}{30,000,000} \quad (2)$$

If the shaft is solid, the factor  $C$  is taken from [Table 1](#); if it is hollow and the hub is of steel, factor  $C$  is taken from [Table 2](#); if it is hollow and the hub is of cast iron, the factor is taken from [Table 3](#).

**Table 1. Factors for Calculating Shrinkage Fit Allowances for Steel Shafts and Steel or Cast Iron Hubs**

| Ratio of Diameters<br>$\frac{D_2}{D_1}$ | Steel Hub | Cast-iron Hub | Ratio of Diameters<br>$\frac{D_2}{D_1}$ | Steel Hub | Cast-iron Hub |
|---|-----------|---------------|---|-----------|---------------|
|   | $C$       |               |   | $C$       |               |
| 1.5                                     | 0.227     | 0.234         | 2.8                                     | 0.410     | 0.432         |
| 1.6                                     | 0.255     | 0.263         | 3.0                                     | 0.421     | 0.444         |
| 1.8                                     | 0.299     | 0.311         | 3.2                                     | 0.430     | 0.455         |
| 2.0                                     | 0.333     | 0.348         | 3.4                                     | 0.438     | 0.463         |
| 2.2                                     | 0.359     | 0.377         | 3.6                                     | 0.444     | 0.471         |
| 2.4                                     | 0.380     | 0.399         | 3.8                                     | 0.450     | 0.477         |
| 2.6                                     | 0.397     | 0.417         | 4.0                                     | 0.455     | 0.482         |

Values of factor  $C$  for solid steel shafts of nominal diameter  $D_1$ , and hubs of steel or cast iron of nominal external and internal diameters  $D_2$  and  $D_1$ , respectively.

*Example 1:* A steel crank web 15 inches outside diameter is to be shrunk on a 10-inch solid steel shaft. Required the allowance per inch of shaft diameter to produce a maximum tensile stress in the crank of 25,000 pounds per square inch, assuming the stresses in the crank to be equivalent to those in a ring of the diameter given.

The ratio of the external to the internal diameters equals  $15 \div 10 = 1.5$ ;  $T = 25,000$  pounds; from [Table 1](#),  $C = 0.227$ . Substituting in [Formula \(2\)](#):

$$A = \frac{25,000 \times (1 + 0.227)}{30,000,000} = 0.001 \text{ inch}$$

*Example 2:* Find the allowance per inch of diameter for a 10-inch shaft having a 5-inch axial through hole, other conditions being the same as in [Example 1](#).

The ratio of external to internal diameters of the hub equals  $15 \div 10 = 1.5$ , as before, and the ratio of external to internal diameters of the shaft equals  $10 \div 5 = 2$ . From [Table 2](#), we find that factor  $C = 0.455$ ;  $T = 25,000$  pounds. Substituting these values in [Formula \(2\)](#):

$$A = \frac{25,000(1 + 0.455)}{30,000,000} = 0.0012 \text{ inch}$$

The allowance is increased, as compared with [Example 1](#), because the hollow shaft is more compressible.

*Example 3:* If the crank web in [Example 1](#) is of cast iron and 4000 pounds per square inch is the maximum tensile stress in the hub, what is the allowance per inch of diameter?

$$\frac{D_2}{D_1} = 1.5 \quad T = 4000$$

In [Table 1](#), we find that  $C = 0.234$ . Substituting in [Formula \(1\)](#), for cast-iron hubs,  $A = 0.0003$  inch, which, owing to the lower tensile strength of cast iron, is about one-third the shrinkage allowance in [Example 1](#), although the stress is two-thirds of the elastic limit.

**Temperatures for Shrinkage Fits.**—The temperature to which the outer member in a shrinkage fit should be heated for clearance in assembling the parts depends on the total

**Table 2. Factors for Calculating Shrinkage Fit Allowances for Hollow Steel Shafts and Steel Hubs**

| $\frac{D_2}{D_1}$ | $\frac{D_1}{D_0}$ | $C^a$ | $\frac{D_2}{D_1}$ | $\frac{D_1}{D_0}$ | $C^a$ | $\frac{D_2}{D_1}$ | $\frac{D_1}{D_0}$ | $C^a$ |
|-------------------|-------------------|-------|-------------------|-------------------|-------|-------------------|-------------------|-------|
| 1.5               | 2.0               | 0.455 | 2.4               | 2.0               | 0.760 | 3.4               | 2.0               | 0.876 |
|                   | 2.5               | 0.357 |                   | 2.5               | 0.597 |                   | 2.5               | 0.689 |
|                   | 3.0               | 0.313 |                   | 3.0               | 0.523 |                   | 3.0               | 0.602 |
|                   | 3.5               | 0.288 |                   | 3.5               | 0.481 |                   | 3.5               | 0.555 |
| 1.6               | 2.0               | 0.509 | 2.6               | 2.0               | 0.793 | 3.6               | 2.0               | 0.888 |
|                   | 2.5               | 0.400 |                   | 2.5               | 0.624 |                   | 2.5               | 0.698 |
|                   | 3.0               | 0.350 |                   | 3.0               | 0.546 |                   | 3.0               | 0.611 |
|                   | 3.5               | 0.322 |                   | 3.5               | 0.502 |                   | 3.5               | 0.562 |
| 1.8               | 2.0               | 0.599 | 2.8               | 2.0               | 0.820 | 3.8               | 2.0               | 0.900 |
|                   | 2.5               | 0.471 |                   | 2.5               | 0.645 |                   | 2.5               | 0.707 |
|                   | 3.0               | 0.412 |                   | 3.0               | 0.564 |                   | 3.0               | 0.619 |
|                   | 3.5               | 0.379 |                   | 3.5               | 0.519 |                   | 3.5               | 0.570 |
| 2.0               | 2.0               | 0.667 | 3.0               | 2.0               | 0.842 | 4.0               | 2.0               | 0.909 |
|                   | 2.5               | 0.524 |                   | 2.5               | 0.662 |                   | 2.5               | 0.715 |
|                   | 3.0               | 0.459 |                   | 3.0               | 0.580 |                   | 3.0               | 0.625 |
|                   | 3.5               | 0.422 |                   | 3.5               | 0.533 |                   | 3.5               | 0.576 |
| 2.2               | 2.0               | 0.718 | 3.2               | 2.0               | 0.860 | ...               | ...               | ...   |
|                   | 2.5               | 0.565 |                   | 2.5               | 0.676 | ...               | ...               | ...   |
|                   | 3.0               | 0.494 |                   | 3.0               | 0.591 | ...               | ...               | ...   |
|                   | 3.5               | 0.455 |                   | 3.5               | 0.544 | ...               | ...               | ...   |

<sup>a</sup> Values of factor  $C$  for hollow steel shafts of external and internal diameters  $D_1$  and  $D_0$ , respectively, and steel hubs of nominal external diameter  $D_2$ .

**Table 3. Factors for Calculating Shrinkage Fit Allowances for Hollow Steel Shafts and Cast-iron Hubs**

| $\frac{D_2}{D_1}$ | $\frac{D_1}{D_0}$ | $C^a$ | $\frac{D_2}{D_1}$ | $\frac{D_1}{D_0}$ | $C^a$ | $\frac{D_2}{D_1}$ | $\frac{D_1}{D_0}$ | $C^a$ |
|-------------------|-------------------|-------|-------------------|-------------------|-------|-------------------|-------------------|-------|
| 1.5               | 2.0               | 0.468 | 2.4               | 2.0               | 0.798 | 3.4               | 2.0               | 0.926 |
|                   | 2.5               | 0.368 |                   | 2.5               | 0.628 |                   | 2.5               | 0.728 |
|                   | 3.0               | 0.322 |                   | 3.0               | 0.549 |                   | 3.0               | 0.637 |
|                   | 3.5               | 0.296 |                   | 3.5               | 0.506 |                   | 3.5               | 0.587 |
| 1.6               | 2.0               | 0.527 | 2.6               | 2.0               | 0.834 | 3.6               | 2.0               | 0.941 |
|                   | 2.5               | 0.414 |                   | 2.5               | 0.656 |                   | 2.5               | 0.740 |
|                   | 3.0               | 0.362 |                   | 3.0               | 0.574 |                   | 3.0               | 0.647 |
|                   | 3.5               | 0.333 |                   | 3.5               | 0.528 |                   | 3.5               | 0.596 |
| 1.8               | 2.0               | 0.621 | 2.8               | 2.0               | 0.864 | 3.8               | 2.0               | 0.953 |
|                   | 2.5               | 0.488 |                   | 2.5               | 0.679 |                   | 2.5               | 0.749 |
|                   | 3.0               | 0.427 |                   | 3.0               | 0.594 |                   | 3.0               | 0.656 |
|                   | 3.5               | 0.393 |                   | 3.5               | 0.547 |                   | 3.5               | 0.603 |
| 2.0               | 2.0               | 0.696 | 3.0               | 2.0               | 0.888 | 4.0               | 2.0               | 0.964 |
|                   | 2.5               | 0.547 |                   | 2.5               | 0.698 |                   | 2.5               | 0.758 |
|                   | 3.0               | 0.479 |                   | 3.0               | 0.611 |                   | 3.0               | 0.663 |
|                   | 3.5               | 0.441 |                   | 3.5               | 0.562 |                   | 3.5               | 0.610 |
| 2.2               | 2.0               | 0.753 | 3.2               | 2.0               | 0.909 | ...               | ...               | ...   |
|                   | 2.5               | 0.592 |                   | 2.5               | 0.715 | ...               | ...               | ...   |
|                   | 3.0               | 0.518 |                   | 3.0               | 0.625 | ...               | ...               | ...   |
|                   | 3.5               | 0.477 |                   | 3.5               | 0.576 | ...               | ...               | ...   |

<sup>a</sup> Values of factor  $C$  for hollow steel shafts and cast-iron hubs. Notation as in Table 2.

expansion required and on the coefficient  $\alpha$  of linear expansion of the metal (i.e., the increase in length of any section of the metal in any direction for an increase in temperature of 1 degree F). The total expansion in diameter that is required consists of the total allowance for shrinkage and an added amount for clearance. The value of the coefficient  $\alpha$  is, for nickel-steel, 0.000007; for steel in general, 0.0000065; for cast iron, 0.0000062. As an example, take an outer member of steel to be expanded 0.005 inch per inch of internal diameter, 0.001 being the shrinkage allowance and the remainder for clearance. Then

$$\alpha \times t^{\circ} = 0.005$$

$$t = \frac{0.005}{0.0000065} = 769 \text{ degrees F}$$

The value  $t$  is the number of degrees F that the temperature of the member must be raised above that of the room temperature.

### ANSI Standard Limits and Fits

This American National Standard for Preferred Limits and Fits for Cylindrical Parts, ANSI B4.1-1967 (R1999), presents definitions of terms applying to fits between plain (non threaded) cylindrical parts and makes recommendations on preferred sizes, allowances, tolerances, and fits for use wherever they are applicable. This standard is in accord with the recommendations of American-British-Canadian (ABC) conferences up to a diameter of 20 inches. Experimental work is being carried on with the objective of reaching agreement in the range above 20 inches. The recommendations in the standard are presented for guidance and for use where they might serve to improve and simplify products, practices, and facilities. They should have application for a wide range of products.

As revised in 1967, and reaffirmed in 1999, the definitions in ANSI B4.1 have been expanded and some of the limits in certain classes have been changed.

**Factors Affecting Selection of Fits.**—Many factors, such as length of engagement, bearing load, speed, lubrication, temperature, humidity, and materials must be taken into consideration in the selection of fits for a particular application, and modifications in the ANSI recommendations may be required to satisfy extreme conditions. Subsequent adjustments may also be found desirable as a result of experience in a particular application to suit critical functional requirements or to permit optimum manufacturing economy.

**Definitions.**—The following terms are defined in this standard:

*Nominal Size:* The nominal size is the designation used for the purpose of general identification.

*Dimension:* A dimension is a geometrical characteristic such as diameter, length, angle, or center distance.

*Size:* Size is a designation of magnitude. When a value is assigned to a dimension, it is referred to as the size of that dimension. (It is recognized that the words "dimension" and "size" are both used at times to convey the meaning of magnitude.)

*Allowance:* An allowance is a prescribed difference between the maximum material limits of mating parts. (See definition of *Fit*). It is a minimum clearance (positive allowance) or maximum interference (negative allowance) between such parts.

*Tolerance:* A tolerance is the total permissible variation of a size. The tolerance is the difference between the limits of size.

*Basic Size:* The basic size is that size from which the limits of size are derived by the application of allowances and tolerances.

*Design Size:* The design size is the basic size with allowance applied, from which the limits of size are derived by the application of tolerances. Where there is no allowance, the design size is the same as the basic size.

*Actual Size:* An actual size is a measured size.

*Limits of Size:* The limits of size are the applicable maximum and minimum sizes.



**Maximum Material Limit:** A maximum material limit is that limit of size that provides the maximum amount of material for the part. Normally it is the maximum limit of size of an external dimension or the minimum limit of size of an internal dimension.\*

**Minimum Material Limit:** A minimum material limit is that limit of size that provides the minimum amount of material for the part. Normally it is the minimum limit of size of an external dimension or the maximum limit of size of an internal dimension.\*

**Tolerance Limit:** A tolerance limit is the variation, positive or negative, by which a size is permitted to depart from the design size.

**Unilateral Tolerance:** A unilateral tolerance is a tolerance in which variation is permitted in only one direction from the design size.

**Bilateral Tolerance:** A bilateral tolerance is a tolerance in which variation is permitted in both directions from the design size.

**Unilateral Tolerance System:** A design plan that uses only unilateral tolerances is known as a Unilateral Tolerance System.

**Bilateral Tolerance System:** A design plan that uses only bilateral tolerances is known as a Bilateral Tolerance System.

**Fits.—Fit:** Fit is the general term used to signify the range of tightness that may result from the application of a specific combination of allowances and tolerances in the design of mating parts.

**Actual Fit:** The actual fit between two mating parts is the relation existing between them with respect to the amount of clearance or interference that is present when they are assembled. (Fits are of three general types: clearance, transition, and interference.)

**Clearance Fit:** A clearance fit is one having limits of size so specified that a clearance always results when mating parts are assembled.

**Interference Fit:** An interference fit is one having limits of size so specified that an interference always results when mating parts are assembled.

**Transition Fit:** A transition fit is one having limits of size so specified that either a clearance or an interference may result when mating parts are assembled.

**Basic Hole System:** A basic hole system is a system of fits in which the design size of the hole is the basic size and the allowance, if any, is applied to the shaft.

**Basic Shaft System:** A basic shaft system is a system of fits in which the design size of the shaft is the basic size and the allowance, if any, is applied to the hole.

**Preferred Basic Sizes.—**In specifying fits, the basic size of mating parts shall be chosen from the decimal series or the fractional series in [Table 4](#).

**Preferred Series for Tolerances and Allowances.—**All fundamental tolerances and allowances of all shafts and holes have been taken from the series given in [Table 5](#).

**Standard Tolerances.—**The series of standard tolerances shown in [Table 6](#) are so arranged that for any one grade they represent approximately similar production difficulties throughout the range of sizes. This table provides a suitable range from which appropriate tolerances for holes and shafts can be selected and enables standard gages to be used. The tolerances shown in [Table 6](#) have been used in the succeeding tables for different classes of fits.

[Table 7](#) graphically illustrates the range of tolerance grades that various machining processes may produce under normal conditions.

**ANSI Standard Fits.—**[Tables 8a](#) through [12](#) inclusive show a series of standard types and classes of fits on a unilateral hole basis, such that the fit produced by mating parts in any one class will produce approximately similar performance throughout the range of sizes. These tables prescribe the fit for any given size, or type of fit; they also prescribe the

\* An example of exceptions: an exterior corner radius where the maximum radius is the minimum material limit and the minimum radius is the maximum material limit.

**Table 4. Preferred Basic Sizes ANSI B4.1-1967 (R1999)**

| Decimal <sup>a</sup> |      |       | Fractional <sup>a</sup> |          |                |        |                 |         |
|----------------------|------|-------|-------------------------|----------|----------------|--------|-----------------|---------|
| 0.010                | 2.00 | 8.50  | $\frac{1}{64}$          | 0.015625 | $2\frac{1}{4}$ | 2.2500 | $9\frac{1}{2}$  | 9.5000  |
| 0.012                | 2.20 | 9.00  | $\frac{1}{32}$          | 0.03125  | $2\frac{1}{2}$ | 2.5000 | 10              | 10.0000 |
| 0.016                | 2.40 | 9.50  | $\frac{1}{16}$          | 0.0625   | $2\frac{3}{4}$ | 2.7500 | $10\frac{1}{2}$ | 10.5000 |
| 0.020                | 2.60 | 10.00 | $\frac{3}{32}$          | 0.09375  | 3              | 3.0000 | 11              | 11.0000 |
| 0.025                | 2.80 | 10.50 | $\frac{1}{8}$           | 0.1250   | $3\frac{1}{4}$ | 3.2500 | $11\frac{1}{2}$ | 11.5000 |
| 0.032                | 3.00 | 11.00 | $\frac{3}{32}$          | 0.15625  | $3\frac{1}{2}$ | 3.5000 | 12              | 12.0000 |
| 0.040                | 3.20 | 11.50 | $\frac{3}{16}$          | 0.1875   | $3\frac{3}{4}$ | 3.7500 | $12\frac{1}{2}$ | 12.5000 |
| 0.05                 | 3.40 | 12.00 | $\frac{1}{4}$           | 0.2500   | 4              | 4.0000 | 13              | 13.0000 |
| 0.06                 | 3.60 | 12.50 | $\frac{5}{16}$          | 0.3125   | $4\frac{1}{4}$ | 4.2500 | $13\frac{1}{2}$ | 13.5000 |
| 0.08                 | 3.80 | 13.00 | $\frac{3}{8}$           | 0.3750   | $4\frac{1}{2}$ | 4.5000 | 14              | 14.0000 |
| 0.10                 | 4.00 | 13.50 | $\frac{7}{16}$          | 0.4375   | $4\frac{3}{4}$ | 4.7500 | $14\frac{1}{2}$ | 14.5000 |
| 0.12                 | 4.20 | 14.00 | $\frac{1}{2}$           | 0.5000   | 5              | 5.0000 | 15              | 15.0000 |
| 0.16                 | 4.40 | 14.50 | $\frac{9}{16}$          | 0.5625   | $5\frac{1}{4}$ | 5.2500 | $15\frac{1}{2}$ | 15.5000 |
| 0.20                 | 4.60 | 15.00 | $\frac{5}{8}$           | 0.6250   | $5\frac{1}{2}$ | 5.5000 | 16              | 16.0000 |
| 0.24                 | 4.80 | 15.50 | $\frac{11}{16}$         | 0.6875   | $5\frac{3}{4}$ | 5.7500 | $16\frac{1}{2}$ | 16.5000 |
| 0.30                 | 5.00 | 16.00 | $\frac{3}{4}$           | 0.7500   | 6              | 6.0000 | 17              | 17.0000 |
| 0.40                 | 5.20 | 16.50 | $\frac{7}{8}$           | 0.8750   | $6\frac{1}{2}$ | 6.5000 | $17\frac{1}{2}$ | 17.5000 |
| 0.50                 | 5.40 | 17.00 | 1                       | 1.0000   | 7              | 7.0000 | 18              | 18.0000 |
| 0.60                 | 5.60 | 17.50 | $1\frac{1}{4}$          | 1.2500   | $7\frac{1}{2}$ | 7.5000 | $18\frac{1}{2}$ | 18.5000 |
| 0.80                 | 5.80 | 18.00 | $1\frac{1}{2}$          | 1.5000   | 8              | 8.0000 | 19              | 19.0000 |
| 1.00                 | 6.00 | 18.50 | $1\frac{3}{4}$          | 1.7500   | $8\frac{1}{2}$ | 8.5000 | $19\frac{1}{2}$ | 19.5000 |
| 1.20                 | 6.50 | 19.00 | 2                       | 2.0000   | 9              | 9.0000 | 20              | 20.0000 |
| 1.40                 | 7.00 | 19.50 | ...                     | ...      | ...            | ...    | ...             | ...     |
| 1.60                 | 7.50 | 20.00 | ...                     | ...      | ...            | ...    | ...             | ...     |
| 1.80                 | 8.00 | ...   | ...                     | ...      | ...            | ...    | ...             | ...     |

<sup>a</sup> All dimensions are in inches.**Table 5. Preferred Series of Tolerances and Allowances<sup>a</sup> ANSI B4.1-1967 (R1999)**

|      |     |    |     |     |     |     |     |
|------|-----|----|-----|-----|-----|-----|-----|
| 0.1  | 1   | 10 | 100 | 0.3 | 3   | 30  | ... |
| ...  | 1.2 | 12 | 125 | ... | 3.5 | 35  | ... |
| 0.15 | 1.4 | 14 | ... | 0.4 | 4   | 40  | ... |
| ...  | 1.6 | 16 | 160 | ... | 4.5 | 45  | ... |
| ...  | 1.8 | 18 | ... | 0.5 | 5   | 50  | ... |
| 0.2  | 2   | 20 | 200 | 0.6 | 6   | 60  | ... |
| ...  | 2.2 | 22 | ... | 0.7 | 7   | 70  | ... |
| 0.25 | 2.5 | 25 | 250 | 0.8 | 8   | 80  | ... |
| ...  | 2.8 | 28 | ... | 0.9 | 9   | ... | ... |

<sup>a</sup> All values in thousandths of an inch

standard limits for the mating parts that will produce the fit. The fits listed in these tables contain all those that appear in the approved American-British-Canadian proposal.

**Selection of Fits:** In selecting limits of size for any application, the type of fit is determined first, based on the use or service required from the equipment being designed; then the limits of size of the mating parts are established, to insure that the desired fit will be produced.

Theoretically, an infinite number of fits could be chosen, but the number of standard fits shown in the accompanying tables should cover most applications.

**Designation of Standard Fits:** Standard fits are designated by means of the following symbols which, facilitate reference to classes of fit for educational purposes. The symbols are not intended to be shown on manufacturing drawings; instead, sizes should be specified on drawings.

STANDARD FITS

**Table 6. ANSI Standard Tolerances ANSI B4.1-1967 (R1999)**

| Nominal Size,<br>Inches |       | Grade   |      |      |     |     |     |     |     |     |     |
|-------------------------|-------|---|------|------|-----|-----|-----|-----|-----|-----|-----|
|                         |       | 4   | 5    | 6    | 7   | 8   | 9   | 10  | 11  | 12  | 13  |
| Over                    | To    | Tolerances in thousandths of an inch <sup>a</sup> |      |      |     |     |     |     |     |     |     |
| 0                       | 0.12  | 0.12  | 0.15 | 0.25 | 0.4 | 0.6 | 1.0 | 1.6 | 2.5 | 4   | 6   |
| 0.12                    | 0.24  | 0.15  | 0.20 | 0.3  | 0.5 | 0.7 | 1.2 | 1.8 | 3.0 | 5   | 7   |
| 0.24                    | 0.40  | 0.15  | 0.25 | 0.4  | 0.6 | 0.9 | 1.4 | 2.2 | 3.5 | 6   | 9   |
| 0.40                    | 0.71  | 0.2   | 0.3  | 0.4  | 0.7 | 1.0 | 1.6 | 2.8 | 4.0 | 7   | 10  |
| 0.71                    | 1.19  | 0.25  | 0.4  | 0.5  | 0.8 | 1.2 | 2.0 | 3.5 | 5.0 | 8   | 12  |
| 1.19                    | 1.97  | 0.3   | 0.4  | 0.6  | 1.0 | 1.6 | 2.5 | 4.0 | 6   | 10  | 16  |
| 1.97                    | 3.15  | 0.3   | 0.5  | 0.7  | 1.2 | 1.8 | 3.0 | 4.5 | 7   | 12  | 18  |
| 3.15                    | 4.73  | 0.4   | 0.6  | 0.9  | 1.4 | 2.2 | 3.5 | 5   | 9   | 14  | 22  |
| 4.73                    | 7.09  | 0.5   | 0.7  | 1.0  | 1.6 | 2.5 | 4.0 | 6   | 10  | 16  | 25  |
| 7.09                    | 9.85  | 0.6   | 0.8  | 1.2  | 1.8 | 2.8 | 4.5 | 7   | 12  | 18  | 28  |
| 9.85                    | 12.41 | 0.6   | 0.9  | 1.2  | 2.0 | 3.0 | 5.0 | 8   | 12  | 20  | 30  |
| 12.41                   | 15.75 | 0.7   | 1.0  | 1.4  | 2.2 | 3.5 | 6   | 9   | 14  | 22  | 35  |
| 15.75                   | 19.69 | 0.8   | 1.0  | 1.6  | 2.5 | 4   | 6   | 10  | 16  | 25  | 40  |
| 19.69                   | 30.09 | 0.9   | 1.2  | 2.0  | 3   | 5   | 8   | 12  | 20  | 30  | 50  |
| 30.09                   | 41.49 | 1.0   | 1.6  | 2.5  | 4   | 6   | 10  | 16  | 25  | 40  | 60  |
| 41.49                   | 56.19 | 1.2   | 2.0  | 3    | 5   | 8   | 12  | 20  | 30  | 50  | 80  |
| 56.19                   | 76.39 | 1.6   | 2.5  | 4    | 6   | 10  | 16  | 25  | 40  | 60  | 100 |
| 76.39                   | 100.9 | 2.0   | 3    | 5    | 8   | 12  | 20  | 30  | 50  | 80  | 125 |
| 100.9                   | 131.9 | 2.5   | 4    | 6    | 10  | 16  | 25  | 40  | 60  | 100 | 160 |
| 131.9                   | 171.9 | 3   | 5    | 8    | 12  | 20  | 30  | 50  | 80  | 125 | 200 |
| 171.9                   | 200   | 4   | 6    | 10   | 16  | 25  | 40  | 60  | 100 | 160 | 250 |

<sup>a</sup> All tolerances above heavy line are in accordance with American-British-Canadian (ABC) agreements.

**Table 7. Relation of Machining Processes to Tolerance Grades ANSI B4.1-1967 (R1999)**

|  | MACHINING OPERATION  | TOLERANCE GRADES |   |   |   |   |   |    |    |    |    |
|--|----------------------|------------------|---|---|---|---|---|----|----|----|----|
|  |                      | 4                | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|  | Lapping & Honing     | █                | █ |   |   |   |   |    |    |    |    |
|  | Cylindrical Grinding | █                | █ | █ |   |   |   |    |    |    |    |
|  | Surface Grinding     | █                | █ | █ | █ |   |   |    |    |    |    |
|  | Diamond Turning      | █                | █ | █ | █ | █ |   |    |    |    |    |
|  | Diamond Boring       | █                | █ | █ | █ | █ | █ |    |    |    |    |
|  | Broaching            | █                | █ | █ | █ | █ | █ | █  |    |    |    |
|  | Reaming              | █                | █ | █ | █ | █ | █ | █  | █  |    |    |
|  | Turning              | █                | █ | █ | █ | █ | █ | █  | █  | █  | █  |
|  | Boring               | █                | █ | █ | █ | █ | █ | █  | █  | █  | █  |
|  | Milling              | █                | █ | █ | █ | █ | █ | █  | █  | █  | █  |
|  | Planing & Shaping    | █                | █ | █ | █ | █ | █ | █  | █  | █  | █  |
|  | Drilling             | █                | █ | █ | █ | █ | █ | █  | █  | █  | █  |

The letter symbols used to designate standard fits are as follows:

- RC = Running or Sliding Clearance Fit    LC = Locational Clearance Fit
- LT = Transition Clearance or Interference Fit
- LN = Locational Interference Fit
- FN = Force or Shrink Fit

These letter symbols are used in conjunction with numbers representing the class of fit; thus FN 4 represents a Class 4, force fit.

Each of these symbols (two letters and a number) represents a complete fit for which the minimum and maximum clearance or interference and the limits of size for the mating parts are given directly in the tables.

**Description of Fits.**—The classes of fits are arranged in three general groups: running and sliding fits, locational fits, and force fits.

*Running and Sliding Fits (RC):* Running and sliding fits, for which limits of clearance are given in [Table 8a](#), are intended to provide a similar running performance, with suitable lubrication allowance, throughout the range of sizes. The clearances for the first two classes, used chiefly as slide fits, increase more slowly with the diameter than for the other classes, so that accurate location is maintained even at the expense of free relative motion.

These fits may be described as follows:

RC 1 *Close sliding fits* are intended for the accurate location of parts that must assemble without perceptible play.

RC 2 *Sliding fits* are intended for accurate location, but with greater maximum clearance than class RC 1. Parts made to this fit move and turn easily but are not intended to run freely, and in the larger sizes may seize with small temperature changes.

RC 3 *Precision running fits* are about the closest fits that can be expected to run freely, and are intended for precision work at slow speeds and light journal pressures, but are not suitable where appreciable temperature differences are likely to be encountered.

RC 4 *Close running fits* are intended chiefly for running fits on accurate machinery with moderate surface speeds and journal pressures, where accurate location and minimum play are desired.

RC 5 and RC 6 *Medium running fits* are intended for higher running speeds, or heavy journal pressures, or both.

RC 7 *Free running fits* are intended for use where accuracy is not essential, or where large temperature variations are likely to be encountered, or under both these conditions.

RC 8 and RC 9 *Loose running fits* are intended for use where wide commercial tolerances may be necessary, together with an allowance, on the external member.

*Locational Fits (LC, LT, and LN):* Locational fits are fits intended to determine only the location of the mating parts; they may provide rigid or accurate location, as with interference fits, or provide some freedom of location, as with clearance fits. Accordingly, they are divided into three groups: clearance fits (LC), transition fits (LT), and interference fits (LN).

These are described as follows:

LC *Locational clearance fits* are intended for parts which are normally stationary, but that can be freely assembled or disassembled. They range from snug fits for parts requiring accuracy of location, through the medium clearance fits for parts such as spigots, to the looser fastener fits where freedom of assembly is of prime importance.

LT *Locational transition fits* are a compromise between clearance and interference fits, for applications where accuracy of location is important, but either a small amount of clearance or interference is permissible.

LN *Locational interference fits* are used where accuracy of location is of prime importance, and for parts requiring rigidity and alignment with no special requirements for bore pressure. Such fits are not intended for parts designed to transmit frictional loads from one part to another by virtue of the tightness of fit. These conditions are covered by force fits.

*Force Fits: (FN):* Force or shrink fits constitute a special type of interference fit, normally characterized by maintenance of constant bore pressures throughout the range of sizes. The interference therefore varies almost directly with diameter, and the difference

between its minimum and maximum value is small, to maintain the resulting pressures within reasonable limits.

These fits are described as follows:

FN 1 *Light drive fits* are those requiring light assembly pressures, and produce more or less permanent assemblies. They are suitable for thin sections or long fits, or in cast-iron external members.

FN 2 *Medium drive fits* are suitable for ordinary steel parts, or for shrink fits on light sections. They are about the tightest fits that can be used with high-grade cast-iron external members.

FN 3 *Heavy drive fits* are suitable for heavier steel parts or for shrink fits in medium sections.

FN 4 and FN 5 *Force fits* are suitable for parts that can be highly stressed, or for shrink fits where the heavy pressing forces required are impractical.

**Graphical Representation of Limits and Fits.**—A visual comparison of the hole and shaft tolerances and the clearances or interferences provided by the various types and classes of fits can be obtained from the diagrams on page 657. These diagrams have been drawn to scale for a nominal diameter of 1 inch.

**Use of Standard Fit Tables.**—*Example 1:* A Class RC 1 fit is to be used in assembling a mating hole and shaft of 2-inch nominal diameter. This class of fit was selected because the application required accurate location of the parts with no perceptible play (see *Description of Fits*, RC 1 close sliding fits). From the data in [Table 8a](#), establish the limits of size and clearance of the hole and shaft.

Maximum hole =  $2 + 0.0005 = 2.0005$ ; minimum hole = 2 inches

Maximum shaft =  $2 - 0.0004 = 1.9996$ ; minimum shaft =  $2 - 0.0007 = 1.9993$  inches

Minimum clearance = 0.0004; maximum clearance = 0.0012 inch

**Modified Standard Fits.**—Fits having the same limits of clearance or interference as those shown in [Tables 8a to 12](#) may sometimes have to be produced by using holes or shafts having limits of size other than those shown in these tables. These modifications may be accomplished by using either a *Bilateral Hole System (Symbol B)* or a *Basic Shaft System (Symbol S)*. Both methods will result in nonstandard holes and shafts.

*Bilateral Hole Fits (Symbol B):* The common situation is where holes are produced with fixed tools such as drills or reamers; to provide a longer wear life for such tools, a bilateral tolerance is desired.

The symbols used for these fits are identical with those used for standard fits except that they are followed by the letter B. Thus, LC 4B is a clearance locational fit, Class 4, except that it is produced with a bilateral hole.

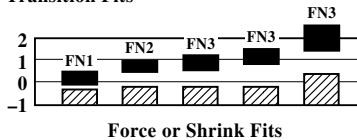
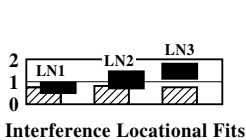
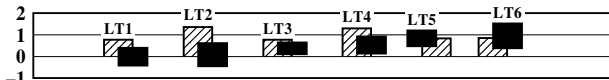
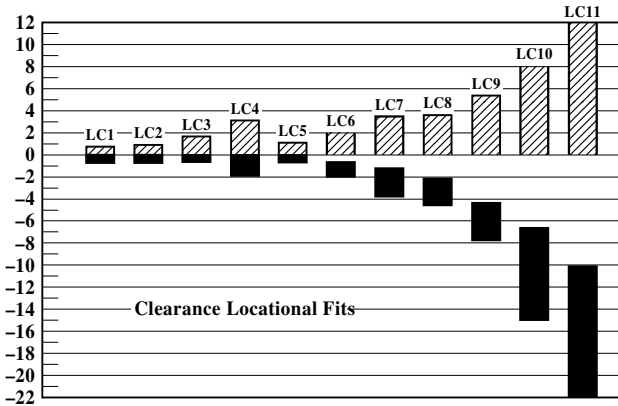
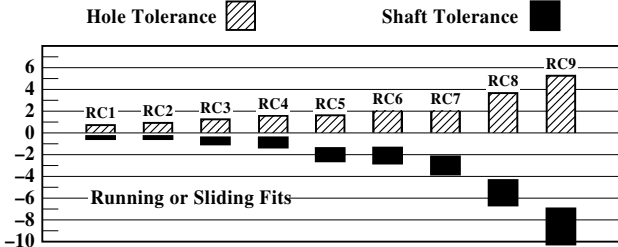
The limits of clearance or interference are identical with those shown in [Tables 8a to 12](#) for the corresponding fits.

The hole tolerance, however, is changed so that the plus limit is that for one grade finer than the value shown in the tables and the minus limit equals the amount by which the plus limit was lowered. The shaft limits are both lowered by the same amount as the lower limit of size of the hole. The finer grade of tolerance required to make these modifications may be obtained from [Table 6](#). For example, an LC 4B fit for a 6-inch diameter hole would have tolerance limits of  $+4.0, -2.0$  ( $+0.0040$  inch,  $-0.0020$  inch); the shaft would have tolerance limits of  $-2.0, -6.0$  ( $-0.0020$  inch,  $-0.0060$  inch).

*Basic Shaft Fits (Symbol S):* For these fits, the maximum size of the shaft is basic. The limits of clearance or interference are identical with those shown in [Tables 8a to 12](#) for the corresponding fits and the symbols used for these fits are identical with those used for standard fits except that they are followed by the letter S. Thus, LC 4S is a clearance locational fit, Class 4, except that it is produced on a basic shaft basis.

The limits for hole and shaft as given in Tables 8a to 12 are increased for clearance fits (decreased for transition or interference fits) by the value of the upper shaft limit; that is, by the amount required to change the maximum shaft to the basic size.

**Graphical Representation of ANSI Standard Limits and Fits**  
ANSI B4.1-1967 (R1999)



Diagrams show disposition of hole and shaft tolerances (in thousandths of an inch) with respect to basic size (0) for a diameter of 1 inch.

Table 8a. American National Standard Running and Sliding Fits ANSI B4.1-1967 (R1999)

| Nominal<br>Size Range,<br>Inches | Class RC 1                                       |                           |                | Class RC 2             |                           |                | Class RC 3             |                           |               | Class RC 4             |                           |              |
|----------------------------------|--|---------------------------|----------------|------------------------|---------------------------|----------------|------------------------|---------------------------|---------------|------------------------|---------------------------|--------------|
|                                  | Clearance <sup>a</sup>                           | Standard Tolerance Limits |                | Clearance <sup>a</sup> | Standard Tolerance Limits |                | Clearance <sup>a</sup> | Standard Tolerance Limits |               | Clearance <sup>a</sup> | Standard Tolerance Limits |              |
|                                  |  | Hole<br>H5                | Shaft<br>g4    |                        | Hole<br>H6                | Shaft<br>g5    |                        | Hole<br>H7                | Shaft<br>f6   |                        | Hole<br>H8                | Shaft<br>f7  |
| Over To                          | Values shown below are in thousandths of an inch |                           |                |                        |                           |                |                        |                           |               |                        |                           |              |
| 0 – 0.12                         | 0.1<br>0.45                                      | +0.2<br>0                 | -0.1<br>-0.25  | 0.1<br>0.55            | +0.25<br>0                | -0.1<br>-0.3   | 0.3<br>0.95            | +0.4<br>0                 | -0.3<br>-0.55 | 0.3<br>1.3             | +0.6<br>0                 | -0.3<br>-0.7 |
| 0.12 – 0.24                      | 0.15<br>0.5                                      | +0.2<br>0                 | -0.15<br>-0.3  | 0.15<br>0.65           | +0.3<br>0                 | -0.15<br>-0.35 | 0.4<br>1.12            | +0.5<br>0                 | -0.4<br>-0.7  | 0.4<br>1.6             | +0.7<br>0                 | -0.4<br>-0.9 |
| 0.24 – 0.40                      | 0.2<br>0.6                                       | +0.25<br>0                | -0.2<br>-0.35  | 0.2<br>0.85            | +0.4<br>0                 | -0.2<br>-0.45  | 0.5<br>1.5             | +0.6<br>0                 | -0.5<br>-0.9  | 0.5<br>2.0             | +0.9<br>0                 | -0.5<br>-1.1 |
| 0.40 – 0.71                      | 0.25<br>0.75                                     | +0.3<br>0                 | -0.25<br>-0.45 | 0.25<br>0.95           | +0.4<br>0                 | -0.25<br>-0.55 | 0.6<br>1.7             | +0.7<br>0                 | -0.6<br>-1.0  | 0.6<br>2.3             | +1.0<br>0                 | -0.6<br>-1.3 |
| 0.71 – 1.19                      | 0.3<br>0.95                                      | +0.4<br>0                 | -0.3<br>-0.55  | 0.3<br>1.2             | +0.5<br>0                 | -0.3<br>-0.7   | 0.8<br>2.1             | +0.8<br>0                 | -0.8<br>-1.3  | 0.8<br>2.8             | +1.2<br>0                 | -0.8<br>-1.6 |
| 1.19 – 1.97                      | 0.4<br>1.1                                       | +0.4<br>0                 | -0.4<br>-0.7   | 0.4<br>1.4             | +0.6<br>0                 | -0.4<br>-0.8   | 1.0<br>2.6             | +1.0<br>0                 | -1.0<br>-1.6  | 1.0<br>3.6             | +1.6<br>0                 | -1.0<br>-2.0 |
| 1.97 – 3.15                      | 0.4<br>1.2                                       | +0.5<br>0                 | -0.4<br>-0.7   | 0.4<br>1.6             | +0.7<br>0                 | -0.4<br>-0.9   | 1.2<br>3.1             | +1.2<br>0                 | -1.2<br>-1.9  | 1.2<br>4.2             | +1.8<br>0                 | -1.2<br>-2.4 |
| 3.15 – 4.73                      | 0.5<br>1.5                                       | +0.6<br>0                 | -0.5<br>-0.9   | 0.5<br>2.0             | +0.9<br>0                 | -0.5<br>-1.1   | 1.4<br>3.7             | +1.4<br>0                 | -1.4<br>-2.3  | 1.4<br>5.0             | +2.2<br>0                 | -1.4<br>-2.8 |
| 4.73 – 7.09                      | 0.6<br>1.8                                       | +0.7<br>0                 | -0.6<br>-1.1   | 0.6<br>2.3             | +1.0<br>0                 | -0.6<br>-1.3   | 1.6<br>4.2             | +1.6<br>0                 | -1.6<br>-2.6  | 1.6<br>5.7             | +2.5<br>0                 | -1.6<br>-3.2 |
| 7.09 – 9.85                      | 0.6<br>2.0                                       | +0.8<br>0                 | -0.6<br>-1.2   | 0.6<br>2.6             | +1.2<br>0                 | -0.6<br>-1.4   | 2.0<br>5.0             | +1.8<br>0                 | -2.0<br>-3.2  | 2.0<br>6.6             | +2.8<br>0                 | -2.0<br>-3.8 |
| 9.85 – 12.41                     | 0.8<br>2.3                                       | +0.9<br>0                 | -0.8<br>-1.4   | 0.8<br>2.9             | +1.2<br>0                 | -0.8<br>-1.7   | 2.5<br>5.7             | +2.0<br>0                 | -2.5<br>-3.7  | 2.5<br>7.5             | +3.0<br>0                 | -2.5<br>-4.5 |
| 12.41 – 15.75                    | 1.0<br>2.7                                       | +1.0<br>0                 | -1.0<br>-1.7   | 1.0<br>3.4             | +1.4<br>0                 | -1.0<br>-2.0   | 3.0<br>6.6             | +2.2<br>0                 | -3.0<br>-4.4  | 3.0<br>8.7             | +3.5<br>0                 | -3.0<br>-5.2 |
| 15.75 – 19.69                    | 1.2<br>3.0                                       | +1.0<br>0                 | -1.2<br>-2.0   | 1.2<br>3.8             | +1.6<br>0                 | -1.2<br>-2.2   | 4.0<br>8.1             | +2.5<br>0                 | -4.0<br>-5.6  | 4.0<br>10.5            | +4.0<br>0                 | -4.0<br>-6.5 |

**Table 8b. American National Standard Running and Sliding Fits ANSI B4.1-1967 (R1999)**

| Nominal<br>Size Range,<br>Inches | Class RC 5                                       |                           |                 | Class RC 6                  |                           |                 | Class RC 7                  |                           |                  | Class RC 8                  |                           |                  | Class RC 9                  |                           |                  |
|----------------------------------|--|---------------------------|-----------------|-----------------------------|---------------------------|-----------------|-----------------------------|---------------------------|------------------|-----------------------------|---------------------------|------------------|-----------------------------|---------------------------|------------------|
|                                  | Clear-<br>ance <sup>a</sup>                      | Standard Tolerance Limits |                 | Clear-<br>ance <sup>a</sup> | Standard Tolerance Limits |                 | Clear-<br>ance <sup>a</sup> | Standard Tolerance Limits |                  | Clear-<br>ance <sup>a</sup> | Standard Tolerance Limits |                  | Clear-<br>ance <sup>a</sup> | Standard Tolerance Limits |                  |
|                                  |  | Hole<br>H8                | Shaft<br>e7     |                             | Hole<br>H9                | Shaft<br>e8     |                             | Hole<br>H9                | Shaft<br>d8      |                             | Hole<br>H10               | Shaft<br>e9      |                             | Hole<br>H11               | Shaft            |
| Over To                          | Values shown below are in thousandths of an inch |                           |                 |                             |                           |                 |                             |                           |                  |                             |                           |                  |                             |                           |                  |
| 0 – 0.12                         | 0.6<br>1.6                                       | +0.6<br>0                 | - 0.6<br>- 1.0  | 0.6<br>2.2                  | +1.0<br>0                 | - 0.6<br>- 1.2  | 1.0<br>2.6                  | +1.0<br>0                 | - 1.0<br>- 1.6   | 2.5<br>5.1                  | +1.6<br>0                 | - 2.5<br>- 3.5   | 4.0<br>8.1                  | +2.5<br>0                 | - 4.0<br>- 5.6   |
| 0.12 – 0.24                      | 0.8<br>2.0                                       | +0.7<br>0                 | - 0.8<br>- 1.3  | 0.8<br>2.7                  | +1.2<br>0                 | - 0.8<br>- 1.5  | 1.2<br>3.1                  | +1.2<br>0                 | - 1.2<br>- 1.9   | 2.8<br>5.8                  | +1.8<br>0                 | - 2.8<br>- 4.0   | 4.5<br>9.0                  | +3.0<br>0                 | - 4.5<br>- 6.0   |
| 0.24 – 0.40                      | 1.0<br>2.5                                       | +0.9<br>0                 | - 1.0<br>- 1.6  | 1.0<br>3.3                  | +1.4<br>0                 | - 1.0<br>- 1.9  | 1.6<br>3.9                  | +1.4<br>0                 | - 1.6<br>- 2.5   | 3.0<br>6.6                  | +2.2<br>0                 | - 3.0<br>- 4.4   | 5.0<br>10.7                 | +3.5<br>0                 | - 5.0<br>- 7.2   |
| 0.40 – 0.71                      | 1.2<br>2.9                                       | +1.0<br>0                 | - 1.2<br>- 1.9  | 1.2<br>3.8                  | +1.6<br>0                 | - 1.2<br>- 2.2  | 2.0<br>4.6                  | +1.6<br>0                 | - 2.0<br>- 3.0   | 3.5<br>7.9                  | +2.8<br>0                 | - 3.5<br>- 5.1   | 6.0<br>12.8                 | +4.0<br>0                 | - 6.0<br>- 8.8   |
| 0.71 – 1.19                      | 1.6<br>3.6                                       | +1.2<br>0                 | - 1.6<br>- 2.4  | 1.6<br>4.8                  | +2.0<br>0                 | - 1.6<br>- 2.8  | 2.5<br>5.7                  | +2.0<br>0                 | - 2.5<br>- 3.7   | 4.5<br>10.0                 | +3.5<br>0                 | - 4.5<br>- 6.5   | 7.0<br>15.5                 | +5.0<br>0                 | - 7.0<br>- 10.5  |
| 1.19 – 1.97                      | 2.0<br>4.6                                       | +1.6<br>0                 | - 2.0<br>- 3.0  | 2.0<br>6.1                  | +2.5<br>0                 | - 2.0<br>- 3.6  | 3.0<br>7.1                  | +2.5<br>0                 | - 3.0<br>- 4.6   | 5.0<br>11.5                 | +4.0<br>0                 | - 5.0<br>- 7.5   | 8.0<br>18.0                 | +6.0<br>0                 | - 8.0<br>- 12.0  |
| 1.97 – 3.15                      | 2.5<br>5.5                                       | +1.8<br>0                 | - 2.5<br>- 3.7  | 2.5<br>7.3                  | +3.0<br>0                 | - 2.5<br>- 4.3  | 4.0<br>8.8                  | +3.0<br>0                 | - 4.0<br>- 5.8   | 6.0<br>13.5                 | +4.5<br>0                 | - 6.0<br>- 9.0   | 9.0<br>20.5                 | +7.0<br>0                 | - 9.0<br>- 13.5  |
| 3.15 – 4.73                      | 3.0<br>6.6                                       | +2.2<br>0                 | - 3.0<br>- 4.4  | 3.0<br>8.7                  | +3.5<br>0                 | - 3.0<br>- 5.2  | 5.0<br>10.7                 | +3.5<br>0                 | - 5.0<br>- 7.2   | 7.0<br>15.5                 | +5.0<br>0                 | - 7.0<br>- 10.5  | 10.0<br>24.0                | +9.0<br>0                 | - 10.0<br>- 15.0 |
| 4.73 – 7.09                      | 3.5<br>7.6                                       | +2.5<br>0                 | - 3.5<br>- 5.1  | 3.5<br>10.0                 | +4.0<br>0                 | - 3.5<br>- 6.0  | 6.0<br>12.5                 | +4.0<br>0                 | - 6.0<br>- 8.5   | 8.0<br>18.0                 | +6.0<br>0                 | - 8.0<br>- 12.0  | 12.0<br>28.0                | +10.0<br>0                | - 12.0<br>- 18.0 |
| 7.09 – 9.85                      | 4.0<br>8.6                                       | +2.8<br>0                 | - 4.0<br>- 5.8  | 4.0<br>11.3                 | +4.5<br>0                 | - 4.0<br>- 6.8  | 7.0<br>14.3                 | +4.5<br>0                 | - 7.0<br>- 9.8   | 10.0<br>21.5                | +7.0<br>0                 | - 10.0<br>- 14.5 | 15.0<br>34.0                | +12.0<br>0                | - 15.0<br>- 22.0 |
| 9.85 – 12.41                     | 5.0<br>10.0                                      | +3.0<br>0                 | - 5.0<br>- 7.0  | 5.0<br>13.0                 | +5.0<br>0                 | - 5.0<br>- 8.0  | 8.0<br>16.0                 | +5.0<br>0                 | - 8.0<br>- 11.0  | 12.0<br>25.0                | +8.0<br>0                 | - 12.0<br>- 17.0 | 18.0<br>38.0                | +12.0<br>0                | - 18.0<br>- 26.0 |
| 12.41 – 15.75                    | 6.0<br>11.7                                      | +3.5<br>0                 | - 6.0<br>- 8.2  | 6.0<br>15.5                 | +6.0<br>0                 | - 6.0<br>- 9.5  | 10.0<br>19.5                | +6.0<br>0                 | - 10.0<br>- 13.5 | 14.0<br>29.0                | +9.0<br>0                 | - 14.0<br>- 20.0 | 22.0<br>45.0                | +14.0<br>0                | - 22.0<br>- 31.0 |
| 15.75 – 19.69                    | 8.0<br>14.5                                      | +4.0<br>0                 | - 8.0<br>- 10.5 | 8.0<br>18.0                 | +6.0<br>0                 | - 8.0<br>- 12.0 | 12.0<br>22.0                | +6.0<br>0                 | - 12.0<br>- 16.0 | 16.0<br>32.0                | +10.0<br>0                | - 16.0<br>- 22.0 | 25.0<br>51.0                | +16.0<br>0                | - 25.0<br>- 35.0 |

<sup>a</sup> Pairs of values shown represent minimum and maximum amounts of clearance resulting from application of standard tolerance limits.

Tolerance limits given in body of table are added to or subtracted from basic size (as indicated by + or - sign) to obtain maximum and minimum sizes of mating parts.

All data above heavy lines are in accord with ABC agreements. Symbols H5, g4, etc. are hole and shaft designations in ABC system. Limits for sizes above 19.69 inches are also given in the ANSI Standard.



Table 9a. American National Standard Clearance Locational Fits ANSI B4.1-1967 (R1999)

| Nominal<br>Size Range,<br>Inches | Class LC 1                                       |                           |             | Class LC 2                  |                           |             | Class LC 3                  |                           |             | Class LC 4                  |                           |             | Class LC 5                  |                           |                |
|----------------------------------|--|---------------------------|-------------|-----------------------------|---------------------------|-------------|-----------------------------|---------------------------|-------------|-----------------------------|---------------------------|-------------|-----------------------------|---------------------------|----------------|
|                                  | Clear-<br>ance <sup>a</sup>                      | Standard Tolerance Limits |             | Clear-<br>ance <sup>a</sup> | Standard Tolerance Limits |             | Clear-<br>ance <sup>a</sup> | Standard Tolerance Limits |             | Clear-<br>ance <sup>a</sup> | Standard Tolerance Limits |             | Clear-<br>ance <sup>a</sup> | Standard Tolerance Limits |                |
|                                  |  | Hole<br>H6                | Shaft<br>h5 |                             | Hole<br>H7                | Shaft<br>h6 |                             | Hole<br>H8                | Shaft<br>h7 |                             | Hole<br>H10               | Shaft<br>h9 |                             | Hole<br>H7                | Shaft<br>g6    |
| Over To                          | Values shown below are in thousandths of an inch |                           |             |                             |                           |             |                             |                           |             |                             |                           |             |                             |                           |                |
| 0- 0.12                          | 0<br>0.45  | +0.25<br>0                | 0<br>-0.2   | 0<br>0.65                   | +0.4<br>0                 | 0<br>-0.25  | 0<br>1                      | +0.6<br>0                 | 0<br>-0.4   | 0<br>2.6                    | +1.6<br>0                 | 0<br>-1.0   | 0.1<br>0.75                 | +0.4<br>0                 | -0.1<br>-0.35  |
| 0.12- 0.24                       | 0<br>0.5   | +0.3<br>0                 | 0<br>-0.2   | 0<br>0.8                    | +0.5<br>0                 | 0<br>-0.3   | 0<br>1.2                    | +0.7<br>0                 | 0<br>-0.5   | 0<br>3.0                    | +1.8<br>0                 | 0<br>-1.2   | 0.15<br>0.95                | +0.5<br>0                 | -0.15<br>-0.45 |
| 0.24- 0.40                       | 0<br>0.65  | +0.4<br>0                 | 0<br>-0.25  | 0<br>1.0                    | +0.6<br>0                 | 0<br>-0.4   | 0<br>1.5                    | +0.9<br>0                 | 0<br>-0.6   | 0<br>3.6                    | +2.2<br>0                 | 0<br>-1.4   | 0.2<br>1.2                  | +0.6<br>0                 | -0.2<br>-0.6   |
| 0.40- 0.71                       | 0<br>0.7   | +0.4<br>0                 | 0<br>-0.3   | 0<br>1.1                    | +0.7<br>0                 | 0<br>-0.4   | 0<br>1.7                    | +1.0<br>0                 | 0<br>-0.7   | 0<br>4.4                    | +2.8<br>0                 | 0<br>-1.6   | 0.25<br>1.35                | +0.7<br>0                 | -0.25<br>-0.65 |
| 0.71- 1.19                       | 0<br>0.9   | +0.5<br>0                 | 0<br>-0.4   | 0<br>1.3                    | +0.8<br>0                 | 0<br>-0.5   | 0<br>2                      | +1.2<br>0                 | 0<br>-0.8   | 0<br>5.5                    | +3.5<br>0                 | 0<br>-2.0   | 0.3<br>1.6                  | +0.8<br>0                 | -0.3<br>-0.8   |
| 1.19- 1.97                       | 0<br>1.0   | +0.6<br>0                 | 0<br>-0.4   | 0<br>1.6                    | +1.0<br>0                 | 0<br>-0.6   | 0<br>2.6                    | +1.6<br>0                 | 0<br>-1     | 0<br>6.5                    | +4.0<br>0                 | 0<br>-2.5   | 0.4<br>2.0                  | +1.0<br>0                 | -0.4<br>-1.0   |
| 1.97- 3.15                       | 0<br>1.2   | +0.7<br>0                 | 0<br>-0.5   | 0<br>1.9                    | +1.2<br>0                 | 0<br>-0.7   | 0<br>3                      | +1.8<br>0                 | 0<br>-1.2   | 0<br>7.5                    | +4.5<br>0                 | 0<br>-3     | 0.4<br>2.3                  | +1.2<br>0                 | -0.4<br>-1.1   |
| 3.15- 4.73                       | 0<br>1.5   | +0.9<br>0                 | 0<br>-0.6   | 0<br>2.3                    | +1.4<br>0                 | 0<br>-0.9   | 0<br>3.6                    | +2.2<br>0                 | 0<br>-1.4   | 0<br>8.5                    | +5.0<br>0                 | 0<br>-3.5   | 0.5<br>2.8                  | +1.4<br>0                 | -0.5<br>-1.4   |
| 4.73- 7.09                       | 0<br>1.7   | +1.0<br>0                 | 0<br>-0.7   | 0<br>2.6                    | +1.6<br>0                 | 0<br>-1.0   | 0<br>4.1                    | +2.5<br>0                 | 0<br>-1.6   | 0<br>10.0                   | +6.0<br>0                 | 0<br>-4     | 0.6<br>3.2                  | +1.6<br>0                 | -0.6<br>-1.6   |
| 7.09- 9.85                       | 0<br>2.0   | +1.2<br>0                 | 0<br>-0.8   | 0<br>3.0                    | +1.8<br>0                 | 0<br>-1.2   | 0<br>4.6                    | +2.8<br>0                 | 0<br>-1.8   | 0<br>11.5                   | +7.0<br>0                 | 0<br>-4.5   | 0.6<br>3.6                  | +1.8<br>0                 | -0.6<br>-1.8   |
| 9.85- 12.41                      | 0<br>2.1   | +1.2<br>0                 | 0<br>-0.9   | 0<br>3.2                    | +2.0<br>0                 | 0<br>-1.2   | 0<br>5                      | +3.0<br>0                 | 0<br>-2.0   | 0<br>13.0                   | +8.0<br>0                 | 0<br>-5     | 0.7<br>3.9                  | +2.0<br>0                 | -0.7<br>-1.9   |
| 12.41- 15.75                     | 0<br>2.4   | +1.4<br>0                 | 0<br>-1.0   | 0<br>3.6                    | +2.2<br>0                 | 0<br>-1.4   | 0<br>5.7                    | +3.5<br>0                 | 0<br>-2.2   | 0<br>15.0                   | +9.0<br>0                 | 0<br>-6     | 0.7<br>4.3                  | +2.2<br>0                 | -0.7<br>-2.1   |
| 15.75- 19.69                     | 0<br>2.6   | +1.6<br>0                 | 0<br>-1.0   | 0<br>4.1                    | +2.5<br>0                 | 0<br>-1.6   | 0<br>6.5                    | +4<br>0                   | 0<br>-2.5   | 0<br>16.0                   | +10.0<br>0                | 0<br>-6     | 0.8<br>4.9                  | +2.5<br>0                 | -0.8<br>-2.4   |

**Table 9b. American National Standard Clearance Locational Fits ANSI B4.1-1967 (R1999)**

| Nominal<br>Size Range,<br>Inches |       | Class LC 6                                       |            |              | Class LC 7                  |             |              | Class LC 8                  |             |              | Class LC 9                  |             |               | Class LC 10                 |             |              | Class LC 11                 |             |            |
|----------------------------------|-------|--|------------|--------------|-----------------------------|-------------|--------------|-----------------------------|-------------|--------------|-----------------------------|-------------|---------------|-----------------------------|-------------|--------------|-----------------------------|-------------|------------|
|                                  |       | Std. Tolerance Limits                            |            |              | Std. Tolerance Limits       |             |              | Std. Tolerance Limits       |             |              | Std. Tolerance Limits       |             |               | Std. Tolerance Limits       |             |              | Std. Tolerance Limits       |             |            |
|                                  |       | Clear-<br>ance <sup>a</sup>                      | Hole<br>H9 | Shaft<br>f8  | Clear-<br>ance <sup>a</sup> | Hole<br>H10 | Shaft<br>e9  | Clear-<br>ance <sup>a</sup> | Hole<br>H10 | Shaft<br>d9  | Clear-<br>ance <sup>a</sup> | Hole<br>H11 | Shaft<br>c10  | Clear-<br>ance <sup>a</sup> | Hole<br>H12 | Shaft        | Clear-<br>ance <sup>a</sup> | Hole<br>H13 | Shaft      |
| Over                             | To    | Values shown below are in thousandths of an inch |            |              |                             |             |              |                             |             |              |                             |             |               |                             |             |              |                             |             |            |
| 0 -                              | 0.12  | 0.3<br>1.9                                       | +1.0<br>0  | -0.3<br>-0.9 | 0.6<br>3.2                  | +1.6<br>0   | -0.6<br>-1.6 | 1.0<br>2.0                  | +1.6<br>0   | -1.0<br>-2.0 | 2.5<br>6.6                  | +2.5<br>0   | -2.5<br>-4.1  | 4<br>12                     | +4<br>0     | -4<br>-8     | 5<br>17                     | +6<br>0     | -5<br>-11  |
| 0.12 -                           | 0.24  | 0.4<br>2.3                                       | +1.2<br>0  | -0.4<br>-1.1 | 0.8<br>3.8                  | +1.8<br>0   | -0.8<br>-2.0 | 1.2<br>4.2                  | +1.8<br>0   | -1.2<br>-2.4 | 2.8<br>7.6                  | +3.0<br>0   | -2.8<br>-4.6  | 4.5<br>14.5                 | +5<br>0     | -4.5<br>-9.5 | 6<br>20                     | +7<br>0     | -6<br>-13  |
| 0.24 -                           | 0.40  | 0.5<br>2.8                                       | +1.4<br>0  | -0.5<br>-1.4 | 1.0<br>4.6                  | +2.2<br>0   | -1.0<br>-2.4 | 1.6<br>5.2                  | +2.2<br>0   | -1.6<br>-3.0 | 3.0<br>8.7                  | +3.5<br>0   | -3.0<br>-5.2  | 5<br>17                     | +6<br>0     | -5<br>-11    | 7<br>25                     | +9<br>0     | -7<br>-16  |
| 0.40 -                           | 0.71  | 0.6<br>3.2                                       | +1.6<br>0  | -0.6<br>-1.6 | 1.2<br>5.6                  | +2.8<br>0   | -1.2<br>-2.8 | 2.0<br>6.4                  | +2.8<br>0   | -2.0<br>-3.6 | 3.5<br>10.3                 | +4.0<br>0   | -3.5<br>-6.3  | 6<br>20                     | +7<br>0     | -6<br>-13    | 8<br>28                     | +10<br>0    | -8<br>-18  |
| 0.71 -                           | 1.19  | 0.8<br>4.0                                       | +2.0<br>0  | -0.8<br>-2.0 | 1.6<br>7.1                  | +3.5<br>0   | -1.6<br>-3.6 | 2.5<br>8.0                  | +3.5<br>0   | -2.5<br>-4.5 | 4.5<br>13.0                 | +5.0<br>0   | -4.5<br>-8.0  | 7<br>23                     | +8<br>0     | -7<br>-15    | 10<br>34                    | +12<br>0    | -10<br>-22 |
| 1.19 -                           | 1.97  | 1.0<br>5.1                                       | +2.5<br>0  | -1.0<br>-2.6 | 2.0<br>8.5                  | +4.0<br>0   | -2.0<br>-4.5 | 3.6<br>9.5                  | +4.0<br>0   | -3.0<br>-5.5 | 5.0<br>15.0                 | +6<br>0     | -5.0<br>-9.0  | 8<br>28                     | +10<br>0    | -8<br>-18    | 12<br>44                    | +16<br>0    | -12<br>-28 |
| 1.97 -                           | 3.15  | 1.2<br>6.0                                       | +3.0<br>0  | -1.0<br>-3.0 | 2.5<br>10.0                 | +4.5<br>0   | -2.5<br>-5.5 | 4.0<br>11.5                 | +4.5<br>0   | -4.0<br>-7.0 | 6.0<br>17.5                 | +7<br>0     | -6.0<br>-10.5 | 10<br>34                    | +12<br>0    | -10<br>-22   | 14<br>50                    | +18<br>0    | -14<br>-32 |
| 3.15 -                           | 4.73  | 1.4<br>7.1                                       | +3.5<br>0  | -1.4<br>-3.6 | 3.0<br>11.5                 | +5.0<br>0   | -3.0<br>-6.5 | 5.0<br>13.5                 | +5.0<br>0   | -5.0<br>-8.5 | 7<br>21                     | +9<br>0     | -7<br>-12     | 11<br>39                    | +14<br>0    | -11<br>-25   | 16<br>60                    | +22<br>0    | -16<br>-38 |
| 4.73 -                           | 7.09  | 1.6<br>8.1                                       | +4.0<br>0  | -1.6<br>-4.1 | 3.5<br>13.5                 | +6.0<br>0   | -3.5<br>-7.5 | 6<br>16                     | +6<br>0     | -6<br>-10    | 8<br>24                     | +10<br>0    | -8<br>-14     | 12<br>44                    | +16<br>0    | -12<br>-28   | 18<br>68                    | +25<br>0    | -18<br>-43 |
| 7.09 -                           | 9.85  | 2.0<br>9.3                                       | +4.5<br>0  | -2.0<br>-4.8 | 4.0<br>15.5                 | +7.0<br>0   | -4.0<br>-8.5 | 7<br>18.5                   | +7<br>0     | -7<br>-11.5  | 10<br>29                    | +12<br>0    | -10<br>-17    | 16<br>52                    | +18<br>0    | -16<br>-34   | 22<br>78                    | +28<br>0    | -22<br>-50 |
| 9.85 -                           | 12.41 | 2.2<br>10.2                                      | +5.0<br>0  | -2.2<br>-5.2 | 4.5<br>17.5                 | +8.0<br>0   | -4.5<br>-9.5 | 7<br>20                     | +8<br>0     | -7<br>-12    | 12<br>32                    | +12<br>0    | -12<br>-20    | 20<br>60                    | +20<br>0    | -20<br>-40   | 28<br>88                    | +30<br>0    | -28<br>-58 |
| 12.41 -                          | 15.75 | 2.5<br>12.0                                      | +6.0<br>0  | -2.5<br>-6.0 | 5.0<br>20.0                 | +9.0<br>0   | -5<br>-11    | 8<br>23                     | +9<br>0     | -8<br>-14    | 14<br>37                    | +14<br>0    | -14<br>-23    | 22<br>66                    | +22<br>0    | -22<br>-44   | 30<br>100                   | +35<br>0    | -30<br>-65 |
| 15.75 -                          | 19.69 | 2.8<br>12.8                                      | +6.0<br>0  | -2.8<br>-6.8 | 5.0<br>21.0                 | +10.0<br>0  | -5<br>-11    | 9<br>25                     | +10<br>0    | -9<br>-15    | 16<br>42                    | +16<br>0    | -16<br>-26    | 25<br>75                    | +25<br>0    | -25<br>-50   | 35<br>115                   | +40<br>0    | -35<br>-75 |

<sup>a</sup> Pairs of values shown represent minimum and maximum amounts of interference resulting from application of standard tolerance limits.

Tolerance limits given in body of table are added or subtracted to basic size (as indicated by + or - sign) to obtain maximum and minimum sizes of mating parts. All data above heavy lines are in accordance with American-British-Canadian (ABC) agreements. Symbols H6, H7, s6, etc. are hole and shaft designations in ABC system. Limits for sizes above 19.69 inches are not covered by ABC agreements but are given in the ANSI Standard.

**Table 10. ANSI Standard Transition Locational Fits ANSI B4.1-1967 (R1999)**

| Nominal<br>Size Range,<br>Inches | Class LT 1                                       |                       |                | Class LT 2       |                       |                | Class LT 3       |                       |              | Class LT 4       |                       |              | Class LT 5       |                       |              | Class LT 6       |                       |             |                |              |
|----------------------------------|--|-----------------------|----------------|------------------|-----------------------|----------------|------------------|-----------------------|--------------|------------------|-----------------------|--------------|------------------|-----------------------|--------------|------------------|-----------------------|-------------|----------------|--------------|
|                                  | Fit <sup>a</sup>                                 | Std. Tolerance Limits |                | Fit <sup>a</sup> | Std. Tolerance Limits |                | Fit <sup>a</sup> | Std. Tolerance Limits |              | Fit <sup>a</sup> | Std. Tolerance Limits |              | Fit <sup>a</sup> | Std. Tolerance Limits |              | Fit <sup>a</sup> | Std. Tolerance Limits |             |                |              |
|                                  |  | Hole<br>H7            | Shaft<br>js6   |                  | Hole<br>H8            | Shaft<br>js7   |                  | Hole<br>H7            | Shaft<br>k6  |                  | Hole<br>H8            | Shaft<br>k7  |                  | Hole<br>H7            | Shaft<br>n6  |                  | Hole<br>H7            | Shaft<br>n7 |                |              |
| Over To                          | Values shown below are in thousandths of an inch |                       |                |                  |                       |                |                  |                       |              |                  |                       |              |                  |                       |              |                  |                       |             |                |              |
| 0 – 0.12                         | -0.12<br>+0.52                                   | +0.4<br>0             | +0.12<br>-0.12 | -0.2<br>+0.8     | +0.6<br>0             | +0.2<br>-0.2   |                  |                       |              |                  |                       |              |                  | -0.5<br>+0.15         | +0.4<br>0    | +0.5<br>+0.25    | -0.65<br>+0.15        | +0.4<br>0   | +0.65<br>+0.25 |              |
| 0.12 – 0.24                      | -0.15<br>+0.65                                   | +0.5<br>0             | +0.15<br>-0.15 | -0.25<br>+0.95   | +0.7<br>0             | +0.25<br>-0.25 |                  |                       |              |                  |                       |              |                  | -0.6<br>+0.2          | +0.5<br>0    | +0.6<br>+0.3     | -0.8<br>+0.2          | +0.5<br>0   | +0.8<br>+0.3   |              |
| 0.24 – 0.40                      | -0.2<br>+0.8                                     | +0.6<br>0             | +0.2<br>-0.2   | -0.3<br>+1.2     | +0.9<br>0             | +0.3<br>-0.3   | -0.5<br>+0.5     | +0.6<br>0             | +0.5<br>+0.1 | -0.7<br>+0.8     | +0.9<br>0             | +0.7<br>+0.1 | -0.8<br>+0.8     | +0.6<br>0             | +0.8<br>+0.4 | +0.8<br>+0.2     | -1.0<br>+0.2          | +0.6<br>0   | +1.0<br>+0.4   |              |
| 0.40 – 0.71                      | -0.2<br>+0.9                                     | +0.7<br>0             | +0.2<br>-0.2   | -0.35<br>+1.35   | +1.0<br>0             | +0.35<br>-0.35 | -0.5<br>+0.6     | +0.7<br>0             | +0.5<br>+0.1 | -0.8<br>+0.9     | +1.0<br>0             | +0.8<br>+0.1 | -0.9<br>+0.8     | +0.7<br>+0.2          | +0.9<br>+0.5 | +0.9<br>+0.2     | -1.2<br>+0.2          | +0.7<br>0   | +1.2<br>+0.5   |              |
| 0.71 – 1.19                      | -0.25<br>+1.05                                   | +0.8<br>0             | +0.25<br>-0.25 | -0.4<br>+1.6     | +1.2<br>0             | +0.4<br>-0.4   | -0.6<br>+0.7     | +0.8<br>0             | +0.6<br>+0.1 | -0.9<br>+1.1     | +1.2<br>0             | +0.9<br>+0.1 | -1.1<br>+0.8     | +0.8<br>+0.2          | +1.1<br>+0.6 | +1.1<br>+0.2     | -1.3<br>+0.2          | +1.0<br>0   | +1.3<br>+0.6   | +1.4<br>+0.6 |
| 1.19 – 1.97                      | -0.3<br>+1.3                                     | +1.0<br>0             | +0.3<br>-0.3   | -0.5<br>+2.1     | +1.6<br>0             | +0.5<br>-0.5   | -0.7<br>+0.9     | +1.0<br>0             | +0.7<br>+0.1 | -1.1<br>+1.5     | +1.6<br>0             | +1.1<br>+0.1 | -1.3<br>+0.3     | +1.0<br>0             | +1.3<br>+0.7 | +1.3<br>+0.3     | -1.7<br>+0.3          | +1.0<br>0   | +1.7<br>+0.7   |              |
| 1.97 – 3.15                      | -0.3<br>+1.5                                     | +1.2<br>0             | +0.3<br>-0.3   | -0.6<br>+2.4     | +1.8<br>0             | +0.6<br>-0.6   | -0.8<br>+1.1     | +1.2<br>0             | +0.8<br>+0.1 | -1.3<br>+1.7     | +1.8<br>0             | +1.3<br>+0.1 | -1.5<br>+0.4     | +1.2<br>0             | +1.5<br>+0.8 | +1.5<br>+0.4     | -2.0<br>+0.4          | +1.2<br>0   | +2.0<br>+0.8   |              |
| 3.15 – 4.73                      | -0.4<br>+1.8                                     | +1.4<br>0             | +0.4<br>-0.4   | -0.7<br>+2.9     | +2.2<br>0             | +0.7<br>-0.7   | -1.0<br>+1.3     | +1.4<br>0             | +1.0<br>+0.1 | -1.5<br>+2.1     | +2.2<br>0             | +1.5<br>+0.1 | -1.9<br>+0.4     | +1.4<br>0             | +1.9<br>+1.0 | +1.9<br>+0.4     | -2.4<br>+0.4          | +1.4<br>0   | +2.4<br>+1.0   |              |
| 4.73 – 7.09                      | -0.5<br>+2.1                                     | +1.6<br>0             | +0.5<br>-0.5   | -0.8<br>+3.3     | +2.5<br>0             | +0.8<br>-0.8   | -1.1<br>+1.5     | +1.6<br>0             | +1.1<br>+0.1 | -1.7<br>+2.4     | +2.5<br>0             | +1.7<br>+0.1 | -2.2<br>+0.4     | +1.6<br>0             | +2.2<br>+1.2 | +2.2<br>+0.4     | -2.8<br>+0.4          | +1.6<br>0   | +2.8<br>+1.2   |              |
| 7.09 – 9.85                      | -0.6<br>+2.4                                     | +1.8<br>0             | +0.6<br>-0.6   | -0.9<br>+3.7     | +2.8<br>0             | +0.9<br>-0.9   | -1.4<br>+1.6     | +1.8<br>0             | +1.4<br>+0.2 | -2.0<br>+2.6     | +2.8<br>0             | +2.0<br>+0.2 | -2.6<br>+0.4     | +1.8<br>0             | +2.6<br>+1.4 | +2.6<br>+0.4     | -3.2<br>+0.4          | +1.8<br>0   | +3.2<br>+1.4   |              |
| 9.85 – 12.41                     | -0.6<br>+2.6                                     | +2.0<br>0             | +0.6<br>-0.6   | -1.0<br>+4.0     | +3.0<br>0             | +1.0<br>-1.0   | -1.4<br>+1.8     | +2.0<br>0             | +1.4<br>+0.2 | -2.2<br>+2.8     | +3.0<br>0             | +2.2<br>+0.2 | -2.6<br>+0.6     | +2.0<br>0             | +2.6<br>+1.4 | +2.6<br>+0.4     | -3.4<br>+0.6          | +2.0<br>0   | +3.4<br>+1.4   |              |
| 12.41 – 15.75                    | -0.7<br>+2.9                                     | +2.2<br>0             | +0.7<br>-0.7   | -1.0<br>+4.5     | +3.5<br>0             | +1.0<br>-1.0   | -1.6<br>+2.0     | +2.2<br>0             | +1.6<br>+0.2 | -2.4<br>+3.3     | +3.5<br>0             | +2.4<br>+0.2 | -3.0<br>+0.6     | +2.2<br>0             | +3.0<br>+1.6 | +3.0<br>+0.6     | -3.8<br>+0.6          | +2.2<br>0   | +3.8<br>+1.6   |              |
| 15.75 – 19.69                    | -0.8<br>+3.3                                     | +2.5<br>0             | +0.8<br>-0.8   | -1.2<br>+5.2     | +4.0<br>0             | +1.2<br>-1.2   | -1.8<br>+2.3     | +2.5<br>0             | +1.8<br>+0.2 | -2.7<br>+3.8     | +4.0<br>0             | +2.7<br>+0.2 | -3.4<br>+0.7     | +2.5<br>0             | +3.4<br>+1.8 | +3.4<br>+0.7     | -4.3<br>+0.7          | +2.5<br>0   | +4.3<br>+1.8   |              |

<sup>a</sup>Pairs of values shown represent maximum amount of interference (–) and maximum amount of clearance (+) resulting from application of standard tolerance limits. All data above heavy lines are in accord with ABC agreements. Symbols H7, js6, etc., are hole and shaft designations in the ABC system.

**Table 11. ANSI Standard Force and Shrink Fits ANSI B4.1-1967 (R1999)**

| Nominal<br>Size Range,<br>Inches | Class FN 1                                       |                           |               | Class FN 2                     |                           |               | Class FN 3                     |                           |              | Class FN 4                     |                           |               | Class FN 5                     |                           |              |
|----------------------------------|--|---------------------------|---------------|--------------------------------|---------------------------|---------------|--------------------------------|---------------------------|--------------|--------------------------------|---------------------------|---------------|--------------------------------|---------------------------|--------------|
|                                  | Inter-<br>ference <sup>a</sup>                   | Standard Tolerance Limits |               | Inter-<br>ference <sup>a</sup> | Standard Tolerance Limits |               | Inter-<br>ference <sup>a</sup> | Standard Tolerance Limits |              | Inter-<br>ference <sup>a</sup> | Standard Tolerance Limits |               | Inter-<br>ference <sup>a</sup> | Standard Tolerance Limits |              |
|                                  |  | Hole<br>H6                | Shaft         |                                | Hole<br>H7                | Shaft<br>s6   |                                | Hole<br>H7                | Shaft<br>t6  |                                | Hole<br>H7                | Shaft<br>u6   |                                | Hole<br>H8                | Shaft<br>x7  |
| Over To                          | Values shown below are in thousandths of an inch |                           |               |                                |                           |               |                                |                           |              |                                |                           |               |                                |                           |              |
| 0- 0.12                          | 0.05<br>0.5                                      | +0.25<br>0                | +0.5<br>+0.3  | 0.2<br>0.85                    | +0.4<br>0                 | +0.85<br>+0.6 |                                |                           |              | 0.3<br>0.95                    | +0.4<br>0                 | +0.95<br>+0.7 | 0.3<br>1.3                     | +0.6<br>0                 | +1.3<br>+0.9 |
| 0.12- 0.24                       | 0.1<br>0.6                                       | +0.3<br>0                 | +0.6<br>+0.4  | 0.2<br>1.0                     | +0.5<br>0                 | +1.0<br>+0.7  |                                |                           |              | 0.4<br>1.2                     | +0.5<br>0                 | +1.2<br>+0.9  | 0.5<br>1.7                     | +0.7<br>0                 | +1.7<br>+1.2 |
| 0.24- 0.40                       | 0.1<br>0.75                                      | +0.4<br>0                 | +0.75<br>+0.5 | 0.4<br>1.4                     | +0.6<br>0                 | +1.4<br>+1.0  |                                |                           |              | 0.6<br>1.6                     | +0.6<br>0                 | +1.6<br>+1.2  | 0.5<br>2.0                     | +0.9<br>0                 | +2.0<br>+1.4 |
| 0.40- 0.56                       | 0.1<br>0.8                                       | +0.4<br>0                 | +0.8<br>+0.5  | 0.5<br>1.6                     | +0.7<br>0                 | +1.6<br>+1.2  |                                |                           |              | 0.7<br>1.8                     | +0.7<br>0                 | +1.8<br>+1.4  | 0.6<br>2.3                     | +1.0<br>0                 | +2.3<br>+1.6 |
| 0.56- 0.71                       | 0.2<br>0.9                                       | +0.4<br>0                 | +0.9<br>+0.6  | 0.5<br>1.6                     | +0.7<br>0                 | +1.6<br>+1.2  |                                |                           |              | 0.7<br>1.8                     | +0.7<br>0                 | +1.8<br>+1.4  | 0.8<br>2.5                     | +1.0<br>0                 | +2.5<br>+1.8 |
| 0.71- 0.95                       | 0.2<br>1.1                                       | +0.5<br>0                 | +1.1<br>+0.7  | 0.6<br>1.9                     | +0.8<br>0                 | +1.9<br>+1.4  |                                |                           |              | 0.8<br>2.1                     | +0.8<br>0                 | +2.1<br>+1.6  | 1.0<br>3.0                     | +1.2<br>0                 | +3.0<br>+2.2 |
| 0.95- 1.19                       | 0.3<br>1.2                                       | +0.5<br>0                 | +1.2<br>+0.8  | 0.6<br>1.9                     | +0.8<br>0                 | +1.9<br>+1.4  | 0.8<br>2.1                     | +0.8<br>0                 | +2.1<br>+1.6 | +1.0<br>2.3                    | +0.8<br>0                 | +2.3<br>+1.8  | 1.3<br>3.3                     | +1.2<br>0                 | +3.3<br>+2.5 |
| 1.19- 1.58                       | 0.3<br>1.3                                       | +0.6<br>0                 | +1.3<br>+0.9  | 0.8<br>2.4                     | +1.0<br>0                 | +2.4<br>+1.8  | 1.0<br>2.6                     | +1.0<br>0                 | +2.6<br>+2.0 | 1.5<br>3.1                     | +1.0<br>0                 | +3.1<br>+2.5  | 1.4<br>4.0                     | +1.6<br>0                 | +4.0<br>+3.0 |
| 1.58- 1.97                       | 0.4<br>1.4                                       | +0.6<br>0                 | +1.4<br>+1.0  | 0.8<br>2.4                     | +1.0<br>0                 | +2.4<br>+1.8  | 1.2<br>2.8                     | +1.0<br>0                 | +2.8<br>+2.2 | 1.8<br>3.4                     | +1.0<br>0                 | +3.4<br>+2.8  | 2.4<br>5.0                     | +1.6<br>0                 | +5.0<br>+4.0 |
| 1.97- 2.56                       | 0.6<br>1.8                                       | +0.7<br>0                 | +1.8<br>+1.3  | 0.8<br>2.7                     | +1.2<br>0                 | +2.7<br>+2.0  | 1.3<br>3.2                     | +1.2<br>0                 | +3.2<br>+2.5 | 2.3<br>4.2                     | +1.2<br>0                 | +4.2<br>+3.5  | 3.2<br>6.2                     | +1.8<br>0                 | +6.2<br>+5.0 |
| 2.56- 3.15                       | 0.7<br>1.9                                       | +0.7<br>0                 | +1.9<br>+1.4  | 1.0<br>2.9                     | +1.2<br>0                 | +2.9<br>+2.2  | 1.8<br>3.7                     | +1.2<br>0                 | +3.7<br>+3.0 | 2.8<br>4.7                     | +1.2<br>0                 | +4.7<br>+4.0  | 4.2<br>7.2                     | +1.8<br>0                 | +7.2<br>+6.0 |
| 3.15- 3.94                       | 0.9<br>2.4                                       | +0.9<br>0                 | +2.4<br>+1.8  | 1.4<br>3.7                     | +1.4<br>0                 | +3.7<br>+2.8  | 2.1<br>4.4                     | +1.4<br>0                 | +4.4<br>+3.5 | 3.6<br>5.9                     | +1.4<br>0                 | +5.9<br>+5.0  | 4.8<br>8.4                     | +2.2<br>0                 | +8.4<br>+7.0 |
| 3.94- 4.73                       | 1.1<br>2.6                                       | +0.9<br>0                 | +2.6<br>+2.0  | 1.6<br>3.9                     | +1.4<br>0                 | +3.9<br>+3.0  | 2.6<br>4.9                     | +1.4<br>0                 | +4.9<br>+4.0 | 4.6<br>6.9                     | +1.4<br>0                 | +6.9<br>+6.0  | 5.8<br>9.4                     | +2.2<br>0                 | +9.4<br>+8.0 |

**Table 11. (Continued) ANSI Standard Force and Shrink Fits ANSI B4.1-1967 (R1999)**

| Nominal<br>Size Range,<br>Inches | Class FN 1                                       |                           |              | Class FN 2                     |                           |                | Class FN 3                     |                           |                | Class FN 4                     |                           |                | Class FN 5                     |                           |                |
|----------------------------------|--|---------------------------|--------------|--------------------------------|---------------------------|----------------|--------------------------------|---------------------------|----------------|--------------------------------|---------------------------|----------------|--------------------------------|---------------------------|----------------|
|                                  | Inter-<br>ference <sup>a</sup>                   | Standard Tolerance Limits |              | Inter-<br>ference <sup>a</sup> | Standard Tolerance Limits |                | Inter-<br>ference <sup>a</sup> | Standard Tolerance Limits |                | Inter-<br>ference <sup>a</sup> | Standard Tolerance Limits |                | Inter-<br>ference <sup>a</sup> | Standard Tolerance Limits |                |
|                                  |  | Hole<br>H6                | Shaft        |                                | Hole<br>H7                | Shaft<br>s6    |                                | Hole<br>H7                | Shaft<br>t6    |                                | Hole<br>H7                | Shaft<br>u6    |                                | Hole<br>H8                | Shaft<br>x7    |
| Over To                          | Values shown below are in thousandths of an inch |                           |              |                                |                           |                |                                |                           |                |                                |                           |                |                                |                           |                |
| 4.73– 5.52                       | 1.2<br>2.9                                       | +1.0<br>0                 | +2.9<br>+2.2 | 1.9<br>4.5                     | +1.6<br>0                 | +4.5<br>+3.5   | 3.4<br>6.0                     | +1.6<br>0                 | +6.0<br>+5.0   | 5.4<br>8.0                     | +1.6<br>0                 | +8.0<br>+7.0   | 7.5<br>11.6                    | +2.5<br>0                 | +11.6<br>+10.0 |
| 5.52– 6.30                       | 1.5<br>3.2                                       | +1.0<br>0                 | +3.2<br>+2.5 | 2.4<br>5.0                     | +1.6<br>0                 | +5.0<br>+4.0   | 3.4<br>6.0                     | +1.6<br>0                 | +6.0<br>+5.0   | 5.4<br>8.0                     | +1.6<br>0                 | +8.0<br>+7.0   | 9.5<br>13.6                    | +2.5<br>0                 | +13.6<br>+12.0 |
| 6.30– 7.09                       | 1.8<br>3.5                                       | +1.0<br>0                 | +3.5<br>+2.8 | 2.9<br>5.5                     | +1.6<br>0                 | +5.5<br>+4.5   | 4.4<br>7.0                     | +1.6<br>0                 | +7.0<br>+6.0   | 6.4<br>9.0                     | +1.6<br>0                 | +9.0<br>+8.0   | 9.5<br>13.6                    | +2.5<br>0                 | +13.6<br>+12.0 |
| 7.09– 7.88                       | 1.8<br>3.8                                       | +1.2<br>0                 | +3.8<br>+3.0 | 3.2<br>6.2                     | +1.8<br>0                 | +6.2<br>+5.0   | 5.2<br>8.2                     | +1.8<br>0                 | +8.2<br>+7.0   | 7.2<br>10.2                    | +1.8<br>0                 | +10.2<br>+9.0  | 11.2<br>15.8                   | +2.8<br>0                 | +15.8<br>+14.0 |
| 7.88– 8.86                       | 2.3<br>4.3                                       | +1.2<br>0                 | +4.3<br>+3.5 | 3.2<br>6.2                     | +1.8<br>0                 | +6.2<br>+5.0   | 5.2<br>8.2                     | +1.8<br>0                 | +8.2<br>+7.0   | 8.2<br>11.2                    | +1.8<br>0                 | +11.2<br>+10.0 | 13.2<br>17.8                   | +2.8<br>0                 | +17.8<br>+16.0 |
| 8.86– 9.85                       | 2.3<br>4.3                                       | +1.2<br>0                 | +4.3<br>+3.5 | 4.2<br>7.2                     | +1.8<br>0                 | +7.2<br>+6.0   | 6.2<br>9.2                     | +1.8<br>0                 | +9.2<br>+8.0   | 10.2<br>13.2                   | +1.8<br>0                 | +13.2<br>+12.0 | 13.2<br>17.8                   | +2.8<br>0                 | +17.8<br>+16.0 |
| 9.85– 11.03                      | 2.8<br>4.9                                       | +1.2<br>0                 | +4.9<br>+4.0 | 4.0<br>7.2                     | +2.0<br>0                 | +7.2<br>+6.0   | 7.0<br>10.2                    | +2.0<br>0                 | +10.2<br>+9.0  | 10.0<br>13.2                   | +2.0<br>0                 | +13.2<br>+12.0 | 15.0<br>20.0                   | +3.0<br>0                 | +20.0<br>+18.0 |
| 11.03– 12.41                     | 2.8<br>4.9                                       | +1.2<br>0                 | +4.9<br>+4.0 | 5.0<br>8.2                     | +2.0<br>0                 | +8.2<br>+7.0   | 7.0<br>10.2                    | +2.0<br>0                 | +10.2<br>+9.0  | 12.0<br>15.2                   | +2.0<br>0                 | +15.2<br>+14.0 | 17.0<br>22.0                   | +3.0<br>0                 | +22.0<br>+20.0 |
| 12.41– 13.98                     | 3.1<br>5.5                                       | +1.4<br>0                 | +5.5<br>+4.5 | 5.8<br>9.4                     | +2.2<br>0                 | +9.4<br>+8.0   | 7.8<br>11.4                    | +2.2<br>0                 | +11.4<br>+10.0 | 13.8<br>17.4                   | +2.2<br>0                 | +17.4<br>+16.0 | 18.5<br>24.2                   | +3.5<br>0                 | +24.2<br>+22.0 |
| 13.98– 15.75                     | 3.6<br>6.1                                       | +1.4<br>0                 | +6.1<br>+5.0 | 5.8<br>9.4                     | +2.2<br>0                 | +9.4<br>+8.0   | 9.8<br>13.4                    | +2.2<br>0                 | +13.4<br>+12.0 | 15.8<br>19.4                   | +2.2<br>0                 | +19.4<br>+18.0 | 21.5<br>27.2                   | +3.5<br>0                 | +27.2<br>+25.0 |
| 15.75– 17.72                     | 4.4<br>7.0                                       | +1.6<br>0                 | +7.0<br>+6.0 | 6.5<br>10.6                    | +2.5<br>0                 | +10.6<br>+9.0  | +9.5<br>13.6                   | +2.5<br>0                 | +13.6<br>+12.0 | 17.5<br>21.6                   | +2.5<br>0                 | +21.6<br>+20.0 | 24.0<br>30.5                   | +4.0<br>0                 | +30.5<br>+28.0 |
| 17.72– 19.69                     | 4.4<br>7.0                                       | +1.6<br>0                 | +7.0<br>+6.0 | 7.5<br>11.6                    | +2.5<br>0                 | +11.6<br>+10.0 | 11.5<br>15.6                   | +2.5<br>0                 | +15.6<br>+14.0 | 19.5<br>23.6                   | +2.5<br>0                 | +23.6<br>+22.0 | 26.0<br>32.5                   | +4.0<br>0                 | +32.5<br>+30.0 |

<sup>a</sup> Pairs of values shown represent minimum and maximum amounts of interference resulting from application of standard tolerance limits.

All data above heavy lines are in accordance with American-British-Canadian (ABC) agreements. Symbols H6, H7, s6, etc., are hole and shaft designations in the ABC system. Limits for sizes above 19.69 inches are not covered by ABC agreements but are given in the ANSI standard.

**Table 12. ANSI Standard Interference Location Fits ANSI B4.1-1967 (R1999)**

| Nominal<br>Size Range,<br>Inches | Class LN 1   |                 |                | Class LN 2                     |                 |               | Class LN 3                     |                 |               |
|----------------------------------|--|-----------------|----------------|--------------------------------|-----------------|---------------|--------------------------------|-----------------|---------------|
|                                  | Limits<br>of Inter-<br>ference                         | Standard Limits |                | Limits<br>of Inter-<br>ference | Standard Limits |               | Limits<br>of Inter-<br>ference | Standard Limits |               |
|                                  |  | Hole<br>H6      | Shaft<br>n5    |                                | Hole<br>H7      | Shaft<br>p6   |                                | Hole<br>H7      | Shaft<br>r6   |
| Over To                          | Values shown below are given in thousandths of an inch |                 |                |                                |                 |               |                                |                 |               |
| 0– 0.12                          | 0<br>0.45  | +0.25<br>0      | +0.45<br>+0.25 | 0<br>0.65                      | +0.4<br>0       | +0.65<br>+0.4 | 0.1<br>0.75                    | +0.4<br>0       | +0.75<br>+0.5 |
| 0.12– 0.24                       | 0<br>0.5   | +0.3<br>0       | +0.5<br>+0.3   | 0<br>0.8                       | +0.5<br>0       | +0.8<br>+0.5  | 0.1<br>0.9                     | +0.5<br>0       | +0.9<br>+0.6  |
| 0.24– 0.40                       | 0<br>0.65  | +0.4<br>0       | +0.65<br>+0.4  | 0<br>1.0                       | +0.6<br>0       | +1.0<br>+0.6  | 0.2<br>1.2                     | +0.6<br>0       | +1.2<br>+0.8  |
| 0.40– 0.71                       | 0<br>0.8   | +0.4<br>0       | +0.8<br>+0.4   | 0<br>1.1                       | +0.7<br>0       | +1.1<br>+0.7  | 0.3<br>1.4                     | +0.7<br>0       | +1.4<br>+1.0  |
| 0.71– 1.19                       | 0<br>1.0   | +0.5<br>0       | +1.0<br>+0.5   | 0<br>1.3                       | +0.8<br>0       | +1.3<br>+0.8  | 0.4<br>1.7                     | +0.8<br>0       | +1.7<br>+1.2  |
| 1.19– 1.97                       | 0<br>1.1   | +0.6<br>0       | +1.1<br>+0.6   | 0<br>1.6                       | +1.0<br>0       | +1.6<br>+1.0  | 0.4<br>2.0                     | +1.0<br>0       | +2.0<br>+1.4  |
| 1.97– 3.15                       | 0.1<br>1.3   | +0.7<br>0       | +1.3<br>+0.8   | 0.2<br>2.1                     | +1.2<br>0       | +2.1<br>+1.4  | 0.4<br>2.3                     | +1.2<br>0       | +2.3<br>+1.6  |
| 3.15– 4.73                       | 0.1<br>1.6   | +0.9<br>0       | +1.6<br>+1.0   | 0.2<br>2.5                     | +1.4<br>0       | +2.5<br>+1.6  | 0.6<br>2.9                     | +1.4<br>0       | +2.9<br>+2.0  |
| 4.73– 7.09                       | 0.2<br>1.9   | +1.0<br>0       | +1.9<br>+1.2   | 0.2<br>2.8                     | +1.6<br>0       | +2.8<br>+1.8  | 0.9<br>3.5                     | +1.6<br>0       | +3.5<br>+2.5  |
| 7.09– 9.85                       | 0.2<br>2.2   | +1.2<br>0       | +2.2<br>+1.4   | 0.2<br>3.2                     | +1.8<br>0       | +3.2<br>+2.0  | 1.2<br>4.2                     | +1.8<br>0       | +4.2<br>+3.0  |
| 9.85– 12.41                      | 0.2<br>2.3   | +1.2<br>0       | +2.3<br>+1.4   | 0.2<br>3.4                     | +2.0<br>0       | +3.4<br>+2.2  | 1.5<br>4.7                     | +2.0<br>0       | +4.7<br>+3.5  |
| 12.41– 15.75                     | 0.2<br>2.6   | +1.4<br>0       | +2.6<br>+1.6   | 0.3<br>3.9                     | +2.2<br>0       | +3.9<br>+2.5  | 2.3<br>5.9                     | +2.2<br>0       | +5.9<br>+4.5  |
| 15.75– 19.69                     | 0.2<br>2.8   | +1.6<br>0       | +2.8<br>+1.8   | 0.3<br>4.4                     | +2.5<br>0       | +4.4<br>+2.8  | 2.5<br>6.6                     | +2.5<br>0       | +6.6<br>+5.0  |

All data in this table are in accordance with American-British-Canadian (ABC) agreements.

Limits for sizes above 19.69 inches are not covered by ABC agreements but are given in the ANSI Standard.

Symbols H7, p6, etc., are hole and shaft designations in the ABC system.

Tolerance limits given in body of table are added or subtracted to basic size (as indicated by + or – sign) to obtain maximum and minimum sizes of mating parts.

### American National Standard Preferred Metric Limits and Fits

This standard ANSI B4.2-1978 (R1999) describes the ISO system of metric limits and fits for mating parts as approved for general engineering usage in the United States.

It establishes: 1) the designation symbols used to define dimensional limits on drawings, material stock, related tools, gages, etc.; 2) the preferred basic sizes (first and second choices); 3) the preferred tolerance zones (first, second, and third choices); 4) the preferred limits and fits for sizes (first choice only) up to and including 500 millimeters; and 5) the definitions of related terms.

The general terms “hole” and “shaft” can also be taken to refer to the space containing or contained by two parallel faces of any part, such as the width of a slot, or the thickness of a key.

**Definitions.**—The most important terms relating to limits and fits are shown in Fig. 1 and are defined as follows:

*Basic Size:* The size to which limits of deviation are assigned. The basic size is the same for both members of a fit. For example, it is designated by the numbers 40 in 40H7.

*Deviation:* The algebraic difference between a size and the corresponding basic size.

*Upper Deviation:* The algebraic difference between the maximum limit of size and the corresponding basic size.

*Lower Deviation:* The algebraic difference between the minimum limit of size and the corresponding basic size.

*Fundamental Deviation:* That one of the two deviations closest to the basic size. For example, it is designated by the letter H in 40H7.

*Tolerance:* The difference between the maximum and minimum size limits on a part.

*Tolerance Zone:* A zone representing the tolerance and its position in relation to the basic size.

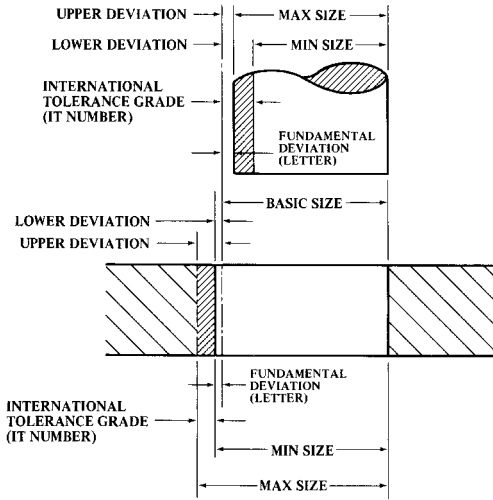


Fig. 1. Illustration of Definitions

*International Tolerance Grade (IT):* A group of tolerances that vary depending on the basic size, but that provide the same relative level of accuracy within a given grade. For example, it is designated by the number 7 in 40H7 or as IT7.

*Hole Basis:* The system of fits where the minimum hole size is basic. The fundamental deviation for a hole basis system is H.

*Shaft Basis:* The system of fits where the maximum shaft size is basic. The fundamental deviation for a shaft basis system is h.

*Clearance Fit:* The relationship between assembled parts when clearance occurs under all tolerance conditions.

*Interference Fit:* The relationship between assembled parts when interference occurs under all tolerance conditions.

*Transition Fit:* The relationship between assembled parts when either a clearance or an interference fit can result, depending on the tolerance conditions of the mating parts.

**Tolerances Designation.**—An “International Tolerance grade” establishes the magnitude of the tolerance zone or the amount of part size variation allowed for external and internal dimensions alike (see Fig. 1). Tolerances are expressed in grade numbers that are consistent with International Tolerance grades identified by the prefix IT, such as IT6, IT11, etc. A smaller grade number provides a smaller tolerance zone.

A fundamental deviation establishes the position of the tolerance zone with respect to the basic size (see Fig. 1). Fundamental deviations are expressed by tolerance position letters. Capital letters are used for internal dimensions and lowercase or small letters for external dimensions.

**Symbols.**—By combining the IT grade number and the tolerance position letter, the tolerance symbol is established that identifies the actual maximum and minimum limits of the part. The toleranced size is thus defined by the basic size of the part followed by a symbol composed of a letter and a number, such as 40H7, 40f7, etc.

A fit is indicated by the basic size common to both components, followed by a symbol corresponding to each component, the internal part symbol preceding the external part symbol, such as 40H8/f7.

Some methods of designating tolerances on drawings are:

$$40H8 \qquad 40H8 \begin{pmatrix} 40.039 \\ 40.000 \end{pmatrix} \qquad \begin{pmatrix} 40.039 \\ 40.000 \end{pmatrix} 40H8$$

The values in parentheses indicate reference only.

**Preferred Metric Fits.**—First-choice tolerance zones are used to establish preferred fits in ANSI B4.2, *Preferred Metric Limits and Fits*, as shown in Figs. 2 and 3. A complete listing of first-, second-, and third- choice tolerance zones is given in the Standard.

Hole basis fits have a fundamental deviation of H on the hole, and shaft basis fits have a fundamental deviation of *h* on the shaft and are shown in Fig. 2 for hole basis and Fig. 3 for shaft basis fits. A description of both types of fits, that have the same relative fit condition, is given in Table 1. Normally, the hole basis system is preferred; however, when a common shaft mates with several holes, the shaft basis system should be used.

The hole basis and shaft basis fits shown in the table *Description of Preferred Fits* on page 669 are combined with the first-choice preferred metric sizes from Table 1 on page 690, to form Tables 2, 3, 4, and 5, in which specific limits as well as the resultant fits are tabulated.

If the required size is not found tabulated in Tables 2 through 5 then the preferred fit can be calculated from numerical values given in an appendix of ANSI B4.2-1978 (R1999). It is anticipated that other fit conditions may be necessary to meet special requirements, and a preferred fit can be loosened or tightened simply by selecting a standard tolerance zone as given in the Standard. Information on how to calculate limit dimensions, clearances, and interferences, for nonpreferred fits and sizes can be found in an appendix of this Standard.

*Conversion of Fits:* It may sometimes be necessary or desirable to modify the tolerance zone on one or both of two mating parts, yet still keep the total tolerance and fit condition the same. Examples of this appear in Table 1 on page 669 when converting from a hole basis fit to a shaft basis fit. The corresponding fits are identical yet the individual tolerance zones are different.

To convert from one type of fit to another, reverse the fundamental deviations between the shaft and hole keeping the IT grade the same on each individual part. The examples below represent preferred fits from Table 1 for a 60-mm basic size. These fits have the same maximum clearance (0.520) and the same minimum clearance (0.140).

Hole basis, loose running fit, values from Table 2

$$\text{Hole } 60H11 \begin{pmatrix} 60.190 \\ 60.000 \end{pmatrix} \qquad \text{Shaft } 60c11 \begin{pmatrix} 59.860 \\ 59.670 \end{pmatrix} \qquad \text{Fit } 60H11/c11 \begin{pmatrix} 0.520 \\ 0.140 \end{pmatrix}$$

Hole basis, loose running fit, values from Table 4

$$\text{Hole } 60C11 \begin{pmatrix} 60.330 \\ 60.140 \end{pmatrix} \qquad \text{Shaft } 60h11 \begin{pmatrix} 60.000 \\ 59.810 \end{pmatrix} \qquad \text{Fit } 60C11/h11 \begin{pmatrix} 0.520 \\ 0.140 \end{pmatrix}$$



PREFERRED METRIC FITS

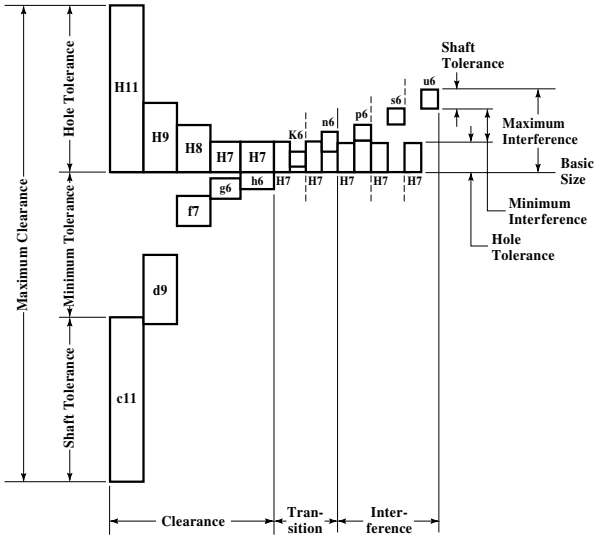


Fig. 2. Preferred Hole Basis Fits

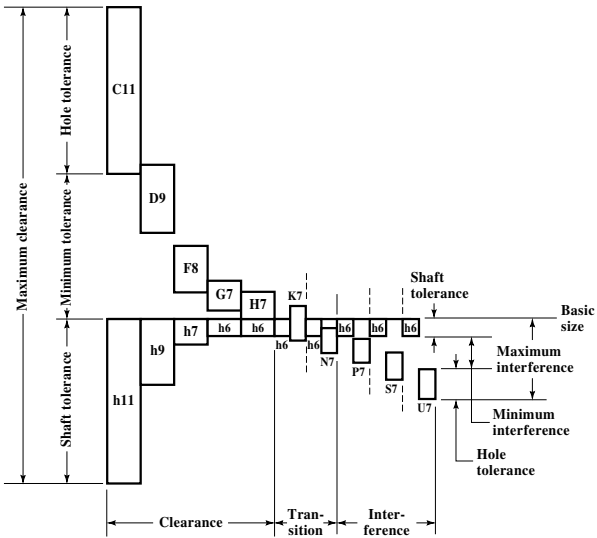


Fig. 3. Preferred Shaft Basis Fits

Table 1. Description of Preferred Fits

|                   | ISO SYMBOL         |             | DESCRIPTION   |                        |
|-------------------|--------------------|-------------|---|------------------------|
|                   | Hole Basis         | Shaft Basis |   |                        |
| Clearance Fits    | H11/c11            | C11/h11     | <i>Loose running</i> fit for wide commercial tolerances or allowances on external members.  | ↑<br>More Clearance    |
|                   | H9/d9              | D9/h9       | <i>Free running</i> fit not for use where accuracy is essential, but good for large temperature variations, high running speeds, or heavy journal pressures.  |                        |
|                   | H8/f7              | F8/h7       | <i>Close Running</i> fit for running on accurate machines and for accurate moderate speeds and journal pressures.   |                        |
|                   | H7/g6              | G7/h6       | <i>Sliding fit</i> not intended to run freely, but to move and turn freely and locate accurately.   |                        |
|                   | H7/h6              | H7/h6       | <i>Locational clearance</i> fit provides snug fit for locating stationary parts; but can be freely assembled and disassembled.                                |                        |
| Transition Fits   | H7/k6              | K7/h6       | <i>Locational transition</i> fit for accurate location, a compromise between clearance and interference.  | ↓<br>More Interference |
|                   | H7/n6              | N7/h6       | <i>Locational transition</i> fit for more accurate location where greater interference is permissible.  |                        |
| Interference Fits | H7/p6 <sup>a</sup> | P7/h6       | <i>Locational interference</i> fit for parts requiring rigidity and alignment with prime accuracy of location but without special bore pressure requirements. |                        |
|                   | H7/s6              | S7/h6       | <i>Medium drive</i> fit for ordinary steel parts or shrink fits on light sections, the tightest fit usable with cast iron.                                    |                        |
|                   | H7/u6              | U7/h6       | <i>Force</i> fit suitable for parts which can be highly stressed or for shrink fits where the heavy pressing forces required are impractical.                 |                        |

<sup>a</sup>Transition fit for basic sizes in range from 0 through 3 mm.

Table 2. American National Standard Preferred Hole Basis Metric Clearance Fits ANSI B4.2-1978 (R1999)

| Basic Size <sup>a</sup> |     | Loose Running |           |                  | Free Running |          |                  | Close Running |          |                  | Sliding |          |                  | Locational Clearance |          |                  |
|-------------------------|-----|---------------|-----------|------------------|--------------|----------|------------------|---------------|----------|------------------|---------|----------|------------------|----------------------|----------|------------------|
|                         |     | Hole H11      | Shaft C11 | Fit <sup>b</sup> | Hole H9      | Shaft d9 | Fit <sup>b</sup> | Hole H8       | Shaft f7 | Fit <sup>b</sup> | Hole H7 | Shaft g6 | Fit <sup>b</sup> | Hole H7              | Shaft h6 | Fit <sup>b</sup> |
| 1                       | Max | 1.060         | 0.940     | 0.180            | 1.025        | 0.980    | 0.070            | 1.014         | 0.994    | 0.030            | 1.010   | 0.998    | 0.018            | 1.010                | 1.000    | 0.016            |
|                         | Min | 1.000         | 0.880     | 0.060            | 1.000        | 0.995    | 0.020            | 1.000         | 0.984    | 0.006            | 1.000   | 0.992    | 0.002            | 1.000                | 0.994    | 0.000            |
| 1.2                     | Max | 1.260         | 1.140     | 0.180            | 1.225        | 1.180    | 0.070            | 1.214         | 1.194    | 0.030            | 1.210   | 1.198    | 0.018            | 1.210                | 1.200    | 0.016            |
|                         | Min | 1.200         | 1.080     | 0.060            | 1.200        | 1.155    | 0.020            | 1.200         | 1.184    | 0.006            | 1.200   | 1.192    | 0.002            | 1.200                | 1.194    | 0.000            |
| 1.6                     | Max | 1.660         | 1.540     | 0.180            | 1.625        | 1.580    | 0.070            | 1.614         | 1.594    | 0.030            | 1.610   | 1.598    | 0.018            | 1.610                | 1.600    | 0.016            |
|                         | Min | 1.600         | 1.480     | 0.060            | 1.600        | 1.555    | 0.020            | 1.600         | 1.584    | 0.006            | 1.600   | 1.592    | 0.002            | 1.600                | 1.594    | 0.000            |
| 2                       | Max | 2.060         | 1.940     | 0.180            | 2.025        | 1.980    | 0.070            | 2.014         | 1.994    | 0.030            | 2.010   | 1.998    | 0.018            | 2.010                | 2.000    | 0.016            |
|                         | Min | 2.000         | 1.880     | 0.060            | 2.000        | 1.955    | 0.020            | 2.000         | 1.984    | 0.006            | 2.000   | 1.992    | 0.002            | 2.000                | 1.994    | 0.000            |
| 2.5                     | Max | 2.560         | 2.440     | 0.180            | 2.525        | 2.480    | 0.070            | 2.514         | 2.494    | 0.030            | 2.510   | 2.498    | 0.018            | 2.510                | 2.500    | 0.016            |
|                         | Min | 2.500         | 2.380     | 0.060            | 2.500        | 2.455    | 0.020            | 2.500         | 2.484    | 0.006            | 2.500   | 2.492    | 0.002            | 2.500                | 2.494    | 0.000            |
| 3                       | Max | 3.060         | 2.940     | 0.180            | 3.025        | 2.980    | 0.070            | 3.014         | 2.994    | 0.030            | 3.010   | 2.998    | 0.018            | 3.010                | 3.000    | 0.016            |
|                         | Min | 3.000         | 2.880     | 0.060            | 3.000        | 2.955    | 0.020            | 3.000         | 2.984    | 0.006            | 3.000   | 2.992    | 0.002            | 3.000                | 2.994    | 0.000            |
| 4                       | Max | 4.075         | 3.930     | 0.220            | 4.030        | 3.970    | 0.090            | 4.018         | 3.990    | 0.040            | 4.012   | 3.996    | 0.024            | 4.012                | 4.000    | 0.020            |
|                         | Min | 4.000         | 3.855     | 0.070            | 4.000        | 3.940    | 0.030            | 4.000         | 3.978    | 0.010            | 4.000   | 3.988    | 0.004            | 4.000                | 3.992    | 0.000            |
| 5                       | Max | 5.075         | 4.930     | 0.220            | 5.030        | 4.970    | 0.090            | 5.018         | 4.990    | 0.040            | 5.012   | 4.996    | 0.024            | 5.012                | 5.000    | 0.020            |
|                         | Min | 5.000         | 4.855     | 0.070            | 5.000        | 4.940    | 0.030            | 5.000         | 4.978    | 0.010            | 5.000   | 4.988    | 0.004            | 5.000                | 4.992    | 0.000            |
| 6                       | Max | 6.075         | 5.930     | 0.220            | 6.030        | 5.970    | 0.090            | 6.018         | 5.990    | 0.040            | 6.012   | 5.996    | 0.024            | 6.012                | 6.000    | 0.020            |
|                         | Min | 6.000         | 5.855     | 0.070            | 6.000        | 5.940    | 0.030            | 6.000         | 5.978    | 0.010            | 6.000   | 5.988    | 0.004            | 6.000                | 5.992    | 0.000            |
| 8                       | Max | 8.090         | 7.920     | 0.260            | 8.036        | 7.960    | 0.112            | 8.022         | 7.987    | 0.050            | 8.015   | 7.995    | 0.029            | 8.015                | 8.000    | 0.024            |
|                         | Min | 8.000         | 7.830     | 0.080            | 8.000        | 7.924    | 0.040            | 8.000         | 7.972    | 0.013            | 8.000   | 7.986    | 0.005            | 8.000                | 7.991    | 0.000            |
| 10                      | Max | 10.090        | 9.920     | 0.260            | 10.036       | 9.960    | 0.112            | 10.022        | 9.987    | 0.050            | 10.015  | 9.995    | 0.029            | 10.015               | 10.000   | 0.024            |
|                         | Min | 10.000        | 9.830     | 0.080            | 10.000       | 9.924    | 0.040            | 10.000        | 9.972    | 0.013            | 10.000  | 9.986    | 0.005            | 10.000               | 9.991    | 0.000            |
| 12                      | Max | 12.110        | 11.905    | 0.315            | 12.043       | 11.956   | 0.136            | 12.027        | 11.984   | 0.061            | 12.018  | 11.994   | 0.035            | 12.018               | 12.000   | 0.029            |
|                         | Min | 12.000        | 11.795    | 0.095            | 12.000       | 11.907   | 0.050            | 12.000        | 11.966   | 0.016            | 12.000  | 11.983   | 0.006            | 12.000               | 11.989   | 0.000            |
| 16                      | Max | 16.110        | 15.905    | 0.315            | 16.043       | 15.950   | 0.136            | 16.027        | 15.984   | 0.061            | 16.018  | 15.994   | 0.035            | 16.018               | 16.000   | 0.029            |
|                         | Min | 16.000        | 15.795    | 0.095            | 16.000       | 15.907   | 0.050            | 16.000        | 15.966   | 0.016            | 16.000  | 15.983   | 0.006            | 16.000               | 15.989   | 0.000            |
| 20                      | Max | 20.130        | 19.890    | 0.370            | 20.052       | 19.935   | 0.169            | 20.033        | 19.980   | 0.074            | 20.021  | 19.993   | 0.041            | 20.021               | 20.000   | 0.034            |
|                         | Min | 20.000        | 19.760    | 0.110            | 20.000       | 19.883   | 0.065            | 20.000        | 19.959   | 0.020            | 20.000  | 19.980   | 0.007            | 20.000               | 19.987   | 0.000            |
| 25                      | Max | 25.130        | 24.890    | 0.370            | 25.052       | 24.935   | 0.169            | 25.033        | 24.980   | 0.074            | 25.021  | 24.993   | 0.041            | 25.021               | 25.000   | 0.034            |
|                         | Min | 25.000        | 24.760    | 0.110            | 25.000       | 24.883   | 0.065            | 25.000        | 24.959   | 0.020            | 25.000  | 24.980   | 0.007            | 25.000               | 24.987   | 0.000            |

**Table 2. (Continued) American National Standard Preferred Hole Basis Metric Clearance Fits ANSI B4.2-1978 (R1999)**

| Basic Size <sup>a</sup> | Loose Running |           |                  | Free Running |          |                  | Close Running |          |                  | Sliding |          |                  | Locational Clearance |          |                  |       |
|-------------------------|---------------|-----------|------------------|--------------|----------|------------------|---------------|----------|------------------|---------|----------|------------------|----------------------|----------|------------------|-------|
|                         | Hole H11      | Shaft C11 | Fit <sup>b</sup> | Hole H9      | Shaft d9 | Fit <sup>b</sup> | Hole H8       | Shaft f7 | Fit <sup>b</sup> | Hole H7 | Shaft g6 | Fit <sup>b</sup> | Hole H7              | Shaft h6 | Fit <sup>b</sup> |       |
| 30                      | Max           | 30.130    | 29.890           | 0.370        | 30.052   | 29.935           | 0.169         | 30.033   | 29.980           | 0.074   | 30.021   | 29.993           | 0.041                | 30.021   | 30.000           | 0.034 |
|                         | Min           | 30.000    | 29.760           | 0.110        | 30.000   | 29.883           | 0.065         | 30.000   | 29.959           | 0.020   | 30.000   | 29.980           | 0.007                | 30.000   | 29.987           | 0.000 |
| 40                      | Max           | 40.160    | 39.880           | 0.440        | 40.062   | 39.920           | 0.204         | 40.039   | 39.975           | 0.089   | 40.025   | 39.991           | 0.050                | 40.025   | 40.000           | 0.041 |
|                         | Min           | 40.000    | 39.720           | 0.120        | 40.000   | 39.858           | 0.080         | 40.000   | 39.950           | 0.025   | 40.000   | 39.975           | 0.009                | 40.000   | 39.984           | 0.000 |
| 50                      | Max           | 50.160    | 49.870           | 0.450        | 50.062   | 49.920           | 0.204         | 50.039   | 49.975           | 0.089   | 50.025   | 49.991           | 0.050                | 50.025   | 50.000           | 0.041 |
|                         | Min           | 50.000    | 49.710           | 0.130        | 50.000   | 49.858           | 0.080         | 50.000   | 49.950           | 0.025   | 50.000   | 49.975           | 0.009                | 50.000   | 49.984           | 0.000 |
| 60                      | Max           | 60.190    | 59.860           | 0.520        | 60.074   | 59.900           | 0.248         | 60.046   | 59.970           | 0.106   | 60.030   | 59.990           | 0.059                | 60.030   | 60.000           | 0.049 |
|                         | Min           | 60.000    | 59.670           | 0.140        | 60.000   | 59.826           | 0.100         | 60.000   | 59.940           | 0.030   | 60.000   | 59.971           | 0.010                | 60.000   | 59.981           | 0.000 |
| 80                      | Max           | 80.190    | 79.850           | 0.530        | 80.074   | 79.900           | 0.248         | 80.046   | 79.970           | 0.106   | 80.030   | 79.990           | 0.059                | 80.030   | 80.000           | 0.049 |
|                         | Min           | 80.000    | 79.660           | 0.150        | 80.000   | 79.826           | 0.100         | 80.000   | 79.940           | 0.030   | 80.000   | 79.971           | 0.010                | 80.000   | 79.981           | 0.000 |
| 100                     | Max           | 100.220   | 99.830           | 0.610        | 100.087  | 99.880           | 0.294         | 100.054  | 99.964           | 0.125   | 100.035  | 99.988           | 0.069                | 100.035  | 100.000          | 0.057 |
|                         | Min           | 100.000   | 99.610           | 0.170        | 100.000  | 99.793           | 0.120         | 100.000  | 99.929           | 0.036   | 100.000  | 99.966           | 0.012                | 100.000  | 99.978           | 0.000 |
| 120                     | Max           | 120.220   | 119.820          | 0.620        | 120.087  | 119.880          | 0.294         | 120.054  | 119.964          | 0.125   | 120.035  | 119.988          | 0.069                | 120.035  | 120.000          | 0.057 |
|                         | Min           | 120.000   | 119.600          | 0.180        | 120.000  | 119.793          | 0.120         | 120.000  | 119.929          | 0.036   | 120.000  | 119.966          | 0.012                | 120.000  | 119.978          | 0.000 |
| 160                     | Max           | 160.250   | 159.790          | 0.710        | 160.100  | 159.855          | 0.345         | 160.063  | 159.957          | 0.146   | 160.040  | 159.986          | 0.079                | 160.040  | 160.000          | 0.065 |
|                         | Min           | 160.000   | 159.540          | 0.210        | 160.000  | 159.755          | 0.145         | 160.000  | 159.917          | 0.043   | 160.000  | 159.961          | 0.014                | 160.000  | 159.975          | 0.000 |
| 200                     | Max           | 200.290   | 199.760          | 0.820        | 200.115  | 199.830          | 0.400         | 200.072  | 199.950          | 0.168   | 200.046  | 199.985          | 0.090                | 200.046  | 200.000          | 0.075 |
|                         | Min           | 200.000   | 199.470          | 0.240        | 200.000  | 199.715          | 0.170         | 200.000  | 199.904          | 0.050   | 200.000  | 199.956          | 0.015                | 200.000  | 199.971          | 0.000 |
| 250                     | Max           | 250.290   | 249.720          | 0.860        | 250.115  | 249.830          | 0.400         | 250.072  | 249.950          | 0.168   | 250.046  | 249.985          | 0.090                | 250.046  | 250.000          | 0.075 |
|                         | Min           | 250.000   | 249.430          | 0.280        | 250.000  | 249.715          | 0.170         | 250.000  | 249.904          | 0.050   | 250.000  | 249.956          | 0.015                | 250.000  | 249.971          | 0.000 |
| 300                     | Max           | 300.320   | 299.670          | 0.970        | 300.130  | 299.810          | 0.450         | 300.081  | 299.944          | 0.189   | 300.052  | 299.983          | 0.101                | 300.052  | 300.000          | 0.084 |
|                         | Min           | 300.000   | 299.350          | 0.330        | 300.000  | 299.680          | 0.190         | 300.000  | 299.892          | 0.056   | 300.000  | 299.951          | 0.017                | 300.000  | 299.968          | 0.000 |
| 400                     | Max           | 400.360   | 399.600          | 1.120        | 400.140  | 399.790          | 0.490         | 400.089  | 399.938          | 0.208   | 400.057  | 399.982          | 0.111                | 400.057  | 400.000          | 0.093 |
|                         | Min           | 400.000   | 399.240          | 0.400        | 400.000  | 399.650          | 0.210         | 400.000  | 399.881          | 0.062   | 400.000  | 399.946          | 0.018                | 400.000  | 399.964          | 0.000 |
| 500                     | Max           | 500.400   | 499.520          | 1.280        | 500.155  | 499.770          | 0.540         | 500.097  | 499.932          | 0.228   | 500.063  | 499.980          | 0.123                | 500.063  | 500.000          | 0.103 |
|                         | Min           | 500.000   | 499.120          | 0.480        | 500.000  | 499.615          | 0.230         | 500.000  | 499.869          | 0.068   | 500.000  | 499.940          | 0.020                | 500.000  | 499.960          | 0.000 |

<sup>a</sup>The sizes shown are first-choice basic sizes (see Table 1). Preferred fits for other sizes can be calculated from data given in ANSI B4.2-1978 (R1999).

<sup>b</sup>All fits shown in this table have clearance.

All dimensions are in millimeters.

**Table 3. American National Standard Preferred Hole Basis Metric Transition and Interference Fits ANSI B4.2-1978 (R1999)**

| Basic Size <sup>a</sup> |     | Locational Transition |          |                  | Locational Transition |          |                  | Locational Interference |          |                  | Medium Drive |          |                  | Force   |          |                  |
|-------------------------|-----|-----------------------|----------|------------------|-----------------------|----------|------------------|-------------------------|----------|------------------|--------------|----------|------------------|---------|----------|------------------|
|                         |     | Hole H7               | Shaft k6 | Fit <sup>b</sup> | Hole H7               | Shaft n6 | Fit <sup>b</sup> | Hole H7                 | Shaft p6 | Fit <sup>b</sup> | Hole H7      | Shaft s6 | Fit <sup>b</sup> | Hole H7 | Shaft u6 | Fit <sup>b</sup> |
| 1                       | Max | 1.010                 | 1.006    | +0.010           | 1.010                 | 1.010    | +0.006           | 1.010                   | 1.012    | +0.004           | 1.010        | 1.020    | -0.004           | 1.010   | 1.024    | -0.008           |
|                         | Min | 1.000                 | 1.000    | -0.006           | 1.000                 | 1.004    | -0.010           | 1.000                   | 1.006    | -0.012           | 1.000        | 1.014    | -0.020           | 1.000   | 1.018    | -0.024           |
| 1.2                     | Max | 1.210                 | 1.206    | +0.010           | 1.210                 | 1.210    | +0.006           | 1.210                   | 1.212    | +0.004           | 1.210        | 1.220    | -0.004           | 1.210   | 1.224    | -0.008           |
|                         | Min | 1.200                 | 1.200    | -0.006           | 1.200                 | 1.204    | -0.010           | 1.200                   | 1.206    | -0.012           | 1.200        | 1.214    | -0.020           | 1.200   | 1.218    | -0.024           |
| 1.6                     | Max | 1.610                 | 1.606    | +0.010           | 1.610                 | 1.610    | +0.006           | 1.610                   | 1.612    | +0.004           | 1.610        | 1.620    | -0.004           | 1.610   | 1.624    | -0.008           |
|                         | Min | 1.600                 | 1.600    | -0.006           | 1.600                 | 1.604    | -0.010           | 1.600                   | 1.606    | -0.012           | 1.600        | 1.614    | -0.020           | 1.600   | 1.618    | -0.024           |
| 2                       | Max | 2.010                 | 2.006    | +0.010           | 2.010                 | 2.010    | +0.006           | 2.010                   | 2.012    | +0.004           | 2.010        | 2.020    | -0.004           | 2.010   | 2.024    | -0.008           |
|                         | Min | 2.000                 | 2.000    | -0.006           | 2.000                 | 2.004    | -0.010           | 2.000                   | 2.006    | -0.012           | 2.000        | 2.014    | -0.020           | 2.000   | 2.018    | -0.024           |
| 2.5                     | Max | 2.510                 | 2.506    | +0.010           | 2.510                 | 2.510    | +0.006           | 2.510                   | 2.512    | +0.004           | 2.510        | 2.520    | -0.004           | 2.510   | 2.524    | -0.008           |
|                         | Min | 2.500                 | 2.500    | -0.006           | 2.500                 | 2.504    | -0.010           | 2.500                   | 2.506    | -0.012           | 2.500        | 2.514    | -0.020           | 2.500   | 2.518    | -0.024           |
| 3                       | Max | 3.010                 | 3.006    | +0.010           | 3.010                 | 3.010    | +0.006           | 3.010                   | 3.012    | +0.004           | 3.010        | 3.020    | -0.004           | 3.010   | 3.024    | -0.008           |
|                         | Min | 3.000                 | 3.000    | -0.006           | 3.000                 | 3.004    | -0.010           | 3.000                   | 3.006    | -0.012           | 3.000        | 3.014    | -0.020           | 3.000   | 3.018    | -0.024           |
| 4                       | Max | 4.012                 | 4.009    | +0.011           | 4.012                 | 4.016    | +0.004           | 4.012                   | 4.020    | 0.000            | 4.012        | 4.027    | -0.007           | 4.012   | 4.031    | -0.011           |
|                         | Min | 4.000                 | 4.001    | -0.009           | 4.000                 | 4.008    | -0.016           | 4.000                   | 4.012    | -0.020           | 4.000        | 4.019    | -0.027           | 4.000   | 4.023    | -0.031           |
| 5                       | Max | 5.012                 | 5.009    | +0.011           | 5.012                 | 5.016    | +0.004           | 5.012                   | 5.020    | 0.000            | 5.012        | 5.027    | -0.007           | 5.012   | 5.031    | -0.011           |
|                         | Min | 5.000                 | 5.001    | -0.009           | 5.000                 | 5.008    | -0.016           | 5.000                   | 5.012    | -0.020           | 5.000        | 5.019    | -0.027           | 5.000   | 5.023    | -0.031           |
| 6                       | Max | 6.012                 | 6.009    | +0.011           | 6.012                 | 6.016    | +0.004           | 6.012                   | 6.020    | 0.000            | 6.012        | 6.027    | -0.007           | 6.012   | 6.031    | -0.011           |
|                         | Min | 6.000                 | 6.001    | -0.009           | 6.000                 | 6.008    | -0.016           | 6.000                   | 6.012    | -0.020           | 6.000        | 6.019    | -0.027           | 6.000   | 6.023    | -0.031           |
| 8                       | Max | 8.015                 | 8.010    | +0.014           | 8.015                 | 8.019    | +0.006           | 8.015                   | 8.024    | 0.000            | 8.015        | 8.032    | -0.008           | 8.015   | 8.037    | -0.013           |
|                         | Min | 8.000                 | 8.001    | -0.010           | 8.000                 | 8.010    | -0.019           | 8.000                   | 8.015    | -0.024           | 8.000        | 8.023    | -0.032           | 8.000   | 8.028    | -0.037           |
| 10                      | Max | 10.015                | 10.010   | +0.014           | 10.015                | 10.019   | +0.005           | 10.015                  | 10.024   | 0.000            | 10.015       | 10.032   | -0.008           | 10.015  | 10.034   | -0.013           |
|                         | Min | 10.000                | 10.001   | -0.010           | 10.000                | 10.010   | -0.019           | 10.000                  | 10.015   | -0.024           | 10.000       | 10.023   | -0.032           | 10.000  | 10.028   | -0.037           |
| 12                      | Max | 12.018                | 12.012   | +0.017           | 12.018                | 12.023   | +0.006           | 12.018                  | 12.029   | 0.000            | 12.018       | 12.039   | -0.010           | 12.018  | 12.044   | -0.015           |
|                         | Min | 12.000                | 12.001   | -0.012           | 12.000                | 12.012   | -0.023           | 12.000                  | 12.018   | -0.029           | 12.000       | 12.028   | -0.039           | 12.000  | 12.033   | -0.044           |
| 16                      | Max | 16.018                | 16.012   | +0.017           | 16.018                | 16.023   | +0.006           | 16.018                  | 16.029   | 0.000            | 16.018       | 16.039   | -0.010           | 16.018  | 16.044   | -0.015           |
|                         | Min | 16.000                | 16.001   | -0.012           | 16.000                | 16.012   | -0.023           | 16.000                  | 16.018   | -0.029           | 16.000       | 16.028   | -0.039           | 16.000  | 16.033   | -0.044           |
| 20                      | Max | 20.021                | 20.015   | +0.019           | 20.021                | 20.028   | +0.006           | 20.021                  | 20.035   | -0.001           | 20.021       | 20.048   | -0.014           | 20.021  | 20.054   | -0.020           |
|                         | Min | 20.000                | 20.002   | -0.015           | 20.000                | 20.015   | -0.028           | 20.000                  | 20.022   | -0.035           | 20.000       | 20.035   | -0.048           | 20.000  | 20.041   | -0.054           |
| 25                      | Max | 25.021                | 25.015   | +0.019           | 25.021                | 25.028   | +0.006           | 25.021                  | 25.035   | -0.001           | 25.021       | 25.048   | -0.014           | 25.021  | 25.061   | -0.027           |
|                         | Min | 25.000                | 25.002   | -0.015           | 25.000                | 25.015   | -0.028           | 25.000                  | 25.022   | -0.035           | 25.000       | 25.035   | -0.048           | 25.000  | 25.048   | -0.061           |

**Table 3. (Continued) American National Standard Preferred Hole Basis Metric Transition and Interference Fits ANSI B4.2-1978 (R1999)**

| Basic Size <sup>a</sup> | Locational Transition |          |                  | Locational Transition |          |                  | Locational Interference |          |                  | Medium Drive |          |                  | Force   |          |                  |        |
|-------------------------|-----------------------|----------|------------------|-----------------------|----------|------------------|-------------------------|----------|------------------|--------------|----------|------------------|---------|----------|------------------|--------|
|                         | Hole H7               | Shaft k6 | Fit <sup>b</sup> | Hole H7               | Shaft n6 | Fit <sup>b</sup> | Hole H7                 | Shaft p6 | Fit <sup>b</sup> | Hole H7      | Shaft s6 | Fit <sup>b</sup> | Hole H7 | Shaft u6 | Fit <sup>b</sup> |        |
| 30                      | Max                   | 30.021   | 30.015           | +0.019                | 30.021   | 30.028           | +0.006                  | 30.021   | 30.035           | -0.001       | 30.021   | 30.048           | -0.014  | 30.021   | 30.061           | -0.027 |
|                         | Min                   | 30.000   | 30.002           | -0.015                | 30.000   | 30.015           | -0.028                  | 30.000   | 30.022           | -0.035       | 30.000   | 30.035           | -0.048  | 30.000   | 30.048           | -0.061 |
| 40                      | Max                   | 40.025   | 40.018           | +0.023                | 40.025   | 40.033           | +0.008                  | 40.025   | 40.042           | -0.001       | 40.025   | 40.059           | -0.018  | 40.025   | 40.076           | -0.035 |
|                         | Min                   | 40.000   | 40.002           | -0.018                | 40.000   | 40.017           | -0.033                  | 40.000   | 40.026           | -0.042       | 40.000   | 40.043           | -0.059  | 40.000   | 40.060           | -0.076 |
| 50                      | Max                   | 50.025   | 50.018           | +0.023                | 50.025   | 50.033           | +0.008                  | 50.025   | 50.042           | -0.001       | 50.025   | 50.059           | -0.018  | 50.025   | 50.086           | -0.045 |
|                         | Min                   | 50.000   | 50.002           | -0.018                | 50.000   | 50.017           | -0.033                  | 50.000   | 50.026           | -0.042       | 50.000   | 50.043           | -0.059  | 50.000   | 50.070           | -0.086 |
| 60                      | Max                   | 60.030   | 60.021           | +0.028                | 60.030   | 60.039           | +0.010                  | 60.030   | 60.051           | -0.002       | 60.030   | 60.072           | -0.023  | 60.030   | 60.106           | -0.057 |
|                         | Min                   | 60.000   | 60.002           | -0.021                | 60.000   | 60.020           | -0.039                  | 60.000   | 60.032           | -0.051       | 60.000   | 60.053           | -0.072  | 60.000   | 60.087           | -0.106 |
| 80                      | Max                   | 80.030   | 80.021           | +0.028                | 80.030   | 80.039           | +0.010                  | 80.030   | 80.051           | -0.002       | 80.030   | 80.078           | -0.029  | 80.030   | 80.121           | -0.072 |
|                         | Min                   | 80.000   | 80.002           | -0.021                | 80.000   | 80.020           | -0.039                  | 80.000   | 80.032           | -0.051       | 80.000   | 80.059           | -0.078  | 80.000   | 80.102           | -0.121 |
| 100                     | Max                   | 100.035  | 100.025          | +0.032                | 100.035  | 100.045          | +0.012                  | 100.035  | 100.059          | -0.002       | 100.035  | 100.093          | -0.036  | 100.035  | 100.146          | -0.089 |
|                         | Min                   | 100.000  | 100.003          | -0.025                | 100.000  | 100.023          | -0.045                  | 100.000  | 100.037          | -0.059       | 100.000  | 100.071          | -0.093  | 100.000  | 100.124          | -0.146 |
| 120                     | Max                   | 120.035  | 120.025          | +0.032                | 120.035  | 120.045          | +0.012                  | 120.035  | 120.059          | -0.002       | 120.035  | 120.101          | -0.044  | 120.035  | 120.166          | -0.109 |
|                         | Min                   | 120.000  | 120.003          | -0.025                | 120.000  | 120.023          | -0.045                  | 120.000  | 120.037          | -0.059       | 120.000  | 120.079          | -0.101  | 120.000  | 120.144          | -0.166 |
| 160                     | Max                   | 160.040  | 160.028          | +0.037                | 160.040  | 160.052          | +0.013                  | 160.040  | 160.068          | -0.003       | 160.040  | 160.125          | -0.060  | 160.040  | 160.215          | -0.150 |
|                         | Min                   | 160.000  | 160.003          | -0.028                | 160.000  | 160.027          | -0.052                  | 160.000  | 160.043          | -0.068       | 160.000  | 160.100          | -0.125  | 160.000  | 160.190          | -0.215 |
| 200                     | Max                   | 200.046  | 200.033          | +0.042                | 200.046  | 200.060          | +0.015                  | 200.046  | 200.079          | -0.004       | 200.046  | 200.151          | -0.076  | 200.046  | 200.265          | -0.190 |
|                         | Min                   | 200.000  | 200.004          | -0.033                | 200.000  | 200.031          | -0.060                  | 200.000  | 200.050          | -0.079       | 200.000  | 200.122          | -0.151  | 200.000  | 200.236          | -0.265 |
| 250                     | Max                   | 250.046  | 250.033          | +0.042                | 250.046  | 250.060          | +0.015                  | 250.046  | 250.079          | -0.004       | 250.046  | 250.169          | -0.094  | 250.046  | 250.313          | -0.238 |
|                         | Min                   | 250.000  | 250.004          | -0.033                | 250.000  | 250.031          | -0.060                  | 250.000  | 250.050          | -0.079       | 250.000  | 250.140          | -0.169  | 250.000  | 250.284          | -0.313 |
| 300                     | Max                   | 300.052  | 300.036          | +0.048                | 300.052  | 300.066          | +0.018                  | 300.052  | 300.088          | -0.004       | 300.052  | 300.202          | -0.118  | 300.052  | 300.382          | -0.298 |
|                         | Min                   | 300.000  | 300.004          | -0.036                | 300.000  | 300.034          | -0.066                  | 300.000  | 300.056          | -0.088       | 300.000  | 300.170          | -0.202  | 300.000  | 300.350          | -0.382 |
| 400                     | Max                   | 400.057  | 400.040          | +0.053                | 400.057  | 400.073          | +0.020                  | 400.057  | 400.098          | -0.005       | 400.057  | 400.244          | -0.151  | 400.057  | 400.471          | -0.378 |
|                         | Min                   | 400.000  | 400.004          | -0.040                | 400.000  | 400.037          | -0.073                  | 400.000  | 400.062          | -0.098       | 400.000  | 400.208          | -0.244  | 400.000  | 400.435          | -0.471 |
| 500                     | Max                   | 500.063  | 500.045          | +0.058                | 500.063  | 500.080          | +0.023                  | 500.063  | 500.108          | -0.005       | 500.063  | 500.292          | -0.189  | 500.063  | 500.580          | -0.477 |
|                         | Min                   | 500.000  | 500.005          | -0.045                | 500.000  | 500.040          | -0.080                  | 500.000  | 500.068          | -0.108       | 500.000  | 500.252          | -0.292  | 500.000  | 500.540          | -0.580 |

<sup>a</sup>The sizes shown are first-choice basic sizes (see Table 1). Preferred fits for other sizes can be calculated from data given in ANSI B4.2-1978 (R1999).

<sup>b</sup>A plus sign indicates clearance; a minus sign indicates interference.

All dimensions are in millimeters.

Table 4. American National Standard Preferred Shaft Basis Metric Clearance Fits ANSI B4.2-1978 (R1999)

| Basic Size <sup>a</sup> |     | Loose Running |           |                  | Free Running |          |                  | Close Running |          |                  | Sliding |          |                  | Locational Clearance |          |                  |
|-------------------------|-----|---------------|-----------|------------------|--------------|----------|------------------|---------------|----------|------------------|---------|----------|------------------|----------------------|----------|------------------|
|                         |     | Hole C11      | Shaft h11 | Fit <sup>b</sup> | Hole D9      | Shaft h9 | Fit <sup>b</sup> | Hole F8       | Shaft h7 | Fit <sup>b</sup> | Hole G7 | Shaft h6 | Fit <sup>b</sup> | Hole H7              | Shaft h6 | Fit <sup>b</sup> |
| 1                       | Max | 1.120         | 1.000     | 0.180            | 1.045        | 1.000    | 0.070            | 1.020         | 1.000    | 0.030            | 1.012   | 1.000    | 0.018            | 1.010                | 1.000    | 0.016            |
|                         | Min | 1.060         | 0.940     | 0.060            | 1.020        | 0.975    | 0.020            | 1.006         | 0.990    | 0.006            | 1.002   | 0.994    | 0.002            | 1.000                | 0.994    | 0.000            |
| 1.2                     | Max | 1.320         | 1.200     | 0.180            | 1.245        | 1.200    | 0.070            | 1.220         | 1.200    | 0.030            | 1.212   | 1.200    | 0.018            | 1.210                | 1.200    | 0.016            |
|                         | Min | 1.260         | 1.140     | 0.060            | 1.220        | 1.175    | 0.020            | 1.206         | 1.190    | 0.006            | 1.202   | 1.194    | 0.002            | 1.200                | 1.194    | 0.000            |
| 1.6                     | Max | 1.720         | 1.600     | 0.180            | 1.645        | 1.600    | 0.070            | 1.620         | 1.600    | 0.030            | 1.612   | 1.600    | 0.018            | 1.610                | 1.600    | 0.016            |
|                         | Min | 1.660         | 1.540     | 0.060            | 1.620        | 1.575    | 0.020            | 1.606         | 1.590    | 0.006            | 1.602   | 1.594    | 0.002            | 1.600                | 1.594    | 0.000            |
| 2                       | Max | 2.120         | 2.000     | 0.180            | 2.045        | 2.000    | 0.070            | 2.020         | 2.000    | 0.030            | 2.012   | 2.000    | 0.018            | 2.010                | 2.000    | 0.016            |
|                         | Min | 2.060         | 1.940     | 0.060            | 2.020        | 1.975    | 0.020            | 2.006         | 1.990    | 0.006            | 2.002   | 1.994    | 0.002            | 2.000                | 1.994    | 0.000            |
| 2.5                     | Max | 2.620         | 2.500     | 0.180            | 2.545        | 2.500    | 0.070            | 2.520         | 2.500    | 0.030            | 2.512   | 2.500    | 0.018            | 2.510                | 2.500    | 0.016            |
|                         | Min | 2.560         | 2.440     | 0.060            | 2.520        | 2.475    | 0.020            | 2.506         | 2.490    | 0.006            | 2.502   | 2.494    | 0.002            | 2.500                | 2.494    | 0.000            |
| 3                       | Max | 3.120         | 3.000     | 0.180            | 3.045        | 3.000    | 0.070            | 3.020         | 3.000    | 0.030            | 3.012   | 3.000    | 0.018            | 3.010                | 3.000    | 0.016            |
|                         | Min | 3.060         | 2.940     | 0.060            | 3.020        | 2.975    | 0.020            | 3.006         | 2.990    | 0.006            | 3.002   | 2.994    | 0.002            | 3.000                | 2.994    | 0.000            |
| 4                       | Max | 4.145         | 4.000     | 0.220            | 4.060        | 4.000    | 0.090            | 4.028         | 4.000    | 0.040            | 4.016   | 4.000    | 0.024            | 4.012                | 4.000    | 0.020            |
|                         | Min | 4.070         | 3.925     | 0.070            | 4.030        | 3.970    | 0.030            | 4.010         | 3.988    | 0.010            | 4.004   | 3.992    | 0.004            | 4.000                | 3.992    | 0.000            |
| 5                       | Max | 5.145         | 5.000     | 0.220            | 5.060        | 5.000    | 0.090            | 5.028         | 5.000    | 0.040            | 5.016   | 5.000    | 0.024            | 5.012                | 5.000    | 0.020            |
|                         | Min | 5.070         | 4.925     | 0.070            | 5.030        | 4.970    | 0.030            | 5.010         | 4.988    | 0.010            | 5.004   | 4.992    | 0.004            | 5.000                | 4.992    | 0.000            |
| 6                       | Max | 6.145         | 6.000     | 0.220            | 6.060        | 6.000    | 0.090            | 6.028         | 6.000    | 0.040            | 6.016   | 6.000    | 0.024            | 6.012                | 6.000    | 0.020            |
|                         | Min | 6.070         | 5.925     | 0.070            | 6.030        | 5.970    | 0.030            | 6.010         | 5.988    | 0.010            | 6.004   | 5.992    | 0.004            | 6.000                | 5.992    | 0.000            |
| 8                       | Max | 8.170         | 8.000     | 0.260            | 8.076        | 8.000    | 0.112            | 8.035         | 8.000    | 0.050            | 8.020   | 8.000    | 0.029            | 8.015                | 8.000    | 0.024            |
|                         | Min | 8.080         | 7.910     | 0.080            | 8.040        | 7.964    | 0.040            | 8.013         | 7.985    | 0.013            | 8.005   | 7.991    | 0.005            | 8.000                | 7.991    | 0.000            |
| 10                      | Max | 10.170        | 10.000    | 0.260            | 10.076       | 10.000   | 0.112            | 10.035        | 10.000   | 0.050            | 10.020  | 10.000   | 0.029            | 10.015               | 10.000   | 0.024            |
|                         | Min | 10.080        | 9.910     | 0.080            | 10.040       | 9.964    | 0.040            | 10.013        | 9.985    | 0.013            | 10.005  | 9.991    | 0.005            | 10.000               | 9.991    | 0.000            |
| 12                      | Max | 12.205        | 12.000    | 0.315            | 12.093       | 12.000   | 0.136            | 12.043        | 12.000   | 0.061            | 12.024  | 12.000   | 0.035            | 12.018               | 12.000   | 0.029            |
|                         | Min | 12.095        | 11.890    | 0.095            | 12.050       | 11.957   | 0.050            | 12.016        | 11.982   | 0.016            | 12.006  | 11.989   | 0.006            | 12.000               | 11.989   | 0.000            |
| 16                      | Max | 16.205        | 16.000    | 0.315            | 16.093       | 16.000   | 0.136            | 16.043        | 16.000   | 0.061            | 16.024  | 16.000   | 0.035            | 16.018               | 16.000   | 0.029            |
|                         | Min | 16.095        | 15.890    | 0.095            | 16.050       | 15.957   | 0.050            | 16.016        | 15.982   | 0.016            | 16.006  | 15.989   | 0.006            | 16.000               | 15.989   | 0.000            |
| 20                      | Max | 20.240        | 20.000    | 0.370            | 20.117       | 20.000   | 0.169            | 20.053        | 20.000   | 0.074            | 20.028  | 20.000   | 0.041            | 20.021               | 20.000   | 0.034            |
|                         | Min | 20.110        | 19.870    | 0.110            | 20.065       | 19.948   | 0.065            | 20.020        | 19.979   | 0.020            | 20.007  | 19.987   | 0.007            | 20.000               | 19.987   | 0.000            |
| 25                      | Max | 25.240        | 25.000    | 0.370            | 25.117       | 25.000   | 0.169            | 25.053        | 25.000   | 0.074            | 25.028  | 25.000   | 0.041            | 25.021               | 25.000   | 0.034            |
|                         | Min | 25.110        | 24.870    | 0.110            | 25.065       | 24.948   | 0.065            | 25.020        | 24.979   | 0.020            | 25.007  | 24.987   | 0.007            | 25.000               | 24.987   | 0.000            |

**Table 4. (Continued) American National Standard Preferred Shaft Basis Metric Clearance Fits ANSI B4.2-1978 (R1999)**

| Basic Size <sup>a</sup> | Loose Running |           |                  | Free Running |          |                  | Close Running |          |                  | Sliding |          |                  | Locational Clearance |          |                  |       |
|-------------------------|---------------|-----------|------------------|--------------|----------|------------------|---------------|----------|------------------|---------|----------|------------------|----------------------|----------|------------------|-------|
|                         | Hole C11      | Shaft h11 | Fit <sup>b</sup> | Hole D9      | Shaft h9 | Fit <sup>b</sup> | Hole F8       | Shaft h7 | Fit <sup>b</sup> | Hole G7 | Shaft h6 | Fit <sup>b</sup> | Hole H7              | Shaft h6 | Fit <sup>b</sup> |       |
| 30                      | Max           | 30.240    | 30.000           | 0.370        | 30.117   | 30.000           | 0.169         | 30.053   | 30.000           | 0.074   | 30.028   | 30.000           | 0.041                | 30.021   | 30.000           | 0.034 |
|                         | Min           | 30.110    | 29.870           | 0.110        | 30.065   | 29.948           | 0.065         | 30.020   | 29.979           | 0.020   | 30.007   | 29.987           | 0.007                | 30.000   | 29.987           | 0.000 |
| 40                      | Max           | 40.280    | 40.000           | 0.440        | 40.142   | 40.000           | 0.204         | 40.064   | 40.000           | 0.089   | 40.034   | 40.000           | 0.050                | 40.025   | 40.000           | 0.041 |
|                         | Min           | 40.120    | 39.840           | 0.120        | 40.080   | 39.938           | 0.080         | 40.025   | 39.975           | 0.025   | 40.009   | 39.984           | 0.009                | 40.000   | 39.984           | 0.000 |
| 50                      | Max           | 50.290    | 50.000           | 0.450        | 50.142   | 50.000           | 0.204         | 50.064   | 50.000           | 0.089   | 50.034   | 50.000           | 0.050                | 50.025   | 50.000           | 0.041 |
|                         | Min           | 50.130    | 49.840           | 0.130        | 50.080   | 49.938           | 0.080         | 50.025   | 49.975           | 0.025   | 50.009   | 49.984           | 0.009                | 50.000   | 49.984           | 0.000 |
| 60                      | Max           | 60.330    | 60.000           | 0.520        | 60.174   | 60.000           | 0.248         | 60.076   | 60.000           | 0.106   | 60.040   | 60.000           | 0.059                | 60.030   | 60.000           | 0.049 |
|                         | Min           | 60.140    | 59.810           | 0.140        | 60.100   | 59.926           | 0.100         | 60.030   | 59.970           | 0.030   | 60.010   | 59.981           | 0.010                | 60.000   | 59.981           | 0.000 |
| 80                      | Max           | 80.340    | 80.000           | 0.530        | 80.174   | 80.000           | 0.248         | 80.076   | 80.000           | 0.106   | 80.040   | 80.000           | 0.059                | 80.030   | 80.000           | 0.049 |
|                         | Min           | 80.150    | 79.810           | 0.150        | 80.100   | 79.926           | 0.100         | 80.030   | 79.970           | 0.030   | 80.010   | 79.981           | 0.010                | 80.000   | 79.981           | 0.000 |
| 100                     | Max           | 100.390   | 100.000          | 0.610        | 100.207  | 100.000          | 0.294         | 100.090  | 100.000          | 0.125   | 100.047  | 100.000          | 0.069                | 100.035  | 100.000          | 0.057 |
|                         | Min           | 100.170   | 99.780           | 0.170        | 100.120  | 99.913           | 0.120         | 100.036  | 99.965           | 0.036   | 100.012  | 99.978           | 0.012                | 100.000  | 99.978           | 0.000 |
| 120                     | Max           | 120.400   | 120.000          | 0.620        | 120.207  | 120.000          | 0.294         | 120.090  | 120.000          | 0.125   | 120.047  | 120.000          | 0.069                | 120.035  | 120.000          | 0.057 |
|                         | Min           | 120.180   | 119.780          | 0.180        | 120.120  | 119.913          | 0.120         | 120.036  | 119.965          | 0.036   | 120.012  | 119.978          | 0.012                | 120.000  | 119.978          | 0.000 |
| 160                     | Max           | 160.460   | 160.000          | 0.710        | 160.245  | 160.000          | 0.345         | 160.106  | 160.000          | 0.146   | 160.054  | 160.000          | 0.079                | 160.040  | 160.000          | 0.065 |
|                         | Min           | 160.210   | 159.750          | 0.210        | 160.145  | 159.900          | 0.145         | 160.043  | 159.960          | 0.043   | 160.014  | 159.975          | 0.014                | 160.000  | 159.975          | 0.000 |
| 200                     | Max           | 200.530   | 200.000          | 0.820        | 200.285  | 200.000          | 0.400         | 200.122  | 200.000          | 0.168   | 200.061  | 200.000          | 0.090                | 200.046  | 200.000          | 0.075 |
|                         | Min           | 200.240   | 199.710          | 0.240        | 200.170  | 199.885          | 0.170         | 200.050  | 199.954          | 0.050   | 200.015  | 199.971          | 0.015                | 200.000  | 199.971          | 0.000 |
| 250                     | Max           | 250.570   | 250.000          | 0.860        | 250.285  | 250.000          | 0.400         | 250.122  | 250.000          | 0.168   | 250.061  | 250.000          | 0.090                | 250.046  | 250.000          | 0.075 |
|                         | Min           | 250.280   | 249.710          | 0.280        | 250.170  | 249.885          | 0.170         | 250.050  | 249.954          | 0.050   | 250.015  | 249.971          | 0.015                | 250.000  | 249.971          | 0.000 |
| 300                     | Max           | 300.650   | 300.000          | 0.970        | 300.320  | 300.000          | 0.450         | 300.137  | 300.000          | 0.189   | 300.069  | 300.000          | 0.101                | 300.052  | 300.000          | 0.084 |
|                         | Min           | 300.330   | 299.680          | 0.330        | 300.190  | 299.870          | 0.190         | 300.056  | 299.948          | 0.056   | 300.017  | 299.968          | 0.017                | 300.000  | 299.968          | 0.000 |
| 400                     | Max           | 400.760   | 400.000          | 1.120        | 400.350  | 400.000          | 0.490         | 400.151  | 400.000          | 0.208   | 400.075  | 400.000          | 0.111                | 400.057  | 400.000          | 0.093 |
|                         | Min           | 400.400   | 399.640          | 0.400        | 400.210  | 399.860          | 0.210         | 400.062  | 399.943          | 0.062   | 400.018  | 399.964          | 0.018                | 400.000  | 399.964          | 0.000 |
| 500                     | Max           | 500.880   | 500.000          | 1.280        | 500.385  | 500.000          | 0.540         | 500.165  | 500.000          | 0.228   | 500.083  | 500.000          | 0.123                | 500.063  | 500.000          | 0.103 |
|                         | Min           | 500.480   | 499.600          | 0.480        | 500.230  | 499.845          | 0.230         | 500.068  | 499.937          | 0.068   | 500.020  | 499.960          | 0.020                | 500.000  | 499.960          | 0.000 |

<sup>a</sup>The sizes shown are first-choice basic sizes (see Table 1). Preferred fits for other sizes can be calculated from data given in ANSI B4.2-1978 (R1999).

<sup>b</sup>All fits shown in this table have clearance.

All dimensions are in millimeters.



Table 5. American National Standard Preferred Shaft Basis Metric Transition and Interference Fits ANSI B4.2-1978 (R1999)

| Basic Size <sup>a</sup> |     | Locational Transition |          |                  | Locational Transition |          |                  | Locational Interference |          |                  | Medium Drive |          |                  | Force   |          |                  |
|-------------------------|-----|-----------------------|----------|------------------|-----------------------|----------|------------------|-------------------------|----------|------------------|--------------|----------|------------------|---------|----------|------------------|
|                         |     | Hole K7               | Shaft h6 | Fit <sup>b</sup> | Hole N7               | Shaft h6 | Fit <sup>b</sup> | Hole P7                 | Shaft h6 | Fit <sup>b</sup> | Hole S7      | Shaft h6 | Fit <sup>b</sup> | Hole U7 | Shaft h6 | Fit <sup>b</sup> |
| 1                       | Max | 1.000                 | 1.000    | +0.006           | 0.996                 | 1.000    | +0.002           | 0.994                   | 1.000    | 0.000            | 0.986        | 1.000    | -0.008           | 0.982   | 1.000    | -0.012           |
|                         | Min | 0.990                 | 0.994    | -0.010           | 0.986                 | 0.994    | -0.014           | 0.984                   | 0.994    | -0.016           | 0.976        | 0.994    | -0.024           | 0.972   | 0.994    | -0.028           |
| 1.2                     | Max | 1.200                 | 1.200    | +0.006           | 1.196                 | 1.200    | +0.002           | 1.194                   | 1.200    | 0.000            | 1.186        | 1.200    | -0.008           | 1.182   | 1.200    | -0.012           |
|                         | Min | 1.190                 | 1.194    | -0.010           | 1.186                 | 1.194    | -0.014           | 1.184                   | 1.194    | -0.016           | 1.176        | 1.194    | -0.024           | 1.172   | 1.194    | -0.028           |
| 1.6                     | Max | 1.600                 | 1.600    | +0.006           | 1.596                 | 1.600    | +0.002           | 1.594                   | 1.600    | 0.000            | 1.586        | 1.600    | -0.008           | 1.582   | 1.600    | -0.012           |
|                         | Min | 1.590                 | 1.594    | -0.010           | 1.586                 | 1.594    | -0.014           | 1.584                   | 1.594    | -0.016           | 1.576        | 1.594    | -0.024           | 1.572   | 1.594    | -0.028           |
| 2                       | Max | 2.000                 | 2.000    | +0.006           | 1.996                 | 2.000    | +0.002           | 1.994                   | 2.000    | 0.000            | 1.986        | 2.000    | -0.008           | 1.982   | 2.000    | -0.012           |
|                         | Min | 1.990                 | 1.994    | -0.010           | 1.986                 | 1.994    | -0.014           | 1.984                   | 1.994    | -0.016           | 1.976        | 1.994    | -0.024           | 1.972   | 1.994    | -0.028           |
| 2.5                     | Max | 2.500                 | 2.500    | +0.006           | 2.496                 | 2.500    | +0.002           | 2.494                   | 2.500    | 0.000            | 2.486        | 2.500    | -0.008           | 2.482   | 2.500    | -0.012           |
|                         | Min | 2.490                 | 2.494    | -0.010           | 2.486                 | 2.494    | -0.014           | 2.484                   | 2.494    | -0.016           | 2.476        | 2.494    | -0.024           | 2.472   | 2.494    | -0.028           |
| 3                       | Max | 3.000                 | 3.000    | +0.006           | 2.996                 | 3.000    | +0.002           | 2.994                   | 3.000    | 0.000            | 2.986        | 3.000    | -0.008           | 2.982   | 3.000    | -0.012           |
|                         | Min | 2.990                 | 2.994    | -0.010           | 2.986                 | 2.994    | -0.014           | 2.984                   | 2.994    | -0.016           | 2.976        | 2.994    | -0.024           | 2.972   | 2.994    | -0.028           |
| 4                       | Max | 4.003                 | 4.000    | +0.011           | 3.996                 | 4.000    | +0.004           | 3.992                   | 4.000    | 0.000            | 3.985        | 4.000    | -0.007           | 3.981   | 4.000    | -0.011           |
|                         | Min | 3.991                 | 3.992    | -0.009           | 3.984                 | 3.992    | -0.016           | 3.980                   | 3.992    | -0.020           | 3.973        | 3.992    | -0.027           | 3.969   | 3.992    | -0.031           |
| 5                       | Max | 5.003                 | 5.000    | +0.011           | 4.996                 | 5.000    | +0.004           | 4.992                   | 5.000    | 0.000            | 4.985        | 5.000    | -0.007           | 4.981   | 5.000    | -0.011           |
|                         | Min | 4.991                 | 4.992    | -0.009           | 4.984                 | 4.992    | -0.016           | 4.980                   | 4.992    | -0.020           | 4.973        | 4.992    | -0.027           | 4.969   | 4.992    | -0.031           |
| 6                       | Max | 6.003                 | 6.000    | +0.011           | 5.996                 | 6.000    | +0.004           | 5.992                   | 6.000    | 0.000            | 5.985        | 6.000    | -0.007           | 5.981   | 6.000    | -0.011           |
|                         | Min | 5.991                 | 5.992    | -0.009           | 5.984                 | 5.992    | -0.016           | 5.980                   | 5.992    | -0.020           | 5.973        | 5.992    | -0.027           | 5.969   | 5.992    | -0.031           |
| 8                       | Max | 8.005                 | 8.000    | +0.014           | 7.996                 | 8.000    | +0.005           | 7.991                   | 8.000    | 0.000            | 7.983        | 8.000    | -0.008           | 7.978   | 8.000    | -0.013           |
|                         | Min | 7.990                 | 7.991    | -0.010           | 7.981                 | 7.991    | -0.019           | 7.976                   | 7.991    | -0.024           | 7.968        | 7.991    | -0.032           | 7.963   | 7.991    | -0.037           |
| 10                      | Max | 10.005                | 10.000   | +0.014           | 9.996                 | 10.000   | +0.005           | 9.991                   | 10.000   | 0.000            | 9.983        | 10.000   | -0.008           | 9.978   | 10.000   | -0.013           |
|                         | Min | 9.990                 | 9.991    | -0.010           | 9.981                 | 9.991    | -0.019           | 9.976                   | 9.991    | -0.024           | 9.968        | 9.991    | -0.032           | 9.963   | 9.991    | -0.037           |
| 12                      | Max | 12.006                | 12.000   | +0.017           | 11.995                | 12.000   | +0.006           | 11.989                  | 12.000   | 0.000            | 11.979       | 12.000   | -0.010           | 11.974  | 12.000   | -0.015           |
|                         | Min | 11.988                | 11.989   | -0.012           | 11.977                | 11.989   | -0.023           | 11.971                  | 11.989   | -0.029           | 11.961       | 11.989   | -0.039           | 11.956  | 11.989   | -0.044           |
| 16                      | Max | 16.006                | 16.000   | +0.017           | 15.995                | 16.000   | +0.006           | 15.989                  | 16.000   | 0.000            | 15.979       | 16.000   | -0.010           | 15.974  | 16.000   | -0.015           |
|                         | Min | 15.988                | 15.989   | -0.012           | 15.977                | 15.989   | -0.023           | 15.971                  | 15.989   | -0.029           | 15.961       | 15.989   | -0.039           | 15.956  | 15.989   | -0.044           |
| 20                      | Max | 20.006                | 20.000   | +0.019           | 19.993                | 20.000   | +0.006           | 19.986                  | 20.000   | -0.001           | 19.973       | 20.000   | -0.014           | 19.967  | 20.000   | -0.020           |
|                         | Min | 19.985                | 19.987   | -0.015           | 19.972                | 19.987   | -0.028           | 19.965                  | 19.987   | -0.035           | 19.952       | 19.987   | -0.048           | 19.946  | 19.987   | -0.054           |
| 25                      | Max | 25.006                | 25.000   | +0.019           | 24.993                | 25.000   | +0.006           | 24.986                  | 25.000   | -0.001           | 24.973       | 25.000   | -0.014           | 24.966  | 25.000   | -0.027           |
|                         | Min | 24.985                | 24.987   | -0.015           | 24.972                | 24.987   | -0.028           | 24.965                  | 24.987   | -0.035           | 24.952       | 24.987   | -0.048           | 24.939  | 24.987   | -0.061           |

**Table 5. (Continued) American National Standard Preferred Shaft Basis Metric Transition and Interference Fits ANSI B4.2-1978 (R1999)**

| Basic Size <sup>a</sup> | Locational Transition |          |                  | Locational Transition |          |                  | Locational Interference |          |                  | Medium Drive |          |                  | Force   |          |                  |        |
|-------------------------|-----------------------|----------|------------------|-----------------------|----------|------------------|-------------------------|----------|------------------|--------------|----------|------------------|---------|----------|------------------|--------|
|                         | Hole K7               | Shaft h6 | Fit <sup>b</sup> | Hole N7               | Shaft h6 | Fit <sup>b</sup> | Hole P7                 | Shaft h6 | Fit <sup>b</sup> | Hole S7      | Shaft h6 | Fit <sup>b</sup> | Hole U7 | Shaft h6 | Fit <sup>b</sup> |        |
| 30                      | Max                   | 30.006   | 30.000           | +0.019                | 29.993   | 30.000           | +0.006                  | 29.986   | 30.000           | -0.001       | 29.973   | 30.000           | -0.014  | 29.960   | 30.000           | -0.027 |
|                         | Min                   | 29.985   | 29.987           | -0.015                | 29.972   | 29.987           | -0.028                  | 29.965   | 29.987           | -0.035       | 29.952   | 29.987           | -0.048  | 29.939   | 29.987           | -0.061 |
| 40                      | Max                   | 40.007   | 40.000           | +0.023                | 39.992   | 40.000           | +0.008                  | 39.983   | 40.000           | -0.001       | 39.966   | 40.000           | -0.018  | 39.949   | 40.000           | -0.035 |
|                         | Min                   | 39.982   | 39.984           | -0.018                | 39.967   | 39.984           | -0.033                  | 39.958   | 39.984           | -0.042       | 39.941   | 39.984           | -0.059  | 39.924   | 39.984           | -0.076 |
| 50                      | Max                   | 50.007   | 50.000           | +0.023                | 49.992   | 50.000           | +0.008                  | 49.983   | 50.000           | -0.001       | 49.966   | 50.000           | -0.018  | 49.939   | 50.000           | -0.045 |
|                         | Min                   | 49.982   | 49.984           | -0.018                | 49.967   | 49.984           | -0.033                  | 49.958   | 49.984           | -0.042       | 49.941   | 49.984           | -0.059  | 49.914   | 49.984           | -0.086 |
| 60                      | Max                   | 60.009   | 60.000           | +0.028                | 59.991   | 60.000           | +0.010                  | 59.979   | 60.000           | -0.002       | 59.958   | 60.000           | -0.023  | 59.924   | 60.000           | -0.087 |
|                         | Min                   | 59.979   | 59.981           | -0.021                | 59.961   | 59.981           | -0.039                  | 59.949   | 59.981           | -0.051       | 59.928   | 59.981           | -0.072  | 59.894   | 59.981           | -0.106 |
| 80                      | Max                   | 80.009   | 80.000           | +0.028                | 79.991   | 80.000           | +0.010                  | 79.979   | 80.000           | -0.002       | 79.952   | 80.000           | -0.029  | 79.909   | 80.000           | -0.072 |
|                         | Min                   | 79.979   | 79.981           | -0.021                | 79.961   | 79.981           | -0.039                  | 79.949   | 79.981           | -0.051       | 79.922   | 79.981           | -0.078  | 79.879   | 79.981           | -0.121 |
| 100                     | Max                   | 100.010  | 100.000          | +0.032                | 99.990   | 100.000          | +0.012                  | 99.976   | 100.000          | -0.002       | 99.942   | 100.000          | -0.036  | 99.889   | 100.000          | -0.089 |
|                         | Min                   | 99.975   | 99.978           | -0.025                | 99.955   | 99.978           | -0.045                  | 99.941   | 99.978           | -0.059       | 99.907   | 99.978           | -0.093  | 99.854   | 99.978           | -0.146 |
| 120                     | Max                   | 120.010  | 120.000          | +0.032                | 119.990  | 120.000          | +0.012                  | 119.976  | 120.000          | -0.002       | 119.934  | 120.000          | -0.044  | 119.869  | 120.000          | -0.109 |
|                         | Min                   | 119.975  | 119.978          | -0.025                | 119.955  | 119.978          | -0.045                  | 119.941  | 119.978          | -0.059       | 119.899  | 119.978          | -0.101  | 119.834  | 119.978          | -0.166 |
| 160                     | Max                   | 160.012  | 160.000          | +0.037                | 159.988  | 160.000          | +0.013                  | 159.972  | 160.000          | -0.003       | 159.915  | 160.000          | -0.060  | 159.825  | 160.000          | -0.150 |
|                         | Min                   | 159.972  | 159.975          | -0.028                | 159.948  | 159.975          | -0.052                  | 159.932  | 159.975          | -0.068       | 159.875  | 159.975          | -0.125  | 159.785  | 159.975          | -0.215 |
| 200                     | Max                   | 200.013  | 200.00           | +0.042                | 199.986  | 200.000          | +0.015                  | 199.967  | 200.000          | -0.004       | 199.895  | 200.000          | -0.076  | 199.781  | 200.000          | -0.190 |
|                         | Min                   | 199.967  | 199.971          | -0.033                | 199.940  | 199.971          | -0.060                  | 199.921  | 199.971          | -0.079       | 199.849  | 199.971          | -0.151  | 199.735  | 199.971          | -0.265 |
| 250                     | Max                   | 250.013  | 250.000          | +0.042                | 249.986  | 250.000          | +0.015                  | 249.967  | 250.000          | -0.004       | 249.877  | 250.000          | -0.094  | 249.733  | 250.000          | -0.238 |
|                         | Min                   | 249.967  | 249.971          | -0.033                | 249.940  | 249.971          | -0.060                  | 249.921  | 249.971          | -0.079       | 249.831  | 249.971          | -0.169  | 249.687  | 249.971          | -0.313 |
| 300                     | Max                   | 300.016  | 300.000          | +0.048                | 299.986  | 300.000          | +0.018                  | 299.964  | 300.000          | -0.004       | 299.850  | 300.000          | -0.118  | 299.670  | 300.000          | -0.298 |
|                         | Min                   | 299.964  | 299.968          | -0.036                | 299.934  | 299.968          | -0.066                  | 299.912  | 299.968          | -0.088       | 299.798  | 299.968          | -0.202  | 299.618  | 299.968          | -0.382 |
| 400                     | Max                   | 400.017  | 400.000          | +0.053                | 399.984  | 400.000          | +0.020                  | 399.959  | 400.000          | -0.005       | 399.813  | 400.000          | -0.151  | 399.586  | 400.000          | -0.378 |
|                         | Min                   | 399.960  | 399.964          | -0.040                | 399.927  | 399.964          | -0.073                  | 399.902  | 399.964          | -0.098       | 399.756  | 399.964          | -0.244  | 399.529  | 399.964          | -0.471 |
| 500                     | Max                   | 500.018  | 500.000          | +0.058                | 499.983  | 500.000          | +0.023                  | 499.955  | 500.000          | -0.005       | 499.771  | 500.000          | -0.189  | 499.483  | 500.000          | -0.477 |
|                         | Min                   | 499.955  | 499.960          | -0.045                | 499.920  | 499.960          | -0.080                  | 499.892  | 499.960          | -0.108       | 499.708  | 499.960          | -0.292  | 499.420  | 499.960          | -0.580 |

<sup>a</sup>The sizes shown are first-choice basic sizes (see Table 1). Preferred fits for other sizes can be calculated from data given in ANSI B4.2-1978 (R1999).

<sup>b</sup>A plus sign indicates clearance; a minus sign indicates interference.

All dimensions are in millimeters.

**Table 6. American National Standard Gagemakers Tolerances**  
*ANSI B4.4M-1981 (R1987)*

| Gagemakers Tolerance   |                         | Workpiece Tolerance |                        |   |
|--|-------------------------|---------------------|------------------------|---|
| Class  | ISO Symbol <sup>a</sup> | IT Grade            | Recommended Gage Usage |   |
| Rejection of Good Parts Increase<br>↑<br>↓<br>Gage Cost Increase | ZM                      | 0.05 IT11           | IT11                   | Low-precision gages recommended to be used to inspect workpieces held to internal (hole) tolerances C11 and H11 and to external (shaft) tolerances c11 and h11.         |
|  | YM                      | 0.05 IT9            | IT9                    | Gages recommended to be used to inspect workpieces held to internal (hole) tolerances D9 and H9 and to external (shaft) tolerances d9 and h9.                           |
|  | XM                      | 0.05 IT8            | IT8                    | Precision gages recommended to be used to inspect workpieces held to internal (hole) tolerances F8 and H8.  |
|  | XXM                     | 0.05 IT7            | IT7                    | Recommended to be used for gages to inspect workpieces held to internal (hole) tolerances G7, H7, K7, N7, P7, S7, and U7, and to external (shaft) tolerances f7 and h7. |
|  | XXXM                    | 0.05 IT6            | IT6                    | High-precision gages recommended to be used to inspect workpieces held to external (shaft) tolerances g6, h6, k6, n6, p6, s6, and u6.                                   |

<sup>a</sup> Gagemakers tolerance is equal to 5 per cent of workpiece tolerance or 5 per cent of applicable IT grade value. See Table 7.

For workpiece tolerance class values, see previous Tables 2 through 5, incl.

**Table 7. American National Standard Gagemakers Tolerances**  
*ANSI B4.4M-1981 (R1987)*

| Basic Size |     | Class ZM    | Class YM   | Class XM   | Class XXM  | Class XXXM |
|------------|-----|-------------|------------|------------|------------|------------|
| Over       | To  | (0.05 IT11) | (0.05 IT9) | (0.05 IT8) | (0.05 IT7) | (0.05 IT6) |
| 0          | 3   | 0.0030      | 0.0012     | 0.0007     | 0.0005     | 0.0003     |
| 3          | 6   | 0.0037      | 0.0015     | 0.0009     | 0.0006     | 0.0004     |
| 6          | 10  | 0.0045      | 0.0018     | 0.0011     | 0.0007     | 0.0005     |
| 10         | 18  | 0.0055      | 0.0021     | 0.0013     | 0.0009     | 0.0006     |
| 18         | 30  | 0.0065      | 0.0026     | 0.0016     | 0.0010     | 0.0007     |
| 30         | 50  | 0.0080      | 0.0031     | 0.0019     | 0.0012     | 0.0008     |
| 50         | 80  | 0.0095      | 0.0037     | 0.0023     | 0.0015     | 0.0010     |
| 80         | 120 | 0.0110      | 0.0043     | 0.0027     | 0.0017     | 0.0011     |
| 120        | 180 | 0.0125      | 0.0050     | 0.0031     | 0.0020     | 0.0013     |
| 180        | 250 | 0.0145      | 0.0057     | 0.0036     | 0.0023     | 0.0015     |
| 250        | 315 | 0.0160      | 0.0065     | 0.0040     | 0.0026     | 0.0016     |
| 315        | 400 | 0.0180      | 0.0070     | 0.0044     | 0.0028     | 0.0018     |
| 400        | 500 | 0.0200      | 0.0077     | 0.0048     | 0.0031     | 0.0020     |

All dimensions are in millimeters. For closer gagemakers tolerance classes than Class XXXM, specify 5 per cent of IT5, IT4, or IT3 and use the designation 0.05 IT5, 0.05 IT4, etc.

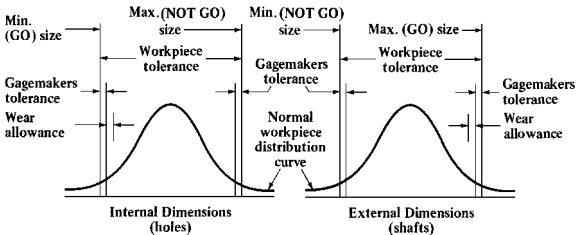


Fig. 4. Relationship between Gagemakers Tolerance, Wear Allowance and Workpiece Tolerance

**Applications.**—Many factors such as length of engagement, bearing load, speed, lubrication, operating temperatures, humidity, surface texture, and materials must be taken into account in fit selections for a particular application.

Choice of other than the preferred fits might be considered necessary to satisfy extreme conditions. Subsequent adjustments might also be desired as the result of experience in a particular application to suit critical functional requirements or to permit optimum manufacturing economy. Selection of a departure from these recommendations will depend upon consideration of the engineering and economic factors that might be involved; however, the benefits to be derived from the use of preferred fits should not be overlooked.

A general guide to machining processes that may normally be expected to produce work within the tolerances indicated by the IT grades given in ANSI B4.2-1978 (R1999) is shown in Table 8. Practical usage of the various IT tolerance grades is shown in Table 9.

**Table 8. Relation of Machining Processes to IT Tolerance Grades**

|                       | IT Grades |   |   |   |   |   |    |    |
|-----------------------|-----------|---|---|---|---|---|----|----|
|                       | 4         | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Lapping & Honing      | ■         |   |   |   |   |   |    |    |
| Cylindrical Grinding  | ■         | ■ |   |   |   |   |    |    |
| Surface Grinding      |           | ■ |   | ■ |   |   |    |    |
| Diamond Turning       |           | ■ |   | ■ |   |   |    |    |
| Diamond Boring        |           | ■ |   | ■ |   |   |    |    |
| Broaching             |           | ■ |   | ■ |   |   |    |    |
| Powder Metal sizes    |           | ■ |   | ■ |   |   |    |    |
| Reaming               |           | ■ |   | ■ |   |   |    |    |
| Turning               |           | ■ |   | ■ |   |   | ■  |    |
| Powder Metal sintered |           | ■ |   | ■ |   |   | ■  |    |
| Boring                |           | ■ |   | ■ |   |   | ■  |    |
| Milling               |           | ■ |   | ■ |   |   | ■  |    |
| Planing & Shaping     |           | ■ |   | ■ |   |   | ■  |    |
| Drilling              |           | ■ |   | ■ |   |   | ■  |    |
| Punching              |           | ■ |   | ■ |   |   | ■  |    |
| Die Casting           |           | ■ |   | ■ |   |   | ■  |    |

**Table 9. Practical Use of International Tolerance Grades**

| IT Grades | For Measuring Tools |   |   |   | For Material |   |   |   |                                    |   |   |    |    |    |    |    |    |    |
|-----------|---------------------|---|---|---|--------------|---|---|---|------------------------------------|---|---|----|----|----|----|----|----|----|
|           | 01                  | 0 | 1 | 2 | 3            | 4 | 5 | 6 | 7                                  | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|           |                     |   |   |   |              |   |   |   |                                    |   |   |    |    |    |    |    |    |    |
|           | For Fits            |   |   |   |              |   |   |   | For Large Manufacturing Tolerances |   |   |    |    |    |    |    |    |    |

### British Standard for Metric ISO Limits and Fits

Based on ISO Recommendation R286, this British Standard BS 4500:1969 is intended to provide a comprehensive range of metric limits and fits for engineering purposes, and meets the requirements of metrication in the United Kingdom. Sizes up to 3,150 mm are covered by the Standard, but the condensed information presented here embraces dimensions up to 500 mm only. The system is based on a series of tolerances graded to suit all classes of work from the finest to the most coarse, and the different types of fits that can be obtained range from coarse clearance to heavy interference. In the Standard, only cylindrical parts, designated holes and shafts are referred to explicitly, but it is emphasized that the recommendations apply equally well to other sections, and the general term *hole* or *shaft*

can be taken to mean the space contained by or containing two parallel faces or tangent planes of any part, such as the width of a slot, or the thickness of a key. It is also strongly emphasized that the grades series of tolerances are intended for the most general application, and should be used wherever possible whether the features of the component involved are members of a fit or not.

**Definitions.**—The definitions given in the Standard include the following:

*Limits of Size:* The maximum and minimum sizes permitted for a feature.

*Basic Size:* The reference size to which the limits of size are fixed. The basic size is the same for both members of a fit.

*Upper Deviation:* The algebraical difference between the maximum limit of size and the corresponding basic size. It is designated as ES for a hole, and as es for a shaft, which stands for the French term *écart supérieur*.

*Lower Deviation:* The algebraical difference between the minimum limit of size and the corresponding basic size. It is designated as EI for a hole, and as ei for a shaft, which stands for the French term *écart inférieur*.

*Zero Line:* In a graphical representation of limits and fits, the straight line to which the deviations are referred. The zero line is the line of zero deviation and represents the basic size.

*Tolerance:* The difference between the maximum limit of size and the minimum limit of size. It is an absolute value without sign.

*Tolerance Zone:* In a graphical representation of tolerances, the zone comprised between the two lines representing the limits of tolerance and defined by its magnitude (tolerance) and by its position in relation to the zero line.

*Fundamental Deviation:* That one of the two deviations, being the one nearest to the zero line, which is conventionally chosen to define the position of the tolerance zone in relation to the zero line.

*Shaft-Basis System of Fits:* A system of fits in which the different clearances and interferences are obtained by associating various holes with a single shaft. In the ISO system, the basic shaft is the shaft the upper deviation of which is zero.

*Hole-Basis System of Fits:* A system of fits in which the different clearances and interferences are obtained by associating various shafts with a single hole. In the ISO system, the basic hole is the hole the lower deviation of which is zero.

**Selected Limits of Tolerance, and Fits.**—The number of fit combinations that can be built up with the ISO system is very large. However, experience shows that the majority of fits required for usual engineering products can be provided by a limited selection of tolerances. Limits of tolerance for selected holes are shown in [Table 1](#), and for shafts, in [Table 2](#). Selected fits, based on combinations of the selected hole and shaft tolerances, are given in [Table 3](#).

**Tolerances and Fundamental Deviations.**—There are 18 tolerance grades intended to meet the requirements of different classes of work, and they are designated IT01, IT0, and IT1 to IT16. (IT stands for ISO series of tolerances.) [Table 4](#) shows the standardized numerical values for the 18 tolerance grades, which are known as standard tolerances. The system provides 27 fundamental deviations for sizes up to and including 500 mm, and [Tables 5a](#) and [5b](#) contain the values for shafts and [Tables 6a](#) and [6b](#) for holes. Uppercase (capital) letters designate hole deviations, and the same letters in lower case designate shaft deviations. The deviation  $j_s$  ( $J_s$  for holes) is provided to meet the need for symmetrical bilateral tolerances. In this instance, there is no fundamental deviation, and the tolerance zone, of whatever magnitude, is equally disposed about the zero line.

**Calculated Limits of Tolerance.**—The deviations and fundamental tolerances provided by the ISO system can be combined in any way that appears necessary to give a required fit. Thus, for example, the deviations H (basic hole) and f (clearance shaft) could be associated, and with each of these deviations any one of the tolerance grades IT01 to IT16 could

be used. All the limits of tolerance that the system is capable of providing for sizes up to and including 500 mm can be calculated from the standard tolerances given in [Table 4](#), and the fundamental deviations given in [Tables 5a](#), [5b](#), [6a](#) and [6b](#). The range includes limits of tolerance for shafts and holes used in small high-precision work and horology.

The system provides for the use of either hole-basis or shaft-basis fits, and the Standard includes details of procedures for converting from one type of fit to the other.

The limits of tolerance for a shaft or hole are designated by the appropriate letter indicating the fundamental deviation, followed by a suffix number denoting the tolerance grade. This suffix number is the numerical part of the tolerance grade designation. Thus, a hole tolerance with deviation H and tolerance grade IT7 is designated H7. Likewise, a shaft with deviation p and tolerance grade IT6 is designated p6. The limits of size of a component feature are defined by the basic size, say, 45 mm, followed by the appropriate tolerance designation, for example, 45 H7 or 45 p6. A fit is indicated by combining the basic size common to both features with the designation appropriate to each of them, for example, 45 H7-p6 or 45 H7/p6.

When calculating the limits of size for a shaft, the upper deviation  $e_s$ , or the lower deviation  $e_i$ , is first obtained from [Tables 5a](#) or [5b](#), depending on the particular letter designation, and nominal dimension. If an upper deviation has been determined, the lower deviation  $e_i = e_s - IT$ . The IT value is obtained from [Table 4](#) for the particular tolerance grade being applied. If a lower deviation has been obtained from [Tables 5a](#) or [5b](#), the upper deviation  $e_s = e_i + IT$ . When the upper deviation ES has been determined for a hole from [Tables 6a](#) or [6b](#), the lower deviation EI = ES - IT. If a lower deviation EI has been obtained from [Table 6a](#), then the upper deviation ES = EI + IT.

The upper deviations for holes K, M, and N with tolerance grades up to and including IT8, and for holes P to ZC with tolerance grades up to and including IT7 must be calculated by adding the delta ( $\Delta$ ) values given in [Table 6b](#) as indicated.

*Example 1:* The limits of size for a part of 133 mm basic size with a tolerance designation g9 are derived as follows:

From [Table 5a](#), the upper deviation ( $e_s$ ) is  $-0.014$  mm. From [Table 4](#), the tolerance grade (IT9) is 0.100 mm. The lower deviation ( $e_i$ ) =  $e_s - IT = 0.114$  mm, and the limits of size are thus 132.986 and 132.886 mm.

*Example 2:* The limits of size for a part 20 mm in size, with tolerance designation D3, are derived as follows: From [Table 6a](#), the lower deviation (EI) is  $+0.065$  mm. From [Table 4](#), the tolerance grade (IT3) is 0.004 mm. The upper deviation (ES) =  $EI + IT = 0.069$  mm, and thus the limits of size for the part are 20.069 and 20.065 mm.

*Example 3:* The limits of size for a part 32 mm in size, with tolerance designation M5, which involves a delta value, are obtained as follows: From [Table 6a](#), the upper deviation ES is  $-0.009$  mm +  $\Delta = -0.005$  mm. (The delta value given at the end of [Table 6b](#) for this size and grade IT5 is 0.004 mm.) From [Table 4](#), the tolerance grade (IT5) is 0.011 mm. The lower deviation (EI) =  $ES - IT = -0.016$  mm, and thus the limits of size for the part are 31.995 and 31.984 mm.

Where the designations h and H or  $j_s$  and  $J_s$  are used, it is only necessary to refer to [Table 4](#). For h and H, the fundamental deviation is always zero, and the disposition of the tolerance is always negative ( - ) for a shaft, and positive ( + ) for a hole.

*Example 4:* The limits for a part 40 mm in size, designated h8 are derived as follows: From [Table 4](#), the tolerance grade (IT8) is 0.039 mm, and the limits are therefore 40.000 and 39.961 mm.

*Example 5:* The limits for a part 60 mm in size, designated  $j_s7$  or  $J_s7$  are derived as follows: From [Table 4](#), the tolerance grade (IT7) is 0.030 mm, and this value is divided equally about the basic size to give limits of 60.015 and 59.985 mm.

**Table 1. British Standard Limits of Tolerance for Selected Holes (Upper and Lower Deviations) BS 4500:1969**

| Nominal Sizes, mm |                     | H7   |    | H8   |    | H9   |    | H11  |    |
|-------------------|---------------------|------|----|------|----|------|----|------|----|
| Over              | Up to and Including | ES + | EI | ES + | EI | ES + | EI | ES + | EI |
| ...               | 3                   | 10   | 0  | 14   | 0  | 25   | 0  | 60   | 0  |
| 3                 | 6                   | 12   | 0  | 18   | 0  | 30   | 0  | 75   | 0  |
| 6                 | 10                  | 15   | 0  | 22   | 0  | 36   | 0  | 90   | 0  |
| 10                | 18                  | 18   | 0  | 27   | 0  | 43   | 0  | 110  | 0  |
| 18                | 30                  | 21   | 0  | 33   | 0  | 52   | 0  | 130  | 0  |
| 30                | 50                  | 25   | 0  | 39   | 0  | 62   | 0  | 160  | 0  |
| 50                | 80                  | 30   | 0  | 46   | 0  | 74   | 0  | 190  | 0  |
| 80                | 120                 | 35   | 0  | 54   | 0  | 87   | 0  | 220  | 0  |
| 120               | 180                 | 40   | 0  | 63   | 0  | 100  | 0  | 250  | 0  |
| 180               | 250                 | 46   | 0  | 72   | 0  | 115  | 0  | 290  | 0  |
| 250               | 315                 | 52   | 0  | 81   | 0  | 130  | 0  | 320  | 0  |
| 315               | 400                 | 57   | 0  | 89   | 0  | 140  | 0  | 360  | 0  |
| 400               | 500                 | 63   | 0  | 97   | 0  | 155  | 0  | 400  | 0  |

ES = Upper deviation, EI = Lower deviation.

The dimensions are given in 0.001 mm, except for the nominal sizes, which are in millimeters.

**Table 2. British Standard Limits of Tolerance for Selected Shafts (Upper and Lower Deviations) BS 4500:1969**

| Nominal Sizes, mm |                 | c11  |      | d10  |      | e9   |      | f7   |      | g6   |      | h6   |      | k6   |      | n6   |      | p6   |      | s6   |      |
|-------------------|-----------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Over              | Up to and Incl. | es - | ei - | es - | ei - | es - | ei - | es - | ei - | es - | ei - | es - | ei - | es + | ei + | es + | ei + | es + | ei + | es + | ei + |
| ...               | 3               | 60   | 120  | 20   | 60   | 14   | 39   | 6    | 16   | 2    | 8    | 0    | 6    | 6    | 0    | 10   | 4    | 12   | 6    | 20   | 14   |
| 3                 | 6               | 70   | 145  | 30   | 78   | 20   | 50   | 10   | 22   | 4    | 12   | 0    | 8    | 9    | 1    | 16   | 8    | 20   | 12   | 27   | 19   |
| 6                 | 10              | 80   | 170  | 40   | 98   | 25   | 61   | 13   | 28   | 5    | 14   | 0    | 9    | 10   | 1    | 19   | 10   | 24   | 15   | 32   | 23   |
| 10                | 18              | 95   | 205  | 50   | 120  | 32   | 75   | 16   | 34   | 6    | 17   | 0    | 11   | 12   | 1    | 23   | 12   | 29   | 18   | 39   | 28   |
| 18                | 30              | 110  | 240  | 65   | 149  | 40   | 92   | 20   | 41   | 7    | 20   | 0    | 13   | 15   | 2    | 28   | 15   | 35   | 22   | 48   | 35   |
| 30                | 40              | 120  | 280  | 80   | 180  | 50   | 112  | 25   | 50   | 9    | 25   | 0    | 16   | 18   | 2    | 33   | 17   | 42   | 26   | 59   | 43   |
| 40                | 50              | 130  | 290  | 80   | 180  | 50   | 112  | 25   | 50   | 9    | 25   | 0    | 16   | 18   | 2    | 33   | 17   | 42   | 26   | 59   | 43   |
| 50                | 65              | 140  | 330  | 100  | 220  | 60   | 134  | 30   | 60   | 10   | 29   | 0    | 19   | 21   | 2    | 39   | 20   | 51   | 32   | 72   | 53   |
| 65                | 80              | 150  | 340  | 100  | 220  | 60   | 134  | 30   | 60   | 10   | 29   | 0    | 19   | 21   | 2    | 39   | 20   | 51   | 32   | 78   | 59   |
| 80                | 100             | 170  | 390  | 120  | 260  | 72   | 159  | 36   | 71   | 12   | 34   | 0    | 22   | 25   | 3    | 45   | 23   | 59   | 37   | 93   | 71   |
| 100               | 120             | 180  | 400  | 120  | 260  | 72   | 159  | 36   | 71   | 12   | 34   | 0    | 22   | 25   | 3    | 45   | 23   | 59   | 37   | 101  | 79   |
| 120               | 140             | 200  | 450  | 145  | 305  | 85   | 185  | 43   | 83   | 14   | 39   | 0    | 25   | 28   | 3    | 52   | 27   | 68   | 43   | 117  | 92   |
| 140               | 160             | 210  | 460  | 145  | 305  | 85   | 185  | 43   | 83   | 14   | 39   | 0    | 25   | 28   | 3    | 52   | 27   | 68   | 43   | 125  | 100  |
| 160               | 180             | 230  | 480  | 145  | 305  | 85   | 185  | 43   | 83   | 14   | 39   | 0    | 25   | 28   | 3    | 52   | 27   | 68   | 43   | 133  | 108  |
| 180               | 200             | 240  | 530  | 170  | 355  | 100  | 215  | 50   | 96   | 15   | 44   | 0    | 29   | 33   | 4    | 60   | 31   | 79   | 50   | 151  | 122  |
| 200               | 225             | 260  | 550  | 170  | 355  | 100  | 215  | 50   | 96   | 15   | 44   | 0    | 29   | 33   | 4    | 60   | 31   | 79   | 50   | 159  | 130  |
| 225               | 250             | 280  | 570  | 170  | 355  | 100  | 215  | 50   | 96   | 15   | 44   | 0    | 29   | 33   | 4    | 60   | 31   | 79   | 50   | 169  | 140  |
| 250               | 280             | 300  | 620  | 190  | 400  | 110  | 240  | 56   | 108  | 17   | 49   | 0    | 32   | 36   | 4    | 66   | 34   | 88   | 56   | 190  | 158  |
| 280               | 315             | 330  | 650  | 190  | 400  | 110  | 240  | 56   | 108  | 17   | 49   | 0    | 32   | 36   | 4    | 66   | 34   | 88   | 56   | 202  | 170  |
| 315               | 355             | 360  | 720  | 210  | 440  | 125  | 265  | 62   | 119  | 18   | 54   | 0    | 36   | 40   | 4    | 73   | 37   | 98   | 62   | 226  | 190  |
| 355               | 400             | 400  | 760  | 210  | 440  | 125  | 265  | 62   | 119  | 18   | 54   | 0    | 36   | 40   | 4    | 73   | 37   | 98   | 62   | 244  | 208  |
| 400               | 450             | 440  | 840  | 230  | 480  | 135  | 290  | 68   | 131  | 20   | 60   | 0    | 40   | 45   | 5    | 80   | 40   | 108  | 68   | 272  | 232  |
| 450               | 500             | 480  | 880  | 230  | 480  | 135  | 290  | 68   | 131  | 20   | 60   | 0    | 40   | 45   | 5    | 80   | 40   | 108  | 68   | 292  | 252  |

es = Upper deviation, ei = Lower deviation.

The dimensions are given in 0.001 mm, except for the nominal sizes, which are in millimeters.

Table 3. British Standard Selected Fits, Minimum and Maximum Clearances BS 4500:1969

| Nominal Sizes,<br>mm |                    | H11—c11 |      | H9—d10 |     | H9—e9 |     | H8—f7 |     | H7—g6 |     | H7—h6 |     | H7—k6 |     | H7—n6 |     | H7—p6 |     | H7—s6 |      |
|----------------------|--------------------|---------|------|--------|-----|-------|-----|-------|-----|-------|-----|-------|-----|-------|-----|-------|-----|-------|-----|-------|------|
| Over                 | Up to and<br>Incl. | Min     | Max  | Min    | Max | Min   | Max | Min   | Max | Min   | Max | Min   | Max | Min   | Max | Min   | Max | Min   | Max | Min   | Max  |
| ...                  | 3                  | 60      | 180  | 20     | 85  | 14    | 64  | 6     | 30  | 2     | 18  | 0     | 16  | -6    | +10 | -10   | +6  | -12   | +4  | -20   | -4   |
| 3                    | 6                  | 70      | 220  | 30     | 108 | 20    | 80  | 10    | 40  | 4     | 24  | 0     | 20  | -9    | +11 | -16   | +4  | -20   | 0   | -27   | -7   |
| 6                    | 10                 | 80      | 260  | 40     | 134 | 25    | 97  | 13    | 50  | 5     | 29  | 0     | 24  | -10   | +14 | -19   | +5  | -24   | 0   | -32   | -8   |
| 10                   | 18                 | 95      | 315  | 50     | 163 | 32    | 118 | 16    | 61  | 6     | 35  | 0     | 29  | -12   | +17 | -23   | +6  | -29   | 0   | -39   | -10  |
| 18                   | 30                 | 110     | 370  | 65     | 201 | 40    | 144 | 20    | 74  | 7     | 41  | 0     | 34  | -15   | +19 | -28   | +6  | -35   | -1  | -48   | -14  |
| 30                   | 40                 | 120     | 440  | 80     | 242 | 50    | 174 | 25    | 89  | 9     | 50  | 0     | 41  | -18   | +23 | -33   | +8  | -42   | -1  | -59   | -18  |
| 40                   | 50                 | 130     | 450  | 80     | 242 | 50    | 174 | 25    | 89  | 9     | 50  | 0     | 41  | -18   | +23 | -33   | +8  | -42   | -1  | -59   | -18  |
| 50                   | 65                 | 140     | 520  | 100    | 294 | 60    | 208 | 30    | 106 | 10    | 59  | 0     | 49  | -21   | +28 | -39   | +10 | -51   | -2  | -72   | -23  |
| 65                   | 80                 | 150     | 530  | 100    | 294 | 60    | 208 | 30    | 106 | 10    | 59  | 0     | 49  | -21   | +28 | -39   | +10 | -51   | -2  | -78   | -29  |
| 80                   | 100                | 170     | 610  | 120    | 347 | 72    | 246 | 36    | 125 | 12    | 69  | 0     | 57  | -25   | +32 | -45   | +12 | -59   | -2  | -93   | -36  |
| 100                  | 120                | 180     | 620  | 120    | 347 | 72    | 246 | 36    | 125 | 12    | 69  | 0     | 57  | -25   | +32 | -45   | +12 | -59   | -2  | -101  | -44  |
| 120                  | 140                | 200     | 700  | 145    | 405 | 85    | 285 | 43    | 146 | 14    | 79  | 0     | 65  | -28   | +37 | -52   | +13 | -68   | -3  | -117  | -52  |
| 140                  | 160                | 210     | 710  | 145    | 405 | 85    | 285 | 43    | 146 | 14    | 79  | 0     | 65  | -28   | +37 | -52   | +13 | -68   | -3  | -125  | -60  |
| 160                  | 180                | 230     | 730  | 145    | 405 | 85    | 285 | 43    | 146 | 14    | 79  | 0     | 65  | -28   | +37 | -52   | +13 | -68   | -3  | -133  | -68  |
| 180                  | 200                | 240     | 820  | 170    | 470 | 100   | 330 | 50    | 168 | 15    | 90  | 0     | 75  | -33   | +42 | -60   | +15 | -79   | -4  | -151  | -76  |
| 200                  | 225                | 260     | 840  | 170    | 470 | 100   | 330 | 50    | 168 | 15    | 90  | 0     | 75  | -33   | +42 | -60   | +15 | -79   | -4  | -159  | -84  |
| 225                  | 250                | 280     | 860  | 170    | 470 | 100   | 330 | 50    | 168 | 15    | 90  | 0     | 75  | -33   | +42 | -60   | +15 | -79   | -4  | -169  | -94  |
| 250                  | 280                | 300     | 940  | 190    | 530 | 110   | 370 | 56    | 189 | 17    | 101 | 0     | 84  | -36   | +48 | -66   | +18 | -88   | -4  | -190  | -126 |
| 280                  | 315                | 330     | 970  | 190    | 530 | 110   | 370 | 56    | 189 | 17    | 101 | 0     | 84  | -36   | +48 | -66   | +18 | -88   | -4  | -202  | -112 |
| 315                  | 355                | 360     | 1080 | 210    | 580 | 125   | 405 | 62    | 208 | 18    | 111 | 0     | 93  | -40   | -53 | -73   | +20 | -98   | -5  | -226  | -133 |
| 355                  | 400                | 400     | 1120 | 210    | 580 | 125   | 405 | 62    | 208 | 18    | 111 | 0     | 93  | -40   | -53 | -73   | +20 | -98   | -5  | -244  | -151 |
| 400                  | 450                | 440     | 1240 | 230    | 635 | 135   | 445 | 68    | 228 | 20    | 123 | 0     | 103 | -45   | +58 | -80   | +23 | -108  | -5  | -272  | -169 |
| 450                  | 500                | 480     | 1280 | 230    | 635 | 135   | 445 | 68    | 228 | 20    | 123 | 0     | 103 | -45   | +58 | -80   | +23 | -108  | -5  | -292  | -189 |

The dimensions are given in 0.001 mm, except for the nominal sizes, which are in millimeters.

Minus (-) sign indicates negative clearance, i.e., interference.



**Table 4. British Standard Limits and Fits BS 4500:1969**

| Nominal Sizes, mm |     | Tolerance Grades |      |      |      |      |      |      |      |      |      |      |       |       |       |       |                    |                    |                    |
|-------------------|-----|------------------|------|------|------|------|------|------|------|------|------|------|-------|-------|-------|-------|--------------------|--------------------|--------------------|
| Over              | To  | IT 01            | IT 0 | IT 1 | IT 2 | IT 3 | IT 4 | IT 5 | IT 6 | IT 7 | IT 8 | IT 9 | IT 10 | IT 11 | IT 12 | IT 13 | IT 14 <sup>a</sup> | IT 15 <sup>a</sup> | IT 16 <sup>a</sup> |
| ...               | 3   | 0.3              | 0.5  | 0.8  | 1.2  | 2    | 3    | 4    | 6    | 10   | 14   | 25   | 40    | 60    | 100   | 140   | 250                | 400                | 600                |
| 3                 | 6   | 0.4              | 0.6  | 1    | 1.5  | 2.5  | 4    | 5    | 8    | 12   | 18   | 30   | 48    | 75    | 120   | 180   | 300                | 480                | 750                |
| 6                 | 10  | 0.4              | 0.6  | 1    | 1.5  | 2.5  | 4    | 6    | 9    | 15   | 22   | 36   | 58    | 90    | 150   | 220   | 360                | 580                | 900                |
| 10                | 18  | 0.5              | 0.8  | 1.2  | 2    | 3    | 5    | 8    | 11   | 18   | 27   | 43   | 70    | 110   | 180   | 270   | 430                | 700                | 1100               |
| 18                | 30  | 0.6              | 1    | 1.5  | 2.5  | 4    | 6    | 9    | 13   | 21   | 33   | 52   | 84    | 130   | 210   | 330   | 520                | 840                | 1300               |
| 30                | 50  | 0.6              | 1    | 1.5  | 2.5  | 4    | 7    | 11   | 16   | 25   | 39   | 62   | 100   | 160   | 250   | 390   | 620                | 1000               | 1600               |
| 50                | 80  | 0.8              | 1.2  | 2    | 3    | 5    | 8    | 13   | 19   | 30   | 46   | 74   | 120   | 190   | 300   | 460   | 740                | 1200               | 1900               |
| 80                | 120 | 1                | 1.5  | 2.5  | 4    | 6    | 10   | 15   | 22   | 35   | 54   | 87   | 140   | 220   | 350   | 540   | 870                | 1400               | 2200               |
| 120               | 180 | 1.2              | 2    | 3.5  | 5    | 8    | 12   | 18   | 25   | 40   | 63   | 100  | 160   | 250   | 400   | 630   | 1000               | 1600               | 2500               |
| 180               | 250 | 2                | 3    | 4.5  | 7    | 10   | 14   | 20   | 29   | 46   | 72   | 115  | 185   | 290   | 460   | 720   | 1150               | 1850               | 2900               |
| 250               | 315 | 2.5              | 4    | 6    | 8    | 12   | 16   | 23   | 32   | 52   | 81   | 130  | 210   | 320   | 520   | 810   | 1300               | 2100               | 3200               |
| 315               | 400 | 3                | 5    | 7    | 9    | 13   | 18   | 25   | 36   | 57   | 89   | 140  | 230   | 360   | 570   | 890   | 1400               | 2300               | 3600               |
| 400               | 500 | 4                | 6    | 8    | 10   | 15   | 20   | 27   | 40   | 63   | 97   | 155  | 250   | 400   | 630   | 970   | 1550               | 2500               | 4000               |

<sup>a</sup>Not applicable to sizes below 1 mm.

The dimensions are given in 0.001 mm, except for the nominal sizes which are in millimeters.

Table 5a. British Standard Fundamental Deviations for Shafts BS 4500:1969

| Nominal<br>Sizes, mm |     | Grade                            |                |      |     |      |      |     |     |     |     |   |                 |                                  |     |     |     |       |
|----------------------|-----|----------------------------------|----------------|------|-----|------|------|-----|-----|-----|-----|---|-----------------|----------------------------------|-----|-----|-----|-------|
|                      |     | 01 to 16                         |                |      |     |      |      |     |     |     |     |   |                 | 5-6                              | 7   | 8   | 4-7 | ≤3 >7 |
|                      |     | Fundamental (Upper) Deviation es |                |      |     |      |      |     |     |     |     |   |                 | Fundamental (Lower) Deviation ei |     |     |     |       |
| Over                 | To  | a <sup>a</sup>                   | b <sup>a</sup> | c    | cd  | d    | e    | ef  | f   | fg  | g   | h | js <sup>b</sup> | j                                |     |     | k   |       |
| ...                  | 3   | -270                             | -140           | -60  | -34 | -20  | -14  | -10 | -6  | -4  | -2  | 0 | ±IT/2           | -2                               | -4  | -6  | 0   | 0     |
| 3                    | 6   | -270                             | -140           | -70  | -46 | -30  | -20  | -14 | -10 | -6  | -4  | 0 |                 | -2                               | -4  | ... | +1  | 0     |
| 6                    | 10  | -280                             | -150           | -80  | -56 | -40  | -25  | -18 | -13 | -8  | -5  | 0 |                 | -2                               | -5  | ... | +1  | 0     |
| 10                   | 14  | -290                             | -150           | -95  | ... | -50  | -32  | ... | -16 | ... | -6  | 0 |                 | -3                               | -6  | ... | +1  | 0     |
| 14                   | 18  | -290                             | -150           | -95  | ... | -50  | -32  | ... | -16 | ... | -6  | 0 |                 | -3                               | -6  | ... | +1  | 0     |
| 18                   | 24  | -300                             | -160           | -110 | ... | -65  | -40  | ... | -20 | ... | -7  | 0 |                 | -4                               | -8  | ... | +2  | 0     |
| 24                   | 30  | -300                             | -160           | -110 | ... | -65  | -40  | ... | -20 | ... | -7  | 0 |                 | -4                               | -8  | ... | +2  | 0     |
| 30                   | 40  | -310                             | -170           | -120 | ... | -80  | -50  | ... | -25 | ... | -9  | 0 |                 | -5                               | -10 | ... | +2  | 0     |
| 40                   | 50  | -320                             | -180           | -130 | ... | -80  | -50  | ... | -25 | ... | -9  | 0 |                 | -5                               | -10 | ... | +2  | 0     |
| 50                   | 65  | -340                             | -190           | -140 | ... | -100 | -60  | ... | -30 | ... | -10 | 0 |                 | -7                               | -12 | ... | +2  | 0     |
| 65                   | 80  | -360                             | -200           | -150 | ... | -100 | -60  | ... | -30 | ... | -10 | 0 |                 | -7                               | -12 | ... | +2  | 0     |
| 80                   | 100 | -380                             | -220           | -170 | ... | -120 | -72  | ... | -36 | ... | -12 | 0 |                 | -9                               | -15 | ... | +3  | 0     |
| 100                  | 120 | -410                             | -240           | -180 | ... | -120 | -72  | ... | -36 | ... | -12 | 0 |                 | -9                               | -15 | ... | +3  | 0     |
| 120                  | 140 | -460                             | -260           | -200 | ... | -145 | -85  | ... | -43 | ... | -14 | 0 |                 | -11                              | -18 | ... | +3  | 0     |
| 140                  | 160 | -520                             | -280           | -210 | ... | -145 | -85  | ... | -43 | ... | -14 | 0 |                 | -11                              | -18 | ... | +3  | 0     |
| 160                  | 180 | -580                             | -310           | -230 | ... | -145 | -85  | ... | -43 | ... | -14 | 0 |                 | -11                              | -18 | ... | +3  | 0     |
| 180                  | 200 | -660                             | -340           | -240 | ... | -170 | -100 | ... | -50 | ... | -15 | 0 |                 | -13                              | -21 | ... | +4  | 0     |
| 200                  | 225 | -740                             | -380           | -260 | ... | -170 | -100 | ... | -50 | ... | -15 | 0 |                 | -13                              | -21 | ... | +4  | 0     |
| 225                  | 250 | -820                             | -420           | -280 | ... | -170 | -100 | ... | -50 | ... | -15 | 0 |                 | -13                              | -21 | ... | +4  | 0     |
| 250                  | 280 | -920                             | -480           | -300 | ... | -190 | -110 | ... | -56 | ... | -17 | 0 |                 | -16                              | -26 | ... | +4  | 0     |
| 280                  | 315 | -1050                            | -540           | -330 | ... | -190 | -110 | ... | -56 | ... | -17 | 0 | -16             | -26                              | ... | +4  | 0   |       |
| 315                  | 355 | -1200                            | -600           | -360 | ... | -210 | -125 | ... | -62 | ... | -18 | 0 | -18             | -28                              | ... | +4  | 0   |       |
| 355                  | 400 | -1350                            | -680           | -400 | ... | -210 | -125 | ... | -62 | ... | -18 | 0 | -18             | -28                              | ... | +4  | 0   |       |
| 400                  | 450 | -1500                            | -760           | -440 | ... | -230 | -135 | ... | -68 | ... | -20 | 0 | -20             | -32                              | ... | +5  | 0   |       |
| 450                  | 500 | -1650                            | -840           | -480 | ... | -230 | -135 | ... | -68 | ... | -20 | 0 | -20             | -32                              | ... | +5  | 0   |       |

<sup>a</sup>Not applicable to sizes up to 1 mm.

<sup>b</sup>In grades 7 to 11, the two symmetrical deviations ±IT/2 should be rounded if the IT value in micrometers is an odd value by replacing it with the even value immediately below. For example, if IT = 175, replace it by 174.

Table 5b. British Standard Fundamental Deviations for Shafts BS 4500:1969

| Nominal<br>Sizes, mm |     | Grade                            |     |     |      |      |      |      |      |      |       |       |       |       |       |
|----------------------|-----|----------------------------------|-----|-----|------|------|------|------|------|------|-------|-------|-------|-------|-------|
|                      |     | 01 to 16                         |     |     |      |      |      |      |      |      |       |       |       |       |       |
|                      |     | Fundamental (Lower) Deviation ei |     |     |      |      |      |      |      |      |       |       |       |       |       |
| Over                 | To  | m                                | n   | p   | r    | s    | t    | u    | v    | x    | y     | z     | za    | zb    | zc    |
| ...                  | 3   | +2                               | +4  | +6  | +10  | +14  | ...  | +18  | ...  | +20  | ...   | +26   | +32   | +40   | +60   |
| 3                    | 6   | +4                               | +8  | +12 | +15  | +19  | ...  | +23  | ...  | +28  | ...   | +35   | +42   | +50   | +80   |
| 6                    | 10  | +6                               | +10 | +15 | +19  | +23  | ...  | +28  | ...  | +34  | ...   | +42   | +52   | +67   | +97   |
| 10                   | 14  | +7                               | +12 | +18 | +23  | +28  | ...  | +33  | ...  | +40  | ...   | +50   | +64   | +90   | +130  |
| 14                   | 18  | +7                               | +12 | +18 | +23  | +28  | ...  | +33  | +39  | +45  | ...   | +60   | +77   | +108  | +150  |
| 18                   | 24  | +8                               | +15 | +22 | +28  | +35  | ...  | +41  | +47  | +54  | +63   | +73   | +98   | +136  | +188  |
| 24                   | 30  | +8                               | +15 | +22 | +28  | +35  | +41  | +48  | +55  | +64  | +75   | +88   | +118  | +160  | +218  |
| 30                   | 40  | +9                               | +17 | +26 | +34  | +43  | +48  | +60  | +68  | +80  | +94   | +112  | +148  | +200  | +274  |
| 40                   | 50  | +9                               | +17 | +26 | +34  | +43  | +54  | +70  | +81  | +97  | +114  | +136  | +180  | +242  | +325  |
| 50                   | 65  | +11                              | +20 | +32 | +41  | +53  | +66  | +87  | +102 | +122 | +144  | +172  | +226  | +300  | +405  |
| 65                   | 80  | +11                              | +20 | +32 | +43  | +59  | +75  | +102 | +120 | +146 | +174  | +210  | +274  | +360  | +480  |
| 80                   | 100 | +13                              | +23 | +37 | +51  | +71  | +91  | +124 | +146 | +178 | +214  | +258  | +335  | +445  | +585  |
| 100                  | 120 | +13                              | +23 | +37 | +54  | +79  | +104 | +144 | +172 | +210 | +254  | +310  | +400  | +525  | +690  |
| 120                  | 140 | +15                              | +27 | +43 | +63  | +92  | +122 | +170 | +202 | +248 | +300  | +365  | +470  | +620  | +800  |
| 140                  | 160 | +15                              | +27 | +43 | +65  | +100 | +134 | +190 | +228 | +280 | +340  | +415  | +535  | +700  | +900  |
| 160                  | 180 | +15                              | +27 | +43 | +68  | +108 | +146 | +210 | +252 | +310 | +380  | +465  | +600  | +780  | +1000 |
| 180                  | 200 | +17                              | +31 | +50 | +77  | +122 | +166 | +236 | +284 | +350 | +425  | +520  | +670  | +880  | +1150 |
| 200                  | 225 | +17                              | +31 | +50 | +80  | +130 | +180 | +258 | +310 | +385 | +470  | +575  | +740  | +960  | +1250 |
| 225                  | 250 | +17                              | +31 | +50 | +84  | +140 | +196 | +284 | +340 | +425 | +520  | +640  | +820  | +1050 | +1350 |
| 250                  | 280 | +20                              | +34 | +56 | +94  | +158 | +218 | +315 | +385 | +475 | +580  | +710  | +920  | +1200 | +1550 |
| 280                  | 315 | +20                              | +34 | +56 | +98  | +170 | +240 | +350 | +425 | +525 | +650  | +790  | +1000 | +1300 | +1700 |
| 315                  | 355 | +21                              | +37 | +62 | +108 | +190 | +268 | +390 | +475 | +590 | +730  | +900  | +1150 | +1500 | +1900 |
| 355                  | 400 | +21                              | +37 | +62 | +114 | +208 | +294 | +435 | +530 | +660 | +820  | +1000 | +1300 | +1650 | +2100 |
| 400                  | 450 | +23                              | +40 | +68 | +126 | +232 | +330 | +490 | +595 | +740 | +920  | +1100 | +1450 | +1850 | +2400 |
| 450                  | 500 | +23                              | +40 | +68 | +132 | +252 | +360 | +540 | +660 | +820 | +1000 | +1250 | +1600 | +2100 | +2600 |

The dimensions are in 0.001 mm, except the nominal sizes, which are in millimeters.

Table 6a. British Standard Fundamental Deviations for Holes BS 4500:1969

| Nominal<br>Sizes, mm |     | Grade                            |                |      |     |      |      |     |     |     |     |   |                                  |     |     |     |                |                 |                |     |                 |                |    |   |
|----------------------|-----|----------------------------------|----------------|------|-----|------|------|-----|-----|-----|-----|---|----------------------------------|-----|-----|-----|----------------|-----------------|----------------|-----|-----------------|----------------|----|---|
|                      |     | 01 to 16                         |                |      |     |      |      |     |     |     |     |   | 6                                | 7   | 8   | ≤8  | >8             | ≤8 <sup>a</sup> | >8             | ≤8  | >8 <sup>b</sup> |                |    |   |
|                      |     | Fundamental (Lower) Deviation EI |                |      |     |      |      |     |     |     |     |   | Fundamental (Upper) Deviation ES |     |     |     |                |                 |                |     |                 |                |    |   |
| Over                 | To  | A <sup>b</sup>                   | B <sup>b</sup> | C    | CD  | D    | E    | EF  | F   | FG  | G   | H | J <sup>c</sup>                   | J   |     |     | K <sup>d</sup> |                 | M <sup>d</sup> |     |                 | N <sup>d</sup> |    |   |
| ...                  | 3   | +270                             | +140           | +60  | +34 | +20  | +14  | +10 | +6  | +4  | +2  | 0 |                                  | +2  | +4  | +6  | 0              | 0               | -2             | -2  | -4              | -4             | -4 | 0 |
| 3                    | 6   | +270                             | +140           | +70  | +46 | +30  | +20  | +14 | +10 | +6  | +4  | 0 |                                  | +5  | +6  | +10 | -1+Δ           | ...             | -4+Δ           | -4  | -8+Δ            | 0              | 0  |   |
| 6                    | 10  | +280                             | +150           | +80  | +56 | +40  | +25  | +18 | +13 | +8  | +5  | 0 |                                  | +5  | +8  | +12 | -1+Δ           | ...             | -6+Δ           | -6  | -10+Δ           | 0              | 0  |   |
| 10                   | 14  | +290                             | +150           | +95  | ... | +50  | +32  | ... | +16 | ... | +6  | 0 |                                  | +6  | +10 | +15 | -1+Δ           | ...             | -7+Δ           | -7  | -12+Δ           | 0              | 0  |   |
| 14                   | 18  | +290                             | +150           | +95  | ... | +50  | +32  | ... | +16 | ... | +6  | 0 |                                  | +6  | +10 | +15 | -1+Δ           | ...             | -7+Δ           | -7  | -12+Δ           | 0              | 0  |   |
| 18                   | 24  | +300                             | +160           | +110 | ... | +65  | +40  | ... | +20 | ... | +7  | 0 |                                  | +8  | +12 | +20 | -2+Δ           | ...             | -8+Δ           | -8  | -15+Δ           | 0              | 0  |   |
| 24                   | 30  | +300                             | +160           | +110 | ... | +65  | +40  | ... | +20 | ... | +7  | 0 |                                  | +8  | +12 | +20 | -2+Δ           | ...             | -8+Δ           | -8  | -15+Δ           | 0              | 0  |   |
| 30                   | 40  | +310                             | +170           | +120 | ... | +80  | +50  | ... | +25 | ... | +9  | 0 |                                  | +10 | +14 | +24 | -2+Δ           | ...             | -9+Δ           | -9  | -17+Δ           | 0              | 0  |   |
| 40                   | 50  | +320                             | +180           | +130 | ... | +80  | +50  | ... | +25 | ... | +9  | 0 |                                  | +10 | +14 | +24 | -2+Δ           | ...             | -9+Δ           | -9  | -17+Δ           | 0              | 0  |   |
| 50                   | 65  | +340                             | +190           | +140 | ... | +100 | +60  | ... | +30 | ... | +10 | 0 |                                  | +13 | +18 | +28 | -2+Δ           | ...             | -11+Δ          | -11 | -20+Δ           | 0              | 0  |   |
| 65                   | 80  | +360                             | +200           | +150 | ... | +100 | +60  | ... | +30 | ... | +10 | 0 |                                  | +13 | +18 | +28 | -2+Δ           | ...             | -11+Δ          | -11 | -20+Δ           | 0              | 0  |   |
| 80                   | 100 | +380                             | +220           | +170 | ... | +120 | +72  | ... | +36 | ... | +12 | 0 |                                  | +16 | +22 | +34 | -3+Δ           | ...             | -13+Δ          | -13 | -23+Δ           | 0              | 0  |   |
| 100                  | 120 | +410                             | +240           | +180 | ... | +120 | +72  | ... | +36 | ... | +12 | 0 | ±IT/2                            | +16 | +22 | +34 | -3+Δ           | ...             | -13+Δ          | -13 | -23+Δ           | 0              | 0  |   |
| 120                  | 140 | +460                             | +260           | +200 | ... | +145 | +85  | ... | +43 | ... | +14 | 0 |                                  | +18 | +26 | +41 | -3+Δ           | ...             | -15+Δ          | -15 | -27+Δ           | 0              | 0  |   |
| 140                  | 160 | +520                             | +280           | +210 | ... | +145 | +85  | ... | +43 | ... | +14 | 0 |                                  | +18 | +26 | +41 | -3+Δ           | ...             | -15+Δ          | -15 | -27+Δ           | 0              | 0  |   |
| 160                  | 180 | +580                             | +310           | +230 | ... | +145 | +85  | ... | +43 | ... | +14 | 0 |                                  | +18 | +26 | +41 | -3+Δ           | ...             | -15+Δ          | -15 | -27+Δ           | 0              | 0  |   |
| 180                  | 200 | +660                             | +340           | +240 | ... | +170 | +100 | ... | +50 | ... | +15 | 0 |                                  | +22 | +30 | +47 | -4+Δ           | ...             | -17+Δ          | -17 | -31+Δ           | 0              | 0  |   |
| 200                  | 225 | +740                             | +380           | +260 | ... | +170 | +100 | ... | +50 | ... | +15 | 0 |                                  | +22 | +30 | +47 | -4+Δ           | ...             | -17+Δ          | -17 | -31+Δ           | 0              | 0  |   |
| 225                  | 250 | +820                             | +420           | +280 | ... | +170 | +100 | ... | +50 | ... | +15 | 0 |                                  | +22 | +30 | +47 | -4+Δ           | ...             | -17+Δ          | -17 | -31+Δ           | 0              | 0  |   |
| 250                  | 280 | +920                             | +480           | +300 | ... | +190 | +110 | ... | +56 | ... | +17 | 0 |                                  | +25 | +36 | +55 | -4+Δ           | ...             | -20+Δ          | -20 | -34+Δ           | 0              | 0  |   |
| 280                  | 315 | +1050                            | +540           | +330 | ... | +190 | +110 | ... | +56 | ... | +17 | 0 |                                  | +25 | +36 | +55 | -4+Δ           | ...             | -20+Δ          | -20 | -34+Δ           | 0              | 0  |   |
| 315                  | 355 | +1200                            | +600           | +360 | ... | +210 | +125 | ... | +62 | ... | +18 | 0 |                                  | +29 | +39 | +60 | -4+Δ           | ...             | -21+Δ          | -21 | -37+Δ           | 0              | 0  |   |
| 355                  | 400 | +1350                            | +680           | +400 | ... | +210 | +125 | ... | +62 | ... | +18 | 0 |                                  | +29 | +39 | +60 | -4+Δ           | ...             | -21+Δ          | -21 | -37+Δ           | 0              | 0  |   |
| 400                  | 450 | +1500                            | +760           | +440 | ... | +230 | +135 | ... | +68 | ... | +20 | 0 |                                  | +33 | +43 | +66 | -5+Δ           | ...             | -23+Δ          | -23 | -40+Δ           | 0              | 0  |   |
| 450                  | 500 | +1650                            | +840           | +480 | ... | +230 | +135 | ... | +68 | ... | +20 | 0 |                                  | +33 | +43 | +66 | -5+Δ           | ...             | -23+Δ          | -23 | -40+Δ           | 0              | 0  |   |

<sup>a</sup> Special case: for M6, ES = -9 for sizes from 250 to 315 mm, instead of -11.

<sup>b</sup> Not applicable to sizes up to 1 mm.

<sup>c</sup> In grades 7 to 11, the two symmetrical deviations ±IT/2 should be rounded if the IT value in micrometers is an odd value, by replacing it with the even value below. For example, if IT = 175, replace it by 174.

<sup>d</sup> When calculating deviations for holes K, M, and N with tolerance grades up to and including IT8, and holes F to ZC with tolerance grades up to and including IT7, the delta (Δ) values are added to the upper deviation ES. For example, for 25 P7, ES = -0.022 + 0.008 = -0.014 mm.

Table 6b. British Standard Fundamental Deviations for Holes BS 4500:1969

| Nominal Sizes, mm |     | Grade  |       |      |      |      |      |      |       |       |       |       |       |       | Values for delta ( $\Delta$ ) <sup>1</sup> |     |    |    |    |    |   |
|-------------------|-----|--|-------|------|------|------|------|------|-------|-------|-------|-------|-------|-------|--|-----|----|----|----|----|---|
|                   |     | $\leq 7$   | $> 7$ |      |      |      |      |      |       |       |       |       |       |       |  |     |    |    |    |    |   |
|                   |     | Fundamental (Upper) Deviation ES                           |       |      |      |      |      |      |       |       |       |       |       |       | Grade                                      |     |    |    |    |    |   |
| Over              | To  | P to ZC  | P     | R    | S    | T    | U    | V    | X     | Y     | Z     | ZA    | ZB    | ZC    | 3  | 4   | 5  | 6  | 7  | 8  |   |
| ...               | 3   | Same deviation as for grades above 7 increased by $\Delta$ | -6    | -10  | -14  | ...  | -18  | ...  | -20   | ...   | -26   | -32   | -40   | -60   | 0  | 0   | 0  | 0  | 0  | 0  |   |
| 3                 | 6   |  | -12   | -15  | -19  | ...  | -23  | ...  | -28   | ...   | -35   | -42   | -50   | -80   | 1  | 1.5 | 1  | 3  | 4  | 6  |   |
| 6                 | 10  |  | -15   | -19  | -23  | ...  | -28  | ...  | -34   | ...   | -42   | -52   | -67   | -97   | 1  | 1.5 | 2  | 3  | 6  | 7  |   |
| 10                | 14  |  | -18   | -23  | -28  | ...  | -33  | ...  | -40   | ...   | -50   | -64   | -90   | -130  | 1  | 2   | 3  | 3  | 7  | 9  |   |
| 14                | 18  |  | -18   | -23  | -28  | ...  | -33  | ...  | -39   | -45   | ...   | -60   | -77   | -108  | -150                                       | 1   | 2  | 3  | 3  | 7  | 9 |
| 18                | 24  |  | -22   | -28  | -35  | ...  | -41  | -47  | -54   | -63   | -73   | -98   | -136  | -188  | 1.5  | 2   | 3  | 4  | 8  | 12 |   |
| 24                | 30  |  | -22   | -28  | -35  | -41  | -48  | -55  | -64   | -75   | -88   | -118  | -160  | -218  | 1.5  | 2   | 3  | 4  | 8  | 12 |   |
| 30                | 40  |  | -26   | -34  | -43  | -48  | -60  | -68  | -80   | -94   | -112  | -148  | -200  | -274  | 1.5  | 3   | 4  | 5  | 9  | 14 |   |
| 40                | 50  |  | -26   | -34  | -43  | -54  | -70  | -81  | -97   | -114  | -136  | -180  | -242  | -325  | 1.5  | 3   | 4  | 5  | 9  | 14 |   |
| 50                | 65  |  | -32   | -41  | -53  | -66  | -87  | -102 | -122  | -144  | -172  | -226  | -300  | -405  | 2  | 3   | 5  | 6  | 11 | 16 |   |
| 65                | 80  |  | -32   | -43  | -59  | -75  | -102 | -120 | -146  | -174  | -210  | -274  | -360  | -480  | 2  | 3   | 5  | 6  | 11 | 16 |   |
| 80                | 100 |  | -37   | -51  | -71  | -91  | -124 | -146 | -178  | -214  | -258  | -335  | -445  | -585  | 2  | 4   | 5  | 7  | 13 | 19 |   |
| 100               | 120 |  | -37   | -54  | -79  | -104 | -144 | -172 | -210  | -254  | -310  | -400  | -525  | -690  | 2  | 4   | 5  | 7  | 13 | 19 |   |
| 120               | 140 |  | -43   | -63  | -92  | -122 | -170 | -202 | -248  | -300  | -365  | -470  | -620  | -800  | 3  | 4   | 6  | 7  | 15 | 23 |   |
| 140               | 160 |  | -43   | -65  | -100 | -134 | -190 | -228 | -280  | -340  | -415  | -535  | -700  | -900  | 3  | 4   | 6  | 7  | 15 | 23 |   |
| 160               | 180 |  | -43   | -68  | -108 | -146 | -210 | -252 | -310  | -380  | -465  | -600  | -780  | -1000 | 3  | 4   | 6  | 7  | 15 | 23 |   |
| 180               | 200 |  | -50   | -77  | -122 | -166 | -226 | -284 | -350  | -425  | -520  | -670  | -880  | -1150 | 3  | 4   | 6  | 9  | 17 | 26 |   |
| 200               | 225 |  | -50   | -80  | -130 | -180 | -258 | -310 | -385  | -470  | -575  | -740  | -960  | -1250 | 3  | 4   | 6  | 9  | 17 | 26 |   |
| 225               | 250 |  | -50   | -84  | -140 | -196 | -284 | -340 | -425  | -520  | -640  | -820  | -1050 | -1350 | 3  | 4   | 6  | 9  | 17 | 26 |   |
| 250               | 280 |  | -56   | -94  | -158 | -218 | -315 | -385 | -475  | -580  | -710  | -920  | -1200 | -1550 | 4  | 4   | 7  | 9  | 20 | 29 |   |
| 280               | 315 | -56  | -98   | -170 | -240 | -350 | -425 | -525 | -650  | -790  | -1000 | -1300 | -1700 | 4     | 4  | 7   | 9  | 20 | 29 |    |   |
| 315               | 355 | -62  | -108  | -190 | -268 | -390 | -475 | -590 | -730  | -900  | -1150 | -1500 | -1800 | 4     | 5  | 7   | 11 | 21 | 32 |    |   |
| 355               | 400 | -62  | -114  | -208 | -294 | -435 | -530 | -660 | -820  | -1000 | -1300 | -1650 | -2100 | 4     | 5  | 7   | 11 | 21 | 32 |    |   |
| 400               | 450 | -68  | -126  | -232 | -330 | -490 | -595 | -740 | -920  | -1100 | -1450 | -1850 | -2400 | 5     | 5  | 7   | 13 | 23 | 34 |    |   |
| 450               | 500 | -68  | -132  | -252 | -360 | -540 | -660 | -820 | -1000 | -1250 | -1600 | -2100 | -2600 | 5     | 5  | 7   | 13 | 23 | 34 |    |   |

The dimensions are given in 0.001 mm, except the nominal sizes, which are in millimeters.

### Preferred Numbers

Preferred numbers are series of numbers selected to be used for standardization purposes in preference to any other numbers. Their use will lead to simplified practice and they should be employed whenever possible for individual standard sizes and ratings, or for a series, in applications similar to the following:

1) Important or characteristic linear dimensions, such as diameters and lengths, areas, volume, weights, capacities.

2) Ratings of machinery and apparatus in horsepower, kilowatts, kilovolt-amperes, voltages, currents, speeds, power-factors, pressures, heat units, temperatures, gas or liquid-flow units, weight-handling capacities, etc.

3) Characteristic ratios of figures for all kinds of units.

**American National Standard for Preferred Numbers.**—This ANSI Standard Z17.1-1973 covers basic series of preferred numbers which are independent of any measurement system and therefore can be used with metric or customary units.

The numbers are rounded values of the following five geometric series of numbers:  $10^{N/5}$ ,  $10^{N/10}$ ,  $10^{N/20}$ ,  $10^{N/40}$ , and  $10^{N/80}$ , where  $N$  is an integer in the series 0, 1, 2, 3, etc. The designations used for the five series are respectively R5, R10, R20, R40, and R80, where R stands for Renard (Charles Renard, originator of the first preferred number system) and the number indicates the root of 10 on which the particular series is based.

The R5 series gives 5 numbers approximately 60 per cent apart, the R10 series gives 10 numbers approximately 25 per cent apart, the R20 series gives 20 numbers approximately 12 per cent apart, the R40 series gives 40 numbers approximately 6 per cent apart, and the R80 series gives 80 numbers approximately 3 per cent apart. The number of sizes for a given purpose can be minimized by using first the R5 series and adding sizes from the R10 and R20 series as needed. The R40 and R80 series are used principally for expressing tolerances in sizes based on preferred numbers. Preferred numbers below 1 are formed by dividing the given numbers by 10, 100, etc., and numbers above 10 are obtained by multiplying the given numbers by 10, 100, etc. Sizes graded according to the system may not be exactly proportional to one another due to the fact that preferred numbers may differ from calculated values by +1.26 per cent to -1.01 per cent. Deviations from preferred numbers are used in some instances — for example, where whole numbers are needed, such as 32 instead of 31.5 for the number of teeth in a gear.

#### Basic Series of Preferred Numbers ANSI Z17.1-1973

| Series Designation |      |      |      |      |      |      |      |      |
|--------------------|------|------|------|------|------|------|------|------|
| R5                 | R10  | R20  | R40  | R40  | R80  | R80  | R80  | R80  |
| Preferred Numbers  |      |      |      |      |      |      |      |      |
| 1.00               | 1.00 | 1.00 | 1.00 | 3.15 | 1.00 | 1.80 | 3.15 | 5.60 |
| 1.60               | 1.25 | 1.12 | 1.06 | 3.35 | 1.03 | 1.85 | 3.25 | 5.80 |
| 2.50               | 1.60 | 1.25 | 1.12 | 3.55 | 1.06 | 1.90 | 3.35 | 6.00 |
| 4.00               | 2.00 | 1.40 | 1.18 | 3.75 | 1.09 | 1.95 | 3.45 | 6.15 |
| 6.30               | 2.50 | 1.60 | 1.25 | 4.00 | 1.12 | 2.00 | 3.55 | 6.30 |
| ...                | 3.15 | 1.80 | 1.32 | 4.25 | 1.15 | 2.06 | 3.65 | 6.50 |
| ...                | 4.00 | 2.00 | 1.40 | 4.50 | 1.18 | 2.12 | 3.75 | 6.70 |
| ...                | 5.00 | 2.24 | 1.50 | 4.75 | 1.22 | 2.18 | 3.87 | 6.90 |
| ...                | 6.30 | 2.50 | 1.60 | 5.00 | 1.25 | 2.24 | 4.00 | 7.10 |
| ...                | 8.00 | 2.80 | 1.70 | 5.30 | 1.28 | 2.30 | 4.12 | 7.30 |
| ...                | ...  | 3.15 | 1.80 | 5.60 | 1.32 | 2.36 | 4.25 | 7.50 |
| ...                | ...  | 3.55 | 1.90 | 6.00 | 1.36 | 2.43 | 4.37 | 7.75 |
| ...                | ...  | 4.00 | 2.00 | 6.30 | 1.40 | 2.50 | 4.50 | 8.00 |
| ...                | ...  | 4.50 | 2.12 | 6.70 | 1.45 | 2.58 | 4.62 | 8.25 |
| ...                | ...  | 5.00 | 2.24 | 7.10 | 1.50 | 2.65 | 4.75 | 8.50 |
| ...                | ...  | 5.60 | 2.36 | 7.50 | 1.55 | 2.72 | 4.87 | 8.75 |
| ...                | ...  | 6.30 | 2.50 | 8.00 | 1.60 | 2.80 | 5.00 | 9.00 |
| ...                | ...  | 7.10 | 2.65 | 8.50 | 1.65 | 2.90 | 5.15 | 9.25 |
| ...                | ...  | 8.00 | 2.80 | 9.00 | 1.70 | 3.00 | 5.20 | 9.50 |
| ...                | ...  | 9.00 | 3.00 | 9.50 | 1.75 | 3.07 | 5.45 | 9.75 |

**Preferred Metric Sizes.**—American National Standard ANSI B32.4M-1980 (R1994), presents series of preferred metric sizes for round, square, rectangular, and hexagonal metal products. Table 1 gives preferred metric diameters from 1 to 320 millimeters for round metal products. Wherever possible, sizes should be selected from the Preferred Series shown in the table. A Second Preference series is also shown. A Third Preference Series not shown in the table is: 1.3, 2.1, 2.4, 2.6, 3.2, 3.8, 4.2, 4.8, 7.5, 8.5, 9.5, 36, 85, and 95.

Most of the Preferred Series of sizes are derived from the American National Standard "10 series" of preferred numbers (see *American National Standard for Preferred Numbers* on page 689). Most of the Second Preference Series are derived from the "20 series" of preferred numbers. Third Preference sizes are generally from the "40 series" of preferred numbers.

For preferred metric diameters less than 1 millimeter, preferred across flat metric sizes of square and hexagon metal products, preferred across flat metric sizes of rectangular metal products, and preferred metric lengths of metal products, reference should be made to the Standard.

**Table 1. American National Standard Preferred Metric Sizes**  
*ANSI B4.2-1978 (R1999)*

| Basic Size, mm |            | Basic Size, mm |            | Basic Size, mm |            | Basic Size, mm |            |
|----------------|------------|----------------|------------|----------------|------------|----------------|------------|
| 1st Choice     | 2nd Choice | 1st Choice     | 2nd Choice | 1st Choice     | 2nd Choice | 1st Choice     | 2nd Choice |
| 1              | ...        | 6              | ...        | 40             | ...        | 250            | ...        |
| ...            | 1.1        | ...            | 7          | ...            | 45         | ...            | 280        |
| 1.2            | ...        | 8              | ...        | 50             | ...        | 300            | ...        |
| ...            | 1.4        | ...            | 9          | ...            | 55         | ...            | 350        |
| 1.6            | ...        | 10             | ...        | 60             | ...        | 400            | ...        |
| ...            | 1.8        | ...            | 11         | ...            | 70         | ...            | 450        |
| 2              | ...        | 12             | ...        | 80             | ...        | 500            | ...        |
| ...            | 2.2        | ...            | 14         | ...            | 90         | ...            | 550        |
| 2.5            | ...        | 16             | ...        | 100            | ...        | 600            | ...        |
| ...            | 2.8        | ...            | 18         | ...            | 110        | ...            | 700        |
| 3              | ...        | 20             | ...        | 120            | ...        | 800            | ...        |
| ...            | 3.5        | ...            | 22         | ...            | 140        | ...            | 900        |
| 4              | ...        | 25             | ...        | 160            | ...        | 1000           | ...        |
| ...            | 4.5        | ...            | 28         | ...            | 180        | ...            | ...        |
| 5              | ...        | 30             | ...        | 200            | ...        | ...            | ...        |
| ...            | 5.5        | ...            | 35         | ...            | 220        | ...            | ...        |

**British Standard Preferred Numbers and Preferred Sizes.**—This British Standard, PD 6481:1977 1983, gives recommendations for the use of preferred numbers and preferred sizes for functional characteristics and dimensions of various products.

The preferred number system is internationally standardized in ISO 3. It is also referred to as the Renard, or R, series (see *American National Standard for Preferred Numbers*, on page 689).

The series in the preferred number system are geometric series, that is, there is a constant ratio between each figure and the succeeding one, within a decimal framework. Thus, the R5 series has five steps between 1 and 10, the R10 series has 10 steps between 1 and 10, the R20 series, 20 steps, and the R40 series, 40 steps, giving increases between steps of approximately 60, 25, 12, and 6 per cent, respectively.

The preferred size series have been developed from the preferred number series by rounding off the inconvenient numbers in the basic series and adjusting for linear measurement in millimeters. These series are shown in Table 2.

After taking all normal considerations into account, it is recommended that (a) for ranges of values of the primary *functional* characteristics (outputs and capacities) of a series of

products, the preferred number series R5 to R40 (see page 689) should be used, and (b) whenever linear sizes are concerned, the preferred sizes as given in the following table should be used. The presentation of preferred sizes gives designers and users a logical selection and the benefits of rational variety reduction.

The second-choice size given should only be used when it is not possible to use the first choice, and the third choice should be applied only if a size from the second choice cannot be selected. With this procedure, common usage will tend to be concentrated on a limited range of sizes, and a contribution is thus made to variety reduction. However, the decision to use a particular size cannot be taken on the basis that one is first choice and the other not. Account must be taken of the effect on the design, the availability of tools, and other relevant factors.

**Table 2. British Standard Preferred Sizes, PD 6481: 1977 (1983)**

| Choice |     |     | Choice |     |     | Choice |     |     | Choice |     |     | Choice |     |     | Choice |     |     |
|--------|-----|-----|--------|-----|-----|--------|-----|-----|--------|-----|-----|--------|-----|-----|--------|-----|-----|
| 1st    | 2nd | 3rd | 1st    | 2nd | 3rd | 1st    | 2nd | 3rd | 1st    | 2nd | 3rd | 1st    | 2nd | 3rd | 1st    | 2nd | 3rd |
| 1      |     |     |        |     | 5.2 |        |     | 23  | 65     |     |     |        |     | 122 |        |     | 188 |
|        | 1.1 |     |        | 5.5 |     |        |     | 24  |        |     | 66  |        | 125 |     | 190    |     |     |
| 1.2    |     |     |        | 5.8 | 25  |        |     | 26  | 70     | 68  |     | 130    |     | 128 |        | 195 | 192 |
|        | 1.4 |     | 6      |     |     | 28     |     |     |        | 72  |     |        |     | 132 |        |     | 198 |
|        |     | 1.3 |        | 6.2 |     |        |     |     |        |     | 74  |        | 135 |     | 200    |     |     |
| 1.6    |     |     |        | 6.5 | 30  |        |     |     | 75     |     | 76  |        | 140 |     | 210    |     | 205 |
|        |     | 1.5 |        | 6.8 |     | 32     |     | 34  |        |     |     |        |     | 138 |        |     |     |
|        | 1.8 |     |        | 7   |     |        |     |     |        | 78  |     |        |     | 142 |        |     | 215 |
|        |     | 1.9 | 8      |     |     |        |     |     | 80     |     |     |        | 145 |     | 220    |     |     |
| 2      |     |     |        | 8.5 |     |        | 38  |     |        |     |     |        |     | 148 |        |     | 225 |
|        |     | 2.1 |        | 9   |     |        | 40  |     |        | 85  |     | 150    |     | 152 |        | 230 |     |
|        | 2.2 |     |        | 9.5 |     |        | 42  |     |        |     | 88  |        |     | 155 |        |     | 235 |
|        |     | 2.4 | 10     |     |     |        |     | 44  | 90     |     |     |        |     | 158 |        | 240 |     |
| 2.5    |     |     |        | 11  |     |        | 45  |     |        |     | 92  |        |     | 160 |        |     | 245 |
|        |     | 2.6 |        | 12  |     |        |     | 46  |        | 95  |     | 165    |     | 162 |        | 250 |     |
| 2.8    |     |     |        | 13  |     |        | 48  |     |        |     |     |        |     | 166 |        |     | 255 |
| 3      |     |     |        | 14  |     |        | 50  |     | 100    |     |     |        |     | 168 |        | 260 |     |
|        |     | 3.2 |        | 15  |     |        |     | 52  |        |     |     |        |     | 170 |        |     | 265 |
|        | 3.5 |     | 16     |     |     |        |     | 54  | 105    |     |     |        | 175 |     |        | 270 |     |
|        |     | 3.8 |        | 17  | 55  |        |     | 56  |        | 110 |     |        |     | 172 |        |     | 275 |
| 4      |     |     |        | 18  |     |        |     | 58  |        |     |     |        | 177 |     | 280    |     |     |
|        |     | 4.2 |        | 19  |     |        |     | 59  |        |     |     |        | 178 |     |        |     | 285 |
|        | 4.5 |     | 20     |     |     |        | 60  |     |        | 115 |     | 180    |     | 182 |        | 290 |     |
|        |     | 4.8 |        | 21  |     |        | 62  |     |        |     | 118 |        |     | 185 |        |     | 295 |
| 5      |     |     |        | 22  |     |        |     | 64  | 120    |     |     |        |     |     | 300    |     |     |

For dimensions above 300, each series continues in a similar manner, i.e., the intervals between each series number are the same as between 200 and 300.



## MEASURING INSTRUMENTS AND INSPECTION METHODS

## Verniers and Micrometers

**Reading a Vernier.**—A general rule for taking readings with a vernier scale is as follows: Note the number of inches and sub-divisions of an inch that the zero mark of the vernier scale has moved along the true scale, and then add to this reading as many thousandths, or hundredths, or whatever fractional part of an inch the vernier reads to, as there are spaces between the vernier zero and that line on the vernier which coincides with one on the true scale. For example, if the zero line of a vernier which reads to thousandths is slightly beyond the 0.5 inch division on the main or true scale, as shown in Fig. 1, and graduation line 10 on the vernier exactly coincides with one on the true scale, the reading is  $0.5 + 0.010$  or 0.510 inch. In order to determine the reading or fractional part of an inch that can be obtained by a vernier, multiply the denominator of the finest sub-division given on the true scale by the total number of divisions on the vernier. For example, if one inch on the true scale is divided into 40 parts or fortieths (as in Fig. 1), and the vernier into twenty-five parts, the vernier will read to thousandths of an inch, as  $25 \times 40 = 1000$ . Similarly, if there are sixteen divisions to the inch on the true scale and a total of eight on the vernier, the latter will enable readings to be taken within one-hundred-twenty-eighths of an inch, as  $8 \times 16 = 128$ .

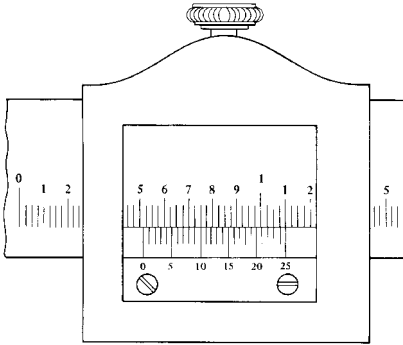


Fig. 1.

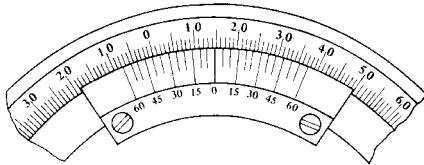


Fig. 2.

If the vernier is on a protractor, note the whole number of degrees passed by the vernier zero mark and then count the spaces between the vernier zero and that line which coincides with a graduation on the protractor scale. If the vernier indicates angles within five minutes or one-twelfth degree (as in Fig. 2), the number of spaces multiplied by 5 will, of course, give the number of minutes to be added to the whole number of degrees. The reading of the protractor set as illustrated would be 14 whole degrees (the number passed by the zero mark on the vernier) plus 30 minutes, as the graduation 30 on the vernier is the only one to

the right of the vernier zero which exactly coincides with a line on the protractor scale. It will be noted that there are duplicate scales on the vernier, one being to the right and the other to the left of zero. The left-hand scale is used when the vernier zero is moved to the left of the zero of the protractor scale, whereas the right-hand graduations are used when the movement is to the right.

**Reading a Metric Vernier.**—The smallest graduation on the bar (true or main scale) of the metric vernier gage shown in Fig. 1, is 0.5 millimeter. The scale is numbered at each twentieth division, and thus increments of 10, 20, 30, 40 millimeters, etc., are indicated. There are 25 divisions on the vernier scale, occupying the same length as 24 divisions on the bar, which is 12 millimeters. Therefore, one division on the vernier scale equals one twenty-fifth of 12 millimeters =  $0.04 \times 12 = 0.48$  millimeter. Thus, the difference between one bar division (0.50 mm) and one vernier division (2.48 mm) is  $0.50 - 0.48 = 0.02$  millimeter, which is the minimum measuring increment that the gage provides. To permit direct readings, the vernier scale has graduations to represent tenths of a millimeter (0.1 mm) and fiftieths of a millimeter (0.02 mm).

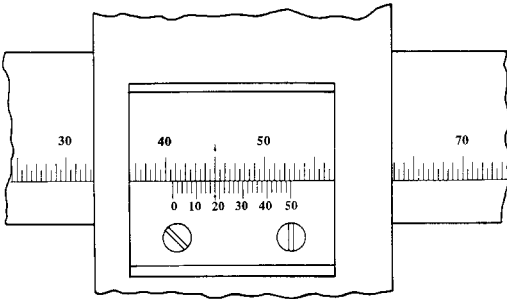


Fig. 1.

To read a vernier gage, first note how many millimeters the zero line on the vernier is from the zero line on the bar. Next, find the graduation on the vernier scale which exactly coincides with a graduation line on the bar, and note the value of the vernier scale graduation. This value is added to the value obtained from the bar, and the result is the total reading.

In the example shown in Fig. 1, the vernier zero is just past the 40.5 millimeters graduation on the bar. The 0.18 millimeter line on the vernier coincides with a line on the bar, and the total reading is therefore  $40.5 + 0.18 = 40.68$  mm.

**Dual Metric-Inch Vernier.**—The vernier gage shown in Fig. 2 has separate metric and inch 50-division vernier scales to permit measurements in either system.

A 50-division vernier has more widely spaced graduations than the 25-division vernier shown on the previous pages, and is thus easier to read. On the bar, the smallest metric graduation is 1 millimeter, and the 50 divisions of the vernier occupy the same length as 49 divisions on the bar, which is 49 mm. Therefore, one division on the vernier scale equals one-fiftieth of 49 millimeters =  $0.02 \times 49 = 0.98$  mm. Thus, the difference between one bar division (1.0 mm) and one vernier division (0.98 mm) is 0.02 mm, which is the minimum measuring increment the gage provides.

The vernier scale is graduated for direct reading to 0.02 mm. In the figure, the vernier zero is just past the 27 mm graduation on the bar, and the 0.42 mm graduation on the vernier coincides with a line on the bar. The total reading is therefore 27.42 mm.

The smallest inch graduation on the bar is 0.05 inch, and the 50 vernier divisions occupy the same length as 49 bar divisions, which is 2.45 inches. Therefore, one vernier division

equals one-fiftieth of 2.45 inches =  $0.02 \times 2.45 = 0.049$  inch. Thus, the difference between the length of a bar division and a vernier division is  $0.050 - 0.049 = 0.001$  inch. The vernier scale is graduated for direct reading to 0.001 inch. In the example, the vernier zero is past the 1.05 graduation on the bar, and the 0.029 graduation on the vernier coincides with a line on the bar. Thus, the total reading is 1.079 inches.

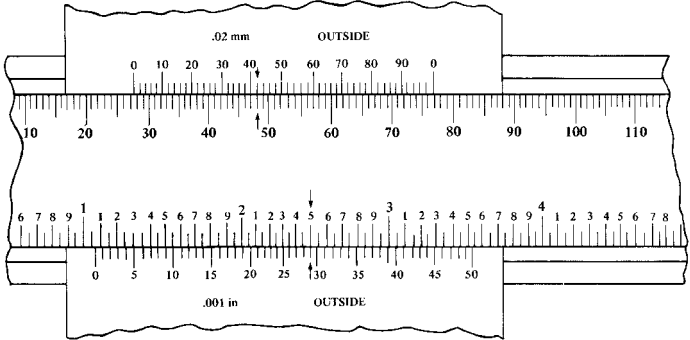


Fig. 2.

**Reading a Micrometer.**—The spindle of an inch-system micrometer has 40 threads per inch, so that one turn moves the spindle axially  $0.025$  inch ( $1 \div 40 = 0.025$ ), equal to the distance between two graduations on the frame. The 25 graduations on the thimble allow the  $0.025$  inch to be further divided, so that turning the thimble through one division moves the spindle axially  $0.001$  inch ( $0.025 \div 25 = 0.001$ ). To read a micrometer, count the number of whole divisions that are visible on the scale of the frame, multiply this number by 25 (the number of thousandths of an inch that each division represents) and add to the product the number of that division on the thimble which coincides with the axial zero line on the frame. The result will be the diameter expressed in thousandths of an inch. As the numbers 1, 2, 3, etc., opposite every fourth sub-division on the frame, indicate hundreds of thousandths, the reading can easily be taken mentally. Suppose the thimble were screwed out so that graduation 2, and three additional sub-divisions, were visible (as shown in Fig. 3), and that graduation 10 on the thimble coincided with the axial line on the frame. The reading then would be  $0.200 + 0.075 + 0.010$ , or  $0.285$  inch.

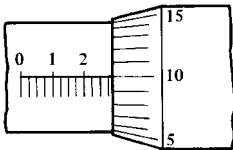


Fig. 3. Inch Micrometer

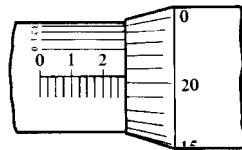


Fig. 4. Inch Micrometer with Vernier

Some micrometers have a vernier scale on the frame in addition to the regular graduations, so that measurements within  $0.0001$  part of an inch can be taken. Micrometers of this type are read as follows: First determine the number of thousandths, as with an ordinary micrometer, and then find a line on the vernier scale that exactly coincides with one on the thimble; the number of this line represents the number of ten-thousandths to be added to the number of thousandths obtained by the regular graduations. The reading shown in the illustration, Fig. 4, is  $0.270 + 0.0003 = 0.2703$  inch.

Micrometers graduated according to the English system of measurement ordinarily have a table of decimal equivalents stamped on the sides of the frame, so that fractions such as sixty-fourths, thirty-seconds, etc., can readily be converted into decimals.

**Reading a Metric Micrometer.**—The spindle of an ordinary metric micrometer has 2 threads per millimeter, and thus one complete revolution moves the spindle through a distance of 0.5 millimeter. The longitudinal line on the frame is graduated with 1 millimeter divisions and 0.5 millimeter sub-divisions. The thimble has 50 graduations, each being 0.01 millimeter (one-hundredth of a millimeter).

To read a metric micrometer, note the number of millimeter divisions visible on the scale of the sleeve, and add the total to the particular division on the thimble which coincides with the axial line on the sleeve. Suppose that the thimble were screwed out so that graduation 5, and one additional 0.5 sub-division were visible (as shown in Fig. 5), and that graduation 28 on the thimble coincided with the axial line on the sleeve. The reading then would be  $5.00 + 0.5 + 0.28 = 5.78$  mm.

Some micrometers are provided with a vernier scale on the sleeve in addition to the regular graduations to permit measurements within 0.002 millimeter to be made. Micrometers of this type are read as follows: First determine the number of whole millimeters (if any) and the number of hundredths of a millimeter, as with an ordinary micrometer, and then find a line on the sleeve vernier scale which exactly coincides

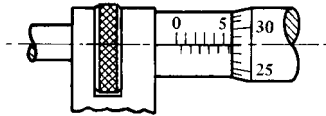


Fig. 5. Metric Micrometer

with one on the thimble. The number of this coinciding vernier line represents the number of two-thousandths of a millimeter to be added to the reading already obtained. Thus, for example, a measurement of 2.958 millimeters would be obtained by reading 2.5 millimeters on the sleeve, adding 0.45 millimeter read from the thimble, and then adding 0.008 millimeter as determined by the vernier.

*Note:* 0.01 millimeter = 0.000393 inch, and 0.002 millimeter = 0.000078 inch (78 millionths). Therefore, metric micrometers provide smaller measuring increments than comparable inch unit micrometers—the smallest graduation of an ordinary inch reading micrometer is 0.001 inch; the vernier type has graduations down to 0.0001 inch. When using either a metric or inch micrometer, without a vernier, smaller readings than those graduated may of course be obtained by visual interpolation between graduations.

### Sine-bar

The sine-bar is used either for very accurate angular measurements or for locating work at a given angle as, for example, in surface grinding templets, gages, etc. The sine-bar is especially useful in measuring or checking angles when the limit of accuracy is 5 minutes or less. Some bevel protractors are equipped with verniers which read to 5 minutes but the setting depends upon the alignment of graduations whereas a sine-bar usually is located by positive contact with precision gage-blocks selected for whatever dimension is required for obtaining a given angle.

**Types of Sine-bars.**—A sine-bar consists of a hardened, ground and lapped steel bar with very accurate cylindrical plugs of equal diameter attached to or near each end. The form illustrated by Fig. 3 has notched ends for receiving the cylindrical plugs so that they are held firmly against both faces of the notch. The standard center-to-center distance *C* between the plugs is either 5 or 10 inches. The upper and lower sides of sine-bars are parallel to the center line of the plugs within very close limits. The body of the sine-bar ordi-

narily has several through holes to reduce the weight. In the making of the sine-bar shown in Fig. 4, if too much material is removed from one locating notch, regrinding the shoulder at the opposite end would make it possible to obtain the correct center distance. That is the reason for this change in form. The type of sine-bar illustrated by Fig. 5 has the cylindrical disks or plugs attached to one side. These differences in form or arrangement do not, of course, affect the principle governing the use of the sine-bar. An accurate surface plate or master flat is always used in conjunction with a sine-bar in order to form the base from which the vertical measurements are made.

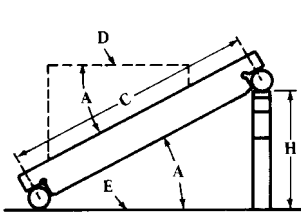


Fig. 1.

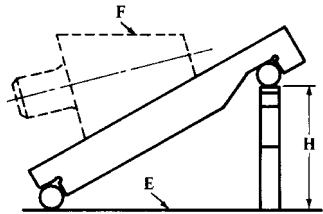


Fig. 2.

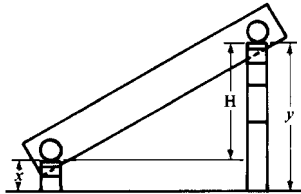


Fig. 3.

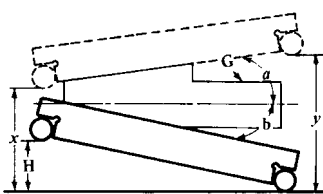


Fig. 4.

**Setting a Sine-bar to a Given Angle.**—To find the vertical distance  $H$ , for setting a sine-bar to the required angle, convert the angle to decimal form on a pocket calculator, take the sine of that angle, and multiply by the distance between the cylinders. For example, if an angle of 31 degrees, 30 minutes is required, the equivalent angle is 31 degrees plus  $\frac{30}{60} = 31 + 0.5$ , or 31.5 degrees. (For conversions from minutes and seconds to decimals of degrees and vice versa, see page 96). The sine of 31.5 degrees is 0.5225 and multiplying this value by the sine-bar length gives 2.613 in. for the height  $H$ , Fig. 1 and 3, of the gage blocks.

**Finding Angle when Height  $H$  of Sine-bar is Known.**—To find the angle equivalent to a given height  $H$ , reverse the above procedure. Thus, if the height  $H$  is 1.4061 in., dividing by 5 gives a sine of 0.28122, which corresponds to an angle of 16.333 degrees, or 16 degrees 20 minutes.

**Checking Angle of Templet or Gage by Using Sine-bar.**—Place templet or gage on sine-bar as indicated by dotted lines, Fig. 1. Clamps may be used to hold work in place. Place upper end of sine-bar on gage blocks having total height  $H$  corresponding to the required angle. If upper edge  $D$  of work is parallel with surface plate  $E$ , then angle  $A$  of work equals angle  $A$  to which sine-bar is set. Parallelism between edge  $D$  and surface plate may be tested by checking the height at each end with a dial gage or some type of indicating comparator.

**Measuring Angle of Templet or Gage with Sine-bar.**—To measure such an angle, adjust height of gage blocks and sine-bar until edge  $D$ , Fig. 1, is parallel with surface plate  $E$ ; then find angle corresponding to height  $H$ , of gage blocks. For example, if height  $H$  is

2.5939 inches when  $D$  and  $E$  are parallel, the calculator will show that the angle  $A$  of the work is 31 degrees, 15 minutes.

**Checking Taper per Foot with Sine-bar.**—As an example, assume that the plug gage in Fig. 2 is supposed to have a taper of  $6\frac{1}{8}$  inches per foot and taper is to be checked by using a 5-inch sine-bar. The table of *Tapers per Foot and Corresponding Angles* on page 714 shows that the included angle for a taper of  $6\frac{1}{8}$  inches per foot is 28 degrees 38 minutes 1 second, or 28.6336 degrees from the calculator. For a 5-inch sine-bar, the calculator gives a value of 2.396 inch for the height  $H$  of the gage blocks. Using this height, if the upper surface  $F$  of the plug gage is parallel to the surface plate the angle corresponds to a taper of  $6\frac{1}{8}$  inches per foot.

**Setting Sine-bar having Plugs Attached to Side.**—If the lower plug does not rest directly on the surface plate, as in Fig. 3, the height  $H$  for the sine-bar is the difference between heights  $x$  and  $y$ , or the difference between the heights of the plugs; otherwise, the procedure in setting the sine-bar and checking angles is the same as previously described.

**Checking Templets Having Two Angles.**—Assume that angle  $a$  of templet, Fig. 4, is 9 degrees, angle  $b$  12 degrees, and that edge  $G$  is parallel to the surface plate. For an angle  $b$  of 12 degrees, the calculator shows that the height  $H$  is 1.03956 inches. For an angle  $a$  of 9 degrees, the difference between measurements  $x$  and  $y$  when the sine-bar is in contact with the upper edge of the templet is 0.78217 inch.

**Using Sine-bar Tables to Set 5-inch and 100-mm Sine-bars to Given Angle.**—The table starting on page 699 gives constants for a 5-inch sine-bar, and starting on page 706 are given constants for a 100-mm sine-bar. These constants represent the vertical height  $H$  for setting a sine-bar of the corresponding length to the required angle.

**Using Sine-bar Tables with Sine-bars of Other Lengths.**—A sine-bar may sometimes be preferred that is longer (or shorter) than that given in available tables because of its longer working surface or because the longer center distance is conducive to greater precision. To use the sine-bar tables with a sine-bar of another length to obtain the vertical distances  $H$ , multiply the value obtained from the table by the fraction (length of sine-bar used  $\div$  length of sine-bar specified in table).

*Example:* Use the 5-inch sine-bar table to obtain the vertical height  $H$  for setting a 10-inch sine-bar to an angle of  $39^\circ$ . The sine of  $39^\circ$  is 0.62932, hence the vertical height  $H$  for setting a 10-inch sine-bar is 6.2932 inches.

*Solution:* The height  $H$  given for  $39^\circ$  in the 5-inch sine-bar table (page 703) is 3.14660. The corresponding height for a 10-inch sine-bar is  $\frac{10}{5} \times 3.14660 = 6.2932$  inches.

**Using a Calculator to Determine Sine-bar Constants for a Given Angle.**—The constant required to set a given angle for a sine-bar of any length can be quickly determined by using a scientific calculator. The required formulas are as follows:

a) angle  $A$  given in degrees and calculator is set to measure angles in radian

or

a) angle  $A$  is given in radian, or  
b) angle  $A$  is given in degrees and calculator is set to measure angles in degrees

$$H = L \times \sin\left(A \times \frac{\pi}{180}\right)$$

$$H = L \times \sin(A)$$

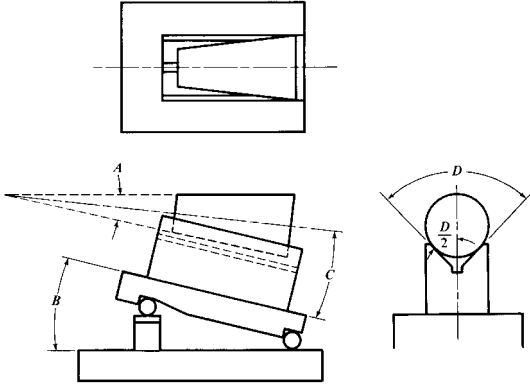
where  $L$  = length of the sine-bar  $A$  = angle to which the sine-bar is to be set

$H$  = vertical height to which one end of sine-bar must be set to obtain angle  $A$

$$\pi = 3.141592654$$

In the previous formulas, the height  $H$  and length  $L$  must be given in the same units, but may be in either metric or US units. Thus, if  $L$  is given in mm, then  $H$  is in mm; and, if  $L$  is given in inches, then  $H$  is in inches.

**Measuring Tapers with Vee-block and Sine-bar.**—The taper on a conical part may be checked or found by placing the part in a vee-block which rests on the surface of a sine-plate or sine-bar as shown in the accompanying diagram. The advantage of this method is that the axis of the vee-block may be aligned with the sides of the sine-bar. Thus when the tapered part is placed in the vee-block it will be aligned perpendicular to the transverse axis of the sine-bar.



The sine-bar is set to angle  $B = (C + A/2)$  where  $A/2$  is one-half the included angle of the tapered part. If  $D$  is the included angle of the precision vee-block, the angle  $C$  is calculated from the formula:

$$\sin C = \frac{\sin(A/2)}{\sin(D/2)}$$

If dial indicator readings show no change across all points along the top of the taper surface, then this checks that the angle  $A$  of the taper is correct.

If the indicator readings vary, proceed as follows to find the actual angle of taper: 1) Adjust the angle of the sine-bar until the indicator reading is constant. Then find the new angle  $B'$  as explained in the paragraph *Measuring Angle of Templet or Gage with Sine-bar* on page 696; and 2) Using the angle  $B'$  calculate the actual half-angle  $A'/2$  of the taper from the formula:

$$\tan \frac{A'}{2} = \frac{\sin B'}{\csc \frac{D}{2} + \cos B'}$$

The taper per foot corresponding to certain half-angles of taper may be found in the table on page 714.

**Dimensioning Tapers.**—At least three methods of dimensioning tapers are in use.

*Standard Tapers:* Give one diameter or width, the length, and insert note on drawing designating the taper by number.

*Special Tapers:* In dimensioning a taper when the slope is specified, the length and only one diameter should be given or the diameters at both ends of the taper should be given and length omitted.

*Precision Work:* In certain cases where very precise measurements are necessary the taper surface, either external or internal, is specified by giving a diameter at a certain distance from a surface and the slope of the taper.

## 5-INCH SINE-BAR CONSTANTS

## Constants for 5-inch Sine-bar

## Constants for Setting a 5-inch Sine-bar for 1° to 7°

| Min. | 0°      | 1°      | 2°      | 3°      | 4°      | 5°      | 6°      | 7°      |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 0.00000 | 0.08726 | 0.17450 | 0.26168 | 0.34878 | 0.43578 | 0.52264 | 0.60935 |
| 1    | 0.00145 | 0.08872 | 0.17595 | 0.26313 | 0.35023 | 0.43723 | 0.52409 | 0.61079 |
| 2    | 0.00291 | 0.09017 | 0.17740 | 0.26458 | 0.35168 | 0.43868 | 0.52554 | 0.61223 |
| 3    | 0.00436 | 0.09162 | 0.17886 | 0.26604 | 0.35313 | 0.44013 | 0.52698 | 0.61368 |
| 4    | 0.00582 | 0.09308 | 0.18031 | 0.26749 | 0.35459 | 0.44157 | 0.52843 | 0.61512 |
| 5    | 0.00727 | 0.09453 | 0.18177 | 0.26894 | 0.35604 | 0.44302 | 0.52987 | 0.61656 |
| 6    | 0.00873 | 0.09599 | 0.18322 | 0.27039 | 0.35749 | 0.44447 | 0.53132 | 0.61801 |
| 7    | 0.01018 | 0.09744 | 0.18467 | 0.27185 | 0.35894 | 0.44592 | 0.53277 | 0.61945 |
| 8    | 0.01164 | 0.09890 | 0.18613 | 0.27330 | 0.36039 | 0.44737 | 0.53421 | 0.62089 |
| 9    | 0.01309 | 0.10035 | 0.18758 | 0.27475 | 0.36184 | 0.44882 | 0.53566 | 0.62234 |
| 10   | 0.01454 | 0.10180 | 0.18903 | 0.27620 | 0.36329 | 0.45027 | 0.53710 | 0.62378 |
| 11   | 0.01600 | 0.10326 | 0.19049 | 0.27766 | 0.36474 | 0.45171 | 0.53855 | 0.62522 |
| 12   | 0.01745 | 0.10471 | 0.19194 | 0.27911 | 0.36619 | 0.45316 | 0.54000 | 0.62667 |
| 13   | 0.01891 | 0.10617 | 0.19339 | 0.28056 | 0.36764 | 0.45461 | 0.54144 | 0.62811 |
| 14   | 0.02036 | 0.10762 | 0.19485 | 0.28201 | 0.36909 | 0.45606 | 0.54289 | 0.62955 |
| 15   | 0.02182 | 0.10907 | 0.19630 | 0.28346 | 0.37054 | 0.45751 | 0.54433 | 0.63099 |
| 16   | 0.02327 | 0.11053 | 0.19775 | 0.28492 | 0.37199 | 0.45896 | 0.54578 | 0.63244 |
| 17   | 0.02473 | 0.11198 | 0.19921 | 0.28637 | 0.37344 | 0.46040 | 0.54723 | 0.63388 |
| 18   | 0.02618 | 0.11344 | 0.20066 | 0.28782 | 0.37489 | 0.46185 | 0.54867 | 0.63532 |
| 19   | 0.02763 | 0.11489 | 0.20211 | 0.28927 | 0.37634 | 0.46330 | 0.55012 | 0.63677 |
| 20   | 0.02909 | 0.11634 | 0.20357 | 0.29072 | 0.37779 | 0.46475 | 0.55156 | 0.63821 |
| 21   | 0.03054 | 0.11780 | 0.20502 | 0.29218 | 0.37924 | 0.46620 | 0.55301 | 0.63965 |
| 22   | 0.03200 | 0.11925 | 0.20647 | 0.29363 | 0.38069 | 0.46765 | 0.55445 | 0.64109 |
| 23   | 0.03345 | 0.12071 | 0.20793 | 0.29508 | 0.38214 | 0.46909 | 0.55590 | 0.64254 |
| 24   | 0.03491 | 0.12216 | 0.20938 | 0.29653 | 0.38360 | 0.47054 | 0.55734 | 0.64398 |
| 25   | 0.03636 | 0.12361 | 0.21083 | 0.29798 | 0.38505 | 0.47199 | 0.55879 | 0.64542 |
| 26   | 0.03782 | 0.12507 | 0.21228 | 0.29944 | 0.38650 | 0.47344 | 0.56024 | 0.64686 |
| 27   | 0.03927 | 0.12652 | 0.21374 | 0.30089 | 0.38795 | 0.47489 | 0.56168 | 0.64830 |
| 28   | 0.04072 | 0.12798 | 0.21519 | 0.30234 | 0.38940 | 0.47633 | 0.56313 | 0.64975 |
| 29   | 0.04218 | 0.12943 | 0.21664 | 0.30379 | 0.39085 | 0.47778 | 0.56457 | 0.65119 |
| 30   | 0.04363 | 0.13088 | 0.21810 | 0.30524 | 0.39230 | 0.47923 | 0.56602 | 0.65263 |
| 31   | 0.04509 | 0.13234 | 0.21955 | 0.30669 | 0.39375 | 0.48068 | 0.56746 | 0.65407 |
| 32   | 0.04654 | 0.13379 | 0.22100 | 0.30815 | 0.39520 | 0.48212 | 0.56891 | 0.65551 |
| 33   | 0.04800 | 0.13525 | 0.22246 | 0.30960 | 0.39665 | 0.48357 | 0.57035 | 0.65696 |
| 34   | 0.04945 | 0.13670 | 0.22391 | 0.31105 | 0.39810 | 0.48502 | 0.57180 | 0.65840 |
| 35   | 0.05090 | 0.13815 | 0.22536 | 0.31250 | 0.39954 | 0.48647 | 0.57324 | 0.65984 |
| 36   | 0.05236 | 0.13961 | 0.22681 | 0.31395 | 0.40099 | 0.48791 | 0.57469 | 0.66128 |
| 37   | 0.05381 | 0.14106 | 0.22827 | 0.31540 | 0.40244 | 0.48936 | 0.57613 | 0.66272 |
| 38   | 0.05527 | 0.14252 | 0.22972 | 0.31686 | 0.40389 | 0.49081 | 0.57758 | 0.66417 |
| 39   | 0.05672 | 0.14397 | 0.23117 | 0.31831 | 0.40534 | 0.49226 | 0.57902 | 0.66561 |
| 40   | 0.05818 | 0.14542 | 0.23263 | 0.31976 | 0.40679 | 0.49370 | 0.58046 | 0.66705 |
| 41   | 0.05963 | 0.14688 | 0.23408 | 0.32121 | 0.40824 | 0.49515 | 0.58191 | 0.66849 |
| 42   | 0.06109 | 0.14833 | 0.23553 | 0.32266 | 0.40969 | 0.49660 | 0.58335 | 0.66993 |
| 43   | 0.06254 | 0.14979 | 0.23699 | 0.32411 | 0.41114 | 0.49805 | 0.58480 | 0.67137 |
| 44   | 0.06399 | 0.15124 | 0.23844 | 0.32556 | 0.41259 | 0.49949 | 0.58624 | 0.67281 |
| 45   | 0.06545 | 0.15269 | 0.23989 | 0.32702 | 0.41404 | 0.50094 | 0.58769 | 0.67425 |
| 46   | 0.06690 | 0.15415 | 0.24134 | 0.32847 | 0.41549 | 0.50239 | 0.58913 | 0.67570 |
| 47   | 0.06836 | 0.15560 | 0.24280 | 0.32992 | 0.41694 | 0.50383 | 0.59058 | 0.67714 |
| 48   | 0.06981 | 0.15705 | 0.24425 | 0.33137 | 0.41839 | 0.50528 | 0.59202 | 0.67858 |
| 49   | 0.07127 | 0.15851 | 0.24570 | 0.33282 | 0.41984 | 0.50673 | 0.59346 | 0.68002 |
| 50   | 0.07272 | 0.15996 | 0.24715 | 0.33427 | 0.42129 | 0.50818 | 0.59491 | 0.68146 |
| 51   | 0.07417 | 0.16141 | 0.24861 | 0.33572 | 0.42274 | 0.50962 | 0.59635 | 0.68290 |
| 52   | 0.07563 | 0.16287 | 0.25006 | 0.33717 | 0.42419 | 0.51107 | 0.59780 | 0.68434 |
| 53   | 0.07708 | 0.16432 | 0.25151 | 0.33863 | 0.42564 | 0.51252 | 0.59924 | 0.68578 |
| 54   | 0.07854 | 0.16578 | 0.25296 | 0.34008 | 0.42708 | 0.51396 | 0.60068 | 0.68722 |
| 55   | 0.07999 | 0.16723 | 0.25442 | 0.34153 | 0.42853 | 0.51541 | 0.60213 | 0.68866 |
| 56   | 0.08145 | 0.16868 | 0.25587 | 0.34298 | 0.42998 | 0.51686 | 0.60357 | 0.69010 |
| 57   | 0.08290 | 0.17014 | 0.25732 | 0.34443 | 0.43143 | 0.51830 | 0.60502 | 0.69154 |
| 58   | 0.08435 | 0.17159 | 0.25877 | 0.34588 | 0.43288 | 0.51975 | 0.60646 | 0.69298 |
| 59   | 0.08581 | 0.17304 | 0.26023 | 0.34733 | 0.43433 | 0.52120 | 0.60790 | 0.69443 |
| 60   | 0.08726 | 0.17450 | 0.26168 | 0.34878 | 0.43578 | 0.52264 | 0.60935 | 0.69587 |



## 5-INCH SINE-BAR CONSTANTS

## Constants for Setting a 5-inch Sine-bar for 8° to 15°

| Min. | 8°      | 9°      | 10°     | 11°     | 12°     | 13°     | 14°     | 15°     |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 0.69587 | 0.78217 | 0.86824 | 0.95404 | 1.03956 | 1.12476 | 1.20961 | 1.29410 |
| 1    | 0.69731 | 0.78361 | 0.86967 | 0.95547 | 1.04098 | 1.12617 | 1.21102 | 1.29550 |
| 2    | 0.69875 | 0.78505 | 0.87111 | 0.95690 | 1.04240 | 1.12759 | 1.21243 | 1.29690 |
| 3    | 0.70019 | 0.78648 | 0.87254 | 0.95833 | 1.04383 | 1.12901 | 1.21384 | 1.29831 |
| 4    | 0.70163 | 0.78792 | 0.87397 | 0.95976 | 1.04525 | 1.13042 | 1.21525 | 1.29971 |
| 5    | 0.70307 | 0.78935 | 0.87540 | 0.96118 | 1.04667 | 1.13184 | 1.21666 | 1.30112 |
| 6    | 0.70451 | 0.79079 | 0.87683 | 0.96261 | 1.04809 | 1.13326 | 1.21808 | 1.30252 |
| 7    | 0.70595 | 0.79223 | 0.87827 | 0.96404 | 1.04951 | 1.13467 | 1.21949 | 1.30393 |
| 8    | 0.70739 | 0.79366 | 0.87970 | 0.96546 | 1.05094 | 1.13609 | 1.22090 | 1.30533 |
| 9    | 0.70883 | 0.79510 | 0.88113 | 0.96689 | 1.05236 | 1.13751 | 1.22231 | 1.30673 |
| 10   | 0.71027 | 0.79653 | 0.88256 | 0.96832 | 1.05378 | 1.13892 | 1.22372 | 1.30814 |
| 11   | 0.71171 | 0.79797 | 0.88399 | 0.96974 | 1.05520 | 1.14034 | 1.22513 | 1.30954 |
| 12   | 0.71314 | 0.79941 | 0.88542 | 0.97117 | 1.05662 | 1.14175 | 1.22654 | 1.31095 |
| 13   | 0.71458 | 0.80084 | 0.88686 | 0.97260 | 1.05805 | 1.14317 | 1.22795 | 1.31235 |
| 14   | 0.71602 | 0.80228 | 0.88829 | 0.97403 | 1.05947 | 1.14459 | 1.22936 | 1.31375 |
| 15   | 0.71746 | 0.80371 | 0.88972 | 0.97545 | 1.06089 | 1.14600 | 1.23077 | 1.31516 |
| 16   | 0.71890 | 0.80515 | 0.89115 | 0.97688 | 1.06231 | 1.14742 | 1.23218 | 1.31656 |
| 17   | 0.72034 | 0.80658 | 0.89258 | 0.97830 | 1.06373 | 1.14883 | 1.23359 | 1.31796 |
| 18   | 0.72178 | 0.80802 | 0.89401 | 0.97973 | 1.06515 | 1.15025 | 1.23500 | 1.31937 |
| 19   | 0.72322 | 0.80945 | 0.89544 | 0.98116 | 1.06657 | 1.15166 | 1.23640 | 1.32077 |
| 20   | 0.72466 | 0.81089 | 0.89687 | 0.98258 | 1.06799 | 1.15308 | 1.23781 | 1.32217 |
| 21   | 0.72610 | 0.81232 | 0.89830 | 0.98401 | 1.06941 | 1.15449 | 1.23922 | 1.32357 |
| 22   | 0.72754 | 0.81376 | 0.89973 | 0.98544 | 1.07084 | 1.15591 | 1.24063 | 1.32498 |
| 23   | 0.72898 | 0.81519 | 0.90117 | 0.98686 | 1.07226 | 1.15732 | 1.24204 | 1.32638 |
| 24   | 0.73042 | 0.81663 | 0.90260 | 0.98829 | 1.07368 | 1.15874 | 1.24345 | 1.32778 |
| 25   | 0.73185 | 0.81806 | 0.90403 | 0.98971 | 1.07510 | 1.16015 | 1.24486 | 1.32918 |
| 26   | 0.73329 | 0.81950 | 0.90546 | 0.99114 | 1.07652 | 1.16157 | 1.24627 | 1.33058 |
| 27   | 0.73473 | 0.82093 | 0.90689 | 0.99256 | 1.07794 | 1.16298 | 1.24768 | 1.33199 |
| 28   | 0.73617 | 0.82237 | 0.90832 | 0.99399 | 1.07936 | 1.16440 | 1.24908 | 1.33339 |
| 29   | 0.73761 | 0.82380 | 0.90975 | 0.99541 | 1.08078 | 1.16581 | 1.25049 | 1.33479 |
| 30   | 0.73905 | 0.82524 | 0.91118 | 0.99684 | 1.08220 | 1.16723 | 1.25190 | 1.33619 |
| 31   | 0.74049 | 0.82667 | 0.91261 | 0.99826 | 1.08362 | 1.16864 | 1.25331 | 1.33759 |
| 32   | 0.74192 | 0.82811 | 0.91404 | 0.99969 | 1.08504 | 1.17006 | 1.25472 | 1.33899 |
| 33   | 0.74336 | 0.82954 | 0.91547 | 1.00112 | 1.08646 | 1.17147 | 1.25612 | 1.34040 |
| 34   | 0.74480 | 0.83098 | 0.91690 | 1.00254 | 1.08788 | 1.17288 | 1.25753 | 1.34180 |
| 35   | 0.74624 | 0.83241 | 0.91833 | 1.00396 | 1.08930 | 1.17430 | 1.25894 | 1.34320 |
| 36   | 0.74768 | 0.83384 | 0.91976 | 1.00539 | 1.09072 | 1.17571 | 1.26035 | 1.34460 |
| 37   | 0.74911 | 0.83528 | 0.92119 | 1.00681 | 1.09214 | 1.17712 | 1.26175 | 1.34600 |
| 38   | 0.75055 | 0.83671 | 0.92262 | 1.00824 | 1.09355 | 1.17854 | 1.26316 | 1.34740 |
| 39   | 0.75199 | 0.83815 | 0.92405 | 1.00966 | 1.09497 | 1.17995 | 1.26457 | 1.34880 |
| 40   | 0.75343 | 0.83958 | 0.92547 | 1.01109 | 1.09639 | 1.18136 | 1.26598 | 1.35020 |
| 41   | 0.75487 | 0.84101 | 0.92690 | 1.01251 | 1.09781 | 1.18278 | 1.26738 | 1.35160 |
| 42   | 0.75630 | 0.84245 | 0.92833 | 1.01394 | 1.09923 | 1.18419 | 1.26879 | 1.35300 |
| 43   | 0.75774 | 0.84388 | 0.92976 | 1.01536 | 1.10065 | 1.18560 | 1.27020 | 1.35440 |
| 44   | 0.75918 | 0.84531 | 0.93119 | 1.01678 | 1.10207 | 1.18702 | 1.27160 | 1.35580 |
| 45   | 0.76062 | 0.84675 | 0.93262 | 1.01821 | 1.10349 | 1.18843 | 1.27301 | 1.35720 |
| 46   | 0.76205 | 0.84818 | 0.93405 | 1.01963 | 1.10491 | 1.18984 | 1.27442 | 1.35860 |
| 47   | 0.76349 | 0.84961 | 0.93548 | 1.02106 | 1.10632 | 1.19125 | 1.27582 | 1.36000 |
| 48   | 0.76493 | 0.85105 | 0.93691 | 1.02248 | 1.10774 | 1.19267 | 1.27723 | 1.36140 |
| 49   | 0.76637 | 0.85248 | 0.93834 | 1.02390 | 1.10916 | 1.19408 | 1.27863 | 1.36280 |
| 50   | 0.76780 | 0.85391 | 0.93976 | 1.02533 | 1.11058 | 1.19549 | 1.28004 | 1.36420 |
| 51   | 0.76924 | 0.85535 | 0.94119 | 1.02675 | 1.11200 | 1.19690 | 1.28145 | 1.36560 |
| 52   | 0.77068 | 0.85678 | 0.94262 | 1.02817 | 1.11342 | 1.19832 | 1.28285 | 1.36700 |
| 53   | 0.77211 | 0.85821 | 0.94405 | 1.02960 | 1.11483 | 1.19973 | 1.28426 | 1.36840 |
| 54   | 0.77355 | 0.85965 | 0.94548 | 1.03102 | 1.11625 | 1.20114 | 1.28566 | 1.36980 |
| 55   | 0.77499 | 0.86108 | 0.94691 | 1.03244 | 1.11767 | 1.20255 | 1.28707 | 1.37119 |
| 56   | 0.77643 | 0.86251 | 0.94833 | 1.03387 | 1.11909 | 1.20396 | 1.28847 | 1.37259 |
| 57   | 0.77786 | 0.86394 | 0.94976 | 1.03529 | 1.12050 | 1.20538 | 1.28988 | 1.37399 |
| 58   | 0.77930 | 0.86538 | 0.95119 | 1.03671 | 1.12192 | 1.20679 | 1.29129 | 1.37539 |
| 59   | 0.78074 | 0.86681 | 0.95262 | 1.03814 | 1.12334 | 1.20820 | 1.29269 | 1.37679 |
| 60   | 0.78217 | 0.86824 | 0.95404 | 1.03956 | 1.12476 | 1.20961 | 1.29410 | 1.37819 |

## Constants for Setting a 5-inch Sine-bar for 16° to 23°

| Min. | 16°     | 17°     | 18°     | 19°     | 20°     | 21°     | 22°     | 23°     |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 1.37819 | 1.46186 | 1.54509 | 1.62784 | 1.71010 | 1.79184 | 1.87303 | 1.95366 |
| 1    | 1.37958 | 1.46325 | 1.54647 | 1.62922 | 1.71147 | 1.79320 | 1.87438 | 1.95499 |
| 2    | 1.38098 | 1.46464 | 1.54785 | 1.63059 | 1.71283 | 1.79456 | 1.87573 | 1.95633 |
| 3    | 1.38238 | 1.46603 | 1.54923 | 1.63197 | 1.71420 | 1.79591 | 1.87708 | 1.95767 |
| 4    | 1.38378 | 1.46742 | 1.55062 | 1.63334 | 1.71557 | 1.79727 | 1.87843 | 1.95901 |
| 5    | 1.38518 | 1.46881 | 1.55200 | 1.63472 | 1.71693 | 1.79863 | 1.87977 | 1.96035 |
| 6    | 1.38657 | 1.47020 | 1.55338 | 1.63609 | 1.71830 | 1.79998 | 1.88112 | 1.96169 |
| 7    | 1.38797 | 1.47159 | 1.55476 | 1.63746 | 1.71966 | 1.80134 | 1.88247 | 1.96302 |
| 8    | 1.38937 | 1.47298 | 1.55615 | 1.63884 | 1.72103 | 1.80270 | 1.88382 | 1.96436 |
| 9    | 1.39076 | 1.47437 | 1.55753 | 1.64021 | 1.72240 | 1.80405 | 1.88516 | 1.96570 |
| 10   | 1.39216 | 1.47576 | 1.55891 | 1.64159 | 1.72376 | 1.80541 | 1.88651 | 1.96704 |
| 11   | 1.39356 | 1.47715 | 1.56029 | 1.64296 | 1.72513 | 1.80677 | 1.88786 | 1.96837 |
| 12   | 1.39496 | 1.47854 | 1.56167 | 1.64433 | 1.72649 | 1.80812 | 1.88920 | 1.96971 |
| 13   | 1.39635 | 1.47993 | 1.56306 | 1.64571 | 1.72786 | 1.80948 | 1.89055 | 1.97105 |
| 14   | 1.39775 | 1.48132 | 1.56444 | 1.64708 | 1.72922 | 1.81083 | 1.89190 | 1.97238 |
| 15   | 1.39915 | 1.48271 | 1.56582 | 1.64845 | 1.73059 | 1.81219 | 1.89324 | 1.97372 |
| 16   | 1.40054 | 1.48410 | 1.56720 | 1.64983 | 1.73195 | 1.81355 | 1.89459 | 1.97506 |
| 17   | 1.40194 | 1.48549 | 1.56858 | 1.65120 | 1.73331 | 1.81490 | 1.89594 | 1.97639 |
| 18   | 1.40333 | 1.48687 | 1.56996 | 1.65257 | 1.73468 | 1.81626 | 1.89728 | 1.97773 |
| 19   | 1.40473 | 1.48826 | 1.57134 | 1.65394 | 1.73604 | 1.81761 | 1.89863 | 1.97906 |
| 20   | 1.40613 | 1.48965 | 1.57272 | 1.65532 | 1.73741 | 1.81897 | 1.89997 | 1.98040 |
| 21   | 1.40752 | 1.49104 | 1.57410 | 1.65669 | 1.73877 | 1.82032 | 1.90132 | 1.98173 |
| 22   | 1.40892 | 1.49243 | 1.57548 | 1.65806 | 1.74013 | 1.82168 | 1.90266 | 1.98307 |
| 23   | 1.41031 | 1.49382 | 1.57687 | 1.65943 | 1.74150 | 1.82303 | 1.90401 | 1.98440 |
| 24   | 1.41171 | 1.49520 | 1.57825 | 1.66081 | 1.74286 | 1.82438 | 1.90535 | 1.98574 |
| 25   | 1.41310 | 1.49659 | 1.57963 | 1.66218 | 1.74422 | 1.82574 | 1.90670 | 1.98707 |
| 26   | 1.41450 | 1.49798 | 1.58101 | 1.66355 | 1.74559 | 1.82709 | 1.90804 | 1.98841 |
| 27   | 1.41589 | 1.49937 | 1.58238 | 1.66492 | 1.74695 | 1.82845 | 1.90939 | 1.98974 |
| 28   | 1.41729 | 1.50075 | 1.58376 | 1.66629 | 1.74831 | 1.82980 | 1.91073 | 1.99108 |
| 29   | 1.41868 | 1.50214 | 1.58514 | 1.66766 | 1.74967 | 1.83115 | 1.91207 | 1.99241 |
| 30   | 1.42008 | 1.50353 | 1.58652 | 1.66903 | 1.75104 | 1.83251 | 1.91342 | 1.99375 |
| 31   | 1.42147 | 1.50492 | 1.58790 | 1.67041 | 1.75240 | 1.83386 | 1.91476 | 1.99508 |
| 32   | 1.42287 | 1.50630 | 1.58928 | 1.67178 | 1.75376 | 1.83521 | 1.91610 | 1.99641 |
| 33   | 1.42426 | 1.50769 | 1.59066 | 1.67315 | 1.75512 | 1.83657 | 1.91745 | 1.99775 |
| 34   | 1.42565 | 1.50908 | 1.59204 | 1.67452 | 1.75649 | 1.83792 | 1.91879 | 1.99908 |
| 35   | 1.42705 | 1.51046 | 1.59342 | 1.67589 | 1.75785 | 1.83927 | 1.92013 | 2.00041 |
| 36   | 1.42844 | 1.51185 | 1.59480 | 1.67726 | 1.75921 | 1.84062 | 1.92148 | 2.00175 |
| 37   | 1.42984 | 1.51324 | 1.59617 | 1.67863 | 1.76057 | 1.84198 | 1.92282 | 2.00308 |
| 38   | 1.43123 | 1.51462 | 1.59755 | 1.68000 | 1.76193 | 1.84333 | 1.92416 | 2.00441 |
| 39   | 1.43262 | 1.51601 | 1.59893 | 1.68137 | 1.76329 | 1.84468 | 1.92550 | 2.00574 |
| 40   | 1.43402 | 1.51739 | 1.60031 | 1.68274 | 1.76465 | 1.84603 | 1.92685 | 2.00708 |
| 41   | 1.43541 | 1.51878 | 1.60169 | 1.68411 | 1.76601 | 1.84738 | 1.92819 | 2.00841 |
| 42   | 1.43680 | 1.52017 | 1.60307 | 1.68548 | 1.76737 | 1.84873 | 1.92953 | 2.00974 |
| 43   | 1.43820 | 1.52155 | 1.60444 | 1.68685 | 1.76873 | 1.85009 | 1.93087 | 2.01107 |
| 44   | 1.43959 | 1.52294 | 1.60582 | 1.68821 | 1.77010 | 1.85144 | 1.93221 | 2.01240 |
| 45   | 1.44098 | 1.52432 | 1.60720 | 1.68958 | 1.77146 | 1.85279 | 1.93355 | 2.01373 |
| 46   | 1.44237 | 1.52571 | 1.60857 | 1.69095 | 1.77282 | 1.85414 | 1.93490 | 2.01506 |
| 47   | 1.44377 | 1.52709 | 1.60995 | 1.69232 | 1.77418 | 1.85549 | 1.93624 | 2.01640 |
| 48   | 1.44516 | 1.52848 | 1.61133 | 1.69369 | 1.77553 | 1.85684 | 1.93758 | 2.01773 |
| 49   | 1.44655 | 1.52986 | 1.61271 | 1.69506 | 1.77689 | 1.85819 | 1.93892 | 2.01906 |
| 50   | 1.44794 | 1.53125 | 1.61408 | 1.69643 | 1.77825 | 1.85954 | 1.94026 | 2.02039 |
| 51   | 1.44934 | 1.53263 | 1.61546 | 1.69779 | 1.77961 | 1.86089 | 1.94160 | 2.02172 |
| 52   | 1.45073 | 1.53401 | 1.61683 | 1.69916 | 1.78097 | 1.86224 | 1.94294 | 2.02305 |
| 53   | 1.45212 | 1.53540 | 1.61821 | 1.70053 | 1.78233 | 1.86359 | 1.94428 | 2.02438 |
| 54   | 1.45351 | 1.53678 | 1.61959 | 1.70190 | 1.78369 | 1.86494 | 1.94562 | 2.02571 |
| 55   | 1.45490 | 1.53817 | 1.62096 | 1.70327 | 1.78505 | 1.86629 | 1.94696 | 2.02704 |
| 56   | 1.45629 | 1.53955 | 1.62234 | 1.70463 | 1.78641 | 1.86764 | 1.94830 | 2.02837 |
| 57   | 1.45769 | 1.54093 | 1.62371 | 1.70600 | 1.78777 | 1.86899 | 1.94964 | 2.02970 |
| 58   | 1.45908 | 1.54232 | 1.62509 | 1.70737 | 1.78912 | 1.87034 | 1.95098 | 2.03103 |
| 59   | 1.46047 | 1.54370 | 1.62647 | 1.70873 | 1.79048 | 1.87168 | 1.95232 | 2.03235 |
| 60   | 1.46186 | 1.54509 | 1.62784 | 1.71010 | 1.79184 | 1.87303 | 1.95366 | 2.03368 |

## 5-INCH SINE-BAR CONSTANTS

## Constants for Setting a 5-inch Sine-bar for 24° to 31°

| Min. | 24°     | 25°     | 26°     | 27°     | 28°     | 29°     | 30°     | 31°     |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 2.03368 | 2.11309 | 2.19186 | 2.26995 | 2.34736 | 2.42405 | 2.50000 | 2.57519 |
| 1    | 2.03501 | 2.11441 | 2.19316 | 2.27125 | 2.34864 | 2.42532 | 2.50126 | 2.57644 |
| 2    | 2.03634 | 2.11573 | 2.19447 | 2.27254 | 2.34993 | 2.42659 | 2.50252 | 2.57768 |
| 3    | 2.03767 | 2.11704 | 2.19578 | 2.27384 | 2.35121 | 2.42786 | 2.50378 | 2.57893 |
| 4    | 2.03900 | 2.11836 | 2.19708 | 2.27513 | 2.35249 | 2.42913 | 2.50504 | 2.58018 |
| 5    | 2.04032 | 2.11968 | 2.19839 | 2.27643 | 2.35378 | 2.43041 | 2.50630 | 2.58142 |
| 6    | 2.04165 | 2.12100 | 2.19970 | 2.27772 | 2.35506 | 2.43168 | 2.50755 | 2.58267 |
| 7    | 2.04298 | 2.12231 | 2.20100 | 2.27902 | 2.35634 | 2.43295 | 2.50881 | 2.58391 |
| 8    | 2.04431 | 2.12363 | 2.20231 | 2.28031 | 2.35763 | 2.43422 | 2.51007 | 2.58516 |
| 9    | 2.04563 | 2.12495 | 2.20361 | 2.28161 | 2.35891 | 2.43549 | 2.51133 | 2.58640 |
| 10   | 2.04696 | 2.12626 | 2.20492 | 2.28290 | 2.36019 | 2.43676 | 2.51259 | 2.58765 |
| 11   | 2.04829 | 2.12758 | 2.20622 | 2.28420 | 2.36147 | 2.43803 | 2.51384 | 2.58889 |
| 12   | 2.04962 | 2.12890 | 2.20753 | 2.28549 | 2.36275 | 2.43930 | 2.51510 | 2.59014 |
| 13   | 2.05094 | 2.13021 | 2.20883 | 2.28678 | 2.36404 | 2.44057 | 2.51636 | 2.59138 |
| 14   | 2.05227 | 2.13153 | 2.21014 | 2.28808 | 2.36532 | 2.44184 | 2.51761 | 2.59262 |
| 15   | 2.05359 | 2.13284 | 2.21144 | 2.28937 | 2.36660 | 2.44311 | 2.51887 | 2.59387 |
| 16   | 2.05492 | 2.13416 | 2.21275 | 2.29066 | 2.36788 | 2.44438 | 2.52013 | 2.59511 |
| 17   | 2.05625 | 2.13547 | 2.21405 | 2.29196 | 2.36916 | 2.44564 | 2.52138 | 2.59635 |
| 18   | 2.05757 | 2.13679 | 2.21536 | 2.29325 | 2.37044 | 2.44691 | 2.52264 | 2.59760 |
| 19   | 2.05890 | 2.13810 | 2.21666 | 2.29454 | 2.37172 | 2.44818 | 2.52389 | 2.59884 |
| 20   | 2.06022 | 2.13942 | 2.21796 | 2.29583 | 2.37300 | 2.44945 | 2.52515 | 2.60008 |
| 21   | 2.06155 | 2.14073 | 2.21927 | 2.29712 | 2.37428 | 2.45072 | 2.52640 | 2.60132 |
| 22   | 2.06287 | 2.14205 | 2.22057 | 2.29842 | 2.37556 | 2.45198 | 2.52766 | 2.60256 |
| 23   | 2.06420 | 2.14336 | 2.22187 | 2.29971 | 2.37684 | 2.45325 | 2.52891 | 2.60381 |
| 24   | 2.06552 | 2.14468 | 2.22318 | 2.30100 | 2.37812 | 2.45452 | 2.53017 | 2.60505 |
| 25   | 2.06685 | 2.14599 | 2.22448 | 2.30229 | 2.37940 | 2.45579 | 2.53142 | 2.60629 |
| 26   | 2.06817 | 2.14730 | 2.22578 | 2.30358 | 2.38068 | 2.45705 | 2.53268 | 2.60753 |
| 27   | 2.06950 | 2.14862 | 2.22708 | 2.30487 | 2.38196 | 2.45832 | 2.53393 | 2.60877 |
| 28   | 2.07082 | 2.14993 | 2.22839 | 2.30616 | 2.38324 | 2.45959 | 2.53519 | 2.61001 |
| 29   | 2.07214 | 2.15124 | 2.22969 | 2.30745 | 2.38452 | 2.46085 | 2.53644 | 2.61125 |
| 30   | 2.07347 | 2.15256 | 2.23099 | 2.30874 | 2.38579 | 2.46212 | 2.53769 | 2.61249 |
| 31   | 2.07479 | 2.15387 | 2.23229 | 2.31003 | 2.38707 | 2.46338 | 2.53894 | 2.61373 |
| 32   | 2.07611 | 2.15518 | 2.23359 | 2.31132 | 2.38835 | 2.46465 | 2.54020 | 2.61497 |
| 33   | 2.07744 | 2.15649 | 2.23489 | 2.31261 | 2.38963 | 2.46591 | 2.54145 | 2.61621 |
| 34   | 2.07876 | 2.15781 | 2.23619 | 2.31390 | 2.39091 | 2.46718 | 2.54270 | 2.61745 |
| 35   | 2.08008 | 2.15912 | 2.23749 | 2.31519 | 2.39218 | 2.46844 | 2.54396 | 2.61869 |
| 36   | 2.08140 | 2.16043 | 2.23880 | 2.31648 | 2.39346 | 2.46971 | 2.54521 | 2.61993 |
| 37   | 2.08273 | 2.16174 | 2.24010 | 2.31777 | 2.39474 | 2.47097 | 2.54646 | 2.62117 |
| 38   | 2.08405 | 2.16305 | 2.24140 | 2.31906 | 2.39601 | 2.47224 | 2.54771 | 2.62241 |
| 39   | 2.08537 | 2.16436 | 2.24270 | 2.32035 | 2.39729 | 2.47350 | 2.54896 | 2.62364 |
| 40   | 2.08669 | 2.16567 | 2.24400 | 2.32163 | 2.39857 | 2.47477 | 2.55021 | 2.62488 |
| 41   | 2.08801 | 2.16698 | 2.24530 | 2.32292 | 2.39984 | 2.47603 | 2.55146 | 2.62612 |
| 42   | 2.08934 | 2.16830 | 2.24660 | 2.32421 | 2.40112 | 2.47729 | 2.55271 | 2.62736 |
| 43   | 2.09066 | 2.16961 | 2.24789 | 2.32550 | 2.40239 | 2.47856 | 2.55397 | 2.62860 |
| 44   | 2.09198 | 2.17092 | 2.24919 | 2.32679 | 2.40367 | 2.47982 | 2.55522 | 2.62983 |
| 45   | 2.09330 | 2.17223 | 2.25049 | 2.32807 | 2.40494 | 2.48108 | 2.55647 | 2.63107 |
| 46   | 2.09462 | 2.17354 | 2.25179 | 2.32936 | 2.40622 | 2.48235 | 2.55772 | 2.63231 |
| 47   | 2.09594 | 2.17485 | 2.25309 | 2.33065 | 2.40749 | 2.48361 | 2.55896 | 2.63354 |
| 48   | 2.09726 | 2.17616 | 2.25439 | 2.33193 | 2.40877 | 2.48487 | 2.56021 | 2.63478 |
| 49   | 2.09858 | 2.17746 | 2.25569 | 2.33322 | 2.41004 | 2.48613 | 2.56146 | 2.63602 |
| 50   | 2.09990 | 2.17877 | 2.25698 | 2.33451 | 2.41132 | 2.48739 | 2.56271 | 2.63725 |
| 51   | 2.10122 | 2.18008 | 2.25828 | 2.33579 | 2.41259 | 2.48866 | 2.56396 | 2.63849 |
| 52   | 2.10254 | 2.18139 | 2.25958 | 2.33708 | 2.41386 | 2.48992 | 2.56521 | 2.63972 |
| 53   | 2.10386 | 2.18270 | 2.26088 | 2.33836 | 2.41514 | 2.49118 | 2.56646 | 2.64096 |
| 54   | 2.10518 | 2.18401 | 2.26217 | 2.33965 | 2.41641 | 2.49244 | 2.56771 | 2.64219 |
| 55   | 2.10650 | 2.18532 | 2.26347 | 2.34093 | 2.41769 | 2.49370 | 2.56895 | 2.64343 |
| 56   | 2.10782 | 2.18663 | 2.26477 | 2.34222 | 2.41896 | 2.49496 | 2.57020 | 2.64466 |
| 57   | 2.10914 | 2.18793 | 2.26606 | 2.34350 | 2.42023 | 2.49622 | 2.57145 | 2.64590 |
| 58   | 2.11045 | 2.18924 | 2.26736 | 2.34479 | 2.42150 | 2.49748 | 2.57270 | 2.64713 |
| 59   | 2.11177 | 2.19055 | 2.26866 | 2.34607 | 2.42278 | 2.49874 | 2.57394 | 2.64836 |
| 60   | 2.11309 | 2.19186 | 2.26995 | 2.34736 | 2.42405 | 2.50000 | 2.57519 | 2.64960 |

## Constants for Setting a 5-inch Sine-bar for 32° to 39°

| Min. | 32°     | 33°     | 34°     | 35°     | 36°     | 37°     | 38°     | 39°     |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 2.64960 | 2.72320 | 2.79596 | 2.86788 | 2.93893 | 3.00908 | 3.07831 | 3.14660 |
| 1    | 2.65083 | 2.72441 | 2.79717 | 2.86907 | 2.94010 | 3.01024 | 3.07945 | 3.14773 |
| 2    | 2.65206 | 2.72563 | 2.79838 | 2.87026 | 2.94128 | 3.01140 | 3.08060 | 3.14886 |
| 3    | 2.65330 | 2.72685 | 2.79958 | 2.87146 | 2.94246 | 3.01256 | 3.08174 | 3.14999 |
| 4    | 2.65453 | 2.72807 | 2.80079 | 2.87265 | 2.94363 | 3.01372 | 3.08289 | 3.15112 |
| 5    | 2.65576 | 2.72929 | 2.80199 | 2.87384 | 2.94481 | 3.01488 | 3.08403 | 3.15225 |
| 6    | 2.65699 | 2.73051 | 2.80319 | 2.87503 | 2.94598 | 3.01604 | 3.08518 | 3.15338 |
| 7    | 2.65822 | 2.73173 | 2.80440 | 2.87622 | 2.94716 | 3.01720 | 3.08632 | 3.15451 |
| 8    | 2.65946 | 2.73295 | 2.80560 | 2.87741 | 2.94833 | 3.01836 | 3.08747 | 3.15564 |
| 9    | 2.66069 | 2.73416 | 2.80681 | 2.87860 | 2.94951 | 3.01952 | 3.08861 | 3.15676 |
| 10   | 2.66192 | 2.73538 | 2.80801 | 2.87978 | 2.95068 | 3.02068 | 3.08976 | 3.15789 |
| 11   | 2.66315 | 2.73660 | 2.80921 | 2.88097 | 2.95185 | 3.02184 | 3.09090 | 3.15902 |
| 12   | 2.66438 | 2.73782 | 2.81042 | 2.88216 | 2.95303 | 3.02300 | 3.09204 | 3.16015 |
| 13   | 2.66561 | 2.73903 | 2.81162 | 2.88335 | 2.95420 | 3.02415 | 3.09318 | 3.16127 |
| 14   | 2.66684 | 2.74025 | 2.81282 | 2.88454 | 2.95538 | 3.02531 | 3.09433 | 3.16240 |
| 15   | 2.66807 | 2.74147 | 2.81402 | 2.88573 | 2.95655 | 3.02647 | 3.09547 | 3.16353 |
| 16   | 2.66930 | 2.74268 | 2.81523 | 2.88691 | 2.95772 | 3.02763 | 3.09661 | 3.16465 |
| 17   | 2.67053 | 2.74390 | 2.81643 | 2.88810 | 2.95889 | 3.02878 | 3.09775 | 3.16578 |
| 18   | 2.67176 | 2.74511 | 2.81763 | 2.88929 | 2.96007 | 3.02994 | 3.09890 | 3.16690 |
| 19   | 2.67299 | 2.74633 | 2.81883 | 2.89048 | 2.96124 | 3.03110 | 3.10004 | 3.16803 |
| 20   | 2.67422 | 2.74754 | 2.82003 | 2.89166 | 2.96241 | 3.03226 | 3.10118 | 3.16915 |
| 21   | 2.67545 | 2.74876 | 2.82123 | 2.89285 | 2.96358 | 3.03341 | 3.10232 | 3.17028 |
| 22   | 2.67668 | 2.74997 | 2.82243 | 2.89403 | 2.96475 | 3.03457 | 3.10346 | 3.17140 |
| 23   | 2.67791 | 2.75119 | 2.82364 | 2.89522 | 2.96592 | 3.03572 | 3.10460 | 3.17253 |
| 24   | 2.67913 | 2.75240 | 2.82484 | 2.89641 | 2.96709 | 3.03688 | 3.10574 | 3.17365 |
| 25   | 2.68036 | 2.75362 | 2.82604 | 2.89759 | 2.96827 | 3.03803 | 3.10688 | 3.17478 |
| 26   | 2.68159 | 2.75483 | 2.82723 | 2.89878 | 2.96944 | 3.03919 | 3.10802 | 3.17590 |
| 27   | 2.68282 | 2.75605 | 2.82843 | 2.89996 | 2.97061 | 3.04034 | 3.10916 | 3.17702 |
| 28   | 2.68404 | 2.75726 | 2.82963 | 2.90115 | 2.97178 | 3.04150 | 3.11030 | 3.17815 |
| 29   | 2.68527 | 2.75847 | 2.83083 | 2.90233 | 2.97294 | 3.04265 | 3.11143 | 3.17927 |
| 30   | 2.68650 | 2.75969 | 2.83203 | 2.90351 | 2.97411 | 3.04381 | 3.11257 | 3.18039 |
| 31   | 2.68772 | 2.76090 | 2.83323 | 2.90470 | 2.97528 | 3.04496 | 3.11371 | 3.18151 |
| 32   | 2.68895 | 2.76211 | 2.83443 | 2.90588 | 2.97645 | 3.04611 | 3.11485 | 3.18264 |
| 33   | 2.69018 | 2.76332 | 2.83563 | 2.90707 | 2.97762 | 3.04727 | 3.11599 | 3.18376 |
| 34   | 2.69140 | 2.76453 | 2.83682 | 2.90825 | 2.97879 | 3.04842 | 3.11712 | 3.18488 |
| 35   | 2.69263 | 2.76575 | 2.83802 | 2.90943 | 2.97996 | 3.04957 | 3.11826 | 3.18600 |
| 36   | 2.69385 | 2.76696 | 2.83922 | 2.91061 | 2.98112 | 3.05073 | 3.11940 | 3.18712 |
| 37   | 2.69508 | 2.76817 | 2.84042 | 2.91180 | 2.98229 | 3.05188 | 3.12053 | 3.18824 |
| 38   | 2.69630 | 2.76938 | 2.84161 | 2.91298 | 2.98346 | 3.05303 | 3.12167 | 3.18936 |
| 39   | 2.69753 | 2.77059 | 2.84281 | 2.91416 | 2.98463 | 3.05418 | 3.12281 | 3.19048 |
| 40   | 2.69875 | 2.77180 | 2.84401 | 2.91534 | 2.98579 | 3.05533 | 3.12394 | 3.19160 |
| 41   | 2.69998 | 2.77301 | 2.84520 | 2.91652 | 2.98696 | 3.05648 | 3.12508 | 3.19272 |
| 42   | 2.70120 | 2.77422 | 2.84640 | 2.91771 | 2.98813 | 3.05764 | 3.12621 | 3.19384 |
| 43   | 2.70243 | 2.77543 | 2.84759 | 2.91889 | 2.98929 | 3.05879 | 3.12735 | 3.19496 |
| 44   | 2.70365 | 2.77664 | 2.84879 | 2.92007 | 2.99046 | 3.05994 | 3.12848 | 3.19608 |
| 45   | 2.70487 | 2.77785 | 2.84998 | 2.92125 | 2.99162 | 3.06109 | 3.12962 | 3.19720 |
| 46   | 2.70610 | 2.77906 | 2.85118 | 2.92243 | 2.99279 | 3.06224 | 3.13075 | 3.19831 |
| 47   | 2.70732 | 2.78027 | 2.85237 | 2.92361 | 2.99395 | 3.06339 | 3.13189 | 3.19943 |
| 48   | 2.70854 | 2.78148 | 2.85357 | 2.92479 | 2.99512 | 3.06454 | 3.13302 | 3.20055 |
| 49   | 2.70976 | 2.78269 | 2.85476 | 2.92597 | 2.99628 | 3.06568 | 3.13415 | 3.20167 |
| 50   | 2.71099 | 2.78389 | 2.85596 | 2.92715 | 2.99745 | 3.06683 | 3.13529 | 3.20278 |
| 51   | 2.71221 | 2.78510 | 2.85715 | 2.92833 | 2.99861 | 3.06798 | 3.13642 | 3.20390 |
| 52   | 2.71343 | 2.78631 | 2.85834 | 2.92950 | 2.99977 | 3.06913 | 3.13755 | 3.20502 |
| 53   | 2.71465 | 2.78752 | 2.85954 | 2.93068 | 3.00094 | 3.07028 | 3.13868 | 3.20613 |
| 54   | 2.71587 | 2.78873 | 2.86073 | 2.93186 | 3.00210 | 3.07143 | 3.13982 | 3.20725 |
| 55   | 2.71709 | 2.78993 | 2.86192 | 2.93304 | 3.00326 | 3.07257 | 3.14095 | 3.20836 |
| 56   | 2.71831 | 2.79114 | 2.86311 | 2.93422 | 3.00443 | 3.07372 | 3.14208 | 3.20948 |
| 57   | 2.71953 | 2.79235 | 2.86431 | 2.93540 | 3.00559 | 3.07487 | 3.14321 | 3.21059 |
| 58   | 2.72076 | 2.79355 | 2.86550 | 2.93657 | 3.00675 | 3.07601 | 3.14434 | 3.21171 |
| 59   | 2.72198 | 2.79476 | 2.86669 | 2.93775 | 3.00791 | 3.07716 | 3.14547 | 3.21282 |
| 60   | 2.72320 | 2.79596 | 2.86788 | 2.93893 | 3.00908 | 3.07831 | 3.14660 | 3.21394 |

## 5-INCH SINE-BAR CONSTANTS

## Constants for Setting a 5-inch Sine-bar for 40° to 47°

| Min. | 40°     | 41°     | 42°     | 43°     | 44°     | 45°     | 46°     | 47°     |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 3.21394 | 3.28030 | 3.34565 | 3.40999 | 3.47329 | 3.53553 | 3.59670 | 3.65677 |
| 1    | 3.21505 | 3.28139 | 3.34673 | 3.41106 | 3.47434 | 3.53656 | 3.59771 | 3.65776 |
| 2    | 3.21617 | 3.28249 | 3.34781 | 3.41212 | 3.47538 | 3.53759 | 3.59872 | 3.65875 |
| 3    | 3.21728 | 3.28359 | 3.34889 | 3.41318 | 3.47643 | 3.53862 | 3.59973 | 3.65974 |
| 4    | 3.21839 | 3.28468 | 3.34997 | 3.41424 | 3.47747 | 3.53965 | 3.60074 | 3.66073 |
| 5    | 3.21951 | 3.28578 | 3.35105 | 3.41531 | 3.47852 | 3.54067 | 3.60175 | 3.66172 |
| 6    | 3.22062 | 3.28688 | 3.35213 | 3.41637 | 3.47956 | 3.54170 | 3.60276 | 3.66271 |
| 7    | 3.22173 | 3.28797 | 3.35321 | 3.41743 | 3.48061 | 3.54273 | 3.60376 | 3.66370 |
| 8    | 3.22284 | 3.28907 | 3.35429 | 3.41849 | 3.48165 | 3.54375 | 3.60477 | 3.66469 |
| 9    | 3.22395 | 3.29016 | 3.35537 | 3.41955 | 3.48270 | 3.54478 | 3.60578 | 3.66568 |
| 10   | 3.22507 | 3.29126 | 3.35645 | 3.42061 | 3.48374 | 3.54580 | 3.60679 | 3.66667 |
| 11   | 3.22618 | 3.29235 | 3.35753 | 3.42168 | 3.48478 | 3.54683 | 3.60779 | 3.66766 |
| 12   | 3.22729 | 3.29345 | 3.35860 | 3.42274 | 3.48583 | 3.54785 | 3.60880 | 3.66865 |
| 13   | 3.22840 | 3.29454 | 3.35968 | 3.42380 | 3.48687 | 3.54888 | 3.60981 | 3.66964 |
| 14   | 3.22951 | 3.29564 | 3.36076 | 3.42486 | 3.48791 | 3.54990 | 3.61081 | 3.67063 |
| 15   | 3.23062 | 3.29673 | 3.36183 | 3.42592 | 3.48895 | 3.55093 | 3.61182 | 3.67161 |
| 16   | 3.23173 | 3.29782 | 3.36291 | 3.42697 | 3.48999 | 3.55195 | 3.61283 | 3.67260 |
| 17   | 3.23284 | 3.29892 | 3.36399 | 3.42803 | 3.49104 | 3.55297 | 3.61383 | 3.67359 |
| 18   | 3.23395 | 3.30001 | 3.36506 | 3.42909 | 3.49208 | 3.55400 | 3.61484 | 3.67457 |
| 19   | 3.23506 | 3.30110 | 3.36614 | 3.43015 | 3.49312 | 3.55502 | 3.61584 | 3.67556 |
| 20   | 3.23617 | 3.30219 | 3.36721 | 3.43121 | 3.49416 | 3.55604 | 3.61684 | 3.67655 |
| 21   | 3.23728 | 3.30329 | 3.36829 | 3.43227 | 3.49520 | 3.55707 | 3.61785 | 3.67753 |
| 22   | 3.23838 | 3.30438 | 3.36936 | 3.43332 | 3.49624 | 3.55809 | 3.61885 | 3.67852 |
| 23   | 3.23949 | 3.30547 | 3.37044 | 3.43438 | 3.49728 | 3.55911 | 3.61986 | 3.67950 |
| 24   | 3.24060 | 3.30656 | 3.37151 | 3.43544 | 3.49832 | 3.56013 | 3.62086 | 3.68049 |
| 25   | 3.24171 | 3.30765 | 3.37259 | 3.43649 | 3.49936 | 3.56115 | 3.62186 | 3.68147 |
| 26   | 3.24281 | 3.30874 | 3.37366 | 3.43755 | 3.50039 | 3.56217 | 3.62286 | 3.68245 |
| 27   | 3.24392 | 3.30983 | 3.37473 | 3.43861 | 3.50143 | 3.56319 | 3.62387 | 3.68344 |
| 28   | 3.24503 | 3.31092 | 3.37581 | 3.43966 | 3.50247 | 3.56421 | 3.62487 | 3.68442 |
| 29   | 3.24613 | 3.31201 | 3.37688 | 3.44072 | 3.50351 | 3.56523 | 3.62587 | 3.68540 |
| 30   | 3.24724 | 3.31310 | 3.37795 | 3.44177 | 3.50455 | 3.56625 | 3.62687 | 3.68639 |
| 31   | 3.24835 | 3.31419 | 3.37902 | 3.44283 | 3.50558 | 3.56727 | 3.62787 | 3.68737 |
| 32   | 3.24945 | 3.31528 | 3.38010 | 3.44388 | 3.50662 | 3.56829 | 3.62887 | 3.68835 |
| 33   | 3.25056 | 3.31637 | 3.38117 | 3.44494 | 3.50766 | 3.56931 | 3.62987 | 3.68933 |
| 34   | 3.25166 | 3.31746 | 3.38224 | 3.44599 | 3.50869 | 3.57033 | 3.63087 | 3.69031 |
| 35   | 3.25277 | 3.31854 | 3.38331 | 3.44704 | 3.50973 | 3.57135 | 3.63187 | 3.69130 |
| 36   | 3.25387 | 3.31963 | 3.38438 | 3.44810 | 3.51077 | 3.57236 | 3.63287 | 3.69228 |
| 37   | 3.25498 | 3.32072 | 3.38545 | 3.44915 | 3.51180 | 3.57338 | 3.63387 | 3.69326 |
| 38   | 3.25608 | 3.32181 | 3.38652 | 3.45020 | 3.51284 | 3.57440 | 3.63487 | 3.69424 |
| 39   | 3.25718 | 3.32289 | 3.38759 | 3.45126 | 3.51387 | 3.57542 | 3.63587 | 3.69522 |
| 40   | 3.25829 | 3.32398 | 3.38866 | 3.45231 | 3.51491 | 3.57643 | 3.63687 | 3.69620 |
| 41   | 3.25939 | 3.32507 | 3.38973 | 3.45336 | 3.51594 | 3.57745 | 3.63787 | 3.69718 |
| 42   | 3.26049 | 3.32615 | 3.39080 | 3.45441 | 3.51697 | 3.57846 | 3.63886 | 3.69816 |
| 43   | 3.26159 | 3.32724 | 3.39187 | 3.45546 | 3.51801 | 3.57948 | 3.63986 | 3.69913 |
| 44   | 3.26270 | 3.32832 | 3.39294 | 3.45651 | 3.51904 | 3.58049 | 3.64086 | 3.70011 |
| 45   | 3.26380 | 3.32941 | 3.39400 | 3.45757 | 3.52007 | 3.58151 | 3.64186 | 3.70109 |
| 46   | 3.26490 | 3.33049 | 3.39507 | 3.45862 | 3.52111 | 3.58252 | 3.64285 | 3.70207 |
| 47   | 3.26600 | 3.33158 | 3.39614 | 3.45967 | 3.52214 | 3.58354 | 3.64385 | 3.70305 |
| 48   | 3.26710 | 3.33266 | 3.39721 | 3.46072 | 3.52317 | 3.58455 | 3.64484 | 3.70402 |
| 49   | 3.26820 | 3.33375 | 3.39827 | 3.46177 | 3.52420 | 3.58557 | 3.64584 | 3.70500 |
| 50   | 3.26930 | 3.33483 | 3.39934 | 3.46281 | 3.52523 | 3.58658 | 3.64683 | 3.70598 |
| 51   | 3.27040 | 3.33591 | 3.40041 | 3.46386 | 3.52627 | 3.58759 | 3.64783 | 3.70695 |
| 52   | 3.27150 | 3.33700 | 3.40147 | 3.46491 | 3.52730 | 3.58861 | 3.64882 | 3.70793 |
| 53   | 3.27260 | 3.33808 | 3.40254 | 3.46596 | 3.52833 | 3.58962 | 3.64982 | 3.70890 |
| 54   | 3.27370 | 3.33916 | 3.40360 | 3.46701 | 3.52936 | 3.59063 | 3.65081 | 3.70988 |
| 55   | 3.27480 | 3.34025 | 3.40467 | 3.46806 | 3.53039 | 3.59164 | 3.65181 | 3.71085 |
| 56   | 3.27590 | 3.34133 | 3.40573 | 3.46910 | 3.53142 | 3.59266 | 3.65280 | 3.71183 |
| 57   | 3.27700 | 3.34241 | 3.40680 | 3.47015 | 3.53245 | 3.59367 | 3.65379 | 3.71280 |
| 58   | 3.27810 | 3.34349 | 3.40786 | 3.47120 | 3.53348 | 3.59468 | 3.65478 | 3.71378 |
| 59   | 3.27920 | 3.34457 | 3.40893 | 3.47225 | 3.53451 | 3.59569 | 3.65578 | 3.71475 |
| 60   | 3.28030 | 3.34565 | 3.40999 | 3.47329 | 3.53553 | 3.59670 | 3.65677 | 3.71572 |

## Constants for Setting a 5-inch Sine-bar for 48° to 55°

| Min. | 48°     | 49°     | 50°     | 51°     | 52°     | 53°     | 54°     | 55°     |
|------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | 3.71572 | 3.77355 | 3.83022 | 3.88573 | 3.94005 | 3.99318 | 4.04508 | 4.09576 |
| 1    | 3.71670 | 3.77450 | 3.83116 | 3.88665 | 3.94095 | 3.99405 | 4.04594 | 4.09659 |
| 2    | 3.71767 | 3.77546 | 3.83209 | 3.88756 | 3.94184 | 3.99493 | 4.04679 | 4.09743 |
| 3    | 3.71864 | 3.77641 | 3.83303 | 3.88847 | 3.94274 | 3.99580 | 4.04765 | 4.09826 |
| 4    | 3.71961 | 3.77736 | 3.83396 | 3.88939 | 3.94363 | 3.99668 | 4.04850 | 4.09909 |
| 5    | 3.72059 | 3.77831 | 3.83489 | 3.89030 | 3.94453 | 3.99755 | 4.04936 | 4.09993 |
| 6    | 3.72156 | 3.77927 | 3.83583 | 3.89122 | 3.94542 | 3.99842 | 4.05021 | 4.10076 |
| 7    | 3.72253 | 3.78022 | 3.83676 | 3.89213 | 3.94631 | 3.99930 | 4.05106 | 4.10159 |
| 8    | 3.72350 | 3.78117 | 3.83769 | 3.89304 | 3.94721 | 4.00017 | 4.05191 | 4.10242 |
| 9    | 3.72447 | 3.78212 | 3.83862 | 3.89395 | 3.94810 | 4.00104 | 4.05277 | 4.10325 |
| 10   | 3.72544 | 3.78307 | 3.83956 | 3.89487 | 3.94899 | 4.00191 | 4.05362 | 4.10409 |
| 11   | 3.72641 | 3.78402 | 3.84049 | 3.89578 | 3.94988 | 4.00279 | 4.05447 | 4.10492 |
| 12   | 3.72738 | 3.78498 | 3.84142 | 3.89669 | 3.95078 | 4.00366 | 4.05532 | 4.10575 |
| 13   | 3.72835 | 3.78593 | 3.84235 | 3.89760 | 3.95167 | 4.00453 | 4.05617 | 4.10658 |
| 14   | 3.72932 | 3.78688 | 3.84328 | 3.89851 | 3.95256 | 4.00540 | 4.05702 | 4.10741 |
| 15   | 3.73029 | 3.78783 | 3.84421 | 3.89942 | 3.95345 | 4.00627 | 4.05787 | 4.10823 |
| 16   | 3.73126 | 3.78877 | 3.84514 | 3.90033 | 3.95434 | 4.00714 | 4.05872 | 4.10906 |
| 17   | 3.73222 | 3.78972 | 3.84607 | 3.90124 | 3.95523 | 4.00801 | 4.05957 | 4.10989 |
| 18   | 3.73319 | 3.79067 | 3.84700 | 3.90215 | 3.95612 | 4.00888 | 4.06042 | 4.11072 |
| 19   | 3.73416 | 3.79162 | 3.84793 | 3.90306 | 3.95701 | 4.00975 | 4.06127 | 4.11155 |
| 20   | 3.73513 | 3.79257 | 3.84886 | 3.90397 | 3.95790 | 4.01062 | 4.06211 | 4.11238 |
| 21   | 3.73609 | 3.79352 | 3.84978 | 3.90488 | 3.95878 | 4.01148 | 4.06296 | 4.11320 |
| 22   | 3.73706 | 3.79446 | 3.85071 | 3.90579 | 3.95967 | 4.01235 | 4.06381 | 4.11403 |
| 23   | 3.73802 | 3.79541 | 3.85164 | 3.90669 | 3.96056 | 4.01322 | 4.06466 | 4.11486 |
| 24   | 3.73899 | 3.79636 | 3.85257 | 3.90760 | 3.96145 | 4.01409 | 4.06550 | 4.11568 |
| 25   | 3.73996 | 3.79730 | 3.85349 | 3.90851 | 3.96234 | 4.01495 | 4.06635 | 4.11651 |
| 26   | 3.74092 | 3.79825 | 3.85442 | 3.90942 | 3.96322 | 4.01582 | 4.06720 | 4.11733 |
| 27   | 3.74189 | 3.79919 | 3.85535 | 3.91032 | 3.96411 | 4.01669 | 4.06804 | 4.11816 |
| 28   | 3.74285 | 3.80014 | 3.85627 | 3.91123 | 3.96500 | 4.01755 | 4.06889 | 4.11898 |
| 29   | 3.74381 | 3.80109 | 3.85720 | 3.91214 | 3.96588 | 4.01842 | 4.06973 | 4.11981 |
| 30   | 3.74478 | 3.80203 | 3.85812 | 3.91304 | 3.96677 | 4.01928 | 4.07058 | 4.12063 |
| 31   | 3.74574 | 3.80297 | 3.85905 | 3.91395 | 3.96765 | 4.02015 | 4.07142 | 4.12145 |
| 32   | 3.74671 | 3.80392 | 3.85997 | 3.91485 | 3.96854 | 4.02101 | 4.07227 | 4.12228 |
| 33   | 3.74767 | 3.80486 | 3.86090 | 3.91576 | 3.96942 | 4.02188 | 4.07311 | 4.12310 |
| 34   | 3.74863 | 3.80581 | 3.86182 | 3.91666 | 3.97031 | 4.02274 | 4.07395 | 4.12392 |
| 35   | 3.74959 | 3.80675 | 3.86274 | 3.91756 | 3.97119 | 4.02361 | 4.07480 | 4.12475 |
| 36   | 3.75056 | 3.80769 | 3.86367 | 3.91847 | 3.97207 | 4.02447 | 4.07564 | 4.12557 |
| 37   | 3.75152 | 3.80863 | 3.86459 | 3.91937 | 3.97296 | 4.02533 | 4.07648 | 4.12639 |
| 38   | 3.75248 | 3.80958 | 3.86551 | 3.92027 | 3.97384 | 4.02619 | 4.07732 | 4.12721 |
| 39   | 3.75344 | 3.81052 | 3.86644 | 3.92118 | 3.97472 | 4.02706 | 4.07817 | 4.12803 |
| 40   | 3.75440 | 3.81146 | 3.86736 | 3.92208 | 3.97560 | 4.02792 | 4.07901 | 4.12885 |
| 41   | 3.75536 | 3.81240 | 3.86828 | 3.92298 | 3.97649 | 4.02878 | 4.07985 | 4.12967 |
| 42   | 3.75632 | 3.81334 | 3.86920 | 3.92388 | 3.97737 | 4.02964 | 4.08069 | 4.13049 |
| 43   | 3.75728 | 3.81428 | 3.87012 | 3.92478 | 3.97825 | 4.03050 | 4.08153 | 4.13131 |
| 44   | 3.75824 | 3.81522 | 3.87104 | 3.92568 | 3.97913 | 4.03136 | 4.08237 | 4.13213 |
| 45   | 3.75920 | 3.81616 | 3.87196 | 3.92658 | 3.98001 | 4.03222 | 4.08321 | 4.13295 |
| 46   | 3.76016 | 3.81710 | 3.87288 | 3.92748 | 3.98089 | 4.03308 | 4.08405 | 4.13377 |
| 47   | 3.76112 | 3.81804 | 3.87380 | 3.92839 | 3.98177 | 4.03394 | 4.08489 | 4.13459 |
| 48   | 3.76207 | 3.81898 | 3.87472 | 3.92928 | 3.98265 | 4.03480 | 4.08572 | 4.13540 |
| 49   | 3.76303 | 3.81992 | 3.87564 | 3.93018 | 3.98353 | 4.03566 | 4.08656 | 4.13622 |
| 50   | 3.76399 | 3.82086 | 3.87656 | 3.93108 | 3.98441 | 4.03652 | 4.08740 | 4.13704 |
| 51   | 3.76495 | 3.82179 | 3.87748 | 3.93198 | 3.98529 | 4.03738 | 4.08824 | 4.13785 |
| 52   | 3.76590 | 3.82273 | 3.87840 | 3.93288 | 3.98616 | 4.03823 | 4.08908 | 4.13867 |
| 53   | 3.76686 | 3.82367 | 3.87931 | 3.93378 | 3.98704 | 4.03909 | 4.08991 | 4.13949 |
| 54   | 3.76782 | 3.82461 | 3.88023 | 3.93468 | 3.98792 | 4.03995 | 4.09075 | 4.14030 |
| 55   | 3.76877 | 3.82554 | 3.88115 | 3.93557 | 3.98880 | 4.04081 | 4.09158 | 4.14112 |
| 56   | 3.76973 | 3.82648 | 3.88207 | 3.93647 | 3.98967 | 4.04166 | 4.09242 | 4.14193 |
| 57   | 3.77068 | 3.82742 | 3.88298 | 3.93737 | 3.99055 | 4.04252 | 4.09326 | 4.14275 |
| 58   | 3.77164 | 3.82835 | 3.88390 | 3.93826 | 3.99143 | 4.04337 | 4.09409 | 4.14356 |
| 59   | 3.77259 | 3.82929 | 3.88481 | 3.93916 | 3.99230 | 4.04423 | 4.09493 | 4.14437 |
| 60   | 3.77355 | 3.83022 | 3.88573 | 3.94005 | 3.99318 | 4.04508 | 4.09576 | 4.14519 |

## 100-MILLIMETER SINE-BAR CONSTANTS

## Constants for 100-millimeter Sine-bar

## Constants for Setting a 100-mm Sine-bar for 0° to 7°

| Min. | 0°       | 1°       | 2°       | 3°       | 4°       | 5°        | 6°        | 7°        |
|------|----------|----------|----------|----------|----------|-----------|-----------|-----------|
| 0    | 0.000000 | 1.745241 | 3.489950 | 5.233596 | 6.975647 | 8.715574  | 10.452847 | 12.186934 |
| 1    | 0.029089 | 1.774325 | 3.519021 | 5.262644 | 7.004666 | 8.744553  | 10.481776 | 12.215807 |
| 2    | 0.058178 | 1.803409 | 3.548091 | 5.291693 | 7.033682 | 8.773529  | 10.510704 | 12.244677 |
| 3    | 0.087266 | 1.832493 | 3.577162 | 5.320741 | 7.062699 | 8.802505  | 10.539631 | 12.273546 |
| 4    | 0.116355 | 1.861577 | 3.606232 | 5.349788 | 7.091714 | 8.831481  | 10.568558 | 12.302414 |
| 5    | 0.145444 | 1.890661 | 3.635301 | 5.378835 | 7.120730 | 8.860456  | 10.597483 | 12.331282 |
| 6    | 0.174533 | 1.919744 | 3.664371 | 5.407881 | 7.149745 | 8.889430  | 10.626408 | 12.360147 |
| 7    | 0.203622 | 1.948828 | 3.693440 | 5.436927 | 7.178759 | 8.918404  | 10.655332 | 12.389013 |
| 8    | 0.232710 | 1.977911 | 3.722509 | 5.465973 | 7.207772 | 8.947375  | 10.684254 | 12.417877 |
| 9    | 0.261799 | 2.006994 | 3.751578 | 5.495018 | 7.236785 | 8.976348  | 10.713176 | 12.446741 |
| 10   | 0.290888 | 2.036077 | 3.780646 | 5.524063 | 7.265797 | 9.005319  | 10.742096 | 12.475602 |
| 11   | 0.319977 | 2.065159 | 3.809714 | 5.553107 | 7.294809 | 9.034289  | 10.771017 | 12.504464 |
| 12   | 0.349065 | 2.094242 | 3.838781 | 5.582151 | 7.323820 | 9.063258  | 10.799935 | 12.533323 |
| 13   | 0.378154 | 2.123324 | 3.867848 | 5.611194 | 7.352830 | 9.092227  | 10.828855 | 12.562182 |
| 14   | 0.407242 | 2.152407 | 3.896915 | 5.640237 | 7.381840 | 9.121195  | 10.857771 | 12.591040 |
| 15   | 0.436331 | 2.181489 | 3.925982 | 5.669279 | 7.410849 | 9.150162  | 10.886688 | 12.619897 |
| 16   | 0.465420 | 2.210570 | 3.955048 | 5.698321 | 7.439858 | 9.179129  | 10.915604 | 12.648753 |
| 17   | 0.494508 | 2.239652 | 3.984114 | 5.727362 | 7.468865 | 9.208094  | 10.944518 | 12.677608 |
| 18   | 0.523596 | 2.268733 | 4.013179 | 5.756403 | 7.497873 | 9.237060  | 10.973432 | 12.706462 |
| 19   | 0.552685 | 2.297815 | 4.042244 | 5.785443 | 7.526879 | 9.266023  | 11.002344 | 12.735313 |
| 20   | 0.581773 | 2.326896 | 4.071309 | 5.814483 | 7.555886 | 9.294987  | 11.031256 | 12.764166 |
| 21   | 0.610861 | 2.355977 | 4.100374 | 5.843522 | 7.584891 | 9.323949  | 11.060166 | 12.793011 |
| 22   | 0.639950 | 2.385057 | 4.129438 | 5.872561 | 7.613896 | 9.352911  | 11.089077 | 12.821865 |
| 23   | 0.669038 | 2.414138 | 4.158502 | 5.901600 | 7.642900 | 9.381871  | 11.117986 | 12.850713 |
| 24   | 0.698126 | 2.443218 | 4.187566 | 5.930638 | 7.671903 | 9.410831  | 11.146894 | 12.879560 |
| 25   | 0.727214 | 2.472298 | 4.216629 | 5.959675 | 7.700905 | 9.439791  | 11.175800 | 12.908405 |
| 26   | 0.756302 | 2.501378 | 4.245691 | 5.988712 | 7.729908 | 9.468750  | 11.204707 | 12.937251 |
| 27   | 0.785390 | 2.530457 | 4.274754 | 6.017748 | 7.758909 | 9.497706  | 11.233611 | 12.966094 |
| 28   | 0.814478 | 2.559537 | 4.303816 | 6.046784 | 7.787910 | 9.526664  | 11.262516 | 12.994938 |
| 29   | 0.843566 | 2.588616 | 4.332878 | 6.075819 | 7.816910 | 9.555620  | 11.291419 | 13.023779 |
| 30   | 0.872654 | 2.617695 | 4.361939 | 6.104854 | 7.845910 | 9.584576  | 11.320322 | 13.052620 |
| 31   | 0.901741 | 2.646774 | 4.391000 | 6.133888 | 7.874909 | 9.613530  | 11.349223 | 13.081459 |
| 32   | 0.930829 | 2.675852 | 4.420060 | 6.162922 | 7.903907 | 9.642484  | 11.378123 | 13.110297 |
| 33   | 0.959916 | 2.704930 | 4.449121 | 6.191956 | 7.932905 | 9.671437  | 11.407023 | 13.139134 |
| 34   | 0.989004 | 2.734009 | 4.478180 | 6.220988 | 7.961901 | 9.700389  | 11.435922 | 13.167971 |
| 35   | 1.018091 | 2.763086 | 4.507240 | 6.250021 | 7.990898 | 9.729341  | 11.464819 | 13.196806 |
| 36   | 1.047179 | 2.792164 | 4.536299 | 6.279052 | 8.019893 | 9.758290  | 11.493715 | 13.225639 |
| 37   | 1.076266 | 2.821241 | 4.565357 | 6.308083 | 8.048887 | 9.787240  | 11.522612 | 13.254473 |
| 38   | 1.105353 | 2.850318 | 4.594416 | 6.337114 | 8.077881 | 9.816189  | 11.551505 | 13.283303 |
| 39   | 1.134440 | 2.879395 | 4.623474 | 6.366144 | 8.106875 | 9.845137  | 11.580400 | 13.312135 |
| 40   | 1.163527 | 2.908472 | 4.652532 | 6.395174 | 8.135867 | 9.874084  | 11.609291 | 13.340963 |
| 41   | 1.192613 | 2.937548 | 4.681589 | 6.424202 | 8.164860 | 9.903030  | 11.638184 | 13.369792 |
| 42   | 1.221700 | 2.966624 | 4.710645 | 6.453231 | 8.193851 | 9.931975  | 11.667073 | 13.398619 |
| 43   | 1.250787 | 2.995700 | 4.739702 | 6.482259 | 8.222842 | 9.960920  | 11.695964 | 13.427444 |
| 44   | 1.279873 | 3.024776 | 4.768757 | 6.511286 | 8.251831 | 9.989863  | 11.724852 | 13.456269 |
| 45   | 1.308960 | 3.053851 | 4.797813 | 6.540313 | 8.280821 | 10.018806 | 11.753740 | 13.485093 |
| 46   | 1.338046 | 3.082927 | 4.826868 | 6.569339 | 8.309810 | 10.047749 | 11.782627 | 13.513916 |
| 47   | 1.367132 | 3.112001 | 4.855923 | 6.598365 | 8.338798 | 10.076690 | 11.811512 | 13.542737 |
| 48   | 1.396218 | 3.141076 | 4.884977 | 6.627390 | 8.367785 | 10.105630 | 11.840398 | 13.571558 |
| 49   | 1.425304 | 3.170151 | 4.914031 | 6.656415 | 8.396770 | 10.134569 | 11.869281 | 13.600377 |
| 50   | 1.454390 | 3.199224 | 4.943084 | 6.685439 | 8.425757 | 10.163508 | 11.898164 | 13.629195 |
| 51   | 1.483476 | 3.228298 | 4.972137 | 6.714462 | 8.454741 | 10.192446 | 11.927045 | 13.658011 |
| 52   | 1.512561 | 3.257372 | 5.001190 | 6.743485 | 8.483727 | 10.221383 | 11.955926 | 13.686828 |
| 53   | 1.541646 | 3.286445 | 5.030242 | 6.772508 | 8.512710 | 10.250319 | 11.984805 | 13.715641 |
| 54   | 1.570732 | 3.315518 | 5.059294 | 6.801529 | 8.541693 | 10.279254 | 12.013684 | 13.744455 |
| 55   | 1.599817 | 3.344591 | 5.088346 | 6.830551 | 8.570675 | 10.308188 | 12.042562 | 13.773267 |
| 56   | 1.628902 | 3.373663 | 5.117396 | 6.859571 | 8.599656 | 10.337122 | 12.071439 | 13.802078 |
| 57   | 1.657987 | 3.402735 | 5.146447 | 6.888591 | 8.628636 | 10.366054 | 12.100314 | 13.830888 |
| 58   | 1.687072 | 3.431807 | 5.175497 | 6.917611 | 8.657617 | 10.394986 | 12.129189 | 13.859696 |
| 59   | 1.716156 | 3.460879 | 5.204546 | 6.946630 | 8.686596 | 10.423916 | 12.158062 | 13.888504 |
| 60   | 1.745241 | 3.489950 | 5.233596 | 6.975647 | 8.715574 | 10.452847 | 12.186934 | 13.917311 |

## Constants for Setting a 100-mm Sine-bar for 8° to 15°

| Min. | 8°        | 9°        | 10°       | 11°       | 12°       | 13°       | 14°       | 15°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 13.917311 | 15.643447 | 17.364819 | 19.080900 | 20.791170 | 22.495106 | 24.192190 | 25.881905 |
| 1    | 13.946115 | 15.672176 | 17.393463 | 19.109453 | 20.819622 | 22.523447 | 24.220413 | 25.910002 |
| 2    | 13.974920 | 15.700907 | 17.422110 | 19.138006 | 20.848074 | 22.551790 | 24.248636 | 25.938907 |
| 3    | 14.003723 | 15.729633 | 17.450752 | 19.166555 | 20.876522 | 22.580128 | 24.276855 | 25.966188 |
| 4    | 14.032524 | 15.758359 | 17.479393 | 19.195105 | 20.904968 | 22.608463 | 24.305073 | 25.994278 |
| 5    | 14.061324 | 15.787084 | 17.508034 | 19.223652 | 20.933413 | 22.636799 | 24.333288 | 26.022366 |
| 6    | 14.090124 | 15.815807 | 17.536674 | 19.252197 | 20.961857 | 22.665133 | 24.361502 | 26.050451 |
| 7    | 14.118922 | 15.844529 | 17.565311 | 19.280741 | 20.990299 | 22.693462 | 24.389713 | 26.078535 |
| 8    | 14.147718 | 15.873250 | 17.593946 | 19.309282 | 21.018738 | 22.721790 | 24.417923 | 26.106615 |
| 9    | 14.176514 | 15.901969 | 17.622580 | 19.337824 | 21.047176 | 22.750118 | 24.446129 | 26.134695 |
| 10   | 14.205309 | 15.930688 | 17.651215 | 19.366364 | 21.075613 | 22.778444 | 24.474335 | 26.162773 |
| 11   | 14.234102 | 15.959404 | 17.679844 | 19.394899 | 21.104048 | 22.806767 | 24.502539 | 26.190845 |
| 12   | 14.262894 | 15.988119 | 17.708475 | 19.423435 | 21.132481 | 22.835087 | 24.530739 | 26.218918 |
| 13   | 14.291684 | 16.016832 | 17.737103 | 19.451969 | 21.160910 | 22.863405 | 24.558937 | 26.246988 |
| 14   | 14.320475 | 16.045546 | 17.765730 | 19.480503 | 21.189341 | 22.891726 | 24.587135 | 26.275057 |
| 15   | 14.349262 | 16.074257 | 17.794355 | 19.509033 | 21.217768 | 22.920040 | 24.615330 | 26.303122 |
| 16   | 14.378049 | 16.102966 | 17.822979 | 19.537561 | 21.246193 | 22.948353 | 24.643522 | 26.331184 |
| 17   | 14.406837 | 16.131676 | 17.851603 | 19.566090 | 21.274618 | 22.976665 | 24.671715 | 26.359247 |
| 18   | 14.435621 | 16.160383 | 17.880222 | 19.594616 | 21.303040 | 23.004974 | 24.699902 | 26.387306 |
| 19   | 14.464404 | 16.189089 | 17.908842 | 19.623138 | 21.331459 | 23.033281 | 24.728088 | 26.415361 |
| 20   | 14.493186 | 16.217793 | 17.937458 | 19.651661 | 21.359877 | 23.061586 | 24.756271 | 26.443417 |
| 21   | 14.521968 | 16.246496 | 17.966076 | 19.680183 | 21.388294 | 23.089891 | 24.784456 | 26.471470 |
| 22   | 14.550748 | 16.275198 | 17.994690 | 19.708702 | 21.416710 | 23.118193 | 24.812635 | 26.499519 |
| 23   | 14.579526 | 16.303898 | 18.023304 | 19.737219 | 21.445122 | 23.146492 | 24.840813 | 26.527567 |
| 24   | 14.608303 | 16.332596 | 18.051914 | 19.765734 | 21.473532 | 23.174789 | 24.868988 | 26.555613 |
| 25   | 14.637080 | 16.361296 | 18.080526 | 19.794249 | 21.501944 | 23.203087 | 24.897163 | 26.583656 |
| 26   | 14.665854 | 16.389990 | 18.109135 | 19.822762 | 21.530350 | 23.231380 | 24.925335 | 26.611696 |
| 27   | 14.694628 | 16.418684 | 18.137741 | 19.851271 | 21.558756 | 23.259672 | 24.953505 | 26.639736 |
| 28   | 14.723400 | 16.447378 | 18.166346 | 19.879780 | 21.587158 | 23.287962 | 24.981672 | 26.667770 |
| 29   | 14.752172 | 16.476070 | 18.194950 | 19.908289 | 21.615562 | 23.316252 | 25.009838 | 26.695807 |
| 30   | 14.780942 | 16.504761 | 18.223553 | 19.936794 | 21.643963 | 23.344538 | 25.038002 | 26.723839 |
| 31   | 14.809710 | 16.533449 | 18.252153 | 19.965298 | 21.672359 | 23.372820 | 25.066162 | 26.751867 |
| 32   | 14.838478 | 16.562140 | 18.280754 | 19.993801 | 21.700758 | 23.401104 | 25.094322 | 26.779896 |
| 33   | 14.867244 | 16.590824 | 18.309351 | 20.022301 | 21.729153 | 23.429384 | 25.122478 | 26.807920 |
| 34   | 14.896008 | 16.619509 | 18.337948 | 20.050800 | 21.757544 | 23.457661 | 25.150633 | 26.835943 |
| 35   | 14.924772 | 16.648193 | 18.366541 | 20.079296 | 21.785934 | 23.485937 | 25.178785 | 26.863964 |
| 36   | 14.953535 | 16.676876 | 18.395136 | 20.107794 | 21.814325 | 23.514212 | 25.206938 | 26.891983 |
| 37   | 14.982296 | 16.705557 | 18.423727 | 20.136286 | 21.842712 | 23.542484 | 25.235085 | 26.920000 |
| 38   | 15.011056 | 16.734236 | 18.452316 | 20.164778 | 21.871098 | 23.570755 | 25.263231 | 26.948013 |
| 39   | 15.039814 | 16.762913 | 18.480906 | 20.193268 | 21.899481 | 23.599022 | 25.291374 | 26.976025 |
| 40   | 15.068572 | 16.791590 | 18.509493 | 20.221758 | 21.927864 | 23.627289 | 25.319517 | 27.004034 |
| 41   | 15.097328 | 16.820265 | 18.538078 | 20.250244 | 21.956244 | 23.655554 | 25.347658 | 27.032042 |
| 42   | 15.126082 | 16.848938 | 18.566662 | 20.278730 | 21.984621 | 23.683815 | 25.375795 | 27.060045 |
| 43   | 15.154835 | 16.877609 | 18.595243 | 20.307213 | 22.012997 | 23.712074 | 25.403931 | 27.088047 |
| 44   | 15.183589 | 16.906282 | 18.623825 | 20.335695 | 22.041372 | 23.740334 | 25.432064 | 27.116049 |
| 45   | 15.212339 | 16.934952 | 18.652405 | 20.364176 | 22.069744 | 23.768589 | 25.460196 | 27.144045 |
| 46   | 15.241088 | 16.963619 | 18.680981 | 20.392654 | 22.098114 | 23.796844 | 25.488325 | 27.172041 |
| 47   | 15.269837 | 16.992287 | 18.709558 | 20.421131 | 22.126484 | 23.825096 | 25.516453 | 27.200035 |
| 48   | 15.298584 | 17.020950 | 18.738132 | 20.449606 | 22.154850 | 23.853346 | 25.544577 | 27.228025 |
| 49   | 15.327330 | 17.049614 | 18.766705 | 20.478079 | 22.183216 | 23.881594 | 25.572699 | 27.256014 |
| 50   | 15.356073 | 17.078276 | 18.795275 | 20.506550 | 22.211578 | 23.909840 | 25.600819 | 27.284000 |
| 51   | 15.384818 | 17.106937 | 18.823847 | 20.535021 | 22.239941 | 23.938086 | 25.628939 | 27.311985 |
| 52   | 15.413560 | 17.135597 | 18.852413 | 20.563488 | 22.268299 | 23.966328 | 25.657055 | 27.339966 |
| 53   | 15.442300 | 17.164253 | 18.880980 | 20.591955 | 22.296656 | 23.994566 | 25.685167 | 27.367945 |
| 54   | 15.471039 | 17.192909 | 18.909544 | 20.620419 | 22.325012 | 24.022804 | 25.713280 | 27.395922 |
| 55   | 15.499778 | 17.221565 | 18.938108 | 20.648882 | 22.353367 | 24.051041 | 25.741390 | 27.423899 |
| 56   | 15.528514 | 17.250219 | 18.966669 | 20.677343 | 22.381718 | 24.079275 | 25.769497 | 27.451870 |
| 57   | 15.557248 | 17.278872 | 18.995230 | 20.705801 | 22.410067 | 24.107506 | 25.797602 | 27.479839 |
| 58   | 15.585982 | 17.307520 | 19.023787 | 20.734259 | 22.438416 | 24.135736 | 25.825705 | 27.507807 |
| 59   | 15.614716 | 17.336170 | 19.052345 | 20.762716 | 22.466763 | 24.163965 | 25.853807 | 27.535774 |
| 60   | 15.643447 | 17.364819 | 19.080900 | 20.791170 | 22.495106 | 24.192190 | 25.881905 | 27.563736 |



## Constants for Setting a 100-mm Sine-bar for 16° to 23°

| Min. | 16°       | 17°       | 18°       | 19°       | 20°       | 21°       | 22°       | 23°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 27.563736 | 29.237171 | 30.901701 | 32.556816 | 34.202015 | 35.836796 | 37.460659 | 39.073112 |
| 1    | 27.591696 | 29.264988 | 30.929363 | 32.584320 | 34.229347 | 35.863953 | 37.487629 | 39.099888 |
| 2    | 27.619656 | 29.292801 | 30.957024 | 32.611816 | 34.256680 | 35.891102 | 37.514595 | 39.126659 |
| 3    | 27.647610 | 29.320612 | 30.984682 | 32.639317 | 34.284004 | 35.918251 | 37.541557 | 39.153427 |
| 4    | 27.675568 | 29.348425 | 31.012341 | 32.666813 | 34.311333 | 35.945400 | 37.568520 | 39.180195 |
| 5    | 27.703518 | 29.376230 | 31.039993 | 32.694302 | 34.338654 | 35.972542 | 37.595474 | 39.206955 |
| 6    | 27.731466 | 29.404034 | 31.067644 | 32.721790 | 34.365971 | 35.999683 | 37.622429 | 39.233715 |
| 7    | 27.759413 | 29.431835 | 31.095291 | 32.749275 | 34.393288 | 36.026817 | 37.649376 | 39.260468 |
| 8    | 27.787357 | 29.459635 | 31.122936 | 32.776760 | 34.420597 | 36.053951 | 37.676323 | 39.287220 |
| 9    | 27.815298 | 29.487431 | 31.150579 | 32.804241 | 34.447906 | 36.081081 | 37.703266 | 39.313965 |
| 10   | 27.843239 | 29.515224 | 31.178219 | 32.831718 | 34.475216 | 36.108212 | 37.730206 | 39.340710 |
| 11   | 27.871176 | 29.543015 | 31.205856 | 32.859192 | 34.502518 | 36.135334 | 37.757145 | 39.367451 |
| 12   | 27.899113 | 29.570807 | 31.233494 | 32.886665 | 34.529823 | 36.162460 | 37.784081 | 39.394192 |
| 13   | 27.927044 | 29.598593 | 31.261126 | 32.914135 | 34.557121 | 36.189579 | 37.811012 | 39.420929 |
| 14   | 27.954975 | 29.626377 | 31.288755 | 32.941601 | 34.584415 | 36.216694 | 37.837940 | 39.447659 |
| 15   | 27.982903 | 29.654158 | 31.316381 | 32.969067 | 34.611706 | 36.243805 | 37.864864 | 39.474388 |
| 16   | 28.010828 | 29.681936 | 31.344006 | 32.996525 | 34.638996 | 36.270912 | 37.891785 | 39.501110 |
| 17   | 28.038757 | 29.709713 | 31.371626 | 33.023983 | 34.666283 | 36.298019 | 37.918701 | 39.527832 |
| 18   | 28.066669 | 29.737488 | 31.399244 | 33.051437 | 34.693565 | 36.325123 | 37.945614 | 39.554550 |
| 19   | 28.094591 | 29.765261 | 31.426865 | 33.078896 | 34.720848 | 36.352226 | 37.972530 | 39.581268 |
| 20   | 28.122507 | 29.793030 | 31.454477 | 33.106342 | 34.748127 | 36.379322 | 37.999439 | 39.607979 |
| 21   | 28.150421 | 29.820797 | 31.482088 | 33.133789 | 34.775398 | 36.406418 | 38.026344 | 39.634686 |
| 22   | 28.178331 | 29.848560 | 31.509697 | 33.161236 | 34.802670 | 36.433506 | 38.053246 | 39.661392 |
| 23   | 28.206240 | 29.876320 | 31.537302 | 33.188675 | 34.829941 | 36.460594 | 38.080143 | 39.688091 |
| 24   | 28.234146 | 29.904079 | 31.564903 | 33.216114 | 34.857204 | 36.487679 | 38.107037 | 39.714790 |
| 25   | 28.262049 | 29.931835 | 31.592505 | 33.243549 | 34.884468 | 36.514759 | 38.133930 | 39.741486 |
| 26   | 28.289951 | 29.959589 | 31.620102 | 33.270981 | 34.911728 | 36.541840 | 38.160820 | 39.768173 |
| 27   | 28.317852 | 29.987343 | 31.647699 | 33.298416 | 34.938988 | 36.568916 | 38.187706 | 39.794865 |
| 28   | 28.345749 | 30.015091 | 31.675291 | 33.325840 | 34.966240 | 36.595989 | 38.214588 | 39.821548 |
| 29   | 28.373644 | 30.042837 | 31.702881 | 33.353264 | 34.993492 | 36.623058 | 38.241470 | 39.848232 |
| 30   | 28.401535 | 30.070581 | 31.730467 | 33.380688 | 35.020741 | 36.650124 | 38.268345 | 39.874908 |
| 31   | 28.429424 | 30.098322 | 31.758051 | 33.408104 | 35.047985 | 36.677185 | 38.295216 | 39.901581 |
| 32   | 28.457312 | 30.126060 | 31.785631 | 33.435520 | 35.075226 | 36.704247 | 38.322086 | 39.928253 |
| 33   | 28.485195 | 30.153795 | 31.813210 | 33.462933 | 35.102463 | 36.731304 | 38.348953 | 39.954922 |
| 34   | 28.513081 | 30.181532 | 31.840790 | 33.490349 | 35.129704 | 36.758358 | 38.375816 | 39.981586 |
| 35   | 28.540960 | 30.209263 | 31.868362 | 33.517754 | 35.156937 | 36.785408 | 38.402679 | 40.008247 |
| 36   | 28.568838 | 30.236990 | 31.895933 | 33.545158 | 35.184166 | 36.812458 | 38.429535 | 40.034904 |
| 37   | 28.596712 | 30.264715 | 31.923500 | 33.572559 | 35.211395 | 36.839500 | 38.456387 | 40.061558 |
| 38   | 28.624586 | 30.292439 | 31.951065 | 33.599960 | 35.238617 | 36.866543 | 38.483238 | 40.088207 |
| 39   | 28.652456 | 30.320160 | 31.978628 | 33.627354 | 35.265839 | 36.893581 | 38.510082 | 40.114857 |
| 40   | 28.680323 | 30.347878 | 32.006187 | 33.654747 | 35.293056 | 36.920616 | 38.536926 | 40.141499 |
| 41   | 28.708189 | 30.375593 | 32.033745 | 33.682137 | 35.320271 | 36.947647 | 38.563766 | 40.168140 |
| 42   | 28.736053 | 30.403309 | 32.061302 | 33.709530 | 35.347488 | 36.974678 | 38.590607 | 40.194778 |
| 43   | 28.763914 | 30.431019 | 32.088852 | 33.736912 | 35.374695 | 37.001705 | 38.617439 | 40.221413 |
| 44   | 28.791773 | 30.458725 | 32.116402 | 33.764294 | 35.401901 | 37.028725 | 38.644272 | 40.248043 |
| 45   | 28.819628 | 30.486431 | 32.143948 | 33.791672 | 35.429104 | 37.055744 | 38.671097 | 40.274670 |
| 46   | 28.847481 | 30.514133 | 32.171490 | 33.819050 | 35.456306 | 37.082760 | 38.697922 | 40.301292 |
| 47   | 28.875332 | 30.541832 | 32.199032 | 33.846420 | 35.483501 | 37.109772 | 38.724743 | 40.327911 |
| 48   | 28.903179 | 30.569530 | 32.226570 | 33.873791 | 35.510696 | 37.136784 | 38.751560 | 40.354530 |
| 49   | 28.931028 | 30.597227 | 32.254108 | 33.901161 | 35.537891 | 37.163792 | 38.778374 | 40.381145 |
| 50   | 28.958872 | 30.624920 | 32.281639 | 33.928528 | 35.565079 | 37.190796 | 38.805187 | 40.407757 |
| 51   | 28.986712 | 30.652609 | 32.309170 | 33.955887 | 35.592262 | 37.217796 | 38.831993 | 40.434361 |
| 52   | 29.014551 | 30.680296 | 32.336697 | 33.983246 | 35.619446 | 37.244793 | 38.858799 | 40.460964 |
| 53   | 29.042387 | 30.707981 | 32.364220 | 34.010601 | 35.646626 | 37.271790 | 38.885597 | 40.487564 |
| 54   | 29.070219 | 30.735662 | 32.391743 | 34.037956 | 35.673801 | 37.298779 | 38.912395 | 40.514160 |
| 55   | 29.098051 | 30.763342 | 32.419262 | 34.065304 | 35.700974 | 37.325768 | 38.939190 | 40.540752 |
| 56   | 29.125879 | 30.791018 | 32.446777 | 34.092651 | 35.728142 | 37.352753 | 38.965981 | 40.567341 |
| 57   | 29.153708 | 30.818695 | 32.474293 | 34.119999 | 35.755314 | 37.379734 | 38.992771 | 40.593929 |
| 58   | 29.181532 | 30.846365 | 32.501804 | 34.147343 | 35.782478 | 37.406712 | 39.019554 | 40.620510 |
| 59   | 29.209352 | 30.874035 | 32.529312 | 34.174679 | 35.809639 | 37.433689 | 39.046337 | 40.647091 |
| 60   | 29.237171 | 30.901701 | 32.556816 | 34.202015 | 35.836796 | 37.460659 | 39.073112 | 40.673664 |

## Constants for Setting a 100-mm Sine-bar for 24° to 31°

| Min. | 24°       | 25°       | 26°       | 27°       | 28°       | 29°       | 30°       | 31°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 40.673664 | 42.261826 | 43.837116 | 45.399052 | 46.947159 | 48.480965 | 50.000000 | 51.503807 |
| 1    | 40.700237 | 42.288189 | 43.863258 | 45.424969 | 46.972839 | 48.506401 | 50.025192 | 51.528740 |
| 2    | 40.726807 | 42.314545 | 43.889397 | 45.450878 | 46.998516 | 48.531837 | 50.050377 | 51.553669 |
| 3    | 40.753372 | 42.340900 | 43.915531 | 45.476788 | 47.024189 | 48.557270 | 50.075558 | 51.578590 |
| 4    | 40.779934 | 42.367252 | 43.941666 | 45.502697 | 47.049862 | 48.582699 | 50.100735 | 51.603512 |
| 5    | 40.806492 | 42.393600 | 43.967796 | 45.528595 | 47.075527 | 48.608120 | 50.125908 | 51.628426 |
| 6    | 40.833046 | 42.419945 | 43.993919 | 45.554493 | 47.101189 | 48.633541 | 50.151077 | 51.653336 |
| 7    | 40.859600 | 42.446285 | 44.020039 | 45.580387 | 47.126846 | 48.658955 | 50.176239 | 51.678242 |
| 8    | 40.886147 | 42.472618 | 44.046154 | 45.606274 | 47.152500 | 48.684364 | 50.201397 | 51.703140 |
| 9    | 40.912689 | 42.498951 | 44.072269 | 45.632160 | 47.178150 | 48.709770 | 50.226555 | 51.728039 |
| 10   | 40.939232 | 42.525280 | 44.098377 | 45.658043 | 47.203796 | 48.735172 | 50.251705 | 51.752930 |
| 11   | 40.965767 | 42.551605 | 44.124481 | 45.683918 | 47.229439 | 48.760571 | 50.276852 | 51.777817 |
| 12   | 40.992306 | 42.577930 | 44.150589 | 45.709797 | 47.255077 | 48.785969 | 50.301998 | 51.802704 |
| 13   | 41.018837 | 42.604248 | 44.176685 | 45.735664 | 47.280712 | 48.811359 | 50.327137 | 51.827583 |
| 14   | 41.045364 | 42.630566 | 44.202778 | 45.761532 | 47.306343 | 48.836742 | 50.352268 | 51.852455 |
| 15   | 41.071888 | 42.656876 | 44.228870 | 45.787392 | 47.331966 | 48.862125 | 50.377399 | 51.877327 |
| 16   | 41.098408 | 42.683182 | 44.254955 | 45.813251 | 47.357590 | 48.887505 | 50.402523 | 51.902191 |
| 17   | 41.124924 | 42.709488 | 44.281040 | 45.839104 | 47.383205 | 48.912876 | 50.427647 | 51.927055 |
| 18   | 41.151436 | 42.735786 | 44.307117 | 45.864956 | 47.408821 | 48.938244 | 50.452763 | 51.951912 |
| 19   | 41.177948 | 42.762085 | 44.333199 | 45.890804 | 47.434433 | 48.963612 | 50.477879 | 51.976768 |
| 20   | 41.204453 | 42.788380 | 44.359268 | 45.916649 | 47.460041 | 48.988976 | 50.502987 | 52.001614 |
| 21   | 41.230957 | 42.814667 | 44.385338 | 45.942486 | 47.485641 | 49.014332 | 50.528091 | 52.026459 |
| 22   | 41.257458 | 42.840954 | 44.411400 | 45.968323 | 47.511238 | 49.039684 | 50.553192 | 52.051300 |
| 23   | 41.283951 | 42.867237 | 44.437462 | 45.994152 | 47.536831 | 49.065033 | 50.578285 | 52.076134 |
| 24   | 41.310444 | 42.893513 | 44.463520 | 46.019978 | 47.562420 | 49.090378 | 50.603378 | 52.100964 |
| 25   | 41.336933 | 42.919788 | 44.489571 | 46.045803 | 47.588009 | 49.115715 | 50.628464 | 52.125790 |
| 26   | 41.363419 | 42.946060 | 44.515621 | 46.071621 | 47.613590 | 49.141052 | 50.653545 | 52.150612 |
| 27   | 41.389900 | 42.972332 | 44.541668 | 46.097439 | 47.639168 | 49.166386 | 50.678627 | 52.175430 |
| 28   | 41.416378 | 42.998592 | 44.567711 | 46.123253 | 47.664742 | 49.191715 | 50.703701 | 52.200245 |
| 29   | 41.442856 | 43.024853 | 44.593750 | 46.149059 | 47.690311 | 49.217037 | 50.728771 | 52.225052 |
| 30   | 41.469326 | 43.051109 | 44.619781 | 46.174862 | 47.715878 | 49.242359 | 50.753838 | 52.249859 |
| 31   | 41.495792 | 43.077362 | 44.645813 | 46.200661 | 47.741440 | 49.267673 | 50.778900 | 52.274658 |
| 32   | 41.522259 | 43.103615 | 44.671841 | 46.226460 | 47.766994 | 49.292984 | 50.803955 | 52.299454 |
| 33   | 41.548717 | 43.129860 | 44.697861 | 46.252251 | 47.792549 | 49.318129 | 50.829010 | 52.324245 |
| 34   | 41.575176 | 43.156105 | 44.723885 | 46.278042 | 47.818100 | 49.343597 | 50.854061 | 52.349033 |
| 35   | 41.601631 | 43.182343 | 44.749901 | 46.303825 | 47.843647 | 49.368983 | 50.879105 | 52.373814 |
| 36   | 41.628082 | 43.208576 | 44.775909 | 46.329605 | 47.869186 | 49.394188 | 50.904144 | 52.398594 |
| 37   | 41.654526 | 43.234806 | 44.801918 | 46.355381 | 47.894726 | 49.419479 | 50.929180 | 52.423367 |
| 38   | 41.680969 | 43.261036 | 44.827923 | 46.381153 | 47.920258 | 49.444763 | 50.954208 | 52.448135 |
| 39   | 41.707409 | 43.287258 | 44.853924 | 46.406921 | 47.945786 | 49.470047 | 50.979237 | 52.472900 |
| 40   | 41.733845 | 43.313480 | 44.879917 | 46.432686 | 47.971313 | 49.495323 | 51.004261 | 52.497658 |
| 41   | 41.760277 | 43.339695 | 44.905910 | 46.458447 | 47.996834 | 49.520596 | 51.029278 | 52.522415 |
| 42   | 41.786709 | 43.365910 | 44.931904 | 46.484207 | 48.022350 | 49.545868 | 51.054295 | 52.547169 |
| 43   | 41.813133 | 43.392120 | 44.957886 | 46.509960 | 48.047863 | 49.571133 | 51.079304 | 52.571915 |
| 44   | 41.839558 | 43.418324 | 44.983868 | 46.535709 | 48.073372 | 49.596394 | 51.104309 | 52.596657 |
| 45   | 41.865974 | 43.444527 | 45.009846 | 46.561455 | 48.098877 | 49.621651 | 51.129311 | 52.621395 |
| 46   | 41.892391 | 43.470726 | 45.035820 | 46.587193 | 48.124378 | 49.646904 | 51.154308 | 52.646126 |
| 47   | 41.918800 | 43.496918 | 45.061787 | 46.612930 | 48.149876 | 49.672153 | 51.179298 | 52.670856 |
| 48   | 41.945210 | 43.523109 | 45.087753 | 46.638664 | 48.175369 | 49.697395 | 51.204288 | 52.695580 |
| 49   | 41.971615 | 43.549301 | 45.113720 | 46.664394 | 48.200859 | 49.722637 | 51.229275 | 52.720303 |
| 50   | 41.998016 | 43.575481 | 45.139679 | 46.690121 | 48.226341 | 49.747875 | 51.254253 | 52.745018 |
| 51   | 42.024414 | 43.601662 | 45.165630 | 46.715843 | 48.251823 | 49.773106 | 51.279228 | 52.769730 |
| 52   | 42.050804 | 43.627838 | 45.191582 | 46.741558 | 48.277298 | 49.798332 | 51.304199 | 52.794434 |
| 53   | 42.077194 | 43.654011 | 45.217529 | 46.767273 | 48.302773 | 49.823555 | 51.329163 | 52.819138 |
| 54   | 42.103580 | 43.680180 | 45.243473 | 46.792980 | 48.328239 | 49.848774 | 51.354126 | 52.843834 |
| 55   | 42.129963 | 43.706345 | 45.269409 | 46.818687 | 48.353703 | 49.873989 | 51.379082 | 52.868526 |
| 56   | 42.156345 | 43.732506 | 45.295345 | 46.844387 | 48.379162 | 49.899200 | 51.404037 | 52.893215 |
| 57   | 42.182724 | 43.758667 | 45.321281 | 46.870090 | 48.404621 | 49.924408 | 51.428989 | 52.917904 |
| 58   | 42.209095 | 43.784821 | 45.347206 | 46.895782 | 48.430073 | 49.949612 | 51.453934 | 52.942581 |
| 59   | 42.235462 | 43.810970 | 45.373131 | 46.921471 | 48.455521 | 49.974808 | 51.478874 | 52.967258 |
| 60   | 42.261826 | 43.837116 | 45.399052 | 46.947159 | 48.480965 | 50.000000 | 51.503807 | 52.991928 |

## Constants for Setting a 100-mm Sine-bar for 32° to 39°

| Min. | 32°       | 33°       | 34°       | 35°       | 36°       | 37°       | 38°       | 39°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 52.991928 | 54.463905 | 55.919292 | 57.357643 | 58.778526 | 60.181503 | 61.566151 | 62.932041 |
| 1    | 53.016594 | 54.488297 | 55.943405 | 57.381470 | 58.802055 | 60.204731 | 61.589069 | 62.954643 |
| 2    | 53.041256 | 54.512688 | 55.967514 | 57.405293 | 58.825584 | 60.227955 | 61.611984 | 62.977242 |
| 3    | 53.065914 | 54.537071 | 55.991615 | 57.429108 | 58.849102 | 60.251175 | 61.634892 | 62.999836 |
| 4    | 53.090565 | 54.561451 | 56.015717 | 57.452919 | 58.872620 | 60.274387 | 61.657795 | 63.022423 |
| 5    | 53.115211 | 54.585827 | 56.039810 | 57.476723 | 58.896130 | 60.297596 | 61.680695 | 63.045002 |
| 6    | 53.139858 | 54.610195 | 56.063900 | 57.500523 | 58.919636 | 60.320797 | 61.703587 | 63.067581 |
| 7    | 53.164497 | 54.634560 | 56.087982 | 57.524323 | 58.943134 | 60.343994 | 61.726475 | 63.090153 |
| 8    | 53.189137 | 54.658928 | 56.112068 | 57.548119 | 58.966637 | 60.367195 | 61.749363 | 63.112724 |
| 9    | 53.213768 | 54.683285 | 56.136143 | 57.571903 | 58.990128 | 60.390381 | 61.772240 | 63.135284 |
| 10   | 53.238392 | 54.707634 | 56.160213 | 57.595684 | 59.013615 | 60.413563 | 61.795113 | 63.157837 |
| 11   | 53.263012 | 54.731983 | 56.184280 | 57.619461 | 59.037094 | 60.436741 | 61.817982 | 63.180389 |
| 12   | 53.287628 | 54.756325 | 56.208340 | 57.643234 | 59.060570 | 60.459915 | 61.840843 | 63.202934 |
| 13   | 53.312241 | 54.780663 | 56.232395 | 57.667000 | 59.084042 | 60.483082 | 61.863697 | 63.225471 |
| 14   | 53.336849 | 54.804996 | 56.256447 | 57.690762 | 59.107506 | 60.506245 | 61.886551 | 63.248005 |
| 15   | 53.361454 | 54.829323 | 56.280495 | 57.714520 | 59.130966 | 60.529400 | 61.909397 | 63.270535 |
| 16   | 53.386051 | 54.853649 | 56.304535 | 57.738274 | 59.154423 | 60.552551 | 61.932236 | 63.293056 |
| 17   | 53.410645 | 54.877968 | 56.328571 | 57.762020 | 59.177872 | 60.575699 | 61.955074 | 63.315575 |
| 18   | 53.435234 | 54.902283 | 56.352604 | 57.785763 | 59.201317 | 60.598839 | 61.977905 | 63.338089 |
| 19   | 53.459820 | 54.926594 | 56.376633 | 57.809502 | 59.224758 | 60.621979 | 62.000729 | 63.360596 |
| 20   | 53.484402 | 54.950897 | 56.400654 | 57.833233 | 59.248196 | 60.645107 | 62.023548 | 63.383095 |
| 21   | 53.508976 | 54.975197 | 56.424675 | 57.856960 | 59.271626 | 60.668236 | 62.046364 | 63.405594 |
| 22   | 53.533546 | 54.999493 | 56.448685 | 57.880684 | 59.295052 | 60.691357 | 62.069172 | 63.428085 |
| 23   | 53.558121 | 55.023792 | 56.472702 | 57.904408 | 59.318478 | 60.714478 | 62.091984 | 63.450573 |
| 24   | 53.582684 | 55.048077 | 56.496704 | 57.928120 | 59.341892 | 60.737587 | 62.114780 | 63.473053 |
| 25   | 53.607243 | 55.072361 | 56.520702 | 57.951828 | 59.365303 | 60.760693 | 62.137577 | 63.495529 |
| 26   | 53.631794 | 55.096638 | 56.544697 | 57.975533 | 59.388710 | 60.783794 | 62.160362 | 63.517998 |
| 27   | 53.656342 | 55.120911 | 56.568687 | 57.999229 | 59.412109 | 60.806889 | 62.183147 | 63.540462 |
| 28   | 53.680889 | 55.145176 | 56.592670 | 58.022926 | 59.435505 | 60.829979 | 62.205925 | 63.562923 |
| 29   | 53.705425 | 55.169441 | 56.616650 | 58.046612 | 59.458893 | 60.853065 | 62.228699 | 63.585377 |
| 30   | 53.729961 | 55.193699 | 56.640625 | 58.070297 | 59.482281 | 60.876144 | 62.251465 | 63.607822 |
| 31   | 53.754494 | 55.217953 | 56.664597 | 58.093975 | 59.505661 | 60.899220 | 62.274227 | 63.630264 |
| 32   | 53.779018 | 55.242203 | 56.688560 | 58.117649 | 59.529037 | 60.922287 | 62.296986 | 63.652702 |
| 33   | 53.803539 | 55.266449 | 56.712521 | 58.141319 | 59.552406 | 60.945354 | 62.319736 | 63.675137 |
| 34   | 53.828056 | 55.290688 | 56.736477 | 58.164982 | 59.575771 | 60.968414 | 62.342484 | 63.697563 |
| 35   | 53.852570 | 55.314922 | 56.760429 | 58.188641 | 59.599133 | 60.991467 | 62.365223 | 63.719982 |
| 36   | 53.877079 | 55.339153 | 56.784374 | 58.212296 | 59.622486 | 61.014515 | 62.387959 | 63.742397 |
| 37   | 53.901581 | 55.363380 | 56.808315 | 58.235947 | 59.645836 | 61.037560 | 62.410690 | 63.764809 |
| 38   | 53.926086 | 55.387608 | 56.832256 | 58.259594 | 59.669186 | 61.060604 | 62.433418 | 63.787220 |
| 39   | 53.950581 | 55.411823 | 56.856190 | 58.283234 | 59.692528 | 61.083637 | 62.456139 | 63.809620 |
| 40   | 53.975067 | 55.436035 | 56.880116 | 58.306870 | 59.715862 | 61.106667 | 62.478855 | 63.832012 |
| 41   | 53.999554 | 55.460243 | 56.904037 | 58.330498 | 59.739193 | 61.129688 | 62.501564 | 63.854401 |
| 42   | 54.024036 | 55.484444 | 56.927956 | 58.354122 | 59.762516 | 61.152706 | 62.524269 | 63.876785 |
| 43   | 54.048512 | 55.508644 | 56.951866 | 58.377743 | 59.785835 | 61.175720 | 62.546967 | 63.899162 |
| 44   | 54.072983 | 55.532837 | 56.975777 | 58.401360 | 59.809151 | 61.198727 | 62.569660 | 63.921535 |
| 45   | 54.097450 | 55.557026 | 56.999676 | 58.424969 | 59.832462 | 61.221729 | 62.592350 | 63.943901 |
| 46   | 54.121910 | 55.581207 | 57.023575 | 58.448574 | 59.855766 | 61.244728 | 62.615032 | 63.966263 |
| 47   | 54.146370 | 55.605389 | 57.047470 | 58.472172 | 59.879066 | 61.267719 | 62.637711 | 63.988621 |
| 48   | 54.170822 | 55.629562 | 57.071358 | 58.495770 | 59.902359 | 61.290707 | 62.660381 | 64.010971 |
| 49   | 54.195271 | 55.653732 | 57.095242 | 58.519360 | 59.925652 | 61.313686 | 62.683048 | 64.033318 |
| 50   | 54.219715 | 55.677895 | 57.119118 | 58.542942 | 59.948933 | 61.336662 | 62.705711 | 64.055656 |
| 51   | 54.244152 | 55.702057 | 57.142994 | 58.566525 | 59.972214 | 61.359634 | 62.728367 | 64.077988 |
| 52   | 54.268589 | 55.726212 | 57.166862 | 58.590099 | 59.995487 | 61.382603 | 62.751019 | 64.100319 |
| 53   | 54.293022 | 55.750370 | 57.190731 | 58.613674 | 60.018761 | 61.405567 | 62.773670 | 64.122650 |
| 54   | 54.317448 | 55.774513 | 57.214592 | 58.637238 | 60.042027 | 61.428524 | 62.796310 | 64.144966 |
| 55   | 54.341869 | 55.798656 | 57.238445 | 58.660801 | 60.065285 | 61.451473 | 62.818943 | 64.167282 |
| 56   | 54.366287 | 55.822792 | 57.262295 | 58.684357 | 60.088539 | 61.474419 | 62.841576 | 64.189590 |
| 57   | 54.390697 | 55.846924 | 57.286140 | 58.707905 | 60.111790 | 61.497360 | 62.864201 | 64.211891 |
| 58   | 54.415104 | 55.871052 | 57.309978 | 58.731449 | 60.135033 | 61.520294 | 62.886818 | 64.234184 |
| 59   | 54.439507 | 55.895172 | 57.333817 | 58.754990 | 60.158272 | 61.543224 | 62.909431 | 64.256477 |
| 60   | 54.463905 | 55.919292 | 57.357643 | 58.778526 | 60.181503 | 61.566151 | 62.932041 | 64.278763 |

## Constants for Setting a 100-mm Sine-bar for 40° to 47°

| Min. | 40°       | 41°       | 42°       | 43°       | 44°       | 45°       | 46°       | 47°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 64.278763 | 65.605904 | 66.913063 | 68.199837 | 69.465836 | 70.710678 | 71.933983 | 73.135368 |
| 1    | 64.301041 | 65.627853 | 66.934677 | 68.221107 | 69.486763 | 70.731247 | 71.954185 | 73.155205 |
| 2    | 64.323318 | 65.649803 | 66.956284 | 68.242371 | 69.507675 | 70.751808 | 71.974380 | 73.175034 |
| 3    | 64.345589 | 65.671738 | 66.977890 | 68.263634 | 69.528587 | 70.772362 | 71.994576 | 73.194855 |
| 4    | 64.367851 | 65.693672 | 66.999481 | 68.284889 | 69.549492 | 70.792908 | 72.014755 | 73.214676 |
| 5    | 64.390106 | 65.715599 | 67.021072 | 68.306137 | 69.570389 | 70.813446 | 72.034935 | 73.234482 |
| 6    | 64.412361 | 65.737526 | 67.042664 | 68.327377 | 69.591278 | 70.833984 | 72.055107 | 73.254288 |
| 7    | 64.434608 | 65.759438 | 67.064240 | 68.348610 | 69.612167 | 70.854515 | 72.075279 | 73.274086 |
| 8    | 64.456856 | 65.781357 | 67.085823 | 68.369850 | 69.633049 | 70.875038 | 72.095444 | 73.293884 |
| 9    | 64.479095 | 65.803261 | 67.107391 | 68.391075 | 69.653923 | 70.895561 | 72.115601 | 73.313667 |
| 10   | 64.501328 | 65.825165 | 67.128952 | 68.412292 | 69.674797 | 70.916069 | 72.135750 | 73.333450 |
| 11   | 64.523552 | 65.847061 | 67.150513 | 68.433502 | 69.695656 | 70.936577 | 72.155891 | 73.353226 |
| 12   | 64.545769 | 65.868950 | 67.172058 | 68.454712 | 69.716515 | 70.957077 | 72.176025 | 73.372986 |
| 13   | 64.567986 | 65.890831 | 67.193611 | 68.475914 | 69.737366 | 70.977570 | 72.196159 | 73.392746 |
| 14   | 64.590195 | 65.912712 | 67.215149 | 68.497108 | 69.758209 | 70.998055 | 72.216278 | 73.412506 |
| 15   | 64.612396 | 65.934586 | 67.236679 | 68.518303 | 69.779045 | 71.018539 | 72.236397 | 73.432251 |
| 16   | 64.634598 | 65.956451 | 67.258209 | 68.539482 | 69.799881 | 71.039017 | 72.256508 | 73.451996 |
| 17   | 64.656792 | 65.978310 | 67.279732 | 68.560661 | 69.820709 | 71.059486 | 72.276619 | 73.471733 |
| 18   | 64.678978 | 66.000168 | 67.301254 | 68.581833 | 69.841530 | 71.079948 | 72.296715 | 73.491463 |
| 19   | 64.701164 | 66.022018 | 67.322762 | 68.603004 | 69.862343 | 71.100403 | 72.316811 | 73.511185 |
| 20   | 64.723335 | 66.043861 | 67.344269 | 68.624161 | 69.883156 | 71.120857 | 72.336899 | 73.530899 |
| 21   | 64.745506 | 66.065704 | 67.365768 | 68.645317 | 69.903961 | 71.141304 | 72.356979 | 73.550613 |
| 22   | 64.767677 | 66.087532 | 67.387268 | 68.666466 | 69.924759 | 71.161743 | 72.377052 | 73.570320 |
| 23   | 64.789841 | 66.109367 | 67.408760 | 68.687614 | 69.945549 | 71.182182 | 72.397125 | 73.590019 |
| 24   | 64.811996 | 66.131187 | 67.430244 | 68.708755 | 69.966339 | 71.202606 | 72.417191 | 73.609711 |
| 25   | 64.834145 | 66.153008 | 67.451721 | 68.729889 | 69.987114 | 71.223030 | 72.437248 | 73.629395 |
| 26   | 64.856285 | 66.174820 | 67.473190 | 68.751015 | 70.007889 | 71.243446 | 72.457298 | 73.649078 |
| 27   | 64.878426 | 66.196625 | 67.494659 | 68.772133 | 70.028656 | 71.263855 | 72.477341 | 73.668755 |
| 28   | 64.900558 | 66.218422 | 67.516121 | 68.793251 | 70.049423 | 71.284256 | 72.497383 | 73.688416 |
| 29   | 64.922684 | 66.240219 | 67.537575 | 68.814354 | 70.070175 | 71.304657 | 72.517410 | 73.708084 |
| 30   | 64.944809 | 66.262009 | 67.559021 | 68.835457 | 70.090927 | 71.325043 | 72.537437 | 73.727737 |
| 31   | 64.966919 | 66.283791 | 67.580467 | 68.856560 | 70.111671 | 71.345428 | 72.557457 | 73.747383 |
| 32   | 64.989037 | 66.305565 | 67.601906 | 68.877647 | 70.132408 | 71.365814 | 72.577469 | 73.767029 |
| 33   | 65.011139 | 66.327339 | 67.623337 | 68.898735 | 70.153145 | 71.386185 | 72.597481 | 73.786659 |
| 34   | 65.033241 | 66.349106 | 67.644760 | 68.919815 | 70.173866 | 71.406555 | 72.617485 | 73.806290 |
| 35   | 65.055336 | 66.370865 | 67.666183 | 68.940887 | 70.194588 | 71.426910 | 72.637474 | 73.825920 |
| 36   | 65.077423 | 66.392624 | 67.687599 | 68.961952 | 70.215302 | 71.447266 | 72.657463 | 73.845535 |
| 37   | 65.099503 | 66.414368 | 67.709007 | 68.983017 | 70.236015 | 71.467613 | 72.677452 | 73.865143 |
| 38   | 65.121590 | 66.436119 | 67.730415 | 69.004074 | 70.256721 | 71.487961 | 72.697433 | 73.884758 |
| 39   | 65.143661 | 66.457855 | 67.751808 | 69.025131 | 70.277420 | 71.508301 | 72.717400 | 73.904350 |
| 40   | 65.165726 | 66.479591 | 67.773201 | 69.046173 | 70.298111 | 71.528633 | 72.737366 | 73.923943 |
| 41   | 65.187790 | 66.501320 | 67.794586 | 69.067207 | 70.318794 | 71.548958 | 72.757324 | 73.943535 |
| 42   | 65.209846 | 66.523041 | 67.815971 | 69.088242 | 70.339470 | 71.569275 | 72.777275 | 73.963112 |
| 43   | 65.231895 | 66.544754 | 67.837341 | 69.109268 | 70.360146 | 71.589592 | 72.797226 | 73.982689 |
| 44   | 65.253937 | 66.566467 | 67.858711 | 69.130295 | 70.380814 | 71.609894 | 72.817162 | 74.002251 |
| 45   | 65.275978 | 66.588165 | 67.880074 | 69.151306 | 70.401474 | 71.630196 | 72.837097 | 74.021812 |
| 46   | 65.298012 | 66.609863 | 67.901436 | 69.172318 | 70.422127 | 71.650490 | 72.857025 | 74.041367 |
| 47   | 65.320038 | 66.631561 | 67.922783 | 69.193321 | 70.442780 | 71.670776 | 72.876945 | 74.060921 |
| 48   | 65.342064 | 66.653244 | 67.944130 | 69.214317 | 70.463425 | 71.691063 | 72.896866 | 74.080460 |
| 49   | 65.364075 | 66.674927 | 67.965469 | 69.235313 | 70.484062 | 71.711334 | 72.916771 | 74.099998 |
| 50   | 65.386093 | 66.696602 | 67.986809 | 69.256294 | 70.504692 | 71.731606 | 72.936676 | 74.119530 |
| 51   | 65.408096 | 66.718277 | 68.008133 | 69.277275 | 70.525314 | 71.751869 | 72.956573 | 74.139053 |
| 52   | 65.430099 | 66.739944 | 68.029457 | 69.298248 | 70.545937 | 71.772133 | 72.976463 | 74.158569 |
| 53   | 65.452095 | 66.761604 | 68.050781 | 69.319221 | 70.566551 | 71.792389 | 72.996353 | 74.178085 |
| 54   | 65.474083 | 66.783257 | 68.072090 | 69.340187 | 70.587158 | 71.812630 | 73.016228 | 74.197586 |
| 55   | 65.496071 | 66.804909 | 68.093399 | 69.361145 | 70.607765 | 71.832870 | 73.036102 | 74.217087 |
| 56   | 65.518044 | 66.826546 | 68.114693 | 69.382095 | 70.628357 | 71.853104 | 73.055969 | 74.236580 |
| 57   | 65.540016 | 66.848183 | 68.135986 | 69.403038 | 70.648949 | 71.873337 | 73.075829 | 74.256065 |
| 58   | 65.561989 | 66.869820 | 68.157280 | 69.423981 | 70.669533 | 71.893555 | 73.095680 | 74.275543 |
| 59   | 65.583946 | 66.891441 | 68.178558 | 69.444908 | 70.690109 | 71.913773 | 73.115532 | 74.295013 |
| 60   | 65.605904 | 66.913063 | 68.199837 | 69.465836 | 70.710678 | 71.933983 | 73.135368 | 74.314484 |

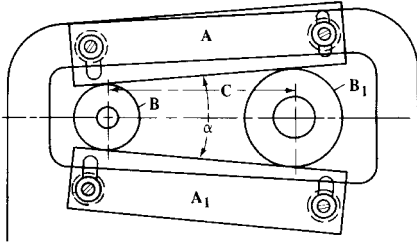
## 100-MILLIMETER SINE-BAR CONSTANTS

## Constants for Setting a 100-mm Sine-bar for 48° to 55°

| Min. | 48°       | 49°       | 50°       | 51°       | 52°       | 53°       | 54°       | 55°       |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0    | 74.314484 | 75.470963 | 76.604446 | 77.714600 | 78.801079 | 79.863556 | 80.901703 | 81.915207 |
| 1    | 74.333946 | 75.490044 | 76.623138 | 77.732903 | 78.818985 | 79.881058 | 80.918793 | 81.931885 |
| 2    | 74.353401 | 75.509117 | 76.641830 | 77.751198 | 78.836884 | 79.898552 | 80.935883 | 81.948563 |
| 3    | 74.372849 | 75.528183 | 76.660507 | 77.769485 | 78.854774 | 79.916039 | 80.952965 | 81.965225 |
| 4    | 74.392288 | 75.547241 | 76.679184 | 77.787766 | 78.872658 | 79.933525 | 80.970039 | 81.981888 |
| 5    | 74.411728 | 75.566299 | 76.697853 | 77.806046 | 78.890533 | 79.950996 | 80.987106 | 81.998543 |
| 6    | 74.431152 | 75.585350 | 76.716515 | 77.824318 | 78.908409 | 79.968468 | 81.004166 | 82.015190 |
| 7    | 74.450577 | 75.604385 | 76.735168 | 77.842575 | 78.926277 | 79.985931 | 81.021217 | 82.031830 |
| 8    | 74.470001 | 75.623428 | 76.753822 | 77.860840 | 78.944138 | 80.003387 | 81.038269 | 82.048462 |
| 9    | 74.489410 | 75.642456 | 76.772469 | 77.879089 | 78.961990 | 80.020836 | 81.055305 | 82.065086 |
| 10   | 74.508812 | 75.661484 | 76.791100 | 77.897331 | 78.979836 | 80.038277 | 81.072342 | 82.081711 |
| 11   | 74.528214 | 75.680496 | 76.809731 | 77.915565 | 78.997673 | 80.055710 | 81.089363 | 82.098320 |
| 12   | 74.547600 | 75.699509 | 76.828354 | 77.933800 | 79.015503 | 80.073143 | 81.106384 | 82.114922 |
| 13   | 74.566986 | 75.718513 | 76.846970 | 77.952019 | 79.033325 | 80.090561 | 81.123398 | 82.131523 |
| 14   | 74.586365 | 75.737511 | 76.865578 | 77.970238 | 79.051147 | 80.107979 | 81.140404 | 82.148109 |
| 15   | 74.605736 | 75.756500 | 76.884186 | 77.988449 | 79.068962 | 80.125381 | 81.157402 | 82.164696 |
| 16   | 74.625107 | 75.775482 | 76.902779 | 78.006653 | 79.086761 | 80.142784 | 81.174393 | 82.181274 |
| 17   | 74.644463 | 75.794464 | 76.921371 | 78.024849 | 79.104561 | 80.160179 | 81.191376 | 82.197845 |
| 18   | 74.663818 | 75.813431 | 76.939957 | 78.043045 | 79.122353 | 80.177567 | 81.208351 | 82.214401 |
| 19   | 74.683167 | 75.832397 | 76.958534 | 78.061226 | 79.140137 | 80.194946 | 81.225327 | 82.230957 |
| 20   | 74.702507 | 75.851357 | 76.977104 | 78.079399 | 79.157921 | 80.212318 | 81.242287 | 82.247513 |
| 21   | 74.721840 | 75.870308 | 76.995667 | 78.097572 | 79.175690 | 80.229683 | 81.259247 | 82.264053 |
| 22   | 74.741173 | 75.889259 | 77.014229 | 78.115738 | 79.193451 | 80.247047 | 81.276199 | 82.280586 |
| 23   | 74.760498 | 75.908203 | 77.032784 | 78.133896 | 79.211220 | 80.264404 | 81.293144 | 82.297119 |
| 24   | 74.779816 | 75.927132 | 77.051331 | 78.152054 | 79.228966 | 80.281754 | 81.310081 | 82.313637 |
| 25   | 74.799118 | 75.946060 | 77.069862 | 78.170197 | 79.246712 | 80.299088 | 81.327011 | 82.330154 |
| 26   | 74.818428 | 75.964984 | 77.088394 | 78.188332 | 79.264450 | 80.316422 | 81.343933 | 82.346664 |
| 27   | 74.837723 | 75.983894 | 77.106926 | 78.206467 | 79.282181 | 80.333748 | 81.360847 | 82.363159 |
| 28   | 74.857010 | 76.002800 | 77.125443 | 78.224586 | 79.299904 | 80.351067 | 81.377754 | 82.379654 |
| 29   | 74.876297 | 76.021706 | 77.143951 | 78.242706 | 79.317627 | 80.368385 | 81.394661 | 82.396141 |
| 30   | 74.895576 | 76.040596 | 77.162460 | 78.260818 | 79.335335 | 80.385689 | 81.411552 | 82.412621 |
| 31   | 74.914848 | 76.059486 | 77.180962 | 78.278923 | 79.353043 | 80.402985 | 81.428444 | 82.429092 |
| 32   | 74.934113 | 76.078369 | 77.199455 | 78.297020 | 79.370735 | 80.420280 | 81.445320 | 82.445557 |
| 33   | 74.953369 | 76.097244 | 77.217941 | 78.315109 | 79.388428 | 80.437561 | 81.462196 | 82.462013 |
| 34   | 74.972618 | 76.116112 | 77.236420 | 78.333199 | 79.406113 | 80.454842 | 81.479065 | 82.478470 |
| 35   | 74.991867 | 76.134972 | 77.254890 | 78.351273 | 79.423790 | 80.472115 | 81.495926 | 82.494911 |
| 36   | 75.011108 | 76.153831 | 77.273354 | 78.369347 | 79.441460 | 80.489380 | 81.512779 | 82.511353 |
| 37   | 75.030342 | 76.172684 | 77.291817 | 78.387413 | 79.459129 | 80.506638 | 81.529625 | 82.527779 |
| 38   | 75.049568 | 76.191528 | 77.310272 | 78.405472 | 79.476791 | 80.523895 | 81.546471 | 82.544205 |
| 39   | 75.068794 | 76.210365 | 77.328720 | 78.423523 | 79.494438 | 80.541138 | 81.563301 | 82.560623 |
| 40   | 75.088005 | 76.229195 | 77.347160 | 78.441566 | 79.512085 | 80.558372 | 81.580132 | 82.577034 |
| 41   | 75.107216 | 76.248016 | 77.365593 | 78.459610 | 79.529716 | 80.575607 | 81.596947 | 82.593437 |
| 42   | 75.126419 | 76.266838 | 77.384026 | 78.477638 | 79.547348 | 80.592827 | 81.613762 | 82.609833 |
| 43   | 75.145615 | 76.285645 | 77.402443 | 78.495667 | 79.564972 | 80.610046 | 81.630569 | 82.626221 |
| 44   | 75.164803 | 76.304451 | 77.420860 | 78.513680 | 79.582588 | 80.627258 | 81.647362 | 82.642601 |
| 45   | 75.183983 | 76.323250 | 77.439262 | 78.531693 | 79.600204 | 80.644463 | 81.664154 | 82.658974 |
| 46   | 75.203156 | 76.342041 | 77.457664 | 78.549698 | 79.617805 | 80.661659 | 81.680939 | 82.675346 |
| 47   | 75.222328 | 76.360825 | 77.476059 | 78.567696 | 79.635399 | 80.678848 | 81.697723 | 82.691704 |
| 48   | 75.241493 | 76.379601 | 77.494446 | 78.585693 | 79.652992 | 80.696030 | 81.714493 | 82.708061 |
| 49   | 75.260651 | 76.398376 | 77.512833 | 78.603676 | 79.670578 | 80.713211 | 81.731255 | 82.724403 |
| 50   | 75.279800 | 76.417145 | 77.531204 | 78.621651 | 79.688156 | 80.730377 | 81.748009 | 82.740746 |
| 51   | 75.298943 | 76.435898 | 77.549576 | 78.639626 | 79.705719 | 80.747543 | 81.764763 | 82.757080 |
| 52   | 75.318085 | 76.454651 | 77.567932 | 78.657593 | 79.723289 | 80.764694 | 81.781502 | 82.773399 |
| 53   | 75.337219 | 76.473404 | 77.586296 | 78.675552 | 79.740845 | 80.781853 | 81.798248 | 82.789726 |
| 54   | 75.356346 | 76.492142 | 77.604645 | 78.693504 | 79.758392 | 80.798988 | 81.814972 | 82.806038 |
| 55   | 75.375458 | 76.510880 | 77.622986 | 78.711449 | 79.775940 | 80.816124 | 81.831696 | 82.822342 |
| 56   | 75.394577 | 76.529602 | 77.641319 | 78.729393 | 79.793472 | 80.833252 | 81.848412 | 82.838638 |
| 57   | 75.413681 | 76.548325 | 77.659653 | 78.747322 | 79.811005 | 80.850380 | 81.865120 | 82.854927 |
| 58   | 75.432777 | 76.567039 | 77.677971 | 78.765244 | 79.828529 | 80.867493 | 81.881821 | 82.871216 |
| 59   | 75.451874 | 76.585747 | 77.696289 | 78.783165 | 79.846046 | 80.884598 | 81.898521 | 82.887489 |
| 60   | 75.470963 | 76.604446 | 77.714600 | 78.801079 | 79.863556 | 80.901703 | 81.915207 | 82.903755 |

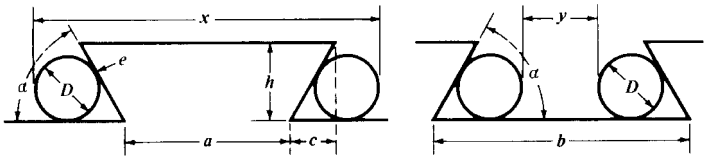
### Accurate Measurement of Angles and Tapers

When great accuracy is required in the measurement of angles, or when originating tapers, disks are commonly used. The principle of the disk method of taper measurement is that if two disks of unequal diameters are placed either in contact or a certain distance apart, lines tangent to their peripheries will represent an angle or taper, the degree of which depends upon the diameters of the two disks and the distance between them.



The gage shown in the accompanying illustration, which is a form commonly used for originating tapers or measuring angles accurately, is set by means of disks. This gage consists of two adjustable straight edges  $A$  and  $A_1$ , which are in contact with disks  $B$  and  $B_1$ . The angle  $\alpha$  or the taper between the straight edges depends, of course, upon the diameters of the disks and the center distance  $C$ , and as these three dimensions can be measured accurately, it is possible to set the gage to a given angle within very close limits. Moreover, if a record of the three dimensions is kept, the exact setting of the gage can be reproduced quickly at any time. The following rules may be used for adjusting a gage of this type, and cover all problems likely to arise in practice. Disks are also occasionally used for the setting of parts in angular positions when they are to be machined accurately to a given angle; the rules are applicable to these conditions also.

**Measuring Dovetail Slides.**—Dovetail slides that must be machined accurately to a given width are commonly gaged by using pieces of cylindrical rod or wire and measuring as indicated by the dimensions  $x$  and  $y$  of the accompanying illustrations.



The rod or wire used should be small enough so that the point of contact  $e$  is somewhat below the corner or edge of the dovetail.

To obtain dimension  $x$  for measuring male dovetails, add 1 to the cotangent of one-half the dovetail angle  $\alpha$ , multiply by diameter  $D$  of the rods used, and add the product to dimension  $a$ .

$$x = D(1 + \cot \frac{1}{2}\alpha) + a \quad c = h \times \cot \alpha$$

To obtain dimension  $y$  for measuring a female dovetail, add 1 to the cotangent of one-half the dovetail angle  $\alpha$ , multiply by diameter  $D$  of the rod used, and subtract the result from dimension  $b$ . Expressing these rules as formulas:

$$y = b - D(1 + \cot \frac{1}{2}\alpha)$$

## Tapers per Foot and Corresponding Angles

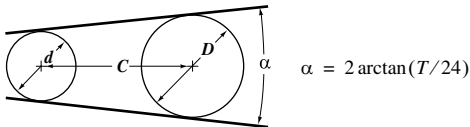
| Taper per Foot  | Included Angle |    |        | Angle with Center Line |        |  | Taper per Foot   | Included Angle |    |        | Angle with Center Line |        |  |
|-----------------|----------------|----|--------|------------------------|--------|--|------------------|----------------|----|--------|------------------------|--------|--|
| $\frac{1}{64}$  | 0.149208°      | 0° | 4' 29" | 0°                     | 2' 14" |  | $1\frac{7}{8}$   | 9.230863°      | 8° | 56' 4" | 4°                     | 28' 2" |  |
| $\frac{1}{32}$  | 0.298415       | 0  | 8 57   | 0                      | 4 29   |  | $1\frac{15}{16}$ | 9.527283       | 9  | 13 51  | 4                      | 36 56  |  |
| $\frac{1}{16}$  | 0.447621       | 0  | 17 54  | 0                      | 8 57   |  | 2                | 10.119738      | 9  | 31 38  | 4                      | 45 49  |  |
| $\frac{3}{32}$  | 0.596826       | 0  | 26 51  | 0                      | 13 26  |  | $2\frac{1}{8}$   | 10.711650      | 10 | 7 11   | 5                      | 3 36   |  |
| $\frac{1}{8}$   | 0.746028       | 0  | 35 49  | 0                      | 17 54  |  | $2\frac{1}{4}$   | 11.302990      | 10 | 42 42  | 5                      | 21 21  |  |
| $\frac{5}{32}$  | 0.895228       | 0  | 44 46  | 0                      | 22 23  |  | $2\frac{3}{8}$   | 11.893726      | 11 | 18 11  | 5                      | 39 5   |  |
| $\frac{3}{16}$  | 1.044425       | 0  | 53 43  | 0                      | 26 51  |  | $2\frac{1}{2}$   | 12.483829      | 11 | 53 37  | 5                      | 56 49  |  |
| $\frac{7}{32}$  | 1.193619       | 1  | 2 40   | 0                      | 31 20  |  | $2\frac{5}{8}$   | 13.073267      | 12 | 29 2   | 6                      | 14 31  |  |
| $\frac{1}{4}$   | 1.342808       | 1  | 11 37  | 0                      | 35 49  |  | $2\frac{3}{4}$   | 13.662012      | 13 | 4 24   | 6                      | 32 12  |  |
| $\frac{9}{32}$  | 1.491993       | 1  | 20 34  | 0                      | 40 17  |  | $2\frac{7}{8}$   | 14.250033      | 13 | 39 43  | 6                      | 49 52  |  |
| $\frac{5}{16}$  | 1.641173       | 1  | 29 31  | 0                      | 44 46  |  | 3                | 14.837300      | 14 | 15 0   | 7                      | 7 30   |  |
| $\frac{11}{32}$ | 1.790347       | 1  | 38 28  | 0                      | 49 14  |  | $3\frac{1}{8}$   | 15.423785      | 14 | 50 14  | 7                      | 25 7   |  |
| $\frac{3}{8}$   | 1.939516       | 1  | 47 25  | 0                      | 53 43  |  | $3\frac{1}{4}$   | 16.009458      | 15 | 25 26  | 7                      | 42 43  |  |
| $\frac{13}{32}$ | 2.088677       | 1  | 56 22  | 0                      | 58 11  |  | $3\frac{3}{8}$   | 16.594290      | 16 | 0 34   | 8                      | 0 17   |  |
| $\frac{7}{16}$  | 2.237832       | 2  | 5 19   | 1                      | 2 40   |  | $3\frac{1}{2}$   | 17.178253      | 16 | 35 39  | 8                      | 17 50  |  |
| $\frac{15}{32}$ | 2.386979       | 2  | 14 16  | 1                      | 7 8    |  | $3\frac{5}{8}$   | 17.761318      | 17 | 10 42  | 8                      | 35 21  |  |
| $\frac{1}{2}$   | 2.536118       | 2  | 23 13  | 1                      | 11 37  |  | $3\frac{3}{4}$   | 18.343458      | 17 | 45 41  | 8                      | 52 50  |  |
| $\frac{17}{32}$ | 2.685248       | 2  | 32 10  | 1                      | 16 5   |  | $3\frac{7}{8}$   | 18.924644      | 18 | 20 36  | 9                      | 10 18  |  |
| $\frac{9}{16}$  | 2.834369       | 2  | 41 7   | 1                      | 20 33  |  | 4                | 19.504850      | 18 | 55 29  | 9                      | 27 44  |  |
| $\frac{19}{32}$ | 2.983481       | 2  | 50 4   | 1                      | 25 2   |  | $4\frac{1}{8}$   | 20.084047      | 19 | 30 17  | 9                      | 45 9   |  |
| $\frac{5}{8}$   | 3.132582       | 2  | 59 1   | 1                      | 29 30  |  | $4\frac{1}{4}$   | 20.662210      | 20 | 5 3    | 10                     | 2 31   |  |
| $\frac{21}{32}$ | 3.281673       | 3  | 7 57   | 1                      | 33 59  |  | $4\frac{3}{8}$   | 21.239311      | 20 | 39 44  | 10                     | 19 52  |  |
| $\frac{11}{16}$ | 3.430753       | 3  | 16 54  | 1                      | 38 27  |  | $4\frac{1}{2}$   | 21.815324      | 21 | 14 22  | 10                     | 37 11  |  |
| $\frac{23}{32}$ | 3.579821       | 3  | 25 51  | 1                      | 42 55  |  | $4\frac{5}{8}$   | 22.390223      | 21 | 48 55  | 10                     | 54 28  |  |
| $\frac{3}{4}$   | 3.728877       | 3  | 34 47  | 1                      | 47 24  |  | $4\frac{3}{4}$   | 22.963983      | 22 | 23 25  | 11                     | 11 42  |  |
| $\frac{25}{32}$ | 3.877921       | 3  | 43 44  | 1                      | 51 52  |  | $4\frac{7}{8}$   | 23.536578      | 22 | 57 50  | 11                     | 28 55  |  |
| $\frac{13}{16}$ | 4.026951       | 3  | 52 41  | 1                      | 56 20  |  | 5                | 24.107983      | 23 | 32 12  | 11                     | 46 6   |  |
| $\frac{27}{32}$ | 4.175968       | 4  | 1 37   | 2                      | 0 49   |  | $5\frac{1}{8}$   | 24.678175      | 24 | 6 29   | 12                     | 3 14   |  |
| $\frac{7}{8}$   | 4.324970       | 4  | 10 33  | 2                      | 5 17   |  | $5\frac{1}{4}$   | 25.247127      | 24 | 40 41  | 12                     | 20 21  |  |
| $\frac{29}{32}$ | 4.473958       | 4  | 19 30  | 2                      | 9 45   |  | $5\frac{3}{8}$   | 25.814817      | 25 | 14 50  | 12                     | 37 25  |  |
| $\frac{15}{16}$ | 4.622931       | 4  | 28 26  | 2                      | 14 13  |  | $5\frac{1}{2}$   | 26.381221      | 25 | 48 53  | 12                     | 54 27  |  |
| $\frac{31}{32}$ | 4.771888       | 4  | 37 23  | 2                      | 18 41  |  | $5\frac{5}{8}$   | 26.946316      | 26 | 22 52  | 13                     | 11 26  |  |
| 1               | 5.069753       | 4  | 46 19  | 2                      | 23 9   |  | $5\frac{3}{4}$   | 27.510079      | 26 | 56 47  | 13                     | 28 23  |  |
| $\frac{1}{16}$  | 5.367550       | 5  | 4 11   | 2                      | 32 6   |  | $5\frac{7}{8}$   | 28.072487      | 27 | 30 36  | 13                     | 45 18  |  |
| $\frac{1}{8}$   | 5.665275       | 5  | 22 3   | 2                      | 41 2   |  | 6                | 28.633518      | 28 | 4 21   | 14                     | 2 10   |  |
| $\frac{13}{16}$ | 5.962922       | 5  | 39 55  | 2                      | 49 57  |  | $6\frac{1}{8}$   | 29.193151      | 28 | 38 1   | 14                     | 19 0   |  |
| $\frac{1}{4}$   | 6.260490       | 5  | 57 47  | 2                      | 58 53  |  | $6\frac{1}{4}$   | 29.751364      | 29 | 11 35  | 14                     | 35 48  |  |
| $\frac{15}{16}$ | 6.557973       | 6  | 15 38  | 3                      | 7 49   |  | $6\frac{3}{8}$   | 30.308136      | 29 | 45 5   | 14                     | 52 32  |  |
| $\frac{1}{8}$   | 6.855367       | 6  | 33 29  | 3                      | 16 44  |  | $6\frac{1}{2}$   | 30.863447      | 30 | 18 29  | 15                     | 9 15   |  |
| $\frac{17}{16}$ | 7.152669       | 6  | 51 19  | 3                      | 25 40  |  | $6\frac{5}{8}$   | 31.417276      | 30 | 51 48  | 15                     | 25 54  |  |
| $\frac{1}{2}$   | 7.449874       | 7  | 9 10   | 3                      | 34 35  |  | $6\frac{3}{4}$   | 31.969603      | 31 | 25 2   | 15                     | 42 31  |  |
| $\frac{19}{16}$ | 7.746979       | 7  | 27 0   | 3                      | 43 30  |  | $6\frac{7}{8}$   | 32.520409      | 31 | 58 11  | 15                     | 59 5   |  |
| $\frac{3}{8}$   | 8.043980       | 7  | 44 49  | 3                      | 52 25  |  | 7                | 33.069676      | 32 | 31 13  | 16                     | 15 37  |  |
| $\frac{11}{16}$ | 8.340873       | 8  | 2 38   | 4                      | 1 19   |  | $7\frac{1}{8}$   | 33.617383      | 33 | 4 11   | 16                     | 32 5   |  |
| $\frac{13}{4}$  | 8.637654       | 8  | 20 27  | 4                      | 10 14  |  | $7\frac{1}{4}$   | 34.163514      | 33 | 37 3   | 16                     | 48 31  |  |
| $\frac{15}{16}$ | 0.149208       | 8  | 38 16  | 4                      | 19 8   |  | $7\frac{3}{8}$   | 9.230863       | 34 | 9 49   | 17                     | 4 54   |  |

Taper per foot represents inches of taper per foot of length. For conversions into decimal degrees and radians see *Conversion Tables of Angular Measure* on page 96.

## Rules for Figuring Tapers

| Given   | To Find   | Rule   |
|---|---|--|
| The taper per foot.   | The taper per inch.                             | Divide the taper per foot by 12.   |
| The taper per inch.   | The taper per foot.                             | Multiply the taper per inch by 12.   |
| End diameters and length of taper in inches.                      | The taper per foot.                             | Subtract small diameter from large; divide by length of taper; and multiply quotient by 12.          |
| Large diameter and length of taper in inches, and taper per foot. | Diameter at small end in inches                 | Divide taper per foot by 12; multiply by length of taper; and subtract result from large diameter.   |
| Small diameter and length of taper in inches, and taper per foot. | Diameter at large end in inches.                | Divide taper per foot by 12; multiply by length of taper; and add result to small diameter.          |
| The taper per foot and two diameters in inches.                   | Distance between two given diameters in inches. | Subtract small diameter from large; divide remainder by taper per foot; and multiply quotient by 12. |
| The taper per foot.   | Amount of taper in a certain length in inches.  | Divide taper per foot by 12; multiply by given length of tapered part.                               |

To find angle  $\alpha$  for given taper  $T$  in inches per foot.—



*Example:* What angle  $\alpha$  is equivalent to a taper of 1.5 inches per foot?

$$\alpha = 2 \times \arctan(1.5/24) = 7.153^\circ$$

To find taper per foot  $T$  given angle  $\alpha$  in degrees.—

$$T = 24 \tan(\alpha/2) \text{ inches per foot}$$

*Example:* What taper  $T$  is equivalent to an angle of  $7.153^\circ$ ?

$$T = 24 \tan(7.153/2) = 1.5 \text{ inches per foot}$$

To find angle  $\alpha$  given dimensions  $D$ ,  $d$ , and  $C$ .— Let  $K$  be the difference in the disk diameters divided by twice the center distance.  $K = (D - d)/(2C)$ , then  $\alpha = 2 \arcsin K$

*Example:* If the disk diameters  $d$  and  $D$  are 1 and 1.5 inches, respectively, and the center distance  $C$  is 5 inches, find the included angle  $\alpha$ .

$$K = (1.5 - 1)/(2 \times 5) = 0.05 \quad \alpha = 2 \times \arcsin 0.05 = 5.732^\circ$$

To find taper  $T$  measured at right angles to a line through the disk centers given dimensions  $D$ ,  $d$ , and distance  $C$ .— Find  $K$  using the formula in the previous example, then  $T = 24K/\sqrt{1 - K^2}$  inches per foot

*Example:* If disk diameters  $d$  and  $D$  are 1 and 1.5 inches, respectively, and the center distance  $C$  is 5 inches, find the taper per foot.

$$K = (1.5 - 1)/(2 \times 5) = 0.05 \quad T = \frac{24 \times 0.05}{\sqrt{1 - (0.05)^2}} = 1.2015 \text{ inches per foot}$$



**To find center distance  $C$  for a given taper  $T$  in inches per foot.—**

$$C = \frac{D-d}{2} \times \frac{\sqrt{1+(T/24)^2}}{T/24} \text{ inches}$$

*Example:* Gage is to be set to  $\frac{3}{4}$  inch per foot, and disk diameters are 1.25 and 1.5 inches, respectively. Find the required center distance for the disks.

$$C = \frac{1.5-1.25}{2} \times \frac{\sqrt{1+(0.75/24)^2}}{0.75/24} = 4.002 \text{ inches}$$

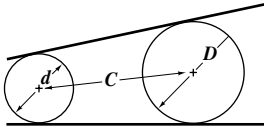
**To find center distance  $C$  for a given angle  $\alpha$  and dimensions  $D$  and  $d$ .—**

$$C = (D-d)/2 \sin(\alpha/2) \text{ inches}$$

*Example:* If an angle  $\alpha$  of  $20^\circ$  is required, and the disks are 1 and 3 inches in diameter, respectively, find the required center distance  $C$ .

$$C = (3-1)/(2 \times \sin 10^\circ) = 5.759 \text{ inches}$$

**To find taper  $T$  measured at right angles to one side.—**When one side is taken as a base line and the taper is measured at right angles to that side, calculate  $K$  as explained above and use the following formula for determining the taper  $T$ :



$$T = 24K \frac{\sqrt{1-K^2}}{1-2K^2} \text{ inches per foot}$$

*Example:* If the disk diameters are 2 and 3 inches, respectively, and the center I distance is 5 inches, what is the taper per foot measured at right angles to one side?

$$K = \frac{3-2}{2 \times 5} = 0.1 \quad T = 24 \times 0.1 \times \frac{\sqrt{1-(0.1)^2}}{1-[2 \times (0.1)^2]} = 2.4367 \text{ in. per ft.}$$

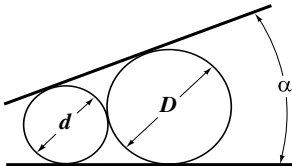
**To find center distance  $C$  when taper  $T$  is measured from one side.—**

$$C = \frac{D-d}{\sqrt{2-2/\sqrt{1+(T/12)^2}}} \text{ inches}$$

*Example:* If the taper measured at right angles to one side is 6.9 inches per foot, and the disks are 2 and 5 inches in diameter, respectively, what is center distance  $C$ ?

$$C = \frac{5-2}{\sqrt{2-2/\sqrt{1+(6.9/12)^2}}} = 5.815 \text{ inches.}$$

**To find diameter  $D$  of a large disk in contact with a small disk of diameter  $d$  given angle  $\alpha$ .—**



$$D = d \times \frac{1 + \sin(\alpha/2)}{1 - \sin(\alpha/2)} \text{ inches}$$

*Example:* The required angle  $\alpha$  is  $15^\circ$ . Find diameter  $D$  of a large disk that is in contact with a standard 1-inch reference disk.

$$D = 1 \times \frac{1 + \sin 7.5^\circ}{1 - \sin 7.5^\circ} = 1.3002 \text{ inches}$$

### Measurement over Pins and Rolls

**Measurement over Pins.**—When the distance across a bolt circle is too large to measure using ordinary measuring tools, then the required distance may be found from the distance across adjacent or alternate holes using one of the methods that follow:

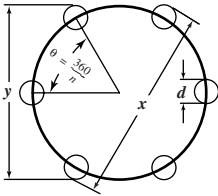


Fig. 1a.

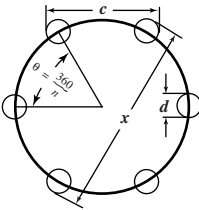


Fig. 1b.

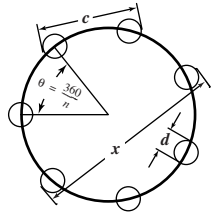


Fig. 1c.

**Even Number of Holes in Circle:** To measure the unknown distance  $x$  over opposite plugs in a bolt circle of  $n$  holes ( $n$  is even and greater than 4), as shown in Fig. 1a, where  $y$  is the distance over alternate plugs,  $d$  is the diameter of the holes, and  $\theta = 360^\circ/n$  is the angle between adjacent holes, use the following general equation for obtaining  $x$ :

$$x = \frac{y-d}{\sin \theta} + d$$

**Example:** In a die that has six  $3/4$ -inch diameter holes equally spaced on a circle, where the distance  $y$  over alternate holes is  $4\frac{1}{2}$  inches, and the angle  $\theta$  between adjacent holes is  $60^\circ$ , then

$$x = \frac{4.500 - 0.7500}{\sin 60^\circ} + 0.7500 = 5.0801$$

In a similar problem, the distance  $c$  over adjacent plugs is given, as shown in Fig. 1b. If the number of holes is even and greater than 4, the distance  $x$  over opposite plugs is given in the following formula:

$$x = 2(c-d) \left( \frac{\sin \left( \frac{180-\theta}{2} \right)}{\sin \theta} \right) + d$$

where  $d$  and  $\theta$  are as defined above.

**Odd Number of Holes in Circle:** In a circle as shown in Fig. 1c, where the number of holes  $n$  is odd and greater than 3, and the distance  $c$  over adjacent holes is given, then  $\theta$  equals  $360/n$  and the distance  $x$  across the most widely spaced holes is given by:

$$x = \frac{c-d}{\sin \frac{\theta}{4}} + d$$

**Checking a V-shaped Groove by Measurement Over Pins.**—In checking a groove of the shape shown in Fig. 2, it is necessary to measure the dimension  $X$  over the pins of radius  $R$ . If values for the radius  $R$ , dimension  $Z$ , and the angles  $\alpha$  and  $\beta$  are known, the problem is

to determine the distance  $Y$ , to arrive at the required overall dimension for  $X$ . If a line  $AC$  is drawn from the bottom of the  $V$  to the center of the pin at the left in Fig. 2, and a line  $CB$  from the center of this pin to its point of tangency with the side of the  $V$ , a right-angled triangle is formed in which one side,  $CB$ , is known and one angle  $CAB$ , can be determined. A line drawn from the center of a circle to the point of intersection of two tangents to the circle bisects the angle made by the tangent lines, and angle  $CAB$  therefore equals  $\frac{1}{2}(\alpha + \beta)$ . The length  $AC$  and the angle  $DAC$  can now be found, and with  $AC$  known in the right-angled triangle  $ADC$ ,  $AD$ , which is equal to  $Y$  can be found.

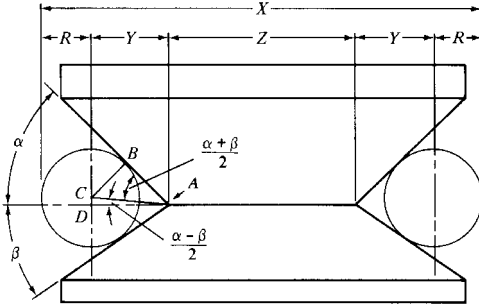


Fig. 2.

The value for  $X$  can be obtained from the formula

$$X = Z + 2R \left( \csc \frac{\alpha + \beta}{2} \cos \frac{\alpha - \beta}{2} + 1 \right)$$

For example, if  $R = 0.500$ ,  $Z = 1.824$ ,  $\alpha = 45$  degrees, and  $\beta = 35$  degrees,

$$X = 1.824 + (2 \times 0.5) \left( \csc \frac{45^\circ + 35^\circ}{2} \cos \frac{45^\circ - 35^\circ}{2} + 1 \right)$$

$$X = 1.824 + \csc 40^\circ \cos 5^\circ + 1$$

$$X = 1.824 + 1.5557 \times 0.99619 + 1$$

$$X = 1.824 + 1.550 + 1 = 4.374$$

**Checking Radius of Arc by Measurement Over Rolls.**—The radius  $R$  of large-radius concave and convex gages of the type shown in Figs. 3a, 3b and 3c can be checked by measurement  $L$  over two rolls with the gage resting on the rolls as shown. If the diameter of the rolls  $D$ , the length  $L$ , and the height  $H$  of the top of the arc above the surface plate (for the concave gage, Fig. 3a) are known or can be measured, the radius  $R$  of the workpiece to be checked can be calculated trigonometrically, as follows.

Referring to Fig. 3a for the concave gage, if  $L$  and  $D$  are known,  $cb$  can be found, and if  $H$  and  $D$  are known,  $ce$  can be found. With  $cb$  and  $ce$  known,  $ab$  can be found by means of a diagram as shown in Fig. 3c.

In diagram Fig. 3c,  $cb$  and  $ce$  are shown at right angles as in Fig. 3a. A line is drawn connecting points  $b$  and  $e$  and line  $ce$  is extended to the right. A line is now drawn from point  $b$  perpendicular to  $be$  and intersecting the extension of  $ce$  at point  $f$ . A semicircle can now be drawn through points  $b$ ,  $e$ , and  $f$  with point  $a$  as the center. Triangles  $bce$  and  $bef$  are similar and have a common side. Thus  $ce:bc::bc:cf$ . With  $ce$  and  $bc$  known,  $cf$  can be found from this proportion and hence  $ef$  which is the diameter of the semicircle and radius  $ab$ . Then  $R = ab + D/2$ .

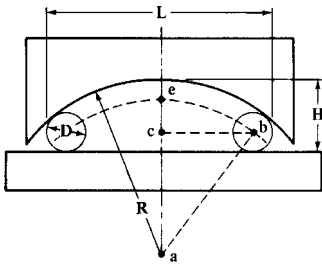


Fig. 3a.

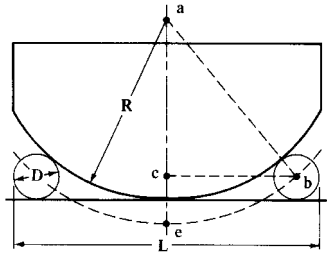


Fig. 3b.

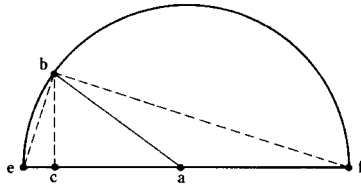


Fig. 3c.

The procedure for the convex gage is similar. The distances  $cb$  and  $ce$  are readily found and from these two distances  $ab$  is computed on the basis of similar triangles as before. Radius  $R$  is then readily found.

The derived formulas for concave and convex gages are as follows:

Formulas:

$$R = \frac{(L-D)^2}{8(H-D)} + \frac{H}{2} \quad (\text{Concave gage Fig. 3a})$$

$$R = \frac{(L-D)^2}{8D} \quad (\text{Convex gage Fig. 3b})$$

For example: For Fig. 3a, let  $L = 17.8$ ,  $D = 3.20$ , and  $H = 5.72$ , then

$$R = \frac{(17.8 - 3.20)^2}{8(5.72 - 3.20)} + \frac{5.72}{2} = \frac{(14.60)^2}{8 \times 2.52} + 2.86$$

$$R = \frac{213.16}{20.16} + 2.86 = 13.43$$

For Fig. 3b, let  $L = 22.28$  and  $D = 3.40$ , then

$$R = \frac{(22.28 - 3.40)^2}{8 \times 3.40} = \frac{356.45}{27.20} = 13.1$$

### Checking Shaft Conditions

**Checking for Various Shaft Conditions.**—An indicating height gage, together with V-blocks can be used to check shafts for ovality, taper, straightness (bending or curving), and concentricity of features (as shown exaggerated in Fig. 4). If a shaft on which work has

been completed shows lack of concentricity. It may be due to the shaft having become bent or bowed because of mishandling or oval or tapered due to poor machine conditions. In checking for concentricity, the first step is to check for ovality, or out-of-roundness, as in Fig. 4a. The shaft is supported in a suitable V-block on a surface table and the dial indicator plunger is placed over the workpiece, which is then rotated beneath the plunger to obtain readings of the amount of eccentricity.

This procedure (sometimes called clocking, owing to the resemblance of the dial indicator to a clock face) is repeated for other shaft diameters as necessary, and, in addition to making a written record of the measurements, the positions of extreme conditions should be marked on the workpiece for later reference.

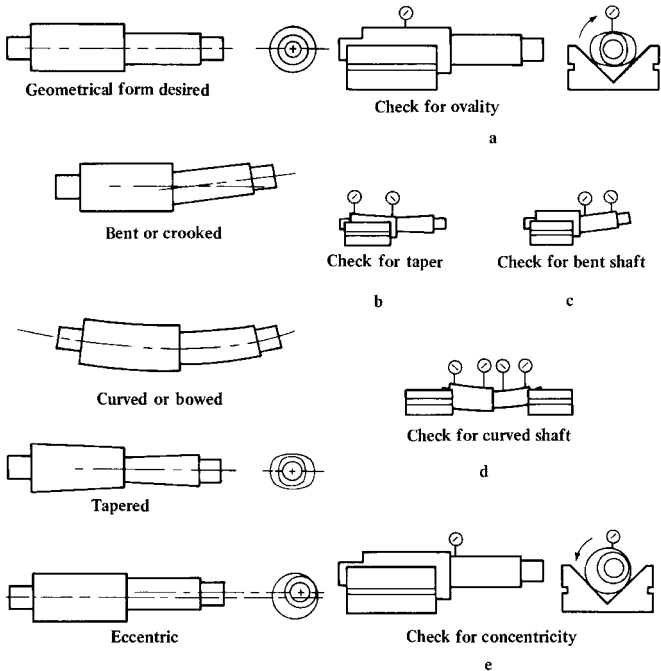


Fig. 4.

To check for taper, the shaft is supported in the V-block and the dial indicator is used to measure the maximum height over the shaft at various positions along its length, as shown in Fig. 4b, without turning the workpiece. Again, the shaft should be marked with the reading positions and values, also the direction of the taper, and a written record should be made of the amount and direction of any taper discovered.

Checking for a bent shaft requires that the shaft be clocked at the shoulder and at the farther end, as shown in Fig. 4c. For a second check the shaft is rotated only  $90^\circ$  or a quarter turn. When the recorded readings are compared with those from the ovality and taper checks, the three conditions can be distinguished.

To detect a curved or bowed condition, the shaft should be suspended in two V-blocks with only about  $\frac{1}{8}$  inch of each end in each vee. Alternatively, the shaft can be placed between centers. The shaft is then clocked at several points, as shown in Fig. 4d, but preferably not at those locations used for the ovality, taper, or crookedness checks. If the single element due to curvature is to be distinguished from the effects of ovality, taper, and crookedness, and its value assessed, great care must be taken to differentiate between the conditions detected by the measurements.

Finally, the amount of eccentricity between one shaft diameter and another may be tested by the setup shown in Fig. 4e. With the indicator plunger in contact with the smaller diameter, close to the shoulder, the shaft is rotated in the V-block and the indicator needle position is monitored to find the maximum and minimum readings.

Curvature, ovality, or crookedness conditions may tend to cancel each other, as shown in Fig. 5, and one or more of these degrees of defectiveness may add themselves to the true eccentricity readings, depending on their angular positions. Fig. 5a shows, for instance, how crookedness and ovality tend to cancel each other, and also shows their effect in falsifying the reading for eccentricity. As the same shaft is turned in the V-block to the position shown in Fig. 5b, the maximum curvature reading could tend to cancel or reduce the maximum eccentricity reading. Where maximum readings for ovality, curvature, or crookedness occur at the same angular position, their values should be subtracted from the eccentricity reading to arrive at a true picture of the shaft condition. Confirmation of eccentricity readings may be obtained by reversing the shaft in the V-block, as shown in Fig. 5c, and clocking the larger diameter of the shaft.

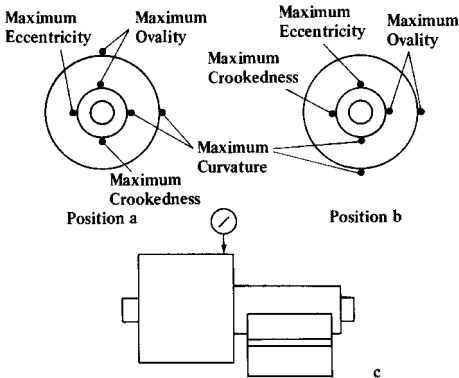


Fig. 5.

**Out-of-Roundness—Lobing.**—With the imposition of finer tolerances and the development of improved measurement methods, it has become apparent that no hole, cylinder, or sphere can be produced with a perfectly symmetrical round shape. Some of the conditions are diagrammed in Fig. 6, where Fig. 6a shows simple ovality and Fig. 6b shows ovality occurring in two directions. From the observation of such conditions have come the terms lobe and lobing. Fig. 6c shows the three-lobed shape common with centerless-ground components, and Fig. 6d is typical of multi-lobed shapes. In Fig. 6e are shown surface waviness, surface roughness, and out-of-roundness, which often are combined with lobing.

## OUT OF ROUNDNESS, LOBING

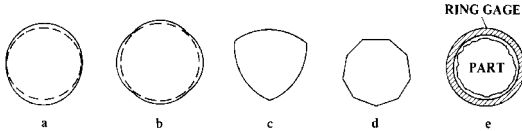


Fig. 6.

In Figs. 6a through 6d, the cylinder (or hole) diameters are shown at full size but the lobes are magnified some 10,000 times to make them visible. In precision parts, the deviation from the round condition is usually only in the range of millionths of an inch, although it occasionally can be 0.0001 inch, 0.0002 inch, or more. For instance, a 3-inch-diameter part may have a lobing condition amounting to an inaccuracy of only 30 millionths (0.000030 inch). Even if the distortion (ovality, waviness, roughness) is small, it may cause hum, vibration, heat buildup, and wear, possibly leading to eventual failure of the component or assembly.

Plain elliptical out-of-roundness (two lobes), or any even number of lobes, can be detected by rotating the part on a surface plate under a dial indicator of adequate resolution, or by using an indicating caliper or snap gage. However, supporting such a part in a V-block during measurement will tend to conceal roundness errors. Ovality in a hole can be detected by a dial-type bore gage or internal measuring machine. Parts with odd numbers of lobes require an instrument that can measure the envelope or complete circumference. Plug and ring gages will tell whether a shaft can be assembled into a bearing, but not whether there will be a good fit, as illustrated in Fig. 6e.

A standard, 90-degree included-angle V-block can be used to detect and count the number of lobes, but to measure the exact amount of lobing indicated by  $R-r$  in Fig. 7 requires a V-block with an angle  $\alpha$ , which is related to the number of lobes. This angle  $\alpha$  can be calculated from the formula  $2\alpha = 180^\circ - 360^\circ/N$ , where  $N$  is the number of lobes. Thus, for a three-lobe form,  $\alpha$  becomes 30 degrees, and the V-block used should have a 60-degree included angle. The distance  $M$ , which is obtained by rotating the part under the comparator plunger, is converted to a value for the radial variation in cylinder contour by the formula  $M = (R - r)(1 + \csc \alpha)$ .

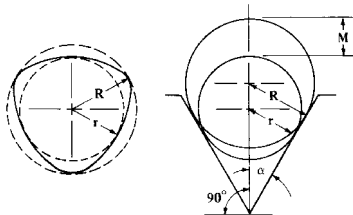


Fig. 7.

Using a V-block (even of appropriate angle) for parts with odd numbers of lobes will give exaggerated readings when the distance  $R - r$  (Fig. 7) is used as the measure of the amount of out-of-roundness. The accompanying table shows the appropriate V-block angles for various odd numbers of lobes, and the factors  $(1 + \csc \alpha)$  by which the readings are increased over the actual out-of-roundness values.

**Table of Lobes, V-block Angles and Exaggeration Factors in Measuring Out-of-round Conditions in Shafts**

| Number of Lobes | Included Angle of V-block (deg) | Exaggeration Factor<br>( $1 + \csc \alpha$ ) |
|-----------------|---------------------------------|--|
| 3               | 60                              | 3.00   |
| 5               | 108                             | 2.24   |
| 7               | 128.57                          | 2.11   |
| 9               | 140                             | 2.06   |

Measurement of a complete circumference requires special equipment, often incorporating a precision spindle running true within two millionths (0.000002) inch. A stylus attached to the spindle is caused to traverse the internal or external cylinder being inspected, and its divergences are processed electronically to produce a polar chart similar to the wavy outline in Fig. 6e. The electronic circuits provide for the variations due to surface effects to be separated from those of lobing and other departures from the "true" cylinder traced out by the spindle.

### Measurements Using Light

**Measuring by Light-wave Interference Bands.**—Surface variations as small as two millionths (0.000002) inch can be detected by light-wave interference methods, using an optical flat. An optical flat is a transparent block, usually of plate glass, clear fused quartz, or borosilicate glass, the faces of which are finished to extremely fine limits (of the order of 1 to 8 millionths [0.000001 to 0.000008] inch, depending on the application) for flatness. When an optical flat is placed on a "flat" surface, as shown in Fig. 8, any small departure from flatness will result in formation of a wedge-shaped layer of air between the work surface and the underside of the flat.

Light rays reflected from the work surface and the underside of the flat either interfere with or reinforce each other. Interference of two reflections results when the air gap measures exactly half the wavelength of the light used, and produces a dark band across the work surface when viewed perpendicularly, under monochromatic helium light. A light band is produced halfway between the dark bands when the rays reinforce each other. With the 0.0000232-inch-wavelength helium light used, the dark bands occur where the optical flat and the work surface are separated by 11.6 millionths (0.0000116) inch, or multiples thereof.

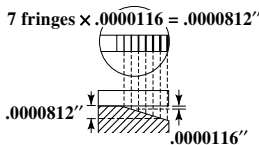


Fig. 8.

For instance, at a distance of seven dark bands from the point of contact, as shown in Fig. 8, the underface of the optical flat is separated from the work surface by a distance of  $7 \times 0.0000116$  inch or 0.0000812 inch. The bands are separated more widely and the indications become increasingly distorted as the viewing angle departs from the perpendicular. If the bands appear straight, equally spaced and parallel with each other, the work surface is flat. Convex or concave surfaces cause the bands to curve correspondingly, and a cylindrical tendency in the work surface will produce unevenly spaced, straight bands.



**SURFACE TEXTURE****American National Standard Surface Texture  
(Surface Roughness, Waviness, and Lay)**

American National Standard ANSI/ASME B46.1-1995 is concerned with the geometric irregularities of surfaces of solid materials, physical specimens for gaging roughness, and the characteristics of stylus instrumentation for measuring roughness. The standard defines surface texture and its constituents: roughness, waviness, lay, and flaws. A set of symbols for drawings, specifications, and reports is established. To ensure a uniform basis for measurements the standard also provides specifications for Precision Reference Specimens, and Roughness Comparison Specimens, and establishes requirements for stylus-type instruments. The standard is not concerned with luster, appearance, color, corrosion resistance, wear resistance, hardness, subsurface microstructure, surface integrity, and many other characteristics that may be governing considerations in specific applications.

The standard is expressed in SI metric units but U.S. customary units may be used without prejudice. The standard does not define the degrees of surface roughness and waviness or type of lay suitable for specific purposes, nor does it specify the means by which any degree of such irregularities may be obtained or produced. However, criteria for selection of surface qualities and information on instrument techniques and methods of producing, controlling and inspecting surfaces are included in Appendixes attached to the standard. The Appendix sections are not considered a part of the standard: they are included for clarification or information purposes only.

Surfaces, in general, are very complex in character. The standard deals only with the height, width, and direction of surface irregularities because these characteristics are of practical importance in specific applications. Surface texture designations as delineated in this standard may not be a sufficient index to performance. Other part characteristics such as dimensional and geometrical relationships, material, metallurgy, and stress must also be controlled.

**Definitions of Terms Relating to the Surfaces of Solid Materials.**—The terms and ratings in the standard relate to surfaces produced by such means as abrading, casting, coating, cutting, etching, plastic deformation, sintering, wear, and erosion.

*Error of form* is considered to be that deviation from the nominal surface caused by errors in machine tool ways, guides, insecure clamping or incorrect alignment of the workpiece or wear, all of which are not included in surface texture. Out-of-roundness and out-of-flatness are examples of errors of form. See ANSI/ASME B46.3.1-1988 for measurement of out-of-roundness.

*Flaws* are unintentional, unexpected, and unwanted interruptions in the topography typical of a part surface and are defined as such only when agreed upon by buyer and seller. If flaws are defined, the surface should be inspected specifically to determine whether flaws are present, and rejected or accepted prior to performing final surface roughness measurements. If defined flaws are not present, or if flaws are not defined, then interruptions in the part surface may be included in roughness measurements.

*Lay* is the direction of the predominant surface pattern, ordinarily determined by the production method used.

*Roughness* consists of the finer irregularities of the surface texture, usually including those irregularities that result from the inherent action of the production process. These irregularities are considered to include traverse feed marks and other irregularities within the limits of the roughness sampling length.

*Surface* is the boundary of an object that separates that object from another object, substance or space.

*Surface, measured* is the real surface obtained by instrumental or other means.

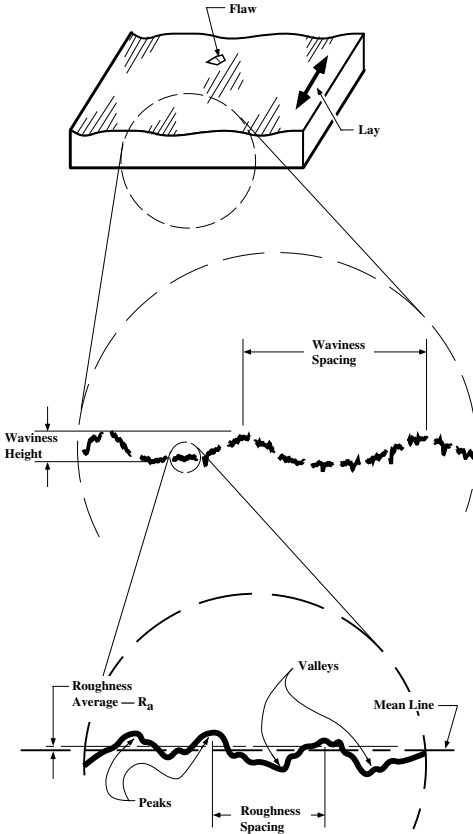


Fig. 1. Pictorial Display of Surface Characteristics

*Surface, nominal* is the intended surface contour (exclusive of any intended surface roughness), the shape and extent of which is usually shown and dimensioned on a drawing or descriptive specification.

*Surface, real* is the actual boundary of the object. Manufacturing processes determine its deviation from the nominal surface.

*Surface texture* is repetitive or random deviations from the real surface that forms the three-dimensional topography of the surface. Surface texture includes roughness, waviness, lay and flaws. Fig. 1 is an example of a unidirectional lay surface. Roughness and waviness parallel to the lay are not represented in the expanded views.

*Waviness* is the more widely spaced component of surface texture. Unless otherwise noted, waviness includes all irregularities whose spacing is greater than the roughness sampling length and less than the waviness sampling length. Waviness may result from

such factors as machine or work deflections, vibration, chatter, heat-treatment or warping strains. Roughness may be considered as being superposed on a 'wavy' surface.

**Definitions of Terms Relating to the Measurement of Surface Texture.**—Terms regarding surface texture pertain to the geometric irregularities of surfaces and include roughness, waviness and lay.

*Profile* is the contour of the surface in a plane measured normal, or perpendicular, to the surface, unless another other angle is specified.

*Graphical centerline.* See Mean Line.

*Height ( $z$ )* is considered to be those measurements of the profile in a direction normal, or perpendicular, to the nominal profile. For digital instruments, the profile  $Z(x)$  is approximated by a set of digitized values. Height parameters are expressed in micrometers ( $\mu\text{m}$ ).

*Height range ( $z$ )* is the maximum peak-to-valley surface height that can be detected accurately with the instrument. It is measurement normal, or perpendicular, to the nominal profile and is another key specification.

*Mean line ( $M$ )* is the line about which deviations are measured and is a line parallel to the general direction of the profile within the limits of the sampling length. See Fig. 2. The mean line may be determined in one of two ways. The filtered mean line is the centerline established by the selected cutoff and its associated circuitry in an electronic roughness average measuring instrument. The least squares mean line is formed by the nominal profile but by dividing into selected lengths the sum of the squares of the deviations minimizes the deviation from the nominal form. The form of the nominal profile could be a curve or a straight line.

*Peak* is the point of maximum height on that portion of a profile that lies above the mean line and between two intersections of the profile with the mean line.

*Profile measured* is a representation of the real profile obtained by instrumental or other means. When the measured profile is a graphical representation, it will usually be distorted through the use of different vertical and horizontal magnifications but shall otherwise be as faithful to the profile as technically possible.

*Profile, modified* is the measured profile where filter mechanisms (including the instrument datum) are used to minimize certain surface texture characteristics and emphasize others. Instrument users apply profile modifications typically to differentiate surface roughness from surface waviness.

*Profile, nominal* is the profile of the nominal surface; it is the intended profile (exclusive of any intended roughness profile). Profile is usually drawn in an x-z coordinate system. See Fig. 2.

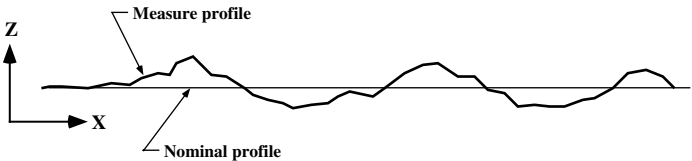


Fig. 2. Nominal and Measured Profiles

*Profile, real* is the profile of the real surface.

*Profile, total* is the measured profile where the heights and spacing may be amplified differently but otherwise no filtering takes place.

*Roughness profile* is obtained by filtering out the longer wavelengths characteristic of waviness.

*Roughness spacing* is the average spacing between adjacent peaks of the measured profile within the roughness sampling length.

*Roughness topography* is the modified topography obtained by filtering out the longer wavelengths of waviness and form error.

*Sampling length* is the nominal spacing within which a surface characteristic is determined. The range of sampling lengths is a key specification of a measuring instrument.

*Spacing* is the distance between specified points on the profile measured parallel to the nominal profile.

*Spatial ( $x$ ) resolution* is the smallest wavelength which can be resolved to 50% of the actual amplitude. This also is a key specification of a measuring instrument.

*System height resolution* is the minimum height that can be distinguished from background noise of the measurement instrument. Background noise values can be determined by measuring approximate rms roughness of a sample surface where actual roughness is significantly less than the background noise of the measuring instrument. It is a key instrumentation specification.

*Topography* is the three-dimensional representation of geometric surface irregularities.

*Topography, measured* is the three-dimensional representation of geometric surface irregularities obtained by measurement.

*Topography, modified* is the three-dimensional representation of geometric surface irregularities obtained by measurement but filtered to minimize certain surface characteristics and accentuate others.

*Valley* is the point of maximum depth on that portion of a profile that lies below the mean line and between two intersections of the profile with the mean line.

*Waviness, evaluation length ( $L$ )*, is the length within which waviness parameters are determined.

*Waviness, long-wavelength cutoff ( $lcw$ )* the spatial wavelength above which the undulations of waviness profile are removed to identify form parameters. A digital Gaussian filter can be used to separate form error from waviness but its use must be specified.

*Waviness profile* is obtained by filtering out the shorter roughness wavelengths characteristic of roughness and the longer wavelengths associated with the part form parameters.

*Waviness sampling length* is a concept no longer used. See waviness long-wavelength cutoff and waviness evaluation length.

*Waviness short-wavelength cutoff ( $lsw$ )* is the spatial wavelength below which roughness parameters are removed by electrical or digital filters.

*Waviness topography* is the modified topography obtained by filtering out the shorter wavelengths of roughness and the longer wavelengths associated with form error.

*Waviness spacing* is the average spacing between adjacent peaks of the measured profile within the waviness sampling length.

**Sampling Lengths.**—Sampling length is the normal interval for a single value of a surface parameter. Generally it is the longest spatial wavelength to be included in the profile measurement. Range of sampling lengths is an important specification for a measuring instrument.

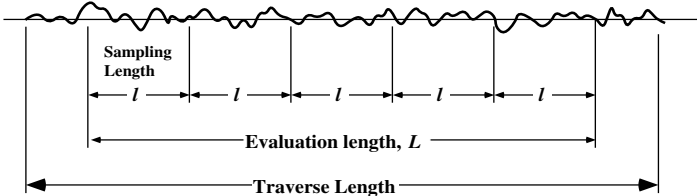


Fig. 3. Traverse Length

*Roughness sampling length ( $l$ )* is the sampling length within which the roughness average is determined. This length is chosen to separate the profile irregularities which are des-

ignated as roughness from those irregularities designated as waviness. It is different from evaluation length ( $L$ ) and the traversing length. See Fig. 3.

*Evaluation length ( $L$ )* is the length the surface characteristics are evaluated. The evaluation length is a key specification of a measuring instrument.

*Traversing length* is profile length traversed to establish a representative evaluation length. It is always longer than the evaluation length. See Section 4.4.4 of ANSI/ASME B46.1-1995 for values which should be used for different type measurements.

*Cutoff* is the electrical response characteristic of the measuring instrument which is selected to limit the spacing of the surface irregularities to be included in the assessment of surface texture. Cutoff is rated in millimeters. In most electrical averaging instruments, the cutoff can be user selected and is a characteristic of the instrument rather than of the surface being measured. In specifying the cutoff, care must be taken to choose a value which will include all the surface irregularities to be assessed.

*Waviness sampling length ( $l$ )* is a concept no longer used. See waviness long-wavelength cutoff and waviness evaluation length.

**Roughness Parameters.**—Roughness is the fine irregularities of the surface texture resulting from the production process or material condition.

*Roughness average ( $R_a$ )*, also known as arithmetic average (AA) is the arithmetic average of the absolute values of the measured profile height deviations divided by the evaluation length,  $L$ . This is shown as the shaded area of Fig. 4 and generally includes sampling lengths or cutoffs. For graphical determinations of roughness average, the height deviations are measured normal, or perpendicular, to the chart center line.

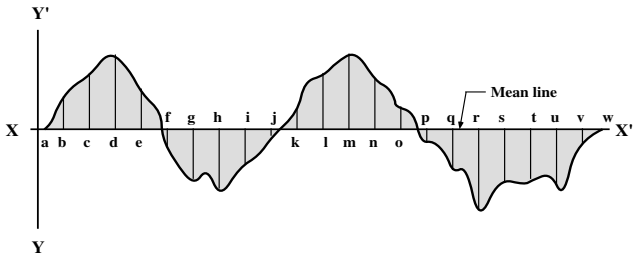


Fig. 4.

Roughness average is expressed in micrometers ( $\mu\text{m}$ ). A micrometer is one millionth of a meter (0.000001 meter). A microinch ( $\mu\text{in}$ ) is one millionth of an inch (0.000001 inch). One microinch equals 0.0254 micrometer ( $1 \mu\text{in} = 0.0254 \mu\text{m}$ ).

*Roughness Average Value ( $R_a$ ) From Continuously Averaging Meter Reading* may be made of readings from stylus-type instruments of the continuously averaging type. To ensure uniform interpretation, it should be understood that the reading that is considered significant is the mean reading around which the needle tends to dwell or fluctuate with a small amplitude.

Roughness is also indicated by the root-mean-square (rms) average, which is the square root of the average value squared, within the evaluation length and measured from the mean line shown in Fig. 4, expressed in micrometers. A roughness-measuring instrument calibrated for rms average usually reads about 11 per cent higher than an instrument calibrated for arithmetical average. Such instruments usually can be recalibrated to read arithmetical average. Some manufacturers consider the difference between rms and AA to be small enough that rms on a drawing may be read as AA for many purposes.

*Roughness evaluation length ( $L$ )*, for statistical purposes should, whenever possible, consist of five sampling lengths ( $l$ ). Use of other than five sampling lengths must be clearly indicated.

**Waviness Parameters.**—Waviness is the more widely spaced component of surface texture. Roughness may be thought of as superimposed on waviness.

*Waviness height* ( $Wt$ ) is the peak-to-valley height of the modified profile with roughness and part form errors removed by filtering, smoothing or other means. This value is typically three or more times the roughness average. The measurement is taken normal, or perpendicular, to the nominal profile within the limits of the waviness sampling length.

*Waviness evaluation length* ( $Lw$ ) is the evaluation length required to determine waviness parameters. For waviness, the sampling length concept is no longer used. Rather, only waviness evaluation length ( $Lw$ ) and waviness long-wavelength cutoff ( $lew$ ) are defined. For better statistics, the waviness evaluation length should be several times the waviness long-wavelength cutoff.

**Relation of Surface Roughness to Tolerances.**—Because the measurement of surface roughness involves the determination of the average linear deviation of the measured surface from the nominal surface, there is a direct relationship between the dimensional tolerance on a part and the permissible surface roughness. It is evident that a requirement for the accurate measurement of a dimension is that the variations introduced by surface roughness should not exceed the dimensional tolerances. If this is not the case, the measurement of the dimension will be subject to an uncertainty greater than the required tolerance, as illustrated in Fig. 5.

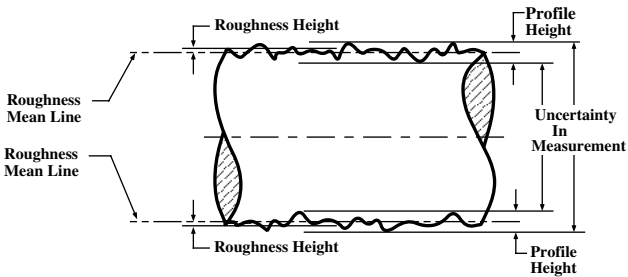


Fig. 5.

The standard method of measuring surface roughness involves the determination of the average deviation from the mean surface. On most surfaces the total profile height of the surface roughness (peak-to-valley height) will be approximately four times ( $4\times$ ) the measured average surface roughness. This factor will vary somewhat with the character of the surface under consideration, but the value of four may be used to establish approximate profile heights.

From these considerations it follows that if the arithmetical average value of surface roughness specified on a part exceeds one eighth of the dimensional tolerance, the whole tolerance will be taken up by the roughness height. In most cases, a smaller roughness specification than this will be found; but on parts where very small dimensional tolerances are given, it is necessary to specify a suitably small surface roughness so useful dimensional measurements can be made. The tables on pages 652 and 679 show the relations between machining processes and working tolerances.

Values for surface roughness produced by common processing methods are shown in Table 1. The ability of a processing operation to produce a specific surface roughness depends on many factors. For example, in surface grinding, the final surface depends on the peripheral speed of the wheel, the speed of the traverse, the rate of feed, the grit size, bonding material and state of dress of the wheel, the amount and type of lubrication at the

**Table 1. Surface Roughness Produced by Common Production Methods**

| Process                | Roughness Average, $R_a$ – Micrometers $\mu\text{m}$ (Microinches $\mu\text{in.}$ ) |              |               |              |              |             |              |              |             |             |             |              |                |
|------------------------|---|--------------|---------------|--------------|--------------|-------------|--------------|--------------|-------------|-------------|-------------|--------------|----------------|
|                        | 50<br>(2000)  | 25<br>(1000) | 12.5<br>(500) | 6.3<br>(250) | 3.2<br>(125) | 1.6<br>(63) | 0.80<br>(32) | 0.40<br>(16) | 0.20<br>(8) | 0.10<br>(4) | 0.05<br>(2) | 0.025<br>(1) | 0.012<br>(0.5) |
| Flame Cutting          |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Snagging               |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Sawing                 |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Planing, Shaping       |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Drilling               |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Chemical Milling       |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Elect. Discharge Mach. |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Milling                |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Broaching              |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Reaming                |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Electron Beam          |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Laser                  |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Electro-Chemical       |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Boring, Turning        |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Barrel Finishing       |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Electrolytic Grinding  |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Roller Burnishing      |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Grinding               |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Honing                 |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Electro-Polish         |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Polishing              |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Lapping                |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Superfinishing         |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Sand Casting           |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Hot Rolling            |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Forging                |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Perm. Mold Casting     |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Investment Casting     |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Extruding              |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Cold Rolling, Drawing  |   |              |               |              |              |             |              |              |             |             |             |              |                |
| Die Casting            |   |              |               |              |              |             |              |              |             |             |             |              |                |

The ranges shown above are typical of the processes listed  
 Higher or lower values may be obtained under special conditions

KEY  Average Application  
 Less Frequent Application

point of cutting, and the mechanical properties of the piece being ground. A small change in any of the above factors can have a marked effect on the surface produced.

**Instrumentation for Surface Texture Measurement.**—Instrumentation used for measurement of surface texture, including roughness and waviness generally falls into six types. These include:

*Type I, Profiling Contact Skidless Instruments:* Used for very smooth to very rough surfaces. Used for roughness and may measure waviness. Can generate filtered or unfiltered profiles and may have a selection of filters and parameters for data analysis. Examples include: 1) skidless stylus-type with LVDT (linear variable differential transformer) vertical transducers; 2) skidless-type using an interferometric transducer; 3) skidless stylus-type using capacitance transducer.

*Type II, Profiling Non-contact Instruments:* Capable of full profiling or topographical analysis. Non-contact operation may be advantageous for softness but may vary with sample type and reflectivity. Can generate filtered or unfiltered profiles but may have difficulty with steeply inclined surfaces. Examples include: 1) interferometric microscope; 2) optical focus sensing; 3) Nomarski differential profiling; 4) laser triangulation; 5) scanning electron microscope (SEM) stereoscopy; 6) confocal optical microscope.

*Type III, Scanned Probe Microscope:* Feature high spatial resolution (at or near the atomic scale) but area of measurement may be limited. Examples include: 1) scanning tunneling microscope (STM) and 2) atomic force microscope (AFM).

*Type IV, Profiling Contact Skidded Instruments:* Uses a skid as a datum to eliminate longer wavelengths; thus cannot be used for waviness or errors of form. May have a selection of filters and parameters and generates an output recording of filtered and skid-modified profiles. Examples include: 1) skidded, stylus-type with LVDT vertical measuring transducer and 2) fringe-field capacitance (FFC) transducer.

*Type V, Skidded Instruments with Parameters Only:* Uses a skid as a datum to eliminate longer wavelengths; thus cannot be used for waviness or errors of form. Does not generate a profile. Filters are typically 2RC type and generate Ra but other parameters may be available. Examples include: 1) skidded, stylus-type with piezoelectric measuring transducer and 2) skidded, stylus-type with moving coil measuring transducer.

*Type VI, Area Averaging Methods:* Used to measure averaged parameters over defined areas but do not generate profiles. Examples include: 1) parallel plate capacitance (PPC) method; 2) total integrated scatter (TIS); 3) angle resolved scatter (ARS)/bi-directional reflectance distribution function (BRDF).

**Selecting Cutoff for Roughness Measurements.**—In general, surfaces will contain irregularities with a large range of widths. Surface texture instruments are designed to respond only to irregularity spacings less than a given value, called cutoff. In some cases, such as surfaces in which actual contact area with a mating surface is important, the largest convenient cutoff will be used. In other cases, such as surfaces subject to fatigue failure only the irregularities of small width will be important, and more significant values will be obtained when a short cutoff is used. In still other cases, such as identifying chatter marks on machined surfaces, information is needed on only the widely spaced irregularities. For such measurements, a large cutoff value and a larger radius stylus should be used.

The effect of variation in cutoff can be understood better by reference to Fig. 6. The profile at the top is the true movement of a stylus on a surface having a roughness spacing of about 1 mm and the profiles below are interpretations of the same surface with cutoff value settings of 0.8 mm, 0.25 mm and 0.08 mm, respectively. It can be seen that the trace based on 0.8 mm cutoff includes most of the coarse irregularities and all of the fine irregularities of the surface. The trace based on 0.25 mm excludes the coarser irregularities but includes the fine and medium fine. The trace based on 0.08 mm cutoff includes only the very fine irregularities. In this example the effect of reducing the cutoff has been to reduce the roughness average indication. However, had the surface been made up only of irregularities as fine as those of the bottom trace, the roughness average values would have been the same for all three cutoff settings.

In other words, all irregularities having a spacing less than the value of the cutoff used are included in a measurement. Obviously, if the cutoff value is too small to include coarser irregularities of a surface, the measurements will not agree with those taken with a larger cutoff. For this reason, care must be taken to choose a cutoff value which will include all of the surface irregularities it is desired to assess.

To become proficient in the use of continuously averaging stylus-type instruments the inspector or machine operator must realize that for uniform interpretation, the reading which is considered significant is the mean reading around which the needle tends to dwell or fluctuate under small amplitude.

**Drawing Practices for Surface Texture Symbols.**—American National Standard ANSI/ASME Y14.36M-1996 establishes the method to designate symbolic controls for surface texture of solid materials. It includes methods for controlling roughness, waviness, and lay, and provides a set of symbols for use on drawings, specifications, or other documents. The standard is expressed in SI metric units but U.S. customary units may be used without prejudice. Units used (metric or non-metric) should be consistent with the other units used on the drawing or documents. Approximate non-metric equivalents are shown for reference.



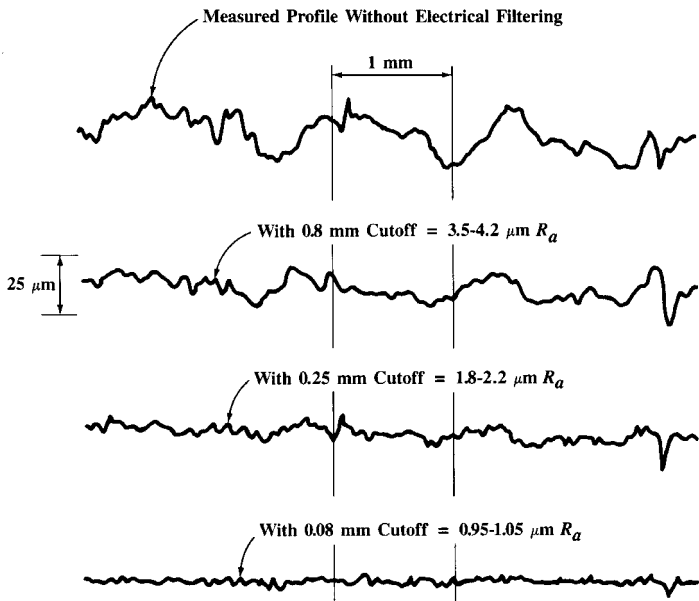


Fig. 6. Effects of Various Cutoff Values






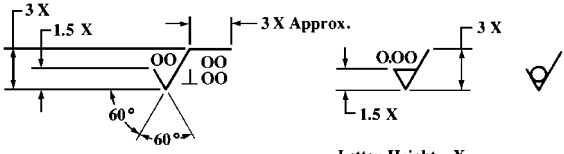
**Surface Texture Symbol.**—The symbol used to designate control of surface irregularities is shown in Fig. 7b and Fig. 7d. Where surface texture values other than roughness average are specified, the symbol must be drawn with the horizontal extension as shown in Fig. 7f.

*Use of Surface Texture Symbols:* When required from a functional standpoint, the desired surface characteristics should be specified. Where no surface texture control is specified, the surface produced by normal manufacturing methods is satisfactory provided it is within the limits of size (and form) specified in accordance with ANSI/ASME Y14.5M-1994, Dimensioning and Tolerancing. It is considered good practice to always specify some maximum value, either specifically or by default (for example, in the manner of the note shown in Fig. 2).

*Material Removal Required or Prohibited:* The surface texture symbol is modified when necessary to require or prohibit removal of material. When it is necessary to indicate that a surface must be produced by removal of material by machining, specify the symbol shown in Fig. 7b. When required, the amount of material to be removed is specified as shown in Fig. 7c, in millimeters for metric drawings and in inches for non-metric drawings. Tolerance for material removal may be added to the basic value shown or specified in a general note. When it is necessary to indicate that a surface must be produced without material removal, specify the machining prohibited symbol as shown in Fig. 7d.

*Proportions of Surface Texture Symbols:* The recommended proportions for drawing the surface texture symbol are shown in Fig. 7f. The letter height and line width should be the same as that for dimensions and dimension lines.

## Surface Texture Symbols and Construction

| Symbol  | Meaning  |
|---|--|
| <br>Fig. 7a.                                 | Basic Surface Texture Symbol. Surface may be produced by any method except when the bar or circle (Fig. 7b or 7d) is specified.  |
| <br>Fig. 7b.                                 | Material Removal By Machining Is Required. The horizontal bar indicates that material removal by machining is required to produce the surface and that material must be provided for that purpose.   |
| <br>Fig. 7c.                                 | Material Removal Allowance. The number indicates the amount of stock to be removed by machining in millimeters (or inches). Tolerances may be added to the basic value shown or in general note.   |
| <br>Fig. 7d.                                 | Material Removal Prohibited. The circle in the vee indicates that the surface must be produced by processes such as casting, forging, hot finishing, cold finishing, die casting, powder metallurgy or injection molding without subsequent removal of material. |
| <br>Fig. 7e.                                 | Surface Texture Symbol. To be used when any surface characteristics are specified above the horizontal line or the right of the symbol. Surface may be produced by any method except when the bar or circle (Fig. 7b and 7d) is specified.                       |
|  <p style="text-align: center;">Fig. 7f.</p> |  |

**Applying Surface Texture Symbols.**—The point of the symbol should be on a line representing the surface, an extension line of the surface, or a leader line directed to the surface, or to an extension line. The symbol may be specified following a diameter dimension. Although ANSI/ASME Y14.5M-1994, “Dimensioning and Tolerancing” specifies that normally all textual dimensions and notes should be read from the bottom of the drawing, the surface texture symbol itself with its textual values may be rotated as required. Regardless, the long leg (and extension) must be to the right as the symbol is read. For parts requiring extensive and uniform surface roughness control, a general note may be added to the drawing which applies to each surface texture symbol specified without values as shown in Fig. 8.

When the symbol is used with a dimension, it affects the entire surface defined by the dimension. Areas of transition, such as chamfers and fillets, shall conform with the roughest adjacent finished area unless otherwise indicated.

Surface texture values, unless otherwise specified, apply to the complete surface. Drawings or specifications for plated or coated parts shall indicate whether the surface texture values apply before plating, after plating, or both before and after plating.

Only those values required to specify and verify the required texture characteristics should be included in the symbol. Values should be in metric units for metric drawing and non-metric units for non-metric drawings. Minority units on dual dimensioned drawings are enclosed in brackets.

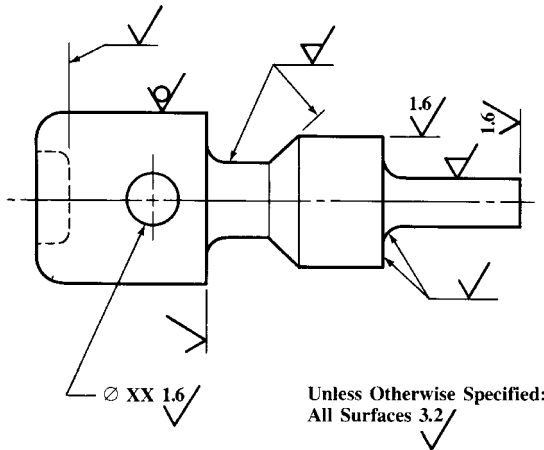


Fig. 8. Application of Surface Texture Symbols

Roughness and waviness measurements, unless otherwise specified, apply in a direction which gives the maximum reading; generally across the lay.

*Cutoff or Roughness Sampling Length, (l):* Standard values are listed in Table 2. When no value is specified, the value 0.8 mm (0.030 in.) applies.

**Table 2. Standard Roughness Sampling Length (Cutoff) Values**

| mm   | in.   | mm   | in. |
|------|-------|------|-----|
| 0.08 | 0.003 | 2.5  | 0.1 |
| 0.25 | 0.010 | 8.0  | 0.3 |
| 0.80 | 0.030 | 25.0 | 1.0 |

*Roughness Average (Ra):* The preferred series of specified roughness average values is given in Table 3.

**Table 3. Preferred Series Roughness Average Values (R<sub>a</sub>)**

| μm                 | μin            | μm                | μin              | μm                | μin               |
|--------------------|----------------|-------------------|------------------|-------------------|-------------------|
| 0.012              | 0.5            | 0.40 <sup>a</sup> | 16 <sup>a</sup>  | 4.0               | 160               |
| 0.025 <sup>a</sup> | 1 <sup>a</sup> | 0.50              | 20               | 5.0               | 200               |
| 0.050 <sup>a</sup> | 2 <sup>a</sup> | 0.63              | 25               | 6.3 <sup>a</sup>  | 250 <sup>a</sup>  |
| 0.075 <sup>a</sup> | 3              | 0.80 <sup>a</sup> | 32 <sup>a</sup>  | 8.0               | 320               |
| 0.10 <sup>a</sup>  | 4 <sup>a</sup> | 1.00              | 40               | 10.0              | 400               |
| 0.125              | 5              | 1.25              | 50               | 12.5 <sup>a</sup> | 500 <sup>a</sup>  |
| 0.15               | 6              | 1.60 <sup>a</sup> | 63 <sup>a</sup>  | 15                | 600               |
| 0.20 <sup>a</sup>  | 8 <sup>a</sup> | 2.0               | 80               | 20                | 800               |
| 0.25               | 10             | 2.5               | 100              | 25 <sup>a</sup>   | 1000 <sup>a</sup> |
| 0.32               | 13             | 3.2 <sup>a</sup>  | 125 <sup>a</sup> | ...               | ...               |

<sup>a</sup>Recommended

*Waviness Height (Wt):* The preferred series of maximum waviness height values is listed in Table 3. Waviness height is not currently shown in U.S. or ISO Standards. It is included here to follow present industry practice in the United States.

**Table 4. Preferred Series Maximum Waviness Height Values**

| mm     | in.     | mm    | in.    | mm   | in.   |
|--------|---------|-------|--------|------|-------|
| 0.0005 | 0.00002 | 0.008 | 0.0003 | 0.12 | 0.005 |
| 0.0008 | 0.00003 | 0.012 | 0.0005 | 0.20 | 0.008 |
| 0.0012 | 0.00005 | 0.020 | 0.0008 | 0.25 | 0.010 |
| 0.0020 | 0.00008 | 0.025 | 0.001  | 0.38 | 0.015 |
| 0.0025 | 0.0001  | 0.05  | 0.002  | 0.50 | 0.020 |
| 0.005  | 0.0002  | 0.08  | 0.003  | 0.80 | 0.030 |

*Lay:* Symbols for designating the direction of lay are shown and interpreted in Table 5.

**Example Designations.**—Table 6 illustrates examples of designations of roughness, waviness, and lay by insertion of values in appropriate positions relative to the symbol.

Where surface roughness control of several operations is required within a given area, or on a given surface, surface qualities may be designated, as in Fig. 9a. If a surface must be produced by one particular process or a series of processes, they should be specified as shown in Fig. 9b. Where special requirements are needed on a designated surface, a note should be added at the symbol giving the requirements and the area involved. An example is illustrated in Fig. 9c.

**Surface Texture of Castings.**—Surface characteristics should not be controlled on a drawing or specification unless such control is essential to functional performance or appearance of the product. Imposition of such restrictions when unnecessary may increase production costs and in any event will serve to lessen the emphasis on the control specified for important surfaces. Surface characteristics of castings should never be considered on the same basis as machined surfaces. Castings are characterized by random distribution of non-directional deviations from the nominal surface.

Surfaces of castings rarely need control beyond that provided by the production method necessary to meet dimensional requirements. Comparison specimens are frequently used for evaluating surfaces having specific functional requirements. Surface texture control should not be specified unless required for appearance or function of the surface. Specification of such requirements may increase cost to the user.

Engineers should recognize that different areas of the same castings may have different surface textures. It is recommended that specifications of the surface be limited to defined areas of the casting. Practicality of and methods of determining that a casting's surface texture meets the specification shall be coordinated with the producer. The Society of Automotive Engineers standard J435 "Automotive Steel Castings" describes methods of evaluating steel casting surface texture used in the automotive and related industries.

**Metric Dimensions on Drawings.**—The length units of the metric system that are most generally used in connection with any work relating to mechanical engineering are the meter (39.37 inches) and the millimeter (0.03937 inch). One meter equals 1000 millimeters. On mechanical drawings, all dimensions are generally given in millimeters, no matter how large the dimensions may be. In fact, dimensions of such machines as locomotives and large electrical apparatus are given exclusively in millimeters. This practice is adopted to avoid mistakes due to misplacing decimal points, or misreading dimensions as when other units are used as well. When dimensions are given in millimeters, many of them can be given without resorting to decimal points, as a millimeter is only a little more than  $\frac{1}{32}$  inch. Only dimensions of precision need be given in decimals of a millimeter; such dimensions are generally given in hundredths of a millimeter—for example, 0.02 millimeter,

## SURFACE TEXTURE





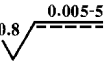



Table 5. Lay Symbols

| Lay Symbol | Meaning  | Example Showing Direction of Tool Marks |
|------------|--|---|
| =          | Lay approximately parallel to the line representing the surface to which the symbol is applied.      |   |
| ⊥          | Lay approximately perpendicular to the line representing the surface to which the symbol is applied. |   |
| X          | Lay angular in both directions to line representing the surface to which the symbol is applied.      |   |
| M          | Lay multidirectional   |   |
| C          | Lay approximately circular relative to the center of the surface to which the symbol is applied.     |   |
| R          | Lay approximately radial relative to the center of the surface to which the symbol is applied.       |   |
| P          | Lay particulate, non-directional, or protuberant   |   |

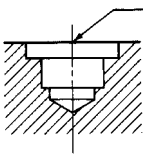


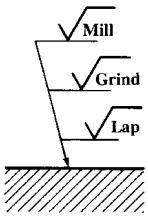
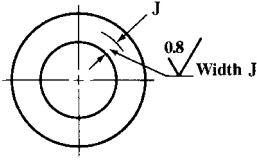
which is equal to 0.0008 inch. As 0.01 millimeter is equal to 0.0004 inch, dimensions are seldom given with greater accuracy than to hundredths of a millimeter.

*Scales of Metric Drawings:* Drawings made to the metric system are not made to scales of  $\frac{1}{2}$ ,  $\frac{1}{4}$ ,  $\frac{1}{8}$ , etc., as with drawings made to the English system. If the object cannot be drawn full size, it may be drawn  $\frac{1}{2}$ ,  $\frac{1}{5}$ ,  $\frac{1}{10}$ ,  $\frac{1}{20}$ ,  $\frac{1}{50}$ ,  $\frac{1}{100}$ ,  $\frac{1}{200}$ ,  $\frac{1}{500}$ , or  $\frac{1}{1000}$  size. If the object is too small and has to be drawn larger, it is drawn 2, 5, or 10 times its actual size.

**Table 6. Application of Surface Texture Values to Symbol**

|   |   |
|---|---|
|  <p>Roughness average rating is placed at the left of the long leg. The specification of only one rating shall indicate the maximum value and any lesser value shall be acceptable. Specify in micrometers (microinch).</p>  |  <p>Material removal by machining is required to produce the surface. The basic amount of stock provided for material removal is specified at the left of the short leg of the symbol. Specify in millimeters (inch).</p>  |
|  <p>The specification of maximum and minimum roughness average values indicates permissible range of roughness. Specify in micrometers (microinch).</p>  |  <p>Removal of material is prohibited.</p>   |
|  <p>Maximum waviness height rating is the first rating placed above the horizontal extension. Any lesser rating shall be acceptable. Specify in millimeters (inch).</p> <p>Maximum waviness spacing rating is the second rating placed above the horizontal extension and to the right of the waviness height rating. Any lesser rating shall be acceptable. Specify in millimeters (inch).</p> |  <p>Lay designation is indicated by the lay symbol placed at the right of the long leg.</p>  <p>Roughness sampling length or cutoff rating is placed below the horizontal extension. When no value is shown, 0.80 mm (0.030 inch) applies. Specify in millimeters (inch).</p>  <p>Where required maximum roughness spacing shall be placed at the right of the lay symbol. Any lesser rating shall be acceptable. Specify in millimeters (inch).</p> |

**Table 7. Examples of Special Designations**

|   |   |
|---|---|
|    | <p> <math>\varnothing</math> XX.XX <math>\pm</math> X.XX<br/> <math>\varnothing</math> XX.XX <math>\pm</math> X.XX <br/> <math>\varnothing</math> XX.XX <math>\pm</math> X.XX  </p> |
| <p>Fig. 9a.</p>   |   |
|  <p style="text-align: center;">Fig. 9b.</p> |  <p style="text-align: center;">Fig. 9c.</p>   |

### ISO Surface Finish

**Differences Between ISO and ANSI Surface Finish Symbology.**—ISO surface finish standards are comprised of numerous individual standards that taken as a whole form a set of standards roughly comparable in scope to American National Standard ANSI/ASME Y14.36M.

The primary standard dealing with surface finish, ISO 1302:1992, is concerned with the methods of specifying surface texture symbology and additional indications on engineering drawings. The parameters in ISO surface finish standards relate to surfaces produced by abrading, casting, coating, cutting, etching, plastic deformation, sintering, wear, erosion, and some other methods.

ISO 1302 defines how surface texture and its constituents, roughness, waviness, and lay, are specified on the symbology. Surface defects are specifically excluded from consideration during inspection of surface texture, but definitions of flaws and imperfections are discussed in ISO 8785.

As with American National Standard ASME Y14.36M, ISO 1302 is not concerned with luster, appearance, color, corrosion resistance, wear resistance, hardness, sub-surface microstructure, surface integrity, and many other characteristics that may govern considerations in specific applications. Visually, the ISO surface finish symbol is similar to the ANSI symbol, but the proportions of the symbol in relationship to text height differs from ANSI, as do some of the parameters as described in Fig. 10. Examples of the application of the ISO surface finish symbol are illustrated in Table 10.

The ISO 1302 standard does not define the degrees of surface roughness and waviness or type of lay for specific purposes, nor does it specify the means by which any degree of such irregularities may be obtained or produced. Also, errors of form such as out-of-roundness and out-of-flatness are not addressed in the ISO surface finish standards.

#### Other ISO Standards Related To Surface Finish

|                |   |
|----------------|---|
| ISO 468:1982   | “Surface roughness — parameters. Their values and general rules for specifying requirements.”   |
| ISO 4287:1997  | “Surface texture: Profile method — Terms, definitions and surface texture parameters.”  |
| ISO 4288:1996  | “Surface texture: Profile method — Rules and procedures for the assessment of surface texture.” Includes specifications for precision reference specimens, and roughness comparison specimens, and establishes requirements for stylus-type instruments.” |
| ISO 8785:1998  | “Surface imperfections — Terms, definitions and parameters.”  |
| ISO 10135-1:CD | “Representation of parts produced by shaping processes — Part 1: Molded parts.”   |

**Rules for Comparing Measured Values to Specified Limits.**—*Max rule:* When a maximum requirement is specified for a surface finish parameter on a drawing (e.g.  $Rz1.5_{max}$ ), none of the inspected values may extend beyond the upper limit over the entire surface. MAX must be added to the parametric symbol in the surface finish symbology on the drawing.

*16% rule:* When upper and lower limits are specified, no more than 16% of all measured values of the selected parameter within the evaluation length may exceed the upper limit. No more than 16% of all measured values of the selected parameter within the evaluation length may be less than the lower limit.

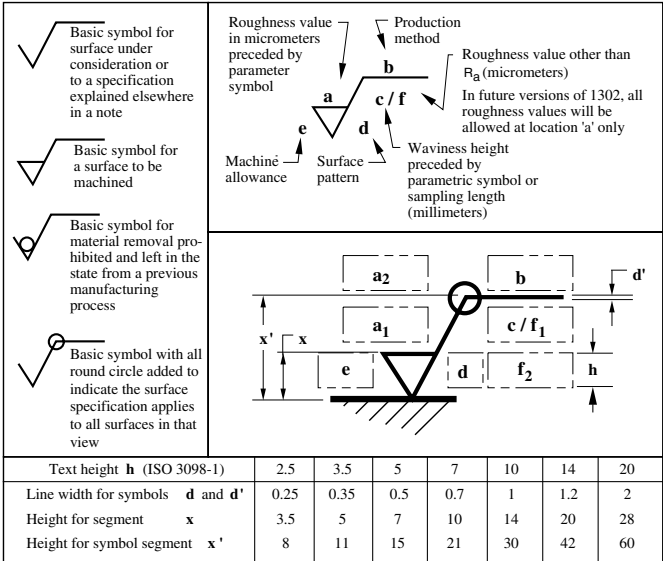


Fig. 10. ISO Surface Finish Symbol

**ISO Surface Parameter Symbols**

|   |   |
|---|---|
| $R_p$ = max height profile                        | $R\delta c$ = profile section height difference |
| $R_v$ = max profile valley depth                  | $l_p$ = sampling length – primary profile       |
| $Rz^*$ = max height of the profile                | $l_w$ = sampling length – waviness profile      |
| $R_c$ = mean height of profile                    | $l_r$ = sampling length – roughness profile     |
| $R_t$ = total height of the profile               | $l_n$ = evaluation length                       |
| $R_a$ = arithmetic mean deviation of the profile  | $Z(x)$ = ordinate value                         |
| $R_q$ = root mean square deviation of the profile | $dZ/dX$ = local slope                           |
| $Rsk$ = skewness of the profile                   | $Z_p$ = profile peak height                     |
| $Rku$ = kurtosis of the profile                   | $Z_v$ = profile valley depth                    |
| $RSm$ = mean width of the profile                 | $Z_r$ = profile element height                  |
| $RDq$ = root mean square slope of the profile     | $X_s$ = profile element width                   |
| $Rmr$ = material ration of the profile            | $MI$ = material length of profile               |

**Exceptions to the 16% rule:** Where the measured values of roughness profiles being inspected follow a normal distribution, the 16% rule may be overridden. This is allowed when greater than 16% of the measured values exceed the upper limit, but the total roughness profile conforms with the sum of the arithmetic mean and standard deviation ( $\mu + \sigma$ ). Effectively this means that the greater the value of  $\sigma$ , the further  $\mu$  must be from the upper limit (see Fig. 11).

**Basic rules for determining cut-off wavelength:** When the sampling length is specified on the drawing or in documentation, the cut-off wavelength  $\lambda_c$  is equal to the sample length. When no sampling length is specified, the cut-off wavelength is estimated using Table 8.



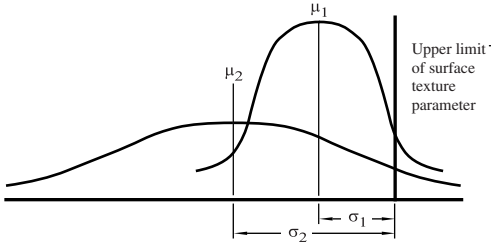


Fig. 11.

**Basic rules for measurement of roughness parameters:** For non-periodic roughness the parameter  $Ra$ ,  $Rz$ ,  $RzI_{max}$  or  $RSm$  are first estimated using visual inspection, comparison to specimens, graphic analysis, etc. The sampling length is then selected from Table 8, based on the use of  $Ra$ ,  $Rz$ ,  $RzI_{max}$  or  $RSm$ . Then with instrumentation, a representative sample is taken using the sampling length chosen above.

**Table 8. Sampling Lengths**

| Curves for Non-periodic Profiles<br>such as Ground Surfaces |                                      | Curves for Periodic and<br>Non-periodic Profiles | Sampling length,<br>$l_r$ (mm) | Evaluation length,<br>$l_n$ (mm) |
|---|--------------------------------------|--|--------------------------------|----------------------------------|
| For $Ra$ , $Rq$ , $Rsk$ , $Rku$ , $R\Delta q$               | For $Rz$ , $Rv$ , $Rp$ , $Rc$ , $Rt$ | For $R$ -parameters and $RSm$                    |                                |                                  |
| $Ra$ , $\mu m$  | $Rz$ , $RzI_{max}$ , $\mu m$         | $RSm$ , $\mu m$                                  |                                |                                  |
| $(0.006) < Ra \leq 0.02$                                    | $(0.025) < Rz, RzI_{max} \leq 0.1$   | $0.013 < RSm \leq 0.04$                          | 0.08                           | 0.4                              |
| $0.02 < Ra \leq 0.1$  | $0.1 < Rz, RzI_{max} \leq 0.5$       | $0.04 < RSm \leq 0.13$                           | 0.25                           | 1.25                             |
| $0.1 < Ra \leq 2$   | $0.5 < Rz, RzI_{max} \leq 10$        | $0.13 < RSm \leq 0.4$                            | 0.8                            | 4                                |
| $2 < Ra \leq 10$  | $10 < Rz, RzI_{max} \leq 50$         | $0.4 < RSm \leq 1.3$                             | 2.5                            | 12.5                             |
| $10 < Ra \leq 80$   | $50 < Rz, RzI_{max} \leq 200$        | $1.3 < RSm \leq 4$                               | 8                              | 40                               |

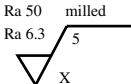
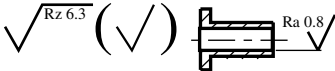
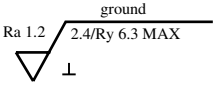
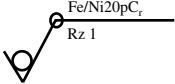
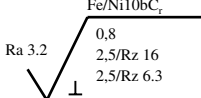
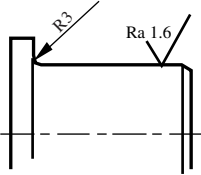
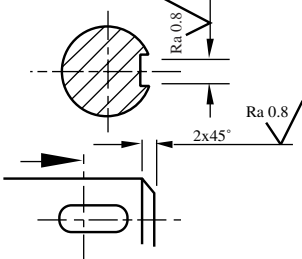
The measured values are then compared to the ranges of values in Table 8 for the particular parameter. If the value is outside the range of values for the estimated sampling length, the measuring instrument is adjusted for the next higher or lower sampling length and the measurement repeated. If the final setting corresponds to Table 8, then both the sampling length setting and  $Ra$ ,  $Rz$ ,  $RzI_{max}$  or  $RSm$  values are correct and a representative measurement of the parameter can be taken.

For periodic roughness, the parameter  $RSm$  is estimated graphically and the recommended cut-off values selected using Table 8. If the value is outside the range of values for the estimated sampling length, the measuring instrument is adjusted for the next higher or lower sampling length and the measurement repeated. If the final setting corresponds to Table 8, then both the sampling length setting and  $RSm$  values are correct and a representative measurement of the parameter can be taken.

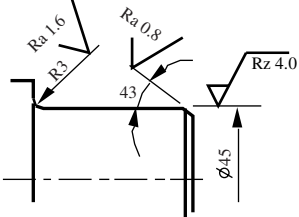
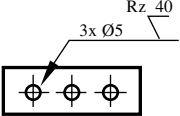
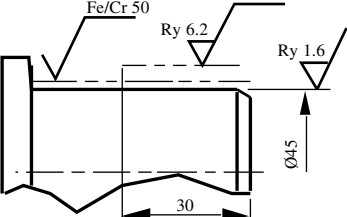
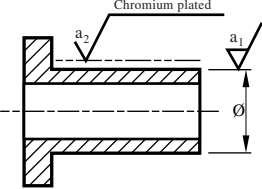
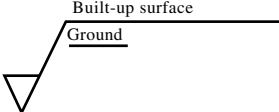
**Table 9. Preferred Roughness Values and Roughness Grades**

| Roughness values, $Ra$ |          | Previous Grade Number<br>from ISO 1302 | Roughness values, $Ra$ |          | Previous Grade Number<br>from ISO 1302 |
|------------------------|----------|--|------------------------|----------|--|
| $\mu m$                | $\mu in$ |  | $\mu m$                | $\mu in$ |  |
| 50                     | 2000     | N12                                    | 0.8                    | 32       | N6                                     |
| 25                     | 1000     | N11                                    | 0.4                    | 16       | N5                                     |
| 12.5                   | 500      | N10                                    | 0.2                    | 8        | N4                                     |
| 6.3                    | 250      | N9                                     | 0.1                    | 4        | N3                                     |
| 3.2                    | 125      | N8                                     | 0.05                   | 2        | N2                                     |
| 1.6                    | 63       | N7                                     | 0.025                  | 1        | N1                                     |

**Table 10. Examples of ISO Applications of Surface Texture Symbology**

| Interpretation   | Example   |
|--|---|
| Surface roughness is produced by milling and between upper limit of $Ra = 50 \mu\text{m}$ and $Ra = 6.3 \mu\text{m}$ ; direction of lay is crossed in oblique directions relative to plane of projection; sampling length is 5 mm.   |    |
| Surface roughness of $Rz = 6.3 \mu\text{m}$ is the default for all surfaces as indicated by the $Rz = 6.3$ specification, plus basic symbol within parentheses. Any deviating specification is called out with local notes such as the $Ra = 0.8 \mu\text{m}$ specification. |    |
| Surface roughness is produced by grinding to $Ra = 1.2 \mu\text{m}$ and limited to $Ry = 6.3 \mu\text{m}$ max; direction of lay is perpendicular relative to the plane of projection; sampling length is 2.4 mm.   |    |
| Surface treatment without any machining; nickel-chrome plated to $Rz = 1 \mu\text{m}$ on all surfaces.   |    |
| Surface is nickel-chrome plated to roughness of $Ra = 3.2 \mu\text{m}$ with a sampling length of 0.8 mm; limited to $Rz = 16 \mu\text{m}$ to $Rz = 6.3 \mu\text{m}$ with a sampling length of 2.5 mm.  |    |
| Surface roughness of $Rz = 6.3 \mu\text{m}$ is the default for all surfaces except the inside diameter which is $Ra = 0.8 \mu\text{m}$ .   |   |
| Surface texture symbology may be combined with dimension leaders and witness (extension) lines.  |  |

**Table 10. (Continued) Examples of ISO Applications of Surface Texture Symbology**

| Interpretation   | Example   |
|--|---|
| <p>Surface texture symbology may be applied to extended extension lines or on extended projection lines.</p>   |    |
| <p>Surface roughness is produced by milling and between upper limit of <math>Ra = 50 \mu\text{m}</math> and <math>Ra = 6.3 \mu\text{m}</math>; direction of lay is crossed in oblique directions relative to plane of projection; sampling length is 5 mm.</p> |    |
| <p>Surface treatment without any machining; nickel-chrome plated to <math>Rz = 1 \mu\text{m}</math> on all surfaces.</p>   |    |
| <p>Surface texture characteristics may be specified both before and after surface treatment.</p>   |   |
| <p>The symbol may be expanded with additional lines for textual information where there is insufficient room on the drawing.</p>   |  |

### Gage Blocks

**Precision Gage Blocks.**—Precision gage blocks are usually purchased in sets comprising a specific number of blocks of different sizes. The nominal gage lengths of individual blocks in a set are determined mathematically so that particular desired lengths can be obtained by combining selected blocks. They are made to several different tolerance grades which categorize them as master blocks, calibration blocks, inspection blocks, and workshop blocks. *Master blocks* are employed as basic reference standards; *calibration blocks* are used for high precision gaging work and calibrating inspection blocks; *inspection blocks* are used as toolroom standards and for checking and setting limit and comparator gages, for example. The *workshop blocks* are working gages used as shop standards for a variety of direct precision measurements and gaging applications, including sine-bar settings.

Federal Specification GGG-G-15C, Gage Blocks (see below), lists typical sets, and gives details of materials, design, and manufacturing requirements, and tolerance grades. When there is in a set no single block of the exact size that is wanted, two or more blocks are combined by “wringing” them together. Wringing is achieved by first placing one block crosswise on the other and applying some pressure. Then a swiveling motion is used to twist the blocks to a parallel position, causing them to adhere firmly to one another.

When combining blocks for a given dimension, the object is to use as few blocks as possible to obtain the dimension. The procedure for selecting blocks is based on successively eliminating the right-hand figure of the desired dimension.

*Example:* Referring to gage block set number 1 in [Table 1](#), determine the blocks required to obtain 3.6742 inches. *Step 1:* Eliminate 0.0002 by selecting a 0.1002 block. Subtract 0.1002 from 3.6743 = 3.5740. *Step 2:* Eliminate 0.004 by selecting a 0.124 block. Subtract 0.124 from 3.5740 = 3.450. *Step 3:* Eliminate 0.450 with a block this size. Subtract 0.450 from 3.450 = 3.000. *Step 4:* Select a 3.000 inch block. The combined blocks are 0.1002 + 0.124 + 0.450 + 3.000 = 3.6742 inches.

**Federal Specification for Gage Blocks, Inch and Metric Sizes.**—This Specification, GGG-G-15C, March 20, 1975, which supersedes GGG-G-15B, November 6, 1970, covers design, manufacturing, and purchasing details for precision gage blocks in inch and metric sizes up to and including 20 inches and 500 millimeters gage lengths. The shapes of blocks are designated Style 1, which is rectangular; Style 2, which is square with a center accessory hole, and Style 3, which defines other shapes as may be specified by the purchaser. Blocks may be made from steel, chromium-plated steel, chromium carbide, or tungsten carbide. There are four tolerance grades, which are designated Grade 0.5 (formerly Grade AAA in the GGG-G-15A issue of the Specification); Grade 1 (formerly Grade AA); Grade 2 (formerly Grade A+); and Grade 3 (a compromise between former Grades A and B). Grade 0.5 blocks are special reference gages used for extremely high precision gaging work, and are not recommended for general use. Grade 1 blocks are laboratory reference standards used for calibrating inspection gage blocks and high precision gaging work. Grade 2 blocks are used as inspection and toolroom standards, and Grade 3 blocks are used as shop standards.

Inch and metric sizes of blocks in specific sets are given in [Tables 1](#) and [2](#), which is not a complete list of available sizes. It should be noted that some gage blocks must be ordered as specials, some may not be available in all materials, and some may not be available from all manufacturers. Gage block set number 4 (88 blocks), listed in the Specification, is not given in [Table 1](#). It is the same as set number 1 (81 blocks) but contains seven additional blocks measuring 0.0625, 0.078125, 0.093750, 0.100025, 0.100050, 0.100075, and 0.109375 inch. In [Table 2](#), gage block set number 3M (112 blocks) is not given. It is similar to set number 2M (88 blocks), and the chief difference is the inclusion of a larger number of blocks in the 0.5 millimeter increment series up to 24.5 mm. Set numbers 5M (88 blocks), 6M (112 blocks), and 7M (17 blocks) also are not listed.

## PRECISION GAGE BLOCKS

**Table 1. Gage Block Sets—Inch Sizes** *Federal Specification GGG-G-15C*

| <b>Set Number 1 (81 Blocks)</b>                  |       |       |       |       |       |       |       |       |      |
|--|-------|-------|-------|-------|-------|-------|-------|-------|------|
| First Series: 0.0001 Inch Increments (9 Blocks)  |       |       |       |       |       |       |       |       |      |
| .1001  | .1002 | .1003 | .1004 | .1005 | .1006 | .1007 | .1008 | .1009 |      |
| Second Series: 0.001 Inch Increments (49 Blocks) |       |       |       |       |       |       |       |       |      |
| .101   | .102  | .103  | .104  | .105  | .106  | .107  | .108  | .109  | .110 |
| .111   | .112  | .113  | .114  | .115  | .116  | .117  | .118  | .119  | .120 |
| .121   | .122  | .123  | .124  | .125  | .126  | .127  | .128  | .129  | .130 |
| .131   | .132  | .133  | .134  | .135  | .136  | .137  | .138  | .139  | .140 |
| .141   | .142  | .143  | .144  | .145  | .146  | .147  | .148  | .149  |      |
| Third Series: 0.050 Inch Increments (19 Blocks)  |       |       |       |       |       |       |       |       |      |
| .050   | .100  | .150  | .200  | .250  | .300  | .350  | .400  | .450  | .500 |
| .550   | .600  | .650  | .700  | .750  | .800  | .850  | .900  | .950  |      |
| Fourth Series: 1.000 Inch Increments (4 Blocks)  |       |       |       |       |       |       |       |       |      |
|  | 1.000 |       | 2.000 |       | 3.000 |       | 4.000 |       |      |
| <b>Set Number 5 (21 Blocks)</b>                  |       |       |       |       |       |       |       |       |      |
| First Series: 0.0001 Inch Increments (9 Blocks)  |       |       |       |       |       |       |       |       |      |
| .0101  | .0102 | .0103 | .0104 | .0105 | .0106 | .0107 | .0108 | .0109 |      |
| Second Series: 0.001 Inch Increments (11 Blocks) |       |       |       |       |       |       |       |       |      |
| .010   | .011  | .012  | .013  | .014  | .015  | .016  | .017  | .018  | .019 |
| .020   |       |       |       |       |       |       |       |       |      |
| One Block 0.01005 Inch                           |       |       |       |       |       |       |       |       |      |
| <b>Set Number 6 (28 Blocks)</b>                  |       |       |       |       |       |       |       |       |      |
| First Series: 0.0001 Inch Increments (9 Blocks)  |       |       |       |       |       |       |       |       |      |
| .0201  | .0202 | .0203 | .0204 | .0205 | .0206 | .0207 | .0208 | .0209 |      |
| Second Series: 0.001 Inch Increments (9 Blocks)  |       |       |       |       |       |       |       |       |      |
| .021   | .022  | .023  | .024  | .025  | .026  | .027  | .028  | .029  |      |
| Third Series: 0.010 Inch Increments (9 Blocks)   |       |       |       |       |       |       |       |       |      |
| .010   | .020  | .030  | .040  | .050  | .060  | .070  | .080  | .090  |      |
| One Block 0.02005 Inch                           |       |       |       |       |       |       |       |       |      |
| <b>Long Gage Block Set Number 7 (8 Blocks)</b>   |       |       |       |       |       |       |       |       |      |
| Whole Inch Series (8 Blocks)                     |       |       |       |       |       |       |       |       |      |
| 5  | 6     | 7     | 8     | 10    | 12    | 16    | 20    |       |      |
| <b>Set Number 8 (36 Blocks)</b>                  |       |       |       |       |       |       |       |       |      |
| First Series: 0.0001 Inch Increments (9 Blocks)  |       |       |       |       |       |       |       |       |      |
| .1001  | .1002 | .1003 | .1004 | .1005 | .1006 | .1007 | .1008 | .1009 |      |
| Second Series: 0.001 Inch Increments (11 Blocks) |       |       |       |       |       |       |       |       |      |
| .100   | .101  | .102  | .103  | .104  | .105  | .106  | .107  | .108  | .109 |
| .110   |       |       |       |       |       |       |       |       |      |
| Third Series: 0.010 Inch Increments (8 Blocks)   |       |       |       |       |       |       |       |       |      |
| .120   | .130  | .140  | .150  | .160  | .170  | .180  | .190  |       |      |
| Fourth Series: 0.100 Inch Increments (4 Blocks)  |       |       |       |       |       |       |       |       |      |
| .200   |       | .300  |       | .400  |       | .500  |       |       |      |
| Whole Inch Series (3 Blocks)                     |       |       |       |       |       |       |       |       |      |
|  | 1     |       |       | 2     |       |       | 4     |       |      |
| One Block 0.050 Inch                             |       |       |       |       |       |       |       |       |      |
| <b>Set Number 9 (20 Blocks)</b>                  |       |       |       |       |       |       |       |       |      |
| First Series: 0.0001 Inch Increments (9 Blocks)  |       |       |       |       |       |       |       |       |      |
| .0501  | .0502 | .0503 | .0504 | .0505 | .0506 | .0507 | .0508 | .0509 |      |
| Second Series: 0.001 Inch Increments (10 Blocks) |       |       |       |       |       |       |       |       |      |
| .050   | .051  | .052  | .053  | .054  | .055  | .056  | .057  | .058  | .059 |
| One Block 0.05005 Inch                           |       |       |       |       |       |       |       |       |      |

Set number 4 is not shown, and the Specification does not list a set 2 or 3. Arranged here in incremental series for convenience of use.

**Table 2. Gage Block Sets—Metric Sizes** *Federal Specification GGG-G-15C*

| <b>Set Number 1M (45 Blocks)</b>                      |       |       |       |       |       |       |       |       |      |
|---|-------|-------|-------|-------|-------|-------|-------|-------|------|
| First Series: 0.001 Millimeter Increments (9 Blocks)  |       |       |       |       |       |       |       |       |      |
| 1.001   | 1.002 | 1.003 | 1.004 | 1.005 | 1.006 | 1.007 | 1.008 | 1.009 |      |
| Second Series: 0.01 Millimeter Increments (9 Blocks)  |       |       |       |       |       |       |       |       |      |
| 1.01  | 1.02  | 1.03  | 1.04  | 1.05  | 1.06  | 1.07  | 1.08  | 1.09  |      |
| Third Series: 0.10 Millimeter Increments (9 Blocks)   |       |       |       |       |       |       |       |       |      |
| 1.10  | 1.20  | 1.30  | 1.40  | 1.50  | 1.60  | 1.70  | 1.80  | 1.90  |      |
| Fourth Series: 1.0 Millimeter Increments (9 Blocks)   |       |       |       |       |       |       |       |       |      |
| 1.0   | 2.0   | 3.0   | 4.0   | 5.0   | 6.0   | 7.0   | 8.0   | 9.0   |      |
| Fifth Series: 10 Millimeter Increments (9 Blocks)     |       |       |       |       |       |       |       |       |      |
| 10  | 20    | 30    | 40    | 50    | 60    | 70    | 80    | 90    |      |
| <b>Set Number 2M (88 Blocks)</b>                      |       |       |       |       |       |       |       |       |      |
| First Series: 0.001 Millimeter Increments (9 Blocks)  |       |       |       |       |       |       |       |       |      |
| 1.001   | 1.002 | 1.003 | 1.004 | 1.005 | 1.006 | 1.007 | 1.008 | 1.009 |      |
| Second Series: 0.01 Millimeter Increments (49 Blocks) |       |       |       |       |       |       |       |       |      |
| 1.01  | 1.02  | 1.03  | 1.04  | 1.05  | 1.06  | 1.07  | 1.08  | 1.09  | 1.10 |
| 1.11  | 1.12  | 1.13  | 1.14  | 1.15  | 1.16  | 1.17  | 1.18  | 1.19  | 1.20 |
| 1.21  | 1.22  | 1.23  | 1.24  | 1.25  | 1.26  | 1.27  | 1.28  | 1.29  | 1.30 |
| 1.31  | 1.32  | 1.33  | 1.34  | 1.35  | 1.36  | 1.37  | 1.38  | 1.39  | 1.40 |
| 1.41  | 1.42  | 1.43  | 1.44  | 1.45  | 1.46  | 1.47  | 1.48  | 1.49  |      |
| Third Series: 0.50 Millimeter Increments (19 Blocks)  |       |       |       |       |       |       |       |       |      |
| 0.5   | 1.0   | 1.5   | 2.0   | 2.5   | 3.0   | 3.5   | 4.0   | 4.5   | 5.0  |
| 5.5   | 6.0   | 6.5   | 7.0   | 7.5   | 8.0   | 8.5   | 9.0   | 9.5   |      |
| Fourth Series: 10 Millimeter Increments (10 Blocks)   |       |       |       |       |       |       |       |       |      |
| 10  | 20    | 30    | 40    | 50    | 60    | 70    | 80    | 90    | 100  |
| One Block 1.0005 mm                                   |       |       |       |       |       |       |       |       |      |
| <b>Set Number 4M (45 Blocks)</b>                      |       |       |       |       |       |       |       |       |      |
| First Series: 0.001 Millimeter Increments (9 Blocks)  |       |       |       |       |       |       |       |       |      |
| 2.001   | 2.002 | 2.003 | 2.004 | 2.005 | 2.006 | 2.007 | 2.008 | 2.009 |      |
| Second Series: 0.01 Millimeter Increments (9 Blocks)  |       |       |       |       |       |       |       |       |      |
| 2.01  | 2.02  | 2.03  | 2.04  | 2.05  | 2.06  | 2.07  | 2.08  | 2.09  |      |
| Third Series: 0.10 Millimeter Increments (9 Blocks)   |       |       |       |       |       |       |       |       |      |
| 2.1   | 2.2   | 2.3   | 2.4   | 2.5   | 2.6   | 2.7   | 2.8   | 2.9   |      |
| Fourth Series: 1 Millimeter Increments (9 Blocks)     |       |       |       |       |       |       |       |       |      |
| 1.0   | 2.0   | 3.0   | 4.0   | 5.0   | 6.0   | 7.0   | 8.0   | 9.0   |      |
| Fifth Series: 10 Millimeter Increments (9 Blocks)     |       |       |       |       |       |       |       |       |      |
| 10  | 20    | 30    | 40    | 50    | 60    | 70    | 80    | 90    |      |
| <b>Long Gage Block Set Number 8M (8 Blocks)</b>       |       |       |       |       |       |       |       |       |      |
| Whole Millimeter Series (8 Blocks)                    |       |       |       |       |       |       |       |       |      |
| 125   | 150   | 175   | 200   | 250   | 300   | 400   | 500   |       |      |

Set numbers 3M, 5M, 6M, and 7M are not listed.

Arranged here in incremental series for convenience of use.

*Note:* Gage blocks measuring 1.09 millimeters and under in set number 1M, blocks measuring 1.5 millimeters and under in set number 2M, and block measuring 1.0 millimeter in set number 4M are not available in tolerance grade 0.5.

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## CUTTING TOOLS

### Terms and Definitions

**Tool Contour.**—Tools for turning, planing, etc., are made in straight, bent, offset, and other forms to place the cutting edges in convenient positions for operating on differently located surfaces. The contour or shape of the cutting edge may also be varied to suit different classes of work. Tool shapes, however, are not only related to the kind of operation, but, in roughing tools particularly, the contour may have a decided effect upon the cutting efficiency of the tool. To illustrate, an increase in the side cutting-edge angle of a roughing tool, or in the nose radius, tends to permit higher cutting speeds because the chip will be thinner for a given feed rate. Such changes, however, may result in chattering or vibrations unless the work and the machine are rigid; hence, the most desirable contour may be a compromise between the ideal form and one that is needed to meet practical requirements.

**Terms and Definitions.**—The terms and definitions relating to single-point tools vary somewhat in different plants, but the following are in general use.

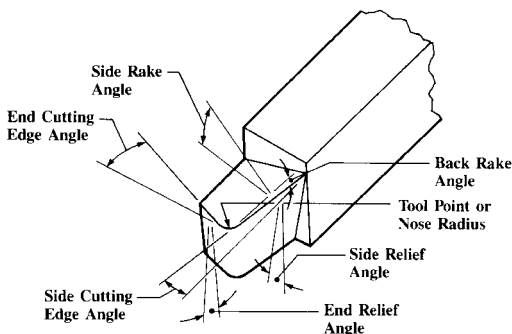


Fig. 1. Terms Applied to Single-point Turning Tools

**Single-point Tool:** This term is applied to tools for turning, planing, boring, etc., which have a cutting edge at one end. This cutting edge may be formed on one end of a solid piece of steel, or the cutting part of the tool may consist of an insert or tip which is held to the body of the tool by brazing, welding, or mechanical means.

**Shank:** The shank is the main body of the tool. If the tool is an inserted cutter type, the shank supports the cutter or bit. (See diagram, Fig. 1.)

**Nose:** A general term sometimes used to designate the cutting end but usually relating more particularly to the rounded tip of the cutting end.

**Face:** The surface against which the chips bear, as they are severed in turning or planing operations, is called the face.

**Flank:** The flank is that end surface adjacent to the cutting edge and below it when the tool is in a horizontal position as for turning.

**Base:** The base is the surface of the tool shank that bears against the supporting tool-holder or block.

**Side Cutting Edge:** The side cutting edge is the cutting edge on the side of the tool. Tools such as shown in Fig. 1 do the bulk of the cutting with this cutting edge and are, therefore, sometimes called side cutting edge tools.

**End Cutting Edge:** The end cutting edge is the cutting edge at the end of the tool.

On side cutting edge tools, the end cutting edge can be used for light plunging and facing cuts. Cutoff tools and similar tools have only one cutting edge located on the end. These

tools and other tools that are intended to cut primarily with the end cutting edge are sometimes called end cutting edge tools.

**Rake:** A metal-cutting tool is said to have rake when the tool face or surface against which the chips bear as they are being severed, is inclined for the purpose of either increasing or diminishing the keenness or bluntness of the edge. The magnitude of the rake is most conveniently measured by two angles called the back rake angle and the side rake angle. The tool shown in Fig. 1 has rake. If the face of the tool did not incline but was parallel to the base, there would be no rake; the rake angles would be zero.

**Positive Rake:** If the inclination of the tool face is such as to make the cutting edge keener or more acute than when the rake angle is zero, the rake angle is defined as positive.

**Negative Rake:** If the inclination of the tool face makes the cutting edge less keen or more blunt than when the rake angle is zero, the rake is defined as negative.

**Back Rake:** The back rake is the inclination of the face toward or away from the end or the end cutting edge of the tool. When the inclination is away from the end cutting edge, as shown in Fig. 1, the back rake is positive. If the inclination is downward toward the end cutting edge the back rake is negative.

**Side Rake:** The side rake is the inclination of the face toward or away from the side cutting edge. When the inclination is away from the side cutting edge, as shown in Fig. 1, the side rake is positive. If the inclination is toward the side cutting edge the side rake is negative.

**Relief:** The flanks below the side cutting edge and the end cutting edge must be relieved to allow these cutting edges to penetrate into the workpiece when taking a cut. If the flanks are not provided with relief, the cutting edges will rub against the workpiece and be unable to penetrate in order to form the chip. Relief is also provided below the nose of the tool to allow it to penetrate into the workpiece. The relief at the nose is usually a blend of the side relief and the end relief.

**End Relief Angle:** The end relief angle is a measure of the relief below the end cutting edge.

**Side Relief Angle:** The side relief angle is a measure of the relief below the side cutting edge.

**Back Rake Angle:** The back rake angle is a measure of the back rake. It is measured in a plane that passes through the side cutting edge and is perpendicular to the base. Thus, the back rake angle can be defined by measuring the inclination of the side cutting edge with respect to a line or plane that is parallel to the base. The back rake angle may be positive, negative, or zero depending upon the magnitude and direction of the back rake.

**Side Rake Angle:** The side rake angle is a measure of the side rake. This angle is always measured in a plane that is perpendicular to the side cutting edge and perpendicular to the base. Thus, the side rake angle is the angle of inclination of the face perpendicular to the side cutting edge with reference to a line or a plane that is parallel to the base.

**End Cutting Edge Angle:** The end cutting edge angle is the angle made by the end cutting edge with respect to a plane perpendicular to the axis of the tool shank. It is provided to allow the end cutting edge to clear the finish machined surface on the workpiece.

**Side Cutting Edge Angle:** The side cutting edge angle is the angle made by the side cutting edge and a plane that is parallel to the side of the shank.

**Nose Radius:** The nose radius is the radius of the nose of the tool. The performance of the tool, in part, is influenced by nose radius so that it must be carefully controlled.

**Lead Angle:** The lead angle, shown in Fig. 2, is not ground on the tool. It is a tool setting angle which has a great influence on the performance of the tool. The lead angle is bounded by the side cutting edge and a plane perpendicular to the workpiece surface when the tool is in position to cut; or, more exactly, the lead angle is the angle between the side cutting edge and a plane perpendicular to the direction of the feed travel.

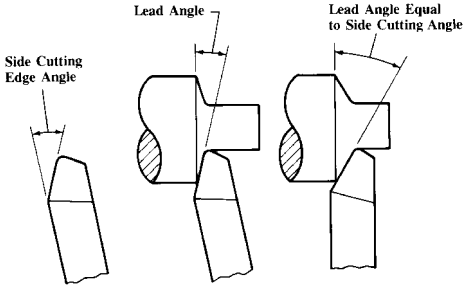


Fig. 2. Lead Angle on Single-point Turning Tool

**Solid Tool:** A solid tool is a cutting tool made from one piece of tool material.

**Brazed Tool:** A brazed tool is a cutting tool having a blank of cutting-tool material permanently brazed to a steel shank.

**Blank:** A blank is an unground piece of cutting-tool material from which a brazed tool is made.

**Tool Bit:** A tool bit is a relatively small cutting tool that is clamped in a holder in such a way that it can readily be removed and replaced. It is intended primarily to be reground when dull and not indexed.

**Tool-bit Blank:** The tool-bit blank is an unground piece of cutting-tool material from which a tool bit can be made by grinding. It is available in standard sizes and shapes.

**Tool-bit Holder:** Usually made from forged steel, the tool-bit holder is used to hold the tool bit, to act as an extended shank for the tool bit, and to provide a means for clamping in the tool post.

**Straight-shank Tool-bit Holder:** A straight-shank tool-bit holder has a straight shank when viewed from the top. The axis of the tool bit is held parallel to the axis of the shank.

**Offset-shank Tool-bit Holder:** An offset-shank tool-bit holder has the shank bent to the right or left, as seen in Fig. 3. The axis of the tool bit is held at an angle with respect to the axis of the shank.

**Side cutting Tool:** A side cutting tool has its major cutting edge on the side of the cutting part of the tool. The major cutting edge may be parallel or at an angle with respect to the axis of the tool.

**Indexable Inserts:** An indexable insert is a relatively small piece of cutting-tool material that is geometrically shaped to have two or several cutting edges that are used until dull. The insert is then indexed on the holder to apply a sharp cutting edge. When all the cutting edges have been dulled, the insert is discarded. The insert is held in a pocket or against other locating surfaces on an indexable insert holder by means of a mechanical clamping device that can be tightened or loosened easily.

**Indexable Insert Holder:** Made of steel, an indexable insert holder is used to hold indexable inserts. It is equipped with a mechanical clamping device that holds the inserts firmly in a pocket or against other seating surfaces.

**Straight-shank Indexable Insert Holder:** A straight-shank indexable insert tool-holder is essentially straight when viewed from the top, although the cutting edge of the insert may be oriented parallel, or at an angle to, the axis of the holder.

**Offset-shank Indexable Insert Holder:** An offset-shank indexable insert holder has the head end, or the end containing the insert pocket, offset to the right or left, as shown in Fig. 3.

3.

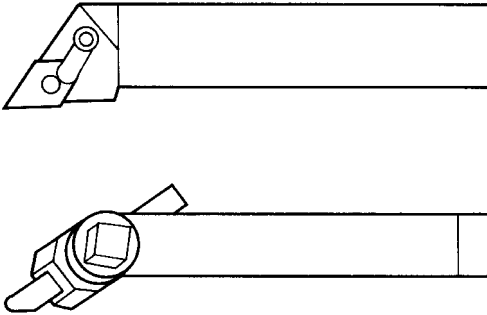


Fig. 3. Top: Right-hand Offset-shank, Indexable Insert Holder  
Bottom: Right-hand Offset-shank Tool-bit Holder

*End cutting Tool:* An end cutting tool has its major cutting edge on the end of the cutting part of the tool. The major cutting edge may be perpendicular or at an angle, with respect to the axis of the tool.

*Curved Cutting-edge Tool:* A curved cutting-edge tool has a continuously variable side cutting edge angle. The cutting edge is usually in the form of a smooth, continuous curve along its entire length, or along a large portion of its length.

*Right-hand Tool:* A right-hand tool has the major, or working, cutting edge on the right-hand side when viewed from the cutting end with the face up. As used in a lathe, such a tool is usually fed into the work from right to left, when viewed from the shank end.

*Left-hand Tool:* A left-hand tool has the major or working cutting edge on the left-hand side when viewed from the cutting end with the face up. As used in a lathe, the tool is usually fed into the work from left to right, when viewed from the shank end.

*Neutral-hand Tool:* A neutral-hand tool is a tool to cut either left to right or right to left; or the cut may be parallel to the axis of the shank as when plunge cutting.

*Chipbreaker:* A groove formed in or on a shoulder on the face of a turning tool back of the cutting edge to break up the chips and prevent the formation of long, continuous chips which would be dangerous to the operator and also bulky and cumbersome to handle. A chipbreaker of the shoulder type may be formed directly on the tool face or it may consist of a separate piece that is held either by brazing or by clamping.

**Relief Angles.**—The end relief angle and the side relief angle on single-point cutting tools are usually, though not invariably, made equal to each other. The relief angle under the nose of the tool is a blend of the side and end relief angles.

The size of the relief angles has a pronounced effect on the performance of the cutting tool. If the relief angles are too large, the cutting edge will be weakened and in danger of breaking when a heavy cutting load is placed on it by a hard and tough material. On finish cuts, rapid wear of the cutting edge may cause problems with size control on the part. Relief angles that are too small will cause the rate of wear on the flank of the tool below the cutting edge to increase, thereby significantly reducing the tool life. In general, when cutting hard and tough materials, the relief angles should be 6 to 8 degrees for high-speed steel tools and 5 to 7 degrees for carbide tools. For medium steels, mild steels, cast iron, and other average work the recommended values of the relief angles are 8 to 12 degrees for high-speed steel tools and 5 to 10 degrees for carbides. Ductile materials having a relatively low modulus of elasticity should be cut using larger relief angles. For example, the relief angles recommended for turning copper, brass, bronze, aluminum, ferritic malleable

iron, and similar metals are 12 to 16 degrees for high-speed steel tools and 8 to 14 degrees for carbides.

Larger relief angles generally tend to produce a better finish on the finish machined surface because less surface of the worn flank of the tool rubs against the workpiece. For this reason, single-point thread-cutting tools should be provided with relief angles that are as large as circumstances will permit. Problems encountered when machining stainless steel may be overcome by increasing the size of the relief angle. The relief angles used should never be smaller than necessary.

**Rake Angles.**—Machinability tests have confirmed that when the rake angle along which the chip slides, called the true rake angle, is made larger in the positive direction, the cutting force and the cutting temperature will decrease. Also, the tool life for a given cutting speed will increase with increases in the true rake angle up to an optimum value, after which it will decrease again. For turning tools which cut primarily with the side cutting edge, the true rake angle corresponds rather closely with the side rake angle except when taking shallow cuts. Increasing the side rake angle in the positive direction lowers the cutting force and the cutting temperature, while at the same time it results in a longer tool life or a higher permissible cutting speed up to an optimum value of the side rake angle. After the optimum value is exceeded, the cutting force and the cutting temperature will continue to drop; however, the tool life and the permissible cutting speed will decrease.

As an approximation, the magnitude of the cutting force will decrease about one per cent per degree increase in the side rake angle. While not exact, this rule of thumb does correspond approximately to test results and can be used to make rough estimates. Of course, the cutting force also increases about one per cent per degree decrease in the side rake angle. The limiting value of the side rake angle for optimum tool life or cutting speed depends upon the work material and the cutting tool material. In general, lower values can be used for hard and tough work materials. Cemented carbides are harder and more brittle than high-speed steel; therefore, the rake angles usually used for cemented carbides are less positive than for high-speed steel.

Negative rake angles cause the face of the tool to slope in the opposite direction from positive rake angles and, as might be expected, they have an opposite effect. For side cutting edge tools, increasing the side rake angle in a negative direction will result in an increase in the cutting force and an increase in the cutting temperature of approximately one per cent per degree change in rake angle. For example, if the side rake angle is changed from 5 degrees positive to 5 degrees negative, the cutting force will be about 10 per cent larger. Usually the tool life will also decrease when negative side rake angles are used, although the tool life will sometimes increase when the negative rake angle is not too large and when a fast cutting speed is used.

Negative side rake angles are usually used in combination with negative back rake angles on single-point cutting tools. The negative rake angles strengthen the cutting edges enabling them to sustain heavier cutting loads and shock loads. They are recommended for turning very hard materials and for heavy interrupted cuts. There is also an economic advantage in favor of using negative rake indexable inserts and tool holders inasmuch as the cutting edges provided on both the top and bottom of the insert can be used.

On turning tools that cut primarily with the side cutting edge, the effect of the back rake angle alone is much less than the effect of the side rake angle although the direction of the change in cutting force, cutting temperature, and tool life is the same. The effect that the back rake angle has can be ignored unless, of course, extremely large changes in this angle are made. A positive back rake angle does improve the performance of the nose of the tool somewhat and is helpful in taking light finishing cuts. A negative back rake angle strengthens the nose of the tool and is helpful when interrupted cuts are taken. The back rake angle has a very significant effect on the performance of end cutting edge tools, such as cut-off tools. For these tools, the effect of the back rake angle is very similar to the effect of the side rake angle on side cutting edge tools.

**Side Cutting Edge and Lead Angles.**—These angles are considered together because the side cutting edge angle is usually designed to provide the desired lead angle when the tool is being used. The side cutting edge angle and the lead angle will be equal when the shank of the cutting tool is positioned perpendicular to the workpiece, or, more correctly, perpendicular to the direction of the feed. When the shank is not perpendicular, the lead angle is determined by the side cutting edge and an imaginary line perpendicular to the feed direction.

The flow of the chips over the face of the tool is approximately perpendicular to the side cutting edge except when shallow cuts are taken. The thickness of the undeformed chip is measured perpendicular to the side cutting edge. As the lead angle is increased, the length of chip in contact with the side cutting edge is increased, and the chip will become longer and thinner. This effect is the same as increasing the depth of cut and decreasing the feed, although the actual depth of cut and feed remain the same and the same amount of metal is removed. The effect of lengthening and thinning the chip by increasing the lead angle is very beneficial as it increases the tool life for a given cutting speed or that speed can be increased. Increasing the cutting speed while the feed and the tool life remain the same leads to faster production.

However, an adverse effect must be considered. Chatter can be caused by a cutting edge that is oriented at a high lead angle when turning and sometimes, when turning long and slender shafts, even a small lead angle can cause chatter. In fact, an unsuitable lead angle of the side cutting edge is one of the principal causes of chatter. When chatter occurs, often simply reducing the lead angle will cure it. Sometimes, very long and slender shafts can be turned successfully with a tool having a zero degree lead angle (and having a small nose radius). Boring bars, being usually somewhat long and slender, are also susceptible to chatter if a large lead angle is used. The lead angle for boring bars should be kept small, and for very long and slender boring bars a zero degree lead angle is recommended. It is impossible to provide a rule that will determine when chatter caused by a lead angle will occur and when it will not. In making a judgment, the first consideration is the length to diameter ratio of the part to be turned, or of the boring bar. Then the method of holding the workpiece must be considered — a part that is firmly held is less apt to chatter. Finally, the overall condition and rigidity of the machine must be considered because they may be the real cause of chatter.

Although chatter can be a problem, the advantages gained from high lead angles are such that the lead angle should be as large as possible at all times.

**End Cutting Edge Angle.**—The size of the end cutting edge angle is important when tool wear by cratering occurs. Frequently, the crater will enlarge until it breaks through the end cutting edge just behind the nose, and tool failure follows shortly. Reducing the size of the end cutting edge angle tends to delay the time of crater breakthrough. When cratering takes place, the recommended end cutting edge angle is 8 to 15 degrees. If there is no cratering, the angle can be made larger. Larger end cutting edge angles may be required to enable profile turning tools to plunge into the work without interference from the end cutting edge.

**Nose Radius.**—The tool nose is a very critical part of the cutting edge since it cuts the finished surface on the workpiece. If the nose is made to a sharp point, the finish machined surface will usually be unacceptable and the life of the tool will be short. Thus, a nose radius is required to obtain an acceptable surface finish and tool life. The surface finish obtained is determined by the feed rate and by the nose radius if other factors such as the work material, the cutting speed, and cutting fluids are not considered. A large nose radius will give a better surface finish and will permit a faster feed rate to be used.

Machinability tests have demonstrated that increasing the nose radius will also improve the tool life or allow a faster cutting speed to be used. For example, high-speed steel tools were used to turn an alloy steel in one series of tests where complete or catastrophic tool failure was used as a criterion for the end of tool life. The cutting speed for a 60-minute tool

life was found to be 125 fpm when the nose radius was  $\frac{1}{16}$  inch and 160 fpm when the nose radius was  $\frac{1}{4}$  inch.

A very large nose radius can often be used but a limit is sometimes imposed because the tendency for chatter to occur is increased as the nose radius is made larger. A nose radius that is too large can cause chatter and when it does, a smaller nose radius must be used on the tool. It is always good practice to make the nose radius as large as is compatible with the operation being performed.

**Chipbreakers.**—Many steel turning tools are equipped with chipbreaking devices to prevent the formation of long continuous chips in connection with the turning of steel at the high speeds made possible by high-speed steel and especially cemented carbide tools. Long steel chips are dangerous to the operator, and cumbersome to handle, and they may twist around the tool and cause damage. Broken chips not only occupy less space, but permit a better flow of coolant to the cutting edge. Several different forms of chipbreakers are illustrated in Fig. 4.

*Angular Shoulder Type:* The angular shoulder type shown at A is one of the commonly used forms. As the enlarged sectional view shows, the chipbreaking shoulder is located back of the cutting edge. The angle  $a$  between the shoulder and cutting edge may vary from 6 to 15 degrees or more, 8 degrees being a fair average. The ideal angle, width  $W$  and depth  $G$ , depend upon the speed and feed, the depth of cut, and the material. As a general rule, width  $W$ , at the end of the tool, varies from  $\frac{3}{32}$  to  $\frac{7}{32}$  inch, and the depth  $G$  may range from  $\frac{1}{64}$  to  $\frac{1}{16}$  inch. The shoulder radius equals depth  $G$ . If the tool has a large nose radius, the corner of the shoulder at the nose end may be beveled off, as illustrated at B, to prevent it from coming into contact with the work. The width  $K$  for type B should equal approximately 1.5 times the nose radius.

*Parallel Shoulder Type:* Diagram C shows a design with a chipbreaking shoulder that is parallel with the cutting edge. With this form, the chips are likely to come off in short curled sections. The parallel form may also be applied to straight tools which do not have a side cutting-edge angle. The tendency with this parallel shoulder form is to force the chips against the work and damage it.

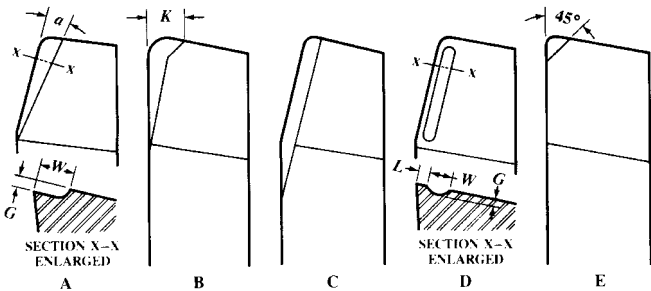


Fig. 4. Different Forms of Chipbreakers for Turning Tools

*Groove Type:* This type (diagram D) has a groove in the face of the tool produced by grinding. Between the groove and the cutting edge, there is a land  $L$ . Under ideal conditions, this width  $L$ , the groove width  $W$ , and the groove depth  $G$ , would be varied to suit the feed, depth of cut and material. For average use,  $L$  is about  $\frac{1}{32}$  inch;  $G$ ,  $\frac{1}{32}$  inch; and  $W$ ,  $\frac{1}{16}$  inch. There are differences of opinion concerning the relative merits of the groove type and



the shoulder type. Both types have proved satisfactory when properly proportioned for a given class of work.

*Chipbreaker for Light Cuts:* Diagram E illustrates a form of chipbreaker that is sometimes used on tools for finishing cuts having a maximum depth of about  $\frac{1}{32}$  inch. This chipbreaker is a shoulder type having an angle of 45 degrees and a maximum width of about  $\frac{1}{16}$  inch. It is important in grinding all chipbreakers to give the chip-bearing surfaces a fine finish, such as would be obtained by honing. This finish greatly increases the life of the tool.

**Planing Tools.**—Many of the principles which govern the shape of turning tools also apply in the grinding of tools for planing. The amount of rake depends upon the hardness of the material, and the direction of the rake should be away from the *working part* of the cutting edge. The angle of clearance should be about 4 or 5 degrees for planer tools, which is less than for lathe tools. This small clearance is allowable because a planer tool is held about square with the platen, whereas a lathe tool, the height and inclination of which can be varied, may not always be clamped in the same position.

*Carbide Tools:* Carbide tools for planing usually have negative rake. Round-nose and square-nose end-cutting tools should have a “negative back rake” (or front rake) of 2 or 3 degrees. Side cutting tools may have a negative back rake of 10 degrees, a negative side rake of 5 degrees, and a side cutting-edge angle of 8 degrees.

### Indexable Inserts

**Introduction.**—A large proportion of the cemented carbide, single-point cutting tools are indexable inserts and indexable insert tool holders. Dimensional specifications for solid sintered carbide indexable inserts are given in American National Standard ANSI B212.12-1991 (R2002). Samples of the many insert shapes are shown in Table 3. Most modern, cemented carbide, face milling cutters are of the indexable insert type. Larger size end milling cutters, side milling or slotting cutters, boring tools, and a wide variety of special tools are made to use indexable inserts. These inserts are primarily made from cemented carbide, although most of the cemented oxide cutting tools are also indexable inserts.

The objective of this type of tooling is to provide an insert with several cutting edges. When an edge is worn, the insert is indexed in the tool holder until all the cutting edges are used up, after which it is discarded. The insert is not intended to be reground. The advantages are that the cutting edges on the tool can be rapidly changed without removing the tool holder from the machine, tool-grinding costs are eliminated, and the cost of the insert is less than the cost of a similar, brazed carbide tool. Of course, the cost of the tool holder must be added to the cost of the insert; however, one tool holder will usually last for a long time before it, too, must be replaced.

Indexable inserts and tool holders are made with a negative rake or with a positive rake. Negative rake inserts have the advantage of having twice as many cutting edges available as comparable positive rake inserts, because the cutting edges on both the top and bottom of negative rake inserts can be used, while only the top cutting edges can be used on positive rake inserts. Positive rake inserts have a distinct advantage when machining long and slender parts, thin-walled parts, or other parts that are subject to bending or chatter when the cutting load is applied to them, because the cutting force is significantly lower as compared to that for negative rake inserts. Indexable inserts can be obtained in the following forms: utility ground, or ground on top and bottom only; precision ground, or ground on all surfaces; prehoned to produce a slight rounding of the cutting edge; and precision molded, which are unground. Positive-negative rake inserts also are available. These inserts are held on a negative-rake tool holder and have a chipbreaker groove that is formed to produce an effective positive-rake angle while cutting. Cutting edges may be available on the top surface only, or on both top and bottom surfaces. The positive-rake chipbreaker surface may be ground or precision molded on the insert.

Many materials, such as gray cast iron, form a discontinuous chip. For these materials an insert that has plain faces without chipbreaker grooves should always be used. Steels and other ductile materials form a continuous chip that must be broken into small segments when machined on lathes and planers having single-point, cemented-carbide and cemented-oxide cutting tools; otherwise, the chips can cause injury to the operator. In this case a chipbreaker must be used. Some inserts are made with chipbreaker grooves molded or ground directly on the insert. When inserts with plain faces are used, a cemented-carbide plate-type chipbreaker is clamped on top of the insert.

**Identification System for Indexable Inserts.**—The size of indexable inserts is determined by the diameter of an inscribed circle (I.C.), except for rectangular and parallelogram inserts where the length and width dimensions are used. To describe an insert in its entirety, a standard ANSI B212.4-2002 identification system is used where each position number designates a feature of the insert. The ANSI Standard includes items now commonly used and facilitates identification of items not in common use. Identification consists of up to ten positions; each position defines a characteristic of the insert as shown below:

|          |          |          |          |          |          |          |                |                |                 |
|----------|----------|----------|----------|----------|----------|----------|----------------|----------------|-----------------|
| 1        | 2        | 3        | 4        | 5        | 6        | 7        | 8 <sup>a</sup> | 9 <sup>a</sup> | 10 <sup>a</sup> |
| <b>T</b> | <b>N</b> | <b>M</b> | <b>G</b> | <b>5</b> | <b>4</b> | <b>3</b> |                |                | <b>A</b>        |

<sup>a</sup> Eighth, Ninth, and Tenth Positions are used only when required.

1) *Shape*: The shape of an insert is designated by a letter: **R** for round; **S**, square; **T**, triangle; **A**, 85° parallelogram; **B**, 82° parallelogram; **C**, 80° diamond; **D**, 55° diamond; **E**, 75° diamond; **H**, hexagon; **K**, 55° parallelogram; **L**, rectangle; **M**, 86° diamond; **O**, octagon; **P**, pentagon; **V**, 35° diamond; and **W**, 80° trigon.

2) *Relief Angle (Clearances)*: The second position is a letter denoting the relief angles: **N** for 0°; **A**, 3°; **B**, 5°; **C**, 7°; **P**, 11°; **D**, 15°; **E**, 20°; **F**, 25°; **G**, 30°; **H**, 0° & 11°; **J**, 0° & 14°; **K**, 0° & 17°; **L**, 0° & 20°; **M**, 11° & 14°; **R**, 11° & 17°; **S**, 11° & 20°. When mounted on a holder, the actual relief angle may be different from that on the insert.

3) *Tolerances*: The third position is a letter and indicates the tolerances which control the indexability of the insert. Tolerances specified do not imply the method of manufacture.

| Symbol   | Tolerance<br>(± from nominal) |                   | Symbol   | Tolerance<br>(± from nominal) |                    |
|----------|-------------------------------|-------------------|----------|-------------------------------|--------------------|
|          | Inscribed<br>Circle, Inch     | Thicknes,<br>Inch |          | Inscribed<br>Circle, Inch     | Thickness,<br>Inch |
| <b>A</b> | 0.001                         | 0.001             | <b>H</b> | 0.0005                        | 0.001              |
| <b>B</b> | 0.001                         | 0.005             | <b>J</b> | 0.002–0.005                   | 0.001              |
| <b>C</b> | 0.001                         | 0.001             | <b>K</b> | 0.002–0.005                   | 0.001              |
| <b>D</b> | 0.001                         | 0.005             | <b>L</b> | 0.002–0.005                   | 0.001              |
| <b>E</b> | 0.001                         | 0.001             | <b>M</b> | 0.002–0.004 <sup>a</sup>      | 0.005              |
| <b>F</b> | 0.0005                        | 0.001             | <b>U</b> | 0.005–0.010 <sup>a</sup>      | 0.005              |
| <b>G</b> | 0.001                         | 0.005             | <b>N</b> | 0.002–0.004 <sup>a</sup>      | 0.001              |

<sup>a</sup> Exact tolerance is determined by size of insert. See ANSI B212.12.

4) *Type*: The type of insert is designated by a letter. **A**, with hole; **B**, with hole and countersink; **C**, with hole and two countersinks; **F**, chip grooves both surfaces, no hole; **G**, same as **F** but with hole; **H**, with hole, one countersink, and chip groove on one rake surface; **J**, with hole, two countersinks and chip grooves on two rake surfaces; **M**, with hole and chip groove on one rake surface; **N**, without hole; **Q**, with hole and two countersinks; **R**, without hole but with chip groove on one rake surface; **T**, with hole, one countersink, and chip

\* Second angle is secondary facet angle, which may vary by ± 1°.

groove on one rake face; **U**, with hole, two countersinks, and chip grooves on two rake faces; and **W**, with hole and one countersink. *Note:* a dash may be used after position 4 to separate the shape-describing portion from the following dimensional description of the insert and is not to be considered a position in the standard description.

5) *Size:* The size of the insert is designated by a one- or a two-digit number. For regular polygons and diamonds, it is the number of eighths of an inch in the nominal size of the inscribed circle, and will be a one- or two-digit number when the number of eighths is a whole number. It will be a two-digit number, including one decimal place, when it is not a whole number. Rectangular and parallelogram inserts require two digits: the first digit indicates the number of eighths of an inch width and the second digit, the number of quarters of an inch length.

6) *Thickness:* The thickness is designated by a one- or two-digit number, which indicates the number of sixteenths of an inch in the thickness of the insert. It is a one-digit number when the number of sixteenths is a whole number; it is a two-digit number carried to one decimal place when the number of sixteenths of an inch is not a whole number.

7) *Cutting Point Configuration:* The cutting point, or nose radius, is designated by a number representing  $\frac{1}{64}$ ths of an inch; a flat at the cutting point or nose, is designated by a letter: **0** for sharp corner; **1**,  $\frac{1}{64}$  inch radius; **2**,  $\frac{1}{32}$  inch radius; **3**,  $\frac{3}{64}$  inch radius; **4**,  $\frac{1}{16}$  inch radius; **5**,  $\frac{5}{64}$  inch radius; **6**,  $\frac{3}{32}$  inch radius; **7**,  $\frac{7}{64}$  inch radius; **8**,  $\frac{1}{8}$  inch radius; **A**, square insert with 45° chamfer; **D**, square insert with 30° chamfer; **E**, square insert with 15° chamfer; **F**, square insert with 3° chamfer; **K**, square insert with 30° double chamfer; **L**, square insert with 15° double chamfer; **M**, square insert with 3° double chamfer; **N**, truncated triangle insert; and **P**, flattened corner triangle insert.

8) *Special Cutting Point Definition:* The eighth position, if it follows a letter in the 7th position, is a number indicating the number of  $\frac{1}{64}$ ths of an inch measured parallel to the edge of the facet.

9) *Hand:* **R**, right; **L**, left; to be used when required in ninth position.

10) *Other Conditions:* The tenth position defines special conditions (such as edge treatment, surface finish) as follows: **A**, honed, 0.0005 inch to less than 0.003 inch; **B**, honed, 0.003 inch to less than 0.005 inch; **C**, honed, 0.005 inch to less than 0.007 inch; **J**, polished, 4 microinch arithmetic average (AA) on rake surfaces only; **T**, chamfered, manufacturer's standard negative land, rake face only.

**Indexable Insert Tool Holders.**—Indexable insert tool holders are made from a good grade of steel which is heat treated to a hardness of 44 to 48 Rc for most normal applications. Accurate pockets that serve to locate the insert in position and to provide surfaces against which the insert can be clamped are machined in the ends of tool holders. A cemented carbide seat usually is provided, and is held in the bottom of the pocket by a screw or by the clamping pin, if one is used. The seat is necessary to provide a flat bearing surface upon which the insert can rest and, in so doing, it adds materially to the ability of the insert to withstand the cutting load. The seating surface of the holder may provide a positive-, negative-, or a neutral-rake orientation to the insert when it is in position on the holder. Holders, therefore, are classified as positive, negative, or neutral rake.

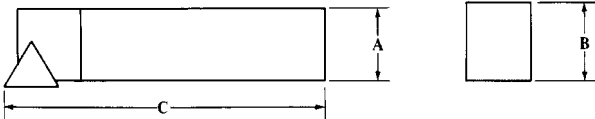
Four basic methods are used to clamp the insert on the holder: 1) Clamping, usually top clamping; 2) Pin-lock clamping; 3) Multiple clamping using a clamp, usually a top clamp, and a pin lock; and 4) Clamping the insert with a machine screw.

All top clamps are actuated by a screw that forces the clamp directly against the insert. When required, a cemented-carbide, plate-type chipbreaker is placed between the clamp and the insert. Pin-lock clamps require an insert having a hole: the pin acts against the walls of the hole to clamp the insert firmly against the seating surfaces of the holder. Multiple or combination clamping, simultaneously using both a pin-lock and a top clamp, is recommended when taking heavier or interrupted cuts. Holders are available on which all the above-mentioned methods of clamping may be used. Other holders are made with only a

top clamp or a pin lock. Screw-on type holders use a machine screw to hold the insert in the pocket. Most standard indexable insert holders are either straight-shank or offset-shank, although special holders are made having a wide variety of configurations.

The common shank sizes of indexable insert tool holders are shown in Table 1. Not all styles are available in every shank size. Positive- and negative-rake tools are also not available in every style or shank size. Some manufacturers provide additional shank sizes for certain tool holder styles. For more complete details the manufacturers' catalogs must be consulted.

**Table 1. Standard Shank Sizes for Indexable Insert Holders**



| Basic Shank Size  | Shank Dimensions for Indexable Insert Holders |       |       |       |                |        |
|---|---|-------|-------|-------|----------------|--------|
|   | A   |       | B     |       | C <sup>a</sup> |        |
|   | In.   | mm    | In.   | mm    | In.            | mm     |
| $\frac{1}{2} \times \frac{1}{2} \times 4\frac{1}{2}$    | 0.500   | 12.70 | 0.500 | 12.70 | 4.500          | 114.30 |
| $\frac{3}{8} \times \frac{3}{8} \times 4\frac{1}{2}$    | 0.625   | 15.87 | 0.625 | 15.87 | 4.500          | 114.30 |
| $\frac{3}{8} \times 1\frac{1}{4} \times 6$              | 0.625   | 15.87 | 1.250 | 31.75 | 6.000          | 152.40 |
| $\frac{3}{4} \times \frac{3}{4} \times 4\frac{1}{2}$    | 0.750   | 19.05 | 0.750 | 19.05 | 4.500          | 114.30 |
| $\frac{3}{4} \times 1 \times 6$                         | 0.750   | 19.05 | 1.000 | 25.40 | 6.000          | 152.40 |
| $\frac{3}{4} \times 1\frac{1}{4} \times 6$              | 0.750   | 19.05 | 1.250 | 31.75 | 6.000          | 152.40 |
| $1 \times 1 \times 6$                                   | 1.000   | 25.40 | 1.000 | 25.40 | 6.000          | 152.40 |
| $1 \times 1\frac{1}{4} \times 6$                        | 1.000   | 25.40 | 1.250 | 31.75 | 6.000          | 152.40 |
| $1 \times 1\frac{1}{2} \times 6$                        | 1.000   | 25.40 | 1.500 | 38.10 | 6.000          | 152.40 |
| $1\frac{1}{2} \times 1\frac{1}{4} \times 7$             | 1.250   | 31.75 | 1.250 | 31.75 | 7.000          | 177.80 |
| $1\frac{1}{4} \times 1\frac{1}{2} \times 8$             | 1.250   | 31.75 | 1.500 | 38.10 | 8.000          | 203.20 |
| $1\frac{3}{8} \times 2\frac{1}{16} \times 6\frac{3}{8}$ | 1.375   | 34.92 | 2.062 | 52.37 | 6.380          | 162.05 |
| $1\frac{1}{2} \times 1\frac{1}{2} \times 7$             | 1.500   | 38.10 | 1.500 | 38.10 | 7.000          | 177.80 |
| $1\frac{3}{4} \times 1\frac{3}{4} \times 9\frac{1}{2}$  | 1.750   | 44.45 | 1.750 | 44.45 | 9.500          | 241.30 |
| $2 \times 2 \times 8$                                   | 2.000   | 50.80 | 2.000 | 50.80 | 8.000          | 203.20 |

<sup>a</sup>Holder length; may vary by manufacturer. Actual shank length depends on holder style.

**Identification System for Indexable Insert Holders.**—The following identification system conforms to the American National Standard, ANSI B212.5-2002, Metric Holders for Indexable Inserts.

Each position in the system designates a feature of the holder in the following sequence:

1 2 3 4 5 — 6 — 7 — 8<sup>a</sup> — 9 — 10<sup>a</sup>  
**C T N A R — 85 — 25 — D — 16 — Q**

1) *Method of Holding Horizontally Mounted Insert:* The method of holding or clamping is designated by a letter: **C**, top clamping, insert without hole; **M**, top and hole clamping, insert with hole; **P**, hole clamping, insert with hole; **S**, screw clamping through hole, insert with hole; **W**, wedge clamping.

2) *Insert Shape:* The insert shape is identified by a letter: **H**, hexagonal; **O**, octagonal; **P**, pentagonal; **S**, square; **T**, triangular; **C**, rhombic, 80° included angle; **D**, rhombic, 55° included angle; **E**, rhombic, 75° included angle; **M**, rhombic, 86° included angle; **V**, rhombic, 35° included angle; **W**, hexagonal, 80° included angle; **L**, rectangular; **A**, parallelogram, 85° included angle; **B**, parallelogram, 82° included angle; **K**, parallelogram, 55° included angle; **R**, round. The included angle is always the smaller angle.

3) *Holder Style*: The holder style designates the shank style and the side cutting edge angle, or end cutting edge angle, or the purpose for which the holder is used. It is designated by a letter: **A**, for straight shank with  $0^\circ$  side cutting edge angle; **B**, straight shank with  $15^\circ$  side cutting edge angle; **C**, straight-shank end cutting tool with  $0^\circ$  end cutting edge angle; **D**, straight shank with  $45^\circ$  side cutting edge angle; **E**, straight shank with  $30^\circ$  side cutting edge angle; **F**, offset shank with  $0^\circ$  end cutting edge angle; **G**, offset shank with  $0^\circ$  side cutting edge angle; **J**, offset shank with negative  $3^\circ$  side cutting edge angle; **K**, offset shank with  $15^\circ$  end cutting edge angle; **L**, offset shank with negative  $5^\circ$  side cutting edge angle and  $5^\circ$  end cutting edge angle; **M**, straight shank with  $40^\circ$  side cutting edge angle; **N**, straight shank with  $27^\circ$  side cutting edge angle; **R**, offset shank with  $15^\circ$  side cutting edge angle; **S**, offset shank with  $45^\circ$  side cutting edge angle; **T**, offset shank with  $30^\circ$  side cutting edge angle; **U**, offset shank with negative  $3^\circ$  end cutting edge angle; **V**, straight shank with  $17\frac{1}{2}^\circ$  side cutting edge angle; **W**, offset shank with  $30^\circ$  end cutting edge angle; **Y**, offset shank with  $5^\circ$  end cutting edge angle.

4) *Normal Clearances*: The normal clearances of inserts are identified by letters: **A**,  $3^\circ$ ; **B**,  $5^\circ$ ; **C**,  $7^\circ$ ; **D**,  $15^\circ$ ; **E**,  $20^\circ$ ; **F**,  $25^\circ$ ; **G**,  $30^\circ$ ; **N**,  $0^\circ$ ; **P**,  $11^\circ$ .

5) *Hand of tool*: The hand of the tool is designated by a letter: **R** for right-hand; **L**, left-hand; and **N**, neutral, or either hand.

6) *Tool Height for Rectangular Shank Cross Sections*: The tool height for tool holders with a rectangular shank cross section and the height of cutting edge equal to shank height is given as a two-digit number representing this value in millimeters. For example, a height of 32 mm would be encoded as 32; 8 mm would be encoded as 08, where the one-digit value is preceded by a zero.

7) *Tool Width for Rectangular Shank Cross Sections*: The tool width for tool holders with a rectangular shank cross section is given as a two-digit number representing this value in millimeters. For example, a width of 25 mm would be encoded as 25; 8 mm would be encoded as 08, where the one-digit value is preceded by a zero.

8) *Tool Length*: The tool length is designated by a letter: **A**, 32 mm; **B**, 40 mm; **C**, 50 mm; **D**, 60 mm; **E**, 70 mm; **F**, 80 mm; **G**, 90 mm; **H**, 100 mm; **J**, 110 mm; **K**, 125 mm; **L**, 140 mm; **M**, 150 mm; **N**, 160 mm; **P**, 170 mm; **Q**, 180 mm; **R**, 200 mm; **S**, 250 mm; **T**, 300 mm; **U**, 350 mm; **V**, 400 mm; **W**, 450 mm; **X**, special length to be specified; **Y**, 500 mm.

9) *Indexable Insert Size*: The size of indexable inserts is encoded as follows: For insert shapes **C**, **D**, **E**, **H**, **M**, **O**, **P**, **R**, **S**, **T**, **V**, the side length (the diameter for **R** inserts) in millimeters is used as a two-digit number, with decimals being disregarded. For example, the symbol for a side length of 16.5 mm is 16. For insert shapes **A**, **B**, **K**, **L**, the length of the main cutting edge or of the longer cutting edge in millimeters is encoded as a two-digit number, disregarding decimals. If the symbol obtained has only one digit, then it should be preceded by a zero. For example, the symbol for a main cutting edge of 19.5 mm is 19; for an edge of 9.5 mm, the symbol is 09.

10) *Special Tolerances*: Special tolerances are indicated by a letter: **Q**, back and end qualified tool; **F**, front and end qualified tool; **B**, back, front, and end qualified tool. A qualified tool is one that has tolerances of  $\pm 0.08$  mm for dimensions *F*, *G*, and *C*. (See Table 2.)

**Table 2. Letter Symbols for Qualification of Tool Holders**  
Position 10 ANSI B212.5-2002

| Qualification of Tool Holder | Letter Symbol               |                              |                                     |
|------------------------------|-----------------------------|------------------------------|-------------------------------------|
|                              | Q                           | F                            | B                                   |
|                              |                             |                              |                                     |
|                              | Back and end qualified tool | Front and end qualified tool | Back, front, and end qualified tool |

**Selecting Indexable Insert Holders.**—A guide for selecting indexable insert holders is provided by [Table 3b](#). Some operations such as deep grooving, cut-off, and threading are not given in this table. However, tool holders designed specifically for these operations are available. The boring operations listed in [Table 3b](#) refer primarily to larger holes, into which the holders will fit. Smaller holes are bored using boring bars. An examination of this table shows that several tool-holder styles can be used and frequently are used for each operation. Selection of the best holder for a given job depends largely on the job and there are certain basic facts that should be considered in making the selection.

*Rake Angle:* A negative-rake insert has twice as many cutting edges available as a comparable positive-rake insert. Sometimes the tool life obtained when using the second face may be less than that obtained on the first face because the tool wear on the cutting edges of the first face may reduce the insert strength. Nevertheless, the advantage of negative-rake inserts and holders is such that they should be considered first in making any choice. Positive-rake holders should be used where lower cutting forces are required, as when machining slender or small-diameter parts, when chatter may occur, and for machining some materials, such as aluminum, copper, and certain grades of stainless steel, when positive-negative rake inserts can sometimes be used to advantage. These inserts are held on negative-rake holders that have their rake surfaces ground or molded to form a positive-rake angle.

*Insert Shape:* The configuration of the workpiece, the operation to be performed, and the lead angle required often determine the insert shape. When these factors need not be considered, the insert shape should be selected on the basis of insert strength and the maximum number of cutting edges available. Thus, a round insert is the strongest and has a maximum number of available cutting edges. It can be used with heavier feeds while producing a good surface finish. Round inserts are limited by their tendency to cause chatter, which may preclude their use. The square insert is the next most effective shape, providing good corner strength and more cutting edges than all other inserts except the round insert. The only limitation of this insert shape is that it must be used with a lead angle. Therefore, the square insert cannot be used for turning square shoulders or for back-facing. Triangle inserts are the most versatile and can be used to perform more operations than any other insert shape. The 80-degree diamond insert is designed primarily for heavy turning and facing operations, using the 100-degree corners, and for turning and back-facing square shoulders using the 80-degree corners. The 55- and 35-degree diamond inserts are intended primarily for tracing.

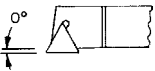
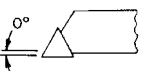
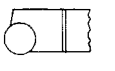
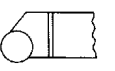
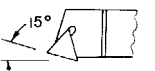
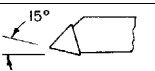
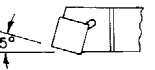

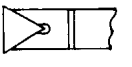
*Lead Angle:* Tool holders should be selected to provide the largest possible lead angle, although limitations are sometimes imposed by the nature of the job. For example, when turning and back-facing a shoulder, a negative lead angle must be used. Slender or small-diameter parts may deflect, causing difficulties in holding size, or chatter when the lead angle is too large.

*End Cutting Edge Angle:* When tracing or contour turning, the plunge angle is determined by the end cutting edge angle. A 2-deg minimum clearance angle should be provided between the workpiece surface and the end cutting edge of the insert. [Table 3a](#) provides the maximum plunge angle for holders commonly used to plunge when tracing where insert shape identifiers are *S* = square, *T* = triangle, *D* = 55-deg diamond, *V* = 35-deg diamond. When severe cratering cannot be avoided, an insert having a small, end cutting edge angle is desirable to delay the crater breakthrough behind the nose. For very heavy cuts a small, end cutting edge angle will strengthen the corner of the tool. Tool holders for numerical control machines are discussed in the NC section, beginning page [1309](#).


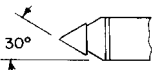

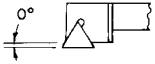

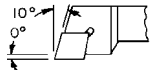
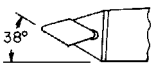
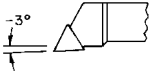


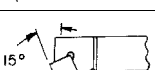
**Table 3a. Maximum Plunge Angle for Tracing or Contour Turning**

| Tool Holder Style | Insert Shape | Maximum Plunge Angle | Tool Holder Style | Insert Shape | Maximum Plunge Angle |
|-------------------|--------------|----------------------|-------------------|--------------|----------------------|
| E                 | T            | 58°                  | J                 | D            | 30°                  |
| D and S           | S            | 43°                  | J                 | V            | 50°                  |
| H                 | D            | 71°                  | N                 | T            | 55°                  |
| J                 | T            | 25°                  | N                 | D            | 58°–60°              |

**Table 3b. Indexable Insert Holder Application Guide**



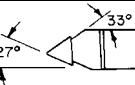
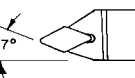
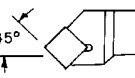
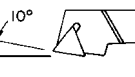
| Tool  | Tool Holder Style | Insert Shape | N-Negative<br>P-Positive | Application |      |               |                   |       |        |         |      |       |
|---|-------------------|--------------|--------------------------|-------------|------|---------------|-------------------|-------|--------|---------|------|-------|
|   |                   |              |                          | Turn        | Face | Turn and Face | Turn and Backface | Trace | Groove | Chamfer | Bore | Plane |
|     | A                 | T            | N                        | ●           | ●    |               |                   |       |        |         | ●    |       |
|   |                   |              | P                        | ●           | ●    |               |                   |       |        |         | ●    |       |
|     | A                 | T            | N                        | ●           | ●    |               |                   | ●     |        |         |      |       |
|   |                   |              | P                        | ●           | ●    |               |                   | ●     |        |         |      |       |
|    | A                 | R            | N                        | ●           | ●    | ●             |                   |       |        |         |      | ●     |
|   |                   |              | P                        |             |      |               |                   |       |        |         |      |       |
|   | A                 | R            | N                        | ●           | ●    | ●             |                   | ●     |        |         |      | ●     |
|   |                   |              | P                        |             |      |               |                   |       |        |         |      |       |
|   | B                 | T            | N                        | ●           | ●    |               |                   |       |        |         | ●    |       |
|   |                   |              | P                        | ●           | ●    |               |                   |       |        |         | ●    |       |
|   | B                 | T            | N                        | ●           | ●    |               |                   | ●     |        |         | ●    |       |
|   |                   |              | P                        | ●           | ●    |               |                   | ●     |        |         | ●    |       |
|   | B                 | S            | N                        | ●           | ●    |               |                   |       |        |         | ●    |       |
|   |                   |              | P                        | ●           | ●    |               |                   |       |        |         | ●    |       |
|   | B                 | C            | N                        | ●           | ●    | ●             |                   |       |        |         | ●    | ●     |
|   |                   |              | P                        |             |      |               |                   |       |        |         |      |       |
|  | C                 | T            | N                        | ●           | ●    |               |                   |       | ●      | ●       |      |       |
|   |                   |              | P                        | ●           | ●    |               |                   |       | ●      | ●       |      |       |

**Table 3b. (Continued) Indexable Insert Holder Application Guide**

| Tool   | Tool Holder Style | Insert Shape | N-Negative<br>P-Positive | Application |      |               |                   |       |        |         |      |       |
|--|-------------------|--------------|--------------------------|-------------|------|---------------|-------------------|-------|--------|---------|------|-------|
|  |                   |              |                          | Turn        | Face | Turn and Face | Turn and Backface | Trace | Groove | Chamfer | Bore | Plane |
|    | D                 | S            | N                        | ●           | ●    | ●             |                   | ●     |        | ●       | ●    | ●     |
|  |                   |              | P                        | ●           | ●    | ●             |                   | ●     |        | ●       | ●    | ●     |
|    | E                 | T            | N                        | ●           | ●    |               |                   | ●     | ●      | ●       |      |       |
|  |                   |              | P                        | ●           | ●    |               |                   | ●     | ●      | ●       |      |       |
|   | F                 | T            | N                        | ●           | ●    |               |                   |       |        |         | ●    |       |
|  |                   |              | P                        | ●           | ●    |               |                   |       |        |         |      | ●     |
|    | G                 | T            | N                        | ●           | ●    |               |                   |       |        |         | ●    |       |
|  |                   |              | P                        | ●           | ●    |               |                   |       |        |         |      | ●     |
|   | G                 | R            | N                        | ●           | ●    | ●             |                   |       |        |         |      |       |
|  |                   |              | P                        |             |      |               |                   |       |        |         |      |       |
|    | G                 | C            | N                        | ●           | ●    | ●             |                   |       |        |         |      |       |
|  |                   |              | P                        | ●           | ●    | ●             |                   |       |        |         |      |       |
|   | H                 | D            | N                        | ●           | ●    |               |                   | ●     |        |         |      |       |
|  |                   |              | P                        |             |      |               |                   |       |        |         |      |       |
|  | J                 | T            | N                        |             |      |               | ●                 | ●     |        |         |      |       |
|  |                   |              | P                        |             |      |               | ●                 | ●     |        |         |      |       |
|  | J                 | D            | N                        |             |      |               | ●                 | ●     |        |         |      |       |
|  |                   |              | P                        |             |      |               |                   |       |        |         |      |       |
|  | J                 | V            | N                        |             |      |               | ●                 | ●     |        |         |      |       |
|  |                   |              | P                        |             |      |               |                   |       |        |         |      |       |
|  | K                 | S            | N                        | ●           | ●    |               |                   |       |        |         | ●    |       |
|  |                   |              | P                        | ●           | ●    |               |                   |       |        |         |      | ●     |



**Table 3b. (Continued) Indexable Insert Holder Application Guide**

| Tool  | Tool Holder Style | Insert Shape | N-Negative<br>P-Positive | Application |      |               |                   |       |        |         |      |       |   |
|---|-------------------|--------------|--------------------------|-------------|------|---------------|-------------------|-------|--------|---------|------|-------|---|
|   |                   |              |                          | Turn        | Face | Turn and Face | Turn and Backface | Trace | Groove | Chamfer | Bore | Plane |   |
|   | K                 | C            | N                        | ●           | ●    |               |                   |       |        |         |      | ●     |   |
|   | L                 | C            | N                        |             |      | ●             | ●                 |       |        |         |      |       |   |
|   | N                 | T            | N                        | ●           | ●    |               |                   | ●     |        |         |      |       |   |
|   |                   |              | P                        | ●           | ●    |               |                   | ●     |        |         |      |       |   |
|   | N                 | D            | N                        | ●           | ●    |               |                   | ●     |        |         |      |       |   |
|   | S                 | S            | N                        | ●           | ●    | ●             |                   | ●     |        |         | ●    | ●     | ● |
|   |                   |              | P                        | ●           | ●    | ●             |                   | ●     |        |         | ●    | ●     | ● |
|  | W                 | S            | N                        | ●           | ●    |               |                   |       |        |         |      |       |   |

**Sintered Carbide Blanks and Cutting Tools**

**Sintered Carbide Blanks.**—As shown in [Table 4](#), American National Standard ANSI B212.1-2002 provides standard sizes and designations for eight styles of sintered carbide blanks. These blanks are the unground solid carbide from which either solid or tipped cutting tools are made. Tipped cutting tools are made by brazing a blank onto a shank to produce the cutting tool; these tools differ from carbide *insert* cutting tools which consist of a carbide insert held mechanically in a tool holder. A typical single-point carbide-tipped cutting tool is shown in [Fig. 1](#) on page 766.

**Single-Point, Sintered-Carbide-Tipped Tools.**—American National Standard ANSI B212.1-2002 covers eight different styles of single-point, carbide-tipped general purpose tools. These styles are designated by the letters A to G inclusive. Styles A, B, F, G, and E with offset point are either right- or left-hand cutting as indicated by the letters R or L. Dimensions of tips and shanks are given in [Tables 5 to 12](#). For dimensions and tolerances not shown, and for the identification system, dimensions, and tolerances of sintered carbide boring tools, see the Standard.

A number follows the letters of the tool style and hand designation and for square shank tools, represents the number of sixteenths of an inch of width, *W*, and height, *H*. With rectangular shanks, the first digit of the number indicates the number of eighths of an inch in the shank width, *W*, and the second digit the number of quarters of an inch in the shank

**Table 4. American National Standard Sizes and Designations for Carbide Blanks**  
ANSI B212.1-2002

| Blank Dimensions <sup>a</sup> |          |          | Style <sup>b</sup> |      | Blank Dimensions <sup>a</sup> |          |          | Style <sup>b</sup> |                    |      |       |
|-------------------------------|----------|----------|--------------------|------|-------------------------------|----------|----------|--------------------|--------------------|------|-------|
|                               |          |          | 1000               | 2000 |                               |          |          | 0000               | 1000               | 3000 | 4000  |
| <i>T</i>                      | <i>W</i> | <i>L</i> | Blank Designation  |      | <i>T</i>                      | <i>W</i> | <i>L</i> | Blank Designation  |                    |      |       |
| 1/16                          | 1/8      | 5/8      | 1010               | 2010 | 1/4                           | 3/8      | 9/16     | 0350               | 1350               | 3350 | 4350  |
| 1/16                          | 5/32     | 1/4      | 1015               | 2015 | 1/4                           | 3/8      | 3/4      | 0360               | 1360               | 3360 | 4360  |
| 1/16                          | 3/16     | 1/4      | 1020               | 2020 | 1/4                           | 7/16     | 5/8      | 0370               | 1370               | 3370 | 4370  |
| 1/16                          | 1/4      | 1/4      | 1025               | 2025 | 1/4                           | 1/2      | 3/4      | 0380               | 1380               | 3380 | 4380  |
| 1/16                          | 1/4      | 5/16     | 1030               | 2030 | 1/4                           | 9/16     | 1        | 0390               | 1390               | 3390 | 4390  |
| 3/32                          | 1/8      | 3/4      | 1035               | 2035 | 1/4                           | 5/8      | 5/8      | 0400               | 1400               | 3400 | 4400  |
| 3/32                          | 3/16     | 5/16     | 1040               | 2040 | 1/4                           | 3/4      | 3/4      | 0405               | 1405               | 3405 | 4405  |
| 3/32                          | 3/16     | 1/2      | 1050               | 2050 | 1/4                           | 1/4      | 3/4      | 0410               | 1410               | 3410 | 4410  |
| 3/32                          | 1/4      | 3/8      | 1060               | 2060 | 1/4                           | 1        | 1        | 0415               | 1415               | 3415 | 4415  |
| 3/32                          | 1/4      | 1/2      | 1070               | 2070 | 5/16                          | 7/16     | 5/8      | 0420               | 1420               | 3420 | 4420  |
| 3/32                          | 5/16     | 3/8      | 1080               | 2080 | 5/16                          | 7/16     | 15/16    | 0430               | 1430               | 3430 | 4430  |
| 3/32                          | 3/8      | 3/8      | 1090               | 2090 | 5/16                          | 1/2      | 3/4      | 0440               | 1440               | 3440 | 4440  |
| 3/32                          | 3/8      | 1/2      | 1100               | 2100 | 5/16                          | 1/2      | 1        | 0450               | 1450               | 3450 | 4450  |
| 3/32                          | 7/16     | 1/2      | 1105               | 2105 | 5/16                          | 5/8      | 1        | 0460               | 1460               | 3460 | 4460  |
| 3/32                          | 5/16     | 3/8      | 1080               | 2080 | 5/16                          | 3/4      | 3/4      | 0470               | 1470               | 3470 | 4470  |
| 1/8                           | 3/16     | 3/4      | 1110               | 2110 | 5/16                          | 3/4      | 1        | 0475               | 1475               | 3475 | 4475  |
| 1/8                           | 1/4      | 1/2      | 1120               | 2120 | 5/16                          | 3/4      | 1 1/4    | 0480               | 1480               | 3480 | 4480  |
| 1/8                           | 1/4      | 5/8      | 1130               | 2130 | 3/8                           | 1/2      | 3/4      | 0490               | 1490               | 3490 | 4490  |
| 1/8                           | 1/4      | 3/4      | 1140               | 2140 | 3/8                           | 1/2      | 1        | 0500               | 1500               | 3500 | 4500  |
| 1/8                           | 5/16     | 7/16     | 1150               | 2150 | 3/8                           | 5/8      | 1        | 0510               | 1510               | 3510 | 4510  |
| 1/8                           | 5/16     | 1/2      | 1160               | 2160 | 3/8                           | 5/8      | 1 1/4    | 0515               | 1515               | 3515 | 4515  |
| 1/8                           | 3/16     | 3/4      | 1110               | 2110 | 3/8                           | 3/4      | 1 1/4    | 0520               | 1520               | 3520 | 4520  |
| 1/8                           | 5/16     | 5/8      | 1170               | 2170 | 3/8                           | 3/4      | 1 1/2    | 0525               | 1525               | 3525 | 4525  |
| 1/8                           | 3/8      | 1/2      | 1180               | 2180 | 1/2                           | 3/4      | 1        | 0530               | 1530               | 3530 | 4530  |
| 1/8                           | 3/8      | 3/4      | 1190               | 2190 | 1/2                           | 3/4      | 1 1/4    | 0540               | 1540               | 3540 | 4540  |
| 1/8                           | 1/2      | 1/2      | 1200               | 2200 | 3/8                           | 1/2      | 3/4      | 0490               | 1490               | 3490 | 4490  |
| 1/8                           | 1/2      | 3/4      | 1210               | 2210 | 1/2                           | 3/4      | 1 1/2    | 0550               | 1550               | 3550 | 4550  |
| 1/8                           | 3/4      | 3/4      | 1215               | 2215 |                               |          |          |                    |                    |      |       |
| 5/32                          | 3/8      | 9/16     | 1220               | 2220 | <i>T</i>                      | <i>W</i> | <i>L</i> | <i>F</i>           | Style <sup>b</sup> |      |       |
| 5/32                          | 3/8      | 3/4      | 1230               | 2230 | 1/16                          | 1/4      | 5/16     | ...                | 5000               | 6000 | 70000 |
| 5/32                          | 5/8      | 5/8      | 1240               | 2240 | 3/32                          | 1/4      | 3/8      | 1/16               | ...                | ...  | 7060  |
| 3/16                          | 5/16     | 7/16     | 1250               | 2250 | 3/32                          | 5/16     | 3/8      | ...                | 5080               | 6080 | ...   |
| 3/16                          | 5/16     | 5/8      | 1260               | 2260 | 3/32                          | 3/8      | 1/2      | ...                | 5100               | 6100 | ...   |
| 3/16                          | 3/8      | 1/2      | 1270               | 2270 | 3/32                          | 7/16     | 1/2      | ...                | 5105               | ...  | ...   |
| 3/16                          | 3/8      | 3/8      | 1280               | 2280 | 1/8                           | 5/16     | 5/8      | 3/32               | ...                | ...  | 7170  |
| 3/16                          | 3/8      | 3/4      | 1290               | 2290 | 3/32                          | 1/4      | 3/8      | 1/16               | ...                | ...  | 7060  |
| 3/16                          | 7/16     | 5/8      | 1300               | 2300 | 1/8                           | 1/2      | 1/2      | ...                | 5200               | 6200 | ...   |
| 3/16                          | 7/16     | 13/16    | 1310               | 2310 | 5/32                          | 3/8      | 3/4      | 1/8                | ...                | ...  | 7230  |
| 3/16                          | 1/2      | 1/2      | 1320               | 2320 | 5/32                          | 5/8      | 5/8      | ...                | 5240               | 6240 | ...   |
| 3/16                          | 1/2      | 3/4      | 1330               | 2330 | 3/16                          | 3/4      | 3/4      | ...                | 5340               | 6340 | ...   |
| 3/16                          | 3/4      | 3/4      | 1340               | 2340 | 1/4                           | 1        | 3/4      | ...                | 5410               | ...  | ...   |

<sup>a</sup> All dimensions are in inches.<sup>b</sup> See Fig. 1 on page 766 for a description of styles.

height, *H*. One exception is the 1 1/2 × 2-inch size which has been arbitrarily assigned the number 90.

A typical single-point carbide tipped cutting tool is shown in Fig. 2. The side rake, side relief, and the clearance angles are normal to the side-cutting edge, rather than the shank, to facilitate its being ground on a tilting-table grinder. The end-relief and clearance angles are

## CARBIDE TIPS AND TOOLS

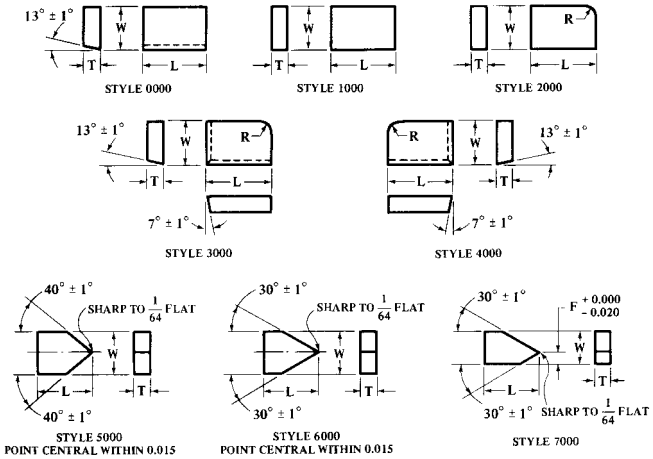


Fig. 1. Eight styles of sintered carbide blanks (see Table 4.)

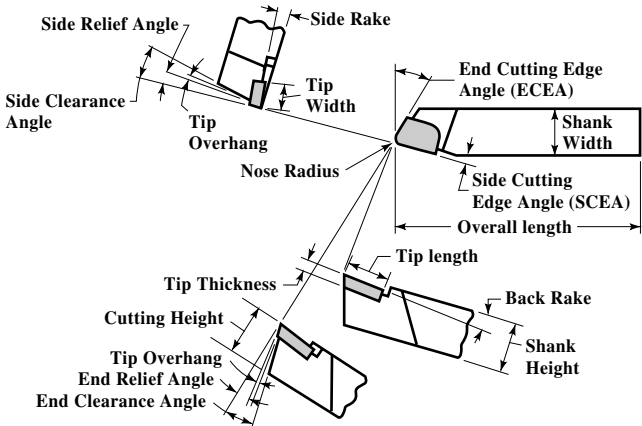


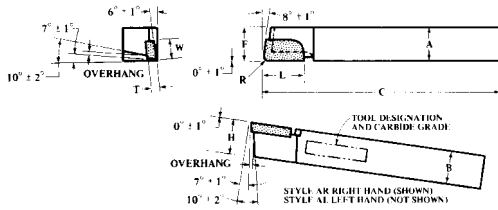
Fig. 2. A typical single-point carbide tipped cutting tool.

normal to the end-cutting edge. The back-rake angle is parallel to the side-cutting edge. The tip of the brazed carbide blank overhangs the shank of the tool by either  $\frac{1}{32}$  or  $\frac{1}{16}$  inch, depending on the size of the tool. For tools in Tables 5, 6, 7, 8, 11 and , the maximum overhang is  $\frac{1}{32}$  inch for shank sizes 4, 5, 6, 7, 8, 10, 12 and 44; for other shank sizes in these tables, the maximum overhang is  $\frac{1}{16}$  inch. In Tables 9 and 10 all tools have maximum overhang of  $\frac{1}{32}$  inch.

**Single-point Tool Nose Radii:** The tool nose radii recommended in the American National Standard are as follows: For square-shank tools up to and including  $\frac{3}{8}$ -inch square tools,  $\frac{1}{64}$  inch; for those over  $\frac{3}{8}$ -inch square through  $1\frac{1}{4}$ -inches square,  $\frac{1}{32}$  inch; and for those above  $1\frac{1}{4}$ -inches square,  $\frac{1}{16}$  inch. For rectangular-shank tools with shank section of  $\frac{1}{2} \times 1$  inch through  $1 \times 1\frac{1}{2}$  inches, the nose radii are  $\frac{1}{32}$  inch, and for  $1 \times 2$  and  $1\frac{1}{2} \times 2$  inch shanks, the nose radius is  $\frac{1}{16}$  inch.

**Single-point Tool Angle Tolerances:** The tool angles shown on the diagrams in the Tables 5 through 12 are general recommendations. Tolerances applicable to these angles are  $\pm 1$  degree on all angles except end and side clearance angles; for these the tolerance is  $\pm 2$  degrees.

**Table 5. American National Standard Style A Carbide Tipped Tools**  
ANSI B212.1-2002



The diagrams illustrate the geometry of Style A carbide tipped tools. The top-left diagram shows a square shank tool with a cutting edge angle of  $7^\circ \pm 1^\circ$ , a side clearance angle of  $10^\circ \pm 2^\circ$ , and a nose radius of  $6'' - 1''$ . The top-right diagram shows a rectangular shank tool with a cutting edge angle of  $7^\circ \pm 1^\circ$ , a side clearance angle of  $10^\circ \pm 2^\circ$ , and a nose radius of  $8'' + 1''$ . The bottom diagram shows a rectangular shank tool with a cutting edge angle of  $7^\circ \pm 1^\circ$ , a side clearance angle of  $10^\circ \pm 2^\circ$ , and a nose radius of  $7'' + 1''$ . Dimensions include shank width (W), shank height (H), shank length (C), tip thickness (T), tip width (B), and tip length (L). The tool designation and carbide grade are indicated on the tool.

| Designation           |                       | Shank Dimensions |                |                | Tip Designation <sup>a</sup> | Tip Dimensions |                |                  |
|-----------------------|-----------------------|------------------|----------------|----------------|------------------------------|----------------|----------------|------------------|
| Style AR <sup>a</sup> | Style AL <sup>a</sup> | Width A          | Height B       | Length C       |                              | Thickness T    | Width W        | Length L         |
| Square Shank          |                       |                  |                |                |                              |                |                |                  |
| AR 4                  | AL 4                  | $\frac{1}{4}$    | $\frac{1}{4}$  | 2              | 2040                         | $\frac{3}{32}$ | $\frac{3}{16}$ | $\frac{5}{16}$   |
| AR 5                  | AL 5                  | $\frac{5}{16}$   | $\frac{5}{16}$ | $2\frac{1}{4}$ | 2070                         | $\frac{3}{32}$ | $\frac{1}{4}$  | $\frac{1}{2}$    |
| AR 6                  | AL 6                  | $\frac{3}{8}$    | $\frac{3}{8}$  | $2\frac{1}{2}$ | 2070                         | $\frac{3}{32}$ | $\frac{1}{4}$  | $\frac{1}{2}$    |
| AR 7                  | AL 7                  | $\frac{7}{16}$   | $\frac{7}{16}$ | 3              | 2070                         | $\frac{3}{32}$ | $\frac{1}{4}$  | $\frac{1}{2}$    |
| AR 8                  | AL 8                  | $\frac{1}{2}$    | $\frac{1}{2}$  | $3\frac{1}{2}$ | 2170                         | $\frac{1}{8}$  | $\frac{5}{16}$ | $\frac{5}{8}$    |
| AR 10                 | AL 10                 | $\frac{5}{8}$    | $\frac{5}{8}$  | 4              | 2230                         | $\frac{5}{32}$ | $\frac{3}{8}$  | $\frac{3}{4}$    |
| AR 12                 | AL 12                 | $\frac{3}{4}$    | $\frac{3}{4}$  | $4\frac{1}{2}$ | 2310                         | $\frac{3}{16}$ | $\frac{7}{16}$ | $1\frac{13}{16}$ |
| AR 16                 | AL 16                 | 1                | 1              | 6              | { P3390, P4390               | $\frac{1}{4}$  | $\frac{9}{16}$ | 1                |
| AR 20                 | AL 20                 | $1\frac{1}{4}$   | $1\frac{1}{4}$ | 7              | { P3460, P4460               | $\frac{5}{16}$ | $\frac{5}{8}$  | 1                |
| AR 24                 | AL 24                 | $1\frac{1}{2}$   | $1\frac{1}{2}$ | 8              | { P3510, P4510               | $\frac{3}{8}$  | $\frac{5}{8}$  | 1                |
| Rectangular Shank     |                       |                  |                |                |                              |                |                |                  |
| AR 44                 | AL 44                 | $\frac{1}{2}$    | 1              | 6              | P2260                        | $\frac{3}{16}$ | $\frac{5}{16}$ | $\frac{5}{8}$    |
| AR 54                 | AL 54                 | $\frac{5}{8}$    | 1              | 6              | { P3360, P4360               | $\frac{1}{4}$  | $\frac{3}{8}$  | $\frac{3}{4}$    |
| AR 55                 | AL 55                 | $\frac{5}{8}$    | $1\frac{1}{4}$ | 7              | { P3360, P4360               | $\frac{1}{4}$  | $\frac{3}{8}$  | $\frac{3}{4}$    |
| AR 64                 | AL 64                 | $\frac{3}{4}$    | 1              | 6              | { P3380, P4380               | $\frac{1}{4}$  | $\frac{1}{2}$  | $\frac{3}{4}$    |
| AR 66                 | AL 66                 | $\frac{3}{4}$    | $1\frac{1}{2}$ | 8              | { P3430, P4430               | $\frac{5}{16}$ | $\frac{7}{16}$ | $1\frac{15}{16}$ |
| AR 85                 | AL 85                 | 1                | $1\frac{1}{4}$ | 7              | { P3460, P4460               | $\frac{5}{16}$ | $\frac{5}{8}$  | 1                |
| AR 86                 | AL 86                 | 1                | $1\frac{1}{2}$ | 8              | { P3510, P4510               | $\frac{3}{8}$  | $\frac{5}{8}$  | 1                |
| AR 88                 | AL 88                 | 1                | 2              | 10             | { P3510, P4510               | $\frac{3}{8}$  | $\frac{5}{8}$  | 1                |
| AR 90                 | AL 90                 | $1\frac{1}{2}$   | 2              | 10             | { P3540, P4540               | $\frac{1}{2}$  | $\frac{3}{4}$  | $1\frac{1}{4}$   |

<sup>a</sup> "A" is straight shank, 0 deg., SCEA (side-cutting-edge angle). "R" is right-cut. "L" is left-cut. Where a pair of tip numbers is shown, the upper number applies to AR tools, the lower to AL tools. All dimensions are in inches.

**Table 6. American National Standard Style B Carbide Tipped Tools with 15-degree Side-cutting-edge Angle ANSI B212.1-2002**

Style GR right hand (shown)  
Style GE left hand (not shown)

| Designation       |          | Shank Dimensions |          |          | Tip Designation <sup>a</sup> | Tip Dimensions |         |          |
|-------------------|----------|------------------|----------|----------|------------------------------|----------------|---------|----------|
| Style BR          | Style BL | Width A          | Height B | Length C |                              | Thickness T    | Width W | Length L |
| Square Shank      |          |                  |          |          |                              |                |         |          |
| BR 4              | BL 4     | 1/4              | 1/4      | 2        | 2015                         | 1/16           | 3/32    | 1/4      |
| BR 5              | BL 5     | 3/16             | 3/16     | 2 1/4    | 2040                         | 3/32           | 3/16    | 5/16     |
| BR 6              | BL 6     | 3/8              | 3/8      | 2 1/2    | 2070                         | 3/32           | 1/4     | 1/2      |
| BR 7              | BL 7     | 7/16             | 7/16     | 3        | 2070                         | 3/32           | 1/4     | 1/2      |
| BR 8              | BL 8     | 1/2              | 1/2      | 3 1/2    | 2170                         | 1/8            | 3/16    | 3/8      |
| BR 10             | BL 10    | 3/8              | 3/8      | 4        | 2230                         | 5/32           | 3/8     | 3/4      |
| BR 12             | BL 12    | 3/4              | 3/4      | 4 1/2    | 2310                         | 3/16           | 7/16    | 13/16    |
| BR 16             | BL 16    | 1                | 1        | 6        | { 3390, 4390                 | 1/4            | 9/16    | 1        |
| BR 20             | BL 20    | 1 1/4            | 1 1/4    | 7        | { 3460, 4460                 | 5/16           | 5/8     | 1        |
| BR 24             | BL 24    | 1 1/2            | 1 1/2    | 8        | { 3510, 4510                 | 3/8            | 3/8     | 1        |
| Rectangular Shank |          |                  |          |          |                              |                |         |          |
| BR 44             | BL 44    | 1/2              | 1        | 6        | 2260                         | 3/16           | 5/16    | 5/8      |
| BR 54             | BL 54    | 3/8              | 1        | 6        | { 3360, 4360                 | 1/4            | 3/8     | 3/4      |
| BR 55             | BL 55    | 3/8              | 1 1/4    | 7        | { 3360, 4360                 | 1/4            | 3/8     | 3/4      |
| BR 64             | BL 64    | 3/4              | 1        | 6        | { 3380, 4380                 | 1/4            | 1/2     | 3/4      |
| BR 66             | BL 66    | 3/4              | 1 1/2    | 8        | { 3430, 4430                 | 5/16           | 7/16    | 15/16    |
| BR 85             | BL 85    | 1                | 1 1/4    | 7        | { 3460, 4460                 | 5/16           | 5/8     | 1        |
| BR 86             | BL 86    | 1                | 1 1/2    | 8        | { 3510, 4510                 | 3/8            | 5/8     | 1        |
| BR 88             | BL 88    | 1                | 2        | 10       | { 3510, 4510                 | 3/8            | 5/8     | 1        |
| BR 90             | BL 90    | 1 1/2            | 2        | 10       | { 3540, 4540                 | 1/2            | 3/4     | 1 1/4    |

<sup>a</sup> Where a pair of tip numbers is shown, the upper number applies to BR tools, the lower to BL tools. All dimensions are in inches.

**Brazing Carbide Tips to Steel Shanks.**—Sintered carbide tips or blanks are attached to steel shanks by brazing. Shanks usually are made of low-alloy steels having carbon contents ranging from 0.40 to 0.60 per cent. *Shank Preparation:* The carbide tip usually is inserted into a milled recess or seat. When a recess is used, the bottom should be flat to provide a firm even support for the tip. The corner radius of the seat should be somewhat smaller than the radius on the tip to avoid contact and insure support along each side of the recess. *Cleaning:* All surfaces to be brazed must be absolutely clean. Surfaces of the tip may be cleaned by grinding lightly or by sand-blasting. *Brazing Materials and Equipment:* The brazing metal may be copper, naval brass such as Tobin bronze, or silver solder. A flux such as borax is used to protect the clean surfaces and prevent oxidation. Heating may be done in a furnace or by oxy-acetylene torch or an oxy-hydrogen torch. Copper brazing usually is done in a furnace, although an oxy-hydrogen torch with excess hydrogen is sometimes used. *Brazing Procedure:* One method using a torch is to place a thin sheet material, such as copper foil, around and beneath the carbide tip, the top of which is covered with flux. The flame is applied to the under side of the tool shank, and, when the materials melt, the tip is pressed firmly into its seat with tongs or with the end of a rod. Brazing material in the form of wire or rod may be used to coat or tin the surfaces of the recess after the flux melts and runs freely. The tip is then inserted, flux is applied to the top, and heating continued until the coatings melt and run freely. The tip, after coating with flux, is placed in the recess and the shank end is heated. Then a small piece of silver solder, having a melting point of 1325 degrees F., is placed on top of the tip. When this solder melts, it runs over the nickel-coated surfaces while the tip is held firmly into its seat. The brazed tool should be cooled slowly to avoid cracking due to unequal contraction between the steel and carbide.

**Table 7. American National Standard Style C Carbide Tipped Tools**  
ANSI B212.1-2002

| Designation | Shank Dimensions |           |           | Tip Designation | Tip Dimensions |          |           |
|-------------|------------------|-----------|-----------|-----------------|----------------|----------|-----------|
|             | Width, A         | Height, B | Length, C |                 | Thickness, T   | Width, W | Length, L |
| C 4         | 1/4              | 1/4       | 2         | 1030            | 1/16           | 1/4      | 5/16      |
| C 5         | 3/16             | 3/16      | 2 1/4     | 1080            | 3/32           | 3/8      | 3/8       |
| C 6         | 3/8              | 3/8       | 2 1/2     | 1090            | 3/32           | 3/8      | 3/8       |
| C 7         | 7/16             | 7/16      | 3         | 1105            | 3/32           | 7/16     | 1/2       |
| C 8         | 1/2              | 1/2       | 3 1/2     | 1200            | 1/8            | 1/2      | 1/2       |
| C 10        | 5/8              | 5/8       | 4         | 1240            | 3/32           | 5/8      | 5/8       |
| C 12        | 3/4              | 3/4       | 4 1/2     | 1340            | 3/16           | 3/4      | 3/4       |
| C 16        | 1                | 1         | 6         | 1410            | 1/4            | 1        | 3/4       |
| C 20        | 1 1/4            | 1 1/4     | 7         | 1480            | 5/16           | 1 1/4    | 3/4       |
| C 44        | 1/2              | 1         | 6         | 1320            | 3/16           | 1/2      | 1/2       |
| C 54        | 5/8              | 1         | 6         | 1400            | 1/4            | 5/8      | 5/8       |
| C 55        | 3/4              | 1 1/4     | 7         | 1400            | 1/4            | 5/8      | 5/8       |
| C 64        | 3/4              | 1         | 6         | 1405            | 1/4            | 3/4      | 3/4       |
| C 66        | 3/4              | 1 1/2     | 8         | 1470            | 3/16           | 3/4      | 3/4       |
| C 86        | 1                | 1 1/2     | 8         | 1475            | 5/16           | 1        | 3/4       |

All dimensions are in inches. Square shanks above horizontal line; rectangular below.

**Table 8. American National Standard Style D, 80-degree Nose-angle Carbide Tipped Tools**  
ANSI B212.1-2002

| Designation | Shank Dimensions |           |           | Tip Designation | Tip Dimensions |          |           |
|-------------|------------------|-----------|-----------|-----------------|----------------|----------|-----------|
|             | Width, A         | Height, B | Length, C |                 | Thickness, T   | Width, W | Length, L |
| D 4         | 1/4              | 1/4       | 2         | 5030            | 1/16           | 1/4      | 5/16      |
| D 5         | 3/16             | 3/16      | 2 1/4     | 5080            | 3/32           | 5/16     | 3/8       |
| D 6         | 3/8              | 3/8       | 2 1/2     | 5100            | 3/32           | 3/8      | 1/2       |
| D 7         | 7/16             | 7/16      | 3         | 5105            | 3/32           | 7/16     | 1/2       |
| D 8         | 1/2              | 1/2       | 3 1/2     | 5200            | 1/8            | 1/2      | 1/2       |
| D 10        | 5/8              | 5/8       | 4         | 5240            | 3/32           | 5/8      | 5/8       |
| D 12        | 3/4              | 3/4       | 4 1/2     | 5340            | 3/16           | 3/4      | 3/4       |
| D 16        | 1                | 1         | 6         | 5410            | 1/4            | 1        | 3/4       |

All dimensions are in inches.

**Table 9. American National Standard Style E, 60-degree Nose-angle, Carbide Tipped Tools ANSI B212.1-2002**

| Designation | Shank Dimensions |          |          | Tip Designation | Tip Dimensions |         |          |
|-------------|------------------|----------|----------|-----------------|----------------|---------|----------|
|             | Width A          | Height B | Length C |                 | Thickness T    | Width W | Length L |
| E 4         | 1/4              | 1/4      | 2        | 6030            | 1/16           | 1/4     | 3/16     |
| E 5         | 5/16             | 5/16     | 2 1/4    | 6080            | 3/32           | 3/16    | 3/8      |
| E 6         | 3/8              | 3/8      | 2 1/2    | 6100            | 3/32           | 3/8     | 1/2      |
| E 8         | 1/2              | 1/2      | 3 1/2    | 6200            | 1/8            | 1/2     | 1/2      |
| E 10        | 5/8              | 5/8      | 4        | 6240            | 5/32           | 5/8     | 5/8      |
| E 12        | 3/4              | 3/4      | 4 1/2    | 6340            | 3/16           | 3/4     | 3/4      |

All dimensions are in inches.

**Table 10. American National Standard Styles ER and EL, 60-degree Nose-angle, Carbide Tipped Tools with Offset Point ANSI B212.1-2002**

| Designation |          | Shank Dimensions |          |          | Tip Designation | Tip Dimensions |         |          |
|-------------|----------|------------------|----------|----------|-----------------|----------------|---------|----------|
| Style ER    | Style EL | Width A          | Height B | Length C |                 | Thick. T       | Width W | Length L |
| ER 4        | EL 4     | 1/4              | 1/4      | 2        | 1020            | 1/16           | 3/16    | 1/4      |
| ER 5        | EL 5     | 5/16             | 5/16     | 2 1/4    | 7060            | 3/32           | 1/4     | 3/8      |
| ER 6        | EL 6     | 3/8              | 3/8      | 2 1/2    | 7060            | 3/32           | 1/4     | 3/8      |
| ER 8        | EL 8     | 1/2              | 1/2      | 3 1/2    | 7170            | 1/8            | 3/16    | 5/8      |
| ER 10       | EL 10    | 5/8              | 5/8      | 4        | 7170            | 5/32           | 5/16    | 5/8      |
| ER 12       | EL 12    | 3/4              | 3/4      | 4 1/2    | 7230            | 3/16           | 3/8     | 3/4      |

All dimensions are in inches.

**Table 11. American National Standard Style F, Offset, End-cutting Carbide Tipped Tools ANSI B212.1-2002**

| Designation       |          | Shank Dimensions |          |          |          |                    | Tip Designation | Tip Dimensions |         |          |
|-------------------|----------|------------------|----------|----------|----------|--------------------|-----------------|----------------|---------|----------|
| Style FR          | Style FL | Width A          | Height B | Length C | Offset G | Length of Offset E |                 | Thickness T    | Width W | Length L |
| Square Shank      |          |                  |          |          |          |                    |                 |                |         |          |
| FR 8              | FL 8     | 1/2              | 1/2      | 3 1/2    | 1/4      | 3/4                | { P4170, P3170  | 1/8            | 5/16    | 5/8      |
| FR 10             | FL 10    | 5/8              | 5/8      | 4        | 3/8      | 1                  | { P1230, P3230  | 5/32           | 3/8     | 3/4      |
| FR 12             | FL 12    | 3/4              | 3/4      | 4 1/2    | 5/8      | 1 1/8              | { P4310, P3310  | 3/16           | 7/16    | 13/16    |
| FR 16             | FL 16    | 1                | 1        | 6        | 3/4      | 1 3/8              | { P4390, P3390  | 1/4            | 9/16    | 1        |
| FR 20             | FL 20    | 1 1/4            | 1 1/4    | 7        | 3/4      | 1 1/2              | { P4460, P3460  | 3/16           | 5/8     | 1        |
| FR 24             | FL 24    | 1 1/2            | 1 1/2    | 8        | 3/4      | 1 1/2              | { P4510, P3510  | 3/8            | 5/8     | 1        |
| Rectangular Shank |          |                  |          |          |          |                    |                 |                |         |          |
| FR 44             | FL 44    | 1/2              | 1        | 6        | 1/2      | 7/8                | { P4260, P1260  | 3/16           | 5/16    | 5/8      |
| FR 55             | FL 55    | 5/8              | 1 1/4    | 7        | 5/8      | 1 1/8              | { P4360, P3360  | 1/4            | 3/8     | 3/4      |
| FR 64             | FL 64    | 3/4              | 1        | 6        | 5/8      | 1 3/16             | { P4380, P3380  | 1/4            | 1/2     | 3/4      |
| FR 66             | FL 66    | 3/4              | 1 1/2    | 8        | 3/4      | 1 1/4              | { P4430, P3430  | 5/16           | 7/16    | 15/16    |
| FR 85             | FL 85    | 1                | 1 1/4    | 7        | 3/4      | 1 1/2              | { P4460, P3460  | 5/16           | 5/8     | 1        |
| FR 86             | FL 86    | 1                | 1 1/2    | 8        | 3/4      | 1 1/2              | { P4510, P3510  | 3/8            | 5/8     | 1        |
| FR 90             | FL 90    | 1 1/2            | 2        | 10       | 3/4      | 1 5/8              | { P4540, P3540  | 1/2            | 3/4     | 1 1/4    |

All dimensions are in inches. Where a pair of tip numbers is shown, the upper number applies to FR tools, the lower number to FL tools.

**Carbide Tools.**—Cemented or sintered carbides are used in the machine building and various other industries, chiefly for cutting tools but also for certain other tools or parts subject to considerable abrasion or wear. Carbide cutting tools, when properly selected to obtain the right combination of strength and hardness, are very effective in machining all classes of iron and steel, non-ferrous alloys, non-metallic materials, hard rubber, synthetic resins, slate, marble, and other materials which would quickly dull steel tools either because of hardness or abrasive action. Carbide cutting tools are not only durable, but capable of exceptionally high cutting speeds. See *CEMENTED CARBIDES* starting on page 773 for more on these materials.

*Tungsten carbide* is used extensively in cutting cast iron, nonferrous metals which form short chips in cutting; plastics and various other non-metallic materials. A grade having a hardness of 87.5 Rockwell A might be used where a strong grade is required, as for roughing cuts, whereas for light high-speed finishing or other cuts, a hardness of about 92 might be preferable. When tungsten carbide is applied to steel, craters or chip cavities are formed



**Table 12. American National Standard Style G, Offset, Side-cutting, Carbide Tipped Tools ANSI B212.1-2002**

| Designation       |          | Shank Dimensions |          |          |          |                    | Tip Designation | Tip Dimensions |         |          |
|-------------------|----------|------------------|----------|----------|----------|--------------------|-----------------|----------------|---------|----------|
| Style GR          | Style GL | Width A          | Height B | Length C | Offset G | Length of Offset E |                 | Thickness T    | Width W | Length L |
| Square Shank      |          |                  |          |          |          |                    |                 |                |         |          |
| GR 8              | GL 8     | 1/2              | 1/2      | 3 1/2    | 1/4      | 1 1/16             | { P3170, P4170  | 1/8            | 5/16    | 5/8      |
| GR 10             | GL 10    | 5/8              | 5/8      | 4        | 3/8      | 1 3/8              | { P3230, P4230  | 5/32           | 3/8     | 3/4      |
| GR 12             | GL 12    | 3/4              | 3/4      | 4 1/2    | 3/8      | 1 1/2              | { P3310, P2310  | 3/16           | 7/16    | 13/16    |
| GR 16             | GL 16    | 1                | 1        | 6        | 1/2      | 1 11/16            | { P3390, P4390  | 1/4            | 9/16    | 1        |
| GR 20             | GL 20    | 1 1/4            | 1 1/4    | 7        | 3/4      | 1 13/16            | { P3460, P4460  | 5/16           | 5/8     | 1        |
| GR 24             | GL 24    | 1 1/2            | 1 1/2    | 8        | 3/4      | 1 13/16            | { P3510, P4510  | 3/8            | 5/8     | 1        |
| Rectangular Shank |          |                  |          |          |          |                    |                 |                |         |          |
| GR 44             | GL 44    | 1/2              | 1        | 6        | 1/4      | 1 1/16             | { P3260, P4260  | 3/16           | 5/16    | 5/8      |
| GR 55             | GL 55    | 5/8              | 1 1/4    | 7        | 3/8      | 1 3/8              | { P3360, P4360  | 1/4            | 3/8     | 3/4      |
| GR 64             | GL 64    | 3/4              | 1        | 6        | 1/2      | 1 7/16             | { P3380, P4380  | 1/4            | 1/2     | 3/4      |
| GR 66             | GL 66    | 3/4              | 1 1/2    | 8        | 1/2      | 1 5/8              | { P3430, P4430  | 5/16           | 7/16    | 15/16    |
| GR 85             | GL 85    | 1                | 1 1/4    | 7        | 1/2      | 1 11/16            | { P3460, P4460  | 5/16           | 5/8     | 1        |
| GR 86             | GL 86    | 1                | 1 1/2    | 8        | 1/2      | 1 13/16            | { P3510, P4510  | 3/8            | 5/8     | 1        |
| GR 90             | GL 90    | 1 1/2            | 2        | 10       | 3/4      | 2 1/16             | { P3540, P4540  | 1/2            | 3/4     | 1 1/4    |

All dimensions are in inches. Where a pair of tip numbers is shown, the upper number applies to GR tools, the lower number to GL tools.

back of the cutting edge; hence other carbides have been developed which offer greater resistance to abrasion.

*Tungsten-titanium carbide* (often called "titanium carbide") is adapted to cutting either heat-treated or unheattreated steels, cast steel, or any tough material which might form chip cavities. It is also applicable to bronzes, monel metal, aluminum alloys, etc.

*Tungsten-tantalum carbide* or "tantalum carbide" cutting tools are also applicable to steels, bronzes or other tough materials. A hardness of 86.8 Rockwell A is recommended by one manufacturer for roughing steel, whereas a grade for finishing might have a hardness ranging from 88.8 to 91.5 Rockwell A.

## CEMENTED CARBIDES

### Cemented Carbides and Other Hard Materials

**Carbides and Carbonitrides.**—Though high-speed steel retains its importance for such applications as drilling and broaching, most metal cutting is carried out with carbide tools. For materials that are very difficult to machine, carbide is now being replaced by carbonitrides, ceramics, and superhard materials. Cemented (or sintered) carbides and carbonitrides, known collectively in most parts of the world as hard metals, are a range of very hard, refractory, wear-resistant alloys made by powder metallurgy techniques. The minute carbide or nitride particles are “cemented” by a binder metal that is liquid at the sintering temperature. Compositions and properties of individual hardmetals can be as different as those of brass and high-speed steel.

All hardmetals are *cermets*, combining *ceramic* particles with a *metallic* binder. It is unfortunate that (owing to a mistranslation) the term *cermet* has come to mean either all hardmetals with a titanium carbide (TiC) base or simply cemented titanium carbonitrides. Although no single element other than carbon is present in all hard-metals, it is no accident that the generic term is “tungsten carbide.” The earliest successful grades were based on carbon, as are the majority of those made today, as listed in [Table 1](#).

The outstanding machining capabilities of high-speed steel are due to the presence of very hard carbide particles, notably tungsten carbide, in the iron-rich matrix. Modern methods of making cutting tools from pure tungsten carbide were based on this knowledge. Early pieces of cemented carbide were much too brittle for industrial use, but it was soon found that mixing tungsten carbide powder with up to 10 per cent of metals such as iron, nickel, or cobalt, allowed pressed compacts to be sintered at about 1500°C to give a product with low porosity, very high hardness, and considerable strength. This combination of properties made the materials ideally suitable for use as tools for cutting metal.

Cemented carbides for cutting tools were introduced commercially in 1927, and although the key discoveries were made in Germany, many of the later developments have taken place in the United States, Austria, Sweden, and other countries. Recent years have seen two “revolutions” in carbide cutting tools, one led by the United States and the other by Europe. These were the change from brazed to clamped carbide inserts and the rapid development of coating technology.

When indexable tips were first introduced, it was found that so little carbide was worn away before they were discarded that a minor industry began to develop, regrinding the so-called “throwaway” tips and selling them for reuse in adapted toolholders. Hardmetal consumption, which had grown dramatically when indexable inserts were introduced, leveled off and began to decline. This situation was changed by the advent and rapid acceptance of carbide, nitride, and oxide coatings. Application of an even harder, more wear-resistant surface to a tougher, more shock-resistant substrate allowed production of new generations of longer-lasting inserts. Regrinding destroyed the enhanced properties of the coatings, so was abandoned for coated tooling.

Brazed tools have the advantage that they can be reground over and over again, until almost no carbide is left, but the tools must always be reset after grinding to maintain machining accuracy. However, all brazed tools suffer to some extent from the stresses left by the brazing process, which in unskilled hands or with poor design can shatter the carbide even before it has been used to cut metal. In present conditions it is cheaper to use indexable inserts, which are tool tips of precise size, clamped in similarly precise holders, needing no time-consuming and costly resetting but usable only until each cutting edge or corner has lost its initial sharpness (see [Introduction](#) and related topics starting on page [756](#) and *Indexable Insert Holders for NC* on page [1309](#)). The absence of brazing stresses and the “one-use” concept also means that harder, longer-lasting grades can be used.

**Table 1. Typical Properties of Tungsten-Carbide-Based Cutting-Tool Hardmetals**

| ISO Application Code | Composition (%) |     |     |    | Density (g/cm <sup>3</sup> ) | Hardness (Vickers) | Transverse Rupture Strength (N/mm <sup>2</sup> ) |
|----------------------|-----------------|-----|-----|----|------------------------------|--------------------|--|
|                      | WC              | TiC | TaC | Co |                              |                    |  |
| P01                  | 50              | 35  | 7   | 6  | 8.5                          | 1900               | 1100   |
| P05                  | 78              | 16  |     | 6  | 11.4                         | 1820               | 1300   |
| P10                  | 69              | 15  | 8   | 8  | 11.5                         | 1740               | 1400   |
| P15                  | 78              | 12  | 3   | 7  | 11.7                         | 1660               | 1500   |
| P20                  | 79              | 8   | 5   | 8  | 12.1                         | 1580               | 1600   |
| P25                  | 82              | 6   | 4   | 8  | 12.9                         | 1530               | 1700   |
| P30                  | 84              | 5   | 2   | 9  | 13.3                         | 1490               | 1850   |
| P40                  | 85              | 5   |     | 10 | 13.4                         | 1420               | 1950   |
| P50                  | 78              | 3   | 3   | 16 | 13.1                         | 1250               | 2300   |
| M10                  | 85              | 5   | 4   | 6  | 13.4                         | 1590               | 1800   |
| M20                  | 82              | 5   | 5   | 8  | 13.3                         | 1540               | 1900   |
| M30                  | 86              | 4   |     | 10 | 13.6                         | 1440               | 2000   |
| M40                  | 84              | 4   | 2   | 10 | 14.0                         | 1380               | 2100   |
| K01                  | 97              |     |     | 3  | 15.2                         | 1850               | 1450   |
| K05                  | 95              |     | 1   | 4  | 15.0                         | 1790               | 1550   |
| K10                  | 92              |     | 2   | 6  | 14.9                         | 1730               | 1700   |
| K20                  | 94              |     |     | 6  | 14.8                         | 1650               | 1950   |
| K30                  | 91              |     |     | 9  | 14.4                         | 1400               | 2250   |
| K40                  | 89              |     |     | 11 | 14.1                         | 1320               | 2500   |

A complementary development was the introduction of ever-more complex chip-breakers, derived from computer-aided design and pressed and sintered to precise shapes and dimensions. Another advance was the application of hot isostatic pressing (HIP), which has moved hardmetals into applications that were formerly uneconomic. This method allows virtually all residual porosity to be squeezed out of the carbide by means of inert gas at high pressure, applied at about the sintering temperature. Toughness, rupture strength, and shock resistance can be doubled or tripled by this method, and the reject rates of very large sintered components are reduced to a fraction of their previous levels.

Further research has produced a substantial number of excellent cutting-tool materials based on titanium carbonitride. Generally called "cermets," as noted previously, carbonitride-based cutting inserts offer excellent performance and considerable prospects for the future.

*Compositions and Structures:* Properties of hardmetals are profoundly influenced by microstructure. The microstructure in turn depends on many factors including basic chemical composition of the carbide and matrix phases; size, shape, and distribution of carbide particles; relative proportions of carbide and matrix phases; degree of intersolubility of carbides; excess or deficiency of carbon; variations in composition and structure caused by diffusion or segregation; production methods generally, but especially milling, carburizing, and sintering methods, and the types of raw materials; post sintering treatments such as hot isostatic pressing; and coatings or diffusion layers applied after initial sintering.

*Tungsten Carbide/Cobalt (WC/Co):* The first commercially available cemented carbides consisted of fine angular particles of tungsten carbide bonded with metallic cobalt. Intended initially for wire-drawing dies, this composition type is still considered to have the greatest resistance to simple abrasive wear and therefore to have many applications in machining.

For maximum hardness to be obtained from closeness of packing, the tungsten carbide grains should be as small as possible, preferably below 1  $\mu\text{m}$  (swaging 0.00004 in.) and considerably less for special purposes. Hardness and abrasion resistance increase as the cobalt content is lowered, provided that a minimum of cobalt is present (2 per cent can be

enough, although 3 per cent is the realistic minimum) to ensure complete sintering. In general, as carbide grain size or cobalt content or both are increased—frequently in unison—tougher and less hard grades are obtained. No porosity should be visible, even under the highest optical magnification.

WC/Co compositions used for cutting tools range from about 2 to 13 per cent cobalt, and from less than 0.5 to more than 5  $\mu\text{m}$  (0.00002–0.0002 in.) in grain size. For stamping tools, swaying dies, and other wear applications for parts subjected to moderate or severe shock, cobalt content can be as much as 30 per cent, and grain size a maximum of about 10  $\mu\text{m}$  (0.0004 in.). In recent years, “micrograin” carbides, combining submicron (less than 0.00004 in.) carbide grains with relatively high cobalt content have found increasing use for machining at low speeds and high feed rates. An early use was in high-speed wood-working cutters such as are used for planing.

For optimum properties, porosity should be at a minimum, carbide grain size as regular as possible, and carbon content of the tungsten carbide phase close to the theoretical (stoichiometric) value. Many tungsten carbide/cobalt compositions are modified by small but important additions—from 0.5 to perhaps 3 per cent of tantalum, niobium, chromium, vanadium, titanium, hafnium, or other carbides. The basic purpose of these additions is generally inhibition of grain growth, so that a consistently fine structure is maintained.

*Tungsten–Titanium Carbide/Cobalt (WC/TiC/Co):* These grades are used for tools to cut steels and other ferrous alloys, the purpose of the TiC content being to resist the high-temperature diffusive attack that causes chemical breakdown and cratering. Tungsten carbide diffuses readily into the chip surface, but titanium carbide is extremely resistant to such diffusion. A solid solution or “mixed crystal” of WC in TiC retains the anticratering property to a great extent.

Unfortunately, titanium carbide and TiC-based solid solutions are considerably more brittle and less abrasion resistant than tungsten carbide. TiC content, therefore, is kept as low as possible, only sufficient TiC being provided to avoid severe cratering wear. Even 2 or 3 per cent of titanium carbide has a noticeable effect, and as the relative content is substantially increased, the cratering tendency becomes more severe.

In the limiting formulation the carbide is tungsten-free and based entirely on TiC, but generally TiC content extends to no more than about 18 per cent. Above this figure the carbide becomes excessively brittle and is very difficult to braze, although this drawback is not a problem with throwaway inserts.

WC/TiC/Co grades generally have two distinct carbide phases, angular crystals of almost pure WC and rounded TiC/WC mixed crystals. Among progressive manufacturers, although WC/TiC/Co hardmetals are very widely used, in certain important respects they are obsolescent, having been superseded by the WC/TiC/Ta(Nb)C/Co series in the many applications where higher strength combined with crater resistance is an advantage. TiC, TiN, and other coatings on tough substrates have also diminished the attractions of high-TiC grades for high-speed machining of steels and ferrous alloys.

*Tungsten-Titanium-Tantalum (-Niobium) Carbide/Cobalt:* Except for coated carbides, tungsten-titanium-tantalum (-niobium) grades could be the most popular class of hardmetals. Used mainly for cutting steel, they combine and improve upon most of the best features of the longer-established WC/TiC/Co compositions. These carbides compete directly with carbonitrides and silicon nitride ceramics, and the best cemented carbides of this class can undertake very heavy cuts at high speeds on all types of steels, including austenitic stainless varieties. These tools also operate well on ductile cast irons and nickel-base superalloys, where great heat and high pressures are generated at the cutting edge. However, they do not have the resistance to abrasive wear possessed by micrograin straight tungsten carbide grades nor the good resistance to cratering of coated grades and titanium carbide-based cermets.

*Titanium Carbide/Molybdenum/Nickel (TiC/Mo/Ni):* The extreme indentation hardness and crater resistance of titanium carbide, allied to the cheapness and availability of its main raw material (titanium dioxide,  $TiO_2$ ), provide a strong inducement to use grades based on this carbide alone. Although developed early in the history of hardmetals, these carbides were difficult to braze satisfactorily and consequently were little used until the advent of clamped, throwaway inserts. Moreover, the carbides were notoriously brittle and could take only fine cuts in minimal-shock conditions.

Titanium-carbide-based grades again came into prominence about 1960, when nickel-molybdenum began to be used as a binder instead of nickel. The new grades were able to perform a wider range of tasks including interrupted cutting and cutting under shock conditions.

The very high indentation hardness values recorded for titanium carbide grades are not accompanied by correspondingly greater resistance to abrasive wear, the apparently less hard tungsten carbide being considerably superior in this property. Moreover, carbonitrides, advanced tantalum-containing multicarbides, and coated variants generally provide better all-round cutting performances.

*Titanium-Base Carbonitrides:* Development of titanium-carbonitride-based cutting-tool materials predates the use of coatings of this type on more conventional hardmetals by many years. Appreciable, though uncontrolled, amounts of carbonitride were often present, if only by accident, when cracked ammonia was used as a less expensive substitute for hydrogen in some stages of the production process in the 1950's and perhaps for two decades earlier.

Much of the recent, more scientific development of this class of materials has taken place in the United States, particularly by Teledyne Firth Sterling with its  $SD_3$  grade and in Japan by several companies. Many of the compositions currently in use are extremely complex, and their structures—even with apparently similar compositions—can vary enormously. For instance, Mitsubishi characterizes its Himet NX series of cermets as  $TiC/WC/Ta(Nb)C/Mo_2C/TiN/Ni/Co/Al$ , with a structure comprising both large and medium-size carbide particles (mainly TiC according to the quoted density) in a superalloy-type matrix containing an aluminum-bearing intermetallic compound.

*Steel- and Alloy-Bonded Titanium Carbide:* The class of material exemplified by Ferro-Tic, as it is known, consists primarily of titanium carbide bonded with heat-treatable steel, but some grades also contain tungsten carbide or are bonded with nickel- or copper-base alloys. These cemented carbides are characterized by high binder contents (typically 50–60 per cent by volume) and lower hardnesses, compared with the more usual hardmetals, and by the great variation in properties obtained by heat treatment.

In the annealed condition, steel-bonded carbides have a relatively soft matrix and can be machined with little difficulty, especially by CBN (superhard cubic boron nitride) tools. After heat treatment, the degree of hardness and wear resistance achieved is considerably greater than that of normal tool steels, although understandably much less than that of traditional sintered carbides. Microstructures are extremely varied, being composed of 40–50 per cent TiC by volume and a matrix appropriate to the alloy composition and the stage of heat treatment. Applications include stamping, blanking and drawing dies, machine components, and similar items where the ability to machine before hardening reduces production costs substantially.

*Coating:* As a final stage in carbide manufacture, coatings of various kinds are applied mainly to cutting tools, where for cutting steel in particular it is advantageous to give the flank and clearance surfaces characteristics that are quite different from those of the body of the insert. Coatings of titanium carbide, nitride, or carbonitride; of aluminum oxide; and of other refractory compounds are applied to a variety of hardmetal substrates by chemical or physical vapor deposition (CVD or PVD) or by newer plasma methods.

The most recent types of coatings include hafnium, tantalum, and zirconium carbides and nitrides; alumina/titanium oxide; and multiple carbide/carbonitride/nitride/oxide, oxynitride or oxycarbonitride combinations. Greatly improved properties have been claimed for variants with as many as 13 distinct CVD coatings. A markedly sharper cutting edge compared with other CVD-coated hardmetals is claimed, permitting finer cuts and the successful machining of soft but abrasive alloys.

The keenest edges on coated carbides are achieved by the techniques of physical vapor deposition. In this process, ions are deposited directionally from the electrodes, rather than evenly on all surfaces, so the sharpness of cutting edges is maintained and may even be enhanced. PVD coatings currently available include titanium nitride and carbonitride, their distinctive gold color having become familiar throughout the world on high-speed steel tooling. The high temperatures required for normal CVD tends to soften heat-treated high-speed steel. PVD-coated hardmetals have been produced commercially for several years, especially for precision milling inserts.

Recent developments in extremely hard coatings, generally involving exotic techniques, include boron carbide, cubic boron nitride, and pure diamond. Almost the ultimate in wear resistance, the commercial applications of thin plasma-generated diamond surfaces at present are mainly in manufacture of semiconductors, where other special properties are important.

For cutting tools the substrate is of equal importance to the coating in many respects, its critical properties including fracture toughness (resistance to crack propagation), elastic modulus, resistance to heat and abrasion, and expansion coefficient. Some manufacturers are now producing inserts with graded composition, so that structures and properties are optimized at both surface and interior, and coatings are less likely to crack or break away.

*Specifications:* Compared with other standardized materials, the world of sintered hardmetals is peculiar. For instance, an engineer who seeks a carbide grade for the finish-machining of a steel component may be told to use *ISO Standard Grade P10* or *Industry Code C7*. If the composition and nominal properties of the designated tool material are then requested, the surprising answer is that, in basic composition alone, the tungsten carbide content of P10 (or of the now superseded C7) can vary from zero to about 75, titanium carbide from 8 to 80, cobalt 0 to 10, and nickel 0 to 15 per cent. There are other possible constituents, also, in this so-called standard alloy, and many basic properties can vary as much as the composition. All that these dissimilar materials have in common, and all that the so-called standards mean, is that their suppliers—and sometimes their suppliers alone—consider them suitable for one particular and ill-defined machining application (which for P10 or C7 is the finish machining of steel).

This peculiar situation arose because the production of cemented carbides in occupied Europe during World War II was controlled by the German Hartmetallzentrale, and no factory other than Krupp was permitted to produce more than one grade. By the end of the war, all German-controlled producers were equipped to make the G, S, H, and F series to German standards. In the postwar years, this series of carbides formed the basis of unofficial European standardization. With the advent of the newer multicarbides, the previous identities of grades were gradually lost. The applications relating to the old grades were retained, however, as a new German DIN standard, eventually being adopted, in somewhat modified form, by the International Standards Organization (ISO) and by ANSI in the United States.

The American cemented carbides industry developed under diverse ownership and solid competition. The major companies actively and independently developed new varieties of hardmetals, and there was little or no standardization, although there were many attempts to compile equivalent charts as a substitute for true standardization. Around 1942, the Buick division of GMC produced a simple classification code that arranged nearly 100 grades derived from 10 manufacturers under only 14 symbols (TC-1 to TC-14). In spite of serious deficiencies, this system remained in use for many years as an American industry

standard; that is, Buick TC-1 was equivalent to industry code C1. Buick itself went much further, using the tremendous influence, research facilities, and purchasing potential of its parent company to standardize the products of each carbide manufacturer by properties that could be tested, rather than by the indeterminate recommended applications. Many large-scale carbide users have developed similar systems in attempts to exert some degree of in-house standardization and quality control. Small and medium-sized users, however, still suffer from so-called industry standards, which only provide a starting point for grade selection.

ISO standard 513, summarized in [Table 2](#), divides all machining grades into three color-coded groups: straight tungsten carbide grades (letter K, color red) for cutting gray cast iron, nonferrous metals, and nonmetallics; highly alloyed grades (letter P, color blue) for machining steel; and less alloyed grades (letter M, color yellow, generally with less TiC than the corresponding P series), which are multipurpose and may be used on steels, nickel-base superalloys, ductile cast irons, and so on. Each grade within a group is also given a number to represent its position in a range from maximum hardness to maximum toughness (shock resistance). Typical applications are described for grades at more or less regular numerical intervals. Although coated grades scarcely existed when the ISO standard was prepared, it is easy to classify coated as uncoated carbides—or carbonitrides, ceramics, and superhard materials—according to this system.

In this situation, it is easy to see how one plant will prefer one manufacturer's carbide and a second plant will prefer that of another. Each has found the carbide most nearly ideal for the particular conditions involved. In these circumstances it pays each manufacturer to make grades that differ in hardness, toughness, and crater resistance, so that they can provide a product that is near the optimum for a specific customer's application.

Although not classified as a hard metal, new particle or powder metallurgical methods of manufacture, coupled with new coating technology have led in recent years to something of an upsurge in the use of high speed steel. Lower cost is a big factor, and the development of such coatings as titanium nitride, cubic boron nitride, and pure diamond, has enabled some high speed steel tools to rival tools made from tungsten and other carbides in their ability to maintain cutting accuracy and prolong tool life. Multiple layers may be used to produce optimum properties in the coating, with adhesive strength where there is contact with the substrate, combined with hardness at the cutting surface to resist abrasion. Total thickness of such coating, even with multiple layers, is seldom more than 15 microns (0.000060 in.).

*Importance of Correct Grades:* A great diversity of hardmetal types is required to cope with all possible combinations of metals and alloys, machining operations, and working conditions. Tough, shock-resistant grades are needed for slow speeds and interrupted cutting, harder grades for high-speed finishing, heat-resisting alloyed grades for machining superalloys, and crater-resistant compositions, including most of the many coated varieties, for machining steels and ductile iron.

**Ceramics.**—Moving up the hardness scale, ceramics provide increasing competition for cemented carbides, both in performance and in cost-effectiveness, though not yet in reliability. Hardmetals themselves consist of ceramics—nonmetallic refractory compounds, usually carbides or carbonitrides—with a metallic binder of much lower melting point. In such systems, densification generally takes place by liquid-phase sintering. Pure ceramics have no metallic binder, but may contain lower-melting-point compounds or ceramic mixtures that permit liquid-phase sintering to take place. Where this condition is not possible, hot pressing or hot isostatic pressing can often be used to make a strong, relatively pore-free component or cutting insert. This section is restricted to those ceramics that compete directly with hardmetals, mainly in the cutting-tool category as shown in [Table 3](#).

Ceramics are hard, completely nonmetallic substances that resist heat and abrasive wear. Increasingly used as clamped indexable tool inserts, ceramics differ significantly from tool

**Table 2. ISO Classifications of Hardmetals (Cemented Carbides and Carbonitrides) by Application**

| Main Types of Chip Removal |  | Groups of Applications |   |  | Direction of Decrease in Characteristic |            |
|----------------------------|--|------------------------|---|--|---|------------|
| Symbol and Color           | Broad Categories of Materials to be Machined                                   | Designation (Grade)    | Specific Material to be Machined  | Use and Working Conditions   | of cut                                  | of carbide |
| P<br>Blue                  | Ferrous with long chips  | P01                    | Steel, steel castings   | Finish turning and boring; high cutting speeds, small chip sections, accurate dimensions, fine finish, vibration-free operations   | ↑<br>speed<br>↑<br>wear                 |            |
|                            |  | P10                    | Steel, steel casting  | Turning, copying, threading, milling; high cutting speeds; small or medium chip sections   |   |            |
|                            |  | P20                    | Steel, steel castings, ductile cast iron with long chips  | Turning, copying, milling; medium cutting speeds and chip sections, planing with small chip sections   |   |            |
|                            |  | P30                    | Steel, steel castings, ductile cast iron with long chips  | Turning, milling, planing; medium or large chip sections, unfavorable machining conditions   |   |            |
|                            |  | P40                    | Steel, steel castings with sand inclusions and cavities   | Turning, planing, slotting; low cutting speeds, large chip sections, with possible large cutting angles, unfavorable cutting conditions, and work on automatic machines                                  |   |            |
|                            |  | P50                    | Steel, steel castings of medium or low tensile strength, with sand inclusions and cavities  | Operations demanding very tough carbides; turning, planing, slotting; low cutting speeds, large chip sections, with possible large cutting angles, unfavorable conditions and work on automatic machines |   |            |
| M<br>Yellow                | Ferrous metals with long or short chips, and non-ferrous metals                | M10                    | Steel, steel castings, manganese steel, gray cast iron, alloy cast iron   | Turning; medium or high cutting speeds, small or medium chip sections  |   |            |
|                            |  | M20                    | Steel, steel castings, austenitic or manganese steel, gray cast iron  | Turning, milling; medium cutting speeds and chip sections  |   |            |
|                            |  | M30                    | Steel, steel castings, austenitic steel, gray cast iron, high-temperature-resistant alloys  | Turning, milling, planing; medium cutting speeds, medium or large chip sections  |   |            |
|                            |  | M40                    | Mild, free-cutting steel, low-tensile steel, non-ferrous metals and light alloys  | Turning, parting off; particularly on automatic machines   |   |            |
| K<br>Red                   | Ferrous metals with short chips, non-ferrous metals and non-metallic materials | K01                    | Very hard gray cast iron, chilled castings over 85 Shore, high-silicon aluminum alloys, hardened steel, highly abrasive plastics, hard cardboard, ceramics                                | Turning, finish turning, boring, milling, scraping   |   |            |
|                            |  | K10                    | Gray cast iron over 220 Brinell, malleable cast iron with short chips, hardened steel, silicon-aluminum and copper alloys, plastics, glass, hard rubber, hard cardboard, porcelain, stone | Turning, milling, drilling, boring, broaching, scraping  |   |            |
|                            |  | K20                    | Gray cast iron up to 220 Brinell, nonferrous metals, copper, brass, aluminum  | Turning, milling, planing, boring, broaching, demanding very tough carbide   |   |            |
|                            |  | K30                    | Low-hardness gray cast iron, low-tensile steel, compressed wood   | Turning, milling, planing, slotting, unfavorable conditions, and possibility of large cutting angles   |   |            |
|                            |  | K40                    | Softwood or hard wood, nonferrous metals  | Turning, milling, planing, slotting, unfavorable conditions, and possibility of large cutting angles   |   |            |
|                            |  |                        |   |  | ↓<br>feed<br>↓<br>toughness             |            |



steels, which are completely metallic. Ceramics also differ from cermets such as cemented carbides and carbonitrides, which comprise minute ceramic particles held together by metallic binders.

**Table 3. Typical Properties of Cutting Tool Ceramics**

| Group   | Alumina  | Alumina/TiC                               | Silicon Nitride  | PCD  | PCBN |
|---|--|---|--|------|------|
| Typical composition types                                 | Al <sub>2</sub> O <sub>3</sub> or Al <sub>2</sub> O <sub>3</sub> /ZrO <sub>2</sub> | 70/30 Al <sub>2</sub> O <sub>3</sub> /TiC | Si <sub>3</sub> N <sub>4</sub> /Y <sub>2</sub> O <sub>3</sub> plus |      |      |
| Density (g/cm <sup>3</sup> )                              | 4.0  | 4.25                                      | 3.27   | 3.4  | 3.1  |
| Transverse rupture strength (N/mm <sup>2</sup> )          | 700  | 750                                       | 800  |      | 800  |
| Compressive strength (kN/mm <sup>2</sup> )                | 4.0  | 4.5                                       | 4.0  | 4.7  | 3.8  |
| Hardness (HV)   | 1750   | 1800                                      | 1600   |      |      |
| Hardness HK (kN/mm <sup>2</sup> )                         |  |   |  | 50   | 28   |
| Young's modulus (kN/mm <sup>2</sup> )                     | 380  | 370                                       | 300  | 925  | 680  |
| Modulus of rigidity (kN/mm <sup>2</sup> )                 | 150  | 160                                       | 150  | 430  | 280  |
| Poisson's ratio   | 0.24   | 0.22                                      | 0.20   | 0.09 | 0.22 |
| Thermal expansion coefficient (10 <sup>-6</sup> /K)       | 8.5  | 7.8                                       | 3.2  | 3.8  | 4.9  |
| Thermal conductivity (W/m K)                              | 23   | 17  | 22   | 120  | 100  |
| Fracture toughness (K <sub>1c</sub> MN/m <sup>3/2</sup> ) | 2.3  | 3.3                                       | 5.0  | 7.9  | 10   |

Alumina-based ceramics were introduced as cutting inserts during World War II, and were for many years considered too brittle for regular machine-shop use. Improved machine tools and finer-grain, tougher compositions incorporating zirconia or silicon carbide “whiskers” now permit their use in a wide range of applications. Silicon nitride, often combined with alumina (aluminum oxide), yttria (yttrium oxide), and other oxides and nitrides, is used for much of the high-speed machining of superalloys, and newer grades have been formulated specifically for cast iron—potentially a far larger market.

In addition to improvements in toolholders, great advances have been made in machine tools, many of which now feature the higher powers and speeds required for the efficient use of ceramic tooling. Brittleness at the cutting edge is no longer a disadvantage, with the improvements made to the ceramics themselves, mainly in toughness, but also in other critical properties.

Although very large numbers of useful ceramic materials are now available, only a few combinations have been found to combine such properties as minimum porosity, hardness, wear resistance, chemical stability, and resistance to shock to the extent necessary for cutting-tool inserts. Most ceramics used for machining are still based on high-purity, fine-grained alumina (aluminum oxide), but embody property-enhancing additions of other ceramics such as zirconia (zirconium oxide), titania (titanium oxide), titanium carbide, tungsten carbide, and titanium nitride. For commercial purposes, those more commonly used are often termed “white” (alumina with or without zirconia) or “black” (roughly 70/30 alumina/titanium carbide). More recent developments are the distinctively green alumina ceramics strengthened with silicon carbide whiskers and the brown-tinged silicon nitride types.

Ceramics benefit from hot isostatic pressing, used to remove the last vestiges of porosity and raise substantially the material's shock resistance, even more than carbide-based hard-metals. Significant improvements are derived by even small parts such as tool inserts, although, in principle, they should not need such treatment if raw materials and manufacturing methods are properly controlled.

*Oxide Ceramics:* Alumina cutting tips have extreme hardness—more than HV 2000 or HRA 94—and give excellent service in their limited but important range of uses such as the machining of chilled iron rolls and brake drums. A substantial family of alumina-based materials has been developed, and fine-grained alumina-based composites now have suf-

ficient strength for milling cast iron at speeds up to 2500 ft/min (800 m/min). Resistance to cratering when machining steel is exceptional.

**Oxide/Carbide Ceramics:** A second important class of alumina-based cutting ceramics combines aluminum oxide or alumina-zirconia with a refractory carbide or carbides, nearly always 30 per cent TiC. The compound is black and normally is hot pressed or hot isostatically pressed (HIPed). As shown in Table 3, the physical and mechanical properties of this material are generally similar to those of the pure alumina ceramics, but strength and shock resistance are generally higher, being comparable with those of higher-toughness simple alumina-zirconia grades. Current commercial grades are even more complex, combining alumina, zirconia, and titanium carbide with the further addition of titanium nitride.

**Silicon Nitride Base:** One of the most effective ceramic cutting-tool materials developed in the UK is Syalon (from SiAlON or silicon-aluminum-oxynitride) though it incorporates a substantial amount of yttria for efficient liquid-phase sintering). The material combines high strength with hot hardness, shock resistance, and other vital properties. Syalon cutting inserts are made by Kennametal and Sandvik and sold as Kyon 2000 and CC680, respectively. The brown Kyon 200 is suitable for machining high-nickel alloys and cast iron, but a later development, Kyon 3000 has good potential for machining cast iron.

Resistance to thermal stress and thermal shock of Kyon 2000 are comparable to those of sintered carbides. Toughness is substantially less than that of carbides, but roughly twice that of oxide-based cutting-tool materials at temperatures up to 850°C. Syon 200 can cut at high edge temperatures and is harder than carbide and some other ceramics at over 700°C, although softer than most at room temperature.

**Whisker-Reinforced Ceramics:** To improve toughness, Greenleaf Corp. has reinforced alumina ceramics with silicon carbide single-crystal “whiskers” that impart a distinctive green color to the material, marketed as WG300. Typically as thin as human hairs, the immensely strong whiskers improve tool life under arduous conditions. Whisker-reinforced ceramics and perhaps hardmetals are likely to become increasingly important as cutting and wear-resistant materials. Their only drawback seems to be the carcinogenic nature of the included fibers, which requires stringent precautions during manufacture.

**Superhard Materials.**—Polycrystalline synthetic diamond (PCD) and cubic boron nitride (PCBN), in the two columns at the right in Table 3, are almost the only cutting-insert materials in the “superhard” category. Both PCD and PCBN are usually made with the highest practicable concentration of the hard constituent, although ceramic or metallic binders can be almost equally important in providing overall strength and optimizing other properties. Variations in grain size are another critical factor in determining cutting characteristics and edge stability. Some manufacturers treat CBN in similar fashion to tungsten carbide, varying the composition and amount of binder within exceptionally wide limits to influence the physical and mechanical properties of the sintered compact.

In comparing these materials, users should note that some inserts comprise solid polycrystalline diamond or CBN and are double-sized to provide twice the number of cutting edges. Others consist of a layer, from 0.020 to 0.040 in. (0.5 to 1 mm) thick, on a tough carbide backing. A third type is produced with a solid superhard material almost surrounded by sintered carbide. A fourth type, used mainly for cutting inserts, comprises solid hard metal with a tiny superhard insert at one or more (usually only one) cutting corners or edges. Superhard cutting inserts are expensive—up to 30 times the cost of equivalent shapes or sizes in ceramic or cemented carbide—but their outstanding properties, exceptional performance and extremely long life can make them by far the most cost-effective for certain applications.

**Diamond:** Diamond is the hardest material found or made. As harder, more abrasive ceramics and other materials came into widespread use, diamond began to be used for grinding-wheel grits. Cemented carbide tools virtually demanded diamond grinding wheels for fine edge finishing. Solid single-crystal diamond tools were and are used to a

small extent for special purposes, such as microtomes, for machining of hard materials, and for exceptionally fine finishes. These diamonds are made from comparatively large, high-quality gem-type diamonds, have isotropic properties, and are very expensive. By comparison, diamond abrasive grits cost only a few dollars a carat.

Synthetic diamonds are produced from graphite using high temperatures and extremely high pressures. The fine diamond particles produced are sintered together in the presence of a metal "catalyst" to produce high-efficiency anisotropic cutting tool inserts. These tools comprise either a solid diamond compact or a layer of sintered diamond on a carbide backing, and are made under conditions similar to, though less severe than, those used in diamond synthesis. Both natural and synthetic diamond can be sintered in this way, although the latter method is the most frequently used.

Polycrystalline diamond (PCD) compacts are immensely hard and can be used to machine many substances, from highly abrasive hardwoods and glass fiber to nonferrous metals, hardmetals, and tough ceramics. Important classes of tools that are also available with cubic boron nitride inserts include brazed-tip drills, single-point turning tools, and face-milling cutters.

*Boron Nitride:* Polycrystalline diamond has one big limitation: it cannot be used to machine steel or any other ferrous material without rapid chemical breakdown. Boron nitride does not have this limitation. Normally soft and slippery like graphite, the soft hexagonal crystals (HBN) become cubic boron nitride (CBN) when subjected to ultrahigh pressures and temperatures, with a structure similar to and hardness second only to diamond. As a solid insert of polycrystalline cubic boron nitride (PCBN), the compound machines even the hardest steel with relative immunity from chemical breakdown or cratering.

Backed by sintered carbide, inserts of PCBN can readily be brazed, increasing the usefulness of the material and the range of tooling in which it can be used. With great hardness and abrasion resistance, coupled with extreme chemical stability when in contact with ferrous alloys at high temperatures, PCBN has the ability to machine both steels and cast irons at high speeds for long operating cycles. Only its currently high cost in relation to hardmetals prevents its wider use in mass-production machining.

Similar in general properties to PCBN, the recently developed "Wurbon" consists of a mixture of ultrafine (0.02  $\mu\text{m}$  grain size) hexagonal and cubic boron nitride with a "wurtzite" structure, and is produced from soft hexagonal boron nitride in a microsecond by an explosive shock-wave.

*Basic Machining Data:* Most mass-production metalcutting operations are carried out with carbide-tipped tools but their correct application is not simple. Even apparently similar batches of the same material vary greatly in their machining characteristics and may require different tool settings to attain optimum performance. Depth of cut, feed, surface speed, cutting rate, desired surface finish, and target tool life often need to be modified to suit the requirements of a particular component.

For the same downtime, the life of an insert between indexings can be less than that of an equivalent brazed tool between regrinds, so a much higher rate of metal removal is possible with the indexable or throwaway insert. It is commonplace for the claims for a new coating to include increases in surface-speed rates of 200–300 per cent, and for a new insert design to offer similar improvements. Many operations are run at metal removal rates that are far from optimum for tool life because the rates used maximize productivity and cost-effectiveness.

Thus any recommendations for cutting speeds and feeds must be oversimplified or extremely complex, and must be hedged with many provisos, dependent on the technical and economic conditions in the manufacturing plant concerned. A preliminary grade selection should be made from the ISO-based tables and manufacturers' literature consulted for recommendations on the chosen grades and tool designs. If tool life is much

greater than that desired under the suggested conditions, speeds, feeds, or depths of cut may be increased. If tools fail by edge breakage, a tougher (more shock-resistant) grade should be selected, with a numerically higher ISO code.

Alternatively, increasing the surface speed and decreasing the feed may be tried. If tools fail prematurely from what appears to be abrasive wear, a harder grade with numerically lower ISO designation should be tried. If cratering is severe, use a grade with higher titanium carbide content; that is, switch from an ISO K to M or M to P grade, use a P grade with lower numerical value, change to a coated grade, or use a coated grade with a (claimed) more-resistant surface layer.

*Built-Up Edge and Cratering:* The big problem in cutting steel with carbide tools is associated with the built-up edge and the familiar phenomenon called cratering. Research has shown that the built-up edge is continuous with the chip itself during normal cutting. Additions of titanium, tantalum, and niobium to the basic carbide mixture have a remarkable effect on the nature and degree of cratering, which is related to adhesion between the tool and the chip.

**Hardmetal Tooling for Wood and Nonmetallics.**—Carbide-tipped circular saws are now conventional for cutting wood, wood products such as chipboard, and plastics, and tipped bandsaws of large size are also gaining in popularity. Tipped handsaws and mechanical equivalents are seldom needed for wood, but they are extremely useful for cutting abrasive building boards, glass-reinforced plastics, and similar material. Like the hardmetal tips used on most other woodworking tools, saw tips generally make use of straight (unalloyed) tungsten carbide/cobalt grades. However, where excessive heat is generated as with the cutting of high-silica hardwoods and particularly abrasive chipboards, the very hard but tough tungsten-titanium-tantalum-niobium carbide solid-solution grades, normally reserved for steel finishing, may be preferred. Saw tips are usually brazed and reground a number of times during service, so coated grades appear to have little immediate potential in this field.

*Cutting Blades and Plane Irons:* These tools comprise long, thin, comparatively wide slabs of carbide on a minimal-thickness steel backing. Compositions are straight tungsten carbide, preferably micrograin (to maintain a keen cutting edge with an included angle of 30° or less), but with relatively high amounts of cobalt, 11–13 per cent, for toughness. Considerable expertise is necessary to braze and grind these cutters without inducing or failing to relieve the excessive stresses that cause distortion or cracking.

*Other Woodworking Cutters:* Routers and other cutters are generally similar to those used on metals and include many indexable-insert designs. The main difference with wood is that rotational and surface speeds can be the maximum available on the machine. High-speed routing of aluminum and magnesium alloys was developed largely from machines and techniques originally designed for work on wood.

*Cutting Other Materials:* The machining of plastics, fiber-reinforced plastics, graphite, asbestos, and other hard and abrasive constructional materials mainly requires abrasion resistance. Cutting pressures and power requirements are generally low. With thermoplastics and some other materials, particular attention must be given to cooling because of softening or degradation of the work material that might be caused by the heat generated in cutting. An important application of cemented carbides is the drilling and routing of printed circuit boards. Solid tungsten carbide drills of extremely small sizes are used for this work.

## FORMING TOOLS

When curved surfaces or those of stepped, angular or irregular shape are required in connection with turning operations, especially on turret lathes and "automatics," forming tools are used. These tools are so made that the contour of the cutting edge corresponds to the shape required and usually they may be ground repeatedly without changing the shape of the cutting edge. There are two general classes of forming tools—the straight type and the circular type. The circular forming tool is generally used on small narrow forms, whereas the straight type is more suitable for wide forming operations. Some straight forming tools are clamped in a horizontal position upon the cut-off slide, whereas the others are held in a vertical position in a special holder. A common form of holder for these vertical tools is one having a dovetail slot in which the forming tool is clamped; hence they are often called "dovetail forming tools." In many cases, two forming tools are used, especially when a very smooth surface is required, one being employed for roughing and the other for finishing.

There was an American standard for forming tool blanks which covered both straight or dovetailed, and circular forms. The formed part of the finished blanks must be shaped to suit whatever job the tool is to be used for. This former standard includes the important dimensions of holders for both straight and circular forms.

**Dimensions of Steps on Straight or Dovetail Forming Tools.**—The diagrams at the top of the accompanying Table 1 illustrate a straight or "dovetail" forming tool. The upper or cutting face lies in the same plane as the center of the work and there is no rake. (Many forming tools have rake to increase the cutting efficiency, and this type will be referred to later.) In making a forming tool, the various steps measured perpendicular to the front face (as at  $d$ ) must be proportioned so as to obtain the required radial dimensions on the work. For example, if  $D$  equals the difference between two radial dimensions on the work, then:

$$\text{Step } d = D \times \text{cosine front clearance angle}$$

**Angles on Straight Forming Tools.**—In making forming tools to the required shape or contour, any angular surfaces (like the steps referred to in the previous paragraph) are affected by the clearance angle. For example, assume that angle  $A$  on the work (see diagram at top of accompanying table) is 20 degrees. The angle on the tool in plane  $x-x$ , in that case, will be slightly less than 20 degrees. In making the tool, this modified or reduced angle is required because of the convenience in machining and measuring the angle square to the front face of the tool or in the plane  $x-x$ .

If the angle on the work is measured from a line parallel to the axis (as at  $A$  in diagram), then the reduced angle on the tool as measured square to the front face (or in plane  $x-x$ ) is found as follows:

$$\tan \text{ reduced angle on tool} = \tan A \times \cos \text{ front clearance angle}$$

If angle  $A$  on the work is larger than, say, 45 degrees, it may be given on the drawing as indicated at  $B$ . In this case, the angle is measured from a plane perpendicular to the axis of the work. When the angle is so specified, the angle on the tool in plane  $x-x$  may be found as follows:

$$\tan \text{ reduced angle on tool} = \frac{\tan B}{\cos \text{ clearance angle}}$$

**Table Giving Step Dimensions and Angles on Straight or Dovetailed Forming Tools.**—The accompanying table gives the required dimensions and angles within its range, direct or without calculation.

**Table 1. Dimensions of Steps and Angles on Straight Forming Tools**

| Radial Depth of Step <i>D</i> | Depth <i>d</i> of step on tool |                     |                     | Radial Depth of Step <i>D</i> | Depth <i>d</i> of step on tool |                     |                     |
|-------------------------------|--------------------------------|---------------------|---------------------|-------------------------------|--------------------------------|---------------------|---------------------|
|                               | When <i>C</i> = 10°            | When <i>C</i> = 15° | When <i>C</i> = 20° |                               | When <i>C</i> = 10°            | When <i>C</i> = 15° | When <i>C</i> = 20° |
| 0.001                         | 0.00098                        | 0.00096             | 0.00094             | 0.040                         | 0.03939                        | 0.03863             | 0.03758             |
| 0.002                         | 0.00197                        | 0.00193             | 0.00187             | 0.050                         | 0.04924                        | 0.04829             | 0.04698             |
| 0.003                         | 0.00295                        | 0.00289             | 0.00281             | 0.060                         | 0.05908                        | 0.05795             | 0.05638             |
| 0.004                         | 0.00393                        | 0.00386             | 0.00375             | 0.070                         | 0.06893                        | 0.06761             | 0.06577             |
| 0.005                         | 0.00492                        | 0.00483             | 0.00469             | 0.080                         | 0.07878                        | 0.07727             | 0.07517             |
| 0.006                         | 0.00590                        | 0.00579             | 0.00563             | 0.090                         | 0.08863                        | 0.08693             | 0.08457             |
| 0.007                         | 0.00689                        | 0.00676             | 0.00657             | 0.100                         | 0.09848                        | 0.09659             | 0.09396             |
| 0.008                         | 0.00787                        | 0.00772             | 0.00751             | 0.200                         | 0.19696                        | 0.19318             | 0.18793             |
| 0.009                         | 0.00886                        | 0.00869             | 0.00845             | 0.300                         | 0.29544                        | 0.28977             | 0.28190             |
| 0.010                         | 0.00984                        | 0.00965             | 0.00939             | 0.400                         | 0.39392                        | 0.38637             | 0.37587             |
| 0.020                         | 0.01969                        | 0.01931             | 0.01879             | 0.500                         | 0.49240                        | 0.48296             | 0.46984             |
| 0.030                         | 0.02954                        | 0.02897             | 0.02819             | ...                           | ...                            | ...                 | ...                 |

Upper section of table gives depth *d* of step on forming tool for a given dimension *D* that equals the actual depth of the step on the work, measured radially and along the cutting face of the tool (see diagram at left). First, locate depth *D* required on work; then find depth *d* on tool under tool clearance angle *C*. Depth *d* is measured perpendicular to front face of tool.

| Angle <i>A</i> in Plane of Tool Cutting Face | Angle on tool in plane <i>x-x</i> |        |                     |     |                     |        |         |
|--|-----------------------------------|--------|---------------------|-----|---------------------|--------|---------|
|  | When <i>C</i> = 10°               |        | When <i>C</i> = 15° |     | When <i>C</i> = 20° |        |         |
| 5°   | 4° 55'                            | 4° 50' | 4° 42'              | 50° | 49° 34'             | 49° 1' | 48° 14' |
| 10   | 9 51                              | 9 40   | 9 24                | 55  | 54 35               | 54 4   | 53 18   |
| 15   | 14 47                             | 14 31  | 14 8                | 60  | 59 37               | 59 8   | 58 26   |
| 20   | 19 43                             | 19 22  | 18 53               | 65  | 64 40               | 64 14  | 63 36   |
| 25   | 24 40                             | 24 15  | 23 40               | 70  | 69 43               | 69 21  | 68 50   |
| 30   | 29 37                             | 29 9   | 28 29               | 75  | 74 47               | 74 30  | 74 5    |
| 35   | 34 35                             | 34 4   | 33 20               | 80  | 79 51               | 79 39  | 79 22   |
| 40   | 39 34                             | 39 1   | 38 15               | 85  | 84 55               | 84 49  | 84 41   |
| 45   | 44 34                             | 44 0   | 43 13               | ... | ...                 | ...    | ...     |

Lower section of table gives angles as measured in plane *x-x* perpendicular to front face of forming tool (see diagram on right). Find in first column the angle *A* required on work; then find reduced angle in plane *x-x* under given clearance angle *C*.

**To Find Dimensions of Steps:** The upper section of **Table 1** is used in determining the dimensions of steps. The radial depth of the step or the actual cutting depth *D* (see left-hand diagram) is given in the first column of the table. The columns that follow give the corresponding depths *d* for a front clearance angle of 10, 15, or 20 degrees. To illustrate the use of the table, suppose a tool is required for turning the part shown in **Fig. 1**, which has diameters of 0.75, 1.25, and 1.75 inches, respectively. The difference between the largest and the smallest radius is 0.5 inch, which is the depth of one step. Assume that the clearance angle is 15 degrees. First, locate 0.5 in the column headed "Radial Depth of Step *D*"; then find depth *d* in the column headed "when *C* = 15°." As will be seen, this depth is 0.48296

inch. Practically the same procedure is followed in determining the depth of the second step on the tool. The difference in the radii in this case equals 0.25. This value is not given directly in the table, so first find the depth equivalent to 0.200 and add to it the depth equivalent to 0.050. Thus, we have  $0.19318 + 0.04829 = 0.24147$ . In using Table 1, it is assumed that the top face of the tool is set at the height of the work axis.

*To Find Angle:* The lower section of Table 1 applies to angles when they are measured relative to the axis of the work. The application of the table will again be illustrated by using the part shown in Fig. 1. The angle used here is 40 degrees (which is also the angle in the plane of the cutting face of the tool). If the clearance angle is 15 degrees, the angle measured in plane  $x-x$  square to the face of the tool is shown by the table to be  $39^{\circ} 1'$  - a reduction of practically 1 degree.

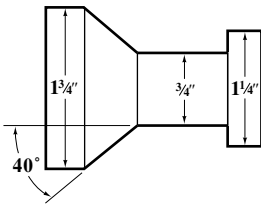


Fig. 1.

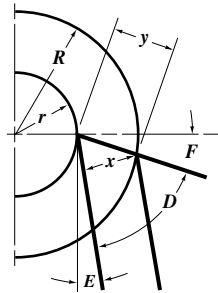


Fig. 2.

If a straight forming tool has rake, the depth  $x$  of each step (see Fig. 2), measured perpendicular to the front or clearance face, is affected not only by the clearance angle, but by the rake angle  $F$  and the radii  $R$  and  $r$  of the steps on the work. First, it is necessary to find three angles, designated  $A$ ,  $B$ , and  $C$ , that are not shown on the drawing.

$$\text{Angle } A = 180^{\circ} - \text{rake angle } F$$

$$\sin B = \frac{r \sin A}{R}$$

$$\text{Angle } C = 180^{\circ} - (A + B)$$

$$y = \frac{R \sin C}{\sin A}$$

$$\text{Angle } D \text{ of tool} = 90^{\circ} - (E + F)$$

$$\text{Depth } x = y \sin D$$

If the work has two or more shoulders, the depth  $x$  for other steps on the tool may be determined for each radius  $r$ . If the work has curved or angular forms, it is more practical to use a tool without rake because its profile, in the plane of the cutting face, duplicates that of the work.

*Example:* Assume that radius  $R$  equals 0.625 inch and radius  $r$  equals 0.375 inch, so that the step on the work has a radial depth of 0.25 inch. The tool has a rake angle  $F$  of 10 degrees and a clearance angle  $E$  of 15 degrees. Then angle  $A = 180 - 10 = 170$  degrees.

$$\sin B = \frac{0.375 \times 0.17365}{0.625} = 0.10419 \quad \text{Angle } B = 5^\circ 59' \text{ nearly.}$$

$$\text{Angle } C = 180 - (170^\circ + 5^\circ 59') = 4^\circ 1'$$

$$\text{Dimension } y = \frac{0.625 \times 0.07005}{0.17365} = 0.25212$$

$$\text{Angle } D = 90^\circ - (15 + 10) = 65 \text{ degrees}$$

$$\text{Depth } x \text{ of step} = 0.25212 \times 0.90631 = 0.2285 \text{ inch}$$

**Circular Forming Tools.**—To provide sufficient peripheral clearance on circular forming tools, the cutting face is offset with relation to the center of the tool a distance  $C$ , as shown in Fig. 3. Whenever a circular tool has two or more diameters, the difference in the radii of the steps on the tool will not correspond exactly to the difference in the steps on the work. The form produced with the tool also changes, although the change is very slight, unless the amount of offset  $C$  is considerable. Assume that a circular tool is required to produce the piece  $A$  having two diameters as shown.

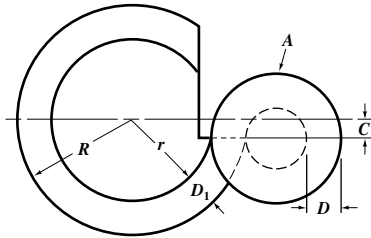


Fig. 3.

If the difference  $D_1$  between the large and small radii of the tool were made equal to dimension  $D$  required on the work,  $D$  would be a certain amount oversize, depending upon the offset  $C$  of the cutting edge. The following formulas can be used to determine the radii of circular forming tools for turning parts to different diameters:

Let  $R$  = largest radius of tool in inches;  $D$  = difference in radii of steps on work;  $C$  = amount cutting edge is offset from center of tool;  $r$  = required radius in inches; then

$$r = \sqrt{\left(\sqrt{R^2 - C^2} - D\right)^2 + C^2} \quad (1)$$

If the small radius  $r$  is given and the large radius  $R$  is required, then

$$R = \sqrt{\left(\sqrt{r^2 - C^2} + D\right)^2 + C^2} \quad (2)$$

To illustrate, if  $D$  (Fig. 3) is to be  $\frac{1}{8}$  inch, the large radius  $R$  is  $1\frac{1}{8}$  inches, and  $C$  is  $\frac{5}{32}$  inch, what radius  $r$  would be required to compensate for the offset  $C$  of the cutting edge? Inserting these values in Formula (1):

$$r = \sqrt{\sqrt{\left(1\frac{1}{8}\right)^2 - \left(\frac{5}{32}\right)^2} - \left(\frac{1}{8}\right)^2 + \left(\frac{5}{32}\right)^2} = 1.0014 \text{ inches}$$

The value of  $r$  is thus found to be 1.0014 inches; hence, the diameter =  $2 \times 1.0014 = 2.0028$  inches instead of 2 inches, as it would have been if the cutting edge had been exactly on the center line. Formulas for circular tools used on different makes of screw machines can be simplified when the values  $R$  and  $C$  are constant for each size of machine. The accompanying Table 2, *Formulas for Circular Forming Tools*, gives the standard values of  $R$  and  $C$  for circular tools used on different automatics. The formulas for determining the



**Table 2. Formulas for Circular Forming Tools<sup>a</sup>**

| Make of Machine | Size of Machine  | Radius $R$ , Inches | Offset $C$ , Inches | Radius $r$ , Inches                  |
|-----------------|------------------|---------------------|---------------------|--------------------------------------|
| Brown & Sharpe  | No. 00           | 0.875               | 0.125               | $r = \sqrt{(0.8660 - D)^2 + 0.0156}$ |
|                 | No. 0            | 1.125               | 0.15625             | $r = \sqrt{(1.1141 - D)^2 + 0.0244}$ |
|                 | No. 2            | 1.50                | 0.250               | $r = \sqrt{(1.4790 - D)^2 + 0.0625}$ |
|                 | No. 6            | 2.00                | 0.3125              | $r = \sqrt{(1.975 - D)^2 + 0.0976}$  |
| Acme            | No. 51           | 0.75                | 0.09375             | $r = \sqrt{(1.7441 - D)^2 + 0.0088}$ |
|                 | No. 515          | 0.75                | 0.09375             | $r = \sqrt{(0.7441 - D)^2 + 0.0088}$ |
|                 | No. 52           | 1.0                 | 0.09375             | $r = \sqrt{(0.9956 - D)^2 + 0.0088}$ |
|                 | No. 53           | 1.1875              | 0.125               | $r = \sqrt{(1.1809 - D)^2 + 0.0156}$ |
|                 | No. 54           | 1.250               | 0.15625             | $r = \sqrt{(1.2402 - D)^2 + 0.0244}$ |
|                 | No. 55           | 1.250               | 0.15625             | $r = \sqrt{(1.2402 - D)^2 + 0.0244}$ |
|                 | No. 56           | 1.50                | 0.1875              | $r = \sqrt{(1.4882 - D)^2 + 0.0352}$ |
| Cleveland       | $\frac{1}{4}$ "  | 0.625               | 0.03125             | $r = \sqrt{(0.6242 - D)^2 + 0.0010}$ |
|                 | $\frac{3}{8}$ "  | 0.084375            | 0.0625              | $r = \sqrt{(0.8414 - D)^2 + 0.0039}$ |
|                 | $\frac{5}{8}$ "  | 1.15625             | 0.0625              | $r = \sqrt{(1.1546 - D)^2 + 0.0039}$ |
|                 | $\frac{7}{8}$ "  | 1.1875              | 0.0625              | $r = \sqrt{(1.1859 - D)^2 + 0.0039}$ |
|                 | $1\frac{1}{4}$ " | 1.375               | 0.0625              | $r = \sqrt{(1.3736 - D)^2 + 0.0039}$ |
|                 | 2"               | 1.375               | 0.0625              | $r = \sqrt{(1.3736 - D)^2 + 0.0039}$ |
|                 | $2\frac{1}{4}$ " | 1.625               | 0.125               | $r = \sqrt{(1.6202 - D)^2 + 0.0156}$ |
|                 | $2\frac{3}{4}$ " | 1.875               | 0.15625             | $r = \sqrt{(1.8685 - D)^2 + 0.0244}$ |
|                 | $3\frac{1}{4}$ " | 1.875               | 0.15625             | $r = \sqrt{(1.8685 - D)^2 + 0.0244}$ |
|                 | $4\frac{1}{4}$ " | 2.50                | 0.250               | $r = \sqrt{(2.4875 - D)^2 + 0.0625}$ |
|                 | 6"               | 2.625               | 0.250               | $r = \sqrt{(2.6131 - D)^2 + 0.0625}$ |

<sup>a</sup>For notation, see Fig. 3

radius  $r$  (see column at right-hand side of table) contain a constant that represents the value of the expression  $\sqrt{R^2 - C^2}$  in Formula (1).

Table 3, *Constant for Determining Diameters of Circular Forming Tools* has been compiled to facilitate proportioning tools of this type and gives constants for computing the various diameters of forming tools, when the cutting face of the tool is  $\frac{1}{8}$ ,  $\frac{3}{16}$ ,  $\frac{1}{4}$ , or  $\frac{5}{16}$  inch below the horizontal center line. As there is no standard distance for the location of the cutting face, the table has been prepared to correspond with distances commonly used. As an example, suppose the tool is required for a part having three diameters of 1.75, 0.75, and 1.25 inches, respectively, as shown in Fig. 1, and that the largest diameter of the tool is 3 inches and the cutting face is  $\frac{1}{4}$  inch below the horizontal center line. The first step would

be to determine approximately the respective diameters of the forming tool and then correct the diameters by the use of the table. To produce the three diameters shown in Fig. 1, with a 3-inch forming tool, the tool diameters would be approximately 2, 3, and 2.5 inches, respectively. The first dimension (2 inches) is 1 inch less in diameter than that of the tool, and the necessary correction should be given in the column "Correction for Difference in Diameter"; but as the table is only extended to half-inch differences, it will be necessary to obtain this particular correction in two steps. On the line for 3-inch diameter and under corrections for  $\frac{1}{2}$  inch, we find 0.0085; then in line with  $2\frac{1}{2}$  and under the same heading, we find 0.0129, hence the total correction would be  $0.0085 + 0.0129 = 0.0214$  inch. This correction is added to the approximate diameter, making the exact diameter of the first step  $2 + 0.0214 = 2.0214$  inches. The next step would be computed in the same way, by noting on the 3-inch line the correction for  $\frac{1}{2}$  inch and adding it to the approximate diameter of the second step, giving an exact diameter of  $2.5 + 0.0085 + 2.5085$  inches. Therefore, to produce the part shown in Fig. 1, the tool should have three steps of 3, 2.0214, and 2.5085 inches, respectively, provided the cutting face is  $\frac{1}{4}$  inch below the center. All diameters are computed in this way, from the largest diameter of the tool.

Tables 4a, 4b, and 4c, *Corrected Diameters of Circular Forming Tools*, are especially applicable to tools used on Brown & Sharpe automatic screw machines. Directions for using these tables are given on page 789.

**Circular Tools Having Top Rake.**—Circular forming tools without top rake are satisfactory for brass, but tools for steel or other tough metals cut better when there is a rake angle of 10 or 12 degrees. For such tools, the small radius  $r$  (see Fig. 3) for an outside radius  $R$  may be found by the formula

$$r = \sqrt{P^2 + R^2 - 2PR \cos \theta}$$

To find the value of  $P$ , proceed as follows:  $\sin \phi =$  small radius on work  $\times$   $\sin$  rake angle  $\div$  large radius on work. Angle  $\beta =$  rake angle  $- \phi$ .  $P =$  large radius on work  $\times$   $\sin \beta \div$   $\sin$  rake angle. Angle  $\theta =$  rake angle  $+ \delta$ .  $\sin \delta =$  vertical height  $C$  from center of tool to center of work  $\div R$ . It is assumed that the tool point is to be set at the same height as the work center.

**Using Tables for "Corrected Diameters of Circular Forming Tools."**—Tables 4a, 4b, and 4c are especially applicable to Brown & Sharpe automatic screw machines. The maximum diameter  $D$  of forming tools for these machines should be as follows: For No. 00 machine,  $1\frac{3}{4}$  inches; for No. 0 machine,  $2\frac{1}{4}$  inches; for No. 2 machine, 3 inches. To find the other diameters of the tool for any piece to be formed, proceed as follows: Subtract the smallest diameter of the work from the diameter of the work that is to be formed by the required tool diameter; divide the remainder by 2; locate the quotient obtained in the column headed "Length  $c$  on Tool," and opposite the figure thus located and in the column headed by the number of the machine used, read off directly the diameter to which the tool is to be made. The quotient obtained, which is located in the column headed "Length  $c$  on Tool," is the length  $c$ , as shown in Fig. 4.

*Example:* A piece of work is to be formed on a No. 0 machine to two diameters, one being  $\frac{1}{4}$  inch and one 0.550 inch; find the diameters of the tool. The maximum tool diameter is  $2\frac{1}{4}$  inches, or the diameter that will cut the  $\frac{1}{4}$ -inch diameter of the work. To find the other diameter, proceed according to the rule given:  $0.550 - \frac{1}{4} = 0.300$ ;  $0.300 \div 2 = 0.150$ . In Table 4b, opposite 0.150, we find that the required tool diameter is 1.9534 inches. These tables are for tools without rakes.

Table 3. Constant for Determining Diameters of Circular Forming Tools

| Dia. of Tool   | Radius of Tool | Cutting Face $\frac{1}{8}$ Inch Below Center |                    |                    | Cutting Face $\frac{3}{16}$ Inch Below Center |                    |                    | Cutting Face $\frac{1}{4}$ Inch Below Center |                    |                    | Cutting Face $\frac{5}{16}$ Inch Below Center |                    |                    |
|----------------|----------------|--|--------------------|--------------------|---|--------------------|--------------------|--|--------------------|--------------------|---|--------------------|--------------------|
|                |                | Correction for Difference in Diameter        |                    |                    | Correction for Difference in Diameter         |                    |                    | Correction for Difference in Diameter        |                    |                    | Correction for Difference in Diameter         |                    |                    |
|                |                | $\frac{1}{8}$ Inch                           | $\frac{1}{4}$ Inch | $\frac{1}{2}$ Inch | $\frac{1}{8}$ Inch                            | $\frac{1}{4}$ Inch | $\frac{1}{2}$ Inch | $\frac{1}{8}$ Inch                           | $\frac{1}{4}$ Inch | $\frac{1}{2}$ Inch | $\frac{1}{8}$ Inch                            | $\frac{1}{4}$ Inch | $\frac{1}{2}$ Inch |
| 1              | 0.500          | ...  | ...                | ...                | ...   | ...                | ...                | ...  | ...                | ...                | ...   | ...                | ...                |
| $1\frac{1}{8}$ | 0.5625         | 0.0036                                       | ...                | ...                | 0.0086  | ...                | ...                | 0.0167                                       | ...                | ...                | 0.0298  | ...                | ...                |
| $1\frac{1}{4}$ | 0.625          | 0.0028                                       | 0.0065             | ...                | 0.0067  | 0.0154             | ...                | 0.0128                                       | 0.0296             | ...                | 0.0221  | 0.0519             | ...                |
| $1\frac{3}{8}$ | 0.6875         | 0.0023                                       | ...                | ...                | 0.0054  | ...                | ...                | 0.0102                                       | ...                | ...                | 0.0172  | ...                | ...                |
| $1\frac{1}{2}$ | 0.750          | 0.0019                                       | 0.0042             | 0.0107             | 0.0045  | 0.0099             | 0.0253             | 0.0083                                       | 0.0185             | 0.0481             | 0.0138  | 0.0310             | 0.0829             |
| $1\frac{5}{8}$ | 0.8125         | 0.0016                                       | ...                | ...                | 0.0037  | ...                | ...                | 0.0069                                       | ...                | ...                | 0.0114  | ...                | ...                |
| $1\frac{3}{4}$ | 0.875          | 0.0014                                       | 0.0030             | ...                | 0.0032  | 0.0069             | ...                | 0.0058                                       | 0.0128             | ...                | 0.0095  | 0.0210             | ...                |
| $1\frac{7}{8}$ | 0.9375         | 0.0012                                       | ...                | ...                | 0.0027  | ...                | ...                | 0.0050                                       | ...                | ...                | 0.0081  | ...                | ...                |
| 2              | 1.000          | 0.0010                                       | 0.0022             | 0.0052             | 0.0024  | 0.0051             | 0.0121             | 0.0044                                       | 0.0094             | 0.0223             | 0.0070  | 0.0152             | 0.0362             |
| $2\frac{1}{8}$ | 1.0625         | 0.0009                                       | ...                | ...                | 0.0021  | ...                | ...                | 0.0038                                       | ...                | ...                | 0.0061  | ...                | ...                |
| $2\frac{1}{4}$ | 1.125          | 0.0008                                       | 0.0017             | ...                | 0.0018  | 0.0040             | ...                | 0.0034                                       | 0.0072             | ...                | 0.0054  | 0.0116             | ...                |
| $2\frac{3}{8}$ | 1.1875         | 0.0007                                       | ...                | ...                | 0.0016  | ...                | ...                | 0.0029                                       | ...                | ...                | 0.0048  | ...                | ...                |
| $2\frac{1}{2}$ | 1.250          | 0.0006                                       | 0.0014             | 0.0031             | 0.0015  | 0.0031             | 0.0071             | 0.0027                                       | 0.0057             | 0.0129             | 0.0043  | 0.0092             | 0.0208             |
| $2\frac{5}{8}$ | 1.3125         | 0.0006                                       | ...                | ...                | 0.0013  | ...                | ...                | 0.0024                                       | ...                | ...                | 0.0038  | ...                | ...                |
| $2\frac{3}{4}$ | 1.375          | 0.0005                                       | 0.0011             | ...                | 0.0012  | 0.0026             | ...                | 0.0022                                       | 0.0046             | ...                | 0.0035  | 0.0073             | ...                |
| $2\frac{7}{8}$ | 1.4375         | 0.0005                                       | ...                | ...                | 0.0011  | ...                | ...                | 0.0020                                       | ...                | ...                | 0.0032  | ...                | ...                |
| 3              | 1.500          | 0.0004                                       | 0.0009             | 0.0021             | 0.0010  | 0.0021             | 0.0047             | 0.0018                                       | 0.0038             | 0.0085             | 0.0029  | 0.0061             | 0.0135             |
| $3\frac{1}{8}$ | 1.5625         | 0.0004                                       | ...                | ...                | 0.0009  | ...                | ...                | 0.0017                                       | ...                | ...                | 0.0027  | ...                | ...                |
| $3\frac{1}{4}$ | 1.625          | 0.0003                                       | 0.0008             | ...                | 0.0008  | 0.0018             | ...                | 0.0015                                       | 0.0032             | ...                | 0.0024  | 0.0051             | ...                |
| $3\frac{3}{8}$ | 1.6875         | 0.0003                                       | ...                | ...                | 0.0008  | ...                | ...                | 0.0014                                       | ...                | ...                | 0.0023  | ...                | ...                |
| $3\frac{1}{2}$ | 1.750          | 0.0003                                       | 0.0007             | 0.0015             | 0.0007  | 0.0015             | 0.0033             | 0.0013                                       | 0.0028             | 0.0060             | 0.0021  | 0.0044             | 0.0095             |
| $3\frac{5}{8}$ | 1.8125         | 0.0003                                       | ...                | ...                | 0.0007  | ...                | ...                | 0.0012                                       | ...                | ...                | 0.0019  | ...                | ...                |
| $3\frac{3}{4}$ | 1.875          | 0.0002                                       | 0.0006             | ...                | 0.0006  | 0.0013             | ...                | 0.0011                                       | 0.0024             | ...                | 0.0018  | 0.0038             | ...                |

Table 4a. Corrected Diameters of Circular Forming Tools

| Length <i>c</i><br>on Tool | Number of B. & S. Automatic<br>Screw Machine |        |        | Length <i>c</i><br>on Tool | Number of B. & S. Automatic<br>Screw Machine |        |        |
|----------------------------|--|--------|--------|----------------------------|--|--------|--------|
|                            | No. 00                                       | No. 0  | No. 2  |                            | No. 00                                       | No. 0  | No. 2  |
| 0.001                      | 1.7480                                       | 2.2480 | 2.9980 | 0.058                      | 1.6353                                       | 2.1352 | 2.8857 |
| 0.002                      | 1.7460                                       | 2.2460 | 2.9961 | 0.059                      | 1.6333                                       | 2.1332 | 2.8837 |
| 0.003                      | 1.7441                                       | 2.2441 | 2.9941 | 0.060                      | 1.6313                                       | 2.1312 | 2.8818 |
| 0.004                      | 1.7421                                       | 2.2421 | 2.9921 | 0.061                      | 1.6294                                       | 2.1293 | 2.8798 |
| 0.005                      | 1.7401                                       | 2.2401 | 2.9901 | 0.062                      | 1.6274                                       | 2.1273 | 2.8778 |
| 0.006                      | 1.7381                                       | 2.2381 | 2.9882 | $\frac{1}{16}$             | 1.6264                                       | 2.1263 | 2.8768 |
| 0.007                      | 1.7362                                       | 2.2361 | 2.9862 | 0.063                      | 1.6254                                       | 2.1253 | 2.8759 |
| 0.008                      | 1.7342                                       | 2.2341 | 2.9842 | 0.064                      | 1.6234                                       | 2.1233 | 2.8739 |
| 0.009                      | 1.7322                                       | 2.2321 | 2.9823 | 0.065                      | 1.6215                                       | 2.1213 | 2.8719 |
| 0.010                      | 1.7302                                       | 2.2302 | 2.9803 | 0.066                      | 1.6195                                       | 2.1194 | 2.8699 |
| 0.011                      | 1.7282                                       | 2.2282 | 2.9783 | 0.067                      | 1.6175                                       | 2.1174 | 2.8680 |
| 0.012                      | 1.7263                                       | 2.2262 | 2.9763 | 0.068                      | 1.6155                                       | 2.1154 | 2.8660 |
| 0.013                      | 1.7243                                       | 2.2243 | 2.9744 | 0.069                      | 1.6136                                       | 2.1134 | 2.8640 |
| 0.014                      | 1.7223                                       | 2.2222 | 2.9724 | 0.070                      | 1.6116                                       | 2.1115 | 2.8621 |
| 0.015                      | 1.7203                                       | 2.2203 | 2.9704 | 0.071                      | 1.6096                                       | 2.1095 | 2.8601 |
| $\frac{1}{64}$             | 1.7191                                       | 2.2191 | 2.9692 | 0.072                      | 1.6076                                       | 2.1075 | 2.8581 |
| 0.016                      | 1.7184                                       | 2.2183 | 2.9685 | 0.073                      | 1.6057                                       | 2.1055 | 2.8561 |
| 0.017                      | 1.7164                                       | 2.2163 | 2.9665 | 0.074                      | 1.6037                                       | 2.1035 | 2.8542 |
| 0.018                      | 1.7144                                       | 2.2143 | 2.9645 | 0.075                      | 1.6017                                       | 2.1016 | 2.8522 |
| 0.019                      | 1.7124                                       | 2.2123 | 2.9625 | 0.076                      | 1.5997                                       | 2.0996 | 2.8503 |
| 0.020                      | 1.7104                                       | 2.2104 | 2.9606 | 0.077                      | 1.5978                                       | 2.0976 | 2.8483 |
| 0.021                      | 1.7085                                       | 2.2084 | 2.9586 | 0.078                      | 1.5958                                       | 2.0956 | 2.8463 |
| 0.022                      | 1.7065                                       | 2.2064 | 2.9566 | $\frac{3}{64}$             | 1.5955                                       | 2.0954 | 2.8461 |
| 0.023                      | 1.7045                                       | 2.2045 | 2.9547 | 0.079                      | 1.5938                                       | 2.0937 | 2.8443 |
| 0.024                      | 1.7025                                       | 2.2025 | 2.9527 | 0.080                      | 1.5918                                       | 2.0917 | 2.8424 |
| 0.025                      | 1.7005                                       | 2.2005 | 2.9507 | 0.081                      | 1.5899                                       | 2.0897 | 2.8404 |
| 0.026                      | 1.6986                                       | 2.1985 | 2.9488 | 0.082                      | 1.5879                                       | 2.0877 | 2.8384 |
| 0.027                      | 1.6966                                       | 2.1965 | 2.9468 | 0.083                      | 1.5859                                       | 2.0857 | 2.8365 |
| 0.028                      | 1.6946                                       | 2.1945 | 2.9448 | 0.084                      | 1.5839                                       | 2.0838 | 2.8345 |
| 0.029                      | 1.6926                                       | 2.1925 | 2.9428 | 0.085                      | 1.5820                                       | 2.0818 | 2.8325 |
| 0.030                      | 1.6907                                       | 2.1906 | 2.9409 | 0.086                      | 1.5800                                       | 2.0798 | 2.8306 |
| 0.031                      | 1.6887                                       | 2.1886 | 2.9389 | 0.087                      | 1.5780                                       | 2.0778 | 2.8286 |
| $\frac{1}{32}$             | 1.6882                                       | 2.1881 | 2.9384 | 0.088                      | 1.5760                                       | 2.0759 | 2.8266 |
| 0.032                      | 1.6867                                       | 2.1866 | 2.9369 | 0.089                      | 1.5740                                       | 2.0739 | 2.8247 |
| 0.033                      | 1.6847                                       | 2.1847 | 2.9350 | 0.090                      | 1.5721                                       | 2.0719 | 2.8227 |
| 0.034                      | 1.6827                                       | 2.1827 | 2.9330 | 0.091                      | 1.5701                                       | 2.0699 | 2.8207 |
| 0.035                      | 1.6808                                       | 2.1807 | 2.9310 | 0.092                      | 1.5681                                       | 2.0679 | 2.8187 |
| 0.036                      | 1.6788                                       | 2.1787 | 2.9290 | 0.093                      | 1.5661                                       | 2.0660 | 2.8168 |
| 0.037                      | 1.6768                                       | 2.1767 | 2.9271 | $\frac{3}{32}$             | 1.5647                                       | 2.0645 | 2.8153 |
| 0.038                      | 1.6748                                       | 2.1747 | 2.9251 | 0.094                      | 1.5642                                       | 2.0640 | 2.8148 |
| 0.039                      | 1.6729                                       | 2.1727 | 2.9231 | 0.095                      | 1.5622                                       | 2.0620 | 2.8128 |
| 0.040                      | 1.6709                                       | 2.1708 | 2.9211 | 0.096                      | 1.5602                                       | 2.0600 | 2.8109 |
| 0.041                      | 1.6689                                       | 2.1688 | 2.9192 | 0.097                      | 1.5582                                       | 2.0581 | 2.8089 |
| 0.042                      | 1.6669                                       | 2.1668 | 2.9172 | 0.098                      | 1.5563                                       | 2.0561 | 2.8069 |
| 0.043                      | 1.6649                                       | 2.1649 | 2.9152 | 0.099                      | 1.5543                                       | 2.0541 | 2.8050 |
| 0.044                      | 1.6630                                       | 2.1629 | 2.9133 | 0.100                      | 1.5523                                       | 2.0521 | 2.8030 |
| 0.045                      | 1.6610                                       | 2.1609 | 2.9113 | 0.101                      | 1.5503                                       | 2.0502 | 2.8010 |
| 0.046                      | 1.6590                                       | 2.1589 | 2.9093 | 0.102                      | 1.5484                                       | 2.0482 | 2.7991 |
| $\frac{3}{64}$             | 1.6573                                       | 2.1572 | 2.9076 | 0.103                      | 1.5464                                       | 2.0462 | 2.7971 |
| 0.047                      | 1.6570                                       | 2.1569 | 2.9073 | 0.104                      | 1.5444                                       | 2.0442 | 2.7951 |
| 0.048                      | 1.6550                                       | 2.1549 | 2.9054 | 0.105                      | 1.5425                                       | 2.0422 | 2.7932 |
| 0.049                      | 1.6531                                       | 2.1529 | 2.9034 | 0.106                      | 1.5405                                       | 2.0403 | 2.7912 |
| 0.050                      | 1.6511                                       | 2.1510 | 2.9014 | 0.107                      | 1.5385                                       | 2.0383 | 2.7892 |
| 0.051                      | 1.6491                                       | 2.1490 | 2.8995 | 0.108                      | 1.5365                                       | 2.0363 | 2.7873 |
| 0.052                      | 1.6471                                       | 2.1470 | 2.8975 | 0.109                      | 1.5346                                       | 2.0343 | 2.7853 |
| 0.053                      | 1.6452                                       | 2.1451 | 2.8955 | $\frac{7}{64}$             | 1.5338                                       | 2.0336 | 2.7846 |
| 0.054                      | 1.6432                                       | 2.1431 | 2.8936 | 0.110                      | 1.5326                                       | 2.0324 | 2.7833 |
| 0.055                      | 1.6412                                       | 2.1411 | 2.8916 | 0.111                      | 1.5306                                       | 2.0304 | 2.7814 |
| 0.056                      | 1.6392                                       | 2.1391 | 2.8896 | 0.112                      | 1.5287                                       | 2.0284 | 2.7794 |
| 0.057                      | 1.6373                                       | 2.1372 | 2.8877 | 0.113                      | 1.5267                                       | 2.0264 | 2.7774 |

**Table 4a. Corrected Diameters of Circular Forming Tools (Continued)**

| Length <i>c</i><br>on Tool | Number of B. & S. Automatic<br>Screw Machine |        |        | Length <i>c</i><br>on Tool | Number of B. & S. Automatic<br>Screw Machine |        |        |
|----------------------------|--|--------|--------|----------------------------|--|--------|--------|
|                            | No. 00                                       | No. 0  | No. 2  |                            | No. 00                                       | No. 0  | No. 2  |
| 0.113                      | 1.5267                                       | 2.0264 | 2.7774 | 0.171                      | 1.4124                                       | 1.9119 | 2.6634 |
| 0.114                      | 1.5247                                       | 2.0245 | 2.7755 | $\frac{11}{64}$            | 1.4107                                       | 1.9103 | 2.6617 |
| 0.115                      | 1.5227                                       | 2.0225 | 2.7735 | 0.172                      | 1.4104                                       | 1.9099 | 2.6614 |
| 0.116                      | 1.5208                                       | 2.0205 | 2.7715 | 0.173                      | 1.4084                                       | 1.9080 | 2.6595 |
| 0.117                      | 1.5188                                       | 2.0185 | 2.7696 | 0.174                      | 1.4065                                       | 1.9060 | 2.6575 |
| 0.118                      | 1.5168                                       | 2.0166 | 2.7676 | 0.175                      | 1.4045                                       | 1.9040 | 2.6556 |
| 0.119                      | 1.5148                                       | 2.0146 | 2.7656 | 0.176                      | 1.4025                                       | 1.9021 | 2.6536 |
| 0.120                      | 1.5129                                       | 2.0126 | 2.7637 | 0.177                      | 1.4006                                       | 1.9001 | 2.6516 |
| 0.121                      | 1.5109                                       | 2.0106 | 2.7617 | 0.178                      | 1.3986                                       | 1.8981 | 2.6497 |
| 0.122                      | 1.5089                                       | 2.0087 | 2.7597 | 0.179                      | 1.3966                                       | 1.8961 | 2.6477 |
| 0.123                      | 1.5070                                       | 2.0067 | 2.7578 | 0.180                      | 1.3947                                       | 1.8942 | 2.6457 |
| 0.124                      | 1.5050                                       | 2.0047 | 2.7558 | 0.181                      | 1.3927                                       | 1.8922 | 2.6438 |
| 0.125                      | 1.5030                                       | 2.0027 | 2.7538 | 0.182                      | 1.3907                                       | 1.8902 | 2.6418 |
| 0.126                      | 1.5010                                       | 2.0008 | 2.7519 | 0.183                      | 1.3888                                       | 1.8882 | 2.6398 |
| 0.127                      | 1.4991                                       | 1.9988 | 2.7499 | 0.184                      | 1.3868                                       | 1.8863 | 2.6379 |
| 0.128                      | 1.4971                                       | 1.9968 | 2.7479 | 0.185                      | 1.3848                                       | 1.8843 | 2.6359 |
| 0.129                      | 1.4951                                       | 1.9948 | 2.7460 | 0.186                      | 1.3829                                       | 1.8823 | 2.6339 |
| 0.130                      | 1.4932                                       | 1.9929 | 2.7440 | 0.187                      | 1.3809                                       | 1.8804 | 2.6320 |
| 0.131                      | 1.4912                                       | 1.9909 | 2.7420 | $\frac{3}{16}$             | 1.3799                                       | 1.8794 | 2.6310 |
| 0.132                      | 1.4892                                       | 1.9889 | 2.7401 | 0.188                      | 1.3789                                       | 1.8784 | 2.6300 |
| 0.133                      | 1.4872                                       | 1.9869 | 2.7381 | 0.189                      | 1.3770                                       | 1.8764 | 2.6281 |
| 0.134                      | 1.4853                                       | 1.9850 | 2.7361 | 0.190                      | 1.3750                                       | 1.8744 | 2.6261 |
| 0.135                      | 1.4833                                       | 1.9830 | 2.7342 | 0.191                      | 1.3730                                       | 1.8725 | 2.6241 |
| 0.136                      | 1.4813                                       | 1.9810 | 2.7322 | 0.192                      | 1.3711                                       | 1.8705 | 2.6222 |
| 0.137                      | 1.4794                                       | 1.9790 | 2.7302 | 0.193                      | 1.3691                                       | 1.8685 | 2.6202 |
| 0.138                      | 1.4774                                       | 1.9771 | 2.7282 | 0.194                      | 1.3671                                       | 1.8665 | 2.6182 |
| 0.139                      | 1.4754                                       | 1.9751 | 2.7263 | 0.195                      | 1.3652                                       | 1.8646 | 2.6163 |
| 0.140                      | 1.4734                                       | 1.9731 | 2.7243 | 0.196                      | 1.3632                                       | 1.8626 | 2.6143 |
| $\frac{1}{64}$             | 1.4722                                       | 1.9719 | 2.7231 | 0.197                      | 1.3612                                       | 1.8606 | 2.6123 |
| 0.141                      | 1.4715                                       | 1.9711 | 2.7224 | 0.198                      | 1.3592                                       | 1.8587 | 2.6104 |
| 0.142                      | 1.4695                                       | 1.9692 | 2.7204 | 0.199                      | 1.3573                                       | 1.8567 | 2.6084 |
| 0.143                      | 1.4675                                       | 1.9672 | 2.7184 | 0.200                      | 1.3553                                       | 1.8547 | 2.6064 |
| 0.144                      | 1.4655                                       | 1.9652 | 2.7165 | 0.201                      | ...  | 1.8527 | 2.6045 |
| 0.145                      | 1.4636                                       | 1.9632 | 2.7145 | 0.202                      | ...  | 1.8508 | 2.6025 |
| 0.146                      | 1.4616                                       | 1.9613 | 2.7125 | 0.203                      | ...  | 1.8488 | 2.6006 |
| 0.147                      | 1.4596                                       | 1.9593 | 2.7106 | $\frac{13}{64}$            | ...  | 1.8466 | 2.6003 |
| 0.148                      | 1.4577                                       | 1.9573 | 2.7086 | 0.204                      | ...  | 1.8468 | 2.5986 |
| 0.149                      | 1.4557                                       | 1.9553 | 2.7066 | 0.205                      | ...  | 1.8449 | 2.5966 |
| 0.150                      | 1.4537                                       | 1.9534 | 2.7047 | 0.206                      | ...  | 1.8429 | 2.5947 |
| 0.151                      | 1.4517                                       | 1.9514 | 2.7027 | 0.207                      | ...  | 1.8409 | 2.5927 |
| 0.152                      | 1.4498                                       | 1.9494 | 2.7007 | 0.208                      | ...  | 1.8390 | 2.5908 |
| 0.153                      | 1.4478                                       | 1.9474 | 2.6988 | 0.209                      | ...  | 1.8370 | 2.5888 |
| 0.154                      | 1.4458                                       | 1.9455 | 2.6968 | 0.210                      | ...  | 1.8350 | 2.5868 |
| 0.155                      | 1.4439                                       | 1.9435 | 2.6948 | 0.211                      | ...  | 1.8330 | 2.5849 |
| 0.156                      | 1.4419                                       | 1.9415 | 2.6929 | 0.212                      | ...  | 1.8311 | 2.5829 |
| $\frac{5}{32}$             | 1.4414                                       | 1.9410 | 2.6924 | 0.213                      | ...  | 1.8291 | 2.5809 |
| 0.157                      | 1.4399                                       | 1.9395 | 2.6909 | 0.214                      | ...  | 1.8271 | 2.5790 |
| 0.158                      | 1.4380                                       | 1.9376 | 2.6889 | 0.215                      | ...  | 1.8252 | 2.5770 |
| 0.159                      | 1.4360                                       | 1.9356 | 2.6870 | 0.216                      | ...  | 1.8232 | 2.5751 |
| 0.160                      | 1.4340                                       | 1.9336 | 2.6850 | 0.217                      | ...  | 1.8212 | 2.5731 |
| 0.161                      | 1.4321                                       | 1.9317 | 2.6830 | 0.218                      | ...  | 1.8193 | 2.5711 |
| 0.162                      | 1.4301                                       | 1.9297 | 2.6811 | $\frac{7}{32}$             | ...  | 1.8178 | 2.5697 |
| 0.163                      | 1.4281                                       | 1.9277 | 2.6791 | 0.219                      | ...  | 1.8173 | 2.5692 |
| 0.164                      | 1.4262                                       | 1.9257 | 2.6772 | 0.220                      | ...  | 1.8153 | 2.5672 |
| 0.165                      | 1.4242                                       | 1.9238 | 2.6752 | 0.221                      | ...  | 1.8133 | 2.5653 |
| 0.166                      | 1.4222                                       | 1.9218 | 2.6732 | 0.222                      | ...  | 1.8114 | 2.5633 |
| 0.167                      | 1.4203                                       | 1.9198 | 2.6713 | 0.223                      | ...  | 1.8094 | 2.5613 |
| 0.168                      | 1.4183                                       | 1.9178 | 2.6693 | 0.224                      | ...  | 1.8074 | 2.5594 |
| 0.169                      | 1.4163                                       | 1.9159 | 2.6673 | 0.225                      | ...  | 1.8055 | 2.5574 |
| 0.170                      | 1.4144                                       | 1.9139 | 2.6654 | 0.226                      | ...  | 1.8035 | 2.5555 |

Table 4b. Corrected Diameters of Circular Forming Tools

| Length <i>c</i><br>on Tool | Number of B. & S.<br>Screw Machine |        | Length <i>c</i><br>on Tool | Number of B. & S.<br>Screw Machine |        | Length <i>c</i><br>on Tool | Number 2<br>B. & S.<br>Machine |
|----------------------------|------------------------------------|--------|----------------------------|------------------------------------|--------|----------------------------|--------------------------------|
|                            | No. 0                              | No. 2  |                            | No. 0                              | No. 2  |                            |                                |
| 0.227                      | 1.8015                             | 2.5535 | 0.284                      | 1.6894                             | 2.4418 | 0.341                      | 2.3303                         |
| 0.228                      | 1.7996                             | 2.5515 | 0.285                      | 1.6874                             | 2.4398 | 0.342                      | 2.3284                         |
| 0.229                      | 1.7976                             | 2.5496 | 0.286                      | 1.6854                             | 2.4378 | 0.343                      | 2.3264                         |
| 0.230                      | 1.7956                             | 2.5476 | 0.287                      | 1.6835                             | 2.4359 | $\frac{11}{32}$            | 2.3250                         |
| 0.231                      | 1.7936                             | 2.5456 | 0.288                      | 1.6815                             | 2.4340 | 0.344                      | 2.3245                         |
| 0.232                      | 1.7917                             | 2.5437 | 0.289                      | 1.6795                             | 2.4320 | 0.345                      | 2.3225                         |
| 0.233                      | 1.7897                             | 2.5417 | 0.290                      | 1.6776                             | 2.4300 | 0.346                      | 2.3206                         |
| 0.234                      | 1.7877                             | 2.5398 | 0.291                      | 1.6756                             | 2.4281 | 0.347                      | 2.3186                         |
| $\frac{15}{64}$            | 1.7870                             | 2.5390 | 0.292                      | 1.6736                             | 2.4261 | 0.348                      | 2.3166                         |
| 0.235                      | 1.7858                             | 2.5378 | 0.293                      | 1.6717                             | 2.4242 | 0.349                      | 2.3147                         |
| 0.236                      | 1.7838                             | 2.5358 | 0.294                      | 1.6697                             | 2.4222 | 0.350                      | 2.3127                         |
| 0.237                      | 1.7818                             | 2.5339 | 0.295                      | 1.6677                             | 2.4203 | 0.351                      | 2.3108                         |
| 0.238                      | 1.7799                             | 2.5319 | 0.296                      | 1.6658                             | 2.4183 | 0.352                      | 2.3088                         |
| 0.239                      | 1.7779                             | 2.5300 | $\frac{19}{64}$            | 1.6641                             | 2.4166 | 0.353                      | 2.3069                         |
| 0.240                      | 1.7759                             | 2.5280 | 0.297                      | 1.6638                             | 2.4163 | 0.354                      | 2.3049                         |
| 0.241                      | 1.7739                             | 2.5260 | 0.298                      | 1.6618                             | 2.4144 | 0.355                      | 2.3030                         |
| 0.242                      | 1.7720                             | 2.5241 | 0.299                      | 1.6599                             | 2.4124 | 0.356                      | 2.3010                         |
| 0.243                      | 1.7700                             | 2.5221 | 0.300                      | 1.6579                             | 2.4105 | 0.357                      | 2.2991                         |
| 0.244                      | 1.7680                             | 2.5201 | 0.301                      | ...                                | 2.4085 | 0.358                      | 2.2971                         |
| 0.245                      | 1.7661                             | 2.5182 | 0.302                      | ...                                | 2.4066 | 0.359                      | 2.2952                         |
| 0.246                      | 1.7641                             | 2.5162 | 0.303                      | ...                                | 2.4046 | $\frac{21}{64}$            | 2.2945                         |
| 0.247                      | 1.7621                             | 2.5143 | 0.304                      | ...                                | 2.4026 | 0.360                      | 2.2932                         |
| 0.248                      | 1.7602                             | 2.5123 | 0.305                      | ...                                | 2.4007 | 0.361                      | 2.2913                         |
| 0.249                      | 1.7582                             | 2.5104 | 0.306                      | ...                                | 2.3987 | 0.362                      | 2.2893                         |
| 0.250                      | 1.7562                             | 2.5084 | 0.307                      | ...                                | 2.3968 | 0.363                      | 2.2874                         |
| 0.251                      | 1.7543                             | 2.5064 | 0.308                      | ...                                | 2.3948 | 0.364                      | 2.2854                         |
| 0.252                      | 1.7523                             | 2.5045 | 0.309                      | ...                                | 2.3929 | 0.365                      | 2.2835                         |
| 0.253                      | 1.7503                             | 2.5025 | 0.310                      | ...                                | 2.3909 | 0.366                      | 2.2815                         |
| 0.254                      | 1.7484                             | 2.5005 | 0.311                      | ...                                | 2.3890 | 0.367                      | 2.2796                         |
| 0.255                      | 1.7464                             | 2.4986 | 0.312                      | ...                                | 2.3870 | 0.368                      | 2.2776                         |
| 0.256                      | 1.7444                             | 2.4966 | $\frac{5}{16}$             | ...                                | 2.3860 | 0.369                      | 2.2757                         |
| 0.257                      | 1.7425                             | 2.4947 | 0.313                      | ...                                | 2.3851 | 0.370                      | 2.2737                         |
| 0.258                      | 1.7405                             | 2.4927 | 0.314                      | ...                                | 2.3831 | 0.371                      | 2.2718                         |
| 0.259                      | 1.7385                             | 2.4908 | 0.315                      | ...                                | 2.3811 | 0.372                      | 2.2698                         |
| 0.260                      | 1.7366                             | 2.4888 | 0.316                      | ...                                | 2.3792 | 0.373                      | 2.2679                         |
| 0.261                      | 1.7346                             | 2.4868 | 0.317                      | ...                                | 2.3772 | 0.374                      | 2.2659                         |
| 0.262                      | 1.7326                             | 2.4849 | 0.318                      | ...                                | 2.3753 | 0.375                      | 2.2640                         |
| 0.263                      | 1.7306                             | 2.4829 | 0.319                      | ...                                | 2.3733 | 0.376                      | 2.2620                         |
| 0.264                      | 1.7287                             | 2.4810 | 0.320                      | ...                                | 2.3714 | 0.377                      | 2.2601                         |
| 0.265                      | 1.7267                             | 2.4790 | 0.321                      | ...                                | 2.3694 | 0.378                      | 2.2581                         |
| $\frac{11}{64}$            | 1.7255                             | 2.4778 | 0.322                      | ...                                | 2.3675 | 0.379                      | 2.2562                         |
| 0.266                      | 1.7248                             | 2.4770 | 0.323                      | ...                                | 2.3655 | 0.380                      | 2.2542                         |
| 0.267                      | 1.7228                             | 2.4751 | 0.324                      | ...                                | 2.3636 | 0.381                      | 2.2523                         |
| 0.268                      | 1.7208                             | 2.4731 | 0.325                      | ...                                | 2.3616 | 0.382                      | 2.2503                         |
| 0.269                      | 1.7189                             | 2.4712 | 0.326                      | ...                                | 2.3596 | 0.383                      | 2.2484                         |
| 0.270                      | 1.7169                             | 2.4692 | 0.327                      | ...                                | 2.3577 | 0.384                      | 2.2464                         |
| 0.271                      | 1.7149                             | 2.4673 | 0.328                      | ...                                | 2.3557 | 0.385                      | 2.2445                         |
| 0.272                      | 1.7130                             | 2.4653 | $\frac{21}{64}$            | ...                                | 2.3555 | 0.386                      | 2.2425                         |
| 0.273                      | 1.7110                             | 2.4633 | 0.329                      | ...                                | 2.3538 | 0.387                      | 2.2406                         |
| 0.274                      | 1.7090                             | 2.4614 | 0.330                      | ...                                | 2.3518 | 0.388                      | 2.2386                         |
| 0.275                      | 1.7071                             | 2.4594 | 0.331                      | ...                                | 2.3499 | 0.389                      | 2.2367                         |
| 0.276                      | 1.7051                             | 2.4575 | 0.332                      | ...                                | 2.3479 | 0.390                      | 2.2347                         |
| 0.277                      | 1.7031                             | 2.4555 | 0.333                      | ...                                | 2.3460 | $\frac{23}{64}$            | 2.2335                         |
| 0.278                      | 1.7012                             | 2.4535 | 0.334                      | ...                                | 2.3440 | 0.391                      | 2.2328                         |
| 0.279                      | 1.6992                             | 2.4516 | 0.335                      | ...                                | 2.3421 | 0.392                      | 2.2308                         |
| 0.280                      | 1.6972                             | 2.4496 | 0.336                      | ...                                | 2.3401 | 0.393                      | 2.2289                         |
| 0.281                      | 1.6953                             | 2.4477 | 0.337                      | ...                                | 2.3381 | 0.394                      | 2.2269                         |
| $\frac{9}{32}$             | 1.6948                             | 2.4472 | 0.338                      | ...                                | 2.3362 | 0.395                      | 2.2250                         |
| 0.282                      | 1.6933                             | 2.4457 | 0.339                      | ...                                | 2.3342 | 0.396                      | 2.2230                         |
| 0.283                      | 1.6913                             | 2.4438 | 0.340                      | ...                                | 2.3323 | 0.397                      | 2.2211                         |

Table 4c. Corrected Diameters of Circular Forming Tools

| Length <i>c</i><br>on Tool | Number 2<br>B. & S.<br>Machine | Length <i>c</i><br>on Tool | Number 2<br>B. & S.<br>Machine | Length <i>c</i><br>on Tool | Number 2<br>B. & S.<br>Machine | Length <i>c</i><br>on Tool | Number 2<br>B. & S.<br>Machine |
|----------------------------|--------------------------------|----------------------------|--------------------------------|----------------------------|--------------------------------|----------------------------|--------------------------------|
| 0.398                      | 2.2191                         | 0.423                      | 2.1704                         | 0.449                      | 2.1199                         | 0.474                      | 2.0713                         |
| 0.399                      | 2.2172                         | 0.424                      | 2.1685                         | 0.450                      | 2.1179                         | 0.475                      | 2.0694                         |
| 0.400                      | 2.2152                         | 0.425                      | 2.1666                         | 0.451                      | 2.1160                         | 0.476                      | 2.0674                         |
| 0.401                      | 2.2133                         | 0.426                      | 2.1646                         | 0.452                      | 2.1140                         | 0.477                      | 2.0655                         |
| 0.402                      | 2.2113                         | 0.427                      | 2.1627                         | 0.453                      | 2.1121                         | 0.478                      | 2.0636                         |
| 0.403                      | 2.2094                         | 0.428                      | 2.1607                         | $\frac{29}{64}$            | 2.1118                         | 0.479                      | 2.0616                         |
| 0.404                      | 2.2074                         | 0.429                      | 2.1588                         | 0.454                      | 2.1101                         | 0.480                      | 2.0597                         |
| 0.405                      | 2.2055                         | 0.430                      | 2.1568                         | 0.455                      | 2.1082                         | 0.481                      | 2.0577                         |
| 0.406                      | 2.2035                         | 0.431                      | 2.1549                         | 0.456                      | 2.1063                         | 0.482                      | 2.0558                         |
| $\frac{13}{32}$            | 2.2030                         | 0.432                      | 2.1529                         | 0.457                      | 2.1043                         | 0.483                      | 2.0538                         |
| 0.407                      | 2.2016                         | 0.433                      | 2.1510                         | 0.458                      | 2.1024                         | 0.484                      | 2.0519                         |
| 0.408                      | 2.1996                         | 0.434                      | 2.1490                         | 0.459                      | 2.1004                         | 0.485                      | 2.0500                         |
| 0.409                      | 2.1977                         | 0.435                      | 2.1471                         | 0.460                      | 2.0985                         | 0.486                      | 2.0480                         |
| 0.410                      | 2.1957                         | 0.436                      | 2.1452                         | 0.461                      | 2.0966                         | 0.487                      | 2.0461                         |
| 0.411                      | 2.1938                         | 0.437                      | 2.1432                         | 0.462                      | 2.0946                         | 0.488                      | 2.0441                         |
| 0.412                      | 2.1919                         | $\frac{7}{16}$             | 2.1422                         | 0.463                      | 2.0927                         | 0.489                      | 2.0422                         |
| 0.413                      | 2.1899                         | 0.438                      | 2.1413                         | 0.464                      | 2.0907                         | 0.490                      | 2.0403                         |
| 0.414                      | 2.1880                         | 0.439                      | 2.1393                         | 0.465                      | 2.0888                         | 0.491                      | 2.0383                         |
| 0.415                      | 2.1860                         | 0.440                      | 2.1374                         | 0.466                      | 2.0868                         | 0.492                      | 2.0364                         |
| 0.416                      | 2.1841                         | 0.441                      | 2.1354                         | 0.467                      | 2.0849                         | 0.493                      | 2.0344                         |
| 0.417                      | 2.1821                         | 0.442                      | 2.1335                         | 0.468                      | 2.0830                         | 0.494                      | 2.0325                         |
| 0.418                      | 2.1802                         | 0.443                      | 2.1315                         | $\frac{15}{32}$            | 2.0815                         | 0.495                      | 2.0306                         |
| 0.419                      | 2.1782                         | 0.444                      | 2.1296                         | 0.469                      | 2.0810                         | 0.496                      | 2.0286                         |
| 0.420                      | 2.1763                         | 0.445                      | 2.1276                         | 0.470                      | 2.0791                         | 0.497                      | 2.0267                         |
| 0.421                      | 2.1743                         | 0.446                      | 2.1257                         | 0.471                      | 2.0771                         | 0.498                      | 2.0247                         |
| $\frac{27}{64}$            | 2.1726                         | 0.447                      | 2.1237                         | 0.472                      | 2.0752                         | 0.499                      | 2.0228                         |
| 0.422                      | 2.1724                         | 0.448                      | 2.1218                         | 0.473                      | 2.0733                         | 0.500                      | 2.0209                         |

Dimensions of Forming Tools for B. &amp; S. Automatic Screw Machines

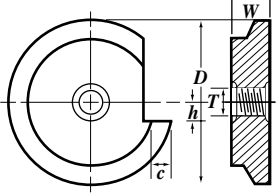
|  | No. of<br>Machine | Max.<br>Dia., <i>D</i> | <i>h</i>          | <i>T</i>          | <i>W</i>      |
|---|-------------------|------------------------|-------------------|-------------------|---------------|
|   | 00                | 1 $\frac{3}{4}$        | $\frac{1}{8}$     | $\frac{3}{8}$ -16 | $\frac{1}{4}$ |
| 0   | 2 $\frac{1}{4}$   | $\frac{5}{32}$         | $\frac{1}{2}$ -14 | $\frac{5}{16}$    |               |
| 2   | 3                 | $\frac{1}{4}$          | $\frac{5}{8}$ -12 | $\frac{3}{8}$     |               |
| 6   | 4                 | $\frac{5}{16}$         | $\frac{3}{4}$ -12 | $\frac{3}{8}$     |               |

Fig. 4.

**Arrangement of Circular Tools.**—When applying circular tools to automatic screw machines, their arrangement has an important bearing on the results obtained. The various ways of arranging the circular tools, with relation to the rotation of the spindle, are shown at A, B, C, and D in Fig. 5. These diagrams represent the view obtained when looking toward the chuck. The arrangement shown at A gives good results on long forming operations on brass and steel because the pressure of the cut on the front tool is downward; the support is more rigid than when the forming tool is turned upside down on the front slide, as shown at B; here the stock, turning up toward the tool, has a tendency to lift the cross-slide, causing chattering; therefore, the arrangement shown at A is recommended when a high-quality finish is desired. The arrangement at B works satisfactorily for short steel pieces that do not require a high finish; it allows the chips to drop clear of the work, and is especially advantageous when making screws, when the forming and cut-off tools operate after the die, as no time is lost in reversing the spindle. The arrangement at C is recommended for heavy cutting on large work, when both tools are used for forming the piece; a

rigid support is then necessary for both tools and a good supply of oil is also required. The arrangement at D is objectionable and should be avoided; it is used only when a left-hand thread is cut on the piece and when the cut-off tool is used on the front slide, leaving the heavy cutting to be performed from the rear slide. In all "cross-forming" work, it is essential that the spindle bearings be kept in good condition, and that the collet or chuck has a parallel contact upon the bar that is being formed.

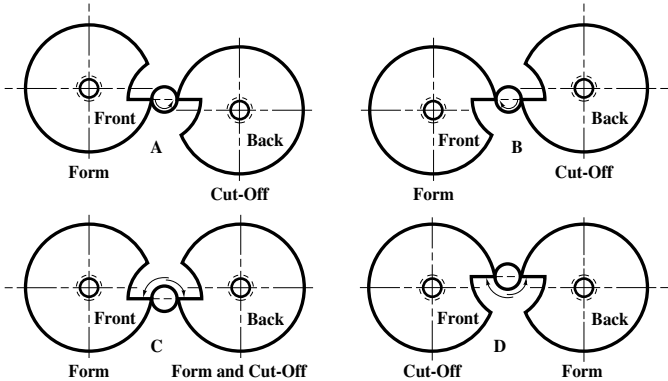


Fig. 5.

**Feeds and Speeds for Forming Tools.**—Approximate feeds and speeds for forming tools are given in the table beginning on page 1132. The feeds and speeds are average values, and if the job at hand has any features out of the ordinary, the figures given should be altered accordingly.

#### Dimensions for Circular Cut-Off Tools

|  | Dia. of Stock   | Soft Brass, Copper    |       | Norway Iron, Machine Steel |       | Drill Rod, Tool Steel |       |
|--|-----------------|-----------------------|-------|----------------------------|-------|-----------------------|-------|
|  |                 | $a = 23 \text{ Deg.}$ |       | $a = 15 \text{ Deg.}$      |       | $a = 12 \text{ Deg.}$ |       |
|  |                 | $T$                   | $x$   | $T$                        | $x$   | $T$                   | $x$   |
|  | $\frac{1}{16}$  | 0.031                 | 0.013 | 0.039                      | 0.010 | 0.043                 | 0.009 |
|  | $\frac{1}{8}$   | 0.044                 | 0.019 | 0.055                      | 0.015 | 0.062                 | 0.013 |
|  | $\frac{3}{16}$  | 0.052                 | 0.022 | 0.068                      | 0.018 | 0.076                 | 0.016 |
|  | $\frac{1}{4}$   | 0.062                 | 0.026 | 0.078                      | 0.021 | 0.088                 | 0.019 |
|  | $\frac{5}{16}$  | 0.069                 | 0.029 | 0.087                      | 0.023 | 0.098                 | 0.021 |
|  | $\frac{3}{8}$   | 0.076                 | 0.032 | 0.095                      | 0.025 | 0.107                 | 0.023 |
|  | $\frac{7}{16}$  | 0.082                 | 0.035 | 0.103                      | 0.028 | 0.116                 | 0.025 |
|  | $\frac{1}{2}$   | 0.088                 | 0.037 | 0.110                      | 0.029 | 0.124                 | 0.026 |
|  | $\frac{9}{16}$  | 0.093                 | 0.039 | 0.117                      | 0.031 | 0.131                 | 0.028 |
|  | $\frac{5}{8}$   | 0.098                 | 0.042 | 0.123                      | 0.033 | 0.137                 | 0.029 |
|  | $\frac{11}{16}$ | 0.103                 | 0.044 | 0.129                      | 0.035 | 0.145                 | 0.031 |
|  | $\frac{3}{4}$   | 0.107                 | 0.045 | 0.134                      | 0.036 | 0.152                 | 0.032 |
|  | $\frac{13}{16}$ | 0.112                 | 0.047 | 0.141                      | 0.038 | 0.158                 | 0.033 |
|  | $\frac{7}{8}$   | 0.116                 | 0.049 | 0.146                      | 0.039 | 0.164                 | 0.035 |
|  | $\frac{15}{16}$ | 0.120                 | 0.051 | 0.151                      | 0.040 | 0.170                 | 0.036 |
|  | 1               | 0.124                 | 0.053 | 0.156                      | 0.042 | 0.175                 | 0.037 |

The length of the blade equals radius of stock  $R + x + r + \frac{1}{32}$  inch (for notation, see illustration above);  $r = \frac{1}{16}$  inch for  $\frac{3}{8}$  to  $\frac{3}{4}$ -inch stock, and  $\frac{3}{32}$  inch for  $\frac{3}{4}$ - to 1-inch stock.



## MILLING CUTTERS

## Selection of Milling Cutters

The most suitable type of milling cutter for a particular milling operation depends on such factors as the kind of cut to be made, the material to be cut, the number of parts to be machined, and the type of milling machine available. Solid cutters of small size will usually cost less, initially, than inserted blade types; for long-run production, inserted-blade cutters will probably have a lower overall cost. Depending on either the material to be cut or the amount of production involved, the use of carbide-tipped cutters in preference to high-speed steel or other cutting tool materials may be justified.

Rake angles depend on both the cutter material and the work material. Carbide and cast alloy cutting tool materials generally have smaller rake angles than high-speed steel tool materials because of their lower edge strength and greater abrasion resistance. Soft work materials permit higher radial rake angles than hard materials; thin cutters permit zero or practically zero axial rake angles; and wide cutters operate smoother with high axial rake angles. See *Rake Angles for Milling Cutters* on page 826.

Cutting edge relief or clearance angles are usually from 3 to 6 degrees for hard or tough materials, 4 to 7 degrees for average materials, and 6 to 12 degrees for easily machined materials. See *Clearance Angles for Milling Cutter Teeth* on page 825.

The number of teeth in the milling cutter is also a factor that should be given consideration, as explained in the next paragraph.

**Number of Teeth in Milling Cutters.**—In determining the number of teeth a milling cutter should have for optimum performance, there is no universal rule.

There are, however, two factors that should be considered in making a choice: 1) The number of teeth should never be so great as to reduce the chip space between the teeth to a point where a free flow of chips is prevented; and 2) The chip space should be smooth and without sharp corners that would cause clogging of the chips in the space.

For milling ductile materials that produce a continuous and curled chip, a cutter with large chip spaces is preferable. Such coarse tooth cutters permit an easier flow of the chips through the chip space than would be obtained with fine tooth cutters, and help to eliminate cutter "chatter." For cutting operations in thin materials, fine tooth cutters reduce cutter and workpiece vibration and the tendency for the cutter teeth to "straddle" the workpiece and dig in. For slitting copper and other soft nonferrous materials, teeth that are either chamfered or alternately flat and V-shaped are best.

As a general rule, to give satisfactory performance the number of teeth in milling cutters should be such that *no more than two teeth at a time are engaged in the cut*. Based on this rule, the following formulas are recommended:

For face milling cutters,

$$T = \frac{6.3D}{W} \quad (1)$$

For peripheral milling cutters,

$$T = \frac{12.6D \cos A}{D + 4d} \quad (2)$$

where  $T$  = number of teeth in cutter;  $D$  = cutter diameter in inches;  $W$  = width of cut in inches;  $d$  = depth of cut in inches; and  $A$  = helix angle of cutter.

To find the number of teeth that a cutter should have when other than two teeth in the cut at the same time is desired, **Formulas (1) and (2)** should be divided by 2 and the result multiplied by the number of teeth desired in the cut.

*Example:* Determine the required number of teeth in a face mill where  $D = 6$  inches and  $W = 4$  inches. Using [Formula \(1\)](#),

$$T = \frac{6.3 \times 6}{4} = 10 \text{ teeth, approximately}$$

*Example:* Determine the required number of teeth in a plain milling cutter where  $D = 4$  inches and  $d = \frac{1}{4}$  inch. Using [Formula \(2\)](#),

$$T = \frac{12.6 \times 4 \times \cos 0^\circ}{4 + (4 \times \frac{1}{4})} = 10 \text{ teeth, approximately}$$

In *high speed milling* with sintered carbide, high-speed steel, and cast non-ferrous cutting tool materials, a formula that permits full use of the power available at the cutter but prevents overloading of the motor driving the milling machine is:

$$T = \frac{K \times H}{F \times N \times d \times W} \quad (3)$$

where  $T$  = number of cutter teeth;  $H$  = horsepower available at the cutter;  $F$  = feed per tooth in inches;  $N$  = revolutions per minute of cutter;  $d$  = depth of cut in inches;  $W$  = width of cut in inches; and  $K$  = a constant which may be taken as 0.65 for average steel, 1.5 for cast iron, and 2.5 for aluminum. These values are conservative and take into account dulling of the cutter in service.

*Example:* Determine the required number of teeth in a sintered carbide tipped face mill for high speed milling of 200 Brinell hardness alloy steel if  $H = 10$  horsepower;  $F = 0.008$  inch;  $N = 272$  rpm;  $d = 0.125$  inch;  $W = 6$  inches; and  $K$  for alloy steel is 0.65. Using [Formula \(3\)](#),

$$T = \frac{0.65 \times 10}{0.008 \times 272 \times 0.125 \times 6} = 4 \text{ teeth, approximately}$$

**American National Standard Milling Cutters.**—According to American National Standard ANSI/ASME B94.19-1997 milling cutters may be classified in two general ways, which are given as follows:

*By Type of Relief on Cutting Edges:* Milling cutters may be described on the basis of one of two methods of providing relief for the cutting edges. *Profile sharpened* cutters are those on which relief is obtained and which are resharpened by grinding a narrow land back of the cutting edges. Profile sharpened cutters may produce flat, curved, or irregular surfaces. *Form relieved* cutters are those which are so relieved that by grinding only the faces of the teeth the original form is maintained throughout the life of the cutters. Form relieved cutters may produce flat, curved or irregular surfaces.

*By Method of Mounting:* Milling cutters may be described by one of two methods used to mount the cutter. *Arbor type* cutters are those which have a hole for mounting on an arbor and usually have a keyway to receive a driving key. These are sometimes called *Shell type*. *Shank type* cutters are those which have a straight or tapered shank to fit the machine tool spindle or adapter.

**Explanation of the "Hand" of Milling Cutters.**—In the ANSI Standard the terms "right hand" and "left hand" are used to describe hand of rotation, hand of cutter and hand of flute helix.

*Hand of Rotation or Hand of Cut:* is described as either "right hand" if the cutter revolves counterclockwise as it cuts when viewed from a position in front of a horizontal milling machine and facing the spindle or "left hand" if the cutter revolves clockwise as it cuts when viewed from the same position.

## American National Standard Plain Milling Cutters ANSI/ASME B94.19-1997

| Cutter Diameter                 |       |       | Range of<br>Face Widths, Nom. <sup>a</sup> | Hole Diameter |         |        |
|---------------------------------|-------|-------|--|---------------|---------|--------|
| Nom.                            | Max.  | Min.  |  | Nom.          | Max.    | Min.   |
| Light-duty Cutters <sup>b</sup> |       |       |  |               |         |        |
| 2½                              | 2.515 | 2.485 | ⅜, ¼, ⅝, ⅜,<br>½, ⅝, ¾, 1, 1½,<br>2 and 3  | 1             | 1.00075 | 1.0000 |
| 3                               | 3.015 | 2.985 | ⅜, ¼, ⅝, ⅜,<br>⅝, ¾, and 1½                | 1             | 1.00075 | 1.0000 |
| 3                               | 3.015 | 2.985 | ½, ⅝, ¾,<br>1, 1¼, 1½, 2<br>and 3          | 1¼            | 1.2510  | 1.2500 |
| 4                               | 4.015 | 3.985 | ¼, ⅝ and ⅜                                 | 1             | 1.00075 | 1.0000 |
| 4                               | 4.015 | 3.985 | ⅜, ½, ⅝, ¾,<br>1, 1½, 2, 3<br>and 4        | 1¼            | 1.2510  | 1.2500 |
| Heavy-duty Cutters <sup>c</sup> |       |       |  |               |         |        |
| 2½                              | 2.515 | 2.485 | 2  | 1             | 1.00075 | 1.0000 |
| 2½                              | 2.515 | 2.485 | 4  | 1             | 1.0010  | 1.0000 |
| 3                               | 3.015 | 2.985 | 2, 2½, 3, 4 and 6                          | 1¼            | 1.2510  | 1.2500 |
| 4                               | 4.015 | 3.985 | 2, 3, 4 and 6                              | 1½            | 1.5010  | 1.5000 |
| High-helix Cutters <sup>d</sup> |       |       |  |               |         |        |
| 3                               | 3.015 | 2.985 | 4 and 6                                    | 1¼            | 1.2510  | 1.2500 |
| 4                               | 4.015 | 3.985 | 8  | 1½            | 1.5010  | 1.5000 |

<sup>a</sup> *Tolerances on Face Widths:* Up to 1 inch, inclusive,  $\pm 0.001$  inch; over 1 to 2 inches, inclusive,  $+0.010, -0.000$  inch; over 2 inches,  $+0.020, -0.000$  inch.

<sup>b</sup> Light-duty plain milling cutters with face widths under ¾ inch have straight teeth. Cutters with ¾-inch face and wider have helix angles of not less than 15 degrees nor greater than 25 degrees.

<sup>c</sup> Heavy-duty plain milling cutters have a helix angle of not less than 25 degrees nor greater than 45 degrees.

<sup>d</sup> High-helix plain milling cutters have a helix angle of not less than 45 degrees nor greater than 52 degrees.

All dimensions are in inches. All cutters are high-speed steel. Plain milling cutters are of cylindrical shape, having teeth on the peripheral surface only.

**Hand of Cutter:** Some types of cutters require special consideration when referring to their hand. These are principally cutters with unsymmetrical forms, face type cutters, or cutters with threaded holes. *Symmetrical* cutters may be reversed on the arbor in the same axial position and rotated in the cutting direction without altering the contour produced on the work-piece, and may be considered as either right or left hand. *Unsymmetrical* cutters reverse the contour produced on the work-piece when reversed on the arbor in the same axial position and rotated in the cutting direction. A *single-angle* cutter is considered to be a right-hand cutter if it revolves counterclockwise, or a left-hand cutter if it revolves clockwise, when cutting as viewed from the side of the larger diameter. The *hand of rotation* of a single angle milling cutter need not necessarily be the same as its *hand of cutter*. A *single corner rounding* cutter is considered to be a right-hand cutter if it revolves counterclockwise, or a left-hand cutter if it revolves clockwise, when cutting as viewed from the side of the smaller diameter.

## American National Standard Side Milling Cutters ANSI/ASME B94.19-1997

| Cutter Diameter                           |       |       | Range of Face Widths<br>Nom. <sup>a</sup>   | Hole Diameter  |         |        |
|---|-------|-------|---|----------------|---------|--------|
| Nom.                                      | Max.  | Min.  |   | Nom.           | Max.    | Min.   |
| Side Cutters <sup>b</sup>                 |       |       |   |                |         |        |
| 2   | 2.015 | 1.985 | $\frac{3}{16}, \frac{1}{4}, \frac{3}{8}$  | $\frac{5}{8}$  | 0.62575 | 0.6250 |
| $2\frac{1}{2}$                            | 2.515 | 2.485 | $\frac{1}{4}, \frac{3}{8}, \frac{1}{2}$   | $\frac{7}{8}$  | 0.87575 | 0.8750 |
| 3   | 3.015 | 2.985 | $\frac{1}{4}, \frac{5}{16}, \frac{3}{8}, \frac{7}{16}, \frac{1}{2}$   | 1              | 1.00075 | 1.0000 |
| 4   | 4.015 | 3.985 | $\frac{1}{4}, \frac{3}{8}, \frac{1}{2}, \frac{5}{8}, \frac{3}{4}, \frac{7}{8}$                                  | 1              | 1.00075 | 1.0000 |
| 4   | 4.015 | 3.985 | $\frac{1}{2}, \frac{5}{8}, \frac{3}{4}$   | $1\frac{1}{4}$ | 1.2510  | 1.2500 |
| 5   | 5.015 | 4.985 | $\frac{1}{2}, \frac{5}{8}, \frac{3}{4}$   | 1              | 1.00075 | 1.0000 |
| 5   | 5.015 | 4.985 | $\frac{1}{2}, \frac{3}{8}, \frac{3}{4}, 1$  | $1\frac{1}{4}$ | 1.2510  | 1.2500 |
| 6   | 6.015 | 5.985 | $\frac{1}{2}$   | 1              | 1.00075 | 1.0000 |
| 6   | 6.015 | 5.985 | $\frac{1}{2}, \frac{5}{8}, \frac{3}{4}, 1$  | $1\frac{1}{4}$ | 1.2510  | 1.2500 |
| 7   | 7.015 | 6.985 | $\frac{3}{4}$   | $1\frac{1}{4}$ | 1.2510  | 1.2500 |
| 7   | 7.015 | 6.985 | $\frac{3}{4}$   | $1\frac{1}{2}$ | 1.5010  | 1.5000 |
| 8   | 8.015 | 7.985 | $\frac{3}{4}, 1$  | $1\frac{1}{4}$ | 1.2510  | 1.2500 |
| 8   | 8.015 | 7.985 | $\frac{3}{4}, 1$  | $1\frac{1}{2}$ | 1.5010  | 1.5000 |
| Staggered-tooth Side Cutters <sup>c</sup> |       |       |   |                |         |        |
| $2\frac{1}{2}$                            | 2.515 | 2.485 | $\frac{1}{4}, \frac{5}{16}, \frac{3}{8}, \frac{1}{2}$   | $\frac{7}{8}$  | 0.87575 | 0.8750 |
| 3   | 3.015 | 2.985 | $\frac{3}{16}, \frac{1}{4}, \frac{5}{16}, \frac{3}{8}$  | 1              | 1.00075 | 1.0000 |
| 3   | 3.015 | 2.985 | $\frac{1}{2}, \frac{5}{8}, \frac{3}{4}$   | $1\frac{1}{4}$ | 1.2510  | 1.2500 |
| 4   | 4.015 | 3.985 | $\frac{1}{4}, \frac{5}{16}, \frac{3}{8}, \frac{7}{16}, \frac{1}{2}, \frac{3}{8}, \frac{3}{4}$ and $\frac{7}{8}$ | $1\frac{1}{4}$ | 1.2510  | 1.2500 |
| 5   | 5.015 | 4.985 | $\frac{1}{2}, \frac{5}{8}, \frac{3}{4}$   | $1\frac{1}{4}$ | 1.2510  | 1.2500 |
| 6   | 6.015 | 5.985 | $\frac{3}{8}, \frac{1}{2}, \frac{5}{8}, \frac{3}{4}, \frac{7}{8}, 1$  | $1\frac{1}{4}$ | 1.2510  | 1.2500 |
| 8   | 8.015 | 7.985 | $\frac{3}{8}, \frac{1}{2}, \frac{5}{8}, \frac{3}{4}, 1$   | $1\frac{1}{2}$ | 1.5010  | 1.5000 |
| Half Side Cutters <sup>d</sup>            |       |       |   |                |         |        |
| 4   | 4.015 | 3.985 | $\frac{3}{4}$   | $1\frac{1}{4}$ | 1.2510  | 1.2500 |
| 5   | 5.015 | 4.985 | $\frac{3}{4}$   | $1\frac{1}{4}$ | 1.2510  | 1.2500 |
| 6   | 6.015 | 5.985 | $\frac{3}{4}$   | $1\frac{1}{4}$ | 1.2510  | 1.2500 |

<sup>a</sup> *Tolerances on Face Widths:* For side cutters, +0.002, -0.001 inch; for staggered-tooth side cutters up to  $\frac{3}{4}$  inch face width, inclusive, +0.000 -0.0005 inch, and over  $\frac{3}{4}$  to 1 inch, inclusive, +0.000 -0.0010 inch; and for half side cutters, +0.015, -0.000 inch.

<sup>b</sup> Side milling cutters have straight peripheral teeth and side teeth on both sides.

<sup>c</sup> Staggered-tooth side milling cutters have peripheral teeth of alternate right- and left-hand helix and alternate side teeth.

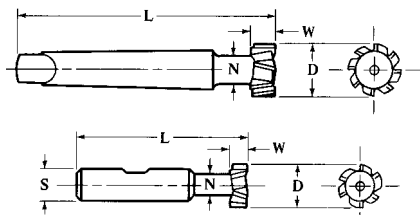
<sup>d</sup> Half side milling cutters have side teeth on one side only. The peripheral teeth are helical of the same hand as the cut. Made either with right-hand or left-hand cut.

All dimensions are in inches. All cutters are high-speed steel. Side milling cutters are of cylindrical shape, having teeth on the periphery and on one or both sides.

**Hand of Flute Helix:** Milling cutters may have *straight flutes* which means that their cutting edges are in planes parallel to the cutter axis. Milling cutters with flute helix in one direction only are described as having a right-hand helix if the flutes twist away from the observer in a clockwise direction when viewed from either end of the cutter or as having a left-hand helix if the flutes twist away from the observer in a counterclockwise direction when viewed from either end of the cutter. *Staggered tooth cutters* are milling cutters with every other flute of opposite (right and left hand) helix.

An illustration describing the various milling cutter elements of both a profile cutter and a form-relieved cutter is given on page 801.

**American National Standard Staggered Teeth, T-Slot Milling Cutters with Brown & Sharpe Taper and Weldon Shanks ANSI/ASME B94.19-1997**



| Bolt Size | Cutter Dia., <i>D</i> | Face Width, <i>W</i> | Neck Dia., <i>N</i> | With B. & S. Taper <sup>a,b</sup> |           | With Weldon Shank |                |
|-----------|-----------------------|----------------------|---------------------|-----------------------------------|-----------|-------------------|----------------|
|           |                       |                      |                     | Length, <i>L</i>                  | Taper No. | Length, <i>L</i>  | Dia., <i>S</i> |
| 1/4       | 9/16                  | 15/64                | 17/64               | ...                               | ...       | 2 29/32           | 1/2            |
| 5/16      | 2 1/32                | 17/64                | 2 1/64              | ...                               | ...       | 2 11/16           | 1/2            |
| 3/8       | 25/32                 | 2 1/64               | 13/32               | ...                               | ...       | 3 1/4             | 3/4            |
| 1/2       | 3 1/32                | 25/64                | 17/32               | 5                                 | 7         | 3 7/16            | 3/4            |
| 5/8       | 1 1/4                 | 3 1/64               | 2 1/32              | 5 1/4                             | 7         | 3 15/16           | 1              |
| 3/4       | 1 15/32               | 5/8                  | 25/32               | 6 7/8                             | 9         | 4 7/16            | 1              |
| 1         | 1 27/32               | 53/64                | 1 1/32              | 7 1/4                             | 9         | 4 13/16           | 1 1/4          |

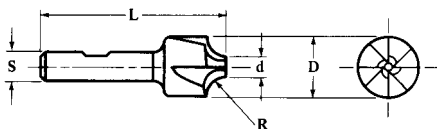
<sup>a</sup> For dimensions of Brown & Sharpe taper shanks, see information given on page 936.

<sup>b</sup> Brown & Sharpe taper shanks have been removed from ANSI/ASME B94.19 they are included for reference only.

All dimensions are in inches. All cutters are high-speed steel and only right-hand cutters are standard.

*Tolerances:* On *D*, +0.000, -0.010 inch; on *W*, +0.000, -0.005 inch; on *N*, +0.000, -0.005 inch; on *L*, ± 1/16 inch; on *S*, -0.0001 to -0.0005 inch.

**American National Standard Form Relieved Corner Rounding Cutters with Weldon Shanks ANSI/ASME B94.19-1997**



| Rad., <i>R</i> | Dia., <i>D</i> | Dia., <i>d</i> | <i>S</i> | <i>L</i> | Rad., <i>R</i> | Dia., <i>D</i> | Dia., <i>d</i> | <i>S</i> | <i>L</i> |
|----------------|----------------|----------------|----------|----------|----------------|----------------|----------------|----------|----------|
| 1/16           | 7/16           | 1/4            | 3/8      | 2 1/2    | 3/8            | 1 1/4          | 3/8            | 1/2      | 3 1/2    |
| 3/32           | 1/2            | 1/4            | 3/8      | 2 1/2    | 3/16           | 7/8            | 5/16           | 3/4      | 3 3/8    |
| 1/8            | 5/8            | 1/4            | 1/2      | 3        | 1/4            | 1              | 3/8            | 3/4      | 3 1/4    |
| 3/32           | 3/4            | 5/16           | 1/2      | 3        | 5/16           | 1 1/8          | 3/8            | 7/8      | 3 1/2    |
| 3/16           | 7/8            | 5/16           | 1/2      | 3        | 3/8            | 1 1/4          | 3/8            | 7/8      | 3 3/4    |
| 1/4            | 1              | 3/8            | 1/2      | 3        | 7/16           | 1 3/8          | 3/8            | 1        | 4        |
| 5/16           | 1 1/8          | 3/8            | 1/2      | 3 1/4    | 1/2            | 1 1/2          | 3/8            | 1        | 4 1/8    |

All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters are standard.

*Tolerances:* On *D*, ±0.010 inch; on diameter of circle, 2*R*, ±0.001 inch for cutters up to and including 1/8-inch radius, +0.002, -0.001 inch for cutters over 1/8-inch radius; on *S*, -0.0001 to -0.0005 inch; and on *L*, ± 1/16 inch.

## American National Standard Metal Slitting Saws ANSI/ASME B94.19-1997

| Cutter Diameter   |        |        | Range of Face Widths<br>Nom. <sup>a</sup>             | Hole Diameter |         |        |
|---|--------|--------|---|---------------|---------|--------|
| Nom.  | Max.   | Min.   |   | Nom.          | Max.    | Min.   |
| <b>Plain Metal Slitting Saws<sup>b</sup></b>                                    |        |        |   |               |         |        |
| 2½  | 2.515  | 2.485  | ½, ¾, ⅞, ⅝, ⅜   | ⅝             | 0.87575 | 0.8750 |
| 3   | 3.015  | 2.985  | ½, ¾, ⅞, ⅝, ⅜, ⅜ and ⅝ <sub>32</sub>                  | 1             | 1.00075 | 1.0000 |
| 4   | 4.015  | 3.985  | ½, ¾, ⅞, ⅝, ⅜, ⅜, ⅝ <sub>32</sub> and ⅜ <sub>16</sub> | 1             | 1.00075 | 1.0000 |
| 5   | 5.015  | 4.985  | ½, ¾, ⅞, ⅝, ⅜   | 1             | 1.00075 | 1.0000 |
| 5   | 5.015  | 4.985  | ½, ¾, ⅞, ⅝  | 1¼            | 1.2510  | 1.2500 |
| 6   | 6.015  | 5.985  | ½, ¾, ⅞, ⅝  | 1             | 1.00075 | 1.0000 |
| 6   | 6.015  | 5.985  | ½, ¾, ⅞, ⅝  | 1¼            | 1.2510  | 1.2500 |
| 8   | 8.015  | 7.985  | ½, ¾, ⅞, ⅝  | 1             | 1.00075 | 1.0000 |
| 8   | 8.015  | 7.985  | ½, ¾, ⅞, ⅝  | 1¼            | 1.2510  | 1.2500 |
| <b>Metal Slitting Saws with Side Teeth<sup>c</sup></b>                          |        |        |   |               |         |        |
| 2½  | 2.515  | 2.485  | ½, ¾, ⅞, ⅝  | ⅝             | 0.87575 | 0.8750 |
| 3   | 3.015  | 2.985  | ½, ¾, ⅞, ⅝, ⅝ <sub>32</sub>                           | 1             | 1.00075 | 1.0000 |
| 4   | 4.015  | 3.985  | ½, ¾, ⅞, ⅝, ⅝ <sub>32</sub> , ⅜ <sub>16</sub>         | 1             | 1.00075 | 1.0000 |
| 5   | 5.015  | 4.985  | ½, ¾, ⅞, ⅝, ⅝ <sub>32</sub> , ⅜ <sub>16</sub>         | 1             | 1.00075 | 1.0000 |
| 5   | 5.015  | 4.985  | ½, ¾, ⅞, ⅝  | 1¼            | 1.2510  | 1.2500 |
| 6   | 6.015  | 5.985  | ½, ¾, ⅞, ⅝, ⅜ <sub>16</sub>                           | 1             | 1.00075 | 1.0000 |
| 6   | 6.015  | 5.985  | ½, ¾, ⅞, ⅝, ⅜ <sub>16</sub>                           | 1¼            | 1.2510  | 1.2500 |
| 8   | 8.015  | 7.985  | ½, ¾, ⅞, ⅝  | 1             | 1.00075 | 1.0000 |
| 8   | 8.015  | 7.985  | ½, ¾, ⅞, ⅝  | 1¼            | 1.2510  | 1.2500 |
| <b>Metal Slitting Saws with Staggered Peripheral and Side Teeth<sup>d</sup></b> |        |        |   |               |         |        |
| 3   | 3.015  | 2.985  | ¾ <sub>16</sub>                                       | 1             | 1.00075 | 1.0000 |
| 4   | 4.015  | 3.985  | ¾ <sub>16</sub>                                       | 1             | 1.00075 | 1.0000 |
| 5   | 5.015  | 4.985  | ¾ <sub>16</sub> , ¼                                   | 1             | 1.00075 | 1.0000 |
| 6   | 6.015  | 5.985  | ¾ <sub>16</sub> , ¼                                   | 1             | 1.00075 | 1.0000 |
| 6   | 6.015  | 5.985  | ¾ <sub>16</sub> , ¼                                   | 1¼            | 1.2510  | 1.2500 |
| 8   | 8.015  | 7.985  | ¾ <sub>16</sub> , ¼                                   | 1¼            | 1.2510  | 1.2500 |
| 10  | 10.015 | 9.985  | ¾ <sub>16</sub> , ¼                                   | 1¼            | 1.2510  | 1.2500 |
| 12  | 12.015 | 11.985 | ¼, ⅝ <sub>16</sub>                                    | 1½            | 1.5010  | 1.5000 |

<sup>a</sup>Tolerances on face widths are plus or minus 0.001 inch.

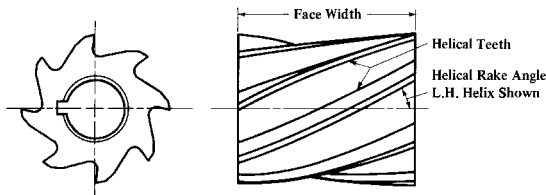
<sup>b</sup>Plain metal slitting saws are relatively thin plain milling cutters having peripheral teeth only. They are furnished with or without hub and their sides are concaved to the arbor hole or hub.

<sup>c</sup>Metal slitting saws with side teeth are relatively thin side milling cutters having both peripheral and side teeth.

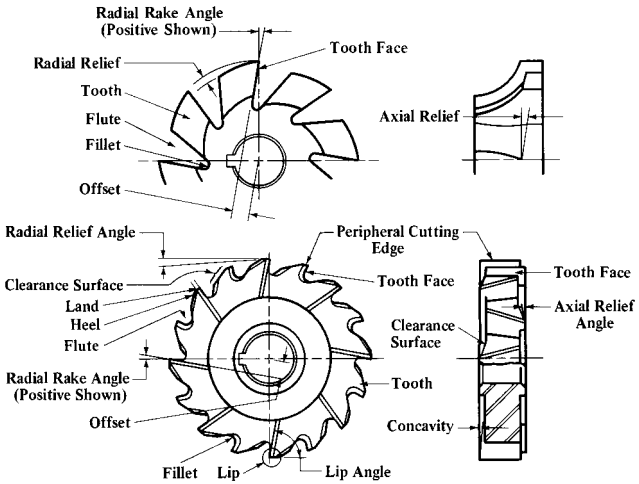
<sup>d</sup>Metal slitting saws with staggered peripheral and side teeth are relatively thin staggered tooth milling cutters having peripheral teeth of alternate right- and left-hand helix and alternate side teeth.

All dimensions are in inches. All saws are high-speed steel. Metal slitting saws are similar to plain or side milling cutters but are relatively thin.

## Milling Cutter Terms



## Milling Cutter Terms (Continued)



**American National Standard Single- and Double-Angle  
Milling Cutters ANSI/ASME B94.19-1997**

| Cutter Diameter                   |       |       | Nominal Face Width <sup>a</sup> | Hole Diameter               |         |        |
|-----------------------------------|-------|-------|---------------------------------|-----------------------------|---------|--------|
| Nom.                              | Max.  | Min.  |                                 | Nom.                        | Max.    | Min.   |
| Single-angle Cutters <sup>b</sup> |       |       |                                 |                             |         |        |
| $1\frac{1}{4}$                    | 1.265 | 1.235 | $\frac{7}{16}$                  | $\frac{3}{8}$ -24 UNF-2B RH |         |        |
| $1\frac{1}{8}$                    | 1.640 | 1.610 | $\frac{9}{16}$                  | $\frac{3}{8}$ -24 UNF-2B LH |         |        |
| $2\frac{3}{4}$                    | 2.765 | 2.735 | $\frac{1}{2}$                   | $\frac{1}{2}$ -20 UNF-2B RH |         |        |
| 3                                 | 3.015 | 2.985 | $\frac{1}{2}$                   | 1                           | 1.00075 | 1.0000 |
|                                   |       |       |                                 | $1\frac{1}{4}$              | 1.2510  | 1.2500 |
| Double-angle Cutters <sup>d</sup> |       |       |                                 |                             |         |        |
| $2\frac{3}{4}$                    | 2.765 | 2.735 | $\frac{1}{2}$                   | 1                           | 1.00075 | 1.0000 |

<sup>a</sup> Face width tolerances are plus or minus 0.015 inch.

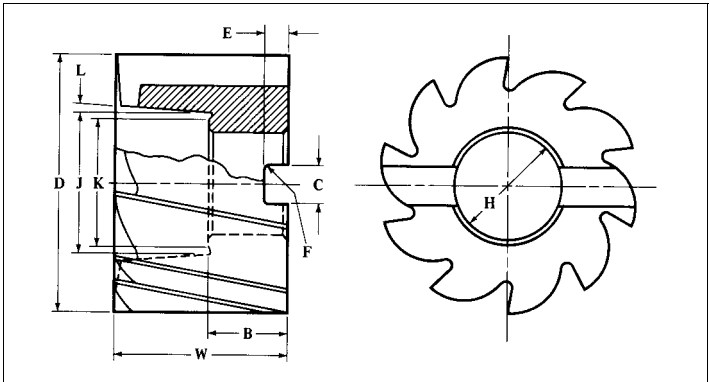
<sup>b</sup> Single-angle milling cutters have peripheral teeth, one cutting edge of which lies in a conical surface and the other in the plane perpendicular to the cutter axis. There are two types: one has a plain keyway hole and has an included tooth angle of either 45 or 60 degrees plus or minus 10 minutes; the other has a threaded hole and has an included tooth angle of 60 degrees plus or minus 10 minutes. Cutters with a right-hand threaded hole have a right-hand hand of rotation and a right-hand hand of cutter. Cutters with a left-hand threaded hole have a left-hand hand of rotation and a left-hand hand of cutter. Cutters with plain keyway holes are standard as either right-hand or left-hand cutters.

<sup>c</sup> These cutters have threaded holes, the sizes of which are given under "Hole Diameter."

<sup>d</sup> Double-angle milling cutters have symmetrical peripheral teeth both sides of which lie in conical surfaces. They are designated by the included angle, which may be 45, 60 or 90 degrees. Tolerances are plus or minus 10 minutes for the half angle on each side of the center.

All dimensions are in inches. All cutters are high-speed steel.

American National Standard Shell Mills ANSI/ASME B94.19-1997

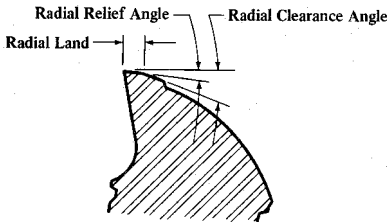


| Dia.,<br>D | Width,<br>W | Dia.,<br>H | Length,<br>B | Width,<br>C | Depth,<br>E | Radius,<br>F | Dia.,<br>J | Dia.,<br>K | Angle,<br>L |
|------------|-------------|------------|--------------|-------------|-------------|--------------|------------|------------|-------------|
| inches     | inches      | inches     | inches       | inches      | inches      | inches       | inches     | degrees    | inches      |
| 1¼         | 1           | ½          | ⅝            | ¼           | ⅜           | ⅜            | 11/16      | ⅝          | 0           |
| 1½         | 1⅛          | ½          | ⅝            | ¼           | ⅜           | ⅜            | 11/16      | ⅝          | 0           |
| 1¾         | 1¼          | ¾          | ¾            | ⅜           | ⅜           | ⅜            | 15/16      | 7/8        | 0           |
| 2          | 1⅜          | ¾          | ¾            | ⅜           | ⅜           | ⅜            | 15/16      | 7/8        | 0           |
| 2¼         | 1½          | 1          | ¾            | ⅜           | 7/32        | 1/32         | 1¼         | 13/16      | 0           |
| 2½         | 1⅝          | 1          | ¾            | ⅜           | 7/32        | 1/32         | 1⅜         | 13/16      | 0           |
| 2¾         | 1⅞          | 1          | ¾            | ⅜           | 7/32        | 1/32         | 1½         | 13/16      | 5           |
| 3          | 1¾          | 1¼         | ¾            | ½           | 9/32        | 1/32         | 1⅝         | 1½         | 5           |
| 3½         | 1⅞          | 1¼         | ¾            | ½           | 9/32        | 1/32         | 1⅞         | 1½         | 5           |
| 4          | 2¼          | 1½         | 1            | ⅝           | ⅜           | 1/16         | 2¼         | 1⅞         | 5           |
| 4½         | 2½          | 1½         | 1            | ⅝           | ⅜           | 1/16         | 2½         | 1⅞         | 10          |
| 5          | 2¾          | 1½         | 1            | ⅝           | ⅜           | 1/16         | 2⅞         | 1⅞         | 10          |
| 6          | 2¼          | 2          | 1            | ¾           | 7/16        | 1/16         | 2⅝         | 2½         | 15          |

All cutters are high-speed steel. Right-hand cutters with right-hand helix and square corners are standard.

Tolerances: On D, +1/64 inch; on W, ±1/64 inch; on H, +0.0005 inch; on B, +1/64 inch; on C, at least +0.008 but not more than +0.012 inch; on E, +1/64 inch; on J, ±1/64 inch; on K, ±1/64 inch.

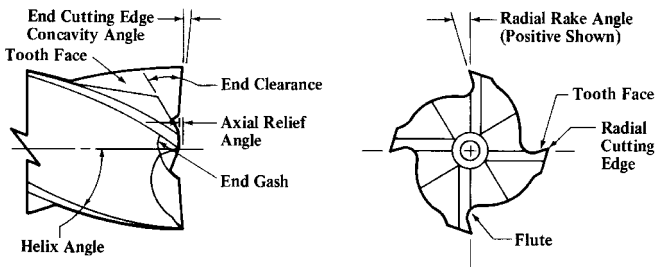
End Mill Terms



Enlarged Section of End Mill Tooth



## End Mill Terms (Continued)



Enlarged Section of End Mill

**American National Standard Multiple- and Two-Flute Single-End Helical End Mills with Plain Straight and Weldon Shanks ANSI/ASME B94.19-1997**

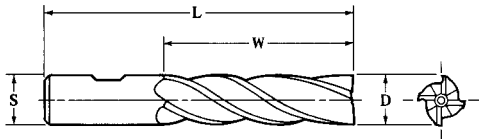
| Cutter Diameter, $D$                            |       |        | Shank Diameter, $S$ |        | Length of Cut, $W$ | Length Overall, $L$ |
|---|-------|--------|---------------------|--------|--------------------|---------------------|
| Nom.  | Max.  | Min.   | Max.                | Min.   |                    |                     |
| Multiple-flute with Plain Straight Shanks       |       |        |                     |        |                    |                     |
| $\frac{1}{8}$                                   | .130  | .125   | .125                | .1245  | $\frac{3}{16}$     | $\frac{1}{4}$       |
| $\frac{3}{16}$                                  | .1925 | .1875  | .1875               | .1870  | $\frac{1}{2}$      | $\frac{1}{8}$       |
| $\frac{1}{4}$                                   | .255  | .250   | .250                | .2495  | $\frac{5}{8}$      | $1\frac{1}{16}$     |
| $\frac{3}{8}$                                   | .380  | .375   | .375                | .3745  | $\frac{3}{4}$      | $1\frac{1}{8}$      |
| $\frac{1}{2}$                                   | .505  | .500   | .500                | .4995  | $\frac{15}{16}$    | $2\frac{1}{4}$      |
| $\frac{3}{4}$                                   | .755  | .750   | .750                | .7495  | $1\frac{1}{4}$     | $2\frac{5}{8}$      |
| Two-flute for Keyway Cutting with Weldon Shanks |       |        |                     |        |                    |                     |
| $\frac{1}{8}$                                   | .125  | .1235  | .375                | .3745  | $\frac{3}{8}$      | $2\frac{5}{16}$     |
| $\frac{3}{16}$                                  | .1875 | .1860  | .375                | .3745  | $\frac{7}{16}$     | $2\frac{5}{16}$     |
| $\frac{1}{4}$                                   | .250  | .2485  | .375                | .3745  | $\frac{1}{2}$      | $2\frac{5}{16}$     |
| $\frac{5}{16}$                                  | .3125 | .3110  | .375                | .3745  | $\frac{9}{16}$     | $2\frac{5}{16}$     |
| $\frac{3}{8}$                                   | .375  | .3735  | .375                | .3745  | $\frac{9}{16}$     | $2\frac{5}{16}$     |
| $\frac{1}{2}$                                   | .500  | .4985  | .500                | .4995  | 1                  | 3                   |
| $\frac{5}{8}$                                   | .625  | .6235  | .625                | .6245  | $1\frac{1}{16}$    | $3\frac{7}{16}$     |
| $\frac{3}{4}$                                   | .750  | .7485  | .750                | .7495  | $1\frac{1}{16}$    | $3\frac{9}{16}$     |
| $\frac{7}{8}$                                   | .875  | .8735  | .875                | .8745  | $1\frac{1}{2}$     | $3\frac{3}{4}$      |
| 1   | 1.000 | .9985  | 1.000               | .9995  | $1\frac{5}{8}$     | $4\frac{1}{8}$      |
| $1\frac{1}{4}$                                  | 1.250 | 1.2485 | 1.250               | 1.2495 | $1\frac{5}{8}$     | $4\frac{1}{8}$      |
| $1\frac{1}{2}$                                  | 1.500 | 1.4985 | 1.250               | 1.2495 | $1\frac{5}{8}$     | $4\frac{1}{8}$      |

All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters with right-hand helix are standard.

The helix angle is not less than 10 degrees for multiple-flute cutters with plain straight shanks; the helix angle is optional with the manufacturer for two-flute cutters with Weldon shanks.

Tolerances: On  $W$ ,  $\pm\frac{1}{32}$  inch; on  $L$ ,  $\pm\frac{1}{16}$  inch.

**ANSI Regular-, Long-, and Extra Long-Length, Multiple-Flute Medium Helix Single-End End Mills with Weldon Shanks ANSI/ASME B94.19-1997**



As Indicated By The Dimensions Given Below, Shank Diameter S May Be Larger, Smaller, Or The Same As The Cutter Diameter D

| Cutter Dia., D    | Regular Mills |       |         |                | Long Mills |       |        |                | Extra Long Mills |       |        |                |
|-------------------|---------------|-------|---------|----------------|------------|-------|--------|----------------|------------------|-------|--------|----------------|
|                   | S             | W     | L       | N <sup>a</sup> | S          | W     | L      | N <sup>a</sup> | S                | W     | L      | N <sup>a</sup> |
| 1/8 <sup>b</sup>  | 3/8           | 3/8   | 2 3/16  | 4              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 3/16 <sup>b</sup> | 3/8           | 1/2   | 2 3/8   | 4              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 1/4 <sup>b</sup>  | 3/8           | 5/8   | 2 7/16  | 4              | 3/8        | 1 1/4 | 3 3/16 | 4              | 3/8              | 1 3/4 | 3 9/16 | 4              |
| 5/16 <sup>b</sup> | 3/8           | 3/4   | 2 1/2   | 4              | 3/8        | 1 3/8 | 3 3/8  | 4              | 3/8              | 2     | 3 3/4  | 4              |
| 3/8 <sup>b</sup>  | 3/8           | 3/4   | 2 1/2   | 4              | 3/8        | 1 1/2 | 3 1/4  | 4              | 3/8              | 2 1/2 | 4 1/4  | 4              |
| 7/16              | 3/8           | 1     | 2 11/16 | 4              | 1/2        | 1 3/4 | 3 3/4  | 4              | ...              | ...   | ...    | ...            |
| 1/2               | 3/8           | 1     | 2 11/16 | 4              | 1/2        | 2     | 4      | 4              | 1/2              | 3     | 5      | 4              |
| 1/2 <sup>b</sup>  | 1/2           | 1 1/4 | 3 1/4   | 4              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 9/16              | 1/2           | 1 3/8 | 3 3/8   | 4              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 5/8               | 1/2           | 1 3/8 | 3 3/8   | 4              | 5/8        | 2 1/2 | 4 5/8  | 4              | 5/8              | 4     | 6 1/8  | 4              |
| 11/16             | 1/2           | 1 5/8 | 3 5/8   | 4              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 3/4               | 1/2           | 1 5/8 | 3 5/8   | 4              | 3/4        | 3     | 5 1/4  | 4              | 3/4              | 4     | 6 1/4  | 4              |
| 5/8 <sup>b</sup>  | 5/8           | 1 5/8 | 3 3/4   | 4              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 11/16             | 5/8           | 1 3/8 | 3 3/4   | 4              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 3/4 <sup>b</sup>  | 5/8           | 1 5/8 | 3 3/4   | 4              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 13/16             | 5/8           | 1 7/8 | 4       | 6              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 7/8               | 5/8           | 1 7/8 | 4       | 6              | 7/8        | 3 1/2 | 5 3/4  | 4              | 7/8              | 5     | 7 1/4  | 4              |
| 1                 | 5/8           | 1 7/8 | 4       | 6              | 1          | 4     | 6 1/2  | 4              | 1                | 6     | 8 1/2  | 4              |
| 7/8               | 7/8           | 1 7/8 | 4 1/8   | 4              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 1                 | 7/8           | 1 7/8 | 4 1/8   | 4              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 1 1/8             | 7/8           | 2     | 4 1/4   | 6              | 1          | 4     | 6 1/2  | 6              | ...              | ...   | ...    | ...            |
| 1 1/4             | 7/8           | 2     | 4 1/4   | 6              | 1          | 4     | 6 1/2  | 6              | 1 1/4            | 6     | 8 1/2  | 6              |
| 1                 | 1             | 2     | 4 1/2   | 4              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 1 1/8             | 1             | 2     | 4 1/2   | 6              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 1 1/4             | 1             | 2     | 4 1/2   | 6              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 1 3/8             | 1             | 2     | 4 1/2   | 6              | ...        | ...   | ...    | ...            | ...              | ...   | ...    | ...            |
| 1 1/2             | 1             | 2     | 4 1/2   | 6              | 1          | 4     | 6 1/2  | 6              | ...              | ...   | ...    | ...            |
| 1 1/4             | 1 1/4         | 2     | 4 1/2   | 6              | 1 1/4      | 4     | 6 1/2  | 6              | ...              | ...   | ...    | ...            |
| 1 1/2             | 1 1/4         | 2     | 4 1/2   | 6              | 1 1/4      | 4     | 6 1/2  | 6              | 1 1/4            | 8     | 10 1/2 | 6              |
| 1 3/4             | 1 1/4         | 2     | 4 1/2   | 6              | 1 1/4      | 4     | 6 1/2  | 6              | ...              | ...   | ...    | ...            |
| 2                 | 1 1/4         | 2     | 4 1/2   | 8              | 1 1/4      | 4     | 6 1/2  | 8              | ...              | ...   | ...    | ...            |

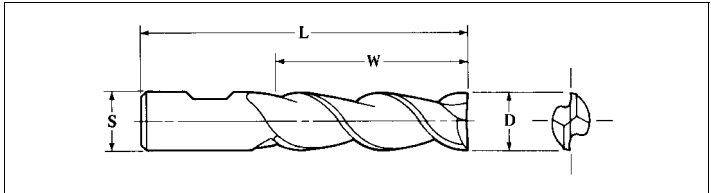
<sup>a</sup>N = Number of flutes.

<sup>b</sup>In this size of regular mill a left-hand cutter with left-hand helix is also standard.

All dimensions are in inches. All cutters are high-speed steel. Helix angle is greater than 19 degrees but not more than 39 degrees. Right-hand cutters with right-hand helix are standard.

Tolerances: On D, +0.003 inch; on S, -0.0001 to -0.0005 inch; on W, ±1/32 inch; on L, ±1/16 inch.

**ANSI Two-Flute, High Helix, Regular-, Long-, and Extra Long-Length, Single-End End Mills with Weldon Shanks ANSI/ASME B94.19-1997**

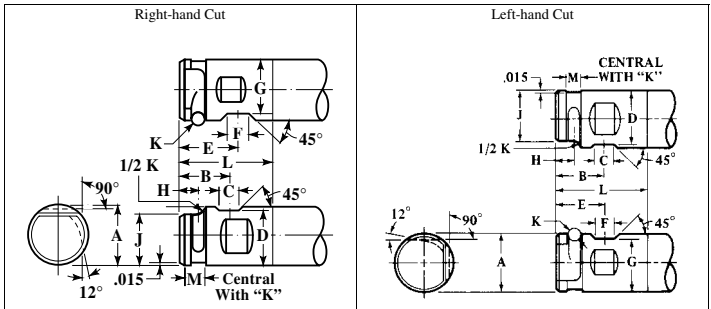


| Cutter Dia., D | Regular Mill |       |         | Long Mill |       |        | Extra Long Mill |       |        |
|----------------|--------------|-------|---------|-----------|-------|--------|-----------------|-------|--------|
|                | S            | W     | L       | S         | W     | L      | S               | W     | L      |
| 1/4            | 3/8          | 5/8   | 2 7/16  | 3/8       | 1 1/4 | 3 1/16 | 3/8             | 1 3/4 | 3 3/16 |
| 5/16           | 3/8          | 3/4   | 2 1/2   | 3/8       | 1 3/8 | 3 1/8  | 3/8             | 2     | 3 3/4  |
| 3/8            | 3/8          | 3/4   | 2 1/2   | 3/8       | 1 1/2 | 3 1/4  | 3/8             | 2 1/2 | 4 1/4  |
| 7/16           | 3/8          | 1     | 2 11/16 | 1/2       | 1 3/4 | 3 3/4  | ...             | ...   | ...    |
| 1/2            | 1/2          | 1 1/4 | 3 1/4   | 1/2       | 2     | 4      | 1/2             | 3     | 5      |
| 5/8            | 5/8          | 1 5/8 | 3 3/4   | 5/8       | 2 1/2 | 4 5/8  | 5/8             | 4     | 6 1/8  |
| 3/4            | 3/4          | 1 3/8 | 3 7/8   | 3/4       | 3     | 5 1/4  | 3/4             | 4     | 6 1/4  |
| 7/8            | 7/8          | 1 7/8 | 4 1/8   | ...       | ...   | ...    | ...             | ...   | ...    |
| 1              | 1            | 2     | 4 1/2   | 1         | 4     | 6 1/2  | 1               | 6     | 8 1/2  |
| 1 1/4          | 1 1/4        | 2     | 4 1/2   | 1 1/4     | 4     | 6 1/2  | 1 1/4           | 6     | 8 1/2  |
| 1 1/2          | 1 1/4        | 2     | 4 1/2   | 1 1/4     | 4     | 6 1/2  | 1 1/4           | 8     | 10 1/2 |
| 2              | 1 1/4        | 2     | 4 1/2   | 1 1/4     | 4     | 6 1/2  | ...             | ...   | ...    |

All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters with right-hand helix are standard. Helix angle is greater than 39 degrees.

Tolerances: On D, +0.003 inch; on S, -0.0001 to -0.0005 inch; on W, ±1/32 inch; and on L, ±1/16 inch.

**Combination Shanks for End Mills ANSI/ASME B94.19-1997**



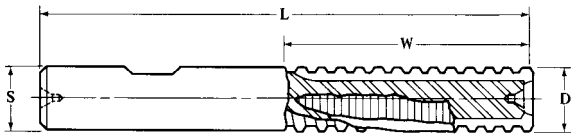
| Dia. A | L <sup>a</sup> | B       | C    | D     | E     | F    | G     | H    | J     | K    | M    |
|--------|----------------|---------|------|-------|-------|------|-------|------|-------|------|------|
| 1 1/2  | 2 11/16        | 1 3/16  | .515 | 1.406 | 1 1/2 | .515 | 1.371 | 9/16 | 1.302 | .377 | 7/16 |
| 2      | 3 1/4          | 1 23/32 | .700 | 1.900 | 1 3/4 | .700 | 1.809 | 5/8  | 1.772 | .440 | 1/2  |
| 2 1/2  | 3 1/2          | 1 15/16 | .700 | 2.400 | 2     | .700 | 2.312 | 3/4  | 2.245 | .503 | 9/16 |

<sup>a</sup>Length of shank.

All dimensions are in inches.

Modified for use as Weldon or Pin Drive shank.

**ANSI Roughing, Single-End End Mills with Weldon Shanks,  
High-Speed Steel ANSI/ASME B94.19-1997**

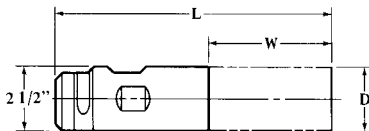


| Diameter |       | Length |         | Diameter |       | Length |         |
|----------|-------|--------|---------|----------|-------|--------|---------|
| Cutter   | Shank | Cut    | Overall | Cutter   | Shank | Cut    | Overall |
| $D$      | $S$   | $W$    | $L$     | $D$      | $S$   | $W$    | $L$     |
| 1/2      | 1/2   | 1      | 3       | 2        | 2     | 2      | 5 1/4   |
| 1/2      | 1/2   | 1 1/4  | 3 1/4   | 2        | 2     | 3      | 6 1/4   |
| 1/2      | 1/2   | 2      | 4       | 2        | 2     | 4      | 7 1/4   |
| 5/8      | 5/8   | 1 1/4  | 3 3/8   | 2        | 2     | 5      | 8 3/4   |
| 5/8      | 5/8   | 1 3/8  | 3 1/2   | 2        | 2     | 6      | 9 1/4   |
| 5/8      | 5/8   | 2 1/2  | 4 5/8   | 2        | 2     | 7      | 10 1/4  |
| 3/4      | 3/4   | 1 1/2  | 3 3/4   | 2        | 2     | 8      | 11 3/4  |
| 3/4      | 3/4   | 1 5/8  | 3 7/8   | 2        | 2     | 10     | 13 3/4  |
| 3/4      | 3/4   | 3      | 5 1/4   | 2        | 2     | 12     | 15 3/4  |
| 1        | 1     | 2      | 4 1/2   | 2 1/2    | 2     | 4      | 7 3/4   |
| 1        | 1     | 4      | 6 1/2   | 2 1/2    | 2     | 6      | 9 3/4   |
| 1 1/4    | 1 1/4 | 2      | 4 1/2   | 2 1/2    | 2     | 8      | 11 3/4  |
| 1 1/4    | 1 1/4 | 4      | 6 1/2   | 2 1/2    | 2     | 10     | 13 3/4  |
| 1 1/2    | 1 1/4 | 2      | 4 1/2   | 3        | 2 1/2 | 4      | 7 3/4   |
| 1 1/2    | 1 1/4 | 4      | 6 1/2   | 3        | 2 1/2 | 6      | 9 3/4   |
| 1 3/4    | 1 1/4 | 2      | 4 1/2   | 3        | 2 1/2 | 8      | 11 3/4  |
| 1 3/4    | 1 1/4 | 4      | 6 1/2   | 3        | 2 1/2 | 10     | 13 3/4  |

All dimensions are in inches. Right-hand cutters with right-hand helix are standard.

Tolerances: Outside diameter, +0.025, -0.005 inch; length of cut, +1/8, -1/32 inch.

**American National Standard Heavy Duty, Medium Helix Single-End End Mills,  
2 1/2-inch Combination Shank, High-Speed Steel ANSI/ASME B94.19-1997**

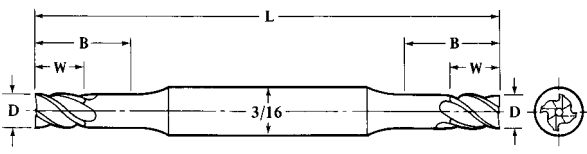


| Dia. of Cutter, $D$ | No. of Flutes | Length of Cut, $W$ | Length Overall, $L$ | Dia. of Cutter, $D$ | No. of Flutes | Length of Cut, $W$ | Length Overall, $L$ |
|---------------------|---------------|--------------------|---------------------|---------------------|---------------|--------------------|---------------------|
| 2 1/2               | 3             | 8                  | 12                  | 3                   | 3             | 4                  | 7 3/4               |
| 2 1/2               | 3             | 10                 | 14                  | 3                   | 3             | 6                  | 9 3/4               |
| 2 1/2               | 6             | 4                  | 8                   | 3                   | 3             | 8                  | 11 3/4              |
| 2 1/2               | 6             | 6                  | 10                  | 3                   | 8             | 4                  | 7 3/4               |
| 2 1/2               | 6             | 8                  | 12                  | 3                   | 8             | 6                  | 9 3/4               |
| 2 1/2               | 6             | 10                 | 14                  | 3                   | 8             | 8                  | 11 3/4              |
| 2 1/2               | 6             | 12                 | 16                  | 3                   | 8             | 10                 | 13 3/4              |
| 3                   | 2             | 4                  | 7 3/4               | 3                   | 8             | 12                 | 15 3/4              |
| 3                   | 2             | 6                  | 9 3/4               | ...                 | ...           | ...                | ...                 |

All dimensions are in inches. For shank dimensions see page 806. Right-hand cutters with right-hand helix are standard. Helix angle is greater than 19 degrees but not more than 39 degrees.

Tolerances: On  $D$ , +0.005 inch; on  $W$ ,  $\pm 1/32$  inch; on  $L$ ,  $\pm 1/16$  inch.

**ANSI Stub-, Regular-, and Long-Length, Four-Flute, Medium Helix, Plain-End, Double-End Miniature End Mills with  $\frac{3}{16}$ -Inch Diameter Straight Shanks**  
ANSI/ASME B94.19-1997



| Dia.<br>$D$    | Stub Length     |     | Regular Length |                |
|----------------|-----------------|-----|----------------|----------------|
|                | $W$             | $L$ | $W$            | $L$            |
| $\frac{1}{16}$ | $\frac{3}{32}$  | 2   | $\frac{3}{16}$ | $2\frac{1}{4}$ |
| $\frac{3}{32}$ | $\frac{9}{64}$  | 2   | $\frac{9}{32}$ | $2\frac{1}{4}$ |
| $\frac{1}{8}$  | $\frac{3}{16}$  | 2   | $\frac{3}{8}$  | $2\frac{1}{4}$ |
| $\frac{5}{32}$ | $\frac{15}{64}$ | 2   | $\frac{7}{16}$ | $2\frac{1}{4}$ |
| $\frac{3}{16}$ | $\frac{9}{32}$  | 2   | $\frac{1}{2}$  | $2\frac{1}{4}$ |

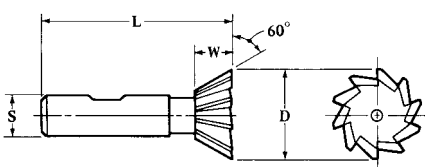
  

| Dia.<br>$D$    | Long Length   |                |                |
|----------------|---------------|----------------|----------------|
|                | $B$           | $W$            | $L$            |
| $\frac{1}{16}$ | $\frac{3}{8}$ | $\frac{7}{32}$ | $2\frac{1}{2}$ |
| $\frac{3}{32}$ | $\frac{1}{2}$ | $\frac{9}{32}$ | $2\frac{5}{8}$ |
| $\frac{1}{8}$  | $\frac{3}{4}$ | $\frac{3}{4}$  | $3\frac{1}{8}$ |
| $\frac{5}{32}$ | $\frac{7}{8}$ | $\frac{7}{8}$  | $3\frac{1}{4}$ |
| $\frac{3}{16}$ | 1             | 1              | $3\frac{3}{8}$ |

All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters with right-hand helix are standard. Helix angle is greater than 19 degrees but not more than 39 degrees.

**Tolerances:** On  $D$ , +0.003 inch (if the shank is the same diameter as the cutting portion, however, then the tolerance on the cutting diameter is -0.0025 inch.); on  $W$ , + $\frac{1}{32}$ , - $\frac{1}{64}$  inch; and on  $L$ ,  $\pm\frac{1}{16}$  inch.

**American National Standard 60-Degree Single-Angle Milling Cutters with Weldon Shanks** ANSI/ASME B94.19-1997

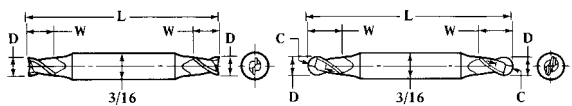


| Dia., $D$      | $S$           | $W$            | $L$            | Dia., $D$      | $S$           | $W$             | $L$            |
|----------------|---------------|----------------|----------------|----------------|---------------|-----------------|----------------|
| $\frac{3}{4}$  | $\frac{3}{8}$ | $\frac{5}{16}$ | $2\frac{1}{8}$ | $1\frac{7}{8}$ | $\frac{7}{8}$ | $\frac{13}{16}$ | $3\frac{1}{4}$ |
| $1\frac{3}{8}$ | $\frac{5}{8}$ | $\frac{9}{16}$ | $2\frac{7}{8}$ | $2\frac{1}{4}$ | 1             | $1\frac{1}{16}$ | $3\frac{3}{4}$ |

All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters are standard.

**Tolerances:** On  $D$ ,  $\pm 0.015$  inch; on  $S$ , -0.0001 to -0.0005 inch; on  $W$ ,  $\pm 0.015$  inch; and on  $L$ ,  $\pm\frac{1}{16}$  inch.

**American National Standard Stub-, Regular-, and Long-Length, Two-Flute, Medium Helix, Plain- and Ball-End, Double-End Miniature End Mills with 3/16-Inch Diameter Straight Shanks ANSI/ASME B94.19-1997**



| Dia.,<br>C and<br>D | Stub Length |   |          |     | Regular Length |       |          |       |
|---------------------|-------------|---|----------|-----|----------------|-------|----------|-------|
|                     | Plain End   |   | Ball End |     | Plain End      |       | Ball End |       |
|                     | W           | L | W        | L   | W              | L     | W        | L     |
| 1/32                | 3/64        | 2 | ...      | ... | 3/32           | 2 1/4 | ...      | ...   |
| 3/64                | 1/16        | 2 | ...      | ... | 9/64           | 2 1/4 | ...      | ...   |
| 1/16                | 3/32        | 2 | 3/32     | 2   | 3/16           | 2 1/4 | 3/16     | 2 1/4 |
| 5/64                | 1/8         | 2 | ...      | ... | 15/64          | 2 1/4 | ...      | ...   |
| 3/32                | 9/64        | 2 | 9/64     | 2   | 9/32           | 2 1/4 | 9/32     | 2 1/4 |
| 7/64                | 5/32        | 2 | ...      | ... | 21/64          | 2 1/4 | ...      | ...   |
| 1/8                 | 3/16        | 2 | 3/16     | 2   | 3/8            | 2 1/4 | 3/8      | 2 1/4 |
| 9/64                | 7/32        | 2 | ...      | ... | 13/32          | 2 1/4 | ...      | ...   |
| 5/32                | 15/64       | 2 | 15/64    | 2   | 7/16           | 2 1/4 | 7/16     | 2 1/4 |
| 11/64               | 1/4         | 2 | ...      | ... | 1/2            | 2 1/4 | ...      | ...   |
| 3/16                | 9/32        | 2 | 9/32     | 2   | 1/2            | 2 1/4 | 1/2      | 2 1/4 |

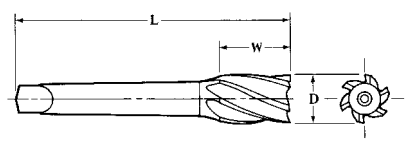
| Dia.,<br>D | Long Length, Plain End |      |       | Dia.,<br>D | Long Length, Plain End |     |       |
|------------|------------------------|------|-------|------------|------------------------|-----|-------|
|            | B <sup>a</sup>         | W    | L     |            | B <sup>a</sup>         | W   | L     |
| 1/16       | 3/8                    | 7/32 | 2 1/2 | 5/32       | 7/8                    | 7/8 | 3 1/4 |
| 3/32       | 1/2                    | 9/32 | 2 5/8 | 3/16       | 1                      | 1   | 3 3/8 |
| 1/8        | 3/4                    | 3/4  | 3 1/8 |            |                        |     |       |

<sup>a</sup>B is the length below the shank.

All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters with right-hand helix are standard. Helix angle is greater than 19 degrees but not more than 39 degrees.

**Tolerances:** On C and D, - 0.0015 inch for stub and regular length; + 0.003 inch for long length (if the shank is the same diameter as the cutting portion, however, then the tolerance on the cutting diameter is - 0.0025 inch.); on W, + 1/32, - 1/64 inch; and on L, ± 1/16 inch.

**American National Standard Multiple Flute, Helical Series End Mills with Brown & Sharpe Taper Shanks**



| Dia., D | W     | L       | Taper No. | Dia., D | W     | L     | Taper No. |
|---------|-------|---------|-----------|---------|-------|-------|-----------|
| 1/2     | 15/16 | 4 15/16 | 7         | 1 1/4   | 2     | 7 1/4 | 9         |
| 3/4     | 1 1/4 | 5 1/4   | 7         | 1 1/2   | 2 1/4 | 7 1/2 | 9         |
| 1       | 1 5/8 | 5 5/8   | 7         | 2       | 2 3/4 | 8     | 9         |

All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters with right-hand helix are standard. Helix angle is not less than 10 degrees.

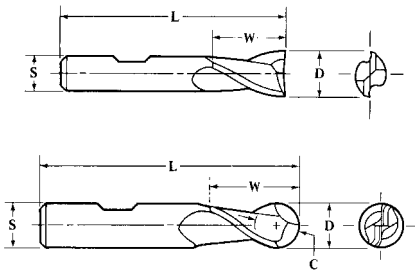
No. 5 taper is standard without tang; Nos. 7 and 9 are standard with tang only.

**Tolerances:** On D, +0.005 inch; on W, ± 1/32 inch; and on L ± 1/16 inch.

For dimensions of B & S taper shanks, see information given on page 936.

MILLING CUTTERS

**American National Standard Stub- and Regular-Length, Two-Flute, Medium Helix, Plain- and Ball-End, Single-End End Mills with Weldon Shanks**  
ANSI/ASME B94.19-1997



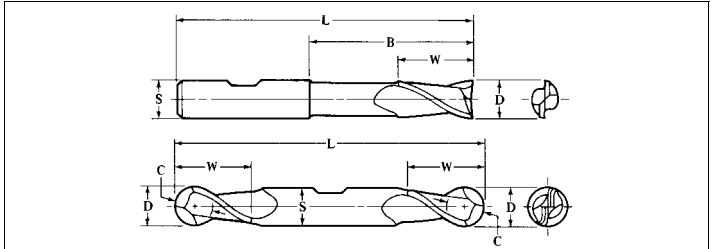
| Regular Length — Plain End |       |        |        | Stub Length — Plain End   |                     |                        |                         |
|----------------------------|-------|--------|--------|---------------------------|---------------------|------------------------|-------------------------|
| Dia.,<br>D                 | S     | W      | L      | Cutter Dia.,<br>D         | Shank Dia.,<br>S    | Length of Cut.<br>W    | Length Overall.<br>L    |
| 1/8                        | 3/8   | 3/8    | 25/16  | 1/8                       | 3/8                 | 3/16                   | 2 1/8                   |
| 3/16                       | 3/8   | 7/16   | 25/16  | 3/16                      | 3/8                 | 9/32                   | 2 3/16                  |
| 1/4                        | 3/8   | 1/2    | 25/16  | 1/4                       | 3/8                 | 3/8                    | 2 1/4                   |
| 5/16                       | 3/8   | 9/16   | 25/16  | Regular Length — Ball End |                     |                        |                         |
| 3/8                        | 3/8   | 9/16   | 25/16  |                           |                     |                        |                         |
| 7/16                       | 3/8   | 13/16  | 2 1/2  | Dia.,<br>C and D          | Shank<br>Dia.,<br>S | Length<br>of Cut.<br>W | Length<br>Overall.<br>L |
| 1/2                        | 3/8   | 13/16  | 2 1/2  |                           |                     |                        |                         |
| 1/2                        | 1/2   | 1      | 3      | 1/8                       | 3/8                 | 3/8                    | 2 3/16                  |
| 9/16                       | 1/2   | 1 1/8  | 3 3/8  | 3/16                      | 3/8                 | 1/2                    | 2 3/8                   |
| 5/8                        | 1/2   | 1 1/8  | 3 3/8  | 1/4                       | 3/8                 | 5/8                    | 2 1/8                   |
| 11/16                      | 1/2   | 1 5/16 | 3 5/16 | 5/16                      | 3/8                 | 3/4                    | 2 1/2                   |
| 3/4                        | 1/2   | 1 9/16 | 3 9/16 | 3/8                       | 3/8                 | 3/4                    | 2 1/2                   |
| 5/8                        | 5/8   | 1 9/16 | 3 7/16 | 7/16                      | 1/2                 | 1                      | 3                       |
| 11/16                      | 5/8   | 1 9/16 | 3 7/16 | 1/2                       | 1/2                 | 1                      | 3                       |
| 3/4                        | 5/8   | 1 9/16 | 3 7/16 | 9/16                      | 1/2                 | 1 1/8                  | 3 3/8                   |
| 13/16                      | 5/8   | 1 1/2  | 3 5/8  | 5/8                       | 1/2                 | 1 1/8                  | 3 3/8                   |
| 7/8                        | 5/8   | 1 1/2  | 3 5/8  | 5/8                       | 5/8                 | 1 3/8                  | 3 1/2                   |
| 1                          | 5/8   | 1 1/2  | 3 5/8  | 3/4                       | 1/2                 | 1 5/16                 | 3 5/16                  |
| 7/8                        | 7/8   | 1 1/2  | 3 3/4  | 3/4                       | 3/4                 | 1 3/8                  | 3 3/8                   |
| 1                          | 7/8   | 1 1/2  | 3 3/4  | 7/8                       | 7/8                 | 2                      | 4 1/4                   |
| 1 1/8                      | 7/8   | 1 5/8  | 3 7/8  | 1                         | 1                   | 2 1/4                  | 4 3/4                   |
| 1 1/4                      | 7/8   | 1 5/8  | 3 7/8  | 1 1/8                     | 1                   | 2 1/4                  | 4 3/4                   |
| 1                          | 1     | 1 5/8  | 4 1/8  | 1 1/4                     | 1 1/4               | 2 1/2                  | 5                       |
| 1 1/8                      | 1     | 1 5/8  | 4 1/8  | 1 1/2                     | 1 1/4               | 2 1/2                  | 5                       |
| 1 1/4                      | 1     | 1 5/8  | 4 1/8  |                           |                     |                        |                         |
| 1 3/8                      | 1     | 1 5/8  | 4 1/8  |                           |                     |                        |                         |
| 1 1/2                      | 1     | 1 5/8  | 4 1/8  |                           |                     |                        |                         |
| 1 1/4                      | 1 1/4 | 1 5/8  | 4 1/8  |                           |                     |                        |                         |
| 1 1/2                      | 1 1/4 | 1 5/8  | 4 1/8  |                           |                     |                        |                         |
| 1 3/4                      | 1 1/4 | 1 5/8  | 4 1/8  |                           |                     |                        |                         |
| 2                          | 1 1/4 | 1 5/8  | 4 1/8  |                           |                     |                        |                         |

All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters with right-hand helix are standard. Helix angle is greater than 19 degrees but not more than 39 degrees.

**Tolerances:** On C and D, -0.0015 inch for stub-length mills, + 0.003 inch for regular-length mills; on S, -0.0001 to -0.0005 inch; on W, ± 1/32 inch; and on L, ± 1/16 inch.

The following single-end end mills are available in premium high speed steel: ball end, two flute, with D ranging from 1/8 to 1 1/2 inches; ball end, multiple flute, with D ranging from 1/8 to 1 inch; and plain end, two flute, with D ranging from 1/8 to 1 1/2 inches.

**American National Standard Long-Length Single-End and Stub-, and Regular Length, Double-End, Plain- and Ball-End, Medium Helix, Two-Flute End Mills with Weldon Shanks ANSI/ASME B94.19-1997**



| Single End          |                         |                |       |        |                        |                |       |         |
|---------------------|-------------------------|----------------|-------|--------|------------------------|----------------|-------|---------|
| Dia.,<br>C and<br>D | Long Length — Plain End |                |       |        | Long Length — Ball End |                |       |         |
|                     | S                       | B <sup>a</sup> | W     | L      | S                      | B <sup>a</sup> | W     | L       |
| 1/8                 | ...                     | ...            | ...   | ...    | 3/8                    | 13/16          | 3/8   | 23/8    |
| 3/16                | ...                     | ...            | ...   | ...    | 3/8                    | 1 1/2          | 1/2   | 2 11/16 |
| 1/4                 | 3/8                     | 1 1/2          | 5/8   | 3 1/16 | 3/8                    | 1 1/2          | 3/8   | 3 1/16  |
| 5/16                | 3/8                     | 1 3/4          | 3/4   | 3 5/16 | 3/8                    | 1 3/4          | 3/4   | 3 5/16  |
| 3/8                 | 3/8                     | 1 3/4          | 3/4   | 3 3/16 | 3/8                    | 1 3/4          | 3/4   | 3 3/16  |
| 7/16                | ...                     | ...            | ...   | ...    | 1/2                    | 1 7/8          | 1     | 3 11/16 |
| 1/2                 | 1/2                     | 2 7/32         | 1     | 4      | 1/2                    | 2 1/4          | 1     | 4       |
| 5/8                 | 5/8                     | 2 3/32         | 1 3/8 | 4 3/8  | 5/8                    | 2 3/4          | 1 3/8 | 4 3/8   |
| 3/4                 | 3/4                     | 3 1/32         | 1 5/8 | 5 3/8  | 3/4                    | 3 3/8          | 1 3/8 | 5 3/8   |
| 1                   | 1                       | 4 31/32        | 2 1/2 | 7 1/4  | 1                      | 5              | 2 1/2 | 7 1/4   |
| 1 1/4               | 1 1/4                   | 4 31/32        | 3     | 7 1/4  | ...                    | ...            | ...   | ...     |

<sup>a</sup>B is the length below the shank.

| Double End          |                            |       |       |                               |        |        |                              |        |        |
|---------------------|----------------------------|-------|-------|-------------------------------|--------|--------|------------------------------|--------|--------|
| Dia.,<br>C and<br>D | Stub Length —<br>Plain End |       |       | Regular Length —<br>Plain End |        |        | Regular Length —<br>Ball End |        |        |
|                     | S                          | W     | L     | S                             | W      | L      | S                            | W      | L      |
| 1/8                 | 3/8                        | 3/16  | 2 1/4 | 3/8                           | 3/8    | 3 1/16 | 3/8                          | 3/8    | 3 1/16 |
| 3/32                | 3/8                        | 15/64 | 2 3/4 | 3/8                           | 7/16   | 3 3/8  | ...                          | ...    | ...    |
| 3/16                | 3/8                        | 3/32  | 2 3/4 | 3/8                           | 7/16   | 3 3/8  | 3/8                          | 7/16   | 3 3/8  |
| 7/32                | 3/8                        | 21/64 | 2 7/8 | 3/8                           | 1/2    | 3 3/8  | ...                          | ...    | ...    |
| 1/4                 | 3/8                        | 3/8   | 2 7/8 | 3/8                           | 1/2    | 3 3/8  | 3/8                          | 1/2    | 3 3/8  |
| 9/32                | ...                        | ...   | ...   | 3/8                           | 9/16   | 3 3/8  | ...                          | ...    | ...    |
| 5/16                | ...                        | ...   | ...   | 3/8                           | 9/16   | 3 3/8  | 3/8                          | 9/16   | 3 3/8  |
| 11/32               | ...                        | ...   | ...   | 3/8                           | 9/16   | 3 3/8  | ...                          | ...    | ...    |
| 3/8                 | ...                        | ...   | ...   | 3/8                           | 9/16   | 3 3/8  | 3/8                          | 9/16   | 3 3/8  |
| 13/32               | ...                        | ...   | ...   | 1/2                           | 13/16  | 3 3/4  | ...                          | ...    | ...    |
| 7/16                | ...                        | ...   | ...   | 1/2                           | 13/16  | 3 3/4  | 1/2                          | 13/16  | 3 3/4  |
| 15/32               | ...                        | ...   | ...   | 1/2                           | 13/16  | 3 3/4  | ...                          | ...    | ...    |
| 1/2                 | ...                        | ...   | ...   | 1/2                           | 13/16  | 3 3/4  | 1/2                          | 13/16  | 3 3/4  |
| 9/16                | ...                        | ...   | ...   | 5/8                           | 1 1/8  | 4 1/2  | ...                          | ...    | ...    |
| 5/8                 | ...                        | ...   | ...   | 5/8                           | 1 1/8  | 4 1/2  | 5/8                          | 1 1/8  | 4 1/2  |
| 11/16               | ...                        | ...   | ...   | 3/4                           | 1 5/16 | 5      | ...                          | ...    | ...    |
| 3/4                 | ...                        | ...   | ...   | 3/4                           | 1 5/16 | 5      | 3/4                          | 1 5/16 | 5      |
| 7/8                 | ...                        | ...   | ...   | 7/8                           | 1 5/16 | 5 1/2  | ...                          | ...    | ...    |
| 1                   | ...                        | ...   | ...   | 1                             | 1 5/8  | 5 7/8  | 1                            | 1 5/8  | 5 7/8  |

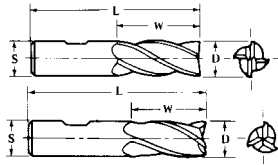
All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters with right-hand helix are standard. Helix angle is greater than 19 degrees but not more than 39 degrees.

Tolerances: On C and D, +0.003 inch for single-end mills, -0.0015 inch for double-end mills; on S, -0.0001 to -0.0005 inch; on W, ±1/32 inch; and on L, ±1/16 inch.



MILLING CUTTERS

**American National Standard Regular-, Long-, and Extra Long-Length, Three- and Four-Flute, Medium Helix, Center Cutting, Single-End End Mills with Weldon Shanks ANSI/ASME B94.19-1997**



| Four Flute |                |       |        |             |       |        |                   |       |        |
|------------|----------------|-------|--------|-------------|-------|--------|-------------------|-------|--------|
| Dia.,<br>D | Regular Length |       |        | Long Length |       |        | Extra Long Length |       |        |
|            | S              | W     | L      | S           | W     | L      | S                 | W     | L      |
| 1/8        | 3/8            | 3/8   | 2 5/16 | ...         | ...   | ...    | ...               | ...   | ...    |
| 3/16       | 3/8            | 1/2   | 2 3/8  | ...         | ...   | ...    | ...               | ...   | ...    |
| 1/4        | 3/8            | 5/8   | 2 7/16 | 3/8         | 1 1/4 | 3 3/16 | 3/8               | 1 3/4 | 3 3/16 |
| 5/16       | 3/8            | 3/4   | 2 1/2  | 3/8         | 1 3/8 | 3 3/8  | 3/8               | 2     | 3 3/4  |
| 3/8        | 3/8            | 3/4   | 2 1/2  | 3/8         | 1 1/2 | 3 3/4  | 3/8               | 2 1/2 | 4 1/4  |
| 1/2        | 1/2            | 1 1/4 | 3 3/4  | 1/2         | 2     | 4      | 1/2               | 3     | 5      |
| 5/8        | 3/8            | 1 3/8 | 3 3/4  | 3/8         | 2 1/2 | 4 3/8  | 3/8               | 4     | 6 1/8  |
| 11/16      | 3/8            | 1 3/8 | 3 3/4  | ...         | ...   | ...    | ...               | ...   | ...    |
| 3/4        | 3/4            | 1 3/8 | 3 3/4  | 3/4         | 3     | 5 1/4  | 3/4               | 4     | 6 1/4  |
| 7/8        | 3/8            | 1 7/8 | 4 1/8  | 7/8         | 3 1/2 | 5 3/4  | 7/8               | 5     | 7 1/4  |
| 1          | 1              | 2     | 4 1/2  | 1           | 4     | 6 1/2  | 1                 | 6     | 8 1/2  |
| 1 1/8      | 1              | 2     | 4 1/2  | ...         | ...   | ...    | ...               | ...   | ...    |
| 1 1/4      | 1 1/4          | 2     | 4 1/2  | 1 1/4       | 4     | 6 1/2  | 1 1/4             | 6     | 8 1/2  |
| 1 1/2      | 1 1/4          | 2     | 4 1/2  | ...         | ...   | ...    | ...               | ...   | ...    |

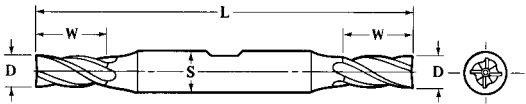
| Three Flute |                |       |         |             |                        |       |         |
|-------------|----------------|-------|---------|-------------|------------------------|-------|---------|
| Dia., D     | S              | W     | L       | Dia., D     | S                      | W     | L       |
|             | Regular Length |       |         |             | Regular Length (cont.) |       |         |
| 1/8         | 3/8            | 3/8   | 2 5/16  | 1 1/8       | 1                      | 2     | 4 1/2   |
| 3/16        | 3/8            | 1/2   | 2 3/8   | 1 1/4       | 1                      | 2     | 4 1/2   |
| 1/4         | 3/8            | 5/8   | 2 7/16  | 1 1/2       | 1                      | 2     | 4 1/2   |
| 5/16        | 3/8            | 3/4   | 2 1/2   | 1 1/4       | 1 1/4                  | 2     | 4 1/2   |
| 3/8         | 3/8            | 3/4   | 2 1/2   | 1 1/2       | 1 1/4                  | 2     | 4 1/2   |
| 7/16        | 3/8            | 1     | 2 11/16 | 1 3/4       | 1 1/4                  | 2     | 4 1/2   |
| 1/2         | 3/8            | 1     | 2 11/16 | 2           | 1 1/4                  | 2     | 4 1/2   |
| 5/16        | 1/2            | 1 1/4 | 3 1/4   | Long Length |                        |       |         |
| 3/8         | 1/2            | 1 3/8 | 3 3/8   |             |                        |       |         |
| 1/2         | 1/2            | 1 3/8 | 3 3/8   | 1/4         | 3/8                    | 1 1/4 | 3 11/16 |
| 5/8         | 1/2            | 1 3/8 | 3 3/8   | 3/16        | 3/8                    | 1 3/8 | 3 3/8   |
| 3/4         | 1/2            | 1 5/8 | 3 3/8   | 7/16        | 3/8                    | 1 1/2 | 3 3/4   |
| 7/8         | 3/8            | 1 5/8 | 3 3/4   | 1/2         | 1/2                    | 2     | 4       |
| 1           | 3/8            | 1 7/8 | 4       | 5/8         | 3/8                    | 2 1/2 | 4 3/8   |
| 1 1/8       | 3/8            | 1 7/8 | 4       | 3/4         | 3/4                    | 3     | 5 1/4   |
| 1 1/4       | 3/4            | 1 5/8 | 3 7/8   | 1           | 1                      | 4     | 6 1/2   |
| 1 1/2       | 3/4            | 1 7/8 | 4 3/8   | 1 1/4       | 1 1/4                  | 4     | 6 1/2   |
| 1           | 7/8            | 1 7/8 | 4 3/8   | 1 1/2       | 1 1/4                  | 4     | 6 1/2   |
| 1           | 1              | 1 7/8 | 4 3/8   | 1 3/4       | 1 1/4                  | 4     | 6 1/2   |
| 1           | 1              | 2     | 4 1/2   | 2           | 1 1/4                  | 4     | 6 1/2   |

All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters with right-hand helix are standard. Helix angle is greater than 19 degrees but not more than 39 degrees.

Tolerances: On D, +0.003 inch; on S, -0.0001 to -0.0005 inch; on W, ±1/32 inch; and on L, ±1/16 inch.

The following center-cutting, single-end end mills are available in premium high speed steel: regular length, multiple flute, with D ranging from 1/8 to 1 1/2 inches; long length, multiple flute, with D ranging from 3/8 to 1 1/4 inches; and extra long-length, multiple flute, with D ranging from 3/8 to 1 1/4 inches.

**American National Standard Stub- and Regular-length, Four-flute, Medium Helix, Double-end End Mills with Weldon Shanks ANSI/ASME B94.19-1997**



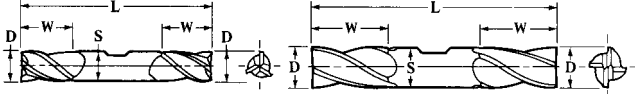
| Dia.,<br>D        | S   | W     | L      | Dia.,<br>D       | S   | W     | L     | Dia.,<br>D       | S   | W     | L     |
|-------------------|-----|-------|--------|------------------|-----|-------|-------|------------------|-----|-------|-------|
| Stub Length       |     |       |        |                  |     |       |       |                  |     |       |       |
| 1/8               | 3/8 | 3/16  | 2 3/4  | 3/16             | 3/8 | 9/32  | 2 3/4 | 1/4              | 3/8 | 3/8   | 2 7/8 |
| 5/32              | 3/8 | 15/64 | 2 3/4  | 7/32             | 3/8 | 21/64 | 2 7/8 | ...              | ... | ...   | ...   |
| Regular Length    |     |       |        |                  |     |       |       |                  |     |       |       |
| 1/8 <sup>a</sup>  | 3/8 | 3/8   | 3 1/16 | 11/32            | 3/8 | 3/4   | 3 1/2 | 5/8 <sup>a</sup> | 3/8 | 1 1/8 | 5     |
| 5/32 <sup>a</sup> | 3/8 | 7/16  | 3 1/8  | 3/8 <sup>a</sup> | 3/8 | 3/4   | 3 1/2 | 11/16            | 3/4 | 1 1/8 | 5 5/8 |
| 3/16 <sup>a</sup> | 3/8 | 1/2   | 3 1/4  | 15/32            | 1/2 | 1     | 4 1/8 | 3/4 <sup>a</sup> | 3/4 | 1 1/8 | 5 5/8 |
| 7/32              | 3/8 | 9/16  | 3 1/4  | 7/16             | 1/2 | 1     | 4 1/8 | 13/16            | 7/8 | 1 1/8 | 6 1/8 |
| 1/4 <sup>a</sup>  | 3/8 | 5/8   | 3 3/8  | 15/32            | 1/2 | 1     | 4 1/8 | 7/8              | 7/8 | 1 7/8 | 6 1/8 |
| 9/32              | 3/8 | 11/16 | 3 3/8  | 1/2 <sup>a</sup> | 1/2 | 1     | 4 1/8 | 1                | 1   | 1 7/8 | 6 3/8 |
| 5/16 <sup>a</sup> | 3/8 | 3/4   | 3 1/2  | 9/16             | 3/8 | 1 3/8 | 5     | ...              | ... | ...   | ...   |

<sup>a</sup> In this size of regular mill a left-hand cutter with a left-hand helix is also standard.

All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters with right-hand helix are standard. Helix angle is greater than 19 degrees but not more than 39 degrees.

**Tolerances:** On *D*, +0.003 inch (if the shank is the same diameter as the cutting portion, however, then the tolerance on the cutting diameter is -0.0025 inch); on *S*, -0.0001 to -0.0005 inch; on *W*, ±1/32 inch; and on *L*, ±1/16 inch.

**American National Standard Stub- and Regular-Length, Four-Flute, Medium Helix, Double-End End Mills with Weldon Shanks ANSI/ASME B94.19-1997**



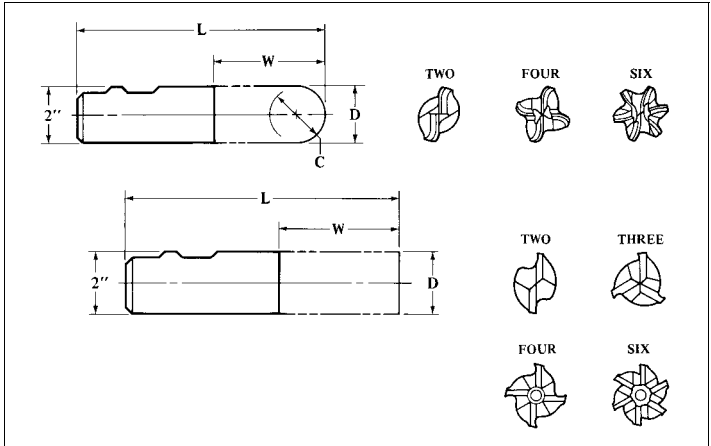
| Dia.,<br>D  | S   | W     | L      | Dia.,<br>D | S   | W     | L      |
|-------------|-----|-------|--------|------------|-----|-------|--------|
| Three Flute |     |       |        | Four Flute |     |       |        |
| 1/8         | 3/8 | 3/8   | 3 1/16 | 1/8        | 3/8 | 3/8   | 3 1/16 |
| 3/16        | 3/8 | 1/2   | 3 1/4  | 3/16       | 3/8 | 1/2   | 3 3/4  |
| 1/4         | 3/8 | 5/8   | 3 3/8  | 1/4        | 3/8 | 3/8   | 3 3/8  |
| 5/16        | 3/8 | 3/4   | 3 1/2  | 5/16       | 3/8 | 3/4   | 3 1/2  |
| 3/8         | 3/8 | 3/4   | 3 1/2  | 3/8        | 3/8 | 3/4   | 3 1/2  |
| 7/16        | 1/2 | 1     | 4 1/8  | 1/2        | 1/2 | 1     | 4 1/8  |
| 1/2         | 1/2 | 1     | 4 1/8  | 3/8        | 3/8 | 1 3/8 | 5      |
| 9/16        | 3/8 | 1 1/8 | 5      | 3/4        | 3/4 | 1 3/8 | 5 5/8  |
| 5/8         | 3/8 | 1 3/8 | 5      | 7/8        | 3/8 | 1 7/8 | 6 1/8  |
| 3/4         | 3/4 | 1 3/8 | 5 5/8  | 1          | 1   | 1 7/8 | 6 3/8  |
| 1           | 1   | 1 7/8 | 6 3/8  | ...        | ... | ...   | ...    |

All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters with right-hand helix are standard. Helix angle is greater than 19 degrees but not more than 39 degrees.

**Tolerances:** On *D*, +0.0015 inch; on *S*, -0.0001 to -0.0005 inch; on *W*, ±1/32 inch; and on *L*, ±1/16 inch.

MILLING CUTTERS

**American National Standard Plain- and Ball-End, Heavy Duty, Medium Helix, Single-End End Mills with 2-Inch Diameter Shanks ANSI/ASME B94.19-1997**



| Dia.,<br>C and D | Plain End |     |               | Ball End |     |               |
|------------------|-----------|-----|---------------|----------|-----|---------------|
|                  | W         | L   | No. of Flutes | W        | L   | No. of Flutes |
| 2                | 2         | 5¼  | 2, 4, 6       | ...      | ... | ...           |
| 2                | 3         | 6¼  | 2, 3          | ...      | ... | ...           |
| 2                | 4         | 7¼  | 2, 3, 4, 6    | 4        | 7¾  | 6             |
| 2                | ...       | ... | ...           | 5        | 8¾  | 2, 4          |
| 2                | 6         | 9¼  | 2, 3, 4, 6    | 6        | 9¾  | 6             |
| 2                | 8         | 11¼ | 6             | 8        | 11¾ | 6             |
| 2½               | 4         | 7¼  | 2, 3, 4, 6    | ...      | ... | ...           |
| 2½               | ...       | ... | ...           | 5        | 8¾  | 4             |
| 2½               | 6         | 9¼  | 2, 4, 6       | ...      | ... | ...           |
| 2½               | 8         | 11¼ | 6             | ...      | ... | ...           |

All dimensions are in inches. All cutters are high-speed steel. Right-hand cutters with right-hand helix are standard. Helix angle is greater than 19 degrees but not more than 39 degrees.

Tolerances: On C and D, + 0.005 inch for 2, 3, 4 and 6 flutes; on W, ± 1/16 inch; and on L, ± 1/16 inch.

**Dimensions of American National Standard Weldon Shanks ANSI/ASME B94.19-1997**

| Shank |         | Flat           |                     | Shank |         | Flat           |                     |
|-------|---------|----------------|---------------------|-------|---------|----------------|---------------------|
| Dia.  | Length  | X <sup>a</sup> | Length <sup>b</sup> | Dia.  | Length  | X <sup>a</sup> | Length <sup>b</sup> |
| 3/8   | 1 9/16  | 0.325          | 0.280               | 1     | 2 1/2   | 0.925          | 0.515               |
| 1/2   | 1 29/32 | 0.440          | 0.330               | 1 1/4 | 2 7/32  | 1.156          | 0.515               |
| 5/8   | 1 29/32 | 0.560          | 0.400               | 1 1/2 | 2 11/16 | 1.406          | 0.515               |
| 3/4   | 2 1/32  | 0.675          | 0.455               | 2     | 3 1/4   | 1.900          | 0.700               |
| 7/8   | 2 1/32  | 0.810          | 0.455               | 2 1/2 | 3 1/2   | 2.400          | 0.700               |

<sup>a</sup>X is distance from bottom of flat to opposite side of shank.

<sup>b</sup>Minimum.

All dimensions are in inches.

Centerline of flat is at half-length of shank except for 1 1/2-, 2- and 2 1/2-inch shanks where it is 1 3/16, 1 27/32 and 1 15/16 from shank end, respectively.

Tolerance on shank diameter, - 0.0001 to - 0.0005 inch.

**American National Standard Form Relieved, Concave, Convex, and  
Corner-Rounding Arbor-Type Cutters ANSI/ASME B94.19-1997**

| Concave                              |        |        | Convex               |                         | Corner-rounding      |         |         |
|--------------------------------------|--------|--------|----------------------|-------------------------|----------------------|---------|---------|
| Diameter $C$ or Radius $R$           |        |        | Cutter<br>Dia. $D^a$ | Width<br>$W \pm .010^b$ | Diameter of Hole $H$ |         |         |
| Nom.                                 | Max.   | Min.   |                      |                         | Nom.                 | Max.    | Min.    |
| Concave Cutters <sup>c</sup>         |        |        |                      |                         |                      |         |         |
| $\frac{1}{8}$                        | 0.1270 | 0.1240 | $2\frac{1}{4}$       | $\frac{1}{4}$           | 1                    | 1.00075 | 1.00000 |
| $\frac{3}{16}$                       | 0.1895 | 0.1865 | $2\frac{1}{4}$       | $\frac{3}{8}$           | 1                    | 1.00075 | 1.00000 |
| $\frac{1}{4}$                        | 0.2520 | 0.2490 | $2\frac{1}{2}$       | $\frac{7}{16}$          | 1                    | 1.00075 | 1.00000 |
| $\frac{5}{16}$                       | 0.3145 | 0.3115 | $2\frac{3}{4}$       | $\frac{9}{16}$          | 1                    | 1.00075 | 1.00000 |
| $\frac{3}{8}$                        | 0.3770 | 0.3740 | $2\frac{3}{4}$       | $\frac{5}{8}$           | 1                    | 1.00075 | 1.00000 |
| $\frac{7}{16}$                       | 0.4395 | 0.4365 | 3                    | $\frac{3}{4}$           | 1                    | 1.00075 | 1.00000 |
| $\frac{1}{2}$                        | 0.5040 | 0.4980 | 3                    | $1\frac{1}{16}$         | 1                    | 1.00075 | 1.00000 |
| $\frac{5}{8}$                        | 0.6290 | 0.6230 | $3\frac{1}{2}$       | 1                       | $1\frac{1}{4}$       | 1.251   | 1.250   |
| $\frac{3}{4}$                        | 0.7540 | 0.7480 | $3\frac{3}{4}$       | $1\frac{3}{16}$         | $1\frac{1}{4}$       | 1.251   | 1.250   |
| $\frac{7}{8}$                        | 0.8790 | 0.8730 | 4                    | $1\frac{3}{8}$          | $1\frac{1}{4}$       | 1.251   | 1.250   |
| 1                                    | 1.0040 | 0.9980 | $4\frac{1}{4}$       | $1\frac{9}{16}$         | $1\frac{1}{4}$       | 1.251   | 1.250   |
| Convex Cutters <sup>c</sup>          |        |        |                      |                         |                      |         |         |
| $\frac{1}{8}$                        | 0.1270 | 0.1230 | $2\frac{1}{4}$       | $\frac{1}{8}$           | 1                    | 1.00075 | 1.00000 |
| $\frac{3}{16}$                       | 0.1895 | 0.1855 | $2\frac{1}{4}$       | $\frac{3}{16}$          | 1                    | 1.00075 | 1.00000 |
| $\frac{1}{4}$                        | 0.2520 | 0.2480 | $2\frac{1}{2}$       | $\frac{1}{4}$           | 1                    | 1.00075 | 1.00000 |
| $\frac{5}{16}$                       | 0.3145 | 0.3105 | $2\frac{3}{4}$       | $\frac{5}{16}$          | 1                    | 1.00075 | 1.00000 |
| $\frac{3}{8}$                        | 0.3770 | 0.3730 | $2\frac{3}{4}$       | $\frac{3}{8}$           | 1                    | 1.00075 | 1.00000 |
| $\frac{7}{16}$                       | 0.4395 | 0.4355 | 3                    | $\frac{7}{16}$          | 1                    | 1.00075 | 1.00000 |
| $\frac{1}{2}$                        | 0.5020 | 0.4980 | 3                    | $\frac{1}{2}$           | 1                    | 1.00075 | 1.00000 |
| $\frac{5}{8}$                        | 0.6270 | 0.6230 | $3\frac{1}{2}$       | $\frac{5}{8}$           | $1\frac{1}{4}$       | 1.251   | 1.250   |
| $\frac{3}{4}$                        | 0.7520 | 0.7480 | $3\frac{3}{4}$       | $\frac{3}{4}$           | $1\frac{1}{4}$       | 1.251   | 1.250   |
| $\frac{7}{8}$                        | 0.8770 | 0.8730 | 4                    | $\frac{7}{8}$           | $1\frac{1}{4}$       | 1.251   | 1.250   |
| 1                                    | 1.0020 | 0.9980 | $4\frac{1}{4}$       | 1                       | $1\frac{1}{4}$       | 1.251   | 1.250   |
| Corner-rounding Cutters <sup>d</sup> |        |        |                      |                         |                      |         |         |
| $\frac{1}{8}$                        | 0.1260 | 0.1240 | $2\frac{1}{2}$       | $\frac{1}{4}$           | 1                    | 1.00075 | 1.00000 |
| $\frac{1}{4}$                        | 0.2520 | 0.2490 | 3                    | $1\frac{1}{32}$         | 1                    | 1.00075 | 1.00000 |
| $\frac{3}{8}$                        | 0.3770 | 0.3740 | $3\frac{3}{4}$       | $\frac{9}{16}$          | $1\frac{1}{4}$       | 1.251   | 1.250   |
| $\frac{1}{2}$                        | 0.5020 | 0.4990 | 4 $\frac{1}{2}$      | $\frac{3}{4}$           | $1\frac{1}{4}$       | 1.251   | 1.250   |
| $\frac{5}{8}$                        | 0.6270 | 0.6240 | $4\frac{1}{4}$       | $1\frac{15}{16}$        | $1\frac{1}{4}$       | 1.251   | 1.250   |

<sup>a</sup> Tolerances on cutter diameter are  $+\frac{1}{16}$ ,  $-\frac{1}{16}$  inch for all sizes.

<sup>b</sup> Tolerance does not apply to convex cutters.

<sup>c</sup> Size of cutter is designated by specifying diameter  $C$  of circular form.

<sup>d</sup> Size of cutter is designated by specifying radius  $R$  of circular form.

All dimensions in inches. All cutters are high-speed steel and are form relieved.

Right-hand corner rounding cutters are standard, but left-hand cutter for  $\frac{1}{4}$ -inch size is also standard.

For key and keyway dimensions for these cutters, see page 819.

**American National Standard Roughing and Finishing Gear Milling Cutters for Gears with 14½-Degree Pressure Angles ANSI/ASME B94.19-1997**

| ROUGHING                       |                          |                        |                 | FINISHING                |                        |                 |                          |                        |
|--------------------------------|--------------------------|------------------------|-----------------|--------------------------|------------------------|-----------------|--------------------------|------------------------|
| Diametral Pitch                | Dia. of Cutter, <i>D</i> | Dia. of Hole, <i>H</i> | Diametral Pitch | Dia. of Cutter, <i>D</i> | Dia. of Hole, <i>H</i> | Diametral Pitch | Dia. of Cutter, <i>D</i> | Dia. of Hole, <i>H</i> |
| Roughing Gear Milling Cutters  |                          |                        |                 |                          |                        |                 |                          |                        |
| 1                              | 8½                       | 2                      | 3               | 5¼                       | 1½                     | 5               | 3⅝                       | 1                      |
| 1¼                             | 7¾                       | 2                      | 3               | 4¾                       | 1¼                     | 6               | 3⅝                       | 1½                     |
| 1½                             | 7                        | 1¾                     | 4               | 4¾                       | 1¾                     | 6               | 3½                       | 1¼                     |
| 1¾                             | 6½                       | 1¾                     | 4               | 4½                       | 1½                     | 6               | 3⅝                       | 1                      |
| 2                              | 6½                       | 1¾                     | 4               | 4¼                       | 1¼                     | 7               | 3⅝                       | 1¼                     |
| 2                              | 5¾                       | 1½                     | 4               | 3⅝                       | 1                      | 7               | 2⅞                       | 1                      |
| 2½                             | 6⅝                       | 1¾                     | 5               | 4⅝                       | 1¾                     | 8               | 3¼                       | 1¼                     |
| 2½                             | 5¾                       | 1½                     | 5               | 4¼                       | 1½                     | 8               | 2⅞                       | 1                      |
| 3                              | 5⅝                       | 1¾                     | 5               | 3¾                       | 1¼                     | ...             | ...                      | ...                    |
| Finishing Gear Milling Cutters |                          |                        |                 |                          |                        |                 |                          |                        |
| 1                              | 8½                       | 2                      | 6               | 3⅝                       | 1½                     | 14              | 2⅞                       | ⅞                      |
| 1¼                             | 7¾                       | 2                      | 6               | 3½                       | 1¼                     | 16              | 2½                       | 1                      |
| 1½                             | 7                        | 1¾                     | 6               | 3⅝                       | 1                      | 16              | 2⅞                       | ⅞                      |
| 1¾                             | 6½                       | 1¾                     | 7               | 3⅝                       | 1½                     | 18              | 2⅞                       | 1                      |
| 2                              | 6½                       | 1¾                     | 7               | 3⅝                       | 1¼                     | 18              | 2                        | ⅞                      |
| 2                              | 5¾                       | 1½                     | 7               | 2⅞                       | 1                      | 20              | 2⅞                       | 1                      |
| 2½                             | 6⅝                       | 1¾                     | 8               | 3½                       | 1½                     | 20              | 2                        | ⅞                      |
| 2½                             | 5¾                       | 1½                     | 8               | 3¼                       | 1¼                     | 22              | 2¼                       | 1                      |
| 3                              | 5⅝                       | 1¾                     | 8               | 2⅞                       | 1                      | 22              | 2                        | ⅞                      |
| 3                              | 5¼                       | 1½                     | 9               | 3⅝                       | 1¼                     | 24              | 2¼                       | 1                      |
| 3                              | 4¾                       | 1¼                     | 9               | 2¾                       | 1                      | 24              | 1¾                       | ⅞                      |
| 4                              | 4¾                       | 1¾                     | 10              | 3                        | 1¼                     | 26              | 1¾                       | ⅞                      |
| 4                              | 4½                       | 1½                     | 10              | 2¾                       | 1                      | 28              | 1¾                       | ⅞                      |
| 4                              | 4¼                       | 1¼                     | 10              | 2⅞                       | ⅞                      | 30              | 1¾                       | ⅞                      |
| 4                              | 3⅝                       | 1                      | 11              | 2⅞                       | 1                      | 32              | 1¾                       | ⅞                      |
| 5                              | 4⅝                       | 1¾                     | 11              | 2⅞                       | ⅞                      | 36              | 1¾                       | ⅞                      |
| 5                              | 4¼                       | 1½                     | 12              | 2⅞                       | 1¼                     | 40              | 1¾                       | ⅞                      |
| 5                              | 3¾                       | 1¼                     | 12              | 2⅞                       | 1                      | 48              | 1¾                       | ⅞                      |
| 5                              | 3⅝                       | 1                      | 12              | 2¼                       | ⅞                      | ...             | ...                      | ...                    |
| 6                              | 4¼                       | 1¾                     | 14              | 2½                       | 1                      | ...             | ...                      | ...                    |

All dimensions are in inches.

All gear milling cutters are high-speed steel and are form relieved.

For keyway dimensions see page 819.

*Tolerances:* On outside diameter, + 1/16, -1/16 inch; on hole diameter, through 1-inch hole diameter, +0.00075 inch, over 1-inch and through 2-inch hole diameter, +0.0010 inch.

For cutter number relative to numbers of gear teeth, see page 2052. Roughing cutters are made with No. 1 cutter form only.

**American National Standard Gear Milling Cutters for Mitre and Bevel  
Gears with 14½-Degree Pressure Angles ANSI/ASME B94.19-1997**

| Diametral Pitch | Diameter of Cutter, <i>D</i> | Diameter of Hole, <i>H</i> | Diametral Pitch | Diameter of Cutter, <i>D</i> | Diameter of Hole, <i>H</i> |
|-----------------|------------------------------|----------------------------|-----------------|------------------------------|----------------------------|
| 3               | 4                            | 1¼                         | 10              | 2⅝                           | ⅞                          |
| 4               | 3⅝                           | 1¼                         | 12              | 2¼                           | ⅞                          |
| 5               | 3⅝                           | 1¼                         | 14              | 2⅝                           | ⅞                          |
| 6               | 3⅝                           | 1                          | 16              | 2⅝                           | ⅞                          |
| 7               | 2⅞                           | 1                          | 20              | 2                            | ⅞                          |
| 8               | 2⅞                           | 1                          | 24              | 1¾                           | ⅞                          |

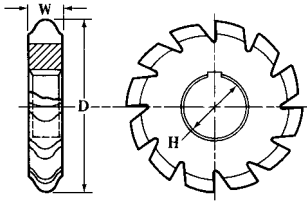
All dimensions are in inches.

All cutters are high-speed steel and are form relieved.

For keyway dimensions see page 819. For cutter selection see page 2091.

**Tolerances:** On outside diameter, + $\frac{1}{16}$ , - $\frac{1}{16}$  inch; on hole diameter, through 1-inch hole diameter, +0.00075 inch, for 1¼-inch hole diameter, +0.0010 inch.

To select the cutter number for bevel gears with the axis at any angle, double the back cone radius and multiply the result by the diametral pitch. This procedure gives the number of equivalent spur gear teeth and is the basis for selecting the cutter number from the table on page 2054.



**American National Standard  
Roller Chain Sprocket  
Milling Cutters**

**American National Standard Roller Chain Sprocket  
Milling Cutters ANSI/ASME B94.19-1997**

| Chain Pitch | Dia. of Roll | No. of Teeth in Sprocket | Dia. of Cutter, <i>D</i> | Width of Cutter, <i>W</i> | Dia. of Hole, <i>H</i> |
|-------------|--------------|--------------------------|--------------------------|---------------------------|------------------------|
| ¼           | 0.130        | 6                        | 2¾                       | ⅝ <sub>16</sub>           | 1                      |
| ¼           | 0.130        | 7-8                      | 2¾                       | ⅝ <sub>16</sub>           | 1                      |
| ¼           | 0.130        | 9-11                     | 2¾                       | ⅝ <sub>16</sub>           | 1                      |
| ¼           | 0.130        | 12-17                    | 2¾                       | ⅝ <sub>16</sub>           | 1                      |
| ¼           | 0.130        | 18-34                    | 2¾                       | ⅞ <sub>32</sub>           | 1                      |
| ¼           | 0.130        | 35 and over              | 2¾                       | ⅞ <sub>32</sub>           | 1                      |
| ⅜           | 0.200        | 6                        | 2¾                       | 15 <sub>32</sub>          | 1                      |
| ⅜           | 0.200        | 7-8                      | 2¾                       | 15 <sub>32</sub>          | 1                      |
| ⅜           | 0.200        | 9-11                     | 2¾                       | 15 <sub>32</sub>          | 1                      |
| ⅜           | 0.200        | 12-17                    | 2¾                       | 7 <sub>16</sub>           | 1                      |
| ⅜           | 0.200        | 18-34                    | 2¾                       | 7 <sub>16</sub>           | 1                      |
| ⅜           | 0.200        | 35 and over              | 2¾                       | 13 <sub>32</sub>          | 1                      |
| ½           | 0.313        | 6                        | 3                        | ¾                         | 1                      |
| ½           | 0.313        | 7-8                      | 3                        | ¾                         | 1                      |
| ½           | 0.313        | 9-11                     | 3⅝                       | ¾                         | 1                      |
| ½           | 0.313        | 12-17                    | 3⅝                       | ¾                         | 1                      |
| ½           | 0.313        | 18-34                    | 3⅝                       | 23 <sub>32</sub>          | 1                      |
| ½           | 0.313        | 35 and over              | 3⅝                       | 11 <sub>16</sub>          | 1                      |
| ⅝           | 0.400        | 6                        | 3⅝                       | ¾                         | 1                      |
| ⅝           | 0.400        | 7-8                      | 3⅝                       | ¾                         | 1                      |
| ⅝           | 0.400        | 9-11                     | 3¼                       | ¾                         | 1                      |
| ⅝           | 0.400        | 12-17                    | 3¼                       | ¾                         | 1                      |
| ⅝           | 0.400        | 18-34                    | 3¼                       | 23 <sub>32</sub>          | 1                      |
| ⅝           | 0.400        | 35 and over              | 3¼                       | 11 <sub>16</sub>          | 1                      |

**American National Standard Roller Chain Sprocket  
Milling Cutters ANSI/ASME B94.19-1997(Continued)**

| Chain Pitch    | Dia. of Roll | No. of Teeth in Sprocket | Dia. of Cutter, $D$ | Width of Cutter, $W$ | Dia. of Hole, $H$ |
|----------------|--------------|--------------------------|---------------------|----------------------|-------------------|
| $\frac{3}{4}$  | 0.469        | 6                        | $3\frac{1}{4}$      | $\frac{29}{32}$      | 1                 |
| $\frac{3}{4}$  | 0.469        | 7-8                      | $3\frac{1}{4}$      | $\frac{29}{32}$      | 1                 |
| $\frac{3}{4}$  | 0.469        | 9-11                     | $3\frac{3}{8}$      | $\frac{29}{32}$      | 1                 |
| $\frac{3}{4}$  | 0.469        | 12-17                    | $3\frac{3}{8}$      | $\frac{7}{8}$        | 1                 |
| $\frac{3}{4}$  | 0.469        | 18-34                    | $3\frac{3}{8}$      | $\frac{27}{32}$      | 1                 |
| $\frac{3}{4}$  | 0.469        | 35 and over              | $3\frac{3}{8}$      | $\frac{13}{16}$      | 1                 |
| 1              | 0.625        | 6                        | $3\frac{3}{8}$      | $1\frac{1}{2}$       | $1\frac{1}{4}$    |
| 1              | 0.625        | 7-8                      | 4                   | $1\frac{1}{2}$       | $1\frac{1}{4}$    |
| 1              | 0.625        | 9-11                     | $4\frac{1}{8}$      | $1\frac{15}{32}$     | $1\frac{1}{4}$    |
| 1              | 0.625        | 18-34                    | $4\frac{1}{4}$      | $1\frac{13}{32}$     | $1\frac{1}{4}$    |
| 1              | 0.625        | 35 and over              | $4\frac{1}{4}$      | $1\frac{11}{32}$     | $1\frac{1}{4}$    |
| $1\frac{1}{4}$ | 0.750        | 6                        | $4\frac{1}{4}$      | $1\frac{13}{16}$     | $1\frac{1}{4}$    |
| $1\frac{1}{4}$ | 0.750        | 7-8                      | $4\frac{3}{8}$      | $1\frac{13}{16}$     | $1\frac{1}{4}$    |
| $1\frac{1}{4}$ | 0.750        | 9-11                     | $4\frac{1}{2}$      | $1\frac{25}{32}$     | $1\frac{1}{4}$    |
| $1\frac{1}{4}$ | 0.750        | 18-34                    | $4\frac{3}{4}$      | $1\frac{11}{16}$     | $1\frac{1}{4}$    |
| $1\frac{1}{4}$ | 0.750        | 35 and over              | $4\frac{3}{8}$      | $1\frac{5}{8}$       | $1\frac{1}{4}$    |
| $1\frac{1}{2}$ | 0.875        | 6                        | $4\frac{3}{8}$      | $1\frac{13}{16}$     | $1\frac{1}{4}$    |
| $1\frac{1}{2}$ | 0.875        | 7-8                      | $4\frac{1}{2}$      | $1\frac{13}{16}$     | $1\frac{1}{4}$    |
| $1\frac{1}{2}$ | 0.875        | 9-11                     | $4\frac{3}{8}$      | $1\frac{25}{32}$     | $1\frac{1}{4}$    |
| $1\frac{1}{2}$ | 0.875        | 12-17                    | $4\frac{3}{8}$      | $1\frac{3}{4}$       | $1\frac{1}{4}$    |
| $1\frac{1}{2}$ | 0.875        | 18-34                    | $4\frac{3}{4}$      | $1\frac{11}{16}$     | $1\frac{1}{4}$    |
| $1\frac{1}{2}$ | 0.875        | 35 and over              | $4\frac{3}{4}$      | $1\frac{3}{8}$       | $1\frac{1}{4}$    |
| $1\frac{3}{4}$ | 1.000        | 6                        | 5                   | $2\frac{3}{32}$      | $1\frac{1}{2}$    |
| $1\frac{3}{4}$ | 1.000        | 7-8                      | $5\frac{1}{8}$      | $2\frac{3}{32}$      | $1\frac{1}{2}$    |
| $1\frac{3}{4}$ | 1.000        | 9-11                     | $5\frac{1}{4}$      | $2\frac{1}{16}$      | $1\frac{1}{2}$    |
| $1\frac{3}{4}$ | 1.000        | 12-17                    | $5\frac{3}{8}$      | $2\frac{1}{32}$      | $1\frac{1}{2}$    |
| $1\frac{3}{4}$ | 1.000        | 18-34                    | $5\frac{1}{2}$      | $2\frac{13}{32}$     | $1\frac{1}{2}$    |
| $1\frac{3}{4}$ | 1.000        | 35 and over              | $5\frac{1}{2}$      | $1\frac{7}{8}$       | $1\frac{1}{2}$    |
| 2              | 1.125        | 6                        | $5\frac{3}{8}$      | $2\frac{13}{32}$     | $1\frac{1}{2}$    |
| 2              | 1.125        | 7-8                      | $5\frac{1}{2}$      | $2\frac{13}{32}$     | $1\frac{1}{2}$    |
| 2              | 1.125        | 9-11                     | $5\frac{3}{8}$      | $2\frac{3}{8}$       | $1\frac{1}{2}$    |
| 2              | 1.125        | 12-17                    | $5\frac{3}{4}$      | $2\frac{3}{16}$      | $1\frac{1}{2}$    |
| 2              | 1.125        | 18-34                    | $5\frac{7}{8}$      | $2\frac{1}{4}$       | $1\frac{1}{2}$    |
| 2              | 1.125        | 35 and over              | $5\frac{7}{8}$      | $2\frac{3}{32}$      | $1\frac{1}{2}$    |
| $2\frac{1}{4}$ | 1.406        | 6                        | $5\frac{7}{8}$      | $2\frac{11}{16}$     | $1\frac{1}{2}$    |
| $2\frac{1}{4}$ | 1.406        | 7-8                      | 6                   | $2\frac{11}{16}$     | $1\frac{1}{2}$    |
| $2\frac{1}{4}$ | 1.406        | 9-11                     | $6\frac{1}{4}$      | $2\frac{17}{32}$     | $1\frac{1}{2}$    |
| $2\frac{1}{4}$ | 1.406        | 12-17                    | $6\frac{3}{8}$      | $2\frac{19}{32}$     | $1\frac{1}{2}$    |
| $2\frac{1}{4}$ | 1.406        | 18-34                    | $6\frac{1}{2}$      | $2\frac{15}{32}$     | $1\frac{1}{2}$    |
| $2\frac{1}{4}$ | 1.406        | 35 and over              | $6\frac{1}{2}$      | $2\frac{13}{32}$     | $1\frac{1}{2}$    |
| $2\frac{1}{2}$ | 1.563        | 6                        | $6\frac{3}{8}$      | 3                    | $1\frac{3}{4}$    |
| $2\frac{1}{2}$ | 1.563        | 7-8                      | $6\frac{3}{8}$      | 3                    | $1\frac{3}{4}$    |
| $2\frac{1}{2}$ | 1.563        | 9-11                     | $6\frac{3}{4}$      | $2\frac{15}{16}$     | $1\frac{3}{4}$    |
| $2\frac{1}{2}$ | 1.563        | 12-17                    | $6\frac{7}{8}$      | $2\frac{29}{32}$     | $1\frac{3}{4}$    |
| $2\frac{1}{2}$ | 1.563        | 18-34                    | $7$                 | $2\frac{3}{4}$       | $1\frac{3}{4}$    |
| $2\frac{1}{2}$ | 1.563        | 35 and over              | $7\frac{1}{8}$      | $2\frac{11}{16}$     | $1\frac{3}{4}$    |
| 3              | 1.875        | 6                        | $7\frac{1}{2}$      | $3\frac{19}{32}$     | 2                 |
| 3              | 1.875        | 7-8                      | $7\frac{3}{4}$      | $3\frac{19}{32}$     | 2                 |
| 3              | 1.875        | 9-11                     | $7\frac{7}{8}$      | $3\frac{17}{32}$     | 2                 |
| 3              | 1.875        | 12-17                    | 8                   | $3\frac{15}{32}$     | 2                 |
| 3              | 1.875        | 18-34                    | 8                   | $3\frac{11}{32}$     | 2                 |
| 3              | 1.875        | 35 and over              | $8\frac{1}{4}$      | $3\frac{7}{32}$      | 2                 |

All dimensions are in inches.

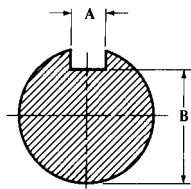
All cutters are high-speed steel and are form relieved.

For keyway dimensions see page 819.

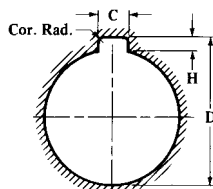
*Tolerances:* Outside diameter,  $+\frac{1}{16}$ ,  $-\frac{1}{16}$  inch; hole diameter, through 1-inch diameter,  $+0.00075$  inch, above 1-inch diameter and through 2-inch diameter,  $+0.0010$  inch.

For tooth form, see ANSI sprocket tooth form table on page 2458.

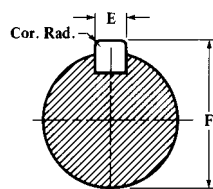
## American National Standard Keys and Keyways for Milling Cutters and Arbors ANSI/ASME B94.19-1997



ARBOR AND KEYSEAT



CUTTER HOLE AND KEYWAY



ARBOR AND KEY

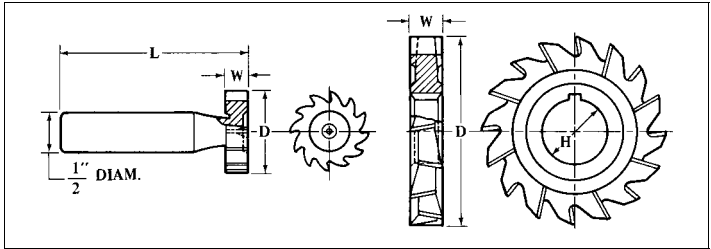
| Nom. Arbor and Cutter Hole Dia. | Nom. Size Key (Square) | Arbor and Keyseat |        |        |        | Hole and Keyway |        |                     |        |               | Arbor and Key |        |        |        |
|---------------------------------|------------------------|-------------------|--------|--------|--------|-----------------|--------|---------------------|--------|---------------|---------------|--------|--------|--------|
|                                 |                        | A Max.            | A Min. | B Max. | B Min. | C Max.          | C Min. | D <sup>a</sup> Min. | H Nom. | Corner Radius | E Max.        | E Min. | F Max. | F Min. |
| 1/2                             | 3/32                   | 0.0947            | 0.0937 | 0.4531 | 0.4481 | 0.106           | 0.099  | 0.5578              | 3/64   | 0.020         | 0.0932        | 0.0927 | 0.5468 | 0.5408 |
| 3/8                             | 1/8                    | 0.1260            | 0.1250 | 0.5625 | 0.5575 | 0.137           | 0.130  | 0.6985              | 1/16   | 1/32          | 0.1245        | 0.1240 | 0.6875 | 0.6815 |
| 1/4                             | 3/16                   | 0.1260            | 0.1250 | 0.6875 | 0.6825 | 0.137           | 0.130  | 0.8225              | 1/16   | 1/32          | 0.1245        | 0.1240 | 0.8125 | 0.8065 |
| 3/8                             | 1/8                    | 0.1260            | 0.1250 | 0.8125 | 0.8075 | 0.137           | 0.130  | 0.9475              | 1/16   | 1/32          | 0.1245        | 0.1240 | 0.9375 | 0.9315 |
| 1                               | 1/4                    | 0.2510            | 0.2500 | 0.8438 | 0.8388 | 0.262           | 0.255  | 1.1040              | 3/32   | 3/64          | 0.2495        | 0.2490 | 1.0940 | 1.0880 |
| 1 1/4                           | 3/16                   | 0.3135            | 0.3125 | 1.0630 | 1.0580 | 0.343           | 0.318  | 1.3850              | 1/8    | 1/16          | 0.3120        | 0.3115 | 1.3750 | 1.3690 |
| 1 1/2                           | 3/8                    | 0.3760            | 0.3750 | 1.2810 | 1.2760 | 0.410           | 0.385  | 1.6660              | 5/32   | 1/16          | 0.3745        | 0.3740 | 1.6560 | 1.6500 |
| 1 3/4                           | 7/16                   | 0.4385            | 0.4375 | 1.5000 | 1.4950 | 0.473           | 0.448  | 1.9480              | 3/16   | 1/16          | 0.4370        | 0.4365 | 1.9380 | 1.9320 |
| 2                               | 1/2                    | 0.5010            | 0.5000 | 1.6870 | 1.6820 | 0.535           | 0.510  | 2.1980              | 3/16   | 1/16          | 0.4995        | 0.4990 | 2.1880 | 2.1820 |
| 2 1/2                           | 5/8                    | 0.6260            | 0.6250 | 2.0940 | 2.0890 | 0.660           | 0.635  | 2.7330              | 7/32   | 1/16          | 0.6245        | 0.6240 | 2.7180 | 2.7120 |
| 3                               | 3/4                    | 0.7510            | 0.7500 | 2.5000 | 2.4950 | 0.785           | 0.760  | 3.2650              | 1/4    | 3/32          | 0.7495        | 0.7490 | 3.2500 | 3.2440 |
| 3 1/2                           | 7/8                    | 0.8760            | 0.8750 | 3.0000 | 2.9950 | 0.910           | 0.885  | 3.8900              | 5/8    | 3/32          | 0.8745        | 0.8740 | 3.8750 | 3.8690 |
| 4                               | 1                      | 1.0010            | 1.0000 | 3.3750 | 3.3700 | 1.035           | 1.010  | 4.3900              | 3/8    | 3/32          | 0.9995        | 0.9990 | 4.3750 | 4.3690 |
| 4 1/2                           | 1 1/8                  | 1.1260            | 1.1250 | 3.8130 | 3.8080 | 1.160           | 1.135  | 4.9530              | 7/16   | 1/8           | 1.1245        | 1.1240 | 4.9380 | 4.9320 |
| 5                               | 1 1/4                  | 1.2510            | 1.2500 | 4.2500 | 4.2450 | 1.285           | 1.260  | 5.5150              | 1/2    | 1/8           | 1.2495        | 1.2490 | 5.5000 | 5.4940 |

<sup>a</sup> D max. is 0.010 inch larger than D min.

All dimensions given in inches.



**American National Standard Woodruff Keyseat Cutters—Shank-Type Straight-Teeth and Arbor-Type Staggered-Teeth ANSI/ASME B94.19-1997**



Shank-type Cutters

| Cutter Number | Nom. Dia. of Cutter, D | Width of Face, W | Length Over-all, L | Cutter Number | Nom. Dia. of Cutter, D | Width of Face, W | Length Over-all, L | Cutter Number | Nom. Dia. of Cutter, D | Width of Face, W | Length Over-all, L |
|---------------|------------------------|------------------|--------------------|---------------|------------------------|------------------|--------------------|---------------|------------------------|------------------|--------------------|
| 202           | 1/4                    | 1/16             | 2 1/16             | 506           | 3/4                    | 5/32             | 2 3/32             | 809           | 1 1/8                  | 1/4              | 2 1/4              |
| 202 1/2       | 5/16                   | 1/16             | 2 1/16             | 606           | 3/4                    | 3/16             | 2 3/16             | 1009          | 1 1/8                  | 5/16             | 2 5/16             |
| 302 1/2       | 5/16                   | 3/32             | 2 3/32             | 806           | 3/4                    | 1/4              | 2 1/4              | 610           | 1 1/4                  | 3/16             | 2 3/16             |
| 203           | 3/8                    | 1/16             | 2 1/16             | 507           | 7/8                    | 5/32             | 2 3/32             | 710           | 1 1/4                  | 7/32             | 2 7/32             |
| 303           | 3/8                    | 3/32             | 2 3/32             | 607           | 7/8                    | 3/16             | 2 3/16             | 810           | 1 1/4                  | 1/4              | 2 1/4              |
| 403           | 3/8                    | 1/8              | 2 1/8              | 707           | 7/8                    | 7/32             | 2 7/32             | 1010          | 1 1/4                  | 5/16             | 2 5/16             |
| 204           | 1/2                    | 1/16             | 2 1/16             | 807           | 7/8                    | 1/4              | 2 1/4              | 1210          | 1 1/4                  | 3/8              | 2 3/8              |
| 304           | 1/2                    | 3/32             | 2 3/32             | 608           | 1                      | 3/16             | 2 3/16             | 811           | 1 3/8                  | 1/4              | 2 1/4              |
| 404           | 1/2                    | 1/8              | 2 1/8              | 708           | 1                      | 7/32             | 2 7/32             | 1011          | 1 3/8                  | 5/16             | 2 5/16             |
| 305           | 5/8                    | 3/32             | 2 3/32             | 808           | 1                      | 1/4              | 2 1/4              | 1211          | 1 3/8                  | 3/8              | 2 3/8              |
| 405           | 5/8                    | 1/8              | 2 1/8              | 1008          | 1                      | 5/16             | 2 5/16             | 812           | 1 1/2                  | 1/4              | 2 1/4              |
| 505           | 5/8                    | 5/32             | 2 5/32             | 1208          | 1                      | 3/8              | 2 3/8              | 1012          | 1 1/2                  | 5/16             | 2 5/16             |
| 605           | 5/8                    | 3/16             | 2 3/16             | 609           | 1 1/8                  | 3/16             | 2 3/16             | 1212          | 1 1/2                  | 3/8              | 2 3/8              |
| 406           | 3/4                    | 1/8              | 2 1/8              | 709           | 1 1/8                  | 7/32             | 2 7/32             | ...           | ...                    | ...              | ...                |

Arbor-type Cutters

| Cutter Number | Nom. Dia. of Cutter, D | Width of Face, W | Dia. of Hole, H | Cutter Number | Nom. Dia. of Cutter, D | Width of Face, W | Dia. of Hole, H | Cutter Number | Nom. Dia. of Cutter, D | Width of Face, W | Dia. of Hole, H |
|---------------|------------------------|------------------|-----------------|---------------|------------------------|------------------|-----------------|---------------|------------------------|------------------|-----------------|
| 617           | 2 1/8                  | 3/16             | 3/4             | 1022          | 2 3/4                  | 5/8              | 1               | 1628          | 3 1/2                  | 1/2              | 1               |
| 817           | 2 1/8                  | 1/4              | 3/4             | 1222          | 2 3/4                  | 3/8              | 1               | 1828          | 3 1/2                  | 5/16             | 1               |
| 1017          | 2 1/8                  | 5/16             | 3/4             | 1422          | 2 3/4                  | 7/16             | 1               | 2028          | 3 1/2                  | 5/8              | 1               |
| 1217          | 2 1/8                  | 3/8              | 3/4             | 1622          | 2 3/4                  | 1/2              | 1               | 2428          | 3 1/2                  | 3/4              | 1               |
| 822           | 2 3/4                  | 1/4              | 1               | 1228          | 3 1/2                  | 3/8              | 1               | ...           | ...                    | ...              | ...             |

All dimensions are given in inches. All cutters are high-speed steel.

Shank type cutters are standard with right-hand cut and straight teeth. All sizes have 1/2-inch diameter straight shank.

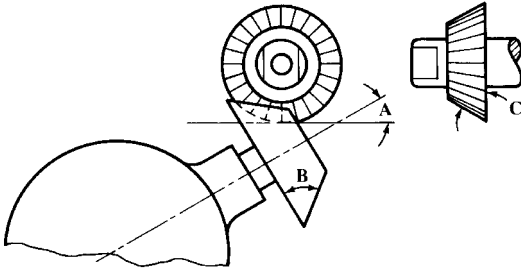
Arbor type cutters have staggered teeth.

For Woodruff key and key-slot dimensions, see pages 2369 through 2371.

Tolerances: Face with W for shank type cutters: 1/16 - to 5/32-inch face, +0.0000, -0.0005; 3/16 to 7/32, -0.0002, -0.0007; 1/4, -0.0003, -0.0008; 5/16, -0.0004, -0.0009; 3/8, -0.0005, -0.0010 inch. Face width W for arbor type cutters; 3/16 inch face, -0.0002, -0.0007; 1/4, -0.0003, -0.0008; 5/16, -0.0004, -0.0009; 3/8 and over, -0.0005, -0.0010 inch. Hole size H: +0.00075, -0.0000 inch. Diameter D for shank type cutters: 1/4 - through 3/4-inch diameter, +0.010, +0.015, 7/8 through 1 1/8, +0.012, +0.017; 1 1/4

through  $1\frac{1}{2}$ ,  $+0.015$ ,  $+0.020$  inch. These tolerances include an allowance for sharpening. For arbor type cutters diameter  $D$  is furnished  $\frac{1}{32}$  inch larger than listed and a tolerance of  $\pm 0.002$  inch applies to the oversize diameter.

**Setting Angles for Milling Straight Teeth of Uniform Land Width in End Mills, Angular Cutters, and Taper Reamers.**—The accompanying tables give setting angles for the dividing head when straight teeth, having a land of uniform width throughout their length, are to be milled using single-angle fluting cutters. These setting angles depend upon three factors: the number of teeth to be cut; the angle of the blank in which the teeth are to be cut; and the angle of the fluting cutter. Setting angles for various combinations of these three factors are given in the tables. For example, assume that 12 teeth are to be cut on the end of an end mill using a 60-degree cutter. By following the horizontal line from 12 teeth, read in the column under 60 degrees that the dividing head should be set to an angle of 70 degrees and 32 minutes.



The following formulas, which were used to compile these tables, may be used to calculate the setting-angles for combinations of number of teeth, blank angle, and cutter angle not covered by the tables. In these formulas,  $A$  = setting-angle for dividing head,  $B$  = angle of blank in which teeth are to be cut,  $C$  = angle of fluting cutter,  $N$  = number of teeth to be cut, and  $D$  and  $E$  are angles not shown on the accompanying diagram and which are used only to simplify calculations.

$$\tan D = \cos(360^\circ/N) \times \cot B \quad (1)$$

$$\sin E = \tan(360^\circ/N) \times \cot C \times \sin D \quad (2)$$

$$\text{Setting-angle } A = D - E \quad (3)$$

*Example:* Suppose 9 teeth are to be cut in a 35-degree blank using a 55-degree single-angle fluting cutter. Then,  $N = 9$ ,  $B = 35^\circ$ , and  $C = 55^\circ$ .

$$\tan D = \cos(360^\circ/9) \times \cot 35^\circ = 0.76604 \times 1.4281 = 1.0940; \text{ and } D = 47^\circ 34'$$

$$\sin E = \tan(360^\circ/9) \times \cot 55^\circ \times \sin 47^\circ 34' = 0.83910 \times 0.70021 \times 0.73806 \\ = 0.43365; \text{ and } E = 25^\circ 42'$$

$$\text{Setting angle } A = 47^\circ 34' - 25^\circ 42' = 21^\circ 52'$$

For end mills and side mills the angle of the blank  $B$  is 0 degrees and the following simplified formula may be used to find the setting angle  $A$

$$\cos A = \tan(360^\circ/N) \times \cot C \quad (4)$$

*Example:* If in the previous example the blank angle was 0 degrees,

$$\cos A = \tan(360^\circ/9) \times \cot 55^\circ = 0.83910 \times 0.70021 = 0.58755, \\ \text{and setting-angle } A = 54^\circ 1'$$

## MILLING CUTTERS

## Angles of Elevation for Milling Straight Teeth in 0-, 5-, 10-, 15-, 20-, 25-, 30-, and 35-degree Blanks Using Single-Angle Fluting Cutters

| No. of Teeth | Angle of Fluting Cutter |         |         |       |         |           |         |         |       |         |         |
|--------------|-------------------------|---------|---------|-------|---------|-----------|---------|---------|-------|---------|---------|
|              | 90°                     | 80°     | 70°     | 60°   | 50°     | 90°       | 80°     | 70°     | 60°   | 50°     |         |
| 6            | 0° Blank (End Mill)     |         |         |       |         | 5° Blank  |         |         |       |         |         |
|              | ...                     | 72° 13' | 50° 55' | ...   | ...     | 80° 4'    | 62° 34' | 41° 41' | ...   | ...     |         |
|              | 8                       | ...     | 79 51   | 68 39 | 54° 44' | 32° 57'   | 82 57   | 72 52   | 61 47 | 48° 0'  | 25° 40' |
|              | 10                      | ...     | 82 38   | 74 40 | 65 12   | 52 26     | 83 50   | 76 31   | 68 35 | 59 11   | 46 4    |
|              | 12                      | ...     | 84 9    | 77 52 | 70 32   | 61 2      | 84 14   | 78 25   | 72 10 | 64 52   | 55 5    |
|              | 14                      | ...     | 85 8    | 79 54 | 73 51   | 66 10     | 84 27   | 79 36   | 74 24 | 68 23   | 60 28   |
|              | 16                      | ...     | 85 49   | 81 20 | 76 10   | 69 40     | 84 35   | 80 25   | 75 57 | 70 49   | 64 7    |
|              | 18                      | ...     | 86 19   | 82 23 | 77 52   | 72 13     | 84 41   | 81 1    | 77 6  | 72 36   | 66 47   |
|              | 20                      | ...     | 86 43   | 83 13 | 79 11   | 74 11     | 84 45   | 81 29   | 77 59 | 73 59   | 68 50   |
|              | 22                      | ...     | 87 2    | 83 52 | 80 14   | 75 44     | 84 47   | 81 50   | 78 40 | 75 4    | 70 26   |
| 24           | ...                     | 87 18   | 84 24   | 81 6  | 77 0    | 84 49     | 82 7    | 79 15   | 75 57 | 71 44   |         |
| 6            | 10° Blank               |         |         |       |         | 15° Blank |         |         |       |         |         |
|              | 70° 34'                 | 53° 50' | 34° 5'  | ...   | ...     | 61° 49'   | 46° 12' | 28° 4'  | ...   | ...     |         |
|              | 8                       | 76 0    | 66 9    | 55 19 | 41° 56' | 20° 39'   | 69 15   | 59 46   | 49 21 | 36° 34' | 17° 34' |
|              | 10                      | 77 42   | 70 31   | 62 44 | 53 30   | 40 42     | 71 40   | 64 41   | 57 8  | 48 12   | 36 18   |
|              | 12                      | 78 30   | 72 46   | 66 37 | 59 26   | 49 50     | 72 48   | 67 13   | 61 13 | 54 14   | 45 13   |
|              | 14                      | 78 56   | 74 9    | 69 2  | 63 6    | 55 19     | 73 26   | 68 46   | 63 46 | 57 59   | 50 38   |
|              | 16                      | 79 12   | 75 5    | 70 41 | 65 37   | 59 1      | 73 50   | 69 49   | 65 30 | 60 33   | 54 20   |
|              | 18                      | 79 22   | 75 45   | 71 53 | 67 27   | 61 43     | 74 5    | 70 33   | 66 46 | 62 26   | 57 0    |
|              | 20                      | 79 30   | 76 16   | 72 44 | 68 52   | 63 47     | 74 16   | 71 6    | 67 44 | 63 52   | 59 3    |
|              | 22                      | 79 35   | 76 40   | 73 33 | 69 59   | 65 25     | 74 24   | 71 32   | 68 29 | 65 0    | 60 40   |
| 24           | 79 39                   | 76 59   | 74 9    | 70 54 | 66 44   | 74 30     | 71 53   | 69 6    | 65 56 | 61 59   |         |
| 6            | 20° Blank               |         |         |       |         | 25° Blank |         |         |       |         |         |
|              | 53° 57'                 | 39° 39' | 23° 18' | ...   | ...     | 47° 0'    | 34° 6'  | 19° 33' | ...   | ...     |         |
|              | 8                       | 62 46   | 53 45   | 43 53 | 31° 53' | 14° 31'   | 56 36   | 48 8    | 38 55 | 27° 47' | 11° 33' |
|              | 10                      | 65 47   | 59 4    | 51 50 | 43 18   | 32 1      | 60 2    | 53 40   | 46 47 | 38 43   | 27 47   |
|              | 12                      | 67 12   | 61 49   | 56 2  | 49 18   | 40 40     | 61 42   | 56 33   | 51 2  | 44 38   | 36 10   |
|              | 14                      | 68 0    | 63 29   | 58 39 | 53 4    | 46 0      | 62 38   | 58 19   | 53 41 | 48 20   | 41 22   |
|              | 16                      | 68 30   | 64 36   | 60 26 | 55 39   | 49 38     | 63 13   | 59 29   | 55 29 | 50 53   | 44 57   |
|              | 18                      | 68 50   | 65 24   | 61 44 | 57 32   | 52 17     | 63 37   | 60 19   | 56 48 | 52 46   | 47 34   |
|              | 20                      | 69 3    | 65 59   | 62 43 | 58 58   | 54 18     | 63 53   | 60 56   | 57 47 | 54 11   | 49 33   |
|              | 22                      | 69 14   | 66 28   | 63 30 | 60 7    | 55 55     | 64 5    | 61 25   | 58 34 | 55 19   | 51 9    |
| 24           | 69 21                   | 66 49   | 64 7    | 61 2  | 57 12   | 64 14     | 61 47   | 59 12   | 56 13 | 52 26   |         |
| 6            | 30° Blank               |         |         |       |         | 35° Blank |         |         |       |         |         |
|              | 40° 54'                 | 29° 22' | 16° 32' | ...   | ...     | 35° 32'   | 25° 19' | 14° 3'  | ...   | ...     |         |
|              | 8                       | 50 46   | 42 55   | 34 24 | 24° 12' | 10° 14'   | 45 17   | 38 5    | 30 18 | 21° 4'  | 8° 41'  |
|              | 10                      | 54 29   | 48 30   | 42 3  | 34 31   | 24 44     | 49 7    | 43 33   | 37 35 | 30 38   | 21 40   |
|              | 12                      | 56 18   | 51 26   | 46 14 | 40 12   | 32 32     | 51 3    | 46 30   | 41 39 | 36 2    | 28 55   |
|              | 14                      | 57 21   | 53 15   | 48 52 | 43 49   | 37 27     | 52 9    | 48 19   | 44 12 | 39 28   | 33 33   |
|              | 16                      | 58 0    | 54 27   | 50 39 | 46 19   | 40 52     | 52 50   | 49 20   | 45 56 | 41 51   | 36 45   |
|              | 18                      | 58 26   | 55 18   | 51 57 | 48 7    | 43 20     | 53 18   | 50 21   | 47 12 | 43 36   | 39 8    |
|              | 20                      | 58 44   | 55 55   | 52 56 | 49 30   | 45 15     | 53 38   | 50 59   | 48 10 | 44 57   | 40 57   |
|              | 22                      | 58 57   | 56 24   | 53 42 | 50 36   | 46 46     | 53 53   | 51 29   | 48 56 | 46 1    | 42 24   |
| 24           | 59 8                    | 56 48   | 54 20   | 51 30 | 48 0    | 54 4      | 51 53   | 49 32   | 46 52 | 43 35   |         |

**Angles of Elevation for Milling Straight Teeth in 40-, 45-, 50-, 55-, 60-, 65-, 70-, and 75-degree Blanks Using Single-Angle Fluting Cutters**

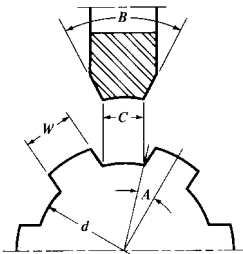
| No. of Teeth | Angle of Fluting Cutter |         |         |         |        |           |         |         |         |        |
|--------------|-------------------------|---------|---------|---------|--------|-----------|---------|---------|---------|--------|
|              | 90°                     | 80°     | 70°     | 60°     | 50°    | 90°       | 80°     | 70°     | 60°     | 50°    |
| 6            | 40° Blank               |         |         |         |        | 45° Blank |         |         |         |        |
|              | 30° 48'                 | 21° 48' | 11° 58' | ...     | ...    | 26° 34'   | 18° 43' | 10° 11' | ...     | ...    |
|              | 40 7                    | 33 36   | 26 33   | 18° 16' | 7° 23' | 35 16     | 29 25   | 23 8    | 15° 48' | 5° 58' |
|              | 43 57                   | 38 51   | 33 32   | 27 3    | 18 55  | 38 58     | 34 21   | 29 24   | 23 40   | 16 10  |
|              | 45 54                   | 41 43   | 37 14   | 32 3    | 25 33  | 40 54     | 37 5    | 33 0    | 28 18   | 22 13  |
|              | 47 3                    | 43 29   | 39 41   | 35 19   | 29 51  | 42 1      | 38 46   | 35 17   | 31 18   | 26 9   |
|              | 47 45                   | 44 39   | 41 21   | 37 33   | 32 50  | 42 44     | 39 54   | 36 52   | 33 24   | 28 57  |
|              | 48 14                   | 45 29   | 42 34   | 39 13   | 35 5   | 43 13     | 40 42   | 38 1    | 34 56   | 30 1   |
|              | 48 35                   | 46 7    | 43 30   | 40 30   | 36 47  | 43 34     | 41 18   | 38 53   | 36 8    | 32 37  |
|              | 48 50                   | 46 36   | 44 13   | 41 30   | 38 8   | 43 49     | 41 46   | 39 34   | 37 5    | 34 53  |
| 24           | 49 1                    | 46 58   | 44 48   | 42 19   | 39 15  | 44 0      | 42 7    | 40 7    | 37 50   | 35 55  |
| 6            | 50° Blank               |         |         |         |        | 55° Blank |         |         |         |        |
|              | 22° 45'                 | 15° 58' | 8° 38'  | ...     | ...    | 19° 17'   | 13° 30' | 7° 15'  | ...     | ...    |
|              | 30 41                   | 25 31   | 19 59   | 13° 33' | 5° 20' | 26 21     | 21 52   | 17 3    | 11° 30' | 4° 17' |
|              | 34 10                   | 30 2    | 25 39   | 20 32   | 14 9   | 29 32     | 25 55   | 22 3    | 17 36   | 11 52  |
|              | 36 0                    | 32 34   | 28 53   | 24 42   | 19 27  | 31 14     | 28 12   | 24 59   | 21 17   | 16 32  |
|              | 37 5                    | 34 9    | 31 1    | 27 26   | 22 58  | 32 15     | 29 39   | 26 53   | 23 43   | 19 40  |
|              | 37 47                   | 35 13   | 32 29   | 29 22   | 25 30  | 32 54     | 30 38   | 28 12   | 25 26   | 21 54  |
|              | 38 15                   | 35 58   | 33 33   | 30 46   | 27 21  | 33 21     | 31 20   | 29 10   | 26 43   | 23 35  |
|              | 38 35                   | 36 32   | 34 21   | 31 52   | 28 47  | 33 40     | 31 51   | 29 54   | 27 42   | 24 53  |
|              | 38 50                   | 36 58   | 34 59   | 32 44   | 29 57  | 33 54     | 32 15   | 30 29   | 28 28   | 25 55  |
| 24           | 39 1                    | 37 19   | 35 30   | 33 25   | 30 52  | 34 5      | 32 34   | 30 57   | 29 7    | 26 46  |
| 6            | 60° Blank               |         |         |         |        | 65° Blank |         |         |         |        |
|              | 16° 6'                  | 11° 12' | 6° 2'   | ...     | ...    | 13° 7'    | 9° 8'   | 4° 53'  | ...     | ...    |
|              | 22 13                   | 18 24   | 14 19   | 9° 37'  | 3° 44' | 18 15     | 15 6    | 11 42   | 7° 50'  | 3° 1'  |
|              | 25 2                    | 21 56   | 18 37   | 14 49   | 10 5   | 20 40     | 18 4    | 15 19   | 12 9    | 8 15   |
|              | 26 34                   | 23 57   | 21 10   | 17 59   | 14 13  | 21 59     | 19 48   | 17 28   | 14 49   | 11 32  |
|              | 27 29                   | 25 14   | 22 51   | 20 6    | 16 44  | 22 48     | 20 55   | 18 54   | 16 37   | 13 48  |
|              | 28 5                    | 26 7    | 24 1    | 21 37   | 18 40  | 23 18     | 21 39   | 19 53   | 17 53   | 15 24  |
|              | 28 29                   | 26 44   | 24 52   | 22 44   | 20 6   | 23 40     | 22 11   | 20 37   | 18 50   | 16 37  |
|              | 28 46                   | 27 11   | 25 30   | 23 35   | 21 14  | 23 55     | 22 35   | 21 10   | 19 33   | 17 34  |
|              | 29 0                    | 27 34   | 26 2    | 24 17   | 22 8   | 24 6      | 22 53   | 21 36   | 20 8    | 18 20  |
| 24           | 29 9                    | 27 50   | 26 26   | 24 50   | 22 52  | 24 15     | 23 8    | 21 57   | 20 36   | 18 57  |
| 6            | 70° Blank               |         |         |         |        | 75° Blank |         |         |         |        |
|              | 10° 18'                 | 7° 9'   | 3° 48'  | ...     | ...    | 7° 38'    | 5° 19'  | 2° 50'  | ...     | ...    |
|              | 14 26                   | 11 55   | 9 14    | 6° 9'   | 2° 21' | 10 44     | 8 51    | 6 51    | 4° 34'  | 1° 45' |
|              | 16 25                   | 14 21   | 12 8    | 9 37    | 6 30   | 12 14     | 10 40   | 9 1     | 7 8     | 4 49   |
|              | 17 30                   | 15 45   | 13 53   | 11 45   | 9 8    | 13 4      | 11 45   | 10 21   | 8 45    | 6 47   |
|              | 18 9                    | 16 38   | 15 1    | 13 11   | 10 55  | 13 34     | 12 26   | 11 13   | 9 50    | 8 7    |
|              | 18 35                   | 17 15   | 15 50   | 14 13   | 12 13  | 13 54     | 12 54   | 11 50   | 10 37   | 9 7    |
|              | 18 53                   | 17 42   | 16 26   | 14 59   | 13 13  | 14 8      | 13 14   | 12 17   | 11 12   | 9 51   |
|              | 19 6                    | 18 1    | 16 53   | 15 35   | 13 59  | 14 18     | 13 29   | 12 38   | 11 39   | 10 27  |
|              | 19 15                   | 18 16   | 17 15   | 16 3    | 14 35  | 14 25     | 13 41   | 12 53   | 12 0    | 10 54  |
| 24           | 19 22                   | 18 29   | 17 33   | 16 25   | 15 5   | 14 31     | 13 50   | 13 7    | 12 18   | 11 18  |

CUTTER GRINDING

Angles of Elevation for Milling Straight Teeth in 80- and 85-degree Blanks Using Single-Angle Fluting Cutters

| No. of Teeth | Angle of Fluting Cutter |        |        |       |       |           |        |        |        |        |
|--------------|-------------------------|--------|--------|-------|-------|-----------|--------|--------|--------|--------|
|              | 90°                     | 80°    | 70°    | 60°   | 50°   | 90°       | 80°    | 70°    | 60°    | 50°    |
|              | 80° Blank               |        |        |       |       | 85° Blank |        |        |        |        |
| 6            | 5° 2'                   | 3° 30' | 1° 52' | ...   | ...   | 2° 30'    | 1° 44' | 0° 55' | ...    | ...    |
| 8            | 7 6                     | 5 51   | 4 31   | 3° 2' | 1° 8' | 3 32      | 2 55   | 2 15   | 1° 29' | 0° 34' |
| 10           | 8 7                     | 7 5    | 5 59   | 4 44  | 3 11  | 4 3       | 3 32   | 2 59   | 2 21   | 1 35   |
| 12           | 8 41                    | 7 48   | 6 52   | 5 48  | 4 29  | 4 20      | 3 53   | 3 25   | 2 53   | 2 15   |
| 14           | 9 2                     | 8 16   | 7 28   | 6 32  | 5 24  | 4 30      | 4 7    | 3 43   | 3 15   | 2 42   |
| 16           | 9 15                    | 8 35   | 7 51   | 7 3   | 6 3   | 4 37      | 4 17   | 3 56   | 3 30   | 3 1    |
| 18           | 9 24                    | 8 48   | 8 10   | 7 26  | 6 33  | 4 42      | 4 24   | 4 5    | 3 43   | 3 16   |
| 20           | 9 31                    | 8 58   | 8 24   | 7 44  | 6 56  | 4 46      | 4 29   | 4 12   | 3 52   | 3 28   |
| 22           | 9 36                    | 9 6    | 8 35   | 7 59  | 7 15  | 4 48      | 4 33   | 4 18   | 3 59   | 3 37   |
| 24           | 9 40                    | 9 13   | 8 43   | 8 11  | 7 30  | 4 50      | 4 36   | 4 22   | 4 5    | 3 45   |

**Spline-Shaft Milling Cutter.**—The most efficient method of forming splines on shafts is by hobbing, but special milling cutters may also be used. Since the cutter forms the space between adjacent splines, it must be made to suit the number of splines and the root diameter of the shaft. The cutter angle *B* equals 360 degrees divided by the number of splines. The following formulas are for determining the chordal width *C* at the root of the splines or the chordal width across the concave edge of the cutter. In these formulas, *A* = angle between center line of spline and a radial line passing through the intersection of the root circle and one side of the spline; *W* = width of spline; *d* = root diameter of splined shaft; *C* = chordal width at root circle between adjacent splines; *N* = number of splines.



$$\sin A = \frac{W}{d} \quad C = d \times \sin\left(\frac{180}{N} - A\right)$$

Splines of involute form are often used in preference to the straight-sided type. Dimensions of the American Standard involute splines and hobs are given in the section on splines.

**Cutter Grinding**

**Wheels for Sharpening Milling Cutters.**—Milling cutters may be sharpened either by using the periphery of a disk wheel or the face of a cup wheel. The latter grinds the lands of the teeth flat, whereas the periphery of a disk wheel leaves the teeth slightly concave back of the cutting edges. The concavity produced by disk wheels reduces the effective clearance angle on the teeth, the effect being more pronounced for wheels of small diameter than for wheels of large diameter. For this reason, large diameter wheels are preferred when sharpening milling cutters with disk type wheels. Irrespective of what type of wheel is used to sharpen a milling cutter, any burrs resulting from grinding should be carefully

removed by a hand stoning operation. Stoning also helps to reduce the roughness of grinding marks and improves the quality of the finish produced on the surface being machined. Unless done very carefully, hand stoning may dull the cutting edge. Stoning may be avoided and a sharper cutting edge produced if the wheel rotates toward the cutting edge, which requires that the operator maintain contact between the tool and the rest while the wheel rotation is trying to move the tool away from the rest. Though slightly more difficult, this method will eliminate the burr.

### Specifications of Grinding Wheels for Sharpening Milling Cutters

| Cutter Material                                     | Operation             | Grinding Wheel      |                   |              |                        |
|---|-----------------------|---------------------|-------------------|--------------|------------------------|
|   |                       | Abrasive Material   | Grain Size        | Grade        | Bond                   |
| Carbon Tool Steel                                   | Roughing<br>Finishing | Aluminum Oxide      | 46–60<br>100      | K<br>H       | Vitrified<br>Vitrified |
| High-speed Steel:                                   |                       |                     |                   |              |                        |
| 18-4-1 {  | Roughing              | Aluminum Oxide      | 60                | K,H          | Vitrified              |
|   | Finishing             |                     | 100               | H            | Vitrified              |
| 18-4-2 {  | Roughing              |                     | 80                | F,G,H        | Vitrified              |
|   | Finishing             |                     | 100               | H            | Vitrified              |
| Cast Non-Ferrous Tool Material                      | Roughing<br>Finishing | Aluminum Oxide      | 46<br>100–120     | H,K,L,N<br>H | Vitrified<br>Vitrified |
| Sintered Carbide                                    | Roughing              | Silicon Carbide     | 60                | G            | Vitrified              |
|   | after<br>Brazing      | Diamond             | 100               | a            | Resinoid               |
|   | Roughing<br>Finishing | Diamond             | Up to 500         | a            | Resinoid               |
| Carbon Tool Steel and High-Speed Steel <sup>b</sup> | Roughing<br>Finishing | Cubic Boron Nitride | 80–100<br>100–120 | R,P<br>S,T   | Resinoid<br>Resinoid   |

<sup>a</sup> Not indicated in diamond wheel markings.

<sup>b</sup> For hardnesses above Rockwell C 56.

**Wheel Speeds and Feeds for Sharpening Milling Cutters.**—Relatively low cutting speeds should be used when sharpening milling cutters to avoid tempering and heat checking. Dry grinding is recommended in all cases except when diamond wheels are employed. The surface speed of grinding wheels should be in the range of 4500 to 6500 feet per minute for grinding milling cutters of high-speed steel or cast non-ferrous tool material. For sintered carbide cutters, 5000 to 5500 feet per minute should be used.

The maximum stock removed per pass of the grinding wheel should not exceed about 0.0004 inch for sintered carbide cutters; 0.003 inch for large high-speed steel and cast non-ferrous tool material cutters; and 0.0015 inch for narrow saws and slotting cutters of high-speed steel or cast non-ferrous tool material. The stock removed per pass of the wheel may be increased for backing-off operations such as the grinding of secondary clearance behind the teeth since there is usually a sufficient body of metal to carry off the heat.

**Clearance Angles for Milling Cutter Teeth.**—The clearance angle provided on the cutting edges of milling cutters has an important bearing on cutter performance, cutting efficiency, and cutter life between sharpenings. It is desirable in all cases to use a clearance angle as small as possible so as to leave more metal back of the cutting edges for better heat dissipation and to provide maximum support. Excessive clearance angles not only weaken the cutting edges, but also increase the likelihood of “chatter” which will result in poor finish on the machined surface and reduce the life of the cutter. According to The Cincinnati Milling Machine Co., milling cutters used for general purpose work and having diameters from  $\frac{1}{8}$  to 3 inches should have clearance angles from 13 to 5 degrees, respectively, decreasing proportionately as the diameter increases. General purpose cutters over 3

inches in diameter should be provided with a clearance angle of 4 to 5 degrees. The land width is usually  $\frac{1}{64}$ ,  $\frac{1}{32}$ , and  $\frac{1}{16}$  inch, respectively, for small, medium, and large cutters.

The primary clearance or relief angle for best results varies according to the material being milled about as follows: low carbon, high carbon, and alloy steels, 3 to 5 degrees; cast iron and medium and hard bronze, 4 to 7 degrees; brass, soft bronze, aluminum, magnesium, plastics, etc., 10 to 12 degrees. When milling cutters are resharpened, it is customary to grind a secondary clearance angle of 3 to 5 degrees behind the primary clearance angle to reduce the land width to its original value and thus avoid interference with the surface to be milled. A general formula for plain milling cutters, face mills, and form relieved cutters which gives the clearance angle  $C$ , in degrees, necessitated by the feed per revolution  $F$ , in inches, the width of land  $L$ , in inches, the depth of cut  $d$ , in inches, the cutter diameter  $D$ , in inches, and the Brinell hardness number  $B$  of the work being cut is:

$$C = \frac{45860}{DB} \left( 1.5L + \frac{F}{\pi D} \sqrt{d(D-d)} \right)$$

**Rake Angles for Milling Cutters.**—In peripheral milling cutters, the rake angle is generally defined as the angle in degrees that the tooth face deviates from a radial line to the cutting edge. In face milling cutters, the teeth are inclined with respect to both the radial and axial lines. These angles are called *radial* and *axial* rake, respectively. The radial and axial rake angles may be positive, zero, or negative.

Positive rake angles should be used whenever possible for all types of high-speed steel milling cutters. For sintered carbide tipped cutters, zero and negative rake angles are frequently employed to provide more material back of the cutting edge to resist shock loads.

**Rake Angles for High-speed Steel Cutters:** Positive rake angles of 10 to 15 degrees are satisfactory for milling steels of various compositions with plain milling cutters. For softer materials such as magnesium and aluminum alloys, the rake angle may be 25 degrees or more. Metal slitting saws for cutting alloy steel usually have rake angles from 5 to 10 degrees, whereas zero and sometimes negative rake angles are used for saws to cut copper and other soft non-ferrous metals to reduce the tendency to "hog in." Form relieved cutters usually have rake angles of 0, 5, or 10 degrees. Commercial face milling cutters usually have 10 degrees positive radial and axial rake angles for general use in milling cast iron, forged and alloy steel, brass, and bronze; for milling castings and forgings of magnesium and free-cutting aluminum and their alloys, the rake angles may be increased to 25 degrees positive or more, depending on the operating conditions; a smaller rake angle is used for abrasive or difficult to machine aluminum alloys.

**Cast Non-ferrous Tool Material Milling Cutters:** Positive rake angles are generally provided on milling cutters using cast non-ferrous tool materials although negative rake angles may be used advantageously for some operations such as those where shock loads are encountered or where it is necessary to eliminate vibration when milling thin sections.

**Sintered Carbide Milling Cutters:** Peripheral milling cutters such as slab mills, slotting cutters, saws, etc., tipped with sintered carbide, generally have negative radial rake angles of 5 degrees for soft low carbon steel and 10 degrees or more for alloy steels. Positive axial rake angles of 5 and 10 degrees, respectively, may be provided, and for slotting saws and cutters, 0 degree axial rake may be used. On soft materials such as free-cutting aluminum alloys, positive rake angles of 10 to 20 degrees are used. For milling abrasive or difficult to machine aluminum alloys, small positive or even negative rake angles are used.

**Eccentric Type Radial Relief.**—When the radial relief angles on peripheral teeth of milling cutters are ground with a disc type grinding wheel in the conventional manner the ground surfaces on the lands are slightly concave, conforming approximately to the radius of the wheel. A flat land is produced when the radial relief angle is ground with a cup wheel. Another entirely different method of grinding the radial angle is by the eccentric method, which produces a slightly convex surface on the land. If the radial relief angle at

the cutting edge is equal for all of the three types of land mentioned, it will be found that the land with the eccentric relief will drop away from the cutting edge a somewhat greater distance for a given distance around the land than will the others. This is evident from a study of Table 1 entitled, *Indicator Drops for Checking the Radial Relief Angle on Peripheral Teeth*. This feature is an advantage of the eccentric type relief which also produces an excellent finish.

**Table 1. Indicator Drops for Checking the Radial Relief Angle on Peripheral Teeth**

| Cutter Diameter, Inch | Rec. Range of Radial Relief Angles, Degrees | Checking Distance, Inch | Indicator Drops, Inches     |       |                      |       | Rec. Max. Primary Land Width, Inch |
|-----------------------|---|-------------------------|-----------------------------|-------|----------------------|-------|------------------------------------|
|                       |   |                         | For Flat and Concave Relief |       | For Eccentric Relief |       |                                    |
|                       |   |                         | Min.                        | Max.  | Min.                 | Max.  |                                    |
| $\frac{1}{16}$        | 20-25                                       | .005                    | .0014                       | .0019 | .0020                | .0026 | .007                               |
| $\frac{3}{32}$        | 16-20                                       | .005                    | .0012                       | .0015 | .0015                | .0019 | .007                               |
| $\frac{1}{8}$         | 15-19                                       | .010                    | .0018                       | .0026 | .0028                | .0037 | .015                               |
| $\frac{5}{32}$        | 13-17                                       | .010                    | .0017                       | .0024 | .0024                | .0032 | .015                               |
| $\frac{3}{16}$        | 12-16                                       | .010                    | .0016                       | .0023 | .0022                | .0030 | .015                               |
| $\frac{7}{32}$        | 11-15                                       | .010                    | .0015                       | .0022 | .0020                | .0028 | .015                               |
| $\frac{1}{4}$         | 10-14                                       | .015                    | .0017                       | .0028 | .0027                | .0039 | .020                               |
| $\frac{9}{32}$        | 10-14                                       | .015                    | .0018                       | .0029 | .0027                | .0039 | .020                               |
| $\frac{5}{16}$        | 10-13                                       | .015                    | .0019                       | .0027 | .0027                | .0035 | .020                               |
| $\frac{11}{32}$       | 10-13                                       | .015                    | .0020                       | .0028 | .0027                | .0035 | .020                               |
| $\frac{3}{8}$         | 10-13                                       | .015                    | .0020                       | .0029 | .0027                | .0035 | .020                               |
| $\frac{13}{32}$       | 9-12  | .020                    | .0022                       | .0032 | .0032                | .0044 | .025                               |
| $\frac{7}{16}$        | 9-12  | .020                    | .0022                       | .0033 | .0032                | .0043 | .025                               |
| $\frac{15}{32}$       | 9-12  | .020                    | .0023                       | .0034 | .0032                | .0043 | .025                               |
| $\frac{1}{2}$         | 9-12  | .020                    | .0024                       | .0034 | .0032                | .0043 | .025                               |
| $\frac{9}{16}$        | 9-12  | .020                    | .0024                       | .0035 | .0032                | .0043 | .025                               |
| $\frac{5}{8}$         | 8-11  | .020                    | .0022                       | .0032 | .0028                | .0039 | .025                               |
| $\frac{11}{16}$       | 8-11  | .030                    | .0029                       | .0045 | .0043                | .0059 | .035                               |
| $\frac{3}{4}$         | 8-11  | .030                    | .0030                       | .0046 | .0043                | .0059 | .035                               |
| $\frac{13}{16}$       | 8-11  | .030                    | .0031                       | .0047 | .0043                | .0059 | .035                               |
| $\frac{7}{8}$         | 8-11  | .030                    | .0032                       | .0048 | .0043                | .0059 | .035                               |
| $\frac{15}{16}$       | 7-10  | .030                    | .0027                       | .0043 | .0037                | .0054 | .035                               |
| 1                     | 7-10  | .030                    | .0028                       | .0044 | .0037                | .0054 | .035                               |
| $1\frac{1}{8}$        | 7-10  | .030                    | .0029                       | .0045 | .0037                | .0053 | .035                               |
| $1\frac{1}{4}$        | 6-9   | .030                    | .0024                       | .0040 | .0032                | .0048 | .035                               |
| $1\frac{3}{8}$        | 6-9   | .030                    | .0025                       | .0041 | .0032                | .0048 | .035                               |
| $1\frac{1}{2}$        | 6-9   | .030                    | .0026                       | .0041 | .0032                | .0048 | .035                               |
| $1\frac{5}{8}$        | 6-9   | .030                    | .0026                       | .0042 | .0032                | .0048 | .035                               |
| $1\frac{3}{4}$        | 6-9   | .030                    | .0026                       | .0042 | .0032                | .0048 | .035                               |
| $1\frac{7}{8}$        | 6-9   | .030                    | .0027                       | .0043 | .0032                | .0048 | .035                               |
| 2                     | 6-9   | .030                    | .0027                       | .0043 | .0032                | .0048 | .035                               |
| $2\frac{1}{4}$        | 5-8   | .030                    | .0022                       | .0038 | .0026                | .0042 | .040                               |
| $2\frac{1}{2}$        | 5-8   | .030                    | .0023                       | .0039 | .0026                | .0042 | .040                               |
| $2\frac{3}{4}$        | 5-8   | .030                    | .0023                       | .0039 | .0026                | .0042 | .040                               |
| 3                     | 5-8   | .030                    | .0023                       | .0039 | .0026                | .0042 | .040                               |
| $3\frac{1}{2}$        | 5-8   | .030                    | .0024                       | .0040 | .0026                | .0042 | .047                               |
| 4                     | 5-8   | .030                    | .0024                       | .0040 | .0026                | .0042 | .047                               |
| 5                     | 4-7   | .030                    | .0019                       | .0035 | .0021                | .0037 | .047                               |
| 6                     | 4-7   | .030                    | .0019                       | .0035 | .0021                | .0037 | .047                               |
| 7                     | 4-7   | .030                    | .0020                       | .0036 | .0021                | .0037 | .060                               |
| 8                     | 4-7   | .030                    | .0020                       | .0036 | .0021                | .0037 | .060                               |
| 10                    | 4-7   | .030                    | .0020                       | .0036 | .0021                | .0037 | .060                               |
| 12                    | 4-7   | .030                    | .0020                       | .0036 | .0021                | .0037 | .060                               |



The setup for grinding an eccentric relief is shown in Fig. 1. In this setup the point of contact between the cutter and the tooth rest must be in the same plane as the centers, or axes, of the grinding wheel and the cutter. A wide face is used on the grinding wheel, which is trued and dressed at an angle with respect to the axis of the cutter. An alternate method is to tilt the wheel at this angle. Then as the cutter is traversed and rotated past the grinding wheel while in contact with the tooth rest, an eccentric relief will be generated by the angular face of the wheel. This type of relief can only be ground on the peripheral teeth on milling cutters having helical flutes because the combination of the angular wheel face and the twisting motion of the cutter is required to generate the eccentric relief. Therefore, an eccentric relief cannot be ground on the peripheral teeth of straight fluted cutters.

Table 2 is a table of wheel angles for grinding an eccentric relief for different combinations of relief angles and helix angles. When angles are required that cannot be found in this table, the wheel angle,  $W$ , can be calculated by using the following formula, in which  $R$  is the radial relief angle and  $H$  is the helix angle of the flutes on the cutter.

$$\tan W = \tan R \times \tan H$$

**Table 2. Grinding Wheel Angles for Grinding Eccentric Type Radial Relief Angle**

| Radial Relief Angle, $R$ , Degrees | Helix Angle of Cutter Flutes, $H$ , Degrees |       |       |        |        |        |        |        |
|------------------------------------|---|-------|-------|--------|--------|--------|--------|--------|
|                                    | 12  | 18    | 20    | 30     | 40     | 45     | 50     | 52     |
|                                    | Wheel Angle, $W$ , Degrees                  |       |       |        |        |        |        |        |
| 1                                  | 0°13'                                       | 0°19' | 0°22' | 0°35'  | 0°50'  | 1°00'  | 1°12'  | 1°17'  |
| 2                                  | 0°26'                                       | 0°39' | 0°44' | 1°09'  | 1°41'  | 2°00'  | 2°23'  | 2°34'  |
| 3                                  | 0°38'                                       | 0°59' | 1°06' | 1°44'  | 2°31'  | 3°00'  | 3°34'  | 3°50'  |
| 4                                  | 0°51'                                       | 1°18' | 1°27' | 2°19'  | 3°21'  | 4°00'  | 4°46'  | 5°07'  |
| 5                                  | 1°04'                                       | 1°38' | 1°49' | 2°53'  | 4°12'  | 5°00'  | 5°57'  | 6°23'  |
| 6                                  | 1°17'                                       | 1°57' | 2°11' | 3°28'  | 5°02'  | 6°00'  | 7°08'  | 7°40'  |
| 7                                  | 1°30'                                       | 2°17' | 2°34' | 4°03'  | 5°53'  | 7°00'  | 8°19'  | 8°56'  |
| 8                                  | 1°43'                                       | 2°37' | 2°56' | 4°38'  | 6°44'  | 8°00'  | 9°30'  | 10°12' |
| 9                                  | 1°56'                                       | 2°57' | 3°18' | 5°13'  | 7°34'  | 9°00'  | 10°41' | 11°28' |
| 10                                 | 2°09'                                       | 3°17' | 3°40' | 5°49'  | 8°25'  | 10°00' | 11°52' | 12°43' |
| 11                                 | 2°22'                                       | 3°37' | 4°03' | 6°24'  | 9°16'  | 11°00' | 13°03' | 13°58' |
| 12                                 | 2°35'                                       | 3°57' | 4°25' | 7°00'  | 10°07' | 12°00' | 14°13' | 15°13' |
| 13                                 | 2°49'                                       | 4°17' | 4°48' | 7°36'  | 10°58' | 13°00' | 15°23' | 16°28' |
| 14                                 | 3°02'                                       | 4°38' | 5°11' | 8°11'  | 11°49' | 14°00' | 16°33' | 17°42' |
| 15                                 | 3°16'                                       | 4°59' | 5°34' | 8°48'  | 12°40' | 15°00' | 17°43' | 18°56' |
| 16                                 | 3°29'                                       | 5°19' | 5°57' | 9°24'  | 13°32' | 16°00' | 18°52' | 20°09' |
| 17                                 | 3°43'                                       | 5°40' | 6°21' | 10°01' | 14°23' | 17°00' | 20°01' | 21°22' |
| 18                                 | 3°57'                                       | 6°02' | 6°45' | 10°37' | 15°15' | 18°00' | 21°10' | 22°35' |
| 19                                 | 4°11'                                       | 6°23' | 7°09' | 11°15' | 16°07' | 19°00' | 22°19' | 23°47' |
| 20                                 | 4°25'                                       | 6°45' | 7°33' | 11°52' | 16°59' | 20°00' | 23°27' | 24°59' |
| 21                                 | 4°40'                                       | 7°07' | 7°57' | 12°30' | 17°51' | 21°00' | 24°35' | 26°10' |
| 22                                 | 4°55'                                       | 7°29' | 8°22' | 13°08' | 18°44' | 22°00' | 25°43' | 27°21' |
| 23                                 | 5°09'                                       | 7°51' | 8°47' | 13°46' | 19°36' | 23°00' | 26°50' | 28°31' |
| 24                                 | 5°24'                                       | 8°14' | 9°12' | 14°25' | 20°29' | 24°00' | 27°57' | 29°41' |
| 25                                 | 5°40'                                       | 8°37' | 9°38' | 15°04' | 21°22' | 25°00' | 29°04' | 30°50' |

**Indicator Drop Method of Checking Relief and Rake Angles.**—The most convenient and inexpensive method of checking the relief and rake angles on milling cutters is by the indicator drop method. Three tables, [Tables 1, 3 and 4](#), of indicator drops are provided in this section, for checking radial relief angles on the peripheral teeth, relief angles on side and end teeth, and rake angles on the tooth faces.

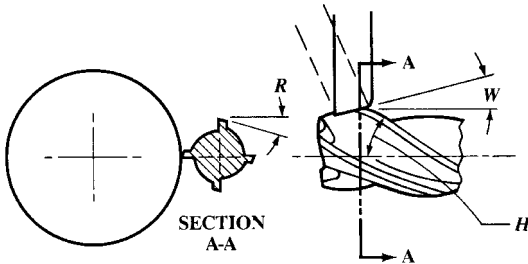


Fig. 1. Setup for Grinding Eccentric Type Radial Relief Angle

**Table 3. Indicator Drops for Checking Relief Angles on Side Teeth and End Teeth**

| Checking Distance, Inch | Given Relief Angle   |        |        |        |       |       |       |       |       |
|-------------------------|----------------------|--------|--------|--------|-------|-------|-------|-------|-------|
|                         | 1°                   | 2°     | 3°     | 4°     | 5°    | 6°    | 7°    | 8°    | 9°    |
|                         | Indicator Drop, inch |        |        |        |       |       |       |       |       |
| .005                    | .00009               | .00017 | .00026 | .00035 | .0004 | .0005 | .0006 | .0007 | .0008 |
| .010                    | .00017               | .00035 | .00052 | .0007  | .0009 | .0011 | .0012 | .0014 | .0016 |
| .015                    | .00026               | .0005  | .00079 | .0010  | .0013 | .0016 | .0018 | .0021 | .0024 |
| .031                    | .00054               | .0011  | .0016  | .0022  | .0027 | .0033 | .0038 | .0044 | .0049 |
| .047                    | .00082               | .0016  | .0025  | .0033  | .0041 | .0049 | .0058 | .0066 | .0074 |
| .062                    | .00108               | .0022  | .0032  | .0043  | .0054 | .0065 | .0076 | .0087 | .0098 |

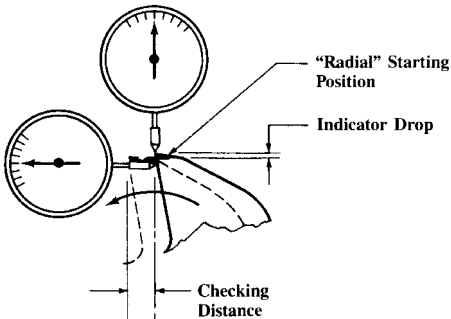
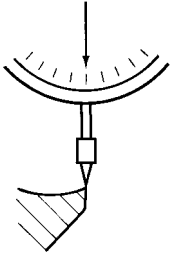


Fig. 2. Setup for Checking the Radial Relief Angle by Indicator Drop Method

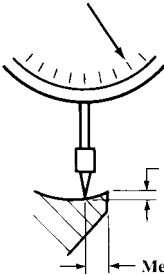
The setup for checking the radial relief angle is illustrated in [Fig. 2](#). Two dial test indicators are required, one of which should have a sharp pointed contact point. This indicator is positioned so that the axis of its spindle is vertical, passing through the axis of the cutter. The cutter may be held by its shank in the spindle of a tool and cutter grinder workhead, or

between centers while mounted on a mandrel. The cutter is rotated to the position where the vertical indicator contacts a cutting edge. The second indicator is positioned with its spindle axis horizontal and with the contact point touching the tool face just below the cutting edge. With both indicators adjusted to read zero, the cutter is rotated a distance equal to the checking distance, as determined by the reading on the second indicator. Then the indicator drop is read on the vertical indicator and checked against the values in the tables. The indicator drops for radial relief angles ground by a disc type grinding wheel and those ground with a cup wheel are so nearly equal that the values are listed together; values for the eccentric type relief are listed separately, since they are larger. A similar procedure is used to check the relief angles on the side and end teeth of milling cutters; however, only one indicator is used. Also, instead of rotating the cutter, the indicator or the cutter must be moved a distance equal to the checking distance in a straight line.

**Table 4. Indicator Drops for Checking Rake Angles on Milling Cutter Face**



Set indicator to read zero on horizontal plane passing through cutter axis.  
Zero cutting edge against indicator.

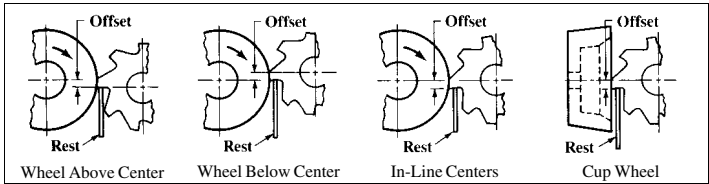


Move cutter or indicator measuring distance.

| Rate Angle, Deg. | Measuring Distance, inch |       |       |       | Rate Angle, Deg. | Measuring Distance, inch |       |       |       |
|------------------|--------------------------|-------|-------|-------|------------------|--------------------------|-------|-------|-------|
|                  | .031                     | .062  | .094  | .125  |                  | .031                     | .062  | .094  | .125  |
|                  | Indicator Drop, inch     |       |       |       |                  | Indicator Drop, inch     |       |       |       |
| 1                | .0005                    | .0011 | .0016 | .0022 | 11               | .0060                    | .0121 | .0183 | .0243 |
| 2                | .0011                    | .0022 | .0033 | .0044 | 12               | .0066                    | .0132 | .0200 | .0266 |
| 3                | .0016                    | .0032 | .0049 | .0066 | 13               | .0072                    | .0143 | .0217 | .0289 |
| 4                | .0022                    | .0043 | .0066 | .0087 | 14               | .0077                    | .0155 | .0234 | .0312 |
| 5                | .0027                    | .0054 | .0082 | .0109 | 15               | .0083                    | .0166 | .0252 | .0335 |
| 6                | .0033                    | .0065 | .0099 | .0131 | 16               | .0089                    | .0178 | .0270 | .0358 |
| 7                | .0038                    | .0076 | .0115 | .0153 | 17               | .0095                    | .0190 | .0287 | .0382 |
| 8                | .0044                    | .0087 | .0132 | .0176 | 18               | .0101                    | .0201 | .0305 | .0406 |
| 9                | .0049                    | .0098 | .0149 | .0198 | 19               | .0107                    | .0213 | .0324 | .0430 |
| 10               | .0055                    | .0109 | .0166 | .0220 | 20               | .0113                    | .0226 | .0342 | .0455 |

**Relieving Attachments.**—A relieving attachment is a device applied to lathes (especially those used in tool-rooms) for imparting a reciprocating motion to the tool-slide and tool, in order to provide relief or clearance for the cutting edges of milling cutters, taps, hobs, etc. For example, in making a milling cutter of the formed type, such as is used for cutting gears, it is essential to provide clearance for the teeth and so form them that they may be ground repeatedly without changing the contour or shape of the cutting edge. This may be accomplished by using a relieving attachment. The tool for “backing off” or giving clearance to the teeth corresponds to the shape required, and it is given a certain amount of reciprocating movement, so that it forms a surface back of each cutting edge, which is of uniform cross-section on a radial plane but eccentric to the axis of the cutter sufficiently to provide the necessary clearance for the cutting edges.

## Various Set-ups Used in Grinding the Clearance Angle on Milling Cutter Teeth



## Distance to Set Center of Wheel Above the Cutter Center (Disk Wheel)

| Dia. of Wheel, Inches | Desired Clearance Angle, Degrees                            |      |      |      |      |      |      |      |      |      |      |       |
|-----------------------|---|------|------|------|------|------|------|------|------|------|------|-------|
|                       | 1   | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12    |
|                       | Distance to Offset Wheel Center Above Cutter Center, Inches |      |      |      |      |      |      |      |      |      |      |       |
| 3                     | .026  | .052 | .079 | .105 | .131 | .157 | .183 | .209 | .235 | .260 | .286 | .312  |
| 4                     | .035  | .070 | .105 | .140 | .174 | .209 | .244 | .278 | .313 | .347 | .382 | .416  |
| 5                     | .044  | .087 | .131 | .174 | .218 | .261 | .305 | .348 | .391 | .434 | .477 | .520  |
| 6                     | .052  | .105 | .157 | .209 | .261 | .314 | .366 | .417 | .469 | .521 | .572 | .624  |
| 7                     | .061  | .122 | .183 | .244 | .305 | .366 | .427 | .487 | .547 | .608 | .668 | .728  |
| 8                     | .070  | .140 | .209 | .279 | .349 | .418 | .488 | .557 | .626 | .695 | .763 | .832  |
| 9                     | .079  | .157 | .236 | .314 | .392 | .470 | .548 | .626 | .704 | .781 | .859 | .936  |
| 10                    | .087  | .175 | .262 | .349 | .436 | .523 | .609 | .696 | .782 | .868 | .954 | 1.040 |

<sup>a</sup> Calculated from the formula: Offset = Wheel Diameter  $\times \frac{1}{2} \times$  Sine of Clearance Angle.

## Distance to Set Center of Wheel Below the Cutter Center (Disk Wheel)

| Dia. of Cutter, Inches | Desired Clearance Angle, Degrees                            |      |      |      |      |      |      |      |      |      |      |       |
|------------------------|---|------|------|------|------|------|------|------|------|------|------|-------|
|                        | 1   | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12    |
|                        | Distance to Offset Wheel Center Below Cutter Center, Inches |      |      |      |      |      |      |      |      |      |      |       |
| 2                      | .017  | .035 | .052 | .070 | .087 | .105 | .122 | .139 | .156 | .174 | .191 | .208  |
| 3                      | .026  | .052 | .079 | .105 | .131 | .157 | .183 | .209 | .235 | .260 | .286 | .312  |
| 4                      | .035  | .070 | .105 | .140 | .174 | .209 | .244 | .278 | .313 | .347 | .382 | .416  |
| 5                      | .044  | .087 | .131 | .174 | .218 | .261 | .305 | .348 | .391 | .434 | .477 | .520  |
| 6                      | .052  | .105 | .157 | .209 | .261 | .314 | .366 | .417 | .469 | .521 | .572 | .624  |
| 7                      | .061  | .122 | .183 | .244 | .305 | .366 | .427 | .487 | .547 | .608 | .668 | .728  |
| 8                      | .070  | .140 | .209 | .279 | .349 | .418 | .488 | .557 | .626 | .695 | .763 | .832  |
| 9                      | .079  | .157 | .236 | .314 | .392 | .470 | .548 | .626 | .704 | .781 | .859 | .936  |
| 10                     | .087  | .175 | .262 | .349 | .436 | .523 | .609 | .696 | .782 | .868 | .954 | 1.040 |

<sup>a</sup> Calculated from the formula: Offset = Cutter Diameter  $\times \frac{1}{2} \times$  Sine of Clearance Angle.

**Distance to Set Tooth Rest Below Center Line of Wheel and Cutter.**—When the clearance angle is ground with a disk type wheel by keeping the center line of the wheel in line with the center line of the cutter, the tooth rest should be lowered by an amount given by the following formula:

$$\text{Offset} = \frac{\text{Wheel Diam.} \times \text{Cutter Dia.} \times \text{Sine of One-half the Clearance Angle}}{\text{Wheel Dia.} + \text{Cutter Dia.}}$$

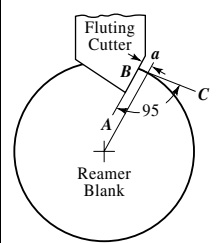
**Distance to Set Tooth Rest Below Cutter Center When Cup Wheel is Used.**—When the clearance is ground with a cup wheel, the tooth rest is set below the center of the cutter the same amount as given in the table for *Distance to Set Center of Wheel Below the Cutter Center (Disk Wheel)*.

## REAMERS

**Hand Reamers.**—Hand reamers are made with both straight and helical flutes. Helical flutes provide a shearing cut and are especially useful in reaming holes having keyways or grooves, as these are bridged over by the helical flutes, thus preventing binding or chattering. Hand reamers are made in both solid and expansion forms. The American standard dimensions for solid forms are given in the accompanying table. The expansion type is useful whenever, in connection with repair or other work, it is necessary to enlarge a reamed hole by a few thousandths of an inch. The expansion form is split through the fluted section and a slight amount of expansion is obtained by screwing in a tapering plug. The diameter increase may vary from 0.005 to 0.008 inch for reamers up to about 1 inch diameter and from 0.010 to 0.012 inch for diameters between 1 and 2 inches. Hand reamers are tapered slightly on the end to facilitate starting them properly. The actual diameter of the shanks of commercial reamers may be from 0.002 to 0.005 inch under the reamer size. That part of the shank that is squared should be turned smaller in diameter than the shank itself, so that, when applying a wrench, no burr may be raised that may mar the reamed hole if the reamer is passed clear through it.

When fluting reamers, the cutter is so set with relation to the center of the reamer blank that the tooth gets a slight negative rake; that is, the cutter should be set *ahead* of the center, as shown in the illustration accompanying the table giving the amount to set the cutter ahead of the radial line. The amount is so selected that a tangent to the circumference of the reamer at the cutting point makes an angle of approximately 95 degrees with the front face of the cutting edge.

Amount to Set Cutter Ahead of Radial Line to Obtain Negative Front Rake

| Fluting Cutter | Size of Reamer  | $a$ , Inches  | Size of Reamer | $a$ , Inches  | Size of Reamer | $a$ , Inches |
|----------------|---|---------------|----------------|---------------|----------------|--------------|
|                |  | $\frac{1}{4}$ | 0.011          | $\frac{7}{8}$ | 0.038          | 2            |
|                | $\frac{3}{8}$   | 0.016         | 1              | 0.044         | $2\frac{1}{4}$ | 0.098        |
|                | $\frac{1}{2}$   | 0.022         | $1\frac{1}{4}$ | 0.055         | $2\frac{1}{2}$ | 0.109        |
|                | $\frac{5}{8}$   | 0.027         | $1\frac{1}{2}$ | 0.066         | $2\frac{3}{4}$ | 0.120        |
|                | $\frac{3}{4}$   | 0.033         | $1\frac{3}{4}$ | 0.076         | 3              | 0.131        |

When fluting reamers, it is necessary to “break up the flutes”; that is, to space the cutting edges unevenly around the reamer. The difference in spacing should be very slight and need not exceed two degrees one way or the other. The manner in which the breaking up of the flutes is usually done is to move the index head to which the reamer is fixed a certain amount more or less than it would be moved if the spacing were regular. A table is given showing the amount of this additional movement of the index crank for reamers with different numbers of flutes. When a reamer is provided with helical flutes, the angle of spiral should be such that the cutting edges make an angle of about 10 or at most 15 degrees with the axis of the reamer.

The relief of the cutting edges should be comparatively slight. An eccentric relief, that is, one where the land back of the cutting edge is convex, rather than flat, is used by one or two manufacturers, and is preferable for finishing reamers, as the reamer will hold its size longer. When hand reamers are used merely for removing stock, or simply for enlarging holes, the flat relief is better, because the reamer has a keener cutting edge. The width of the land of the cutting edges should be about  $\frac{1}{32}$  inch for a  $\frac{1}{4}$ -inch,  $\frac{1}{16}$  inch for a 1-inch, and  $\frac{3}{32}$  inch for a 3-inch reamer.

## Irregular Spacing of Teeth in Reamers

| Number of flutes in reamer | 4  | 6      | 8      | 10     | 12     | 14     | 16     |
|----------------------------|--|--------|--------|--------|--------|--------|--------|
| Index circle to use        | 39   | 39     | 39     | 39     | 39     | 49     | 20     |
| Before cutting             | Move Spindle the Number of Holes below More or Less than for Regular Spacing |        |        |        |        |        |        |
| 2d flute                   | 8 less   | 4 less | 3 less | 2 less | 4 less | 3 less | 2 less |
| 3d flute                   | 4 more   | 5 more | 5 more | 3 more | 4 more | 2 more | 2 more |
| 4th flute                  | 6 less   | 7 less | 2 less | 5 less | 1 less | 2 less | 1 less |
| 5th flute                  | ...  | 6 more | 4 more | 2 more | 3 more | 4 more | 2 more |
| 6th flute                  | ...  | 5 less | 6 less | 2 less | 4 less | 1 less | 2 less |
| 7th flute                  | ...  | ...    | 2 more | 3 more | 4 more | 3 more | 1 more |
| 8th flute                  | ...  | ...    | 3 less | 2 less | 3 less | 2 less | 2 less |
| 9th flute                  | ...  | ...    | ...    | 5 more | 2 more | 1 more | 2 more |
| 10th flute                 | ...  | ...    | ...    | 1 less | 2 less | 3 less | 2 less |
| 11th flute                 | ...  | ...    | ...    | ...    | 3 more | 3 more | 1 more |
| 12th flute                 | ...  | ...    | ...    | ...    | 4 less | 2 less | 2 less |
| 13th flute                 | ...  | ...    | ...    | ...    | ...    | 2 more | 2 more |
| 14th flute                 | ...  | ...    | ...    | ...    | ...    | 3 less | 1 less |
| 15th flute                 | ...  | ...    | ...    | ...    | ...    | ...    | 2 more |
| 16th flute                 | ...  | ...    | ...    | ...    | ...    | ...    | 2 less |

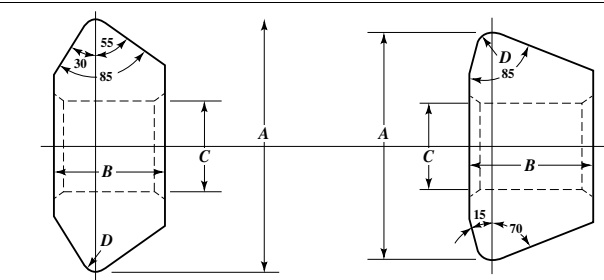
**Threaded-end Hand Reamers.**—Hand reamers are sometimes provided with a thread at the extreme point in order to give them a uniform feed when reaming. The diameter on the top of this thread at the point of the reamer is slightly smaller than the reamer itself, and the thread tapers upward until it reaches a dimension of from 0.003 to 0.008 inch, according to size, below the size of the reamer; at this point, the thread stops and a short neck about  $\frac{1}{16}$  inch wide separates the threaded portion from the actual reamer, which is provided with a short taper from  $\frac{3}{16}$  to  $\frac{7}{16}$  inch long up to where the standard diameter is reached. The length of the threaded portion and the number of threads per inch for reamers of this kind are given in the accompanying table. The thread employed is a sharp V-thread.

## Dimensions for Threaded-End Hand Reamers

| Sizes of Reamers                | Length of Threaded Part | No. of Threads per Inch | Dia. of Thread at Point of Reamer | Sizes of Reamers                 | Length of Threaded Part | No. of Threads per Inch | Dia. of Thread at Point of Reamer |
|---------------------------------|-------------------------|-------------------------|-----------------------------------|----------------------------------|-------------------------|-------------------------|-----------------------------------|
|                                 |                         |                         | Full diameter                     |                                  |                         |                         | Full diameter                     |
| $\frac{1}{8}$ – $\frac{5}{16}$  | $\frac{3}{8}$           | 32                      | –0.006                            | $1\frac{1}{32}$ – $1\frac{1}{2}$ | $\frac{9}{16}$          | 18                      | –0.010                            |
| $\frac{11}{32}$ – $\frac{1}{2}$ | $\frac{7}{16}$          | 28                      | –0.006                            | $1\frac{7}{32}$ –2               | $\frac{9}{16}$          | 18                      | –0.012                            |
| $\frac{17}{32}$ – $\frac{3}{4}$ | $\frac{1}{2}$           | 24                      | –0.008                            | $2\frac{1}{32}$ – $2\frac{1}{2}$ | $\frac{9}{16}$          | 18                      | –0.015                            |
| $\frac{23}{32}$ –1              | $\frac{9}{16}$          | 18                      | –0.008                            | $2\frac{17}{32}$ –3              | $\frac{9}{16}$          | 18                      | –0.020                            |

**Fluted Chucking Reamers.**—Reamers of this type are used in turret lathes, screw machines, etc., for enlarging holes and finishing them smooth and to the required size. The best results are obtained with a floating type of holder that permits a reamer to align itself with the hole being reamed. These reamers are intended for removing a small amount of metal, 0.005 to 0.010 inch being common allowances. Fluted chucking reamers are provided either with a straight shank or a standard taper shank. (See table for standard dimensions.)

## Fluting Cutters for Reamers



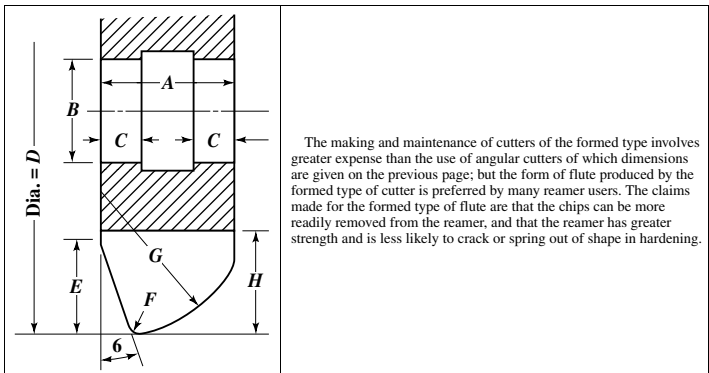
| Reamer Dia.    | Fluting Cutter Dia. | Fluting Cutter Thickness | Hole Dia. in Cutter | Radius between Cutting Faces | Reamer Dia.    | Fluting Cutter Dia. | Fluting Cutter Thickness | Hole Dia. in Cutter | Radius between Cutting Faces |
|----------------|---------------------|--------------------------|---------------------|------------------------------|----------------|---------------------|--------------------------|---------------------|------------------------------|
|                | A                   | B                        | C                   | D                            |                | A                   | B                        | C                   | D                            |
| $\frac{1}{8}$  | $1\frac{3}{4}$      | $\frac{3}{16}$           | $\frac{3}{4}$       | none <sup>a</sup>            | $1\frac{1}{4}$ | $2\frac{1}{4}$      | $\frac{9}{16}$           | 1                   | $\frac{1}{16}$               |
| $\frac{3}{16}$ | $1\frac{3}{4}$      | $\frac{3}{16}$           | $\frac{3}{4}$       | none <sup>a</sup>            | $1\frac{1}{2}$ | $2\frac{1}{4}$      | $\frac{5}{8}$            | 1                   | $\frac{1}{16}$               |
| $\frac{1}{4}$  | $1\frac{3}{4}$      | $\frac{3}{16}$           | $\frac{3}{4}$       | $\frac{1}{64}$               | $1\frac{3}{4}$ | $2\frac{1}{4}$      | $\frac{5}{8}$            | 1                   | $\frac{5}{64}$               |
| $\frac{3}{8}$  | 2                   | $\frac{1}{4}$            | $\frac{3}{4}$       | $\frac{1}{64}$               | 2              | $2\frac{1}{2}$      | $\frac{3}{4}$            | 1                   | $\frac{5}{64}$               |
| $\frac{1}{2}$  | 2                   | $\frac{3}{16}$           | $\frac{3}{4}$       | $\frac{1}{32}$               | $2\frac{1}{4}$ | $2\frac{1}{2}$      | $\frac{3}{4}$            | 1                   | $\frac{5}{64}$               |
| $\frac{5}{8}$  | 2                   | $\frac{3}{8}$            | $\frac{3}{4}$       | $\frac{1}{32}$               | $2\frac{1}{2}$ | $2\frac{1}{2}$      | $\frac{7}{8}$            | 1                   | $\frac{3}{16}$               |
| $\frac{3}{4}$  | 2                   | $\frac{7}{16}$           | $\frac{3}{4}$       | $\frac{3}{64}$               | $2\frac{3}{4}$ | $2\frac{1}{2}$      | $\frac{7}{8}$            | 1                   | $\frac{3}{16}$               |
| 1              | $2\frac{1}{4}$      | $\frac{1}{2}$            | 1                   | $\frac{3}{64}$               | 3              | $2\frac{1}{2}$      | 1                        | 1                   | $\frac{3}{16}$               |

<sup>a</sup> Sharp corner, no radius

**Rose Chucking Reamers.**—The rose type of reamer is used for enlarging cored or other holes. The cutting edges at the end are ground to a 45-degree bevel. This type of reamer will remove considerable metal in one cut. The cylindrical part of the reamer has no cutting edges, but merely grooves cut for the full length of the reamer body, providing a way for the chips to escape and a channel for lubricant to reach the cutting edges. There is no relief on the cylindrical surface of the body part, but it is slightly back-tapered so that the diameter at the point with the beveled cutting edges is slightly larger than the diameter farther back. The back-taper should not exceed 0.001 inch per inch. This form of reamer usually produces holes slightly larger than its size and it is, therefore, always made from 0.005 to 0.010 inch smaller than its nominal size, so that it may be followed by a fluted reamer for finishing. The grooves on the cylindrical portion are cut by a convex cutter having a width equal to from one-fifth to one-fourth the diameter of the rose reamer itself. The depth of the groove should be from one-eighth to one-sixth the diameter of the reamer. The teeth at the end of the reamer are milled with a 75-degree angular cutter; the width of the land of the cutting edge should be about one-fifth the distance from tooth to tooth. If an angular cutter is preferred to a convex cutter for milling the grooves on the cylindrical portion, because of the higher cutting speed possible when milling, an 80-degree angular cutter slightly rounded at the point may be used.

**Cutters for Fluting Rose Chucking Reamers.**—The cutters used for fluting rose chucking reamers on the end are 80-degree angular cutters for  $\frac{1}{4}$ - and  $\frac{5}{16}$ -inch diameter reamers; 75-degree angular cutters for  $\frac{3}{8}$ - and  $\frac{7}{16}$ -inch reamers; and 70-degree angular cutters for all larger sizes. The grooves on the cylindrical portion are milled with convex cutters of approximately the following sizes for given diameters of reamers:  $\frac{5}{32}$ -inch convex cutter

## Dimensions of Formed Reamer Fluting Cutters



The making and maintenance of cutters of the formed type involves greater expense than the use of angular cutters of which dimensions are given on the previous page; but the form of flute produced by the formed type of cutter is preferred by many reamer users. The claims made for the formed type of flute are that the chips can be more readily removed from the reamer, and that the reamer has greater strength and is less likely to crack or spring out of shape in hardening.

| Reamer Size                      | No. of Teeth in Reamer | Cutter Dia. D  | Cutter Width A  | Hole Dia. B   | Bearing Width C | Bevel Length E | Radius F | Radius G        | Tooth Depth H | No. of Cutter Teeth |
|----------------------------------|------------------------|----------------|-----------------|---------------|-----------------|----------------|----------|-----------------|---------------|---------------------|
| $\frac{1}{8}$ - $\frac{3}{16}$   | 6                      | $1\frac{3}{4}$ | $\frac{3}{16}$  | $\frac{7}{8}$ | ...             | 0.125          | 0.016    | $\frac{7}{32}$  | 0.21          | 14                  |
| $\frac{1}{4}$ - $\frac{5}{16}$   | 6                      | $1\frac{3}{4}$ | $\frac{1}{4}$   | $\frac{7}{8}$ | ...             | 0.152          | 0.022    | $\frac{9}{32}$  | 0.25          | 13                  |
| $\frac{3}{8}$ - $\frac{7}{16}$   | 6                      | $1\frac{7}{8}$ | $\frac{3}{8}$   | $\frac{7}{8}$ | $\frac{1}{8}$   | 0.178          | 0.029    | $\frac{1}{2}$   | 0.28          | 12                  |
| $\frac{1}{2}$ - $\frac{11}{16}$  | 6-8                    | 2              | $\frac{7}{16}$  | $\frac{7}{8}$ | $\frac{1}{8}$   | 0.205          | 0.036    | $\frac{9}{16}$  | 0.30          | 12                  |
| $\frac{3}{4}$ -1                 | 8                      | $2\frac{1}{8}$ | $\frac{1}{2}$   | $\frac{7}{8}$ | $\frac{5}{32}$  | 0.232          | 0.042    | $\frac{11}{16}$ | 0.32          | 12                  |
| $1\frac{1}{16}$ - $1\frac{1}{2}$ | 10                     | $2\frac{1}{4}$ | $\frac{9}{16}$  | $\frac{7}{8}$ | $\frac{5}{32}$  | 0.258          | 0.049    | $\frac{3}{4}$   | 0.38          | 11                  |
| $1\frac{9}{16}$ - $2\frac{1}{8}$ | 12                     | $2\frac{3}{8}$ | $\frac{5}{8}$   | $\frac{7}{8}$ | $\frac{3}{16}$  | 0.285          | 0.056    | $\frac{27}{32}$ | 0.40          | 11                  |
| $2\frac{1}{4}$ -3                | 14                     | $2\frac{5}{8}$ | $1\frac{1}{16}$ | $\frac{7}{8}$ | $\frac{3}{16}$  | 0.312          | 0.062    | $\frac{7}{8}$   | 0.44          | 10                  |

for  $\frac{1}{2}$ -inch reamers;  $\frac{5}{16}$ -inch cutter for 1-inch reamers;  $\frac{3}{8}$ -inch cutter for  $1\frac{1}{2}$ -inch reamers;  $\frac{13}{32}$ -inch cutters for 2-inch reamers; and  $\frac{15}{32}$ -inch cutters for  $2\frac{1}{2}$ -inch reamers. The smaller sizes of reamers, from  $\frac{1}{4}$  to  $\frac{3}{8}$  inch in diameter, are often milled with regular double-angle reamer fluting cutters having a radius of  $\frac{1}{64}$  inch for  $\frac{1}{4}$ -inch reamer, and  $\frac{1}{32}$  inch for  $\frac{5}{16}$ - and  $\frac{3}{8}$ -inch sizes.

**Reamer Terms and Definitions.**—*Reamer:* A rotary cutting tool with one or more cutting elements used for enlarging to size and contour a previously formed hole. Its principal support during the cutting action is obtained from the workpiece. (See Fig. 1.)

*Actual Size:* The actual measured diameter of a reamer, usually slightly larger than the nominal size to allow for wear.

*Angle Of Taper:* The included angle of taper on a taper tool or taper shank.

*Arbor Hole:* The central mounting hole in a shell reamer.

*Axis:* the imaginary straight line which forms the longitudinal centerline of a reamer, usually established by rotating the reamer between centers.

*Back Taper:* A slight decrease in diameter, from front to back, in the flute length of reamers.

*Bevel:* An unrelieved angular surface of revolution (not to be confused with chamfer).

*Body:* The fluted full diameter portion of a reamer, inclusive of the chamfer, starting taper, and bevel.

*Chamfer:* The angular cutting portion at the entering end of a reamer (see also *Secondary Chamfer*).



## Vertical Adjustment of Tooth-rest for Grinding Clearance on Reamers

| Size of Reamer | Hand Reamer for Steel. Cutting Clearance Land 0.006 inch Wide |                      | Hand Reamer for Cast Iron and Bronze. Cutting Clearance Land 0.025 inch Wide |                      | Chucking Reamer for Cast Iron and Bronze. Cutting Clearance Land 0.025 inch Wide |                      | Rose Chucking Reamers for Steel              |
|----------------|---|----------------------|--|----------------------|--|----------------------|--|
|                | For Cutting Clearance   | For Second Clearance | For Cutting Clearance  | For Second Clearance | For Cutting Clearance  | For Second Clearance | For Cutting Clearance on Angular Edge at End |
| $\frac{1}{2}$  | 0.012   | 0.052                | 0.032  | 0.072                | 0.040  | 0.080                | 0.080  |
| $\frac{5}{8}$  | 0.012   | 0.062                | 0.032  | 0.072                | 0.040  | 0.090                | 0.090  |
| $\frac{3}{4}$  | 0.012   | 0.072                | 0.035  | 0.095                | 0.040  | 0.100                | 0.100  |
| $\frac{7}{8}$  | 0.012   | 0.082                | 0.040  | 0.120                | 0.045  | 0.125                | 0.125  |
| 1              | 0.012   | 0.092                | 0.040  | 0.120                | 0.045  | 0.125                | 0.125  |
| $1\frac{1}{8}$ | 0.012   | 0.102                | 0.040  | 0.120                | 0.045  | 0.125                | 0.125  |
| $1\frac{1}{4}$ | 0.012   | 0.112                | 0.045  | 0.145                | 0.050  | 0.160                | 0.160  |
| $1\frac{3}{8}$ | 0.012   | 0.122                | 0.045  | 0.145                | 0.050  | 0.160                | 0.175  |
| $1\frac{1}{2}$ | 0.012   | 0.132                | 0.048  | 0.168                | 0.055  | 0.175                | 0.175  |
| $1\frac{5}{8}$ | 0.012   | 0.142                | 0.050  | 0.170                | 0.060  | 0.200                | 0.200  |
| $1\frac{3}{4}$ | 0.012   | 0.152                | 0.052  | 0.192                | 0.060  | 0.200                | 0.200  |
| $1\frac{7}{8}$ | 0.012   | 0.162                | 0.056  | 0.196                | 0.060  | 0.200                | 0.200  |
| 2              | 0.012   | 0.172                | 0.056  | 0.216                | 0.064  | 0.224                | 0.225  |
| $2\frac{1}{8}$ | 0.012   | 0.172                | 0.059  | 0.219                | 0.064  | 0.224                | 0.225  |
| $2\frac{1}{4}$ | 0.012   | 0.172                | 0.063  | 0.223                | 0.064  | 0.224                | 0.225  |
| $2\frac{3}{8}$ | 0.012   | 0.172                | 0.063  | 0.223                | 0.068  | 0.228                | 0.230  |
| $2\frac{1}{2}$ | 0.012   | 0.172                | 0.065  | 0.225                | 0.072  | 0.232                | 0.230  |
| $2\frac{5}{8}$ | 0.012   | 0.172                | 0.065  | 0.225                | 0.075  | 0.235                | 0.235  |
| $2\frac{3}{4}$ | 0.012   | 0.172                | 0.065  | 0.225                | 0.077  | 0.237                | 0.240  |
| $2\frac{7}{8}$ | 0.012   | 0.172                | 0.070  | 0.230                | 0.080  | 0.240                | 0.240  |
| 3              | 0.012   | 0.172                | 0.072  | 0.232                | 0.080  | 0.240                | 0.240  |
| $3\frac{1}{8}$ | 0.012   | 0.172                | 0.075  | 0.235                | 0.083  | 0.240                | 0.240  |
| $3\frac{1}{4}$ | 0.012   | 0.172                | 0.078  | 0.238                | 0.083  | 0.243                | 0.245  |
| $3\frac{3}{8}$ | 0.012   | 0.172                | 0.081  | 0.241                | 0.087  | 0.247                | 0.245  |
| $3\frac{1}{2}$ | 0.012   | 0.172                | 0.084  | 0.244                | 0.090  | 0.250                | 0.250  |
| $3\frac{5}{8}$ | 0.012   | 0.172                | 0.087  | 0.247                | 0.093  | 0.253                | 0.250  |
| $3\frac{3}{4}$ | 0.012   | 0.172                | 0.090  | 0.250                | 0.097  | 0.257                | 0.255  |
| $3\frac{7}{8}$ | 0.012   | 0.172                | 0.093  | 0.253                | 0.100  | 0.260                | 0.255  |
| 4              | 0.012   | 0.172                | 0.096  | 0.256                | 0.104  | 0.264                | 0.260  |
| $4\frac{1}{8}$ | 0.012   | 0.172                | 0.096  | 0.256                | 0.104  | 0.264                | 0.260  |
| $4\frac{1}{4}$ | 0.012   | 0.172                | 0.096  | 0.256                | 0.106  | 0.266                | 0.265  |
| $4\frac{3}{8}$ | 0.012   | 0.172                | 0.096  | 0.256                | 0.108  | 0.268                | 0.265  |
| $4\frac{1}{2}$ | 0.012   | 0.172                | 0.100  | 0.260                | 0.108  | 0.268                | 0.265  |
| $4\frac{5}{8}$ | 0.012   | 0.172                | 0.100  | 0.260                | 0.110  | 0.270                | 0.270  |
| $4\frac{3}{4}$ | 0.012   | 0.172                | 0.104  | 0.264                | 0.114  | 0.274                | 0.275  |
| $4\frac{7}{8}$ | 0.012   | 0.172                | 0.106  | 0.266                | 0.116  | 0.276                | 0.275  |
| 5              | 0.012   | 0.172                | 0.110  | 0.270                | 0.118  | 0.278                | 0.275  |

**Chamfer Angle:** The angle between the axis and the cutting edge of the chamfer measured in an axial plane at the cutting edge.

**Chamfer Length:** The length of the chamfer measured parallel to the axis at the cutting edge.

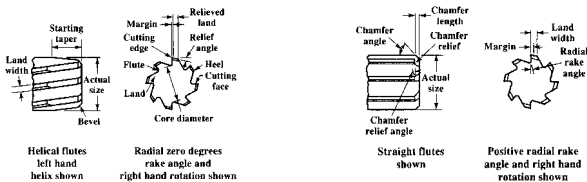
**Chamfer Relief Angle:** See under *Relief*.

**Chamfer Relief:** See under *Relief*.

**Chip Breakers:** Notches or grooves in the cutting edges of some taper reamers designed to break the continuity of the chips.

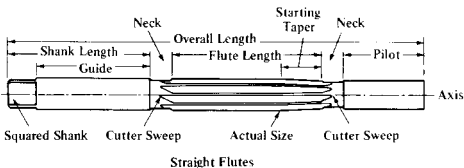
**Circular Land:** See preferred term *Margin*.

## Illustration of Terms Applying to Reamers



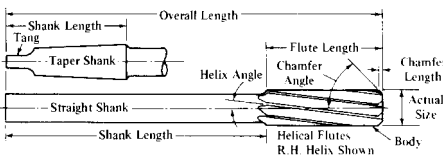
Hand Reamer

Machine Reamer



Straight Flutes

Hand Reamer, Pilot and Guide



Chucking Reamer, Straight and Taper Shank

**Clearance:** The space created by the relief behind the cutting edge or margin of a reamer.

**Core:** The central portion of a reamer below the flutes which joins the lands.

**Core Diameter:** The diameter at a given point along the axis of the largest circle which does not project into the flutes.

**Cutter Sweep:** The section removed by the milling cutter or grinding wheel in entering or leaving a flute.

**Cutting Edge:** The leading edge of the relieved land in the direction of rotation for cutting.

**Cutting Face:** The leading side of the relieved land in the direction of rotation for cutting on which the chip impinges.

**External Center:** The pointed end of a reamer. The included angle varies with manufacturing practice.

**Flutes:** Longitudinal channels formed in the body of the reamer to provide cutting edges, permit passage of chips, and allow cutting fluid to reach the cutting edges.

**Angular Flute:** A flute which forms a cutting face lying in a plane intersecting the reamer axis at an angle. It is unlike a helical flute in that it forms a cutting face which lies in a single plane.

**Helical Flute:** Sometimes called spiral flute, a flute which is formed in a helical path around the axis of a reamer.

**Spiral flute:** 1) On a taper reamer, a flute of constant lead; or, 2) in reference to a straight reamer, see preferred term helical flute.

**Straight Flute:** A flute which forms a cutting edge lying in an axial plane.

**Flute Length:** The length of the flutes not including the cutter sweep.

*Guide:* A cylindrical portion following the flutes of a reamer to maintain alignment.

*Heel:* The trailing edge of the land in the direction of rotation for cutting.

*Helix Angle:* The angle which a helical cutting edge at a given point makes with an axial plane through the same point.

*Hook:* A concave condition of a cutting face. The rake of a hooked cutting face must be determined at a given point.

*Internal Center:* A 60 degree countersink with clearance at the bottom, in one or both ends of a tool, which establishes the tool axis.

*Irregular Spacing:* A deliberate variation from uniform spacing of the reamer cutting edges.

*Land:* The section of the reamer between adjacent flutes.

*Land Width:* The distance between the leading edge of the land and the heel measured at a right angle to the leading edge.

*Lead of Flute:* The axial advance of a helical or spiral cutting edge in one turn around the reamer axis.

*Length:* The dimension of any reamer element measured parallel to the reamer axis.

*Limits:* The maximum and minimum values designated for a specific element.

*Margin:* The unrelieved part of the periphery of the land adjacent to the cutting edge.

*Margin Width:* The distance between the cutting edge and the primary relief measured at a right angle to the cutting edge.

*Neck:* The section of reduced diameter connecting shank to body, or connecting other portions of the reamer.

*Nominal Size:* The designated basic size of a reamer overall length—the extreme length of the complete reamer from end to end, but not including external centers or expansion screws.

*Periphery:* The outside circumference of a reamer.

*Pilot:* A cylindrical portion preceding the entering end of the reamer body to maintain alignment.

*Rake:* The angular relationship between the cutting face, or a tangent to the cutting face at a given point and a given reference plane or line.

*Axial Rake:* Applies to angular (not helical or spiral) cutting faces. It is the angle between a plane containing the cutting face, or tangent to the cutting face at a given point, and the reamer axis.

*Helical Rake:* Applies only to helical and spiral cutting faces (not angular). It is the angle between a plane, tangent to the cutting face at a given point on the cutting edge, and the reamer axis.

*Negative Rake:* Describes a cutting face in rotation whose cutting edge lags the surface of the cutting face.

*Positive Rake:* Describes a cutting face in rotation whose cutting edge leads the surface of the cutting face.

*Radial Rake Angle:* The angle in a transverse plane between a straight cutting face and a radial line passing through the cutting edge.

*Relief:* The result of the removal of tool material behind or adjacent to the cutting edge to provide clearance and prevent rubbing (heel drag).

*Axial Relief:* The relief measured in the axial direction between a plane perpendicular to the axis and the relieved surface. It can be measured by the amount of indicator drop at a given radius in a given amount of angular rotation.

*Cam Relief:* The relief from the cutting edge to the heel of the land produced by a cam action.

*Chamfer Relief Angle:* The axial relief angle at the outer corner of the chamfer. It is measured by projection into a plane tangent to the periphery at the outer corner of the chamfer.

*Chamfer Relief:* The axial relief on the chamfer of the reamer.

*Eccentric Relief:* A convex relieved surface behind the cutting edge.

*Flat Relief:* A relieved surface behind the cutting edge which is essentially flat.

*Radial Relief:* Relief in a radial direction measured in the plane of rotation. It can be measured by the amount of indicator drop at a given radius in a given amount of angular rotation.

*Primary Relief:* The relief immediately behind the cutting edge or margin. Properly called relief.

*Secondary Relief:* An additional relief behind the primary relief.

*Relief Angle:* The angle, measured in a transverse plane, between the relieved surface and a plane tangent to the periphery at the cutting edge.

*Secondary Chamfer:* A slight relieved chamfer adjacent to and following the initial chamfer on a reamer.

*Shank:* The portion of the reamer by which it is held and driven.

*Squared Shank:* A cylindrical shank having a driving square on the back end.

*Starting Radius:* A relieved radius at the entering end of a reamer in place of a chamfer.

*Starting Taper:* A slight relieved taper on the front end of a reamer.

*Straight Shank:* A cylindrical shank.

*Tang:* The flattened end of a taper shank which fits a slot in the socket.

*Taper per Foot:* The difference in diameter between two points 12 in. apart measured along the axis.

*Taper Shank:* A shank made to fit a specific (conical) taper socket.

**Direction of Rotation and Helix.**—The terms “right hand” and “left hand” are used to describe both direction of rotation and direction of flute helix or reamers.

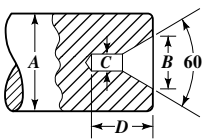
*Hand of Rotation (or Hand of Cut): Right-hand Rotation (or Right-hand Cut):* When viewed from the cutting end, the reamer must revolve counterclockwise to cut

*Left-hand Rotation (or Left-hand Cut):* When viewed from the cutting end, the reamer must revolve clockwise to cut

*Hand of Flute Helix: Right-hand Helix:* When the flutes twist away from the observer in a clockwise direction when viewed from either end of the reamer.

*Left-hand helix:* When the flutes twist away from the observer in a counterclockwise direction when viewed from either end of the reamer. The standard reamers on the tables that follow are all right-hand rotation.

**Dimensions of Centers for Reamers and Arbors**



| Arbor Dia. A | Large Center Dia. B | Drill No. C | Hole Depth D | Arbor Dia. A | Large Center Dia. B | Drill No. C | Hole Depth D |
|--------------|---------------------|-------------|--------------|--------------|---------------------|-------------|--------------|
| 3/4          | 3/8                 | 25          | 7/16         | 2 1/2        | 1 1/16              | J           | 2 7/32       |
| 1 1/16       | 1 3/32              | 20          | 1/2          | 2 3/8        | 4 5/64              | K           | 7/8          |
| 7/8          | 7/16                | 17          | 1 7/32       | 2 3/4        | 2 3/32              | L           | 2 29/32      |
| 1 5/16       | 1 5/32              | 12          | 9/16         | 2 7/8        | 4 7/64              | M           | 2 29/32      |
| 1            | 1/2                 | 8           | 1 19/32      | 3            | 3/4                 | N           | 1 5/16       |
| 1 1/8        | 3 3/64              | 5           | 5/8          | 3 1/8        | 4 9/64              | N           | 3 1/32       |
| 1 1/4        | 1 17/32             | 3           | 2 1/32       | 3 1/4        | 2 25/32             | O           | 3 1/32       |
| 1 3/8        | 3 35/64             | 2           | 2 1/32       | 3 3/8        | 5 1/64              | O           | 1            |
| 1 1/2        | 9/16                | 1           | 1 11/16      | 3 1/2        | 3 1/16              | P           | 1            |
| ...          | ...                 | Letter      | ...          | 3 5/8        | 5 3/64              | Q           | 1 1/16       |
| 1/4          | 1/8                 | 55          | 5/32         | 3 3/4        | 2 27/32             | R           | 1 1/16       |
| 5/16         | 5/32                | 52          | 3/16         | 3 7/8        | 5 55/64             | R           | 1 1/16       |
| 3/8          | 3/16                | 48          | 7/32         | 4            | 7/8                 | S           | 1 1/8        |
| 7/16         | 7/32                | 43          | 1/4          | 4 1/4        | 2 29/32             | T           | 1 1/8        |
| 1/2          | 1/4                 | 39          | 5/16         | 4 1/2        | 1 15/16             | V           | 1 3/16       |
| 9/16         | 9/32                | 33          | 1 11/32      | 4 3/4        | 3 31/32             | W           | 1 1/4        |
| 5/8          | 5/16                | 30          | 3/8          | 5            | 1                   | X           | 1 1/4        |
| 1 1/16       | 1 11/32             | 29          | 1 13/32      |              |                     |             |              |

**Straight Shank Center Reamers and Machine Countersinks**  
ANSI B94.2-1983 (R1988)

| Center Reamers (Short Countersinks) |                           |                    |                  | Machine Countersinks |                           |                    |                  |
|-------------------------------------|---------------------------|--------------------|------------------|----------------------|---------------------------|--------------------|------------------|
| Dia. of Cut                         | Approx. Length Overall, A | Length of Shank, S | Dia. of Shank, D | Dia. of Cut          | Approx. Length Overall, A | Length of Shank, S | Dia. of Shank, D |
| $\frac{1}{4}$                       | $1\frac{1}{2}$            | $\frac{3}{4}$      | $\frac{3}{16}$   | $\frac{1}{2}$        | $3\frac{3}{8}$            | $2\frac{1}{4}$     | $\frac{1}{2}$    |
| $\frac{3}{8}$                       | $1\frac{3}{4}$            | $\frac{7}{8}$      | $\frac{1}{4}$    | $\frac{5}{8}$        | 4                         | $2\frac{1}{4}$     | $\frac{1}{2}$    |
| $\frac{1}{2}$                       | 2                         | 1                  | $\frac{3}{8}$    | $\frac{3}{4}$        | $4\frac{1}{8}$            | $2\frac{1}{4}$     | $\frac{1}{2}$    |
| $\frac{5}{8}$                       | $2\frac{1}{4}$            | 1                  | $\frac{3}{8}$    | $\frac{7}{8}$        | $4\frac{1}{4}$            | $2\frac{1}{4}$     | $\frac{1}{2}$    |
| $\frac{3}{4}$                       | $2\frac{5}{8}$            | $1\frac{1}{4}$     | $\frac{1}{2}$    | 1                    | $4\frac{3}{8}$            | $2\frac{1}{4}$     | $\frac{1}{2}$    |

All dimensions are given in inches. Material is high-speed steel. Reamers and countersinks have 3 or 4 flutes. Center reamers are standard with 60, 82, 90, or 100 degrees included angle. Machine countersinks are standard with either 60 or 82 degrees included angle.

**Tolerances:** On overall length A, the tolerance is  $\pm\frac{1}{8}$  inch for center reamers in a size range of from  $\frac{1}{4}$  to  $\frac{3}{8}$  inch, incl., and machine countersinks in a size range of from  $\frac{1}{2}$  to  $\frac{5}{8}$  inch, incl.;  $\pm\frac{3}{16}$  inch for center reamers,  $\frac{1}{2}$  to  $\frac{3}{4}$  inch, incl.; and machine countersinks,  $\frac{3}{4}$  to 1 inch, incl. On shank diameter D, the tolerance is  $-0.0005$  to  $-0.002$  inch. On shank length S, the tolerance is  $\pm\frac{1}{16}$  inch.

**Reamer Difficulties.**—Certain frequently occurring problems in reaming require remedial measures. These difficulties include the production of oversize holes, bellmouth holes, and holes with a poor finish. The following is taken from suggestions for correction of these difficulties by the National Twist Drill and Tool Co. and Winter Brothers Co.\*

**Oversize Holes:** The cutting of a hole oversize from the start of the reaming operations usually indicates a mechanical defect in the setup or reamer. Thus, the wrong reamer for the workpiece material may have been used or there may be inadequate workpiece support, inadequate or worn guide bushings, or misalignment of the spindles, bushings, or workpiece or runout of the spindle or reamer holder. The reamer itself may be defective due to chamfer runout or runout of the cutting end due to a bent or nonconcentric shank.

When reamers gradually start to cut oversize, it is due to pickup or galling, principally on the reamer margins. This condition is partly due to the workpiece material. Mild steels, certain cast irons, and some aluminum alloys are particularly troublesome in this respect.

Corrective measures include reducing the reamer margin widths to about 0.005 to 0.010 inch, use of hard case surface treatments on high-speed-steel reamers, either alone or in combination with black oxide treatments, and the use of a high-grade finish on the reamer faces, margins, and chamfer relief surfaces.

**Bellmouth Holes:** The cutting of a hole that becomes oversize at the entry end with the oversize decreasing gradually along its length always reflects misalignment of the cutting portion of the reamer with respect to the hole. The obvious solution is to provide improved guiding of the reamer by the use of accurate bushings and pilot surfaces. If this solution is not feasible, and the reamer is cutting in a vertical position, a flexible element may be employed to hold the reamer in such a way that it has both radial and axial float, with the hope that the reamer will follow the original hole and prevent the bellmouth condition.

In horizontal setups where the reamer is held fixed and the workpiece rotated, any misalignment exerts a sideways force on the reamer as it is fed to depth, resulting in the forma-

\*"Some Aspects of Reamer Design and Operation," *Metal Cuttings*, April 1963.

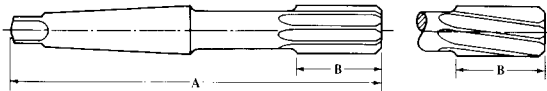
tion of a tapered hole. This type of bellmouthing can frequently be reduced by shortening the bearing length of the cutting portion of the reamer. One way to do this is to reduce the reamer diameter by 0.010 to 0.030 inch, depending on size and length, behind a short full-diameter section,  $\frac{1}{8}$  to  $\frac{1}{2}$  inch long according to length and size, following the chamfer. The second method is to grind a high back taper, 0.008 to 0.015 inch per inch, behind the short full-diameter section. Either of these modifications reduces the length of the reamer tooth that can cause the bellmouth condition.

**Poor Finish:** The most obvious step toward producing a good finish is to reduce the reamer feed per revolution. Feeds as low as 0.0002 to 0.0005 inch per tooth have been used successfully. However, reamer life will be better if the maximum feasible feed is used.

The minimum practical amount of reaming stock allowance will often improve finish by reducing the volume of chips and the resulting heat generated on the cutting portion of the chamfer. Too little reamer stock, however, can be troublesome in that the reamer teeth may not cut freely but will deflect or push the work material out of the way. When this happens, excessive heat, poor finish, and rapid reamer wear can occur.

Because of their superior abrasion resistance, carbide reamers are often used when fine finishes are required. When properly conditioned, carbide reamers can produce a large number of good-quality holes. Careful honing of the carbide reamer edges is very important.

### American National Standard Fluted Taper Shank Chucking Reamers— Straight and Helical Flutes, Fractional Sizes ANSI B94.2-1983 (R1988)



| Reamer Dia.     | Length Overall A | Flute Length B | No. of Morse Taper Shank <sup>a</sup> | No. of Flutes | Reamer Dia.     | Length Overall A | Flute Length B | No. of Morse Taper Shank <sup>a</sup> | No. of Flutes |
|-----------------|------------------|----------------|---------------------------------------|---------------|-----------------|------------------|----------------|---------------------------------------|---------------|
| $\frac{1}{4}$   | 6                | $1\frac{1}{2}$ | 1                                     | 4 to 6        | $\frac{27}{32}$ | $9\frac{1}{2}$   | $2\frac{1}{2}$ | 2                                     | 8 to 10       |
| $\frac{3}{16}$  | 6                | $1\frac{1}{2}$ | 1                                     | 4 to 6        | $\frac{7}{8}$   | 10               | $2\frac{3}{8}$ | 2                                     | 8 to 10       |
| $\frac{3}{8}$   | 7                | $1\frac{3}{4}$ | 1                                     | 4 to 6        | $\frac{29}{32}$ | 10               | $2\frac{5}{8}$ | 2                                     | 8 to 10       |
| $\frac{7}{16}$  | 7                | $1\frac{3}{4}$ | 1                                     | 6 to 8        | $\frac{15}{16}$ | 10               | $2\frac{5}{8}$ | 3                                     | 8 to 10       |
| $\frac{1}{2}$   | 8                | 2              | 1                                     | 6 to 8        | $\frac{31}{32}$ | 10               | $2\frac{5}{8}$ | 3                                     | 8 to 10       |
| $\frac{17}{32}$ | 8                | 2              | 1                                     | 6 to 8        | 1               | $10\frac{1}{2}$  | $2\frac{3}{4}$ | 3                                     | 8 to 12       |
| $\frac{9}{16}$  | 8                | 2              | 1                                     | 6 to 8        | $\frac{11}{16}$ | $10\frac{1}{2}$  | $2\frac{3}{4}$ | 3                                     | 8 to 12       |
| $\frac{19}{32}$ | 8                | 2              | 1                                     | 6 to 8        | $\frac{1}{8}$   | 11               | $2\frac{7}{8}$ | 3                                     | 8 to 12       |
| $\frac{5}{8}$   | 9                | $2\frac{1}{4}$ | 2                                     | 6 to 8        | $\frac{13}{16}$ | 11               | $2\frac{7}{8}$ | 3                                     | 8 to 12       |
| $\frac{21}{32}$ | 9                | $2\frac{1}{4}$ | 2                                     | 6 to 8        | $1\frac{1}{4}$  | $11\frac{1}{2}$  | 3              | 4                                     | 8 to 12       |
| $\frac{11}{16}$ | 9                | $2\frac{1}{4}$ | 2                                     | 6 to 8        | $\frac{13}{16}$ | $11\frac{1}{2}$  | 3              | 4                                     | 8 to 12       |
| $\frac{23}{32}$ | 9                | $2\frac{1}{4}$ | 2                                     | 6 to 8        | $\frac{3}{8}$   | 12               | $3\frac{1}{4}$ | 4                                     | 10 to 12      |
| $\frac{3}{4}$   | $9\frac{1}{2}$   | $2\frac{1}{2}$ | 2                                     | 6 to 8        | $\frac{17}{16}$ | 12               | $3\frac{1}{4}$ | 4                                     | 10 to 12      |
| $\frac{25}{32}$ | $9\frac{1}{2}$   | $2\frac{1}{2}$ | 2                                     | 8 to 10       | $1\frac{1}{2}$  | $12\frac{1}{2}$  | $3\frac{1}{2}$ | 4                                     | 10 to 12      |
| $\frac{13}{16}$ | $9\frac{1}{2}$   | $2\frac{1}{2}$ | 2                                     | 8 to 10       | ...             | ...              | ...            | ...                                   | ...           |

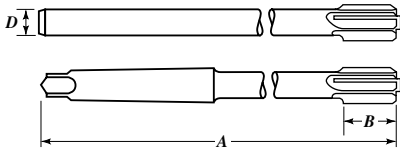
<sup>a</sup> American National Standard self-holding tapers (see Table 7a on page 933.)

All dimensions are given in inches. Material is high-speed steel.

Helical flute reamers with right-hand helical flutes are standard.

**Tolerances:** On reamer diameter,  $\frac{1}{4}$ -inch size, +.0001 to +.0004 inch; over  $\frac{1}{4}$ - to 1-inch size, +.0001 to +.0005 inch; over 1-inch size, +.0002 to +.0006 inch. On length overall A and flute length B,  $\frac{1}{4}$ - to 1-inch size, incl.,  $\pm\frac{1}{16}$  inch;  $\frac{1}{16}$ - to  $1\frac{1}{2}$ -inch size, incl.,  $\frac{3}{32}$  inch.

**Expansion Chucking Reamers—Straight and Taper Shanks**  
ANSI B94.2-1983 (R1988)



| Dia of Reamer   | Length, A       | Flute Length, B | Shank Dia., D |        | Dia. of Reamer               | Length, A       | Flute Length, B | Shank Dia., D |        |
|-----------------|-----------------|-----------------|---------------|--------|------------------------------|-----------------|-----------------|---------------|--------|
|                 |                 |                 | Max.          | Min.   |                              |                 |                 | Max.          | Min.   |
| $\frac{3}{8}$   | 7               | $\frac{3}{4}$   | 0.3105        | 0.3095 | $1\frac{3}{32}$              | $10\frac{1}{2}$ | $1\frac{1}{8}$  | 0.8745        | 0.8730 |
| $1\frac{1}{32}$ | 7               | $\frac{3}{4}$   | 0.3105        | 0.3095 | $1\frac{1}{8}$               | 11              | $1\frac{3}{4}$  | 0.8745        | 0.8730 |
| $\frac{7}{16}$  | 7               | $\frac{7}{8}$   | 0.3730        | 0.3720 | $1\frac{1}{2}$               | 11              | $1\frac{3}{4}$  | 0.8745        | 0.8730 |
| $1\frac{1}{32}$ | 7               | $\frac{7}{8}$   | 0.3730        | 0.3720 | $1\frac{3}{16}$              | 11              | $1\frac{3}{4}$  | 0.9995        | 0.9980 |
| $\frac{1}{2}$   | 8               | 1               | 0.4355        | 0.4345 | $1\frac{1}{2}$               | 11              | $1\frac{3}{4}$  | 0.9995        | 0.9980 |
| $1\frac{1}{32}$ | 8               | 1               | 0.4355        | 0.4345 | $1\frac{1}{4}$               | $11\frac{1}{2}$ | $1\frac{1}{8}$  | 0.9995        | 0.9980 |
| $\frac{9}{16}$  | 8               | $1\frac{1}{8}$  | 0.4355        | 0.4345 | $1\frac{1}{16}$              | $11\frac{1}{2}$ | $1\frac{1}{8}$  | 0.9995        | 0.9980 |
| $1\frac{1}{32}$ | 8               | $1\frac{1}{8}$  | 0.4355        | 0.4345 | $1\frac{3}{8}$               | 12              | 2               | 0.9995        | 0.9980 |
| $\frac{5}{8}$   | 9               | $1\frac{1}{4}$  | 0.5620        | 0.5605 | $1\frac{1}{16}$              | 12              | 2               | 1.2495        | 1.2480 |
| $2\frac{1}{32}$ | 9               | $1\frac{1}{4}$  | 0.5620        | 0.5605 | $1\frac{1}{2}$               | $12\frac{1}{2}$ | $2\frac{1}{8}$  | 1.2495        | 1.2480 |
| $1\frac{1}{16}$ | 9               | $1\frac{1}{4}$  | 0.5620        | 0.5605 | $1\frac{1}{16}$ <sup>a</sup> | $12\frac{1}{2}$ | $2\frac{1}{8}$  | 1.2495        | 1.2480 |
| $2\frac{1}{32}$ | 9               | $1\frac{1}{4}$  | 0.5620        | 0.5605 | $1\frac{3}{8}$               | 13              | $2\frac{1}{4}$  | 1.2495        | 1.2480 |
| $\frac{3}{4}$   | $9\frac{1}{2}$  | $1\frac{3}{8}$  | 0.6245        | 0.6230 | $1\frac{1}{16}$ <sup>a</sup> | 13              | $2\frac{1}{4}$  | 1.2495        | 1.2480 |
| $2\frac{1}{32}$ | $9\frac{1}{2}$  | $1\frac{3}{8}$  | 0.6245        | 0.6230 | $1\frac{1}{4}$               | $13\frac{1}{2}$ | $2\frac{3}{8}$  | 1.2495        | 1.2480 |
| $1\frac{1}{16}$ | $9\frac{1}{2}$  | $1\frac{3}{8}$  | 0.6245        | 0.6230 | $1\frac{1}{16}$ <sup>a</sup> | $13\frac{1}{2}$ | $2\frac{3}{8}$  | 1.4995        | 1.4980 |
| $2\frac{1}{32}$ | $9\frac{1}{2}$  | $1\frac{3}{8}$  | 0.6245        | 0.6230 | $1\frac{7}{8}$               | 14              | $2\frac{1}{2}$  | 1.4995        | 1.4980 |
| $\frac{7}{8}$   | 10              | $1\frac{1}{2}$  | 0.7495        | 0.7480 | $1\frac{1}{16}$ <sup>a</sup> | 14              | $2\frac{1}{2}$  | 1.4995        | 1.4980 |
| $2\frac{1}{32}$ | 10              | $1\frac{1}{2}$  | 0.7495        | 0.7480 | 2                            | 14              | $2\frac{1}{2}$  | 1.4995        | 1.4980 |
| $1\frac{5}{16}$ | 10              | $1\frac{1}{2}$  | 0.7495        | 0.7480 | $2\frac{1}{8}$ <sup>b</sup>  | $14\frac{1}{2}$ | $2\frac{3}{4}$  | ...           | ...    |
| $3\frac{1}{32}$ | 10              | $1\frac{1}{2}$  | 0.7495        | 0.7480 | $2\frac{1}{4}$ <sup>b</sup>  | $14\frac{1}{2}$ | $2\frac{3}{4}$  | ...           | ...    |
| 1               | $10\frac{1}{2}$ | $1\frac{5}{8}$  | 0.8745        | 0.8730 | $2\frac{3}{8}$ <sup>b</sup>  | 15              | 3               | ...           | ...    |
| $1\frac{1}{32}$ | $10\frac{1}{2}$ | $1\frac{5}{8}$  | 0.8745        | 0.8730 | $2\frac{1}{2}$ <sup>b</sup>  | 15              | 3               | ...           | ...    |
| $1\frac{1}{16}$ | $10\frac{1}{2}$ | $1\frac{5}{8}$  | 0.8745        | 0.8730 | ...                          | ...             | ...             | ...           | ...    |

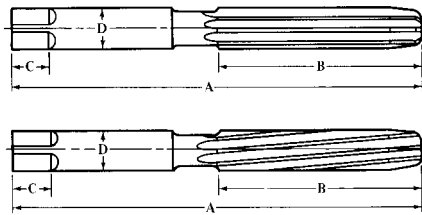
<sup>a</sup> Straight shank only.<sup>b</sup> Taper shank only.

All dimensions in inches. Material is high-speed steel. The number of flutes is as follows:  $\frac{3}{8}$ - to  $1\frac{5}{32}$ -inch sizes, 4 to 6;  $\frac{1}{2}$ - to  $3\frac{1}{32}$ -inch sizes, 6 to 8; 1- to  $1\frac{1}{16}$ -inch sizes, 8 to 10;  $1\frac{3}{4}$ - to  $1\frac{15}{16}$ -inch sizes, 8 to 12; 2- to  $2\frac{1}{4}$ -inch sizes, 10 to 12;  $2\frac{3}{8}$ - and  $2\frac{1}{2}$ -inch sizes, 10 to 14. The expansion feature of these reamers provides a means of adjustment that is important in reaming holes to close tolerances. When worn undersize, they may be expanded and reground to the original size.

**Tolerances:** On reamer diameter,  $\frac{3}{8}$ - to 1-inch sizes, incl., +0.0001 to +0.0005 inch; over 1-inch size, +0.0002 to +0.0006 inch. On length A and flute length B,  $\frac{3}{8}$ - to 1-inch sizes, incl.,  $\pm\frac{1}{16}$  inch;  $1\frac{1}{32}$ - to 2-inch sizes, incl.,  $\pm\frac{3}{32}$  inch; over 2-inch sizes,  $\pm\frac{1}{8}$  inch.

Taper is Morse taper: No. 1 for sizes  $\frac{3}{8}$  to  $1\frac{19}{32}$  inch, incl.; No. 2 for sizes  $\frac{5}{8}$  to  $2\frac{29}{32}$  inch, incl.; No. 3 for sizes  $1\frac{1}{16}$  to  $1\frac{1}{32}$  inch, incl.; No. 4 for sizes  $1\frac{1}{4}$  to  $1\frac{5}{8}$  inch, incl.; and No. 5 for sizes  $1\frac{3}{4}$  to  $2\frac{1}{2}$  inch, incl. For amount of taper, see [Table 1b](#) on page 928.

## Hand Reamers—Straight and Helical Flutes ANSI B94.2-1983 (R1988)



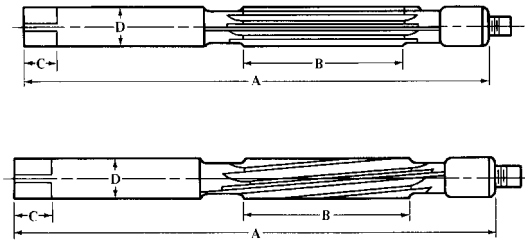
| Reamer Diameter |                |                    | Length Overall<br>A | Flute Length<br>B | Square Length<br>C | Size of Square | No. of Flutes |
|-----------------|----------------|--------------------|---------------------|-------------------|--------------------|----------------|---------------|
| Straight Flutes | Helical Flutes | Decimal Equivalent |                     |                   |                    |                |               |
| 1/8             | ...            | 0.1250             | 3                   | 1 1/2             | 5/32               | 0.095          | 4 to 6        |
| 5/32            | ...            | 0.1562             | 3 1/4               | 1 3/8             | 7/32               | 0.115          | 4 to 6        |
| 3/16            | ...            | 0.1875             | 3 1/2               | 1 3/4             | 7/32               | 0.140          | 4 to 6        |
| 7/32            | ...            | 0.2188             | 3 3/4               | 1 7/8             | 1/4                | 0.165          | 4 to 6        |
| 1/4             | 1/4            | 0.2500             | 4                   | 2                 | 1/4                | 0.185          | 4 to 6        |
| 9/32            | ...            | 0.2812             | 4 1/4               | 2 1/8             | 1/4                | 0.210          | 4 to 6        |
| 5/16            | 5/16           | 0.3125             | 4 1/2               | 2 1/4             | 5/16               | 0.235          | 4 to 6        |
| 11/32           | ...            | 0.3438             | 4 3/4               | 2 3/8             | 5/16               | 0.255          | 4 to 6        |
| 3/8             | 3/8            | 0.3750             | 5                   | 2 1/2             | 3/8                | 0.280          | 4 to 6        |
| 13/32           | ...            | 0.4062             | 5 1/4               | 2 5/8             | 3/8                | 0.305          | 6 to 8        |
| 7/16            | 7/16           | 0.4375             | 5 1/2               | 2 3/4             | 7/16               | 0.330          | 6 to 8        |
| 15/32           | ...            | 0.4688             | 5 3/4               | 2 7/8             | 7/16               | 0.350          | 6 to 8        |
| 1/2             | 1/2            | 0.5000             | 6                   | 3                 | 1/2                | 0.375          | 6 to 8        |
| 17/32           | ...            | 0.5312             | 6 1/4               | 3 1/8             | 1/2                | 0.400          | 6 to 8        |
| 9/16            | 9/16           | 0.5625             | 6 1/2               | 3 1/4             | 9/16               | 0.420          | 6 to 8        |
| 19/32           | ...            | 0.5938             | 6 3/4               | 3 3/8             | 9/16               | 0.445          | 6 to 8        |
| 5/8             | 5/8            | 0.6250             | 7                   | 3 1/2             | 5/8                | 0.470          | 6 to 8        |
| 21/32           | ...            | 0.6562             | 7 1/8               | 3 11/16           | 5/8                | 0.490          | 6 to 8        |
| 11/16           | 11/16          | 0.6875             | 7 3/4               | 3 7/8             | 11/16              | 0.515          | 6 to 8        |
| 23/32           | ...            | 0.7188             | 8 1/8               | 4 1/16            | 11/16              | 0.540          | 6 to 8        |
| 3/4             | 3/4            | 0.7500             | 8 3/8               | 4 3/16            | 3/4                | 0.560          | 6 to 8        |
| ...             | 13/16          | 0.8125             | 9 1/8               | 4 9/16            | 13/16              | 0.610          | 8 to 10       |
| 7/8             | 7/8            | 0.8750             | 9 3/4               | 4 7/8             | 7/8                | 0.655          | 8 to 10       |
| ...             | 15/16          | 0.9375             | 10 1/4              | 5 1/8             | 15/16              | 0.705          | 8 to 10       |
| 1               | 1              | 1.0000             | 10 7/8              | 5 1/2             | 1                  | 0.750          | 8 to 10       |
| 1 1/8           | 1 1/8          | 1.1250             | 11 3/8              | 5 13/16           | 1                  | 0.845          | 8 to 10       |
| 1 1/4           | 1 1/4          | 1.2500             | 12 1/4              | 6 1/8             | 1                  | 0.935          | 8 to 12       |
| 1 3/8           | 1 3/8          | 1.3750             | 12 5/8              | 6 3/16            | 1                  | 1.030          | 10 to 12      |
| 1 1/2           | 1 1/2          | 1.5000             | 13                  | 6 1/2             | 1 1/8              | 1.125          | 10 to 14      |

All dimensions in inches. Material is high-speed steel. The nominal shank diameter  $D$  is the same as the reamer diameter. Helical-flute hand reamers with left-hand helical flutes are standard. Reamers are tapered slightly on the end to facilitate proper starting.

**Tolerances:** On diameter of reamer, up to 1/4-inch size, incl., +.0001 to +.0004 inch; over 1/4- to 1-inch size, incl., +.0001 to +.0005 inch; over 1-inch size, +.0002 to +.0006 inch. On length overall  $A$  and flute length  $B$ , 1/8- to 1-inch size, incl.,  $\pm 1/16$  inch; 1 1/8- to 1 1/2-inch size, incl.,  $\pm 3/32$  inch. On length of square  $C$ , 1/8- to 1 inch size, incl.,  $\pm 1/32$  inch; 1 1/8- to 1 1/2-inch size, incl.,  $\pm 1/16$  inch. On shank diameter  $D$ , 1/8- to 1-inch size, incl.,  $-0.001$  to  $-0.005$  inch; 1 1/8- to 1 1/2-inch size, incl.,  $-0.0015$  to  $-0.006$  inch. On size of square, 1/8- to 1/2-inch size, incl.,  $-0.004$  inch; 7/32- to 1-inch size, incl.,  $-0.006$  inch; 1 1/8- to 1 1/2-inch size, incl.,  $-0.008$  inch.



**American National Standard Expansion Hand Reamers—Straight and Helical Flutes, Squared Shank ANSI B94.2-1983 (R1988)**

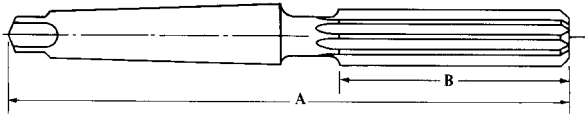


| Reamer Dia.     | Length Overall A |       | Flute Length B |       | Length of Square C | Shank Dia. D | Size of Square | Number of Flutes |
|-----------------|------------------|-------|----------------|-------|--------------------|--------------|----------------|------------------|
|                 | Max              | Min   | Max            | Min   |                    |              |                |                  |
| Straight Flutes |                  |       |                |       |                    |              |                |                  |
| 1/4             | 4 3/8            | 3 3/4 | 1 3/4          | 1 1/2 | 1/4                | 1/4          | 0.185          | 6 to 8           |
| 5/16            | 4 3/8            | 4     | 1 7/8          | 1 1/2 | 3/16               | 3/16         | 0.235          | 6 to 8           |
| 3/8             | 5 3/8            | 4 1/4 | 2              | 1 3/4 | 3/8                | 3/8          | 0.280          | 6 to 9           |
| 7/16            | 5 3/8            | 4 1/2 | 2              | 1 3/4 | 7/16               | 7/16         | 0.330          | 6 to 9           |
| 1/2             | 6 1/2            | 5     | 2 1/2          | 1 3/4 | 1/2                | 1/2          | 0.375          | 6 to 9           |
| 9/16            | 6 1/2            | 5 3/8 | 2 1/2          | 1 7/8 | 9/16               | 9/16         | 0.420          | 6 to 9           |
| 5/8             | 7                | 5 3/4 | 3              | 2 1/4 | 5/8                | 5/8          | 0.470          | 6 to 9           |
| 11/16           | 7 5/8            | 6 1/4 | 3              | 2 1/2 | 11/16              | 11/16        | 0.515          | 6 to 10          |
| 3/4             | 8                | 6 1/2 | 3 1/2          | 2 5/8 | 3/4                | 3/4          | 0.560          | 6 to 10          |
| 7/8             | 9                | 7 1/2 | 4              | 3 3/8 | 7/8                | 7/8          | 0.655          | 8 to 10          |
| 1               | 10               | 8 3/8 | 4 1/2          | 3 3/8 | 1                  | 1            | 0.750          | 8 to 10          |
| 1 1/8           | 10 1/2           | 9     | 4 3/4          | 3 1/2 | 1                  | 1 1/8        | 0.845          | 8 to 12          |
| 1 1/4           | 11               | 9 3/4 | 5              | 4 1/4 | 1                  | 1 1/4        | 0.935          | 8 to 12          |
| Helical Flutes  |                  |       |                |       |                    |              |                |                  |
| 1/4             | 4 3/8            | 3 7/8 | 1 3/4          | 1 1/2 | 1/4                | 1/4          | 0.185          | 6 to 8           |
| 5/16            | 4 3/8            | 4     | 1 3/4          | 1 1/2 | 5/16               | 5/16         | 0.235          | 6 to 8           |
| 3/8             | 6 1/8            | 4 1/4 | 2              | 1 3/4 | 3/8                | 3/8          | 0.280          | 6 to 9           |
| 7/16            | 6 1/4            | 4 1/2 | 2              | 1 3/4 | 7/16               | 7/16         | 0.330          | 6 to 9           |
| 1/2             | 6 1/2            | 5     | 2 1/2          | 1 3/4 | 1/2                | 1/2          | 0.375          | 6 to 9           |
| 5/8             | 8                | 6     | 3              | 2 1/4 | 5/8                | 5/8          | 0.470          | 6 to 9           |
| 3/4             | 8 3/8            | 6 1/2 | 3 1/2          | 2 5/8 | 3/4                | 3/4          | 0.560          | 6 to 10          |
| 7/8             | 9 3/8            | 7 1/2 | 4              | 3 3/8 | 7/8                | 7/8          | 0.655          | 6 to 10          |
| 1               | 10 1/4           | 8 3/8 | 4 1/2          | 3 3/8 | 1                  | 1            | 0.750          | 6 to 10          |
| 1 1/4           | 11 3/8           | 9 3/4 | 5              | 4 1/4 | 1                  | 1 1/4        | 0.935          | 8 to 12          |

All dimensions are given in inches. Material is carbon steel. Reamers with helical flutes that are left hand are standard. Expansion hand reamers are primarily designed for work where it is necessary to enlarge reamed holes by a few thousandths. The pilots and guides on these reamers are ground under-size for clearance. The maximum expansion on these reamers is as follows: .006 inch for the 1/4 to 7/16-inch sizes, .010 inch for the 1/2 to 7/8-inch sizes and .012 inch for the 1- to 1 1/4-inch sizes.

**Tolerances:** On length overall A and flute length B,  $\pm 1/16$  inch for 1/4- to 1-inch sizes,  $\pm 3/32$  inch for 1 1/8- to 1 1/4-inch sizes; on length of square C,  $\pm 1/32$  inch for 1/4- to 1-inch sizes,  $\pm 1/16$  inch for 1 1/8- to 1 1/4-inch sizes; on shank diameter D,  $-0.001$  to  $-0.005$  inch for 1/4- to 1-inch sizes,  $-0.0015$  to  $-0.006$  inch for 1 1/8- to 1 1/4-inch sizes; on size of square,  $-0.004$  inch for 1/4- to 1/2-inch sizes,  $-0.006$  inch for 9/16- to 1-inch sizes, and  $-0.008$  inch for 1 1/8- to 1 1/4-inch sizes.

## Taper Shank Jobbers Reamers—Straight Flutes ANSI B94.2-1983 (R1988)



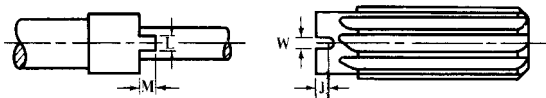
| Reamer Diameter |             | Length Overall A | Length of Flute B | No. of Morse Taper Shank <sup>a</sup> | No. of Flutes |
|-----------------|-------------|------------------|-------------------|---------------------------------------|---------------|
| Fractional      | Dec. Equiv. |                  |                   |                                       |               |
| 1/4             | 0.2500      | 5 3/16           | 2                 | 1                                     | 6 to 8        |
| 5/16            | 0.3125      | 5 1/2            | 2 1/4             | 1                                     | 6 to 8        |
| 3/8             | 0.3750      | 5 13/16          | 2 1/2             | 1                                     | 6 to 8        |
| 7/16            | 0.4375      | 6 1/8            | 2 3/4             | 1                                     | 6 to 8        |
| 1/2             | 0.5000      | 6 7/16           | 3                 | 1                                     | 6 to 8        |
| 9/16            | 0.5625      | 6 3/4            | 3 1/4             | 1                                     | 6 to 8        |
| 5/8             | 0.6250      | 7 9/16           | 3 1/2             | 2                                     | 6 to 8        |
| 1 1/16          | 0.6875      | 8                | 3 3/4             | 2                                     | 8 to 10       |
| 3/4             | 0.7500      | 8 3/8            | 4 3/16            | 2                                     | 8 to 10       |
| 13/16           | 0.8125      | 8 13/16          | 4 9/16            | 2                                     | 8 to 10       |
| 7/8             | 0.8750      | 9 3/16           | 4 7/8             | 2                                     | 8 to 10       |
| 15/16           | 0.9375      | 10               | 5 1/8             | 3                                     | 8 to 10       |
| 1               | 1.0000      | 10 3/8           | 5 7/16            | 3                                     | 8 to 10       |
| 1 1/16          | 1.0625      | 10 5/8           | 5 3/4             | 3                                     | 8 to 10       |
| 1 1/8           | 1.1250      | 10 7/8           | 5 13/16           | 3                                     | 8 to 10       |
| 1 3/16          | 1.1875      | 11 1/8           | 6                 | 3                                     | 8 to 12       |
| 1 1/4           | 1.2500      | 12 1/16          | 6 1/8             | 4                                     | 8 to 12       |
| 1 3/8           | 1.3750      | 12 13/16         | 6 5/16            | 4                                     | 10 to 12      |
| 1 1/2           | 1.5000      | 13 3/8           | 6 1/2             | 4                                     | 10 to 12      |

<sup>a</sup> American National Standard self-holding tapers (Table 7a on page 933.)

All dimensions in inches. Material is high-speed steel.

**Tolerances:** On reamer diameter, 1/4-inch size, +.0001 to +.0004 inch; over 1/4- to 1-inch size, incl., +.0001 to +.0005 inch; over 1-inch size, +.0002 to +.0006 inch. On overall length A and length of flute B, 1/4- to 1-inch size, incl., ±1/16 inch; and 1 1/16- to 1 1/2-inch size, incl., ±3/32 inch.

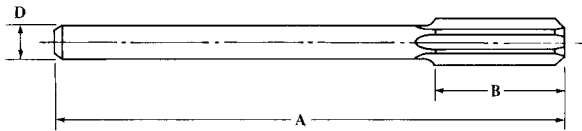
## American National Standard Driving Slots and Lugs for Shell Reamers or Shell Reamer Arbors ANSI B94.2-1983 (R1988)



| Arbor Size No. | Fitting Reamer Sizes | Driving Slot |         | Lug on Arbor |         | Reamer Hole Dia. at Large End |
|----------------|----------------------|--------------|---------|--------------|---------|-------------------------------|
|                |                      | Width W      | Depth J | Width L      | Depth M |                               |
| 4              | 3/4                  | 5/32         | 3/16    | 9/64         | 5/32    | 0.375                         |
| 5              | 13/16 to 1           | 3/16         | 1/4     | 11/64        | 7/32    | 0.500                         |
| 6              | 1 1/16 to 1 1/4      | 3/16         | 1/4     | 11/64        | 7/32    | 0.625                         |
| 7              | 1 5/16 to 1 5/8      | 1/4          | 5/16    | 15/64        | 9/32    | 0.750                         |
| 8              | 1 11/16 to 2         | 1/4          | 5/16    | 15/64        | 9/32    | 1.000                         |
| 9              | 2 1/16 to 2 1/2      | 5/16         | 3/8     | 19/64        | 11/32   | 1.250                         |

All dimension are given in inches. The hole in shell reamers has a taper of 1/8 inch per foot, with arbors tapered to correspond. Shell reamer arbor tapers are made to permit a driving fit with the reamer.

**Straight Shank Chucking Reamers—Straight Flutes, Wire Gage Sizes**  
ANSI B94.2-1983 (R1988)

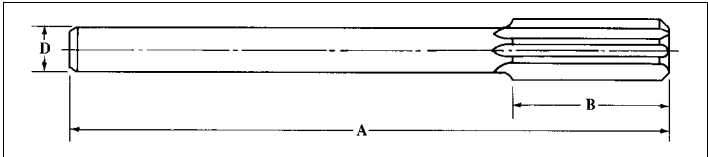


| Reamer Diameter |       | Lgth. Overall A | Lgth. of Flute B | Shank Dia. D |       | No. of Flutes | Reamer Diameter |       | Lgth. Overall A | Lgth. of Flute B | Shank Dia. D |       | No. of Flutes |
|-----------------|-------|-----------------|------------------|--------------|-------|---------------|-----------------|-------|-----------------|------------------|--------------|-------|---------------|
| Wire Gage       | Inch  |                 |                  | Max          | Min   |               | Wire Gage       | Inch  |                 |                  | Max          | Min   |               |
| 60              | .0400 | 2½              | ½                | .0390        | .0380 | 4             | 49              | .0730 | 3               | ¾                | .0660        | .0650 | 4             |
| 59              | .0410 | 2½              | ½                | .0390        | .0380 | 4             | 48              | .0760 | 3               | ¾                | .0720        | .0710 | 4             |
| 58              | .0420 | 2½              | ½                | .0390        | .0380 | 4             | 47              | .0785 | 3               | ¾                | .0720        | .0710 | 4             |
| 57              | .0430 | 2½              | ½                | .0390        | .0380 | 4             | 46              | .0810 | 3               | ¾                | .0771        | .0701 | 4             |
| 56              | .0465 | 2½              | ½                | .0455        | .0445 | 4             | 45              | .0820 | 3               | ¾                | .0771        | .0761 | 4             |
| 55              | .0520 | 2½              | ½                | .0510        | .0500 | 4             | 44              | .0860 | 3               | ¾                | .0810        | .0800 | 4             |
| 54              | .0550 | 2½              | ½                | .0510        | .0500 | 4             | 43              | .0890 | 3               | ¾                | .0810        | .0800 | 4             |
| 53              | .0595 | 2½              | ½                | .0585        | .0575 | 4             | 42              | .0935 | 3               | ¾                | .0880        | .0870 | 4             |
| 52              | .0635 | 2½              | ½                | .0585        | .0575 | 4             | 41              | .0960 | 3½              | ⅞                | .0928        | .0918 | 4 to 6        |
| 51              | .0670 | 3               | ¾                | .0660        | .0650 | 4             | 40              | .0980 | 3½              | ⅞                | .0928        | .0918 | 4 to 6        |
| 50              | .0700 | 3               | ¾                | .0660        | .0650 | 4             | 39              | .0995 | 3½              | ⅞                | .0928        | .0918 | 4 to 6        |
| 38              | .1015 | 3½              | ⅞                | .0950        | .0940 | 4 to 6        | 19              | .1660 | 4½              | 1⅞               | .1595        | .1585 | 4 to 6        |
| 37              | .1040 | 3½              | ⅞                | .0950        | .0940 | 4 to 6        | 18              | .1695 | 4½              | 1⅞               | .1595        | .1585 | 4 to 6        |
| 36              | .1065 | 3½              | ⅞                | .1030        | .1020 | 4 to 6        | 17              | .1730 | 4½              | 1⅞               | .1645        | .1635 | 4 to 6        |
| 35              | .1100 | 3½              | ⅞                | .1030        | .1020 | 4 to 6        | 16              | .1770 | 4½              | 1⅞               | .1704        | .1694 | 4 to 6        |
| 34              | .1110 | 3½              | ⅞                | .1055        | .1045 | 4 to 6        | 15              | .1800 | 4½              | 1⅞               | .1755        | .1745 | 4 to 6        |
| 33              | .1130 | 3½              | ⅞                | .1055        | .1045 | 4 to 6        | 14              | .1820 | 4½              | 1⅞               | .1755        | .1745 | 4 to 6        |
| 32              | .1160 | 3½              | ⅞                | .1120        | .1110 | 4 to 6        | 13              | .1850 | 4½              | 1⅞               | .1805        | .1795 | 4 to 6        |
| 31              | .1200 | 3½              | ⅞                | .1120        | .1110 | 4 to 6        | 12              | .1890 | 4½              | 1⅞               | .1805        | .1795 | 4 to 6        |
| 30              | .1285 | 3½              | ⅞                | .1190        | .1180 | 4 to 6        | 11              | .1910 | 5               | 1¼               | .1860        | .1850 | 4 to 6        |
| 29              | .1360 | 4               | 1                | .1275        | .1265 | 4 to 6        | 10              | .1935 | 5               | 1¼               | .1860        | .1850 | 4 to 6        |
| 28              | .1405 | 4               | 1                | .1350        | .1340 | 4 to 6        | 9               | .1960 | 5               | 1¼               | .1895        | .1885 | 4 to 6        |
| 27              | .1440 | 4               | 1                | .1350        | .1340 | 4 to 6        | 8               | .1990 | 5               | 1¼               | .1895        | .1885 | 4 to 6        |
| 26              | .1470 | 4               | 1                | .1430        | .1420 | 4 to 6        | 7               | .2010 | 5               | 1¼               | .1945        | .1935 | 4 to 6        |
| 25              | .1495 | 4               | 1                | .1430        | .1420 | 4 to 6        | 6               | .2040 | 5               | 1¼               | .1945        | .1935 | 4 to 6        |
| 24              | .1520 | 4               | 1                | .1460        | .1450 | 4 to 6        | 5               | .2055 | 5               | 1¼               | .2016        | .2006 | 4 to 6        |
| 23              | .1540 | 4               | 1                | .1460        | .1450 | 4 to 6        | 4               | .2090 | 5               | 1¼               | .2016        | .2006 | 4 to 6        |
| 22              | .1570 | 4               | 1                | .1510        | .1500 | 4 to 6        | 3               | .2130 | 5               | 1¼               | .2075        | .2065 | 4 to 6        |
| 21              | .1590 | 4½              | 1⅞               | .1530        | .1520 | 4 to 6        | 2               | 2210  | 6               | 1½               | .2173        | .2163 | 4 to 6        |
| 20              | .1610 | 4½              | 1⅞               | .1530        | .1520 | 4 to 6        | 1               | .2280 | 6               | 1½               | .2173        | .2163 | 4 to 6        |

All dimensions in inches. Material is high-speed steel.

*Tolerances:* On diameter of reamer, plus .0001 to plus .0004 inch. On overall length A, plus or minus ⅓<sub>16</sub> inch. On length of flute B, plus or minus ⅓<sub>16</sub> inch.

**Straight Shank Chucking Reamers—Straight Flutes, Letter Sizes**  
ANSI B94.2-1983 (R1988)

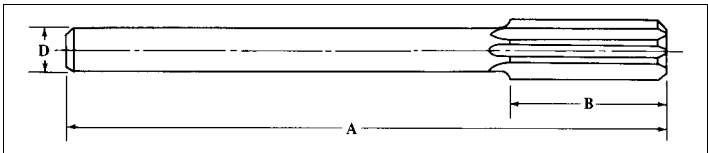


| Reamer Diameter |        | Lgth. Overall A | Lgth. of Flute B | Shank Dia. D |       | No. of Flutes | Reamer Diameter |        | Lgth. Overall A | Lgth. of Flute B | Shank Dia. D |        | No. of Flutes |
|-----------------|--------|-----------------|------------------|--------------|-------|---------------|-----------------|--------|-----------------|------------------|--------------|--------|---------------|
| Letter          | Inch   |                 |                  | Max          | Min   |               | Letter          | Inch   |                 |                  | Max          | Min    |               |
| A               | 0.2340 | 6               | 1½               | 0.2265       | .2255 | 4 to 6        | N               | 0.3020 | 6               | 1½               | 0.2792       | 0.2782 | 4 to 6        |
| B               | 0.2380 | 6               | 1½               | 0.2329       | .2319 | 4 to 6        | O               | 0.3160 | 6               | 1½               | 0.2792       | 0.2782 | 4 to 6        |
| C               | 0.2420 | 6               | 1½               | 0.2329       | .2319 | 4 to 6        | P               | 0.3230 | 6               | 1½               | 0.2792       | 0.2782 | 4 to 6        |
| D               | 0.2460 | 6               | 1½               | 0.2329       | .2319 | 4 to 6        | Q               | 0.3320 | 6               | 1½               | 0.2792       | 0.2782 | 4 to 6        |
| E               | 0.2500 | 6               | 1½               | 0.2405       | .2395 | 4 to 6        | R               | 0.3390 | 6               | 1½               | 0.2792       | 0.2782 | 4 to 6        |
| F               | 0.2570 | 6               | 1½               | 0.2485       | .2475 | 4 to 6        | S               | 0.3480 | 7               | 1¾               | 0.3105       | 0.3095 | 4 to 6        |
| G               | 0.2610 | 6               | 1½               | 0.2485       | .2475 | 4 to 6        | T               | 0.3580 | 7               | 1¾               | 0.3105       | 0.3095 | 4 to 6        |
| H               | 0.2660 | 6               | 1½               | 0.2485       | .2475 | 4 to 6        | U               | 0.3680 | 7               | 1¾               | 0.3105       | 0.3095 | 4 to 6        |
| I               | 0.2720 | 6               | 1½               | 0.2485       | .2475 | 4 to 6        | V               | 0.3770 | 7               | 1¾               | 0.3105       | 0.3095 | 4 to 6        |
| J               | 0.2770 | 6               | 1½               | 0.2485       | .2475 | 4 to 6        | W               | 0.3860 | 7               | 1¾               | 0.3105       | 0.3095 | 4 to 6        |
| K               | 0.2810 | 6               | 1½               | 0.2485       | .2475 | 4 to 6        | X               | 0.3970 | 7               | 1¾               | 0.3105       | 0.3095 | 4 to 6        |
| L               | 0.2900 | 6               | 1½               | 0.2792       | .2782 | 4 to 6        | Y               | 0.4040 | 7               | 1¾               | 0.3105       | 0.3095 | 4 to 6        |
| M               | 0.2950 | 6               | 1½               | 0.2792       | .2782 | 4 to 6        | Z               | 0.4130 | 7               | 1¾               | 0.3730       | 0.3720 | 6 to 8        |

All dimensions in inches. Material is high-speed steel.

*Tolerances:* On diameter of reamer, for sizes A to E, incl., plus .0001 to plus .0004 inch and for sizes F to Z, incl., plus .0001 to plus .0005 inch. On overall length A, plus or minus 1/16 inch. On length of flute B, plus or minus 1/16 inch.

**Straight Shank Chucking Reamers—Straight Flutes, Decimal Sizes**  
ANSI B94.2-1983 (R1988)

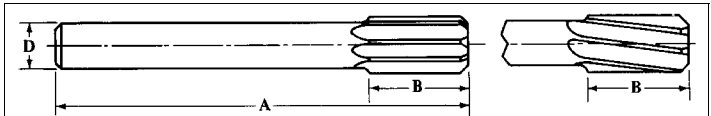


| Reamer Dia. | Lgth. Overall A | Lgth. of Flute B | Shank Diameter D |        | No. of Flutes | Reamer Dia. | Lgth. Overall A | Lgth. of Flute B | Shank Diameter D |        | No. of Flutes |
|-------------|-----------------|------------------|------------------|--------|---------------|-------------|-----------------|------------------|------------------|--------|---------------|
|             |                 |                  | Max.             | Min.   |               |             |                 |                  | Max.             | Min.   |               |
| 0.1240      | 3½              | 7/8              | 0.1190           | 0.1180 | 4 to 6        | 0.3135      | 6               | 1½               | 0.2792           | 0.2782 | 4 to 6        |
| 0.1260      | 3½              | 7/8              | 0.1190           | 0.1180 | 4 to 6        | 0.3740      | 7               | 1¾               | 0.3105           | 0.3095 | 6 to 8        |
| 0.1865      | 4½              | 1⅛               | 0.1805           | 0.1795 | 4 to 6        | 0.3760      | 7               | 1¾               | 0.3105           | 0.3095 | 6 to 8        |
| 0.1885      | 4½              | 1⅛               | 0.1805           | 0.1795 | 4 to 6        | 0.4365      | 7               | 1¾               | 0.3730           | 0.3720 | 6 to 8        |
| 0.2490      | 6               | 1½               | 0.2405           | 0.2395 | 4 to 6        | 0.4385      | 7               | 1¾               | 0.3730           | 0.3720 | 6 to 8        |
| 0.2510      | 6               | 1½               | 0.2405           | 0.2395 | 4 to 6        | 0.4990      | 8               | 2                | 0.4355           | 0.4345 | 6 to 8        |
| 0.3115      | 6               | 1½               | 0.2792           | 0.2782 | 4 to 6        | 0.5010      | 8               | 2                | 0.4355           | 0.4345 | 6 to 8        |

All dimensions in inches. Material is high-speed steel.

*Tolerances:* On diameter of reamer, for 0.124 to 0.249-inch sizes, plus .0001 to plus .0004 inch and for 0.251 to 0.501-inch sizes, plus .0001 to plus .0005 inch. On overall length A, plus or minus 1/16 inch. On length of flute B, plus or minus 1/16 inch.

**American National Standard Straight Shank Rose Chucking and Chucking Reamers—Straight and Helical Flutes, Fractional Sizes ANSI B94.2-1983 (R1988)**



| Reamer Diameter   |                   | Length Overall A | Flute Length B | Shank Dia. D |        | No. of Flutes |
|-------------------|-------------------|------------------|----------------|--------------|--------|---------------|
| Chucking          | Rose Chucking     |                  |                | Max          | Min    |               |
| 3/64 <sup>a</sup> | ...               | 2 1/2            | 1/2            | 0.0455       | 0.0445 | 4             |
| 1/16              | ...               | 2 1/2            | 1/2            | 0.0585       | 0.0575 | 4             |
| 5/64              | ...               | 3                | 3/4            | 0.0720       | 0.0710 | 4             |
| 3/32              | ...               | 3                | 3/4            | 0.0880       | 0.0870 | 4             |
| 7/64              | ...               | 3 1/2            | 7/8            | 0.1030       | 0.1020 | 4 to 6        |
| 1/8               | 1/8 <sup>a</sup>  | 3 1/2            | 7/8            | 0.1190       | 0.1180 | 4 to 6        |
| 9/64              | ...               | 4                | 1              | 0.1350       | 0.1340 | 4 to 6        |
| 5/32              | ...               | 4                | 1              | 0.1510       | 0.1500 | 4 to 6        |
| 11/64             | ...               | 4 1/2            | 1 1/8          | 0.1645       | 0.1635 | 4 to 6        |
| 3/16              | 3/16 <sup>a</sup> | 4 1/2            | 1 1/8          | 0.1805       | 0.1795 | 4 to 6        |
| 13/64             | ...               | 5                | 1 1/4          | 0.1945       | 0.1935 | 4 to 6        |
| 7/32              | ...               | 5                | 1 1/4          | 0.2075       | 0.2065 | 4 to 6        |
| 15/64             | ...               | 6                | 1 1/2          | 0.2265       | 0.2255 | 4 to 6        |
| 1/4               | 1/4 <sup>a</sup>  | 6                | 1 1/2          | 0.2405       | 0.2395 | 4 to 6        |
| 17/64             | ...               | 6                | 1 1/2          | 0.2485       | 0.2475 | 4 to 6        |
| 9/32              | ...               | 6                | 1 1/2          | 0.2485       | 0.2475 | 4 to 6        |
| 19/64             | ...               | 6                | 1 1/2          | 0.2792       | 0.2782 | 4 to 6        |
| 5/16              | 5/16 <sup>a</sup> | 6                | 1 1/2          | 0.2792       | 0.2782 | 4 to 6        |
| 21/64             | ...               | 6                | 1 1/2          | 0.2792       | 0.2782 | 4 to 6        |
| 11/32             | ...               | 6                | 1 1/2          | 0.2792       | 0.2782 | 4 to 6        |
| 23/64             | ...               | 7                | 1 3/4          | 0.3105       | 0.3095 | 4 to 6        |
| 3/8               | 3/8 <sup>a</sup>  | 7                | 1 3/4          | 0.3105       | 0.3095 | 4 to 6        |
| 25/64             | ...               | 7                | 1 3/4          | 0.3105       | 0.3095 | 4 to 6        |
| 13/32             | ...               | 7                | 1 3/4          | 0.3105       | 0.3095 | 4 to 6        |
| 27/64             | ...               | 7                | 1 3/4          | 0.3730       | 0.3720 | 6 to 8        |
| 7/16              | 7/16 <sup>a</sup> | 7                | 1 3/4          | 0.3730       | 0.3720 | 6 to 8        |
| 29/64             | ...               | 7                | 1 3/4          | 0.3730       | 0.3720 | 6 to 8        |
| 15/32             | ...               | 7                | 1 3/4          | 0.3730       | 0.3720 | 6 to 8        |
| 31/64             | ...               | 8                | 2              | 0.4355       | 0.4345 | 6 to 8        |
| 1/2               | 1/2 <sup>a</sup>  | 8                | 2              | 0.4355       | 0.4345 | 6 to 8        |
| 17/32             | ...               | 8                | 2              | 0.4355       | 0.4345 | 6 to 8        |
| 9/16              | ...               | 8                | 2              | 0.4355       | 0.4345 | 6 to 8        |
| 19/32             | ...               | 8                | 2              | 0.4355       | 0.4345 | 6 to 8        |
| 5/8               | ...               | 9                | 2 1/4          | 0.5620       | 0.5605 | 6 to 8        |
| 23/32             | ...               | 9                | 2 1/4          | 0.5620       | 0.5605 | 6 to 8        |
| 11/16             | ...               | 9                | 2 1/4          | 0.5620       | 0.5605 | 6 to 8        |
| 23/32             | ...               | 9                | 2 1/4          | 0.5620       | 0.5605 | 6 to 8        |
| 3/4               | ...               | 9 1/2            | 2 1/2          | 0.6245       | 0.6230 | 6 to 8        |
| 25/32             | ...               | 9 1/2            | 2 1/2          | 0.6245       | 0.6230 | 8 to 10       |
| 13/16             | ...               | 9 1/2            | 2 1/2          | 0.6245       | 0.6230 | 8 to 10       |
| 27/32             | ...               | 9 1/2            | 2 1/2          | 0.6245       | 0.6230 | 8 to 10       |
| 7/8               | ...               | 10               | 2 3/8          | 0.7495       | 0.7480 | 8 to 10       |
| 29/32             | ...               | 10               | 2 3/8          | 0.7495       | 0.7480 | 8 to 10       |
| 15/16             | ...               | 10               | 2 3/8          | 0.7495       | 0.7480 | 8 to 10       |
| 31/32             | ...               | 10               | 2 3/8          | 0.7495       | 0.7480 | 8 to 10       |
| 1                 | ...               | 10 1/2           | 2 3/4          | 0.8745       | 0.8730 | 8 to 12       |
| 1 1/16            | ...               | 10 1/2           | 2 3/4          | 0.8745       | 0.8730 | 8 to 12       |
| 1 1/8             | ...               | 11               | 2 3/8          | 0.8745       | 0.8730 | 8 to 12       |
| 1 1/16            | ...               | 11               | 2 3/8          | 0.9995       | 0.9980 | 8 to 12       |
| 1 1/4             | ...               | 11 1/2           | 3              | 0.9995       | 0.9980 | 8 to 12       |
| 1 5/16            | ...               | 11 1/2           | 3              | 0.9995       | 0.9980 | 10 to 12      |
| 1 3/8             | ...               | 12               | 3 1/4          | 0.9995       | 0.9980 | 10 to 12      |
| 1 7/16            | ...               | 12               | 3 1/4          | 1.2495       | 1.2480 | 10 to 12      |
| 1 1/2             | ...               | 12 1/2           | 3 1/2          | 1.2495       | 1.2480 | 10 to 12      |

<sup>a</sup> Reamer with straight flutes is standard only.

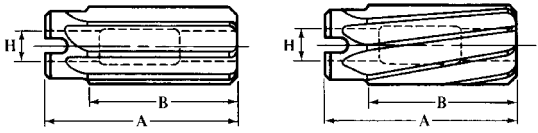
<sup>b</sup> Reamer with helical flutes is standard only.

All dimensions are given in inches. Material is high-speed steel. Chucking reamers are end cutting on the chamfer and the relief for the outside diameter is ground in back of the margin for the full length of land. Lands of rose chucking reamers are not relieved on the periphery but have a relatively large amount of back taper.

**Tolerances:** On reamer diameter, up to  $\frac{1}{4}$ -inch size, incl., +.0001 to +.0004 inch; over  $\frac{1}{4}$ - to 1-inch size, incl., +.0001 to +.0005 inch; over 1-inch size, +.0002 to +.0006 inch. On length overall *A* and flute length *B*, up to 1-inch size, incl.,  $\pm\frac{1}{16}$  inch;  $1\frac{1}{16}$ - to  $1\frac{1}{2}$ -inch size, incl.,  $\pm\frac{3}{32}$  inch.

Helical flutes are right- or left-hand helix, right-hand cut, except sizes  $1\frac{1}{16}$  through  $1\frac{1}{2}$  inches, which are right-hand helix only.

### Shell Reamers—Straight and Helical Flutes ANSI B94.2-1983 (R1988)



| Diameter of Reamer           | Length Overall <i>A</i> | Flute Length <i>B</i> | Hole Diameter Large End <i>H</i> | Fitting Arbor No. | Number of Flutes |
|------------------------------|-------------------------|-----------------------|----------------------------------|-------------------|------------------|
| $\frac{3}{4}$                | $2\frac{1}{4}$          | $1\frac{1}{2}$        | 0.375                            | 4                 | 8 to 10          |
| $\frac{7}{8}$                | $2\frac{1}{2}$          | $1\frac{3}{4}$        | 0.500                            | 5                 | 8 to 10          |
| $1\frac{5}{16}$ <sup>a</sup> | $2\frac{1}{2}$          | $1\frac{3}{4}$        | 0.500                            | 5                 | 8 to 10          |
| 1                            | $2\frac{1}{2}$          | $1\frac{3}{4}$        | 0.500                            | 5                 | 8 to 10          |
| $1\frac{1}{16}$              | $2\frac{3}{4}$          | 2                     | 0.625                            | 6                 | 8 to 12          |
| $1\frac{1}{8}$               | $2\frac{3}{4}$          | 2                     | 0.625                            | 6                 | 8 to 12          |
| $1\frac{3}{16}$              | $2\frac{3}{4}$          | 2                     | 0.625                            | 6                 | 8 to 12          |
| $1\frac{1}{4}$               | $2\frac{3}{4}$          | 2                     | 0.625                            | 6                 | 8 to 12          |
| $1\frac{5}{16}$              | 3                       | $2\frac{1}{4}$        | 0.750                            | 7                 | 8 to 12          |
| $1\frac{3}{8}$               | 3                       | $2\frac{1}{4}$        | 0.750                            | 7                 | 8 to 12          |
| $1\frac{7}{16}$              | 3                       | $2\frac{1}{4}$        | 0.750                            | 7                 | 8 to 12          |
| $1\frac{1}{2}$               | 3                       | $2\frac{1}{4}$        | 0.750                            | 7                 | 10 to 14         |
| $1\frac{9}{16}$              | 3                       | $2\frac{1}{4}$        | 0.750                            | 7                 | 10 to 14         |
| $1\frac{5}{8}$               | 3                       | $2\frac{1}{4}$        | 0.750                            | 7                 | 10 to 14         |
| $1\frac{11}{16}$             | $3\frac{1}{2}$          | $2\frac{1}{2}$        | 1.000                            | 8                 | 10 to 14         |
| $1\frac{3}{4}$               | $3\frac{1}{2}$          | $2\frac{1}{2}$        | 1.000                            | 8                 | 12 to 14         |
| $1\frac{13}{16}$             | $3\frac{1}{2}$          | $2\frac{1}{2}$        | 1.000                            | 8                 | 12 to 14         |
| $1\frac{7}{8}$               | $3\frac{1}{2}$          | $2\frac{1}{2}$        | 1.000                            | 8                 | 12 to 14         |
| $1\frac{15}{16}$             | $3\frac{1}{2}$          | $2\frac{1}{2}$        | 1.000                            | 8                 | 12 to 14         |
| 2                            | $3\frac{1}{2}$          | $2\frac{1}{2}$        | 1.000                            | 8                 | 12 to 14         |
| $2\frac{1}{16}$ <sup>a</sup> | $3\frac{3}{4}$          | $2\frac{3}{4}$        | 1.250                            | 9                 | 12 to 16         |
| $2\frac{1}{8}$               | $3\frac{3}{4}$          | $2\frac{3}{4}$        | 1.250                            | 9                 | 12 to 16         |
| $2\frac{3}{16}$ <sup>a</sup> | $3\frac{3}{4}$          | $2\frac{3}{4}$        | 1.250                            | 9                 | 12 to 16         |
| $2\frac{1}{4}$               | $3\frac{3}{4}$          | $2\frac{3}{4}$        | 1.250                            | 9                 | 12 to 16         |
| $2\frac{3}{8}$ <sup>a</sup>  | $3\frac{3}{4}$          | $2\frac{3}{4}$        | 1.250                            | 9                 | 14 to 16         |
| $2\frac{1}{2}$ <sup>a</sup>  | $3\frac{3}{4}$          | $2\frac{3}{4}$        | 1.250                            | 9                 | 14 to 16         |

<sup>a</sup> Helical flutes only.

All dimensions are given in inches. Material is high-speed steel. Helical flute shell reamers with left-hand helical flutes are standard. Shell reamers are designed as a sizing or finishing reamer and are held on an arbor provided with driving lugs. The holes in these reamers are ground with a taper of  $\frac{1}{8}$  inch per foot.

**Tolerances:** On diameter of reamer,  $\frac{3}{4}$ - to 1-inch size, incl., +.0001 to +.0005 inch; over 1-inch size, +.0002 to +.0006 inch. On length overall *A* and flute length *B*,  $\frac{3}{4}$ - to 1-inch size, incl.,  $\pm\frac{1}{16}$  inch;  $1\frac{1}{16}$ - to 2-inch size, incl.,  $\pm\frac{3}{32}$  inch;  $2\frac{1}{16}$ - to  $2\frac{1}{2}$ -inch size, incl.,  $\pm\frac{1}{8}$  inch.

**American National Standard Arbors for Shell Reamers—  
Straight and Taper Shanks ANSI B94.2-1983 (R1988)**

| Arbor Size No. | Overall Length A | Approx. Length of Taper L | Reamer Size | Taper Shank No. <sup>a</sup> | Straight Shank Dia. D | Arbor Size No. | Overall Length A | Approx. Length of Taper L | Reamer Size | Taper Shank No. <sup>a</sup> | Straight Shank Dia. D |
|----------------|------------------|---------------------------|-------------|------------------------------|-----------------------|----------------|------------------|---------------------------|-------------|------------------------------|-----------------------|
| 4              | 9                | 2¼                        | ¾           | 2                            | ½                     | 7              | 11               | 3                         | 1⅝ to 1⅜    | 3                            | ⅞                     |
| 5              | 9½               | 2½                        | ⅞ to 1      | 2                            | ⅝                     | 8              | 12               | 3½                        | 1⅞ to 2     | 4                            | 1⅛                    |
| 6              | 10               | 2¾                        | 1⅞ to 1¼    | 3                            | ¾                     | 9              | 13               | 3¾                        | 2⅞ to 2½    | 4                            | 1⅜                    |

<sup>a</sup> American National Standard self-holding tapers (see Table 7a on page 933.)

All dimensions are given in inches. These arbors are designed to fit standard shell reamers (see table). End which fits reamer has taper of ⅛ inch per foot.

**Stub Screw Machine Reamers—Helical Flutes ANSI B94.2-1983 (R1988)**

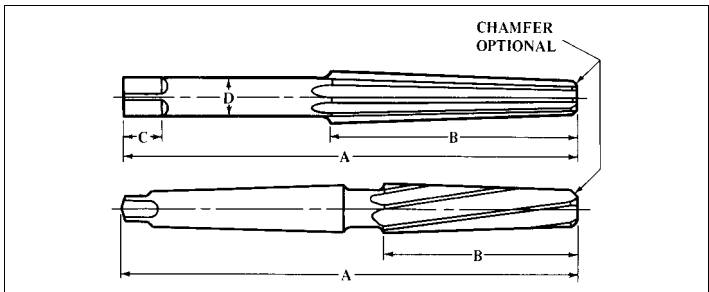
| Series No. | Diameter Range | Length Overall A | Length of Flute B | Dia. of Shank D | Size of Hole H | Flute No. | Series No. | Diameter Range | Length Overall A | Length of Flute B | Dia. of Shank D | Size of Hole H | Flute No. |
|------------|----------------|------------------|-------------------|-----------------|----------------|-----------|------------|----------------|------------------|-------------------|-----------------|----------------|-----------|
| 00         | .0600-.066     | 1¾               | ½                 | ⅞               | ⅞              | 4         | 12         | .3761-.407     | 2½               | 1¼                | ½               | ⅞              | 6         |
| 0          | .0661-.074     | 1¾               | ½                 | ⅞               | ⅞              | 4         | 13         | .4071-.439     | 2½               | 1¼                | ½               | ⅞              | 6         |
| 1          | .0741-.084     | 1¾               | ½                 | ⅞               | ⅞              | 4         | 14         | .4391-.470     | 2½               | 1¼                | ½               | ⅞              | 6         |
| 2          | .0841-.096     | 1¾               | ½                 | ⅞               | ⅞              | 4         | 15         | .4701-.505     | 2½               | 1¼                | ½               | ⅞              | 6         |
| 3          | .0961-.126     | 2                | ¾                 | ⅞               | ⅞              | 4         | 16         | .5051-.567     | 3                | 1½                | ⅞               | ¼              | 6         |
| 4          | .1261-.158     | 2¼               | 1                 | ¼               | ⅞              | 4         | 17         | .5671-.630     | 3                | 1½                | ⅞               | ¼              | 6         |
| 5          | .1581-.188     | 2¼               | 1                 | ¼               | ⅞              | 4         | 18         | .6301-.692     | 3                | 1½                | ⅞               | ¼              | 6         |
| 6          | .1881-.219     | 2¼               | 1                 | ¼               | ⅞              | 6         | 19         | .6921-.755     | 3                | 1½                | ¾               | ⅞              | 8         |
| 7          | .2191-.251     | 2¼               | 1                 | ¼               | ⅞              | 6         | 20         | .7551-.817     | 3                | 1½                | ¾               | ⅞              | 8         |
| 8          | .2511-.282     | 2¼               | 1                 | ⅞               | ⅞              | 6         | 21         | .8171-.880     | 3                | 1½                | ¾               | ⅞              | 8         |
| 9          | .2821-.313     | 2¼               | 1                 | ⅞               | ⅞              | 6         | 22         | .8801-.942     | 3                | 1½                | ¾               | ⅞              | 8         |
| 10         | .3131-.344     | 2½               | 1¼                | ⅞               | ⅞              | 6         | 23         | .9421-1.010    | 3                | 1½                | ¾               | ⅞              | 8         |
| 11         | .3441-.376     | 2½               | 1¼                | ⅞               | ⅞              | 6         | ...        | ...            | ...              | ...               | ...             | ...            | ...       |

All dimensions in inches. Material is high-speed steel.

These reamers are standard with right-hand cut and left-hand helical flutes within the size ranges shown.

**Tolerances:** On diameter of reamer, for sizes 00 to 7, incl., plus .0001 to plus .0004 inch and for sizes 8 to 23, incl., plus .0001 to plus .0005 inch. On overall length A, plus or minus ⅞ inch. On length of flute B, plus or minus ⅞ inch. On diameter of shank D, minus .0005 to minus .002 inch.

**American National Standard Morse Taper Finishing Reamers**  
ANSI B94.2-1983 (R1988)



Straight Flutes and Squared Shank

| Taper No. <sup>a</sup> | Small End Dia. (Ref.) | Large End Dia. (Ref.) | Length Overall A | Flute Length B  | Square Length C | Shank Dia. D    | Square Size |
|------------------------|-----------------------|-----------------------|------------------|-----------------|-----------------|-----------------|-------------|
| 0                      | 0.2503                | 0.3674                | 3 $\frac{3}{4}$  | 2 $\frac{1}{4}$ | $\frac{5}{16}$  | $\frac{5}{16}$  | 0.235       |
| 1                      | 0.3674                | 0.5170                | 5                | 3               | $\frac{7}{16}$  | $\frac{7}{16}$  | 0.330       |
| 2                      | 0.5696                | 0.7444                | 6                | 3 $\frac{1}{2}$ | $\frac{5}{8}$   | $\frac{5}{8}$   | 0.470       |
| 3                      | 0.7748                | 0.9881                | 7 $\frac{1}{4}$  | 4 $\frac{1}{4}$ | $\frac{7}{8}$   | $\frac{7}{8}$   | 0.655       |
| 4                      | 1.0167                | 1.2893                | 8 $\frac{1}{2}$  | 5 $\frac{1}{4}$ | 1               | 1 $\frac{1}{8}$ | 0.845       |
| 5                      | 1.4717                | 1.8005                | 9 $\frac{3}{4}$  | 6 $\frac{1}{4}$ | 1 $\frac{1}{8}$ | 1 $\frac{1}{2}$ | 1.125       |

Straight and Spiral Flutes and Taper Shank

| Taper No. <sup>a</sup> | Small End Dia. (Ref.) | Large End Dia. (Ref.) | Length Overall A | Flute Length B  | Taper Shank No. <sup>a</sup> | Squared and Taper Shank Number of Flutes |
|------------------------|-----------------------|-----------------------|------------------|-----------------|------------------------------|--|
| 0                      | 0.2503                | 0.3674                | 5 $\frac{1}{32}$ | 2 $\frac{1}{4}$ | 0                            | 4 to 6 incl.                             |
| 1                      | 0.3674                | 0.5170                | 6 $\frac{5}{16}$ | 3               | 1                            | 6 to 8 incl.                             |
| 2                      | 0.5696                | 0.7444                | 7 $\frac{3}{8}$  | 3 $\frac{1}{2}$ | 2                            | 6 to 8 incl.                             |
| 3                      | 0.7748                | 0.9881                | 8 $\frac{7}{8}$  | 4 $\frac{1}{4}$ | 3                            | 8 to 10 incl.                            |
| 4                      | 1.0167                | 1.2893                | 10 $\frac{7}{8}$ | 5 $\frac{1}{4}$ | 4                            | 8 to 10 incl.                            |
| 5                      | 1.4717                | 1.8005                | 13 $\frac{1}{8}$ | 6 $\frac{1}{4}$ | 5                            | 10 to 12 incl.                           |

<sup>a</sup>Morse. For amount of taper see [Table 1b](#) on page 928.

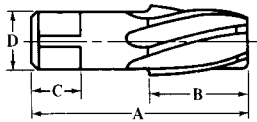
All dimensions are given in inches. Material is high-speed steel. The chamfer on the cutting end of the reamer is optional. Squared shank reamers are standard with straight flutes. Tapered shank reamers are standard with straight or spiral flutes. Spiral flute reamers are standard with left-hand spiral flutes.

**Tolerances:** On overall length *A* and flute length *B*, in taper numbers 0 to 3, incl.,  $\pm\frac{1}{16}$  inch, in taper numbers 4 and 5,  $\pm\frac{3}{32}$  inch. On length of square *C*, in taper numbers 0 to 3, incl.,  $\pm\frac{1}{32}$  inch; in taper numbers 4 and 5,  $\pm\frac{1}{16}$  inch. On shank diameter *D*,  $-.0005$  to  $-.002$  inch. On size of square, in taper numbers 0 and 1,  $-.004$  inch; in taper numbers 2 and 3,  $-.006$  inch; in taper numbers 4 and 5,  $-.008$  inch.

**Center Reamers.**—A “center reamer” is a reamer the teeth of which meet in a point. By their use small conical holes may be reamed in the ends of parts to be machined as on lathe centers. When large holes—usually cored—must be center-reamed, a large reamer is ordinarily used in which the teeth do not meet in a point, the reamer forming the frustum of a cone. Center reamers for such work are called “bull” or “pipe” center reamers.

**Bull Center Reamer:** A conical reamer used for reaming the ends of large holes—usually cored—so that they will fit on a lathe center. The cutting part of the reamer is generally in the shape of a frustum of a cone. It is also known as a pipe center reamer.



**Taper Pipe Reamers—Spiral Flutes ANSI B94.2-1983 (R1988)**

| Nom. Size | Diameter  |           | Length Overall A | Flute Length B | Square Length C | Shank Diameter D | Size of Square | No. of Flutes |
|-----------|-----------|-----------|------------------|----------------|-----------------|------------------|----------------|---------------|
|           | Large End | Small End |                  |                |                 |                  |                |               |
| 1/8       | 0.362     | 0.316     | 2 1/8            | 3/4            | 3/8             | 0.4375           | 0.328          | 4 to 6        |
| 1/4       | 0.472     | 0.406     | 2 1/16           | 1 1/16         | 7/16            | 0.5625           | 0.421          | 4 to 6        |
| 3/8       | 0.606     | 0.540     | 2 1/16           | 1 1/16         | 1/2             | 0.7000           | 0.531          | 4 to 6        |
| 1/2       | 0.751     | 0.665     | 3 3/8            | 1 3/8          | 5/8             | 0.6875           | 0.515          | 4 to 6        |
| 3/4       | 0.962     | 0.876     | 3 3/4            | 1 3/8          | 1 1/16          | 0.9063           | 0.679          | 6 to 10       |
| 1         | 1.212     | 1.103     | 3 3/4            | 1 3/4          | 1 1/16          | 1.1250           | 0.843          | 6 to 10       |
| 1 1/4     | 1.553     | 1.444     | 4                | 1 3/4          | 1 5/16          | 1.3125           | 0.984          | 6 to 10       |
| 1 1/2     | 1.793     | 1.684     | 4 1/4            | 1 3/4          | 1               | 1.5000           | 1.125          | 6 to 10       |
| 2         | 2.268     | 2.159     | 4 1/2            | 1 3/4          | 1 1/8           | 1.8750           | 1.406          | 8 to 12       |

All dimensions are given in inches. These reamers are tapered 3/4 inch per foot and are intended for reaming holes to be tapped with American National Standard Taper Pipe Thread taps. Material is high-speed steel. Reamers are standard with left-hand spiral flutes.

**Tolerances:** On length overall A and flute length B, 1/8- to 3/4-inch size, incl., ±1/16 inch; 1- to 1 1/2-inch size, incl., ±3/32 inch; 2-inch size, ±1/8 inch. On length of square C, 1/8- to 3/4-inch size, incl., ±1/32 inch; 1- to 2-inch size, incl., ±1/16 inch. On shank diameter D, 1/8-inch size, - .0015 inch; 1/4- to 1-inch size, incl., - .002 inch; 1 1/4- to 2-inch size, incl., - .003 inch. On size of square, 1/8-inch size, - .004 inch; 1/4- to 3/4-inch size, incl., - .006 inch; 1- to 2-inch size, incl., - .008 inch.

**B & S Taper Reamers—Straight and Spiral Flutes, Squared Shank**

| Taper No. <sup>a</sup> | Dia., Small End | Dia., Large End | Overall Length | Square Length | Flute Length | Dia. of Shank | Size of Square | No. of Flutes |
|------------------------|-----------------|-----------------|----------------|---------------|--------------|---------------|----------------|---------------|
| 1                      | 0.1974          | 0.3176          | 4 3/4          | 1/4           | 2 7/8        | 9/32          | 0.210          | 4 to 6        |
| 2                      | 0.2474          | 0.3781          | 5 1/8          | 5/16          | 3 1/8        | 1 1/32        | 0.255          | 4 to 6        |
| 3                      | 0.3099          | 0.4510          | 5 1/2          | 3/8           | 3 3/8        | 1 1/32        | 0.305          | 4 to 6        |
| 4                      | 0.3474          | 0.5017          | 5 7/8          | 7/16          | 3 1 1/16     | 7/16          | 0.330          | 4 to 6        |
| 5                      | 0.4474          | 0.6145          | 6 3/8          | 1/2           | 4            | 9/16          | 0.420          | 4 to 6        |
| 6                      | 0.4974          | 0.6808          | 6 7/8          | 5/8           | 4 3/8        | 5/8           | 0.470          | 4 to 6        |
| 7                      | 0.5974          | 0.8011          | 7 1/2          | 3/4           | 4 7/8        | 3/4           | 0.560          | 6 to 8        |
| 8                      | 0.7474          | 0.9770          | 8 1/8          | 13/16         | 5 1/2        | 1 1/16        | 0.610          | 6 to 8        |
| 9                      | 0.8974          | 1.1530          | 8 7/8          | 7/8           | 6 1/8        | 1             | 0.750          | 6 to 8        |
| 10                     | 1.0420          | 1.3376          | 9 3/4          | 1             | 6 7/8        | 1 1/8         | 0.845          | 6 to 8        |


<sup>a</sup> For taper per foot, see Table 10 on page 936.

These reamers are no longer ANSI Standard.

All dimensions are given in inches. Material is high-speed steel. The chamfer on the cutting end of the reamer is optional. All reamers are finishing reamers. Spiral flute reamers are standard with left-hand spiral flutes. (Tapered reamers, especially those with left-hand spirals, should not have circular lands because cutting must take place on the outer diameter of the tool.) B & S taper reamers are designed for use in reaming out Brown & Sharpe standard taper sockets.

**Tolerances:** On length overall A and flute length B, taper nos. 1 to 7, incl., ±1/16 inch; taper nos. 8 to 10, incl., ±3/32 inch. On length of square C, taper nos. 1 to 9, incl., ±1/32 inch; taper no. 10, ±1/16 inch. On shank diameter D, - .0005 to - .002 inch. On size of square, taper nos. 1 to 3, incl., - .004 inch; taper nos. 4 to 9, incl., - .006 inch; taper no. 10, - .008 inch.

American National Standard Die-Maker's Reamers ANSI B94.2-1983 (R1988)




| Letter Size | Diameter  |           | Length |    | Letter Size | Diameter  |           | Length |    | Letter Size | Diameter  |           | Length |    |
|-------------|-----------|-----------|--------|----|-------------|-----------|-----------|--------|----|-------------|-----------|-----------|--------|----|
|             | Small End | Large End | A      | B  |             | Small End | Large End | A      | B  |             | Small End | Large End | A      | B  |
| AAA         | 0.055     | 0.070     | 2¼     | 1¼ | G           | 0.135     | 0.158     | 3      | 1¾ | O           | 0.250     | 0.296     | 5      | 3½ |
| AA          | 0.065     | 0.080     | 2¼     | 1¼ | H           | 0.145     | 0.169     | 3¼     | 1¾ | P           | 0.275     | 0.327     | 5½     | 4  |
| A           | 0.075     | 0.090     | 2¼     | 1¼ | I           | 0.160     | 0.184     | 3¼     | 1¾ | Q           | 0.300     | 0.358     | 6      | 4½ |
| B           | 0.085     | 0.103     | 2¾     | 1¾ | J           | 0.175     | 0.199     | 3¼     | 1¾ | R           | 0.335     | 0.397     | 6½     | 4¾ |
| C           | 0.095     | 0.113     | 2½     | 1¾ | K           | 0.190     | 0.219     | 3½     | 2¼ | S           | 0.370     | 0.435     | 6¾     | 5  |
| D           | 0.105     | 0.126     | 2¾     | 1¾ | L           | 0.205     | 0.234     | 3½     | 2¼ | T           | 0.405     | 0.473     | 7      | 5¼ |
| E           | 0.115     | 0.136     | 2¾     | 1¾ | M           | 0.220     | 0.252     | 4      | 2½ | U           | 0.440     | 0.511     | 7¼     | 5½ |
| F           | 0.125     | 0.148     | 3      | 1¾ | N           | 0.235     | 0.274     | 4½     | 3  | ...         | ...       | ...       | ...    |    |

All dimensions in inches. Material is high-speed steel. These reamers are designed for use in die-making, have a taper of ¾ degree included angle or 0.013 inch per inch, and have 2 or 3 flutes. Reamers are standard with left-hand spiral flutes.

Tip of reamer may have conical end.

Tolerances: On length overall A and flute length B, ±1/16 inch.

Taper Pin Reamers — Straight and Left-Hand Spiral Flutes, Squared Shank; and Left-Hand High-Spiral Flutes, Round Shank ANSI B94.2-1983 (R1988)



| No. of Taper Pin Reamer | Diameter at Large End of Reamer (Ref.) | Diameter at Small End of Reamer (Ref.) | Overall Length of Reamer A | Length of Flute B | Length of Square C <sup>a</sup> | Diameter of Shank D | Size of Square <sup>b</sup> |
|-------------------------|--|--|----------------------------|-------------------|---------------------------------|---------------------|-----------------------------|
| 8/0 <sup>b</sup>        | 0.0514                                 | 0.0351                                 | 1¼                         | 25/32             | ...                             | 1/16                | ...                         |
| 7/0                     | 0.0666                                 | 0.0497                                 | 1 13/16                    | 13/16             | 5/32                            | 5/64                | 0.060                       |
| 6/0                     | 0.0806                                 | 0.0611                                 | 1 15/16                    | 15/16             | 5/32                            | 3/32                | 0.070                       |
| 5/0                     | 0.0966                                 | 0.0719                                 | 2 1/8                      | 1 1/8             | 5/32                            | 7/64                | 0.080                       |
| 4/0                     | 0.1142                                 | 0.0869                                 | 2 5/16                     | 1 5/16            | 5/32                            | 1/8                 | 0.095                       |
| 3/0                     | 0.1302                                 | 0.1029                                 | 2 3/8                      | 1 3/8             | 5/32                            | 9/64                | 0.105                       |
| 2/0                     | 0.1462                                 | 0.1137                                 | 2 7/16                     | 1 7/16            | 5/32                            | 5/32                | 0.115                       |
| 0                       | 0.1638                                 | 0.1287                                 | 2 15/16                    | 1 11/16           | 7/32                            | 1/16                | 0.130                       |
| 1                       | 0.1798                                 | 0.1447                                 | 2 15/16                    | 1 11/16           | 7/32                            | 3/16                | 0.140                       |
| 2                       | 0.2008                                 | 0.1605                                 | 3 3/8                      | 1 15/16           | 1/4                             | 13/64               | 0.150                       |
| 3                       | 0.2294                                 | 0.1813                                 | 3 11/16                    | 2 5/16            | 1/4                             | 15/64               | 0.175                       |
| 4                       | 0.2604                                 | 0.2071                                 | 4 1/8                      | 2 3/8             | 1/4                             | 1/16                | 0.200                       |
| 5                       | 0.2994                                 | 0.2409                                 | 4 5/8                      | 2 13/16           | 5/16                            | 5/16                | 0.235                       |
| 6                       | 0.3540                                 | 0.2773                                 | 5 7/16                     | 3 11/16           | 3/8                             | 23/64               | 0.270                       |
| 7                       | 0.4220                                 | 0.3297                                 | 6 3/8                      | 4 3/8             | 3/8                             | 13/32               | 0.305                       |
| 8                       | 0.5050                                 | 0.3971                                 | 7 3/8                      | 5 3/8             | 7/16                            | 7/16                | 0.330                       |
| 9                       | 0.6066                                 | 0.4805                                 | 8 5/8                      | 6 1/8             | 9/16                            | 9/16                | 0.420                       |
| 10                      | 0.7216                                 | 0.5799                                 | 9 5/8                      | 6 13/16           | 5/8                             | 5/8                 | 0.470                       |

<sup>a</sup> Not applicable to high-spiral flute reamers.

<sup>b</sup> Not applicable to straight and left-hand spiral fluted, squared shank reamers.

All dimensions in inches. Reamers have a taper of ¼ inch per foot and are made of high-speed steel. Straight flute reamers of carbon steel are also standard. The number of flutes is as follows; 3 or 4, for 7/0 to 4/0 sizes; 4 to 6, for 3/0 to 0 sizes; 5 or 6, for 1 to 5 sizes; 6 to 8, for 6 to 9 sizes; 7 or 8, for the 10 size in the case of straight- and spiral-flute reamers; and 2 or 3, for 8/0 to 8 sizes; 2 to 4, for the 9 and 10 sizes in the case of high-spiral flute reamers.

Tolerances: On length overall A and flute length B, ±1/16 inch. On length of square C, ±1/32 inch. On shank diameter D, -.001 to -.005 inch for straight- and spiral-flute reamers and -.0005 to -.002 inch for high-spiral flute reamers. On size of square, -.004 inch for 7/0 to 7 sizes and -.006 inch for 8 to 10 sizes.

## TWIST DRILLS AND COUNTERBORES

Twist drills are rotary end-cutting tools having one or more cutting lips and one or more straight or helical flutes for the passage of chips and cutting fluids. Twist drills are made with straight or tapered shanks, but most have straight shanks. All but the smaller sizes are ground with "back taper," reducing the diameter from the point toward the shank, to prevent binding in the hole when the drill is worn.

*Straight Shank Drills:* Straight shank drills have cylindrical shanks which may be of the same or of a different diameter than the body diameter of the drill and may be made with or without driving flats, tang, or grooves.

*Taper Shank Drills:* Taper shank drills are preferable to the straight shank type for drilling medium and large size holes. The taper on the shank conforms to one of the tapers in the American Standard (Morse) Series.

**American National Standard.**—American National Standard B94.11M-1993 covers nomenclature, definitions, sizes and tolerances for High Speed Steel Straight and Taper Shank Drills and Combined Drills and Countersinks, Plain and Bell types. It covers both inch and metric sizes. Dimensional tables from the Standard will be found on the following pages.

**Definitions of Twist Drill Terms.**—The following definitions are included in the Standard.

*Axis:* The imaginary straight line which forms the longitudinal center of the drill.

*Back Taper:* A slight decrease in diameter from point to back in the body of the drill.

*Body:* The portion of the drill extending from the shank or neck to the outer corners of the cutting lips.

*Body Diameter Clearance:* That portion of the land that has been cut away so it will not rub against the wall of the hole.

*Chisel Edge:* The edge at the ends of the web that connects the cutting lips.

*Chisel Edge Angle:* The angle included between the chisel edge and the cutting lip as viewed from the end of the drill.

*Clearance Diameter:* The diameter over the cutaway portion of the drill lands.

*Drill Diameter:* The diameter over the margins of the drill measured at the point.

*Flutes:* Helical or straight grooves cut or formed in the body of the drill to provide cutting lips, to permit removal of chips, and to allow cutting fluid to reach the cutting lips.

*Helix Angle:* The angle made by the leading edge of the land with a plane containing the axis of the drill.

*Land:* The peripheral portion of the drill body between adjacent flutes.

*Land Width:* The distance between the leading edge and the heel of the land measured at a right angle to the leading edge.

*Lips—Two Flute Drill:* The cutting edges extending from the chisel edge to the periphery.

*Lips—Three or Four Flute Drill (Core Drill):* The cutting edges extending from the bottom of the chamfer to the periphery.

*Lip Relief:* The axial relief on the drill point.

*Lip Relief Angle:* The axial relief angle at the outer corner of the lip. It is measured by projection into a plane tangent to the periphery at the outer corner of the lip. (Lip relief angle is usually measured across the margin of the twist drill.)

*Margin:* The cylindrical portion of the land which is not cut away to provide clearance.

*Neck:* The section of reduced diameter between the body and the shank of a drill.

*Overall Length:* The length from the extreme end of the shank to the outer corners of the cutting lips. It does not include the conical shank end often used on straight shank drills, nor does it include the conical cutting point used on both straight and taper shank drills. (For core drills with an external center on the cutting end it is the same as for two-flute

drills. For core drills with an internal center on the cutting end, the overall length is to the extreme ends of the tool.)

**Point:** The cutting end of a drill made up of the ends of the lands, the web, and the lips. In form, it resembles a cone, but departs from a true cone to furnish clearance behind the cutting lips.

**Point Angle:** The angle included between the lips projected upon a plane parallel to the drill axis and parallel to the cutting lips.

**Shank:** The part of the drill by which it is held and driven.

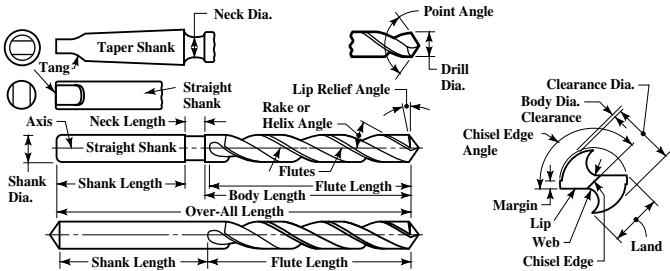
**Tang:** The flattened end of a taper shank, intended to fit into a driving slot in the socket.

**Tang Drive:** Two opposite parallel driving flats on the end of a straight shank.

**Web:** The central portion of the body that joins the end of the lands. The end of the web forms the chisel edge on a two-flute drill.

**Web Thickness:** The thickness of the web at the point unless another specific location is indicated.

**Web Thinning:** The operation of reducing the web thickness at the point to reduce drill-thrust.



ANSI Standard Twist Drill Nomenclature

**Types of Drills.**—Drills may be classified based on the type of shank, number of flutes or hand of cut.

**Straight Shank Drills:** Those having cylindrical shanks which may be the same or different diameter than the body of the drill. The shank may be with or without driving flats, tang, grooves, or threads.

**Taper Shank Drills:** Those having conical shanks suitable for direct fitting into tapered holes in machine spindles, driving sleeves, or sockets. Tapered shanks generally have a driving tang.

**Two-Flute Drills:** The conventional type of drill used for originating holes.

**Three-Flute Drills (Core Drills):** Drill commonly used for enlarging and finishing drilled, cast or punched holes. They will not produce original holes.

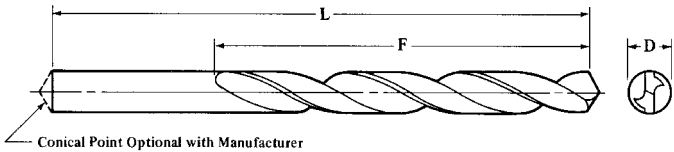
**Four-Flute Drills (Core Drills):** Used interchangeably with three-flute drills. They are of similar construction except for the number of flutes.

**Right-Hand Cut:** When viewed from the cutting point, the counterclockwise rotation of a drill in order to cut.

**Left-Hand Cut:** When viewed from the cutting point, the clockwise rotation of a drill in order to cut.

**Teat Drill:** The cutting edges of a teat drill are at right angles to the axis, and in the center there is a small teat of pyramid shape which leads the drill and holds it in position. This form is used for squaring the bottoms of holes made by ordinary twist drills or for drilling the entire hole, especially if it is not very deep and a square bottom is required. For instance, when drilling holes to form clearance spaces at the end of a keyseat, preparatory to cutting it out by planing or chipping, the teat drill is commonly used.

TWIST DRILLS



**Table 1. ANSI Straight Shank Twist Drills — Jobbers Length through 17.5 mm, Taper Length through 12.7 mm, and Screw Machine Length through 25.4 mm Diameter ANSI/ASME B94.11M-1993**

| Drill Diameter, $D^{\circ}$ |      |             |       | Jobbers Length |     |         |    | Taper Length |     |         |     | Screw Machine Length |     |         |    |
|-----------------------------|------|-------------|-------|----------------|-----|---------|----|--------------|-----|---------|-----|----------------------|-----|---------|----|
| Fraction No. or Ltr.        | mm   | Equivalent  |       | Flute          |     | Overall |    | Flute        |     | Overall |     | Flute                |     | Overall |    |
|                             |      | Decimal In. | mm    | $F$            |     | $L$     |    | $F$          |     | $L$     |     | $F$                  |     | $L$     |    |
|                             |      |             |       | Inch           | mm  | Inch    | mm | Inch         | mm  | Inch    | mm  | Inch                 | mm  | Inch    | mm |
| 97                          | 0.15 | 0.0059      | 0.150 | 1/16           | 1.6 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 96                          | 0.16 | 0.0063      | 0.160 | 1/16           | 1.6 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 95                          | 0.17 | 0.0067      | 0.170 | 1/16           | 1.6 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 94                          | 0.18 | 0.0071      | 0.180 | 1/16           | 1.6 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 93                          | 0.19 | 0.0075      | 0.190 | 1/16           | 1.6 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 92                          | 0.20 | 0.0079      | 0.200 | 1/16           | 1.6 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 91                          |      | 0.0083      | 0.211 | 5/64           | 2.0 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 90                          | 0.22 | 0.0087      | 0.221 | 5/64           | 2.0 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 89                          |      | 0.0091      | 0.231 | 5/64           | 2.0 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 88                          |      | 0.0095      | 0.241 | 5/64           | 2.0 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
|                             | 0.25 | 0.0098      | 0.250 | 5/64           | 2.0 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 87                          |      | 0.0100      | 0.254 | 5/64           | 2.0 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 86                          |      | 0.0105      | 0.267 | 3/32           | 2.4 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 85                          | 0.28 | 0.0110      | 0.280 | 3/32           | 2.4 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 84                          |      | 0.0115      | 0.292 | 3/32           | 2.4 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
|                             | 0.30 | 0.0118      | 0.300 | 3/32           | 2.4 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 83                          |      | 0.0120      | 0.305 | 3/32           | 2.4 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 82                          |      | 0.0125      | 0.318 | 3/32           | 2.4 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
|                             | 0.32 | 0.0126      | 0.320 | 3/32           | 2.4 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 81                          |      | 0.0130      | 0.330 | 3/32           | 2.4 | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 80                          |      | 0.0135      | 0.343 | 1/8            | 3   | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
|                             | 0.35 | 0.0138      | 0.350 | 1/8            | 3   | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 79                          |      | 0.0145      | 0.368 | 1/8            | 3   | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
|                             | 0.38 | 0.0150      | 0.380 | 3/16           | 5   | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 1/64                        |      | 0.0156      | 0.396 | 3/16           | 5   | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
|                             | 0.40 | 0.0157      | 0.400 | 3/16           | 5   | 3/4     | 19 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 78                          |      | 0.0160      | 0.406 | 3/16           | 5   | 7/8     | 22 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
|                             | 0.42 | 0.0165      | 0.420 | 3/16           | 5   | 7/8     | 22 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
|                             | 0.45 | 0.0177      | 0.450 | 3/16           | 5   | 7/8     | 22 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 77                          |      | 0.0180      | 0.457 | 3/16           | 5   | 7/8     | 22 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
|                             | 0.48 | 0.0189      | 0.480 | 3/16           | 5   | 7/8     | 22 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
|                             | 0.50 | 0.0197      | 0.500 | 3/16           | 5   | 7/8     | 22 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 76                          |      | 0.0200      | 0.508 | 3/16           | 5   | 7/8     | 22 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 75                          |      | 0.0210      | 0.533 | 1/4            | 6   | 1       | 25 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
|                             | 0.55 | 0.0217      | 0.550 | 1/4            | 6   | 1       | 25 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
| 74                          |      | 0.0225      | 0.572 | 1/4            | 6   | 1       | 25 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |
|                             | 0.60 | 0.0236      | 0.600 | 5/16           | 8   | 1 1/8   | 29 | ...          | ... | ...     | ... | ...                  | ... | ...     |    |

**Table 1. (Continued) ANSI Straight Shank Twist Drills — Jobbers Length through 17.5 mm, Taper Length through 12.7 mm, and Screw Machine Length through 25.4 mm Diameter ANSI/ASME B94.11M-1993**

| Drill Diameter, $D^a$           |      |                |       | Jobbers Length  |    |                |    | Taper Length   |     |                |     | Screw Machine Length |     |                  |     |
|---------------------------------|------|----------------|-------|-----------------|----|----------------|----|----------------|-----|----------------|-----|----------------------|-----|------------------|-----|
| Frac-<br>tion<br>No. or<br>Ltr. | mm   | Equivalent     |       | Flute           |    | Overall        |    | Flute          |     | Overall        |     | Flute                |     | Overall          |     |
|                                 |      | Decimal<br>In. | mm    | $F$             |    | $L$            |    | $F$            |     | $L$            |     | $F$                  |     | $L$              |     |
|                                 |      |                |       | Inch            | mm | Inch           | mm | Inch           | mm  | Inch           | mm  | Inch                 | mm  | Inch             | mm  |
| 73                              |      | 0.0240         | 0.610 | $\frac{5}{16}$  | 8  | $1\frac{1}{8}$ | 29 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| 72                              |      | 0.0250         | 0.635 | $\frac{5}{16}$  | 8  | $1\frac{1}{8}$ | 29 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
|                                 | 0.65 | 0.0256         | 0.650 | $\frac{3}{8}$   | 10 | $1\frac{1}{4}$ | 32 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| 71                              |      | 0.0260         | 0.660 | $\frac{3}{8}$   | 10 | $1\frac{1}{4}$ | 32 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
|                                 | 0.70 | 0.0276         | 0.700 | $\frac{3}{8}$   | 10 | $1\frac{1}{4}$ | 32 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| 70                              |      | 0.0280         | 0.711 | $\frac{3}{8}$   | 10 | $1\frac{1}{4}$ | 32 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| 69                              |      | 0.0292         | 0.742 | $\frac{1}{2}$   | 13 | $1\frac{3}{8}$ | 35 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
|                                 | 0.75 | 0.0295         | 0.750 | $\frac{1}{2}$   | 13 | $1\frac{3}{8}$ | 35 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| 68                              |      | 0.0310         | 0.787 | $\frac{1}{2}$   | 13 | $1\frac{3}{8}$ | 35 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| $\frac{1}{32}$                  |      | 0.0312         | 0.792 | $\frac{1}{2}$   | 13 | $1\frac{3}{8}$ | 35 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
|                                 | 0.80 | 0.0315         | 0.800 | $\frac{1}{2}$   | 13 | $1\frac{3}{8}$ | 35 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| 67                              |      | 0.0320         | 0.813 | $\frac{1}{2}$   | 13 | $1\frac{3}{8}$ | 35 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| 66                              |      | 0.0330         | 0.838 | $\frac{1}{2}$   | 13 | $1\frac{3}{8}$ | 35 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
|                                 | 0.85 | 0.0335         | 0.850 | $\frac{5}{8}$   | 16 | $1\frac{1}{2}$ | 38 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| 65                              |      | 0.0350         | 0.889 | $\frac{5}{8}$   | 16 | $1\frac{1}{2}$ | 38 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
|                                 | 0.90 | 0.0354         | 0.899 | $\frac{5}{8}$   | 16 | $1\frac{1}{2}$ | 38 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| 64                              |      | 0.0360         | 0.914 | $\frac{5}{8}$   | 16 | $1\frac{1}{2}$ | 38 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| 63                              |      | 0.0370         | 0.940 | $\frac{5}{8}$   | 16 | $1\frac{1}{2}$ | 38 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
|                                 | 0.95 | 0.0374         | 0.950 | $\frac{5}{8}$   | 16 | $1\frac{1}{2}$ | 38 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| 62                              |      | 0.0380         | 0.965 | $\frac{5}{8}$   | 16 | $1\frac{1}{2}$ | 38 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
| 61                              |      | 0.0390         | 0.991 | $\frac{11}{16}$ | 17 | $1\frac{3}{8}$ | 41 | ...            | ... | ...            | ... | ...                  | ... | ...              | ... |
|                                 | 1.00 | 0.0394         | 1.000 | $\frac{11}{16}$ | 17 | $1\frac{3}{8}$ | 41 | $1\frac{1}{8}$ | 29  | $2\frac{1}{4}$ | 57  | $\frac{1}{2}$        | 13  | $1\frac{3}{8}$   | 35  |
| 60                              |      | 0.0400         | 1.016 | $\frac{11}{16}$ | 17 | $1\frac{3}{8}$ | 41 | $1\frac{1}{8}$ | 29  | $2\frac{1}{4}$ | 57  | $\frac{1}{2}$        | 13  | $1\frac{3}{8}$   | 35  |
| 59                              |      | 0.0410         | 1.041 | $\frac{11}{16}$ | 17 | $1\frac{3}{8}$ | 41 | $1\frac{1}{8}$ | 29  | $2\frac{1}{4}$ | 57  | $\frac{1}{2}$        | 13  | $1\frac{3}{8}$   | 35  |
|                                 | 1.05 | 0.0413         | 1.050 | $\frac{11}{16}$ | 17 | $1\frac{3}{8}$ | 41 | $1\frac{1}{8}$ | 29  | $2\frac{1}{4}$ | 57  | $\frac{1}{2}$        | 13  | $1\frac{3}{8}$   | 35  |
| 58                              |      | 0.0420         | 1.067 | $\frac{11}{16}$ | 17 | $1\frac{3}{8}$ | 41 | $1\frac{1}{8}$ | 29  | $2\frac{1}{4}$ | 57  | $\frac{1}{2}$        | 13  | $1\frac{3}{8}$   | 35  |
| 57                              |      | 0.0430         | 1.092 | $\frac{3}{4}$   | 19 | $1\frac{3}{4}$ | 44 | $1\frac{1}{8}$ | 29  | $2\frac{1}{4}$ | 57  | $\frac{1}{2}$        | 13  | $1\frac{3}{8}$   | 35  |
|                                 | 1.10 | 0.0433         | 1.100 | $\frac{3}{4}$   | 19 | $1\frac{3}{4}$ | 44 | $1\frac{1}{8}$ | 29  | $2\frac{1}{4}$ | 57  | $\frac{1}{2}$        | 13  | $1\frac{3}{8}$   | 35  |
|                                 | 1.15 | 0.0453         | 1.150 | $\frac{3}{4}$   | 19 | $1\frac{3}{4}$ | 44 | $1\frac{1}{8}$ | 29  | $2\frac{1}{4}$ | 57  | $\frac{1}{2}$        | 13  | $1\frac{3}{8}$   | 35  |
| 56                              |      | 0.0465         | 1.181 | $\frac{3}{4}$   | 19 | $1\frac{3}{4}$ | 44 | $1\frac{1}{8}$ | 29  | $2\frac{1}{4}$ | 57  | $\frac{1}{2}$        | 13  | $1\frac{3}{8}$   | 35  |
| $\frac{3}{64}$                  |      | 0.0469         | 1.191 | $\frac{3}{4}$   | 19 | $1\frac{3}{4}$ | 44 | $1\frac{1}{8}$ | 29  | $2\frac{1}{4}$ | 57  | $\frac{1}{2}$        | 13  | $1\frac{3}{8}$   | 35  |
|                                 | 1.20 | 0.0472         | 1.200 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | $1\frac{3}{4}$ | 44  | 3              | 76  | $\frac{5}{8}$        | 16  | $1\frac{3}{8}$   | 41  |
|                                 | 1.25 | 0.0492         | 1.250 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | $1\frac{3}{4}$ | 44  | 3              | 76  | $\frac{5}{8}$        | 16  | $1\frac{3}{8}$   | 41  |
|                                 | 1.30 | 0.0512         | 1.300 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | $1\frac{3}{4}$ | 44  | 3              | 76  | $\frac{5}{8}$        | 16  | $1\frac{3}{8}$   | 41  |
| 55                              |      | 0.0520         | 1.321 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | $1\frac{3}{4}$ | 44  | 3              | 76  | $\frac{5}{8}$        | 16  | $1\frac{3}{8}$   | 41  |
|                                 | 1.35 | 0.0531         | 1.350 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | $1\frac{3}{4}$ | 44  | 3              | 76  | $\frac{5}{8}$        | 16  | $1\frac{3}{8}$   | 41  |
| 54                              |      | 0.0550         | 1.397 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | $1\frac{3}{4}$ | 44  | 3              | 76  | $\frac{5}{8}$        | 16  | $1\frac{3}{8}$   | 41  |
|                                 | 1.40 | 0.0551         | 1.400 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | $1\frac{3}{4}$ | 44  | 3              | 76  | $\frac{5}{8}$        | 16  | $1\frac{3}{8}$   | 41  |
|                                 | 1.45 | 0.0571         | 1.450 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | $1\frac{3}{4}$ | 44  | 3              | 76  | $\frac{5}{8}$        | 16  | $1\frac{3}{8}$   | 41  |
|                                 | 1.50 | 0.0591         | 1.500 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | $1\frac{3}{4}$ | 44  | 3              | 76  | $\frac{5}{8}$        | 16  | $1\frac{3}{8}$   | 41  |
| 53                              |      | 0.0595         | 1.511 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | $1\frac{3}{4}$ | 44  | 3              | 76  | $\frac{5}{8}$        | 16  | $1\frac{3}{8}$   | 41  |
|                                 | 1.55 | 0.0610         | 1.550 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | $1\frac{3}{4}$ | 44  | 3              | 76  | $\frac{5}{8}$        | 16  | $1\frac{3}{8}$   | 41  |
| $\frac{1}{16}$                  |      | 0.0625         | 1.588 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | $1\frac{3}{4}$ | 44  | 3              | 76  | $\frac{5}{8}$        | 16  | $1\frac{3}{8}$   | 41  |
|                                 | 1.60 | 0.0630         | 1.600 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | 2              | 51  | $3\frac{3}{4}$ | 95  | $\frac{11}{16}$      | 17  | $1\frac{11}{16}$ | 43  |
| 52                              |      | 0.0635         | 1.613 | $\frac{7}{8}$   | 22 | $1\frac{7}{8}$ | 48 | 2              | 51  | $3\frac{3}{4}$ | 95  | $\frac{11}{16}$      | 17  | $1\frac{11}{16}$ | 43  |
|                                 | 1.65 | 0.0650         | 1.650 | 1               | 25 | 2              | 51 | 2              | 51  | $3\frac{3}{4}$ | 95  | $\frac{11}{16}$      | 17  | $1\frac{11}{16}$ | 43  |

**Table 1. (Continued) ANSI Straight Shank Twist Drills — Jobbers Length through 17.5 mm, Taper Length through 12.7 mm, and Screw Machine Length through 25.4 mm Diameter ANSI/ASME B94.11M-1993**

| Drill Diameter, $D^a$           |                | Jobbers Length |       |                  |    |                 |    | Taper Length    |    |                 |     | Screw Machine Length |     |                  |    |
|---------------------------------|----------------|----------------|-------|------------------|----|-----------------|----|-----------------|----|-----------------|-----|----------------------|-----|------------------|----|
| Frac-<br>tion<br>No. or<br>Ltr. | mm             | Equivalent     |       | Flute            |    | Overall         |    | Flute           |    | Overall         |     | Flute                |     | Overall          |    |
|                                 |                | Decimal<br>In. | mm    | $F$              |    | $L$             |    | $F$             |    | $L$             |     | $F$                  |     | $L$              |    |
|                                 |                |                |       | Inch             | mm | Inch            | mm | Inch            | mm | Inch            | mm  | Inch                 | mm  | Inch             | mm |
| 51                              | 1.70           | 0.0669         | 1.700 | 1                | 25 | 2               | 51 | 2               | 51 | 3 $\frac{3}{4}$ | 95  | 1 $\frac{1}{16}$     | 17  | 1 $\frac{1}{16}$ | 43 |
|                                 |                | 0.0670         | 1.702 | 1                | 25 | 2               | 51 | 2               | 51 | 3 $\frac{3}{4}$ | 95  | 1 $\frac{1}{16}$     | 17  | 1 $\frac{1}{16}$ | 43 |
|                                 | 1.75           | 0.0689         | 1.750 | 1                | 25 | 2               | 51 | 2               | 51 | 3 $\frac{3}{4}$ | 95  | 1 $\frac{1}{16}$     | 17  | 1 $\frac{1}{16}$ | 43 |
| 50                              |                | 0.0700         | 1.778 | 1                | 25 | 2               | 51 | 2               | 51 | 3 $\frac{3}{4}$ | 95  | 1 $\frac{1}{16}$     | 17  | 1 $\frac{1}{16}$ | 43 |
|                                 | 1.80           | 0.0709         | 1.800 | 1                | 25 | 2               | 51 | 2               | 51 | 3 $\frac{3}{4}$ | 95  | 1 $\frac{1}{16}$     | 17  | 1 $\frac{1}{16}$ | 43 |
|                                 | 1.85           | 0.0728         | 1.850 | 1                | 25 | 2               | 51 | 2               | 51 | 3 $\frac{3}{4}$ | 95  | 1 $\frac{1}{16}$     | 17  | 1 $\frac{1}{16}$ | 43 |
| 49                              |                | 0.0730         | 1.854 | 1                | 25 | 2               | 51 | 2               | 51 | 3 $\frac{3}{4}$ | 95  | 1 $\frac{1}{16}$     | 17  | 1 $\frac{1}{16}$ | 43 |
|                                 | 1.90           | 0.0748         | 1.900 | 1                | 25 | 2               | 51 | 2               | 51 | 3 $\frac{3}{4}$ | 95  | 1 $\frac{1}{16}$     | 17  | 1 $\frac{1}{16}$ | 43 |
| 48                              |                | 0.0760         | 1.930 | 1                | 25 | 2               | 51 | 2               | 51 | 3 $\frac{3}{4}$ | 95  | 1 $\frac{1}{16}$     | 17  | 1 $\frac{1}{16}$ | 43 |
|                                 | 1.95           | 0.0768         | 1.950 | 1                | 25 | 2               | 51 | 2               | 51 | 3 $\frac{3}{4}$ | 95  | 1 $\frac{1}{16}$     | 17  | 1 $\frac{1}{16}$ | 43 |
| $\frac{5}{64}$                  |                | 0.0781         | 1.984 | 1                | 25 | 2               | 51 | 2               | 51 | 3 $\frac{3}{4}$ | 95  | 1 $\frac{1}{16}$     | 17  | 1 $\frac{1}{16}$ | 43 |
| 47                              |                | 0.0785         | 1.994 | 1                | 25 | 2               | 51 | 2               | 51 | 2 $\frac{1}{4}$ | 57  | 4 $\frac{1}{4}$      | 108 | 1 $\frac{1}{16}$ | 43 |
|                                 | 2.00           | 0.0787         | 2.000 | 1                | 25 | 2               | 51 | 2               | 51 | 2 $\frac{1}{4}$ | 57  | 4 $\frac{1}{4}$      | 108 | 1 $\frac{1}{16}$ | 43 |
|                                 | 2.05           | 0.0807         | 2.050 | 1 $\frac{1}{8}$  | 29 | 2 $\frac{1}{8}$ | 54 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
| 46                              |                | 0.0810         | 2.057 | 1 $\frac{1}{8}$  | 29 | 2 $\frac{1}{8}$ | 54 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
| 45                              |                | 0.0820         | 2.083 | 1 $\frac{1}{8}$  | 29 | 2 $\frac{1}{8}$ | 54 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
|                                 | 2.10           | 0.0827         | 2.100 | 1 $\frac{1}{8}$  | 29 | 2 $\frac{1}{8}$ | 54 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
|                                 | 2.15           | 0.0846         | 2.150 | 1 $\frac{1}{8}$  | 29 | 2 $\frac{1}{8}$ | 54 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
| 44                              |                | 0.0860         | 2.184 | 1 $\frac{1}{8}$  | 29 | 2 $\frac{1}{8}$ | 54 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
|                                 | 2.20           | 0.0866         | 2.200 | 1 $\frac{1}{4}$  | 32 | 2 $\frac{1}{4}$ | 57 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
|                                 | 2.25           | 0.0886         | 2.250 | 1 $\frac{1}{4}$  | 32 | 2 $\frac{1}{4}$ | 57 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
| 43                              |                | 0.0890         | 2.261 | 1 $\frac{1}{4}$  | 32 | 2 $\frac{1}{4}$ | 57 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
|                                 | 2.30           | 0.0906         | 2.300 | 1 $\frac{1}{4}$  | 32 | 2 $\frac{1}{4}$ | 57 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
|                                 | 2.35           | 0.0925         | 2.350 | 1 $\frac{1}{4}$  | 32 | 2 $\frac{1}{4}$ | 57 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
| 42                              |                | 0.0935         | 2.375 | 1 $\frac{1}{4}$  | 32 | 2 $\frac{1}{4}$ | 57 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
|                                 | $\frac{1}{32}$ | 0.0938         | 2.383 | 1 $\frac{1}{4}$  | 32 | 2 $\frac{1}{4}$ | 57 | 2 $\frac{1}{4}$ | 57 | 4 $\frac{1}{4}$ | 108 | $\frac{3}{4}$        | 19  | 1 $\frac{3}{4}$  | 44 |
|                                 | 2.40           | 0.0945         | 2.400 | 1 $\frac{3}{8}$  | 35 | 2 $\frac{3}{8}$ | 60 | 2 $\frac{1}{2}$ | 64 | 4 $\frac{5}{8}$ | 117 | 1 $\frac{3}{16}$     | 21  | 1 $\frac{3}{16}$ | 46 |
| 41                              |                | 0.0960         | 2.438 | 1 $\frac{3}{8}$  | 35 | 2 $\frac{3}{8}$ | 60 | 2 $\frac{1}{2}$ | 64 | 4 $\frac{5}{8}$ | 117 | 1 $\frac{3}{16}$     | 21  | 1 $\frac{3}{16}$ | 46 |
|                                 | 2.46           | 0.0965         | 2.450 | 1 $\frac{3}{8}$  | 35 | 2 $\frac{3}{8}$ | 60 | 2 $\frac{1}{2}$ | 64 | 4 $\frac{5}{8}$ | 117 | 1 $\frac{3}{16}$     | 21  | 1 $\frac{3}{16}$ | 46 |
| 40                              |                | 0.0980         | 2.489 | 1 $\frac{3}{8}$  | 35 | 2 $\frac{3}{8}$ | 60 | 2 $\frac{1}{2}$ | 64 | 4 $\frac{5}{8}$ | 117 | 1 $\frac{3}{16}$     | 21  | 1 $\frac{3}{16}$ | 46 |
|                                 | 2.50           | 0.0984         | 2.500 | 1 $\frac{3}{8}$  | 35 | 2 $\frac{3}{8}$ | 60 | 2 $\frac{1}{2}$ | 64 | 4 $\frac{5}{8}$ | 117 | 1 $\frac{3}{16}$     | 21  | 1 $\frac{3}{16}$ | 46 |
| 39                              |                | 0.0995         | 2.527 | 1 $\frac{3}{8}$  | 35 | 2 $\frac{3}{8}$ | 60 | 2 $\frac{1}{2}$ | 64 | 4 $\frac{5}{8}$ | 117 | 1 $\frac{3}{16}$     | 21  | 1 $\frac{3}{16}$ | 46 |
| 38                              |                | 0.1015         | 2.578 | 1 $\frac{7}{16}$ | 37 | 2 $\frac{1}{2}$ | 64 | 2 $\frac{1}{2}$ | 64 | 4 $\frac{5}{8}$ | 117 | 1 $\frac{3}{16}$     | 21  | 1 $\frac{3}{16}$ | 46 |
|                                 | 2.60           | 0.1024         | 2.600 | 1 $\frac{7}{16}$ | 37 | 2 $\frac{1}{2}$ | 64 | 2 $\frac{1}{2}$ | 64 | 4 $\frac{5}{8}$ | 117 | 1 $\frac{3}{16}$     | 21  | 1 $\frac{3}{16}$ | 46 |
| 37                              |                | 0.1040         | 2.642 | 1 $\frac{7}{16}$ | 37 | 2 $\frac{1}{2}$ | 64 | 2 $\frac{1}{2}$ | 64 | 4 $\frac{5}{8}$ | 117 | 1 $\frac{3}{16}$     | 21  | 1 $\frac{3}{16}$ | 46 |
|                                 | 2.70           | 0.1063         | 2.700 | 1 $\frac{7}{16}$ | 37 | 2 $\frac{1}{2}$ | 64 | 2 $\frac{1}{2}$ | 64 | 4 $\frac{5}{8}$ | 117 | 1 $\frac{3}{16}$     | 21  | 1 $\frac{3}{16}$ | 46 |
| 36                              |                | 0.1065         | 2.705 | 1 $\frac{7}{16}$ | 37 | 2 $\frac{1}{2}$ | 64 | 2 $\frac{1}{2}$ | 64 | 4 $\frac{5}{8}$ | 117 | 1 $\frac{3}{16}$     | 21  | 1 $\frac{3}{16}$ | 46 |
| $\frac{3}{64}$                  |                | 0.1094         | 2.779 | 1 $\frac{1}{2}$  | 38 | 2 $\frac{5}{8}$ | 67 | 2 $\frac{1}{2}$ | 64 | 4 $\frac{5}{8}$ | 117 | 1 $\frac{3}{16}$     | 21  | 1 $\frac{3}{16}$ | 46 |
| 35                              |                | 0.1100         | 2.794 | 1 $\frac{1}{2}$  | 38 | 2 $\frac{5}{8}$ | 67 | 2 $\frac{3}{4}$ | 70 | 5 $\frac{1}{8}$ | 130 | $\frac{7}{8}$        | 22  | 1 $\frac{7}{8}$  | 48 |
|                                 | 2.80           | 0.1102         | 2.800 | 1 $\frac{1}{2}$  | 38 | 2 $\frac{5}{8}$ | 67 | 2 $\frac{3}{4}$ | 70 | 5 $\frac{1}{8}$ | 130 | $\frac{7}{8}$        | 22  | 1 $\frac{7}{8}$  | 48 |
| 34                              |                | 0.1110         | 2.819 | 1 $\frac{1}{2}$  | 38 | 2 $\frac{5}{8}$ | 67 | 2 $\frac{3}{4}$ | 70 | 5 $\frac{1}{8}$ | 130 | $\frac{7}{8}$        | 22  | 1 $\frac{7}{8}$  | 48 |
| 33                              |                | 0.1130         | 2.870 | 1 $\frac{1}{2}$  | 38 | 2 $\frac{5}{8}$ | 67 | 2 $\frac{3}{4}$ | 70 | 5 $\frac{1}{8}$ | 130 | $\frac{7}{8}$        | 22  | 1 $\frac{7}{8}$  | 48 |
|                                 | 2.90           | 0.1142         | 2.900 | 1 $\frac{3}{8}$  | 41 | 2 $\frac{3}{4}$ | 70 | 2 $\frac{3}{4}$ | 70 | 5 $\frac{1}{8}$ | 130 | $\frac{7}{8}$        | 22  | 1 $\frac{7}{8}$  | 48 |
| 32                              |                | 0.1160         | 2.946 | 1 $\frac{3}{8}$  | 41 | 2 $\frac{3}{4}$ | 70 | 2 $\frac{3}{4}$ | 70 | 5 $\frac{1}{8}$ | 130 | $\frac{7}{8}$        | 22  | 1 $\frac{7}{8}$  | 48 |
|                                 | 3.00           | 0.1181         | 3.000 | 1 $\frac{3}{8}$  | 41 | 2 $\frac{3}{4}$ | 70 | 2 $\frac{3}{4}$ | 70 | 5 $\frac{1}{8}$ | 130 | $\frac{7}{8}$        | 22  | 1 $\frac{7}{8}$  | 48 |
| 31                              |                | 0.1200         | 3.048 | 1 $\frac{3}{8}$  | 41 | 2 $\frac{3}{4}$ | 70 | 2 $\frac{3}{4}$ | 70 | 5 $\frac{1}{8}$ | 130 | $\frac{7}{8}$        | 22  | 1 $\frac{7}{8}$  | 48 |

**Table 1. (Continued) ANSI Straight Shank Twist Drills — Jobbers Length through 17.5 mm, Taper Length through 12.7 mm, and Screw Machine Length through 25.4 mm Diameter ANSI/ASME B94.11M-1993**

| Drill Diameter, $D^a$ |      | Jobbers Length |       |        |    |         |    | Taper Length |    |         |     | Screw Machine Length |    |         |    |
|-----------------------|------|----------------|-------|--------|----|---------|----|--------------|----|---------|-----|----------------------|----|---------|----|
| Fraction No. or Ltr.  | mm   | Equivalent     |       | Flute  |    | Overall |    | Flute        |    | Overall |     | Flute                |    | Overall |    |
|                       |      | Decimal In.    | mm    | $F$    |    | $L$     |    | $F$          |    | $L$     |     | $F$                  |    | $L$     |    |
|                       |      |                |       | Inch   | mm | Inch    | mm | Inch         | mm | Inch    | mm  | Inch                 | mm | Inch    | mm |
| 1/8                   | 3.10 | 0.1220         | 3.100 | 1 5/8  | 41 | 2 3/4   | 70 | 2 3/4        | 70 | 5 1/8   | 130 | 7/8                  | 22 | 1 7/8   | 48 |
|                       |      | 0.1250         | 3.175 | 1 5/8  | 41 | 2 3/4   | 70 | 2 3/4        | 70 | 5 1/8   | 130 | 7/8                  | 22 | 1 7/8   | 48 |
| 30                    | 3.20 | 0.1260         | 3.200 | 1 5/8  | 41 | 2 3/4   | 70 | 3            | 76 | 5 3/8   | 137 | 15/16                | 24 | 1 15/16 | 49 |
|                       |      | 0.1285         | 3.264 | 1 5/8  | 41 | 2 3/4   | 70 | 3            | 76 | 5 3/8   | 137 | 15/16                | 24 | 1 15/16 | 49 |
| 29                    | 3.30 | 0.1299         | 3.300 | 1 3/4  | 44 | 2 7/8   | 73 | 3            | 76 | 5 3/8   | 137 | 15/16                | 24 | 1 15/16 | 49 |
|                       |      | 0.1339         | 3.400 | 1 3/4  | 44 | 2 7/8   | 73 | 3            | 76 | 5 3/8   | 137 | 15/16                | 24 | 1 15/16 | 49 |
| 28                    | 3.40 | 0.1360         | 3.454 | 1 3/4  | 44 | 2 7/8   | 73 | 3            | 76 | 5 3/8   | 137 | 15/16                | 24 | 1 15/16 | 49 |
|                       |      | 0.1378         | 3.500 | 1 3/4  | 44 | 2 7/8   | 73 | 3            | 76 | 5 3/8   | 137 | 15/16                | 24 | 1 15/16 | 49 |
| 27                    | 3.50 | 0.1405         | 3.569 | 1 3/4  | 44 | 2 7/8   | 73 | 3            | 76 | 5 3/8   | 137 | 15/16                | 24 | 1 15/16 | 49 |
|                       |      | 0.1406         | 3.571 | 1 3/4  | 44 | 2 7/8   | 73 | 3            | 76 | 5 3/8   | 137 | 15/16                | 24 | 1 15/16 | 49 |
| 26                    | 3.60 | 0.1417         | 3.600 | 1 3/8  | 48 | 3       | 76 | 3            | 76 | 5 3/8   | 137 | 1                    | 25 | 2 1/16  | 52 |
|                       |      | 0.1440         | 3.658 | 1 3/8  | 48 | 3       | 76 | 3            | 76 | 5 3/8   | 137 | 1                    | 25 | 2 1/16  | 52 |
| 25                    | 3.70 | 0.1457         | 3.700 | 1 3/8  | 48 | 3       | 76 | 3            | 76 | 5 3/8   | 137 | 1                    | 25 | 2 1/16  | 52 |
|                       |      | 0.1470         | 3.734 | 1 3/8  | 48 | 3       | 76 | 3            | 76 | 5 3/8   | 137 | 1                    | 25 | 2 1/16  | 52 |
| 24                    | 3.80 | 0.1495         | 3.797 | 1 3/8  | 48 | 3       | 76 | 3            | 76 | 5 3/8   | 137 | 1                    | 25 | 2 1/16  | 52 |
|                       |      | 0.1496         | 3.800 | 1 3/8  | 48 | 3       | 76 | 3            | 76 | 5 3/8   | 137 | 1                    | 25 | 2 1/16  | 52 |
| 23                    | 3.90 | 0.1520         | 3.861 | 2      | 51 | 3 1/8   | 79 | 3            | 76 | 5 3/8   | 137 | 1                    | 25 | 2 1/16  | 52 |
|                       |      | 0.1535         | 3.900 | 2      | 51 | 3 1/8   | 79 | 3            | 76 | 5 3/8   | 137 | 1                    | 25 | 2 1/16  | 52 |
| 22                    | 4.00 | 0.1540         | 3.912 | 2      | 51 | 3 1/8   | 79 | 3            | 76 | 5 3/8   | 137 | 1                    | 25 | 2 1/16  | 52 |
|                       |      | 0.1562         | 3.967 | 2      | 51 | 3 1/8   | 79 | 3            | 76 | 5 3/8   | 137 | 1                    | 25 | 2 1/16  | 52 |
| 21                    | 4.10 | 0.1570         | 3.988 | 2      | 51 | 3 1/8   | 79 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/16               | 27 | 2 1/8   | 54 |
|                       |      | 0.1575         | 4.000 | 2 1/8  | 54 | 3 1/4   | 83 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/16               | 27 | 2 1/8   | 54 |
| 20                    | 4.20 | 0.1590         | 4.039 | 2 1/8  | 54 | 3 1/4   | 83 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/16               | 27 | 2 1/8   | 54 |
|                       |      | 0.1610         | 4.089 | 2 1/8  | 54 | 3 1/4   | 83 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/16               | 27 | 2 1/8   | 54 |
| 19                    | 4.30 | 0.1614         | 4.100 | 2 1/8  | 54 | 3 1/4   | 83 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/16               | 27 | 2 1/8   | 54 |
|                       |      | 0.1654         | 4.200 | 2 1/8  | 54 | 3 1/4   | 83 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/16               | 27 | 2 1/8   | 54 |
| 18                    | 4.40 | 0.1660         | 4.216 | 2 1/8  | 54 | 3 1/4   | 83 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/16               | 27 | 2 1/8   | 54 |
|                       |      | 0.1693         | 4.300 | 2 1/8  | 54 | 3 1/4   | 83 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/16               | 27 | 2 1/8   | 54 |
| 17                    | 4.50 | 0.1695         | 4.305 | 2 1/8  | 54 | 3 1/4   | 83 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/16               | 27 | 2 1/8   | 54 |
|                       |      | 0.1719         | 4.366 | 2 1/8  | 54 | 3 1/4   | 83 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/16               | 27 | 2 1/8   | 54 |
| 16                    | 4.60 | 0.1730         | 4.394 | 2 3/16 | 56 | 3 3/8   | 86 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/8                | 29 | 2 3/16  | 56 |
|                       |      | 0.1732         | 4.400 | 2 3/16 | 56 | 3 3/8   | 86 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/8                | 29 | 2 3/16  | 56 |
| 15                    | 4.70 | 0.1770         | 4.496 | 2 3/16 | 56 | 3 3/8   | 86 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/8                | 29 | 2 3/16  | 56 |
|                       |      | 0.1772         | 4.500 | 2 3/16 | 56 | 3 3/8   | 86 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/8                | 29 | 2 3/16  | 56 |
| 14                    | 4.80 | 0.1800         | 4.572 | 2 3/16 | 56 | 3 3/8   | 86 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/8                | 29 | 2 3/16  | 56 |
|                       |      | 0.1811         | 4.600 | 2 3/16 | 56 | 3 3/8   | 86 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/8                | 29 | 2 3/16  | 56 |
| 13                    | 4.90 | 0.1820         | 4.623 | 2 3/16 | 56 | 3 3/8   | 86 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/8                | 29 | 2 3/16  | 56 |
|                       |      | 0.1850         | 4.700 | 2 3/16 | 59 | 3 1/2   | 89 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/8                | 29 | 2 3/16  | 56 |
| 12                    | 5.00 | 0.1875         | 4.762 | 2 5/16 | 59 | 3 1/2   | 89 | 3 3/8        | 86 | 5 3/4   | 146 | 1 1/8                | 29 | 2 3/16  | 56 |
|                       |      | 0.1890         | 4.800 | 2 5/16 | 59 | 3 1/2   | 89 | 3 3/8        | 92 | 6       | 152 | 1 3/16               | 30 | 2 1/4   | 57 |
| 11                    | 5.10 | 0.1910         | 4.851 | 2 5/16 | 59 | 3 1/2   | 89 | 3 3/8        | 92 | 6       | 152 | 1 3/16               | 30 | 2 1/4   | 57 |
|                       |      | 0.1929         | 4.900 | 2 7/16 | 62 | 3 3/8   | 92 | 3 3/8        | 92 | 6       | 152 | 1 3/16               | 30 | 2 1/4   | 57 |
| 10                    | 5.20 | 0.1935         | 4.915 | 2 7/16 | 62 | 3 3/8   | 92 | 3 3/8        | 92 | 6       | 152 | 1 3/16               | 30 | 2 1/4   | 57 |
|                       |      | 0.1960         | 4.978 | 2 7/16 | 62 | 3 3/8   | 92 | 3 3/8        | 92 | 6       | 152 | 1 3/16               | 30 | 2 1/4   | 57 |
| 9                     | 5.30 | 0.1969         | 5.000 | 2 7/16 | 62 | 3 3/8   | 92 | 3 3/8        | 92 | 6       | 152 | 1 3/16               | 30 | 2 1/4   | 57 |
|                       |      | 0.1990         | 5.054 | 2 7/16 | 62 | 3 3/8   | 92 | 3 3/8        | 92 | 6       | 152 | 1 3/16               | 30 | 2 1/4   | 57 |



**Table 1. (Continued) ANSI Straight Shank Twist Drills — Jobbers Length through 17.5 mm, Taper Length through 12.7 mm, and Screw Machine Length through 25.4 mm Diameter ANSI/ASME B94.11M-1993**

| Drill Diameter, $D^a$ |      | Jobbers Length |       |                  |    |                 |     | Taper Length    |     |                 |     | Screw Machine Length |    |                   |    |
|-----------------------|------|----------------|-------|------------------|----|-----------------|-----|-----------------|-----|-----------------|-----|----------------------|----|-------------------|----|
| Frac-tion No. or Ltr. | mm   | Equivalent     |       | Flute            |    | Overall         |     | Flute           |     | Overall         |     | Flute                |    | Overall           |    |
|                       |      | Decimal In.    | mm    | $F$              |    | $L$             |     | $F$             |     | $L$             |     | $F$                  |    | $L$               |    |
|                       |      |                |       | Inch             | mm | Inch            | mm  | Inch            | mm  | Inch            | mm  | Inch                 | mm | Inch              | mm |
| 7                     | 5.10 | 0.2008         | 5.100 | 2 $\frac{1}{16}$ | 62 | 3 $\frac{3}{8}$ | 92  | 3 $\frac{3}{8}$ | 92  | 6               | 152 | 1 $\frac{3}{16}$     | 30 | 2 $\frac{1}{4}$   | 57 |
|                       |      | 0.2010         | 5.105 | 2 $\frac{1}{16}$ | 62 | 3 $\frac{3}{8}$ | 92  | 3 $\frac{3}{8}$ | 92  | 6               | 152 | 1 $\frac{3}{16}$     | 30 | 2 $\frac{1}{4}$   | 57 |
| 1 $\frac{3}{64}$      | 5.10 | 0.2031         | 5.159 | 2 $\frac{1}{16}$ | 62 | 3 $\frac{3}{8}$ | 92  | 3 $\frac{3}{8}$ | 92  | 6               | 152 | 1 $\frac{3}{16}$     | 30 | 2 $\frac{1}{4}$   | 57 |
|                       |      | 0.2040         | 5.182 | 2 $\frac{1}{2}$  | 64 | 3 $\frac{3}{4}$ | 95  | 3 $\frac{3}{8}$ | 92  | 6               | 152 | 1 $\frac{1}{4}$      | 32 | 2 $\frac{3}{8}$   | 60 |
| 6                     | 5.20 | 0.2047         | 5.200 | 2 $\frac{1}{2}$  | 64 | 3 $\frac{3}{4}$ | 95  | 3 $\frac{3}{8}$ | 92  | 6               | 152 | 1 $\frac{1}{4}$      | 32 | 2 $\frac{3}{8}$   | 60 |
|                       |      | 0.2055         | 5.220 | 2 $\frac{1}{2}$  | 64 | 3 $\frac{3}{4}$ | 95  | 3 $\frac{3}{8}$ | 92  | 6               | 152 | 1 $\frac{1}{4}$      | 32 | 2 $\frac{3}{8}$   | 60 |
| 5                     | 5.30 | 0.2087         | 5.300 | 2 $\frac{1}{2}$  | 64 | 3 $\frac{3}{4}$ | 95  | 3 $\frac{3}{8}$ | 92  | 6               | 152 | 1 $\frac{1}{4}$      | 32 | 2 $\frac{3}{8}$   | 60 |
|                       |      | 0.2090         | 5.309 | 2 $\frac{1}{2}$  | 64 | 3 $\frac{3}{4}$ | 95  | 3 $\frac{3}{8}$ | 92  | 6               | 152 | 1 $\frac{1}{4}$      | 32 | 2 $\frac{3}{8}$   | 60 |
| 4                     | 5.40 | 0.2126         | 5.400 | 2 $\frac{1}{2}$  | 64 | 3 $\frac{3}{4}$ | 95  | 3 $\frac{3}{8}$ | 92  | 6               | 152 | 1 $\frac{1}{4}$      | 32 | 2 $\frac{3}{8}$   | 60 |
|                       |      | 0.2130         | 5.410 | 2 $\frac{1}{2}$  | 64 | 3 $\frac{3}{4}$ | 95  | 3 $\frac{3}{8}$ | 92  | 6               | 152 | 1 $\frac{1}{4}$      | 32 | 2 $\frac{3}{8}$   | 60 |
| 3                     | 5.50 | 0.2165         | 5.500 | 2 $\frac{1}{2}$  | 64 | 3 $\frac{3}{4}$ | 95  | 3 $\frac{3}{8}$ | 92  | 6               | 152 | 1 $\frac{1}{4}$      | 32 | 2 $\frac{3}{8}$   | 60 |
|                       |      | 0.2188         | 5.558 | 2 $\frac{1}{2}$  | 64 | 3 $\frac{3}{4}$ | 95  | 3 $\frac{3}{8}$ | 92  | 6               | 152 | 1 $\frac{1}{4}$      | 32 | 2 $\frac{3}{8}$   | 60 |
| 2                     | 5.60 | 0.2205         | 5.600 | 2 $\frac{3}{8}$  | 67 | 3 $\frac{3}{8}$ | 98  | 3 $\frac{3}{4}$ | 95  | 6 $\frac{1}{4}$ | 156 | 1 $\frac{5}{16}$     | 33 | 2 $\frac{7}{16}$  | 62 |
|                       |      | 0.2210         | 5.613 | 2 $\frac{3}{8}$  | 67 | 3 $\frac{3}{8}$ | 98  | 3 $\frac{3}{4}$ | 95  | 6 $\frac{1}{8}$ | 156 | 1 $\frac{5}{16}$     | 33 | 2 $\frac{7}{16}$  | 62 |
| 1                     | 5.70 | 0.2244         | 5.700 | 2 $\frac{3}{8}$  | 67 | 3 $\frac{3}{8}$ | 98  | 3 $\frac{3}{4}$ | 95  | 6 $\frac{1}{8}$ | 156 | 1 $\frac{5}{16}$     | 33 | 2 $\frac{7}{16}$  | 62 |
|                       |      | 0.2280         | 5.791 | 2 $\frac{3}{8}$  | 67 | 3 $\frac{3}{8}$ | 98  | 3 $\frac{3}{4}$ | 95  | 6 $\frac{1}{4}$ | 156 | 1 $\frac{5}{16}$     | 33 | 2 $\frac{7}{16}$  | 62 |
| A                     | 5.80 | 0.2283         | 5.800 | 2 $\frac{3}{8}$  | 67 | 3 $\frac{3}{8}$ | 98  | 3 $\frac{3}{4}$ | 95  | 6 $\frac{1}{8}$ | 156 | 1 $\frac{5}{16}$     | 33 | 2 $\frac{7}{16}$  | 62 |
|                       |      | 0.2323         | 5.900 | 2 $\frac{3}{8}$  | 67 | 3 $\frac{3}{8}$ | 98  | 3 $\frac{3}{4}$ | 95  | 6 $\frac{1}{8}$ | 156 | 1 $\frac{5}{16}$     | 33 | 2 $\frac{7}{16}$  | 62 |
| 1 $\frac{5}{64}$      | 6.00 | 0.2340         | 5.944 | 2 $\frac{3}{8}$  | 67 | 3 $\frac{3}{8}$ | 98  | ...             | ... | ...             | ... | 1 $\frac{5}{16}$     | 33 | 2 $\frac{7}{16}$  | 62 |
|                       |      | 0.2344         | 5.954 | 2 $\frac{3}{8}$  | 67 | 3 $\frac{3}{8}$ | 98  | 3 $\frac{3}{4}$ | 95  | 6 $\frac{1}{8}$ | 156 | 1 $\frac{5}{16}$     | 33 | 2 $\frac{7}{16}$  | 62 |
| B                     | 6.00 | 0.2362         | 6.000 | 2 $\frac{3}{4}$  | 70 | 4               | 102 | 3 $\frac{3}{4}$ | 95  | 6 $\frac{1}{8}$ | 156 | 1 $\frac{3}{8}$      | 35 | 2 $\frac{1}{2}$   | 64 |
|                       |      | 0.2380         | 6.045 | 2 $\frac{3}{4}$  | 70 | 4               | 102 | ...             | ... | ...             | ... | 1 $\frac{3}{8}$      | 35 | 2 $\frac{1}{2}$   | 64 |
| C                     | 6.10 | 0.2402         | 6.100 | 2 $\frac{3}{4}$  | 70 | 4               | 102 | 3 $\frac{3}{4}$ | 95  | 6 $\frac{1}{8}$ | 156 | 1 $\frac{3}{8}$      | 35 | 2 $\frac{1}{2}$   | 64 |
|                       |      | 0.2420         | 6.147 | 2 $\frac{3}{4}$  | 70 | 4               | 102 | ...             | ... | ...             | ... | 1 $\frac{3}{8}$      | 35 | 2 $\frac{1}{2}$   | 64 |
| D                     | 6.20 | 0.2441         | 6.200 | 2 $\frac{3}{4}$  | 70 | 4               | 102 | 3 $\frac{3}{4}$ | 95  | 6 $\frac{1}{8}$ | 156 | 1 $\frac{3}{8}$      | 35 | 2 $\frac{1}{2}$   | 64 |
|                       |      | 0.2460         | 6.248 | 2 $\frac{3}{4}$  | 70 | 4               | 102 | ...             | ... | ...             | ... | 1 $\frac{3}{8}$      | 35 | 2 $\frac{1}{2}$   | 64 |
| E, 1/4                | 6.30 | 0.2480         | 6.300 | 2 $\frac{3}{4}$  | 70 | 4               | 102 | 3 $\frac{3}{4}$ | 95  | 6 $\frac{1}{8}$ | 156 | 1 $\frac{3}{8}$      | 35 | 2 $\frac{1}{2}$   | 64 |
|                       |      | 0.2500         | 6.350 | 2 $\frac{3}{4}$  | 70 | 4               | 102 | 3 $\frac{3}{4}$ | 95  | 6 $\frac{1}{8}$ | 156 | 1 $\frac{3}{8}$      | 35 | 2 $\frac{1}{2}$   | 64 |
| F                     | 6.40 | 0.2520         | 6.400 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | 3 $\frac{7}{8}$ | 98  | 6 $\frac{1}{4}$ | 159 | 1 $\frac{7}{16}$     | 37 | 2 $\frac{5}{8}$   | 67 |
|                       |      | 0.2559         | 6.500 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | 3 $\frac{7}{8}$ | 98  | 6 $\frac{1}{4}$ | 159 | 1 $\frac{7}{16}$     | 37 | 2 $\frac{5}{8}$   | 67 |
| G                     | 6.50 | 0.2570         | 6.528 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | ...             | ... | ...             | ... | 1 $\frac{7}{16}$     | 37 | 2 $\frac{5}{8}$   | 67 |
|                       |      | 0.2598         | 6.600 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | ...             | ... | ...             | ... | 1 $\frac{7}{16}$     | 37 | 2 $\frac{5}{8}$   | 67 |
| H                     | 6.60 | 0.2610         | 6.629 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | ...             | ... | ...             | ... | 1 $\frac{7}{16}$     | 37 | 2 $\frac{5}{8}$   | 67 |
|                       |      | 0.2638         | 6.700 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | ...             | ... | ...             | ... | 1 $\frac{7}{16}$     | 37 | 2 $\frac{5}{8}$   | 67 |
| I                     | 6.70 | 0.2656         | 6.746 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | 3 $\frac{7}{8}$ | 98  | 6 $\frac{1}{4}$ | 159 | 1 $\frac{7}{16}$     | 37 | 2 $\frac{5}{8}$   | 67 |
|                       |      | 0.2660         | 6.756 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | ...             | ... | ...             | ... | 1 $\frac{1}{2}$      | 38 | 2 $\frac{11}{16}$ | 68 |
| J                     | 6.80 | 0.2677         | 6.800 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | 3 $\frac{7}{8}$ | 98  | 6 $\frac{1}{4}$ | 159 | 1 $\frac{1}{2}$      | 38 | 2 $\frac{11}{16}$ | 68 |
|                       |      | 0.2717         | 6.900 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | ...             | ... | ...             | ... | 1 $\frac{1}{2}$      | 38 | 2 $\frac{11}{16}$ | 68 |
| K                     | 6.90 | 0.2720         | 6.909 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | ...             | ... | ...             | ... | 1 $\frac{1}{2}$      | 38 | 2 $\frac{11}{16}$ | 68 |
|                       |      | 0.2756         | 7.000 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | 3 $\frac{7}{8}$ | 98  | 6 $\frac{1}{4}$ | 159 | 1 $\frac{1}{2}$      | 38 | 2 $\frac{11}{16}$ | 68 |
| L                     | 7.00 | 0.2770         | 7.036 | 2 $\frac{7}{8}$  | 73 | 4 $\frac{1}{8}$ | 105 | ...             | ... | ...             | ... | 1 $\frac{1}{2}$      | 38 | 2 $\frac{11}{16}$ | 68 |
|                       |      | 0.2795         | 7.100 | 2 $\frac{5}{16}$ | 75 | 4 $\frac{1}{4}$ | 108 | ...             | ... | ...             | ... | 1 $\frac{1}{2}$      | 38 | 2 $\frac{11}{16}$ | 68 |
| M                     | 7.10 | 0.2810         | 7.137 | 2 $\frac{5}{16}$ | 75 | 4 $\frac{1}{4}$ | 108 | ...             | ... | ...             | ... | 1 $\frac{1}{2}$      | 38 | 2 $\frac{11}{16}$ | 68 |
|                       |      | 0.2812         | 7.142 | 2 $\frac{5}{16}$ | 75 | 4 $\frac{1}{4}$ | 108 | 3 $\frac{7}{8}$ | 98  | 6 $\frac{1}{4}$ | 159 | 1 $\frac{1}{2}$      | 38 | 2 $\frac{11}{16}$ | 68 |
| N                     | 7.20 | 0.2835         | 7.200 | 2 $\frac{5}{16}$ | 75 | 4 $\frac{1}{4}$ | 108 | 4               | 102 | 6 $\frac{3}{8}$ | 162 | 1 $\frac{9}{16}$     | 40 | 2 $\frac{3}{4}$   | 70 |
|                       |      | 0.2874         | 7.300 | 2 $\frac{5}{16}$ | 75 | 4 $\frac{1}{4}$ | 108 | ...             | ... | ...             | ... | 1 $\frac{9}{16}$     | 40 | 2 $\frac{3}{4}$   | 70 |

**Table 1. (Continued) ANSI Straight Shank Twist Drills — Jobbers Length through 17.5 mm, Taper Length through 12.7 mm, and Screw Machine Length through 25.4 mm Diameter ANSI/ASME B94.11M-1993**

| Drill Diameter, $D^a$          |      | Jobbers Length |        |                                 |    |                               |     | Taper Length                  |     |                               |     | Screw Machine Length            |    |                                 |    |
|--------------------------------|------|----------------|--------|---------------------------------|----|-------------------------------|-----|-------------------------------|-----|-------------------------------|-----|---------------------------------|----|---------------------------------|----|
| Frac-tion No. or Ltr.          | mm   | Equivalent     |        | Flute                           |    | Overall                       |     | Flute                         |     | Overall                       |     | Flute                           |    | Overall                         |    |
|                                |      | Decimal In.    | mm     | $F$                             |    | $L$                           |     | $F$                           |     | $L$                           |     | $F$                             |    | $L$                             |    |
|                                |      |                |        | Inch                            | mm | Inch                          | mm  | Inch                          | mm  | Inch                          | mm  | Inch                            | mm | Inch                            | mm |
| L                              | 7.40 | 0.2900         | 7.366  | 2 <sup>15</sup> / <sub>16</sub> | 75 | 4 <sup>1</sup> / <sub>4</sub> | 108 | ...                           | ... | ...                           | ... | 1 <sup>1</sup> / <sub>16</sub>  | 40 | 2 <sup>3</sup> / <sub>4</sub>   | 70 |
|                                |      | 0.2913         | 7.400  | 3 <sup>1</sup> / <sub>16</sub>  | 78 | 4 <sup>3</sup> / <sub>8</sub> | 111 | ...                           | ... | ...                           | ... | 1 <sup>1</sup> / <sub>16</sub>  | 40 | 2 <sup>3</sup> / <sub>4</sub>   | 70 |
| M                              | 7.50 | 0.2950         | 7.493  | 3 <sup>1</sup> / <sub>16</sub>  | 78 | 4 <sup>3</sup> / <sub>8</sub> | 111 | ...                           | ... | ...                           | ... | 1 <sup>1</sup> / <sub>16</sub>  | 40 | 2 <sup>3</sup> / <sub>4</sub>   | 70 |
|                                |      | 0.2953         | 7.500  | 3 <sup>1</sup> / <sub>16</sub>  | 78 | 4 <sup>3</sup> / <sub>8</sub> | 111 | 4                             | 102 | 6 <sup>3</sup> / <sub>8</sub> | 162 | 1 <sup>1</sup> / <sub>16</sub>  | 40 | 2 <sup>3</sup> / <sub>4</sub>   | 70 |
| 9 <sup>1</sup> / <sub>64</sub> | 7.60 | 0.2969         | 7.541  | 3 <sup>1</sup> / <sub>16</sub>  | 78 | 4 <sup>3</sup> / <sub>8</sub> | 111 | 4                             | 102 | 6 <sup>3</sup> / <sub>8</sub> | 162 | 1 <sup>1</sup> / <sub>16</sub>  | 40 | 2 <sup>3</sup> / <sub>4</sub>   | 70 |
|                                |      | 0.2992         | 7.600  | 3 <sup>1</sup> / <sub>16</sub>  | 78 | 4 <sup>3</sup> / <sub>8</sub> | 111 | ...                           | ... | ...                           | ... | 1 <sup>5</sup> / <sub>8</sub>   | 41 | 2 <sup>13</sup> / <sub>16</sub> | 71 |
| N                              | 7.70 | 0.3020         | 7.671  | 3 <sup>1</sup> / <sub>16</sub>  | 78 | 4 <sup>3</sup> / <sub>8</sub> | 111 | ...                           | ... | ...                           | ... | 1 <sup>5</sup> / <sub>8</sub>   | 41 | 2 <sup>13</sup> / <sub>16</sub> | 71 |
|                                |      | 0.3031         | 7.700  | 3 <sup>1</sup> / <sub>16</sub>  | 81 | 4 <sup>1</sup> / <sub>2</sub> | 114 | ...                           | ... | ...                           | ... | 1 <sup>5</sup> / <sub>8</sub>   | 41 | 2 <sup>13</sup> / <sub>16</sub> | 71 |
| 5 <sup>1</sup> / <sub>16</sub> | 8.00 | 0.3071         | 7.800  | 3 <sup>1</sup> / <sub>16</sub>  | 81 | 4 <sup>1</sup> / <sub>2</sub> | 114 | 4                             | 102 | 6 <sup>3</sup> / <sub>8</sub> | 162 | 1 <sup>5</sup> / <sub>8</sub>   | 41 | 2 <sup>13</sup> / <sub>16</sub> | 71 |
|                                |      | 0.3110         | 7.900  | 3 <sup>1</sup> / <sub>16</sub>  | 81 | 4 <sup>1</sup> / <sub>2</sub> | 114 | ...                           | ... | ...                           | ... | 1 <sup>5</sup> / <sub>8</sub>   | 41 | 2 <sup>13</sup> / <sub>16</sub> | 71 |
| O                              | 8.10 | 0.3125         | 7.938  | 3 <sup>1</sup> / <sub>16</sub>  | 81 | 4 <sup>1</sup> / <sub>2</sub> | 114 | 4                             | 102 | 6 <sup>3</sup> / <sub>8</sub> | 162 | 1 <sup>5</sup> / <sub>8</sub>   | 41 | 2 <sup>13</sup> / <sub>16</sub> | 71 |
|                                |      | 0.3150         | 8.000  | 3 <sup>1</sup> / <sub>16</sub>  | 81 | 4 <sup>1</sup> / <sub>2</sub> | 114 | 4 <sup>1</sup> / <sub>8</sub> | 105 | 6 <sup>1</sup> / <sub>2</sub> | 165 | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 2 <sup>15</sup> / <sub>16</sub> | 75 |
| P                              | 8.20 | 0.3160         | 8.026  | 3 <sup>1</sup> / <sub>16</sub>  | 81 | 4 <sup>1</sup> / <sub>2</sub> | 114 | ...                           | ... | ...                           | ... | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 2 <sup>15</sup> / <sub>16</sub> | 75 |
|                                |      | 0.3189         | 8.100  | 3 <sup>1</sup> / <sub>16</sub>  | 84 | 4 <sup>5</sup> / <sub>8</sub> | 117 | ...                           | ... | ...                           | ... | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 2 <sup>15</sup> / <sub>16</sub> | 75 |
| 2 <sup>1</sup> / <sub>64</sub> | 8.30 | 0.3228         | 8.200  | 3 <sup>1</sup> / <sub>16</sub>  | 84 | 4 <sup>5</sup> / <sub>8</sub> | 117 | 4 <sup>1</sup> / <sub>8</sub> | 105 | 6 <sup>1</sup> / <sub>2</sub> | 165 | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 2 <sup>15</sup> / <sub>16</sub> | 75 |
|                                |      | 0.3230         | 8.204  | 3 <sup>1</sup> / <sub>16</sub>  | 84 | 4 <sup>5</sup> / <sub>8</sub> | 117 | ...                           | ... | ...                           | ... | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 2 <sup>15</sup> / <sub>16</sub> | 75 |
| Q                              | 8.40 | 0.3268         | 8.300  | 3 <sup>1</sup> / <sub>16</sub>  | 84 | 4 <sup>5</sup> / <sub>8</sub> | 117 | ...                           | ... | ...                           | ... | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 2 <sup>15</sup> / <sub>16</sub> | 75 |
|                                |      | 0.3281         | 8.334  | 3 <sup>1</sup> / <sub>16</sub>  | 84 | 4 <sup>5</sup> / <sub>8</sub> | 117 | 4 <sup>1</sup> / <sub>8</sub> | 105 | 6 <sup>1</sup> / <sub>2</sub> | 165 | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 2 <sup>15</sup> / <sub>16</sub> | 75 |
| R                              | 8.50 | 0.3307         | 8.400  | 3 <sup>1</sup> / <sub>16</sub>  | 87 | 4 <sup>3</sup> / <sub>4</sub> | 121 | ...                           | ... | ...                           | ... | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 3                               | 76 |
|                                |      | 0.3320         | 8.433  | 3 <sup>1</sup> / <sub>16</sub>  | 87 | 4 <sup>3</sup> / <sub>4</sub> | 121 | ...                           | ... | ...                           | ... | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 3                               | 76 |
| 1 <sup>1</sup> / <sub>32</sub> | 8.60 | 0.3346         | 8.500  | 3 <sup>1</sup> / <sub>16</sub>  | 87 | 4 <sup>3</sup> / <sub>4</sub> | 121 | 4 <sup>1</sup> / <sub>8</sub> | 105 | 6 <sup>1</sup> / <sub>2</sub> | 165 | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 3                               | 76 |
|                                |      | 0.3386         | 8.600  | 3 <sup>1</sup> / <sub>16</sub>  | 87 | 4 <sup>3</sup> / <sub>4</sub> | 121 | ...                           | ... | ...                           | ... | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 3                               | 76 |
| S                              | 8.70 | 0.3390         | 8.611  | 3 <sup>1</sup> / <sub>16</sub>  | 87 | 4 <sup>3</sup> / <sub>4</sub> | 121 | ...                           | ... | ...                           | ... | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 3                               | 76 |
|                                |      | 0.3425         | 8.700  | 3 <sup>1</sup> / <sub>16</sub>  | 87 | 4 <sup>3</sup> / <sub>4</sub> | 121 | ...                           | ... | ...                           | ... | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 3                               | 76 |
| T                              | 8.80 | 0.3438         | 8.733  | 3 <sup>1</sup> / <sub>16</sub>  | 87 | 4 <sup>3</sup> / <sub>4</sub> | 121 | 4 <sup>1</sup> / <sub>8</sub> | 105 | 6 <sup>1</sup> / <sub>2</sub> | 165 | 1 <sup>1</sup> / <sub>16</sub>  | 43 | 3                               | 76 |
|                                |      | 0.3465         | 8.800  | 3 <sup>1</sup> / <sub>2</sub>   | 89 | 4 <sup>7</sup> / <sub>8</sub> | 124 | 4 <sup>1</sup> / <sub>4</sub> | 108 | 6 <sup>3</sup> / <sub>4</sub> | 171 | 1 <sup>3</sup> / <sub>4</sub>   | 44 | 3 <sup>1</sup> / <sub>16</sub>  | 78 |
| U                              | 8.90 | 0.3480         | 8.839  | 3 <sup>1</sup> / <sub>2</sub>   | 89 | 4 <sup>7</sup> / <sub>8</sub> | 124 | ...                           | ... | ...                           | ... | 1 <sup>3</sup> / <sub>4</sub>   | 44 | 3 <sup>1</sup> / <sub>16</sub>  | 78 |
|                                |      | 0.3504         | 8.900  | 3 <sup>1</sup> / <sub>2</sub>   | 89 | 4 <sup>7</sup> / <sub>8</sub> | 124 | ...                           | ... | ...                           | ... | 1 <sup>3</sup> / <sub>4</sub>   | 44 | 3 <sup>1</sup> / <sub>16</sub>  | 78 |
| V                              | 9.00 | 0.3543         | 9.000  | 3 <sup>1</sup> / <sub>2</sub>   | 89 | 4 <sup>7</sup> / <sub>8</sub> | 124 | 4 <sup>1</sup> / <sub>4</sub> | 108 | 6 <sup>3</sup> / <sub>4</sub> | 171 | 1 <sup>3</sup> / <sub>4</sub>   | 44 | 3 <sup>1</sup> / <sub>16</sub>  | 78 |
|                                |      | 0.3580         | 9.093  | 3 <sup>1</sup> / <sub>2</sub>   | 89 | 4 <sup>7</sup> / <sub>8</sub> | 124 | ...                           | ... | ...                           | ... | 1 <sup>3</sup> / <sub>4</sub>   | 44 | 3 <sup>1</sup> / <sub>16</sub>  | 78 |
| W                              | 9.10 | 0.3583         | 9.100  | 3 <sup>1</sup> / <sub>2</sub>   | 89 | 4 <sup>7</sup> / <sub>8</sub> | 124 | ...                           | ... | ...                           | ... | 1 <sup>3</sup> / <sub>4</sub>   | 44 | 3 <sup>1</sup> / <sub>16</sub>  | 78 |
|                                |      | 0.3594         | 9.129  | 3 <sup>1</sup> / <sub>2</sub>   | 89 | 4 <sup>7</sup> / <sub>8</sub> | 124 | 4 <sup>1</sup> / <sub>4</sub> | 108 | 6 <sup>3</sup> / <sub>4</sub> | 171 | 1 <sup>3</sup> / <sub>4</sub>   | 44 | 3 <sup>1</sup> / <sub>16</sub>  | 78 |
| 2 <sup>1</sup> / <sub>64</sub> | 9.20 | 0.3622         | 9.200  | 3 <sup>1</sup> / <sub>2</sub>   | 92 | 5                             | 127 | 4 <sup>1</sup> / <sub>4</sub> | 108 | 6 <sup>3</sup> / <sub>4</sub> | 171 | 1 <sup>3</sup> / <sub>16</sub>  | 46 | 3 <sup>1</sup> / <sub>8</sub>   | 79 |
|                                |      | 0.3661         | 9.300  | 3 <sup>5</sup> / <sub>8</sub>   | 92 | 5                             | 127 | ...                           | ... | ...                           | ... | 1 <sup>13</sup> / <sub>16</sub> | 46 | 3 <sup>1</sup> / <sub>8</sub>   | 79 |
| 3 <sup>1</sup> / <sub>8</sub>  | 9.30 | 0.3680         | 9.347  | 3 <sup>5</sup> / <sub>8</sub>   | 92 | 5                             | 127 | ...                           | ... | ...                           | ... | 1 <sup>13</sup> / <sub>16</sub> | 46 | 3 <sup>1</sup> / <sub>8</sub>   | 79 |
|                                |      | 0.3701         | 9.400  | 3 <sup>5</sup> / <sub>8</sub>   | 92 | 5                             | 127 | ...                           | ... | ...                           | ... | 1 <sup>13</sup> / <sub>16</sub> | 46 | 3 <sup>1</sup> / <sub>8</sub>   | 79 |
| 4 <sup>1</sup> / <sub>8</sub>  | 9.40 | 0.3740         | 9.500  | 3 <sup>5</sup> / <sub>8</sub>   | 92 | 5                             | 127 | 4 <sup>1</sup> / <sub>4</sub> | 108 | 6 <sup>3</sup> / <sub>4</sub> | 171 | 1 <sup>13</sup> / <sub>16</sub> | 46 | 3 <sup>1</sup> / <sub>8</sub>   | 79 |
|                                |      | 0.3750         | 9.525  | 3 <sup>5</sup> / <sub>8</sub>   | 92 | 5                             | 127 | 4 <sup>1</sup> / <sub>4</sub> | 108 | 6 <sup>3</sup> / <sub>4</sub> | 171 | 1 <sup>13</sup> / <sub>16</sub> | 46 | 3 <sup>1</sup> / <sub>8</sub>   | 79 |
| 5 <sup>1</sup> / <sub>8</sub>  | 9.50 | 0.3770         | 9.576  | 3 <sup>5</sup> / <sub>8</sub>   | 92 | 5                             | 127 | ...                           | ... | ...                           | ... | 1 <sup>7</sup> / <sub>8</sub>   | 48 | 3 <sup>1</sup> / <sub>4</sub>   | 83 |
|                                |      | 0.3780         | 9.600  | 3 <sup>5</sup> / <sub>8</sub>   | 95 | 5 <sup>1</sup> / <sub>8</sub> | 130 | ...                           | ... | ...                           | ... | 1 <sup>7</sup> / <sub>8</sub>   | 48 | 3 <sup>1</sup> / <sub>4</sub>   | 83 |
| 6 <sup>1</sup> / <sub>8</sub>  | 9.60 | 0.3819         | 9.700  | 3 <sup>3</sup> / <sub>4</sub>   | 95 | 5 <sup>1</sup> / <sub>8</sub> | 130 | ...                           | ... | ...                           | ... | 1 <sup>7</sup> / <sub>8</sub>   | 48 | 3 <sup>1</sup> / <sub>4</sub>   | 83 |
|                                |      | 0.3858         | 9.800  | 3 <sup>3</sup> / <sub>4</sub>   | 95 | 5 <sup>1</sup> / <sub>8</sub> | 130 | 4 <sup>3</sup> / <sub>8</sub> | 111 | 7                             | 178 | 1 <sup>7</sup> / <sub>8</sub>   | 48 | 3 <sup>1</sup> / <sub>4</sub>   | 83 |
| 7 <sup>1</sup> / <sub>8</sub>  | 9.70 | 0.3860         | 9.804  | 3 <sup>3</sup> / <sub>4</sub>   | 95 | 5 <sup>1</sup> / <sub>8</sub> | 130 | ...                           | ... | ...                           | ... | 1 <sup>7</sup> / <sub>8</sub>   | 48 | 3 <sup>1</sup> / <sub>4</sub>   | 83 |
|                                |      | 0.3898         | 9.900  | 3 <sup>3</sup> / <sub>4</sub>   | 95 | 5 <sup>1</sup> / <sub>8</sub> | 130 | ...                           | ... | ...                           | ... | 1 <sup>7</sup> / <sub>8</sub>   | 48 | 3 <sup>1</sup> / <sub>4</sub>   | 83 |
| 8 <sup>1</sup> / <sub>8</sub>  | 9.80 | 0.3906         | 9.921  | 3 <sup>3</sup> / <sub>4</sub>   | 95 | 5 <sup>1</sup> / <sub>8</sub> | 130 | 4 <sup>3</sup> / <sub>8</sub> | 111 | 7                             | 178 | 1 <sup>7</sup> / <sub>8</sub>   | 48 | 3 <sup>1</sup> / <sub>4</sub>   | 83 |
|                                |      | 0.3937         | 10.000 | 3 <sup>3</sup> / <sub>4</sub>   | 95 | 5 <sup>1</sup> / <sub>8</sub> | 130 | 4 <sup>3</sup> / <sub>8</sub> | 111 | 7                             | 178 | 1 <sup>15</sup> / <sub>16</sub> | 49 | 3 <sup>5</sup> / <sub>16</sub>  | 84 |

**Table 1. (Continued) ANSI Straight Shank Twist Drills — Jobbers Length through 17.5 mm, Taper Length through 12.7 mm, and Screw Machine Length through 25.4 mm Diameter ANSI/ASME B94.11M-1993**

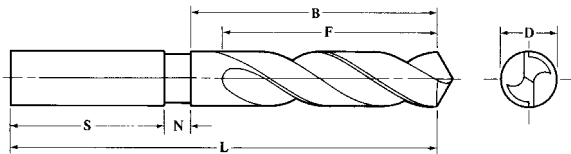
| Drill Diameter, $D^a$ |       | Jobbers Length |        |                   |     |                 |     | Taper Length    |     |                 |     | Screw Machine Length |    |                   |     |
|-----------------------|-------|----------------|--------|-------------------|-----|-----------------|-----|-----------------|-----|-----------------|-----|----------------------|----|-------------------|-----|
| Fraction No. or Ltr.  | mm    | Equivalent     |        | Flute             |     | Overall         |     | Flute           |     | Overall         |     | Flute                |    | Overall           |     |
|                       |       | Decimal In.    | mm     | $F$               |     | $L$             |     | $F$             |     | $L$             |     | $F$                  |    | $L$               |     |
|                       |       |                |        | Inch              | mm  | Inch            | mm  | Inch            | mm  | Inch            | mm  | Inch                 | mm | Inch              | mm  |
| X                     | 10.20 | 0.3970         | 10.084 | 3 $\frac{3}{8}$   | 95  | 5 $\frac{1}{8}$ | 130 | ...             | ... | ...             | ... | 1 $\frac{5}{16}$     | 49 | 3 $\frac{5}{16}$  | 84  |
|                       |       | 0.4016         | 10.200 | 3 $\frac{3}{8}$   | 98  | 5 $\frac{1}{4}$ | 133 | 4 $\frac{3}{8}$ | 111 | 7               | 178 | 1 $\frac{5}{16}$     | 49 | 3 $\frac{5}{16}$  | 84  |
| Y                     | 10.50 | 0.4040         | 10.262 | 3 $\frac{3}{8}$   | 98  | 5 $\frac{1}{4}$ | 133 | ...             | ... | ...             | ... | 1 $\frac{5}{16}$     | 49 | 3 $\frac{5}{16}$  | 84  |
|                       |       | 0.4062         | 10.317 | 3 $\frac{3}{8}$   | 98  | 5 $\frac{1}{4}$ | 133 | 4 $\frac{3}{8}$ | 111 | 7               | 178 | 1 $\frac{5}{16}$     | 49 | 3 $\frac{5}{16}$  | 84  |
| Z                     | 10.50 | 0.4130         | 10.490 | 3 $\frac{3}{8}$   | 98  | 5 $\frac{1}{4}$ | 133 | ...             | ... | ...             | ... | 2                    | 51 | 3 $\frac{3}{8}$   | 86  |
|                       |       | 0.4134         | 10.500 | 3 $\frac{3}{8}$   | 98  | 5 $\frac{1}{4}$ | 133 | 4 $\frac{3}{8}$ | 117 | 7 $\frac{1}{4}$ | 184 | 2                    | 51 | 3 $\frac{3}{8}$   | 86  |
| 27/64                 | 10.80 | 0.4219         | 10.716 | 3 $\frac{15}{16}$ | 100 | 5 $\frac{3}{8}$ | 137 | 4 $\frac{3}{8}$ | 117 | 7 $\frac{1}{4}$ | 184 | 2                    | 51 | 3 $\frac{3}{8}$   | 86  |
|                       |       | 0.4252         | 10.800 | 4 $\frac{1}{16}$  | 103 | 5 $\frac{1}{2}$ | 140 | 4 $\frac{5}{8}$ | 117 | 7 $\frac{1}{4}$ | 184 | 2 $\frac{1}{16}$     | 52 | 3 $\frac{7}{16}$  | 87  |
| 7/16                  | 11.00 | 0.4331         | 11.000 | 4 $\frac{1}{16}$  | 103 | 5 $\frac{1}{2}$ | 140 | 4 $\frac{5}{8}$ | 117 | 7 $\frac{1}{4}$ | 184 | 2 $\frac{1}{16}$     | 52 | 3 $\frac{7}{16}$  | 87  |
|                       |       | 0.4375         | 11.112 | 4 $\frac{1}{16}$  | 103 | 5 $\frac{1}{2}$ | 140 | 4 $\frac{5}{8}$ | 117 | 7 $\frac{1}{4}$ | 184 | 2 $\frac{1}{16}$     | 52 | 3 $\frac{7}{16}$  | 87  |
| 11.20                 | 11.20 | 0.4409         | 11.200 | 4 $\frac{3}{16}$  | 106 | 5 $\frac{5}{8}$ | 143 | 4 $\frac{3}{4}$ | 121 | 7 $\frac{1}{2}$ | 190 | 2 $\frac{1}{8}$      | 54 | 3 $\frac{9}{16}$  | 90  |
|                       |       | 0.4528         | 11.500 | 4 $\frac{3}{16}$  | 106 | 5 $\frac{5}{8}$ | 143 | 4 $\frac{3}{4}$ | 121 | 7 $\frac{1}{2}$ | 190 | 2 $\frac{1}{8}$      | 54 | 3 $\frac{9}{16}$  | 90  |
| 29/64                 | 11.50 | 0.4531         | 11.509 | 4 $\frac{3}{16}$  | 106 | 5 $\frac{5}{8}$ | 143 | 4 $\frac{3}{4}$ | 121 | 7 $\frac{1}{2}$ | 190 | 2 $\frac{1}{8}$      | 54 | 3 $\frac{9}{16}$  | 90  |
|                       |       | 0.4646         | 11.800 | 4 $\frac{3}{16}$  | 110 | 5 $\frac{3}{4}$ | 146 | 4 $\frac{3}{4}$ | 121 | 7 $\frac{1}{2}$ | 190 | 2 $\frac{1}{8}$      | 54 | 3 $\frac{5}{8}$   | 92  |
| 15/32                 | 11.80 | 0.4688         | 11.908 | 4 $\frac{5}{16}$  | 110 | 5 $\frac{3}{4}$ | 146 | 4 $\frac{3}{4}$ | 121 | 7 $\frac{1}{2}$ | 190 | 2 $\frac{1}{8}$      | 54 | 3 $\frac{5}{8}$   | 92  |
|                       |       | 0.4724         | 12.000 | 4 $\frac{3}{8}$   | 111 | 5 $\frac{7}{8}$ | 149 | 4 $\frac{3}{4}$ | 121 | 7 $\frac{3}{4}$ | 197 | 2 $\frac{1}{16}$     | 56 | 3 $\frac{11}{16}$ | 94  |
| 12.20                 | 12.20 | 0.4803         | 12.200 | 4 $\frac{3}{8}$   | 111 | 5 $\frac{7}{8}$ | 149 | 4 $\frac{3}{4}$ | 121 | 7 $\frac{3}{4}$ | 197 | 2 $\frac{1}{16}$     | 56 | 3 $\frac{11}{16}$ | 94  |
|                       |       | 0.4844         | 12.304 | 4 $\frac{3}{8}$   | 111 | 5 $\frac{7}{8}$ | 149 | 4 $\frac{3}{4}$ | 121 | 7 $\frac{3}{4}$ | 197 | 2 $\frac{1}{16}$     | 56 | 3 $\frac{11}{16}$ | 94  |
| 31/64                 | 12.50 | 0.4921         | 12.500 | 4 $\frac{1}{2}$   | 114 | 6               | 152 | 4 $\frac{3}{4}$ | 121 | 7 $\frac{3}{4}$ | 197 | 2 $\frac{1}{4}$      | 57 | 3 $\frac{3}{4}$   | 95  |
|                       |       | 0.5000         | 12.700 | 4 $\frac{1}{2}$   | 114 | 6               | 152 | 4 $\frac{3}{4}$ | 121 | 7 $\frac{3}{4}$ | 197 | 2 $\frac{1}{4}$      | 57 | 3 $\frac{3}{4}$   | 95  |
| 12.80                 | 12.80 | 0.5039         | 12.800 | 4 $\frac{1}{2}$   | 114 | 6               | 152 | ...             | ... | ...             | ... | 2 $\frac{3}{8}$      | 60 | 3 $\frac{3}{8}$   | 98  |
|                       |       | 0.5118         | 13.000 | 4 $\frac{1}{2}$   | 114 | 6               | 152 | ...             | ... | ...             | ... | 2 $\frac{3}{8}$      | 60 | 3 $\frac{3}{8}$   | 98  |
| 33/64                 | 13.00 | 0.5156         | 13.096 | 4 $\frac{15}{16}$ | 122 | 6 $\frac{5}{8}$ | 168 | ...             | ... | ...             | ... | 2 $\frac{3}{8}$      | 60 | 3 $\frac{3}{8}$   | 98  |
|                       |       | 0.5197         | 13.200 | 4 $\frac{15}{16}$ | 122 | 6 $\frac{5}{8}$ | 168 | ...             | ... | ...             | ... | 2 $\frac{3}{8}$      | 60 | 3 $\frac{3}{8}$   | 98  |
| 17/32                 | 13.20 | 0.5312         | 13.492 | 4 $\frac{15}{16}$ | 122 | 6 $\frac{5}{8}$ | 168 | ...             | ... | ...             | ... | 2 $\frac{3}{8}$      | 60 | 3 $\frac{3}{8}$   | 98  |
|                       |       | 0.5315         | 13.500 | 4 $\frac{15}{16}$ | 122 | 6 $\frac{5}{8}$ | 168 | ...             | ... | ...             | ... | 2 $\frac{3}{8}$      | 60 | 3 $\frac{3}{8}$   | 98  |
| 13.80                 | 13.80 | 0.5433         | 13.800 | 4 $\frac{15}{16}$ | 122 | 6 $\frac{5}{8}$ | 168 | ...             | ... | ...             | ... | 2 $\frac{1}{2}$      | 64 | 4                 | 102 |
|                       |       | 0.5469         | 13.891 | 4 $\frac{15}{16}$ | 122 | 6 $\frac{5}{8}$ | 168 | ...             | ... | ...             | ... | 2 $\frac{1}{2}$      | 64 | 4                 | 102 |
| 35/64                 | 14.00 | 0.5512         | 14.000 | 4 $\frac{15}{16}$ | 122 | 6 $\frac{5}{8}$ | 168 | ...             | ... | ...             | ... | 2 $\frac{1}{2}$      | 64 | 4                 | 102 |
|                       |       | 0.5610         | 14.250 | 4 $\frac{15}{16}$ | 122 | 6 $\frac{5}{8}$ | 168 | ...             | ... | ...             | ... | 2 $\frac{1}{2}$      | 64 | 4                 | 102 |
| 9/16                  | 14.25 | 0.5625         | 14.288 | 4 $\frac{15}{16}$ | 122 | 6 $\frac{5}{8}$ | 168 | ...             | ... | ...             | ... | 2 $\frac{1}{2}$      | 64 | 4                 | 102 |
|                       |       | 0.5709         | 14.500 | 4 $\frac{15}{16}$ | 122 | 6 $\frac{5}{8}$ | 168 | ...             | ... | ...             | ... | 2 $\frac{3}{8}$      | 67 | 4 $\frac{1}{8}$   | 105 |
| 37/64                 | 14.50 | 0.5781         | 14.684 | 4 $\frac{15}{16}$ | 122 | 6 $\frac{5}{8}$ | 168 | ...             | ... | ...             | ... | 2 $\frac{3}{8}$      | 67 | 4 $\frac{1}{8}$   | 105 |
|                       |       | 0.5807         | 14.750 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{3}{8}$      | 67 | 4 $\frac{1}{8}$   | 105 |
| 15.00                 | 15.00 | 0.5906         | 15.000 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{3}{8}$      | 67 | 4 $\frac{1}{8}$   | 105 |
|                       |       | 0.5938         | 15.083 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{3}{8}$      | 67 | 4 $\frac{1}{8}$   | 105 |
| 19/32                 | 15.25 | 0.6004         | 15.250 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{3}{4}$      | 70 | 4 $\frac{1}{4}$   | 108 |
|                       |       | 0.6094         | 15.479 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{3}{4}$      | 70 | 4 $\frac{1}{4}$   | 108 |
| 39/64                 | 15.50 | 0.6102         | 15.500 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{3}{4}$      | 70 | 4 $\frac{1}{4}$   | 108 |
|                       |       | 0.6201         | 15.750 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{3}{4}$      | 70 | 4 $\frac{1}{4}$   | 108 |
| 5/8                   | 15.75 | 0.6250         | 15.875 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{3}{4}$      | 70 | 4 $\frac{1}{4}$   | 108 |
|                       |       | 0.6299         | 16.000 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{7}{8}$      | 73 | 4 $\frac{1}{2}$   | 114 |
| 16.00                 | 16.00 | 0.6398         | 16.250 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{7}{8}$      | 73 | 4 $\frac{1}{2}$   | 114 |
|                       |       | 0.6406         | 16.271 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{7}{8}$      | 73 | 4 $\frac{1}{2}$   | 114 |
| 41/64                 | 16.50 | 0.6496         | 16.500 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{7}{8}$      | 73 | 4 $\frac{1}{2}$   | 114 |
|                       |       | 0.6562         | 16.669 | 5 $\frac{1}{16}$  | 132 | 7 $\frac{1}{8}$ | 181 | ...             | ... | ...             | ... | 2 $\frac{7}{8}$      | 73 | 4 $\frac{1}{2}$   | 114 |

**Table 1. (Continued) ANSI Straight Shank Twist Drills — Jobbers Length through 17.5 mm, Taper Length through 12.7 mm, and Screw Machine Length through 25.4 mm Diameter ANSI/ASME B94.11M-1993**

| Drill Diameter, $D^a$ |       | Jobbers Length |        |       |     |         |     | Taper Length |     |         |     | Screw Machine Length |     |         |     |
|-----------------------|-------|----------------|--------|-------|-----|---------|-----|--------------|-----|---------|-----|----------------------|-----|---------|-----|
| Fraction No. or Ltr.  | mm    | Equivalent     |        | Flute |     | Overall |     | Flute        |     | Overall |     | Flute                |     | Overall |     |
|                       |       | Decimal In.    | mm     | $F$   |     | $L$     |     | $F$          |     | $L$     |     | $F$                  |     | $L$     |     |
|                       |       |                |        | Inch  | mm  | Inch    | mm  | Inch         | mm  | Inch    | mm  | Inch                 | mm  | Inch    | mm  |
| 3/64                  | 16.75 | 0.6594         | 16.750 | 5/8   | 143 | 7/8     | 194 | ...          | ... | ...     | ... | 27/8                 | 73  | 4 1/2   | 114 |
|                       | 17.00 | 0.6693         | 17.000 | 5/8   | 143 | 7/8     | 194 | ...          | ... | ...     | ... | 27/8                 | 73  | 4 1/2   | 114 |
|                       |       | 0.6719         | 17.066 | 5/8   | 143 | 7/8     | 194 | ...          | ... | ...     | ... | 27/8                 | 73  | 4 1/2   | 114 |
| 11/16                 | 17.25 | 0.6791         | 17.250 | 5/8   | 143 | 7/8     | 194 | ...          | ... | ...     | ... | 27/8                 | 73  | 4 1/2   | 114 |
|                       |       | 0.6875         | 17.462 | 5/8   | 143 | 7/8     | 194 | ...          | ... | ...     | ... | 27/8                 | 73  | 4 1/2   | 114 |
| 45/64                 | 17.50 | 0.6890         | 17.500 | 5/8   | 143 | 7/8     | 194 | ...          | ... | ...     | ... | 3                    | 76  | 4 3/4   | 121 |
|                       |       | 0.7031         | 17.859 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3                    | 76  | 4 3/4   | 121 |
| 23/32                 | 18.00 | 0.7087         | 18.000 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3                    | 76  | 4 3/4   | 121 |
|                       |       | 0.7188         | 18.258 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3                    | 76  | 4 3/4   | 121 |
| 47/64                 | 18.50 | 0.7283         | 18.500 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/8                | 79  | 5       | 127 |
|                       |       | 0.7344         | 18.654 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/8                | 79  | 5       | 127 |
| 3/4                   | 19.00 | 0.7480         | 19.000 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/8                | 79  | 5       | 127 |
|                       |       | 0.7500         | 19.050 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/8                | 79  | 5       | 127 |
| 49/64                 | 19.50 | 0.7656         | 19.446 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/4                | 83  | 5 1/8   | 130 |
|                       |       | 0.7677         | 19.500 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/4                | 83  | 5 1/8   | 130 |
| 25/32                 | 20.00 | 0.7812         | 19.845 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/4                | 83  | 5 1/8   | 130 |
|                       |       | 0.7879         | 20.000 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 3/8                | 86  | 5 1/4   | 133 |
| 51/64                 | 20.50 | 0.7969         | 20.241 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 3/8                | 86  | 5 1/4   | 133 |
|                       |       | 0.8071         | 20.500 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 3/8                | 86  | 5 1/4   | 133 |
| 13/16                 | 21.00 | 0.8125         | 20.638 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 3/8                | 86  | 5 1/4   | 133 |
|                       |       | 0.8268         | 21.000 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/2                | 89  | 5 3/8   | 137 |
| 53/64                 | 21.50 | 0.8281         | 21.034 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/2                | 89  | 5 3/8   | 137 |
|                       |       | 0.8438         | 21.433 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/2                | 89  | 5 3/8   | 137 |
| 27/32                 | 21.50 | 0.8465         | 21.500 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/2                | 89  | 5 3/8   | 137 |
|                       |       | 0.8594         | 21.829 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/2                | 89  | 5 3/8   | 137 |
| 55/64                 | 22.00 | 0.8661         | 22.000 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/2                | 89  | 5 3/8   | 137 |
|                       |       | 0.8750         | 22.225 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 1/2                | 89  | 5 3/8   | 137 |
| 7/8                   | 22.50 | 0.8858         | 22.500 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 3/8                | 92  | 5 5/8   | 143 |
|                       |       | 0.8906         | 22.621 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 3/8                | 92  | 5 5/8   | 143 |
| 57/64                 | 23.00 | 0.9055         | 23.000 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 3/8                | 92  | 5 5/8   | 143 |
|                       |       | 0.9062         | 23.017 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 3/8                | 92  | 5 5/8   | 143 |
| 29/32                 | 23.50 | 0.9219         | 23.416 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 3/4                | 95  | 5 3/4   | 146 |
|                       |       | 0.9252         | 23.500 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 3/4                | 95  | 5 3/4   | 146 |
| 15/16                 | 24.00 | 0.9375         | 23.812 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 3/4                | 95  | 5 3/4   | 146 |
|                       |       | 0.9449         | 24.000 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 3/8                | 98  | 5 7/8   | 149 |
| 61/64                 | 24.50 | 0.9531         | 24.209 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 7/8                | 98  | 5 7/8   | 149 |
|                       |       | 0.9646         | 24.500 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 7/8                | 98  | 5 7/8   | 149 |
| 31/32                 | 24.50 | 0.9688         | 24.608 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 3 7/8                | 98  | 5 7/8   | 149 |
|                       |       | 0.9843         | 25.000 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 4                    | 102 | 6       | 152 |
| 63/64                 | 25.00 | 0.9844         | 25.004 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 4                    | 102 | 6       | 152 |
|                       |       | 1.0000         | 25.400 | ...   | ... | ...     | ... | ...          | ... | ...     | ... | 4                    | 102 | 6       | 152 |

<sup>a</sup>Fractional inch, number, letter, and metric sizes.

## TWIST DRILLS



Nominal Shank Size is Same as Nominal Drill Size

**Table 2. ANSI Straight Shank Twist Drills — Taper Length — Over ½ in. (12.7 mm) Dia., Fractional and Metric Sizes ANSI/ASME B94.11M-1993**

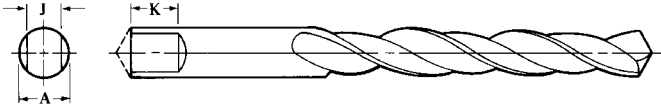
| Diameter of Drill |       |             |            | Flute Length |     | Overall Length |     | Length of Body |     | Minimum Length of Shk. |    | Maximum Length of Neck |    |
|-------------------|-------|-------------|------------|--------------|-----|----------------|-----|----------------|-----|------------------------|----|------------------------|----|
| D                 |       | Decimal     | Millimeter | F            |     | L              |     | B              |     | S                      |    | N                      |    |
| Frac.             | mm    | Inch Equiv. | Equiv.     | Inch         | mm  | Inch           | mm  | Inch           | mm  | Inch                   | mm | Inch                   | mm |
| 33/64             | 12.80 | 0.5039      | 12.800     | 4 3/4        | 121 | 8              | 203 | 4 7/8          | 124 | 2 3/8                  | 66 | 1/2                    | 13 |
|                   | 13.00 | 0.5117      | 13.000     | 4 3/4        | 121 | 8              | 203 | 4 7/8          | 124 | 2 3/8                  | 66 | 1/2                    | 13 |
|                   |       | 0.5156      | 13.096     | 4 3/4        | 121 | 8              | 203 | 4 7/8          | 124 | 2 3/8                  | 66 | 1/2                    | 13 |
|                   | 13.20 | 0.5197      | 13.200     | 4 3/4        | 121 | 8              | 203 | 4 7/8          | 124 | 2 3/8                  | 66 | 1/2                    | 13 |
| 17/32             |       | 0.5312      | 13.492     | 4 3/4        | 121 | 8              | 203 | 4 7/8          | 124 | 2 3/8                  | 66 | 1/2                    | 13 |
|                   | 13.50 | 0.5315      | 13.500     | 4 3/4        | 121 | 8              | 203 | 4 7/8          | 124 | 2 3/8                  | 66 | 1/2                    | 13 |
|                   | 13.80 | 0.5433      | 13.800     | 4 7/8        | 124 | 8 1/4          | 210 | 5              | 127 | 2 3/4                  | 70 | 1/2                    | 13 |
|                   |       | 0.5419      | 13.891     | 4 7/8        | 124 | 8 1/4          | 210 | 5              | 127 | 2 3/4                  | 70 | 1/2                    | 13 |
| 35/64             |       | 0.5512      | 14.000     | 4 7/8        | 124 | 8 1/4          | 210 | 5              | 127 | 2 3/4                  | 70 | 1/2                    | 13 |
|                   | 14.00 | 0.5610      | 14.250     | 4 7/8        | 124 | 8 1/4          | 210 | 5              | 127 | 2 3/4                  | 70 | 1/2                    | 13 |
|                   | 14.25 | 0.5625      | 14.288     | 4 7/8        | 124 | 8 1/4          | 210 | 5              | 127 | 2 3/4                  | 70 | 1/2                    | 13 |
|                   | 14.50 | 0.5709      | 14.500     | 4 7/8        | 124 | 8 3/4          | 222 | 5              | 127 | 3 3/8                  | 79 | 3/8                    | 16 |
| 37/64             |       | 0.5781      | 14.684     | 4 7/8        | 124 | 8 3/4          | 222 | 5              | 127 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 14.75 | 0.5807      | 14.750     | 4 7/8        | 124 | 8 3/4          | 222 | 5              | 127 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 15.00 | 0.5906      | 15.000     | 4 7/8        | 124 | 8 3/4          | 222 | 5              | 127 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   |       | 0.5938      | 15.083     | 4 7/8        | 124 | 8 3/4          | 222 | 5              | 127 | 3 3/8                  | 79 | 3/8                    | 16 |
| 19/32             | 15.25 | 0.6004      | 15.250     | 4 7/8        | 124 | 8 3/4          | 222 | 5              | 127 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   |       | 0.6094      | 15.479     | 4 7/8        | 124 | 8 3/4          | 222 | 5              | 127 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 15.50 | 0.6102      | 15.500     | 4 7/8        | 124 | 8 3/4          | 222 | 5              | 127 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 15.75 | 0.6201      | 15.750     | 4 7/8        | 124 | 8 3/4          | 222 | 5              | 127 | 3 3/8                  | 79 | 3/8                    | 16 |
| 5/8               |       | 0.6250      | 15.875     | 4 7/8        | 124 | 8 3/4          | 222 | 5              | 127 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 16.00 | 0.6299      | 16.000     | 5 1/8        | 130 | 9              | 228 | 5 1/4          | 133 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 16.25 | 0.6398      | 16.250     | 5 1/8        | 130 | 9              | 228 | 5 1/4          | 133 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   |       | 0.6406      | 16.271     | 5 1/8        | 130 | 9              | 228 | 5 1/4          | 133 | 3 3/8                  | 79 | 3/8                    | 16 |
| 41/64             | 16.50 | 0.6496      | 16.500     | 5 1/8        | 130 | 9              | 228 | 5 1/4          | 133 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   |       | 0.6562      | 16.667     | 5 1/8        | 130 | 9              | 228 | 5 1/4          | 133 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 16.75 | 0.6594      | 16.750     | 5 3/8        | 137 | 9 1/4          | 235 | 5 1/2          | 140 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 17.00 | 0.6693      | 17.000     | 5 3/8        | 137 | 9 1/4          | 235 | 5 1/2          | 140 | 3 3/8                  | 79 | 3/8                    | 16 |
| 43/64             |       | 0.6719      | 17.066     | 5 3/8        | 137 | 9 1/4          | 235 | 5 1/2          | 140 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 17.25 | 0.6791      | 17.250     | 5 3/8        | 137 | 9 1/4          | 235 | 5 1/2          | 140 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   |       | 0.6875      | 17.462     | 5 3/8        | 137 | 9 1/4          | 235 | 5 1/2          | 140 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 17.50 | 0.6890      | 17.500     | 5 3/8        | 143 | 9 1/2          | 241 | 5 3/4          | 146 | 3 3/8                  | 79 | 3/8                    | 16 |
| 45/64             |       | 0.7031      | 17.859     | 5 3/8        | 143 | 9 1/2          | 241 | 5 3/4          | 146 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 18.00 | 0.7087      | 18.000     | 5 3/8        | 143 | 9 1/2          | 241 | 5 3/4          | 146 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   |       | 0.7188      | 18.258     | 5 3/8        | 143 | 9 1/2          | 241 | 5 3/4          | 146 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 18.50 | 0.7283      | 18.500     | 5 3/8        | 149 | 9 3/4          | 247 | 6              | 152 | 3 3/8                  | 79 | 3/8                    | 16 |
| 47/64             |       | 0.7344      | 18.654     | 5 3/8        | 149 | 9 3/4          | 247 | 6              | 152 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 19.00 | 0.7480      | 19.000     | 5 3/8        | 149 | 9 3/4          | 247 | 6              | 152 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   |       | 0.7500      | 19.050     | 5 3/8        | 149 | 9 3/4          | 247 | 6              | 152 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 19.50 | 0.7656      | 19.446     | 6            | 152 | 9 7/8          | 251 | 6 1/8          | 156 | 3 3/8                  | 79 | 3/8                    | 16 |
| 49/64             |       | 0.7677      | 19.500     | 6            | 152 | 9 7/8          | 251 | 6 1/8          | 156 | 3 3/8                  | 79 | 3/8                    | 16 |
|                   | 19.50 | 0.7812      | 19.842     | 6            | 152 | 9 7/8          | 251 | 6 1/8          | 156 | 3 3/8                  | 79 | 3/8                    | 16 |

**Table 2. (Continued) ANSI Straight Shank Twist Drills — Taper Length — Over 1/2 in. (12.7 mm) Dia., Fractional and Metric Sizes ANSI/ASME B94.11M-1993**

| Diameter of Drill |       |                     | Flute Length      |       | Overall Length |        | Length of Body |       | Minimum Length of Shk. |       | Maximum Length of Neck |      |    |
|-------------------|-------|---------------------|-------------------|-------|----------------|--------|----------------|-------|------------------------|-------|------------------------|------|----|
| D                 |       | Decimal Inch Equiv. | Millimeter Equiv. | F     |                | L      |                | B     |                        | S     |                        | N    |    |
| Frac.             | mm    |                     |                   | Inch  | mm             | Inch   | mm             | Inch  | mm                     | Inch  | mm                     | Inch | mm |
|                   | 20.00 | 0.7874              | 20.000            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   |       | 0.7969              | 20.241            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   | 20.50 | 0.8071              | 20.500            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   |       | 0.8125              | 20.638            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   | 21.00 | 0.8268              | 21.000            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   |       | 0.8281              | 21.034            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   |       | 0.8438              | 21.433            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   | 21.50 | 0.8465              | 21.500            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   |       | 0.8594              | 21.829            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   | 22.00 | 0.8661              | 22.000            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   |       | 0.8750              | 22.225            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   | 22.50 | 0.8858              | 22.500            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   |       | 0.8906              | 22.621            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   | 23.00 | 0.9055              | 23.000            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   |       | 0.9062              | 23.017            | 6 1/8 | 156            | 10     | 254            | 6 1/4 | 159                    | 3 3/8 | 79                     | 5/8  | 16 |
|                   |       | 0.9219              | 23.416            | 6 1/8 | 156            | 10 3/4 | 273            | 6 1/4 | 159                    | 3 3/8 | 98                     | 5/8  | 16 |
|                   | 23.50 | 0.9252              | 23.500            | 6 1/8 | 156            | 10 3/4 | 273            | 6 1/4 | 159                    | 3 3/8 | 98                     | 5/8  | 16 |
|                   |       | 0.9375              | 23.812            | 6 1/8 | 156            | 10 3/4 | 273            | 6 1/4 | 159                    | 3 3/8 | 98                     | 5/8  | 16 |
|                   | 24.00 | 0.9449              | 24.000            | 6 3/8 | 162            | 11     | 279            | 6 1/2 | 165                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 0.9531              | 24.209            | 6 3/8 | 162            | 11     | 279            | 6 1/2 | 165                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 24.50 | 0.9646              | 24.500            | 6 3/8 | 162            | 11     | 279            | 6 1/2 | 165                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 0.9688              | 24.608            | 6 3/8 | 162            | 11     | 279            | 6 1/2 | 165                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 25.00 | 0.9843              | 25.000            | 6 3/8 | 162            | 11     | 279            | 6 1/2 | 165                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 0.9844              | 25.004            | 6 3/8 | 162            | 11     | 279            | 6 1/2 | 165                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 1     | 1.0000              | 25.400            | 6 3/8 | 162            | 11     | 279            | 6 1/2 | 165                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 25.50 | 1.0039              | 25.500            | 6 1/2 | 165            | 11 1/8 | 282            | 6 3/8 | 168                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.0156              | 25.796            | 6 1/2 | 165            | 11 1/8 | 282            | 6 3/8 | 168                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 26.00 | 1.0236              | 26.000            | 6 1/2 | 165            | 11 1/8 | 282            | 6 3/8 | 168                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.0312              | 26.192            | 6 1/2 | 165            | 11 1/8 | 282            | 6 3/8 | 168                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 26.50 | 1.0433              | 26.560            | 6 3/8 | 168            | 11 1/4 | 286            | 6 3/4 | 172                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.0469              | 26.591            | 6 3/8 | 168            | 11 1/4 | 286            | 6 3/4 | 172                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.0625              | 26.988            | 6 3/8 | 168            | 11 1/4 | 286            | 6 3/4 | 172                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 27.00 | 1.0630              | 27.000            | 6 3/8 | 168            | 11 1/4 | 286            | 6 3/4 | 172                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.0781              | 27.384            | 6 3/8 | 175            | 11 1/2 | 292            | 7     | 178                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 27.50 | 1.0827              | 27.500            | 6 7/8 | 175            | 11 1/2 | 292            | 7     | 178                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.0938              | 27.783            | 6 7/8 | 175            | 11 1/2 | 292            | 7     | 178                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 28.00 | 1.1024              | 28.000            | 7 1/8 | 181            | 11 3/4 | 298            | 7 1/4 | 184                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.1094              | 28.179            | 7 1/8 | 181            | 11 3/4 | 298            | 7 1/4 | 184                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 28.50 | 1.1220              | 28.500            | 7 1/8 | 181            | 11 3/4 | 298            | 7 1/4 | 184                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.1250              | 28.575            | 7 1/8 | 181            | 11 3/4 | 298            | 7 1/4 | 184                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.1406              | 28.971            | 7 1/4 | 184            | 11 7/8 | 301            | 7 3/8 | 187                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 29.00 | 1.1417              | 29.000            | 7 1/4 | 184            | 11 7/8 | 301            | 7 3/8 | 187                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.1562              | 29.367            | 7 1/4 | 184            | 11 7/8 | 301            | 7 3/8 | 187                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 29.50 | 1.1614              | 29.500            | 7 3/8 | 187            | 12     | 305            | 7 1/2 | 191                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.1719              | 29.766            | 7 3/8 | 187            | 12     | 305            | 7 1/2 | 191                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 30.00 | 1.1811              | 30.000            | 7 3/8 | 187            | 12     | 305            | 7 1/2 | 191                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.1875              | 30.162            | 7 3/8 | 187            | 12     | 305            | 7 1/2 | 191                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 30.50 | 1.2008              | 30.500            | 7 1/2 | 190            | 12 1/8 | 308            | 7 3/8 | 194                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.2031              | 30.559            | 7 1/2 | 190            | 12 1/8 | 308            | 7 3/8 | 194                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.2188              | 30.958            | 7 1/2 | 190            | 12 1/8 | 308            | 7 3/8 | 194                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 31.00 | 1.2205              | 31.000            | 7 7/8 | 200            | 12 1/2 | 317            | 8     | 203                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   |       | 1.2344              | 31.354            | 7 7/8 | 200            | 12 1/2 | 317            | 8     | 203                    | 3 7/8 | 98                     | 5/8  | 16 |
|                   | 31.50 | 1.2402              | 31.500            | 7 7/8 | 200            | 12 1/2 | 317            | 8     | 203                    | 3 7/8 | 98                     | 5/8  | 16 |

**Table 2. (Continued) ANSI Straight Shank Twist Drills — Taper Length — Over ½ in. (12.7 mm) Dia., Fractional and Metric Sizes ANSI/ASME B94.11M-1993**

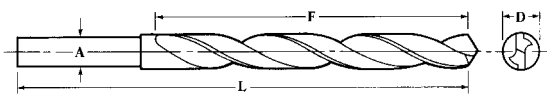
| Diameter of Drill |       |                     | Flute Length      |      | Overall Length |      | Length of Body |      | Minimum Length of Shk. |      | Maximum Length of Neck |      |    |
|-------------------|-------|---------------------|-------------------|------|----------------|------|----------------|------|------------------------|------|------------------------|------|----|
| D                 |       | Decimal Inch Equiv. | Millimeter Equiv. | F    |                | L    |                | B    |                        | S    |                        | N    |    |
| Frac.             | mm    |                     |                   | Inch | mm             | Inch | mm             | Inch | mm                     | Inch | mm                     | Inch | mm |
| 1¼                |       | 1.2500              | 31.750            | 7⅞   | 200            | 12½  | 317            | 8    | 203                    | 3⅞   | 98                     | ⅝    | 16 |
|                   | 32.00 | 1.2598              | 32.000            | 8½   | 216            | 14¼  | 359            | 8⅝   | 219                    | 4⅞   | 124                    | ⅝    | 16 |
|                   | 32.50 | 1.2795              | 32.500            | 8½   | 216            | 14⅛  | 359            | 8⅝   | 219                    | 4⅞   | 124                    | ⅝    | 16 |
| 1⅝                |       | 1.2812              | 32.542            | 8½   | 216            | 14⅛  | 359            | 8⅝   | 219                    | 4⅞   | 124                    | ⅝    | 16 |
|                   | 33.00 | 1.2992              | 33.000            | 8⅝   | 219            | 14¼  | 362            | 8¾   | 222                    | 4⅞   | 124                    | ⅝    | 16 |
|                   |       | 1.3125              | 33.338            | 8⅝   | 219            | 14¼  | 362            | 8¾   | 222                    | 4⅞   | 124                    | ⅝    | 16 |
| 1⅞                |       | 1.3189              | 33.500            | 8¾   | 222            | 14⅜  | 365            | 8⅞   | 225                    | 4⅞   | 124                    | ⅝    | 16 |
|                   | 33.50 | 1.3386              | 34.000            | 8¾   | 222            | 14⅜  | 365            | 8⅞   | 225                    | 4⅞   | 124                    | ⅝    | 16 |
|                   | 34.00 | 1.3438              | 34.133            | 8¾   | 222            | 14⅜  | 365            | 8⅞   | 225                    | 4⅞   | 124                    | ⅝    | 16 |
| 1½                |       | 1.3583              | 34.500            | 8⅞   | 225            | 14½  | 368            | 9    | 229                    | 4⅞   | 124                    | ⅝    | 16 |
|                   | 34.50 | 1.3583              | 34.500            | 8⅞   | 225            | 14½  | 368            | 9    | 229                    | 4⅞   | 124                    | ⅝    | 16 |
|                   |       | 1.3750              | 34.925            | 8⅞   | 225            | 14½  | 368            | 9    | 229                    | 4⅞   | 124                    | ⅝    | 16 |
| 1⅜                |       | 1.3780              | 35.000            | 9    | 229            | 14⅝  | 372            | 9⅛   | 232                    | 4⅞   | 124                    | ⅝    | 16 |
|                   | 35.00 | 1.3976              | 35.500            | 9    | 229            | 14⅝  | 372            | 9⅛   | 232                    | 4⅞   | 124                    | ⅝    | 16 |
|                   |       | 1.4062              | 35.717            | 9    | 229            | 14⅝  | 372            | 9⅛   | 232                    | 4⅞   | 124                    | ⅝    | 16 |
| 1⅓                |       | 1.4173              | 36.000            | 9⅞   | 232            | 14¾  | 375            | 9¼   | 235                    | 4⅞   | 124                    | ⅝    | 16 |
|                   | 36.00 | 1.4370              | 36.500            | 9⅞   | 232            | 14¾  | 375            | 9¼   | 235                    | 4⅞   | 124                    | ⅝    | 16 |
|                   | 36.50 | 1.4370              | 36.500            | 9⅞   | 232            | 14¾  | 375            | 9¼   | 235                    | 4⅞   | 124                    | ⅝    | 16 |
| 1⅞                |       | 1.4375              | 36.512            | 9⅞   | 232            | 14¾  | 375            | 9¼   | 235                    | 4⅞   | 124                    | ⅝    | 16 |
|                   | 37.00 | 1.4567              | 37.000            | 9¼   | 235            | 14⅞  | 378            | 9⅝   | 238                    | 4⅞   | 124                    | ⅝    | 16 |
|                   |       | 1.4688              | 37.308            | 9¼   | 235            | 14⅞  | 378            | 9⅝   | 238                    | 4⅞   | 124                    | ⅝    | 16 |
| 1½                |       | 1.4764              | 37.500            | 9⅝   | 238            | 15   | 381            | 9½   | 241                    | 4⅞   | 124                    | ⅝    | 16 |
|                   | 37.50 | 1.4764              | 37.500            | 9⅝   | 238            | 15   | 381            | 9½   | 241                    | 4⅞   | 124                    | ⅝    | 16 |
|                   | 38.00 | 1.4961              | 38.000            | 9⅝   | 238            | 15   | 381            | 9½   | 241                    | 4⅞   | 124                    | ⅝    | 16 |
| 1½                |       | 1.5000              | 38.100            | 9⅝   | 238            | 15   | 381            | 9½   | 241                    | 4⅞   | 124                    | ⅝    | 16 |
| 1⅞                |       | 1.5625              | 39.688            | 9⅝   | 244            | 15¼  | 387            | 9¾   | 247                    | 4⅞   | 124                    | ⅝    | 16 |
| 1⅝                |       | 1.6250              | 41.275            | 9⅝   | 251            | 15⅝  | 397            | 10   | 254                    | 4⅞   | 124                    | ⅝    | 19 |
| 1¾                |       | 1.7500              | 44.450            | 10½  | 267            | 16¼  | 413            | 10⅝  | 270                    | 4⅞   | 124                    | ⅝    | 19 |



**Table 3. American National Standard Tangs for Straight Shank Drills ANSI/ASME B94.11M-1993**

| Nominal Diameter of Drill Shank, A |                       | Thickness of Tang, J |       |             |       | Length of Tang, K |             |
|------------------------------------|-----------------------|----------------------|-------|-------------|-------|-------------------|-------------|
| Inches                             | Millimeters           | Inches               |       | Millimeters |       | Inches            | Millimeters |
|                                    |                       | Max.                 | Min.  | Max.        | Min.  |                   |             |
| ⅓ thru ⅜                           | 3.18 thru 4.76        | 0.094                | 0.090 | 2.39        | 2.29  | ⅞                 | 7.0         |
| over ⅜ thru ¼                      | over 4.76 thru 6.35   | 0.122                | 0.118 | 3.10        | 3.00  | ⅞                 | 8.0         |
| over ¼ thru ⅜                      | over 6.35 thru 7.94   | 0.162                | 0.158 | 4.11        | 4.01  | 1⅝                | 8.5         |
| over ⅜ thru ⅝                      | over 7.94 thru 9.53   | 0.203                | 0.199 | 5.16        | 5.06  | ⅝                 | 9.5         |
| over ⅝ thru 1⅝                     | over 9.53 thru 11.91  | 0.243                | 0.239 | 6.17        | 6.07  | ⅞                 | 11.0        |
| over 1⅝ thru 1⅞                    | over 11.91 thru 14.29 | 0.303                | 0.297 | 7.70        | 7.55  | ½                 | 12.5        |
| over 1⅞ thru 2⅝                    | over 14.29 thru 16.67 | 0.373                | 0.367 | 9.47        | 9.32  | ⅞                 | 14.5        |
| over 2⅝ thru ¾                     | over 16.67 thru 19.05 | 0.443                | 0.437 | 11.25       | 11.10 | ⅝                 | 16.0        |
| over ¾ thru ⅞                      | over 19.05 thru 22.23 | 0.514                | 0.508 | 13.05       | 12.90 | 1⅞                | 17.5        |
| over ⅞ thru 1                      | over 22.23 thru 25.40 | 0.609                | 0.601 | 15.47       | 15.27 | ¾                 | 19.0        |
| over 1 thru 1⅞                     | over 25.40 thru 30.16 | 0.700                | 0.692 | 17.78       | 17.58 | 1⅞                | 20.5        |
| over 1⅞ thru 1⅝                    | over 30.16 thru 34.93 | 0.817                | 0.809 | 20.75       | 20.55 | ⅞                 | 22.0        |

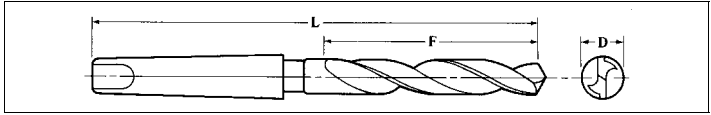
To fit split sleeve collet type drill drivers. See page 878.

**Table 4. American National Standard Straight Shank Twist Drills — Screw Machine Length — Over 1 in. (25.4 mm) Dia. ANSI/ASME B94.11M-1993**


| Diameter of Drill |       |                         |                       | Flute Length |     | Overall Length |     | Shank Diameter |       |
|-------------------|-------|-------------------------|-----------------------|--------------|-----|----------------|-----|----------------|-------|
| D                 |       | Decimal Inch Equivalent | Millimeter Equivalent | F            |     | L              |     | A              |       |
| Frac.             | mm    |                         |                       | Inch         | mm  | Inch           | mm  | Inch           | mm    |
| 1 1/16            | 25.50 | 1.0039                  | 25.500                | 4            | 102 | 6              | 152 | 0.9843         | 25.00 |
|                   | 26.00 | 1.0236                  | 26.000                | 4            | 102 | 6              | 152 | 0.9843         | 25.00 |
|                   | 28.00 | 1.1024                  | 28.000                | 4            | 102 | 6              | 152 | 1.0000         | 25.40 |
| 1 1/8             | 30.00 | 1.1811                  | 30.000                | 4 1/4        | 108 | 6 5/8          | 168 | 0.9843         | 25.00 |
|                   | 32.00 | 1.2598                  | 32.000                | 4 3/8        | 111 | 7              | 178 | 1.2402         | 31.50 |
| 1 3/16            | 34.00 | 1.3386                  | 34.000                | 4 1/2        | 114 | 7 1/8          | 181 | 1.2402         | 31.50 |
|                   | 36.00 | 1.4173                  | 36.000                | 4 3/4        | 121 | 7 3/8          | 187 | 1.2402         | 31.50 |
| 1 1/4             | 38.00 | 1.4961                  | 38.000                | 4 7/8        | 124 | 7 1/2          | 190 | 1.2402         | 31.50 |
|                   | 40.00 | 1.5748                  | 40.000                | 4 7/8        | 124 | 7 3/4          | 197 | 1.4961         | 38.00 |
| 1 1/2             | 42.00 | 1.6535                  | 42.000                | 5 1/8        | 130 | 8              | 203 | 1.4961         | 38.00 |
|                   | 44.00 | 1.7323                  | 44.000                | 5 1/8        | 130 | 8              | 203 | 1.4961         | 38.00 |
| 1 5/8             | 46.00 | 1.8110                  | 46.000                | 5 3/8        | 137 | 8 1/4          | 210 | 1.4961         | 38.00 |
|                   | 48.00 | 1.8898                  | 48.000                | 5 3/8        | 137 | 8 1/2          | 216 | 1.4961         | 38.00 |
| 1 7/8             | 50.00 | 1.9685                  | 50.000                | 5 3/8        | 143 | 8 1/2          | 216 | 1.4961         | 38.00 |
|                   | 52.00 | 2.0473                  | 52.000                | 5 3/8        | 143 | 8 3/4          | 222 | 1.4961         | 38.00 |
| 2                 | 54.00 | 2.1260                  | 54.000                | 5 3/8        | 143 | 8 3/4          | 222 | 1.4961         | 38.00 |
|                   | 56.00 | 2.2048                  | 56.000                | 5 3/8        | 143 | 8 3/4          | 222 | 1.4961         | 38.00 |



TWIST DRILLS



**Table 5. American National Taper Shank Twist Drills  
Fractional and Metric Sizes ANSINASME B94.11M-1993**

| Drill Diameter, <i>D</i> |            |              |        | Regular Shank   |              |    |                | Larger or Smaller Shank <sup>a</sup> |                 |              |     |                |     |
|--------------------------|------------|--------------|--------|-----------------|--------------|----|----------------|--------------------------------------|-----------------|--------------|-----|----------------|-----|
| Fraction                 | Equivalent |              |        | Morse Taper No. | Flute Length |    | Overall Length |                                      | Morse Taper No. | Flute Length |     | Overall Length |     |
|                          | mm         | Decimal Inch | mm     |                 | <i>F</i>     |    | <i>L</i>       |                                      |                 | <i>F</i>     |     | <i>L</i>       |     |
|                          |            |              |        |                 | Inch         | mm | Inch           | mm                                   |                 | Inch         | mm  | Inch           | mm  |
| 1/8                      | 3.00       | 0.1181       | 3.000  | 1               | 1 7/8        | 48 | 5 1/8          | 130                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.1250       | 3.175  | 1               | 1 7/8        | 48 | 5 1/8          | 130                                  | ...             | ...          | ... | ...            |     |
|                          | 3.20       | 0.1260       | 3.200  | 1               | 2 1/8        | 54 | 5 3/8          | 137                                  | ...             | ...          | ... | ...            |     |
| 3/16                     | 3.50       | 0.1378       | 3.500  | 1               | 2 1/8        | 54 | 5 3/8          | 137                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.1406       | 3.571  | 1               | 2 1/8        | 54 | 5 3/8          | 137                                  | ...             | ...          | ... | ...            |     |
|                          | 3.80       | 0.1496       | 3.800  | 1               | 2 1/8        | 54 | 5 3/8          | 137                                  | ...             | ...          | ... | ...            |     |
| 1/4                      | 4.00       | 0.1562       | 3.967  | 1               | 2 1/8        | 54 | 5 3/8          | 137                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.1575       | 4.000  | 1               | 2 1/2        | 64 | 5 3/4          | 146                                  | ...             | ...          | ... | ...            |     |
|                          | 4.20       | 0.1654       | 4.200  | 1               | 2 1/2        | 64 | 5 3/4          | 146                                  | ...             | ...          | ... | ...            |     |
| 5/16                     | 4.50       | 0.1719       | 4.366  | 1               | 2 1/2        | 64 | 5 3/4          | 146                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.1772       | 4.500  | 1               | 2 1/2        | 64 | 5 3/4          | 146                                  | ...             | ...          | ... | ...            |     |
|                          | 4.80       | 0.1875       | 4.762  | 1               | 2 1/2        | 64 | 5 3/4          | 146                                  | ...             | ...          | ... | ...            |     |
| 3/8                      | 5.00       | 0.1890       | 4.800  | 1               | 2 3/4        | 70 | 6              | 152                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.1969       | 5.000  | 1               | 2 3/4        | 70 | 6              | 152                                  | ...             | ...          | ... | ...            |     |
|                          | 5.20       | 0.2031       | 5.159  | 1               | 2 3/4        | 70 | 6              | 152                                  | ...             | ...          | ... | ...            |     |
| 7/16                     | 5.50       | 0.2047       | 5.200  | 1               | 2 3/4        | 70 | 6              | 152                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.2165       | 5.500  | 1               | 2 3/4        | 70 | 6              | 152                                  | ...             | ...          | ... | ...            |     |
|                          | 5.80       | 0.2183       | 5.558  | 1               | 2 3/4        | 70 | 6              | 152                                  | ...             | ...          | ... | ...            |     |
| 1/2                      | 6.00       | 0.2223       | 5.800  | 1               | 2 3/8        | 73 | 6 1/8          | 156                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.2344       | 5.954  | 1               | 2 3/8        | 73 | 6 1/8          | 156                                  | ...             | ...          | ... | ...            |     |
|                          | 6.20       | 0.2362       | 6.000  | 1               | 2 3/8        | 73 | 6 1/8          | 156                                  | ...             | ...          | ... | ...            |     |
| 5/8                      | 6.50       | 0.2441       | 6.200  | 1               | 2 3/8        | 73 | 6 1/8          | 156                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.2500       | 6.350  | 1               | 2 3/8        | 73 | 6 1/8          | 156                                  | ...             | ...          | ... | ...            |     |
|                          | 6.80       | 0.2559       | 6.500  | 1               | 3            | 76 | 6 1/4          | 159                                  | ...             | ...          | ... | ...            |     |
| 3/4                      | 7.00       | 0.2656       | 6.746  | 1               | 3            | 76 | 6 1/4          | 159                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.2677       | 6.800  | 1               | 3            | 76 | 6 1/4          | 159                                  | ...             | ...          | ... | ...            |     |
|                          | 7.20       | 0.2756       | 7.000  | 1               | 3            | 76 | 6 1/4          | 159                                  | ...             | ...          | ... | ...            |     |
| 7/8                      | 7.50       | 0.2812       | 7.142  | 1               | 3            | 76 | 6 1/4          | 159                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.2835       | 7.200  | 1               | 3 1/8        | 79 | 6 3/8          | 162                                  | ...             | ...          | ... | ...            |     |
|                          | 7.80       | 0.2953       | 7.500  | 1               | 3 1/8        | 79 | 6 3/8          | 162                                  | ...             | ...          | ... | ...            |     |
| 1 1/16                   | 8.00       | 0.2969       | 7.541  | 1               | 3 1/8        | 79 | 6 3/8          | 162                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.3071       | 7.800  | 1               | 3 1/8        | 79 | 6 3/8          | 162                                  | ...             | ...          | ... | ...            |     |
|                          | 8.20       | 0.3125       | 7.938  | 1               | 3 1/8        | 79 | 6 3/8          | 162                                  | ...             | ...          | ... | ...            |     |
| 1 1/8                    | 8.50       | 0.3150       | 8.000  | 1               | 3 1/4        | 83 | 6 1/2          | 165                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.3228       | 8.200  | 1               | 3 1/4        | 83 | 6 1/2          | 165                                  | ...             | ...          | ... | ...            |     |
|                          | 8.80       | 0.3281       | 8.334  | 1               | 3 1/4        | 83 | 6 1/2          | 165                                  | ...             | ...          | ... | ...            |     |
| 1 1/4                    | 9.00       | 0.3346       | 8.500  | 1               | 3 1/4        | 83 | 6 1/2          | 165                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.3438       | 8.733  | 1               | 3 1/2        | 89 | 6 3/4          | 171                                  | ...             | ...          | ... | ...            |     |
|                          | 9.20       | 0.3465       | 8.800  | 1               | 3 1/2        | 89 | 6 3/4          | 171                                  | ...             | ...          | ... | ...            |     |
| 1 3/8                    | 9.50       | 0.3543       | 9.000  | 1               | 3 1/2        | 89 | 6 3/4          | 171                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.3594       | 9.129  | 1               | 3 1/2        | 89 | 6 3/4          | 171                                  | ...             | ...          | ... | ...            |     |
|                          | 9.80       | 0.3622       | 9.200  | 1               | 3 1/2        | 89 | 6 3/4          | 171                                  | ...             | ...          | ... | ...            |     |
| 1 1/2                    | 10.00      | 0.3740       | 9.500  | 1               | 3 1/2        | 89 | 6 3/4          | 171                                  | ...             | ...          | ... | ...            |     |
|                          |            | 0.3750       | 9.525  | 1               | 3 1/2        | 89 | 6 3/4          | 171                                  | 2               | 3 1/2        | 89  | 7 3/8          | 187 |
|                          | 10.20      | 0.3858       | 9.800  | 1               | 3 3/8        | 92 | 7              | 178                                  | ...             | ...          | ... | ...            |     |
| 1 5/8                    | 10.50      | 0.3906       | 9.921  | 1               | 3 3/8        | 92 | 7              | 178                                  | 2               | 3 3/8        | 92  | 7 1/2          | 190 |
|                          |            | 0.3937       | 10.000 | 1               | 3 3/8        | 92 | 7              | 178                                  | ...             | ...          | ... | ...            | ... |

**Table 5. (Continued) American National Taper Shank Twist Drills  
Fractional and Metric Sizes ANSI/ASME B94.11M-1993**

| Drill Diameter, <i>D</i> |        |                 |        | Regular Shank         |              |       |                | Larger or Smaller Shank <sup>a</sup> |                       |              |       |                |     |
|--------------------------|--------|-----------------|--------|-----------------------|--------------|-------|----------------|--------------------------------------|-----------------------|--------------|-------|----------------|-----|
| Frac-<br>tion            | mm     | Equivalent      |        | Morse<br>Taper<br>No. | Flute Length |       | Overall Length |                                      | Morse<br>Taper<br>No. | Flute Length |       | Overall Length |     |
|                          |        | Decimal<br>Inch | mm     |                       | <i>F</i>     |       | <i>L</i>       |                                      |                       | <i>F</i>     |       | <i>L</i>       |     |
|                          |        |                 |        |                       | Inch         | mm    | Inch           | mm                                   |                       | Inch         | mm    | Inch           | mm  |
| 13/32                    | 10.20  | 0.4016          | 10.200 | 1                     | 3 3/8        | 92    | 7              | 178                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.4062          | 10.320 | 1                     | 3 3/8        | 92    | 7              | 178                                  | 2                     | 3 3/8        | 92    | 7 1/2          | 190 |
| 7/64                     | 10.50  | 0.4134          | 10.500 | 1                     | 3 3/8        | 98    | 7 1/4          | 184                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.4219          | 10.716 | 1                     | 3 3/8        | 98    | 7 1/4          | 184                                  | 2                     | 3 3/8        | 98    | 7 3/4          | 197 |
| 10.80                    | 0.4252 | 10.800          | 1      | 3 3/8                 | 98           | 7 1/4 | 184            | ...                                  | ...                   | ...          | ...   | ...            |     |
|                          | 11.00  | 0.4331          | 11.000 | 1                     | 3 3/8        | 98    | 7 1/4          | 184                                  | ...                   | ...          | ...   | ...            |     |
| 7/16                     |        | 0.4375          | 11.112 | 1                     | 3 3/8        | 98    | 7 1/4          | 184                                  | 2                     | 3 3/8        | 98    | 7 3/4          | 197 |
|                          | 11.20  | 0.4409          | 11.200 | 1                     | 4 1/8        | 105   | 7 1/2          | 190                                  | ...                   | ...          | ...   | ...            |     |
| 11.50                    | 0.4528 | 11.500          | 1      | 4 1/8                 | 105          | 7 1/2 | 190            | ...                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.4531          | 11.509 | 1                     | 4 1/8        | 105   | 7 1/2          | 190                                  | 2                     | 4 1/8        | 105   | 8              | 203 |
| 29/64                    | 11.80  | 0.4646          | 11.800 | 1                     | 4 1/8        | 105   | 7 1/2          | 190                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.4688          | 11.906 | 1                     | 4 1/8        | 105   | 7 1/2          | 190                                  | 2                     | 4 1/8        | 105   | 8              | 203 |
| 15/32                    | 12.00  | 0.4724          | 12.000 | 2                     | 4 3/8        | 111   | 8 1/4          | 210                                  | 1                     | 4 3/8        | 111   | 7 3/4          | 197 |
|                          | 12.20  | 0.4803          | 12.200 | 2                     | 4 3/8        | 111   | 8 1/4          | 210                                  | 1                     | 4 3/8        | 111   | 7 3/4          | 197 |
| 31/64                    |        | 0.4844          | 12.304 | 2                     | 4 3/8        | 111   | 8 1/4          | 210                                  | 1                     | 4 3/8        | 111   | 7 3/4          | 197 |
|                          | 12.50  | 0.4921          | 12.500 | 2                     | 4 3/8        | 111   | 8 1/4          | 210                                  | 1                     | 4 3/8        | 111   | 7 3/4          | 197 |
| 1/2                      |        | 0.5000          | 12.700 | 2                     | 4 3/8        | 111   | 8 1/4          | 210                                  | 1                     | 4 3/8        | 111   | 7 3/4          | 197 |
|                          | 12.80  | 0.5034          | 12.800 | 2                     | 4 3/8        | 117   | 8 1/2          | 216                                  | 1                     | 4 3/8        | 117   | 8              | 203 |
| 13.00                    | 0.5118 | 13.000          | 2      | 4 3/8                 | 117          | 8 1/2 | 216            | 1                                    | 4 3/8                 | 117          | 8     | 203            |     |
|                          |        | 0.5156          | 13.096 | 2                     | 4 3/8        | 117   | 8 1/2          | 216                                  | 1                     | 4 3/8        | 117   | 8              | 203 |
| 33/64                    | 13.20  | 0.5197          | 13.200 | 2                     | 4 3/8        | 117   | 8 1/2          | 216                                  | 1                     | 4 3/8        | 117   | 8              | 203 |
|                          |        | 0.5312          | 13.492 | 2                     | 4 3/8        | 117   | 8 1/2          | 216                                  | 1                     | 4 3/8        | 117   | 8              | 203 |
| 17/32                    | 13.50  | 0.5315          | 13.500 | 2                     | 4 3/8        | 117   | 8 1/2          | 216                                  | 1                     | 4 3/8        | 117   | 8              | 203 |
|                          | 13.80  | 0.5433          | 13.800 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | 1                     | 4 3/8        | 124   | 8 1/4          | 210 |
| 35/64                    |        | 0.5469          | 13.891 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | 1                     | 4 3/8        | 124   | 8 1/4          | 210 |
|                          | 14.00  | 0.5572          | 14.000 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | 1                     | 4 3/8        | 124   | 8 1/4          | 210 |
| 14.25                    | 0.5610 | 14.250          | 2      | 4 3/8                 | 124          | 8 3/4 | 222            | 1                                    | 4 3/8                 | 124          | 8 1/4 | 210            |     |
|                          |        | 0.5625          | 14.288 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | 1                     | 4 3/8        | 124   | 8 1/4          | 210 |
| 9/16                     | 14.50  | 0.5709          | 14.500 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.5781          | 14.684 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | ...                   | ...          | ...   | ...            |     |
| 37/64                    | 14.75  | 0.5807          | 14.750 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.5906          | 15.000 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | ...                   | ...          | ...   | ...            |     |
| 19/32                    | 15.00  | 0.5938          | 15.083 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.6004          | 15.250 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | ...                   | ...          | ...   | ...            |     |
| 39/64                    | 15.25  | 0.6094          | 15.479 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.6102          | 15.500 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | ...                   | ...          | ...   | ...            |     |
| 15.75                    | 0.6201 | 15.750          | 2      | 4 3/8                 | 124          | 8 3/4 | 222            | ...                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.6250          | 15.875 | 2                     | 4 3/8        | 124   | 8 3/4          | 222                                  | ...                   | ...          | ...   | ...            |     |
| 5/8                      | 16.00  | 0.6299          | 16.000 | 2                     | 5 1/8        | 130   | 9              | 229                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.6398          | 16.250 | 2                     | 5 1/8        | 130   | 9              | 229                                  | ...                   | ...          | ...   | ...            |     |
| 41/64                    | 16.25  | 0.6406          | 16.271 | 2                     | 5 1/8        | 130   | 9              | 229                                  | 3                     | 5 1/8        | 130   | 9 3/4          | 248 |
|                          |        | 0.6496          | 16.500 | 2                     | 5 1/8        | 130   | 9              | 229                                  | ...                   | ...          | ...   | ...            |     |
| 21/32                    | 16.50  | 0.6562          | 16.667 | 2                     | 5 1/8        | 130   | 9              | 229                                  | 3                     | 5 1/8        | 130   | 9 3/4          | 248 |
|                          |        | 0.6594          | 16.750 | 2                     | 5 3/8        | 137   | 9 1/4          | 235                                  | ...                   | ...          | ...   | ...            |     |
| 17.00                    | 0.6693 | 17.000          | 2      | 5 3/8                 | 137          | 9 1/4 | 235            | ...                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.6719          | 17.066 | 2                     | 5 3/8        | 137   | 9 1/4          | 235                                  | 3                     | 5 3/8        | 137   | 10             | 254 |
| 43/64                    | 17.25  | 0.6791          | 17.250 | 2                     | 5 3/8        | 137   | 9 1/4          | 235                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.6875          | 17.462 | 2                     | 5 3/8        | 137   | 9 1/4          | 235                                  | 3                     | 5 3/8        | 137   | 10             | 254 |
| 11/16                    | 17.50  | 0.6880          | 17.500 | 2                     | 5 3/8        | 143   | 9 1/2          | 241                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.7031          | 17.859 | 2                     | 5 3/8        | 143   | 9 1/2          | 241                                  | 3                     | 5 3/8        | 143   | 10 1/4         | 260 |
| 45/64                    | 18.00  | 0.7087          | 18.000 | 2                     | 5 3/8        | 143   | 9 1/2          | 241                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.7188          | 18.258 | 2                     | 5 3/8        | 143   | 9 1/2          | 241                                  | 3                     | 5 3/8        | 143   | 10 1/4         | 260 |
| 23/32                    | 18.50  | 0.7283          | 18.500 | 2                     | 5 3/8        | 149   | 9 3/4          | 248                                  | ...                   | ...          | ...   | ...            |     |
|                          |        | 0.7344          | 18.654 | 2                     | 5 7/8        | 149   | 9 3/4          | 248                                  | 3                     | 5 7/8        | 149   | 10 1/2         | 267 |

**Table 5. (Continued) American National Taper Shank Twist Drills**  
**Fractional and Metric Sizes ANSI/ASME B94.11M-1993**

| Drill Diameter, <i>D</i> |       |                 |        | Regular Shank         |                 |     |                  | Larger or Smaller Shank <sup>a</sup> |                       |                 |     |                  |     |
|--------------------------|-------|-----------------|--------|-----------------------|-----------------|-----|------------------|--------------------------------------|-----------------------|-----------------|-----|------------------|-----|
| Frac-<br>tion            | mm    | Equivalent      |        | Morse<br>Taper<br>No. | Flute Length    |     | Overall Length   |                                      | Morse<br>Taper<br>No. | Flute Length    |     | Overall Length   |     |
|                          |       | Decimal<br>Inch | mm     |                       | <i>F</i>        |     | <i>L</i>         |                                      |                       | <i>F</i>        |     | <i>L</i>         |     |
|                          |       |                 |        |                       | Inch            | mm  | Inch             | mm                                   |                       | Inch            | mm  | Inch             | mm  |
|                          | 19.00 | 0.7480          | 19.000 | 2                     | 5 $\frac{1}{8}$ | 149 | 9 $\frac{3}{4}$  | 248                                  | ...                   | ...             | ... | ...              | ... |
| $\frac{3}{4}$            |       | 0.7500          | 19.050 | 2                     | 5 $\frac{7}{8}$ | 149 | 9 $\frac{3}{4}$  | 248                                  | 3                     | 5 $\frac{7}{8}$ | 149 | 10 $\frac{1}{2}$ | 267 |
| $\frac{49}{64}$          |       | 0.7656          | 19.446 | 2                     | 6               | 152 | 9 $\frac{7}{8}$  | 251                                  | 3                     | 6               | 152 | 10 $\frac{5}{8}$ | 270 |
|                          | 19.50 | 0.7677          | 19.500 | 2                     | 6               | 152 | 9 $\frac{7}{8}$  | 251                                  | ...                   | ...             | ... | ...              | ... |
| $\frac{25}{32}$          |       | 0.7812          | 19.843 | 2                     | 6               | 152 | 9 $\frac{7}{8}$  | 251                                  | 3                     | 6               | 152 | 10 $\frac{5}{8}$ | 270 |
|                          | 20.00 | 0.7821          | 20.000 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
| $\frac{51}{64}$          |       | 0.7969          | 20.241 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
|                          | 20.50 | 0.8071          | 20.500 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
| $\frac{13}{16}$          |       | 0.8125          | 20.638 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
|                          | 21.00 | 0.8268          | 21.000 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
| $\frac{53}{64}$          |       | 0.8281          | 21.034 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
| $\frac{27}{32}$          |       | 0.8438          | 21.433 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
|                          | 21.50 | 0.8465          | 21.500 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
| $\frac{55}{64}$          |       | 0.8594          | 21.829 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
|                          | 22.00 | 0.8661          | 22.000 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
| $\frac{7}{8}$            |       | 0.8750          | 22.225 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
|                          | 22.50 | 0.8858          | 22.500 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
| $\frac{57}{64}$          |       | 0.8906          | 22.621 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
|                          | 23.00 | 0.9055          | 23.000 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
| $\frac{29}{32}$          |       | 0.9062          | 23.017 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | 2                     | 6 $\frac{1}{8}$ | 156 | 10               | 254 |
| $\frac{59}{64}$          |       | 0.9219          | 23.416 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | ...                   | ...             | ... | ...              | ... |
|                          | 23.50 | 0.9252          | 23.500 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | ...                   | ...             | ... | ...              | ... |
| $\frac{15}{16}$          |       | 0.9375          | 23.813 | 3                     | 6 $\frac{1}{8}$ | 156 | 10 $\frac{3}{4}$ | 273                                  | ...                   | ...             | ... | ...              | ... |
|                          | 24.00 | 0.9449          | 24.000 | 3                     | 6 $\frac{3}{8}$ | 162 | 11               | 279                                  | ...                   | ...             | ... | ...              | ... |
| $\frac{61}{64}$          |       | 0.9531          | 24.209 | 3                     | 6 $\frac{3}{8}$ | 162 | 11               | 279                                  | ...                   | ...             | ... | ...              | ... |
|                          | 24.50 | 0.9646          | 24.500 | 3                     | 6 $\frac{3}{8}$ | 162 | 11               | 279                                  | ...                   | ...             | ... | ...              | ... |
| $\frac{31}{32}$          |       | 0.9688          | 24.608 | 3                     | 6 $\frac{3}{8}$ | 162 | 11               | 279                                  | ...                   | ...             | ... | ...              | ... |
|                          | 25.00 | 0.9843          | 25.000 | 3                     | 6 $\frac{3}{8}$ | 162 | 11               | 279                                  | ...                   | ...             | ... | ...              | ... |
| $\frac{63}{64}$          |       | 0.9844          | 25.004 | 3                     | 6 $\frac{3}{8}$ | 162 | 11               | 279                                  | ...                   | ...             | ... | ...              | ... |
| 1                        |       | 1.0000          | 25.400 | 3                     | 6 $\frac{3}{8}$ | 162 | 11               | 279                                  | 4                     | 6 $\frac{3}{8}$ | 162 | 12               | 305 |
|                          | 25.50 | 1.0039          | 25.500 | 3                     | 6 $\frac{1}{2}$ | 165 | 11 $\frac{1}{8}$ | 283                                  | ...                   | ...             | ... | ...              | ... |
| $\frac{11}{64}$          |       | 1.0156          | 25.796 | 3                     | 6 $\frac{1}{2}$ | 165 | 11 $\frac{1}{8}$ | 283                                  | ...                   | ...             | ... | ...              | ... |
|                          | 26.00 | 1.0236          | 26.000 | 3                     | 6 $\frac{1}{2}$ | 165 | 11 $\frac{1}{8}$ | 283                                  | ...                   | ...             | ... | ...              | ... |
| $\frac{11}{32}$          |       | 1.0312          | 26.192 | 3                     | 6 $\frac{1}{2}$ | 165 | 11 $\frac{1}{8}$ | 283                                  | 4                     | 6 $\frac{1}{2}$ | 165 | 12 $\frac{1}{8}$ | 308 |
|                          | 26.50 | 1.0433          | 26.500 | 3                     | 6 $\frac{3}{8}$ | 168 | 11 $\frac{1}{4}$ | 286                                  | ...                   | ...             | ... | ...              | ... |
| $\frac{13}{64}$          |       | 1.0469          | 26.591 | 3                     | 6 $\frac{3}{8}$ | 168 | 11 $\frac{1}{4}$ | 286                                  | ...                   | ...             | ... | ...              | ... |
| $\frac{11}{16}$          |       | 1.0625          | 26.988 | 3                     | 6 $\frac{3}{8}$ | 168 | 11 $\frac{1}{4}$ | 286                                  | 4                     | 6 $\frac{3}{8}$ | 168 | 12 $\frac{1}{4}$ | 311 |
|                          | 27.00 | 1.0630          | 27.000 | 3                     | 6 $\frac{3}{8}$ | 168 | 11 $\frac{1}{4}$ | 286                                  | ...                   | ...             | ... | ...              | ... |
| $\frac{13}{64}$          |       | 1.0781          | 27.384 | 4                     | 6 $\frac{3}{8}$ | 175 | 12 $\frac{1}{2}$ | 318                                  | 3                     | 6 $\frac{3}{8}$ | 175 | 11 $\frac{1}{2}$ | 292 |
|                          | 27.50 | 1.0827          | 27.500 | 4                     | 6 $\frac{3}{8}$ | 175 | 12 $\frac{1}{2}$ | 318                                  | 3                     | 6 $\frac{3}{8}$ | 175 | 11 $\frac{1}{2}$ | 292 |
| $\frac{13}{32}$          |       | 1.0938          | 27.783 | 4                     | 6 $\frac{3}{8}$ | 175 | 12 $\frac{1}{2}$ | 318                                  | 3                     | 6 $\frac{3}{8}$ | 175 | 11 $\frac{1}{2}$ | 292 |
|                          | 28.00 | 1.1024          | 28.000 | 4                     | 7 $\frac{1}{8}$ | 181 | 12 $\frac{3}{4}$ | 324                                  | 3                     | 7 $\frac{1}{8}$ | 181 | 11 $\frac{3}{4}$ | 298 |
| $\frac{17}{64}$          |       | 1.1094          | 28.179 | 4                     | 7 $\frac{1}{8}$ | 181 | 12 $\frac{3}{4}$ | 324                                  | 3                     | 7 $\frac{1}{8}$ | 181 | 11 $\frac{3}{4}$ | 298 |
|                          | 28.50 | 1.1220          | 28.500 | 4                     | 7 $\frac{1}{8}$ | 181 | 12 $\frac{3}{4}$ | 324                                  | 3                     | 7 $\frac{1}{8}$ | 181 | 11 $\frac{3}{4}$ | 298 |
| $\frac{11}{8}$           |       | 1.1250          | 28.575 | 4                     | 7 $\frac{1}{8}$ | 181 | 12 $\frac{3}{4}$ | 324                                  | 3                     | 7 $\frac{1}{8}$ | 181 | 11 $\frac{3}{4}$ | 298 |
| $\frac{19}{64}$          |       | 1.1406          | 28.971 | 4                     | 7 $\frac{1}{4}$ | 184 | 12 $\frac{7}{8}$ | 327                                  | 3                     | 7 $\frac{1}{4}$ | 184 | 11 $\frac{7}{8}$ | 302 |
|                          | 29.00 | 1.1417          | 29.000 | 4                     | 7 $\frac{1}{4}$ | 184 | 12 $\frac{7}{8}$ | 327                                  | 3                     | 7 $\frac{1}{4}$ | 184 | 11 $\frac{7}{8}$ | 302 |
| $\frac{15}{32}$          |       | 1.1562          | 29.367 | 4                     | 7 $\frac{1}{4}$ | 184 | 12 $\frac{7}{8}$ | 327                                  | 3                     | 7 $\frac{1}{4}$ | 184 | 11 $\frac{7}{8}$ | 302 |
|                          | 29.50 | 1.1614          | 29.500 | 4                     | 7 $\frac{3}{8}$ | 187 | 13               | 330                                  | 3                     | 7 $\frac{3}{8}$ | 187 | 12               | 305 |
| $\frac{11}{64}$          |       | 1.1719          | 29.797 | 4                     | 7 $\frac{3}{8}$ | 187 | 13               | 330                                  | 3                     | 7 $\frac{3}{8}$ | 187 | 12               | 305 |
|                          | 30.00 | 1.1811          | 30.000 | 4                     | 7 $\frac{3}{8}$ | 187 | 13               | 330                                  | 3                     | 7 $\frac{3}{8}$ | 187 | 12               | 305 |
| $\frac{13}{16}$          |       | 1.1875          | 30.162 | 4                     | 7 $\frac{3}{8}$ | 187 | 13               | 330                                  | 3                     | 7 $\frac{3}{8}$ | 187 | 12               | 305 |
|                          | 30.50 | 1.2008          | 30.500 | 4                     | 7 $\frac{1}{2}$ | 190 | 13 $\frac{1}{8}$ | 333                                  | 3                     | 7 $\frac{1}{2}$ | 190 | 12 $\frac{1}{8}$ | 308 |
| $\frac{13}{64}$          |       | 1.2031          | 30.559 | 4                     | 7 $\frac{1}{2}$ | 190 | 13 $\frac{1}{8}$ | 333                                  | 3                     | 7 $\frac{1}{2}$ | 190 | 12 $\frac{1}{8}$ | 308 |

**Table 5. (Continued) American National Taper Shank Twist Drills**  
**Fractional and Metric Sizes ANSI/ASME B94.11M-1993**

| Drill Diameter, <i>D</i> |       |              |        | Regular Shank   |              |     |                | Larger or Smaller Shank <sup>a</sup> |                 |              |     |                |     |
|--------------------------|-------|--------------|--------|-----------------|--------------|-----|----------------|--------------------------------------|-----------------|--------------|-----|----------------|-----|
| Fraction                 | mm    | Equivalent   |        | Morse Taper No. | Flute Length |     | Overall Length |                                      | Morse Taper No. | Flute Length |     | Overall Length |     |
|                          |       | Decimal Inch | mm     |                 | <i>F</i>     |     | <i>L</i>       |                                      |                 | <i>F</i>     |     | <i>L</i>       |     |
|                          |       |              |        |                 | Inch         | mm  | Inch           | mm                                   |                 | Inch         | mm  | Inch           | mm  |
| 1 1/32                   | 31.00 | 1.2188       | 30.958 | 4               | 7 1/2        | 190 | 13 3/8         | 333                                  | 3               | 7 1/2        | 190 | 12 1/2         | 308 |
|                          |       | 1.2205       | 31.000 | 4               | 7 7/8        | 200 | 13 1/2         | 343                                  | 3               | 7 7/8        | 200 | 12 1/2         | 318 |
| 1 5/64                   | 31.50 | 1.2344       | 31.354 | 4               | 7 7/8        | 200 | 13 1/2         | 343                                  | 3               | 7 7/8        | 200 | 12 1/2         | 318 |
|                          |       | 1.2402       | 31.500 | 4               | 7 7/8        | 200 | 13 1/2         | 343                                  | 3               | 7 7/8        | 200 | 12 1/2         | 318 |
| 1 1/4                    | 32.00 | 1.2500       | 31.750 | 4               | 7 7/8        | 200 | 13 1/2         | 343                                  | 3               | 7 7/8        | 200 | 12 1/2         | 318 |
|                          |       | 1.2598       | 32.000 | 4               | 8 1/2        | 216 | 14 1/8         | 359                                  | ...             | ...          | ... | ...            | ... |
| 1 7/64                   | 32.50 | 1.2656       | 32.146 | 4               | 8 1/2        | 216 | 14 1/8         | 359                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.2795       | 32.500 | 4               | 8 1/2        | 216 | 14 1/8         | 359                                  | ...             | ...          | ... | ...            | ... |
| 1 9/32                   | 33.00 | 1.2812       | 32.542 | 4               | 8 1/2        | 216 | 14 1/8         | 359                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.2969       | 32.941 | 4               | 8 3/8        | 219 | 14 1/4         | 362                                  | ...             | ...          | ... | ...            | ... |
| 1 9/64                   | 33.00 | 1.2992       | 33.000 | 4               | 8 3/8        | 219 | 14 1/4         | 362                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.3125       | 33.338 | 4               | 8 3/8        | 219 | 14 1/4         | 362                                  | ...             | ...          | ... | ...            | ... |
| 1 5/16                   | 33.50 | 1.3189       | 33.500 | 4               | 8 3/4        | 222 | 14 3/8         | 365                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.3281       | 33.734 | 4               | 8 3/4        | 222 | 14 3/8         | 365                                  | ...             | ...          | ... | ...            | ... |
| 1 1/2                    | 34.00 | 1.3386       | 34.000 | 4               | 8 3/4        | 222 | 14 3/8         | 365                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.3438       | 34.133 | 4               | 8 3/4        | 222 | 14 3/8         | 365                                  | ...             | ...          | ... | ...            | ... |
| 1 11/32                  | 34.50 | 1.3583       | 34.500 | 4               | 8 7/8        | 225 | 14 1/2         | 368                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.3594       | 34.529 | 4               | 8 7/8        | 225 | 14 1/2         | 368                                  | ...             | ...          | ... | ...            | ... |
| 1 3/8                    | 35.00 | 1.3750       | 34.925 | 4               | 8 7/8        | 225 | 14 1/2         | 368                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.3780       | 35.000 | 4               | 9            | 229 | 14 5/8         | 371                                  | ...             | ...          | ... | ...            | ... |
| 1 25/64                  | 35.50 | 1.3906       | 35.321 | 4               | 9            | 229 | 14 5/8         | 371                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.3976       | 35.500 | 4               | 9            | 229 | 14 5/8         | 371                                  | ...             | ...          | ... | ...            | ... |
| 1 13/32                  | 36.00 | 1.4062       | 35.717 | 4               | 9            | 229 | 14 5/8         | 371                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.4173       | 36.000 | 4               | 9 1/8        | 232 | 14 3/4         | 375                                  | ...             | ...          | ... | ...            | ... |
| 1 7/16                   | 36.50 | 1.4219       | 36.116 | 4               | 9 1/8        | 232 | 14 3/4         | 375                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.4370       | 36.500 | 4               | 9 1/8        | 232 | 14 3/4         | 375                                  | ...             | ...          | ... | ...            | ... |
| 1 7/64                   | 37.00 | 1.4375       | 36.512 | 4               | 9 1/8        | 232 | 14 3/4         | 375                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.4531       | 36.909 | 4               | 9 1/4        | 235 | 14 1/2         | 378                                  | ...             | ...          | ... | ...            | ... |
| 1 5/16                   | 37.00 | 1.4567       | 37.000 | 4               | 9 1/4        | 235 | 14 7/8         | 378                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.4688       | 37.308 | 4               | 9 1/4        | 235 | 14 7/8         | 378                                  | ...             | ...          | ... | ...            | ... |
| 1 9/32                   | 37.50 | 1.4764       | 37.500 | 4               | 9 3/8        | 238 | 15             | 381                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.4844       | 37.704 | 4               | 9 3/8        | 238 | 15             | 381                                  | ...             | ...          | ... | ...            | ... |
| 1 31/64                  | 38.00 | 1.4961       | 38.000 | 4               | 9 3/8        | 238 | 15             | 381                                  | ...             | ...          | ... | ...            | ... |
|                          |       | 1.5000       | 38.100 | 4               | 9 3/8        | 238 | 15             | 381                                  | ...             | ...          | ... | ...            | ... |
| 1 1/2                    | 39.00 | 1.5156       | 38.496 | ...             | ...          | ... | ...            | ...                                  | 4               | 9 3/4        | 238 | 15             | 381 |
|                          |       | 1.5312       | 38.892 | 5               | 9 3/8        | 238 | 16 3/8         | 416                                  | 4               | 9 3/8        | 238 | 15             | 381 |
| 1 17/32                  | 39.00 | 1.5354       | 39.000 | 5               | 9 3/8        | 244 | 16 3/8         | 422                                  | 4               | 9 3/8        | 244 | 15 1/4         | 387 |
|                          |       | 1.5469       | 39.291 | ...             | ...          | ... | ...            | ...                                  | 4               | 9 3/8        | 244 | 15 1/4         | 387 |
| 1 35/64                  | 40.00 | 1.5625       | 39.688 | 5               | 9 3/8        | 244 | 16 3/8         | 422                                  | 4               | 9 3/8        | 244 | 15 1/4         | 387 |
|                          |       | 1.5748       | 40.000 | 5               | 9 7/8        | 251 | 16 1/2         | 429                                  | 4               | 9 7/8        | 251 | 15 1/2         | 394 |
| 1 7/16                   | 40.00 | 1.5781       | 40.084 | ...             | ...          | ... | ...            | ...                                  | 4               | 9 7/8        | 251 | 15 1/2         | 394 |
|                          |       | 1.5938       | 40.483 | 5               | 9 7/8        | 251 | 16 7/8         | 429                                  | 4               | 9 7/8        | 251 | 15 1/2         | 394 |
| 1 9/16                   | 41.00 | 1.6094       | 40.879 | ...             | ...          | ... | ...            | ...                                  | 4               | 10           | 254 | 15 3/8         | 397 |
|                          |       | 1.6142       | 41.000 | 5               | 10           | 254 | 17             | 432                                  | 4               | 10           | 254 | 15 3/8         | 397 |
| 1 5/8                    | 42.00 | 1.6250       | 41.275 | 5               | 10           | 254 | 17             | 432                                  | 4               | 10           | 254 | 15 3/8         | 397 |
|                          |       | 1.6406       | 41.671 | ...             | ...          | ... | ...            | ...                                  | 4               | 10 1/8       | 257 | 15 3/4         | 400 |
| 1 41/64                  | 42.00 | 1.6535       | 42.000 | 5               | 10 1/8       | 257 | 17 1/8         | 435                                  | 4               | 10 1/8       | 257 | 15 3/4         | 400 |
|                          |       | 1.6562       | 42.067 | 5               | 10 3/8       | 257 | 17 1/8         | 435                                  | 4               | 10 3/8       | 257 | 15 3/4         | 400 |
| 1 21/32                  | 43.00 | 1.6719       | 42.466 | ...             | ...          | ... | ...            | ...                                  | 4               | 10 3/8       | 257 | 15 3/4         | 400 |
|                          |       | 1.6875       | 42.862 | 5               | 10 3/8       | 257 | 17 1/8         | 435                                  | 4               | 10 3/8       | 257 | 15 3/4         | 400 |
| 1 43/64                  | 43.00 | 1.6929       | 43.000 | 5               | 10 3/8       | 257 | 17 1/8         | 435                                  | 4               | 10 3/8       | 257 | 15 3/4         | 400 |
|                          |       | 1.7031       | 43.259 | ...             | ...          | ... | ...            | ...                                  | 4               | 10 3/8       | 257 | 15 3/4         | 400 |
| 1 11/16                  | 44.00 | 1.7188       | 43.658 | 5               | 10 3/8       | 257 | 17 1/8         | 435                                  | 4               | 10 3/8       | 257 | 15 3/4         | 400 |
|                          |       | 1.7323       | 44.000 | 5               | 10 7/8       | 257 | 17 1/8         | 435                                  | 4               | 10 3/8       | 264 | 16 1/4         | 413 |

TWIST DRILLS

**Table 5. (Continued) American National Taper Shank Twist Drills  
Fractional and Metric Sizes ANSI/ASME B94.11M-1993**

| Drill Diameter, <i>D</i>        |       |                 |        | Regular Shank         |                                |     |                                | Larger or Smaller Shank <sup>a</sup> |                                |                                |                                |                                |     |
|---------------------------------|-------|-----------------|--------|-----------------------|--------------------------------|-----|--------------------------------|--------------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|-----|
| Frac-<br>tion                   | mm    | Equivalent      |        | Morse<br>Taper<br>No. | Flute Length                   |     | Overall Length                 |                                      | Morse<br>Taper<br>No.          | Flute Length                   |                                | Overall Length                 |     |
|                                 |       | Decimal<br>Inch | mm     |                       | <i>F</i>                       |     | <i>L</i>                       |                                      |                                | <i>F</i>                       |                                | <i>L</i>                       |     |
|                                 |       |                 |        |                       | Inch                           | mm  | Inch                           | mm                                   |                                | Inch                           | mm                             | Inch                           | mm  |
| 1 <sup>47</sup> / <sub>64</sub> |       | 1.7344          | 44.054 | ...                   | ...                            | ... | ...                            | 4                                    | 10 <sup>3</sup> / <sub>8</sub> | 264                            | 16 <sup>1</sup> / <sub>4</sub> | 413                            |     |
| 1 <sup>3</sup> / <sub>4</sub>   | 45.00 | 1.7500          | 44.450 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435                                  | 4                              | 10 <sup>3</sup> / <sub>8</sub> | 264                            | 16 <sup>1</sup> / <sub>4</sub> | 413 |
|                                 |       | 1.7717          | 45.000 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435                                  | 4                              | 10 <sup>3</sup> / <sub>8</sub> | 264                            | 16 <sup>1</sup> / <sub>4</sub> | 413 |
| 1 <sup>29</sup> / <sub>32</sub> | 46.00 | 1.7812          | 45.242 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435                                  | 4                              | 10 <sup>3</sup> / <sub>8</sub> | 264                            | 16 <sup>1</sup> / <sub>4</sub> | 413 |
|                                 |       | 1.8110          | 46.000 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435                                  | 4                              | 10 <sup>3</sup> / <sub>8</sub> | 264                            | 16 <sup>1</sup> / <sub>4</sub> | 413 |
| 1 <sup>13</sup> / <sub>16</sub> | 47.00 | 1.8125          | 46.038 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435                                  | 4                              | 10 <sup>3</sup> / <sub>8</sub> | 264                            | 16 <sup>1</sup> / <sub>4</sub> | 413 |
|                                 |       | 1.8438          | 46.833 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435                                  | 4                              | 10 <sup>3</sup> / <sub>8</sub> | 264                            | 16 <sup>1</sup> / <sub>4</sub> | 413 |
| 1 <sup>27</sup> / <sub>32</sub> | 48.00 | 1.8504          | 47.000 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | 4                              | 10 <sup>1</sup> / <sub>2</sub> | 267                            | 16 <sup>1</sup> / <sub>2</sub> | 419 |
|                                 |       | 1.8750          | 47.625 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | 4                              | 10 <sup>1</sup> / <sub>2</sub> | 267                            | 16 <sup>1</sup> / <sub>2</sub> | 419 |
| 1 <sup>29</sup> / <sub>32</sub> | 49.00 | 1.8898          | 48.000 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | 4                              | 10 <sup>1</sup> / <sub>2</sub> | 267                            | 16 <sup>1</sup> / <sub>2</sub> | 419 |
|                                 |       | 1.9062          | 48.417 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | 4                              | 10 <sup>1</sup> / <sub>2</sub> | 267                            | 16 <sup>1</sup> / <sub>2</sub> | 419 |
| 1 <sup>15</sup> / <sub>16</sub> | 50.00 | 1.9291          | 49.000 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | 4                              | 10 <sup>3</sup> / <sub>8</sub> | 270                            | 16 <sup>5</sup> / <sub>8</sub> | 422 |
|                                 |       | 1.9375          | 49.212 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | 4                              | 10 <sup>3</sup> / <sub>8</sub> | 270                            | 16 <sup>5</sup> / <sub>8</sub> | 422 |
| 1 <sup>31</sup> / <sub>32</sub> | 51.00 | 1.9625          | 50.000 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | 4                              | 10 <sup>3</sup> / <sub>8</sub> | 270                            | 16 <sup>5</sup> / <sub>8</sub> | 422 |
|                                 |       | 1.9688          | 50.008 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | 4                              | 10 <sup>3</sup> / <sub>8</sub> | 270                            | 16 <sup>5</sup> / <sub>8</sub> | 422 |
| 2                               | 52.00 | 2.0000          | 50.800 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | 4                              | 10 <sup>3</sup> / <sub>8</sub> | 270                            | 16 <sup>5</sup> / <sub>8</sub> | 422 |
|                                 |       | 2.0079          | 51.000 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>1</sup> / <sub>32</sub>  | 53.00 | 2.0312          | 51.592 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.0472          | 52.000 | 5                     | 10 <sup>1</sup> / <sub>4</sub> | 260 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>1</sup> / <sub>16</sub>  | 54.00 | 2.0625          | 52.388 | 5                     | 10 <sup>1</sup> / <sub>4</sub> | 260 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.0866          | 53.000 | 5                     | 10 <sup>1</sup> / <sub>4</sub> | 260 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>3</sup> / <sub>32</sub>  | 55.00 | 2.0938          | 53.183 | 5                     | 10 <sup>1</sup> / <sub>4</sub> | 260 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.1250          | 53.975 | 5                     | 10 <sup>1</sup> / <sub>4</sub> | 260 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>1</sup> / <sub>8</sub>   | 56.00 | 2.1260          | 54.000 | 5                     | 10 <sup>1</sup> / <sub>4</sub> | 260 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.1562          | 54.767 | 5                     | 10 <sup>1</sup> / <sub>4</sub> | 260 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>5</sup> / <sub>32</sub>  | 57.00 | 2.1654          | 55.000 | 5                     | 10 <sup>1</sup> / <sub>4</sub> | 260 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.1875          | 55.563 | 5                     | 10 <sup>1</sup> / <sub>4</sub> | 260 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>3</sup> / <sub>16</sub>  | 58.00 | 2.2000          | 56.000 | 5                     | 10 <sup>1</sup> / <sub>4</sub> | 257 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.2188          | 56.358 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>7</sup> / <sub>32</sub>  | 59.00 | 2.2441          | 57.000 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.2500          | 57.150 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>1</sup> / <sub>4</sub>   | 60.00 | 2.2835          | 58.000 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.3125          | 58.738 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>5</sup> / <sub>16</sub>  | 61.00 | 2.3228          | 59.000 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.3622          | 60.000 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>3</sup> / <sub>8</sub>   | 62.00 | 2.3750          | 60.325 | 5                     | 10 <sup>3</sup> / <sub>8</sub> | 257 | 17 <sup>3</sup> / <sub>8</sub> | 441                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.4016          | 61.000 | 5                     | 11 <sup>1</sup> / <sub>4</sub> | 286 | 18 <sup>3</sup> / <sub>4</sub> | 476                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>7</sup> / <sub>16</sub>  | 63.00 | 2.4375          | 61.912 | 5                     | 11 <sup>1</sup> / <sub>4</sub> | 286 | 18 <sup>3</sup> / <sub>4</sub> | 476                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.4409          | 62.000 | 5                     | 11 <sup>1</sup> / <sub>4</sub> | 286 | 18 <sup>3</sup> / <sub>4</sub> | 476                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>1</sup> / <sub>2</sub>   | 64.00 | 2.4803          | 63.000 | 5                     | 11 <sup>1</sup> / <sub>4</sub> | 286 | 18 <sup>3</sup> / <sub>4</sub> | 476                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.5000          | 63.500 | 5                     | 11 <sup>1</sup> / <sub>4</sub> | 286 | 18 <sup>3</sup> / <sub>4</sub> | 476                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>9</sup> / <sub>16</sub>  | 65.00 | 2.5197          | 64.000 | 5                     | 11 <sup>3</sup> / <sub>8</sub> | 302 | 19 <sup>1</sup> / <sub>2</sub> | 495                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.5591          | 65.000 | 5                     | 11 <sup>3</sup> / <sub>8</sub> | 302 | 19 <sup>1</sup> / <sub>2</sub> | 495                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>5</sup> / <sub>8</sub>   | 66.00 | 2.5625          | 65.088 | 5                     | 11 <sup>3</sup> / <sub>8</sub> | 302 | 19 <sup>1</sup> / <sub>2</sub> | 495                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.5984          | 66.000 | 5                     | 11 <sup>3</sup> / <sub>8</sub> | 302 | 19 <sup>1</sup> / <sub>2</sub> | 495                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>11</sup> / <sub>16</sub> | 67.00 | 2.6250          | 66.675 | 5                     | 11 <sup>3</sup> / <sub>8</sub> | 302 | 19 <sup>1</sup> / <sub>2</sub> | 495                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.6378          | 67.000 | 5                     | 12 <sup>1</sup> / <sub>4</sub> | 324 | 20 <sup>3</sup> / <sub>8</sub> | 518                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>3</sup> / <sub>4</sub>   | 68.00 | 2.6772          | 68.000 | 5                     | 12 <sup>1</sup> / <sub>4</sub> | 324 | 20 <sup>3</sup> / <sub>8</sub> | 518                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.6875          | 68.262 | 5                     | 12 <sup>3</sup> / <sub>4</sub> | 324 | 20 <sup>3</sup> / <sub>8</sub> | 518                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>13</sup> / <sub>16</sub> | 69.00 | 2.7165          | 69.000 | 5                     | 12 <sup>3</sup> / <sub>4</sub> | 324 | 20 <sup>3</sup> / <sub>8</sub> | 518                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.7500          | 69.850 | 5                     | 12 <sup>3</sup> / <sub>4</sub> | 324 | 20 <sup>3</sup> / <sub>8</sub> | 518                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>7</sup> / <sub>8</sub>   | 70.00 | 2.7559          | 70.000 | 5                     | 13 <sup>3</sup> / <sub>8</sub> | 340 | 21 <sup>1</sup> / <sub>8</sub> | 537                                  | ...                            | ...                            | ...                            | ...                            |     |
|                                 |       | 2.7953          | 71.000 | 5                     | 13 <sup>3</sup> / <sub>8</sub> | 340 | 21 <sup>1</sup> / <sub>8</sub> | 537                                  | ...                            | ...                            | ...                            | ...                            |     |
| 2 <sup>15</sup> / <sub>16</sub> | 71.00 | 2.8125          | 71.438 | 5                     | 13 <sup>3</sup> / <sub>8</sub> | 340 | 21 <sup>1</sup> / <sub>8</sub> | 537                                  | ...                            | ...                            | ...                            | ...                            |     |

**Table 5. (Continued) American National Taper Shank Twist Drills  
Fractional and Metric Sizes ANSI/ASME B94.11M-1993**

| Drill Diameter, <i>D</i> |        |              |        | Regular Shank   |              |     |                | Larger or Smaller Shank <sup>a</sup> |                 |              |     |                |     |
|--------------------------|--------|--------------|--------|-----------------|--------------|-----|----------------|--------------------------------------|-----------------|--------------|-----|----------------|-----|
| Fraction                 | mm     | Equivalent   |        | Morse Taper No. | Flute Length |     | Overall Length |                                      | Morse Taper No. | Flute Length |     | Overall Length |     |
|                          |        | Decimal Inch | mm     |                 | <i>F</i>     |     | <i>L</i>       |                                      |                 | <i>F</i>     |     | <i>L</i>       |     |
|                          |        |              |        |                 | Inch         | mm  | Inch           | mm                                   |                 | Inch         | mm  | Inch           | mm  |
| 2 7/8                    | 72.00  | 2.8346       | 72.000 | 5               | 13 3/8       | 340 | 21 1/8         | 537                                  | ...             | ...          | ... | ...            | ... |
|                          | 73.00  | 2.8740       | 73.000 | 5               | 13 3/8       | 340 | 21 1/8         | 537                                  | ...             | ...          | ... | ...            | ... |
|                          |        | 2.8750       | 73.025 | 5               | 13 3/8       | 340 | 21 1/8         | 537                                  | ...             | ...          | ... | ...            | ... |
| 2 15/16                  | 74.00  | 2.9134       | 74.000 | 5               | 14           | 356 | 21 3/4         | 552                                  | ...             | ...          | ... | ...            | ... |
|                          |        | 2.9375       | 74.612 | 5               | 14           | 356 | 21 3/4         | 552                                  | ...             | ...          | ... | ...            | ... |
|                          | 75.00  | 2.9528       | 75.000 | 5               | 14           | 356 | 21 3/4         | 552                                  | ...             | ...          | ... | ...            | ... |
| 3                        | 76.00  | 2.9921       | 76.000 | 5               | 14           | 356 | 21 3/4         | 552                                  | ...             | ...          | ... | ...            | ... |
|                          |        | 3.0000       | 76.200 | 5               | 14           | 356 | 21 3/4         | 552                                  | ...             | ...          | ... | ...            | ... |
|                          | 77.00  | 3.0315       | 77.000 | 6               | 14 3/8       | 371 | 24 1/2         | 622                                  | 5               | 14 3/4       | 362 | 22             | 559 |
| 3 1/8                    | 78.00  | 3.0709       | 78.000 | 6               | 14 3/8       | 371 | 24 1/2         | 622                                  | 5               | 14 3/4       | 362 | 22             | 559 |
|                          |        | 3.1250       | 79.375 | 6               | 14 3/8       | 371 | 24 1/2         | 622                                  | 5               | 14 3/4       | 362 | 22             | 559 |
|                          | 3 1/4  | 3.2500       | 82.550 | 6               | 15 1/2       | 394 | 25 1/2         | 648                                  | 5               | 15 1/4       | 387 | 23             | 584 |
| 3 1/2                    | 3.5000 | 88.900       | ...    | ...             | ...          | ... | ...            | 5                                    | 16 1/4          | 413          | 24  | 610            |     |

<sup>a</sup> Larger or smaller than regular shank.

**Table 6. American National Standard Combined Drills and Countersinks —  
Plain and Bell Types ANSI/ASME B94.11M-1993**

PLAIN TYPE

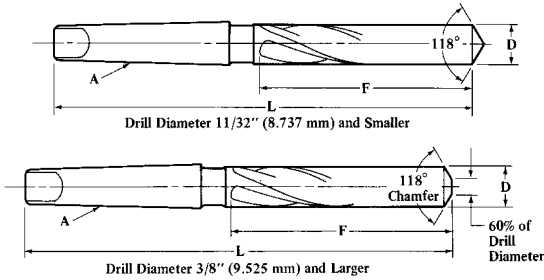
BELL TYPE

| Size Designation | Body Diameter |             | Drill Diameter |             | Drill Length |             | Overall Length |             |
|------------------|---------------|-------------|----------------|-------------|--------------|-------------|----------------|-------------|
|                  | <i>A</i>      |             | <i>D</i>       |             | <i>C</i>     |             | <i>L</i>       |             |
|                  | Inches        | Millimeters | Inches         | Millimeters | Inches       | Millimeters | Inches         | Millimeters |
| 00               | 1/8           | 3.18        | .025           | 0.64        | .030         | 0.76        | 1 1/8          | 29          |
| 0                | 1/8           | 3.18        | 1/32           | 0.79        | .038         | 0.97        | 1 1/8          | 29          |
| 1                | 1/8           | 3.18        | 3/64           | 1.19        | 3/64         | 1.19        | 1 1/4          | 32          |
| 2                | 3/16          | 4.76        | 5/64           | 1.98        | 5/64         | 1.98        | 1 3/4          | 48          |
| 3                | 1/4           | 6.35        | 3/64           | 2.78        | 3/64         | 2.78        | 2              | 51          |
| 4                | 5/16          | 7.94        | 1/8            | 3.18        | 1/8          | 3.18        | 2 1/8          | 54          |
| 5                | 7/16          | 11.11       | 3/16           | 4.76        | 3/16         | 4.76        | 2 3/4          | 70          |
| 6                | 1/2           | 12.70       | 7/32           | 5.56        | 7/32         | 5.56        | 3              | 76          |
| 7                | 5/8           | 15.88       | 1/4            | 6.35        | 1/4          | 6.35        | 3 1/4          | 83          |
| 8                | 3/4           | 19.05       | 5/16           | 7.94        | 5/16         | 7.94        | 3 1/2          | 89          |

| Size Designation | Body Diameter |       | Drill Diameter |      | Bell Diameter |      | Drill Length |      | Overall Length |    |
|------------------|---------------|-------|----------------|------|---------------|------|--------------|------|----------------|----|
|                  | <i>A</i>      |       | <i>D</i>       |      | <i>E</i>      |      | <i>C</i>     |      | <i>L</i>       |    |
|                  | Inches        | mm    | Inches         | mm   | Inches        | mm   | Inches       | mm   | Inches         | mm |
| 11               | 1/8           | 3.18  | 3/64           | 1.19 | 0.10          | 2.5  | 3/64         | 1.19 | 1 1/4          | 32 |
| 12               | 3/16          | 4.76  | 1/16           | 1.59 | 0.15          | 3.8  | 1/16         | 1.59 | 1 3/8          | 48 |
| 13               | 1/4           | 6.35  | 3/32           | 2.38 | 0.20          | 5.1  | 3/32         | 2.38 | 2              | 51 |
| 14               | 5/16          | 7.94  | 7/64           | 2.78 | 0.25          | 6.4  | 7/64         | 2.78 | 2 1/8          | 54 |
| 15               | 3/8           | 11.11 | 3/32           | 3.97 | 0.35          | 8.9  | 3/32         | 3.97 | 2 3/4          | 70 |
| 16               | 1/2           | 12.70 | 3/16           | 4.76 | 0.40          | 10.2 | 3/16         | 4.76 | 3              | 76 |
| 17               | 5/8           | 15.88 | 7/32           | 5.56 | 0.50          | 12.7 | 7/32         | 5.56 | 3 1/4          | 83 |
| 18               | 3/4           | 19.05 | 1/4            | 6.35 | 0.60          | 15.2 | 1/4          | 6.35 | 3 1/2          | 89 |

TWIST DRILLS



**Table 7. American National Standard Three- and Four-Flute Taper Shank Core Drills — Fractional Sizes Only ANS/ASME B94.11M-1993**

| Drill Diameter, <i>D</i> |              |        | Three-Flute Drills |              |          |                |          | Four-Flute Drills |              |     |                |     |
|--------------------------|--------------|--------|--------------------|--------------|----------|----------------|----------|-------------------|--------------|-----|----------------|-----|
| Inch                     | Equivalent   |        | Morse Taper No.    | Flute Length |          | Overall Length |          | Morse Taper No.   | Flute Length |     | Overall Length |     |
|                          | Decimal Inch | mm     |                    | <i>F</i>     | <i>L</i> | <i>F</i>       | <i>L</i> |                   |              |     |                |     |
|                          |              |        | A                  | Inch         | mm       | Inch           | mm       | A                 | Inch         | mm  | Inch           | mm  |
| 1/4                      | 0.2500       | 6.350  | 1                  | 2 7/8        | 73       | 6 3/8          | 156      | ...               | ...          | ... | ...            | ... |
| 9/32                     | 0.2812       | 7.142  | 1                  | 3            | 76       | 6 1/4          | 159      | ...               | ...          | ... | ...            | ... |
| 5/16                     | 0.3175       | 7.938  | 1                  | 3 1/8        | 79       | 6 3/8          | 162      | ...               | ...          | ... | ...            | ... |
| 11/32                    | 0.3438       | 8.733  | 1                  | 3 1/4        | 83       | 6 1/2          | 165      | ...               | ...          | ... | ...            | ... |
| 3/8                      | 0.3750       | 9.525  | 1                  | 3 1/2        | 89       | 6 3/4          | 171      | ...               | ...          | ... | ...            | ... |
| 13/32                    | 0.4062       | 10.319 | 1                  | 3 5/8        | 92       | 7              | 178      | ...               | ...          | ... | ...            | ... |
| 7/16                     | 0.4375       | 11.112 | 1                  | 3 7/8        | 98       | 7 1/4          | 184      | ...               | ...          | ... | ...            | ... |
| 15/32                    | 0.4688       | 11.908 | 1                  | 4 1/8        | 105      | 7 1/2          | 190      | ...               | ...          | ... | ...            | ... |
| 1/2                      | 0.5000       | 12.700 | 2                  | 4 3/8        | 111      | 8 1/4          | 210      | 2                 | 4 3/8        | 111 | 8 1/4          | 210 |
| 17/32                    | 0.5312       | 13.492 | 2                  | 4 5/8        | 117      | 8 1/2          | 216      | 2                 | 4 5/8        | 117 | 8 1/2          | 216 |
| 9/16                     | 0.5625       | 14.288 | 2                  | 4 7/8        | 124      | 8 3/4          | 222      | 2                 | 4 7/8        | 124 | 8 3/4          | 222 |
| 19/32                    | 0.5938       | 15.083 | 2                  | 4 7/8        | 124      | 8 3/4          | 222      | 2                 | 4 7/8        | 124 | 8 3/4          | 222 |
| 5/8                      | 0.6250       | 15.815 | 2                  | 4 7/8        | 124      | 8 3/4          | 222      | 2                 | 4 7/8        | 124 | 8 3/4          | 222 |
| 21/32                    | 0.6562       | 16.668 | 2                  | 5 1/8        | 130      | 9              | 229      | 2                 | 5 1/8        | 130 | 9              | 229 |
| 11/16                    | 0.6875       | 17.462 | 2                  | 5 3/8        | 137      | 9 1/4          | 235      | 2                 | 5 3/8        | 137 | 9 1/4          | 235 |
| 23/32                    | 0.7188       | 18.258 | 2                  | 5 5/8        | 143      | 9 1/2          | 241      | 2                 | 5 5/8        | 143 | 9 1/2          | 241 |
| 3/4                      | 0.7500       | 19.050 | 2                  | 5 5/8        | 149      | 9 3/4          | 248      | 2                 | 5 5/8        | 149 | 9 3/4          | 248 |
| 25/32                    | 0.7812       | 19.842 | 2                  | 6            | 152      | 9 7/8          | 251      | 2                 | 6            | 152 | 9 7/8          | 251 |
| 13/16                    | 0.8125       | 20.638 | 3                  | 6 1/8        | 156      | 10 3/4         | 273      | 3                 | 6 1/8        | 156 | 10 3/4         | 273 |
| 27/32                    | 0.8438       | 21.433 | 3                  | 6 1/8        | 156      | 10 3/4         | 273      | 3                 | 6 1/8        | 156 | 10 3/4         | 273 |
| 7/8                      | 0.8750       | 22.225 | 3                  | 6 1/8        | 156      | 10 3/4         | 273      | 3                 | 6 1/8        | 156 | 10 3/4         | 273 |
| 29/32                    | 0.9062       | 23.019 | 3                  | 6 1/8        | 156      | 10 3/4         | 273      | 3                 | 6 1/8        | 156 | 10 3/4         | 273 |
| 15/16                    | 0.9375       | 23.812 | 3                  | 6 1/8        | 156      | 10 3/4         | 273      | 3                 | 6 1/8        | 156 | 10 3/4         | 273 |
| 31/32                    | 0.9688       | 24.608 | 3                  | 6 3/8        | 162      | 11             | 279      | 3                 | 6 3/8        | 162 | 11             | 279 |
| 1                        | 1.0000       | 25.400 | 3                  | 6 3/8        | 162      | 11             | 279      | 3                 | 6 3/8        | 162 | 11             | 279 |
| 1 1/32                   | 1.0312       | 26.192 | 3                  | 6 1/2        | 165      | 11 1/8         | 283      | 3                 | 6 1/2        | 165 | 11 1/8         | 283 |
| 1 1/16                   | 1.0625       | 26.988 | 3                  | 6 5/8        | 168      | 11 1/4         | 286      | 3                 | 6 5/8        | 168 | 11 1/4         | 286 |
| 1 1/32                   | 1.0938       | 27.783 | 4                  | 6 5/8        | 175      | 12 1/2         | 318      | 4                 | 6 5/8        | 175 | 12 1/2         | 318 |
| 1 1/8                    | 1.1250       | 28.575 | 4                  | 7 1/8        | 181      | 12 3/4         | 324      | 4                 | 7 1/8        | 181 | 12 3/4         | 324 |
| 1 5/32                   | 1.1562       | 29.367 | 4                  | 7 1/4        | 184      | 12 7/8         | 327      | 4                 | 7 1/4        | 184 | 12 7/8         | 327 |
| 1 3/16                   | 1.1875       | 30.162 | 4                  | 7 3/8        | 187      | 13             | 330      | 4                 | 7 3/8        | 187 | 13             | 330 |
| 1 7/32                   | 1.2188       | 30.958 | 4                  | 7 7/8        | 190      | 13 3/8         | 333      | 4                 | 7 7/8        | 190 | 13 3/8         | 333 |
| 1 1/4                    | 1.2500       | 31.750 | 4                  | 7 7/8        | 200      | 13 1/2         | 343      | 4                 | 7 7/8        | 200 | 13 1/2         | 343 |
| 1 5/32                   | 1.2812       | 32.542 | ...                | ...          | ...      | ...            | ...      | 4                 | 8 1/2        | 216 | 14 1/8         | 359 |

**Table 7. American National Standard Three- and Four-Flute Taper Shank Core Drills — Fractional Sizes Only ANSI/ASME B94.11M-1993**

| Drill Diameter, <i>D</i>        |              |        | Three-Flute Drills |              |     |                |     | Four-Flute Drills |                                |     |                                |     |
|---------------------------------|--------------|--------|--------------------|--------------|-----|----------------|-----|-------------------|--------------------------------|-----|--------------------------------|-----|
| Inch                            | Equivalent   |        | Morse Taper No.    | Flute Length |     | Overall Length |     | Morse Taper No.   | Flute Length                   |     | Overall Length                 |     |
|                                 | Decimal Inch | mm     |                    | <i>F</i>     |     | <i>L</i>       |     |                   | <i>F</i>                       |     | <i>L</i>                       |     |
|                                 |              |        | A                  | Inch         | mm  | Inch           | mm  | A                 | Inch                           | mm  | Inch                           | mm  |
| 1 <sup>5</sup> / <sub>16</sub>  | 1.3125       | 33.338 | ...                | ...          | ... | ...            | ... | 4                 | 8 <sup>5</sup> / <sub>8</sub>  | 219 | 14 <sup>1</sup> / <sub>4</sub> | 362 |
| 1 <sup>11</sup> / <sub>32</sub> | 1.3438       | 34.133 | ...                | ...          | ... | ...            | ... | 4                 | 8 <sup>3</sup> / <sub>4</sub>  | 222 | 14 <sup>3</sup> / <sub>8</sub> | 365 |
| 1 <sup>3</sup> / <sub>8</sub>   | 1.3750       | 34.925 | ...                | ...          | ... | ...            | ... | 4                 | 8 <sup>7</sup> / <sub>8</sub>  | 225 | 14 <sup>1</sup> / <sub>2</sub> | 368 |
| 1 <sup>13</sup> / <sub>32</sub> | 1.4062       | 35.717 | ...                | ...          | ... | ...            | ... | 4                 | 9                              | 229 | 14 <sup>5</sup> / <sub>8</sub> | 371 |
| 1 <sup>7</sup> / <sub>16</sub>  | 1.4375       | 36.512 | ...                | ...          | ... | ...            | ... | 4                 | 9 <sup>1</sup> / <sub>8</sub>  | 232 | 14 <sup>3</sup> / <sub>4</sub> | 375 |
| 1 <sup>15</sup> / <sub>32</sub> | 1.4688       | 37.306 | ...                | ...          | ... | ...            | ... | 4                 | 9 <sup>1</sup> / <sub>4</sub>  | 235 | 14 <sup>7</sup> / <sub>8</sub> | 378 |
| 1 <sup>1</sup> / <sub>2</sub>   | 1.5000       | 38.100 | ...                | ...          | ... | ...            | ... | 4                 | 9 <sup>3</sup> / <sub>8</sub>  | 238 | 15                             | 381 |
| 1 <sup>17</sup> / <sub>32</sub> | 1.5312       | 38.892 | ...                | ...          | ... | ...            | ... | 5                 | 9 <sup>3</sup> / <sub>8</sub>  | 238 | 16 <sup>3</sup> / <sub>8</sub> | 416 |
| 1 <sup>9</sup> / <sub>16</sub>  | 1.5675       | 39.688 | ...                | ...          | ... | ...            | ... | 5                 | 9 <sup>5</sup> / <sub>8</sub>  | 244 | 16 <sup>5</sup> / <sub>8</sub> | 422 |
| 1 <sup>19</sup> / <sub>32</sub> | 1.5938       | 40.483 | ...                | ...          | ... | ...            | ... | 5                 | 9 <sup>7</sup> / <sub>8</sub>  | 251 | 16 <sup>7</sup> / <sub>8</sub> | 429 |
| 1 <sup>5</sup> / <sub>8</sub>   | 1.6250       | 41.275 | ...                | ...          | ... | ...            | ... | 5                 | 10                             | 254 | 17                             | 432 |
| 1 <sup>21</sup> / <sub>32</sub> | 1.6562       | 42.067 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>1</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435 |
| 1 <sup>11</sup> / <sub>16</sub> | 1.6875       | 42.862 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>1</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435 |
| 1 <sup>23</sup> / <sub>32</sub> | 1.7188       | 43.658 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>1</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435 |
| 1 <sup>3</sup> / <sub>4</sub>   | 1.7500       | 44.450 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>1</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435 |
| 1 <sup>25</sup> / <sub>32</sub> | 1.7812       | 45.244 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>1</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435 |
| 1 <sup>13</sup> / <sub>16</sub> | 1.8125       | 46.038 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>1</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435 |
| 1 <sup>27</sup> / <sub>32</sub> | 1.8438       | 46.833 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>1</sup> / <sub>8</sub> | 257 | 17 <sup>1</sup> / <sub>8</sub> | 435 |
| 1 <sup>7</sup> / <sub>8</sub>   | 1.8750       | 47.625 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441 |
| 1 <sup>29</sup> / <sub>32</sub> | 1.9062       | 48.417 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441 |
| 1 <sup>15</sup> / <sub>16</sub> | 1.9375       | 49.212 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441 |
| 1 <sup>31</sup> / <sub>32</sub> | 1.9688       | 50.008 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441 |
| 2                               | 2.0000       | 50.800 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>3</sup> / <sub>8</sub> | 264 | 17 <sup>3</sup> / <sub>8</sub> | 441 |
| 2 <sup>1</sup> / <sub>8</sub>   | 2.1250       | 53.975 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>1</sup> / <sub>4</sub> | 260 | 17 <sup>3</sup> / <sub>8</sub> | 441 |
| 2 <sup>1</sup> / <sub>4</sub>   | 2.2500       | 57.150 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>5</sup> / <sub>8</sub> | 257 | 17 <sup>3</sup> / <sub>8</sub> | 441 |
| 2 <sup>3</sup> / <sub>8</sub>   | 2.3750       | 60.325 | ...                | ...          | ... | ...            | ... | 5                 | 10 <sup>5</sup> / <sub>8</sub> | 257 | 17 <sup>3</sup> / <sub>8</sub> | 441 |
| 2 <sup>1</sup> / <sub>2</sub>   | 2.5000       | 63.500 | ...                | ...          | ... | ...            | ... | 5                 | 11 <sup>1</sup> / <sub>4</sub> | 286 | 18 <sup>3</sup> / <sub>4</sub> | 476 |

**Table 8. American National Standard Drill Drivers — Split-Sleeve, Collet Type ANSI B94.35-1972 (R1995)**

| Taper Number   | <i>G</i> Overall Length | <i>H</i> Diameter at Gage Line | <i>J</i> Taper per Foot <sup>a</sup> | <i>K</i> Length to Gage Line | <i>L</i> Driver Projection |
|----------------|-------------------------|--------------------------------|--------------------------------------|------------------------------|----------------------------|
| 0 <sup>b</sup> | 2.38                    | 0.356                          | 0.62460                              | 2.22                         | 0.16                       |
| 1              | 2.62                    | 0.475                          | 0.59858                              | 2.44                         | 0.19                       |
| 2              | 3.19                    | 0.700                          | 0.59941                              | 2.94                         | 0.25                       |

<sup>a</sup> Taper rate in accordance with ANSI/ASME B5.10-1994 (R2002), Machine Tapers.

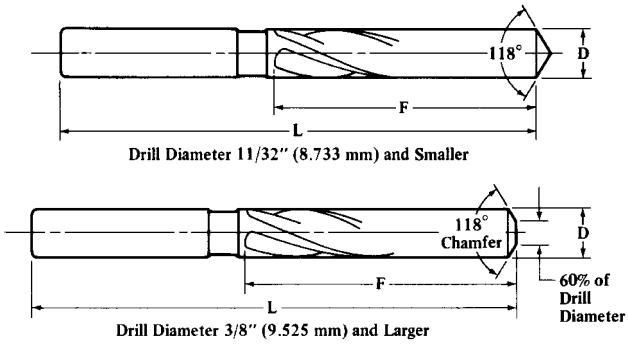
<sup>b</sup> Size 0 is not an American National Standard but is included here to meet special needs.

All dimensions are in inches.



TWIST DRILLS

**Table 9. ANSI Three- and Four-Flute Straight Shank Core Drills — Fractional Sizes Only ANSI/ASME B94.11M-1993**



Nominal Shank Size is same as Nominal Drill Size

| Drill Diameter, <i>D</i> |              |        | Three-Flute Drills |     |                |     | Four-Flute Drills |     |                |     |
|--------------------------|--------------|--------|--------------------|-----|----------------|-----|-------------------|-----|----------------|-----|
| Inch                     | Equivalent   |        | Flute Length       |     | Overall Length |     | Flute Length      |     | Overall Length |     |
|                          | Decimal Inch | mm     | <i>F</i>           |     | <i>L</i>       |     | <i>F</i>          |     | <i>L</i>       |     |
|                          |              |        | Inch               | mm  | Inch           | mm  | Inch              | mm  | Inch           | mm  |
| 1/4                      | 0.2500       | 6.350  | 3 3/4              | 95  | 6 1/8          | 156 | ...               | ... | ...            | ... |
| 5/32                     | 0.2812       | 7.142  | 3 7/8              | 98  | 6 1/4          | 159 | ...               | ... | ...            | ... |
| 3/16                     | 0.3125       | 7.938  | 4                  | 102 | 6 3/8          | 162 | ...               | ... | ...            | ... |
| 11/32                    | 0.3438       | 8.733  | 4 1/8              | 105 | 6 1/2          | 165 | ...               | ... | ...            | ... |
| 3/8                      | 0.3750       | 9.525  | 4 1/8              | 105 | 6 3/4          | 171 | ...               | ... | ...            | ... |
| 13/32                    | 0.4062       | 10.317 | 4 3/8              | 111 | 7              | 178 | ...               | ... | ...            | ... |
| 7/16                     | 0.4375       | 11.112 | 4 5/8              | 117 | 7 1/4          | 184 | ...               | ... | ...            | ... |
| 15/32                    | 0.4688       | 11.908 | 4 3/4              | 121 | 7 1/2          | 190 | ...               | ... | ...            | ... |
| 1/2                      | 0.5000       | 12.700 | 4 3/4              | 121 | 7 3/4          | 197 | 4 3/4             | 121 | 7 3/4          | 197 |
| 17/32                    | 0.5312       | 13.492 | 4 3/4              | 121 | 8              | 203 | 4 3/4             | 121 | 8              | 203 |
| 9/16                     | 0.5625       | 14.288 | 4 7/8              | 124 | 8 1/4          | 210 | 4 7/8             | 124 | 8 1/4          | 210 |
| 19/32                    | 0.5938       | 15.083 | 4 7/8              | 124 | 8 3/4          | 222 | 4 7/8             | 124 | 8 3/4          | 222 |
| 5/8                      | 0.6250       | 15.875 | 4 7/8              | 124 | 8 3/4          | 222 | 4 7/8             | 124 | 8 3/4          | 222 |
| 21/32                    | 0.6562       | 16.667 | 5 1/8              | 130 | 9              | 229 | 5 1/8             | 130 | 9              | 229 |
| 11/16                    | 0.6875       | 17.462 | 5 3/8              | 137 | 9 1/4          | 235 | 5 3/8             | 137 | 9 1/4          | 235 |
| 23/32                    | 0.7188       | 18.258 | ...                | ... | ...            | ... | 5 7/8             | 143 | 9 1/2          | 241 |
| 3/4                      | 0.7500       | 19.050 | 5 7/8              | 149 | 9 3/4          | 248 | 5 7/8             | 149 | 9 3/4          | 248 |
| 25/32                    | 0.7812       | 19.842 | ...                | ... | ...            | ... | 6                 | 152 | 9 7/8          | 251 |
| 13/16                    | 0.8125       | 20.638 | ...                | ... | ...            | ... | 6 1/8             | 156 | 10             | 254 |
| 27/32                    | 0.8438       | 21.433 | ...                | ... | ...            | ... | 6 1/8             | 156 | 10             | 254 |
| 7/8                      | 0.8750       | 22.225 | ...                | ... | ...            | ... | 6 1/8             | 156 | 10             | 254 |
| 29/32                    | 0.9062       | 23.017 | ...                | ... | ...            | ... | 6 1/8             | 156 | 10             | 254 |
| 15/16                    | 0.9375       | 23.812 | ...                | ... | ...            | ... | 6 1/8             | 156 | 10 3/4         | 273 |
| 31/32                    | 0.9688       | 24.608 | ...                | ... | ...            | ... | 6 3/8             | 162 | 11             | 279 |
| 1                        | 1.0000       | 25.400 | ...                | ... | ...            | ... | 6 3/8             | 162 | 11             | 279 |
| 1 1/32                   | 1.0312       | 26.192 | ...                | ... | ...            | ... | 6 1/2             | 165 | 11 1/8         | 283 |
| 1 1/16                   | 1.0625       | 26.988 | ...                | ... | ...            | ... | 6 3/8             | 168 | 11 1/4         | 286 |
| 1 3/32                   | 1.0938       | 27.783 | ...                | ... | ...            | ... | 6 3/8             | 175 | 11 1/2         | 292 |
| 1 1/8                    | 1.1250       | 28.575 | ...                | ... | ...            | ... | 7 1/8             | 181 | 11 3/4         | 298 |
| 1 1/4                    | 1.2500       | 31.750 | ...                | ... | ...            | ... | 7 7/8             | 200 | 12 1/2         | 318 |

Table 10. Length of Point on Twist Drills and Centering Tools

| Size of Drill | Decimal Equivalent | Length of Point when Included Angle = 90° | Length of Point when Included Angle = 118° | Size of Drill | Decimal Equivalent | Length of Point when Included Angle = 90° | Length of Point when Included Angle = 118° | Size or Dia. of Drill | Decimal Equivalent | Length of Point when Included Angle = 90° | Length of Point when Included Angle = 118° | Dia. of Drill   | Decimal Equivalent | Length of Point when Included Angle = 90° | Length of Point when Included Angle = 118° |
|---------------|--------------------|---|--|---------------|--------------------|---|--|-----------------------|--------------------|---|--|-----------------|--------------------|---|--|
| 60            | 0.0400             | 0.020                                     | 0.012                                      | 37            | 0.1040             | 0.052                                     | 0.031                                      | 14                    | 0.1820             | 0.091                                     | 0.055                                      | $\frac{3}{8}$   | 0.3750             | 0.188                                     | 0.113                                      |
| 59            | 0.0410             | 0.021                                     | 0.012                                      | 36            | 0.1065             | 0.054                                     | 0.032                                      | 13                    | 0.1850             | 0.093                                     | 0.056                                      | $\frac{25}{64}$ | 0.3906             | 0.195                                     | 0.117                                      |
| 58            | 0.0420             | 0.021                                     | 0.013                                      | 35            | 0.1100             | 0.055                                     | 0.033                                      | 12                    | 0.1890             | 0.095                                     | 0.057                                      | $\frac{13}{32}$ | 0.4063             | 0.203                                     | 0.122                                      |
| 57            | 0.0430             | 0.022                                     | 0.013                                      | 34            | 0.1110             | 0.056                                     | 0.033                                      | 11                    | 0.1910             | 0.096                                     | 0.057                                      | $\frac{27}{64}$ | 0.4219             | 0.211                                     | 0.127                                      |
| 56            | 0.0465             | 0.023                                     | 0.014                                      | 33            | 0.1130             | 0.057                                     | 0.034                                      | 10                    | 0.1935             | 0.097                                     | 0.058                                      | $\frac{7}{16}$  | 0.4375             | 0.219                                     | 0.131                                      |
| 55            | 0.0520             | 0.026                                     | 0.016                                      | 32            | 0.1160             | 0.058                                     | 0.035                                      | 9                     | 0.1960             | 0.098                                     | 0.059                                      | $\frac{29}{64}$ | 0.4531             | 0.227                                     | 0.136                                      |
| 54            | 0.0550             | 0.028                                     | 0.017                                      | 31            | 0.1200             | 0.060                                     | 0.036                                      | 8                     | 0.1990             | 0.100                                     | 0.060                                      | $\frac{15}{32}$ | 0.4688             | 0.234                                     | 0.141                                      |
| 53            | 0.0595             | 0.030                                     | 0.018                                      | 30            | 0.1285             | 0.065                                     | 0.039                                      | 7                     | 0.2010             | 0.101                                     | 0.060                                      | $\frac{31}{64}$ | 0.4844             | 0.242                                     | 0.145                                      |
| 52            | 0.0635             | 0.032                                     | 0.019                                      | 29            | 0.1360             | 0.068                                     | 0.041                                      | 6                     | 0.2040             | 0.102                                     | 0.061                                      | $\frac{1}{2}$   | 0.5000             | 0.250                                     | 0.150                                      |
| 51            | 0.0670             | 0.034                                     | 0.020                                      | 28            | 0.1405             | 0.070                                     | 0.042                                      | 5                     | 0.2055             | 0.103                                     | 0.062                                      | $\frac{33}{64}$ | 0.5156             | 0.258                                     | 0.155                                      |
| 50            | 0.0700             | 0.035                                     | 0.021                                      | 27            | 0.1440             | 0.072                                     | 0.043                                      | 4                     | 0.2090             | 0.105                                     | 0.063                                      | $\frac{17}{32}$ | 0.5313             | 0.266                                     | 0.159                                      |
| 49            | 0.0730             | 0.037                                     | 0.022                                      | 26            | 0.1470             | 0.074                                     | 0.044                                      | 3                     | 0.2130             | 0.107                                     | 0.064                                      | $\frac{35}{64}$ | 0.5469             | 0.273                                     | 0.164                                      |
| 48            | 0.0760             | 0.038                                     | 0.023                                      | 25            | 0.1495             | 0.075                                     | 0.045                                      | 2                     | 0.2210             | 0.111                                     | 0.067                                      | $\frac{9}{16}$  | 0.5625             | 0.281                                     | 0.169                                      |
| 47            | 0.0785             | 0.040                                     | 0.024                                      | 24            | 0.1520             | 0.076                                     | 0.046                                      | 1                     | 0.2280             | 0.114                                     | 0.068                                      | $\frac{37}{64}$ | 0.5781             | 0.289                                     | 0.173                                      |
| 46            | 0.0810             | 0.041                                     | 0.024                                      | 23            | 0.1540             | 0.077                                     | 0.046                                      | $\frac{15}{64}$       | 0.2344             | 0.117                                     | 0.070                                      | $\frac{19}{32}$ | 0.5938             | 0.297                                     | 0.178                                      |
| 45            | 0.0820             | 0.041                                     | 0.025                                      | 22            | 0.1570             | 0.079                                     | 0.047                                      | $\frac{1}{4}$         | 0.2500             | 0.125                                     | 0.075                                      | $\frac{39}{64}$ | 0.6094             | 0.305                                     | 0.183                                      |
| 44            | 0.0860             | 0.043                                     | 0.026                                      | 21            | 0.1590             | 0.080                                     | 0.048                                      | $\frac{17}{64}$       | 0.2656             | 0.133                                     | 0.080                                      | $\frac{5}{8}$   | 0.6250             | 0.313                                     | 0.188                                      |
| 43            | 0.0890             | 0.045                                     | 0.027                                      | 20            | 0.1610             | 0.081                                     | 0.048                                      | $\frac{9}{32}$        | 0.2813             | 0.141                                     | 0.084                                      | $\frac{41}{64}$ | 0.6406             | 0.320                                     | 0.192                                      |
| 42            | 0.0935             | 0.047                                     | 0.028                                      | 19            | 0.1660             | 0.083                                     | 0.050                                      | $\frac{19}{64}$       | 0.2969             | 0.148                                     | 0.089                                      | $\frac{21}{32}$ | 0.6563             | 0.328                                     | 0.197                                      |
| 41            | 0.0960             | 0.048                                     | 0.029                                      | 18            | 0.1695             | 0.085                                     | 0.051                                      | $\frac{5}{16}$        | 0.3125             | 0.156                                     | 0.094                                      | $\frac{43}{64}$ | 0.6719             | 0.336                                     | 0.202                                      |
| 40            | 0.0980             | 0.049                                     | 0.029                                      | 17            | 0.1730             | 0.087                                     | 0.052                                      | $\frac{21}{64}$       | 0.3281             | 0.164                                     | 0.098                                      | $\frac{11}{16}$ | 0.6875             | 0.344                                     | 0.206                                      |
| 39            | 0.0995             | 0.050                                     | 0.030                                      | 16            | 0.1770             | 0.089                                     | 0.053                                      | $\frac{11}{32}$       | 0.3438             | 0.171                                     | 0.103                                      | $\frac{23}{32}$ | 0.7188             | 0.359                                     | 0.216                                      |
| 38            | 0.1015             | 0.051                                     | 0.030                                      | 15            | 0.1800             | 0.090                                     | 0.054                                      | $\frac{23}{64}$       | 0.3594             | 0.180                                     | 0.108                                      | $\frac{3}{4}$   | 0.7500             | 0.375                                     | 0.225                                      |

**British Standard Combined Drills and Countersinks (Center Drills).**—BS 328: Part 2: 1972 (1990) provides dimensions of combined drills and countersinks for center holes. Three types of drill and countersink combinations are shown in this standard but are not given here. These three types will produce center holes without protecting chamfers, with protecting chamfers, and with protecting chamfers of radius form.

**Drill Drivers—Split-Sleeve, Collet Type.**—American National Standard ANSI B94.35-1972 (R1995) covers split-sleeve, collet-type drivers for driving straight shank drills, reamers, and similar tools, without tangs from 0.0390-inch through 0.1220-inch diameter, and with tangs from 0.1250-inch through 0.7500-inch diameter, including metric sizes.

For sizes 0.0390 through 0.0595 inch, the standard taper number is 1 and the optional taper number is 0. For sizes 0.0610 through 0.1875 inch, the standard taper number is 1, first optional taper number is 0, and second optional taper number is 2. For sizes 0.1890 through 0.2520 inch, the standard taper number is 1, first optional taper number is 2, and second optional taper number is 0. For sizes 0.2570 through 0.3750 inch, the standard taper number is 1 and the optional taper number is 2. For sizes 0.3860 through 0.5625 inch, the standard taper number is 2 and the optional taper number is 3. For sizes 0.5781 through 0.7500 inch, the standard taper number is 3 and the optional taper number is 4.

The depth  $B$  that the drill enters the driver is 0.44 inch for sizes 0.0390 through 0.0781 inch; 0.50 inch for sizes 0.0785 through 0.0938 inch; 0.56 inch for sizes 0.0960 through 0.1094 inch; 0.62 inch for sizes 0.1100 through 0.1220 inch; 0.75 inch for sizes 0.1250 through 0.1875 inch; 0.88 inch for sizes 0.1890 through 0.2500 inch; 1.00 inch for sizes 0.2520 through 0.3125 inch; 1.12 inches for sizes 0.3160 through 0.3750 inch; 1.25 inches for sizes 0.3860 through 0.4688 inch; 1.31 inches for sizes 0.4844 through 0.5625 inch; 1.47 inches for sizes 0.5781 through 0.6562 inch; and 1.62 inches for sizes 0.6719 through 0.7500 inch.

**British Standard Metric Twist Drills.**—BS 328: Part 1:1959 (incorporating amendments issued March 1960 and March 1964) covers twist drills made to inch and metric dimensions that are intended for general engineering purposes. ISO recommendations are taken into account. The accompanying tables give the standard metric sizes of Morse taper shank twist drills and core drills, parallel shank jobbing and long series drills, and stub drills.

All drills are right-hand cutting unless otherwise specified, and normal, slow, or quick helix angles may be provided. A “back-taper” is ground on the diameter from point to shank to provide longitudinal clearance. Core drills may have three or four flutes, and are intended for opening up cast holes or enlarging machined holes, for example. The parallel shank jobber, and long series drills, and stub drills are made without driving tenons.

Morse taper shank drills with oversize dimensions are also listed, and [Table 11](#) shows metric drill sizes superseding gage and letter size drills, which are now obsolete in Britain. To meet special requirements, the Standard lists nonstandard sizes for the various types of drills.

The limits of tolerance on cutting diameters, as measured across the lands at the outer corners of a drill, shall be  $h8$ , in accordance with BS 1916, Limits and Fits for Engineering (Part I, Limits and Tolerances), and [Table 14](#) shows the values common to the different types of drills mentioned before.

The drills shall be permanently and legibly marked whenever possible, preferably by rolling, showing the size, and the manufacturer's name or trademark. If they are made from high-speed steel, they shall be marked with the letters H.S. where practicable.

*Drill Elements:* The following definitions of drill elements are given.

*Axis:* The longitudinal center line.

*Body:* That portion of the drill extending from the extreme cutting end to the commencement of the shank.

*Shank:* That portion of the drill by which it is held and driven.

*Flutes:* The grooves in the body of the drill that provide lips and permit the removal of chips and allow cutting fluid to reach the lips.

*Web (Core):* The central portion of the drill situated between the roots of the flutes and extending from the point end toward the shank; the point end of the web or core forms the chisel edge.

*Lands:* The cylindrical-ground surfaces on the leading edges of the drill flutes. The width of the land is measured at right angles to the flute helix.

*Body Clearance:* The portion of the body surface that is reduced in diameter to provide diametral clearance.

*Heel:* The edge formed by the intersection of the flute surface and the body clearance.

*Point:* The sharpened end of the drill, consisting of all that part of the drill that is shaped to produce lips, faces, flanks, and chisel edge.

*Face:* That portion of the flute surface adjacent to the lip on which the chip impinges as it is cut from the work.

*Flank:* The surface on a drill point that extends behind the lip to the following flute.

*Lip (Cutting Edge):* The edge formed by the intersection of the flank and face.

*Relative Lip Height:* The relative position of the lips measured at the outer corners in a direction parallel to the drill axis.

*Outer Corner:* The corner formed by the intersection of the lip and the leading edge of the land.

*Chisel Edge:* The edge formed by the intersection of the flanks.

*Chisel Edge Corner:* The corner formed by the intersection of a lip and the chisel edge.

**Table 11. British Standard Drills — Metric Sizes Superseding Gauge and Letter Sizes BS 328: Part 1:1959, Appendix B**

| Obsolete Drill Size | Recommended Metric Size (mm) | Obsolete Drill Size | Recommended Metric Size (mm) | Obsolete Drill Size | Recommended Metric Size (mm) | Obsolete Drill Size | Recommended Metric Size (mm) | Obsolete Drill Size | Recommended Metric Size (mm) |
|---------------------|------------------------------|---------------------|------------------------------|---------------------|------------------------------|---------------------|------------------------------|---------------------|------------------------------|
| 80                  | 0.35                         | 58                  | 1.05                         | 36                  | 2.70                         | 14                  | 4.60                         | I                   | 6.90                         |
| 79                  | 0.38                         | 57                  | 1.10                         | 35                  | 2.80                         | 13                  | 4.70                         | J                   | 7.00                         |
| 78                  | 0.40                         | 56                  | $\frac{3}{64}$ in.           | 34                  | 2.80                         | 12                  | 4.80                         | K                   | $\frac{9}{32}$ in.           |
| 77                  | 0.45                         | 55                  | 1.30                         | 33                  | 2.85                         | 11                  | 4.90                         | L                   | 7.40                         |
| 76                  | 0.50                         | 54                  | 1.40                         | 32                  | 2.95                         | 10                  | 4.90                         | M                   | 7.50                         |
| 75                  | 0.52                         | 53                  | 1.50                         | 31                  | 3.00                         | 9                   | 5.00                         | N                   | 7.70                         |
| 74                  | 0.58                         | 52                  | 1.60                         | 30                  | 3.30                         | 8                   | 5.10                         | O                   | 8.00                         |
| 73                  | 0.60                         | 51                  | 1.70                         | 29                  | 3.50                         | 7                   | 5.10                         | P                   | 8.20                         |
| 72                  | 0.65                         | 50                  | 1.80                         | 28                  | $\frac{5}{64}$ in.           | 6                   | 5.20                         | Q                   | 8.40                         |
| 71                  | 0.65                         | 49                  | 1.85                         | 27                  | 3.70                         | 5                   | 5.20                         | R                   | 8.60                         |
| 70                  | 0.70                         | 48                  | 1.95                         | 26                  | 3.70                         | 4                   | 5.30                         | S                   | 8.80                         |
| 69                  | 0.75                         | 47                  | 2.00                         | 25                  | 3.80                         | 3                   | 5.40                         | T                   | 9.10                         |
| 68                  | $\frac{1}{32}$ in.           | 46                  | 2.05                         | 24                  | 3.90                         | 2                   | 5.60                         | U                   | 9.30                         |
| 67                  | 0.82                         | 45                  | 2.10                         | 23                  | 3.90                         | 1                   | 5.80                         | V                   | $\frac{3}{8}$ in.            |
| 66                  | 0.85                         | 44                  | 2.20                         | 22                  | 4.00                         | A                   | $\frac{15}{64}$ in.          | W                   | 9.80                         |
| 65                  | 0.90                         | 43                  | 2.25                         | 21                  | 4.00                         | B                   | 6.00                         | X                   | 10.10                        |
| 64                  | 0.92                         | 42                  | $\frac{3}{32}$ in.           | 20                  | 4.10                         | C                   | 6.10                         | Y                   | 10.30                        |
| 63                  | 0.95                         | 41                  | 2.45                         | 19                  | 4.20                         | D                   | 6.20                         | Z                   | 10.50                        |
| 62                  | 0.98                         | 40                  | 2.50                         | 18                  | 4.30                         | E                   | $\frac{1}{4}$ in.            | ...                 | ...                          |
| 61                  | 1.00                         | 39                  | 2.55                         | 17                  | 4.40                         | F                   | 6.50                         | ...                 | ...                          |
| 60                  | 1.00                         | 38                  | 2.60                         | 16                  | 4.50                         | G                   | 6.60                         | ...                 | ...                          |
| 59                  | 1.05                         | 37                  | 2.65                         | 15                  | 4.60                         | H                   | $\frac{17}{64}$ in.          | ...                 | ...                          |

Gauge and letter size drills are now obsolete in the United Kingdom and should not be used in the production of new designs. The table is given to assist users in changing over to the recommended standard sizes.

**Table 12. British Standard Morse Taper Shank Twist Drills and Core Drills — Standard Metric Sizes BS 328: Part 1:1959**

| Diameter | Flute Length | Overall Length | Diameter | Flute Length | Overall Length | Diameter | Flute Length | Overall Length |
|----------|--------------|----------------|----------|--------------|----------------|----------|--------------|----------------|
| 3.00     | 33           | 114            | 16.75    |              |                | 30.25    |              |                |
| 3.20     | 36           | 117            | 17.00    | 125          | 223            | 30.50    |              |                |
| 3.50     | 39           | 120            | 17.25    |              |                | 30.75    | 180          | 301            |
| 3.80     |              |                | 17.50    | 130          | 228            | 31.00    |              |                |
| 4.00     | 43           | 123            | 17.75    |              |                | 31.25    |              |                |
| 4.20     |              |                | 18.00    |              |                | 31.50    |              |                |
| 4.50     | 47           | 128            | 18.25    |              |                | 31.75    | 185          | 306            |
| 4.80     |              |                | 18.50    | 135          | 233            | 32.00    |              |                |
| 5.00     | 52           | 133            | 18.75    |              |                | 32.50    | 185          | 334            |
| 5.20     |              |                | 19.00    |              |                | 33.00    |              |                |
| 5.50     |              |                | 19.25    |              |                | 33.50    |              |                |
| 5.80     | 57           | 138            | 19.50    | 140          | 238            | 34.00    |              |                |
| 6.00     |              |                | 19.75    |              |                | 34.50    | 190          | 339            |
| 6.20     | 63           | 144            | 20.00    |              |                | 35.00    |              |                |
| 6.50     |              |                | 20.25    |              |                | 35.50    |              |                |
| 6.80     |              |                | 20.50    | 145          | 243            | 36.00    |              |                |
| 7.00     | 69           | 150            | 20.75    |              |                | 36.50    | 195          | 344            |
| 7.20     |              |                | 21.00    |              |                | 37.00    |              |                |
| 7.50     |              |                | 21.25    |              |                | 37.50    |              |                |
| 7.80     |              |                | 21.50    | 150          | 248            | 38.00    |              |                |
| 8.00     | 75           | 156            | 21.75    |              |                | 38.50    | 200          | 349            |
| 8.20     |              |                | 22.00    |              |                | 39.00    |              |                |
| 8.50     |              |                | 22.25    |              |                | 39.50    |              |                |
| 8.80     |              |                | 22.50    |              |                | 40.00    |              |                |
| 9.00     | 81           | 162            | 22.75    | 155          | 253            | 40.50    |              |                |
| 9.20     |              |                | 23.00    |              |                | 41.00    |              |                |
| 9.50     |              |                | 23.25    |              |                | 41.50    | 205          | 354            |
| 9.80     |              |                | 23.50    | 155          | 276            | 42.00    |              |                |
| 10.00    | 87           | 168            | 23.75    |              |                | 42.50    |              |                |
| 10.20    |              |                | 24.00    |              |                | 43.00    |              |                |
| 10.50    |              |                | 24.25    | 160          | 281            | 43.50    | 210          | 359            |
| 10.80    |              |                | 24.50    |              |                | 44.00    |              |                |
| 11.00    | 94           | 175            | 24.75    |              |                | 44.50    |              |                |
| 11.20    |              |                | 25.00    |              |                | 45.00    |              |                |
| 11.50    |              |                | 25.25    |              |                | 45.50    |              |                |
| 11.80    |              |                | 25.50    |              |                | 46.00    |              |                |
| 12.00    |              |                | 25.75    | 165          | 286            | 46.50    | 215          | 364            |
| 12.20    |              |                | 26.00    |              |                | 47.00    |              |                |
| 12.50    | 101          | 182            | 26.25    |              |                | 47.50    |              |                |
| 12.80    |              |                | 26.50    |              |                | 48.00    |              |                |
| 13.00    |              |                | 26.75    |              |                | 48.50    |              |                |
| 13.20    |              |                | 27.00    |              |                | 49.00    | 220          | 369            |
| 13.50    |              |                | 27.25    | 170          | 291            | 49.50    |              |                |
| 13.80    | 108          | 189            | 27.50    |              |                | 50.00    |              |                |
| 14.00    |              |                | 27.75    |              |                | 50.50    | 225          | 374            |
| 14.25    |              |                | 28.00    |              |                | 51.00    |              |                |
| 14.50    | 114          | 212            | 28.25    |              |                | 52.00    | 225          | 412            |
| 14.75    |              |                | 28.50    |              |                | 53.00    |              |                |
| 15.00    |              |                | 28.75    | 175          | 296            | 54.00    |              |                |
| 15.25    |              |                | 29.00    |              |                | 55.00    | 230          | 417            |
| 15.50    | 120          | 218            | 29.25    |              |                | 56.00    |              |                |
| 15.75    |              |                |          |              |                | 57.00    |              |                |
| 16.00    |              |                | 29.50    |              |                | 58.00    |              |                |
| 16.25    |              |                | 29.75    | 175          | 296            | 59.00    | 235          | 422            |
| 16.50    | 125          | 223            | 30.00    |              |                | 60.00    |              |                |

**Table 12. (Continued) British Standard Morse Taper Shank Twist Drills and Core Drills — Standard Metric Sizes BS 328: Part 1:1959**

| Diameter | Flute Length | Overall Length | Diameter | Flute Length | Overall Length | Diameter | Flute Length | Overall Length |
|----------|--------------|----------------|----------|--------------|----------------|----------|--------------|----------------|
| 61.00    | 240          | 427            | 76.00    | 260          | 477            | 91.00    | 275          | 529            |
| 62.00    |              |                | 77.00    | 260          | 514            | 92.00    |              |                |
| 63.00    |              |                | 78.00    |              |                | 93.00    |              |                |
| 64.00    | 245          | 432            | 79.00    | 265          | 519            | 94.00    | 280          | 534            |
| 65.00    |              |                | 80.00    |              |                | 95.00    |              |                |
| 66.00    |              |                | 81.00    |              |                | 96.00    |              |                |
| 67.00    | 250          | 437            | 82.00    | 270          | 524            | 97.00    | 280          | 534            |
| 68.00    |              |                | 83.00    |              |                | 98.00    |              |                |
| 69.00    |              |                | 84.00    |              |                | 99.00    |              |                |
| 70.00    | 250          | 437            | 85.00    | 270          | 524            | 100.00   | 280          | 534            |
| 71.00    |              |                | 86.00    |              |                |          |              |                |
| 72.00    |              |                | 87.00    |              |                |          |              |                |
| 73.00    | 255          | 442            | 88.00    | 270          | 524            |          | 280          | 534            |
| 74.00    |              |                | 89.00    |              |                |          |              |                |
| 75.00    |              |                | 90.00    |              |                |          |              |                |

All dimensions are in millimeters. Tolerances on diameters are given in the table below.

Table 13, shows twist drills that may be supplied with the shank and length oversize, but they should be regarded as nonpreferred.

The Morse taper shanks of these twist and core drills are as follows: 3.00 to 14.00 mm diameter, M.T. No. 1; 14.25 to 23.00 mm diameter, M.T. No. 2; 23.25 to 31.50 mm diameter, M.T. No. 3; 31.75 to 50.50 mm diameter, M.T. No. 4; 51.00 to 76.00 mm diameter, M.T. No. 5; 77.00 to 100.00 mm diameter, M.T. No. 6.

**Table 13. British Standard Morse Taper Shank Twist Drills — Metric Oversize Shank and Length Series BS 328: Part 1:1959**

| Dia. Range     | Overall Length | M. T. No. | Dia. Range     | Overall Length | M. T. No. | Dia. Range     | Overall Length | M. T. No. |
|----------------|----------------|-----------|----------------|----------------|-----------|----------------|----------------|-----------|
| 12.00 to 13.20 | 199            | 2         | 22.50 to 23.00 | 276            | 3         | 45.50 to 47.50 | 402            | 5         |
| 13.50 to 14.00 | 206            | 2         | 26.75 to 28.00 | 319            | 4         | 48.00 to 50.00 | 407            | 5         |
| 18.25 to 19.00 | 256            | 3         | 29.00 to 30.00 | 324            | 4         | 50.50          | 412            | 5         |
| 19.25 to 20.00 | 251            | 3         | 30.25 to 31.50 | 329            | 4         | 64.00 to 67.00 | 499            | 6         |
| 20.25 to 21.00 | 266            | 3         | 40.50 to 42.50 | 392            | 5         | 68.00 to 71.00 | 504            | 6         |
| 21.25 to 22.25 | 271            | 3         | 43.00 to 45.00 | 397            | 5         | 72.00 to 75.00 | 509            | 6         |

Diameters and lengths are given in millimeters. For the individual sizes within the diameter ranges given, see Table 12.

This series of drills should be regarded as non-preferred.

**Table 14. British Standard Limits of Tolerance on Diameter for Twist Drills and Core Drills — Metric Series BS 328: Part 1:1959**

| Drill Size<br>(Diameter measured across lands at outer corners) | Tolerance (h8)            |
|---|---------------------------|
| 0 to 1 inclusive  | Plus 0.000 to Minus 0.014 |
| Over 1 to 3 inclusive   | Plus 0.000 to Minus 0.014 |
| Over 3 to 6 inclusive   | Plus 0.000 to Minus 0.018 |
| Over 6 to 10 inclusive  | Plus 0.000 to Minus 0.022 |
| Over 10 to 18 inclusive   | Plus 0.000 to Minus 0.027 |
| Over 18 to 30 inclusive   | Plus 0.000 to Minus 0.033 |
| Over 30 to 50 inclusive   | Plus 0.000 to Minus 0.039 |
| Over 50 to 80 inclusive   | Plus 0.000 to Minus 0.046 |
| Over 80 to 120 inclusive  | Plus 0.000 to Minus 0.054 |

All dimensions are given in millimeters.

**Table 15. British Standard Parallel Shank Jobber Series Twist Drills — Standard Metric Sizes BS 328: Part 1:1959**

| Diameter | Flute Length | Overall Length | Diameter | Flute Length | Overall Length | Diameter | Flute Length | Overall Length | Diameter | Flute Length | Overall Length |
|----------|--------------|----------------|----------|--------------|----------------|----------|--------------|----------------|----------|--------------|----------------|
| 0.20     | 2.5          | 19             | 1.75     | 22           | 46             | 5.40     | 57           | 93             | 10.20    | 87           | 133            |
| 0.22     |              |                | 1.80     |              |                | 5.50     |              |                | 10.30    |              |                |
| 0.25     | 3.0          | 19             | 1.85     | 24           | 49             | 5.60     | 63           | 101            | 10.40    | 94           | 142            |
| 0.28     |              |                | 1.90     |              |                | 5.70     |              |                | 10.50    |              |                |
| 0.30     | 4            | 19             | 1.95     | 27           | 53             | 5.80     | 69           | 109            | 10.60    | 101          | 151            |
| 0.32     |              |                | 2.00     |              |                | 5.80     |              |                | 10.70    |              |                |
| 0.35     |              |                | 2.05     |              |                | 5.90     |              |                | 10.80    |              |                |
| 0.38     |              |                | 2.10     |              |                | 6.00     |              |                | 10.90    |              |                |
| 0.40     | 5            | 20             | 2.15     | 30           | 57             | 6.10     | 75           | 117            | 11.00    | 108          | 160            |
| 0.42     |              |                | 2.20     |              |                | 6.20     |              |                | 11.10    |              |                |
| 0.45     |              |                | 2.25     |              |                | 6.30     |              |                | 11.20    |              |                |
| 0.48     |              |                | 2.30     |              |                | 6.40     |              |                | 11.30    |              |                |
| 0.50     | 6            | 22             | 2.35     | 33           | 61             | 6.50     | 81           | 125            | 11.40    | 114          | 169            |
| 0.52     |              |                | 2.40     |              |                | 6.60     |              |                | 11.50    |              |                |
| 0.55     | 7            | 24             | 2.45     | 36           | 65             | 6.70     | 87           | 133            | 11.60    | 120          | 178            |
| 0.58     |              |                | 2.50     |              |                | 6.80     |              |                | 11.70    |              |                |
| 0.60     |              |                | 2.55     |              |                | 6.90     |              |                | 11.80    |              |                |
| 0.62     | 8            | 26             | 2.60     | 39           | 70             | 7.00     | 91           | 133            | 11.90    | 121          | 179            |
| 0.65     |              |                | 2.65     |              |                | 7.10     |              |                | 12.00    |              |                |
| 0.68     | 9            | 28             | 2.70     | 43           | 75             | 7.20     | 97           | 139            | 12.10    | 122          | 180            |
| 0.70     |              |                | 2.75     |              |                | 7.30     |              |                | 12.20    |              |                |
| 0.72     |              |                | 2.80     |              |                | 7.40     |              |                | 12.30    |              |                |
| 0.75     |              |                | 2.85     |              |                | 7.50     |              |                | 12.40    |              |                |
| 0.78     | 10           | 30             | 2.90     | 47           | 80             | 7.60     | 103          | 145            | 12.50    | 123          | 181            |
| 0.80     |              |                | 2.95     |              |                | 7.70     |              |                | 12.60    |              |                |
| 0.82     |              |                | 3.00     |              |                | 7.80     |              |                | 12.70    |              |                |
| 0.85     |              |                | 3.10     |              |                | 7.90     |              |                | 12.80    |              |                |
| 0.88     | 11           | 32             | 3.20     | 51           | 85             | 8.00     | 109          | 151            | 12.90    | 124          | 182            |
| 0.90     |              |                | 3.30     |              |                | 8.10     |              |                | 13.00    |              |                |
| 0.92     |              |                | 3.40     |              |                | 8.20     |              |                | 13.10    |              |                |
| 0.95     | 12           | 34             | 3.50     | 55           | 90             | 8.30     | 115          | 157            | 13.20    | 125          | 183            |
| 0.98     |              |                | 3.60     |              |                | 8.40     |              |                | 13.30    |              |                |
| 1.00     | 14           | 36             | 3.70     | 59           | 95             | 8.50     | 121          | 163            | 13.40    | 126          | 184            |
| 1.05     |              |                | 3.80     |              |                | 8.60     |              |                | 13.50    |              |                |
| 1.10     |              |                | 3.90     |              |                | 8.70     |              |                | 13.60    |              |                |
| 1.15     |              |                | 4.00     |              |                | 8.80     |              |                | 13.70    |              |                |
| 1.20     | 16           | 38             | 4.10     | 63           | 100            | 8.80     | 127          | 169            | 13.80    | 127          | 185            |
| 1.25     |              |                | 4.20     |              |                | 8.90     |              |                | 13.90    |              |                |
| 1.30     |              |                | 4.30     |              |                | 9.00     |              |                | 14.00    |              |                |
| 1.35     |              |                | 4.40     |              |                | 9.10     |              |                | 14.10    |              |                |
| 1.40     | 18           | 40             | 4.50     | 67           | 105            | 9.20     | 133          | 175            | 14.25    | 128          | 186            |
| 1.45     |              |                | 4.60     |              |                | 9.30     |              |                | 14.50    |              |                |
| 1.50     |              |                | 4.70     |              |                | 9.40     |              |                | 14.75    |              |                |
| 1.55     |              |                | 4.80     |              |                | 9.50     |              |                | 15.00    |              |                |
| 1.60     | 20           | 43             | 4.90     | 71           | 110            | 9.60     | 139          | 181            | 15.25    | 129          | 187            |
| 1.65     |              |                | 5.00     |              |                | 9.70     |              |                | 15.50    |              |                |
| 1.70     |              |                | 5.10     |              |                | 9.80     |              |                | 15.75    |              |                |
|          |              |                | 5.20     |              |                | 9.90     |              |                | 16.00    |              |                |
|          |              |                | 5.30     | 52           | 86             | 10.00    |              |                |          |              |                |
|          |              |                |          |              |                | 10.10    |              |                |          |              |                |

All dimensions are in millimeters. Tolerances on diameters are given in [Table 14](#).

**Table 16. British Standard Parallel Shank Long Series Twist Drills — Standard Metric Sizes BS 328: Part 1:1959**

| Diameter | Flute Length | Overall Length | Diameter | Flute Length | Overall Length | Diameter | Flute Length | Overall Length |
|----------|--------------|----------------|----------|--------------|----------------|----------|--------------|----------------|
| 2.00     | 56           | 85             | 6.80     | 102          | 156            | 12.70    | 134          | 205            |
| 2.05     |              |                | 6.90     |              |                | 12.80    |              |                |
| 2.10     |              |                | 7.00     |              |                | 12.90    |              |                |
| 2.15     | 7.10         | 13.00          |          |              |                |          |              |                |
| 2.20     | 7.20         | 13.10          |          |              |                |          |              |                |
| 2.25     | 7.30         | 13.20          |          |              |                |          |              |                |
| 2.30     | 59           | 90             | 7.40     | 109          | 165            | 13.30    | 140          | 214            |
| 2.35     |              |                | 7.50     |              |                | 13.40    |              |                |
| 2.40     |              |                | 7.60     |              |                | 13.50    |              |                |
| 2.45     | 7.70         | 13.60          |          |              |                |          |              |                |
| 2.50     | 7.80         | 13.70          |          |              |                |          |              |                |
| 2.55     | 7.90         | 13.80          |          |              |                |          |              |                |
| 2.60     | 62           | 95             | 8.00     | 115          | 175            | 13.90    | 144          | 220            |
| 2.65     |              |                | 8.10     |              |                | 14.00    |              |                |
| 2.70     |              |                | 8.20     |              |                | 14.25    |              |                |
| 2.75     | 8.30         | 14.50          |          |              |                |          |              |                |
| 2.80     | 8.40         | 14.75          |          |              |                |          |              |                |
| 2.85     | 8.50         | 15.00          |          |              |                |          |              |                |
| 2.90     | 66           | 100            | 8.60     | 121          | 184            | 15.25    | 149          | 227            |
| 2.95     |              |                | 8.70     |              |                | 15.50    |              |                |
| 3.00     |              |                | 8.80     |              |                | 15.75    |              |                |
| 3.10     | 8.90         | 16.00          |          |              |                |          |              |                |
| 3.20     | 9.00         | 16.25          |          |              |                |          |              |                |
| 3.30     | 9.10         | 16.50          |          |              |                |          |              |                |
| 3.40     | 73           | 112            | 9.20     | 128          | 195            | 16.75    | 154          | 235            |
| 3.50     |              |                | 9.30     |              |                | 17.00    |              |                |
| 3.60     |              |                | 9.40     |              |                | 17.25    |              |                |
| 3.70     | 9.50         | 17.50          |          |              |                |          |              |                |
| 3.80     | 9.60         | 17.75          |          |              |                |          |              |                |
| 3.90     | 9.70         | 18.00          |          |              |                |          |              |                |
| 4.00     | 78           | 119            | 9.80     | 134          | 205            | 18.25    | 158          | 241            |
| 4.10     |              |                | 9.90     |              |                | 18.50    |              |                |
| 4.20     |              |                | 10.00    |              |                | 18.75    |              |                |
| 4.30     | 10.10        | 19.00          |          |              |                |          |              |                |
| 4.40     | 10.20        | 19.25          |          |              |                |          |              |                |
| 4.50     | 10.30        | 19.50          |          |              |                |          |              |                |
| 4.60     | 82           | 126            | 10.40    | 139          | 211            | 19.75    | 162          | 247            |
| 4.70     |              |                | 10.50    |              |                | 20.00    |              |                |
| 4.80     |              |                | 10.60    |              |                | 20.25    |              |                |
| 4.90     | 10.70        | 20.50          |          |              |                |          |              |                |
| 5.00     | 10.80        | 20.75          |          |              |                |          |              |                |
| 5.10     | 10.90        | 21.00          |          |              |                |          |              |                |
| 5.20     | 87           | 132            | 11.00    | 148          | 222            | 21.25    | 171          | 261            |
| 5.30     |              |                | 11.10    |              |                | 21.50    |              |                |
| 5.40     |              |                | 11.20    |              |                | 21.75    |              |                |
| 5.50     | 11.30        | 22.00          |          |              |                |          |              |                |
| 5.60     | 11.40        | 22.25          |          |              |                |          |              |                |
| 5.70     | 11.50        | 22.50          |          |              |                |          |              |                |
| 5.80     | 91           | 139            | 11.60    | 156          | 234            | 22.75    | 176          | 268            |
| 5.90     |              |                | 11.70    |              |                | 23.00    |              |                |
| 6.00     |              |                | 11.80    |              |                | 23.25    |              |                |
| 6.10     | 11.90        | 23.50          |          |              |                |          |              |                |
| 6.20     | 12.00        | 23.75          |          |              |                |          |              |                |
| 6.30     | 12.10        | 24.00          |          |              |                |          |              |                |
| 6.40     | 97           | 148            | 12.20    | 165          | 246            | 24.25    | 180          | 275            |
| 6.50     |              |                | 12.30    |              |                | 24.50    |              |                |
| 6.60     |              |                | 12.40    |              |                | 24.75    |              |                |
| 6.70     | 12.50        | 25.00          |          |              |                |          |              |                |
|          | 12.60        |                |          |              |                |          |              |                |

All dimensions are in millimeters. Tolerances on diameters are given in [Table 14](#).



**Table 17. British Standard Stub Drills — Metric Sizes BS 328: Part 1:1959**

| Diameter | Flute Length | Overall Length | Diameter | Flute Length | Overall Length | Diameter | Flute Length | Overall Length | Diameter | Flute Length | Overall Length |
|----------|--------------|----------------|----------|--------------|----------------|----------|--------------|----------------|----------|--------------|----------------|
| 0.50     | 3            | 20             | 5.00     |              |                | 9.50     | 40           | 84             | 14.00    | 54           | 107            |
| 0.80     | 5            | 24             | 5.20     | 26           | 62             | 9.80     |              |                | 14.50    | 56           | 111            |
| 1.00     | 6            | 26             | 5.50     |              |                | 10.00    | 43           | 89             | 15.00    |              |                |
| 1.20     | 8            | 30             | 5.80     | 28           | 66             | 10.20    |              |                | 15.50    | 58           | 115            |
| 1.50     | 9            | 32             | 6.00     |              |                | 10.50    |              |                | 16.00    |              |                |
| 1.80     | 11           | 36             |          |              |                |          |              |                |          |              |                |
| 2.00     | 12           | 38             | 6.20     | 31           | 70             | 10.80    |              |                | 16.50    | 60           | 119            |
| 2.20     | 13           | 40             | 6.50     |              |                | 11.00    |              |                | 17.00    |              |                |
| 2.50     | 14           | 43             | 6.80     |              |                | 11.20    | 47           | 95             | 17.50    | 62           | 123            |
| 2.80     |              |                | 7.00     | 34           | 74             | 11.50    |              |                | 18.00    |              |                |
| 3.00     | 16           | 46             | 7.20     |              |                | 11.80    |              |                | 18.50    | 64           | 127            |
| 3.20     | 18           | 49             | 7.50     |              |                | 12.00    |              |                | 19.00    |              |                |
| 3.50     | 20           | 52             | 7.80     |              |                | 12.20    |              |                | 19.50    | 66           | 131            |
|          |              |                | 8.00     | 37           | 79             | 12.50    |              |                | 20.00    | 66           | 131            |
| 3.80     |              |                | 8.20     |              |                | 12.80    | 51           | 102            | 21.00    | 68           | 136            |
| 4.00     | 22           | 55             | 8.50     |              |                | 13.00    |              |                | 22.00    | 70           | 141            |
| 4.20     |              |                | 8.80     |              |                | 13.20    |              |                | 23.00    | 72           | 146            |
| 4.50     | 24           | 58             | 9.00     | 40           | 84             | 13.50    |              |                | 24.00    | 75           | 151            |
| 4.80     | 26           | 62             | 9.20     |              |                | 13.80    | 54           | 107            | 25.00    |              |                |

All dimensions are given in millimeters. Tolerances on diameters are given in Table 14.

**Steels for Twist Drills.**—Twist drill steels need good toughness, abrasion resistance, and ability to resist softening due to heat generated by cutting. The amount of heat generated indicates the type of steel that should be used.

*Carbon Tool Steel* may be used where little heat is generated during drilling.

*High-Speed Steel* is preferred because of its combination of red hardness and wear resistance, which permit higher operating speeds and increased productivity. Optimum properties can be obtained by selection of alloy analysis and heat treatment.

*Cobalt High-Speed Steel* alloys have higher red hardness than standard high-speed steels, permitting drilling of materials such as heat-resistant alloys and materials with hardness greater than Rockwell 38 C. These high-speed drills can withstand cutting speeds beyond the range of conventional high-speed-steel drills and have superior resistance to abrasion but are not equal to tungsten-carbide tipped tools.

**Accuracy of Drilled Holes.**—Normally the diameter of drilled holes is not given a tolerance; the size of the hole is expected to be as close to the drill size as can be obtained.

The accuracy of holes drilled with a two-fluted twist drill is influenced by many factors, which include: the accuracy of the drill point; the size of the drill; length and shape of the chisel edge; whether or not a bushing is used to guide the drill; the work material; length of the drill; runout of the spindle and the chuck; rigidity of the machine tool, workpiece, and the setup; and also the cutting fluid used, if any.

The diameter of the drilled holes will be oversize in most materials. The table *Oversize Diameters in Drilling* on page 885 provides the results of tests reported by The United States Cutting Tool Institute in which the diameters of over 2800 holes drilled in steel and cast iron were measured. The values in this table indicate what might be expected under average shop conditions; however, when the drill point is accurately ground and the other machining conditions are correct, the resulting hole size is more likely to be between the mean and average minimum values given in this table. If the drill is ground and used incorrectly, holes that are even larger than the average maximum values can result.

## Oversize Diameters in Drilling

| Drill Dia.,<br>Inch | Amount Oversize, Inch |        |              | Drill Dia.,<br>Inch | Amount Oversize, Inch |       |              |
|---------------------|-----------------------|--------|--------------|---------------------|-----------------------|-------|--------------|
|                     | Average Max.          | Mean   | Average Min. |                     | Average Max.          | Mean  | Average Min. |
| $\frac{1}{16}$      | 0.002                 | 0.0015 | 0.001        | $\frac{1}{2}$       | 0.008                 | 0.005 | 0.003        |
| $\frac{1}{8}$       | 0.0045                | 0.003  | 0.001        | $\frac{3}{4}$       | 0.008                 | 0.005 | 0.003        |
| $\frac{1}{4}$       | 0.0065                | 0.004  | 0.0025       | 1                   | 0.009                 | 0.007 | 0.004        |

Courtesy of The United States Cutting Tool Institute

Some conditions will cause the drilled hole to be undersize. For example, holes drilled in light metals and in other materials having a high coefficient of thermal expansion such as plastics, may contract to a size that is smaller than the diameter of the drill as the material surrounding the hole is cooled after having been heated by the drilling. The elastic action of the material surrounding the hole may also cause the drilled hole to be undersize when drilling high strength materials with a drill that is dull at its outer corner.

The accuracy of the drill point has a great effect on the accuracy of the drilled hole. An inaccurately ground twist drill will produce holes that are excessively over-size. The drill point must be symmetrical; i.e., the point angles must be equal, as well as the lip lengths and the axial height of the lips. Any alterations to the lips or to the chisel edge, such as thinning the web, must be done carefully to preserve the symmetry of the drill point. Adequate relief should be provided behind the chisel edge to prevent heel drag. On conventionally ground drill points this relief can be estimated by the chisel edge angle.

When drilling a hole, as the drill point starts to enter the workpiece, the drill will be unstable and will tend to wander. Then as the body of the drill enters the hole the drill will tend to stabilize. The result of this action is a tendency to drill a bellmouth shape in the hole at the entrance and perhaps beyond. Factors contributing to bellmouthing are: an unsymmetrically ground drill point; a large chisel edge length; inadequate relief behind the chisel edge; runout of the spindle and the chuck; using a slender drill that will bend easily; and lack of rigidity of the machine tool, workpiece, or the setup. Correcting these conditions as required will reduce the tendency for bellmouthing to occur and improve the accuracy of the hole diameter and its straightness. Starting the hole with a short stiff drill, such as a center drill, will quickly stabilize the drill that follows and reduce or eliminate bellmouthing; this procedure should always be used when drilling in a lathe, where the work is rotating. Bellmouthing can also be eliminated almost entirely and the accuracy of the hole improved by using a close fitting drill jig bushing placed close to the workpiece. Although specific recommendations cannot be made, many cutting fluids will help to increase the accuracy of the diameters of drilled holes. Double margin twist drills, available in the smaller sizes, will drill a more accurate hole than conventional twist drills having only a single margin at the leading edge of the land. The second land, located on the trailing edge of each land, provides greater stability in the drill bushing and in the hole. These drills are especially useful in drilling intersecting off-center holes. Single and double margin step drills, also available in the smaller sizes, will produce very accurate drilled holes, which are usually less than 0.002 inch larger than the drill size.

**Counterboring.**—Counterboring (called spot-facing if the depth is shallow) is the enlargement of a previously formed hole. Counterbores for screw holes are generally made in sets. Each set contains three counterbores: one with the body of the size of the screw head and the pilot the size of the hole to admit the body of the screw; one with the body the size of the head of the screw and the pilot the size of the tap drill; and the third with the body the size of the body of the screw and the pilot the size of the tap drill. Counterbores are usually provided with helical flutes to provide positive effective rake on the cutting edges. The four flutes are so positioned that the end teeth cut ahead of center to provide a shearing action and eliminate chatter in the cut. Three designs are most common: solid, two-piece, and three-piece. Solid designs have the body, cutter, and pilot all in one piece. Two-piece designs have an integral shank and counterbore cutter, with an interchangeable pilot, and provide true concentricity of the cutter diameter with the shank, but allowing use of various

pilot diameters. Three-piece counterbores have separate holder, counterbore cutter, and pilot, so that a holder will take any size of counterbore cutter. Each counterbore cutter, in turn, can be fitted with any suitable size diameter of pilot. Counterbores for brass are fluted straight.

### Counterbores with Interchangeable Cutters and Guides

| No. of Holder | No. of Morse Taper Shank | Range of Cutter Diameters, A      | Range of Pilot Diameters, B      | Total Length, C | Length of Cutter Body, D | Length of Pilot, E | Dia. of Shank, F |
|---------------|--------------------------|-----------------------------------|----------------------------------|-----------------|--------------------------|--------------------|------------------|
| 1             | 1 or 2                   | $\frac{3}{4}$ - $1\frac{1}{16}$   | $\frac{1}{2}$ - $\frac{3}{4}$    | $7\frac{1}{4}$  | 1                        | $\frac{5}{8}$      | $\frac{3}{4}$    |
| 2             | 2 or 3                   | $1\frac{1}{16}$ - $1\frac{9}{16}$ | $1\frac{1}{16}$ - $1\frac{1}{8}$ | $9\frac{1}{2}$  | $1\frac{3}{8}$           | $\frac{7}{8}$      | $1\frac{1}{8}$   |
| 3             | 3 or 4                   | $1\frac{5}{8}$ - $2\frac{1}{16}$  | $\frac{7}{8}$ - $1\frac{5}{8}$   | $12\frac{1}{2}$ | $1\frac{3}{4}$           | $1\frac{1}{8}$     | $1\frac{5}{8}$   |
| 4             | 4 or 5                   | $2\frac{1}{8}$ - $3\frac{1}{2}$   | $1$ - $2\frac{1}{8}$             | 15              | $2\frac{1}{4}$           | $1\frac{3}{8}$     | $2\frac{1}{8}$   |

### Solid Counterbores with Integral Pilot

| Counterbore Diameters | Pilot Diameters |                 |                 | Straight Shank Diameter | Overall Length |                |
|-----------------------|-----------------|-----------------|-----------------|-------------------------|----------------|----------------|
|                       | Nominal         | $+\frac{1}{64}$ | $+\frac{1}{32}$ |                         | Short          | Long           |
| $\frac{13}{32}$       | $\frac{1}{4}$   | $\frac{17}{64}$ | $\frac{9}{32}$  | $\frac{3}{8}$           | $3\frac{1}{2}$ | $5\frac{1}{2}$ |
| $\frac{1}{2}$         | $\frac{5}{16}$  | $\frac{21}{64}$ | $\frac{11}{32}$ | $\frac{3}{8}$           | $3\frac{1}{2}$ | $5\frac{1}{2}$ |
| $\frac{19}{32}$       | $\frac{3}{8}$   | $\frac{25}{64}$ | $\frac{13}{32}$ | $\frac{1}{2}$           | 4              | 6              |
| $1\frac{1}{16}$       | $\frac{7}{16}$  | $\frac{29}{64}$ | $\frac{15}{32}$ | $\frac{1}{2}$           | 4              | 6              |
| $\frac{25}{32}$       | $\frac{1}{2}$   | $\frac{33}{64}$ | $\frac{17}{32}$ | $\frac{1}{2}$           | 5              | 7              |
| 0.110                 | 0.060           | 0.076           | ...             | $\frac{7}{64}$          | $2\frac{1}{2}$ | ...            |
| 0.133                 | 0.073           | 0.089           | ...             | $\frac{1}{8}$           | $2\frac{1}{2}$ | ...            |
| 0.155                 | 0.086           | 0.102           | ...             | $\frac{5}{32}$          | $2\frac{1}{2}$ | ...            |
| 0.176                 | 0.099           | 0.115           | ...             | $\frac{11}{64}$         | $2\frac{1}{2}$ | ...            |
| 0.198                 | 0.112           | 0.128           | ...             | $\frac{3}{16}$          | $2\frac{1}{2}$ | ...            |
| 0.220                 | 0.125           | 0.141           | ...             | $\frac{3}{16}$          | $2\frac{1}{2}$ | ...            |
| 0.241                 | 0.138           | 0.154           | ...             | $\frac{7}{32}$          | $2\frac{1}{2}$ | ...            |
| 0.285                 | 0.164           | 0.180           | ...             | $\frac{1}{4}$           | $2\frac{1}{2}$ | ...            |
| 0.327                 | 0.190           | 0.206           | ...             | $\frac{9}{32}$          | $2\frac{3}{4}$ | ...            |
| 0.372                 | 0.216           | 0.232           | ...             | $\frac{5}{16}$          | $2\frac{3}{4}$ | ...            |

All dimensions are in inches.

Small counterbores are often made with three flutes, but should then have the size plainly stamped on them before fluting, as they cannot afterwards be conveniently measured. The flutes should be deep enough to come below the surface of the pilot. The counterbore should be relieved on the end of the body only, and not on the cylindrical surface. To facilitate the relieving process, a small neck is turned between the guide and the body for clearance. The amount of clearance on the cutting edges is, for general work, from 4 to 5 degrees. The accompanying table gives dimensions for straight shank counterbores.

**Three Piece Counterbores.**—Data shown for the first two styles of counterbores are for straight shank designs. These tools are also available with taper shanks in most sizes. Sizes of taper shanks for cutter diameters of  $\frac{1}{4}$  to  $\frac{9}{16}$  in. are No. 1, for  $\frac{19}{32}$  to  $\frac{7}{8}$  in., No. 2; for  $\frac{15}{16}$  to  $1\frac{3}{8}$  in., No. 3; for  $1\frac{1}{2}$  to 2 in., No. 4; and for  $2\frac{1}{2}$  to  $2\frac{1}{2}$  in., No. 5.

**Counterbore Sizes for Hex-head Bolts and Nuts.**—Table 2, page 1531, shows the maximum socket wrench dimensions for standard  $\frac{1}{4}$ -,  $\frac{1}{2}$ - and  $\frac{3}{4}$ -inch drive socket sets. For a given socket size (nominal size equals the maximum width across the flats of nut or bolt head), the dimension *K* given in the table is the minimum counterbore diameter required to provide socket wrench clearance for access to the bolt or nut.

**Sintered Carbide Boring Tools.**—Industrial experience has shown that the shapes of tools used for boring operations need to be different from those of single-point tools ordinarily used for general applications such as lathe work. Accordingly, Section 5 of American National Standard ANSI B212.1-2002 gives standard sizes, styles and designations for four basic types of sintered carbide boring tools, namely: solid carbide square; carbide-tipped square; solid carbide round; and carbide-tipped round boring tools. In addition to these ready-to-use standard boring tools, solid carbide round and square unsharpened boring tool bits are provided.

*Style Designations for Carbide Boring Tools:* Table 1 shows designations used to specify the styles of American Standard sintered carbide boring tools. The first letter denotes solid (S) or tipped (T). The second letter denotes square (S) or round (R). The side cutting edge angle is denoted by a third letter (A through H) to complete the style designation. Solid square and round bits with the mounting surfaces ground but the cutting edges unsharpened (Table 3) are designated using the same system except that the third letter indicating the side cutting edge angle is omitted.

**Table 1. American National Standard Sintered Carbide Boring Tools — Style Designations ANSI B212.1-2002**

| Side Cutting Edge Angle <i>E</i> |             | Boring Tool Styles |                    |                  |                   |
|----------------------------------|-------------|--------------------|--------------------|------------------|-------------------|
| Degrees                          | Designation | Solid Square (SS)  | Tipped Square (TS) | Solid Round (SR) | Tipped Round (TR) |
| 0                                | A           |                    | TSA                |                  |                   |
| 10                               | B           |                    | TSB                |                  |                   |
| 30                               | C           | SSC                | TSC                | SRC              | TRC               |
| 40                               | D           |                    | TSD                |                  |                   |
| 45                               | E           | SSE                | TSE                | SRE              | TRE               |
| 55                               | F           |                    | TSF                |                  |                   |
| 90 (0° Rake)                     | G           |                    |                    |                  | TRG               |
| 90 (10° Rake)                    | H           |                    |                    |                  | TRH               |

*Size Designation of Carbide Boring Tools:* Specific sizes of boring tools are identified by the addition of numbers after the style designation. The first number denotes the diameter or square size in number of  $\frac{1}{32}$ nds for types SS and SR and in number of  $\frac{1}{16}$ ths for types TS and TR. The second number denotes length in number of 1/8ths for types SS and SR. For styles TRG and TRH, a letter "U" after the number denotes a semi-finished tool (cutting edges unsharpened). Complete designations for the various standard sizes of carbide boring tools are given in Tables 2 through 7. In the diagrams in the tables, angles shown without tolerance are  $\pm 1^\circ$ .

*Examples of Tool Designation:* The designation TSC-8 indicates: a carbide-tipped tool (T); square cross-section (S); 30-degree side cutting edge angle (C); and  $\frac{8}{16}$  or  $\frac{1}{2}$  inch square size (8).

The designation SRE-66 indicates: a solid carbide tool (S); round cross-section (R); 45 degree side cutting edge angle (E);  $\frac{6}{32}$  or  $\frac{3}{16}$  inch diameter (6); and  $\frac{6}{8}$  or  $\frac{3}{4}$  inch long (6).

The designation SS-610 indicates: a solid carbide tool (S); square cross-section (S);  $\frac{6}{32}$  or  $\frac{3}{16}$  inch square size (6);  $\frac{10}{8}$  or  $1\frac{1}{4}$  inches long (10).

It should be noted in this last example that the absence of a third letter (from A to H) indicates that the tool has its mounting surfaces ground but that the cutting edges are unsharpened.

**Table 2. ANSI Carbide-Tipped Round General-Purpose Square-End Boring Tools Style TRG with 0° Rake and Style TRH with 10° Rake ANSI B212.1-2002**

| Tool Designation |                            | Shank Dimensions, Inches |          |                  |               |                  | Rake Angle Deg. | Tip No. | Tip Dimensions, Inches |      |     |
|------------------|----------------------------|--------------------------|----------|------------------|---------------|------------------|-----------------|---------|------------------------|------|-----|
| Finished         | Semi-finished <sup>a</sup> | Dia. D                   | Length C | Dim. Over Flat B | Nose Height H | Set-back M (Min) |                 |         | T                      | W    | L   |
| TRG-5            | TRG-5U                     | 5/16                     | 1 1/2    | 1/64             | 3/16          | 3/16             | 0               | 1025    | 1/16                   | 1/4  | 1/4 |
| TRH-5            | TRH-5U                     | 5/16                     | 1 1/2    | ±.005            | 7/32          | 3/16             | 10              |         |                        |      |     |
| TRG-6            | TRG-6U                     | 3/8                      | 1 3/4    | 1/32             | 7/32          | 3/16             | 0               | 1030    | 1/16                   | 5/16 | 1/4 |
| TRH-6            | TRH-6U                     | 3/8                      | 1 3/4    | ±.010            | 1/4           | 3/16             | 10              |         |                        |      |     |
| TRG-7            | TRG-7U                     | 7/16                     | 2 1/2    | 1/32             | 1/4           | 3/16             | 0               | 1080    | 3/32                   | 5/16 | 3/8 |
| TRH-7            | TRH-7U                     | 7/16                     | 2 1/2    | ±.010            | 5/16          | 3/16             | 10              |         |                        |      |     |
| TRG-8            | TRG-8U                     | 1/2                      | 2 1/2    | 1/32             | 9/32          | 1/4              | 0               | 1090    | 3/32                   | 3/8  | 3/8 |
| TRH-8            | TRH-8U                     | 1/2                      | 2 1/2    | ±.010            | 11/32         | 1/4              | 10              |         |                        |      |     |

<sup>a</sup> Semifinished tool will be without Flat (B) and carbide unground on the end.

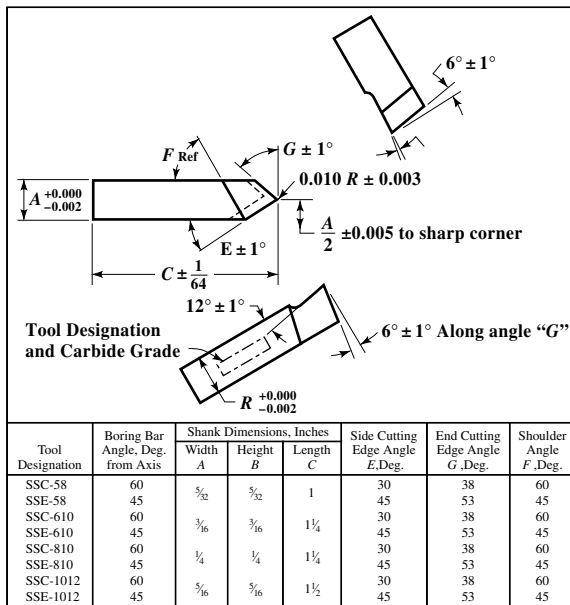
**Table 3. Solid Carbide Square and Round Boring Tool Bits**

| Square Bits      |      |      | Round Bits |                  |      |     |                  |      |       |                  |      |       |
|------------------|------|------|------------|------------------|------|-----|------------------|------|-------|------------------|------|-------|
| Tool Designation | A    | B    | C          | Tool Designation | D    | C   | Tool Designation | D    | C     | Tool Designation | D    | C     |
| SS-58            | 5/32 | 5/32 | 1          | SR-33            | 3/32 | 3/8 | SR-55            | 5/32 | 5/8   | SR-88            | 1/4  | 1     |
| SS-610           | 3/16 | 3/16 | 1 1/4      | SR-34            | 3/32 | 1/2 | SR-64            | 3/16 | 1/2   | SR-810           | 1/4  | 1 1/4 |
| SS-810           | 1/4  | 1/4  | 1 1/4      | SR-44            | 1/8  | 1/2 | SR-66            | 3/16 | 3/4   | SR-1010          | 5/16 | 1 1/4 |
| SS-1012          | 5/16 | 5/16 | 1 1/2      | SR-46            | 1/8  | 3/4 | SR-69            | 3/16 | 1 1/8 | ...              | ...  | ...   |
| SS-1214          | 3/8  | 3/8  | 1 3/4      | SR-48            | 1/8  | 1   | SR-77            | 7/32 | 7/8   | ...              | ...  | ...   |

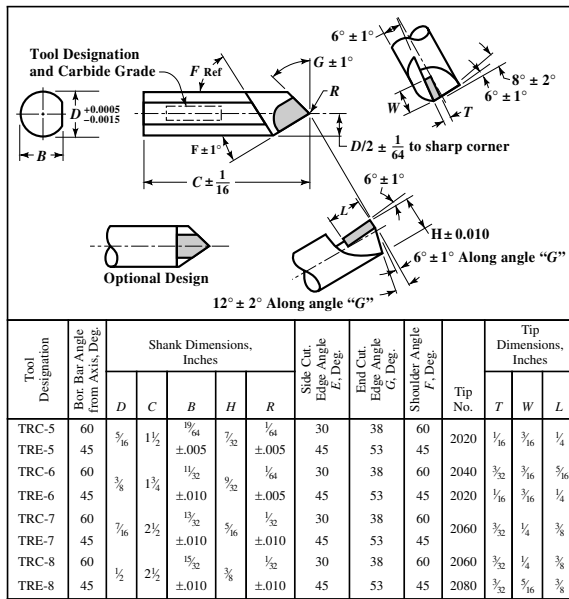
All dimensions are in inches.

Tolerance on Length: Through 1 inch, + 1/32, - 0; over 1 inch, + 1/16, - 0.

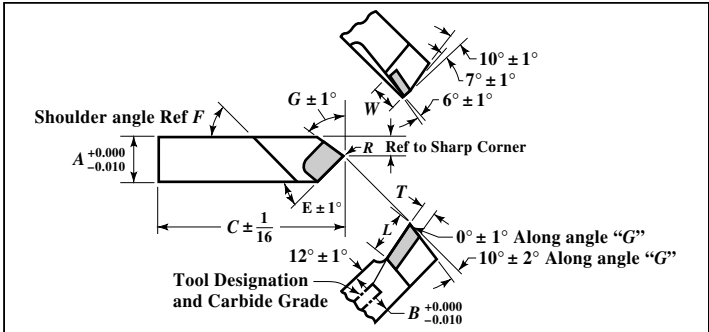
**Table 4. ANSI Solid Carbide Square Boring Tools**  
**Style SSC for 60° Boring Bar and Style SSE for 45° Boring Bar**  
 ANSI B212.1-2002



**Table 5. ANSI Carbide-Tipped Round Boring Tools**  
**Style TRC for 60° Boring Bar and Style TRE for 45° Boring Bar**  
 ANSI B212.1-2002

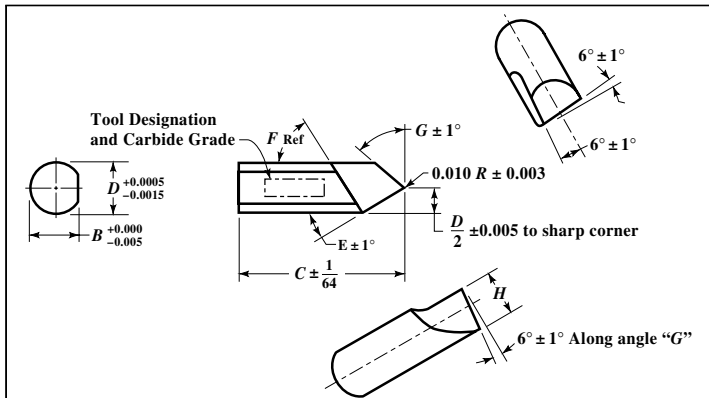


**Table 6. ANSI Carbide-Tipped Square Boring Tools — ANSI B212.1-2002**  
**Styles TSA and TSB for 90° Boring Bar, Styles TSC and TSD for 60° Boring Bar,**  
**and Styles TSE and TSF for 45° Boring Bar**



| Tool Designation | Bor. Bar Angle from Axis, Deg. | Shank Dimensions, Inches |      |       |                    | Side Cut. Edge Angle E, Deg. | End Cut. Edge Angle G, Deg. | Shoulder Angle F, Deg. | Tip No. | Tip Dimensions, Inches |      |      |
|------------------|--------------------------------|--------------------------|------|-------|--------------------|------------------------------|-----------------------------|------------------------|---------|------------------------|------|------|
|                  |                                | A                        | B    | C     | R                  |                              |                             |                        |         | T                      | W    | L    |
| TSA-5            | 90                             | 5/16                     | 5/16 | 1 1/2 | 1/64<br>±<br>0.005 | 0                            | 8                           | 90                     | 2040    | 3/32                   | 3/16 | 5/16 |
| TSB-5            | 90                             | 5/16                     | 5/16 | 1 1/2 |                    | 10                           | 8                           | 90                     | 2040    | 3/32                   | 3/16 | 5/16 |
| TSC-5            | 60                             | 5/16                     | 5/16 | 1 1/2 |                    | 30                           | 38                          | 60                     | 2040    | 3/32                   | 3/16 | 5/16 |
| TSD-5            | 60                             | 5/16                     | 5/16 | 1 1/2 |                    | 40                           | 38                          | 60                     | 2040    | 3/32                   | 3/16 | 5/16 |
| TSE-5            | 45                             | 5/16                     | 5/16 | 1 1/2 |                    | 45                           | 53                          | 45                     | 2040    | 3/32                   | 3/16 | 5/16 |
| TSF-5            | 45                             | 5/16                     | 5/16 | 1 1/2 |                    | 55                           | 53                          | 45                     | 2040    | 3/32                   | 3/16 | 5/16 |
| TSA-6            | 90                             | 3/8                      | 3/8  | 1 3/4 | 1/64<br>±<br>0.005 | 0                            | 8                           | 90                     | 2040    | 3/32                   | 3/16 | 5/16 |
| TSB-6            | 90                             | 3/8                      | 3/8  | 1 3/4 |                    | 10                           | 8                           | 90                     | 2040    | 3/32                   | 3/16 | 5/16 |
| TSC-6            | 60                             | 3/8                      | 3/8  | 1 3/4 |                    | 30                           | 38                          | 60                     | 2040    | 3/32                   | 3/16 | 5/16 |
| TSD-6            | 60                             | 3/8                      | 3/8  | 1 3/4 |                    | 40                           | 38                          | 60                     | 2040    | 3/32                   | 3/16 | 5/16 |
| TSE-6            | 45                             | 3/8                      | 3/8  | 1 3/4 |                    | 45                           | 53                          | 45                     | 2040    | 3/32                   | 3/16 | 5/16 |
| TSF-6            | 45                             | 3/8                      | 3/8  | 1 3/4 |                    | 55                           | 53                          | 45                     | 2040    | 3/32                   | 3/16 | 5/16 |
| TSA-7            | 90                             | 7/16                     | 7/16 | 2 1/2 | 1/32<br>±<br>0.010 | 0                            | 8                           | 90                     | 2060    | 3/32                   | 1/4  | 3/8  |
| TSB-7            | 90                             | 7/16                     | 7/16 | 2 1/2 |                    | 10                           | 8                           | 90                     | 2060    | 3/32                   | 1/4  | 3/8  |
| TSC-7            | 60                             | 7/16                     | 7/16 | 2 1/2 |                    | 30                           | 38                          | 60                     | 2060    | 3/32                   | 1/4  | 3/8  |
| TSD-7            | 60                             | 7/16                     | 7/16 | 2 1/2 |                    | 40                           | 38                          | 60                     | 2060    | 3/32                   | 1/4  | 3/8  |
| TSE-7            | 45                             | 7/16                     | 7/16 | 2 1/2 |                    | 45                           | 53                          | 45                     | 2060    | 3/32                   | 1/4  | 3/8  |
| TSF-7            | 45                             | 7/16                     | 7/16 | 2 1/2 |                    | 55                           | 53                          | 45                     | 2060    | 3/32                   | 1/4  | 3/8  |
| TSA-8            | 90                             | 1/2                      | 1/2  | 2 1/2 | 1/32<br>±<br>0.010 | 0                            | 8                           | 90                     | 2150    | 1/8                    | 5/16 | 7/16 |
| TSB-8            | 90                             | 1/2                      | 1/2  | 2 1/2 |                    | 10                           | 8                           | 90                     | 2150    | 1/8                    | 5/16 | 7/16 |
| TSC-8            | 60                             | 1/2                      | 1/2  | 2 1/2 |                    | 30                           | 38                          | 60                     | 2150    | 1/8                    | 5/16 | 7/16 |
| TSD-8            | 60                             | 1/2                      | 1/2  | 2 1/2 |                    | 40                           | 38                          | 60                     | 2150    | 1/8                    | 5/16 | 7/16 |
| TSE-8            | 45                             | 1/2                      | 1/2  | 2 1/2 |                    | 45                           | 53                          | 45                     | 2150    | 1/8                    | 5/16 | 7/16 |
| TSF-8            | 45                             | 1/2                      | 1/2  | 2 1/2 |                    | 55                           | 53                          | 45                     | 2150    | 1/8                    | 5/16 | 7/16 |
| TSA-10           | 90                             | 3/8                      | 3/8  | 3     | 1/32<br>±<br>0.010 | 0                            | 8                           | 90                     | 2220    | 5/32                   | 3/8  | 9/16 |
| TSB-10           | 90                             | 3/8                      | 3/8  | 3     |                    | 10                           | 8                           | 90                     | 2220    | 5/32                   | 3/8  | 9/16 |
| TSC-10           | 60                             | 3/8                      | 3/8  | 3     |                    | 30                           | 38                          | 60                     | 2220    | 5/32                   | 3/8  | 9/16 |
| TSD-10           | 60                             | 3/8                      | 3/8  | 3     |                    | 40                           | 38                          | 60                     | 2220    | 5/32                   | 3/8  | 9/16 |
| TSE-10           | 45                             | 3/8                      | 3/8  | 3     |                    | 45                           | 53                          | 45                     | 2220    | 5/32                   | 3/8  | 9/16 |
| TSF-10           | 45                             | 3/8                      | 3/8  | 3     |                    | 55                           | 53                          | 45                     | 2220    | 5/32                   | 3/8  | 9/16 |
| TSA-12           | 90                             | 3/4                      | 3/4  | 3 1/2 | 1/32<br>±<br>0.010 | 0                            | 8                           | 90                     | 2300    | 3/16                   | 7/16 | 5/8  |
| TSB-12           | 90                             | 3/4                      | 3/4  | 3 1/2 |                    | 10                           | 8                           | 90                     | 2300    | 3/16                   | 7/16 | 5/8  |
| TSC-12           | 60                             | 3/4                      | 3/4  | 3 1/2 |                    | 30                           | 38                          | 60                     | 2300    | 3/16                   | 7/16 | 5/8  |
| TSD-12           | 60                             | 3/4                      | 3/4  | 3 1/2 |                    | 40                           | 38                          | 60                     | 2300    | 3/16                   | 7/16 | 5/8  |
| TSE-12           | 45                             | 3/4                      | 3/4  | 3 1/2 |                    | 45                           | 53                          | 45                     | 2300    | 3/16                   | 7/16 | 5/8  |
| TSF-12           | 45                             | 3/4                      | 3/4  | 3 1/2 |                    | 55                           | 53                          | 45                     | 2300    | 3/16                   | 7/16 | 5/8  |

**Table 7. ANSI Solid Carbide Round Boring Tools — ANSI B212.1-2002 Style SRC for 60° Boring Bar and Style SRE for 45° Boring Bar**



| Tool Designation | Bor. Bar Angle from Axis, Deg. | Shank Dimensions, Inches |                |                  |               | Side Cut. Edge Angle E, Deg. | End Cut. Edge Angle G, Deg. | Shoulder Angle F, Deg. |    |
|------------------|--------------------------------|--------------------------|----------------|------------------|---------------|------------------------------|-----------------------------|------------------------|----|
|                  |                                | Dia. D                   | Length C       | Dim. Over Flat B | Nose Height H |                              |                             |                        |    |
| SRC-33           | 60                             | $\frac{3}{32}$           | $\frac{3}{8}$  | 0.088            | 0.070         | [+0.000<br>-0.005]           | 30                          | 38                     | 60 |
| SRE-33           | 45                             | $\frac{3}{32}$           | $\frac{3}{8}$  | 0.088            | 0.070         |                              | 45                          | 53                     | 45 |
| SRC-44           | 60                             | $\frac{1}{8}$            | $\frac{1}{2}$  | 0.118            | 0.094         | [+0.000<br>-0.005]           | 30                          | 38                     | 60 |
| SRE-44           | 45                             | $\frac{1}{8}$            | $\frac{1}{2}$  | 0.118            | 0.094         |                              | 45                          | 53                     | 45 |
| SRC-55           | 60                             | $\frac{5}{32}$           | $\frac{5}{8}$  | 0.149            | 0.117         | ±0.005                       | 30                          | 38                     | 60 |
| SRE-55           | 45                             | $\frac{5}{32}$           | $\frac{5}{8}$  | 0.149            | 0.117         | ±0.005                       | 45                          | 53                     | 45 |
| SRC-66           | 60                             | $\frac{3}{16}$           | $\frac{3}{4}$  | 0.177            | 0.140         | ±0.005                       | 30                          | 38                     | 60 |
| SRE-66           | 45                             | $\frac{3}{16}$           | $\frac{3}{4}$  | 0.177            | 0.140         | ±0.005                       | 45                          | 53                     | 45 |
| SRC-88           | 60                             | $\frac{1}{4}$            | 1              | 0.240            | 0.187         | ±0.005                       | 30                          | 38                     | 60 |
| SRE-88           | 45                             | $\frac{1}{4}$            | 1              | 0.240            | 0.187         | ±0.005                       | 45                          | 53                     | 45 |
| SRC-1010         | 60                             | $\frac{5}{16}$           | $1\frac{1}{4}$ | 0.300            | 0.235         | ±0.005                       | 30                          | 38                     | 60 |
| SRE-1010         | 45                             | $\frac{5}{16}$           | $1\frac{1}{4}$ | 0.300            | 0.235         | ±0.005                       | 45                          | 53                     | 45 |

**Boring Machines, Origin.**—The first boring machine was built by John Wilkinson, in 1775. Smeaton had built one in 1769 which had a large rotary head, with inserted cutters, carried on the end of a light, overhanging shaft. The cylinder to be bored was fed forward against the cutter on a rude carriage, running on a track laid in the floor. The cutter head followed the inaccuracies of the bore, doing little more than to smooth out local roughness of the surface. Watt's first steam cylinders were bored on this machine and he complained that one, 18 inches in diameter, was  $\frac{3}{8}$  inch out of true. Wilkinson thought of the expedient, which had escaped both Smeaton and Watt, of extending the boring-bar completely through the cylinder and giving it an out-board bearing, at the same time making it much larger and stiffer. With this machine cylinders 57 inches in diameter were bored which were within  $\frac{1}{16}$  inch of true. Its importance can hardly be overestimated as it insured the commercial success of Watt's steam engine which, up to that time, had not passed the experimental stage.



## TAPS AND THREADING DIES

## Taps

General dimensions and tap markings given in the ASME B94.9 Standard for straight fluted taps, spiral pointed taps, spiral pointed only taps, spiral fluted taps, fast spiral fluted taps, thread forming taps, pulley taps, nut taps, and pipe taps are shown in the tables on the pages that follow. This Standard also gives the thread limits for taps with cut threads and ground threads. The thread limits for cut thread and ground thread taps for screw threads are given in [Tables 1](#) through [5](#) and [Tables 4a](#) and [4b](#); thread limits for cut thread and ground thread taps for pipe threads are given in [Tables 6a](#) through [7c](#). Taps recommended for various classes of Unified screw threads are given in [Tables 8a](#) through [11](#) in numbered sizes and [Table 9](#) for nuts in fractional sizes.

**Types of Taps.**—Taps included in ASME B94.9 are categorized either by the style of fluting or by the specific application for which the taps are designed. The following types 1 through 6 are generally short in length, and were originally called “Hand Taps” but this design is generally used in machine applications. The remaining types have special lengths, which are detailed in the tables.

The thread size specifications for these types may be fractional or machine screw inch sizes, or metric sizes. The thread form may be ground or cut (unground) as further defined in each table. Additionally, the cutting chamfer on the thread may be Bottoming (B), Plug (P), or Taper (T).

(1) *Straight Flute Taps:* These taps have straight flutes of a number specified as either standard or optional, and are for general purpose applications.

(2) *Spiral Pointed Taps:* These taps have straight flutes and the cutting face of the first few threads is ground at an angle to force the chips ahead and prevent clogging in the flutes.

(3) *Spiral Pointed Only Taps:* These taps are made with the spiral point feature only without longitudinal flutes. These taps are especially suitable for tapping thin materials.

(4) *Spiral Fluted Taps:* These taps have right-hand helical flutes with a helix angle of 25 to 35 deg. These features are designed to help draw chips from the hole or to bridge a keyway.

(5) *Fast Spiral Fluted Taps:* These taps are similar to spiral fluted taps, except the helix angle is from 45 to 60 deg.

(6) *Thread Forming Taps:* These taps are fluteless except as optionally designed with one or more lubricating grooves. The thread form on the tap is lobed, so that there are a finite number of points contacting the work thread form. The tap does not cut, but forms the thread by extrusion.

(7) *Pulley Taps:* These taps have shanks that are extended in length by a standard amount for use where added reach is required. The shank is the same nominal diameter as the thread.

(8) *Nut Taps:* These taps are designed for tapping nuts on a low-production basis. Approximately one-half to three-quarters of the threaded portion has a chamfered section, which distributes the cutting over many teeth and facilitates entering the hole to be tapped. The length overall, the length of the thread, and the length of the shank are appreciably longer than on a regular straight fluted tap. Nut taps have been removed from ASME B94.9 but are retained for reference.

(9) *Pipe Taps:* These taps are used to produce standard straight or tapered pipe threads.

**Definitions of Tap Terms.**—The definitions that follow are taken from ASME B94.9 but include only the more important terms. Some tap terms are the same as screw thread terms; therefore, see *Definitions of Screw Threads* starting on page [1727](#).

*Back Taper:* A gradual decrease in the diameter of the thread form on a tap from the chamfered end of the land toward the back, which creates a slight radial relief in the threads.

**Base of Thread:** Coincides with the cylindrical or conical surface from which the thread projects.

**Chamfer:** Tapering of the threads at the front end of each land or chaser of a tap by cutting away and relieving the crest of the first few teeth to distribute the cutting action over several teeth.

**Chamfer Angle:** Angle formed between the chamfer and the axis of the tap measured in an axial plane at the cutting edge.

**Chamfer Relief Angle:** Complement of the angle formed between a tangent to the relieved surface at the cutting edge and a radial line to the same point on the cutting edge.

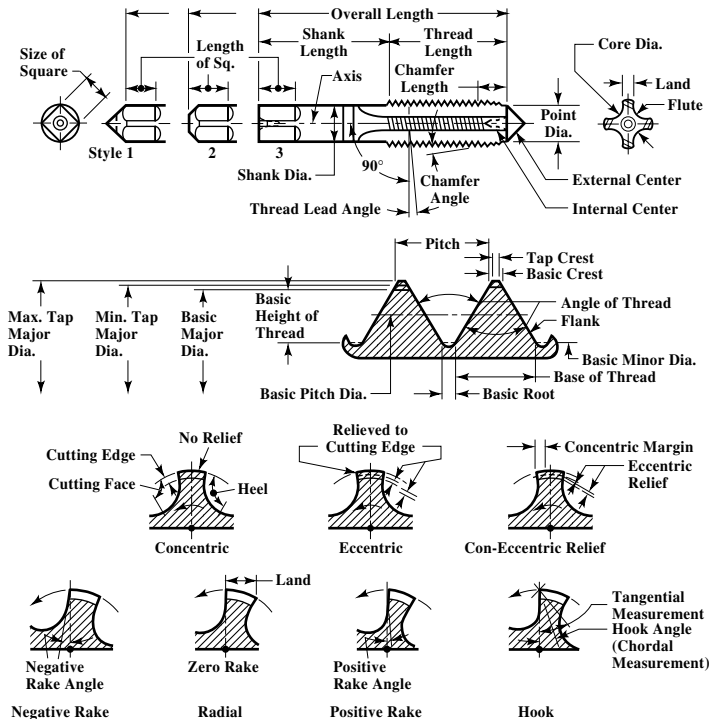
**Core Diameter:** Diameter of a circle which is tangent to the bottom of the flutes at a given point on the axis.

**First Full Thread:** First full thread on the cutting edge back of the chamfer. It is at this point that rake, hook, and thread elements are measured.

**Crest Clearance:** Radial distance between the root of the internal thread and the crest of the external thread of the coaxially assembled design forms of mating threads.

**Class of Thread:** Designation of the class that determines the specification of the size, allowance, and tolerance to which a given threaded product is to be manufactured. It is not applicable to the tools used for threading.

Tap Terms



*Flank Angle:* Angle between the individual flank and the perpendicular to the axis of the thread, measured in an axial plane. A flank angle of a symmetrical thread is commonly termed the "half angle of thread."

*Flank—Leading:* 1) Flank of a thread facing toward the chamfered end of a threading tool; and 2) The leading flank of a thread is the one which, when the thread is about to be assembled with a mating thread, faces the mating thread.

*Flank—Trailing:* The trailing flank of a thread is the one opposite the leading flank.

*Flutes:* Longitudinal channels formed in a tap to create cutting edges on the thread profile and to provide chip spaces and cutting fluid passages. On a parallel or straight thread tap they may be straight, angular or helical; on a taper thread tap they may be straight, angular or spiral.

*Flute-Angular:* A flute lying in a plane intersecting the tool axis at an angle.

*Flute-Helical:* A flute with uniform axial lead and constant helix in a helical path around the axis of a cylindrical tap.

*Flute-Spiral:* A flute with uniform axial lead in a spiral path around the axis of a conical tap.

*Flute Lead Angle:* Angle at which a helical or spiral cutting edge at a given point makes with an axial plane through the same point.

*Flute-Straight:* A flute which forms a cutting edge lying in an axial plane.

*Front Taper:* A gradual increase in the diameter of the thread form on a tap from the leading end of the tool toward the back.

*Heel:* Edge of the land opposite the cutting edge.

*Hook Angle:* Inclination of a concave cutting face, usually specified either as Chordal Hook or Tangential Hook.

*Hook-Chordal Angle:* Angle between the chord passing through the root and crest of a thread form at the cutting face, and a radial line through the crest at the cutting edge.

*Hook-Tangential Angle:* Angle between a line tangent to a hook cutting face at the cutting edge and a radial line to the same point.

*Interrupted Thread Tap:* A tap having an odd number of lands with alternate teeth in the thread helix removed. In some designs alternate teeth are removed only for a portion of the thread length.

*Land:* One of the threaded sections between the flutes of a tap.

*Lead:* Distance a screw thread advances axially in one complete turn.

*Lead Error:* Deviation from prescribed limits.

*Lead Deviation:* Deviation from the basic nominal lead.

*Progressive Lead Deviation:* (1) On a straight thread the deviation from a true helix where the thread helix advances uniformly. (2) On a taper thread the deviation from a true spiral where the thread spiral advances uniformly.

*Length of Thread:* The length of the thread of the tap includes the chamfered threads and the full threads but does not include an external center. It is indicated by the letter "B" in the illustrations at the heads of the tables.

*Limits:* The limits of size are the applicable maximum and minimum sizes.

*Major Diameter:* On a straight thread the major diameter is that of the major cylinder. On a taper thread the major diameter at a given position on the thread axis is that of the major cone at that position.

*Minor Diameter:* On a straight thread the minor diameter is that of the minor cylinder. On a taper thread the minor diameter at a given position on the thread axis is that of the minor cone at that position.

*Pitch Diameter (Simple Effective Diameter):* On a straight thread, the pitch diameter is the diameter of the imaginary coaxial cylinder, the surface of which would pass through the thread profiles at such points as to make the width of the groove equal to one-half the basic pitch. On a perfect thread this coincidence occurs at the point where the widths of the thread and groove are equal. On a taper thread, the pitch diameter at a given position on the thread axis is the diameter of the pitch cone at that position.

*Point Diameter:* Diameter at the cutting edge of the leading end of the chamfered section.

*Rake:* Angular relationship of the straight cutting face of a tooth with respect to a radial line through the crest of the tooth at the cutting edge. Positive rake means that the crest of the cutting face is angularly ahead of the balance of the cutting face of the tooth. Negative rake means that the crest of the cutting face is angularly behind the balance of the cutting face of the tooth. Zero rake means that the cutting face is directly on a radial line.

*Relief:* Removal of metal behind the cutting edge to provide clearance between the part being threaded and the threaded land.

*Relief-Center:* Clearance produced on a portion of the tap land by reducing the diameter of the entire thread form between cutting edge and heel.

*Relief-Chamfer:* Gradual decrease in land height from cutting edge to heel on the chamfered portion of the land on a tap to provide radial clearance for the cutting edge.

*Relief-Con-eccentric Thread:* Radial relief in the thread form starting back of a concentric margin.

*Relief-Double Eccentric Thread:* Combination of a slight radial relief in the thread form starting at the cutting edge and continuing for a portion of the land width, and a greater radial relief for the balance of the land.

*Relief-Eccentric Thread:* Radial relief in the thread form starting at the cutting edge and continuing to the heel.

*Relief-Flatted Land:* Clearance produced on a portion of the tap land by truncating the thread between cutting edge and heel.

*Relief-Grooved Land:* Clearance produced on a tap land by forming a longitudinal groove in the center of the land.

*Relief-Radial:* Clearance produced by removal of metal from behind the cutting edge. Taps should have the chamfer relieved and should have back taper, but may or may not have relief in the angle and on the major diameter of the threads. When the thread angle is relieved, starting at the cutting edge and continuing to the heel, the tap is said to have "eccentric" relief. If the thread angle is relieved back of a concentric margin (usually one-third of land width), the tap is said to have "con-eccentric" relief.

*Size-Actual:* Measured size of an element on an individual part.

*Size-Basic:* That size from which the limits of size are derived by the application of allowances and tolerances.

*Size-Functional:* The functional diameter of an external or internal thread is the pitch diameter of the enveloping thread of perfect pitch, lead and flank angles, having full depth of engagement but clear at crests and roots, and of a specified length of engagement. It may be derived by adding to the pitch diameter in an external thread, or subtracting from the pitch diameter in an internal thread, the cumulative effects of deviations from specified profile, including variations in lead and flank angle over a specified length of engagement. The effects of taper, out-of-roundness, and surface defects may be positive or negative on either external or internal threads.

*Size-Nominal:* Designation used for the purpose of general identification.

*Spiral Flute:* See *Flutes*.

*Spiral Point:* Angular fluting in the cutting face of the land at the chamfered end. It is formed at an angle with respect to the tap axis of opposite hand to that of rotation. Its length is usually greater than the chamfer length and its angle with respect to the tap axis is usually made great enough to direct the chips ahead of the tap. The tap may or may not have longitudinal flutes.

*Thread Lead Angle:* On a straight thread, the lead angle is the angle made by the helix of the thread at the pitch line with a plane perpendicular to the axis. On a taper thread, the lead angle at a given axial position is the angle made by the conical spiral of the thread, with the plane perpendicular to the axis, at the pitch line.

## TAPS AND THREADING DIES

**Table 1. ANSI Standard Fraction-Size Taps — Cut Thread Limits**  
ASME B94.9-1999

| Tap Size | Threads per Inch |        |        | Major Diameter |        |        | Pitch Diameter |        |        |
|----------|------------------|--------|--------|----------------|--------|--------|----------------|--------|--------|
|          | NC UNC           | NF UNF | NS UNS | Basic          | Min.   | Max.   | Basic          | Min.   | Max.   |
| 1/8      | ...              | ...    | 40     | 0.1250         | 0.1266 | 0.1286 | 0.1088         | 0.1090 | 0.1105 |
| 5/32     | ...              | ...    | 32     | 0.1563         | 0.1585 | 0.1605 | 0.1360         | 0.1365 | 0.1380 |
| 3/16     | ...              | ...    | 24     | 0.1875         | 0.1903 | 0.1923 | 0.1604         | 0.1609 | 0.1624 |
| 3/16     | ...              | ...    | 32     | 0.1875         | 0.1897 | 0.1917 | 0.1672         | 0.1677 | 0.1692 |
| 1/4      | 20               | ...    | ...    | 0.2500         | 0.2532 | 0.2557 | 0.2175         | 0.2180 | 0.2200 |
| 1/4      | ...              | 28     | ...    | 0.2500         | 0.2524 | 0.2549 | 0.2268         | 0.2273 | 0.2288 |
| 5/16     | 18               | ...    | ...    | 0.3125         | 0.3160 | 0.3185 | 0.2764         | 0.2769 | 0.2789 |
| 5/16     | ...              | 24     | ...    | 0.3125         | 0.3153 | 0.3178 | 0.2854         | 0.2859 | 0.2874 |
| 3/8      | 16               | ...    | ...    | 0.3750         | 0.3789 | 0.3814 | 0.3344         | 0.3349 | 0.3369 |
| 3/8      | ...              | 24     | ...    | 0.3750         | 0.3778 | 0.3803 | 0.3479         | 0.3484 | 0.3499 |
| 7/16     | 14               | ...    | ...    | 0.4375         | 0.4419 | 0.4449 | 0.3911         | 0.3916 | 0.3941 |
| 7/16     | ...              | 20     | ...    | 0.4375         | 0.4407 | 0.4437 | 0.4050         | 0.4055 | 0.4075 |
| 1/2      | 13               | ...    | ...    | 0.5000         | 0.5047 | 0.5077 | 0.4500         | 0.4505 | 0.4530 |
| 1/2      | ...              | 20     | ...    | 0.5000         | 0.5032 | 0.5062 | 0.4675         | 0.4680 | 0.4700 |
| 9/16     | 12               | ...    | ...    | 0.5625         | 0.5675 | 0.5705 | 0.5084         | 0.5089 | 0.5114 |
| 9/16     | ...              | 18     | ...    | 0.5625         | 0.5660 | 0.5690 | 0.5264         | 0.5269 | 0.5289 |
| 5/8      | 11               | ...    | ...    | 0.6250         | 0.6304 | 0.6334 | 0.5660         | 0.5665 | 0.5690 |
| 5/8      | ...              | 18     | ...    | 0.6250         | 0.6285 | 0.6315 | 0.5889         | 0.5894 | 0.5914 |
| 3/4      | 10               | ...    | ...    | 0.7500         | 0.7559 | 0.7599 | 0.6850         | 0.6855 | 0.6885 |
| 3/4      | ...              | 16     | ...    | 0.7500         | 0.7539 | 0.7579 | 0.7094         | 0.7099 | 0.7124 |
| 7/8      | 9                | ...    | ...    | 0.8750         | 0.8820 | 0.8860 | 0.8028         | 0.8038 | 0.8068 |
| 7/8      | ...              | 14     | ...    | 0.8750         | 0.8799 | 0.8839 | 0.8286         | 0.8296 | 0.8321 |
| 1        | 8                | ...    | ...    | 1.0000         | 1.0078 | 1.0118 | 0.9188         | 0.9198 | 0.9228 |
| 1        | ...              | 12     | ...    | 1.0000         | 1.0055 | 1.0095 | 0.9459         | 0.9469 | 0.9494 |
| 1        | ...              | ...    | 14     | 1.0000         | 1.0049 | 1.0089 | 0.9536         | 0.9546 | 0.9571 |
| 1 1/8    | 7                | ...    | ...    | 1.1250         | 1.1337 | 1.1382 | 1.0322         | 1.0332 | 1.0367 |
| 1 1/8    | ...              | 12     | ...    | 1.1250         | 1.1305 | 1.1350 | 1.0709         | 1.0719 | 1.0749 |
| 1 1/4    | 7                | ...    | ...    | 1.2500         | 1.2587 | 1.2632 | 1.1572         | 1.1582 | 1.1617 |
| 1 1/4    | ...              | 12     | ...    | 1.2500         | 1.2555 | 1.2600 | 1.1959         | 1.1969 | 1.1999 |
| 1 3/8    | 6                | ...    | ...    | 1.3750         | 1.3850 | 1.3895 | 1.2667         | 1.2677 | 1.2712 |
| 1 3/8    | ...              | 12     | ...    | 1.3750         | 1.3805 | 1.3850 | 1.3209         | 1.3219 | 1.3249 |
| 1 1/2    | 6                | ...    | ...    | 1.5000         | 1.5100 | 1.5145 | 1.3917         | 1.3927 | 1.3962 |
| 1 1/2    | ...              | 12     | ...    | 1.5000         | 1.5055 | 1.5100 | 1.4459         | 1.4469 | 1.4499 |
| 1 3/4    | 5                | ...    | ...    | 1.7500         | 1.7602 | 1.7657 | 1.6201         | 1.6216 | 1.6256 |
| 2        | 4 1/2            | ...    | ...    | 2.0000         | 2.0111 | 2.0166 | 1.8557         | 1.8572 | 1.8612 |

All dimensions are given in inches.

*Lead Tolerance:* Plus or minus 0.003 inch max. per inch of thread.*Angle Tolerance:* Plus or minus 35 min. in half angle or 53 min. in full angle for 4 1/2 to 5 1/2 thds. per in.; 40 min. half angle and 60 min. full angle for 6 to 9 thds.; 45 min. half angle and 68 min. full angle for 10 to 28 thds.; 60 min. half angle and 90 min. full angle for 30 to 64 thds. per in.

Table 2. ANSI Standard Fractional-Size Taps—Ground Thread Limits ASME B94.9-1999

| Size<br>in. | Threads per Inch |           |           | Major Diameter |        |        | Pitch Diameter      |  |        |          |        |                             |                     |  |                       |  |                       |                     |
|-------------|------------------|-----------|-----------|----------------|--------|--------|---------------------|--|--------|----------|--------|-----------------------------|---------------------|--|-----------------------|--|-----------------------|---------------------|
|             | NC<br>UNC        | NF<br>UNF | NS<br>UNS | Basic          | Min.   | Max.   | Basic<br>Pitch Dia. | H1 Limit   |        | H2 Limit |        | H3 & H4 <sup>a</sup> Limits |                     | H4 <sup>a</sup> , H5 <sup>b</sup> , H6 <sup>c</sup> Limits |                       | H7 <sup>c</sup> , H8 <sup>f</sup> Limits |                       |                     |
|             |                  |           |           |                |        |        |                     | Min.   | Max.   | Min.     | Max.   | Min.                        | Max.                | Min.   | Max.                  | Min.                                     | Max.                  |                     |
| 1/4         | 20               | ...       | ...       | 0.2500         | 0.2532 | 0.2565 | 0.2175              | 0.2175   | 0.2180 | 0.2180   | 0.2185 | 0.2185                      | 0.2190              | 0.2195 <sup>b,d</sup>                                      | 0.2200 <sup>b,d</sup> | ...                                      | ...                   |                     |
| 1/4         | ...              | 28        | ...       | 0.2500         | 0.2523 | 0.2546 | 0.2268              | 0.2268   | 0.2273 | 0.2273   | 0.2278 | 0.2278                      | 0.2283              | 0.2283 <sup>a</sup>  | 0.2288 <sup>a</sup>   | ...                                      | ...                   |                     |
| 5/16        | 18               | ...       | ...       | 0.3125         | 0.3161 | 0.3197 | 0.2764              | 0.2764   | 0.2769 | 0.2769   | 0.2774 | 0.2774                      | 0.2779              | 0.2784 <sup>b,d</sup>                                      | 0.2789 <sup>b,d</sup> | 0.2794 <sup>e,h</sup>                    | 0.2799 <sup>e,h</sup> |                     |
| 5/16        | ...              | 24        | ...       | 0.3125         | 0.3152 | 0.3179 | 0.2854              | 0.2854   | 0.2859 | 0.2864   | 0.2864 | 0.2869                      | 0.2869 <sup>a</sup> | 0.2874 <sup>a</sup>  | 0.2884 <sup>e,h</sup> | 0.2889 <sup>e,h</sup>                    | 0.2899 <sup>e,h</sup> |                     |
| 3/8         | 16               | ...       | ...       | 0.3750         | 0.3790 | 0.3831 | 0.3344              | 0.3344   | 0.3349 | 0.3349   | 0.3354 | 0.3354                      | 0.3359              | 0.3364 <sup>b,d</sup>                                      | 0.3369 <sup>b,d</sup> | 0.3374 <sup>e,h</sup>                    | 0.3379 <sup>e,h</sup> |                     |
| 3/8         | ...              | 24        | ...       | 0.3750         | 0.3777 | 0.3804 | 0.3479              | 0.3479   | 0.3484 | 0.3484   | 0.3489 | 0.3489                      | 0.3494              | 0.3494 <sup>a</sup>  | 0.3499 <sup>a</sup>   | 0.3509 <sup>e,h</sup>                    | 0.3514 <sup>e,h</sup> |                     |
| 7/16        | 14               | ...       | ...       | 0.4375         | 0.4422 | 0.4468 | 0.3911              | ...  | ...    | 0.3916   | 0.3921 | 0.3921                      | 0.3926              | 0.3931 <sup>b,d</sup>                                      | 0.3936 <sup>b,d</sup> | 0.3946 <sup>f</sup>                      | 0.3951 <sup>f</sup>   |                     |
| 7/16        | ...              | 20        | ...       | 0.4375         | 0.4407 | 0.4440 | 0.4050              | ...  | ...    | ...      | ...    | 0.4060                      | 0.4065              | 0.4070 <sup>b,d</sup>                                      | 0.4075 <sup>b,d</sup> | 0.4085 <sup>f</sup>                      | 0.4090 <sup>f</sup>   |                     |
| 1/2         | 13               | ...       | ...       | 0.5000         | 0.5050 | 0.5100 | 0.4500              | 0.4500   | 0.4505 | 0.4505   | 0.4510 | 0.4510                      | 0.4515              | 0.4520 <sup>b,d</sup>                                      | 0.4525 <sup>b,d</sup> | 0.4536 <sup>f</sup>                      | 0.4240 <sup>f</sup>   |                     |
| 1/2         | ...              | 20        | ...       | 0.5000         | 0.5032 | 0.5065 | 0.4675              | 0.4675   | 0.4680 | 0.4680   | 0.4685 | 0.4685                      | 0.4690              | 0.4695 <sup>b,d</sup>                                      | 0.4700 <sup>b,d</sup> | 0.4710 <sup>f</sup>                      | 0.4715 <sup>f</sup>   |                     |
| 9/16        | 12               | ...       | ...       | 0.5625         | 0.5679 | 0.5733 | 0.5084              | ...  | ...    | ...      | ...    | 0.5094                      | 0.5099              | 0.5104 <sup>b,d</sup>                                      | 0.5109 <sup>b,d</sup> | 0.5114 <sup>e,h</sup>                    | 0.5119 <sup>e,h</sup> |                     |
| 9/16        | ...              | 18        | ...       | 0.5625         | 0.5661 | 0.5697 | 0.5264              | ...  | ...    | 0.5269   | 0.5274 | 0.5274                      | 0.5279              | 0.5284 <sup>b,d</sup>                                      | 0.5289 <sup>b,d</sup> | 0.5294 <sup>e,h</sup>                    | 0.5299 <sup>e,h</sup> |                     |
| 5/8         | 11               | ...       | ...       | 0.6250         | 0.6309 | 0.6368 | 0.5660              | ...  | ...    | 0.5665   | 0.5670 | 0.5670                      | 0.5675              | 0.5680 <sup>b,d</sup>                                      | 0.5685 <sup>b,d</sup> | 0.5690 <sup>e,h</sup>                    | 0.5695 <sup>e,h</sup> |                     |
| 5/8         | ...              | 18        | ...       | 0.6250         | 0.6286 | 0.6322 | 0.5889              | ...  | ...    | 0.5894   | 0.5899 | 0.5899                      | 0.5904              | 0.5909 <sup>b,d</sup>                                      | 0.5914 <sup>b,d</sup> | 0.5919 <sup>e,h</sup>                    | 0.5924 <sup>e,h</sup> |                     |
| 11/16       | ...              | ...       | 11        | 0.6875         | 0.6934 | 0.6993 | 0.6285              | ...  | ...    | ...      | ...    | 0.6295                      | 0.6300              | ...  | ...                   | ...                                      | ...                   |                     |
| 11/16       | ...              | ...       | 16        | 0.6875         | 0.6915 | 0.6956 | 0.6469              | ...  | ...    | ...      | ...    | 0.6479                      | 0.6484              | ...  | ...                   | ...                                      | ...                   |                     |
| 3/4         | 10               | ...       | ...       | 0.7500         | 0.7565 | 0.7630 | 0.6850              | ...  | ...    | 0.6855   | 0.6860 | 0.6860                      | 0.6865              | 0.6870 <sup>b,d</sup>                                      | 0.6875 <sup>b,d</sup> | 0.6880 <sup>e,i</sup>                    | 0.6885 <sup>e,i</sup> |                     |
| 3/4         | ...              | 16        | ...       | 0.7500         | 0.7540 | 0.7581 | 0.7094              | 0.7094   | 0.7099 | 0.7099   | 0.7104 | 0.7104                      | 0.7109              | 0.7114 <sup>b,d</sup>                                      | 0.7119 <sup>b,d</sup> | 0.7124 <sup>e,i</sup>                    | 0.7129 <sup>e,i</sup> |                     |
| 7/8         | 9                | ...       | ...       | 0.8750         | 0.8822 | 0.8894 | 0.8028              | ...  | ...    | ...      | ...    | 0.8043 <sup>a</sup>         | 0.8048 <sup>a</sup> | 0.8053 <sup>c</sup>  | 0.8058 <sup>c</sup>   | ...                                      | ...                   |                     |
| 7/8         | ...              | 14        | ...       | 0.8750         | 0.8797 | 0.8843 | 0.8286              | ...  | ...    | 0.8291   | 0.8296 | 0.8301 <sup>a</sup>         | 0.8306 <sup>a</sup> | ...  | ...                   | ...                                      | ...                   |                     |
| 1           | 8                | ...       | ...       | 1.0000         | 1.0082 | 1.0163 | 0.9188              | Notes:<br><sup>a</sup> H4 limit value; <sup>b</sup> H5 limit value; <sup>c</sup> H6 limit value; <sup>d</sup> H7 limit value; <sup>e</sup> H8 limit value. |        |          |        |                             | 0.9203 <sup>a</sup> | 0.9208 <sup>a</sup>  | 0.9213 <sup>c</sup>   | 0.9218 <sup>c</sup>                      | ...                   | ...                 |
| 1           | ...              | 12        | ...       | 1.0000         | 1.0054 | 1.0108 | 0.9459              |  |        |          |        |                             | 0.9474 <sup>a</sup> | 0.9479 <sup>a</sup>  | 0.9484 <sup>a</sup>   | 0.9489 <sup>a</sup>                      | 0.9494 <sup>a</sup>   | 0.9499 <sup>a</sup> |
| 1           | ...              | 14        | ...       | 1.0000         | 1.0047 | 1.0093 | 0.9536              |  |        |          |        |                             | 0.9551 <sup>a</sup> | 0.9556 <sup>a</sup>  | ...                   | ...                                      | ...                   | ...                 |
| 1 1/8       | 7                | ...       | ...       | 1.1250         | 1.1343 | 1.1436 | 1.0322              |  |        |          |        |                             | 1.0337 <sup>a</sup> | 1.0342 <sup>a</sup>  | ...                   | ...                                      | ...                   | ...                 |
| 1 1/8       | ...              | 12        | ...       | 1.1250         | 1.1304 | 1.1358 | 1.0709              |  |        |          |        |                             | 1.0724 <sup>a</sup> | 1.0729 <sup>a</sup>  | ...                   | ...                                      | ...                   | ...                 |
| 1 1/8       | 7                | ...       | ...       | 1.2500         | 1.2593 | 1.2686 | 1.1572              |  |        |          |        |                             | 1.1587 <sup>a</sup> | 1.1592 <sup>a</sup>  | ...                   | ...                                      | ...                   | ...                 |
| 1 1/4       | ...              | 12        | ...       | 1.2500         | 1.2554 | 1.2608 | 1.1959              |  |        |          |        |                             | 1.1974 <sup>a</sup> | 1.1979 <sup>a</sup>  | ...                   | ...                                      | ...                   | ...                 |
| 1 3/8       | 6                | ...       | ...       | 1.3750         | 1.3859 | 1.3967 | 1.2667              |  |        |          |        |                             | 1.2682 <sup>a</sup> | 1.2687 <sup>a</sup>  | ...                   | ...                                      | ...                   | ...                 |
| 1 3/8       | ...              | 12        | ...       | 1.3750         | 1.3804 | 1.3858 | 1.3209              |  |        |          |        |                             | 1.3224 <sup>a</sup> | 1.3229 <sup>a</sup>  | ...                   | ...                                      | ...                   | ...                 |
| 1 1/2       | 6                | ...       | ...       | 1.5000         | 1.5109 | 1.5217 | 1.3917              |  |        |          |        |                             | 1.3932 <sup>a</sup> | 1.3937 <sup>a</sup>  | ...                   | ...                                      | ...                   | ...                 |
| 1 1/2       | ...              | 12        | ...       | 1.5000         | 1.5054 | 1.5108 | 1.4459              |  |        |          |        |                             | 1.4474 <sup>a</sup> | 1.4479 <sup>a</sup>  | ...                   | ...                                      | ...                   | ...                 |
| 1 3/4       | ...              | 5         | ...       | 1.7500         | 1.7630 | 1.7760 | 1.6201              |  |        |          |        |                             | 1.6216 <sup>a</sup> | 1.6221 <sup>a</sup>  | ...                   | ...                                      | ...                   | ...                 |
| 2           | ...              | 4.5       | ...       | 2.0000         | 2.0145 | 2.0289 | 1.8557              |  |        |          |        |                             | 1.8572 <sup>a</sup> | 1.8577 <sup>a</sup>  | ...                   | ...                                      | ...                   | ...                 |

All dimensions are given in inches. Limits listed in the above table are the most commonly used in industry. Not all styles of taps are available with all limits listed. For calculation of limits not listed see ASME B94.9-1999

Table 3. ANSI Standard Machine Screw Taps — Ground Thread Limits ASME B94.9-1999

| Size | Threads per Inch |           |           | Major Diameter |        |        | Pitch Diameter Limits |          |        |          |        |  |        |   |        |        |
|------|------------------|-----------|-----------|----------------|--------|--------|-----------------------|----------|--------|----------|--------|--|--------|---|--------|--------|
|      | NC<br>UNC        | NF<br>UNF | NS<br>UNS | Basic          | Min.   | Max.   | Basic<br>Pitch Dia.   | H1 Limit |        | H2 Limit |        | H3 <sup>a</sup> , H4 <sup>b</sup> , H5 <sup>c</sup> Limits   |        | H6 <sup>d</sup> , H7 <sup>e</sup> , H10 <sup>f</sup> Limits |        |        |
|      |                  |           |           |                |        |        |                       | Min.     | Max.   | Min.     | Max.   | Min.   | Max.   | Min.  | Max.   |        |
| 0    | ...              | 80        | ...       | 0.0600         | 0.0605 | 0.0616 | 0.0519                | 0.0519   | 0.0524 | 0.0524   | 0.0529 | <i>Notes:</i><br><sup>a</sup> H3 limit value; <sup>b</sup> H4 limit value; <sup>c</sup> H5 limit value;<br><sup>d</sup> H6 limit value; <sup>e</sup> H7 limit value; <sup>f</sup> H10 limit value.<br>Minimum and maximum major diameters are:<br><sup>g</sup> 0.0010 larger than shown; <sup>h</sup> 0.0020 larger than shown;<br><sup>i</sup> 0.0035 larger than shown; <sup>j</sup> 0.0015 larger than shown. |        |   |        |        |
| 1    | 64               | ...       | ...       | 0.0730         | 0.0736 | 0.0750 | 0.0629                | 0.0629   | 0.0634 | 0.0634   | 0.0639 |  |        |   |        |        |
| 1    | ...              | 72        | ...       | 0.0730         | 0.0736 | 0.0748 | 0.0640                | 0.0640   | 0.0645 | 0.0645   | 0.0650 |  |        |   |        |        |
| 2    | 56               | ...       | ...       | 0.0860         | 0.0867 | 0.0883 | 0.0744                | 0.0744   | 0.0749 | 0.0749   | 0.0754 |  |        |   |        |        |
| 2    | ...              | 64        | ...       | 0.0860         | 0.0866 | 0.0880 | 0.0759                | ...      | ...    | 0.0764   | 0.0769 |  |        |   |        |        |
| 3    | 48               | ...       | ...       | 0.0990         | 0.0999 | 0.1017 | 0.0855                | ...      | ...    | 0.0860   | 0.0865 |  |        |   |        |        |
| 3    | ...              | 56        | ...       | 0.0990         | 0.0997 | 0.1013 | 0.0874                | 0.0874   | 0.0879 | 0.0879   | 0.0884 |  |        |   |        |        |
| 4    | 40               | ...       | ...       | 0.1120         | 0.1134 | 0.1152 | 0.0958                | 0.0958   | 0.0963 | 0.0963   | 0.0968 |  |        |   |        |        |
| 4    | ...              | 48        | ...       | 0.1120         | 0.1129 | 0.1147 | 0.0985                | 0.0985   | 0.0990 | 0.0990   | 0.0995 |  |        |   |        |        |
| 4    | ...              | ...       | 36        | 0.1120         | 0.1135 | 0.1156 | 0.0940                | 0.0940   | 0.0945 | 0.0945   | 0.0950 |  |        |   |        |        |
| 5    | 40               | ...       | ...       | 0.1250         | 0.1264 | 0.1283 | 0.1088                | 0.1088   | 0.1093 | 0.1093   | 0.1103 | 0.1113   | ...    | ...   |        |        |
| 5    | ...              | 44        | ...       | 0.1250         | 0.1263 | 0.1280 | 0.1102                | ...      | ...    | 0.1107   | 0.1112 | 0.1122   | 0.1127 | ...   | ...    |        |
| 6    | 32               | ...       | ...       | 0.1380         | 0.1401 | 0.1421 | 0.1177                | 0.1177   | 0.1182 | 0.1182   | 0.1187 | 0.1187   | 0.1187 | 0.1192  | 0.1207 | 0.1212 |
| 6    | ...              | 40        | ...       | 0.1380         | 0.1394 | 0.1413 | 0.1218                | 0.1218   | 0.1223 | 0.1223   | 0.1228 | 0.1238   | 0.1243 | 0.1253  | 0.1263 | 0.1273 |
| 8    | 32               | ...       | ...       | 0.1640         | 0.1661 | 0.1681 | 0.1437                | 0.1437   | 0.1442 | 0.1442   | 0.1447 | 0.1447   | 0.1447 | 0.1452  | 0.1467 | 0.1472 |
| 8    | ...              | 36        | ...       | 0.1640         | 0.1655 | 0.1676 | 0.1460                | ...      | ...    | 0.1465   | 0.1470 | 0.1480   | 0.1485 | 0.1495  | 0.1505 | 0.1515 |
| 10   | 24               | ...       | ...       | 0.1900         | 0.1927 | 0.1954 | 0.1629                | 0.1629   | 0.1634 | 0.1634   | 0.1639 | 0.1639   | 0.1639 | 0.1644  | 0.1654 | 0.1659 |
| 10   | ...              | 32        | ...       | 0.1900         | 0.1921 | 0.1941 | 0.1697                | 0.1697   | 0.1702 | 0.1702   | 0.1707 | 0.1707   | 0.1707 | 0.1712  | 0.1722 | 0.1727 |
| 10   | ...              | ...       | ...       | 0.1900         | 0.1921 | 0.1941 | 0.1697                | 0.1697   | 0.1702 | 0.1702   | 0.1707 | 0.1707   | 0.1707 | 0.1712  | 0.1722 | 0.1727 |
| 12   | 24               | ...       | ...       | 0.2160         | 0.2187 | 0.2214 | 0.1889                | ...      | ...    | ...      | ...    | 0.1899   | 0.1904 | 0.1914  | 0.1919 | 0.1924 |
| 12   | ...              | 28        | ...       | 0.2160         | 0.2183 | 0.2206 | 0.1928                | ...      | ...    | ...      | ...    | 0.1938   | 0.1943 | 0.1953  | 0.1958 | 0.1963 |

All dimensions are given in inches. Limits listed in table are most commonly used in industry. Not all style of taps are available with all limits listed.

**Table 4a. ANSI Standard Metric Tap Ground Thread Limits in Inches — M Profile ASME B94.9-1999**

| Nominal Diam, mm | Pitch, mm | Major Diameter (Inches) |         |         | Pitch Diameter (Inches) |         |         |
|------------------|-----------|-------------------------|---------|---------|-------------------------|---------|---------|
|                  |           | Basic                   | Min     | Max     | Basic                   | Min     | Max     |
| 1.6              | 0.35      | 0.06299                 | 0.06409 | 0.06508 | 0.05406                 | 0.05500 | 0.05559 |
| 2                | 0.4       | 0.07874                 | 0.08000 | 0.08098 | 0.06850                 | 0.06945 | 0.07004 |
| 2.5              | 0.45      | 0.09843                 | 0.09984 | 0.10083 | 0.08693                 | 0.08787 | 0.08846 |
| 3                | 0.5       | 0.11811                 | 0.11969 | 0.12067 | 0.10531                 | 0.10626 | 0.10685 |
| 3.5              | 0.6       | 0.13780                 | 0.13969 | 0.14067 | 0.12244                 | 0.12370 | 0.12449 |
| 4                | 0.7       | 0.15748                 | 0.15969 | 0.16130 | 0.13957                 | 0.14083 | 0.14161 |
| 4.5              | 0.75      | 0.17717                 | 0.17953 | 0.18114 | 0.15799                 | 0.15925 | 0.16004 |
| 5                | 0.8       | 0.19685                 | 0.19937 | 0.20098 | 0.17638                 | 0.17764 | 0.17843 |
| 6                | 1         | 0.23622                 | 0.23937 | 0.24098 | 0.21063                 | 0.21220 | 0.21319 |
| 7                | 1         | 0.27559                 | 0.27874 | 0.28035 | 0.25000                 | 0.25157 | 0.25256 |
| 8                | 1.25      | 0.31496                 | 0.31890 | 0.32142 | 0.28299                 | 0.28433 | 0.28555 |
| 10               | 1.5       | 0.39370                 | 0.39843 | 0.40094 | 0.35535                 | 0.35720 | 0.35843 |
| 12               | 1.75      | 0.47244                 | 0.47795 | 0.48047 | 0.42768                 | 0.42953 | 0.43075 |
| 14               | 2         | 0.55118                 | 0.55748 | 0.56000 | 0.50004                 | 0.50201 | 0.50362 |
| 16               | 2         | 0.62992                 | 0.63622 | 0.63874 | 0.57878                 | 0.58075 | 0.58236 |
| 20               | 2.5       | 0.78740                 | 0.79538 | 0.79780 | 0.72346                 | 0.72543 | 0.72705 |
| 24               | 3         | 0.94488                 | 0.95433 | 0.95827 | 0.86815                 | 0.87063 | 0.87224 |
| 30               | 3.5       | 1.18110                 | 1.19213 | 1.19606 | 1.09161                 | 1.09417 | 1.09622 |
| 36               | 4         | 1.41732                 | 1.42992 | 1.43386 | 1.31504                 | 1.31760 | 1.31965 |
| 42               | 4.5       | 1.65354                 | 1.66772 | 1.71102 | 1.53846                 | 1.54154 | 1.54358 |
| 48               | 5         | 1.88976                 | 1.90551 | 1.98819 | 1.76189                 | 1.76496 | 1.76701 |

Basic pitch diameter is the same as minimum pitch diameter of internal thread, Class 6H as shown in table starting on page 1798.

Pitch diameter limits are designated in the Standard as D3 for 1.6 to 3 mm diameter sizes, incl.; D4 for 3.5 to 5 mm sizes, incl.; D5 for 6 and 8 mm sizes; D6 for 10 and 12 mm sizes; D7 for 14 to 20 mm sizes, incl.; D8 for 24 mm size; and D9 for 30 and 36 mm sizes.

Angle tolerances are plus or minus 30 minutes in half angle for pitches ranging from 0.35 through 2.5 mm, incl. and plus or minus 25 minutes in half angle for pitches ranging from 3 to 4 mm, incl.

A maximum deviation of plus or minus 0.0005 inch within any two threads not farther apart than one inch is permitted.

**Table 4b. ANSI Standard Metric Tap Ground Thread Limits in Millimeters — M Profile ASME B94.9-1999**

| Nominal Diam, mm | Pitch, mm | Major Diameter (mm) |        |        | Pitch Diameter (mm) |        |        |
|------------------|-----------|---------------------|--------|--------|---------------------|--------|--------|
|                  |           | Basic               | Min    | Max    | Basic               | Min    | Max    |
| 1.6              | 0.35      | 1.600               | 1.628  | 1.653  | 1.373               | 1.397  | 1.412  |
| 2                | 0.4       | 2.000               | 2.032  | 2.057  | 1.740               | 1.764  | 1.779  |
| 2.5              | 0.45      | 2.500               | 2.536  | 2.561  | 2.208               | 2.232  | 2.247  |
| 3                | 0.5       | 3.000               | 3.040  | 3.065  | 2.675               | 2.699  | 2.714  |
| 3.5              | 0.6       | 3.500               | 3.548  | 3.573  | 3.110               | 3.142  | 3.162  |
| 4                | 0.7       | 4.000               | 4.056  | 4.097  | 3.545               | 3.577  | 3.597  |
| 4.5              | 0.75      | 4.500               | 4.560  | 4.601  | 4.013               | 4.045  | 4.065  |
| 5                | 0.8       | 5.000               | 5.064  | 5.105  | 4.480               | 4.512  | 4.532  |
| 6                | 1         | 6.000               | 6.080  | 6.121  | 5.350               | 5.390  | 5.415  |
| 7                | 1         | 7.000               | 7.080  | 7.121  | 6.350               | 6.390  | 6.415  |
| 8                | 1.25      | 8.000               | 8.100  | 8.164  | 7.188               | 7.222  | 7.253  |
| 10               | 1.5       | 10.000              | 10.120 | 10.184 | 9.026               | 9.073  | 9.104  |
| 12               | 1.75      | 12.000              | 12.140 | 12.204 | 10.863              | 10.910 | 10.941 |
| 14               | 2         | 14.000              | 14.160 | 14.224 | 12.701              | 12.751 | 12.792 |
| 16               | 2         | 16.000              | 16.160 | 16.224 | 14.701              | 14.751 | 14.792 |
| 20               | 2.5       | 20.000              | 20.200 | 20.264 | 18.376              | 18.426 | 18.467 |
| 24               | 3         | 24.000              | 24.240 | 24.340 | 22.051              | 22.114 | 22.155 |
| 30               | 3.5       | 30.000              | 30.280 | 30.380 | 27.727              | 27.792 | 27.844 |
| 36               | 4         | 36.000              | 36.320 | 36.420 | 33.402              | 33.467 | 33.519 |
| 42               | 4.5       | 42.000              | 42.360 | 43.460 | 39.077              | 39.155 | 39.207 |
| 48               | 5         | 48.000              | 48.400 | 50.500 | 44.752              | 44.830 | 44.882 |

Basic pitch diameter is the same as minimum pitch diameter of internal thread, Class 6H as shown in table starting on page 1798.

Pitch diameter limits are designated in the Standard as D3 for 1.6 to 3 mm diameter sizes, incl.; D4 for 3.5 to 5 mm sizes, incl.; D5 for 6 and 8 mm sizes; D6 for 10 and 12 mm sizes; D7 for 14 to 20 mm sizes, incl.; D8 for 24 mm size; D9 for 30 and 36 mm sizes; D10 for 42 and 48 mm sizes.



TAPS AND THREADING DIES

**Table 5. ANSI Standard Machine Screw Taps — Cut Threads Limits ASME B94.9-1999**

| Size | Threads per Inch |        |        | Major Diameter |        |        | Pitch Diameter |        |        |
|------|------------------|--------|--------|----------------|--------|--------|----------------|--------|--------|
|      | NC UNC           | NF UNF | NS UNS | Basic          | Min.   | Max.   | Basic          | Min.   | Max.   |
| 0    | ...              | 80     | ...    | 0.0600         | 0.0609 | 0.0624 | 0.0519         | 0.0521 | 0.0531 |
| 1    | 64               | ...    | ...    | 0.0730         | 0.0740 | 0.0755 | 0.0629         | 0.0631 | 0.0641 |
| 1    | ...              | 72     | ...    | 0.0730         | 0.0740 | 0.0755 | 0.0640         | 0.0642 | 0.0652 |
| 2    | 56               | ...    | ...    | 0.0860         | 0.0872 | 0.0887 | 0.0744         | 0.0746 | 0.0756 |
| 2    | ...              | 64     | ...    | 0.0860         | 0.0870 | 0.0885 | 0.0759         | 0.0761 | 0.0771 |
| 3    | 48               | ...    | ...    | 0.0990         | 0.1003 | 0.1018 | 0.0855         | 0.0857 | 0.0867 |
| 3    | ...              | 56     | ...    | 0.0990         | 0.1002 | 0.1017 | 0.0874         | 0.0876 | 0.0886 |
| 4    | ...              | ...    | 36     | 0.1120         | 0.1137 | 0.1157 | 0.0940         | 0.0942 | 0.0957 |
| 4    | 40               | ...    | ...    | 0.1120         | 0.1136 | 0.1156 | 0.0958         | 0.0960 | 0.0975 |
| 4    | ...              | 48     | ...    | 0.1120         | 0.1133 | 0.1153 | 0.0985         | 0.0987 | 0.1002 |
| 5    | 40               | ...    | ...    | 0.1250         | 0.1266 | 0.1286 | 0.1088         | 0.1090 | 0.1105 |
| 6    | 32               | ...    | ...    | 0.1380         | 0.1402 | 0.1422 | 0.1177         | 0.1182 | 0.1197 |
| 6    | ...              | ...    | 36     | 0.1380         | 0.1397 | 0.1417 | 0.1200         | 0.1202 | 0.1217 |
| 6    | ...              | 40     | ...    | 0.1380         | 0.1396 | 0.1416 | 0.1218         | 0.1220 | 0.1235 |
| 8    | 32               | ...    | ...    | 0.1640         | 0.1662 | 0.1682 | 0.1437         | 0.1442 | 0.1457 |
| 8    | ...              | 36     | ...    | 0.1640         | 0.1657 | 0.1677 | 0.1460         | 0.1462 | 0.1477 |
| 8    | ...              | ...    | 40     | 0.1640         | 0.1656 | 0.1676 | 0.1478         | 0.1480 | 0.1495 |
| 10   | 24               | ...    | ...    | 0.1900         | 0.1928 | 0.1948 | 0.1629         | 0.1634 | 0.1649 |
| 10   | ...              | 32     | ...    | 0.1900         | 0.1922 | 0.1942 | 0.1697         | 0.1702 | 0.1717 |
| 12   | 24               | ...    | ...    | 0.2160         | 0.2188 | 0.2208 | 0.1889         | 0.1894 | 0.1909 |
| 12   | ...              | 28     | ...    | 0.2160         | 0.2184 | 0.2204 | 0.1928         | 0.1933 | 0.1948 |
| 14   | ...              | ...    | 24     | 0.2420         | 0.2448 | 0.2473 | 0.2149         | 0.2154 | 0.2174 |

All dimensions are given in inches.

*Lead Tolerance:* Plus or minus 0.003 inch per inch of thread. *Angle Tolerance:* Plus or minus 45 min. in half angle and 65 min. in full angle for 20 to 28 threads per inch; plus or minus 60 min. in half angle and 90 min. in full angle for 30 or more threads per inch.

**Table 6a. ANSI Standard Taper Pipe Taps — Cut Thread Tolerances for NPT and Ground Thread Tolerances for NPT, NPTF, and ANPT ASME B94.9-1999**

| Nominal Size       | Threads per Inch NPT, NPTF, or ANPT | Gage Measurement <sup>a</sup> |                         |               | Taper per Inch on Diameter, Inches |                    |                    |                    |
|--------------------|-------------------------------------|-------------------------------|-------------------------|---------------|------------------------------------|--------------------|--------------------|--------------------|
|                    |                                     | Projection Inches             | Tolerance Plus or Minus |               | Cut Thread                         |                    | Ground Thread      |                    |
|                    |                                     |                               | Cut Thread              | Ground Thread | Min.                               | Max.               | Min.               | Max.               |
| 1/16               | 27                                  | 0.312                         | 0.0625                  | 0.0625        | 0.0599                             | 0.0703             | 0.0599             | 0.0651             |
| 1/8                | 27                                  | 0.312                         | 0.0625                  | 0.0625        | 0.0599                             | 0.0703             | 0.0599             | 0.0651             |
| 1/4                | 18                                  | 0.459                         | 0.0625                  | 0.0625        | 0.0599                             | 0.0703             | 0.0599             | 0.0651             |
| 3/8                | 18                                  | 0.454                         | 0.0625                  | 0.0625        | 0.0599                             | 0.0703             | 0.0599             | 0.0651             |
| 1/2                | 14                                  | 0.579                         | 0.0625                  | 0.0625        | 0.0599                             | 0.0677             | 0.0599             | 0.0651             |
| 3/4                | 14                                  | 0.565                         | 0.0625                  | 0.0625        | 0.0599                             | 0.0677             | 0.0599             | 0.0651             |
| 1                  | 11 1/2                              | 0.678                         | 0.0937                  | 0.0937        | 0.0599                             | 0.0677             | 0.0599             | 0.0651             |
| 1 1/4              | 11 1/2                              | 0.686                         | 0.0937                  | 0.0937        | 0.0599                             | 0.0677             | 0.0599             | 0.0651             |
| 1 1/2              | 11 1/2                              | 0.699                         | 0.0937                  | 0.0937        | 0.0599                             | 0.0677             | 0.0599             | 0.0651             |
| 2                  | 11 1/2                              | 0.667                         | 0.0937                  | 0.0937        | 0.0599                             | 0.0677             | 0.0599             | 0.0651             |
| 2 1/2              | 8                                   | 0.925                         | 0.0937                  | 0.0937        | 0.0612                             | 0.0664             | 0.0612             | 0.0651             |
| 3                  | 8                                   | 0.925                         | 0.0937                  | 0.0937        | 0.0612                             | 0.0664             | 0.0612             | 0.0651             |
| 3 1/2 <sup>b</sup> | 8                                   | 0.938                         | 1/8                     | 1/8           | 47/64 <sup>c</sup>                 | 51/64 <sup>c</sup> | 47/64 <sup>c</sup> | 25/32 <sup>c</sup> |
| 4 <sup>b</sup>     | 8                                   | 0.950                         | 1/8                     | 1/8           | 47/64 <sup>c</sup>                 | 51/64 <sup>c</sup> | 47/64 <sup>c</sup> | 25/32 <sup>c</sup> |

<sup>a</sup>Distance that small end of tap projects through L1 taper ring gage (see ANSI B1.20.3).

<sup>b</sup>No longer included in ASME B94.9-1999 shown for reference only.

<sup>c</sup>Taper per foot, inches.

All dimensions are given in inches.

*Lead Tolerance:* Plus or minus 0.003 inch per inch of cut thread and plus or minus 0.0005 inch per inch of ground thread.

*Angle Tolerance:* Plus or minus 40 min. in half angle and 60 min. in full angle for 8 cut threads per inch; plus or minus 45 min. in half angle and 60 min. in full angle for 11 1/2 to 27 cut threads per inch; plus or minus 25 min. in half angle for 8 ground threads per inch; and plus and minus 30 min. in half angle for 11 1/2 to 27 ground threads per inch.

**Table 6b. ANSI Taper Pipe Thread — Widths of Flats at Tap Crests and Roots for Cut Thread NPT and Ground Thread NPT, ANPT, and NPTF ASME B94.9-1999**

| Threads per Inch | Tap Flat Width at | Column I<br>NPT—Cut and Ground Thread<br>ANPT—Ground Thread |         | Column II<br>NPTF—Cut and Ground Thread |         |
|------------------|-------------------|---|---------|---|---------|
|                  |                   | Minimum <sup>a</sup>  | Maximum | Minimum <sup>a</sup>                    | Maximum |
| 27               | { Major Diameter  | 0.0014  | 0.0041  | 0.0040                                  | 0.0055  |
|                  | { Minor Diameter  | ...   | 0.0041  | ...                                     | 0.0040  |
| 18               | { Major Diameter  | 0.0021  | 0.0057  | 0.0050                                  | 0.0065  |
|                  | { Minor Diameter  | ...   | 0.0057  | ...                                     | 0.0050  |
| 14               | { Major Diameter  | 0.0027  | 0.0064  | 0.0050                                  | 0.0065  |
|                  | { Minor Diameter  | ...   | 0.0064  | ...                                     | 0.0050  |
| 11½              | { Major Diameter  | 0.0033  | 0.0073  | 0.0060                                  | 0.0083  |
|                  | { Minor Diameter  | ...   | 0.0073  | ...                                     | 0.0060  |
| 8                | { Major Diameter  | 0.0048  | 0.0090  | 0.0080                                  | 0.0103  |
|                  | { Minor Diameter  | ...   | 0.0090  | ...                                     | 0.0080  |

<sup>a</sup> Minimum minor diameter flats are not specified. May be sharp as practicable.

All dimensions are given in inches.

Note: Cut Thread taps made to Column I are marked NPT but are not recommended for ANPT applications. Ground Thread taps made to Column I are marked NPT and may be used for NPT and ANPT applications. Ground Thread taps made to Column II are marked NPTF and used for Dryseal application.

**Table 7a. ANSI Standard Straight Pipe Taps (NPSF—Dryseal) Ground Thread Limits ASME B94.9-1999**

| Nominal Size, Inches | Threads per Inch | Major Diameter |        | Plug at Gaging Notch<br>E | Pitch Diameter |        | Minor <sup>a</sup> Dia. Flat, Max. |
|----------------------|------------------|----------------|--------|---------------------------|----------------|--------|------------------------------------|
|                      |                  | Min. G         | Max. H |                           | Min. K         | Max. L |                                    |
| 1/16                 | 27               | 0.3008         | 0.3018 | 0.2812                    | 0.2772         | 0.2777 | 0.004                              |
| 1/8                  | 27               | 0.3932         | 0.3942 | 0.3736                    | 0.3696         | 0.3701 | 0.004                              |
| 1/4                  | 18               | 0.5239         | 0.5249 | 0.4916                    | 0.4859         | 0.4864 | 0.005                              |
| 3/8                  | 18               | 0.6593         | 0.6603 | 0.6270                    | 0.6213         | 0.6218 | 0.005                              |
| 1/2                  | 14               | 0.8230         | 0.8240 | 0.7784                    | 0.7712         | 0.7717 | 0.005                              |
| 3/4                  | 14               | 1.0335         | 1.0345 | 0.9889                    | 0.9817         | 0.9822 | 0.005                              |

<sup>a</sup> As specified or sharper.

| Formulas For American Dryseal (NPSF) Ground Thread Taps |                |                  |                |         |                 |
|---|----------------|------------------|----------------|---------|-----------------|
| Nominal Size, Inches                                    | Major Diameter |                  | Pitch Diameter |         | Max. Minor Dia. |
|   | Min. G         | Max. H           | Min. K         | Max. L  |                 |
| 1/16  | $H - 0.0010$   | $K + Q - 0.0005$ | $L - 0.0005$   | $E - F$ | $M - Q$         |
| 1/8   | $H - 0.0010$   | $K + Q - 0.0005$ | $L - 0.0005$   | $E - F$ | $M - Q$         |
| 1/4   | $H - 0.0010$   | $K + Q - 0.0005$ | $L - 0.0005$   | $E - F$ | $M - Q$         |
| 3/8   | $H - 0.0010$   | $K + Q - 0.0005$ | $L - 0.0005$   | $E - F$ | $M - Q$         |
| 1/2   | $H - 0.0010$   | $K + Q - 0.0005$ | $L - 0.0005$   | $E - F$ | $M - Q$         |
| 3/4   | $H - 0.0010$   | $K + Q - 0.0005$ | $L - 0.0005$   | $E - F$ | $M - Q$         |

| Values to Use in Formulas |  |        |                                |        |
|---------------------------|--|--------|--------------------------------|--------|
| Threads per Inch          | E                                      | F      | M                              | Q      |
| 27                        |  | 0.0035 |                                | 0.0251 |
| 18                        | Pitch diameter of plug at gaging notch | 0.0052 | Actual measured pitch diameter | 0.0395 |
| 14                        |  | 0.0067 |                                | 0.0533 |

All dimensions are given in inches.

Lead Tolerance: Plus or minus 0.0005 inch within any two threads not farther apart than one inch.

Angle Tolerance: Plus or minus 30 min. in half angle for 14 to 27 threads per inch.

TAPS AND THREADING DIES

**Table 7b. ANSI Standard Straight Pipe Taps (NPS)  
Cut Thread Limits ASME B94.9-1999**

| Nominal Size | Threads per Inch, NPS, NPSC | Size at Gaging Notch | Pitch Diameter |        | Values to Use in Formulas |        |        |
|--------------|-----------------------------|----------------------|----------------|--------|---------------------------|--------|--------|
|              |                             |                      | Min.           | Max.   | A                         | B      | C      |
| 1/8          | 27                          | 0.3736               | 0.3721         | 0.3751 | 0.0267                    | 0.0296 | 0.0257 |
| 1/4          | 18                          | 0.4916               | 0.4908         | 0.4938 | } 0.0408                  | 0.0444 | 0.0401 |
| 3/8          | 18                          | 0.6270               | 0.6257         | 0.6292 |                           |        |        |
| 1/2          | 14                          | 0.7784               | 0.7776         | 0.7811 | } 0.0535                  | 0.0571 | 0.0525 |
| 3/4          | 14                          | 0.9889               | 0.9876         | 0.9916 |                           |        |        |
| 1            | 11 1/2                      | 1.2386               | 1.2372         | 1.2412 | 0.0658                    | 0.0696 | 0.0647 |

The following are approximate formulas, in which *M* = measured pitch diameter in inches:

Major dia., min. =  $M + A$

Major dia., max. =  $M + B$

Minor dia., max. =  $M - C$

All dimensions are given in inches.

*Lead Tolerance:* Plus or minus 0.003 inch per inch of thread.

*Angle Tolerance:* All pitches, plus or minus 45 min. in half angle and 68 min. in full angle. Taps made to these specifications are to be marked NPS and used for NPSC thread form.

**Table 7c. ANSI Standard Straight Pipe Taps (NPS)  
Ground Thread Limits ASME B94.9-1999**

| Nominal Size, Inches | Threads per Inch, NPS, NPSC, NPSM | Major Diameter       |               |               | Pitch Diameter                |               |               |
|----------------------|-----------------------------------|----------------------|---------------|---------------|-------------------------------|---------------|---------------|
|                      |                                   | Plug at Gaging Notch | Min. <i>G</i> | Max. <i>H</i> | Plug at Gaging Notch <i>E</i> | Min. <i>K</i> | Max. <i>L</i> |
| 1/8                  | 27                                | 0.3983               | 0.4022        | 0.4032        | 0.3736                        | 0.3746        | 0.3751        |
| 1/4                  | 18                                | 0.5286               | 0.5347        | 0.5357        | 0.4916                        | 0.4933        | 0.4938        |
| 3/8                  | 18                                | 0.6640               | 0.6701        | 0.6711        | 0.6270                        | 0.6287        | 0.6292        |
| 1/2                  | 14                                | 0.8260               | 0.8347        | 0.8357        | 0.7784                        | 0.7806        | 0.7811        |
| 3/4                  | 14                                | 1.0364               | 1.0447        | 1.0457        | 0.9889                        | 0.9906        | 0.9916        |
| 1                    | 11 1/2                            | 1.2966               | 1.3062        | 1.3077        | 1.2386                        | 1.2402        | 1.2412        |

Formulas for NPS Ground Thread Taps<sup>a</sup>

| Nominal Size | Major Diameter |                    | Minor Dia. | Threads per Inch | A      | B      |
|--------------|----------------|--------------------|------------|------------------|--------|--------|
|              | Min. <i>G</i>  | Max. <i>H</i>      | Max.       |                  |        |        |
| 1/8          | $H - 0.0010$   | $(K + A) - 0.0010$ | $M - B$    | 27               | 0.0296 | 0.0257 |
| 1/4 to 3/4   | $H - 0.0010$   | $(K + A) - 0.0020$ | $M - B$    | 18               | 0.0444 | 0.0401 |
| 1            | $H - 0.0015$   | $(K + A) - 0.0021$ | $M - B$    | 14               | 0.0571 | 0.0525 |
|              |                |                    |            | 11 1/2           | 0.0696 | 0.0647 |

The maximum Pitch Diameter of tap is based upon an allowance deducted from the maximum product pitch diameter of NPSC or NPSM, whichever is smaller.

The minimum Pitch Diameter of tap is derived by subtracting the ground thread pitch diameter tolerance for actual equivalent size.

<sup>a</sup>In the formulas, *M* equals the actual measured pitch diameter.

All dimensions are given in inches.

*Lead tolerance:* Plus or minus 0.0005 inch within any two threads not farther apart than one inch.

*Angle Tolerance:* All pitches, plus or minus 30 min. in half angle. Taps made to these specifications are to be marked NPS and used for NPSC and NPSM.

**Table 8a. ANSI Standard Ground Thread Straight Fluted Taps  
Machine Screw Sizes ASME B94.9-1999**

| Size | Basic Major Diameter | Threads per Inch |        |        | No. of Flutes  | Pitch Dia.Limits and Chamfers <sup>a</sup> |     |     |     | Length Overall A               | Length of Thread B             | Length of Square C             | Diameter of Shank D | E     |
|------|----------------------|------------------|--------|--------|----------------|--|-----|-----|-----|--------------------------------|--------------------------------|--------------------------------|---------------------|-------|
|      |                      | NC UNC           | NF UNF | NS UNS |                | H1   | H2  | H3  | H7  |                                |                                |                                |                     |       |
| 0    | 0.060                | ...              | 80     | ...    | 2              | TPB  | PB  | ... | ... | 1 <sup>5</sup> / <sub>8</sub>  | 3 <sup>3</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 1    | 0.073                | 64               | ...    | ...    | 2              | TPB  | P   | ... | ... | 1 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 1    | 0.073                | ...              | 72     | ...    | 2              | TPB  | PB  | ... | ... | 1 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>8</sub>  | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 2    | 0.086                | 56               | ...    | ...    | 2 <sup>b</sup> | ...  | PB  | ... | ... | 1 <sup>3</sup> / <sub>4</sub>  | 7 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 2    | 0.086                | 56               | ...    | ...    | 3              | TPB  | TPB | ... | ... | 1 <sup>3</sup> / <sub>4</sub>  | 7 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 2    | 0.086                | ...              | 64     | ...    | 3              | ...  | TPB | ... | ... | 1 <sup>3</sup> / <sub>4</sub>  | 7 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 3    | 0.099                | 48               | ...    | ...    | 2 <sup>b</sup> | ...  | PB  | ... | ... | 1 <sup>3</sup> / <sub>16</sub> | 1 <sup>1</sup> / <sub>2</sub>  | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 3    | 0.099                | 48               | ...    | ...    | 3              | P  | TPB | ... | ... | 1 <sup>3</sup> / <sub>16</sub> | 1 <sup>1</sup> / <sub>2</sub>  | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 3    | 0.099                | ...              | 56     | ...    | 3              | ...  | TPB | ... | ... | 1 <sup>3</sup> / <sub>16</sub> | 1 <sup>1</sup> / <sub>2</sub>  | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 4    | 0.112                | ...              | ...    | 36     | 3              | ...  | TPB | ... | ... | 1 <sup>3</sup> / <sub>8</sub>  | 9 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 4    | 0.112                | 40               | ...    | ...    | 2 <sup>b</sup> | P  | PB  | ... | ... | 1 <sup>7</sup> / <sub>8</sub>  | 9 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 4    | 0.112                | 40               | ...    | ...    | 3              | ...  | TPB | ... | ... | 1 <sup>7</sup> / <sub>8</sub>  | 9 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 4    | 0.112                | ...              | 48     | ...    | 3              | ...  | TPB | ... | ... | 1 <sup>7</sup> / <sub>8</sub>  | 9 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 5    | 0.125                | 40               | ...    | ...    | 2 <sup>b</sup> | ...  | PB  | ... | ... | 1 <sup>5</sup> / <sub>16</sub> | 5 <sup>3</sup> / <sub>8</sub>  | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 5    | 0.125                | 40               | ...    | ...    | 3              | P  | TPB | ... | ... | 1 <sup>5</sup> / <sub>16</sub> | 5 <sup>3</sup> / <sub>8</sub>  | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 5    | 0.125                | ...              | 44     | ...    | 3              | ...  | TPB | ... | ... | 1 <sup>5</sup> / <sub>16</sub> | 5 <sup>3</sup> / <sub>8</sub>  | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 6    | 0.138                | 32               | ...    | ...    | 2 <sup>b</sup> | P  | PB  | PB  | ... | 2                              | 1 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 6    | 0.138                | 32               | ...    | ...    | 3              | TPB  | TPB | TPB | PB  | 2                              | 1 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 6    | 0.138                | ...              | 40     | ...    | 2 <sup>b</sup> | ...  | P   | ... | ... | 2                              | 1 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 6    | 0.138                | ...              | 40     | ...    | 3              | P  | TPB | ... | ... | 2                              | 1 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110 |
| 8    | 0.164                | 32               | ...    | ...    | 2 <sup>b</sup> | P  | PB  | PB  | ... | 2 <sup>3</sup> / <sub>8</sub>  | 3 <sup>3</sup> / <sub>4</sub>  | 1 <sup>1</sup> / <sub>4</sub>  | 0.168               | 0.131 |
| 8    | 0.164                | 32               | ...    | ...    | 3 <sup>b</sup> | ...  | PB  | PB  | PB  | 2 <sup>3</sup> / <sub>8</sub>  | 3 <sup>3</sup> / <sub>4</sub>  | 1 <sup>1</sup> / <sub>4</sub>  | 0.168               | 0.131 |
| 8    | 0.164                | 32               | ...    | ...    | 4              | TPB  | TPB | TPB | PB  | 2 <sup>3</sup> / <sub>8</sub>  | 3 <sup>3</sup> / <sub>4</sub>  | 1 <sup>1</sup> / <sub>4</sub>  | 0.168               | 0.131 |
| 8    | 0.164                | ...              | 36     | ...    | 4              | ...  | TPB | ... | ... | 2 <sup>3</sup> / <sub>8</sub>  | 3 <sup>3</sup> / <sub>4</sub>  | 1 <sup>1</sup> / <sub>4</sub>  | 0.168               | 0.131 |
| 10   | 0.190                | 24               | ...    | ...    | 2*             | ...  | PB  | PB  | ... | 2 <sup>3</sup> / <sub>8</sub>  | 7 <sup>3</sup> / <sub>8</sub>  | 1 <sup>1</sup> / <sub>4</sub>  | 0.194               | 0.152 |
| 10   | 0.190                | 24               | ...    | ...    | 3 <sup>b</sup> | ...  | P   | PB  | ... | 2 <sup>3</sup> / <sub>8</sub>  | 7 <sup>3</sup> / <sub>8</sub>  | 1 <sup>1</sup> / <sub>4</sub>  | 0.194               | 0.152 |
| 10   | 0.190                | ...              | 32     | ...    | 2 <sup>b</sup> | P  | PB  | PB  | ... | 2 <sup>3</sup> / <sub>8</sub>  | 7 <sup>3</sup> / <sub>8</sub>  | 1 <sup>1</sup> / <sub>4</sub>  | 0.194               | 0.152 |
| 10   | 0.190                | ...              | 32     | ...    | 3 <sup>b</sup> | ...  | PB  | PB  | PB  | 2 <sup>3</sup> / <sub>8</sub>  | 7 <sup>3</sup> / <sub>8</sub>  | 1 <sup>1</sup> / <sub>4</sub>  | 0.194               | 0.152 |
| 10   | 0.190                | 24               | 32     | ...    | 4              | TPB  | TPB | TPB | PB  | 2 <sup>3</sup> / <sub>8</sub>  | 7 <sup>3</sup> / <sub>8</sub>  | 1 <sup>1</sup> / <sub>4</sub>  | 0.194               | 0.152 |
| 12   | 0.216                | 24               | ...    | ...    | 4              | ...  | ... | TPB | ... | 2 <sup>3</sup> / <sub>8</sub>  | 1 <sup>5</sup> / <sub>16</sub> | 9 <sup>1</sup> / <sub>32</sub> | 0.220               | 0.165 |
| 12   | 0.216                | ...              | 28     | ...    | 4              | ...  | ... | TPB | ... | 2 <sup>3</sup> / <sub>8</sub>  | 1 <sup>5</sup> / <sub>16</sub> | 9 <sup>1</sup> / <sub>32</sub> | 0.220               | 0.165 |

<sup>a</sup> Chamfer designations are: T = taper, P = plug, and B = bottoming.

<sup>b</sup> Optional number of flutes.

All dimensions are given in inches.

These taps are standard as high-speed steel taps with ground threads, with standard and optional number of flutes and pitch diameter limits and chamfers as given in the table.

These are style 1 taps and have external centers on thread and shank ends (may be removed on thread end of bottoming taps).

For standard thread limits see Table 3. For eccentricity tolerances see Table 22.

Tolerances: Numbers 0 to 12 size range — A, ± 1/32; B, ± 3/64; C, ± 1/32; D, -0.0015; E, -0.004.

TAPS AND THREADING DIES

**Table 8b. ANSI Standard Cut Thread Straight Fluted Taps  
Machine Screw Sizes ASME B94.9-1999**

| Size | Basic Major Diameter | Threads per Inch |                 |                 |                 |        |   | Number of Flutes                | Dimensions                     |                                |                     |                      |                   |
|------|----------------------|------------------|-----------------|-----------------|-----------------|--------|---|---------------------------------|--------------------------------|--------------------------------|---------------------|----------------------|-------------------|
|      |                      | Carbon Steel     |                 |                 | HS Steel        |        |   |                                 | Length Overall, A              | Length of Thread, B            | Length of Square, C | Diameter of Shank, D | Size of Square, E |
|      |                      | NC UNC           | NF UNF          | NS UNS          | NC UNC          | NF UNF |   |                                 |                                |                                |                     |                      |                   |
| 0    | 0.060                | ...              | 80 <sup>a</sup> | ...             | ...             | ...    | 2 | 1 <sup>5</sup> / <sub>8</sub>   | 5 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110                |                   |
| 1    | 0.073                | 64 <sup>a</sup>  | 72 <sup>a</sup> | ...             | ...             | ...    | 2 | 1 <sup>11</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>8</sub>  | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110                |                   |
| 2    | 0.086                | 56               | 64 <sup>a</sup> | ...             | ...             | ...    | 3 | 1 <sup>3</sup> / <sub>4</sub>   | 7 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110                |                   |
| 3    | 0.099                | 48 <sup>a</sup>  | 56 <sup>a</sup> | ...             | ...             | ...    | 3 | 1 <sup>13</sup> / <sub>16</sub> | 1 <sup>1</sup> / <sub>2</sub>  | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110                |                   |
| 4    | 0.112                | 40               | 48 <sup>a</sup> | 36 <sup>a</sup> | 40 <sup>a</sup> | ...    | 3 | 1 <sup>7</sup> / <sub>8</sub>   | 9 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110                |                   |
| 5    | 0.125                | 40               | ...             | ...             | 40 <sup>a</sup> | ...    | 3 | 1 <sup>15</sup> / <sub>16</sub> | 5 <sup>3</sup> / <sub>8</sub>  | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110                |                   |
| 6    | 0.138                | 32               | 40 <sup>a</sup> | 36 <sup>a</sup> | 32              | ...    | 3 | 2                               | 1 <sup>1</sup> / <sub>16</sub> | 3 <sup>3</sup> / <sub>16</sub> | 0.141               | 0.110                |                   |
| 8    | 0.164                | 32               | 36 <sup>a</sup> | 40 <sup>a</sup> | 32              | ...    | 4 | 2 <sup>1</sup> / <sub>8</sub>   | 3 <sup>3</sup> / <sub>4</sub>  | 1 <sup>1</sup> / <sub>4</sub>  | 0.168               | 0.131                |                   |
| 10   | 0.190                | 24               | 32              | ...             | 24              | 32     | 4 | 2 <sup>3</sup> / <sub>8</sub>   | 7 <sup>1</sup> / <sub>8</sub>  | 1 <sup>1</sup> / <sub>4</sub>  | 0.194               | 0.152                |                   |
| 12   | 0.216                | 24               | 28 <sup>a</sup> | ...             | 24              | ...    | 4 | 2 <sup>3</sup> / <sub>8</sub>   | 1 <sup>5</sup> / <sub>16</sub> | 9 <sup>1</sup> / <sub>32</sub> | 0.220               | 0.165                |                   |
| 14   | 0.242                | ...              | ...             | 24 <sup>a</sup> | ...             | ...    | 4 | 2 <sup>1</sup> / <sub>2</sub>   | 1                              | 5 <sup>1</sup> / <sub>16</sub> | 0.255               | 0.191                |                   |

<sup>a</sup>These taps are standard with plug chamfer only. All others are standard with taper, plug or bottoming chamfer.

| Tolerances for General Dimensions |              |           |                      |              |           |
|-----------------------------------|--------------|-----------|----------------------|--------------|-----------|
| Element                           | Range        | Tolerance | Element              | Range        | Tolerance |
| Length Overall, A                 | 0 to 14 incl | ±1/32     | Diameter of Shank, D | 0 to 12 incl | -0.004    |
| Length of Thread, B               | 0 to 12 incl | ±3/64     |                      | 14           | -0.005    |
| Length of Square, C               | 0 to 14 incl | ±1/32     | Size of Square, E    | 0 to 14 incl | -0.004    |

All dimensions are given in inches.

Styles 1 and 2 cut thread taps have optional style centers on thread and shank ends.

For standard thread limits see Table 5. For eccentricity tolerances see Table 22.

**Table 9. ANSI Standard Nut Taps (formerly ANSI/ASME B94.9-1987)**

| Dia. of Tap | Threads per Inch NC,UNC | Number of Flutes | Length Overall, A | Length of Thread, B             | Length of Square, C            | Diameter of Shank, D | Size of Square, E |
|-------------|-------------------------|------------------|-------------------|---------------------------------|--------------------------------|----------------------|-------------------|
| 1/4         | 20                      | 4                | 5                 | 1 <sup>3</sup> / <sub>8</sub>   | 9 <sup>1</sup> / <sub>16</sub> | 0.185                | 0.139             |
| 5/16        | 18                      | 4                | 5 1/2             | 1 <sup>13</sup> / <sub>16</sub> | 5 <sup>3</sup> / <sub>8</sub>  | 0.240                | 0.180             |
| 3/8         | 16                      | 4                | 6                 | 2                               | 1 <sup>1</sup> / <sub>16</sub> | 0.294                | 0.220             |
| 1/2         | 13                      | 4                | 7                 | 2 1/2                           | 7 <sup>1</sup> / <sub>8</sub>  | 0.400                | 0.300             |

| Tolerances for General Dimensions |                |           |                   |                |           |
|-----------------------------------|----------------|-----------|-------------------|----------------|-----------|
| Element                           | Diameter Range | Tolerance | Element           | Diameter Range | Tolerance |
| Overall Length, A                 | 1/4 to 1/2     | ±1/16     | Shank Diameter, D | 1/4 to 1/2     | -0.005    |
| Thread Length, B                  | 1/4 to 1/2     | ±1/16     | Size of Square, E | 1/4 to 1/2     | -0.004    |
| Square Length, C                  | 1/4 to 1/2     | ±1/32     |                   |                |           |

All dimensions are given in inches. These ground thread high-speed steel taps are standard in H3 limit only. All taps have an internal center in thread end. For standard limits see Table 2.

Chamfer J is made 1/2 to 3/4 the thread length of B.

**Table 10. ANSI Standard Spiral-Pointed Taps**  
Machine Screw Sizes ASME B94.9-1999

| STYLE 1   |                      |                                |                                |                   |               |                                 |                                 |                                 |                                |                                 |                                 |                                |                      |                   |
|---|----------------------|--------------------------------|--------------------------------|-------------------|---------------|---------------------------------|---------------------------------|---------------------------------|--------------------------------|---------------------------------|---------------------------------|--------------------------------|----------------------|-------------------|
| High-Speed Steel Taps with Ground Threads         |                      |                                |                                |                   |               |                                 |                                 |                                 |                                |                                 |                                 |                                |                      |                   |
| Size  | Basic Major Diameter | Threads per Inch               |                                |                   | No. of Flutes | Pitch Dia. Limits and Chamfers† |                                 |                                 |                                | Length Overall, A               | Length of Thread, B             | Length of Square, C            | Diameter of Shank, D | Size of Square, E |
|   |                      | NC UNC                         | NF UNF                         | NS UNS            |               | H1                              | H2                              | H3                              | H7                             |                                 |                                 |                                |                      |                   |
| 0   | 0.060                | ...                            | 80                             | ...               | 2             | PB                              | PB                              | ...                             | ...                            | 1 <sup>5</sup> / <sub>8</sub>   | 5 <sup>7</sup> / <sub>16</sub>  | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 1   | 0.073                | 64                             | 72                             | ...               | 2             | P                               | P                               | ...                             | ...                            | 1 <sup>11</sup> / <sub>16</sub> | 3 <sup>7</sup> / <sub>8</sub>   | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 2   | 0.086                | 56                             | ...                            | ...               | 2             | PB                              | PB                              | ...                             | ...                            | 1 <sup>3</sup> / <sub>4</sub>   | 7 <sup>7</sup> / <sub>16</sub>  | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 2   | 0.086                | ...                            | 64                             | ...               | 2             | ...                             | P                               | ...                             | ...                            | 1 <sup>3</sup> / <sub>4</sub>   | 7 <sup>7</sup> / <sub>16</sub>  | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 3   | 0.099                | 48                             | ...                            | ...               | 2             | ...                             | PB                              | ...                             | ...                            | 1 <sup>13</sup> / <sub>16</sub> | 1 <sup>1</sup> / <sub>2</sub>   | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 3   | 0.099                | ...                            | 56                             | ...               | 2             | P                               | P                               | ...                             | ...                            | 1 <sup>13</sup> / <sub>16</sub> | 1 <sup>1</sup> / <sub>2</sub>   | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 4   | 0.112                | ...                            | ...                            | 36                | 2             | ...                             | P                               | ...                             | ...                            | 1 <sup>7</sup> / <sub>8</sub>   | 9 <sup>7</sup> / <sub>16</sub>  | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 4   | 0.112                | 40                             | ...                            | ...               | 2             | P                               | PB                              | ...                             | ...                            | 1 <sup>7</sup> / <sub>8</sub>   | 9 <sup>7</sup> / <sub>16</sub>  | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 4   | 0.112                | ...                            | 48                             | ...               | 2             | P                               | PB                              | ...                             | ...                            | 1 <sup>7</sup> / <sub>8</sub>   | 9 <sup>7</sup> / <sub>16</sub>  | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 5   | 0.125                | 40                             | ...                            | ...               | 2             | P                               | PB                              | ...                             | ...                            | 1 <sup>15</sup> / <sub>16</sub> | 5 <sup>7</sup> / <sub>8</sub>   | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 5   | 0.125                | ...                            | 44                             | ...               | 2             | ...                             | P                               | ...                             | ...                            | 1 <sup>15</sup> / <sub>16</sub> | 5 <sup>7</sup> / <sub>8</sub>   | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 6   | 0.138                | 32                             | ...                            | ...               | 2             | P                               | PB                              | PB                              | PB                             | 2                               | 1 <sup>11</sup> / <sub>16</sub> | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 6   | 0.138                | ...                            | 40                             | ...               | 2             | ...                             | PB                              | ...                             | ...                            | 2                               | 1 <sup>11</sup> / <sub>16</sub> | 3 <sup>7</sup> / <sub>16</sub> | 0.141                | 0.110             |
| 8   | 0.164                | 32                             | ...                            | ...               | 2             | P                               | PB                              | PB                              | PB                             | 2 <sup>3</sup> / <sub>8</sub>   | 3 <sup>7</sup> / <sub>4</sub>   | 1 <sup>1</sup> / <sub>4</sub>  | 0.168                | 0.131             |
| 8   | 0.164                | ...                            | 36                             | ...               | 2             | ...                             | P                               | ...                             | ...                            | 2 <sup>3</sup> / <sub>8</sub>   | 3 <sup>7</sup> / <sub>4</sub>   | 1 <sup>1</sup> / <sub>4</sub>  | 0.168                | 0.131             |
| 10  | 0.190                | 24                             | ...                            | ...               | 2             | P                               | PB                              | PB                              | P                              | 2 <sup>3</sup> / <sub>8</sub>   | 7 <sup>7</sup> / <sub>8</sub>   | 1 <sup>1</sup> / <sub>4</sub>  | 0.194                | 0.152             |
| 10  | 0.190                | ...                            | 32                             | ...               | 2             | PB                              | PB                              | PB                              | P                              | 2 <sup>3</sup> / <sub>8</sub>   | 7 <sup>7</sup> / <sub>8</sub>   | 1 <sup>1</sup> / <sub>4</sub>  | 0.194                | 0.152             |
| 12  | 0.216                | 24                             | ...                            | ...               | 2             | ...                             | ...                             | PB                              | ...                            | 2 <sup>3</sup> / <sub>8</sub>   | 1 <sup>5</sup> / <sub>16</sub>  | 9 <sup>7</sup> / <sub>32</sub> | 0.220                | 0.165             |
| 12  | 0.216                | ...                            | 28                             | ...               | 2             | ...                             | ...                             | P                               | ...                            | 2 <sup>3</sup> / <sub>8</sub>   | 1 <sup>5</sup> / <sub>16</sub>  | 9 <sup>7</sup> / <sub>32</sub> | 0.220                | 0.165             |
| High-Speed and Carbon Steel Taps with Cut Threads |                      |                                |                                |                   |               |                                 |                                 |                                 |                                |                                 |                                 |                                |                      |                   |
| Size  | Basic Major Diameter | Threads per Inch               |                                |                   |               | No. of Flutes                   | Length Overall, A               | Length of Thread, B             | Length of Square, C            | Diameter of Shank, D            | Size of Square, E               |                                |                      |                   |
|   |                      | Carbon Steel                   |                                | HS Steel          |               |                                 |                                 |                                 |                                |                                 |                                 |                                |                      |                   |
|   |                      | NC UNC                         | NF UNF                         | NC UNC            | NF UNF        |                                 |                                 |                                 |                                |                                 |                                 |                                |                      |                   |
| 4   | 0.112                | ...                            | ...                            | 40                | ...           | 2                               | 1 <sup>7</sup> / <sub>8</sub>   | 9 <sup>7</sup> / <sub>16</sub>  | 3 <sup>7</sup> / <sub>16</sub> | 0.141                           | 0.110                           |                                |                      |                   |
| 5   | 0.125                | ...                            | ...                            | 40                | ...           | 2                               | 1 <sup>15</sup> / <sub>16</sub> | 5 <sup>7</sup> / <sub>8</sub>   | 3 <sup>7</sup> / <sub>16</sub> | 0.141                           | 0.110                           |                                |                      |                   |
| 6   | 0.138                | 32                             | ...                            | 32                | ...           | 2                               | 2                               | 1 <sup>11</sup> / <sub>16</sub> | 3 <sup>7</sup> / <sub>16</sub> | 0.141                           | 0.110                           |                                |                      |                   |
| 8   | 0.164                | 32                             | ...                            | 32                | ...           | 2                               | 2 <sup>3</sup> / <sub>8</sub>   | 3 <sup>7</sup> / <sub>4</sub>   | 1 <sup>1</sup> / <sub>4</sub>  | 0.168                           | 0.131                           |                                |                      |                   |
| 10  | 0.190                | 24                             | 32                             | 24                | 32            | 2                               | 2 <sup>3</sup> / <sub>8</sub>   | 7 <sup>7</sup> / <sub>8</sub>   | 1 <sup>1</sup> / <sub>4</sub>  | 0.194                           | 0.152                           |                                |                      |                   |
| 12  | 0.216                | ...                            | ...                            | 24                | ...           | 2                               | 2 <sup>3</sup> / <sub>8</sub>   | 1 <sup>5</sup> / <sub>16</sub>  | 9 <sup>7</sup> / <sub>32</sub> | 0.220                           | 0.165                           |                                |                      |                   |
| Tolerances for General Dimensions                 |                      |                                |                                |                   |               |                                 |                                 |                                 |                                |                                 |                                 |                                |                      |                   |
| Element   | Size Range           | Tolerance                      |                                | Element           | Size Range    | Tolerance                       |                                 |                                 |                                |                                 |                                 |                                |                      |                   |
|   |                      | Ground Thread                  | Cut Thread                     |                   |               | Ground Thread                   | Cut Thread                      |                                 |                                |                                 |                                 |                                |                      |                   |
| Overall Length, A                                 | 0 to 12              | ± <sup>1</sup> / <sub>32</sub> | ± <sup>1</sup> / <sub>32</sub> | Shank Diameter, D | 0 to 12       | -0.0015                         | -0.004                          |                                 |                                |                                 |                                 |                                |                      |                   |
| Thread Length, B                                  | 0 to 12              | ± <sup>3</sup> / <sub>64</sub> | ± <sup>3</sup> / <sub>64</sub> | Size of Square, E | 0 to 12       | -0.004                          | -0.004                          |                                 |                                |                                 |                                 |                                |                      |                   |
| Square Length, C                                  | 0 to 12              | ± <sup>1</sup> / <sub>32</sub> | ± <sup>1</sup> / <sub>32</sub> |                   |               |                                 |                                 |                                 |                                |                                 |                                 |                                |                      |                   |

All dimensions are in inches. Chamfer designations are: P = plug and B = bottoming. Cut thread taps are standard with plug chamfer only. Style 1 ground thread taps have external centers on thread and shank ends (may be removed on thread end of bottoming taps). Style 1 cut thread taps have optional style centers on thread and shank ends. Standard thread limits for ground threads are given in Table 3 and for cut threads in Table 5. For eccentricity tolerances see Table 22.

**Table 11. ANSI Standard Spiral Pointed Only and Regular and Fast Spiral-Fluted Taps — Machine Screw Sizes ASME B94.9-1999**

| STYLE 1  |                      |                  |        |                                 |   |     |                                 |                                |                     |                      |                   |
|--|----------------------|------------------|--------|---------------------------------|---|-----|---------------------------------|--------------------------------|---------------------|----------------------|-------------------|
| <p style="text-align: center;"><b>SPIRAL POINTED ONLY TAPS</b></p>   |                      |                  |        |                                 |   |     |                                 |                                |                     |                      |                   |
| <p style="text-align: center;"><b>REGULAR SPIRAL FLUTED TAPS</b></p> |                      |                  |        |                                 |   |     |                                 |                                |                     |                      |                   |
| <p style="text-align: center;"><b>FAST SPIRAL FLUTED TAPS</b></p>    |                      |                  |        |                                 |   |     |                                 |                                |                     |                      |                   |
| Size   | Basic Major Diameter | Threads per Inch |        | No. of Flutes                   | Pitch Dia. Limits & Chamfers <sup>a</sup> |     | Length Overall, A               | Length of Thread, B            | Length of Square, C | Diameter of Shank, D | Size of Square, E |
|  |                      | NC UNC           | NF UNF |                                 | H2  | H3  |                                 |                                |                     |                      |                   |
| 3 <sup>b</sup>   | 0.099                | 48               | ...    | 2                               | PB  | ... | 1 <sup>13</sup> / <sub>16</sub> | 1/2                            | 3/16                | 0.141                | 0.110             |
| 4  | 0.112                | 40               | ...    | 2                               | PB  | ... | 1 <sup>7</sup> / <sub>8</sub>   | 9/16                           | 3/16                | 0.141                | 0.110             |
| 5  | 0.125                | 40               | ...    | 2                               | PB  | ... | 1 <sup>15</sup> / <sub>16</sub> | 5/8                            | 3/16                | 0.141                | 0.110             |
| 6  | 0.138                | 32               | ...    | 2                               | ...                                       | PB  | 2                               | 1 <sup>1</sup> / <sub>16</sub> | 3/16                | 0.141                | 0.110             |
| 8  | 0.164                | 32               | ...    | 2 <sup>c</sup> , 3 <sup>b</sup> | ...                                       | PB  | 2 <sup>1</sup> / <sub>8</sub>   | 3/4                            | 1/4                 | 0.168                | 0.131             |
| 10   | 0.190                | 24               | 32     | 2 <sup>c</sup> , 3 <sup>b</sup> | ...                                       | PB  | 2 <sup>3</sup> / <sub>8</sub>   | 7/8                            | 1/4                 | 0.194                | 0.152             |
| 12 <sup>d</sup>  | 0.216                | 24               | ...    | 2 <sup>c</sup> , 3 <sup>b</sup> | ...                                       | PB  | 2 <sup>3</sup> / <sub>8</sub>   | 1 <sup>5</sup> / <sub>16</sub> | 9/32                | 0.220                | 0.165             |

<sup>a</sup> Bottom chamfer applies only to regular and fast spiral-fluted machine screw taps.

<sup>b</sup> Applies only to fast spiral-fluted machine screw taps.

<sup>c</sup> Does not apply to fast spiral-fluted machine screw taps.

<sup>d</sup> Does not apply to regular spiral-fluted machine screw taps.

| Tolerances for General Dimensions |            |            |                   |            |           |
|-----------------------------------|------------|------------|-------------------|------------|-----------|
| Element                           | Size Range | Tolerance  | Element           | Size Range | Tolerance |
| Overall Length, A                 | 3 to 12    | $\pm 1/32$ | Shank Diameter, D | 3 to 12    | -0.0015   |
| Thread Length, B                  | 3 to 12    | $\pm 3/64$ | Size of Square, E | 3 to 12    | -0.004    |
| Square Length, C                  | 3 to 12    | $\pm 1/32$ |                   |            |           |

All dimensions are given in inches. These standard taps are made of high-speed steel with ground threads. For standard thread limits see [Table 3](#). For eccentricity tolerances see [Table 22](#).

**Spiral Pointed Only Taps:** These taps are standard with plug chamfer only. They are provided with a spiral point only; the balance of the threaded section is left unfluted. These Style 1 taps have external centers on thread and shank ends.

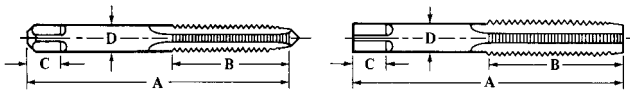
**Regular Spiral Fluted Taps:** These taps have right-hand spiral flutes with a helix angle of from 25 to 35 degrees.

**Fast Spiral Fluted Taps:** These taps have right-hand spiral flutes with a helix angle of from 45 to 60 degrees.

Both regular and fast spiral-fluted Style 1 taps have external centers on thread and shank ends (may be removed on thread end of bottoming taps).

Chamfer designations: P = plug and B = bottoming.

**Table 12a. ANSI Standard Ground Thread Straight Fluted Taps  
Fractional Sizes ASME B94.9-1999**



| Dia. of Tap        | Threads per Inch |                 | No. of Flutes | Pitch Diameter Limits and Chamfers |     |     |     |     | Dimensions        |                     |                     |                  |                   |
|--------------------|------------------|-----------------|---------------|------------------------------------|-----|-----|-----|-----|-------------------|---------------------|---------------------|------------------|-------------------|
|                    | NC UNC           | NF UNF          |               | H1                                 | H2  | H3  | H4  | H5  | Length Overall, A | Length of Thread, B | Length of Square, C | Dia. of Shank, D | Size of Square, E |
|                    | 1/4              | 20              |               | ...                                | 4   | TPB | TPB | TPB | ...               | PB                  | 2 1/2               | 1                | 5/16              |
| ...                | ...              | 28              | 4             | PB                                 | PB  | TBP | PB  | ... | 2 1/2             | 1                   | 5/16                | 0.255            | 0.191             |
| 5/16               | 18               | ...             | 4             | PB                                 | PB  | TPB | ... | PB  | 2 23/32           | 1 1/8               | 3/8                 | 0.318            | 0.238             |
| ...                | ...              | 24              | 4             | PB                                 | P   | TPB | PB  | ... | 2 23/32           | 1 1/8               | 3/8                 | 0.318            | 0.238             |
| 3/8                | 16               | ...             | 4             | PB                                 | PB  | TPB | ... | PB  | 2 15/16           | 1 1/4               | 7/16                | 0.381            | 0.286             |
| ...                | ...              | 24              | 4             | PB                                 | PB  | TPB | PB  | ... | 2 15/16           | 1 1/4               | 7/16                | 0.381            | 0.286             |
| 7/16               | 14               | 20              | 4             | ...                                | ... | TPB | ... | PB  | 3 5/32            | 1 7/16              | 13/32               | 0.323            | 0.242             |
| 1/2                | 13               | ...             | 4             | P                                  | ... | TPB | ... | PB  | 3 3/8             | 1 21/32             | 7/16                | 0.367            | 0.275             |
| ...                | ...              | 20              | 4             | PB                                 | ... | TPB | ... | P   | 3 3/8             | 1 21/32             | 7/16                | 0.367            | 0.275             |
| 9/16               | 12               | ...             | 4             | ...                                | ... | TPB | ... | P   | 3 9/32            | 1 21/32             | 1/2                 | 0.429            | 0.322             |
| ...                | ...              | 18              | 4             | ...                                | P   | TPB | ... | P   | 3 9/32            | 1 21/32             | 1/2                 | 0.429            | 0.322             |
| 5/8                | 11               | ...             | 4             | ...                                | P   | TPB | ... | PB  | 3 13/16           | 1 13/16             | 9/16                | 0.480            | 0.360             |
| ...                | ...              | 18              | 4             | ...                                | P   | TPB | ... | PB  | 3 13/16           | 1 13/16             | 9/16                | 0.480            | 0.360             |
| 11/16 <sup>a</sup> | ...              | ...             | 4             | ...                                | ... | TPB | ... | ... | 4 1/32            | 1 13/16             | 5/8                 | 0.542            | 0.406             |
| 3/4                | 10               | ...             | 4             | ...                                | P   | TPB | ... | PB  | 4 1/4             | 2                   | 11/16               | 0.590            | 0.442             |
| ...                | ...              | 16              | 4             | P                                  | P   | TPB | ... | PB  | 4 1/4             | 2                   | 11/16               | 0.590            | 0.442             |
| 7/8 <sup>b</sup>   | 9                | ...             | 4             | ...                                | ... | ... | TPB | ... | 4 11/16           | 2 7/32              | 3/4                 | 0.697            | 0.523             |
| ...                | ...              | 14              | 4             | ...                                | P   | ... | TPB | ... | 4 11/16           | 2 7/32              | 3/4                 | 0.697            | 0.523             |
| 1 <sup>b</sup>     | 8                | ...             | 4             | ...                                | ... | ... | TPB | ... | 5 5/8             | 2 1/2               | 13/16               | 0.800            | 0.600             |
| 1                  | ...              | 12              | 4             | ...                                | ... | ... | TPB | ... | 5 5/8             | 2 1/2               | 13/16               | 0.800            | 0.600             |
| 1 <sup>c</sup>     | ...              | ...             | 4             | ...                                | ... | ... | TPB | ... | 5 7/8             | 2 1/2               | 13/16               | 0.800            | 0.600             |
| 1 1/8              | 7                | 12              | 4             | ...                                | ... | ... | TPB | ... | 5 7/8             | 2 1/2               | 13/16               | 0.896            | 0.672             |
| 1 1/4              | 7                | 12 <sup>d</sup> | 4             | ...                                | ... | ... | TPB | ... | 5 3/4             | 2 9/16              | 1                   | 1.021            | 0.766             |
| 1 3/8              | 6                | 12 <sup>d</sup> | 4             | ...                                | ... | ... | TPB | ... | 6 1/16            | 3                   | 1 1/16              | 1.108            | 0.831             |
| 1 1/2              | 6                | 12 <sup>d</sup> | 4             | ...                                | ... | ... | TPB | ... | 6 3/8             | 3                   | 1 1/8               | 1.233            | 0.925             |

<sup>a</sup> This size has 11 or 16 threads per inch NS-UNS.  
<sup>b</sup> These sizes are also available with plug chamfer in H6 pitch diameter limits.  
<sup>c</sup> This size has 14 threads per inch NS-UNS.  
<sup>d</sup> In these sizes NF-UNF thread taps have six flutes.

| Tolerances for General Dimensions |                     |           |                      |                      |           |
|-----------------------------------|---------------------|-----------|----------------------|----------------------|-----------|
| Element                           | Diameter Range      | Tolerance | Element              | Diameter Range       | Tolerance |
| Length Overall, A                 | 1/4 to 1 incl       | ±1/32     | Diameter of Shank, D | 1/4 to 3/8 incl      | -0.0015   |
|                                   | 1 1/8 to 1 1/2 incl | ±1/16     |                      | 1 1/16 to 1 1/2 incl | -0.002    |
| Length of Thread, B               | 1/4 to 1/2 incl     | ±1/16     | Size of Square, E    | 1/4 to 1/2 incl      | -0.004    |
|                                   | 3/16 to 1 1/2 incl  | ±3/32     |                      | 9/16 to 1 incl       | -0.006    |
| Length of Square, C               | 1/4 to 1 incl       | ±1/32     | 1 1/8 to 1 1/2 incl  | -0.008               |           |
|                                   | 1 1/8 to 1 1/2 incl | ±1/16     |                      |                      |           |

All dimensions are given in inches.  
 These taps are standard in high-speed steel.  
 Chamfer designations are: T = taper, P = plug, and B = bottoming.  
 Style 2 taps, 3/8 inch and smaller, have external center on thread end (may be removed on bottoming taps) and external partial cone center on shank end with length of come approximately one-quarter of diameter of shank.  
 Style 3 taps, larger than 3/8 inch, have internal center in thread and shank ends.  
 For standard thread limits see Table 2. For eccentricity tolerances see Table 22.



TAPS AND THREADING DIES

**Table 12b. ANSI Standard Cut Thread Straight Fluted Taps**  
**Fractional Sizes ASME B94.9-1999**

| Dia. of Tap | Threads Per Inch   |                  |                 |          |        | No. of Flutes | Dimensions        |                     |                     |                  |                   |
|-------------|--------------------|------------------|-----------------|----------|--------|---------------|-------------------|---------------------|---------------------|------------------|-------------------|
|             | Carbon Steel       |                  |                 | HS Steel |        |               | Length Overall, A | Length of Thread, B | Length of Square, C | Dia. of Shank, D | Size of Square, E |
|             | NC UNC             | NF UNF           | NS UNS          | NC UNC   | NF UNF |               |                   |                     |                     |                  |                   |
| 1/8         | ...                | ...              | 40              | ...      | ...    | 3             | 1 15/16           | 5/8                 | 3/16                | 0.141            | 0.110             |
| 5/32        | ...                | ...              | 32              | ...      | ...    | 4             | 2 1/8             | 3/4                 | 1/4                 | 0.168            | 0.131             |
| 3/16        | ...                | ...              | 24, 32          | ...      | ...    | 4             | 2 3/8             | 7/8                 | 1/4                 | 0.194            | 0.152             |
| 1/4         | 20                 | 28               | ...             | 20       | 28     | 4             | 2 1/2             | 1                   | 5/16                | 0.255            | 0.191             |
| 5/16        | 18                 | 24               | ...             | 18       | 24     | 4             | 2 23/32           | 1 1/8               | 3/8                 | 0.318            | 0.238             |
| 3/8         | 16                 | 24               | ...             | 16       | 24     | 4             | 2 15/16           | 1 1/4               | 7/16                | 0.381            | 0.286             |
| 7/16        | 14                 | 20               | ...             | 14       | 20     | 4             | 3 5/32            | 1 7/16              | 13/32               | 0.323            | 0.242             |
| 1/2         | 13                 | 20               | ...             | 13       | 20     | 4             | 3 3/8             | 1 23/32             | 7/16                | 0.367            | 0.275             |
| 9/16        | 12                 | 18               | ...             | 12       | ...    | 4             | 3 9/32            | 1 21/32             | 1/2                 | 0.429            | 0.322             |
| 5/8         | 11                 | 18               | ...             | 11       | 18     | 4             | 3 13/16           | 1 13/16             | 9/16                | 0.480            | 0.360             |
| 3/4         | 10                 | 16               | ...             | 10       | 16     | 4             | 4 1/4             | 2                   | 1 1/16              | 0.590            | 0.442             |
| 7/8         | 9                  | 14               | ...             | 9        | 14     | 4             | 4 1 1/16          | 2 7/32              | 3/4                 | 0.697            | 0.523             |
| 1           | 8                  | ...              | 14 <sup>a</sup> | 8        | ...    | 4             | 5 1/8             | 2 1/2               | 13/16               | 0.800            | 0.600             |
| 1 1/8       | 7                  | 12               | ...             | ...      | ...    | 4             | 5 7/16            | 2 9/16              | 7/8                 | 0.896            | 0.672             |
| 1 1/4       | 7                  | 12 <sup>b</sup>  | ...             | ...      | ...    | 4             | 5 3/4             | 2 9/16              | 1                   | 1.021            | 0.766             |
| 1 3/8       | 6 <sup>a</sup>     | 12 <sup>ba</sup> | ...             | ...      | ...    | 4             | 6 1/16            | 3                   | 1 1/16              | 1.108            | 0.831             |
| 1 1/2       | 6                  | 12 <sup>ba</sup> | ...             | ...      | ...    | 4             | 6 3/8             | 3                   | 1 3/8               | 1.233            | 0.925             |
| 1 3/4       | 5 <sup>a</sup>     | ...              | ...             | ...      | ...    | 6             | 7                 | 3 3/16              | 1 3/4               | 1.430            | 1.072             |
| 2           | 4 1/2 <sup>a</sup> | ...              | ...             | ...      | ...    | 6             | 7 5/8             | 3 9/16              | 1 3/8               | 1.644            | 1.233             |

<sup>a</sup> Standard in plug chamfer only.

<sup>b</sup> In these sizes NF-UNF thread taps have six flutes.

| Tolerances for General Dimensions |               |           |                      |                   |           |
|-----------------------------------|---------------|-----------|----------------------|-------------------|-----------|
| Elements                          | Range         | Tolerance | Elements             | Tolerance         |           |
| Length Overall, A                 | 1/16 to 1     | ±1/32     | Diameter of Shank, D | -0.004            |           |
|                                   | 1 1/8 to 2    | ±1/16     |                      |                   |           |
| Length of Thread, B               | 1/16 to 3/16  | ±1/64     |                      | Size of Square, E | -0.007    |
|                                   | 1/4 to 1/2    | ±1/16     |                      |                   |           |
|                                   | 5/16 to 1 1/2 | ±3/32     |                      |                   |           |
| Length of Square, C               | 1 1/8 to 2    | ±1/8      | 1/16 to 1/2          | -0.004            |           |
|                                   | 1/16 to 1     | ±1/32     |                      |                   | 1/16 to 1 |
|                                   | 1 1/8 to 2    | ±1/16     | 1/8 to 2             | -0.008            |           |

All dimensions are given in inches.

These taps are standard in carbon steel and high-speed steel.

Except where indicated, these taps are standard with taper, plug, or bottoming chamfer.

Cut thread taps, sizes 3/8 inch and smaller have optional style center on thread and shank ends; sizes larger than 3/8 inch have internal centers in thread and shank ends.

For standard thread limits see Table 1. For eccentricity tolerances see Table 22.

**Table 13. ANSI Standard Straight Fluted (Optional Number of Flutes) and Spiral Pointed Taps—Fractional Sizes ASME B94.9-1999**

| Dia. of Tap  | Threads per Inch |                 | No. of Flutes | Pitch Diameter Limits and Chamfers <sup>ab</sup> |                |    |     |                | Length Overall, A | Length of Thread, B | Length of Square, C | Dia. of Shank, D | Size of Square, E |  |
|--|------------------|-----------------|---------------|--|----------------|----|-----|----------------|-------------------|---------------------|---------------------|------------------|-------------------|--|
|  | NC, UNC          | NF, UNF         |               | H1   | H2             | H3 | H4  | H5             |                   |                     |                     |                  |                   |  |
| Ground Thread High-Speed-Steel Straight Fluted Taps                                |                  |                 |               |  |                |    |     |                |                   |                     |                     |                  |                   |  |
| 1/4  | 20               | ...             | 2             | ...  | ...            | PB | ... | ...            | 2 1/2             | 1                   | 5/16                | 0.255            | 0.191             |  |
| 1/4  | 20               | ...             | 3             | P  | P              | PB | ... | P              | 2 1/2             | 1                   | 5/16                | 0.255            | 0.191             |  |
| 1/4  | ...              | 28              | 2, 3          | ...  | ...            | PB | ... | ...            | 2 1/2             | 1                   | 5/16                | 0.255            | 0.191             |  |
| 5/16   | 18               | ...             | 2             | ...  | ...            | PB | ... | ...            | 2 3/32            | 1 1/8               | 3/8                 | 0.318            | 0.238             |  |
| 5/16   | 18               | ...             | 3             | ...  | ...            | PB | ... | ...            | 2 3/32            | 1 1/8               | 3/8                 | 0.318            | 0.238             |  |
| 5/16   | ...              | 24              | 3             | ...  | ...            | PB | ... | ...            | 2 3/32            | 1 1/8               | 3/8                 | 0.318            | 0.238             |  |
| 3/8  | 16               | ...             | 3             | ...  | ...            | PB | ... | ...            | 2 15/16           | 1 1/4               | 7/16                | 0.381            | 0.286             |  |
| 3/8  | ...              | 24              | 3             | ...  | ...            | PB | ... | ...            | 2 15/16           | 1 1/4               | 7/16                | 0.381            | 0.286             |  |
| 7/16   | 14               | ...             | 3             | ...  | ...            | P  | ... | ...            | 3 5/32            | 1 7/16              | 13/32               | 0.323            | 0.242             |  |
| 7/16   | ...              | 20              | 3             | ...  | ...            | P  | ... | ...            | 3 5/32            | 1 7/16              | 13/32               | 0.323            | 0.242             |  |
| 1/2  | 13               | ...             | 3             | ...  | ...            | PB | ... | ...            | 3 3/8             | 1 21/32             | 7/16                | 0.367            | 0.275             |  |
| 1/2  | ...              | 20              | 3             | ...  | ...            | P  | ... | ...            | 3 3/8             | 1 21/32             | 7/16                | 0.367            | 0.275             |  |
| Ground Thread High-Speed-Steel and Cut Thread High-Speed-Steel Spiral Pointed Taps |                  |                 |               |  |                |    |     |                |                   |                     |                     |                  |                   |  |
| 1/4  | 20               | ...             | 2             | P  | P              | PB | ... | P              | 2 1/2             | 1                   | 5/16                | 0.255            | 0.191             |  |
| 1/4 <sup>a</sup>   | 20               | ...             | 3             | ...  | ...            | P  | ... | P              | 2 1/2             | 1                   | 5/16                | 0.255            | 0.191             |  |
| 1/4  | ...              | 28              | 2             | P  | P              | PB | P   | ...            | 2 1/2             | 1                   | 5/16                | 0.255            | 0.191             |  |
| 1/4 <sup>a</sup>   | ...              | 28              | 3             | ...  | ...            | P  | ... | P              | 2 1/2             | 1                   | 5/16                | 0.255            | 0.191             |  |
| 5/16   | 18               | ...             | 2             | P  | P              | PB | ... | P              | 2 3/32            | 1 1/8               | 3/8                 | 0.318            | 0.238             |  |
| 5/16 <sup>a</sup>  | 18               | ...             | 3             | ...  | ...            | P  | ... | P              | 2 3/32            | 1 1/8               | 3/8                 | 0.318            | 0.238             |  |
| 5/16   | ...              | 24              | 2             | P  | P              | PB | P   | ...            | 2 3/32            | 1 1/8               | 3/8                 | 0.318            | 0.238             |  |
| 5/16 <sup>a</sup>  | ...              | 24              | 3             | ...  | P              | P  | P   | ...            | 2 3/32            | 1 1/8               | 3/8                 | 0.318            | 0.238             |  |
| 3/8  | 16               | ...             | 3             | P  | P              | P  | ... | P              | 2 15/16           | 1 1/4               | 7/16                | 0.381            | 0.286             |  |
| 3/8  | ...              | 24              | 3             | P  | P              | P  | ... | P              | 2 15/16           | 1 1/4               | 7/16                | 0.381            | 0.286             |  |
| 7/16 <sup>a</sup>  | 14               | 20              | 3             | ...  | P <sup>c</sup> | P  | ... | P              | 3 5/32            | 1 7/16              | 13/32               | 0.323            | 0.242             |  |
| 1/2  | 13               | 20 <sup>a</sup> | 3             | P  | P              | P  | ... | P              | 3 3/8             | 1 21/32             | 7/16                | 0.367            | 0.275             |  |
| 3/4 <sup>a</sup>   | 11               | 18              | 3             | ...  | ...            | P  | ... | P <sup>d</sup> | 3 13/16           | 1 13/16             | 9/16                | 0.480            | 0.360             |  |
| 3/4 <sup>a</sup>   | 10               | 16              | 3             | ...  | ...            | P  | ... | P <sup>e</sup> | 4 1/4             | 2                   | 1 1/16              | 0.590            | 0.442             |  |

<sup>a</sup> Applies only to ground thread high-speed-steel taps.  
<sup>b</sup> Cut thread high-speed-steel taps are standard with plug chamfer only.  
<sup>c</sup> Applies only to 7/16-14 tap.  
<sup>d</sup> Applies only to 5/8-11 tap.  
<sup>e</sup> Applies only to 3/4-10 tap. For eccentricity tolerances see Table 22.

| Tolerances for General Dimensions |                |               |            |                   |                |                    |               |
|-----------------------------------|----------------|---------------|------------|-------------------|----------------|--------------------|---------------|
| Element                           | Diameter Range | Tolerance     |            | Element           | Diameter Range | Tolerance          |               |
|                                   |                | Ground Thread | Cut Thread |                   |                | Ground Thread      | Cut Thread    |
| Overall Length, A                 | 1/4 to 3/4     | ±1/32         | ±1/32      | Shank Diameter, D | 1/4 to 5/8     | -0.0015<br>-0.0020 | -0.005<br>... |
| Thread Length, B                  | 1/4 to 1/2     | ±1/16         | ±1/16      | Size of Square, E | 1/4 to 1/2     | -0.0040<br>-0.0060 | -0.004<br>... |
| Square Length, C                  | 1/4 to 3/4     | ±1/32         |            |                   | 3/8 to 3/4     |                    |               |

All dimensions are given in inches. P = plug and B = bottoming. Ground thread taps — Style 2, 3/8 inch and smaller, have external center on thread end (may be removed on bottoming taps) and external partial cone center on shank end, with length of cone approximately 1/4 of shank diameter. Ground thread taps—Style 3, larger than 3/8 inch, have internal center in thread and shank ends. Cut thread-taps, 3/8 inch and smaller have optional style center on thread and shank ends; sizes larger than 3/8 inch have internal centers in thread and shank ends. For standard thread limits see Tables 1 and 2.

Table 14. Other Types of ANSI Standard Taps ASME B94.9-1999

| Dia. of Tap       | Threads per Inch |                 | Number of Flutes                  | Length Overall, A | Length of Thread, B | Length of Square, C | Dia. of Shank, D | Size of Square, E |
|-------------------|------------------|-----------------|-----------------------------------|-------------------|---------------------|---------------------|------------------|-------------------|
|                   | NC UNC           | NF UNF          |                                   |                   |                     |                     |                  |                   |
| 1/4               | 20               | 28 <sup>a</sup> | 2 <sup>b,c</sup> , 3 <sup>a</sup> | 2 1/2             | 1                   | 5/16                | 0.255            | 0.191             |
| 5/16              | 18               | 24 <sup>a</sup> | 2 <sup>d</sup> , 3 <sup>a</sup>   | 2 23/32           | 1 1/8               | 3/8                 | 0.318            | 0.238             |
| 3/8               | 16               | 24 <sup>a</sup> | 3                                 | 2 15/16           | 1 1/4               | 7/16                | 0.381            | 0.286             |
| 7/16 <sup>e</sup> | 14               | 20              | 3                                 | 3 3/32            | 1 7/16              | 13/32               | 0.323            | 0.242             |
| 1/2               | 13               | 20 <sup>a</sup> | 3                                 | 3 3/8             | 1 23/32             | 7/16                | 0.367            | 0.275             |

<sup>a</sup> Does not apply to spiral pointed only taps.

<sup>b</sup> Does not apply to spiral fluted taps with 28 threads per inch.

<sup>c</sup> Does not apply to fast spiral fluted taps.

<sup>d</sup> Applies only to spiral pointed only taps.

<sup>e</sup> Applies only to fast spiral fluted taps.

| Tolerances for General Dimensions |                |           |                   |                |           |
|-----------------------------------|----------------|-----------|-------------------|----------------|-----------|
| Element                           | Diameter Range | Tolerance | Element           | Diameter Range | Tolerance |
| Overall Length, A                 | 1/4 to 1/2     | ±1/32     | Shank Diameter, D | 1/4 to 1/2     | -0.0015   |
| Thread Length, B                  | 1/4 to 1/2     | ±1/16     | Size of Square, E | 1/4 to 1/2     | -0.004    |
| Square Length, C                  | 1/4 to 1/2     | ±1/32     |                   |                |           |

All dimensions are given in inches. These standard taps are made of high-speed steel with ground threads. For standard thread limits see Table 2.

**Spiral Pointed Only Taps:** These taps are standard with plug chamfer only in H3 limit. They are provided with spiral point only. The balance of the threaded section is left unfluted.

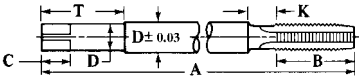
**Spiral Fluted Taps:** These taps are standard with plug or bottoming chamfer in H3 limit and have right-hand spiral flutes with a helix angle of from 25 to 35 degrees.

**Fast Spiral Fluted Taps:** These taps are standard with plug or bottoming chamfer in H3 limit and have right-hand spiral flutes with a helix angle of from 45 to 60 degrees.

Style 2 taps, 3/8 inch and smaller, have external center on thread end (may be removed on bottoming taps) and external partial cone center on shank end with cone length approximately 1/4 shank diameter.

Style 3 taps larger than 3/8 inch have internal center in thread and shank ends.

For standard thread limits see Table 2. For eccentricity tolerances see Table 22.

**Table 15. ANSI Standard Pulley Taps ASME B94.9-1999**


| Dia. of Tap | Threads per Inch NC UNC | Number of Flutes | Length Overall, A | Length of Thread, B | Length of Square, C | Dia. of Shank, D | Length of Shank Close Tolerance, T <sup>a</sup> | Size of Square, E <sup>b</sup> | Length of Neck, K <sup>c</sup> |
|-------------|-------------------------|------------------|-------------------|---------------------|---------------------|------------------|---|--------------------------------|--------------------------------|
| 1/4         | 20                      | 4                | 6, 8              | 1.00                | 0.31                | 0.2550           | 1.50  | 0.191                          | 0.38                           |
| 5/16        | 18                      | 4                | 6, 8              | 1.13                | 0.38                | 0.3180           | 1.56  | 0.238                          | 0.38                           |
| 3/8         | 16                      | 4                | 6, 8, 10          | 1.25                | 0.44                | 0.3810           | 1.63  | 0.286                          | 0.38                           |
| 7/16        | 14                      | 4                | 6, 8              | 1.44                | 0.50                | 0.4440           | 1.69  | 0.333                          | 0.44                           |
| 1/2         | 13                      | 4                | 6, 8, 10, 12      | 1.66                | 0.56                | 0.5070           | 1.69  | 0.380                          | 0.50                           |
| 5/8         | 11                      | 4                | 6,8,10,12         | 1.81                | 0.69                | 0.6330           | 2.00  | 0.475                          | 0.63                           |
| 3/4         | 10                      | 4                | 10, 12            | 2.00                | 0.75                | 0.7590           | 2.25  | 0.569                          | 0.75                           |

<sup>a</sup> T is minimum length of shank which is held to eccentricity tolerances.

<sup>b</sup> Size of square is equal to 0.75D to the nearest 0.001 inch.

<sup>c</sup> K neck optional with manufacturer.

Tolerances for General Dimensions

| Element           | Diameter Range | Tolerance | Element           | Diameter Range | Tolerance |
|-------------------|----------------|-----------|-------------------|----------------|-----------|
| Overall Length, A | 1/4 to 3/4     | ±0.06     | Shank Diameter, D | 1/4 to 3/4     | -0.0050   |
| Thread Length, B  | 1/4 to 3/4     | ±0.06     | Size of Square, E | 1/4 to 1/2     | -0.004    |
| Square Length, C  | 1/4 to 3/4     | ±0.03     |                   | 5/8 to 3/4     | -0.006    |

All dimensions are given in inches. These ground thread high-speed steel taps are standard with plug chamfer in H3 limit only. All taps have an internal center in thread end. For standard thread limits see Table 2. For eccentricity tolerances see Table 22.

**Table 16. ANSI Standard Ground Thread Spark Plug Taps Metric Sizes ASME B94.9-1999**

| Tap Diameter, mm | Pitch, mm | Number of Flutes | Overall Length, In. A           | Thread Length, In. B            | Square Length, In. C | Shank Dia., In. D | Square Size, In. E |
|------------------|-----------|------------------|---------------------------------|---------------------------------|----------------------|-------------------|--------------------|
| 14               | 1.25      | 4                | 3 <sup>19</sup> / <sub>32</sub> | 1 <sup>21</sup> / <sub>32</sub> | 1/2                  | 0.429             | 0.322              |
| 18               | 1.50      | 4                | 4 <sup>1</sup> / <sub>32</sub>  | 1 <sup>13</sup> / <sub>16</sub> | 5/8                  | 0.542             | 0.406              |

These are high-speed steel Style 3 taps and have internal center in thread and shank ends. They are standard with plug chamfer only, right-hand threads with 60-degree form of thread.

Tolerances: Overall length, ± 1/32 inch; thread length, ± 1/32 inch; square length, ± 1/32 inch; shank diameter, 14 mm, -0.0015 inch, 18 mm, -0.0020 inch; and size of square, -0.0040 inch.

TAPS AND THREADING DIES

**Table 17a. ANSI Standard Ground Thread Straight Fluted Taps  
M Profile — Metric Sizes ASME B94.9-1999**

| Nom. Dia. mm. | Pitch mm | No. of Flutes | Pitch Diameter Limits and Chamfers |     |     |     |     |     |     | Length Overall<br>A | Length of Thread<br>B | Length of Square<br>C | Dia. of Square<br>D | Size of Square<br>E |
|---------------|----------|---------------|------------------------------------|-----|-----|-----|-----|-----|-----|---------------------|-----------------------|-----------------------|---------------------|---------------------|
|               |          |               | D3                                 | D4  | D5  | D6  | D7  | D8  | D9  |                     |                       |                       |                     |                     |
| 1.6           | 0.35     | 2             | PB                                 | ... | ... | ... | ... | ... | ... | 1 $\frac{1}{8}$     | $\frac{5}{16}$        | $\frac{3}{16}$        | 0.141               | 0.110               |
| 2             | 0.4      | 3             | PB                                 | ... | ... | ... | ... | ... | ... | 1 $\frac{3}{4}$     | $\frac{7}{16}$        | $\frac{3}{16}$        | 0.141               | 0.110               |
| 2.5           | 0.45     | 3             | PB                                 | ... | ... | ... | ... | ... | ... | 1 $\frac{13}{16}$   | $\frac{1}{2}$         | $\frac{3}{16}$        | 0.141               | 0.110               |
| 3             | 0.5      | 3             | PB                                 | ... | ... | ... | ... | ... | ... | 1 $\frac{15}{16}$   | $\frac{5}{8}$         | $\frac{3}{16}$        | 0.141               | 0.110               |
| 3.5           | 0.6      | 3             | ...                                | PB  | ... | ... | ... | ... | ... | 2                   | $\frac{11}{16}$       | $\frac{3}{16}$        | 0.141               | 0.110               |
| 4             | 0.7      | 4             | ...                                | PB  | ... | ... | ... | ... | ... | 2 $\frac{1}{8}$     | $\frac{3}{4}$         | $\frac{1}{4}$         | 0.168               | 0.131               |
| 4.5           | 0.75     | 4             | ...                                | PB  | ... | ... | ... | ... | ... | 2 $\frac{3}{8}$     | $\frac{7}{8}$         | $\frac{1}{4}$         | 0.194               | 0.152               |
| 5             | 0.8      | 4             | ...                                | PB  | ... | ... | ... | ... | ... | 2 $\frac{3}{8}$     | $\frac{7}{8}$         | $\frac{1}{4}$         | 0.194               | 0.152               |
| 6             | 1        | 4             | ...                                | ... | PB  | ... | ... | ... | ... | 2 $\frac{1}{2}$     | 1                     | $\frac{5}{16}$        | 0.255               | 0.191               |
| 7             | 1        | 4             | ...                                | ... | PB  | ... | ... | ... | ... | 2 $\frac{29}{32}$   | 1 $\frac{1}{8}$       | $\frac{3}{8}$         | 0.318               | 0.238               |
| 8             | 1.25     | 4             | ...                                | ... | PB  | ... | ... | ... | ... | 2 $\frac{29}{32}$   | 1 $\frac{1}{8}$       | $\frac{3}{8}$         | 0.318               | 0.238               |
| 10            | 1.5      | 4             | ...                                | ... | ... | PB  | ... | ... | ... | 2 $\frac{15}{16}$   | 1 $\frac{1}{4}$       | $\frac{7}{16}$        | 0.381               | 0.286               |
| 12            | 1.75     | 4             | ...                                | ... | ... | PB  | ... | ... | ... | 3 $\frac{3}{8}$     | 1 $\frac{29}{32}$     | $\frac{7}{16}$        | 0.367               | 0.275               |
| 14            | 2        | 4             | ...                                | ... | ... | ... | PB  | ... | ... | 3 $\frac{19}{32}$   | 1 $\frac{29}{32}$     | $\frac{1}{2}$         | 0.429               | 0.322               |
| 16            | 2        | 4             | ...                                | ... | ... | ... | PB  | ... | ... | 3 $\frac{13}{16}$   | 1 $\frac{13}{16}$     | $\frac{9}{16}$        | 0.480               | 0.360               |
| 20            | 2.5      | 4             | ...                                | ... | ... | ... | PB  | ... | ... | 4 $\frac{15}{32}$   | 2                     | $\frac{11}{16}$       | 0.652               | 0.489               |
| 24            | 3        | 4             | ...                                | ... | ... | ... | ... | PB  | ... | 4 $\frac{29}{32}$   | 2 $\frac{7}{32}$      | $\frac{3}{4}$         | 0.760               | 0.570               |
| 30            | 3.5      | 4             | ...                                | ... | ... | ... | ... | ... | PB  | 5 $\frac{7}{16}$    | 2 $\frac{9}{16}$      | 1                     | 1.021               | 0.766               |
| 36            | 4        | 4             | ...                                | ... | ... | ... | ... | ... | PB  | 6 $\frac{1}{16}$    | 3                     | 1 $\frac{1}{8}$       | 1.233               | 0.925               |

| Tolerances        |  |   |                   |  |                            |
|-------------------|--|---|-------------------|--|----------------------------|
| Element           | Nom. Dia. Range, mm                                | Toler., Inch  | Element           | Nom. Dia. Range, mm                                    | Toler., Inch               |
| Overall Length, A | M1.6 to M24, incl.<br>M30 and M36                  | $\pm\frac{1}{32}$<br>$\pm\frac{1}{16}$                      | Shank Diameter, D | M1.6 to M14, incl.<br>M16 to M36                       | -0.0015<br>-0.002          |
| Thread Length, B  | M1.6 to M5, incl.<br>M6 to M12 incl.<br>M14 to M36 | $\pm\frac{3}{64}$<br>$\pm\frac{1}{16}$<br>$\pm\frac{3}{32}$ |                   |  |                            |
| Square Length, C  | M1.6 to M24, incl.<br>M30 and M36                  | $\pm\frac{1}{32}$<br>$\pm\frac{1}{16}$                      | Size of Square, E | M1.6 to M12, incl.<br>M14 to M24, incl.<br>M30 and M36 | -0.004<br>-0.006<br>-0.008 |

All dimensions are in inches except where otherwise stated.  
 Chamfer Designation: P — Plug, B — Bottoming. These taps are high-speed steel.  
 Style 1 taps, sizes M1.6 through M5, have external center on thread and shank ends (may be removed on thread end of bottoming taps).  
 Style 2 taps, sizes M6, M7, M8, and M10, have external center on thread end (may be removed on bottoming taps) and external partial cone center on shank end with length of cone approximately  $\frac{1}{4}$  of diameter of shank.  
 Style 3 taps, sizes larger than M10 have external center on thread and shank ends.  
 For standard thread limits see [Tables 4a](#) and [4b](#).  
 For eccentricity tolerances of tap elements see [Table 22](#).

**Table 17b. ANSI Standard Spiral Pointed Ground Thread Taps  
M Profile — Metric Sizes ASME B94.9-1999**

| Tolerances               |   |  |  |                          |                                  |   |                   |                  |  |  |  |  |
|--------------------------|---|--|--|--------------------------|----------------------------------|---|-------------------|------------------|--|--|--|--|
| Element                  | Nom. Dia. Range, mm                                 |  | Toler., Inch   | Element                  | Nom. Dia. Range, mm              |   | Toler., Inch      |                  |  |  |  |  |
| Overall Length, <i>A</i> | M1.6 to M20, incl.                                  |  | $\pm \frac{1}{32}$   | Shank Diameter, <i>D</i> | M1.6 to M14, incl.<br>M16 to M20 |   | -0.0015<br>-0.002 |                  |  |  |  |  |
| Thread Length, <i>B</i>  | M1.6 to M5, incl.<br>M16 to M12 incl.<br>M14 to M20 |  | $\pm \frac{3}{64}$<br>$\pm \frac{1}{16}$<br>$\pm \frac{3}{32}$ |                          | Size of Square, <i>E</i>         | M1.6 to M12, incl.<br>M14 to M20, incl. |                   | -0.004<br>-0.006 |  |  |  |  |
| Square Length, <i>C</i>  | M1.6 to M20   |  | $\pm \frac{1}{32}$   |                          |                                  |   |                   |                  |  |  |  |  |

| Nom. Dia. mm. | Pitch mm | No. of Flutes | Pitch Diameter Limits and Styles |     |     |     |     | Length Overall <i>A</i> | Length of Thread <i>B</i> | Length of Square <i>C</i> | Dia. of Square <i>D</i> | Size of Square <i>E</i> |
|---------------|----------|---------------|----------------------------------|-----|-----|-----|-----|-------------------------|---------------------------|---------------------------|-------------------------|-------------------------|
|               |          |               | D3                               | D4  | D5  | D6  | D7  |                         |                           |                           |                         |                         |
| 1.6           | 0.35     | 2             | P                                | ... | ... | ... | ... | $1\frac{5}{8}$          | $\frac{3}{16}$            | $\frac{3}{16}$            | 0.141                   | 0.110                   |
| 2             | 0.4      | 2             | P                                | ... | ... | ... | ... | $1\frac{3}{4}$          | $\frac{3}{16}$            | $\frac{3}{16}$            | 0.141                   | 0.110                   |
| 2.5           | 0.45     | 2             | P                                | ... | ... | ... | ... | $1\frac{13}{16}$        | $\frac{1}{2}$             | $\frac{3}{16}$            | 0.141                   | 0.110                   |
| 3             | 0.5      | 2             | P                                | ... | ... | ... | ... | $1\frac{15}{16}$        | $\frac{5}{8}$             | $\frac{3}{16}$            | 0.141                   | 0.110                   |
| 3.5           | 0.6      | 2             | ...                              | P   | ... | ... | ... | 2                       | $\frac{11}{16}$           | $\frac{3}{16}$            | 0.141                   | 0.110                   |
| 4             | 0.7      | 2             | ...                              | P   | ... | ... | ... | $2\frac{1}{8}$          | $\frac{3}{4}$             | $\frac{1}{4}$             | 0.168                   | 0.131                   |
| 5             | 0.8      | 2             | ...                              | P   | ... | ... | ... | $2\frac{3}{8}$          | $\frac{7}{8}$             | $\frac{1}{4}$             | 0.194                   | 0.152                   |
| 6             | 1        | 2             | ...                              | ... | P   | ... | ... | $2\frac{1}{2}$          | 1                         | $\frac{5}{16}$            | 0.255                   | 0.191                   |
| 8             | 1.25     | 2             | ...                              | ... | P   | ... | ... | $2\frac{23}{32}$        | $1\frac{1}{8}$            | $\frac{3}{8}$             | 0.318                   | 0.238                   |
| 10            | 1.5      | 3             | ...                              | ... | ... | P   | ... | $2\frac{15}{16}$        | $1\frac{1}{4}$            | $\frac{7}{16}$            | 0.381                   | 0.286                   |
| 12            | 1.75     | 3             | ...                              | ... | ... | P   | ... | $3\frac{3}{8}$          | $1\frac{23}{32}$          | $\frac{7}{16}$            | 0.367                   | 0.275                   |
| 14            | 2        | 3             | ...                              | ... | ... | P   | ... | $3\frac{19}{32}$        | $1\frac{23}{32}$          | $\frac{1}{2}$             | 0.429                   | 0.322                   |
| 16            | 2        | 3             | ...                              | ... | ... | P   | ... | $3\frac{13}{16}$        | $1\frac{13}{16}$          | $\frac{9}{16}$            | 0.480                   | 0.360                   |
| 20            | 2.5      | 3             | ...                              | ... | ... | P   | ... | $4\frac{15}{32}$        | 2                         | $\frac{11}{16}$           | 0.652                   | 0.489                   |

All dimensions are in inches except where otherwise stated.

Chamfer Designation: P — Plug. These taps are high-speed steel.

Style 1 taps, sizes M1.6 through M5, have external center on thread and shank ends.

Style 2 taps, sizes M6, M8 and M10, have external center on thread end and external partial cone center on shank end with length of cone approximately  $\frac{1}{4}$  of diameter of shank.

Style 3 taps, sizes larger than M10 have external center on thread and shank ends.

For standards thread limits see [Table 4a](#) and [4b](#).

For eccentricity tolerances of tap elements see [Table 22](#).

**Table 18. ANSI Standard Taper and Straight Pipe Taps ASME B94.9-1999**

|                    |              | TAPER PIPE TAP   |         |                  | STRAIGHT PIPE TAP |                     |                     |                      |                   |  |
|--------------------|--------------|------------------|---------|------------------|-------------------|---------------------|---------------------|----------------------|-------------------|--|
|                    |              | Threads per Inch |         | Number of Flutes |                   | Dimensions          |                     |                      |                   |  |
| Nominal Size       | Carbon Steel | High-Speed Steel | Regular | Interrupted      | Length Overall, A | Length of Thread, B | Length of Square, C | Diameter of Shank, D | Size of Square, E |  |
| Taper Pipe Taps    |              |                  |         |                  |                   |                     |                     |                      |                   |  |
| 1/16 <sup>a</sup>  | ...          | 27               | 4       | ...              | 2 1/8             | 1 1/16              | 3/8                 | 0.3125               | 0.234             |  |
| 1/8                | 27           | 27               | 4       | 5                | 2 1/8             | 3/4                 | 3/8                 | 0.3125               | 0.234             |  |
| 1/8                | 27           | 27               | 4       | 5                | 2 1/8             | 3/4                 | 3/8                 | 0.4375               | 0.328             |  |
| 1/4                | 18           | 18               | 4       | 5                | 2 7/16            | 1 1/16              | 7/16                | 0.5625               | 0.421             |  |
| 3/8                | 18           | 18               | 4       | 5                | 2 9/16            | 1 1/16              | 1/2                 | 0.7000               | 0.531             |  |
| 1/2                | 14           | 14               | 4       | 5                | 3 1/8             | 1 3/8               | 5/8                 | 0.6875               | 0.515             |  |
| 3/4                | 14           | 14               | 5       | 5                | 3 1/8             | 1 3/8               | 1 1/16              | 0.9063               | 0.679             |  |
| 1                  | 11 1/2       | 11 1/2           | 5       | 5                | 3 3/4             | 1 3/4               | 1 3/16              | 1.1250               | 0.843             |  |
| 1 1/4              | 11 1/2       | 11 1/2           | 5       | 5                | 4                 | 1 3/4               | 1 5/16              | 1.3125               | 0.984             |  |
| 1 1/2              | 11 1/2       | 11 1/2           | 7       | 7 <sup>ba</sup>  | 4 1/2             | 1 3/4               | 1                   | 1.5000               | 1.125             |  |
| 2                  | 11 1/2       | 11 1/2           | 7       | 7 <sup>ba</sup>  | 4 1/2             | 1 3/4               | 1 1/8               | 1.8750               | 1.406             |  |
| 2 1/2 <sup>c</sup> | 8            | ...              | 8       | ...              | 5 1/2             | 2 3/16              | 1 1/4               | 2.2500               | 1.687             |  |
| 3 <sup>c</sup>     | 8            | ...              | 8       | ...              | 6                 | 2 5/8               | 1 3/8               | 2.6250               | 1.968             |  |
| Straight Pipe Taps |              |                  |         |                  |                   |                     |                     |                      |                   |  |
| 1/8 <sup>a</sup>   | ...          | 27               | 4       | ...              | 2 1/8             | 3/4                 | 3/8                 | 0.3125               | 0.234             |  |
| 1/8                | ...          | 27               | 4       | ...              | 2 1/8             | 3/4                 | 3/8                 | 0.4375               | 0.328             |  |
| 1/4                | ...          | 18               | 4       | ...              | 2 7/16            | 1 1/16              | 7/16                | 0.5625               | 0.421             |  |
| 3/8                | ...          | 18               | 4       | ...              | 2 9/16            | 1 1/16              | 1/2                 | 0.7000               | 0.531             |  |
| 1/2                | ...          | 14               | 4       | ...              | 3 1/8             | 1 3/8               | 5/8                 | 0.6875               | 0.515             |  |
| 3/4                | ...          | 14               | 5       | ...              | 3 1/8             | 1 3/8               | 1 1/16              | 0.9063               | 0.679             |  |
| 1                  | ...          | 11 1/2           | 5       | ...              | 3 3/4             | 1 3/4               | 1 3/16              | 1.1250               | 0.843             |  |

<sup>a</sup> Ground thread taps only.

<sup>b</sup> Standard in NPT form of thread only.

<sup>c</sup> Cut thread taps only.

| Tolerances for General Dimensions |                |            |               |                   |                   |             |               |
|-----------------------------------|----------------|------------|---------------|-------------------|-------------------|-------------|---------------|
| Element                           | Diameter Range | Tolerance  |               | Element           | Diameter Range    | Tolerance   |               |
|                                   |                | Cut Thread | Ground Thread |                   |                   | Cut Thread  | Ground Thread |
| Overall Length, A                 | 1/16 to 3/4    | ±1/32      | ±1/32         | Shank Diameter, D | 1/16 to 1/8       | ...         | -0.0015       |
|                                   | 1 to 3         | ±1/16      | ±1/16         |                   | 1/8 to 1/2        | -0.007      | ...           |
| Thread Length, B                  | 1/16 to 3/4    | ±1/16      | ±1/16         |                   | 1/4 to 1          | ...         | -0.002        |
|                                   | 1 to 1 1/4     | ±3/32      | ±3/32         |                   | 3/4 to 3          | -0.009      | ...           |
|                                   | 1 1/2 to 3     | ±1/8       | ±1/8          |                   | 1 1/4 to 2        | ...         | -0.003        |
| Square Length, C                  | 1/16 to 3/4    | ±1/32      | ±1/32         |                   | Size of Square, E | 1/16 to 1/8 | -0.004        |
|                                   | 1 to 3         | ±1/16      | ±1/16         | 1/4 to 3/4        |                   | -0.006      | -0.006        |
|                                   |                |            |               |                   | 1 to 3            | -0.008      | -0.008        |

All dimensions are given in inches. These taps have an internal center in the thread end. *Taper Pipe Threads:* The 1/8-inch pipe tap is furnished with large size shank unless the small shank is specified. These taps have 2 to 3 1/2 threads chamfer. The first few threads on interrupted thread pipe taps are left full. The following styles and sizes are standard: 1/16 to 2 inches regular ground thread, NPT, NPTF, and ANPT; 1/8 to 2 inches interrupted ground thread, NPT, NPTF and ANPT; 1/8 to 3 inches carbon steel regular cut thread, NPT; 1/8 to 2 inches high-speed steel, regular cut thread, NPT; 1/8 to 1 1/4 inches high-speed steel interrupted cut thread, NPT. For standard thread limits see [Tables 6a](#) and [6b](#). *Straight Pipe Threads:* The 1/8-inch pipe tap is furnished with large size shank unless the small size is specified. These taps are standard with plug chamfer only. The following styles and sizes are standard: ground threads — 1/8 to 1 inch, NPSC and NPSM; 1/8 to 3/4 inch, NPSF; cut threads — 1/8 to 1 inch, NPSC and NPSM. For standard thread limits see [Tables 7a](#), [7b](#), and [7c](#). For eccentricity tolerances see [Table 22](#).

**Table 19. Taps Recommended for Classes 2B and 3B Unified Screw Threads Numbered and Fractional Sizes ASME B94.9-1999**

| Size                             | Threads per Inch |           | Recommended Tap For Class of Thread |          | Pitch Diameter Limits For Class of Thread |                 |                 |
|----------------------------------|------------------|-----------|-------------------------------------|----------|---|-----------------|-----------------|
|                                  | NC<br>UNC        | NF<br>UNF | Class 2B <sup>a</sup>               | Class 3B | Min, All<br>Classes (Basic)               | Max<br>Class 2B | Max<br>Class 3B |
| Machine Screw Numbered Size Taps |                  |           |                                     |          |   |                 |                 |
| 0                                | ...              | 80        | G H2                                | G H1     | 0.0519                                    | 0.0542          | 0.0536          |
| 1                                | 64               | ...       | G H2                                | G H1     | 0.0629                                    | 0.0655          | 0.0648          |
| 1                                | ...              | 72        | G H2                                | G H1     | 0.0640                                    | 0.0665          | 0.0659          |
| 2                                | 56               | ...       | G H2                                | G H1     | 0.0744                                    | 0.0772          | 0.0765          |
| 2                                | ...              | 64        | G H2                                | G H1     | 0.0759                                    | 0.0786          | 0.0779          |
| 3                                | 48               | ...       | G H2                                | G H1     | 0.0855                                    | 0.0885          | 0.0877          |
| 3                                | ...              | 56        | G H2                                | G H1     | 0.0874                                    | 0.0902          | 0.0895          |
| 4                                | 40               | ...       | G H2                                | G H2     | 0.0958                                    | 0.0991          | 0.0982          |
| 4                                | ...              | 48        | G H2                                | G H1     | 0.0985                                    | 0.1016          | 0.1008          |
| 5                                | 40               | ...       | G H2                                | G H2     | 0.1088                                    | 0.1121          | 0.1113          |
| 5                                | ...              | 44        | G H2                                | G H1     | 0.1102                                    | 0.1134          | 0.1126          |
| 6                                | 32               | ...       | G H3                                | G H2     | 0.1177                                    | 0.1214          | 0.1204          |
| 6                                | ...              | 40        | G H2                                | G H2     | 0.1218                                    | 0.1252          | 0.1243          |
| 8                                | 32               | ...       | G H3                                | G H2     | 0.1437                                    | 0.1475          | 0.1465          |
| 8                                | ...              | 36        | G H2                                | G H2     | 0.1460                                    | 0.1496          | 0.1487          |
| 10                               | 24               | ...       | G H3                                | G H3     | 0.1629                                    | 0.1672          | 0.1661          |
| 10                               | ...              | 32        | G H3                                | G H2     | 0.1697                                    | 0.1736          | 0.1726          |
| 12                               | 24               | ...       | G H3                                | G H3     | 0.1889                                    | 0.1933          | 0.1922          |
| 12                               | ...              | 28        | G H3                                | G H3     | 0.1928                                    | 0.1970          | 0.1959          |
| Fractional Size Taps             |                  |           |                                     |          |   |                 |                 |
| 1/4                              | 20               | ...       | G H5                                | G H3     | 0.2175                                    | 0.2224          | 0.2211          |
| 1/4                              | ...              | 28        | G H4                                | G H3     | 0.2268                                    | 0.2311          | 0.2300          |
| 5/16                             | 18               | ...       | G H5                                | G H3     | 0.2764                                    | 0.2817          | 0.2803          |
| 5/16                             | ...              | 24        | G H4                                | G H3     | 0.2854                                    | 0.2902          | 0.2890          |
| 3/8                              | 16               | ...       | G H5                                | G H3     | 0.3344                                    | 0.3401          | 0.3387          |
| 3/8                              | ...              | 24        | G H4                                | G H3     | 0.3479                                    | 0.3528          | 0.3516          |
| 7/16                             | 14               | ...       | G H5                                | G H3     | 0.3911                                    | 0.3972          | 0.3957          |
| 7/16                             | ...              | 20        | G H5                                | G H3     | 0.4050                                    | 0.4104          | 0.4091          |
| 1/2                              | 13               | ...       | G H5                                | G H3     | 0.4500                                    | 0.4565          | 0.4548          |
| 1/2                              | ...              | 20        | G H5                                | G H3     | 0.4675                                    | 0.4731          | 0.4717          |
| 5/8                              | 12               | ...       | G H5                                | G H3     | 0.5084                                    | 0.5152          | 0.5135          |
| 5/8                              | ...              | 18        | G H5                                | G H3     | 0.5264                                    | 0.5323          | 0.5308          |
| 5/8                              | 11               | ...       | G H5                                | G H3     | 0.5660                                    | 0.5732          | 0.5714          |
| 5/8                              | ...              | 18        | G H5                                | G H3     | 0.5889                                    | 0.5949          | 0.5934          |
| 3/4                              | 10               | ...       | G H5                                | G H5     | 0.6850                                    | 0.6927          | 0.6907          |
| 3/4                              | ...              | 16        | G H5                                | G H3     | 0.7094                                    | 0.7159          | 0.7143          |
| 7/8                              | 9                | ...       | G H6 <sup>b</sup>                   | G H4     | 0.8028                                    | 0.8110          | 0.8089          |
| 7/8                              | ...              | 14        | G H6 <sup>b</sup>                   | G H4     | 0.8286                                    | 0.8356          | 0.8339          |
| 1                                | 8                | ...       | G H6 <sup>b</sup>                   | G H4     | 0.9188                                    | 0.9276          | 0.9254          |
| 1                                | ...              | 12        | G H6 <sup>b</sup>                   | G H4     | 0.9459                                    | 0.9535          | 0.9516          |
| 1                                | 14NS             | ...       | G H6 <sup>b</sup>                   | G H4     | 0.9536                                    | 0.9609          | 0.9590          |
| 1 1/8                            | 7                | ...       | G H8 <sup>b</sup>                   | G H4     | 1.0322                                    | 1.0416          | 1.0393          |
| 1 1/8                            | ...              | 12        | G H6 <sup>b</sup>                   | G H4     | 1.0709                                    | 1.0787          | 1.0768          |
| 1 1/4                            | 7                | ...       | G H8 <sup>b</sup>                   | G H4     | 1.1572                                    | 1.1668          | 1.1644          |
| 1 1/4                            | ...              | 12        | G H6 <sup>b</sup>                   | G H4     | 1.1959                                    | 1.2039          | 1.2019          |
| 1 3/8                            | 6                | ...       | G H8 <sup>b</sup>                   | G H4     | 1.2667                                    | 1.2771          | 1.2745          |
| 1 3/8                            | ...              | 12        | G H6 <sup>b</sup>                   | G H4     | 1.3209                                    | 1.3291          | 1.3270          |
| 1 1/2                            | 6                | ...       | G H8 <sup>b</sup>                   | G H4     | 1.3917                                    | 1.4022          | 1.3996          |
| 1 1/2                            | ...              | 12        | G H6 <sup>b</sup>                   | G H4     | 1.4459                                    | 1.4542          | 1.4522          |

<sup>a</sup> Cut thread taps in all fractional sizes and in numbered sizes 3 to 12 NC and NF may be used under normal conditions and in average materials to produce tapped holes in this classification.

<sup>b</sup> Standard G H4 taps are also suitable for this class of thread.

All dimensions are given in inches.

The above recommended taps normally produce the class of thread indicated in average materials when used with reasonable care. However, if the tap specified does not give a satisfactory gage fit in the work, a choice of some other limit tap will be necessary.



**Standard System of Tap Marking.**—Ground thread taps, inch screw threads, are marked with the nominal size, number of threads per inch, the proper symbol to identify the thread form, “HS” for high-speed steel, “G” for ground thread, and designators for tap pitch diameter and special features, such as left-hand and multi-start threads.

Cut thread taps, inch screw threads, are marked with the nominal size, number of threads per inch, and the proper symbol to identify the thread form. High-speed steel taps are marked “HS,” but carbon steel taps need not be marked.

Ground thread taps made with metric screw threads, M profile, are marked with “M,” followed by the nominal size and pitch in millimeters, separated by “x.” Marking also includes “HS” for high-speed steel, “G” for ground thread, designators for tap pitch diameter and special features, such as left-hand and multi-start threads.

Thread symbol designators are listed in the accompanying table. Tap pitch diameter designators, systems of limits, special features, and examples for ground threads are given in the following section.

**Standard System Tap Thread Limits and Identification for Unified Inch Screw Threads, Ground Thread.**—*H or L Limits:* For Unified inch screw threads, when the maximum tap pitch diameter is over basic pitch diameter by an even multiple of 0.0005 in. or the minimum tap pitch diameter limit is under basic pitch diameter by an even multiple of 0.0005 in., the taps are marked “H” or “L,” respectively, followed by a limit number, determined as follows:

H limit number = Amount maximum tap PD limit is over basic PD divided by 0.0005

L limit number = Amount minimum tap PD limit is under basic PD divided by 0.0005

**Table 20. Thread Series Designations**

| Standard Tap Marking             | Product Thread Designation | Third Series  |
|----------------------------------|----------------------------|---|
| M                                | M                          | Metric Screw Threads—M Profile, with basic ISO 68 profile   |
| M                                | MJ                         | Metric Screw Threads—M Profile, with rounded root of radius 0.15011 <i>P</i> to 0.18042 <i>P</i><br>Class 5 interference-fit thread |
| NC                               | NC5IF                      | Entire ferrous material range   |
| NC                               | NC5INF                     | Entire nonferrous material range  |
| NPS                              | NPSC                       | American Standard straight pipe threads in pipe couplings   |
| NPSF                             | NPSF                       | Dry seal American Standard fuel internal straight pipe threads  |
| NPSH                             | NPSH                       | American Standard straight hose coupling threads for joining to American Standard taper pipe threads                                |
| NPSI                             | NPSI                       | Dryseal American Standard intermediate internal straight pipe threads   |
| NPSL                             | NPSL                       | American Standard straight pipe threads for loose-fitting mechanical joints with locknuts   |
| NPS                              | NPSM                       | American Standard straight pipe threads for free-fitting mechanical joints for fixtures   |
| NPT                              | NPT                        | American Standard taper pipe threads for general use  |
| NPTF                             | NPTF                       | Dryseal American Standard taper pipe threads  |
| NPTR                             | NPTR                       | American Standard taper pipe threads for railing joints   |
| <b>Unified Inch Screw Thread</b> |                            |   |
| N                                | UN                         | Constant-pitch series   |
| NC                               | UNC                        | Coarse pitch series   |
| NF                               | UNF                        | Fine pitch series   |
| NEF                              | UNEF                       | Extra-fine pitch series   |
| N                                | UNJ                        | Constant-pitch series, with rounded root of radius 0.15011 <i>P</i> to 0.18042 <i>P</i> (ext. thd. only)                            |
| NC                               | UNJC                       | Coarse pitch series, with rounded root of radius 0.15011 <i>P</i> to 0.18042 <i>P</i> (ext. thd. only)                              |
| NF                               | UNJF                       | Fine pitch series, with rounded root of radius 0.15011 <i>P</i> to 0.18042 <i>P</i> (ext. thd. only)                                |
| NEF                              | UNJEF                      | Extra-fine pitch series, with rounded root of radius 0.15011 <i>P</i> to 0.18042 <i>P</i> (ext. thd. only)                          |
| N                                | UNR                        | Constant-pitch series, with rounded root of radius not less than 0.108 <i>P</i> (ext. thd. only)                                    |
| NC                               | UNRC                       | Coarse thread series, with rounded root of radius not less than 0.108 <i>P</i> (ext. thd. only)                                     |
| NF                               | UNRF                       | Fine pitch series, with rounded root of radius not less than 0.108 <i>P</i> (ext. thd. only)  |
| NEF                              | UNREF                      | Extra-fine pitch series, with rounded root of radius not less than 0.108 <i>P</i> (ext. thd. only)                                  |
| NS                               | UNS                        | Special diameter pitch, or length of engagement   |

The PD limits for various H limit numbers are given in [Table 2](#). The PD limits for L limit numbers are determined as follows. The minimum tap PD equals the basic PD minus the number of half-thousandths (0.0005 in.) represented by the limit number. The maximum tap PD equals the minimum PD plus the PD tolerance given in [Table 21](#).

**Table 21. PD Tolerance for Unified Inch Screw Threads  
Ground Thread ASME B94.9-1999**

| Threads per Inch | To 1 in., incl. | Over 1 in. to 1½ in., incl. | Over 1½ to 2½ in., incl. | Over 2½ in. |
|------------------|-----------------|-----------------------------|--------------------------|-------------|
| 80-28            | 0.0005          | 0.0010                      | 0.0010                   | 0.0015      |
| 24-18            | 0.0005          | 0.0010                      | 0.0015                   | 0.0015      |
| 16-18            | 0.0005          | 0.0010                      | 0.0015                   | 0.0020      |
| 7-6              | 0.0010          | 0.0010                      | 0.0020                   | 0.0025      |
| 5½-4             | 0.0010          | 0.0015                      | 0.0020                   | 0.0025      |

*Example:*  $\frac{3}{8}$ -16 NC HS H1

Max. tap PD = 0.3349

Min. tap PD = 0.3344

*Example:*  $\frac{3}{8}$ -16 NC HS G L2

Min. tap PD = Basic PD - 0.0010 in. = 0.3344 - 0.0010 = 0.3334

Max. tap PD = Min. Tap PD + 0.0005 = 0.3334 + 0.0005 = 0.3339

*Overize or Undersize:* When the maximum tap PD over basic PD or the minimum tap PD under basic PD is not an even multiple of 0.0005, the tap PD is usually designated as an amount overize or undersize. The amount overize is added to the basic PD to establish the *minimum* tap PD. The amount undersize is subtracted from the basic PD to establish the *minimum* tap PD. The PD tolerance in [Table 21](#) is added to the minimum tap PD to establish the maximum tap PD for both.

*Example:*  $\frac{7}{16}$ -14 NC plus 0.0017 HS G

Min. tap PD = Basic PD + 0.0017 in.

Max. tap PD = Min. tap PD + 0.0005 in.

Whenever possible for overize or other special tap PD requirements, the maximum and minimum tap PD requirements should be specified.

*Special Tap Pitch Diameter:* Taps not made to H or L limit numbers, to [Table 22](#), or to the formula for overize or undersize taps, may be marked with the letter "S" enclosed by a circle or by some other special identifier. *Example:*  $\frac{1}{2}$ -16 NC HS G.

**Table 22. ANSI Standard Runout and Location Tolerance of Tap Elements  
ASME B94.9-1999**

| Element                                  | Range Sizes are Inclusive |          |                                  | Cut Thread   |                  | Ground Thread |                  | Location, inch |
|--|---------------------------|----------|----------------------------------|--------------|------------------|---------------|------------------|----------------|
|  | Hand, Mch. Screw          | Metric   | Pipe                             | Eccentricity | tiv <sup>a</sup> | Eccentricity  | tiv <sup>a</sup> |                |
| Square<br>(at central point)             | #0-½"                     | M1.6-M12 | $\frac{1}{16}$ - $\frac{1}{8}$ " | ...          | ...              | ...           | ...              | 0.0060         |
|  | $\frac{1}{32}$ -4"        | M14-M100 | $\frac{1}{4}$ -4"                | ...          | ...              | ...           | ...              | 0.0080         |
| Shank                                    | #0- $\frac{5}{16}$ "      | M1.6-M8  | $\frac{1}{16}$ "                 | 0.0030       | 0.0060           | 0.0005        | 0.0010           | ...            |
|  | $\frac{1}{32}$ -4"        | M10-M100 | $\frac{1}{8}$ -4"                | 0.0040       | 0.0080           | 0.0008        | 0.0016           | ...            |
| Major Diameter                           | #0- $\frac{5}{16}$ "      | M1.6-M8  | $\frac{1}{16}$ "                 | 0.0025       | 0.0050           | 0.0005        | 0.0010           | ...            |
|  | $\frac{1}{32}$ -4"        | M10-M100 | $\frac{1}{8}$ -4"                | 0.0040       | 0.0080           | 0.0008        | 0.0016           | ...            |
| Pitch Diameter<br>(at first full thread) | #0- $\frac{5}{16}$ "      | M1.6-M8  | $\frac{1}{16}$ "                 | 0.0025       | 0.0050           | 0.0005        | 0.0010           | ...            |
|  | $\frac{1}{32}$ -4"        | M10-M100 | $\frac{1}{8}$ -4"                | 0.0040       | 0.0080           | 0.0008        | 0.0016           | ...            |
| Chamfer <sup>b</sup>                     | #0-½"                     | M1.6-M12 | $\frac{1}{16}$ - $\frac{1}{8}$ " | 0.0020       | 0.0040           | 0.0010        | 0.0020           | ...            |
|  | $\frac{1}{32}$ -4"        | M14-M100 | $\frac{1}{4}$ -4"                | 0.0030       | 0.0060           | 0.0015        | 0.0030           | ...            |

<sup>a</sup> tiv = total indicator variation. This data no longer included in Standard, but for reference figures are given for both eccentricity and total indicator variation to avoid misunderstanding.

<sup>b</sup> Chamfer should preferably be inspected by light projection to avoid errors due to indicator contact points dropping into the thread groove.

All dimensions are given in inches.

*Left-Hand Taps:* Taps with left-hand threads are marked "LEFT HAND" or "LH."

*Example:*  $\frac{3}{8}$ -16 NC LH HS G H3.

*Multiple-Start Threads:* Taps with multiple-start threads are marked with the lead designated as a fraction, also "Double," "Triple," etc. The Unified Screw Thread form symbol is always designated as "NS" for multiple-start threads. *Example:*  $\frac{3}{8}$ -16 NS Double  $\frac{1}{8}$  Lead HS G H5.

**Standard System of Ground Thread Tap Limits and Identification for Metric Screw Threads, M Profile.**—All calculations for metric taps use millimeter values. When U.S. customary values are needed, they are translated from the three-place millimeter tap diameters only after the calculations are completed.

**Table 23. PD Tolerance for Metric Screw Threads  
M Profile—Ground Threads ASME B94.9-1999**

| Pitch, $P$ (mm) | M1.6 to M6.3,<br>inclusive. | Over M6.3 to M25,<br>inclusive | Over M25 to M90,<br>inclusive | Over M90 |
|-----------------|-----------------------------|--------------------------------|-------------------------------|----------|
| 0.3             | 0.015                       | 0.015                          | 0.020                         | 0.020    |
| 0.35            | 0.015                       | 0.015                          | 0.020                         | 0.020    |
| 0.4             | 0.015                       | 0.015                          | 0.020                         | 0.025    |
| 0.45            | 0.015                       | 0.020                          | 0.020                         | 0.025    |
| 0.5             | 0.015                       | 0.020                          | 0.025                         | 0.025    |
| 0.6             | 0.020                       | 0.020                          | 0.025                         | 0.025    |
| 0.7             | 0.020                       | 0.020                          | 0.025                         | 0.025    |
| 0.75            | 0.020                       | 0.025                          | 0.025                         | 0.031    |
| 0.8             | 0.020                       | 0.025                          | 0.025                         | 0.031    |
| 0.9             | 0.020                       | 0.025                          | 0.025                         | 0.031    |
| 1               | 0.025                       | 0.025                          | 0.031                         | 0.031    |
| 1.25            | 0.025                       | 0.031                          | 0.031                         | 0.041    |
| 1.5             | 0.025                       | 0.031                          | 0.031                         | 0.041    |
| 1.75            | ...                         | 0.031                          | 0.041                         | 0.041    |
| 2               | ...                         | 0.041                          | 0.041                         | 0.041    |
| 2.5             | ...                         | 0.041                          | 0.041                         | 0.052    |
| 3               | ...                         | 0.041                          | 0.052                         | 0.052    |
| 3.5             | ...                         | 0.041                          | 0.052                         | 0.052    |
| 4               | ...                         | 0.052                          | 0.052                         | 0.064    |
| 4.5             | ...                         | 0.052                          | 0.052                         | 0.064    |
| 5               | ...                         | ...                            | 0.064                         | 0.064    |
| 5.5             | ...                         | ...                            | 0.064                         | 0.064    |
| 6               | ...                         | ...                            | 0.064                         | 0.064    |

*D or DU Limits:* When the maximum tap pitch diameter is over basic pitch diameter by an even multiple of 0.013 mm (0.000512 in. reference), or the minimum tap pitch diameter limit is under basic pitch diameter by an even multiple of 0.013 mm, the taps are marked with the letters "D" or "DU," respectively, followed by a limit number. The limit number is determined as follows:

D limit number = Amount maximum tap PD limit is over basic PD divided by 0.013

DU limit number = Amount minimum tap PD limit is under basic PD divided by 0.013

The PD limits for various D limit numbers are given in [Table 4b](#). The PD limits for DU limit numbers are determined as follows. The minimum tap PD equals the basic PD minus the number of millimeters represented by the limit number (multiples of 0.013 mm). The maximum tap PD equals the minimum tap PD plus the PD tolerance given in [Table 23](#).

*Example:* M1.6 × 0.35 HS G D3

Max. tap PD = 1.412

Min. tap PD = 1.397

M6 × 1 HS G DU4

Min. tap PD = Basic PD - 0.052 mm = 5.350 - 0.052 = 5.298

Max. tap PD = Min. tap PD + 0.025 mm = 5.323

Metric oversize or undersize taps, taps with special pitch diameters, and left-hand taps follow the marking system given for inch taps.

*Examples:* M12 × 1.75 + 0.044 HS G

M10 × 1.5 HS G

M10 × 1.5 LH HS G D6

*Multiple-Start Threads:* Metric taps with multiple-start threads are marked with the lead designated in millimeters preceded by the letter "L," the pitch in millimeters preceded by the letter "P," and the words "(2 starts)," "(3 starts)," etc.

*Examples:* M16 × L4-P2 (2 starts) HS G D8

M14 × L6-P2 (3 starts) HS G D7

### Acme and Square-Threaded Taps

These taps are usually made in sets, three taps in a set being the most common. For very fine pitches, two taps in a set will be found sufficient, whereas as many as five taps in a set are used for coarse pitches. The table on the next page gives dimensions for proportioning both Acme and square-threaded taps when made in sets. In cutting the threads of square-threaded taps, one leading tap maker uses the following rules: The width of the groove between two threads is made equal to one-half the pitch of the thread, less 0.004 inch, making the width of the thread itself equal to one-half of the pitch, plus 0.004 inch. The depth of the thread is made equal to 0.45 times the pitch, plus 0.0025 inch. This latter rule produces a thread that for all the ordinarily used pitches for square-threaded taps has a depth less than the generally accepted standard depth, this latter depth being equal to one-half the pitch. The object of this shallow thread is to ensure that if the hole to be threaded by the tap is not bored out so as to provide clearance at the bottom of the thread, the tap will cut its own clearance. The hole should, however, always be drilled out large enough so that the cutting of the clearance is not required of the tap.

The table, *Dimensions of Acme Threads Taps in Sets of Three Taps*, may also be used for the length dimensions for Acme taps. The dimensions in this table apply to single-threaded taps. For multiple-threaded taps or taps with very coarse pitch, relative to the diameter, the length of the chamfered part of the thread may be increased. Square-threaded taps are made to the same table as Acme taps, with the exception of the figures in column *K*, which for square-threaded taps should be equal to the nominal diameter of the tap, no oversize allowance being customary in these taps. The first tap in a set of Acme taps (not square-threaded taps) should be turned to a taper at the bottom of the thread for a distance of about one-quarter of the length of the threaded part. The taper should be so selected that the root diameter is about  $\frac{1}{32}$  inch smaller at the point than the proper root diameter of the tap. The first tap should preferably be provided with a short pilot at the point. For very coarse pitches, the first tap may be provided with spiral flutes at right angles to the angle of the thread. Acme and square-threaded taps should be relieved or backed off on the top of the thread of the chamfered portion on all the taps in the set. When the taps are used as machine taps, rather than as hand taps, they should be relieved in the angle of the thread, as well as on the top,

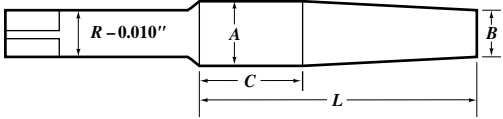
**Table 24. Dimensions of Acme Threads Taps in Sets of Three Taps**

The diagram illustrates the dimensions of three different Acme thread taps in a set. The 1st Tap in Set has dimensions A, B, C, D, and E. The 2nd Tap in Set has dimensions F and G. The Finishing Tap has dimensions H, I, and K. All three taps have a root diameter of -0.010 inches.

| Nominal Dia. | A      | B       | C       | D       | E       | F      | G       | H      | I      | K     |
|--------------|--------|---------|---------|---------|---------|--------|---------|--------|--------|-------|
| 1/2          | 4 1/4  | 1 7/8   | 2 3/8   | 1/2     | 1 7/8   | 5/8    | 1 3/4   | 7/8    | 1 1/2  | 0.520 |
| 9/16         | 4 7/8  | 2 1/8   | 2 3/4   | 9/16    | 2 3/16  | 3/4    | 2       | 1      | 1 3/4  | 0.582 |
| 5/8          | 5 1/2  | 2 3/8   | 3 3/8   | 5/8     | 2 1/2   | 7/8    | 2 1/4   | 1 1/8  | 2      | 0.645 |
| 11/16        | 6      | 2 1/2   | 3 1/2   | 3 13/16 | 2 13/16 | 15/16  | 2 1/16  | 1 1/4  | 2 1/4  | 0.707 |
| 3/4          | 6 1/2  | 2 11/16 | 3 13/16 | 1 1/16  | 3 3/8   | 1      | 2 13/16 | 1 3/8  | 2 7/16 | 0.770 |
| 13/16        | 6 7/8  | 2 13/16 | 4 1/16  | 3/4     | 3 5/16  | 1 1/16 | 3       | 1 7/16 | 2 5/8  | 0.832 |
| 7/8          | 7 1/4  | 3       | 4 1/4   | 3/4     | 3 1/2   | 1 1/8  | 3 3/8   | 1 1/2  | 2 3/4  | 0.895 |
| 15/16        | 7 7/16 | 3 1/8   | 4 7/16  | 13/16   | 3 3/8   | 1 3/16 | 3 1/4   | 1 9/16 | 2 7/8  | 0.957 |
| 1            | 7 7/8  | 3 1/4   | 4 5/8   | 13/16   | 3 13/16 | 1 1/4  | 3 3/8   | 1 5/8  | 3      | 1.020 |
| 1 1/8        | 8 1/2  | 3 9/16  | 4 15/16 | 7/8     | 4 1/16  | 1 5/16 | 3 5/8   | 1 3/4  | 3 3/16 | 1.145 |
| 1 1/4        | 9      | 3 3/4   | 5 1/4   | 15/16   | 4 5/16  | 1 3/8  | 3 7/8   | 1 7/8  | 3 3/8  | 1.270 |
| 1 3/8        | 9 1/2  | 4       | 5 1/2   | 1       | 4 1/2   | 1 7/16 | 4 1/16  | 2      | 3 1/2  | 1.395 |
| 1 1/2        | 10     | 4 1/4   | 5 3/4   | 1       | 4 3/4   | 1 1/2  | 4 1/4   | 2 1/8  | 3 5/8  | 1.520 |
| 1 5/8        | 10 1/2 | 4 1/2   | 6       | 1       | 5       | 1 1/2  | 4 1/2   | 2 1/8  | 3 7/8  | 1.645 |
| 1 3/4        | 11     | 4 3/4   | 6 1/4   | 1 1/16  | 5 3/16  | 1 9/16 | 4 11/16 | 2 1/4  | 4      | 1.770 |
| 1 7/8        | 11 3/8 | 4 7/8   | 6 1/2   | 1 1/16  | 5 7/16  | 1 9/16 | 4 15/16 | 2 1/4  | 4 1/4  | 1.895 |
| 2            | 11 3/4 | 5       | 6 3/4   | 1 1/8   | 5 5/8   | 1 5/8  | 5 1/8   | 2 3/8  | 4 3/8  | 2.020 |
| 2 1/4        | 12 1/2 | 5 1/4   | 7 1/4   | 1 1/8   | 6 3/8   | 1 3/16 | 5 1/2   | 2 1/2  | 4 3/4  | 2.270 |
| 2 1/2        | 13 1/4 | 5 1/2   | 7 3/4   | 1 3/4   | 6 9/16  | 1 7/8  | 5 7/8   | 2 5/8  | 5 1/8  | 2.520 |
| 2 3/4        | 14     | 5 3/4   | 8 1/4   | 1 1/4   | 7       | 2      | 6 1/4   | 2 3/4  | 5 1/2  | 2.770 |
| 3            | 15     | 6 1/4   | 8 3/4   | 1 1/4   | 7 1/2   | 2      | 6 3/4   | 3      | 5 3/4  | 3.020 |

for the whole length of the chamfered portion. Acme taps should also always be relieved on the front side of the thread to within 1/32 inch of the cutting edge.

*Adjustable Taps:* Many adjustable taps are now used, especially for accurate work. Some taps of this class are made of a solid piece of tool steel that is split and provided with means of expanding sufficiently to compensate for wear. Most of the larger adjustable taps have inserted blades or chasers that are held rigidly, but are capable of radial adjustment. The use of taps of this general class enables standard sizes to be maintained readily.

**Table 25. Proportions of Acme and Square-Threaded Taps Made in Sets**


$R =$  root diameter of thread.  $D =$  full diameter of tap.  
 $T =$  double depth of full thread.

| Kind of Tap      | No. of Taps in Set   | Order of Tap in Set | A            | B                    | C                                |
|------------------|----------------------|---------------------|--------------|----------------------|----------------------------------|
| Acme Thread Taps | 2                    | 1st                 | $R + 0.65T$  | $R + 0.010$          | $\frac{1}{8}L$ to $\frac{1}{6}L$ |
|                  |                      | 2d                  | $D$          | A on 1st tap - 0.005 | $\frac{1}{4}L$ to $\frac{1}{3}L$ |
|                  | 3                    | 1st                 | $R + 0.45T$  | $R + 0.010$          | $\frac{1}{8}L$ to $\frac{1}{6}L$ |
|                  |                      | 2d                  | $R + 0.80T$  | A on 1st tap - 0.005 | $\frac{1}{6}L$ to $\frac{1}{4}L$ |
|                  |                      | 3d                  | $D$          | A on 2d tap - 0.005  | $\frac{1}{4}L$ to $\frac{1}{3}L$ |
|                  | 4                    | 1st                 | $R + 0.40T$  | $R + 0.010$          | $\frac{1}{8}L$                   |
|                  |                      | 2d                  | $R + 0.70T$  | A on 1st tap - 0.005 | $\frac{1}{6}L$                   |
|                  |                      | 3d                  | $R + 0.90T$  | A on 2d tap - 0.005  | $\frac{1}{5}L$                   |
|                  |                      | 4th                 | $D$          | A on 3d tap - 0.005  | $\frac{1}{4}L$ to $\frac{1}{3}L$ |
|                  | 5                    | 1st                 | $R + 0.37T$  | $R + 0.010$          | $\frac{1}{8}L$                   |
|                  |                      | 2d                  | $R + 0.63T$  | A on 1st tap - 0.005 | $\frac{1}{6}L$                   |
|                  |                      | 3d                  | $R + 0.82T$  | A on 2d tap - 0.005  | $\frac{1}{5}L$                   |
|                  |                      | 4th                 | $R + 0.94T$  | A on 3d tap - 0.005  | $\frac{1}{5}L$ to $\frac{1}{4}L$ |
|                  |                      | 5th                 | $D$          | A on 4th tap - 0.005 | $\frac{1}{4}L$ to $\frac{1}{3}L$ |
|                  | Square-Threaded Taps | 2                   | 1st          | $R + 0.67T$          | $R$                              |
| 2d               |                      |                     | $D$          | A on 1st tap - 0.005 | $\frac{1}{4}L$ to $\frac{1}{3}L$ |
| 3                |                      | 1st                 | $R + 0.41T$  | $R$                  | $\frac{1}{8}L$ to $\frac{1}{6}L$ |
|                  |                      | 2d                  | $R + 0.080T$ | A on 1st tap - 0.005 | $\frac{1}{6}L$ to $\frac{1}{4}L$ |
|                  |                      | 3d                  | $D$          | A on 2d tap - 0.005  | $\frac{1}{4}L$ to $\frac{1}{3}L$ |
| 4                |                      | 1st                 | $R + 0.32T$  | $R$                  | $\frac{1}{8}L$                   |
|                  |                      | 2d                  | $R + 0.62T$  | A on 1st tap - 0.005 | $\frac{1}{6}L$                   |
|                  |                      | 3d                  | $R + 0.90T$  | A on 2d tap - 0.005  | $\frac{1}{5}L$                   |
|                  |                      | 4th                 | $D$          | A on 3d tap - 0.005  | $\frac{1}{4}L$ to $\frac{1}{3}L$ |
| 5                |                      | 1st                 | $R + 0.26T$  | $R$                  | $\frac{1}{8}L$                   |
|                  |                      | 2d                  | $R + 0.50T$  | A on 1st tap - 0.005 | $\frac{1}{6}L$                   |
|                  |                      | 3d                  | $R + 0.72T$  | A on 2d tap - 0.005  | $\frac{1}{5}L$                   |
|                  |                      | 4th                 | $R + 0.92T$  | A on 3d tap - 0.005  | $\frac{1}{5}L$ to $\frac{1}{4}L$ |
|                  |                      | 5th                 | $D$          | A on 4th tap - 0.005 | $\frac{1}{4}L$ to $\frac{1}{3}L$ |

**Drill Hole Sizes for Acme Threads.**—Many tap and die manufacturers and vendors make available to their customers computer programs designed to calculate drill hole sizes for all the Acme threads in their ranges from the basic dimensions. The large variety and combination of dimensions for such tools prevent inclusion of a complete set of tables of tap drills for Acme taps in this Handbook. The following formulas (dimensions in inches) for calculating drill hole sizes for Acme threads are derived from the American National Standard, ANSI/ASME B1.5-1997, Acme Screw Threads.

To select a tap drill size for an Acme thread, first calculate the maximum and minimum internal product minor diameters for the thread to be produced. (Dimensions for general purpose, centralizing, and stub Acme screw threads are given in the Threads and Threading section, starting on page 1825.) Then select a drill that will yield a finished hole somewhere between the established maximum and minimum product minor diameters. Consider staying close to the maximum product limit in selecting the hole size, to reduce the amount of material to be removed when cutting the thread. If there is no standard drill size that matches the hole diameter selected, it may be necessary to drill and ream, or bore the hole to size, to achieve the required hole diameter.

*Diameters of General-Purpose Acme Screw Threads of Classes 2G, 3G, and 4G* may be calculated from:

minimum diameter = basic major diameter – pitch

maximum diameter = minimum minor diameter +  $0.05 \times$  pitch

pitch =  $1/\text{number of threads per inch}$

*Example:*  $\frac{1}{2}$ -10 Acme 2G, pitch =  $1/10 = 0.1$

minimum diameter =  $0.5 - 0.1 = 0.4$

maximum diameter =  $0.4 + (0.05 \times 0.1) = 0.405$

drill selected = letter X or  $0.3970 + 0.0046$  (probable oversize) = 0.4016

*Diameters of Acme Centralizing Screw Threads of Classes 2C, 3C, and 4C* may be calculated from:

minimum diameter = basic major diameter –  $0.9 \times$  pitch

maximum diameter = minimum minor diameter +  $0.05 \times$  pitch

pitch =  $1/\text{number of threads per inch}$

*Example:*  $\frac{1}{2}$ -10 Acme 2C, pitch =  $1/10 = 0.1$

minimum diameter =  $0.5 - (0.9 \times 0.1) = 0.41$

maximum diameter =  $0.41 + (0.05 \times 0.1) = 0.415$

drill selected =  $\frac{13}{32}$  or  $0.4062 + 0.0046$  (probable oversize) = 0.4108.

*Diameters for Acme Centralizing Screw Threads of Classes 5C and 6C:* These classes are not recommended for new designs, but may be calculated from:

minimum diameter = [basic major diameter –  $(0.025 \sqrt{\text{basic major diameter}})$ ] –  $0.9 \times$  pitch

maximum diameter = minimum minor diameter +  $0.05 \times$  pitch

pitch =  $1/\text{number of threads per inch}$

*Example:*  $\frac{1}{2}$ -10 Acme 5C, pitch =  $1/10 = 0.1$

minimum diameter =  $[0.5 - (0.025 \sqrt{0.5})] - (0.9 \times 0.1) = 0.3923$

maximum diameter =  $0.3923 + (0.05 \times 0.1) = 0.3973$

drill selected =  $\frac{25}{64}$  or  $0.3906 + 0.0046$  (probable oversize) = 0.3952

**British Standard Screwing Taps for ISO Metric Threads.**—BS 949: Part 1:1976 provides dimensions and tolerances for screwing taps for ISO metric coarse-pitch series threads in accordance with BS 3643: Part 2; and for metric fine-pitch series threads in accordance with BS 3643: Part 3.

Table 26 provides dimensional data for the cutting portion of cut-thread taps for coarse-series threads of ISO metric sizes. The sizes shown were selected from the first-choice combinations of diameter and pitch listed in BS 3643:Part 1:1981 (1998). Table 13 provides similar data for ground-thread taps for both coarse- and fine-pitch series threads of ISO metric sizes.

**Table 26. British Standard Screwing Taps for ISO Metric Threads  
Dimensional Limits for the Threaded Portion of Cut Taps—  
Coarse Pitch Series BS 949: Part 1:1976**

| Designation | Pitch | Major Diameter       |        | Pitch Diameter |        |      | Tolerance on Thread Angle, Degrees |
|-------------|-------|----------------------|--------|----------------|--------|------|------------------------------------|
|             |       | Minimum <sup>a</sup> | Basic  | Max.           | Min.   | Min. |                                    |
| M1          | 0.25  | 1.030                | 0.838  | 0.875          | 0.848  | 4.0  |                                    |
| M1.2        | 0.25  | 1.230                | 1.038  | 1.077          | 1.048  | 4.0  |                                    |
| M1.6        | 0.35  | 1.636                | 1.373  | 1.417          | 1.385  | 3.4  |                                    |
| M2          | 0.40  | 2.036                | 1.740  | 1.786          | 1.752  | 3.2  |                                    |
| M2.5        | 0.45  | 2.539                | 2.208  | 2.259          | 2.221  | 3.0  |                                    |
| M3          | 0.50  | 3.042                | 2.675  | 2.730          | 2.689  | 2.9  |                                    |
| M4          | 0.70  | 4.051                | 3.545  | 3.608          | 3.562  | 2.4  |                                    |
| M5          | 0.80  | 5.054                | 4.480  | 4.547          | 4.498  | 2.3  |                                    |
| M6          | 1.00  | 6.060                | 5.350  | 5.424          | 5.370  | 2.0  |                                    |
| M8          | 1.25  | 8.066                | 7.188  | 7.270          | 7.210  | 1.8  |                                    |
| M10         | 1.50  | 10.072               | 9.026  | 9.116          | 9.050  | 1.6  |                                    |
| M12         | 1.75  | 12.078               | 10.863 | 10.961         | 10.889 | 1.5  |                                    |
| M16         | 2.00  | 16.084               | 14.701 | 14.811         | 14.729 | 1.4  |                                    |
| M20         | 2.50  | 20.093               | 18.376 | 18.497         | 18.407 | 1.3  |                                    |
| M24         | 3.00  | 24.102               | 22.051 | 22.183         | 22.085 | 1.2  |                                    |
| M30         | 3.50  | 30.111               | 27.727 | 27.874         | 27.764 | 1.1  |                                    |
| M36         | 4.00  | 36.117               | 33.402 | 33.563         | 33.441 | 1.0  |                                    |

<sup>a</sup> See notes under Table 27.

**Table 27. British Standard Screwing Taps for ISO Metric Threads  
Dimensional Limits for the Threaded Portion of Ground Taps—  
Coarse-and Fine-Pitch BS 949: Part 1:1976**

| Thread                            |                                |           | All Classes of Taps         |                        | Class 1 Taps   |            | Class 2 Taps |            | Class 3 Taps |            | Tolerance on $\frac{1}{2}$ Thd Angle |
|-----------------------------------|--------------------------------|-----------|-----------------------------|------------------------|----------------|------------|--------------|------------|--------------|------------|--------------------------------------|
| Designation                       | Nominal Major Dia. (basic) $d$ | Pitch $p$ | Min. Major Dia. $d_{min}^a$ | Basic Pitch Dia. $d_2$ | Pitch Diameter |            |              |            |              |            |                                      |
|                                   |                                |           |                             |                        | $d_{2min}$     | $d_{2max}$ | $d_{2min}$   | $d_{2max}$ | $d_{2min}$   | $d_{2max}$ |                                      |
| <b>COARSE-PITCH THREAD SERIES</b> |                                |           |                             |                        |                |            |              |            |              |            |                                      |
| M1                                | 1                              | 0.25      | 1.022                       | 0.838                  | 0.844          | 0.855      | ...          | ...        | ...          | ...        | ±60'                                 |
| M1.2                              | 1.2                            | 0.25      | 1.222                       | 1.038                  | 1.044          | 1.055      | ...          | ...        | ...          | ...        | ±60'                                 |
| M1.6                              | 1.6                            | 0.35      | 1.627                       | 1.373                  | 1.380          | 1.393      | 1.393        | 1.407      | ...          | ...        | ±50'                                 |
| M2                                | 2                              | 0.40      | 2.028                       | 1.740                  | 1.747          | 1.761      | 1.761        | 1.776      | ...          | ...        | ±40'                                 |
| M2.5                              | 2.5                            | 0.45      | 2.530                       | 2.208                  | 2.216          | 2.231      | 2.231        | 2.246      | ...          | ...        | ±38'                                 |
| M3                                | 3                              | 0.50      | 3.032                       | 2.675                  | 2.683          | 2.699      | 2.699        | 2.715      | 2.715        | 2.731      | ±36'                                 |
| M4                                | 4                              | 0.70      | 4.038                       | 3.545                  | 3.555          | 3.574      | 3.574        | 3.593      | 3.593        | 3.612      | ±30'                                 |
| M5                                | 5                              | 0.80      | 5.040                       | 4.480                  | 4.490          | 4.510      | 4.510        | 4.530      | 4.530        | 4.550      | ±26'                                 |
| M6                                | 6                              | 1.00      | 6.047                       | 5.350                  | 5.362          | 5.385      | 5.385        | 5.409      | 5.409        | 5.433      | ±24'                                 |
| M8                                | 8                              | 1.25      | 8.050                       | 7.188                  | 7.201          | 7.226      | 7.226        | 7.251      | 7.251        | 7.276      | ±22'                                 |
| M10                               | 10                             | 1.50      | 10.056                      | 9.026                  | 9.040          | 9.068      | 9.068        | 9.096      | 9.096        | 9.124      | ±20'                                 |
| M12                               | 12                             | 1.75      | 12.064                      | 10.863                 | 10.879         | 10.911     | 10.911       | 10.943     | 10.943       | 10.975     | ±19'                                 |
| M16                               | 16                             | 2.00      | 16.068                      | 14.701                 | 14.718         | 14.752     | 14.752       | 14.786     | 14.786       | 14.820     | ±18'                                 |
| M20                               | 20                             | 2.50      | 20.072                      | 18.376                 | 18.394         | 18.430     | 18.430       | 18.466     | 18.466       | 18.502     | ±16'                                 |
| M24                               | 24                             | 3.00      | 24.085                      | 22.051                 | 22.072         | 22.115     | 22.115       | 22.157     | 22.157       | 22.199     | ±14'                                 |



**Table 27. (Continued) British Standard Screwing Taps for ISO Metric Threads  
Dimensional Limits for the Threaded Portion of Ground Taps—  
Coarse and Fine-Pitch BS 949: Part 1:1976**

| Thread                  |                                |           | All Classes of Taps          |                        | Class 1 Taps   |             | Class 2 Taps |             | Class 3 Taps |             | Tolerance on $\frac{1}{2}$ Thd Angle |
|-------------------------|--------------------------------|-----------|------------------------------|------------------------|----------------|-------------|--------------|-------------|--------------|-------------|--------------------------------------|
| Designation             | Nominal Major Dia. (basic) $d$ | Pitch $p$ | Min. Major Dia. $d_{\min}^a$ | Basic Pitch Dia. $d_2$ | Pitch Diameter |             |              |             |              |             |                                      |
|                         |                                |           |                              |                        | $d_{2\min}$    | $d_{2\max}$ | $d_{2\min}$  | $d_{2\max}$ | $d_{2\min}$  | $d_{2\max}$ |                                      |
| M30                     | 30                             | 3.50      | 30.090                       | 27.727                 | 27.749         | 27.794      | 27.794       | 27.839      | 27.839       | 27.884      | $\pm 13'$                            |
| M36                     | 36                             | 4.00      | 36.094                       | 33.402                 | 33.426         | 33.473      | 33.473       | 33.520      | 33.520       | 33.567      | $\pm 12'$                            |
| FINE-PITCH THREAD SIZES |                                |           |                              |                        |                |             |              |             |              |             |                                      |
| M1 $\times$ 0.2         | 1                              | 0.20      | 1.020                        | 0.870                  | 0.875          | 0.885       | ...          | ...         | ...          | ...         | $\pm 70'$                            |
| M1.2 $\times$ 0.2       | 1.2                            | 0.20      | 1.220                        | 1.070                  | 1.075          | 1.085       | ...          | ...         | ...          | ...         | $\pm 70'$                            |
| M1.6 $\times$ 0.2       | 1.6                            | 0.20      | 1.621                        | 1.470                  | 1.475          | 1.485       | ...          | ...         | ...          | ...         | $\pm 70'$                            |
| M2 $\times$ 0.25        | 2                              | 0.25      | 2.024                        | 1.838                  | 1.844          | 1.856       | ...          | ...         | ...          | ...         | $\pm 60'$                            |
| M2.5 $\times$ 0.35      | 2.5                            | 0.35      | 2.527                        | 2.273                  | 2.280          | 2.293       | 2.293        | 2.307       | ...          | ...         | $\pm 50'$                            |
| M3 $\times$ 0.35        | 3                              | 0.35      | 3.028                        | 2.773                  | 2.780          | 2.794       | 2.794        | 2.809       | ...          | ...         | $\pm 50'$                            |
| M4 $\times$ 0.5         | 4                              | 0.50      | 4.032                        | 3.675                  | 3.683          | 3.699       | 3.699        | 3.715       | 3.715        | 3.731       | $\pm 36'$                            |
| M5 $\times$ 0.5         | 5                              | 0.50      | 5.032                        | 4.675                  | 4.683          | 4.699       | 4.699        | 4.715       | 4.715        | 4.731       | $\pm 36'$                            |
| M6 $\times$ 0.75        | 6                              | 0.75      | 6.042                        | 5.513                  | 5.524          | 5.545       | 5.545        | 5.566       | 5.566        | 5.587       | $\pm 28'$                            |
| M8 $\times$ 1           | 8                              | 1.00      | 8.047                        | 7.350                  | 7.362          | 7.385       | 7.385        | 7.409       | 7.409        | 7.433       | $\pm 24'$                            |
| M10 $\times$ 1.25       | 10                             | 1.25      | 10.050                       | 9.188                  | 9.201          | 9.226       | 9.226        | 9.251       | 9.251        | 9.276       | $\pm 22'$                            |
| M12 $\times$ 1.25       | 12                             | 1.25      | 12.056                       | 11.188                 | 11.202         | 11.230      | 11.230       | 11.258      | 11.258       | 11.286      | $\pm 22'$                            |
| M16 $\times$ 1.5        | 16                             | 1.50      | 16.060                       | 15.026                 | 15.041         | 15.071      | 15.071       | 15.101      | 15.101       | 15.131      | $\pm 20'$                            |
| M20 $\times$ 1.5        | 20                             | 1.50      | 20.060                       | 19.026                 | 19.041         | 19.071      | 19.071       | 19.101      | 19.101       | 19.131      | $\pm 20'$                            |
| M24 $\times$ 2          | 24                             | 2.00      | 24.072                       | 22.701                 | 22.719         | 22.755      | 22.755       | 22.791      | 22.791       | 22.827      | $\pm 18'$                            |
| M30 $\times$ 2          | 30                             | 2.00      | 30.072                       | 28.701                 | 28.719         | 28.755      | 28.755       | 28.791      | 28.791       | 28.827      | $\pm 18'$                            |

<sup>a</sup> The maximum tap major diameter,  $d_{\max}$ , is not specified and is left to the manufacturer's discretion.

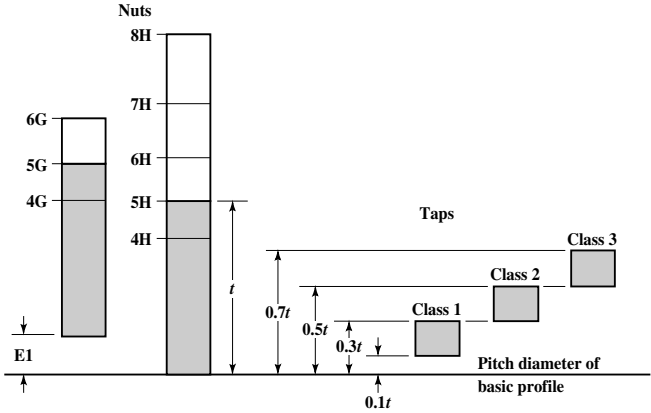
All dimension are in millimeters. The thread sizes in the table have been selected from the preferred series shown in BS 3643:Part 1:1981 (1998). For other sizes, and for second and third choice combinations of diameters and pitches, see the Standard.

**Tolerance Classes of Taps:** Three tolerance classes (class 1, class 2, and class 3) are used for the designation of taps used for the production of nuts of the following classes:

nut classes 4H, 5H, 6H, 7H, and 8H, all having zero minimum clearance;

nut classes 4G, 5G, and 6G, all having positive minimum clearance.

The tolerances for the three classes of taps are stated in terms of a tolerance unit  $t$ , the value of which is equal to the pitch diameter tolerance,  $T_{D_2}$ , grade 5, of the nut. Thus,  $t = T_{D_2}$ , grade 5, of the nut. Taps of the different classes vary in the limits of size of the tap pitch diameter. The tolerance on the tap pitch diameter,  $T_{d_2}$ , is the same for all three classes of taps (20 percent of  $t$ ), but the position of the tolerance zone with respect to the basic pitch diameter depends upon the lower deviation value  $Em$  which is: for tap class 1,  $Em = +0.1t$ ; for tap class 2,  $Em = +0.3t$ ; and for tap class 3,  $Em = +0.5t$ .



The disposition of the tolerances described is shown in the accompanying illustration of nut class tolerances compared against tap class tolerances. The distance  $EI$  shown in this illustration is the minimum clearance, which is zero for  $H$  classes and positive for  $G$  classes of nuts.

**Choice of Tap Tolerance Class:** Unless otherwise specified, class 1 taps are used for nuts of classes 4H and 5H; class 2 taps for nuts of classes 6H, 4G, and 5G; and class 3 taps for nuts of classes 7H, 8H, and 6G. This relationship of tap and nut classes is a general one, since the accuracy of tapping varies with a number of factors such as the material being tapped, the condition of the machine tool used, the tapping attachment used, the tapping speed, and the lubricant.

**Tap Major Diameter:** Except when a screwed connection has to be tight against gaseous or liquid pressure, it is undesirable for the mating threads to bear on the roots and crests. By avoiding contact in these regions of the threads, the opposite flanks of the two threads are allowed to make proper load bearing contact when the connection is tightened. In general, the desired clearance between crests and roots of mating threads is obtained by increasing the major and minor diameters of the internal thread. Such an increase in the minor diameter is already provided on threads such as the ISO metric thread, in which there is a basic clearance between the crests of minimum size nuts and the roots of maximum size bolts. For this reason, and the fact that taps are susceptible to wear on the crests of their threads, a minimum size is specified for the major diameter of new taps which provides a reasonable margin for the wear of their crests and at the same time provides the desired clearance at the major diameter of the hole. These minimum major diameters for taps are shown in [Tables 26 and 13](#). The maximum tap major diameter is not specified and is left to the manufacturer to take advantage of this concession to produce taps with as liberal a margin possible for wear on the major diameter.

**Tapping Square Threads.**—If it is necessary to tap square threads, this should be done by using a set of taps that will form the thread by a progressive cutting action, the taps varying in size in order to distribute the work, especially for threads of comparatively coarse pitch. From three to five taps may be required in a set, depending upon the pitch. Each tap should have a pilot to steady it. The pilot of the first tap has a smooth cylindrical end from 0.003 to 0.005 inch smaller than the hole, and the pilots of following taps should have teeth.

## STANDARD TAPERS

## Standard Tapers

Certain types of small tools and machine parts, such as twist drills, end mills, arbors, lathe centers, etc., are provided with taper shanks which fit into spindles or sockets of corresponding taper, thus providing not only accurate alignment between the tool or other part and its supporting member, but also more or less frictional resistance for driving the tool. There are several standards for "self-holding" tapers, but the American National, Morse, and the Brown & Sharpe are the standards most widely used by American manufacturers.

The name *self-holding* has been applied to the smaller tapers—like the Morse and the Brown & Sharpe—because, where the angle of the taper is only 2 or 3 degrees, the shank of a tool is so firmly seated in its socket that there is considerable frictional resistance to any force tending to turn or rotate the tool relative to the socket. The term "self-holding" is used to distinguish relatively small tapers from the larger or *self-releasing* type. A milling machine spindle having a taper of  $3\frac{1}{2}$  inches per foot is an example of a self-releasing taper. The included angle in this case is over 16 degrees and the tool or arbor requires a positive locking device to prevent slipping, but the shank may be released or removed more readily than one having a smaller taper of the self-holding type.

**Morse Taper.**—Dimensions relating to Morse standard taper shanks and sockets may be found in an accompanying table. The taper for different numbers of Morse tapers is slightly different, but it is approximately  $\frac{5}{8}$  inch per foot in most cases. The table gives the actual tapers, accurate to five decimal places. Morse taper shanks are used on a variety of tools, and exclusively on the shanks of twist drills. Dimensions for *Morse Stub Taper Shanks* are given in [Table 1a](#), and for *Morse Standard Taper Shanks* in [Table 1b](#).

**Brown & Sharpe Taper.**—This standard taper is used for taper shanks on tools such as end mills and reamers, the taper being approximately  $\frac{1}{2}$  inch per foot for all sizes except for taper No. 10, where the taper is 0.5161 inch per foot. Brown & Sharpe taper sockets are used for many arbors, collets, and machine tool spindles, especially milling machines and grinding machines. In many cases there are a number of different lengths of sockets corresponding to the same number of taper; all these tapers, however, are of the same diameter at the small end.

**Jarno Taper.**—The Jarno taper was originally proposed by Oscar J. Beale of the Brown & Sharpe Mfg. Co. This taper is based on such simple formulas that practically no calculations are required when the number of taper is known. The taper per foot of all Jarno taper sizes is 0.600 inch on the diameter. The diameter at the large end is as many eighths, the diameter at the small end is as many tenths, and the length as many half inches as are indicated by the number of the taper. For example, a No. 7 Jarno taper is  $\frac{7}{8}$  inch in diameter at the large end;  $\frac{7}{10}$ , or 0.700 inch at the small end; and  $\frac{7}{2}$ , or  $3\frac{1}{2}$  inches long; hence, diameter at large end = No. of taper  $\div$  8; diameter at small end = No. of taper  $\div$  10; length of taper = No. of taper  $\div$  2. The Jarno taper is used on various machine tools, especially profiling machines and die-sinking machines. It has also been used for the headstock and tailstock spindles of some lathes.

*American National Standard Machine Tapers:* This standard includes a self-holding series ([Tables 2, 3, 4, 5](#) and [7a](#)) and a steep taper series, [Table 6](#). The self-holding taper series consists of 22 sizes which are listed in [Table 7a](#). The reference gage for the self-holding tapers is a plug gage. [Table 7b](#) gives the dimensions and tolerances for both plug and ring gages applying to this series. [Tables 2](#) through [5](#) inclusive give the dimensions for self-holding taper shanks and sockets which are classified as to (1) means of transmitting torque from spindle to the tool shank, and (2) means of retaining the shank in the socket. The steep machine tapers consist of a preferred series (bold-face type, [Table 6](#)) and an intermediate series (light-face type). A self-holding taper is defined as "a taper with an

angle small enough to hold a shank in place ordinarily by friction without holding means. (Sometimes referred to as slow taper.)" A steep taper is defined as "a taper having an angle sufficiently large to insure the easy or self-releasing feature." The term "gage line" indicates the basic diameter at or near the large end of the taper.

Table 1a. Morse Stub Taper Shanks

| No. of Taper | Taper per Foot <sup>a</sup> | Taper per Inch <sup>b</sup> | Small End of Plug, <sup>b</sup> <i>D</i> | Dia. End of Socket, <sup>a</sup> <i>A</i> | Shank                  |                                   | Tang                |                  |
|--------------|-----------------------------|-----------------------------|--|---|------------------------|-----------------------------------|---------------------|------------------|
|              |                             |                             |  |   | Total Length, <i>B</i> | Depth, <i>C</i>                   | Thickness, <i>E</i> | Length, <i>F</i> |
| 1            | 0.59858                     | 0.049882                    | 0.4314                                   | 0.475                                     | $1\frac{5}{16}$        | $1\frac{1}{8}$                    | $\frac{13}{64}$     | $\frac{5}{16}$   |
| 2            | 0.59941                     | 0.049951                    | 0.6469                                   | 0.700                                     | $1\frac{11}{16}$       | $1\frac{7}{16}$                   | $\frac{19}{64}$     | $\frac{7}{16}$   |
| 3            | 0.60235                     | 0.050196                    | 0.8753                                   | 0.938                                     | 2                      | $1\frac{3}{4}$                    | $\frac{25}{64}$     | $\frac{9}{16}$   |
| 4            | 0.62326                     | 0.051938                    | 1.1563                                   | 1.231                                     | $2\frac{3}{8}$         | $2\frac{1}{16}$                   | $\frac{33}{64}$     | $1\frac{1}{16}$  |
| 5            | 0.63151                     | 0.052626                    | 1.6526                                   | 1.748                                     | 3                      | $2\frac{11}{16}$                  | $\frac{3}{4}$       | $1\frac{5}{16}$  |
| No. of Taper | Tang                        |                             | Socket                                   |   |                        | Tang Slot                         |                     |                  |
|              | Radius of Mill, <i>G</i>    | Diameter, <i>H</i>          | Plug Depth, <i>P</i>                     | Min. Depth of Tapered Hole                |                        | Socket End to Tang Slot, <i>M</i> | Width, <i>N</i>     | Length, <i>O</i> |
|              |                             | Drilled <i>X</i>            |  | Reamed <i>Y</i>                           |                        |                                   |                     |                  |
| 1            | $\frac{3}{16}$              | $\frac{13}{32}$             | $\frac{7}{8}$                            | $\frac{5}{16}$                            | $\frac{29}{32}$        | $\frac{25}{32}$                   | $\frac{7}{32}$      | $\frac{23}{32}$  |
| 2            | $\frac{7}{32}$              | $\frac{39}{64}$             | $1\frac{1}{16}$                          | $1\frac{5}{32}$                           | $1\frac{7}{64}$        | $\frac{15}{16}$                   | $\frac{5}{16}$      | $1\frac{5}{16}$  |
| 3            | $\frac{9}{32}$              | $\frac{13}{16}$             | $1\frac{1}{4}$                           | $1\frac{3}{8}$                            | $1\frac{5}{16}$        | $1\frac{1}{16}$                   | $\frac{13}{32}$     | $1\frac{1}{8}$   |
| 4            | $\frac{3}{8}$               | $1\frac{3}{32}$             | $1\frac{7}{16}$                          | $1\frac{9}{16}$                           | $1\frac{1}{2}$         | $1\frac{3}{16}$                   | $\frac{17}{32}$     | $1\frac{3}{8}$   |
| 5            | $\frac{9}{16}$              | $1\frac{19}{32}$            | $1\frac{13}{16}$                         | $1\frac{15}{16}$                          | $1\frac{7}{8}$         | $1\frac{7}{16}$                   | $\frac{25}{32}$     | $1\frac{3}{4}$   |

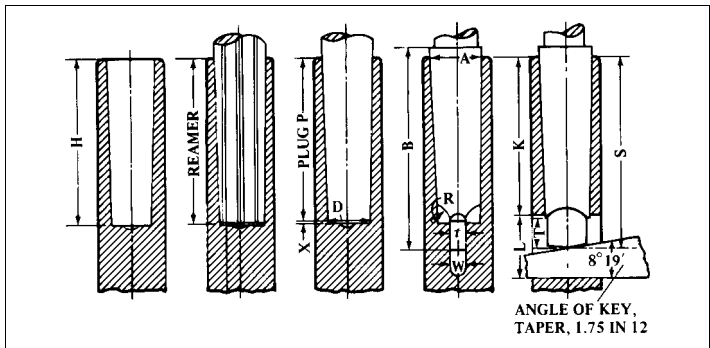
<sup>a</sup>These are basic dimensions.

<sup>b</sup>These dimensions are calculated for reference only.

All dimensions in inches.

Radius *J* is  $\frac{3}{64}$ ,  $\frac{1}{16}$ ,  $\frac{5}{64}$ ,  $\frac{3}{32}$ , and  $\frac{1}{8}$  inch respectively for Nos. 1, 2, 3, 4, and 5 tapers.

Table 1b. Morse Standard Taper Shanks



| No. of Taper    | Taper per Foot | Taper per Inch | Small End of Plug $D$ | Diameter End of Socket $A$ | Shank            |                  | Depth of Hole $H$ |
|-----------------|----------------|----------------|-----------------------|----------------------------|------------------|------------------|-------------------|
|                 |                |                |                       |                            | Length $B$       | Depth $S$        |                   |
| 0               | 0.62460        | 0.05205        | 0.252                 | 0.3561                     | $2\frac{11}{32}$ | $2\frac{7}{32}$  | $2\frac{1}{32}$   |
| 1               | 0.59858        | 0.04988        | 0.369                 | 0.475                      | $2\frac{9}{16}$  | $2\frac{7}{16}$  | $2\frac{5}{32}$   |
| 2               | 0.59941        | 0.04995        | 0.572                 | 0.700                      | $3\frac{1}{8}$   | $2\frac{15}{16}$ | $2\frac{39}{64}$  |
| 3               | 0.60235        | 0.05019        | 0.778                 | 0.938                      | $3\frac{3}{8}$   | $3\frac{11}{16}$ | $3\frac{1}{4}$    |
| 4               | 0.62326        | 0.05193        | 1.020                 | 1.231                      | $4\frac{7}{8}$   | $4\frac{5}{8}$   | $4\frac{1}{8}$    |
| 5               | 0.63151        | 0.05262        | 1.475                 | 1.748                      | $6\frac{1}{8}$   | $5\frac{7}{8}$   | $5\frac{1}{4}$    |
| 6               | 0.62565        | 0.05213        | 2.116                 | 2.494                      | $8\frac{8}{16}$  | $8\frac{1}{4}$   | $7\frac{21}{64}$  |
| 7               | 0.62400        | 0.05200        | 2.750                 | 3.270                      | $11\frac{5}{8}$  | $11\frac{1}{4}$  | $10\frac{5}{64}$  |
| Plug Depth $P$  | Tang or Tongue |                |                       |                            | Keyway           |                  | Keyway to End $K$ |
|                 | Thickness $t$  | Length $T$     | Radius $R$            | Dia.                       | Width $W$        | Length $L$       |                   |
| 2               | 0.1562         | $\frac{1}{4}$  | $\frac{5}{32}$        | 0.235                      | $\frac{11}{64}$  | $\frac{9}{16}$   | $1\frac{15}{16}$  |
| $2\frac{1}{8}$  | 0.2031         | $\frac{3}{8}$  | $\frac{3}{16}$        | 0.343                      | 0.218            | $\frac{3}{4}$    | $2\frac{1}{16}$   |
| $2\frac{1}{16}$ | 0.2500         | $\frac{7}{16}$ | $\frac{1}{4}$         | $\frac{17}{32}$            | 0.266            | $\frac{7}{8}$    | $2\frac{1}{2}$    |
| $3\frac{3}{16}$ | 0.3125         | $\frac{9}{16}$ | $\frac{9}{32}$        | $2\frac{29}{32}$           | 0.328            | $1\frac{13}{16}$ | $3\frac{1}{16}$   |
| $4\frac{1}{16}$ | 0.4687         | $\frac{5}{8}$  | $\frac{5}{16}$        | $3\frac{1}{32}$            | 0.484            | $1\frac{1}{4}$   | $3\frac{3}{8}$    |
| $5\frac{3}{16}$ | 0.6250         | $\frac{3}{4}$  | $\frac{3}{8}$         | $1\frac{13}{32}$           | 0.656            | $1\frac{1}{2}$   | $4\frac{15}{16}$  |
| $7\frac{1}{4}$  | 0.7500         | $1\frac{1}{8}$ | $\frac{1}{2}$         | 2                          | 0.781            | $1\frac{3}{4}$   | 7                 |
| 10              | 1.1250         | $1\frac{3}{8}$ | $\frac{3}{4}$         | $2\frac{5}{8}$             | 1.156            | $2\frac{5}{8}$   | $9\frac{1}{2}$    |

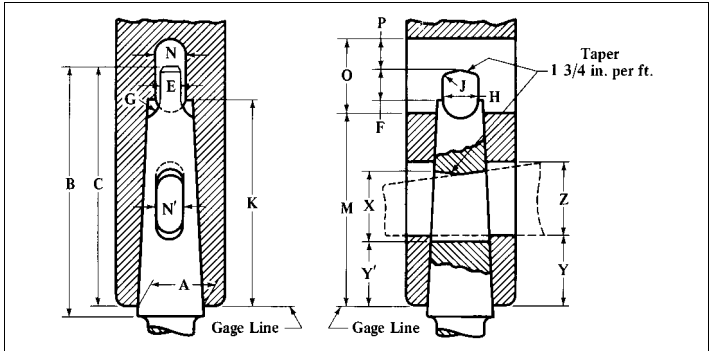
Tolerances on rate of taper: all sizes 0.002 in. per foot. This tolerance may be applied on shanks only in the direction that increases the rate of taper, and on sockets only in the direction that decreases the rate of taper.

**Table 2. American National Standard Taper Drive with Tang, Self-Holding Tapers ANSI/ASME B5.10-1994 (R2002)**

| No. of Taper | Diameter at Gage Line (1) A | Shank                   |                             | Tang                     |          |                  |                                  |
|--------------|-----------------------------|-------------------------|-----------------------------|--------------------------|----------|------------------|----------------------------------|
|              |                             | Total Length of Shank B | Gage Line to End of Shank C | Thickness E              | Length F | Radius of Mill G | Diameter H                       |
| 0.239        | 0.23922                     | 1.28                    | 1.19                        | 0.125                    | 0.19     | 0.19             | 0.18                             |
| 0.299        | 0.29968                     | 1.59                    | 1.50                        | 0.156                    | 0.25     | 0.19             | 0.22                             |
| 0.375        | 0.37525                     | 1.97                    | 1.88                        | 0.188                    | 0.31     | 0.19             | 0.28                             |
| 1            | 0.47500                     | 2.56                    | 2.44                        | 0.203                    | 0.38     | 0.19             | 0.34                             |
| 2            | 0.70000                     | 3.13                    | 2.94                        | 0.250                    | 0.44     | 0.25             | 0.53                             |
| 3            | 0.93800                     | 3.88                    | 3.69                        | 0.312                    | 0.56     | 0.22             | 0.72                             |
| 4            | 1.23100                     | 4.88                    | 4.63                        | 0.469                    | 0.63     | 0.31             | 0.97                             |
| 4½           | 1.50000                     | 5.38                    | 5.13                        | 0.562                    | 0.69     | 0.38             | 1.20                             |
| 5            | 1.74800                     | 6.12                    | 5.88                        | 0.625                    | 0.75     | 0.38             | 1.41                             |
| 6            | 2.49400                     | 8.25                    | 8.25                        | 0.750                    | 1.13     | 0.50             | 2.00                             |
| No. of Taper | Radius J                    | Socket                  |                             | Tang Slot                |          |                  |                                  |
|              |                             | Min. Depth of Hole K    |                             | Gage Line to Tang Slot M | Width N  | Length O         | Shank End to Back of Tang Slot P |
|              |                             | Drilled                 | Reamed                      |                          |          |                  |                                  |
| 0.239        | 0.03                        | 1.06                    | 1.00                        | 0.94                     | 0.141    | 0.38             | 0.13                             |
| 0.299        | 0.03                        | 1.31                    | 1.25                        | 1.17                     | 0.172    | 0.50             | 0.17                             |
| 0.375        | 0.05                        | 1.63                    | 1.56                        | 1.47                     | 0.203    | 0.63             | 0.22                             |
| 1            | 0.05                        | 2.19                    | 2.16                        | 2.06                     | 0.218    | 0.75             | 0.38                             |
| 2            | 0.06                        | 2.66                    | 2.61                        | 2.50                     | 0.266    | 0.88             | 0.44                             |
| 3            | 0.08                        | 3.31                    | 3.25                        | 3.06                     | 0.328    | 1.19             | 0.56                             |
| 4            | 0.09                        | 4.19                    | 4.13                        | 3.88                     | 0.484    | 1.25             | 0.50                             |
| 4½           | 0.13                        | 4.62                    | 4.56                        | 4.31                     | 0.578    | 1.38             | 0.56                             |
| 5            | 0.13                        | 5.31                    | 5.25                        | 4.94                     | 0.656    | 1.50             | 0.56                             |
| 6            | 0.16                        | 7.41                    | 7.33                        | 7.00                     | 0.781    | 1.75             | 0.50                             |

All dimensions are in inches. (1) See [Table 7b](#) for plug and ring gage dimensions.

**Tolerances:** For shank diameter A at gage line, + 0.002 – 0.000; for hole diameter A, + 0.000 – 0.002. For tang thickness E up to No. 5 inclusive, + 0.000 – 0.006; No. 6, + 0.000 – 0.008. For width N of tang slot up to No. 5 inclusive, + 0.006; – 0.000; No. 6, + 0.008 – 0.000. For centrality of tang E with center line of taper, 0.0025 (0.005 total indicator variation). These centrality tolerances also apply to the tang slot N. On rate of taper, all sizes 0.002 per foot. This tolerance may be applied on *shanks* only in the direction which *increases* the rate of taper and on *sockets* only in the direction which *decreases* the rate of taper. Tolerances for two-decimal dimensions are plus or minus 0.010, unless otherwise specified.

**Table 3. American National Standard Taper Drive with Keeper Key Slot, Self-Holding Tapers ANSI/ASME B5.10-1994 (R2002)**

| No. of Taper | Dia. at Gage Line (1) A | Shank          |                    | Tang        |          |                  |            |          |                      | Socket |                          |  |
|--------------|-------------------------|----------------|--------------------|-------------|----------|------------------|------------|----------|----------------------|--------|--------------------------|--|
|              |                         | Total Length B | Gage Line to End C | Thickness E | Length F | Radius of Mill G | Diameter H | Radius J | Min. Depth of Hole K |        | Gage Line to Tang Slot M |  |
|              |                         |                |                    |             |          |                  |            |          | Drill                | Ream   |                          |  |
| 3            | 0.938                   | 3.88           | 3.69               | 0.312       | 0.56     | 0.28             | 0.78       | 0.08     | 3.31                 | 3.25   | 3.06                     |  |
| 4            | 1.231                   | 4.88           | 4.63               | 0.469       | 0.63     | 0.31             | 0.97       | 0.09     | 4.19                 | 4.13   | 3.88                     |  |
| 4½           | 1.500                   | 5.38           | 5.13               | 0.562       | 0.69     | 0.38             | 1.20       | 0.13     | 4.63                 | 4.56   | 4.32                     |  |
| 5            | 1.748                   | 6.13           | 5.88               | 0.625       | 0.75     | 0.38             | 1.41       | 0.13     | 5.31                 | 5.25   | 4.94                     |  |
| 6            | 2.494                   | 8.56           | 8.25               | 0.750       | 1.13     | 0.50             | 2.00       | 0.16     | 7.41                 | 7.33   | 7.00                     |  |
| 7            | 3.270                   | 11.63          | 11.25              | 1.125       | 1.38     | 0.75             | 2.63       | 0.19     | 10.16                | 10.08  | 9.50                     |  |

| No. of Taper | Tang Slot |          |                             | Keeper Slot in Shank           |          |          | Keeper Slot in Socket        |          |          |
|--------------|-----------|----------|-----------------------------|--------------------------------|----------|----------|------------------------------|----------|----------|
|              | Width N   | Length O | Shank End to Back of Slot P | Gage Line to Bottom of Slot Y' | Length X | Width N' | Gage Line to Front of Slot Y | Length Z | Width N' |
| 3            | 0.328     | 1.19     | 0.56                        | 1.03                           | 1.13     | 0.266    | 1.13                         | 1.19     | 0.266    |
| 4            | 0.484     | 1.25     | 0.50                        | 1.41                           | 1.19     | 0.391    | 1.50                         | 1.25     | 0.391    |
| 4½           | 0.578     | 1.38     | 0.56                        | 1.72                           | 1.25     | 0.453    | 1.81                         | 1.38     | 0.453    |
| 5            | 0.656     | 1.50     | 0.56                        | 2.00                           | 1.38     | 0.516    | 2.13                         | 1.50     | 0.516    |
| 6            | 0.781     | 1.75     | 0.50                        | 2.13                           | 1.63     | 0.641    | 2.25                         | 1.75     | 0.641    |
| 7            | 1.156     | 2.63     | 0.88                        | 2.50                           | 1.69     | 0.766    | 2.63                         | 1.81     | 0.766    |

All dimensions are in inches. (1) See [Table 7b](#) for plug and ring gage dimensions.

**Tolerances:** For shank diameter A at gage line, +0.002, -0; for hole diameter A, +0, -0.002. For tang thickness E up to No. 5 inclusive, +0, -0.006; larger than No. 5, +0, -0.008. For width of slots N and N' up to No. 5 inclusive, +0.006, -0; larger than No. 5, +0.008, -0. For centrality of tang E with center line of taper 0.0025 (0.005 total indicator variation). These centrality tolerances also apply to slots N and N'. On rate of taper, see footnote in [Table 2](#). Tolerances for two-decimal dimensions are ±0.010 unless otherwise specified.

**Table 4. American National Standard Nose Key Drive with Keeper Key Slot, Self-Holding Tapers ANSI/ASME B5.10-1994 (R2002)**

| Taper | A(1)   | B'              | C     | Q     | I'    | I     | R     | S     |
|-------|--------|-----------------|-------|-------|-------|-------|-------|-------|
| 200   | 2.000  | 5.13            |       | 0.25  | 1.38  | 1.63  | 1.010 | 0.562 |
| 250   | 2.500  | 5.88            |       | 0.25  | 1.38  | 2.06  | 1.010 | 0.562 |
| 300   | 3.000  | 6.63            | Min   | 0.25  | 1.63  | 2.50  | 2.010 | 0.562 |
| 350   | 3.500  | 7.44            | 0.003 | 0.31  | 2.00  | 2.94  | 2.010 | 0.562 |
| 400   | 4.000  | 8.19            | Max   | 0.31  | 2.13  | 3.31  | 2.010 | 0.562 |
| 450   | 4.500  | 9.00            | 0.035 | 0.38  | 2.38  | 3.81  | 3.010 | 0.812 |
| 500   | 5.000  | 9.75            | for   | 0.38  | 2.50  | 4.25  | 3.010 | 0.812 |
| 600   | 6.000  | 11.31           | all   | 0.44  | 3.00  | 5.19  | 3.010 | 0.812 |
| 800   | 8.000  | 14.38           | sizes | 0.50  | 3.50  | 7.00  | 4.010 | 1.062 |
| 1000  | 10.000 | 17.44           |       | 0.63  | 4.50  | 8.75  | 4.010 | 1.062 |
| 1200  | 12.000 | 20.50           |       | 0.75  | 5.38  | 10.50 | 4.010 | 1.062 |
| Taper | D      | D' <sup>a</sup> | W     | X     | N'    | R'    | S'    | T     |
| 200   | 1.41   | 0.375           | 3.44  | 1.56  | 0.656 | 1.000 | 0.50  | 4.75  |
| 250   | 1.66   | 0.375           | 3.69  | 1.56  | 0.781 | 1.000 | 0.50  | 5.50  |
| 300   | 2.25   | 0.375           | 4.06  | 1.56  | 1.031 | 2.000 | 0.50  | 6.25  |
| 350   | 2.50   | 0.375           | 4.88  | 2.00  | 1.031 | 2.000 | 0.50  | 6.94  |
| 400   | 2.75   | 0.375           | 5.31  | 2.25  | 1.031 | 2.000 | 0.50  | 7.69  |
| 450   | 3.00   | 0.500           | 5.88  | 2.44  | 1.031 | 3.000 | 0.75  | 8.38  |
| 500   | 3.25   | 0.500           | 6.44  | 2.63  | 1.031 | 3.000 | 0.75  | 9.13  |
| 600   | 3.75   | 0.500           | 7.44  | 3.00  | 1.281 | 3.000 | 0.75  | 10.56 |
| 800   | 4.75   | 0.500           | 9.56  | 4.00  | 1.781 | 4.000 | 1.00  | 13.50 |
| 1000  | ...    | ...             | 11.50 | 4.75  | 2.031 | 4.000 | 1.00  | 16.31 |
| 1200  | ...    | ...             | 13.75 | 5.75  | 2.031 | 4.000 | 1.00  | 19.00 |
| Taper | U      | V               | M     | N     | O     | P     | Y     | Z     |
| 200   | 1.81   | 1.00            | 4.50  | 0.656 | 1.56  | 0.94  | 2.00  | 1.69  |
| 250   | 2.25   | 1.00            | 5.19  | 0.781 | 1.94  | 1.25  | 2.25  | 1.69  |
| 300   | 2.75   | 1.00            | 5.94  | 1.031 | 2.19  | 1.50  | 2.63  | 1.69  |
| 350   | 3.19   | 1.25            | 6.75  | 1.031 | 2.19  | 1.50  | 3.00  | 2.13  |
| 400   | 3.63   | 1.25            | 7.50  | 1.031 | 2.19  | 1.50  | 3.25  | 2.38  |
| 450   | 4.19   | 1.50            | 8.00  | 1.031 | 2.75  | 1.75  | 3.63  | 2.56  |
| 500   | 4.63   | 1.50            | 8.75  | 1.031 | 2.75  | 1.75  | 4.00  | 2.75  |
| 600   | 5.50   | 1.75            | 10.13 | 1.281 | 3.25  | 2.06  | 4.63  | 3.25  |
| 800   | 7.38   | 2.00            | 12.88 | 1.781 | 4.25  | 2.75  | 5.75  | 4.25  |
| 1000  | 9.19   | 2.50            | 15.75 | 2.031 | 5.00  | 3.31  | 7.00  | 5.00  |
| 1200  | 11.00  | 3.00            | 18.50 | 2.531 | 6.00  | 4.00  | 8.25  | 6.00  |

<sup>a</sup> Thread is UNF-2B for hole; UNF-2A for screw. (1) See Table 7b for plug and ring gage dimensions.

All dimensions are in inches. AE is 0.005 greater than one-half of A.

Width of drive key R'' is 0.001 less than width R'' of keyway.

**Tolerances:** For diameter A of hole at gage line, +0, -0.002; for diameter A of shank at gage line, +0.002, -0; for width of slots N and N', +0.008, -0; for width of drive keyway R' in socket, +0, -0.001; for width of drive keyway R in shank, 0.010, -0; for centrality of slots N and N' with center line of spindle, 0.007; for centrality of keyway with spindle center line: for R, 0.004 and for R', 0.002 T.I.V. On rate of taper, see footnote in Table 2. Two-decimal dimensions, ±0.010 unless otherwise specified.



**Table 5. American National Standard Nose Key Drive with Drawbolt, Self-Holding Tapers ANSI/ASME B5.10-1994 (R2002)**

| Sockets      |                         |                                    |                               |              |            |            |                                  |                    |                     |                            |
|--------------|-------------------------|------------------------------------|-------------------------------|--------------|------------|------------|----------------------------------|--------------------|---------------------|----------------------------|
| No. of Taper | Dia. at Gage Line $A^a$ | Screw Holes                        |                               | Drive Keyway |            |            | Gage Line to Front of Relief $T$ | Dia. of Relief $U$ | Depth of Relief $V$ | Dia. of Draw Bolt Hole $d$ |
|              |                         | Center Line to Center of Screw $D$ | UNF 2B Hole UNF 2A Screw $D'$ | Width $R'$   | Width $R'$ | Depth $S'$ |                                  |                    |                     |                            |
| 200          | 2000                    | 1.41                               | 0.38                          | 0.999        | 1.000      | 0.50       | 4.75                             | 1.81               | 1.00                | 1.00                       |
| 250          | 2500                    | 1.66                               | 0.38                          | 0.999        | 1.000      | 0.50       | 5.50                             | 2.25               | 1.00                | 1.00                       |
| 300          | 3000                    | 2.25                               | 0.38                          | 1.999        | 2.000      | 0.50       | 6.25                             | 2.75               | 1.00                | 1.13                       |
| 350          | 3500                    | 2.50                               | 0.38                          | 1.999        | 2.000      | 0.50       | 6.94                             | 3.19               | 1.25                | 1.13                       |
| 400          | 4000                    | 2.75                               | 0.38                          | 1.999        | 2.000      | 0.50       | 7.69                             | 3.63               | 1.25                | 1.63                       |
| 450          | 4500                    | 3.00                               | 0.50                          | 2.999        | 3.000      | 0.75       | 8.38                             | 4.19               | 1.50                | 1.63                       |
| 500          | 5000                    | 3.25                               | 0.50                          | 2.999        | 3.000      | 0.75       | 9.13                             | 4.63               | 1.50                | 1.63                       |
| 600          | 6000                    | 3.75                               | 0.50                          | 2.999        | 3.000      | 0.75       | 10.56                            | 5.50               | 1.75                | 2.25                       |
| 800          | 8000                    | 4.75                               | 0.50                          | 3.999        | 4.000      | 1.00       | 13.50                            | 7.38               | 2.00                | 2.25                       |
| 1000         | 10000                   | ...                                | ...                           | 3.999        | 4.000      | 1.00       | 16.31                            | 9.19               | 2.50                | 2.25                       |
| 1200         | 12000                   | ...                                | ...                           | 3.999        | 4.000      | 1.00       | 19.00                            | 11.00              | 3.00                | 2.25                       |

<sup>a</sup> See Table 7b for plug and ring gage dimensions.

| Shanks       |                            |                  |                           |                      |                          |                                |                          |           |           |                                      |
|--------------|----------------------------|------------------|---------------------------|----------------------|--------------------------|--------------------------------|--------------------------|-----------|-----------|--------------------------------------|
| No. of Taper | Length from Gage Line $B'$ | Drawbar Hole     |                           |                      |                          |                                | Drive Keyway             |           |           |                                      |
|              |                            | Dia. UNC-2B $AL$ | Depth of Drilled Hole $E$ | Depth of Thread $AP$ | Dia. of Counter Bore $G$ | Gage Line to First Thread $AO$ | Depth of 60° Chamfer $J$ | Width $R$ | Depth $S$ | Center Line to Bottom of Keyway $AE$ |
| 200          | 5.13                       | $\frac{7}{8}$ -9 | 2.44                      | 1.75                 | 0.91                     | 4.78                           | 0.13                     | 1.010     | 0.562     | 1.005                                |
| 250          | 5.88                       | $\frac{7}{8}$ -9 | 2.44                      | 1.75                 | 0.91                     | 5.53                           | 0.13                     | 1.010     | 0.562     | 1.255                                |
| 300          | 6.63                       | 1-8              | 2.75                      | 2.00                 | 1.03                     | 6.19                           | 0.19                     | 2.010     | 0.562     | 1.505                                |
| 350          | 7.44                       | 1-8              | 2.75                      | 2.00                 | 1.03                     | 7.00                           | 0.19                     | 2.010     | 0.562     | 1.755                                |
| 400          | 8.19                       | 1½-6             | 4.00                      | 3.00                 | 1.53                     | 7.50                           | 0.31                     | 2.010     | 0.562     | 2.005                                |
| 450          | 9.00                       | 1½-6             | 4.00                      | 3.00                 | 1.53                     | 8.31                           | 0.31                     | 3.010     | 0.812     | 2.255                                |
| 500          | 9.75                       | 1½-6             | 4.00                      | 3.00                 | 1.53                     | 9.06                           | 0.31                     | 3.010     | 0.812     | 2.505                                |
| 600          | 11.31                      | 2-4½             | 5.31                      | 4.00                 | 2.03                     | 10.38                          | 0.50                     | 3.010     | 0.812     | 3.005                                |
| 800          | 14.38                      | 2-4½             | 5.31                      | 4.00                 | 2.03                     | 13.44                          | 0.50                     | 4.010     | 1.062     | 4.005                                |
| 1000         | 17.44                      | 2-4½             | 5.31                      | 4.00                 | 2.03                     | 16.50                          | 0.50                     | 4.010     | 1.062     | 5.005                                |
| 1200         | 20.50                      | 2-4½             | 5.31                      | 4.00                 | 2.03                     | 19.56                          | 0.50                     | 4.010     | 1.062     | 6.005                                |

All dimensions in inches.

Exposed length  $C$  is 0.003 minimum and 0.035 maximum for all sizes.

Drive Key  $D'$  screw sizes are  $\frac{3}{8}$ -24 UNF-2A up to taper No. 400 inclusive and  $\frac{1}{2}$ -20 UNF-2A for larger tapers.

**Tolerances:** For diameter  $A$  of hole at gage line, +0.000, -0.002 for all sizes; for diameter  $A$  of shank at gage line, +0.002, -0.000; for all sizes; for width of drive keyway  $R'$  in socket, +0.000, -0.001; for width of drive keyway  $R$  in shank, +0.010, -0.000; for centrality of drive keyway  $R'$ , with center line of shank, 0.004 total indicator variation, and for drive keyway  $R'$ , with center line of spindle, 0.002. On rate of taper, see footnote in Table 2. Tolerances for two-decimal dimensions are ±0.010 unless otherwise specified.

**Table 6. ANSI Standard Steep Machine Tapers** *ANSI/ASME B5.10-1994 (R2002)*

| No. of Taper | Taper per Foot <sup>a</sup> | Dia. at Gage Line <sup>b</sup> | Length Along Axis | No. of Taper | Taper per Foot <sup>a</sup> | Dia. at Gage Line <sup>b</sup> | Length Along Axis |
|--------------|-----------------------------|--------------------------------|-------------------|--------------|-----------------------------|--------------------------------|-------------------|
| 5            | 3.500                       | 0.500                          | 0.6875            | 35           | 3.500                       | 1.500                          | 2.2500            |
| <b>10</b>    | <b>3.500</b>                | <b>0.625</b>                   | <b>0.8750</b>     | <b>40</b>    | <b>3.500</b>                | <b>1.750</b>                   | <b>2.5625</b>     |
| 15           | 3.500                       | 0.750                          | 1.0625            | 45           | 3.500                       | 2.250                          | 3.3125            |
| <b>20</b>    | <b>3.500</b>                | <b>0.875</b>                   | <b>1.3125</b>     | <b>50</b>    | <b>3.500</b>                | <b>2.750</b>                   | <b>4.0000</b>     |
| 25           | 3.500                       | 1.000                          | 1.5625            | 55           | 3.500                       | 3.500                          | 5.1875            |
| <b>30</b>    | <b>3.500</b>                | <b>1.250</b>                   | <b>1.8750</b>     | <b>60</b>    | <b>3.500</b>                | <b>4.250</b>                   | <b>6.3750</b>     |

<sup>a</sup>This taper corresponds to an included angle of 16°, 35', 39.4".

<sup>b</sup>The basic diameter at gage line is at large end of taper.

All dimensions given in inches.

The tapers numbered 10, 20, 30, 40, 50, and 60 that are printed in heavy-faced type are designated as the "Preferred Series." The tapers numbered 5, 15, 25, 35, 45, and 55 that are printed in light-faced type are designated as the "Intermediate Series."

**Table 7a. American National Standard Self-holding Tapers — Basic Dimensions** *ANSI/ASME B5.10-1994 (R2002)*

| No. of Taper | Taper per Foot | Dia. at Gage Line <sup>a</sup><br>A | Means of Driving and Holding <sup>a</sup>                    | Origin of Series             |
|--------------|----------------|-------------------------------------|--|------------------------------|
| .239         | 0.50200        | 0.23922                             | } Tang Drive With Shank Held in by Friction<br>(See Table 2) | Brown & Sharpe Taper Series  |
| .299         | 0.50200        | 0.29968                             |  |                              |
| .375         | 0.50200        | 0.37525                             |  |                              |
| 1            | 0.59858        | 0.47500                             | } Tang Drive With Shank Held in by Key<br>(See Table 3)      | Morse Taper Series           |
| 2            | 0.59941        | 0.70000                             |  |                              |
| 3            | 0.60235        | 0.93800                             |  |                              |
| 4            | 0.62326        | 1.23100                             |  |                              |
| 4½           | 0.62400        | 1.50000                             |  |                              |
| 5            | 0.63151        | 1.74800                             |  |                              |
| 6            | 0.62565        | 2.49400                             |  |                              |
| 7            | 0.62400        | 3.27000                             |  |                              |
| 200          | 0.750          | 2.000                               | } Key Drive With Shank Held in by Key<br>(See Table 4)       | ¾ Inch per Foot Taper Series |
| 250          | 0.750          | 2.500                               |  |                              |
| 300          | 0.750          | 3.000                               | } Key Drive With Shank Held in by Draw-bolt<br>(See Table 5) |                              |
| 350          | 0.750          | 3.500                               |  |                              |
| 400          | 0.750          | 4.000                               |  |                              |
| 450          | 0.750          | 4.500                               |  |                              |
| 500          | 0.750          | 5.000                               |  |                              |
| 600          | 0.750          | 6.000                               |  |                              |
| 800          | 0.750          | 8.000                               |  |                              |
| 1000         | 0.750          | 10.000                              |  |                              |
| 1200         | 0.750          | 12.000                              |  |                              |

<sup>a</sup>See illustrations above Tables 2 through 5.

All dimensions given in inches.

**Table 7b. American National Standard Plug and Ring Gages for the Self-Holding Taper Series ANSI/ASME B5.10-1994 (R2002)**

| No. of Taper | Taper <sup>a</sup> per Foot | Diameter <sup>a</sup> at Gage Line A | Tolerances for Diameter A <sup>b</sup> |              |              | Diameter at Small End A' | Length Gage Line to End L | Depth of Gaging-Notch, Plug Gage L' |
|--------------|-----------------------------|--------------------------------------|--|--------------|--------------|--------------------------|---------------------------|-------------------------------------|
|              |                             |                                      | Class X Gage                           | Class Y Gage | Class Z Gage |                          |                           |                                     |
| 0.239        | 0.50200                     | 0.23922                              | 0.00004                                | 0.00007      | 0.00010      | 0.20000                  | 0.94                      | 0.048                               |
| 0.299        | 0.50200                     | 0.29968                              | 0.00004                                | 0.00007      | 0.00010      | 0.25000                  | 1.19                      | 0.048                               |
| 0.375        | 0.50200                     | 0.37525                              | 0.00004                                | 0.00007      | 0.00010      | 0.31250                  | 1.50                      | 0.048                               |
| 1            | 0.59858                     | 0.47500                              | 0.00004                                | 0.00007      | 0.00010      | 0.36900                  | 2.13                      | 0.040                               |
| 2            | 0.59941                     | 0.70000                              | 0.00004                                | 0.00007      | 0.00010      | 0.57200                  | 2.56                      | 0.040                               |
| 3            | 0.60235                     | 0.93800                              | 0.00006                                | 0.00009      | 0.00012      | 0.77800                  | 3.19                      | 0.040                               |
| 4            | 0.62326                     | 1.23100                              | 0.00006                                | 0.00009      | 0.00012      | 1.02000                  | 4.06                      | 0.038                               |
| 4½           | 0.62400                     | 1.50000                              | 0.00006                                | 0.00009      | 0.00012      | 1.26600                  | 4.50                      | 0.038                               |
| 5            | 0.63151                     | 1.74800                              | 0.00008                                | 0.00012      | 0.00016      | 1.47500                  | 5.19                      | 0.038                               |
| 6            | 0.62565                     | 2.49400                              | 0.00008                                | 0.00012      | 0.00016      | 2.11600                  | 7.25                      | 0.038                               |
| 7            | 0.62400                     | 3.27000                              | 0.00010                                | 0.00015      | 0.00020      | 2.75000                  | 10.00                     | 0.038                               |
| 200          | 0.75000                     | 2.00000                              | 0.00008                                | 0.00012      | 0.00016      | 1.703                    | 4.75                      | 0.032                               |
| 250          | 0.75000                     | 2.50000                              | 0.00008                                | 0.00012      | 0.00016      | 2.156                    | 5.50                      | 0.032                               |
| 300          | 0.75000                     | 3.00000                              | 0.00010                                | 0.00015      | 0.00020      | 2.609                    | 6.25                      | 0.032                               |
| 350          | 0.75000                     | 3.50000                              | 0.00010                                | 0.00015      | 0.00020      | 3.063                    | 7.00                      | 0.032                               |
| 400          | 0.75000                     | 4.00000                              | 0.00010                                | 0.00015      | 0.00020      | 3.516                    | 7.75                      | 0.032                               |
| 450          | 0.75000                     | 4.50000                              | 0.00010                                | 0.00015      | 0.00020      | 3.969                    | 8.50                      | 0.032                               |
| 500          | 0.75000                     | 5.00000                              | 0.00013                                | 0.00019      | 0.00025      | 4.422                    | 9.25                      | 0.032                               |
| 600          | 0.75000                     | 6.00000                              | 0.00013                                | 0.00019      | 0.00025      | 5.328                    | 10.75                     | 0.032                               |
| 800          | 0.75000                     | 8.00000                              | 0.00016                                | 0.00024      | 0.00032      | 7.141                    | 13.75                     | 0.032                               |
| 1000         | 0.75000                     | 10.00000                             | 0.00020                                | 0.00030      | 0.00040      | 8.953                    | 16.75                     | 0.032                               |
| 1200         | 0.75000                     | 12.00000                             | 0.00020                                | 0.00030      | 0.00040      | 10.766                   | 19.75                     | 0.032                               |

<sup>a</sup> The taper per foot and diameter A at gage line are basic dimensions. Dimensions in Column A' are calculated for reference only.

<sup>b</sup> Tolerances for diameter A are plus for plug gages and minus for ring gages.

All dimensions are in inches.

The amount of taper deviation for Class X, Class Y, and Class Z gages are the same, respectively, as the amounts shown for tolerances on diameter A. Taper deviation is the permissible allowance from true taper at any point of diameter in the length of the gage. On taper *plug* gages, this deviation may be applied only in the direction which *decreases* the rate of taper. On taper *ring* gages, this deviation may be applied only in the direction which *increases* the rate of taper. Tolerances on two-decimal dimensions are  $\pm 0.010$ .

**British Standard Tapers.**—British Standard 1660: 1972, "Machine Tapers, Reduction Sleeves, and Extension Sockets," contains dimensions for self-holding and self-releasing tapers, reduction sleeves, extension sockets, and turret sockets for tools having Morse and metric 5 per cent taper shanks. Adapters for use with  $\frac{7}{24}$  tapers and dimensions for spindle noses and tool shanks with self-release tapers and cotter slots are included in this Standard.

Table 8. Dimensions of Morse Taper Sleeves

The diagram shows a Morse Taper Sleeve with various dimensions labeled. A is the number of Morse Taper Outside, and B is the number of Morse Taper Inside. Dimensions C, D, E, F, G, H, I, K, L, and M are indicated with arrows and lines. C is the total length, D is the outer diameter at the large end, E is the diameter at the small end, F is the diameter of the hole at the small end, G is the diameter of the hole at the large end, H is the length of the hole, I is the taper diameter, K is the length of the sleeve, L is the length of the hole, and M is the diameter of the hole at the large end.

| A | B | C                               | D     | E     | F     | G     | H     | I     | K       | L      | M     |
|---|---|---------------------------------|-------|-------|-------|-------|-------|-------|---------|--------|-------|
| 2 | 1 | 3 <sup>15</sup> / <sub>16</sub> | 0.700 | 5/8   | 1/4   | 7/16  | 23/16 | 0.475 | 2 1/16  | 3/4    | 0.213 |
| 3 | 1 | 3 15/16                         | 0.938 | 1/4   | 5/16  | 9/16  | 23/16 | 0.475 | 2 1/16  | 3/4    | 0.213 |
| 3 | 2 | 4 7/16                          | 0.938 | 3/4   | 5/16  | 9/16  | 25/8  | 0.700 | 2 1/2   | 7/8    | 0.260 |
| 4 | 1 | 4 7/8                           | 1.231 | 1/4   | 15/32 | 5/8   | 23/16 | 0.475 | 2 1/16  | 3/4    | 0.213 |
| 4 | 2 | 4 7/8                           | 1.231 | 1/4   | 15/32 | 5/8   | 25/8  | 0.700 | 2 1/2   | 7/8    | 0.260 |
| 4 | 3 | 5 3/8                           | 1.231 | 3/4   | 15/32 | 5/8   | 3 1/4 | 0.938 | 3 1/16  | 1 3/16 | 0.322 |
| 5 | 1 | 6 1/8                           | 1.748 | 1/4   | 5/8   | 3/4   | 23/16 | 0.475 | 2 1/16  | 3/4    | 0.213 |
| 5 | 2 | 6 1/8                           | 1.748 | 1/4   | 5/8   | 3/4   | 25/8  | 0.700 | 2 1/2   | 7/8    | 0.260 |
| 5 | 3 | 6 1/8                           | 1.748 | 1/4   | 5/8   | 3/4   | 3 1/4 | 0.938 | 3 1/16  | 1 3/16 | 0.322 |
| 5 | 4 | 6 5/8                           | 1.748 | 3/4   | 5/8   | 3/4   | 4 1/8 | 1.231 | 3 7/8   | 1 1/4  | 0.478 |
| 6 | 1 | 8 5/8                           | 2.494 | 3/8   | 3/4   | 1 1/8 | 23/16 | 0.475 | 2 1/16  | 3/4    | 0.213 |
| 6 | 2 | 8 5/8                           | 2.494 | 3/8   | 3/4   | 1 1/8 | 25/8  | 0.700 | 2 1/2   | 7/8    | 0.260 |
| 6 | 3 | 8 5/8                           | 2.494 | 3/8   | 3/4   | 1 1/8 | 3 1/4 | 0.938 | 3 1/16  | 1 3/16 | 0.322 |
| 6 | 4 | 8 5/8                           | 2.494 | 3/8   | 3/4   | 1 1/8 | 4 1/8 | 1.231 | 3 7/8   | 1 1/4  | 0.478 |
| 6 | 5 | 8 5/8                           | 2.494 | 3/8   | 3/4   | 1 1/8 | 5 1/4 | 1.748 | 4 15/16 | 1 1/2  | 0.635 |
| 7 | 3 | 11 3/8                          | 3.270 | 3/8   | 1 1/8 | 1 3/8 | 3 1/4 | 0.938 | 3 1/16  | 1 3/16 | 0.322 |
| 7 | 4 | 11 3/8                          | 3.270 | 3/8   | 1 1/8 | 1 3/8 | 4 1/8 | 1.231 | 3 7/8   | 1 1/4  | 0.478 |
| 7 | 5 | 11 3/8                          | 3.270 | 3/8   | 1 1/8 | 1 3/8 | 5 1/4 | 1.748 | 4 15/16 | 1 1/2  | 0.635 |
| 7 | 6 | 12 1/2                          | 3.270 | 1 1/4 | 1 1/8 | 1 3/8 | 7 3/8 | 2.494 | 7       | 1 3/4  | 0.760 |

Table 9. Morse Taper Sockets — Hole and Shank Sizes

The diagram shows a Morse Taper Socket with a hole and a shank. The hole is shown with a dashed line, and the shank is shown with a solid line. The hole and shank are both tapered.

| Size   | Morse Taper |       | Size   | Morse Taper |       | Size   | Morse Taper |       |
|--------|-------------|-------|--------|-------------|-------|--------|-------------|-------|
|        | Hole        | Shank |        | Hole        | Shank |        | Hole        | Shank |
| 1 by 2 | No. 1       | No. 2 | 2 by 5 | No. 2       | No. 5 | 4 by 4 | No. 4       | No. 4 |
| 1 by 3 | No. 1       | No. 3 | 3 by 2 | No. 3       | No. 2 | 4 by 5 | No. 4       | No. 5 |
| 1 by 4 | No. 1       | No. 4 | 3 by 3 | No. 3       | No. 3 | 4 by 6 | No. 4       | No. 6 |
| 1 by 5 | No. 1       | No. 5 | 3 by 4 | No. 3       | No. 4 | 5 by 4 | No. 5       | No. 4 |
| 2 by 3 | No. 2       | No. 3 | 3 by 5 | No. 3       | No. 5 | 5 by 5 | No. 5       | No. 5 |
| 2 by 4 | No. 2       | No. 4 | 4 by 3 | No. 4       | No. 3 | 5 by 6 | No. 5       | No. 6 |

STANDARD TAPERS

Table 10. Brown & Sharpe Taper Shanks

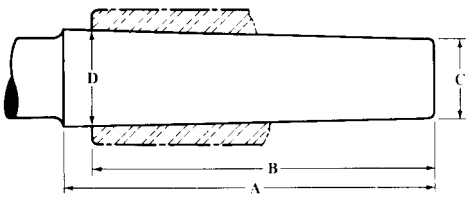
| Number of Taper | Taper per Foot (inch) | Dia. of Plug at Small End<br><i>D</i> | Plug Depth, <i>P</i>        |                      |          | Keyway from End of Spindle<br><i>K</i> | Shank Depth<br><i>S</i> | Length of Key-way <sup>a</sup><br><i>L</i> | Width of Key-way<br><i>W</i> | Length of Arbor Tongue<br><i>T</i> | Diameter of Arbor Tongue<br><i>d</i> | Thickness of Arbor Tongue<br><i>t</i> |
|-----------------|-----------------------|---------------------------------------|-----------------------------|----------------------|----------|--|-------------------------|--|------------------------------|------------------------------------|--------------------------------------|---------------------------------------|
|                 |                       |                                       | B & S <sup>b</sup> Standard | Mill. Mach. Standard | Miscell. |  |                         |  |                              |                                    |                                      |                                       |
| 1 <sup>c</sup>  | .50200                | .20000                                | 15/16                       | ...                  | ...      | 15/16                                  | 1 3/16                  | 3/8  | .135                         | 3/16                               | .170                                 | 1/8                                   |
| 2 <sup>c</sup>  | .50200                | .25000                                | 1 1/16                      | ...                  | ...      | 1 1/64                                 | 1 1/2                   | 1/2  | .166                         | 1/4                                | .220                                 | 3/32                                  |
| 3 <sup>c</sup>  | .50200                | .31250                                | 1 1/2                       | ...                  | ...      | 1 15/32                                | 1 7/8                   | 5/8  | .197                         | 5/16                               | .282                                 | 3/16                                  |
|                 |                       |                                       | ...                         | ...                  | 1 3/4    | 1 23/32                                | 2 1/8                   | 5/8  | .197                         | 5/16                               | .282                                 | 3/16                                  |
| 4               | .50240                | .35000                                | ...                         | 1 1/4                | ...      | 1 13/64                                | 1 21/32                 | 11/16                                      | .228                         | 11/32                              | .320                                 | 7/32                                  |
|                 |                       |                                       | ...                         | 1 11/16              | ...      | 1 41/64                                | 2 3/32                  | 11/16                                      | .228                         | 11/32                              | .320                                 | 7/32                                  |
| 5               | .50160                | .45000                                | ...                         | 1 3/4                | ...      | 1 15/16                                | 2 3/16                  | 3/4  | .260                         | 3/8                                | .420                                 | 1/4                                   |
|                 |                       |                                       | ...                         | ...                  | 2        | 1 15/16                                | 2 7/16                  | 3/4  | .260                         | 3/8                                | .420                                 | 1/4                                   |
| 6               | .50329                | .50000                                | 2 3/8                       | ...                  | ...      | 2 1/64                                 | 2 7/8                   | 3/8  | .291                         | 7/16                               | .460                                 | 9/32                                  |
|                 |                       |                                       | ...                         | ...                  | 2 1/2    | 2 13/32                                | 3 1/32                  | 15/16                                      | .322                         | 15/32                              | .560                                 | 5/16                                  |
| 7               | .50147                | .60000                                | 2 3/8                       | ...                  | ...      | 2 25/32                                | 3 13/32                 | 15/16                                      | .322                         | 15/32                              | .560                                 | 5/16                                  |
|                 |                       |                                       | ...                         | ...                  | 3        | 2 29/32                                | 3 17/32                 | 15/16                                      | .322                         | 15/32                              | .560                                 | 5/16                                  |
| 8               | .50100                | .75000                                | 3 3/16                      | ...                  | ...      | 3 29/64                                | 4 1/8                   | 1  | .353                         | 1/2                                | .710                                 | 1 1/32                                |
| 9               | .50085                | .90010                                | ...                         | 4                    | ...      | 3 7/8                                  | 4 5/8                   | 1 1/8                                      | .385                         | 9/16                               | .860                                 | 3/8                                   |
| 10              | .51612                | 1.04465                               | 4 1/4                       | ...                  | ...      | 4 3/8                                  | 4 7/8                   | 1 1/8                                      | .385                         | 9/16                               | .860                                 | 3/8                                   |
|                 |                       |                                       | ...                         | ...                  | ...      | 4 7/8                                  | 5 23/32                 | 1 5/16                                     | .447                         | 21/32                              | 1.010                                | 7/16                                  |
| 11              | .50100                | 1.24995                               | ...                         | 5 11/16              | ...      | 5 17/32                                | 6 13/32                 | 1 1/16                                     | .447                         | 21/32                              | 1.010                                | 7/16                                  |
|                 |                       |                                       | ...                         | ...                  | 6 7/32   | 6 1/16                                 | 6 15/16                 | 1 5/16                                     | .447                         | 21/32                              | 1.010                                | 7/16                                  |
| 12              | .49973                | 1.50010                               | 5 5/16                      | ...                  | ...      | 5 25/32                                | 6 21/32                 | 1 1/16                                     | .447                         | 21/32                              | 1.210                                | 7/16                                  |
|                 |                       |                                       | ...                         | ...                  | ...      | 6 3/4                                  | 6 19/32                 | 1 1/16                                     | .447                         | 21/32                              | 1.210                                | 7/16                                  |
| 13              | .50020                | 1.75005                               | 7 3/4                       | ...                  | ...      | 7 1/16                                 | 8 3/16                  | 1 1/2                                      | .510                         | 3/4                                | 1.460                                | 1/2                                   |
|                 |                       |                                       | ...                         | ...                  | 6 1/4    | ...                                    | ...                     | ...  | ...                          | ...                                | ...                                  | ...                                   |
| 14              | .50000                | 2.00000                               | 8 3/4                       | 8 1/4                | ...      | 8 1/32                                 | 9 5/32                  | 1 11/16                                    | .572                         | 27/32                              | 1.960                                | 9/16                                  |
| 15              | .5000                 | 2.25000                               | 8 3/4                       | ...                  | ...      | 8 17/32                                | 9 21/32                 | 1 11/16                                    | .572                         | 27/32                              | 2.210                                | 9/16                                  |
| 16              | .50000                | 2.50000                               | 9 1/4                       | ...                  | ...      | 9                                      | 10 1/4                  | 1 7/8                                      | .635                         | 15/16                              | 2.450                                | 3/8                                   |
| 17              | .50000                | 2.75000                               | 9 3/4                       | ...                  | ...      | ...                                    | ...                     | ...  | ...                          | ...                                | ...                                  | ...                                   |
| 18              | .50000                | 3.00000                               | 10 1/4                      | ...                  | ...      | ...                                    | ...                     | ...  | ...                          | ...                                | ...                                  | ...                                   |

<sup>a</sup> Special lengths of keyway are used instead of standard lengths in some places. Standard lengths need not be used when keyway is for driving only and not for admitting key to force out tool.

<sup>b</sup> "B & S Standard" Plug Depths are not used in all cases.

<sup>c</sup> Adopted by American Standards Association.

Table 11. Jarno Taper Shanks



$$D = \frac{\text{no. of taper}}{8} \quad C = \frac{\text{no. of taper}}{10} \quad B = \frac{\text{no. of taper}}{2}$$

| Number of Taper | Length A          | Length B        | Diameter C | Diameter D | Taper per foot |
|-----------------|-------------------|-----------------|------------|------------|----------------|
| 2               | 1 $\frac{1}{8}$   | 1               | 0.20       | 0.250      | 0.600          |
| 3               | 1 $\frac{3}{8}$   | 1 $\frac{1}{2}$ | 0.30       | 0.375      | 0.600          |
| 4               | 2 $\frac{3}{16}$  | 2               | 0.40       | 0.500      | 0.600          |
| 5               | 2 $\frac{11}{16}$ | 2 $\frac{1}{2}$ | 0.50       | 0.625      | 0.600          |
| 6               | 3 $\frac{3}{16}$  | 3               | 0.60       | 0.750      | 0.600          |
| 7               | 3 $\frac{11}{16}$ | 3 $\frac{1}{2}$ | 0.70       | 0.875      | 0.600          |
| 8               | 4 $\frac{3}{16}$  | 4               | 0.80       | 1.000      | 0.600          |
| 9               | 4 $\frac{11}{16}$ | 4 $\frac{1}{2}$ | 0.90       | 1.125      | 0.600          |
| 10              | 5 $\frac{1}{4}$   | 5               | 1.00       | 1.250      | 0.600          |
| 11              | 5 $\frac{3}{4}$   | 5 $\frac{1}{2}$ | 1.10       | 1.375      | 0.600          |
| 12              | 6 $\frac{1}{4}$   | 6               | 1.20       | 1.500      | 0.600          |
| 13              | 6 $\frac{3}{4}$   | 6 $\frac{1}{2}$ | 1.30       | 1.625      | 0.600          |
| 14              | 7 $\frac{1}{4}$   | 7               | 1.40       | 1.750      | 0.600          |
| 15              | 7 $\frac{3}{4}$   | 7 $\frac{1}{2}$ | 1.50       | 1.875      | 0.600          |
| 16              | 8 $\frac{5}{16}$  | 8               | 1.60       | 2.000      | 0.600          |
| 17              | 8 $\frac{13}{16}$ | 8 $\frac{1}{2}$ | 1.70       | 2.125      | 0.600          |
| 18              | 9 $\frac{5}{16}$  | 9               | 1.80       | 2.250      | 0.600          |
| 19              | 9 $\frac{13}{16}$ | 9 $\frac{1}{2}$ | 1.90       | 2.375      | 0.600          |
| 20              | 10 $\frac{5}{16}$ | 10              | 2.00       | 2.500      | 0.600          |

**Tapers for Machine Tool Spindles.**—Most lathe spindles have Morse tapers, most milling machine spindles have American Standard tapers, almost all smaller milling machine spindles have R8 tapers, and large vertical milling machine spindles have American Standard tapers. The spindles of drilling machines and the taper shanks of twist drills are made to fit the Morse taper. For lathes, the Morse taper is generally used, but lathes may have the Jarno, Brown & Sharpe, or a special taper. Of 33 lathe manufacturers, 20 use the Morse taper; 5, the Jarno; 3 use special tapers of their own; 2 use modified Morse (longer than the standard but the same taper); 2 use Reed (which is a short Jarno); 1 uses the Brown & Sharpe standard. For grinding machine centers, Jarno, Morse, and Brown & Sharpe tapers are used. Of ten grinding machine manufacturers, 3 use Brown & Sharpe; 3 use Morse; and 4 use Jarno. The Brown & Sharpe taper is used extensively for milling machine and dividing head spindles. The standard milling machine spindle adopted in 1927 by the milling machine manufacturers of the National Machine Tool Builders' Association (now The Association for Manufacturing Technology [AMT]), has a taper of 3 $\frac{1}{2}$  inches per foot. This comparatively steep taper was adopted to ensure easy release of arbors.

**Table 12. American National Standard Plug and Ring Gages for Steep Machine Tapers ANSI/ASME B5.10-1994 (R2002)**

| No. of Taper | Taper per Foot <sup>a</sup> (Basic) | Diameter at Gage Line <sup>a</sup> A | Tolerances for Diameter A <sup>b</sup> |              |              | Diameter at Small End <sup>a</sup> A' | Length Gage Line to Small End L | Overall Length of Gage Body B | Dia. of Opening C |
|--------------|-------------------------------------|--------------------------------------|--|--------------|--------------|---------------------------------------|---------------------------------|-------------------------------|-------------------|
|              |                                     |                                      | Class X Gage                           | Class Y Gage | Class Z Gage |                                       |                                 |                               |                   |
| 5            | 3.500                               | 0.500                                | 0.00004                                | 0.00007      | 0.00010      | 0.2995                                | 0.6875                          | 0.81                          | 0.30              |
| 10           | 3.500                               | 0.625                                | 0.00004                                | 0.00007      | 0.00010      | 0.3698                                | 0.8750                          | 1.00                          | 0.36              |
| 15           | 3.500                               | 0.750                                | 0.00004                                | 0.00007      | 0.00010      | 0.4401                                | 1.0625                          | 1.25                          | 0.44              |
| 20           | 3.500                               | 0.875                                | 0.00006                                | 0.00009      | 0.00012      | 0.4922                                | 1.3125                          | 1.50                          | 0.48              |
| 25           | 3.500                               | 1.000                                | 0.00006                                | 0.00009      | 0.00012      | 0.5443                                | 1.5625                          | 1.75                          | 0.53              |
| 30           | 3.500                               | 1.250                                | 0.00006                                | 0.00009      | 0.00012      | 0.7031                                | 1.8750                          | 2.06                          | 0.70              |
| 35           | 3.500                               | 1.500                                | 0.00006                                | 0.00009      | 0.00012      | 0.8438                                | 2.2500                          | 2.44                          | 0.84              |
| 40           | 3.500                               | 1.750                                | 0.00008                                | 0.00012      | 0.00016      | 1.0026                                | 2.5625                          | 2.75                          | 1.00              |
| 45           | 3.500                               | 2.250                                | 0.00008                                | 0.00012      | 0.00016      | 1.2839                                | 3.3125                          | 3.50                          | 1.00              |
| 50           | 3.500                               | 2.750                                | 0.00010                                | 0.00015      | 0.00020      | 1.5833                                | 4.0000                          | 4.25                          | 1.00              |
| 55           | 3.500                               | 3.500                                | 0.00010                                | 0.00015      | 0.00020      | 1.9870                                | 5.1875                          | 5.50                          | 1.00              |
| 60           | 3.500                               | 4.250                                | 0.00010                                | 0.00015      | 0.00020      | 2.3906                                | 6.3750                          | 6.75                          | 2.00              |

<sup>a</sup>The taper per foot and diameter A at gage line are basic dimensions. Dimensions in Column A' are calculated for reference only.

<sup>b</sup>Tolerances for diameter A are plus for plug gages and minus for ring gages.

All dimensions are in inches.

The amounts of taper deviation for Class X, Class Y, and Class Z gages are the same, respectively, as the amounts shown for tolerances on diameter A. Taper deviation is the permissible allowance from true taper at any point of diameter in the length of the gage. On taper *plug* gages, this deviation may be applied only in the direction which *decreases* the rate of taper. On taper *ring* gages, this deviation may be applied only in the direction which *increases* the rate of taper. Tolerances on two-decimal dimensions are  $\pm 0.010$ .

**Table 13. Jacobs Tapers and Threads for Drill Chucks and Spindles**

American Standard Thread Form

| Taper Series       | A      | B       | C       | Taper per Ft. | Taper Series | A      | B      | C      | Taper per Ft. |
|--------------------|--------|---------|---------|---------------|--------------|--------|--------|--------|---------------|
| No. 0              | 0.2500 | 0.22844 | 0.43750 | 0.59145       | No. 4        | 1.1240 | 1.0372 | 1.6563 | 0.62886       |
| No. 1              | 0.3840 | 0.33341 | 0.65625 | 0.92508       | No. 5        | 1.4130 | 1.3161 | 1.8750 | 0.62010       |
| No. 2              | 0.5590 | 0.48764 | 0.87500 | 0.97861       | No. 6        | 0.6760 | 0.6241 | 1.0000 | 0.62292       |
| No. 2 <sup>a</sup> | 0.5488 | 0.48764 | 0.75000 | 0.97861       | No. 33       | 0.6240 | 0.5605 | 1.0000 | 0.76194       |
| No. 3              | 0.8110 | 0.74610 | 1.21875 | 0.63898       | ...          | ...    | ...    | ...    | ...           |

<sup>a</sup>These dimensions are for the No. 2 "short" taper.

| Thread Size | Diameter <i>D</i> |       | Diameter <i>E</i> |        | Dimension <i>F</i> |       |
|-------------|-------------------|-------|-------------------|--------|--------------------|-------|
|             | Max.              | Min.  | Max.              | Min.   | Max.               | Min.  |
| 5/16-24     | 0.531             | 0.516 | 0.3245            | 0.3195 | 0.135              | 0.115 |
| 5/16-24     | 0.633             | 0.618 | 0.3245            | 0.3195 | 0.135              | 0.115 |
| 3/8-24      | 0.633             | 0.618 | 0.385             | 0.380  | 0.135              | 0.115 |
| 1/2-20      | 0.860             | 0.845 | 0.510             | 0.505  | 0.135              | 0.115 |
| 5/8-11      | 1.125             | 1.110 | 0.635             | 0.630  | 0.166              | 0.146 |
| 5/8-16      | 1.125             | 1.110 | 0.635             | 0.630  | 0.166              | 0.146 |
| 45/64-16    | 1.250             | 1.235 | 0.713             | 0.708  | 0.166              | 0.146 |
| 3/4-16      | 1.250             | 1.235 | 0.760             | 0.755  | 0.166              | 0.146 |
| 1-8         | 1.437             | 1.422 | 1.036             | 1.026  | 0.281              | 0.250 |
| 1-10        | 1.437             | 1.422 | 1.036             | 1.026  | 0.281              | 0.250 |
| 1 1/2-8     | 1.871             | 1.851 | 1.536             | 1.526  | 0.343              | 0.312 |

| Thread <sup>a</sup> Size | <i>G</i> |        | <i>H</i> <sup>b</sup> | Plug Gage Pitch Dia. |        | Ring Gage Pitch Dia. |        |
|--------------------------|----------|--------|-----------------------|----------------------|--------|----------------------|--------|
|                          | Max      | Min    |                       | Go                   | Not Go | Go                   | Not Go |
| 5/16-24                  | 0.3114   | 0.3042 | 0.437 <sup>c</sup>    | 0.2854               | 0.2902 | 0.2843               | 0.2806 |
| 3/8-24                   | 0.3739   | 0.3667 | 0.562 <sup>d</sup>    | 0.3479               | 0.3528 | 0.3468               | 0.3430 |
| 1/2-20                   | 0.4987   | 0.4906 | 0.562                 | 0.4675               | 0.4731 | 0.4662               | 0.4619 |
| 5/8-11                   | 0.6234   | 0.6113 | 0.687                 | 0.5660               | 0.5732 | 0.5644               | 0.5589 |
| 5/8-16                   | 0.6236   | 0.6142 | 0.687                 | 0.5844               | 0.5906 | 0.5830               | 0.5782 |
| 45/64-16                 | 0.7016   | 0.6922 | 0.687                 | 0.6625               | 0.6687 | 0.6610               | 0.6561 |
| 3/4-16                   | 0.7485   | 0.7391 | 0.687                 | 0.7094               | 0.7159 | 0.7079               | 0.7029 |
| 1-8                      | 1.000    | 0.9848 | 1.000                 | 0.9188               | 0.9242 | 0.9188               | 0.9134 |
| 1-10                     | 1.000    | 0.9872 | 1.000                 | 0.9350               | 0.9395 | 0.9350               | 0.9305 |
| 1 1/2-8                  | 1.500    | 1.4848 | 1.000                 | 1.4188               | 1.4242 | 1.4188               | 1.4134 |

<sup>a</sup>Except for 1-8, 1-10, 1 1/2-8 all threads are now manufactured to the American National Standard Unified Screw Thread System, Internal Class 2B, External Class 2A. Effective date 1976.

<sup>b</sup>Tolerances for dimension *H* are as follows: 0.030 inch for thread sizes 5/16-24 to 3/4-16, inclusive and 0.125 inch for thread sizes 1-8 to 1 1/2-8, inclusive.

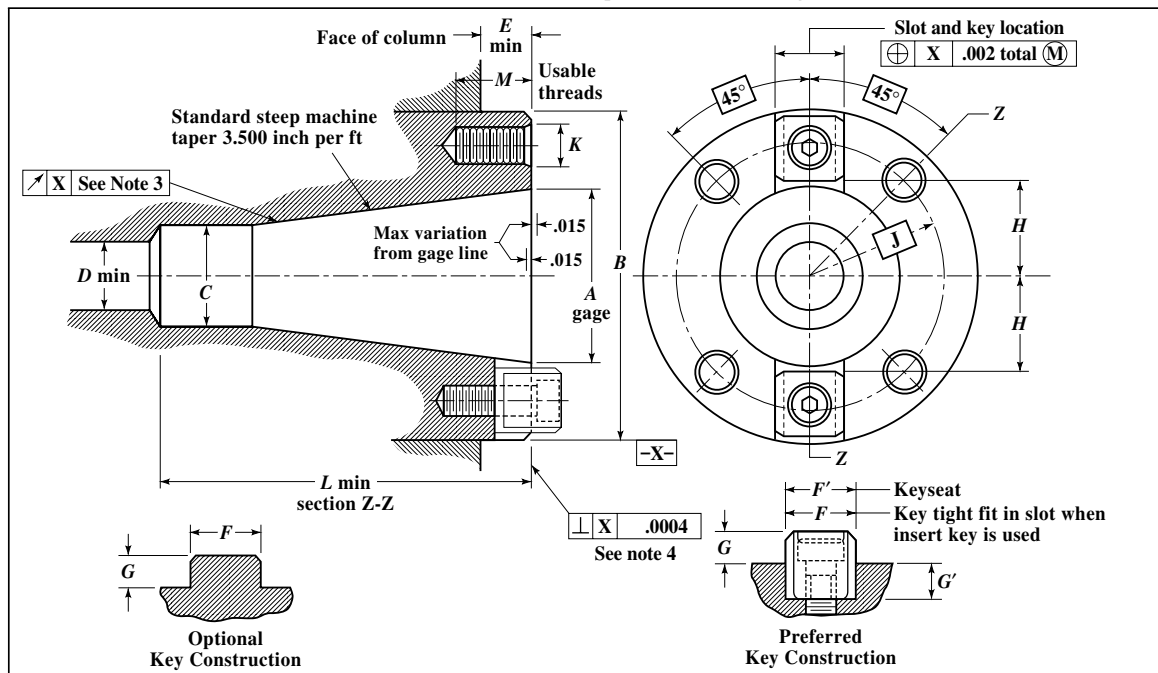
<sup>c</sup>Length for Jacobs 0B5/16 chuck is 0.375 inch, length for 1B5/16 chuck is 0.437 inch.

<sup>d</sup>Length for Jacobs No. 1BS chuck is 0.437 inch.

*Usual Chuck Capacities for Different Taper Series Numbers:* No. 0 taper, drill diameters, 0-5/32 inch; No. 1, 0-1/4 inch; No. 2, 0-1/2 inch; No. 2 "Short," 0-5/16 inch; No. 3, 0-1/2, 1/8-5/8, 3/16-3/4, or 1/4-13/16 inch; No. 4, 1/8-3/4 inch; No. 5, 3/8-1; No. 6, 0-1/2 inch; No. 33, 0-1/2 inch.

*Usual Chuck Capacities for Different Thread Sizes:* Size 5/16-24, drill diameters 0-1/4 inch; size 3/8-24, drill diameters 0-3/8, 1/16-3/8, or 5/64-1/2 inch; size 1/2-20, drill diameters 0-1/2, 1/16-3/8, or 5/64-1/2 inch; size 5/8-11, drill diameters 0-1/2 inch; size 5/8-16, drill diameters 0-1/2, 1/8-5/8, or 3/16-3/4 inch; size 45/64-16, drill diameters 0-1/2 inch; size 3/4-16, drill diameters 0-1/2 or 3/16-3/4.



Table 1. Essential Dimensions of American National Standard Spindle Noses for Milling Machines *ANSI B5.18-1972 (R1998)*

**Table 1. (Continued) Essential Dimensions of American National Standard Spindle Noses for Milling Machines ANSI B5.18-1972 (R1998)**

| Size No. | Gage Dia. of Taper <i>A</i> | Dia. of Spindle <i>B</i> | Pilot Dia. <i>C</i> | Clearance Hole for Draw-in Bolt Min. <i>D</i> | Minimum Dimension Spindle End to Column <i>E</i> | Width of Driving Key <i>F</i> | Width of Keyseat <i>F'</i> | Maximum Height of Driving Key <i>G</i> | Minimum Depth of Keyseat <i>G'</i> | Distance from Center to Driving Keys <i>H</i> | Radius of Bolt Hole Circle <i>J</i> | Size of Threads for Bolt Holes UNC-2B <i>K</i> | Full Depth of Arbor Hole in Spindle Min. <i>L</i> | Depth of Usable Thread for Bolt Hole <i>M</i> |
|----------|-----------------------------|--------------------------|---------------------|---|--|-------------------------------|----------------------------|--|------------------------------------|---|-------------------------------------|--|---|---|
| 30       | 1.250                       | 2.7493<br>2.7488         | 0.692<br>0.685      | 0.66  | 0.50   | 0.6255<br>0.6252              | 0.624<br>0.625             | 0.31                                   | 0.31                               | 0.660<br>0.654                                | 1.0625<br>(Note 1)                  | 0.375-16                                       | 2.88  | 0.62  |
| 40       | 1.750                       | 3.4993<br>3.4988         | 1.005<br>0.997      | 0.66  | 0.62   | 0.6255<br>0.6252              | 0.624<br>0.625             | 0.31                                   | 0.31                               | 0.910<br>0.904                                | 1.3125<br>(Note 1)                  | 0.500-13                                       | 3.88  | 0.81  |
| 45       | 2.250                       | 3.9993<br>3.9988         | 1.286<br>1.278      | 0.78  | 0.62   | 0.7505<br>0.7502              | 0.749<br>0.750             | 0.38                                   | 0.38                               | 1.160<br>1.154                                | 1.500<br>(Note 1)                   | 0.500-13                                       | 4.75  | 0.81  |
| 50       | 2.750                       | 5.0618<br>5.0613         | 1.568<br>1.559      | 1.06  | 0.75   | 1.0006<br>1.0002              | 0.999<br>1.000             | 0.50                                   | 0.50                               | 1.410<br>1.404                                | 2.000<br>(Note 2)                   | 0.625-11                                       | 5.50  | 1.00  |
| 60       | 4.250                       | 8.7180<br>8.7175         | 2.381<br>2.371      | 1.38  | 1.50   | 1.0006<br>1.0002              | 0.999<br>1.000             | 0.50                                   | 0.50                               | 2.420<br>2.414                                | 3.500<br>(Note 2)                   | 0.750-10                                       | 8.62  | 1.25  |

All dimensions are given in inches.

**Tolerances:**

Two-digit decimal dimensions  $\pm 0.010$  unless otherwise specified.

*A*—Taper: Tolerance on rate of taper to be 0.001 inch per foot applied only in direction which decreases rate of taper.

*F'*—Centrality of keyway with axis of taper 0.002 total at maximum material condition. (0.002 Total indicator variation)

*F*—Centrality of solid key with axis of taper 0.002 total at maximum material condition. (0.002 Total indicator variation)

*Note 1*: Holes spaced as shown and located within 0.006 inch diameter of true position.

*Note 2*: Holes spaced as shown and located within 0.010 inch diameter of true position.

*Note 3*: Maximum turnout on test plug:

0.0004 at 1 inch projection from gage line.

0.0010 at 12 inch projection from gage line.

*Note 4*: Squareness of mounting face measured near mounting bolt hole circle.

**Table 2. Essential Dimensions of American National Standard Tool Shanks for Milling Machines ANSI B5.18-1972 (R1998)**

| Size No. | Gage Dia. of Taper $N$ | Tap Drill Size for Draw-in Thread $O$ | Dia. of Neck $P$ | Size of Thread for Draw-in Bolt UNC-2B $M$ | Pilot Dia. $R$ | Length of Pilot $S$ | Minimum Length of Usable Thread $T$ | Minimum Depth of Clearance Hole $U$ |
|----------|------------------------|---------------------------------------|------------------|--|----------------|---------------------|-------------------------------------|-------------------------------------|
| 30       | 1.250                  | 0.422<br>0.432                        | 0.66<br>0.65     | 0.500-13                                   | 0.675<br>0.670 | 0.81                | 1.00                                | 2.00                                |
| 40       | 1.750                  | 0.531<br>0.541                        | 0.94<br>0.93     | 0.625-11                                   | 0.987<br>0.980 | 1.00                | 1.12                                | 2.25                                |
| 45       | 2.250                  | 0.656<br>0.666                        | 1.19<br>1.18     | 0.750-10                                   | 1.268<br>1.260 | 1.00                | 1.50                                | 2.75                                |
| 50       | 2.750                  | 0.875<br>0.885                        | 1.50<br>1.49     | 1.000-8                                    | 1.550<br>1.540 | 1.00                | 1.75                                | 3.50                                |
| 60       | 4.250                  | 1.109<br>1.119                        | 2.28<br>2.27     | 1.250-7                                    | 2.360<br>2.350 | 1.75                | 2.25                                | 4.25                                |

| Size No. | Distance from Rear of Flange to End of Arbor $V$ | Clearance of Flange from Gage Diameter $W$ | Tool Shank Centerline to Driving Slot $X$ | Width of Driving Slot $Y$ | Distance from Gage Line to Bottom of C'bore $Z$ | Depth of 60° Center $K$ | Diameter of C'bore $L$ |
|----------|--|--|---|---------------------------|---|-------------------------|------------------------|
| 30       | 2.75   | 0.045<br>0.075                             | 0.640<br>0.625                            | 0.635<br>0.645            | 2.50  | 0.05<br>0.07            | 0.525<br>0.530         |
| 40       | 3.75   | 0.045<br>0.075                             | 0.890<br>0.875                            | 0.635<br>0.645            | 3.50  | 0.05<br>0.07            | 0.650<br>0.655         |
| 45       | 4.38   | 0.105<br>0.135                             | 1.140<br>1.125                            | 0.760<br>0.770            | 4.06  | 0.05<br>0.07            | 0.775<br>0.780         |
| 50       | 5.12   | 0.105<br>0.135                             | 1.390<br>1.375                            | 1.010<br>1.020            | 4.75  | 0.05<br>0.12            | 1.025<br>1.030         |
| 60       | 8.25   | 0.105<br>0.135                             | 2.400<br>2.385                            | 1.010<br>1.020            | 7.81  | 0.05<br>0.12            | 1.307<br>1.312         |

All dimensions are given in inches.

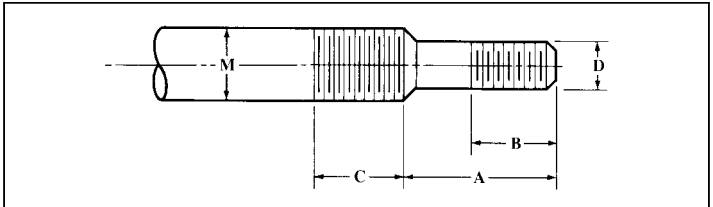
*Tolerances:* Two digit decimal dimensions  $\pm 0.010$  inch unless otherwise specified.

*M*—Permissible for Class 2B “NoGo” gage to enter five threads before interference.

*N*—Taper tolerance on rate of taper to be 0.001 inch per foot applied only in direction which increases rate of taper.

*Y*—Centrality of drive slot with axis of taper shank 0.004 inch at maximum material condition. (0.004 inch total indicator variation)

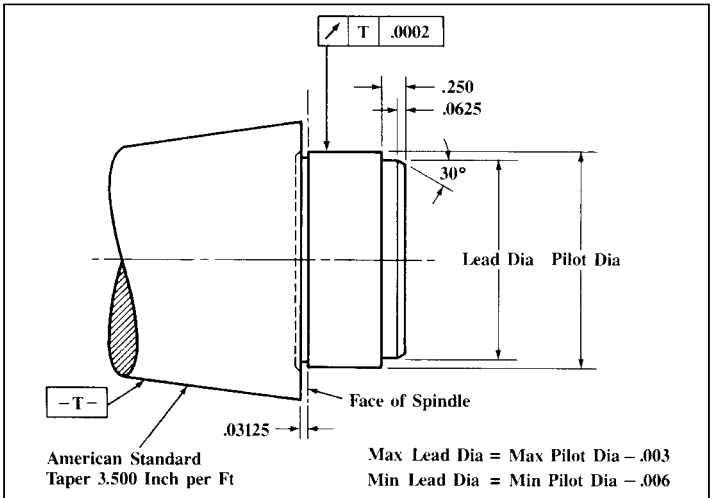
**Table 3. American National Standard Draw-in Bolt Ends**  
ANSI B5.18-1972 (R1998)



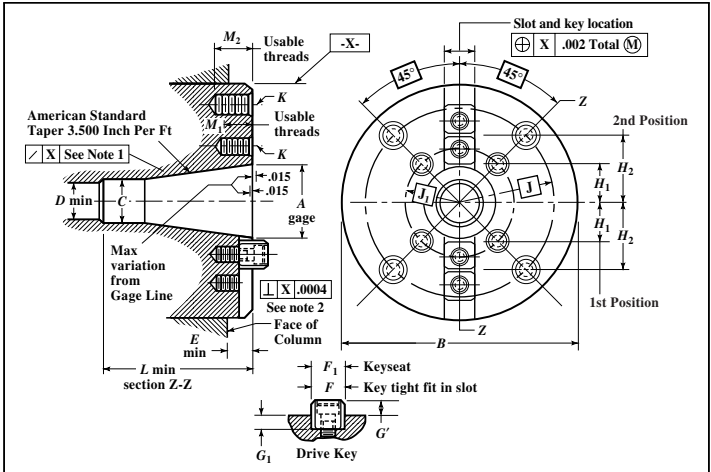
| Size No. | Length of Small End<br><i>A</i> | Length of Usable Thread at Small End<br><i>B</i> | Length of Usable Thread on Large Diameter<br><i>C</i> | Size of Thread for Large End<br>UNC-2A<br><i>M</i> | Size of Thread for Small End<br>UNC-2A<br><i>D</i> |
|----------|---------------------------------|--|---|--|--|
| 30       | 1.06                            | 0.75   | 0.75  | 0.500-13   | 0.375-16   |
| 40       | 1.25                            | 1.00   | 1.12  | 0.625-11   | 0.500-13   |
| 45       | 1.50                            | 1.12   | 1.25  | 0.750-10   | 0.625-11   |
| 50       | 1.50                            | 1.25   | 1.38  | 1.000-8  | 0.625-11   |
| 60       | 1.75                            | 1.37   | 2.00  | 1.250-7  | 1.000-8  |

All dimensions are given in inches.

**Table 4. American National Standard Pilot Lead on Centering Plugs for Flatback Milling Cutters**  
ANSI B5.18-1972 (R1998)



**Table 5. Essential Dimensions for American National Standard Spindle Nose with Large Flange ANSI B5.18-1972 (R1998)**



| Size No. | Gage Diam. of Taper A                                | Dia. of Spindle Flange B                 | Pilot Dia. C   | Clearance Hole for Draw-diam Bolt Min. D | Min. Dim. Spindle End to Column E | Width of Driving Key F                     | Height of Driving Key Max. G          | Depth of Keyseat Min. G <sub>1</sub> | Distance from Center to Driving Keys First Position H <sub>1</sub> |
|----------|--|--|----------------|--|-----------------------------------|--|---------------------------------------|--------------------------------------|--|
| 50A      | 2.750  | 8.7180<br>8.7175                         | 1.568<br>1.559 | 1.06                                     | 0.75                              | 1.0006<br>1.0002                           | 0.50                                  | 0.50                                 | 1.410<br>1.404   |
| Size No. | Distance from Center to Driving Keys Second Position | Radius of Bolt Hole Circles (See Note 3) |                | Size of Threads for Bolt Holes UNC-2B    |                                   | Full Depth of Arbor Hole in Spindle Min. L | Depth of Usable Thread for Bolt Holes |                                      | Width of Keyseat F <sub>1</sub>                                    |
|          | H <sub>2</sub>                                       | J <sub>1</sub>                           | J <sub>2</sub> | K <sub>1</sub>                           | K <sub>2</sub>                    |  | M <sub>1</sub>                        | M <sub>2</sub>                       |  |
| 50A      | 2.420<br>2.410                                       | 2.000                                    | 3.500          | 0.625-11                                 | 0.750-10                          | 5.50                                       | 1.00                                  | 1.25                                 | 0.999<br>1.000   |

All dimensions are given in inches.

**Tolerances:** Two-digit decimal dimensions ± 0.010 unless otherwise specified.

A—Tolerance on rate of taper to be 0.001 inch per foot applied only in direction which decreases rate of taper.

F—Centrality of solid key with axis of taper 0.002 inch total at maximum material condition. (0.002 inch Total indicator variation)

F<sub>1</sub>—Centrality of keyseat with axis of taper 0.002 inch total at maximum material condition. (0.002 inch Total indicator variation)

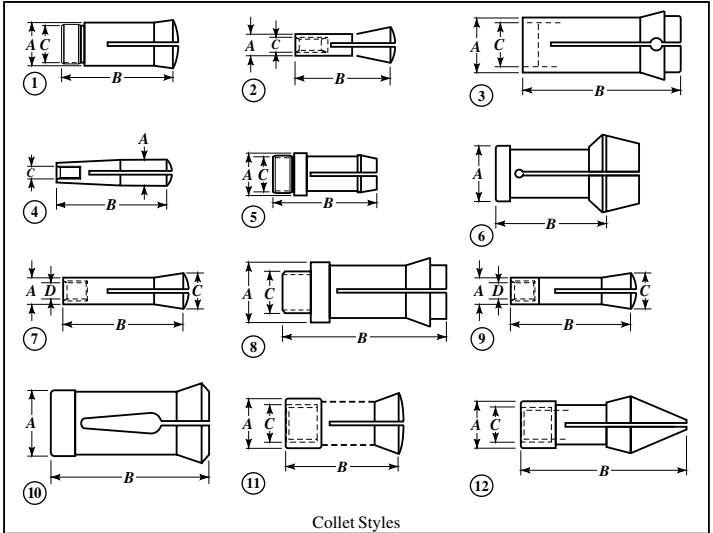
**Note 1:** Maximum runout on test plug: 0.0004 at 1 inch projection from gage line. 0.0010 at 12 inch projection from gage line.

**Note 2:** Squareness of mounting face measured near mounting bolt hole circle.

**Note 3:** Holes located as shown and within 0.010 inch diameter of true position.

Collets

Collets for Lathes, Mills, Grinders, and Fixtures



Collet Styles

Collets for Lathes, Mills, Grinders, and Fixtures

| Collet | Style | Dimensions       |           |               | Max. Capacity (inches) |       |        |
|--------|-------|------------------|-----------|---------------|------------------------|-------|--------|
|        |       | Bearing Diam., A | Length, B | Thread, C     | Round                  | Hex   | Square |
| 1A     | 1     | 0.650            | 2.563     | 0.640 × 26 RH | 0.500                  | 0.438 | 0.344  |
| 1AM    | 1     | 1.125            | 3.906     | 1.118 × 24 RH | 1.000                  | 0.875 | 0.719  |
| 1B     | 2     | 0.437            | 1.750     | 0.312 × 30 RH | 0.313                  | 0.219 | 0.188  |
| 1C     | 1     | 0.335            | 1.438     | 0.322 × 40 RH | 0.250                  | 0.219 | 0.172  |
| 1J     | 1     | 1.250            | 3.000     | 1.238 × 20 RH | 1.063                  | 0.875 | 0.750  |
| 1K     | 3     | 1.250            | 2.813     | None          | 1.000                  | 0.875 | 0.719  |
| 2A     | 1     | 0.860            | 3.313     | 0.850 × 20 RH | 0.688                  | 0.594 | 0.469  |
| 2AB    | 2     | 0.750            | 2.563     | 0.500 × 20 RH | 0.625                  | 0.484 | 0.391  |
| 2AM    | 1     | 0.629            | 3.188     | 0.622 × 24 RH | 0.500                  | 0.438 | 0.344  |
| 2B     | 2     | 0.590            | 2.031     | 0.437 × 26 RH | 0.500                  | 0.438 | 0.344  |
| 2C     | 1     | 0.450            | 1.812     | 0.442 × 30 RH | 0.344                  | 0.594 | 0.234  |
| 2H     | 1     | 0.826            | 4.250     | 0.799 × 20 RH | 0.625                  | 0.531 | 1.000  |
| 2J     | 1     | 1.625            | 3.250     | 1.611 × 18 RH | 1.375                  | 1.188 | 0.438  |
| 2L     | 1     | 0.950            | 3.000     | 0.938 × 20 RH | 0.750                  | 0.656 | 1.000  |
| 2M     | 4     | 2 Morse          | 2.875     | 0.375 × 16 RH | 0.500                  | 0.438 | 0.344  |
| 2NS    | 1     | 0.324            | 1.562     | 0.318 × 40 RH | 0.250                  | 0.203 | 0.172  |
| 2OS    | 1     | 0.299            | 1.250     | 0.263 × 40 RH | 0.188                  | 0.156 | 0.125  |
| 2S     | 1     | 0.750            | 3.234     | 0.745 × 18 RH | 0.563                  | 0.484 | 0.391  |
| 2VB    | 2     | 0.595            | 2.438     | 0.437 × 26 RH | 0.500                  | 0.438 | 0.344  |
| 3AM    | 1     | 0.750            | 3.188     | 0.742 × 24 RH | 0.625                  | 0.531 | 0.438  |
| 3AT    | 1     | 0.687            | 2.313     | 0.637 × 26 RH | 0.500                  | 0.438 | 0.344  |

## Collets for Lathes, Mills, Grinders, and Fixtures (Continued)

| Collet | Style | Dimensions       |           |                                 | Max. Capacity (inches) |       |        |
|--------|-------|------------------|-----------|---------------------------------|------------------------|-------|--------|
|        |       | Bearing Diam., A | Length, B | Thread, C                       | Round                  | Hex   | Square |
| 3B     | 2     | 0.875            | 3.438     | 0.625 × 16 RH                   | 0.750                  | 0.641 | 0.531  |
| 3C     | 1     | 0.650            | 2.688     | 0.640 × 26 RH                   | 0.500                  | 0.438 | 0.344  |
| 3H     | 1     | 1.125            | 4.438     | 1.050 × 20 RH                   | 0.875                  | 0.750 | 0.625  |
| 3J     | 1     | 2.000            | 3.750     | 1.988 × 20 RH                   | 1.750                  | 1.500 | 1.250  |
| 3NS    | 1     | 0.687            | 2.875     | 0.647 × 20 RH                   | 0.500                  | 0.438 | 0.344  |
| 3OS    | 1     | 0.589            | 2.094     | 0.518 × 26 RH                   | 0.375                  | 0.313 | 0.266  |
| 3PN    | 1     | 0.650            | 2.063     | 0.645 × 24 RH                   | 0.500                  | 0.438 | 0.344  |
| 3PO    | 1     | 0.599            | 2.063     | 0.500 × 24 RH                   | 0.375                  | 0.313 | 0.266  |
| 3S     | 1     | 1.000            | 4.594     | 0.995 × 20 RH                   | 0.750                  | 0.656 | 0.531  |
| 3SC    | 1     | 0.350            | 1.578     | 0.293 × 36 RH                   | 0.188                  | 0.156 | 0.125  |
| 3SS    | 1     | 0.589            | 2.125     | 0.515 × 26 RH                   | 0.375                  | 0.313 | 0.266  |
| 4C     | 1     | 0.950            | 3.000     | 0.938 × 20 RH                   | 0.750                  | 0.656 | 0.531  |
| 4NS    | 1     | 0.826            | 3.500     | 0.800 × 20 RH                   | 0.625                  | 0.531 | 0.438  |
| 4OS    | 1     | 0.750            | 2.781     | 0.660 × 20 RH                   | 0.500                  | 0.438 | 0.344  |
| 4PN    | 1     | 1.000            | 2.906     | 0.995 × 16 RH                   | 0.750                  | 0.656 | 0.531  |
| 4S     | 1     | 0.998            | 3.250     | 0.982 × 20 RH                   | 0.750                  | 0.656 | 0.531  |
| 5C     | 1     | 1.250            | 3.281     | 1.238 × 20 RH <sup>a</sup>      | 1.063                  | 0.906 | 0.750  |
| 5M     | 5     | 1.438            | 3.438     | 1.238 × 20 RH                   | 0.875                  | 0.750 | 0.625  |
| 5NS    | 1     | 1.062            | 4.219     | 1.050 × 20 RH                   | 0.875                  | 0.750 | 0.625  |
| 5OS    | 1     | 3.500            | 3.406     | 0.937 × 18 RH                   | 0.750                  | 0.641 | 0.516  |
| 5P     | 1     | 0.812            | 3.687     | 0.807 × 24 RH                   | 0.625                  | 0.531 | 0.438  |
| 5PN    | 1     | 1.312            | 3.406     | 1.307 × 16 RH                   | 1.000                  | 0.875 | 0.719  |
| 5SC    | 1     | 0.600            | 2.438     | 0.500 × 26 RH                   | 0.375                  | 0.328 | 0.266  |
| 5ST    | 1     | 1.250            | 3.281     | 1.238 × 20 RH                   | 1.063                  | 0.906 | 0.750  |
| 5V     | 1     | 0.850            | 3.875     | 0.775 × 18 RH                   | 0.563                  | 0.484 | 0.391  |
| 6H     | 1     | 1.375            | 4.750     | 1.300 × 10 RH                   | 1.125                  | 0.969 | 0.797  |
| 6K     | 1     | 0.842            | 3.000     | 0.762 × 26 RH                   | 0.625                  | 0.531 | 0.438  |
| 6L     | 1     | 1.250            | 4.438     | 1.178 × 20 RH                   | 1.000                  | 0.875 | 0.719  |
| 6NS    | 1     | 1.312            | 5.906     | 1.234 × 14 RH                   | 1.000                  | 0.859 | 0.703  |
| 6R     | 1     | 1.375            | 4.938     | 1.300 × 20 RH                   | 1.125                  | 0.969 | 0.781  |
| 7B     | 4     | 7 B&S            | 3.125     | 0.375 × 16 RH                   | 0.500                  | 0.406 | 0.344  |
| 7 B&S  | 4     | 7 B&S            | 2.875     | 0.375 × 16 RH                   | 0.500                  | 0.406 | 0.344  |
| 7P     | 1     | 1.125            | 4.750     | 1.120 × 20 RH                   | 0.875                  | 0.750 | 0.625  |
| 7R     | 6     | 1.062            | 3.500     | None                            | 0.875                  | 0.750 | 0.625  |
| 8H     | 1     | 1.500            | 4.750     | 1.425 × 20 RH                   | 1.250                  | 1.063 | 0.875  |
| 8ST    | 1     | 2.375            | 5.906     | 2.354 × 12 RH                   | 2.125                  | 1.844 | 1.500  |
| 8WN    | 1     | 1.250            | 3.875     | 1.245 × 16 RH                   | 1.000                  | 0.875 | 0.719  |
| 9B     | 4     | 9 B&S            | 4.125     | 0.500 × 13 RH                   | 0.750                  | 0.641 | 0.531  |
| 10L    | 1     | 1.562            | 5.500     | 1.490 × 18 RH                   | 1.250                  | 1.063 | 0.875  |
| 10P    | 1     | 1.500            | 4.750     | 1.495 × 20 RH                   | 1.250                  | 1.063 | 0.875  |
| 16C    | 1     | 1.889            | 4.516     | 1.875 × 1.75 mm RH <sup>b</sup> | 1.625                  | 1.406 | 1.141  |
| 20W    | 1     | 0.787            | 2.719     | 0.775 × 6-1 cm                  | 0.563                  | 0.484 | 0.391  |
| 22J    | 1     | 2.562            | 4.000     | 2.550 × 18 RH                   | 2.250                  | 1.938 | 1.563  |
| 32S    | 1     | 0.703            | 2.563     | 0.690 × 24 RH                   | 0.500                  | 0.438 | 0.344  |
| 35J    | 1     | 3.875            | 5.000     | 3.861 × 18 RH                   | 3.500                  | 3.000 | 2.438  |
| 42S    | 1     | 1.250            | 3.688     | 1.236 × 20 RH                   | 1.000                  | 0.875 | 0.719  |
| 50V    | 8     | 1.250            | 4.000     | 1.125 × 24 RH                   | 0.938                  | 0.813 | 0.656  |
| 52SC   | 1     | 0.800            | 3.688     | 0.795 × 20 RH                   | 0.625                  | 0.531 | 0.438  |
| 115    | 1     | 1.344            | 3.500     | 1.307 × 20 LH                   | 1.125                  | 0.969 | 0.797  |

## Collets for Lathes, Mills, Grinders, and Fixtures (Continued)

| Collet | Style | Dimensions       |           |               | Max. Capacity (inches) |       |        |
|--------|-------|------------------|-----------|---------------|------------------------|-------|--------|
|        |       | Bearing Diam., A | Length, B | Thread, C     | Round                  | Hex   | Square |
| 215    | 1     | 2.030            | 4.750     | 1.990 × 18 LH | 1.750                  | 1.500 | 1.219  |
| 315    | 1     | 3.687            | 5.500     | 3.622 × 16 LH | 3.250                  | 2.813 | 2.250  |
| B3     | 7     | 0.650            | 3.031     | 0.437 × 20 RH | 0.500                  | 0.438 | 0.344  |
| D5     | 7     | 0.780            | 3.031     | 0.500 × 20 RH | 0.625                  | 0.531 | 0.438  |
| GTM    | 7     | 0.625            | 2.437     | 0.437 × 20 RH | 0.500                  | 0.438 | 0.344  |
| J&L    | 9     | 0.999            | 4.375     | None          | 0.750                  | 0.641 | 0.516  |
| JC     | 8     | 1.360            | 4.000     | None          | 1.188                  | 1.000 | 0.813  |
| LB     | 10    | 0.687            | 2.000     | None          | 0.500                  | 0.438 | 0.344  |
| RO     | 11    | 1.250            | 2.938     | 0.875 × 16 RH | 1.125                  | 0.969 | 0.781  |
| RO     | 12    | 1.250            | 4.437     | 0.875 × 16 RH | 0.800                  | 0.688 | 0.563  |
| RO     | 12    | 1.250            | 4.437     | 0.875 × 16 RH | 1.125                  | 0.969 | 0.781  |
| RO     | 11    | 1.250            | 2.938     | 0.875 × 16 RH | 0.800                  | 0.688 | 0.563  |
| R8     | 7     | 0.950            | 4.000     | 0.437 × 20 RH | 0.750                  | 0.641 | 0.531  |

<sup>a</sup> Internal stop thread is 1.041 × 24 RH.

<sup>b</sup> Internal stop thread is 1.687 × 20 RH.

Dimensions in inches unless otherwise noted. Courtesy of Hardinge Brothers, Inc.

## DIN 6388, Type B, and DIN 6499, ER Type Collets

|                      |       | Dimensions |        |        |     |
|----------------------|-------|------------|--------|--------|-----|
| Collet Standard      | Type  | B (mm)     | L (mm) | A (mm) | C   |
| Type B,<br>DIN 6388  | 16    | 25.50      | 40     | 4.5–16 | ... |
|                      | 20    | 29.80      | 45     | 5.5–20 | ... |
|                      | 25    | 35.05      | 52     | 5.5–25 | ... |
|                      | 32    | 43.70      | 60     | 9.5–32 | ... |
| ER Type,<br>DIN 6499 | ERA8  | 8.50       | 13.5   | 0.5–5  | 8°  |
|                      | ERA11 | 11.50      | 18     | 0.5–7  | 8°  |
|                      | ERA16 | 17         | 27     | 0.5–10 | 8°  |
|                      | ERA20 | 21         | 31     | 0.5–13 | 8°  |
|                      | ERA25 | 26         | 35     | 0.5–16 | 8°  |
|                      | ERA32 | 33         | 40     | 2–20   | 8°  |
|                      | ERA40 | 41         | 46     | 3–26   | 8°  |
|                      |       | 41         | 39     | 26–30  | 8°  |
| ERA50                | 52    | 60         | 5–34   | 8°     |     |



## ARBORS, CHUCKS, AND SPINDLES

## Portable Tool Spindles

**Circular Saw Arbors.**—ANSI Standard B107.4-1982 “Driving and Spindle Ends for Portable Hand, Air, and Air Electric Tools” calls for a round arbor of  $\frac{5}{8}$ -inch diameter for nominal saw blade diameters of 6 to 8.5 inches, inclusive, and a  $\frac{3}{4}$ -inch diameter round arbor for saw blade diameters of 9 to 12 inches, inclusive.

**Spindles for Geared Chucks.**—Recommended threaded and tapered spindles for portable tool geared chucks of various sizes are as given in the following table:

Recommended Spindle Sizes

| Chuck Sizes,<br>Inch                    | Recommended Spindles                   |                    |
|---|--|--------------------|
|   | Threaded                               | Taper <sup>a</sup> |
| $\frac{3}{16}$ and $\frac{1}{4}$ Light  | $\frac{3}{8}$ -24                      | 1                  |
| $\frac{1}{4}$ and $\frac{5}{16}$ Medium | $\frac{3}{8}$ -24 or $\frac{1}{2}$ -20 | 2 Short            |
| $\frac{3}{8}$ Light                     | $\frac{3}{8}$ -24 or $\frac{1}{2}$ -20 | 2                  |
| $\frac{3}{8}$ Medium                    | $\frac{1}{2}$ -20 or $\frac{5}{8}$ -16 | 2                  |
| $\frac{1}{2}$ Light                     | $\frac{1}{2}$ -20 or $\frac{5}{8}$ -16 | 33                 |
| $\frac{1}{2}$ Medium                    | $\frac{5}{8}$ -16 or $\frac{3}{4}$ -16 | 6                  |
| $\frac{5}{8}$ and $\frac{3}{4}$ Medium  | $\frac{5}{8}$ -16 or $\frac{3}{4}$ -16 | 3                  |

<sup>a</sup>Jacobs number.

**Vertical and Angle Portable Tool Grinder Spindles.**—The  $\frac{5}{8}$ -11 spindle with a length of  $1\frac{1}{8}$  inches shown on page 950 is designed to permit the use of a jam nut with threaded cup wheels. When a revolving guard is used, the length of the spindle is measured from the wheel bearing surface of the guard. For unthreaded wheels with a  $\frac{7}{8}$ -inch hole, a safety sleeve nut is recommended. The unthreaded wheel with  $\frac{5}{8}$ -inch hole is not recommended because a jam nut alone may not resist the inertia effect when motor power is cut off.

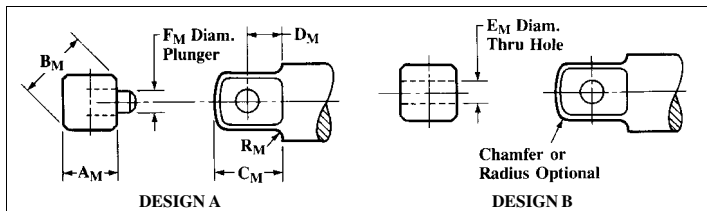
**Straight Grinding Wheel Spindles for Portable Tools.**—Portable grinders with pneumatic or induction electric motors should be designed for the use of organic bond wheels rated 9500 feet per minute. Light-duty electric grinders may be designed for vitrified wheels rated 6500 feet per minute. Recommended maximum sizes of wheels of both types are as given in the following table:

Recommended Maximum Grinding Wheel Sizes for Portable Tools

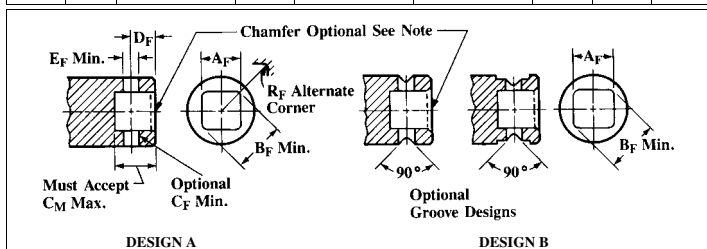
| Spindle<br>Size                    | Maximum Wheel Dimensions |                       |                      |                       |
|------------------------------------|--------------------------|-----------------------|----------------------|-----------------------|
|                                    | 9500 fpm                 |                       | 6500 fpm             |                       |
|                                    | Diameter<br><i>D</i>     | Thickness<br><i>T</i> | Diameter<br><i>D</i> | Thickness<br><i>T</i> |
| $\frac{3}{8}$ -24 × $1\frac{1}{8}$ | $2\frac{1}{2}$           | $\frac{1}{2}$         | 4                    | $\frac{1}{2}$         |
| $\frac{1}{2}$ -13 × $1\frac{3}{4}$ | 4                        | $\frac{3}{4}$         | 5                    | $\frac{3}{4}$         |
| $\frac{5}{8}$ -11 × $2\frac{1}{8}$ | 8                        | 1                     | 8                    | 1                     |
| $\frac{5}{8}$ -11 × $3\frac{1}{8}$ | 6                        | 2                     | ...                  | ...                   |
| $\frac{5}{8}$ -11 × $3\frac{3}{8}$ | 8                        | $1\frac{1}{2}$        | ...                  | ...                   |
| $\frac{3}{4}$ -10 × $3\frac{1}{4}$ | 8                        | 2                     | ...                  | ...                   |

Minimum *T* with the first three spindles is about  $\frac{1}{8}$  inch to accommodate cutting off wheels. Flanges are assumed to be according to ANSI B7.1 and threads to ANSI B1.1.

**American Standard Square Drives for Portable Air  
and Electric Tools ASA B5.38-1958**



| Drive Size | Design n. | Male End |       |               |       |       |       |       |               |               |               |
|------------|-----------|----------|-------|---------------|-------|-------|-------|-------|---------------|---------------|---------------|
|            |           | $A_M$    |       | $B_M$<br>Max. | $C_M$ |       | $D_M$ |       | $E_M$<br>Min. | $F_M$<br>Max. | $R_M$<br>Max. |
|            |           | Max.     | Min.  |               | Max.  | Min.  | Max.  | Min.  |               |               |               |
| 1/4        | A         | 0.252    | 0.247 | 0.330         | 0.312 | 0.265 | 0.165 | 0.153 | ...           | 0.078         | 0.015         |
| 3/8        | A         | 0.377    | 0.372 | 0.500         | 0.438 | 0.406 | 0.227 | 0.215 | ...           | 0.156         | 0.031         |
| 1/2        | A         | 0.502    | 0.497 | 0.665         | 0.625 | 0.531 | 0.321 | 0.309 | ...           | 0.187         | 0.031         |
| 5/8        | A         | 0.627    | 0.622 | 0.834         | 0.656 | 0.594 | 0.321 | 0.309 | ...           | 0.187         | 0.047         |
| 3/4        | B         | 0.752    | 0.747 | 1.000         | 0.938 | 0.750 | 0.415 | 0.403 | 0.216         | ...           | 0.047         |
| 1          | B         | 1.002    | 0.997 | 1.340         | 1.125 | 1.000 | 0.602 | 0.590 | 0.234         | ...           | 0.063         |
| 1 1/2      | B         | 1.503    | 1.498 | 1.968         | 1.625 | 1.562 | 0.653 | 0.641 | 0.310         | ...           | 0.094         |



| Drive Size | Design | Female End |       |               |       |       |               |               |
|------------|--------|------------|-------|---------------|-------|-------|---------------|---------------|
|            |        | $A_F$      |       | $B_F$<br>Min. | $D_F$ |       | $E_F$<br>Min. | $R_F$<br>Max. |
|            |        | Max.       | Min.  |               | Max.  | Min.  |               |               |
| 1/4        | A      | 0.258      | 0.253 | 0.335         | 0.159 | 0.147 | 0.090         | ...           |
| 3/8        | A      | 0.383      | 0.378 | 0.505         | 0.221 | 0.209 | 0.170         | ...           |
| 1/2        | A      | 0.508      | 0.503 | 0.670         | 0.315 | 0.303 | 0.201         | ...           |
| 5/8        | A      | 0.633      | 0.628 | 0.839         | 0.315 | 0.303 | 0.201         | ...           |
| 3/4        | B      | 0.758      | 0.753 | 1.005         | 0.409 | 0.397 | 0.216         | 0.047         |
| 1          | B      | 1.009      | 1.004 | 1.350         | 0.596 | 0.584 | 0.234         | 0.062         |
| 1 1/2      | B      | 1.510      | 1.505 | 1.983         | 0.647 | 0.635 | 0.310         | 0.125         |

All dimensions in inches.

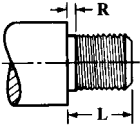
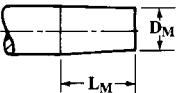
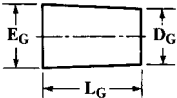
Incorporating fillet radius ( $R_M$ ) at shoulder of male tang precludes use of minimum diameter cross-hole in socket ( $E_F$ ), unless female drive end is chamfered (shown as optional).

If female drive end is not chamfered, socket cross-hole diameter ( $E_F$ ) is increased to compensate for fillet radius  $R_M$ , max.

Minimum clearance across flats male to female is 0.001 inch through 3/4-inch size; 0.002 inch in 1- and 1 1/2-inch sizes. For impact wrenches  $A_M$  should be held as close to maximum as practical.

$C_F$ , min. for both designs A and B should be equal to  $C_M$ , max.

**American Standard Threaded and Tapered Spindles for Portable Air and Electric Tools ASA B5.38-1958**

|  |            |  |      |  |                  |                |                |                |                |                |                             |
|--|------------|---|------|---|------------------|----------------|----------------|----------------|----------------|----------------|-----------------------------|
| <b>Threaded Spindle</b>  |            | <b>Taper Spindle (Jacobs)</b>   |      | <b>Master Plug Gage</b>   |                  |                |                |                |                |                |                             |
| Nom. Dia. and Thd.   | Pitch Dia. |   | R    | L   | No. <sup>a</sup> | D <sub>M</sub> | L <sub>M</sub> | E <sub>G</sub> | D <sub>G</sub> | L <sub>G</sub> | Taper per Foot <sup>b</sup> |
|  | Max.       | Min.  |      |   |                  |                |                |                |                |                |                             |
| 3/8-24   | 0.3479     | 0.3455  | 1/16 | 9/16 <sup>c</sup>   | 1                | 0.335-0.333    | 0.656          | 0.38400        | 0.33341        | 0.65625        | 0.92508                     |
| 1/2-20   | 0.4675     | 0.4649  | 1/16 | 9/16  | 2                | 0.490-0.488    | 0.875          | 0.54880        | 0.48764        | 0.7500         | 0.97861                     |
|  |            |   |      |   | 33               | 0.563-0.561    | 1.000          | 0.62401        | 0.56051        | 1.000          | 0.76194                     |
| 5/8-16   | 0.5844     | 0.5812  | 3/32 | 11/16   | 6                | 0.626-0.624    | 1.000          | 0.67600        | 0.62409        | 1.000          | 0.62292                     |
| 3/4-16   | 0.7094     | 0.7062  | 3/32 | 11/16   | 3                | 0.748-0.746    | 1.219          | 0.81100        | 0.74610        | 1.21875        | 0.63898                     |

<sup>a</sup> Jacobs taper number.

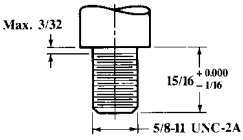
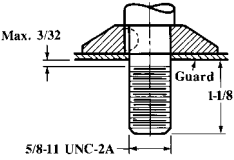
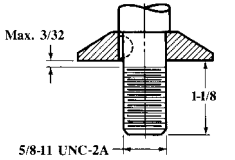
<sup>b</sup> Calculated from E<sub>G</sub>, D<sub>G</sub>, L<sub>G</sub> for the master plug gage.

<sup>c</sup> Also 7/16 inch.

<sup>d</sup> 2S stands for 2 Short.

All dimensions in inches. Threads are per inch and right-hand. *Tolerances:* On R, plus or minus 1/64 inch; on L, plus 0.000, minus 0.030 inch.

**American Standard Abrasion Tool Spindles for Portable Air and Electric Tools ASA B5.38-1958**

|   |   |
|---|---|
| Sanders and Polishers   |   |
|                                   |   |
| Vertical and Angle Grinders   |   |
|  <p>With Revolving Cup Guard</p> |  <p>Stationary Guard</p> |

**American Standard Abrasion Tool Spindles for Portable Air and Electric Tools ASA B5.38-1958 (Continued)**

| Straight Wheel Grinders |          |          | Cone Wheel Grinders |          |
|-------------------------|----------|----------|---------------------|----------|
|                         |          |          |                     |          |
| <i>H</i>                | <i>R</i> | <i>L</i> | <i>D</i>            | <i>L</i> |
| 3/8-24 UNF-2A           | 1/4      | 1 1/8    | 3/8-24 UNF-2A       | 9/16     |
| 1/2-13 UNC-2A           | 3/8      | 1 3/4    | 1/2-13 UNC-2A       | 11/16    |
| 5/8-11 UNC-2A           | 1/2      | 2 1/8    | 5/8-11 UNC-2A       | 15/16    |
| 3/4-10 UNC-2A           | 1        | 3 1/8    |                     |          |
|                         | 1        | 3 1/4    |                     |          |

All dimensions in inches. Threads are right-hand.

**American Standard Hexagonal Chucks and Shanks for Portable Air and Electric Tools ASA B5.38-1958**

| Nominal Hexagon | <i>H</i> |       | <i>B</i> | <i>L</i> Max. | Nominal Hexagon | <i>H</i> |       | <i>B</i> | <i>L</i> Max. |
|-----------------|----------|-------|----------|---------------|-----------------|----------|-------|----------|---------------|
|                 | Min.     | Max.  |          |               |                 | Min.     | Max.  |          |               |
| 1/4             | 0.253    | 0.255 | 3/8      | 15/16         | 5/8             | 0.630    | 0.632 | 11/32    | 1 3/8         |
| 5/16            | 0.314    | 0.316 | 13/64    | 1             | 3/4             | 0.755    | 0.758 | 11/32    | 1 7/8         |
| 7/16            | 0.442    | 0.444 | 17/64    | 1 1/8         | ...             | ...      | ...   | ...      | ...           |
| Shanks          |          |       |          |               |                 |          |       |          |               |
|                 |          |       |          |               |                 |          |       |          |               |

All dimensions in inches. Tolerances on *B* is plus or minus 0.005 inch.

**Mounted Wheels and Mounted Points**

These wheels and points are used in hard-to-get-at places and are available with a vitrified bond. The wheels are available with aluminum oxide or silicon carbide abrasive grains. The aluminum oxide wheels are used to grind tough and tempered die steels and the silicon carbide wheels, cast iron, chilled iron, bronze, and other non-ferrous metals.

The illustrations on pages 952 and 953 give the standard shapes of mounted wheels and points as published by the Grinding Wheel Institute. A note about the maximum operating speed for these wheels is given at the bottom of the first page of illustrations. Metric sizes are given on page 954.

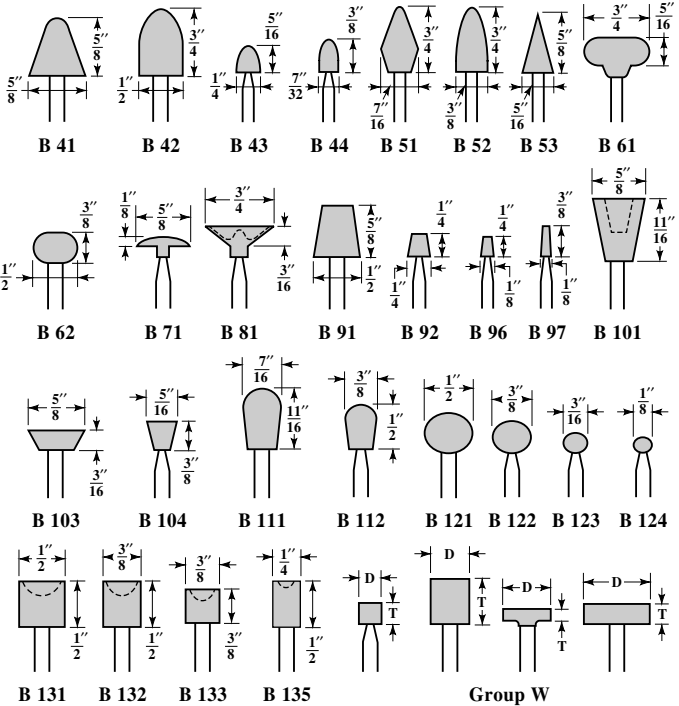


Fig. 1a. Standard Shapes and Sizes of Mounted Wheels and Points ANSI B74.2-1982

See Table 1 for inch sizes of Group W shapes, and for metric sizes for all shapes

The maximum speeds of mounted vitrified wheels and points of average grade range from about 38,000 to 152,000 rpm for diameters of 1 inch down to 1/4 inch. However, the safe operating speed usually is limited by the critical speed (speed at which vibration or whip tends to become excessive) which varies according to wheel or point dimensions, spindle diameter, and overhang.

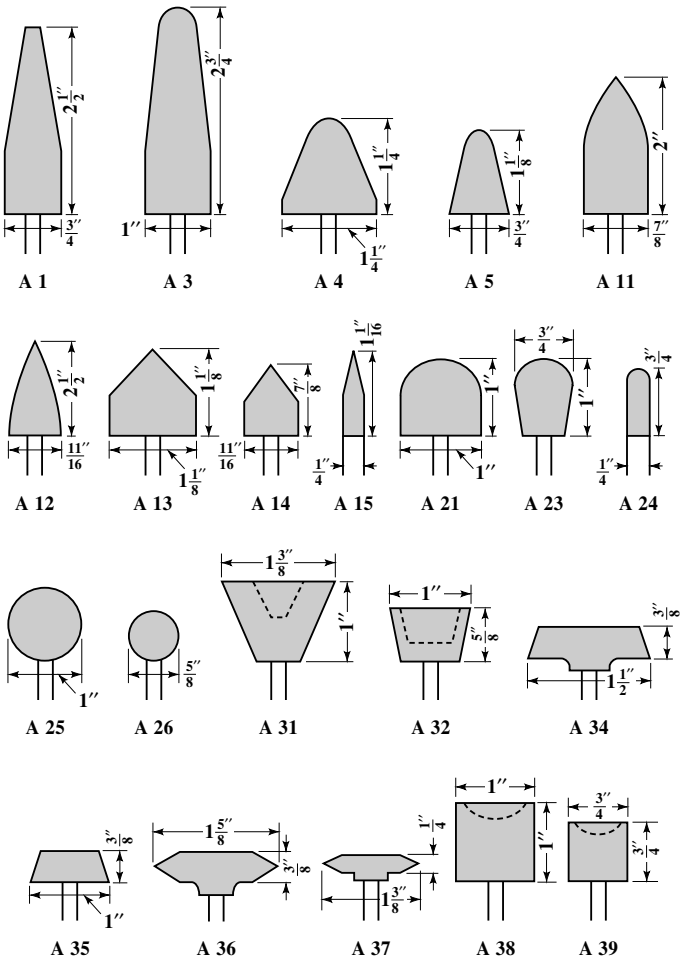


Fig. 1b. Standard Shapes and Sizes of Mounted Wheels and Points ANSI B74.2-1982

**Table 1. Shapes and Sizes of Mounted Wheels and Points ANSI B74.2-1982**

| Abrasive Shape No. <sup>a</sup> | Abrasive Shape Size |                 | Abrasive Shape No. <sup>a</sup> | Abrasive Shape Size |                 |
|---------------------------------|---------------------|-----------------|---------------------------------|---------------------|-----------------|
|                                 | Diameter<br>mm      | Thickness<br>mm |                                 | Diameter<br>mm      | Thickness<br>mm |
| A 1                             | 20                  | 65              | A 24                            | 6                   | 20              |
| A 3                             | 22                  | 70              | A 25                            | 25                  | ...             |
| A 4                             | 30                  | 30              | A 26                            | 16                  | ...             |
| A 5                             | 20                  | 28              | A 31                            | 35                  | 26              |
| A 11                            | 21                  | 45              | A 32                            | 25                  | 20              |
| A 12                            | 18                  | 30              | A 34                            | 38                  | 10              |
| A 13                            | 25                  | 25              | A 35                            | 25                  | 10              |
| A 14                            | 18                  | 22              | A 36                            | 40                  | 10              |
| A 15                            | 6                   | 25              | A 37                            | 30                  | 6               |
| A 21                            | 25                  | 25              | A 38                            | 25                  | 25              |
| A 23                            | 20                  | 25              | A 39                            | 20                  | 20              |
| B 41                            | 16                  | 16              | B 97                            | 3                   | 10              |
| B 42                            | 13                  | 20              | B 101                           | 16                  | 18              |
| B 43                            | 6                   | 8               | B 103                           | 16                  | 5               |
| B 44                            | 5.6                 | 10              | B 104                           | 8                   | 10              |
| B 51                            | 11                  | 20              | B 111                           | 11                  | 18              |
| B 52                            | 10                  | 20              | B 112                           | 10                  | 13              |
| B 53                            | 8                   | 16              | B 121                           | 13                  | ...             |
| B 61                            | 20                  | 8               | B 122                           | 10                  | ...             |
| B 62                            | 13                  | 10              | B 123                           | 5                   | ...             |
| B 71                            | 16                  | 3               | B 124                           | 3                   | ...             |
| B 81                            | 20                  | 5               | B 131                           | 13                  | 13              |
| B 91                            | 13                  | 16              | B 132                           | 10                  | 13              |
| B 92                            | 6                   | 6               | B 133                           | 10                  | 10              |
| B 96                            | 3                   | 6               | B 135                           | 6                   | 13              |

| Abrasive Shape No. <sup>a</sup> | Abrasive Shape Size |         |           |           | Abrasive Shape No. <sup>a</sup> | Abrasive Shape Size |         |           |           |
|---------------------------------|---------------------|---------|-----------|-----------|---------------------------------|---------------------|---------|-----------|-----------|
|                                 | D<br>mm             | T<br>mm | D<br>inch | T<br>inch |                                 | D<br>mm             | T<br>mm | D<br>inch | T<br>inch |
| W 144                           | 3                   | 6       | 1/8       | 1/4       | W 196                           | 16                  | 26      | 5/8       | 1         |
| W 145                           | 3                   | 10      | 1/8       | 3/8       | W 197                           | 16                  | 50      | 3/8       | 2         |
| W 146                           | 3                   | 13      | 1/8       | 1/2       | W 200                           | 20                  | 3       | 3/4       | 1/8       |
| W 152                           | 5                   | 6       | 3/16      | 1/4       | W 201                           | 20                  | 6       | 3/4       | 1/4       |
| W 153                           | 5                   | 10      | 3/16      | 3/8       | W 202                           | 20                  | 10      | 3/4       | 3/8       |
| W 154                           | 5                   | 13      | 3/16      | 1/2       | W 203                           | 20                  | 13      | 3/4       | 1/2       |
| W 158                           | 6                   | 3       | 1/4       | 1/8       | W 204                           | 20                  | 20      | 3/4       | 3/4       |
| W 160                           | 6                   | 6       | 1/4       | 1/4       | W 205                           | 20                  | 25      | 3/4       | 1         |
| W 162                           | 6                   | 10      | 1/4       | 3/8       | W 207                           | 20                  | 40      | 3/4       | 1 1/2     |
| W 163                           | 6                   | 13      | 1/4       | 1/2       | W 208                           | 20                  | 50      | 3/4       | 2         |
| W 164                           | 6                   | 20      | 1/4       | 3/4       | W 215                           | 25                  | 3       | 1         | 1/8       |
| W 174                           | 10                  | 6       | 3/8       | 1/4       | W 216                           | 25                  | 6       | 1         | 1/4       |
| W 175                           | 10                  | 10      | 3/8       | 3/8       | W 217                           | 25                  | 10      | 1         | 3/8       |
| W 176                           | 10                  | 13      | 3/8       | 1/2       | W 218                           | 25                  | 13      | 1         | 1/2       |
| W 177                           | 10                  | 20      | 3/8       | 3/4       | W 220                           | 25                  | 25      | 1         | 1         |
| W 178                           | 10                  | 25      | 3/8       | 1         | W 221                           | 25                  | 40      | 1         | 1 1/2     |
| W 179                           | 10                  | 30      | 3/8       | 1 1/4     | W 222                           | 25                  | 50      | 1         | 2         |
| W 181                           | 13                  | 1.5     | 1/2       | 1/16      | W 225                           | 30                  | 6       | 1 1/4     | 1/4       |
| W 182                           | 13                  | 3       | 1/2       | 1/8       | W 226                           | 30                  | 10      | 1 1/4     | 3/8       |
| W 183                           | 13                  | 6       | 1/2       | 1/4       | W 228                           | 30                  | 20      | 1 1/4     | 3/4       |
| W 184                           | 13                  | 10      | 1/2       | 3/8       | W 230                           | 30                  | 30      | 1 1/4     | 1 1/4     |
| W 185                           | 13                  | 13      | 1/2       | 1/2       | W 232                           | 30                  | 50      | 1 1/4     | 2         |
| W 186                           | 13                  | 20      | 1/2       | 3/4       | W 235                           | 40                  | 6       | 1 1/2     | 1/4       |
| W 187                           | 13                  | 25      | 1/2       | 1         | W 236                           | 40                  | 13      | 1 1/2     | 1/2       |
| W 188                           | 13                  | 40      | 1/2       | 1 1/2     | W 237                           | 40                  | 25      | 1 1/2     | 1         |
| W 189                           | 13                  | 50      | 1/2       | 2         | W 238                           | 40                  | 40      | 1 1/2     | 1 1/2     |
| W 195                           | 16                  | 20      | 3/8       | 3/4       | W 242                           | 50                  | 25      | 2         | 1         |

<sup>a</sup> See shape diagrams in Figs. 1a and 1b on pages 952 and 953.

## BROACHES AND BROACHING

### The Broaching Process

The broaching process may be applied in machining holes or other internal surfaces and also to many flat or other external surfaces. Internal broaching is applied in forming either symmetrical or irregular holes, grooves, or slots in machine parts, especially when the size or shape of the opening, or its length in proportion to diameter or width, make other machining processes impracticable. Broaching originally was utilized for such work as cutting keyways, machining round holes into square, hexagonal, or other shapes, forming splined holes, and for a large variety of other internal operations. The development of broaching machines and broaches finally resulted in extensive application of the process to external, flat, and other surfaces. Most external or surface broaching is done on machines of vertical design, but horizontal machines are also used for some classes of work. The broaching process is very rapid, accurate, and it leaves a finish of good quality. It is employed extensively in automotive and other plants where duplicate parts must be produced in large quantities and for dimensions within small tolerances.

**Types of Broaches.**—A number of typical broaches and the operations for which they are intended are shown by the diagrams, Fig. 1. Broach *A* produces a round-cornered, square hole. Prior to broaching square holes, it is usually the practice to drill a round hole having a diameter  $d$  somewhat larger than the width of the square. Hence, the sides are not completely finished, but this unfinished part is not objectionable in most cases. In fact, this clearance space is an advantage during the broaching operation in that it serves as a channel for the broaching lubricant; moreover, the broach has less metal to remove. Broach *B* is for finishing round holes. Broaching is superior to reaming for some classes of work, because the broach will hold its size for a much longer period, thus insuring greater accuracy. Broaches *C* and *D* are for cutting single and double keyways, respectively. Broach *C* is of rectangular section and, when in use, slides through a guiding bushing which is inserted in the hole. Broach *E* is for forming four integral splines in a hub. The broach at *F* is for producing hexagonal holes. Rectangular holes are finished by broach *G*. The teeth on the sides of this broach are inclined in opposite directions, which has the following advantages: The broach is stronger than it would be if the teeth were opposite and parallel to each other; thin work cannot drop between the inclined teeth, as it tends to do when the teeth are at right angles, because at least two teeth are always cutting; the inclination in opposite directions neutralizes the lateral thrust. The teeth on the edges are staggered, the teeth on one side being midway between the teeth on the other edge, as shown by the dotted line. A double cut broach is shown at *H*. This type is for finishing, simultaneously, both sides  $f$  of a slot, and for similar work. Broach *I* is the style used for forming the teeth in internal gears. It is practically a series of gear-shaped cutters, the outside diameters of which gradually increase toward the finishing end of the broach. Broach *J* is for round holes but differs from style *B* in that it has a continuous helical cutting edge. Some prefer this form because it gives a shearing cut. Broach *K* is for cutting a series of helical grooves in a hub or bushing. In helical broaching, either the work or the broach is rotated to form the helical grooves as the broach is pulled through.

In addition to the typical broaches shown in Fig. 1, many special designs are now in use for performing more complex operations. Two surfaces on opposite sides of a casting or forging are sometimes machined simultaneously by twin broaches and, in other cases, three or four broaches are drawn through a part at the same time, for finishing as many duplicate holes or surfaces. Notable developments have been made in the design of broaches for external or "surface" broaching.

**Burnishing Broach:** This is a broach having teeth or projections which are rounded on the top instead of being provided with a cutting edge, as in the ordinary type of broach. The teeth are highly polished, the tool being used for broaching bearings and for operations on



## BROACHING

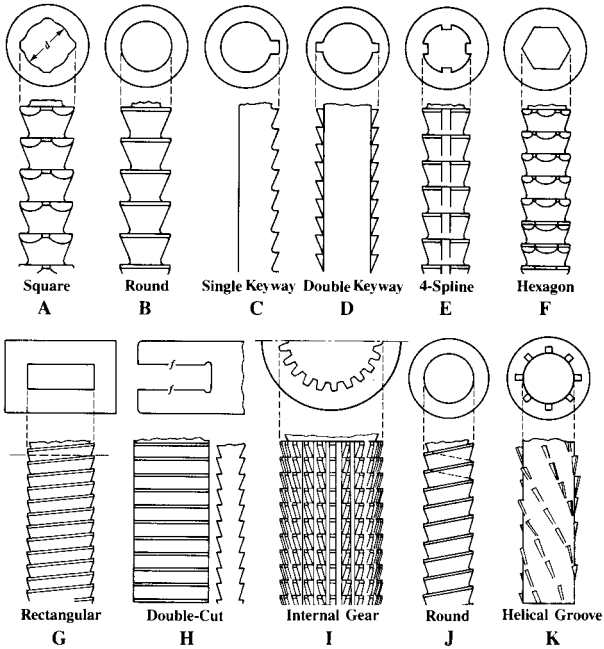


Fig. 1. Types of Broaches

other classes of work where the metal is relatively soft. The tool compresses the metal, thus making the surface hard and smooth. The amount of metal that can be displaced by a smooth-toothed burnishing broach is about the same as that removed by reaming. Such broaches are primarily intended for use on babbitt, white metal, and brass, but may also be satisfactorily used for producing a glazed surface on cast iron. This type of broach is also used when it is only required to accurately size a hole.

**Pitch of Broach Teeth.**—The pitch of broach teeth depends upon the depth of cut or chip thickness, length of cut, the cutting force required and power of the broaching machine. In the pitch formulas which follow

$L$  = length, in inches, of layer to be removed by broaching

$d$  = depth of cut per tooth as shown by Table 1 (For internal broaches,  $d$  = depth of cut as measured on one side of broach or one-half difference in diameters of successive teeth in case of a round broach)

$F$  = a factor. (For brittle types of material,  $F = 3$  or  $4$  for roughing teeth, and  $6$  for finishing teeth. For ductile types of material,  $F = 4$  to  $7$  for roughing teeth and  $8$  for finishing teeth.)

$b$  = width of inches, of layer to be removed by broaching

$P$  = pressure required in tons per square inch, of an area equal to depth of cut times width of cut, in inches (Table 2)

$T$  = usable capacity, in tons, of broaching machine = 70% of maximum tonnage

**Table 1. Designing Data for Surface Broaches**

| Material to be Broached        | Depth of Cut per Tooth, Inch |           | Face Angle or Rake, Degrees | Clearance Angle, Degrees |           |
|--------------------------------|------------------------------|-----------|-----------------------------|--------------------------|-----------|
|                                | Roughing <sup>a</sup>        | Finishing |                             | Roughing                 | Finishing |
| Steel, High Tensile Strength   | 0.0015–0.002                 | 0.0005    | 10–12                       | 1.5–3                    | 0.5–1     |
| Steel, Medium Tensile Strength | 0.0025–0.005                 | 0.0005    | 14–18                       | 1.5–3                    | 0.5–1     |
| Cast Steel                     | 0.0025–0.005                 | 0.0005    | 10                          | 1.53                     | 0.5       |
| Malleable Iron                 | 0.0025–0.005                 | 0.0005    | 7                           | 1.5–3                    | 0.5       |
| Cast Iron, Soft                | 0.006 –0.010                 | 0.0005    | 10–15                       | 1.5–3                    | 0.5       |
| Cast Iron, Hard                | 0.003 –0.005                 | 0.0005    | 5                           | 1.5–3                    | 0.5       |
| Zinc Die Castings              | 0.005 –0.010                 | 0.0010    | 12 <sup>b</sup>             | 5                        | 2         |
| Cast Bronze                    | 0.010 –0.025                 | 0.0005    | 8                           | 0                        | 0         |
| Wrought Aluminum               |                              |           |                             |                          |           |
| Alloys                         | 0.005 –0.010                 | 0.0010    | 15 <sup>b</sup>             | 3                        | 1         |
| Cast Aluminum Alloys           | 0.005 –0.010                 | 0.0010    | 12 <sup>b</sup>             | 3                        | 1         |
| Magnesium Die Castings         | 0.010 –0.015                 | 0.0010    | 20 <sup>b</sup>             | 3                        | 1         |

<sup>a</sup> The lower depth-of-cut values for roughing are recommended when work is not very rigid, the tolerance is small, a good finish is required, or length of cut is comparatively short.

<sup>b</sup> In broaching these materials, smooth surfaces for tooth and chip spaces are especially recommended.

**Table 2. Broaching Pressure *P* for Use in Pitch Formula (2)**

| Material to be Broached   | Depth <i>d</i> of Cut per Tooth, Inch     |       |       |       |       | Pressure <i>P</i> , Side-cutting Broaches |
|---------------------------|---|-------|-------|-------|-------|---|
|                           | 0.024                                     | 0.010 | 0.004 | 0.002 | 0.001 |   |
|                           | Pressure <i>P</i> in Tons per Square Inch |       |       |       |       |   |
| Steel, High Ten. Strength | ...                                       | ...   | ...   | 250   | 312   | 200-.004"cut                              |
| Steel, Med. Ten. Strength | ...                                       | ...   | 158   | 185   | 243   | 143-.006"cut                              |
| Cast Steel                | ...                                       | ...   | 128   | 158   | ...   | 115-.006" cut                             |
| Malleable Iron            | ...                                       | ...   | 108   | 128   | ...   | 100-.006" cut                             |
| Cast Iron                 | ...                                       | 115   | 115   | 143   | ...   | 115-.020" cut                             |
| Cast Brass                | ...                                       | 50    | 50    | ...   | ...   | .....                                     |
| Brass, Hot Pressed        | ...                                       | 85    | 85    | ...   | ...   | .....                                     |
| Zinc Die Castings         | ...                                       | 70    | 70    | ...   | ...   | .....                                     |
| Cast Bronze               | 35  | 35    | ...   | ...   | ...   | .....                                     |
| Wrought Aluminum          | ...                                       | 70    | 70    | ...   | ...   | .....                                     |
| Cast Aluminum             | ...                                       | 85    | 85    | ...   | ...   | .....                                     |
| Magnesium Alloy           | 35  | 35    | ...   | ...   | ...   | .....                                     |

The minimum pitch shown by Formula (1) is based upon the receiving capacity of the chip space. The minimum, however, should not be less than 0.2 inch unless a smaller pitch is required for exceptionally short cuts to provide at least two teeth in contact simultaneously, with the part being broached. A reduction below 0.2 inch is seldom required in surface broaching but it may be necessary in connection with internal broaching.

$$\text{Minimum pitch} = 3\sqrt{LdF} \tag{1}$$

Whether the minimum pitch may be used or not depends upon the power of the available machine. The factor *F* in the formula provides for the increase in volume as the material is broached into chips. If a broach has adjustable inserts for the finishing teeth, the pitch of the finishing teeth may be smaller than the pitch of the roughing teeth because of the smaller depth *d* of the cut. The higher value of *F* for finishing teeth prevents the pitch from becoming too small, so that the spirally curled chips will not be crowded into too small a space.

The pitch of the roughing and finishing teeth should be equal for broaches without separate inserts (notwithstanding the different values of  $d$  and  $F$ ) so that some of the finishing teeth may be ground into roughing teeth after wear makes this necessary.

$$\text{Allowable pitch} = \frac{dLbP}{T} \quad (2)$$

If the pitch obtained by [Formula \(2\)](#) is larger than the minimum obtained by [Formula \(1\)](#), this larger value should be used because it is based upon the usable power of the machine. As the notation indicates, 70 per cent of the maximum tonnage  $T$  is taken as the usable capacity. The 30 per cent reduction is to provide a margin for the increase in broaching load resulting from the gradual dulling of the cutting edges. The procedure in calculating both minimum and allowable pitches will be illustrated by an example.

*Example:* Determine pitch of broach for cast iron when  $L = 9$  inches;  $d = 0.004$ ; and  $F = 4$ .

$$\text{Minimum pitch} = 3\sqrt{9 \times 0.004 \times 4} = 1.14$$

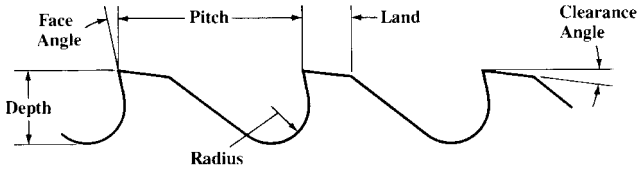
Next, apply [Formula \(2\)](#). Assume that  $b = 3$  and  $T = 10$ ; for cast iron and depth  $d$  of 0.004,  $P = 115$  ([Table 2](#)). Then,

$$\text{Allowable pitch} = \frac{0.004 \times 9 \times 3 \times 115}{10} = 1.24$$

This pitch is safely above the minimum. If in this case the usable tonnage of an available machine were, say, 8 tons instead of 10 tons, the pitch as shown by [Formula \(2\)](#) might be increased to about 1.5 inches, thus reducing the number of teeth cutting simultaneously and, consequently, the load on the machine; or the cut per tooth might be reduced instead of increasing the pitch, especially if only a few teeth are in cutting contact, as might be the case with a short length of cut. If the usable tonnage in the preceding example were, say, 15, then a pitch of 0.84 would be obtained by [Formula \(2\)](#); hence the pitch in this case should not be less than the minimum of approximately 1.14 inches.

**Depth of Cut per Tooth.**—The term “depth of cut” as applied to surface or external broaches means the difference in the heights of successive teeth. This term, as applied to internal broaches for round, hexagonal or other holes, may indicate the total increase in the diameter of successive teeth; however, to avoid confusion, the term as here used means in all cases and regardless of the type of broach, the depth of cut as measured on one side.

In broaching free cutting steel, the Broaching Tool Institute recommends 0.003 to 0.006 inch depth of cut for surface broaching; 0.002 to 0.003 inch for multispline broaching; and 0.0007 to 0.0015 inch for round hole broaching. The accompanying table contains data from a German source and applies specifically to surface broaches. All data relating to depth of cut are intended as a general guide only. While depth of cut is based primarily upon the machinability of the material, some reduction from the depth thus established may be required particularly when the work supporting fixture in surface broaching is not sufficiently rigid to resist the thrust from the broaching operation. In some cases, the pitch and cutting length may be increased to reduce the thrust force. Another possible remedy in surface broaching certain classes of work is to use a side-cutting broach instead of the ordinary depth cutting type. A broach designed for side cutting takes relatively deep narrow cuts which extend nearly to the full depth required. The side cutting section is followed by teeth arranged for depth cutting to obtain the required size and surface finish on the work. In general, small tolerances in surface broaching require a reduced cut per tooth to minimize work deflection resulting from the pressure of the cut. See [Cutting Speed for Broaching](#) starting on page [1074](#) for broaching speeds.



Terms Commonly Used in Broach Design

**Face Angle or Rake.**—The face angle (see diagram) of broach teeth affects the chip flow and varies considerably for different materials. While there are some variations in practice, even for the same material, the angles given in the accompanying table are believed to represent commonly used values. Some broach designers increase the rake angle for finishing teeth in order to improve the finish on the work.

**Clearance Angle.**—The clearance angle (see illustration) for roughing steel varies from 1.5 to 3 degrees and for finishing steel from 0.5 to 1 degree. Some recommend the same clearance angles for cast iron and others, larger clearance angles varying from 2 to 4 or 5 degrees. Additional data will be found in [Table 1](#).

**Land Width.**—The width of the land usually is about  $0.25 \times$  pitch. It varies, however, from about one-fourth to one-third of the pitch. The land width is selected so as to obtain the proper balance between tooth strength and chip space.

**Depth of Broach Teeth.**—The tooth depth as established experimentally and on the basis of experience, usually varies from about 0.37 to 0.40 of the pitch. This depth is measured radially from the cutting edge to the bottom of the tooth fillet.

**Radius of Tooth Fillet.**—The “gullet” or bottom of the chip space between the teeth should have a rounded fillet to strengthen the broach, facilitate curling of the chips, and safeguard against cracking in connection with the hardening operation. One rule is to make the radius equal to one-fourth the pitch. Another is to make it equal 0.4 to 0.6 the tooth depth. A third method preferred by some broach designers is to make the radius equal one-third of the sum obtained by adding together the land width, one-half the tooth depth, and one-fourth of the pitch.

**Total Length of Broach.**—After the depth of cut per tooth has been determined, the total amount of material to be removed by a broach is divided by this decimal to ascertain the number of cutting teeth required. This number of teeth multiplied by the pitch gives the length of the active portion of the broach. By adding to this dimension the distance over three or four straight teeth, the length of a pilot to be provided at the finishing end of the broach, and the length of a shank which must project through the work and the faceplate of the machine to the draw-head, the overall length of the broach is found. This calculated length is often greater than the stroke of the machine, or greater than is practical for a broach of the diameter required. In such cases, a set of broaches must be used.

**Chip Breakers.**—The teeth of broaches frequently have rounded chip-breaking grooves located at intervals along the cutting edges. These grooves break up wide curling chips and prevent them from clogging the chip spaces, thus reducing the cutting pressure and strain on the broach. These chip-breaking grooves are on the roughing teeth only. They are staggered and applied to both round and flat or surface broaches. The grooves are formed by a round edged grinding wheel and usually vary in width from about  $\frac{1}{32}$  to  $\frac{3}{32}$  inch depending upon the size of broach. The more ductile the material, the wider the chip breaker grooves should be and the smaller the distance between them. Narrow slotting broaches may have the right- and left-hand corners of alternate teeth beveled to obtain chip-breaking action.

**Shear Angle.**—The teeth of surface broaches ordinarily are inclined so they are not at right angles to the broaching movement. The object of this inclination is to obtain a shearing cut which results in smoother cutting action and an improvement in surface finish. The shearing cut also tends to eliminate troublesome vibration. Shear angles for surface broaches are not suitable for broaching slots or any profiles that resist the outward movement of the chips. When the teeth are inclined, the fixture should be designed to resist the resulting thrusts unless it is practicable to incline the teeth of right- and left-hand sections in opposite directions to neutralize the thrust. The shear angle usually varies from 10 to 25 degrees.

**Types of Broaching Machines.**—Broaching machines may be divided into horizontal and vertical designs, and they may be classified further according to the method of operation, as, for example, whether a broach in a vertical machine is pulled up or pulled down in forcing it through the work. Horizontal machines usually pull the broach through the work in internal broaching but short rigid broaches may be pushed through. External surface broaching is also done on some machines of horizontal design, but usually vertical machines are employed for flat or other external broaching. Although parts usually are broached by traversing the broach itself, some machines are designed to hold the broach or broaches stationary during the actual broaching operation. This principle has been applied both to internal and surface broaching.

*Vertical Duplex Type:* The vertical duplex type of surface broaching machine has two slides or rams which move in opposite directions and operate alternately. While the broach connected to one slide is moving downward on the cutting stroke, the other broach and slide is returning to the starting position, and this returning time is utilized for reloading the fixture on that side; consequently, the broaching operation is practically continuous. Each ram or slide may be equipped to perform a separate operation on the same part when two operations are required.

*Pull-up Type:* Vertical hydraulically operated machines which pull the broach or broaches up through the work are used for internal broaching of holes of various shapes, for broaching bushings, splined holes, small internal gears, etc. A typical machine of this kind is so designed that all broach handling is done automatically.

*Pull-down Type:* The various movements in the operating cycle of a hydraulic pull-down type of machine equipped with an automatic broach-handling slide, are the reverse of the pull-up type. The broaches for a pull-down type of machine have shanks on each end, there being an upper one for the broach-handling slide and a lower one for pulling through the work.

*Hydraulic Operation:* Modern broaching machines, as a general rule, are operated hydraulically rather than by mechanical means. Hydraulic operation is efficient, flexible in the matter of speed adjustments, low in maintenance cost, and the "smooth" action required for fine precision finishing may be obtained. The hydraulic pressures required, which frequently are 800 to 1000 pounds per square inch, are obtained from a motor-driven pump forming part of the machine. The cutting speeds of broaching machines frequently are between 20 and 30 feet per minute, and the return speeds often are double the cutting speed, or higher, to reduce the idle period.

**Ball-Broaching.**—Ball-broaching is a method of securing bushings, gears, or other components without the need for keys, pins, or splines. A series of axial grooves, separated by ridges, is formed in the bore of the workpiece by cold plastic deformation of the metal when a tool, having a row of three rotating balls around its periphery, is pressed through the parts. When the bushing is pressed into a broached bore, the ridges displace the softer material of the bushing into the grooves—thus securing the assembly. The balls can be made of high-carbon chromium steel or carbide, depending on the hardness of the component.

**Broaching Difficulties.**—The accompanying table has been compiled from information supplied by the National Broach and Machine Co. and presents some of the common broaching difficulties, their causes and means of correction.

### Causes of Broaching Difficulties

| Broaching Difficulty                                   | Possible Causes   |
|--|---|
| Stuck broach   | <p>Insufficient machine capacity; dulled teeth; clogged chip gullets; failure of power during cutting stroke.</p> <p>To remove a stuck broach, workpiece and broach are removed from the machine as a unit; never try to back out broach by reversing machine. If broach does not loosen by tapping workpiece lightly and trying to slide it off its starting end, mount workpiece and broach in a lathe and turn down workpiece to the tool surface. Workpiece may be sawed longitudinally into several sections in order to free the broach.</p> <p>Check broach design, perhaps tooth relief (back off) angle is too small or depth of cut per tooth is too great.</p> |
| Galling and pickup                                     | <p>Lack of homogeneity of material being broached—uneven hardness, porosity; improper or insufficient coolant; poor broach design, mutilated broach; dull broach; improperly sharpened broach; improperly designed or outworn fixtures.</p> <p>Good broach design will do away with possible chip build-up on tooth faces and excessive heating. Grinding of teeth should be accurate so that the correct gullet contour is maintained. Contour should be fair and smooth.</p>  |
| Broach breakage  | <p>Overloading; broach dullness; improper sharpening; interrupted cutting stroke; backing up broach with workpiece in fixture; allowing broach to pass entirely through guide hole; ill fitting and/or sharp edged key; crooked holes; untrue locating surface; excessive hardness of workpiece; insufficient clearance angle; sharp corners on pull end of broach.</p> <p>When grinding bevels on pull end of broach use wheel that is not too pointed.</p>  |
| Chatter  | <p>Too few teeth in cutting contact simultaneously; excessive hardness of material being broached; loose or poorly constructed tooling; surging of ram due to load variations.</p> <p>Chatter can be alleviated by changing the broaching speed, by using shear cutting teeth instead of right angle teeth, and by changing the coolant and the face and relief angles of the teeth.</p>  |
| Drifting or misalignment of tool during cutting stroke | <p>Lack of proper alignment when broach is sharpened in grinding machine, which may be caused by dirt in the female center of the broach; inadequate support of broach during the cutting stroke, on a horizontal machine especially; body diameter too small; cutting resistance variable around I.D. of hole due to lack of symmetry of surfaces to be cut; variations in hardness around I.D. of hole; too few teeth in cutting contact.</p>   |
| Streaks in broached surface                            | <p>Lands too wide; presence of forging, casting or annealing scale; metal pickup; presence of grinding burrs and grinding and cleaning abrasives.</p>   |
| Rings in the broached hole                             | <p>Due to surging resulting from uniform pitch of teeth; presence of sharpening burrs on broach; tooth clearance angle too large; locating face not smooth or square; broach not supported for all cutting teeth passing through the work. The use of differential tooth spacing or shear cutting teeth helps in preventing surging. Sharpening burrs on a broach may be removed with a wood block.</p>   |

## FILES AND BURS

### Files

**Definitions of File Terms.**—The following file terms apply to hand files but not to rotary files and burs.

*Axis:* Imaginary line extending the entire length of a file equidistant from faces and edges.

*Back:* The convex side of a file having the same or similar cross-section as a half-round file.

*Bastard Cut:* A grade of file coarseness between coarse and second cut of American pattern files and rasps.

*Blank:* A file in any process of manufacture before being cut.

*Blunt:* A file whose cross-sectional dimensions from point to tang remain unchanged.

*Coarse Cut:* The coarsest of all American pattern file and rasp cuts.

*Coarseness:* Term describing the relative number of teeth per unit length, the coarsest having the least number of file teeth per unit length; the smoothest, the most. American pattern files and rasps have four degrees of coarseness: coarse, bastard, second and smooth. Swiss pattern files usually have seven degrees of coarseness: 00, 0, 1, 2, 3, 4, 6 (from coarsest to smoothest). Curved tooth files have three degrees of coarseness: standard, fine and smooth.

*Curved Cut:* File teeth which are made in curved contour across the file blank.

*Cut:* Term used to describe file teeth with respect to their coarseness or their character (single, double, rasp, curved, special).

*Double Cut:* A file tooth arrangement formed by two series of cuts, namely the overcut followed, at an angle, by the upcut.

*Edge:* Surface joining faces of a file. May have teeth or be smooth.

*Face:* Widest cutting surface or surfaces that are used for filing.

*Heel or Shoulder:* That portion of a file that abuts the tang.

*Hopped:* A term used among file makers to represent a very wide skip or spacing between file teeth.

*Length:* The distance from the heel to the point.

*Overcut:* The first series of teeth put on a double-cut file.

*Point:* The front end of a file; the end opposite the tang.

*Rasp Cut:* A file tooth arrangement of round-topped teeth, usually not connected, that are formed individually by means of a narrow, punch-like tool.

*Re-cut:* A worn-out file which has been re-cut and re-hardened after annealing and grinding off the old teeth.

*Safe Edge:* An edge of a file that is made smooth or uncut, so that it will not injure that portion or surface of the workplace with which it may come in contact during filing.

*Second Cut:* A grade of file coarseness between bastard and smooth of American pattern files and rasps.

*Set:* To blunt the sharp edges or corners of file blanks before and after the overcut is made, in order to prevent weakness and breakage of the teeth along such edges or corners when the file is put to use.

*Shoulder or Heel:* See *Heel or Shoulder*.

*Single Cut:* A file tooth arrangement where the file teeth are composed of single unbroken rows of parallel teeth formed by a single series of cuts.

*Smooth Cut:* An American pattern file and rasp cut that is smoother than second cut.

*Tang:* The narrowed portion of a file which engages the handle.

*Upcut:* The series of teeth superimposed on the overcut, and at an angle to it, on a double-cut file.

**File Characteristics.**—Files are classified according to their shape or cross-section and according to the pitch or spacing of their teeth and the nature of the cut.

*Cross-section and Outline:* The cross-section may be quadrangular, circular, triangular, or some special shape. The outline or contour may be tapered or blunt. In the former, the point is more or less reduced in width and thickness by a gradually narrowing section that extends for one-half to two-thirds of the length. In the latter the cross-section remains uniform from tang to point.

*Cut:* The character of the teeth is designated as single, double, rasp or curved. The *single cut file* (or *float* as the coarser cuts are sometimes called) has a single series of parallel teeth extending across the face of the file at an angle of from 45 to 85 degrees with the axis of the file. This angle depends upon the form of the file and the nature of the work for which it is intended. The single cut file is customarily used with a light pressure to produce a smooth finish. The *double cut file* has a multiplicity of small pointed teeth inclining toward the point of the file arranged in two series of diagonal rows that cross each other. For general work, the angle of the first series of rows is from 40 to 45 degrees and of the second from 70 to 80 degrees. For *double cut finishing files* the first series has an angle of about 30 degrees and the second, from 80 to 87 degrees. The second, or upcut, is almost always deeper than the first or overcut. Double cut files are usually employed, under heavier pressure, for fast metal removal and where a rougher finish is permissible. The *rasp* is formed by raising a series of individual rounded teeth from the surface of the file blank with a sharp narrow, punch-like cutting tool and is used with a relatively heavy pressure on soft substances for fast removal of material. The curved tooth file has teeth that are in the form of parallel arcs extending across the face of the file, the middle portion of each arc being closest to the point of the file. The teeth are usually single cut and are relatively coarse. They may be formed by steel displacement but are more commonly formed by milling.

With reference to coarseness of cut the terms *coarse*, *bastard*, *second* and *smooth cuts* are used, the coarse or bastard files being used on the heavier classes of work and the second or smooth cut files for the finishing or more exacting work. These degrees of coarseness are only comparable when files of the same length are compared, as the number or teeth per inch of length decreases as the length of the file increases. The number of teeth per inch varies considerably for different sizes and shapes and for files of different makes. The coarseness range for the curved tooth files is given as standard, fine and smooth. In the case of Swiss pattern files, a series of numbers is used to designate coarseness instead of names; Nos. 00, 0, 1, 2, 3, 4 and 6 being the most common with No. 00 the coarsest and No. 6 the finest.

**Classes of Files.**—There are five main classes of files: mill or saw files; machinists' files; curved tooth files; Swiss pattern files; and rasps. The first two classes are commonly referred to as American pattern files.

*Mill or Saw Files:* These are used for sharpening mill or circular saws, large crosscut saws; for lathe work; for draw filing; for filing brass and bronze; and for smooth filing generally. The number identifying the following files refers to the illustration in [Fig. 1](#)

- 1) *Cantsaw files* have an obtuse isosceles triangular section, a blunt outline, are single cut and are used for sharpening saws having "M"-shaped teeth and teeth of less than 60-degree angle; 2) *Crosscut files* have a narrow triangular section with short side rounded, a blunt outline, are single cut and are used to sharpen crosscut saws. The rounded portion is used to deepen the gullets of saw teeth and the sides are used to sharpen the teeth themselves. ;
- 3) *Double ender files* have a triangular section, are tapered from the middle to both ends, are tangless are single cut and are used reversibly for sharpening saws; 4) The *mill file* itself, is usually single cut, tapered in width, and often has two square cutting edges in addition to the cutting sides. Either or both edges may be rounded, however, for filing the gul-



lets of saw teeth. The *blunt mill file* has a uniform rectangular cross-section from tip to tang; 5) The *triangular saw files or taper saw files* have an equilateral triangular section, are tapered, are single cut and are used for filing saws with 60-degree angle teeth. They come in taper, slim taper, extra slim taper and double extra slim taper thicknesses *Blunt triangular* and *blunt hand saw files* are without taper; and 6) *Web saw files* have a diamond-shaped section, a blunt outline, are single cut and are used for sharpening pulpwood or web saws. .

*Machinists' Files:* These files are used throughout industry where metal must be removed rapidly and finish is of secondary importance. Except for certain exceptions in the round and half-round shapes, all are double cut. 7) *Flat files* have a rectangular section, are tapered in width and thickness, are cut on both sides and edges and are used for general utility work; 8) *Halfround files* have a circular segmental section, are tapered in width and thickness, have their flat side double cut, their rounded side mostly double but sometimes single cut, and are used to file rounded holes, concave corners, etc. in general filing work; 9) *Hand files* are similar to flat files but taper in thickness only. One edge is uncut or "safe."; and 10) *Knife files* have a "knife-blade" section, are tapered in width only, are double cut, and are used by tool and die makers on work having acute angles.

*Machinist's general purpose files* have a rectangular section, are tapered and have single cut teeth divided by angular serrations which produce short cutting edges. These edges help stock removal but still leave a smooth finish and are suitable for use on various materials including aluminum, bronze, cast iron, malleable iron, mild steels and annealed tool steels.

11) *Pillar files* are similar to hand files but are thicker and not as wide; 12) *Round files* have a circular section, are tapered, single cut, and are generally used to file circular openings or curved surfaces; 13) *Square files* have a square section, are tapered, and are used for filing slots, keyways and for general surface filing where a heavier section is preferred; 14) *Three square files* have an equilateral triangular section and are tapered on all sides. They are double cut and have sharp corners as contrasted with taper triangular files which are single cut and have somewhat rounded corners. They are used for filing accurate internal angles, for clearing out square corners, and for filing taps and cutters; and 15) *Warding files* have a rectangular section, and taper in width to a narrow point. They are used for general narrow space filing. .

*Wood files* are made in the same sections as flat and half round files but with coarser teeth especially suited for working on wood.

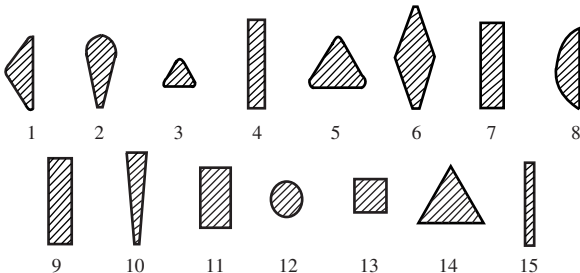


Fig. 1. Styles of Mill or Saw Files

*Curved Tooth Files:* Regular curved tooth files are made in both rigid and flexible forms. The rigid type has either a tang for a conventional handle or is made plain with a hole at each end for mounting in a special holder. The flexible type is furnished for use in special holders only. The curved tooth files come in standard fine and smooth cuts and in parallel

flat, square, pillar, pillar narrow, half round and shell types. A special curved tooth file is available with teeth divided by long angular serrations. The teeth are cut in an "off center" arc. When moved across the work toward one edge of the file a fast cutting action is provided; when moved toward the other edge, a smoothing action; thus the file is made to serve a dual purpose.

*Swiss Pattern Files:* These are used by tool and die makers, model makers and delicate instrument parts finishers. They are made to closer tolerances than the conventional American pattern files although with similar cross-sections. The points of the Swiss pattern files are smaller, the tapers are longer and they are available in much finer cuts. They are primarily finishing tools for removing burrs left from previous finishing operations truing up narrow grooves, notches and keyways, cleaning out corners and smoothing small parts. For very fine work, *round and square handled needle files*, available in numerous cross-sectional shapes in overall lengths from 4 to 7  $\frac{3}{4}$  inches, are used. Die sinkers use *die sinkers files* and *die sinkers rifflers*. The files, also made in many different cross-sectional shapes, are 3  $\frac{1}{2}$  inches in length and are available in the cut Nos. 0, 1, 2, and 4. The rifflers are from 5  $\frac{1}{2}$  to 6  $\frac{3}{4}$  inches long, have cutting surfaces on either end, and come in numerous cross-sectional shapes in cut Nos. 0, 2, 3, 4 and 6. These rifflers are used by die makers for getting into corners, crevices, holes and contours of intricate dies and molds. Used in the same fashion as die sinkers rifflers, *silversmiths rifflers*, that have a much heavier cross-section, are available in lengths from 6  $\frac{7}{8}$  to 8 inches and in cuts Nos. 0, 1, 2, and 3. *Blunt machine files* in Cut Nos. 00, 0, and 2 for use in ordinary and bench filing machines are available in many different cross-sectional shapes, in lengths from 3 to 8 inches.

*Rasps:* Rasps are employed for work on relatively soft substances such as wood, leather, and lead where fast removal or material is required. They come in rectangular and half round cross-sections, the latter with and without a sharp edge.

*Special Purpose Files:* Falling under one of the preceding five classes of files, but modified to meet the requirements of some particular function, are a number of special purpose files. The *long angle lathe file* is used for filing work that is rotating in a lathe. The long tooth angle provides a clean shear, eliminates drag or tear and is self-clearing. This file has safe or uncut edges to protect shoulders of the work which are not to be filed. The *foundry file* has especially sturdy teeth with heavy set edges for the snagging of castings—the removing of fins, sprues, and other projections. The *die casting file* has extra strong teeth on corners and edges as well as sides for working on die castings of magnesium, zinc, or aluminum alloys. A special file for stainless steel is designed to stand up under the abrasive action of stainless steel alloys. *Aluminum rasps and files* are designed to eliminate clogging. A special tooth construction is used in one type of aluminum tile which breaks up the filings, allows the file to clear itself and overcomes chatter. A *brass file* is designed so that with a little pressure the sharp, high-cut teeth bite deep while with less pressure, their short uncut angle produces a smoothing effect. The *lead float* has coarse, single cut teeth at almost right angles to the file axis. These shear away the metal under ordinary pressure and produce a smoothing effect under light pressure. The *shear tooth file* has a coarse single cut with a long angle for soft metals or alloys, plastics, hard rubber and wood. *Chain saw files* are designed to sharpen all types of chain saw teeth. These files come in round, rectangular, square and diamond-shaped sections. The round and square sectioned files have either double or single cut teeth, the rectangular files have single cut teeth and the diamond-shaped files have double cut teeth.

**Effectiveness of Rotary Files and Burs.**—There is very little difference in the efficiency of rotary files or burs when used in electric tools and when used in air tools, provided the speeds have been reasonably well selected. Flexible-shaft and other machines used as a source of power for these tools have a limited number of speeds which govern the revolutions per minute at which the tools can be operated.

The carbide bur may be used on hard or soft materials with equally good results. The principle difference in construction of the carbide bur is that its teeth or flutes are provided with a negative rather than a radial rake. Carbide burs are relatively brittle, and must be treated more carefully than ordinary burs. They should be kept cutting freely, in order to prevent too much pressure, which might result in crumbling of the cutting epics.

At the same speeds, both high-speed steel and carbide burs remove approximately the same amount of metal. However, when carbide burs are used at their most efficient speeds, the rate of stock removal may be as much as four times that of ordinary burs. In certain cases, speeds much higher than those shown in the table can be used. It has been demonstrated that a carbide bur will last up to 100 times as long as a high-speed steel bur of corresponding size and shape.

### Approximate Speeds of Rotary Files and Burs

| Tool<br>Diam.,<br>Inches | Medium Cut, High-Speed Steel Bur or File |           |        |          |           | Carbide Bur   |             |
|--------------------------|--|-----------|--------|----------|-----------|---------------|-------------|
|                          | Mild Steel                               | Cast Iron | Bronze | Aluminum | Magnesium | Medium<br>Cut | Fine<br>Cut |
|                          | Speed, Revolutions per Minute            |           |        |          |           | Any Material  |             |
| 1/8                      | 4600                                     | 7000      | 15,000 | 20,000   | 30,000    | 45,000        | 30,000      |
| 1/4                      | 3450                                     | 5250      | 11,250 | 15,000   | 22,500    | 30,000        | 20,000      |
| 3/8                      | 2750                                     | 4200      | 9000   | 12,000   | 18,000    | 24,000        | 16,000      |
| 1/2                      | 2300                                     | 3500      | 7500   | 10,000   | 15,000    | 20,000        | 13,350      |
| 5/8                      | 2000                                     | 3100      | 6650   | 8900     | 13,350    | 18,000        | 12,000      |
| 3/4                      | 1900                                     | 2900      | 6200   | 8300     | 12,400    | 16,000        | 10,650      |
| 7/8                      | 1700                                     | 2600      | 5600   | 7500     | 11,250    | 14,500        | 9650        |
| 1                        | 1600                                     | 2400      | 5150   | 6850     | 10,300    | 13,000        | 8650        |
| 1 1/8                    | 1500                                     | 2300      | 4850   | 6500     | 9750      | ...           | ...         |
| 1 1/4                    | 1400                                     | 2100      | 4500   | 6000     | 9000      | ...           | ...         |

As recommended by the Nicholson File Company.

**Steel Wool.**—Steel wool is made by shaving thin layers of steel from wire. The wire is pulled, by special machinery built for the purpose, past cutting tools or through cutting dies which shave off chips from the outside. Steel wool consists of long, relatively strong, and resilient steel shavings having sharp edges. This characteristic renders it an excellent abrasive. The fact that the cutting characteristics of steel wool vary with the size of the fiber, which is readily controlled in manufacture, has adapted it to many applications.

Metals other than steel have been made into wool by the same processes as steel, and when so manufactured have the same general characteristics. Thus wool has been made from copper, lead, aluminum, bronze, brass, monel metal, and nickel. The wire from which steel wool is made may be produced by either the Bessemer, or the basic or acid open-hearth processes. It should contain from 0.10 to 0.20 per cent carbon; from 0.50 to 1.00 per cent manganese; from 0.020 to 0.090 per cent sulphur; from 0.050 to 0.120 per cent phosphorus; and from 0.001 to 0.010 per cent silicon. When drawn on a standard tensile-strength testing machine, a sample of the steel should show an ultimate strength of not less than 120,000 pounds per square inch.

### Steel Wool Grades

| Description | Grade | Fiber Thickness |            | Description   | Grade | Fiber Thickness |            |
|-------------|-------|-----------------|------------|---------------|-------|-----------------|------------|
|             |       | Inch            | Millimeter |               |       | Inch            | Millimeter |
| Super Fine  | 0000  | 0.001           | 0.025      | Medium        | 1     | 0.0025          | 0.06       |
| Extra Fine  | 000   | 0.0015          | 0.035      | Medium Coarse | 2     | 0.003           | 0.075      |
| Very Fine   | 00    | 0.0018          | 0.04       | Coarse        | 3     | 0.0035          | 0.09       |
| Fine        | 0     | 0.002           | 0.05       | Extra Coarse  | 4     | 0.004           | 0.10       |

## TOOL WEAR AND SHARPENING

Metal cutting tools wear constantly when they are being used. A normal amount of wear should not be a cause for concern until the size of the worn region has reached the point where the tool should be replaced. Normal wear cannot be avoided and should be differentiated from abnormal tool breakage or excessively fast wear. Tool breakage and an excessive rate of wear indicate that the tool is not operating correctly and steps should be taken to correct this situation.

There are several basic mechanisms that cause tool wear. It is generally understood that tools wear as a result of abrasion which is caused by hard particles of work material plowing over the surface of the tool. Wear is also caused by diffusion or alloying between the work material and the tool material. In regions where the conditions of contact are favorable, the work material reacts with the tool material causing an attrition of the tool material. The rate of this attrition is dependent upon the temperature in the region of contact and the reactivity of the tool and the work materials with each other. Diffusion or alloying also occurs where particles of the work material are welded to the surface of the tool. These welded deposits are often quite visible in the form of a built-up edge, as particles or a layer of work material inside a crater or as small mounds attached to the face of the tool. The diffusion or alloying occurring between these deposits and the tool weakens the tool material below the weld. Frequently these deposits are again rejoined to the chip by welding or they are simply broken away by the force of collision with the passing chip. When this happens, a small amount of the tool material may remain attached to the deposit and be plucked from the surface of the tool, to be carried away with the chip. This mechanism can cause chips to be broken from the cutting edge and the formation of small craters on the tool face called pull-outs. It can also contribute to the enlargement of the larger crater that sometimes forms behind the cutting edge. Among the other mechanisms that can cause tool wear are severe thermal gradients and thermal shocks, which cause cracks to form near the cutting edge, ultimately leading to tool failure. This condition can be caused by improper tool grinding procedures, heavy interrupted cuts, or by the improper application of cutting fluids when machining at high cutting speeds. Chemical reactions between the active constituents in some cutting fluids sometimes accelerate the rate of tool wear. Oxidation of the heated metal near the cutting edge also contributes to tool wear, particularly when fast cutting speeds and high cutting temperatures are encountered. Breakage of the cutting edge caused by overloading, heavy shock loads, or improper tool design is not normal wear and should be corrected.

The wear mechanisms described bring about visible manifestations of wear on the tool which should be understood so that the proper corrective measures can be taken, when required. These visible signs of wear are described in the following paragraphs and the corrective measures that might be required are given in the accompanying Tool Trouble-Shooting Check List. The best procedure when trouble shooting is to try to correct only one condition at a time. When a correction has been made it should be checked. After one condition has been corrected, work can then start to correct the next condition.

*Flank Wear:* Tool wear occurring on the flank of the tool below the cutting edge is called flank wear. Flank wear always takes place and cannot be avoided. It should not give rise to concern unless the rate of flank wear is too fast or the flank wear land becomes too large in size. The size of the flank wear can be measured as the distance between the top of the cutting edge and the bottom of the flank wear land. In practice, a visual estimate is usually made instead of a precise measurement, although in many instances flank wear is ignored and the tool wear is "measured" by the loss of size on the part. The best measure of tool wear, however, is flank wear. When it becomes too large, the rubbing action of the wear land against the workpiece increases and the cutting edge must be replaced. Because conditions vary, it is not possible to give an exact amount of flank wear at which the tool should be replaced. Although there are many exceptions, as a rough estimate, high-speed steel

tools should be replaced when the width of the flank wear land reaches 0.005 to 0.010 inch for finish turning and 0.030 to 0.060 inch for rough turning; and for cemented carbides 0.005 to 0.010 inch for finish turning and 0.020 to 0.040 inch for rough turning.

Under ideal conditions which, surprisingly, occur quite frequently, the width of the flank wear land will be very uniform along its entire length. When the depth of cut is uneven, such as when turning out-of-round stock, the bottom edge of the wear land may become somewhat slanted, the wear land being wider toward the nose. A jagged-appearing wear land usually is evidence of chipping at the cutting edge. Sometimes, only one or two sharp depressions of the lower edge of the wear land will appear, to indicate that the cutting edge has chipped above these depressions. A deep notch will sometimes occur at the "depth of cut line," or that part of the cutting opposite the original surface of the work. This can be caused by a hard surface scale on the work, by a work-hardened surface layer on the work, or when machining high-temperature alloys. Often the size of the wear land is enlarged at the nose of the tool. This can be a sign of crater breakthrough near the nose or of chipping in this region. Under certain conditions, when machining with carbides, it can be an indication of deformation of the cutting edge in the region of the nose.

When a sharp tool is first used, the initial amount of flank wear is quite large in relation to the subsequent total amount. Under normal operating conditions, the width of the flank wear land will increase at a uniform rate until it reaches a critical size after which the cutting edge breaks down completely. This is called catastrophic failure and the cutting edge should be replaced before this occurs. When cutting at slow speeds with high-speed steel tools, there may be long periods when no increase in the flank wear can be observed. For a given work material and tool material, the rate of flank wear is primarily dependent on the cutting speed and then the feed rate.

*Cratering:* A deep crater will sometimes form on the face of the tool which is easily recognizable. The crater forms at a short distance behind the side cutting edge leaving a small shelf between the cutting edge and the edge of the crater. This shelf is sometimes covered with the built-up edge and at other times it is uncovered. Often the bottom of the crater is obscured with work material that is welded to the tool in this region. Under normal operating conditions, the crater will gradually enlarge until it breaks through a part of the cutting edge. Usually this occurs on the end cutting edge just behind the nose. When this takes place, the flank wear at the nose increases rapidly and complete tool failure follows shortly. Sometimes cratering cannot be avoided and a slow increase in the size of the crater is considered normal. However, if the rate of crater growth is rapid, leading to a short tool life, corrective measures must be taken.

*Cutting Edge Chipping:* Small chips are sometimes broken from the cutting edge which accelerates tool wear but does not necessarily cause immediate tool failure. Chipping can be recognized by the appearance of the cutting edge and the flank wear land. A sharp depression in the lower edge of the wear land is a sign of chipping and if this edge of the wear land has a jagged appearance it indicates that a large amount of chipping has taken place. Often the vacancy or cleft in the cutting edge that results from chipping is filled up with work material that is tightly welded in place. This occurs very rapidly when chipping is caused by a built-up edge on the face of the tool. In this manner the damage to the cutting edge is healed; however, the width of the wear land below the chip is usually increased and the tool life is shortened.

*Deformation:* Deformation occurs on carbide cutting tools when taking a very heavy cut using a slow cutting speed and a high feed rate. A large section of the cutting edge then becomes very hot and the heavy cutting pressure compresses the nose of the cutting edge, thereby lowering the face of the tool in the area of the nose. This reduces the relief under the nose, increases the width of the wear land in this region, and shortens the tool life.

*Surface Finish:* The finish on the machined surface does not necessarily indicate poor cutting tool performance unless there is a rapid deterioration. A good surface finish is,

however, sometimes a requirement. The principal cause of a poor surface finish is the built-up edge which forms along the edge of the cutting tool. The elimination of the built-up edge will always result in an improvement of the surface finish. The most effective way to eliminate the built-up edge is to increase the cutting speed. When the cutting speed is increased beyond a certain critical cutting speed, there will be a rather sudden and large improvement in the surface finish. Cemented carbide tools can operate successfully at higher cutting speeds, where the built-up edge does not occur and where a good surface finish is obtained. Whenever possible, cemented carbide tools should be operated at cutting speeds where a good surface finish will result. There are times when such speeds are not possible. Also, high-speed tools cannot be operated at the speed where the built-up edge does not form. In these conditions the most effective method of obtaining a good surface finish is to employ a cutting fluid that has active sulphur or chlorine additives.

Cutting tool materials that do not alloy readily with the work material are also effective in obtaining an improved surface finish. Straight titanium carbide and diamond are the two principal tool materials that fall into this category.

The presence of feed marks can mar an otherwise good surface finish and attention must be paid to the feed rate and the nose radius of the tool if a good surface finish is desired. Changes in the tool geometry can also be helpful. A small "flat," or secondary cutting edge, ground on the end cutting edge behind the nose will sometimes provide the desired surface finish. When the tool is in operation, the flank wear should not be allowed to become too large, particularly in the region of the nose where the finished surface is produced.

**Sharpening Twist Drills.**—Twist drills are cutting tools designed to perform concurrently several functions, such as penetrating directly into solid material, ejecting the removed chips outside the cutting area, maintaining the essentially straight direction of the advance movement and controlling the size of the drilled hole. The geometry needed for these multiple functions is incorporated into the design of the twist drill in such a manner that it can be retained even after repeated sharpening operations. Twist drills are resharpened many times during their service life, with the practically complete restitution of their original operational characteristics. However, in order to assure all the benefits which the design of the twist drill is capable of providing, the surfaces generated in the sharpening process must agree with the original form of the tool's operating surfaces, unless a change of shape is required for use on a different work material.

The principal elements of the tool geometry which are essential for the adequate cutting performance of twist drills are shown in Fig. 1. The generally used values for these dimensions are the following:

*Point angle:* Commonly  $118^\circ$ , except for high strength steels,  $118^\circ$  to  $135^\circ$ ; aluminum alloys,  $90^\circ$  to  $140^\circ$ ; and magnesium alloys,  $70^\circ$  to  $118^\circ$ .

*Helix angle:* Commonly  $24^\circ$  to  $32^\circ$ , except for magnesium and copper alloys,  $10^\circ$  to  $30^\circ$ .

*Lip relief angle:* Commonly  $10^\circ$  to  $15^\circ$ , except for high strength or tough steels,  $7^\circ$  to  $12^\circ$ .

The lower values of these angle ranges are used for drills of larger diameter, the higher values for the smaller diameters. For drills of diameters less than  $\frac{1}{4}$  inch, the lip relief angles are increased beyond the listed maximum values up to  $24^\circ$ . For soft and free machining materials,  $12^\circ$  to  $18^\circ$  except for diameters less than  $\frac{1}{4}$  inch,  $20^\circ$  to  $26^\circ$ .

**Relief Grinding of the Tool Flanks.**—In sharpening twist drills the tool flanks containing the two cutting edges are ground. Each flank consists of a curved surface which provides the relief needed for the easy penetration and free cutting of the tool edges. In grinding the flanks, Fig. 2, the drill is swung around the axis *A* of an imaginary cone while resting in a support which holds the drill at one-half the point angle *B* with respect to the face of the grinding wheel. Feed *f* for stock removal is in the direction of the drill axis. The relief angle is usually measured at the periphery of the twist drill and is also specified by that value. It is not a constant but should increase toward the center of the drill.

The relief grinding of the flank surfaces will generate the chisel angle on the web of the twist drill. The value of that angle, typically  $55^\circ$ , which can be measured, for example, with the protractor of an optical projector, is indicative of the correctness of the relief grinding.

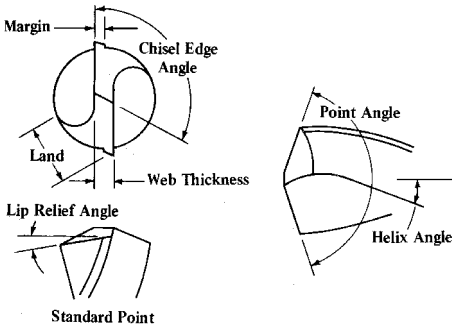


Fig. 1. The principal elements of tool geometry on twist drills.

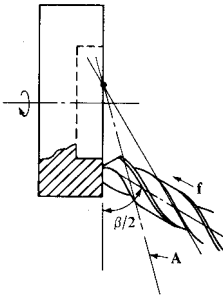


Fig. 2. In grinding the face of the twist drill the tool is swung around the axis *A* of an imaginary cone, while resting in a support tilted by half of the point angle  $\beta$  with respect to the face of the grinding wheel. Feed *f* for stock removal is in the direction of the drill axis.

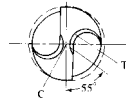


Fig. 3. The chisel edge *C* after thinning the web by grinding off area *T*.

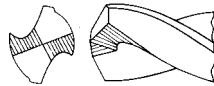


Fig. 4. Split point or "crankshaft" type web thinning.

**Drill Point Thinning.**—The chisel edge is the least efficient operating surface element of the twist drill because it does not cut, but actually squeezes or extrudes the work material. To improve the inefficient cutting conditions caused by the chisel edge, the point width is often reduced in a drill-point thinning operation, resulting in a condition such as that shown in Fig. 3. Point thinning is particularly desirable on larger size drills and also on those which become shorter in usage, because the thickness of the web increases toward the shaft of the twist drill, thereby adding to the length of the chisel edge. The extent of point thinning is limited by the minimum strength of the web needed to avoid splitting of the drill point under the influence of cutting forces.

Both sharpening operations—the relieved face grinding and the point thinning—should be carried out in special drill grinding machines or with twist drill grinding fixtures mounted on general-purpose tool grinding machines, designed to assure the essential accu-

racy of the required tool geometry. Off-hand grinding may be used for the important web thinning when a special machine is not available; however, such operation requires skill and experience.

Improperly sharpened twist drills, e.g. those with unequal edge length or asymmetrical point angle, will tend to produce holes with poor diameter and directional control.

For deep holes and also drilling into stainless steel, titanium alloys, high temperature alloys, nickel alloys, very high strength materials and in some cases tool steels, split point grinding, resulting in a "crankshaft" type drill point, is recommended. In this type of pointing, see Fig. 4, the chisel edge is entirely eliminated, extending the positive rake cutting edges to the center of the drill, thereby greatly reducing the required thrust in drilling. Points on modified-point drills must be restored after sharpening to maintain their increased drilling efficiency.

**Sharpening Carbide Tools.**—Cemented carbide indexable inserts are usually not resharpened but sometimes they require a special grind in order to form a contour on the cutting edge to suit a special purpose. Brazed type carbide cutting tools are resharpened after the cutting edge has become worn. On brazed carbide tools the cutting-edge wear should not be allowed to become excessive before the tool is re-sharpened. One method of determining when brazed carbide tools need resharpening is by periodic inspection of the flank wear and the condition of the face. Another method is to determine the amount of production which is normally obtained before excessive wear has taken place, or to determine the equivalent period of time. One disadvantage of this method is that slight variations in the work material will often cause the wear rate not to be uniform and the number of parts machined before regrinding will not be the same each time. Usually, sharpening should not require the removal of more than 0.005 to 0.010 inch of carbide.

*General Procedure in Carbide Tool Grinding:* The general procedure depends upon the kind of grinding operation required. If the operation is to resharpen a dull tool, a diamond wheel of 100 to 120 grain size is recommended although a finer wheel—up to 150 grain size—is sometimes used to obtain a better finish. If the tool is new or is a "standard" design and changes in shape are necessary, a 100-grit diamond wheel is recommended for roughing and a finer grit diamond wheel can be used for finishing. Some shops prefer to rough grind the carbide with a vitrified silicon carbide wheel, the finish grinding being done with a diamond wheel. A final operation commonly designated as lapping may or may not be employed for obtaining an extra-fine finish.

*Wheel Speeds:* The speed of silicon carbide wheels usually is about 5000 feet per minute. The speeds of diamond wheels generally range from 5000 to 6000 feet per minute; yet lower speeds (550 to 3000 fpm) can be effective.

*Offhand Grinding:* In grinding single-point tools (excepting chip breakers) the common practice is to hold the tool by hand, press it against the wheel face and traverse it continuously across the wheel face while the tool is supported on the machine rest or table which is adjusted to the required angle. This is known as "offhand grinding" to distinguish it from the machine grinding of cutters as in regular cutter grinding practice. The selection of wheels adapted to carbide tool grinding is very important.

**Silicon Carbide Wheels.**—The green colored silicon carbide wheels generally are preferred to the dark gray or gray-black variety, although the latter are sometimes used.

*Grain or Grit Sizes:* For roughing, a grain size of 60 is very generally used. For finish grinding with silicon carbide wheels, a finer grain size of 100 or 120 is common. A silicon carbide wheel such as C60-I-7V may be used for grinding both the steel shank and carbide tip. However, for under-cutting steel shanks up to the carbide tip, it may be advantageous to use an aluminum oxide wheel suitable for grinding softer, carbon steel.

*Grade:* According to the standard system of marking, different grades from soft to hard are indicated by letters from A to Z. For carbide tool grinding fairly soft grades such as G, H, I, and J are used. The usual grades for roughing are I or J and for finishing H, I, and J. The



grade should be such that a sharp free-cutting wheel will be maintained without excessive grinding pressure. Harder grades than those indicated tend to overheat and crack the carbide.

*Structure:* The common structure numbers for carbide tool grinding are 7 and 8. The larger cup-wheels (10 to 14 inches) may be of the porous type and be designated as 12P. The standard structure numbers range from 1 to 15 with progressively higher numbers indicating less density and more open wheel structure.

**Diamond Wheels.**—Wheels with diamond-impregnated grinding faces are fast and cool cutting and have a very low rate of wear. They are used extensively both for resharpening and for finish grinding of carbide tools when preliminary roughing is required. Diamond wheels are also adapted for sharpening multi-tooth cutters such as milling cutters, reamers, etc., which are ground in a cutter grinding machine.

*Resinoid bonded* wheels are commonly used for grinding chip breakers, milling cutters, reamers or other multi-tooth cutters. They are also applicable to precision grinding of carbide dies, gages, and various external, internal and surface grinding operations. Fast, cool cutting action is characteristic of these wheels.

*Metal bonded* wheels are often used for offhand grinding of single-point tools especially when durability or long life and resistance to grooving of the cutting face, are considered more important than the rate of cutting. *Vitrified bonded* wheels are used both for roughing of chipped or very dull tools and for ordinary resharpening and finishing. They provide rigidity for precision grinding, a porous structure for fast cool cutting, sharp cutting action and durability.

**Diamond Wheel Grit Sizes.**—For roughing with diamond wheels a grit size of 100 is the most common both for offhand and machine grinding.

Grit sizes of 120 and 150 are frequently used in offhand grinding of single point tools 1) for resharpening; 2) for a combination roughing and finishing wheel; and 3) for chip-breaker grinding.

Grit sizes of 220 or 240 are used for ordinary finish grinding all types of tools (offhand and machine) and also for cylindrical, internal and surface finish grinding. Grits of 320 and 400 are used for "lapping" to obtain very fine finishes, and for hand hones. A grit of 500 is for lapping to a mirror finish on such work as carbide gages and boring or other tools for exceptionally fine finishes.

**Diamond Wheel Grades.**—Diamond wheels are made in several different grades to better adapt them to different classes of work. The grades vary for different types and shapes of wheels. Standard Norton grades are H, J, and L, for resinoid bonded wheels, grade N for metal bonded wheels and grades J, L, N, and P, for vitrified wheels. Harder and softer grades than standard may at times be used to advantage.

**Diamond Concentration.**—The relative amount (by carat weight) of diamond in the diamond section of the wheel is known as the "diamond concentration." Concentrations of 100 (high), 50 (medium) and 25 (low) ordinarily are supplied. A concentration of 50 represents one-half the diamond content of 100 (if the depth of the diamond is the same in each case) and 25 equals one-fourth the content of 100 or one-half the content of 50 concentration.

*100 Concentration:* Generally interpreted to mean 72 carats of diamond/in.<sup>3</sup> of abrasive section. (A 75 concentration indicates 54 carats/in.<sup>3</sup>.) Recommended (especially in grit sizes up to about 220) for general machine grinding of carbides, and for grinding cutters and chip breakers. Vitrified and metal bonded wheels usually have 100 concentration.

*50 Concentration:* In the finer grit sizes of 220, 240, 320, 400, and 500, a 50 concentration is recommended for offhand grinding with resinoid bonded cup-wheels.

**25 Concentration:** A low concentration of 25 is recommended for offhand grinding with resinoid bonded cup-wheels with grit sizes of 100, 120 and 150.

**Depth of Diamond Section:** The radial depth of the diamond section usually varies from  $\frac{1}{16}$  to  $\frac{1}{4}$  inch. The depth varies somewhat according to the wheel size and type of bond.

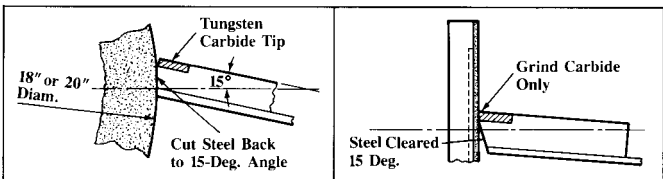
**Dry Versus Wet Grinding of Carbide Tools.**—In using silicon carbide wheels, grinding should be done either absolutely dry or with enough coolant to flood the wheel and tool. Satisfactory results may be obtained either by the wet or dry method. However, dry grinding is the most prevalent usually because, in wet grinding, operators tend to use an inadequate supply of coolant to obtain better visibility of the grinding operation and avoid getting wet; hence checking or cracking in many cases is more likely to occur in wet grinding than in dry grinding.

**Wet Grinding with Silicon Carbide Wheels:** One advantage commonly cited in connection with wet grinding is that an ample supply of coolant permits using wheels about one grade harder than in dry grinding thus increasing the wheel life. Plenty of coolant also prevents thermal stresses and the resulting cracks, and there is less tendency for the wheel to load. A dust exhaust system also is unnecessary.

**Wet Grinding with Diamond Wheels:** In grinding with diamond wheels the general practice is to use a coolant to keep the wheel face clean and promote free cutting. The amount of coolant may vary from a small stream to a coating applied to the wheel face by a felt pad.

**Coolants for Carbide Tool Grinding.**—In grinding either with silicon carbide or diamond wheels a coolant that is used extensively consists of water plus a small amount either of soluble oil, sal soda, or soda ash to prevent corrosion. One prominent manufacturer recommends for silicon carbide wheels about 1 ounce of soda ash per gallon of water and for diamond wheels kerosene. The use of kerosene is quite general for diamond wheels and usually it is applied to the wheel face by a felt pad. Another coolant recommended for diamond wheels consists of 80 per cent water and 20 per cent soluble oil.

**Peripheral Versus Flat Side Grinding.**—In grinding single point carbide tools with silicon carbide wheels, the roughing preparatory to finishing with diamond wheels may be done either by using the flat face of a cup-shaped wheel (side grinding) or the periphery of a “straight” or disk-shaped wheel. Even where side grinding is preferred, the periphery of a straight wheel may be used for heavy roughing as in grinding back chipped or broken tools (see left-hand diagram). Reasons for preferring peripheral grinding include faster cutting with less danger of localized heating and checking especially in grinding broad surfaces. The advantages usually claimed for side grinding are that proper rake or relief angles are easier to obtain and the relief or land is ground flat. The diamond wheels used for tool sharpening are designed for side grinding. (See right-hand diagram.)



**Lapping Carbide Tools.**—Carbide tools may be finished by lapping, especially if an exceptionally fine finish is required on the work as, for example, tools used for precision boring or turning non-ferrous metals. If the finishing is done by using a diamond wheel of very fine grit (such as 240, 320, or 400), the operation is often called “lapping.” A second lapping method is by means of a power-driven lapping disk charged with diamond dust, Norbide powder, or silicon carbide finishing compound. A third method is by using a hand lap or hone usually of 320 or 400 grit. In many plants the finishes obtained with carbide tools meet requirements without a special lapping operation. In all cases any feather edge which may be left on tools should be removed and it is good practice to bevel the edges of roughing tools at 45 degrees to leave a chamfer 0.005 to 0.010 inch wide. This is done by hand honing and the object is to prevent crumbling or flaking off at the edges when hard scale or heavy chip pressure is encountered.

*Hand Honing:* The cutting edge of carbide tools, and tools made from other tool materials, is sometimes hand honed before it is used in order to strengthen the cutting edge. When interrupted cuts or heavy roughing cuts are to be taken, or when the grade of carbide is slightly too hard, hand honing is beneficial because it will prevent chipping, or even possibly, breakage of the cutting edge. Whenever chipping is encountered, hand honing the cutting edge before use will be helpful. It is important, however, to hone the edge lightly and only when necessary. Heavy honing will always cause a reduction in tool life. Normally, removing 0.002 to 0.004 inch from the cutting edge is sufficient. When indexable inserts are used, the use of pre-honed inserts is preferred to hand honing although sometimes an additional amount of honing is required. Hand honing of carbide tools in between cuts is sometimes done to defer grinding or to increase the life of a cutting edge on an indexable insert. If correctly done, so as not to change the relief angle, this procedure is sometimes helpful. If improperly done, it can result in a reduction in tool life.

**Chip Breaker Grinding.**—For this operation a straight diamond wheel is used on a universal tool and cutter grinder, a small surface grinder, or a special chipbreaker grinder. A resinoid bonded wheel of the grade J or N commonly is used and the tool is held rigidly in an adjustable holder or vise. The width of the diamond wheel usually varies from  $\frac{1}{8}$  to  $\frac{1}{4}$  inch. A vitrified bond may be used for wheels as thick as  $\frac{1}{4}$  inch, and a resinoid bond for relatively narrow wheels.

**Summary of Miscellaneous Points.**—In grinding a single-point carbide tool, traverse it across the wheel face continuously to avoid localized heating. This traverse movement should be quite rapid in using silicon carbide wheels and comparatively slow with diamond wheels. A hand traversing and feeding movement, whenever practicable, is generally recommended because of greater sensitivity. In grinding, maintain a constant, moderate pressure. Manipulating the tool so as to keep the contact area with the wheel as small as possible will reduce heating and increase the rate of stock removal. Never cool a hot tool by dipping it in a liquid, as this may crack the tip. Wheel rotation should preferably be *against* the cutting edge or from the front face toward the back. If the grinder is driven by a reversing motor, opposite sides of a cup wheel can be used for grinding right- and left-hand tools and with rotation against the cutting edge. If it is necessary to grind the top face of a single-point tool, this should precede the grinding of the side and front relief, and top-face grinding should be minimized to maintain the tip thickness. In machine grinding with a diamond wheel, limit the feed per traverse to 0.001 inch for 100 to 120 grit; 0.0005 inch for 150 to 240 grit; and 0.0002 inch for 320 grit and finer.

## JIGS AND FIXTURES

## Jig Bushings

**Material for Jig Bushings.**—Bushings are generally made of a good grade of tool steel to ensure hardening at a fairly low temperature and to lessen the danger of fire cracking. They can also be made from machine steel, which will answer all practical purposes, provided the bushings are properly casehardened to a depth of about  $\frac{1}{16}$  inch. Sometimes, bushings for guiding tools may be made of cast iron, but only when the cutting tool is of such a design that no cutting edges come within the bushing itself. For example, bushings used simply to support the smooth surface of a boring-bar or the shank of a reamer might, in some instances, be made of cast iron, but hardened steel bushings should always be used for guiding drills, reamers, taps, etc., when the cutting edges come in direct contact with the guiding surfaces. If the outside diameter of the bushing is very large, as compared with the diameter of the cutting tool, the cost of the bushing can sometimes be reduced by using an outer cast-iron body and inserting a hardened tool steel bushing.

When tool steel bushings are made and hardened, it is recommended that A-2 steel be used. The furnace should be set to 1750°F and the bushing placed in the furnace and held there approximately 20 minutes after the furnace reaches temperature. Remove the bushing and cool in still air. After the part cools to 100–150°F, immediately place in a tempering furnace that has been heated to 300°F. Remove the bushing after one hour and cool in still air. If an atmospherically controlled furnace is unavailable, the part should be wrapped in stainless foil to prevent scaling and oxidation at the 1750°F temperature.

**American National Standard Jig Bushings.**—Specifications for the following types of jig bushings are given in American National Standard B94.33-1974 (R1986). Head Type Press Fit Wearing Bushings, Type H (Fig. 1 and Tables 1 and 3); Headless Type Press Fit Wearing Bushings, Type P (Fig. 2 and Tables 1 and 3); Slip Type Renewable Wearing Bushings, Type S (Fig. 3 and Tables 4 and 5); Fixed Type Renewable Wearing Bushings, Type F (Fig. 4 and Tables 5 and 6); Headless Type Liner Bushings, Type L (Fig. 5 and Table 7); and Head Type Liner Bushings, Type HL (Fig. 6 and Table 8). Specifications for locking mechanisms are also given in Table 9.

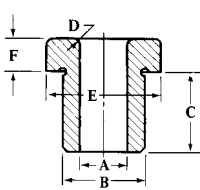


Fig. 1. Head Type Press Fit Wearing Bushings — Type H

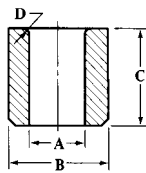


Fig. 2. Headless Type Press Fit Wearing Bushings — Type P

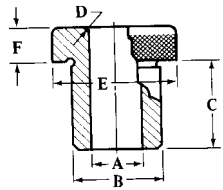


Fig. 3. Slip Type Renewable Wearing Bushings — Type S

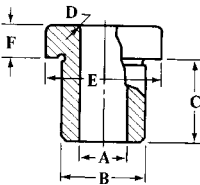


Fig. 4. Fixed Type Renewable Wearing Bushings — Type F

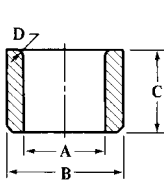


Fig. 5. Headless Type Liner Bushings — Type L

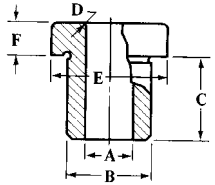


Fig. 6. Head Type Liner Bushings — Type HL

**Table 1. American National Standard Head Type Press Fit Wearing Bushings — Type H ANSI B94.33-1974 (R1986)**

| Range of Hole Sizes<br>A                   | Body Diameter B |            |       |          |        | Body Length<br>C   | Radius<br>D | Head Diam.<br>E<br>Max | Head Thickness<br>F<br>Max | Number  |
|--|-----------------|------------|-------|----------|--------|--|-------------|------------------------|----------------------------|---|
|  | Nom             | Unfinished |       | Finished |        |  |             |                        |                            |   |
|  |                 | Max        | Min   | Max      | Min    |  |             |                        |                            |   |
| 0.0135<br>up to and<br>including<br>0.0625 | 0.156           | 0.166      | 0.161 | 0.1578   | 0.1575 | 0.250<br>0.312<br>0.375<br>0.500                                     | 0.016       | 0.250                  | 0.094                      | H-10-4<br>H-10-5<br>H-10-6<br>H-10-8  |
| 0.0630<br>to<br>0.0995                     | 0.203           | 0.213      | 0.208 | 0.2046   | 0.2043 | 0.250<br>0.312<br>0.375<br>0.500<br>0.750                            | 0.016       | 0.312                  | 0.094                      | H-13-4<br>H-13-5<br>H-13-6<br>H-13-8<br>H-13-12                                   |
| 0.1015<br>to<br>0.1405                     | 0.250           | 0.260      | 0.255 | 0.2516   | 0.2513 | 0.250<br>0.312<br>0.375<br>0.500<br>0.750                            | 0.016       | 0.375                  | 0.094                      | H-16-4<br>H-16-5<br>H-16-6<br>H-16-8<br>H-16-12                                   |
| 0.1406<br>to<br>0.1875                     | 0.312           | 0.327      | 0.322 | 0.3141   | 0.3138 | 0.250<br>0.312<br>0.375<br>0.500<br>0.750<br>1.000                   | 0.031       | 0.438                  | 0.125                      | H-20-4<br>H-20-5<br>H-20-6<br>H-20-8<br>H-20-12<br>H-20-16                        |
| 0.189<br>to<br>0.2500                      | 0.406           | 0.421      | 0.416 | 0.4078   | 0.4075 | 0.250<br>0.312<br>0.375<br>0.500<br>0.750<br>1.000<br>1.375<br>1.750 | 0.031       | 0.531                  | 0.156                      | H-26-4<br>H-26-5<br>H-26-6<br>H-26-8<br>H-26-12<br>H-26-16<br>H-26-22<br>H-26-28  |
| 0.2570<br>to<br>0.3125                     | 0.500           | 0.520      | 0.515 | 0.5017   | 0.5014 | 0.312<br>0.375<br>0.500<br>0.750<br>1.000<br>1.375<br>1.750          | 0.047       | 0.625                  | 0.219                      | H-32-5<br>H-32-6<br>H-32-8<br>H-32-12<br>H-32-16<br>H-32-22<br>H-32-28            |
| 0.3160<br>to<br>0.4219                     | 0.625           | 0.645      | 0.640 | 0.6267   | 0.6264 | 0.312<br>0.375<br>0.500<br>0.750<br>1.000<br>1.375<br>1.750<br>2.125 | 0.047       | 0.812                  | 0.219                      | H-40-5<br>H-40-6<br>H-40-8<br>H-40-12<br>H-40-16<br>H-40-22<br>H-40-28<br>H-40-34 |
| 0.4375<br>to<br>0.5000                     | 0.750           | 0.770      | 0.765 | 0.7518   | 0.7515 | 0.500<br>0.750<br>1.000<br>1.375<br>1.750<br>2.125                   | 0.062       | 0.938                  | 0.219                      | H-48-8<br>H-48-12<br>H-48-16<br>H-48-22<br>H-48-28<br>H-48-34                     |
| 0.5156<br>to<br>0.6250                     | 0.875           | 0.895      | 0.890 | 0.8768   | 0.8765 | 0.500<br>0.750<br>1.000<br>1.375<br>1.750<br>2.125<br>2.500          | 0.062       | 0.125                  | 0.250                      | H-56-8<br>H-56-12<br>H-56-16<br>H-56-22<br>H-56-28<br>H-56-34<br>H-56-40          |

**Table 1. (Continued) American National Standard Head Type Press Fit Wearing Bushings — Type H ANSI B94.33-1974 (R1986)**

| Range of Hole Sizes<br><i>A</i> | Body Diameter <i>B</i> |            |       |          |        | Body Length<br><i>C</i> | Radius<br><i>D</i> | Head Diam.<br><i>E</i><br>Max | Head Thickness<br><i>F</i><br>Max | Number   |
|---------------------------------|------------------------|------------|-------|----------|--------|-------------------------|--------------------|-------------------------------|-----------------------------------|----------|
|                                 | Nom                    | Unfinished |       | Finished |        |                         |                    |                               |                                   |          |
|                                 |                        | Max        | Min   | Max      | Min    |                         |                    |                               |                                   |          |
| 0.6406<br>to<br>0.7500          | 1.000                  | 1.020      | 1.015 | 1.0018   | 1.0015 | 0.500                   | 0.094              | 1.250                         | 0.312                             | H-64-8   |
|                                 |                        |            |       |          |        | 0.750                   |                    |                               |                                   | H-64-12  |
|                                 |                        |            |       |          |        | 1.000                   |                    |                               |                                   | H-64-16  |
|                                 |                        |            |       |          |        | 1.375                   |                    |                               |                                   | H-64-22  |
|                                 |                        |            |       |          |        | 1.750                   |                    |                               |                                   | H-64-28  |
|                                 |                        |            |       |          |        | 2.125                   |                    |                               |                                   | H-64-34  |
| 2.500                           | H-64-40                |            |       |          |        |                         |                    |                               |                                   |          |
| 0.7656<br>to<br>1.0000          | 1.375                  | 1.395      | 1.390 | 1.3772   | 1.3768 | 0.750                   | 0.094              | 1.625                         | 0.375                             | H-88-12  |
|                                 |                        |            |       |          |        | 1.000                   |                    |                               |                                   | H-88-16  |
|                                 |                        |            |       |          |        | 1.375                   |                    |                               |                                   | H-88-22  |
|                                 |                        |            |       |          |        | 1.750                   |                    |                               |                                   | H-88-28  |
|                                 |                        |            |       |          |        | 2.125                   |                    |                               |                                   | H-88-34  |
|                                 |                        |            |       |          |        | 2.500                   |                    |                               |                                   | H-88-40  |
| 1.0156<br>to<br>1.3750          | 1.750                  | 1.770      | 1.765 | 1.7523   | 1.7519 | 1.000                   | 0.094              | 2.000                         | 0.375                             | H-112-16 |
|                                 |                        |            |       |          |        | 1.375                   |                    |                               |                                   | H-112-22 |
|                                 |                        |            |       |          |        | 1.750                   |                    |                               |                                   | H-112-28 |
|                                 |                        |            |       |          |        | 2.125                   |                    |                               |                                   | H-112-34 |
|                                 |                        |            |       |          |        | 2.500                   |                    |                               |                                   | H-112-40 |
|                                 |                        |            |       |          |        | 3.000                   |                    |                               |                                   | H-112-48 |
| 1.3906<br>to<br>1.7500          | 2.250                  | 2.270      | 2.265 | 2.2525   | 2.2521 | 1.000                   | 0.094              | 2.500                         | 0.375                             | H-144-16 |
|                                 |                        |            |       |          |        | 1.375                   |                    |                               |                                   | H-144-22 |
|                                 |                        |            |       |          |        | 1.750                   |                    |                               |                                   | H-144-28 |
|                                 |                        |            |       |          |        | 2.125                   |                    |                               |                                   | H-144-34 |
|                                 |                        |            |       |          |        | 2.500                   |                    |                               |                                   | H-144-40 |
|                                 |                        |            |       |          |        | 3.000                   |                    |                               |                                   | H-144-48 |

All dimensions are in inches.

See also [Table 3](#) for additional specifications.

**Table 2. American National Standard Headless Type Press Fit Wearing Bushings — Type P ANSI B94.33-1974 (R1986)**

| Range of Hole Sizes<br><i>A</i>            | Body Diameter <i>B</i> |            |       |          |        | Body Length<br><i>C</i> | Radius<br><i>D</i> | Number  |
|--|------------------------|------------|-------|----------|--------|-------------------------|--------------------|---------|
|  | Nom                    | Unfinished |       | Finished |        |                         |                    |         |
|  |                        | Max        | Min   | Max      | Min    |                         |                    |         |
| 0.0135<br>up to and<br>including<br>0.0625 | 0.156                  | 0.166      | 0.161 | 0.1578   | 0.1575 | 0.250                   | 0.016              | P-10-4  |
|  |                        |            |       |          |        | 0.312                   |                    | P-10-5  |
|  |                        |            |       |          |        | 0.375                   |                    | P-10-6  |
|  |                        |            |       |          |        | 0.500                   |                    | P-10-8  |
| 0.0630<br>to<br>0.0995                     | 0.203                  | 0.213      | 0.208 | 0.2046   | 0.2043 | 0.250                   | 0.016              | P-13-4  |
|  |                        |            |       |          |        | 0.312                   |                    | P-13-5  |
|  |                        |            |       |          |        | 0.375                   |                    | P-13-6  |
|  |                        |            |       |          |        | 0.500                   |                    | P-13-8  |
|  |                        |            |       |          |        | 0.750                   |                    | P-13-12 |
| 0.1015<br>to<br>0.1405                     | 0.250                  | 0.260      | 0.255 | 0.2516   | 0.2513 | 0.250                   | 0.016              | P-16-4  |
|  |                        |            |       |          |        | 0.312                   |                    | P-16-5  |
|  |                        |            |       |          |        | 0.375                   |                    | P-16-6  |
|  |                        |            |       |          |        | 0.500                   |                    | P-16-8  |
| 0.750                                      | P-16-12                |            |       |          |        |                         |                    |         |
| 0.1406<br>to<br>0.1875                     | 0.312                  | 0.327      | 0.322 | 0.3141   | 0.3138 | 0.250                   | 0.031              | P-20-4  |
|  |                        |            |       |          |        | 0.312                   |                    | P-20-5  |
|  |                        |            |       |          |        | 0.375                   |                    | P-20-6  |
|  |                        |            |       |          |        | 0.500                   |                    | P-20-8  |
|  |                        |            |       |          |        | 0.750                   |                    | P-20-12 |
| 1.000                                      | P-20-16                |            |       |          |        |                         |                    |         |

**Table 2. (Continued) American National Standard Headless Type Press Fit Wearing Bushings — Type P ANSI B94.33-1974 (R1986)**

| Range of Hole Sizes<br><i>A</i> | Body Diameter <i>B</i> |            |       |          |        | Body Length<br><i>C</i> | Radius<br><i>D</i> | Number   |
|---------------------------------|------------------------|------------|-------|----------|--------|-------------------------|--------------------|----------|
|                                 | Nom                    | Unfinished |       | Finished |        |                         |                    |          |
|                                 |                        | Max        | Min   | Max      | Min    |                         |                    |          |
| 0.1890<br>to<br>0.2500          | 0.406                  | 0.421      | 0.416 | 0.4078   | 0.4075 | 0.250                   | 0.031              | P-26-4   |
|                                 |                        |            |       |          |        | 0.312                   |                    | P-26-5   |
|                                 |                        |            |       |          |        | 0.375                   |                    | P-26-6   |
|                                 |                        |            |       |          |        | 0.500                   |                    | P-26-8   |
|                                 |                        |            |       |          |        | 0.750                   |                    | P-26-12  |
|                                 |                        |            |       |          |        | 1.000                   |                    | P-26-16  |
|                                 |                        |            |       |          |        | 1.375                   |                    | P-26-22  |
|                                 |                        |            |       |          |        | 1.750                   |                    | P-26-28  |
| 0.2570<br>to<br>0.3125          | 0.500                  | 0.520      | 0.515 | 0.5017   | 0.5014 | 0.312                   | 0.047              | P-32-5   |
|                                 |                        |            |       |          |        | 0.375                   |                    | P-32-6   |
|                                 |                        |            |       |          |        | 0.500                   |                    | P-32-8   |
|                                 |                        |            |       |          |        | 0.750                   |                    | P-32-12  |
|                                 |                        |            |       |          |        | 1.000                   |                    | P-32-16  |
|                                 |                        |            |       |          |        | 1.375                   |                    | P-32-22  |
| 1.750                           | P-32-28                |            |       |          |        |                         |                    |          |
| 0.3160<br>to<br>0.4219          | 0.625                  | 0.645      | 0.640 | 0.6267   | 0.6264 | 0.312                   | 0.047              | P-40-5   |
|                                 |                        |            |       |          |        | 0.375                   |                    | P-40-6   |
|                                 |                        |            |       |          |        | 0.500                   |                    | P-40-8   |
|                                 |                        |            |       |          |        | 0.750                   |                    | P-40-12  |
|                                 |                        |            |       |          |        | 1.000                   |                    | P-40-16  |
|                                 |                        |            |       |          |        | 1.375                   |                    | P-40-22  |
|                                 |                        |            |       |          |        | 1.750                   |                    | P-40-28  |
|                                 |                        |            |       |          |        | 2.125                   |                    | P-40-34  |
| 0.4375 to 0.5000                | 0.750                  | 0.770      | 0.765 | 0.7518   | 0.7515 | 0.500                   | 0.062              | P-48-8   |
|                                 |                        |            |       |          |        | 0.750                   |                    | P-48-12  |
|                                 |                        |            |       |          |        | 1.000                   |                    | P-48-16  |
|                                 |                        |            |       |          |        | 1.375                   |                    | P-48-22  |
|                                 |                        |            |       |          |        | 1.750                   |                    | P-48-28  |
|                                 |                        |            |       |          |        | 2.125                   |                    | P-48-34  |
| 0.5156<br>to<br>0.6250          | 0.875                  | 0.895      | 0.890 | 0.8768   | 0.8765 | 0.500                   | 0.062              | P-56-8   |
|                                 |                        |            |       |          |        | 0.750                   |                    | P-56-12  |
|                                 |                        |            |       |          |        | 1.000                   |                    | P-56-16  |
|                                 |                        |            |       |          |        | 1.375                   |                    | P-56-22  |
|                                 |                        |            |       |          |        | 1.750                   |                    | P-56-28  |
|                                 |                        |            |       |          |        | 2.125                   |                    | P-56-34  |
| 2.500                           | P-56-40                |            |       |          |        |                         |                    |          |
| 0.6406<br>to<br>0.7500          | 1.000                  | 1.020      | 1.015 | 1.0018   | 1.0015 | 0.500                   | 0.062              | P-64-8   |
|                                 |                        |            |       |          |        | 0.750                   |                    | P-64-12  |
|                                 |                        |            |       |          |        | 1.000                   |                    | P-64-16  |
|                                 |                        |            |       |          |        | 1.375                   |                    | P-64-22  |
|                                 |                        |            |       |          |        | 1.750                   |                    | P-64-28  |
|                                 |                        |            |       |          |        | 2.125                   |                    | P-64-34  |
| 2.500                           | P-64-40                |            |       |          |        |                         |                    |          |
| 0.7656<br>to<br>1.0000          | 1.375                  | 1.395      | 1.390 | 1.3772   | 1.3768 | 0.750                   | 0.094              | P-88-12  |
|                                 |                        |            |       |          |        | 1.000                   |                    | P-88-16  |
|                                 |                        |            |       |          |        | 1.375                   |                    | P-88-22  |
|                                 |                        |            |       |          |        | 1.750                   |                    | P-88-28  |
|                                 |                        |            |       |          |        | 2.125                   |                    | P-88-34  |
|                                 |                        |            |       |          |        | 2.500                   |                    | P-88-40  |
| 1.0156<br>to<br>1.3750          | 1.750                  | 1.770      | 1.765 | 1.7523   | 1.7519 | 1.000                   | 0.094              | P-112-16 |
|                                 |                        |            |       |          |        | 1.375                   |                    | P-112-22 |
|                                 |                        |            |       |          |        | 1.750                   |                    | P-112-28 |
|                                 |                        |            |       |          |        | 2.125                   |                    | P-112-34 |
|                                 |                        |            |       |          |        | 2.500                   |                    | P-112-40 |
|                                 |                        |            |       |          |        | 3.000                   |                    | P-112-48 |
| 1.3906<br>to<br>1.7500          | 2.250                  | 2.270      | 2.265 | 2.2525   | 2.2521 | 1.000                   | 0.094              | P-144-16 |
|                                 |                        |            |       |          |        | 1.375                   |                    | P-144-22 |
|                                 |                        |            |       |          |        | 1.750                   |                    | P-144-28 |
|                                 |                        |            |       |          |        | 2.125                   |                    | P-144-34 |
|                                 |                        |            |       |          |        | 2.500                   |                    | P-144-40 |
|                                 |                        |            |       |          |        | 3.000                   |                    | P-144-48 |

All dimensions are in inches. See [Table 3](#) for additional specifications.

**Table 3. Specifications for Head Type H and Headless Type P Press Fit Wearing Bushings ANSI B94.33-1974 (R1986)**

All dimensions given in inches. Tolerance on dimensions where not otherwise specified shall be  $\pm 0.010$  inch.  
 Size and type of chamfer on lead end to be manufacturer's option.  
 The length, *C*, is the overall length for the headless type and length underhead for the head type.  
 The head design shall be in accordance with the manufacturer's practice.  
 Diameter *A* must be concentric to diameter *B* within 0.0005 T.I.V. on finish ground bushings.  
 The body diameter, *B*, for unfinished bushings is larger than the nominal diameter in order to provide grinding stock for fitting to jig plate holes. The grinding allowance is:  
     0.005 to 0.010 in. for sizes 0.156, 0.203 and 0.250 in.  
     0.010 to 0.015 in. for sizes 0.312 and 0.406 in.  
     0.015 to 0.020 in. for sizes 0.500 in. and up.  
 Hole sizes are in accordance with American National Standard Twist Drill Sizes.  
 The maximum and minimum values of the hole size, *A*, shall be as follows:

| Nominal Size of Hole              | Maximum              | Minimum              |
|-----------------------------------|----------------------|----------------------|
| Above 0.0135 to 0.2500 in., incl. | Nominal + 0.0004 in. | Nominal + 0.0001 in. |
| Above 0.2500 to 0.7500 in., incl. | Nominal + 0.0005 in. | Nominal + 0.0001 in. |
| Above 0.7500 to 1.5000 in., incl. | Nominal + 0.0006 in. | Nominal + 0.0002 in. |
| Above 1.5000 in.                  | Nominal + 0.0007 in. | Nominal + 0.0003 in. |

Bushings in the size range from 0.0135 through 0.3125 will be counterbored to provide for lubrication and chip clearance.  
 Bushings without counterbore are optional and will be furnished upon request.  
 The size of the counterbore shall be inside diameter of the bushing + 0.031 inch.  
 The included angle at the bottom of the counterbore shall be 118 deg.  $\pm$  2 deg.  
 The depth of the counterbore shall be in accordance with the table below to provide adequate drill bearing.

| Body Length | Drill Bushing Hole Size           |       |                  |       |                  |       |                  |       |                  |       |                  |       |       |
|-------------|-----------------------------------|-------|------------------|-------|------------------|-------|------------------|-------|------------------|-------|------------------|-------|-------|
|             | 0.0135 to 0.0625                  |       | 0.0630 to 0.0995 |       | 0.1015 to 0.1405 |       | 0.1406 to 0.1875 |       | 0.1890 to 0.2500 |       | 0.2570 to 0.3125 |       |       |
|             | P                                 | H     | P                | H     | P                | H     | P                | H     | P                | H     | P                | H     |       |
|             | Minimum Drill Bearing Length—Inch |       |                  |       |                  |       |                  |       |                  |       |                  |       |       |
| 0.250       | X                                 | 0.250 | X                | X     | X                | X     | X                | X     | X                | X     | X                | X     | X     |
| 0.312       | X                                 | 0.250 | X                | X     | X                | X     | X                | X     | X                | X     | X                | X     | X     |
| 0.375       | 0.250                             | 0.250 | X                | X     | X                | X     | X                | X     | X                | X     | X                | X     | X     |
| 0.500       | 0.250                             | 0.250 | X                | 0.312 | X                | 0.312 | X                | 0.375 | X                | X     | X                | X     | X     |
| 0.750       | +                                 | +     | 0.375            | 0.375 | 0.375            | 0.375 | X                | 0.375 | X                | X     | X                | X     | X     |
| 1.000       | +                                 | +     | +                | +     | +                | +     | 0.625            | 0.625 | 0.625            | 0.625 | 0.625            | 0.625 | 0.625 |
| 1.375       | +                                 | +     | +                | +     | +                | +     | +                | +     | 0.625            | 0.625 | 0.625            | 0.625 | 0.625 |
| 1.750       | +                                 | +     | +                | +     | +                | +     | +                | +     | 0.625            | 0.625 | 0.625            | 0.625 | 0.625 |

All dimensions are in inches.

X indicates no counterbore.

+ indicates not American National Standard

**Table 4. American National Standard Slip Type Renewable Wearing Bushings — Type S ANSI B94.33-1974 (R1986)**

| Range of Hole Sizes <i>A</i>      | Body Diameter <i>B</i> |        |        | Length UnderHead <i>C</i>                          | Radius <i>D</i> | Head Diam. <i>E</i> Max | Head Thickness <i>F</i> Max | Number  |
|-----------------------------------|------------------------|--------|--------|--|-----------------|-------------------------|-----------------------------|---|
|                                   | Nom                    | Max    | Min    |  |                 |                         |                             |   |
| 0.0135 up to and including 0.0469 | 0.188                  | 0.1875 | 0.1873 | 0.250<br>0.312<br>0.375<br>0.500                   | 0.031           | 0.312                   | 0.188                       | S-12-4<br>S-12-5<br>S-12-6<br>S-12-8                          |
| 0.0492 to 0.1562                  | 0.312                  | 0.3125 | 0.3123 | 0.312<br>0.500<br>0.750<br>1.000                   | 0.047           | 0.562                   | 0.375                       | S-20-5<br>S-20-8<br>S-20-12<br>S-20-16                        |
| 0.1570 to 0.3125                  | 0.500                  | 0.5000 | 0.4998 | 0.312<br>0.500<br>0.750<br>1.000<br>1.375<br>1.750 | 0.047           | 0.812                   | 0.438                       | S-32-5<br>S-32-8<br>S-32-12<br>S-32-16<br>S-32-22<br>S-32-28  |
| 0.3160 to 0.5000                  | 0.750                  | 0.7500 | 0.7498 | 0.500<br>0.750<br>1.000<br>1.375<br>1.750<br>2.125 | 0.094           | 1.062                   | 0.438                       | S-48-8<br>S-48-12<br>S-48-16<br>S-48-22<br>S-48-28<br>S-48-34 |



**Table 4. (Continued) American National Standard Slip Type Renewable Wearing Bushings — Type S ANSI B94.33-1974 (R1986)**

| Range of Hole Sizes<br>A | Body Diameter B |        |        | Length Under Head<br>C | Radius<br>D | Head Diam.<br>E<br>Max | Head Thickness<br>F<br>Max | Number   |
|--------------------------|-----------------|--------|--------|------------------------|-------------|------------------------|----------------------------|----------|
|                          | Nom             | Max    | Min    |                        |             |                        |                            |          |
| 0.5156<br>to<br>0.7500   | 1.000           | 1.0000 | 0.9998 | 0.500                  | 0.094       | 1.438                  | 0.438                      | S-64-8   |
|                          |                 |        |        | 0.750                  |             |                        |                            | S-64-12  |
|                          |                 |        |        | 1.000                  |             |                        |                            | S-64-16  |
|                          |                 |        |        | 1.375                  |             |                        |                            | S-64-22  |
|                          |                 |        |        | 1.750                  |             |                        |                            | S-64-28  |
|                          |                 |        |        | 2.125                  |             |                        |                            | S-64-34  |
| 0.7656<br>to<br>1.0000   | 1.375           | 1.3750 | 1.3747 | 2.500                  | 0.094       | 1.812                  | 0.438                      | S-64-40  |
|                          |                 |        |        | 0.750                  |             |                        |                            | S-88-12  |
|                          |                 |        |        | 1.000                  |             |                        |                            | S-88-16  |
|                          |                 |        |        | 1.375                  |             |                        |                            | S-88-22  |
|                          |                 |        |        | 1.750                  |             |                        |                            | S-88-28  |
|                          |                 |        |        | 2.125                  |             |                        |                            | S-88-34  |
| 1.0156<br>to<br>1.3750   | 1.750           | 1.7500 | 1.7497 | 2.500                  | 0.125       | 2.312                  | 0.625                      | S-88-40  |
|                          |                 |        |        | 1.000                  |             |                        |                            | S-112-16 |
|                          |                 |        |        | 1.375                  |             |                        |                            | S-112-22 |
|                          |                 |        |        | 1.750                  |             |                        |                            | S-112-28 |
|                          |                 |        |        | 2.125                  |             |                        |                            | S-112-34 |
|                          |                 |        |        | 2.500                  |             |                        |                            | S-112-40 |
| 1.3906<br>to<br>1.7500   | 2.250           | 2.2500 | 2.2496 | 3.000                  | 0.125       | 2.812                  | 0.625                      | S-112-48 |
|                          |                 |        |        | 1.000                  |             |                        |                            | S-144-16 |
|                          |                 |        |        | 1.375                  |             |                        |                            | S-144-22 |
|                          |                 |        |        | 1.750                  |             |                        |                            | S-144-28 |
|                          |                 |        |        | 2.125                  |             |                        |                            | S-144-34 |
|                          |                 |        |        | 2.500                  |             |                        |                            | S-144-40 |
| 3.000                    | S-144-48        |        |        |                        |             |                        |                            |          |

All dimensions are in inches. See also Table 5 for additional specifications.

**Table 5. Specifications for Slip Type S and Fixed Type F Renewable Wearing Bushings ANSI B94.33-1974 (R1986)**

|   |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
|---|-------------------------|-------|----------------------|-------|------------------|-------|----------------------|-------|------------------|-------|------------------|-------|
| Tolerance on dimensions where not otherwise specified shall be plus or minus 0.010 inch.  |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| Hole sizes are in accordance with the American Standard Twist Drill Sizes.  |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| The maximum and minimum values of hole size, A, shall be as follows:  |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| Nominal Size of Hole  |                         |       | Maximum              |       |                  |       | Minimum              |       |                  |       |                  |       |
| Above 0.0135 to 0.2500 in. incl.  |                         |       | Nominal + 0.0004 in. |       |                  |       | Nominal + 0.0001 in. |       |                  |       |                  |       |
| Above 0.2500 to 0.7500 in. incl.  |                         |       | Nominal + 0.0005 in. |       |                  |       | Nominal + 0.0001 in. |       |                  |       |                  |       |
| Above 0.7500 to 1.5000 in. incl.  |                         |       | Nominal + 0.0006 in. |       |                  |       | Nominal + 0.0002 in. |       |                  |       |                  |       |
| Above 1.5000  |                         |       | Nominal + 0.0007 in. |       |                  |       | Nominal + 0.0003 in. |       |                  |       |                  |       |
| The head design shall be in accordance with the manufacturer's practice.  |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| Head of slip type is usually knurled.   |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| When renewable wearing bushings are used with liner bushings of the head type, the length under the head will still be equal to the thickness of the jig plate, because the head of the liner bushing will be countersunk into the jig plate. |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| Diameter A must be concentric to diameter B within 0.0005 T.I.R. on finish ground bushings.   |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| Size and type of chamfer on lead end to be manufacturer's option.   |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| Bushings in the size range from 0.0135 through 0.3125 will be counterbored to provide for lubrication and chip clearance.   |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| Bushings without counterbore are optional and will be furnished upon request.   |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| The size of the counterbore shall be inside diameter of the bushings plus 0.031 inch.   |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| The included angle at the bottom of the counterbore shall be 118 deg., plus or minus 2 deg.   |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| The depth of the counterbore shall be in accordance with the table below to provide adequate drill bearing.   |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| Body Length   | Drill Bearing Hole Size |       |                      |       |                  |       |                      |       |                  |       |                  |       |
|   | 0.0135 to 0.0625        |       | 0.0630 to 0.0995     |       | 0.1015 to 0.1405 |       | 0.1406 to 0.1875     |       | 0.1890 to 0.2500 |       | 0.2500 to 0.3125 |       |
|   | S                       | F     | S                    | F     | S                | F     | S                    | F     | S                | F     | S                | F     |
| Minimum Drill Bearing Length  |                         |       |                      |       |                  |       |                      |       |                  |       |                  |       |
| 0.250   | 0.250                   | 0.250 | 0.375                | 0.375 | X                | X     | X                    | X     | X                | X     | X                | X     |
| 0.312   | 0.250                   | 0.250 | 0.375                | 0.375 | 0.375            | 0.375 | 0.375                | 0.375 | 0.375            | 0.375 | X                | X     |
| 0.375   | 0.250                   | 0.250 | 0.375                | 0.375 | 0.375            | 0.375 | 0.375                | 0.375 | 0.375            | 0.375 | X                | X     |
| 0.500   | 0.250                   | 0.250 | 0.375                | 0.375 | 0.375            | 0.375 | 0.375                | 0.375 | 0.375            | 0.375 | X                | X     |
| 0.750   | 0.250                   | 0.250 | 0.375                | 0.375 | 0.375            | 0.375 | 0.375                | 0.375 | 0.625            | 0.625 | 0.625            | 0.625 |
| 1.000   | 0.312                   | 0.312 | 0.375                | 0.375 | 0.375            | 0.375 | 0.625                | 0.625 | 0.625            | 0.625 | 0.625            | 0.625 |
| 1.375   | +                       | +     | +                    | +     | +                | +     | 0.625                | 0.625 | 0.625            | 0.625 | 0.625            | 0.625 |
| 1.750   | +                       | +     | +                    | +     | +                | +     | 0.625                | 0.625 | 0.625            | 0.625 | 0.625            | 0.625 |

All dimensions are in inches.

X indicates no counterbore, + indicates not American National Standard length.

**Table 6. American National Standard Fixed Type Renewable Wearing Bushings — Type F ANSI B94.33-1974 (R1986)**

| Range of Hole Sizes <i>A</i>      | Body Diameter <i>B</i> |        |        | Length Under Head <i>C</i>                                  | Radius <i>D</i> | Head Diam. <i>E</i> Max | Head Thickness <i>F</i> Max | Number   |
|-----------------------------------|------------------------|--------|--------|---|-----------------|-------------------------|-----------------------------|--|
|                                   | Nom                    | Max    | Min    |   |                 |                         |                             |  |
| 0.0135 up to and including 0.0469 | 0.188                  | 0.1875 | 0.1873 | 0.250<br>0.312<br>0.375<br>0.500                            | 0.031           | 0.312                   | 0.188                       | F-12-4<br>F-12-5<br>F-12-6<br>F-12-8                                     |
| 0.0492 to 0.1562                  | 0.312                  | 0.3125 | 0.3123 | 0.312<br>0.500<br>0.750<br>1.000                            | 0.047           | 0.562                   | 0.250                       | F-20-5<br>F-20-8<br>F-20-12<br>F-20-16                                   |
| 0.1570 to 0.3125                  | 0.500                  | 0.5000 | 0.4998 | 0.312<br>0.500<br>0.750<br>1.000<br>1.375<br>1.750          | 0.047           | 0.812                   | 0.250                       | F-32-5<br>F-32-8<br>F-32-12<br>F-32-16<br>F-32-22<br>F-32-28             |
| 0.3160 to 0.5000                  | 0.750                  | 0.7500 | 0.7498 | 0.500<br>0.750<br>1.000<br>1.375<br>1.750<br>2.125          | 0.094           | 1.062                   | 0.250                       | F-48-8<br>F-48-12<br>F-48-16<br>F-48-22<br>F-48-28<br>F-48-34            |
| 0.5156 to 0.7500                  | 1.000                  | 1.0000 | 0.9998 | 0.500<br>0.750<br>1.000<br>1.375<br>1.750<br>2.125<br>2.500 | 0.094           | 1.438                   | 0.375                       | F-64-8<br>F-64-12<br>F-64-16<br>F-64-22<br>F-64-28<br>F-64-34<br>F-64-40 |
| 0.7656 to 1.0000                  | 1.375                  | 1.3750 | 1.3747 | 0.750<br>1.000<br>1.375<br>1.750<br>2.125<br>2.500          | 0.094           | 1.812                   | 0.375                       | F-88-12<br>F-88-16<br>F-88-22<br>F-88-28<br>F-88-34<br>F-88-40           |
| 1.0156 to 1.3750                  | 1.750                  | 1.7500 | 1.7497 | 1.000<br>1.375<br>1.750<br>2.125<br>2.500<br>3.000          | 0.125           | 2.312                   | 0.375                       | F-112-16<br>F-112-22<br>F-112-28<br>F-112-34<br>F-112-40<br>F-112-48     |
| 1.3906 to 1.7500                  | 2.250                  | 2.2500 | 2.2496 | 1.000<br>1.375<br>1.750<br>2.125<br>2.500<br>3.000          | 0.125           | 2.812                   | 0.375                       | F-144-16<br>F-144-22<br>F-144-28<br>F-144-34<br>F-144-40<br>F-144-48     |

All dimensions are in inches. See also [Table 5](#) for additional specifications.

**Table 7. American National Standard Headless Type Liner Bushings —  
Type L ANSI B94.33-1974 (R1986)**

| Range of Hole Sizes in Renewable Bushings | Inside Diameter A |        |        | Body Diameter B |        |          |        |        | Over-all Length C   | Radius D | Number   |
|---|-------------------|--------|--------|-----------------|--------|----------|--------|--------|---|----------|--|
|   |                   |        |        | Unfinished      |        | Finished |        |        |   |          |  |
|   | Nom               | Max    | Min    | Nom             | Max    | Min      | Max    | Min    |   |          |  |
| 0.0135 up to and including 0.0469         | 0.188             | 0.1879 | 0.1876 | 0.312           | 0.3341 | 0.3288   | 0.3141 | 0.3138 | 0.250<br>0.312<br>0.375<br>0.500                            | 0.031    | L-20-4<br>L-20-5<br>L-20-6<br>L-20-8                                     |
| 0.0492 to 0.1562                          | 0.312             | 0.3129 | 0.3126 | 0.500           | 0.520  | 0.515    | 0.5017 | 0.5014 | 0.312<br>0.500<br>0.750<br>1.000                            | 0.047    | L-32-5<br>L-32-8<br>L-32-12<br>L-32-16                                   |
| 0.1570 to 0.3125                          | 0.500             | 0.5005 | 0.5002 | 0.750           | 0.770  | 0.765    | 0.7518 | 0.7515 | 0.312<br>0.500<br>0.750<br>1.000<br>1.375<br>1.750          | 0.062    | L-48-5<br>L-48-8<br>L-48-12<br>L-48-16<br>L-48-22<br>L-48-28             |
| 0.3160 to 0.5000                          | 0.750             | 0.7506 | 0.7503 | 1.000           | 1.020  | 1.015    | 1.0018 | 1.0015 | 0.500<br>0.750<br>1.000<br>1.375<br>1.750<br>2.125          | 0.062    | L-64-8<br>L-64-12<br>L-64-16<br>L-64-22<br>L-64-28<br>L-64-34            |
| 0.5156 to 0.7500                          | 1.000             | 1.0007 | 1.0004 | 1.375           | 1.395  | 1.390    | 1.3772 | 1.3768 | 0.500<br>1.750<br>1.000<br>1.375<br>1.750<br>2.125<br>2.500 | 0.094    | L-88-8<br>L-88-12<br>L-88-16<br>L-88-22<br>L-88-28<br>L-88-34<br>L-88-40 |
| 0.7656 to 1.0000                          | 1.375             | 1.3760 | 1.3756 | 1.750           | 1.770  | 1.765    | 1.7523 | 1.7519 | 0.750<br>1.000<br>1.375<br>1.750<br>2.125<br>2.500          | 0.094    | L-112-12<br>L-112-16<br>L-112-22<br>L-112-28<br>L-112-34<br>L-112-40     |
| 1.0156 to 1.3750                          | 1.750             | 1.7512 | 1.7508 | 2.250           | 2.270  | 2.265    | 2.2525 | 2.2521 | 1.000<br>1.375<br>1.750<br>2.125<br>2.500<br>3.000          | 0.094    | L-144-16<br>L-144-22<br>L-144-28<br>L-144-34<br>L-144-40<br>L-144-48     |
| 1.3906 to 1.7500                          | 2.250             | 2.2515 | 2.2510 | 2.750           | 2.770  | 2.765    | 2.7526 | 2.7522 | 1.000<br>1.375<br>1.750<br>2.125<br>2.500<br>3.000          | 0.125    | L-176-16<br>L-176-22<br>L-176-28<br>L-176-34<br>L-176-40<br>L-176-48     |

All dimensions are in inches.

Tolerances on dimensions where otherwise not specified are  $\pm 0.010$  in.

The body diameter, *B*, for unfinished bushings is 0.015 to 0.020 in. larger than the nominal diameter in order to provide grinding stock for fitting to jig plate holes.

Diameter *A* must be concentric to diameter *B* within 0.0005 T.I.R. on finish ground bushings.

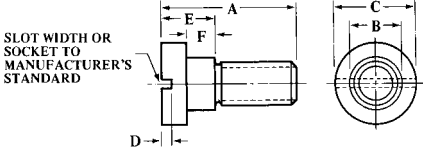
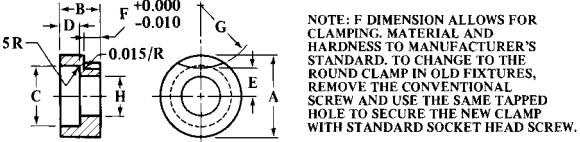
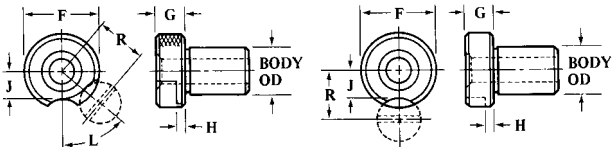
**Table 8. American National Standard Head Type Liner Bushing —  
Type HL ANSI B94.33-1974 (R1986)**

| Range of Hole<br>Sizes in Renewable<br>Bushings | Inside<br>Diameter A |        |        | Body<br>Diameter B |       |       |          |        | Overall<br>Length<br>C                                      | Radius D | Head<br>Dia.<br>E | Head Thickness<br>F Max | Number  |
|---|----------------------|--------|--------|--------------------|-------|-------|----------|--------|---|----------|-------------------|-------------------------|---|
|   |                      |        |        | Unfinished         |       |       | Finished |        |   |          |                   |                         |   |
|   | Nom                  | Max    | Min    | Nom                | Max   | Min   | Max      | Min    |   |          |                   |                         |   |
| 0.0135<br>to<br>0.1562                          | 0.312                | 0.3129 | 0.3126 | 0.500              | 0.520 | 0.515 | 0.5017   | 0.5014 | 0.312<br>0.500<br>0.750<br>1.000                            | 0.047    | 0.625             | 0.094                   | HL-32-5<br>HL-32-8<br>HL-32-12<br>HL-32-16                                      |
|   |                      |        |        | 0.750              | 0.770 | 0.765 | 0.7518   | 0.7515 | 0.312<br>0.500<br>0.750<br>1.000<br>1.375<br>1.750          |          |                   |                         | HL-48-5<br>HL-48-8<br>HL-48-12<br>HL-48-16<br>HL-48-22<br>HL-48-28              |
|   |                      |        |        | 1.000              | 1.020 | 1.015 | 1.0018   | 1.0015 | 0.500<br>0.750<br>1.000<br>1.375<br>1.750<br>2.125          |          |                   |                         | HL-64-8<br>HL-64-12<br>HL-64-16<br>HL-64-22<br>HL-64-28<br>HL-64-34             |
|   |                      |        |        | 1.375              | 1.395 | 1.390 | 1.3772   | 1.3768 | 0.500<br>0.750<br>1.000<br>1.375<br>1.750<br>2.125<br>2.500 |          |                   |                         | HL-88-8<br>HL-88-12<br>HL-88-16<br>HL-88-22<br>HL-88-28<br>HL-88-34<br>HL-88-40 |
| 0.3160<br>to<br>0.5000                          | 0.750                | 0.7506 | 0.7503 | 1.000              | 1.020 | 1.015 | 1.0018   | 1.0015 | 0.500<br>0.750<br>1.000<br>1.375<br>1.750<br>2.125          | 0.062    | 1.125             | 0.125                   | HL-64-8<br>HL-64-12<br>HL-64-16<br>HL-64-22<br>HL-64-28<br>HL-64-34             |
|   |                      |        |        | 1.375              | 1.395 | 1.390 | 1.3772   | 1.3768 | 0.500<br>0.750<br>1.000<br>1.375<br>1.750<br>2.125<br>2.500 |          |                   |                         | HL-88-8<br>HL-88-12<br>HL-88-16<br>HL-88-22<br>HL-88-28<br>HL-88-34<br>HL-88-40 |
|   |                      |        |        | 1.750              | 1.770 | 1.765 | 1.7523   | 1.7519 | 0.750<br>1.000<br>1.375<br>1.750<br>2.125<br>2.500          |          |                   |                         | HL-112-12<br>HL-112-16<br>HL-112-22<br>HL-112-28<br>HL-112-34<br>HL-112-40      |
|   |                      |        |        | 2.125              | 2.270 | 2.265 | 2.2525   | 2.2521 | 1.000<br>1.375<br>1.750<br>2.125<br>2.500<br>3.000          |          |                   |                         | HL-144-16<br>HL-144-22<br>HL-144-28<br>HL-144-34<br>HL-144-40<br>HL-144-48      |
| 0.7656<br>to<br>1.0000                          | 1.375                | 1.3760 | 1.3756 | 1.750              | 1.770 | 1.765 | 1.7523   | 1.7519 | 0.750<br>1.000<br>1.375<br>1.750<br>2.125<br>2.500          | 0.094    | 1.875             | 0.188                   | HL-112-12<br>HL-112-16<br>HL-112-22<br>HL-112-28<br>HL-112-34<br>HL-112-40      |
|   |                      |        |        | 2.125              | 2.270 | 2.265 | 2.2525   | 2.2521 | 1.000<br>1.375<br>1.750<br>2.125<br>2.500<br>3.000          |          |                   |                         | HL-144-16<br>HL-144-22<br>HL-144-28<br>HL-144-34<br>HL-144-40<br>HL-144-48      |
|   |                      |        |        | 2.500              | 2.770 | 2.765 | 2.7526   | 2.7522 | 1.000<br>1.375<br>1.750<br>2.125<br>2.500<br>3.000          |          |                   |                         | HL-176-16<br>HL-176-22<br>HL-176-28<br>HL-176-34<br>HL-176-40<br>HL-176-48      |
|   |                      |        |        | 3.000              | 3.000 | 3.000 | 3.000    | 3.000  | 1.000<br>1.375<br>1.750<br>2.125<br>2.500<br>3.000          |          |                   |                         | HL-176-16<br>HL-176-22<br>HL-176-28<br>HL-176-34<br>HL-176-40<br>HL-176-48      |

All dimensions are in inches.

See also footnotes to [Table 7](#).

**Table 9. American National Standard Locking Mechanisms for Jig Bushings**  
ANSI B94.33-1974 (R1986)

| Lock Screw for Use with Slip or Fixed Renewable Bushings                            |   |                  |       |                                   |       |             |                    |  |                                    |   |                         |
|---|---|------------------|-------|-----------------------------------|-------|-------------|--------------------|--|------------------------------------|---|-------------------------|
|    |   |                  |       |                                   |       |             |                    |  |                                    |   |                         |
| No.   | A   | B                | C     | D                                 | E     | F           | UNC Thread         |  |                                    |   |                         |
| LS-0  | 0.438                                     | 0.188            | 0.312 | Per<br>Manufacturer's<br>Standard | 0.188 | 0.105-0.100 | 8-32               |  |                                    |   |                         |
| LS-1  | 0.625                                     | 0.375            | 0.625 |                                   | 0.250 | 0.138-0.132 | $\frac{5}{16}$ -18 |  |                                    |   |                         |
| LS-2  | 0.875                                     | 0.375            | 0.625 |                                   | 0.375 | 0.200-0.194 | $\frac{5}{16}$ -18 |  |                                    |   |                         |
| LS-3  | 1.000                                     | 0.438            | 0.750 |                                   | 0.375 | 0.200-0.194 | $\frac{3}{8}$ -16  |  |                                    |   |                         |
| Round Clamp Optional Only for Use with Fixed Renewable Bushing                      |   |                  |       |                                   |       |             |                    |  |                                    |   |                         |
|    |   |                  |       |                                   |       |             |                    |  |                                    |   |                         |
| Number  | A   | B                | C     | D                                 | E     | F           | G                  | H  | Use With Socket Head Screw         |   |                         |
| RC-1  | 0.625                                     | 0.312            | 0.484 | 0.150                             | 0.203 | 0.125       | 0.531              | 0.328                                      | $\frac{5}{16}$ -18                 |   |                         |
| RC-2  | 0.625                                     | 0.438            | 0.484 | 0.219                             | 0.187 | 0.188       | 0.906              | 0.328                                      | $\frac{5}{16}$ -18                 |   |                         |
| RC-3  | 0.750                                     | 0.500            | 0.578 | 0.281                             | 0.219 | 0.188       | 1.406              | 0.391                                      | $\frac{3}{8}$ -16                  |   |                         |
| Locking Mechanism Dimensions of Slip and Fixed Renewable Bushings                   |   |                  |       |                                   |       |             |                    |  |                                    |   |                         |
|  |   |                  |       |                                   |       |             |                    |  |                                    |   |                         |
| Body OD   | Max Diam. F When Used With Locking Device | G Head Thickness |       | H ± 0.005                         | J     | L Max       | R                  | Locking Dim. of Lock Screw (Slip or Fixed) | Locking Dim. of Clamp (Fixed Only) | Max Head Diam. of Mating Liner Used to Clear Locking Device | Clamp or Screw LS or RC |
|   |   | Slip             | Fixed |                                   |       |             |                    |  |                                    |   |                         |
| 0.188   | 0.312                                     | 0.188            | 0.188 | 0.094                             | 0.094 | 55°         | 0.266              | 0.105-0.100                                | ...                                | ...   | 0                       |
| 0.312   | 0.562                                     | 0.375            | 0.250 | 0.125                             | 0.172 | 65°         | 0.500              | 0.138-0.132                                | 0.125-0.115                        | 0.625   | 1                       |
| 0.500   | 0.812                                     | 0.438            | 0.250 | 0.125                             | 0.297 | 65°         | 0.625              | 0.138-0.132                                | 0.125-0.115                        | 0.875   | 1                       |
| 0.750   | 1.062                                     | 0.438            | 0.250 | 0.125                             | 0.422 | 50°         | 0.750              | 0.138-0.132                                | 0.125-0.115                        | 1.125   | 1                       |
| 1.000   | 1.438                                     | 0.438            | 0.375 | 0.188                             | 0.594 | 35°         | 0.922              | 0.200-0.194                                | 0.187-0.177                        | 1.500   | 2                       |
| 1.375   | 1.812                                     | 0.438            | 0.375 | 0.188                             | 0.781 | 30°         | 1.109              | 0.200-0.194                                | 0.187-0.177                        | 1.875   | 2                       |
| 1.750   | 2.312                                     | 0.625            | 0.375 | 0.188                             | 1.000 | 30°         | 1.391              | 0.200-0.194                                | 0.187-0.177                        | 2.375   | 3                       |
| 2.250   | 2.812                                     | 0.625            | 0.375 | 0.188                             | 1.250 | 25°         | 1.641              | 0.200-0.194                                | 0.187-0.177                        | 2.875   | 3                       |

All dimensions are in inches.

**Jig Bushing Definitions.**— *Renewable Bushings:* Renewable wearing bushings to guide the tool are for use in liners which in turn are installed in the jig. They are used where the bushing will wear out or become obsolete before the jig or where several bushings are to be interchangeable in one hole. Renewable wearing bushings are divided into two classes, "Fixed" and "Slip." Fixed renewable bushings are installed in the liner with the intention of leaving them in place until worn out. Slip renewable bushings are interchangeable in a given size of liner and, to facilitate removal, they are usually made with a knurled head. They are most frequently used where two or more operations requiring different inside diameters are performed in a single jig, such as where drilling is followed by reaming, tapping, spot facing, counterboring, or some other secondary operation.

*Press Fit Bushings:* Press fit wearing bushings to guide the tool are for installation directly in the jig without the use of a liner and are employed principally where the bushings are used for short production runs and will not require replacement. They are intended also for short center distances.

*Liner Bushings:* Liner bushings are provided with and without heads and are permanently installed in a jig to receive the renewable wearing bushings. They are sometimes called master bushings.

**Jig Plate Thickness.**— The standard length of the press fit portion of jig bushings as established are based on standardized uniform jig plate thicknesses of  $\frac{3}{16}$ ,  $\frac{3}{8}$ ,  $\frac{1}{2}$ ,  $\frac{3}{4}$ , 1,  $1\frac{1}{8}$ ,  $1\frac{3}{4}$ ,  $2\frac{1}{8}$ ,  $2\frac{1}{2}$ , and 3 inches.

**Jig Bushing Designation System.**— *Inside Diameter:* The inside diameter of the hole is specified by a decimal dimension.

*Type Bushing:* The type of bushing is specified by a letter: S for Slip Renewable, F for Fixed Renewable, L for Headless Liner, HL for Head Liner, P for Headless Press Fit, and H for Head Press Fit.

*Body Diameter:* The body diameter is specified in multiples of 0.0156 inch. For example, a 0.500-inch body diameter =  $0.500/0.0156 = 32$ .

*Body Length:* The effective or body length is specified in multiples of 0.0625 inch. For example, a 0.500-inch length =  $0.500/0.0625 = 8$ .

*Unfinished Bushings:* All bushings with grinding stock on the body diameter are designated by the letter U following the number.

*Example:* A slip renewable bushing having a hole diameter of 0.5000 inch, a body diameter of 0.750 inch, and a body length of 1.000 inch would be designated as .5000-S-48-16.

## Jig Boring

**Definition of Jig and Fixture.**— The distinction between a jig and fixture is not easy to define, but, as a general rule, it is as follows: A jig either holds or is held on the work, and, at the same time, contains guides for the various cutting tools, whereas a fixture holds the work while the cutting tools are in operation, but does not contain any special arrangements for guiding the tools. A fixture, therefore, must be securely held or fixed to the machine on which the operation is performed—hence the name. A fixture is sometimes provided with a number of gages and stops, but not with bushings or other devices for guiding and supporting the cutting tools.

**Jig Borers.**— Jig borers are used for precision hole-location work. For this reason, the coordinate measuring systems on these machines are designed to provide longitudinal and transverse movements that are accurate to 0.0001 in. One widely used method of obtaining this accuracy utilizes ultraprecision lead screws. Another measuring system employs precision end measuring rods and a micrometer head that are placed in a trough which is parallel to the table movement. However, the purpose of all coordinate measuring systems used is the same: to provide a method of aligning the spindle at the precise location where a hole is to be produced. Since the work table of a jig borer moves in two directions, the

coordinate system of dimensioning is used, where dimensions are given from two perpendicular reference axes, usually the sides of the workpiece, frequently its upper left-hand corner. See Fig. 1C.

**Jig-Boring Practice.**—The four basic steps to follow to locate and machine a hole on a jig borer are:

*Align and Clamp the Workpiece:* The first consideration in placing the workpiece on the jig-borer table should be the relation of the coordinate measuring system of the jig borer to the coordinate dimensions on the drawing. Therefore, the coordinate measuring system is designed so that the readings of the coordinate measurements are direct when the table is moved toward the left and when it is moved toward the column of the jig borer. The result would be the same if the spindle were moved toward the right and away from the column, with the workpiece situated in such a position that one reference axis is located at the left and the other axis at the back, toward the column.

If the holes to be bored are to pass through the bottom of the workpiece, then the workpiece must be placed on precision parallel bars. In order to prevent the force exerted by the clamps from bending the workpiece the parallel bars are placed directly under the clamps, which hold the workpiece on the table. The reference axes of the workpiece must also be aligned with respect to the transverse and longitudinal table movements before it is firmly clamped. This alignment can be done with a dial-test indicator held in the spindle of the jig borer and bearing against the longitudinal reference edge. As the table is traversed in the longitudinal direction, the workpiece is adjusted until the dial-test indicator readings are the same for all positions.

*Locate the Two Reference Axes of the Workpiece with Respect to the Spindle:* The jig-borer table is now moved to position the workpiece in a precise and known location from where it can be moved again to the location of the holes to be machined. Since all the holes are dimensioned from the two reference axes, the most convenient position to start from is where the axis of the jig-borer spindle and the intersection of the two workpiece reference axes are aligned. This is called the starting position, which is similar to a zero reference position. When so positioned, the longitudinal and transverse measuring systems of the jig borer are set to read zero. Occasionally, the reference axes are located outside the body of the workpiece: a convenient edge or hole on the workpiece is picked up as the starting position, and the dimensions from this point to the reference axes are set on the positioning measuring system.

*Locate the Hole:* Precise coordinate table movements are used to position the workpiece so that the spindle axis is located exactly where the hole is to be machined. When the measuring system has been set to zero at the starting position, the coordinate readings at the hole location will be the same as the coordinate dimensions of the hole center.

The movements to each hole must be made in one direction for both the transverse and longitudinal directions, to eliminate the effect of any backlash in the lead screw. The usual table movements are toward the left and toward the column.

The most convenient sequence on machines using micrometer dials as position indicators (machines with lead screws) is to machine the hole closest to the starting position first and then the next closest, and so on. On jig borers using end measuring rods, the opposite sequence is followed: The farthest hole is machined first and then the next farthest, and so on, since it is easier to remove end rods and replace them with shorter rods.

*Drill and Bore Hole to Size:* The sequence of operations used to produce a hole on a jig borer is as follows: 1) a short, stiff drill, such as a center drill, that will not deflect when cutting should be used to spot a hole when the work and the axis of the machine tool spindle are located at the exact position where the hole is wanted; 2) the initial hole is made by a twist drill; and 3) a single-point boring tool that is set to rotate about the axis of the machine tool spindle is then used to generate a cut surface that is concentric to the axis of rotation.

Heat will be generated by the drilling operation, so it is good practice to drill all the holes first, and then allow the workpiece to cool before the holes are bored to size.

**Transfer of Tolerances.**—All of the dimensions that must be accurately held on precision machines and engine parts are usually given a tolerance. And when such dimensions are changed from the conventional to the coordinate system of dimensioning, the tolerances must also be included. Because of their importance, the transfer of the tolerances must be done with great care, keeping in mind that the sum of the tolerances of any pair of dimensions in the coordinate system must not be larger than the tolerance of the dimension that they replaced in the conventional system. An example is given in Fig. 1.

The first step in the procedure is to change the tolerances given in Fig. 1A to equal, bilateral tolerances given in Fig. 1B. For example, the dimension  $2.125^{+0.003}_{-0.001}$  has a total tolerance of 0.004. The equal, bilateral tolerance would be plus or minus one-half of this value, or  $\pm 0.002$ . Then to keep the limiting dimensions the same, the basic dimension must be changed to 2.126, in order to give the required values of 2.128 and 2.124. When changing to equal, bilateral tolerances, if the upper tolerance is decreased (as in this example), the basic dimension must be increased by a like amount. The upper tolerance was decreased by  $0.003 - 0.002 = 0.001$ ; therefore, the basic dimension was increased by 0.001 to 2.126. Conversely, if the upper tolerance is increased, the basic dimension is decreased.

The next step is to transfer the revised basic dimension to the coordinate dimensioning system. To transfer the 2.126 dimension, the distance of the applicable holes from the left reference axis must be determined. The first holes to the right are 0.8750 from the reference axis. The second hole is 2.126 to the right of the first holes. Therefore, the second hole is  $0.8750 + 2.126 = 3.0010$  to the right of the reference axis. This value is then the coordinate dimension for the second hole, while the 0.8750 value is the coordinate dimension of the first two, vertically aligned holes. This procedure is followed for all the holes to find their distances from the two reference axes. These values are given in Fig. 1C.

The final step is to transfer the tolerances. The 2.126 value in Fig. 1B has been replaced by the 0.8750 and 3.0010 values in Fig. 1C. The 2.126 value has an available tolerance of  $\pm 0.002$ . Dividing this amount equally between the two replacement values gives  $0.8750 \pm 0.001$  and  $3.0010 \pm 0.001$ . The sum of these tolerances is .002, and as required, does not exceed the tolerance that was replaced. Next transfer the tolerance of the 0.502 dimension. Divide the available tolerance,  $\pm 0.002$ , equally between the two replacement values to yield  $3.0010 \pm 0.001$  and  $3.5030 \pm 0.001$ . The sum of these two tolerances equals the replaced tolerance, as required. However, the 1.125 value of the last hole to the right (coordinate dimension 4.6280 in.) has a tolerance of only  $\pm 0.001$ . Therefore, the sum of the tolerances on the 3.5030 and 4.6280 values cannot be larger than 0.001. Dividing this tolerance equally would give  $3.5030 \pm .0005$  and  $4.6280 \pm 0.0005$ . This new, smaller tolerance replaces the  $\pm 0.001$  tolerance on the 3.5030 value in order to satisfy all tolerance sum requirements. This example shows how the tolerance of a coordinate value is affected by more than one other dimensional requirement.

The following discussion will summarize the various tolerances listed in Fig. 1C. For the  $0.8750 \pm 0.0010$  dimension, the  $\pm 0.0010$  tolerance together with the  $\pm 0.0010$  tolerance on the 3.0010 dimension is required to maintain the  $\pm 0.002$  tolerance of the 2.126 dimension. The  $\pm .0005$  tolerances on the 3.5030 and 4.2680 dimensions are required to maintain the  $\pm 0.001$  tolerance of the 1.125 dimension, at the same time as the sum of the  $\pm .0005$  tolerance on the 3.5030 dimension and the  $\pm 0.001$  tolerance on the 3.0010 dimension does not exceed the  $\pm 0.002$  tolerance on the replaced 0.503 dimension. The  $\pm 0.0005$  tolerances on the 1.0000 and 2.0000 values maintain the  $\pm 0.001$  tolerance on the 1.0000 value given at the right in Fig. 1A. The  $\pm 0.0045$  tolerance on the 3.0000 dimension together with the  $\pm 0.0005$  tolerance on the 1.0000 value maintains the  $\pm .005$  tolerance on the 2.0000 dimension of Fig. 1A. It should be noted that the  $2.000 \pm .005$  dimension in Fig. 1A was replaced by the 1.0000 and 3.0000 dimensions in Fig. 1C. Each of these values could have had a tol-



JIG BORING

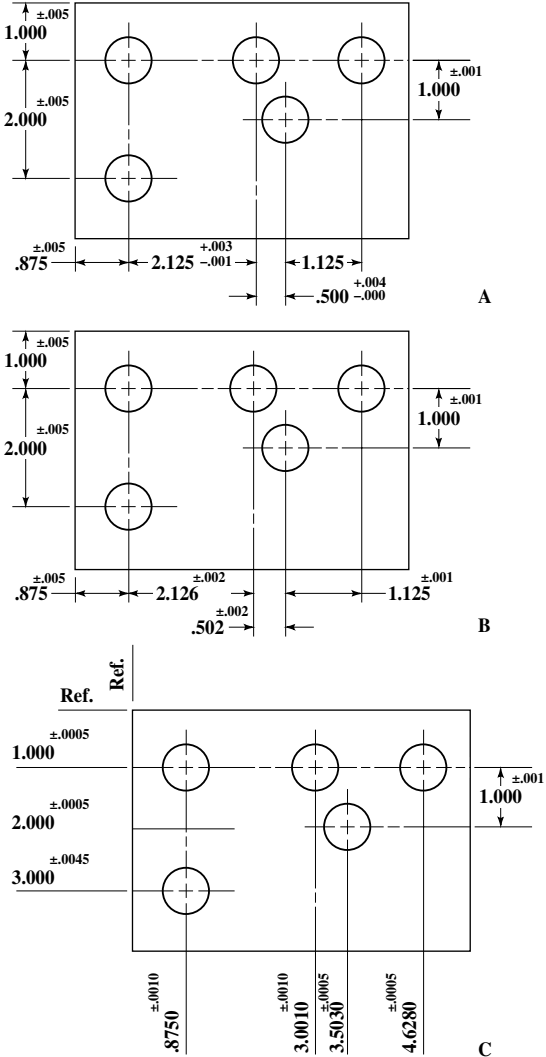


Fig. 1. (A) Conventional Dimensions, Mixed Tolerances; (B) Conventional Dimensions, All Equal, Bilateral Tolerances; and (C) Coordinate Dimensions

erance of  $\pm 0.0025$ , except that the tolerance on the 1.0000 dimension on the left in Fig. 1A is also bound by the  $\pm 0.001$  tolerance on the 1.0000 dimension on the right, thus the  $\pm 0.0005$  tolerance value is used. This procedure requires the tolerance on the 3.0000 value to be increased to  $\pm 0.0045$ .

### Determining Hole Coordinates

On the following pages are given tables of the lengths of chords for spacing off the circumferences of circles. The object of these tables is to make possible the division of the periphery into a number of equal parts without trials with the dividers. The first table, Table 10, is calculated for circles having a diameter equal to 1. For circles of other diameters, the length of chord given in the table should be multiplied by the diameter of the circle. Table 10 may be used by toolmakers when setting "buttons" in circular formation. Assume that it is required to divide the periphery of a circle of 20 inches diameter into thirty-two equal parts. From the table the length of the chord is found to be 0.098017 inch, if the diameter of the circle were 1 inch. With a diameter of 20 inches the length of the chord for one division would be  $20 \times 0.098017 = 1.9603$  inches. Another example in metric units: For a 100 millimeter diameter requiring 5 equal divisions, the length of the chord for one division would be  $100 \times 0.587785 = 58.7785$  millimeters.

Tables 11a and 11b starting on page 991 are additional tables for the spacing off of circles; the tables, in this case, being worked out for diameters from  $\frac{1}{16}$  inch to 14 inches. As an example, assume that it is required to divide a circle having a diameter of  $6\frac{1}{2}$  inches into seven equal parts. Find first, in the column headed "6" and in line with 7 divisions, the length of the chord for a 6-inch circle, which is 2.603 inches. Then find the length of the chord for a  $\frac{1}{2}$ -inch diameter circle, 7 divisions, which is 0.217. The sum of these two values,  $2.603 + 0.217 = 2.820$  inches, is the length of the chord required for spacing off the circumference of a  $6\frac{1}{2}$ -inch circle into seven equal divisions.

As another example, assume that it is required to divide a circle having a diameter of  $9\frac{23}{32}$  inches into 15 equal divisions. First find the length of the chord for a 9-inch circle, which is 1.871 inch. The length of the chord for a  $\frac{23}{32}$ -inch circle can easily be estimated from the table by taking the value that is exactly between those given for  $\frac{11}{16}$  and  $\frac{3}{4}$  inch. The value for  $\frac{11}{16}$  inch is 0.143, and for  $\frac{3}{4}$  inch, 0.156. For  $\frac{23}{32}$  the value would be 0.150. Then,  $1.871 + 0.150 = 2.021$  inches.

**Hole Coordinate Dimension Factors for Jig Boring.**—Tables of hole coordinate dimension factors for use in jig boring are given in Tables 12 through 15 starting on page 993. The coordinate axes shown in the figure accompanying each table are used to reference the tool path; the values listed in each table are for the end points of the tool path. In this machine coordinate system, a positive *Y* value indicates that the effective motion of the tool with reference to the work is toward the front of the jig borer (the actual motion of the jig borer table is toward the column). Similarly, a positive *X* value indicates that the effective motion of the tool with respect to the work is toward the right (the actual motion of the jig borer table is toward the left). When entering data into most computer-controlled jig borers, current practice is to use the more familiar Cartesian coordinate axis system in which the positive *Y* direction is "up" (i.e., pointing toward the column of the jig borer). The computer will automatically change the signs of the entered *Y* values to the signs that they would have in the machine coordinate system. Therefore, before applying the coordinate dimension factors given in the tables, it is important to determine the coordinate system to be used. If a Cartesian coordinate system is to be used for the tool path, then the sign of the *Y* values in the tables must be changed, from positive to negative and from negative to positive. For example, when programming for a three-hole type A circle using Cartesian coordinates, the *Y* values from Table 14 would be  $y_1 = +0.50000$ ,  $y_2 = -0.25000$ , and  $y_3 = -0.25000$ .

**Table 10. Lengths of Chords for Spacing Off the Circumferences of Circles with a Diameter Equal to 1 (English or metric units)**

| No. of Spaces | Length of Chord | No. of Spaces | Length of Chord | No. of Spaces | Length of Chord | No. of Spaces | Length of Chord |
|---------------|-----------------|---------------|-----------------|---------------|-----------------|---------------|-----------------|
| 3             | 0.866025        | 41            | 0.076549        | 79            | 0.039757        | 117           | 0.026848        |
| 4             | 0.707107        | 42            | 0.074730        | 80            | 0.039260        | 118           | 0.026621        |
| 5             | 0.587785        | 43            | 0.072995        | 81            | 0.038775        | 119           | 0.026397        |
| 6             | 0.500000        | 44            | 0.071339        | 82            | 0.038303        | 120           | 0.026177        |
| 7             | 0.433884        | 45            | 0.069756        | 83            | 0.037841        | 121           | 0.025961        |
| 8             | 0.382683        | 46            | 0.068242        | 84            | 0.037391        | 122           | 0.025748        |
| 9             | 0.342020        | 47            | 0.066793        | 85            | 0.036951        | 123           | 0.025539        |
| 10            | 0.309017        | 48            | 0.065403        | 86            | 0.036522        | 124           | 0.025333        |
| 11            | 0.281733        | 49            | 0.064070        | 87            | 0.036102        | 125           | 0.025130        |
| 12            | 0.258819        | 50            | 0.062791        | 88            | 0.035692        | 126           | 0.024931        |
| 13            | 0.239316        | 51            | 0.061561        | 89            | 0.035291        | 127           | 0.024734        |
| 14            | 0.222521        | 52            | 0.060378        | 90            | 0.034899        | 128           | 0.024541        |
| 15            | 0.207912        | 53            | 0.059241        | 91            | 0.034516        | 129           | 0.024351        |
| 16            | 0.195090        | 54            | 0.058145        | 92            | 0.034141        | 130           | 0.024164        |
| 17            | 0.183750        | 55            | 0.057089        | 93            | 0.033774        | 131           | 0.023979        |
| 18            | 0.173648        | 56            | 0.056070        | 94            | 0.033415        | 132           | 0.023798        |
| 19            | 0.164595        | 57            | 0.055088        | 95            | 0.033063        | 133           | 0.023619        |
| 20            | 0.156434        | 58            | 0.054139        | 96            | 0.032719        | 134           | 0.023443        |
| 21            | 0.149042        | 59            | 0.053222        | 97            | 0.032382        | 135           | 0.023269        |
| 22            | 0.142315        | 60            | 0.052336        | 98            | 0.032052        | 136           | 0.023098        |
| 23            | 0.136167        | 61            | 0.051479        | 99            | 0.031728        | 137           | 0.022929        |
| 24            | 0.130526        | 62            | 0.050649        | 100           | 0.031411        | 138           | 0.022763        |
| 25            | 0.125333        | 63            | 0.049846        | 101           | 0.031100        | 139           | 0.022599        |
| 26            | 0.120537        | 64            | 0.049068        | 102           | 0.030795        | 140           | 0.022438        |
| 27            | 0.116093        | 65            | 0.048313        | 103           | 0.030496        | 141           | 0.022279        |
| 28            | 0.111964        | 66            | 0.047582        | 104           | 0.030203        | 142           | 0.022122        |
| 29            | 0.108119        | 67            | 0.046872        | 105           | 0.029915        | 143           | 0.021967        |
| 30            | 0.104528        | 68            | 0.046183        | 106           | 0.029633        | 144           | 0.021815        |
| 31            | 0.101168        | 69            | 0.045515        | 107           | 0.029356        | 145           | 0.021664        |
| 32            | 0.098017        | 70            | 0.044865        | 108           | 0.029085        | 146           | 0.021516        |
| 33            | 0.095056        | 71            | 0.044233        | 109           | 0.028818        | 147           | 0.021370        |
| 34            | 0.092268        | 72            | 0.043619        | 110           | 0.028556        | 148           | 0.021225        |
| 35            | 0.089639        | 73            | 0.043022        | 111           | 0.028299        | 149           | 0.021083        |
| 36            | 0.087156        | 74            | 0.042441        | 112           | 0.028046        | 150           | 0.020942        |
| 37            | 0.084806        | 75            | 0.041876        | 113           | 0.027798        | 151           | 0.020804        |
| 38            | 0.082579        | 76            | 0.041325        | 114           | 0.027554        | 152           | 0.020667        |
| 39            | 0.080467        | 77            | 0.040789        | 115           | 0.027315        | 153           | 0.020532        |
| 40            | 0.078459        | 78            | 0.040266        | 116           | 0.027079        | 154           | 0.020399        |

For circles of other diameters, multiply length given in table by diameter of circle.

*Example:* In a drill jig, 8 holes, each  $\frac{1}{2}$  inch diameter, were spaced evenly on a 6-inch diameter circle. To test the accuracy of the jig, plugs were placed in adjacent holes, and the distance over the plugs was measured with a micrometer. What should be the micrometer reading?

*Solution:* The micrometer reading equals the diameter of one plug plus 6 times the chordal distance between adjacent hole centers given in the table above. Thus, the reading should be  $\frac{1}{2} + (6 \times 0.382683) = 2.796098$  inches.

Table 11a. Table for Spacing Off the Circumferences of Circles

| No. of Divisions | Degrees in Arc     | Diameter of Circle to be Spaced Off |               |                |               |                |               |                |               |                |               |                 |               |                 |               |                 |
|------------------|--------------------|-------------------------------------|---------------|----------------|---------------|----------------|---------------|----------------|---------------|----------------|---------------|-----------------|---------------|-----------------|---------------|-----------------|
|                  |                    | $\frac{1}{16}$                      | $\frac{1}{8}$ | $\frac{3}{16}$ | $\frac{1}{4}$ | $\frac{5}{16}$ | $\frac{3}{8}$ | $\frac{7}{16}$ | $\frac{1}{2}$ | $\frac{9}{16}$ | $\frac{5}{8}$ | $\frac{11}{16}$ | $\frac{3}{4}$ | $\frac{13}{16}$ | $\frac{7}{8}$ | $\frac{15}{16}$ |
|                  |                    | Length of Chord                     |               |                |               |                |               |                |               |                |               |                 |               |                 |               |                 |
| 3                | 120                | 0.054                               | 0.108         | 0.162          | 0.217         | 0.271          | 0.325         | 0.379          | 0.433         | 0.487          | 0.541         | 0.595           | 0.650         | 0.704           | 0.758         | 0.812           |
| 4                | 90                 | 0.044                               | 0.088         | 0.133          | 0.177         | 0.221          | 0.265         | 0.309          | 0.354         | 0.398          | 0.442         | 0.486           | 0.530         | 0.575           | 0.619         | 0.663           |
| 5                | 72                 | 0.037                               | 0.073         | 0.110          | 0.147         | 0.184          | 0.220         | 0.257          | 0.294         | 0.331          | 0.367         | 0.404           | 0.441         | 0.478           | 0.514         | 0.551           |
| 6                | 60                 | 0.031                               | 0.063         | 0.094          | 0.125         | 0.156          | 0.188         | 0.219          | 0.250         | 0.281          | 0.313         | 0.344           | 0.375         | 0.406           | 0.438         | 0.469           |
| 7                | 51 $\frac{3}{4}$   | 0.027                               | 0.054         | 0.081          | 0.108         | 0.136          | 0.163         | 0.190          | 0.217         | 0.244          | 0.271         | 0.298           | 0.325         | 0.353           | 0.380         | 0.407           |
| 8                | 45                 | 0.024                               | 0.048         | 0.072          | 0.096         | 0.120          | 0.144         | 0.167          | 0.191         | 0.215          | 0.239         | 0.263           | 0.287         | 0.311           | 0.335         | 0.359           |
| 9                | 40                 | 0.021                               | 0.043         | 0.064          | 0.086         | 0.107          | 0.128         | 0.150          | 0.171         | 0.192          | 0.214         | 0.235           | 0.257         | 0.278           | 0.299         | 0.321           |
| 10               | 36                 | 0.019                               | 0.039         | 0.058          | 0.077         | 0.097          | 0.116         | 0.135          | 0.155         | 0.174          | 0.193         | 0.212           | 0.232         | 0.251           | 0.270         | 0.290           |
| 11               | 32 $\frac{8}{11}$  | 0.018                               | 0.035         | 0.053          | 0.070         | 0.088          | 0.106         | 0.123          | 0.141         | 0.158          | 0.176         | 0.194           | 0.211         | 0.229           | 0.247         | 0.264           |
| 12               | 30                 | 0.016                               | 0.032         | 0.049          | 0.065         | 0.081          | 0.097         | 0.113          | 0.129         | 0.146          | 0.162         | 0.178           | 0.194         | 0.210           | 0.226         | 0.243           |
| 13               | 27 $\frac{9}{13}$  | 0.015                               | 0.030         | 0.045          | 0.060         | 0.075          | 0.090         | 0.105          | 0.120         | 0.135          | 0.150         | 0.165           | 0.179         | 0.194           | 0.209         | 0.224           |
| 14               | 25 $\frac{5}{7}$   | 0.014                               | 0.028         | 0.042          | 0.056         | 0.069          | 0.083         | 0.097          | 0.111         | 0.125          | 0.139         | 0.153           | 0.167         | 0.181           | 0.195         | 0.209           |
| 15               | 24                 | 0.013                               | 0.026         | 0.039          | 0.052         | 0.065          | 0.078         | 0.091          | 0.104         | 0.117          | 0.130         | 0.143           | 0.156         | 0.169           | 0.182         | 0.195           |
| 16               | 22 $\frac{1}{2}$   | 0.012                               | 0.024         | 0.037          | 0.049         | 0.061          | 0.073         | 0.085          | 0.098         | 0.110          | 0.122         | 0.134           | 0.146         | 0.159           | 0.171         | 0.183           |
| 17               | 21 $\frac{3}{17}$  | 0.011                               | 0.023         | 0.034          | 0.046         | 0.057          | 0.069         | 0.080          | 0.092         | 0.103          | 0.115         | 0.126           | 0.138         | 0.149           | 0.161         | 0.172           |
| 18               | 20                 | 0.011                               | 0.022         | 0.033          | 0.043         | 0.054          | 0.065         | 0.076          | 0.087         | 0.098          | 0.109         | 0.119           | 0.130         | 0.141           | 0.152         | 0.163           |
| 19               | 18 $\frac{9}{19}$  | 0.010                               | 0.021         | 0.031          | 0.041         | 0.051          | 0.062         | 0.072          | 0.082         | 0.093          | 0.103         | 0.113           | 0.123         | 0.134           | 0.144         | 0.154           |
| 20               | 18                 | 0.010                               | 0.020         | 0.029          | 0.039         | 0.049          | 0.059         | 0.068          | 0.078         | 0.088          | 0.098         | 0.108           | 0.117         | 0.127           | 0.137         | 0.147           |
| 21               | 17 $\frac{1}{2}$   | 0.009                               | 0.019         | 0.028          | 0.037         | 0.047          | 0.056         | 0.065          | 0.075         | 0.084          | 0.093         | 0.102           | 0.112         | 0.121           | 0.130         | 0.140           |
| 22               | 16 $\frac{4}{11}$  | 0.009                               | 0.018         | 0.027          | 0.036         | 0.044          | 0.053         | 0.062          | 0.071         | 0.080          | 0.089         | 0.098           | 0.107         | 0.116           | 0.125         | 0.133           |
| 23               | 15 $\frac{15}{23}$ | 0.009                               | 0.017         | 0.026          | 0.034         | 0.043          | 0.051         | 0.060          | 0.068         | 0.077          | 0.085         | 0.094           | 0.102         | 0.111           | 0.119         | 0.128           |
| 24               | 15                 | 0.008                               | 0.016         | 0.024          | 0.033         | 0.041          | 0.049         | 0.057          | 0.065         | 0.073          | 0.082         | 0.090           | 0.098         | 0.106           | 0.114         | 0.122           |
| 25               | 14 $\frac{2}{5}$   | 0.008                               | 0.016         | 0.023          | 0.031         | 0.039          | 0.047         | 0.055          | 0.063         | 0.070          | 0.078         | 0.086           | 0.094         | 0.102           | 0.110         | 0.117           |
| 26               | 13 $\frac{13}{13}$ | 0.008                               | 0.015         | 0.023          | 0.030         | 0.038          | 0.045         | 0.053          | 0.060         | 0.068          | 0.075         | 0.083           | 0.090         | 0.098           | 0.105         | 0.113           |
| 28               | 12 $\frac{7}{7}$   | 0.007                               | 0.014         | 0.021          | 0.028         | 0.035          | 0.042         | 0.049          | 0.056         | 0.063          | 0.070         | 0.077           | 0.084         | 0.091           | 0.098         | 0.105           |
| 30               | 12                 | 0.007                               | 0.013         | 0.020          | 0.026         | 0.033          | 0.039         | 0.046          | 0.052         | 0.059          | 0.065         | 0.072           | 0.078         | 0.085           | 0.091         | 0.098           |
| 32               | 11 $\frac{1}{4}$   | 0.006                               | 0.012         | 0.018          | 0.025         | 0.031          | 0.037         | 0.043          | 0.049         | 0.055          | 0.061         | 0.067           | 0.074         | 0.080           | 0.086         | 0.092           |

Table 11b. Table for Spacing Off the Circumferences of Circles

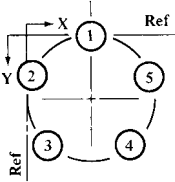
| No. of Divisions | Degrees in Arc | Diameter of Circle to be Spaced Off |       |       |       |       |       |       |       |       |       |       |        |        |        |
|------------------|----------------|-------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|--------|--------|
|                  |                | 1                                   | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 11    | 12     | 13     | 14     |
|                  |                | Length of Chord                     |       |       |       |       |       |       |       |       |       |       |        |        |        |
| 3                | 120            | 0.866                               | 1.732 | 2.598 | 3.464 | 4.330 | 5.196 | 6.062 | 6.928 | 7.794 | 8.660 | 9.526 | 10.392 | 11.258 | 12.124 |
| 4                | 90             | 0.707                               | 1.414 | 2.121 | 2.828 | 3.536 | 4.243 | 4.950 | 5.657 | 6.364 | 7.071 | 7.778 | 8.485  | 9.192  | 9.899  |
| 5                | 72             | 0.588                               | 1.176 | 1.763 | 2.351 | 2.939 | 3.527 | 4.114 | 4.702 | 5.290 | 5.878 | 6.466 | 7.053  | 7.641  | 8.229  |
| 6                | 60             | 0.500                               | 1.000 | 1.500 | 2.000 | 2.500 | 3.000 | 3.500 | 4.000 | 4.500 | 5.000 | 5.500 | 6.000  | 6.500  | 7.000  |
| 7                | 51½            | 0.434                               | 0.868 | 1.302 | 1.736 | 2.169 | 2.603 | 3.037 | 3.471 | 3.905 | 4.339 | 4.773 | 5.207  | 5.640  | 6.074  |
| 8                | 45             | 0.383                               | 0.765 | 1.148 | 1.531 | 1.913 | 2.296 | 2.679 | 3.061 | 3.444 | 3.827 | 4.210 | 4.592  | 4.975  | 5.358  |
| 9                | 40             | 0.342                               | 0.684 | 1.026 | 1.368 | 1.710 | 2.052 | 2.394 | 2.736 | 3.078 | 3.420 | 3.762 | 4.104  | 4.446  | 4.788  |
| 10               | 36             | 0.309                               | 0.618 | 0.927 | 1.236 | 1.545 | 1.854 | 2.163 | 2.472 | 2.781 | 3.090 | 3.399 | 3.708  | 4.017  | 4.326  |
| 11               | 32½            | 0.282                               | 0.563 | 0.845 | 1.127 | 1.409 | 1.690 | 1.972 | 2.254 | 2.536 | 2.817 | 3.099 | 3.381  | 3.663  | 3.944  |
| 12               | 30             | 0.259                               | 0.518 | 0.776 | 1.035 | 1.294 | 1.553 | 1.812 | 2.071 | 2.329 | 2.588 | 2.847 | 3.106  | 3.365  | 3.623  |
| 13               | 27½            | 0.239                               | 0.479 | 0.718 | 0.957 | 1.197 | 1.436 | 1.675 | 1.915 | 2.154 | 2.393 | 2.632 | 2.872  | 3.111  | 3.350  |
| 14               | 25½            | 0.223                               | 0.445 | 0.668 | 0.890 | 1.113 | 1.335 | 1.558 | 1.780 | 2.003 | 2.225 | 2.448 | 2.670  | 2.893  | 3.115  |
| 15               | 24             | 0.208                               | 0.416 | 0.624 | 0.832 | 1.040 | 1.247 | 1.455 | 1.663 | 1.871 | 2.079 | 2.287 | 2.495  | 2.703  | 2.911  |
| 16               | 22½            | 0.195                               | 0.390 | 0.585 | 0.780 | 0.975 | 1.171 | 1.366 | 1.561 | 1.756 | 1.951 | 2.146 | 2.341  | 2.536  | 2.731  |
| 17               | 21¾            | 0.184                               | 0.367 | 0.551 | 0.735 | 0.919 | 1.102 | 1.286 | 1.470 | 1.654 | 1.837 | 2.021 | 2.205  | 2.389  | 2.572  |
| 18               | 20             | 0.174                               | 0.347 | 0.521 | 0.695 | 0.868 | 1.042 | 1.216 | 1.389 | 1.563 | 1.736 | 1.910 | 2.084  | 2.257  | 2.431  |
| 19               | 18½            | 0.165                               | 0.329 | 0.494 | 0.658 | 0.823 | 0.988 | 1.152 | 1.317 | 1.481 | 1.646 | 1.811 | 1.975  | 2.140  | 2.304  |
| 20               | 18             | 0.156                               | 0.313 | 0.469 | 0.626 | 0.782 | 0.939 | 1.095 | 1.251 | 1.408 | 1.564 | 1.721 | 1.877  | 2.034  | 2.190  |
| 21               | 17½            | 0.149                               | 0.298 | 0.447 | 0.596 | 0.745 | 0.894 | 1.043 | 1.192 | 1.341 | 1.490 | 1.639 | 1.789  | 1.938  | 2.087  |
| 22               | 16½            | 0.142                               | 0.285 | 0.427 | 0.569 | 0.712 | 0.854 | 0.996 | 1.139 | 1.281 | 1.423 | 1.565 | 1.708  | 1.850  | 1.992  |
| 23               | 15½            | 0.136                               | 0.272 | 0.408 | 0.545 | 0.681 | 0.817 | 0.953 | 1.089 | 1.225 | 1.362 | 1.498 | 1.634  | 1.770  | 1.906  |
| 24               | 15             | 0.131                               | 0.261 | 0.392 | 0.522 | 0.653 | 0.783 | 0.914 | 1.044 | 1.175 | 1.305 | 1.436 | 1.566  | 1.697  | 1.827  |
| 25               | 14¾            | 0.125                               | 0.251 | 0.376 | 0.501 | 0.627 | 0.752 | 0.877 | 1.003 | 1.128 | 1.253 | 1.379 | 1.504  | 1.629  | 1.755  |
| 26               | 13¾            | 0.121                               | 0.241 | 0.362 | 0.482 | 0.603 | 0.723 | 0.844 | 0.964 | 1.085 | 1.205 | 1.326 | 1.446  | 1.567  | 1.688  |
| 28               | 12½            | 0.112                               | 0.224 | 0.336 | 0.448 | 0.560 | 0.672 | 0.784 | 0.896 | 1.008 | 1.120 | 1.232 | 1.344  | 1.456  | 1.568  |
| 30               | 12             | 0.105                               | 0.209 | 0.314 | 0.418 | 0.523 | 0.627 | 0.732 | 0.836 | 0.941 | 1.045 | 1.150 | 1.254  | 1.359  | 1.463  |
| 32               | 11¼            | 0.098                               | 0.196 | 0.294 | 0.392 | 0.490 | 0.588 | 0.686 | 0.784 | 0.882 | 0.980 | 1.078 | 1.176  | 1.274  | 1.372  |

See *Determining Hole Coordinates* on page 989 for explanatory matter.

**Table 12. Hole Coordinate Dimension Factors for Jig Boring — Type "A" Hole Circles (English or Metric Units)**

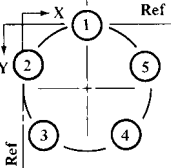
| 3 Holes  |         | 4 Holes  |         | 5 Holes  |         | 6 Holes  |         | 7 Holes  |         | 8 Holes  |         | 9 Holes  |         |
|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|
| x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 |
| y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 |
| x2       | 0.06699 | x2       | 0.00000 | x2       | 0.02447 | x2       | 0.06699 | x2       | 0.10908 | x2       | 0.14645 | x2       | 0.17861 |
| y2       | 0.75000 | y2       | 0.50000 | y2       | 0.34549 | y2       | 0.25000 | y2       | 0.18826 | y2       | 0.14645 | y2       | 0.11698 |
| x3       | 0.93301 | x3       | 0.50000 | x3       | 0.20611 | x3       | 0.06699 | x3       | 0.01254 | x3       | 0.00000 | x3       | 0.00760 |
| y3       | 0.75000 | y3       | 1.00000 | y3       | 0.90451 | y3       | 0.75000 | y3       | 0.61126 | y3       | 0.50000 | y3       | 0.41318 |
|          |         | x4       | 1.00000 | x4       | 0.79389 | x4       | 0.50000 | x4       | 0.28306 | x4       | 0.14645 | x4       | 0.06699 |
|          |         | y4       | 0.50000 | y4       | 0.90451 | y4       | 1.00000 | y4       | 0.95048 | y4       | 0.85355 | y4       | 0.75000 |
|          |         |          |         | x5       | 0.97553 | x5       | 0.93301 | x5       | 0.71694 | x5       | 0.50000 | x5       | 0.32899 |
|          |         |          |         | y5       | 0.34549 | y5       | 0.75000 | y5       | 0.95048 | y5       | 1.00000 | y5       | 0.96985 |
|          |         |          |         |          |         | x6       | 0.93301 | x6       | 0.98746 | x6       | 0.85355 | x6       | 0.67101 |
|          |         |          |         |          |         | y6       | 0.25000 | y6       | 0.61126 | y6       | 0.85355 | y6       | 0.96985 |
|          |         |          |         |          |         |          |         | x7       | 0.89092 | x7       | 1.00000 | x7       | 0.93301 |
|          |         |          |         |          |         |          |         | y7       | 0.18826 | y7       | 0.50000 | y7       | 0.75000 |
|          |         |          |         |          |         |          |         |          |         | x8       | 0.85355 | x8       | 0.99240 |
|          |         |          |         |          |         |          |         |          |         | y8       | 0.14645 | y8       | 0.41318 |
|          |         |          |         |          |         |          |         |          |         |          |         | y9       | 0.82139 |
|          |         |          |         |          |         |          |         |          |         |          |         | x9       | 0.11698 |
| 10 Holes |         | 11 Holes |         | 12 Holes |         | 13 Holes |         | 14 Holes |         | 15 Holes |         | 16 Holes |         |
| x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 |
| y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 |
| x2       | 0.20611 | x2       | 0.22968 | x2       | 0.25000 | x2       | 0.26764 | x2       | 0.28306 | x2       | 0.29663 | x2       | 0.30866 |
| y2       | 0.09549 | y2       | 0.07937 | y2       | 0.06699 | y2       | 0.05727 | y2       | 0.04952 | y2       | 0.04323 | y2       | 0.03806 |
| x3       | 0.02447 | x3       | 0.04518 | x3       | 0.06699 | x3       | 0.08851 | x3       | 0.10908 | x3       | 0.12843 | x3       | 0.14645 |
| y3       | 0.34549 | y3       | 0.29229 | y3       | 0.25000 | y3       | 0.21597 | y3       | 0.18826 | y3       | 0.16543 | y3       | 0.14645 |
| x4       | 0.02447 | x4       | 0.00509 | x4       | 0.00000 | x4       | 0.00365 | x4       | 0.01254 | x4       | 0.02447 | x4       | 0.03806 |
| y4       | 0.65451 | y4       | 0.57116 | y4       | 0.50000 | y4       | 0.43973 | y4       | 0.38874 | y4       | 0.34549 | y4       | 0.30866 |
| x5       | 0.20611 | x5       | 0.12213 | x5       | 0.06699 | x5       | 0.03249 | x5       | 0.01254 | x5       | 0.00274 | x5       | 0.00000 |
| y5       | 0.90451 | y5       | 0.82743 | y5       | 0.75000 | y5       | 0.67730 | y5       | 0.61126 | y5       | 0.55226 | y5       | 0.50000 |
| x6       | 0.50000 | x6       | 0.35913 | x6       | 0.25000 | x6       | 0.16844 | x6       | 0.10908 | x6       | 0.06699 | x6       | 0.03806 |
| y6       | 1.00000 | y6       | 0.97975 | y6       | 0.93301 | y6       | 0.87426 | y6       | 0.81174 | y6       | 0.75000 | y6       | 0.69134 |
| x7       | 0.79389 | x7       | 0.64087 | x7       | 0.50000 | x7       | 0.38034 | x7       | 0.28306 | x7       | 0.20611 | x7       | 0.14645 |
| y7       | 0.90451 | y7       | 0.97975 | y7       | 1.00000 | y7       | 0.98547 | y7       | 0.95048 | y7       | 0.90451 | y7       | 0.85355 |
| x8       | 0.97553 | x8       | 0.87787 | x8       | 0.75000 | x8       | 0.61966 | x8       | 0.50000 | x8       | 0.39604 | x8       | 0.30866 |
| y8       | 0.65451 | y8       | 0.82743 | y8       | 0.93301 | y8       | 0.98547 | y8       | 1.00000 | y8       | 0.98907 | y8       | 0.96194 |
| x9       | 0.97553 | x9       | 0.99491 | x9       | 0.93301 | x9       | 0.83156 | x9       | 0.71694 | x9       | 0.60396 | x9       | 0.50000 |
| y9       | 0.34549 | y9       | 0.57116 | y9       | 0.75000 | y9       | 0.87426 | y9       | 0.95048 | y9       | 0.98907 | y9       | 1.00000 |
| x10      | 0.79389 | x10      | 0.95482 | x10      | 1.00000 | x10      | 0.96751 | x10      | 0.89092 | x10      | 0.79389 | x10      | 0.69134 |
| y10      | 0.09549 | y10      | 0.29229 | y10      | 0.50000 | y10      | 0.67730 | y10      | 0.81174 | y10      | 0.90451 | y10      | 0.96194 |
|          |         | x11      | 0.77032 | x11      | 0.93801 | x11      | 0.99635 | x11      | 0.98746 | x11      | 0.93301 | x11      | 0.85355 |
|          |         | y11      | 0.07937 | y11      | 0.25000 | y11      | 0.43973 | y11      | 0.61126 | y11      | 0.75000 | y11      | 0.85355 |
|          |         |          |         | x12      | 0.75000 | x12      | 0.91149 | x12      | 0.98746 | x12      | 0.99726 | x12      | 0.96194 |
|          |         |          |         | y12      | 0.06699 | y12      | 0.21597 | y12      | 0.38874 | y12      | 0.55226 | y12      | 0.69134 |
|          |         |          |         |          |         | x13      | 0.73236 | x13      | 0.89092 | x13      | 0.97553 | x13      | 1.00000 |
|          |         |          |         |          |         | y13      | 0.05727 | y13      | 0.18826 | y13      | 0.34549 | y13      | 0.50000 |
|          |         |          |         |          |         |          |         | x14      | 0.71694 | x14      | 0.87157 | x14      | 0.96194 |
|          |         |          |         |          |         |          |         | y14      | 0.04952 | y14      | 0.16543 | y14      | 0.30866 |
|          |         |          |         |          |         |          |         |          |         | x15      | 0.70337 | x15      | 0.85355 |
|          |         |          |         |          |         |          |         |          |         | y15      | 0.04323 | y15      | 0.14645 |
|          |         |          |         |          |         |          |         |          |         |          |         | x16      | 0.69134 |
|          |         |          |         |          |         |          |         |          |         |          |         | y16      | 0.03806 |

The diagram shows a type "A" circle for a 5-hole circle. Coordinates  $x$ ,  $y$  are given in the table for hole circles of from 3 to 28 holes. Dimensions are for holes numbered in a counterclockwise direction (as shown). Dimensions given are based upon a hole circle of unit diameter. For a hole circle of, say, 3-inch or 3-centimeter diameter, multiply table values by 3.



**Table 12. (Continued) Hole Coordinate Dimension Factors for Jig Boring — Type "A" Hole Circles (English or Metric Units)**

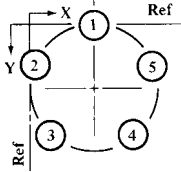
| 17 Holes |         | 18 Holes |         | 19 Holes |         | 20 Holes |         | 21 Holes |         | 22 Holes |         | 23 Holes |         |
|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|
| x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 |
| y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 |
| x2       | 0.31938 | x2       | 0.32899 | x2       | 0.33765 | x2       | 0.34549 | x2       | 0.35262 | x2       | 0.35913 | x2       | 0.36510 |
| y2       | 0.03376 | y2       | 0.03015 | y2       | 0.02709 | y2       | 0.02447 | y2       | 0.02221 | y2       | 0.02025 | y2       | 0.01854 |
| x3       | 0.16315 | x3       | 0.17861 | x3       | 0.19289 | x3       | 0.20611 | x3       | 0.21834 | x3       | 0.22968 | x3       | 0.24021 |
| y3       | 0.13050 | y3       | 0.11698 | y3       | 0.10543 | y3       | 0.09549 | y3       | 0.08688 | y3       | 0.07937 | y3       | 0.07279 |
| x4       | 0.05242 | x4       | 0.06699 | x4       | 0.08142 | x4       | 0.09549 | x4       | 0.10908 | x4       | 0.12213 | x4       | 0.13458 |
| y4       | 0.27713 | y4       | 0.25000 | y4       | 0.22653 | y4       | 0.20611 | y4       | 0.18826 | y4       | 0.17257 | y4       | 0.15872 |
| x5       | 0.00213 | x5       | 0.00760 | x5       | 0.01530 | x5       | 0.02447 | x5       | 0.03456 | x5       | 0.04518 | x5       | 0.05606 |
| y5       | 0.45387 | y5       | 0.41318 | y5       | 0.37726 | y5       | 0.34549 | y5       | 0.31733 | y5       | 0.29229 | y5       | 0.26997 |
| x6       | 0.01909 | x6       | 0.00760 | x6       | 0.00171 | x6       | 0.00000 | x6       | 0.00140 | x6       | 0.00509 | x6       | 0.01046 |
| y6       | 0.63683 | y6       | 0.58682 | y6       | 0.54129 | y6       | 0.50000 | y6       | 0.46263 | y6       | 0.42884 | y6       | 0.39827 |
| x7       | 0.10099 | x7       | 0.06699 | x7       | 0.04211 | x7       | 0.02447 | x7       | 0.01254 | x7       | 0.00509 | x7       | 0.00117 |
| y7       | 0.80132 | y7       | 0.75000 | y7       | 0.70085 | y7       | 0.65451 | y7       | 0.61126 | y7       | 0.57116 | y7       | 0.53412 |
| x8       | 0.23678 | x8       | 0.17861 | x8       | 0.13214 | x8       | 0.09549 | x8       | 0.06699 | x8       | 0.04518 | x8       | 0.02887 |
| y8       | 0.92511 | y8       | 0.88302 | y8       | 0.83864 | y8       | 0.79389 | y8       | 0.75000 | y8       | 0.70771 | y8       | 0.66744 |
| x9       | 0.40813 | x9       | 0.32899 | x9       | 0.26203 | x9       | 0.20611 | x9       | 0.15991 | x9       | 0.12213 | x9       | 0.09152 |
| y9       | 0.99149 | y9       | 0.96985 | y9       | 0.93974 | y9       | 0.90451 | y9       | 0.86653 | y9       | 0.82743 | y9       | 0.78834 |
| x10      | 0.59187 | x10      | 0.50000 | x10      | 0.41770 | x10      | 0.34549 | x10      | 0.28306 | x10      | 0.22968 | x10      | 0.18446 |
| y10      | 0.99149 | y10      | 1.00000 | y10      | 0.99318 | y10      | 0.97553 | y10      | 0.95048 | y10      | 0.92063 | y10      | 0.88786 |
| x11      | 0.76322 | x11      | 0.67101 | x11      | 0.58230 | x11      | 0.50000 | x11      | 0.42548 | x11      | 0.35913 | x11      | 0.30080 |
| y11      | 0.92511 | y11      | 0.96985 | y11      | 0.99318 | y11      | 1.00000 | y11      | 0.99442 | y11      | 0.97975 | y11      | 0.95861 |
| x12      | 0.89901 | x12      | 0.82139 | x12      | 0.73797 | x12      | 0.65451 | x12      | 0.57452 | x12      | 0.50000 | x12      | 0.43192 |
| y12      | 0.80132 | y12      | 0.88302 | y12      | 0.93974 | y12      | 0.97553 | y12      | 0.99442 | y12      | 1.00000 | y12      | 0.99534 |
| x13      | 0.98091 | x13      | 0.93301 | x13      | 0.86786 | x13      | 0.79389 | x13      | 0.71694 | x13      | 0.64087 | x13      | 0.56808 |
| y13      | 0.63683 | y13      | 0.75000 | y13      | 0.83864 | y13      | 0.90451 | y13      | 0.95048 | y13      | 0.97975 | y13      | 0.99534 |
| x14      | 0.99787 | x14      | 0.99240 | x14      | 0.95789 | x14      | 0.90451 | x14      | 0.84009 | x14      | 0.77032 | x14      | 0.69920 |
| y14      | 0.45387 | y14      | 0.58682 | y14      | 0.70085 | y14      | 0.79389 | y14      | 0.86653 | y14      | 0.92063 | y14      | 0.95861 |
| x15      | 0.94758 | x15      | 0.99240 | x15      | 0.99829 | x15      | 0.97553 | x15      | 0.93301 | x15      | 0.87787 | x15      | 0.81554 |
| y15      | 0.27713 | y15      | 0.41318 | y15      | 0.54129 | y15      | 0.65451 | y15      | 0.75000 | y15      | 0.82743 | y15      | 0.88786 |
| x16      | 0.83685 | x16      | 0.93301 | x16      | 0.98470 | x16      | 1.00000 | x16      | 0.98746 | x16      | 0.95482 | x16      | 0.90848 |
| y16      | 0.13050 | y16      | 0.25000 | y16      | 0.37726 | y16      | 0.50000 | y16      | 0.61126 | y16      | 0.70771 | y16      | 0.78834 |
| x17      | 0.68062 | x17      | 0.82139 | x17      | 0.91858 | x17      | 0.97553 | x17      | 0.99860 | x17      | 0.99491 | x17      | 0.97113 |
| y17      | 0.03376 | y17      | 0.11698 | y17      | 0.22658 | y17      | 0.34549 | y17      | 0.46263 | y17      | 0.57116 | y17      | 0.66744 |
|          |         | x18      | 0.67101 | x18      | 0.80711 | x18      | 0.90451 | x18      | 0.96544 | x18      | 0.99491 | x18      | 0.99883 |
|          |         | y18      | 0.03015 | y18      | 0.10543 | y18      | 0.20611 | y18      | 0.31733 | y18      | 0.42884 | y18      | 0.53412 |
|          |         |          |         | x19      | 0.66235 | x19      | 0.79389 | x19      | 0.89092 | x19      | 0.95482 | x19      | 0.98954 |
|          |         |          |         | y19      | 0.02709 | y19      | 0.09549 | y19      | 0.18826 | y19      | 0.29229 | y19      | 0.39827 |
|          |         |          |         |          |         | x20      | 0.65451 | x20      | 0.78166 | x20      | 0.87787 | x20      | 0.94394 |
|          |         |          |         |          |         | y20      | 0.02447 | y20      | 0.08688 | y20      | 0.17257 | y20      | 0.26997 |
|          |         |          |         |          |         |          |         | x21      | 0.64738 | x21      | 0.77032 | x21      | 0.86542 |
|          |         |          |         |          |         |          |         | y21      | 0.02221 | y21      | 0.07937 | y21      | 0.15872 |
|          |         |          |         |          |         |          |         |          |         | x22      | 0.64087 | x22      | 0.75979 |
|          |         |          |         |          |         |          |         |          |         | y22      | 0.02025 | y22      | 0.07279 |
|          |         |          |         |          |         |          |         |          |         |          |         | x23      | 0.63490 |
|          |         |          |         |          |         |          |         |          |         |          |         | y23      | 0.01854 |
| 24Holes  |         | 25 Holes |         | 26 Holes |         | 27 Holes |         | 28 Holes |         |          |         |          |         |
| x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 | x1       | 0.50000 |          |         |          |         |
| y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 | y1       | 0.00000 |          |         |          |         |
| x2       | 0.37059 | x2       | 0.37566 | x2       | 0.38034 | x2       | 0.38469 | x2       | 0.38874 |          |         |          |         |
| y2       | 0.01704 | y2       | 0.01571 | y2       | 0.01453 | y2       | 0.01348 | y2       | 0.01254 |          |         |          |         |
| x3       | 0.25000 | x3       | 0.25912 | x3       | 0.26764 | x3       | 0.27560 | x3       | 0.28306 |          |         |          |         |



The diagram shows a type "A" circle for a 5-hole circle. Coordinates x, y are given in the table for hole circles of from 3 to 28 holes. Dimensions are for holes numbered in a counterclockwise direction (as shown). Dimensions given are based upon a hole circle of unit diameter. For a hole circle of, say, 3-inch or 3-centimeter diameter, multiply table values by 3.

**Table 12. (Continued) Hole Coordinate Dimension Factors for Jig Boring — Type "A" Hole Circles (English or Metric Units)**

| 24Holes |         | 25 Holes |         | 26 Holes |         | 27 Holes |         | 28 Holes |         |
|---------|---------|----------|---------|----------|---------|----------|---------|----------|---------|
| y3      | 0.06699 | y3       | 0.06185 | y3       | 0.05727 | y3       | 0.05318 | y3       | 0.04952 |
| x4      | 0.14645 | x4       | 0.15773 | x4       | 0.16844 | x4       | 0.17861 | x4       | 0.18826 |
| y4      | 0.14645 | y4       | 0.13552 | y4       | 0.12574 | y4       | 0.11698 | y4       | 0.10908 |
| x5      | 0.06699 | x5       | 0.07784 | x5       | 0.08851 | x5       | 0.09894 | x5       | 0.10908 |
| y5      | 0.25000 | y5       | 0.23209 | y5       | 0.21597 | y5       | 0.20142 | y5       | 0.18826 |
| x6      | 0.01704 | x6       | 0.02447 | x6       | 0.03249 | x6       | 0.04089 | x6       | 0.04952 |
| y6      | 0.37059 | y6       | 0.34549 | y6       | 0.32270 | y6       | 0.30196 | y6       | 0.28306 |
| x7      | 0.00000 | x7       | 0.00099 | x7       | 0.00365 | x7       | 0.00760 | x7       | 0.01254 |
| y7      | 0.50000 | y7       | 0.46860 | y7       | 0.43973 | y7       | 0.41318 | y7       | 0.38874 |
| x8      | 0.01704 | x8       | 0.00886 | x8       | 0.00365 | x8       | 0.00085 | x8       | 0.00000 |
| y8      | 0.62941 | y8       | 0.59369 | y8       | 0.56027 | y8       | 0.52907 | y8       | 0.50000 |
| x9      | 0.06699 | x9       | 0.04759 | x9       | 0.03249 | x9       | 0.02101 | x9       | 0.01254 |
| y9      | 0.75000 | y9       | 0.71289 | y9       | 0.67730 | y9       | 0.64340 | y9       | 0.61126 |
| x10     | 0.14645 | x10      | 0.11474 | x10      | 0.08851 | x10      | 0.06699 | x10      | 0.04952 |
| y10     | 0.85355 | y10      | 0.81871 | y10      | 0.78403 | y10      | 0.75000 | y10      | 0.71694 |
| x11     | 0.25000 | x11      | 0.20611 | x11      | 0.16844 | x11      | 0.13631 | x11      | 0.10908 |
| y11     | 0.93301 | y11      | 0.90451 | y11      | 0.87426 | y11      | 0.84312 | y11      | 0.81174 |
| x12     | 0.37059 | x12      | 0.31594 | x12      | 0.26764 | x12      | 0.22525 | x12      | 0.18826 |
| y12     | 0.98296 | y12      | 0.96489 | y12      | 0.94273 | y12      | 0.91774 | y12      | 0.89092 |
| x13     | 0.50000 | x13      | 0.43733 | x13      | 0.38034 | x13      | 0.32899 | x13      | 0.28306 |
| y13     | 1.00000 | y13      | 0.99606 | y13      | 0.98547 | y13      | 0.96985 | y13      | 0.95048 |
| x14     | 0.62941 | x14      | 0.56267 | x14      | 0.50000 | x14      | 0.44195 | x14      | 0.38874 |
| y14     | 0.98296 | y14      | 0.99606 | y14      | 1.00000 | y14      | 0.99662 | y14      | 0.98746 |
| x15     | 0.75000 | x15      | 0.68406 | x15      | 0.61966 | x15      | 0.55805 | x15      | 0.50000 |
| y15     | 0.93301 | y15      | 0.96489 | y15      | 0.98547 | y15      | 0.99662 | y15      | 1.00000 |
| x16     | 0.85355 | x16      | 0.79389 | x16      | 0.73236 | x16      | 0.67101 | x16      | 0.61126 |
| y16     | 0.85355 | y16      | 0.90451 | y16      | 0.94273 | y16      | 0.96985 | y16      | 0.98746 |
| x17     | 0.93301 | x17      | 0.88526 | x17      | 0.83156 | x17      | 0.77475 | x17      | 0.71694 |
| y17     | 0.75000 | y17      | 0.81871 | y17      | 0.87426 | y17      | 0.91774 | y17      | 0.95048 |
| x18     | 0.98296 | x18      | 0.95241 | x18      | 0.91149 | x18      | 0.86369 | x18      | 0.81174 |
| y18     | 0.62941 | y18      | 0.71289 | y18      | 0.78403 | y18      | 0.84312 | y18      | 0.89092 |
| x19     | 1.00000 | x19      | 0.99114 | x19      | 0.96751 | x19      | 0.93301 | x19      | 0.89092 |
| y19     | 0.50000 | y19      | 0.59369 | y19      | 0.67730 | y19      | 0.75000 | y19      | 0.81174 |
| x20     | 0.98296 | x20      | 0.99901 | x20      | 0.99635 | x20      | 0.97899 | x20      | 0.95048 |
| y20     | 0.37059 | y20      | 0.46860 | y20      | 0.56027 | y20      | 0.64340 | y20      | 0.71694 |
| x21     | 0.93301 | x21      | 0.97553 | x21      | 0.99635 | x21      | 0.99915 | x21      | 0.98746 |
| y21     | 0.25000 | y21      | 0.34549 | y21      | 0.43973 | y21      | 0.52907 | y21      | 0.61126 |
| x22     | 0.85355 | x22      | 0.92216 | x22      | 0.96751 | x22      | 0.99240 | x22      | 1.00000 |
| y22     | 0.14645 | y22      | 0.23209 | y22      | 0.32270 | y22      | 0.41318 | y22      | 0.50000 |
| x23     | 0.75000 | x23      | 0.84227 | x23      | 0.91149 | x23      | 0.95911 | x23      | 0.98746 |
| y23     | 0.6699  | y23      | 0.13552 | y23      | 0.21597 | y23      | 0.30196 | y23      | 0.38874 |
| x24     | 0.62941 | x24      | 0.74088 | x24      | 0.83156 | x24      | 0.90106 | x24      | 0.95048 |
| y24     | 0.01704 | y24      | 0.06185 | y24      | 0.12574 | y24      | 0.20142 | y24      | 0.28306 |
|         |         | x25      | 0.62434 | x25      | 0.73236 | x25      | 0.82139 | x25      | 0.89092 |
|         |         | y25      | 0.01571 | y25      | 0.05727 | y25      | 0.11698 | y25      | 0.18826 |
|         |         |          |         | x26      | 0.61966 | x26      | 0.72440 | x26      | 0.81174 |
|         |         |          |         | y26      | 0.01453 | y26      | 0.05318 | y26      | 0.10908 |
|         |         |          |         |          |         | x27      | 0.61531 | x27      | 0.71694 |
|         |         |          |         |          |         | y27      | 0.01348 | y27      | 0.04952 |
|         |         |          |         |          |         |          |         | x28      | 0.61126 |
|         |         |          |         |          |         |          |         | y28      | 0.01254 |

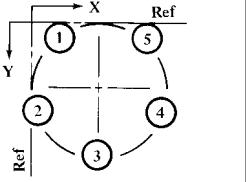


The diagram shows a type "A" circle for a 5-hole circle. Coordinates  $x$ ,  $y$  are given in the table for hole circles of from 3 to 28 holes. Dimensions are for holes numbered in a counterclockwise direction (as shown). Dimensions given are based upon a hole circle of unit diameter. For a hole circle of, say, 3-inch or 3-centimeter diameter, multiply table values by 3.



**Table 13. Hole Coordinate Dimension Factors for Jig Boring — Type "B" Hole Circles (English or Metric Units)**

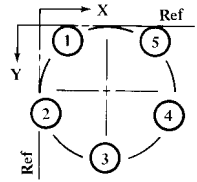
| 3 Holes  |         | 4 Holes  |         | 5 Holes  |         | 6 Holes  |         | 7 Holes  |         | 8 Holes  |         | 9 Holes  |         |
|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|
| x1       | 0.06699 | x1       | 0.14645 | x1       | 0.20611 | x1       | 0.25000 | x1       | 0.28306 | x1       | 0.30866 | x1       | 0.32899 |
| y1       | 0.25000 | y1       | 0.14645 | y1       | 0.09549 | y1       | 0.06699 | y1       | 0.04952 | y1       | 0.03806 | y1       | 0.03015 |
| x2       | 0.50000 | x2       | 0.14645 | x2       | 0.02447 | x2       | 0.00000 | x2       | 0.01254 | x2       | 0.03806 | x2       | 0.06699 |
| y2       | 1.00000 | y2       | 0.85355 | y2       | 0.65451 | y2       | 0.50000 | y2       | 0.38874 | y2       | 0.30866 | y2       | 0.25000 |
| x3       | 0.93301 | x3       | 0.85355 | x3       | 0.50000 | x3       | 0.25000 | x3       | 0.10908 | x3       | 0.03806 | x3       | 0.00760 |
| y3       | 0.25000 | y3       | 0.85355 | y3       | 1.00000 | y3       | 0.93301 | y3       | 0.81174 | y3       | 0.69134 | y3       | 0.58682 |
|          |         | x4       | 0.85355 | x4       | 0.97553 | x4       | 0.75000 | x4       | 0.50000 | x4       | 0.30866 | x4       | 0.17861 |
|          |         | y4       | 0.14645 | y4       | 0.65451 | y4       | 0.93301 | y4       | 1.00000 | y4       | 0.96194 | y4       | 0.88302 |
|          |         |          |         | x5       | 1.00000 | x5       | 1.00000 | x5       | 0.89092 | x5       | 0.69134 | x5       | 0.50000 |
|          |         |          |         | y5       | 0.09549 | y5       | 0.50000 | y5       | 0.81174 | y5       | 0.96194 | y5       | 1.00000 |
|          |         |          |         |          |         | x6       | 0.75000 | x6       | 0.98746 | x6       | 0.96194 | x6       | 0.82139 |
|          |         |          |         |          |         | y6       | 0.06699 | y6       | 0.38874 | y6       | 0.69134 | y6       | 0.88302 |
|          |         |          |         |          |         |          |         | x7       | 0.71694 | x7       | 0.96194 | x7       | 0.99240 |
|          |         |          |         |          |         |          |         | y7       | 0.04952 | y7       | 0.30866 | y7       | 0.58682 |
|          |         |          |         |          |         |          |         |          |         | x8       | 0.69134 | x8       | 0.93301 |
|          |         |          |         |          |         |          |         |          |         | y8       | 0.03806 | y8       | 0.25000 |
|          |         |          |         |          |         |          |         |          |         |          |         | x9       | 0.67101 |
|          |         |          |         |          |         |          |         |          |         |          |         | y9       | 0.03015 |
| 10 Holes |         | 11 Holes |         | 12 Holes |         | 13 Holes |         | 14 Holes |         | 15 Holes |         | 16 Holes |         |
| x1       | 0.34549 | x1       | 0.35913 | x1       | 0.37059 | x1       | 0.38034 | x1       | 0.38874 | x1       | 0.39604 | x1       | 0.40245 |
| y1       | 0.02447 | y1       | 0.02025 | y1       | 0.01704 | y1       | 0.01453 | y1       | 0.01254 | y1       | 0.01093 | y1       | 0.00961 |
| x2       | 0.09549 | x2       | 0.12213 | x2       | 0.14645 | x2       | 0.16844 | x2       | 0.18826 | x2       | 0.20611 | x2       | 0.22221 |
| y2       | 0.20611 | y2       | 0.17257 | y2       | 0.14645 | y2       | 0.12574 | y2       | 0.10908 | y2       | 0.09549 | y2       | 0.08427 |
| x3       | 0.00000 | x3       | 0.00509 | x3       | 0.01704 | x3       | 0.03249 | x3       | 0.04952 | x3       | 0.06699 | x3       | 0.08427 |
| y3       | 0.50000 | y3       | 0.42884 | y3       | 0.37059 | y3       | 0.32270 | y3       | 0.28306 | y3       | 0.25000 | y3       | 0.22221 |
| x4       | 0.09549 | x4       | 0.04518 | x4       | 0.01704 | x4       | 0.00365 | x4       | 0.00000 | x4       | 0.00274 | x4       | 0.00961 |
| y4       | 0.79389 | y4       | 0.70771 | y4       | 0.62941 | y4       | 0.56027 | y4       | 0.50000 | y4       | 0.44774 | y4       | 0.40245 |
| x5       | 0.34549 | x5       | 0.22968 | x5       | 0.14645 | x5       | 0.08851 | x5       | 0.04952 | x5       | 0.02447 | x5       | 0.00961 |
| y5       | 0.97553 | y5       | 0.92063 | y5       | 0.85355 | y5       | 0.78403 | y5       | 0.71694 | y5       | 0.65451 | y5       | 0.59755 |
| x6       | 0.65451 | x6       | 0.50000 | x6       | 0.37059 | x6       | 0.26764 | x6       | 0.18826 | x6       | 0.12843 | x6       | 0.08427 |
| y6       | 0.97553 | y6       | 1.00000 | y6       | 0.98296 | y6       | 0.94273 | y6       | 0.89092 | y6       | 0.83457 | y6       | 0.77779 |
| x7       | 0.90451 | x7       | 0.77032 | x7       | 0.62941 | x7       | 0.50000 | x7       | 0.38874 | x7       | 0.29663 | x7       | 0.22221 |
| y7       | 0.79389 | y7       | 0.92063 | y7       | 0.98296 | y7       | 1.00000 | y7       | 0.98746 | y7       | 0.95677 | y7       | 0.91573 |
| x8       | 1.00000 | x8       | 0.95482 | x8       | 0.85355 | x8       | 0.73236 | x8       | 0.61126 | x8       | 0.50000 | x8       | 0.40245 |
| y8       | 0.50000 | y8       | 0.70771 | y8       | 0.85355 | y8       | 0.94273 | y8       | 0.98746 | y8       | 1.00000 | y8       | 0.99039 |
| x9       | 0.90451 | x9       | 0.99491 | x9       | 0.98296 | x9       | 0.91149 | x9       | 0.81174 | x9       | 0.70337 | x9       | 0.59755 |
| y9       | 0.20611 | y9       | 0.42884 | y9       | 0.62941 | y9       | 0.78403 | y9       | 0.89092 | y9       | 0.95677 | y9       | 0.99039 |
| x10      | 0.65451 | x10      | 0.87787 | x10      | 0.98296 | x10      | 0.99635 | x10      | 0.95048 | x10      | 0.87157 | x10      | 0.77779 |
| y10      | 0.02447 | y10      | 0.17257 | y10      | 0.37059 | y10      | 0.56027 | y10      | 0.71694 | y10      | 0.83457 | y10      | 0.91573 |
|          |         | x11      | 0.64087 | x11      | 0.85355 | x11      | 0.96751 | x11      | 1.00000 | x11      | 0.97553 | x11      | 0.91573 |
|          |         | y11      | 0.02025 | y11      | 0.14645 | y11      | 0.32270 | y11      | 0.50000 | y11      | 0.65451 | y11      | 0.77779 |
|          |         |          |         | x12      | 0.62941 | x12      | 0.83156 | x12      | 0.95048 | x12      | 0.99726 | x12      | 0.99039 |
|          |         |          |         | y12      | 0.01704 | y12      | 0.12574 | y12      | 0.28306 | y12      | 0.44774 | y12      | 0.59755 |
|          |         |          |         |          |         | x13      | 0.61966 | x13      | 0.81174 | x13      | 0.93301 | x13      | 0.99039 |
|          |         |          |         |          |         | y13      | 0.01453 | y13      | 0.10908 | y13      | 0.25000 | y13      | 0.40245 |
|          |         |          |         |          |         |          |         | x14      | 0.61126 | x14      | 0.79389 | x14      | 0.91573 |
|          |         |          |         |          |         |          |         | y14      | 0.01254 | y14      | 0.09549 | y14      | 0.22221 |
|          |         |          |         |          |         |          |         |          |         | x15      | 0.60396 | x15      | 0.77779 |
|          |         |          |         |          |         |          |         |          |         | y15      | 0.01093 | y15      | 0.08427 |
|          |         |          |         |          |         |          |         |          |         |          |         | x16      | 0.59755 |
|          |         |          |         |          |         |          |         |          |         |          |         | y16      | 0.00961 |



The diagram shows a type "B" circle for a 5-hole circle. Coordinates  $x$ ,  $y$  are given in the table for hole circles of from 3 to 28 holes. Dimensions are for holes numbered in a counterclockwise direction (as shown). Dimensions given are based upon a hole circle of unit diameter. For a hole circle of, say, 3-inch or 3-centimeter diameter, multiply table values by 3.

**Table 13. (Continued) Hole Coordinate Dimension Factors for Jig Boring — Type "B" Hole Circles (English or Metric Units)**

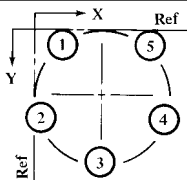
| 17 Holes |         | 18 Holes |          | 19 Holes |         | 20 Holes |         | 21 Holes |         | 22 Holes |         | 23 Holes |         |
|----------|---------|----------|----------|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|
| x1       | 0.40813 | x1       | 0.41318  | x1       | 0.41770 | x1       | 0.42178 | x1       | 0.42548 | x1       | 0.42884 | x1       | 0.43192 |
| y1       | 0.00851 | y1       | 0.00760  | y1       | 0.00682 | y1       | 0.00616 | y1       | 0.00558 | y1       | 0.00509 | y1       | 0.00466 |
| x2       | 0.23678 | x2       | 0.25000  | x2       | 0.26203 | x2       | 0.27300 | x2       | 0.28306 | x2       | 0.29229 | x2       | 0.30080 |
| y2       | 0.07489 | y2       | 0.06699  | y2       | 0.06026 | y2       | 0.05450 | y2       | 0.04952 | y2       | 0.04518 | y2       | 0.04139 |
| x3       | 0.10099 | x3       | 0.111698 | x3       | 0.13214 | x3       | 0.14645 | x3       | 0.15991 | x3       | 0.17257 | x3       | 0.18446 |
| y3       | 0.19868 | y3       | 0.17861  | y3       | 0.16136 | y3       | 0.14645 | y3       | 0.13347 | y3       | 0.12213 | y3       | 0.11214 |
| x4       | 0.01909 | x4       | 0.03015  | x4       | 0.04211 | x4       | 0.05450 | x4       | 0.06699 | x4       | 0.07937 | x4       | 0.09152 |
| y4       | 0.36317 | y4       | 0.32899  | y4       | 0.29915 | y4       | 0.27300 | y4       | 0.25000 | y4       | 0.22968 | y4       | 0.21166 |
| x5       | 0.00213 | x5       | 0.00000  | x5       | 0.00171 | x5       | 0.00616 | x5       | 0.01254 | x5       | 0.02025 | x5       | 0.02887 |
| y5       | 0.54613 | y5       | 0.50000  | y5       | 0.45871 | y5       | 0.42178 | y5       | 0.38874 | y5       | 0.35913 | y5       | 0.33256 |
| x6       | 0.05242 | x6       | 0.03015  | x6       | 0.01530 | x6       | 0.00616 | x6       | 0.00140 | x6       | 0.00000 | x6       | 0.00117 |
| y6       | 0.72287 | y6       | 0.67101  | y6       | 0.62274 | y6       | 0.57822 | y6       | 0.53737 | y6       | 0.50000 | y6       | 0.46588 |
| x7       | 0.16315 | x7       | 0.111698 | x7       | 0.08142 | x7       | 0.05450 | x7       | 0.03456 | x7       | 0.02025 | x7       | 0.01046 |
| y7       | 0.86950 | y7       | 0.82139  | y7       | 0.77347 | y7       | 0.72700 | y7       | 0.68267 | y7       | 0.64087 | y7       | 0.60173 |
| x8       | 0.31938 | x8       | 0.25000  | x8       | 0.19289 | x8       | 0.14645 | x8       | 0.10908 | x8       | 0.07937 | x8       | 0.05606 |
| y8       | 0.96624 | y8       | 0.93301  | y8       | 0.89457 | y8       | 0.85355 | y8       | 0.81174 | y8       | 0.77032 | y8       | 0.73003 |
| x9       | 0.50000 | x9       | 0.41318  | x9       | 0.33765 | x9       | 0.27300 | x9       | 0.21834 | x9       | 0.17257 | x9       | 0.13458 |
| y9       | 1.00000 | y9       | 0.99240  | y9       | 0.97291 | y9       | 0.94550 | y9       | 0.91312 | y9       | 0.87787 | y9       | 0.84128 |
| x10      | 0.68062 | x10      | 0.58682  | x10      | 0.50000 | x10      | 0.42178 | x10      | 0.35262 | x10      | 0.29229 | x10      | 0.24021 |
| y10      | 0.96624 | y10      | 0.99240  | y10      | 1.00000 | y10      | 0.99384 | y10      | 0.97779 | y10      | 0.95482 | y10      | 0.92721 |
| x11      | 0.83685 | x11      | 0.75000  | x11      | 0.66235 | x11      | 0.57822 | x11      | 0.50000 | x11      | 0.42884 | x11      | 0.36510 |
| y11      | 0.86950 | y11      | 0.93301  | y11      | 0.97291 | y11      | 0.99384 | y11      | 1.00000 | y11      | 0.99491 | y11      | 0.98146 |
| x12      | 0.94758 | x12      | 0.88302  | x12      | 0.80711 | x12      | 0.72700 | x12      | 0.64738 | x12      | 0.57116 | x12      | 0.50000 |
| y12      | 0.72287 | y12      | 0.82139  | y12      | 0.89457 | y12      | 0.94550 | y12      | 0.97779 | y12      | 0.99491 | y12      | 1.00000 |
| x13      | 0.99787 | x13      | 0.96985  | x13      | 0.91858 | x13      | 0.85355 | x13      | 0.78166 | x13      | 0.70771 | x13      | 0.63490 |
| y13      | 0.54613 | y13      | 0.67101  | y13      | 0.77347 | y13      | 0.85355 | y13      | 0.91312 | y13      | 0.95482 | y13      | 0.98146 |
| x14      | 0.98091 | x14      | 1.00000  | x14      | 0.98470 | x14      | 0.94550 | x14      | 0.89092 | x14      | 0.82743 | x14      | 0.75979 |
| y14      | 0.36317 | y14      | 0.50000  | y14      | 0.62274 | y14      | 0.72700 | y14      | 0.81174 | y14      | 0.87787 | y14      | 0.92721 |
| x15      | 0.89901 | x15      | 0.96985  | x15      | 0.99829 | x15      | 0.99384 | x15      | 0.96544 | x15      | 0.92063 | x15      | 0.86542 |
| y15      | 0.19868 | y15      | 0.32899  | y15      | 0.45871 | y15      | 0.57822 | y15      | 0.68267 | y15      | 0.77032 | y15      | 0.84128 |
| x16      | 0.76322 | x16      | 0.88302  | x16      | 0.95789 | x16      | 0.99384 | x16      | 0.99860 | x16      | 0.97975 | x16      | 0.94394 |
| y16      | 0.07489 | y16      | 0.17861  | y16      | 0.29915 | y16      | 0.42178 | y16      | 0.53737 | y16      | 0.64087 | y16      | 0.73003 |
| x17      | 0.59187 | x17      | 0.75000  | x17      | 0.86786 | x17      | 0.94550 | x17      | 0.98746 | x17      | 1.00000 | x17      | 0.98954 |
| y17      | 0.00851 | y17      | 0.06699  | y17      | 0.16136 | y17      | 0.27300 | y17      | 0.38874 | y17      | 0.50000 | y17      | 0.60173 |
|          |         | x18      | 0.58682  | x18      | 0.73797 | x18      | 0.85355 | x18      | 0.93301 | x18      | 0.97975 | x18      | 0.99883 |
|          |         | y18      | 0.00760  | y18      | 0.06026 | y18      | 0.14645 | y18      | 0.25000 | y18      | 0.35913 | y18      | 0.46588 |
|          |         |          |          | x19      | 0.58230 | x19      | 0.72700 | x19      | 0.84009 | x19      | 0.92063 | x19      | 0.97113 |
|          |         |          |          | y19      | 0.00682 | y19      | 0.05450 | y19      | 0.13347 | y19      | 0.22968 | y19      | 0.33256 |
|          |         |          |          |          |         | x20      | 0.57822 | x20      | 0.71694 | x20      | 0.82743 | x20      | 0.90848 |
|          |         |          |          |          |         | y20      | 0.00616 | y20      | 0.04952 | y20      | 0.12213 | y20      | 0.21166 |
|          |         |          |          |          |         |          |         | x21      | 0.57452 | x21      | 0.70771 | x21      | 0.81554 |
|          |         |          |          |          |         |          |         | y21      | 0.00558 | y21      | 0.04518 | y21      | 0.11214 |
|          |         |          |          |          |         |          |         |          |         | x22      | 0.57116 | x22      | 0.69920 |
|          |         |          |          |          |         |          |         |          |         | y22      | 0.00509 | y22      | 0.04139 |
|          |         |          |          |          |         |          |         |          |         |          |         | x23      | 0.56808 |
|          |         |          |          |          |         |          |         |          |         |          |         | y23      | 0.00466 |
| 24 Holes |         | 25 Holes |          | 26 Holes |         | 27 Holes |         | 28 Holes |         |          |         |          |         |
| x1       | 0.43474 | x1       | 0.43733  | x1       | 0.43973 | x1       | 0.44195 | x1       | 0.44402 |          |         |          |         |
| y1       | 0.00428 | y1       | 0.00394  | y1       | 0.00365 | y1       | 0.00338 | y1       | 0.00314 |          |         |          |         |
| x2       | 0.30866 | x2       | 0.31594  | x2       | 0.32270 | x2       | 0.32899 | x2       | 0.33486 |          |         |          |         |
| y2       | 0.03806 | y2       | 0.03511  | y2       | 0.03249 | y2       | 0.03015 | y2       | 0.02806 |          |         |          |         |
| x3       | 0.19562 | x3       | 0.20611  | x3       | 0.21597 | x3       | 0.22525 | x3       | 0.23398 |          |         |          |         |
| y3       | 0.10332 | y3       | 0.09549  | y3       | 0.08851 | y3       | 0.08226 | y3       | 0.07664 |          |         |          |         |



The diagram shows a type "B" circle for a 5-hole circle. Coordinates x, y are given in the table for hole circles of from 3 to 28 holes. Dimensions are for holes numbered in a counterclockwise direction (as shown). Dimensions given are based upon a hole circle of unit diameter. For a hole circle of, say, 3-inch or 3-centimeter diameter, multiply table values by 3.

**Table 13. (Continued) Hole Coordinate Dimension Factors for Jig Boring — Type "B" Hole Circles (English or Metric Units)**

| 24 Holes |         | 25 Holes |         | 26 Holes |         | 27 Holes |         | 28 Holes |         |
|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|
| x4       | 0.10332 | x4       | 0.11474 | x4       | 0.12574 | x4       | 0.13631 | x4       | 0.14645 |
| y4       | 0.19562 | y4       | 0.18129 | y4       | 0.16844 | y4       | 0.15688 | y4       | 0.14645 |
| x5       | 0.03806 | x5       | 0.04759 | x5       | 0.05727 | x5       | 0.06699 | x5       | 0.07664 |
| y5       | 0.30866 | y5       | 0.28711 | y5       | 0.26764 | y5       | 0.25000 | y5       | 0.23398 |
| x6       | 0.00428 | x6       | 0.00886 | x6       | 0.01453 | x6       | 0.02101 | x6       | 0.02806 |
| y6       | 0.43474 | y6       | 0.40631 | y6       | 0.38034 | y6       | 0.35660 | y6       | 0.33486 |
| x7       | 0.00428 | x7       | 0.00099 | x7       | 0.00000 | x7       | 0.00085 | x7       | 0.00314 |
| y7       | 0.56526 | y7       | 0.53140 | y7       | 0.50000 | y7       | 0.47093 | y7       | 0.44402 |
| x8       | 0.03806 | x8       | 0.02447 | x8       | 0.01453 | x8       | 0.00760 | x8       | 0.00314 |
| y8       | 0.69134 | y8       | 0.65451 | y8       | 0.61966 | y8       | 0.58682 | y8       | 0.55598 |
| x9       | 0.10332 | x9       | 0.07784 | x9       | 0.05727 | x9       | 0.04089 | x9       | 0.02806 |
| y9       | 0.80438 | y9       | 0.76791 | y9       | 0.73236 | y9       | 0.69804 | y9       | 0.66514 |
| x10      | 0.19562 | x10      | 0.15773 | x10      | 0.12574 | x10      | 0.09894 | x10      | 0.07664 |
| y10      | 0.89668 | y10      | 0.86448 | y10      | 0.83156 | y10      | 0.79858 | y10      | 0.76602 |
| x11      | 0.30866 | x11      | 0.25912 | x11      | 0.21597 | x11      | 0.17861 | x11      | 0.14645 |
| y11      | 0.96194 | y11      | 0.93815 | y11      | 0.91149 | y11      | 0.88302 | y11      | 0.85355 |
| x12      | 0.43474 | x12      | 0.37566 | x12      | 0.32270 | x12      | 0.27560 | x12      | 0.23398 |
| y12      | 0.99572 | y12      | 0.98429 | y12      | 0.96751 | y12      | 0.94682 | y12      | 0.92336 |
| x13      | 0.56526 | x13      | 0.50000 | x13      | 0.43973 | x13      | 0.38469 | x13      | 0.33486 |
| y13      | 0.99572 | y13      | 1.00000 | y13      | 0.99635 | y13      | 0.98652 | y13      | 0.97194 |
| x14      | 0.69134 | x14      | 0.62434 | x14      | 0.56027 | x14      | 0.50000 | x14      | 0.44402 |
| y14      | 0.96194 | y14      | 0.98429 | y14      | 0.99635 | y14      | 1.00000 | y14      | 0.99686 |
| x15      | 0.80438 | x15      | 0.74088 | x15      | 0.67730 | x15      | 0.61531 | x15      | 0.55598 |
| y15      | 0.89668 | y15      | 0.93815 | y15      | 0.96751 | y15      | 0.98652 | y15      | 0.99686 |
| x16      | 0.89668 | x16      | 0.84227 | x16      | 0.78403 | x16      | 0.72440 | x16      | 0.66514 |
| y16      | 0.80438 | y16      | 0.86448 | y16      | 0.91149 | y16      | 0.94682 | y16      | 0.97194 |
| x17      | 0.96194 | x17      | 0.92216 | x17      | 0.87426 | x17      | 0.82139 | x17      | 0.76602 |
| y17      | 0.69134 | y17      | 0.76791 | y17      | 0.83156 | y17      | 0.88302 | y17      | 0.92336 |
| x18      | 0.99572 | x18      | 0.97553 | x18      | 0.94273 | x18      | 0.90106 | x18      | 0.85355 |
| y18      | 0.56526 | y18      | 0.65451 | y18      | 0.73236 | y18      | 0.79858 | y18      | 0.85355 |
| x19      | 0.99572 | x19      | 0.99901 | x19      | 0.98547 | x19      | 0.95911 | x19      | 0.92336 |
| y19      | 0.43474 | y19      | 0.53140 | y19      | 0.61966 | y19      | 0.69804 | y19      | 0.76602 |
| x20      | 0.96194 | x20      | 0.99114 | x20      | 1.00000 | x20      | 0.99240 | x20      | 0.97194 |
| y20      | 0.30866 | y20      | 0.40631 | y20      | 0.50000 | y20      | 0.58682 | y20      | 0.66514 |
| x21      | 0.89668 | x21      | 0.95241 | x21      | 0.98547 | x21      | 0.99915 | x21      | 0.99686 |
| y21      | 0.19562 | y21      | 0.28711 | y21      | 0.38034 | y21      | 0.47093 | y21      | 0.55598 |
| x22      | 0.80438 | x22      | 0.88526 | x22      | 0.94273 | x22      | 0.97899 | x22      | 0.99686 |
| y22      | 0.10332 | y22      | 0.18129 | y22      | 0.26764 | y22      | 0.35660 | y22      | 0.44402 |
| x23      | 0.69134 | x23      | 0.79389 | x23      | 0.87426 | x23      | 0.93301 | x23      | 0.97194 |
| y23      | 0.03806 | y23      | 0.09549 | y23      | 0.16844 | y23      | 0.25000 | y23      | 0.33486 |
| x24      | 0.56526 | x24      | 0.68406 | x24      | 0.78403 | x24      | 0.86369 | x24      | 0.92336 |
| y24      | 0.00428 | y24      | 0.03511 | y24      | 0.08851 | y24      | 0.15688 | y24      | 0.23398 |
|          |         | y25      | 0.56267 | y25      | 0.67730 | y25      | 0.77475 | y25      | 0.85355 |
|          |         | y25      | 0.00394 | y25      | 0.03249 | y25      | 0.08226 | y25      | 0.14645 |
|          |         |          |         | x26      | 0.56027 | x26      | 0.67101 | x26      | 0.76602 |
|          |         |          |         | y26      | 0.00365 | y26      | 0.03015 | y26      | 0.07664 |
|          |         |          |         |          |         | x27      | 0.55805 | x27      | 0.66514 |
|          |         |          |         |          |         | y27      | 0.00338 | y27      | 0.02806 |
|          |         |          |         |          |         |          |         | x28      | 0.55598 |
|          |         |          |         |          |         |          |         | y28      | 0.00314 |

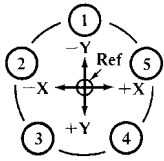


The diagram shows a type "B" circle for a 5-hole circle. Coordinates  $x$ ,  $y$  are given in the table for hole circles of from 3 to 28 holes. Dimensions are for holes numbered in a counterclockwise direction (as shown). Dimensions given are based upon a hole circle of unit diameter. For a hole circle of, say, 3-inch or 3-centimeter diameter, multiply table values by 3.

**Table 14. Hole Coordinate Dimension Factors for Jig Boring — Type "A" Hole Circles, Central Coordinates (English or Metric Units)**

| 3 Holes   |          | 4 Holes  |          | 5 Holes  |          | 6 Holes  |          | 7 Holes  |          | 8 Holes  |          | 9 Holes  |          |
|---|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| <p>The diagram shows a type "A" circle for a 5-hole circle. Coordinates <math>x</math>, <math>y</math> are given in the table for hole circles of from 3 to 28 holes. Dimensions are for holes numbered in a counterclockwise direction (as shown). Dimensions given are based upon a hole circle of unit diameter. For a hole circle of, say, 3-inch or 3-centimeter diameter, multiply table values by 3.</p> |          |          |          |          |          |          |          |          |          |          |          |          |          |
| $x_1$   | 0.00000  | $x_1$    | 0.00000  | $x_1$    | 0.00000  | $x_1$    | 0.00000  | $x_1$    | 0.00000  | $x_1$    | 0.00000  | $x_1$    | 0.00000  |
| $y_1$   | -0.50000 | $y_1$    | -0.50000 | $y_1$    | -0.50000 | $y_1$    | -0.50000 | $y_1$    | -0.50000 | $y_1$    | -0.50000 | $y_1$    | -0.50000 |
| $x_2$   | -0.43301 | $x_2$    | -0.50000 | $x_2$    | -0.47553 | $x_2$    | -0.43301 | $x_2$    | -0.39092 | $x_2$    | -0.35355 | $x_2$    | -0.32139 |
| $y_2$   | +0.25000 | $y_2$    | 0.00000  | $y_2$    | -0.15451 | $y_2$    | -0.25000 | $y_2$    | -0.31174 | $y_2$    | -0.35355 | $y_2$    | -0.38302 |
| $x_3$   | +0.43301 | $x_3$    | 0.00000  | $x_3$    | -0.29389 | $x_3$    | -0.43301 | $x_3$    | -0.48746 | $x_3$    | -0.50000 | $x_3$    | -0.49240 |
| $y_3$   | +0.25000 | $y_3$    | +0.50000 | $y_3$    | +0.40451 | $y_3$    | +0.25000 | $y_3$    | +0.11126 | $y_3$    | 0.00000  | $y_3$    | -0.08682 |
|   |          | $x_4$    | +0.50000 | $x_4$    | +0.29389 | $x_4$    | 0.00000  | $x_4$    | -0.21694 | $x_4$    | -0.35355 | $x_4$    | -0.43301 |
|   |          | $y_4$    | 0.00000  | $y_4$    | +0.40451 | $y_4$    | +0.50000 | $y_4$    | +0.45048 | $y_4$    | +0.35355 | $y_4$    | +0.25000 |
|   |          |          |          | $x_5$    | +0.47553 | $x_5$    | +0.43301 | $x_5$    | +0.21694 | $x_5$    | 0.00000  | $x_5$    | -0.17101 |
|   |          |          |          | $y_5$    | -0.15451 | $y_5$    | +0.25000 | $y_5$    | +0.45048 | $y_5$    | +0.50000 | $y_5$    | +0.46985 |
|   |          |          |          |          |          | $x_6$    | +0.43301 | $x_6$    | +0.48746 | $x_6$    | +0.35355 | $x_6$    | +0.17101 |
|   |          |          |          |          |          | $y_6$    | -0.25000 | $y_6$    | +0.11126 | $y_6$    | +0.35355 | $y_6$    | +0.46985 |
|   |          |          |          |          |          |          |          | $x_7$    | +0.39092 | $x_7$    | +0.50000 | $x_7$    | +0.43301 |
|   |          |          |          |          |          |          |          | $y_7$    | -0.31174 | $y_7$    | 0.00000  | $y_7$    | +0.25000 |
|   |          |          |          |          |          |          |          |          |          | $x_8$    | +0.35355 | $x_8$    | +0.49240 |
|   |          |          |          |          |          |          |          |          |          | $y_8$    | -0.35355 | $y_8$    | -0.08682 |
|   |          |          |          |          |          |          |          |          |          |          |          | $x_9$    | +0.32139 |
|   |          |          |          |          |          |          |          |          |          |          |          | $y_9$    | -0.38302 |
| 10 Holes  |          | 11 Holes |          | 12 Holes |          | 13 Holes |          | 14 Holes |          | 15 Holes |          | 16 Holes |          |
| $x_1$   | 0.00000  | $x_1$    | 0.00000  | $x_1$    | 0.00000  | $x_1$    | 0.00000  | $x_1$    | 0.00000  | $x_1$    | 0.00000  | $x_1$    | 0.00000  |
| $y_1$   | -0.50000 | $y_1$    | -0.50000 | $y_1$    | -0.50000 | $y_1$    | -0.50000 | $y_1$    | -0.50000 | $y_1$    | -0.50000 | $y_1$    | -0.50000 |
| $x_2$   | -0.29389 | $x_2$    | -0.27032 | $x_2$    | -0.25000 | $x_2$    | -0.23236 | $x_2$    | -0.21694 | $x_2$    | -0.20337 | $x_2$    | -0.19134 |
| $y_2$   | -0.40451 | $y_2$    | -0.42063 | $y_2$    | -0.43301 | $y_2$    | -0.44273 | $y_2$    | -0.45048 | $y_2$    | -0.45677 | $y_2$    | -0.46194 |
| $x_3$   | -0.47553 | $x_3$    | -0.45482 | $x_3$    | -0.43301 | $x_3$    | -0.41149 | $x_3$    | -0.39092 | $x_3$    | -0.37157 | $x_3$    | -0.35355 |
| $y_3$   | -0.15451 | $y_3$    | -0.20771 | $y_3$    | -0.25000 | $y_3$    | -0.28403 | $y_3$    | -0.31174 | $y_3$    | -0.33457 | $y_3$    | -0.35355 |
| $x_4$   | -0.47553 | $x_4$    | -0.49491 | $x_4$    | -0.50000 | $x_4$    | -0.49635 | $x_4$    | -0.48746 | $x_4$    | -0.47553 | $x_4$    | -0.46194 |
| $y_4$   | +0.15451 | $y_4$    | +0.07116 | $y_4$    | 0.00000  | $y_4$    | -0.06027 | $y_4$    | -0.11126 | $y_4$    | -0.15451 | $y_4$    | -0.19134 |
| $x_5$   | -0.29389 | $x_5$    | -0.37787 | $x_5$    | -0.43301 | $x_5$    | -0.46751 | $x_5$    | -0.48746 | $x_5$    | -0.49726 | $x_5$    | -0.50000 |
| $y_5$   | +0.40451 | $y_5$    | +0.32743 | $y_5$    | +0.25000 | $y_5$    | +0.17730 | $y_5$    | +0.11126 | $y_5$    | +0.05226 | $y_5$    | 0.00000  |
| $x_6$   | 0.00000  | $x_6$    | -0.14087 | $x_6$    | -0.25000 | $x_6$    | -0.33156 | $x_6$    | -0.39092 | $x_6$    | -0.43301 | $x_6$    | -0.46194 |
| $y_6$   | +0.50000 | $y_6$    | +0.47975 | $y_6$    | +0.43301 | $y_6$    | +0.37426 | $y_6$    | +0.31174 | $y_6$    | +0.25000 | $y_6$    | +0.19134 |
| $x_7$   | +0.29389 | $x_7$    | +0.14087 | $x_7$    | 0.00000  | $x_7$    | -0.11966 | $x_7$    | -0.21694 | $x_7$    | -0.29389 | $x_7$    | -0.35355 |
| $y_7$   | +0.40451 | $y_7$    | +0.47975 | $y_7$    | +0.50000 | $y_7$    | +0.48547 | $y_7$    | +0.45048 | $y_7$    | +0.40451 | $y_7$    | +0.35355 |
| $x_8$   | +0.47553 | $x_8$    | +0.37787 | $x_8$    | +0.25000 | $x_8$    | +0.11966 | $x_8$    | 0.00000  | $x_8$    | -0.10396 | $x_8$    | -0.19134 |
| $y_8$   | +0.15451 | $y_8$    | +0.32743 | $y_8$    | +0.43301 | $y_8$    | +0.48547 | $y_8$    | +0.50000 | $y_8$    | +0.48907 | $y_8$    | +0.46194 |
| $x_9$   | +0.47553 | $x_9$    | +0.49491 | $x_9$    | +0.43301 | $x_9$    | +0.33156 | $x_9$    | +0.21694 | $x_9$    | +0.10396 | $x_9$    | 0.00000  |
| $y_9$   | -0.15451 | $y_9$    | +0.07116 | $y_9$    | +0.25000 | $y_9$    | +0.37426 | $y_9$    | +0.45048 | $y_9$    | +0.48907 | $y_9$    | +0.50000 |
| $x_{10}$  | +0.29389 | $x_{10}$ | +0.45482 | $x_{10}$ | +0.50000 | $x_{10}$ | +0.46751 | $x_{10}$ | +0.39092 | $x_{10}$ | +0.29389 | $x_{10}$ | +0.19134 |
| $y_{10}$  | -0.40451 | $y_{10}$ | -0.20771 | $y_{10}$ | 0.00000  | $y_{10}$ | +0.17730 | $y_{10}$ | +0.31174 | $y_{10}$ | +0.40451 | $y_{10}$ | +0.46194 |
|   |          | $x_{11}$ | +0.27032 | $x_{11}$ | +0.43301 | $x_{11}$ | +0.49635 | $x_{11}$ | +0.48746 | $x_{11}$ | +0.43301 | $x_{11}$ | +0.35355 |
|   |          | $y_{11}$ | -0.42063 | $y_{11}$ | -0.25000 | $y_{11}$ | -0.06027 | $y_{11}$ | +0.11126 | $y_{11}$ | +0.25000 | $y_{11}$ | +0.35355 |
|   |          |          |          | $x_{12}$ | +0.25000 | $x_{12}$ | +0.41149 | $x_{12}$ | +0.48746 | $x_{12}$ | +0.49726 | $x_{12}$ | +0.46194 |
|   |          |          |          | $y_{12}$ | -0.43301 | $y_{12}$ | -0.28403 | $y_{12}$ | -0.11126 | $y_{12}$ | +0.05226 | $y_{12}$ | +0.19134 |
|   |          |          |          |          |          | $x_{13}$ | +0.23236 | $x_{13}$ | +0.39092 | $x_{13}$ | +0.47553 | $x_{13}$ | +0.50000 |
|   |          |          |          |          |          | $y_{13}$ | -0.44273 | $y_{13}$ | -0.31174 | $y_{13}$ | -0.15451 | $y_{13}$ | 0.00000  |
|   |          |          |          |          |          |          |          | $x_{14}$ | +0.21694 | $x_{14}$ | +0.37157 | $x_{14}$ | +0.46194 |
|   |          |          |          |          |          |          |          | $y_{14}$ | -0.45048 | $y_{14}$ | -0.33457 | $y_{14}$ | -0.19134 |
|   |          |          |          |          |          |          |          |          |          | $x_{15}$ | +0.20337 | $x_{15}$ | +0.35355 |
|   |          |          |          |          |          |          |          |          |          | $y_{15}$ | -0.45677 | $y_{15}$ | -0.35355 |
|   |          |          |          |          |          |          |          |          |          |          |          | $x_{16}$ | +0.19134 |
|   |          |          |          |          |          |          |          |          |          |          |          | $y_{16}$ | -0.46194 |

**Table 14. (Continued) Hole Coordinate Dimension Factors for Jig Boring — Type "A" Hole Circles, Central Coordinates (English or Metric Units)**

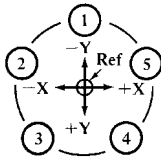


The diagram shows a type "A" circle for a 5-hole circle. Coordinates  $x$ ,  $y$  are given in the table for hole circles of from 3 to 28 holes. Dimensions are for holes numbered in a counterclockwise direction (as shown). Dimensions given are based upon a hole circle of unit diameter. For a hole circle of, say, 3-inch or 3-centimeter diameter, multiply table values by 3.

| 17 Holes |          | 18 Holes |          | 19 Holes |          | 20 Holes |          | 21 Holes |          | 22 Holes |          | 23 Holes |          |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| x1       | 0.00000  | x1       | 0.00000  | x1       | 0.00000  | x1       | 0.000000 | x1       | 0.00000  | x1       | 0.00000  | x1       | 0.00000  |
| y1       | -0.50000 | y1       | -0.50000 | y1       | -0.50000 | y1       | -0.50000 | y1       | -0.50000 | y1       | -0.50000 | y1       | -0.50000 |
| x2       | -0.18062 | x2       | -0.17101 | x2       | -0.16235 | x2       | -0.15451 | x2       | -0.14738 | x2       | -0.14087 | x2       | -0.13490 |
| y2       | -0.46624 | y2       | -0.46985 | y2       | -0.47291 | y2       | -0.47553 | y2       | -0.47779 | y2       | -0.47975 | y2       | -0.48146 |
| x3       | -0.33685 | x3       | +0.32139 | x3       | -0.30711 | x3       | -0.29389 | x3       | -0.28166 | x3       | -0.27032 | x3       | -0.25979 |
| y3       | -0.36950 | y3       | -0.38302 | y3       | -0.39457 | y3       | -0.40451 | y3       | -0.41312 | y3       | -0.42063 | y3       | -0.42721 |
| x4       | -0.44758 | x4       | -0.43301 | x4       | -0.41858 | x4       | -0.40451 | x4       | -0.39092 | x4       | -0.37787 | x4       | -0.36542 |
| y4       | -0.22287 | y4       | -0.25000 | y4       | -0.27347 | y4       | -0.29389 | y4       | -0.31174 | y4       | -0.32743 | y4       | -0.34128 |
| x5       | -0.49787 | x5       | -0.49240 | x5       | -0.48470 | x5       | -0.47553 | x5       | -0.46544 | x5       | -0.45482 | x5       | -0.44394 |
| y5       | -0.04613 | y5       | -0.08682 | y5       | -0.12274 | y5       | -0.15451 | y5       | -0.18267 | y5       | -0.20771 | y5       | -0.23003 |
| x6       | -0.48091 | x6       | -0.49420 | x6       | -0.49829 | x6       | -0.50000 | x6       | -0.49860 | x6       | -0.49491 | x6       | -0.48954 |
| y6       | +0.13683 | y6       | +0.08682 | y6       | +0.04129 | y6       | 0.00000  | y6       | -0.03737 | y6       | -0.07116 | y6       | -0.10173 |
| x7       | -0.39901 | x7       | -0.43301 | x7       | -0.45789 | x7       | -0.47553 | x7       | -0.48746 | x7       | -0.49491 | x7       | -0.49883 |
| y7       | +0.30132 | y7       | +0.25000 | y7       | +0.20085 | y7       | +0.15451 | y7       | +0.11126 | y7       | +0.07116 | y7       | +0.03412 |
| x8       | -0.26322 | x8       | -0.32139 | x8       | -0.36786 | x8       | -0.40451 | x8       | -0.43301 | x8       | -0.45482 | x8       | -0.47113 |
| y8       | +0.42511 | y8       | +0.38302 | y8       | +0.33864 | y8       | +0.29389 | y8       | +0.25000 | y8       | +0.20771 | y8       | +0.16744 |
| x9       | -0.09187 | x9       | -0.17101 | x9       | -0.23797 | x9       | -0.29389 | x9       | -0.34009 | x9       | -0.37787 | x9       | -0.40848 |
| y9       | +0.49149 | y9       | +0.46985 | y9       | +0.43974 | y9       | +0.40451 | y9       | +0.36653 | y9       | +0.32743 | y9       | +0.28834 |
| x10      | +0.09187 | x10      | 0.00000  | x10      | -0.08230 | x10      | -0.15451 | x10      | -0.21694 | x10      | -0.27032 | x10      | -0.31554 |
| y10      | +0.49149 | y10      | +0.50000 | y10      | +0.49318 | y10      | +0.47553 | y10      | +0.45048 | y10      | +0.42063 | y10      | +0.38786 |
| x11      | +0.26322 | x11      | +0.17101 | x11      | +0.08230 | x11      | 0.00000  | x11      | -0.07452 | x11      | -0.14087 | x11      | -0.19920 |
| y11      | +0.42511 | y11      | +0.46985 | y11      | +0.49318 | y11      | +0.50000 | y11      | +0.49442 | y11      | +0.47975 | y11      | +0.45861 |
| x12      | +0.39901 | x12      | +0.32139 | x12      | +0.23797 | x12      | +0.15451 | x12      | +0.07452 | x12      | 0.00000  | x12      | -0.06808 |
| y12      | +0.30132 | y12      | +0.38302 | y12      | +0.43974 | y12      | +0.47553 | y12      | +0.49442 | y12      | +0.50000 | y12      | +0.49534 |
| x13      | +0.48091 | x13      | +0.43301 | x13      | +0.36786 | x13      | +0.29389 | x13      | +0.21694 | x13      | +0.14087 | x13      | +0.06808 |
| y13      | +0.13683 | y13      | +0.25000 | y13      | +0.33864 | y13      | +0.40451 | y13      | +0.45048 | y13      | +0.47975 | y13      | +0.49534 |
| x14      | +0.49787 | x14      | +0.49240 | x14      | +0.45789 | x14      | +0.40451 | x14      | +0.34009 | x14      | +0.27032 | x14      | +0.19920 |
| y14      | -0.04613 | y14      | +0.08682 | y14      | +0.20085 | y14      | +0.29389 | y14      | +0.36653 | y14      | +0.42063 | y14      | +0.45861 |
| x15      | +0.44758 | x15      | +0.49240 | x15      | +0.49829 | x15      | +0.47553 | x15      | +0.43301 | x15      | +0.37787 | x15      | +0.31554 |
| y15      | -0.22287 | y15      | -0.08682 | y15      | +0.04129 | y15      | +0.15451 | y15      | +0.25000 | y15      | +0.32743 | y15      | +0.38786 |
| x16      | -0.33685 | x16      | +0.43301 | x16      | +0.48470 | x16      | +0.50000 | x16      | +0.48746 | x16      | +0.45482 | x16      | +0.40848 |
| y16      | -0.36950 | y16      | -0.25000 | y16      | -0.12274 | y16      | 0.00000  | y16      | +0.11126 | y16      | +0.20771 | y16      | +0.28834 |
| x17      | +0.18062 | x17      | +0.32139 | x17      | +0.41858 | x17      | +0.47553 | x17      | +0.49860 | x17      | +0.49491 | x17      | +0.47113 |
| y17      | -0.46624 | y17      | -0.38302 | y17      | -0.27347 | y17      | -0.15451 | y17      | -0.03737 | y17      | +0.07116 | y17      | +0.16744 |
|          |          | x18      | +0.17101 | x18      | +0.30711 | x18      | +0.40451 | x18      | +0.46544 | x18      | +0.49491 | x18      | +0.49883 |
|          |          | y18      | -0.46985 | y18      | -0.39457 | y18      | -0.29389 | y18      | -0.18267 | y18      | -0.07116 | y18      | +0.03412 |
|          |          |          |          | x19      | +0.16235 | x19      | +0.29389 | x19      | +0.39092 | x19      | +0.45482 | x19      | +0.48954 |
|          |          |          |          | y19      | -0.47291 | y19      | -0.40451 | y19      | -0.31174 | y19      | -0.20771 | y19      | -0.10173 |
|          |          |          |          |          |          | x20      | +0.15451 | x20      | +0.28166 | x20      | +0.37787 | x20      | +0.44394 |
|          |          |          |          |          |          | y20      | -0.47553 | y20      | -0.41312 | y20      | -0.32743 | y20      | -0.23003 |
|          |          |          |          |          |          |          |          | x21      | +0.14738 | x21      | +0.27032 | x21      | +0.36542 |
|          |          |          |          |          |          |          |          | y21      | -0.47779 | y21      | -0.42063 | y21      | -0.34128 |
|          |          |          |          |          |          |          |          |          |          | x22      | +0.14087 | x22      | +0.25979 |
|          |          |          |          |          |          |          |          |          |          | y22      | -0.47975 | y22      | -0.42721 |
|          |          |          |          |          |          |          |          |          |          |          |          | x23      | +0.13490 |
|          |          |          |          |          |          |          |          |          |          |          |          | y23      | -0.48146 |
| 24 Holes |          | 25 Holes |          | 26 Holes |          | 27 Holes |          | 28 Holes |          |          |          |          |          |
| x1       | 0.00000  | x1       | 0.00000  | x1       | 0.00000  | x1       | 0.00000  | x1       | 0.00000  |          |          |          |          |
| y1       | -0.50000 | y1       | -0.50000 | y1       | -0.50000 | y1       | -0.50000 | y1       | -0.50000 |          |          |          |          |
| x2       | -0.12941 | x2       | -0.12434 | x2       | -0.11966 | x2       | -0.11531 | x2       | -0.11126 |          |          |          |          |
| y2       | -0.48296 | y2       | -0.48429 | y2       | -0.48547 | y2       | -0.48652 | y2       | -0.48746 |          |          |          |          |
| x3       | -0.25000 | x3       | -0.24088 | x3       | -0.23236 | x3       | -0.22440 | x3       | -0.21694 |          |          |          |          |
| y3       | -0.43301 | y3       | -0.43815 | y3       | -0.44273 | y3       | -0.44682 | y3       | -0.45048 |          |          |          |          |

**Table 14. (Continued) Hole Coordinate Dimension Factors for Jig Boring — Type "A" Hole Circles, Central Coordinates (English or Metric Units)**

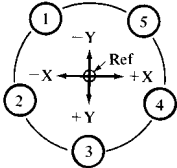
| 24 Holes |          | 25 Holes |          | 26 Holes |          | 27 Holes |          | 28 Holes |          |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| x4       | -0.35355 | x4       | -0.34227 | x4       | -0.33156 | x4       | -0.32139 | x4       | -0.31174 |
| y4       | -0.35355 | y4       | -0.36448 | y4       | -0.37426 | y4       | -0.38302 | y4       | -0.39092 |
| x5       | -0.43301 | x5       | -0.42216 | x5       | -0.41149 | x5       | -0.40106 | x5       | -0.39092 |
| y5       | -0.25000 | y5       | -0.26791 | y5       | -0.28403 | y5       | -0.29858 | y5       | -0.31174 |
| x6       | -0.48296 | x6       | -0.47553 | x6       | -0.46751 | x6       | -0.45911 | x6       | -0.45048 |
| y6       | -0.12941 | y6       | -0.15451 | y6       | -0.17730 | y6       | -0.19804 | y6       | -0.21694 |
| x7       | -0.50000 | x7       | -0.49901 | x7       | -0.49635 | x7       | -0.49240 | x7       | -0.48746 |
| y7       | 0.00000  | y7       | -0.03140 | y7       | -0.06027 | y7       | -0.08682 | y7       | -0.11126 |
| x8       | -0.48296 | x8       | -0.49114 | x8       | -0.49635 | x8       | -0.49915 | x8       | -0.50000 |
| y8       | +0.12941 | y8       | +0.09369 | y8       | +0.06027 | y8       | +0.02907 | y8       | 0.00000  |
| x9       | -0.43301 | x9       | -0.45241 | x9       | -0.46751 | x9       | -0.47899 | x9       | -0.48746 |
| y9       | +0.25000 | y9       | +0.21289 | y9       | +0.17730 | y9       | +0.14340 | y9       | +0.11126 |
| x10      | -0.35355 | x10      | -0.38526 | x10      | -0.41149 | x10      | -0.43301 | x10      | -0.45048 |
| y10      | +0.35355 | y10      | +0.31871 | y10      | +0.28403 | y10      | +0.25000 | y10      | +0.21694 |
| x11      | -0.25000 | x11      | -0.29389 | x11      | -0.33156 | x11      | -0.36369 | x11      | -0.39092 |
| y11      | +0.43301 | y11      | +0.40451 | y11      | +0.37426 | y11      | +0.34312 | y11      | +0.31174 |
| x12      | -0.12941 | x12      | -0.18406 | x12      | -0.23236 | x12      | -0.27475 | x12      | -0.31174 |
| y12      | +0.48296 | y12      | +0.46489 | y12      | +0.44273 | y12      | +0.41774 | y12      | +0.39092 |
| x13      | 0.00000  | x13      | -0.06267 | x13      | -0.11966 | x13      | -0.17101 | x13      | -0.21694 |
| y13      | +0.50000 | y13      | +0.49606 | y13      | +0.48547 | y13      | +0.46985 | y13      | +0.45048 |
| x14      | +0.12941 | x14      | +0.06267 | x14      | 0.00000  | x14      | -0.05805 | x14      | -0.11126 |
| y14      | +0.48296 | y14      | +0.49606 | y14      | +0.50000 | y14      | +0.49662 | y14      | +0.48746 |
| x15      | +0.25000 | x15      | +0.18406 | x15      | +0.11966 | x15      | +0.05805 | x15      | 0.00000  |
| y15      | +0.43301 | y15      | +0.46489 | y15      | +0.48547 | y15      | +0.49662 | y15      | +0.50000 |
| x16      | +0.35355 | x16      | +0.29389 | x16      | +0.23236 | x16      | +0.17101 | x16      | +0.11126 |
| y16      | +0.35355 | y16      | +0.40451 | y16      | +0.44273 | y16      | +0.46985 | y16      | +0.48746 |
| x17      | +0.43301 | x17      | +0.38526 | x17      | +0.33156 | x17      | +0.27475 | x17      | +0.21694 |
| y17      | +0.25000 | y17      | +0.31871 | y17      | +0.37426 | y17      | +0.41774 | y17      | +0.45048 |
| x18      | +0.48296 | x18      | +0.45241 | x18      | +0.41149 | x18      | +0.36369 | x18      | +0.31174 |
| y18      | +0.12941 | y18      | +0.21289 | y18      | +0.28403 | y18      | +0.34312 | y18      | +0.39092 |
| x19      | +0.50000 | x19      | +0.49114 | x19      | +0.46751 | x19      | +0.43301 | x19      | +0.39092 |
| y19      | 0.00000  | y19      | +0.09369 | y19      | +0.17730 | y19      | +0.25000 | y19      | +0.31174 |
| x20      | +0.48296 | x20      | +0.49901 | x20      | +0.49635 | x20      | +0.47899 | x20      | +0.45048 |
| y20      | -0.12941 | y20      | -0.03140 | y20      | +0.06027 | y20      | +0.14340 | y20      | +0.21694 |
| x21      | +0.43301 | x21      | +0.47553 | x21      | +0.49635 | x21      | +0.49915 | x21      | +0.48746 |
| y21      | -0.25000 | y21      | -0.15451 | y21      | -0.06027 | y21      | +0.02907 | y21      | +0.11126 |
| x22      | +0.35355 | x22      | +0.42216 | x22      | +0.46751 | x22      | +0.49240 | x22      | +0.50000 |
| y22      | -0.35355 | y22      | -0.26791 | y22      | -0.17730 | y22      | -0.08682 | y22      | 0.00000  |
| x23      | +0.25000 | x23      | +0.34227 | x23      | +0.41149 | x23      | +0.45911 | x23      | +0.48746 |
| y23      | -0.43301 | y23      | -0.36448 | y23      | -0.28403 | y23      | -0.19804 | y23      | -0.11126 |
| x24      | +0.12941 | x24      | +0.24088 | x24      | +0.33156 | x24      | +0.40106 | x24      | +0.45048 |
| y24      | -0.48296 | y24      | -0.43815 | y24      | -0.37426 | y24      | -0.29858 | y24      | -0.21694 |
|          |          | x25      | +0.12434 | x25      | +0.23236 | x25      | +0.32139 | x25      | +0.39092 |
|          |          | y25      | -0.48429 | y25      | -0.44273 | y25      | -0.38302 | y25      | -0.31174 |
|          |          |          |          | x26      | +0.11966 | x26      | +0.22440 | x26      | +0.31174 |
|          |          |          |          | y26      | -0.48547 | y26      | -0.44682 | y26      | -0.39092 |
|          |          |          |          |          |          | x27      | +0.11531 | x27      | +0.21694 |
|          |          |          |          |          |          | y27      | -0.48652 | y27      | -0.45048 |
|          |          |          |          |          |          |          |          | x28      | +0.11126 |
|          |          |          |          |          |          |          |          | y28      | -0.48746 |



The diagram shows a type "A" circle for a 5-hole circle. Coordinates  $x$ ,  $y$  are given in the table for hole circles of from 3 to 28 holes. Dimensions are for holes numbered in a counterclockwise direction (as shown). Dimensions given are based upon a hole circle of unit diameter. For a hole circle of, say, 3-inch or 3-centimeter diameter, multiply table values by 3.

**Table 15. Hole Coordinate Dimension Factors for Jig Boring — Type "B" Hole Circles Central Coordinates (English or Metric units)**

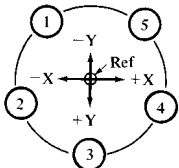
| 3 Holes  |          | 4 Holes  |          | 5 Holes  |          | 6 Holes  |          | 7 Holes  |          | 8 Holes  |          | 9 Holes  |          |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| x1       | -0.43301 | x1       | -0.35355 | x1       | -0.29389 | x1       | -0.25000 | x1       | -0.21694 | x1       | -0.19134 | x1       | -0.17101 |
| y1       | -0.25000 | y1       | -0.35355 | y1       | -0.40451 | y1       | -0.43301 | y1       | -0.45048 | y1       | -0.46194 | y1       | -0.46985 |
| x2       | 0.00000  | x2       | -0.35355 | x2       | -0.47553 | x2       | -0.50000 | x2       | -0.48746 | x2       | -0.46194 | x2       | -0.43301 |
| y2       | +0.50000 | y2       | +0.35355 | y2       | +0.15451 | y2       | 0.00000  | y2       | -0.11126 | y2       | -0.19134 | y2       | -0.25000 |
| x3       | +0.43301 | x3       | +0.35355 | x3       | 0.00000  | x3       | -0.25000 | x3       | -0.39092 | x3       | -0.46194 | x3       | -0.49240 |
| y3       | -0.25000 | y3       | +0.35355 | y3       | +0.50000 | y3       | +0.43301 | y3       | +0.31174 | y3       | +0.19134 | y3       | +0.08682 |
|          |          | x4       | +0.35355 | x4       | +0.47553 | x4       | +0.25000 | x4       | 0.00000  | x4       | -0.19134 | x4       | -0.32139 |
|          |          | y4       | -0.35355 | y4       | +0.15451 | y4       | +0.43301 | y4       | +0.50000 | y4       | +0.46194 | y4       | +0.38302 |
|          |          |          |          | x5       | +0.29389 | x5       | +0.50000 | x5       | +0.39092 | x5       | +0.19134 | x5       | 0.00000  |
|          |          |          |          | y5       | -0.40451 | y5       | 0.00000  | y5       | +0.31174 | y5       | +0.46194 | y5       | +0.50000 |
|          |          |          |          |          |          | x6       | +0.25000 | x6       | +0.48746 | x6       | +0.46194 | x6       | +0.32139 |
|          |          |          |          |          |          | y6       | -0.43301 | y6       | -0.11126 | y6       | +0.19134 | y6       | +0.38302 |
|          |          |          |          |          |          |          |          | x7       | +0.21694 | x7       | +0.46194 | x7       | +0.49240 |
|          |          |          |          |          |          |          |          | y7       | -0.45048 | y7       | -0.19134 | y7       | +0.08682 |
|          |          |          |          |          |          |          |          |          |          | x8       | +0.19134 | x8       | +0.43301 |
|          |          |          |          |          |          |          |          |          |          | y8       | -0.46194 | y8       | -0.25000 |
|          |          |          |          |          |          |          |          |          |          |          |          | x9       | +0.17101 |
|          |          |          |          |          |          |          |          |          |          |          |          | y9       | -0.46985 |
| 10 Holes |          | 11 Holes |          | 12 Holes |          | 13 Holes |          | 14 Holes |          | 15 Holes |          | 16 Holes |          |
| x1       | -0.15451 | x1       | -0.14087 | x1       | -0.12941 | x1       | -0.11966 | x1       | -0.11126 | x1       | -0.10396 | x1       | -0.09755 |
| y1       | -0.47553 | y1       | -0.47975 | y1       | -0.48296 | y1       | -0.48547 | y1       | -0.48746 | y1       | -0.48907 | y1       | -0.49039 |
| x2       | -0.40451 | x2       | -0.37787 | x2       | -0.35355 | x2       | -0.33156 | x2       | -0.31174 | x2       | -0.29389 | x2       | -0.27779 |
| y2       | -0.29389 | y2       | -0.32743 | y2       | -0.35355 | y2       | -0.37426 | y2       | -0.39092 | y2       | -0.40451 | y2       | -0.41573 |
| x3       | -0.50000 | x3       | -0.49491 | x3       | -0.48296 | x3       | -0.46751 | x3       | -0.45048 | x3       | -0.43301 | x3       | -0.41573 |
| y3       | 0.00000  | y3       | -0.07116 | y3       | -0.12941 | y3       | -0.17730 | y3       | -0.21694 | y3       | -0.25000 | y3       | -0.27779 |
| x4       | -0.40451 | x4       | -0.45482 | x4       | -0.48296 | x4       | -0.49635 | x4       | -0.50000 | x4       | -0.49726 | x4       | -0.49039 |
| y4       | +0.29389 | y4       | +0.20771 | y4       | +0.12941 | y4       | +0.06027 | y4       | 0.00000  | y4       | -0.05226 | y4       | -0.09755 |
| x5       | -0.15451 | x5       | -0.27032 | x5       | -0.35355 | x5       | -0.41149 | x5       | -0.45048 | x5       | -0.47553 | x5       | -0.49039 |
| y5       | +0.47553 | y5       | +0.42063 | y5       | +0.35355 | y5       | +0.28403 | y5       | +0.21694 | y5       | +0.15451 | y5       | +0.09755 |
| x6       | +0.15451 | x6       | 0.00000  | x6       | -0.12941 | x6       | -0.23236 | x6       | -0.31174 | x6       | -0.37157 | x6       | -0.41573 |
| y6       | +0.47553 | y6       | +0.50000 | y6       | +0.48296 | y6       | +0.44273 | y6       | +0.39092 | y6       | +0.33457 | y6       | +0.27779 |
| x7       | +0.40451 | x7       | +0.27032 | x7       | +0.12941 | x7       | 0.00000  | x7       | -0.11126 | x7       | -0.20337 | x7       | -0.27779 |
| y7       | +0.29389 | y7       | +0.42063 | y7       | +0.48296 | y7       | +0.50000 | y7       | +0.48746 | y7       | +0.45677 | y7       | +0.41573 |
| x8       | +0.50000 | x8       | +0.45482 | x8       | +0.35355 | x8       | +0.23236 | x8       | +0.11126 | x8       | 0.00000  | x8       | -0.09755 |
| y8       | 0.00000  | y8       | +0.20771 | y8       | +0.35355 | y8       | +0.44273 | y8       | +0.48746 | y8       | +0.50000 | y8       | +0.49039 |
| x9       | +0.40451 | x9       | +0.49491 | x9       | +0.48296 | x9       | +0.41149 | x9       | +0.31174 | x9       | +0.20337 | x9       | +0.09755 |
| y9       | -0.29389 | y9       | -0.07116 | y9       | +0.12941 | y9       | +0.28403 | y9       | +0.39092 | y9       | +0.45677 | y9       | +0.49039 |
| x10      | +0.15451 | x10      | +0.37787 | x10      | +0.48296 | x10      | +0.49635 | x10      | +0.45048 | x10      | +0.37157 | x10      | +0.27779 |
| y10      | -0.47553 | x11      | -0.32743 | y10      | -0.12941 | x11      | +0.06027 | y10      | +0.21694 | x11      | +0.33457 | y10      | +0.41573 |
|          |          | y11      | +0.14087 | x11      | +0.35355 | x11      | +0.46751 | x11      | +0.50000 | x11      | +0.47553 | x11      | +0.41573 |
|          |          | y11      | -0.47975 | y11      | -0.35355 | y11      | -0.17730 | y11      | 0.00000  | x11      | +0.15451 | y11      | -0.27779 |
|          |          |          |          | x12      | +0.12941 | x12      | +0.33156 | x12      | +0.45048 | x12      | +0.49726 | x12      | +0.49039 |
|          |          |          |          | y12      | -0.48296 | y12      | -0.37426 | y12      | -0.21694 | x12      | -0.05226 | y12      | +0.09755 |
|          |          |          |          |          |          | x13      | +0.11966 | x13      | +0.31174 | x13      | +0.43301 | x13      | +0.49039 |
|          |          |          |          |          |          | y13      | -0.48547 | y13      | -0.39092 | y13      | -0.25000 | y13      | -0.09755 |
|          |          |          |          |          |          |          |          | x14      | +0.11126 | x14      | +0.29389 | x14      | +0.41573 |
|          |          |          |          |          |          |          |          | y14      | -0.48746 | y14      | -0.40451 | y14      | -0.27779 |
|          |          |          |          |          |          |          |          |          |          | x15      | +0.10396 | x15      | +0.27779 |
|          |          |          |          |          |          |          |          |          |          | y15      | -0.48907 | y15      | -0.41573 |
|          |          |          |          |          |          |          |          |          |          |          |          | x16      | +0.09755 |
|          |          |          |          |          |          |          |          |          |          |          |          | y16      | -0.49039 |



The diagram shows a type "B" circle for a 5-hole circle. Coordinates x, y are given in the table for hole circles of from 3 to 28 holes. Dimensions are for holes numbered in a counterclockwise direction (as shown). Dimensions given are based upon a hole circle of unit diameter. For a hole circle of, say, 3-inch or 3-centimeter diameter, multiply table values by 3.

**Table 15. (Continued) Hole Coordinate Dimension Factors for Jig Boring — Type "B" Hole Circles Central Coordinates (English or Metric units)**

| 17 Holes |          | 18 Holes |          | 19 Holes |          | 20 Holes |          | 21 Holes |          | 22 Holes |          | 23 Holes |          |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| x1       | -0.09187 | x1       | -0.08682 | x1       | -0.08230 | x1       | -0.07822 | x1       | -0.07452 | x1       | -0.07116 | x1       | -0.06808 |
| y1       | -0.49149 | y1       | -0.49240 | y1       | -0.49318 | y1       | -0.49384 | y1       | -0.49442 | y1       | -0.49491 | y1       | -0.49534 |
| x2       | -0.26322 | x2       | -0.25000 | x2       | -0.23797 | x2       | -0.22700 | x2       | -0.21694 | x2       | -0.20771 | x2       | -0.19920 |
| y2       | -0.42511 | y2       | -0.43301 | y2       | -0.43974 | y2       | -0.44550 | y2       | -0.45048 | y2       | -0.45482 | y2       | -0.45861 |
| x3       | -0.39901 | x3       | -0.38302 | x3       | -0.36786 | x3       | -0.35355 | x3       | -0.34009 | x3       | -0.32743 | x3       | -0.31554 |
| y3       | -0.30132 | y3       | -0.32139 | y3       | -0.33864 | y3       | -0.35355 | y3       | -0.36653 | y3       | -0.37787 | y3       | -0.38786 |
| x4       | -0.48091 | x4       | -0.46985 | x4       | -0.45789 | x4       | -0.44550 | x4       | -0.43301 | x4       | -0.42063 | x4       | -0.40848 |
| y4       | -0.13683 | y4       | -0.17101 | y4       | -0.20085 | y4       | -0.22700 | y4       | -0.25000 | y4       | -0.27032 | y4       | -0.28834 |
| x5       | -0.49787 | x5       | -0.50000 | x5       | -0.49829 | x5       | -0.49384 | x5       | -0.48746 | x5       | -0.47975 | x5       | -0.47113 |
| y5       | +0.04613 | y5       | 0.00000  | y5       | -0.04129 | y5       | -0.07822 | y5       | -0.11126 | y5       | -0.14087 | y5       | -0.16744 |
| x6       | -0.44758 | x6       | -0.46985 | x6       | -0.48470 | x6       | -0.49384 | x6       | -0.49860 | x6       | -0.50000 | x6       | -0.49883 |
| y6       | +0.22287 | y6       | +0.17101 | y6       | +0.12274 | y6       | +0.07822 | y6       | +0.03737 | y6       | 0.00000  | y6       | -0.03412 |
| x7       | -0.33685 | x7       | -0.38302 | x7       | -0.41858 | x7       | -0.44550 | x7       | -0.46544 | x7       | -0.47975 | x7       | -0.48954 |
| y7       | +0.36950 | y7       | +0.32139 | y7       | +0.27347 | y7       | +0.22700 | y7       | +0.18267 | y7       | +0.14087 | y7       | +0.10173 |
| x8       | -0.18062 | x8       | -0.25000 | x8       | -0.30711 | x8       | -0.35355 | x8       | -0.39092 | x8       | -0.42063 | x8       | -0.44394 |
| y8       | +0.46624 | y8       | +0.43301 | y8       | +0.39457 | y8       | +0.35355 | y8       | +0.31174 | y8       | +0.27032 | y8       | +0.23003 |
| x9       | 0.00000  | x9       | -0.08682 | x9       | -0.16235 | x9       | -0.22700 | x9       | -0.28166 | x9       | -0.32743 | x9       | -0.36542 |
| y9       | +0.50000 | y9       | +0.49240 | y9       | +0.47291 | y9       | +0.44550 | y9       | +0.41312 | y9       | +0.37787 | y9       | +0.34128 |
| x10      | +0.18062 | x10      | +0.08682 | x10      | 0.00000  | x10      | -0.07822 | x10      | -0.14738 | x10      | -0.20771 | x10      | -0.25979 |
| y10      | +0.46624 | y10      | +0.49240 | y10      | +0.50000 | y10      | +0.49384 | y10      | +0.47779 | y10      | +0.45482 | y10      | +0.42721 |
| x11      | +0.33685 | x11      | +0.25000 | x11      | +0.16235 | x11      | +0.07822 | x11      | 0.00000  | x11      | -0.07116 | x11      | -0.13490 |
| y11      | +0.36950 | y11      | +0.43301 | y11      | +0.47291 | y11      | +0.49384 | y11      | +0.50000 | y11      | +0.49491 | y11      | +0.48146 |
| x12      | +0.44758 | x12      | +0.38302 | x12      | +0.30711 | x12      | +0.22700 | x12      | +0.14738 | x12      | +0.07116 | x12      | 0.00000  |
| y12      | +0.22287 | y12      | +0.32139 | y12      | +0.39457 | y12      | +0.44550 | y12      | +0.47779 | y12      | +0.49491 | y12      | +0.50000 |
| x13      | +0.49787 | x13      | +0.46985 | x13      | +0.41858 | x13      | +0.35355 | x13      | +0.28166 | x13      | +0.20771 | x13      | +0.13490 |
| y13      | +0.04613 | y13      | +0.17101 | y13      | +0.27347 | y13      | +0.35355 | y13      | +0.41312 | y13      | +0.45482 | y13      | +0.48146 |
| x14      | +0.48091 | x14      | +0.50000 | x14      | +0.48470 | x14      | +0.44550 | x14      | +0.39092 | x14      | +0.32743 | x14      | +0.25979 |
| y14      | -0.13683 | y14      | 0.00000  | y14      | +0.12274 | y14      | +0.22700 | y14      | +0.31174 | y14      | +0.37787 | y14      | +0.42721 |
| x15      | +0.39901 | x15      | +0.46985 | x15      | +0.49829 | x15      | +0.49384 | x15      | +0.46544 | x15      | +0.42063 | x15      | +0.36542 |
| y15      | -0.30132 | y15      | -0.17101 | y15      | -0.04129 | y15      | +0.07822 | y15      | +0.18267 | y15      | +0.27032 | y15      | +0.34128 |
| x16      | +0.26322 | x16      | +0.38302 | x16      | +0.45789 | x16      | +0.49384 | x16      | +0.49860 | x16      | +0.47975 | x16      | +0.44394 |
| y16      | -0.42511 | y16      | -0.32139 | y16      | -0.20085 | y16      | -0.07822 | y16      | +0.03737 | y16      | +0.14087 | y16      | +0.23003 |
| x17      | +0.09187 | x17      | +0.25000 | x17      | +0.36786 | x17      | +0.44550 | x17      | +0.48746 | x17      | +0.50000 | x17      | +0.48954 |
| y17      | -0.49149 | y17      | -0.43301 | y17      | -0.33864 | y17      | -0.22700 | y17      | -0.11126 | y17      | 0.00000  | y17      | +0.10173 |
|          |          | x18      | +0.08682 | x18      | +0.23797 | x18      | +0.35355 | x18      | +0.43301 | x18      | +0.47975 | x18      | +0.49883 |
|          |          | y18      | -0.49240 | y18      | -0.43974 | y18      | -0.35355 | y18      | -0.25000 | y18      | -0.14087 | y18      | -0.03412 |
|          |          |          |          | x19      | +0.08230 | x19      | +0.22700 | x19      | +0.34009 | x19      | +0.42063 | x19      | +0.47113 |
|          |          |          |          | y19      | -0.49318 | y19      | -0.44550 | y19      | -0.36653 | y19      | -0.27032 | y19      | -0.16744 |
|          |          |          |          |          |          | x20      | +0.07822 | x20      | +0.21694 | x20      | +0.32743 | x20      | +0.40848 |
|          |          |          |          |          |          | y20      | -0.49384 | y20      | -0.45048 | y20      | -0.37787 | y20      | -0.28834 |
|          |          |          |          |          |          |          |          | x21      | +0.07452 | x21      | +0.20771 | x21      | +0.31554 |
|          |          |          |          |          |          |          |          | y21      | -0.49442 | y21      | -0.45482 | y21      | -0.38786 |
|          |          |          |          |          |          |          |          |          |          | x22      | +0.07116 | x22      | +0.19920 |
|          |          |          |          |          |          |          |          |          |          | y22      | -0.49491 | y22      | -0.45861 |
|          |          |          |          |          |          |          |          |          |          |          |          | x23      | +0.06808 |
|          |          |          |          |          |          |          |          |          |          |          |          | y23      | -0.49534 |
| 24 Holes |          | 25 Holes |          | 26 Holes |          | 27 Holes |          | 28 Holes |          |          |          |          |          |
| x1       | -0.06526 | x1       | -0.06267 | x1       | -0.06027 | x1       | -0.05805 | x1       | -0.05598 |          |          |          |          |
| y1       | -0.49572 | y1       | -0.49606 | y1       | -0.49635 | y1       | -0.49662 | y1       | -0.49686 |          |          |          |          |
| x2       | -0.19134 | x2       | -0.18406 | x2       | -0.17730 | x2       | -0.17101 | x2       | -0.16514 |          |          |          |          |
| y2       | -0.46194 | y2       | -0.46489 | y2       | -0.46751 | y2       | -0.46985 | y2       | -0.47194 |          |          |          |          |
| x3       | -0.30438 | x3       | -0.29389 | x3       | -0.28403 | x3       | -0.27475 | x3       | -0.26602 |          |          |          |          |
| y3       | -0.39668 | y3       | -0.40451 | y3       | -0.41149 | y3       | -0.41774 | y3       | -0.42336 |          |          |          |          |

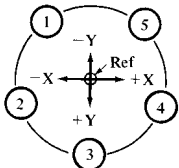


The diagram shows a type "B" circle for a 5-hole circle. Coordinates x, y are given in the table for hole circles of from 3 to 28 holes. Dimensions are for holes numbered in a counterclockwise direction (as shown). Dimensions given are based upon a hole circle of unit diameter. For a hole circle of, say, 3-inch or 3-centimeter diameter, multiply table values by 3.



**Table 15. (Continued) Hole Coordinate Dimension Factors for Jig Boring — Type "B" Hole Circles Central Coordinates (English or Metric units)**

| 24 Holes     |              | 25 Holes     |              | 26 Holes     |              | 27 Holes     |              | 28 Holes     |              |
|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| x4 -0.39668  | y4 -0.30438  | x4 -0.38526  | y4 -0.31871  | x4 -0.37426  | y4 -0.33156  | x4 -0.36369  | y4 -0.34312  | x4 -0.35355  | y4 -0.35355  |
| x5 -0.46194  | y5 -0.19134  | x5 -0.45241  | y5 -0.21289  | x5 -0.44273  | y5 -0.23236  | x5 -0.43301  | y5 -0.25000  | x5 -0.42336  | y5 -0.26602  |
| x6 -0.49572  | y6 -0.06526  | x6 -0.49114  | y6 -0.09369  | x6 -0.48547  | y6 -0.11966  | x6 -0.47899  | y6 -0.14340  | x6 -0.47194  | y6 -0.16514  |
| x7 -0.49572  | y7 +0.06526  | x7 -0.49901  | y7 +0.03140  | x7 -0.50000  | y7 0.00000   | x7 -0.49915  | y7 -0.02907  | x7 -0.49686  | y7 -0.05598  |
| x8 -0.46194  | y8 +0.19134  | x8 -0.47553  | y8 +0.15451  | x8 -0.48547  | y8 +0.11966  | x8 -0.49240  | y8 +0.08682  | x8 -0.49686  | y8 +0.05598  |
| x9 -0.39668  | y9 +0.30438  | x9 -0.42216  | y9 +0.26791  | x9 -0.44273  | y9 +0.23236  | x9 -0.45911  | y9 +0.19804  | x9 -0.47194  | y9 +0.16514  |
| x10 -0.30438 | y10 +0.39668 | x10 -0.34227 | y10 +0.36448 | x10 -0.37426 | y10 +0.33156 | x10 -0.40106 | y10 +0.29858 | x10 -0.42336 | y10 +0.26602 |
| x11 -0.19134 | y11 +0.46194 | x11 -0.24088 | y11 +0.43815 | x11 -0.28403 | y11 +0.41149 | x11 -0.32139 | y11 +0.38302 | x11 -0.35355 | y11 +0.35355 |
| x12 -0.06526 | y12 +0.49572 | x12 -0.12434 | y12 +0.48429 | x12 -0.17730 | y12 +0.46751 | x12 -0.22440 | y12 +0.44682 | x12 -0.26602 | y12 +0.42336 |
| x13 +0.06526 | y13 +0.49572 | x13 0.00000  | y13 +0.50000 | x13 -0.06027 | y13 +0.49635 | x13 -0.11531 | y13 +0.48652 | x13 -0.16514 | y13 +0.47194 |
| x14 +0.19134 | y14 +0.46194 | x14 +0.12434 | y14 +0.48429 | x14 +0.06027 | y14 +0.49635 | x14 0.00000  | y14 +0.50000 | x14 -0.05598 | y14 +0.49686 |
| x15 +0.30438 | y15 +0.39668 | x15 +0.24088 | y15 +0.43815 | x15 +0.17730 | y15 +0.46751 | x15 +0.11531 | y15 +0.48652 | x15 +0.05598 | y15 +0.49686 |
| x16 +0.39668 | y16 +0.30438 | x16 +0.34227 | y16 +0.36448 | x16 +0.28403 | y16 +0.41149 | x16 +0.22440 | y16 +0.44682 | x16 +0.16514 | y16 +0.47194 |
| x17 +0.46194 | y17 +0.19134 | x17 +0.42216 | y17 +0.26791 | x17 +0.37426 | y17 +0.33156 | x17 +0.32139 | y17 +0.38302 | x17 +0.26602 | y17 +0.42336 |
| x18 +0.49572 | y18 +0.06526 | x18 +0.47553 | y18 +0.15451 | x18 +0.44273 | y18 +0.23236 | x18 +0.40106 | y18 +0.29858 | x18 +0.35355 | y18 +0.35355 |
| x19 -0.49572 | y19 -0.06526 | x19 +0.49901 | y19 +0.03140 | x19 +0.48547 | y19 +0.11966 | x19 +0.45911 | y19 +0.19804 | x19 +0.42336 | y19 +0.26602 |
| x20 +0.46194 | y20 +0.19134 | x20 +0.49114 | y20 +0.09369 | x20 +0.50000 | y20 0.00000  | x20 +0.49240 | y20 +0.08682 | x20 +0.47194 | y20 +0.16514 |
| x21 +0.39668 | y21 -0.30438 | x21 +0.45241 | y21 -0.21289 | x21 +0.48547 | y21 -0.11966 | x21 +0.49915 | y21 -0.02907 | x21 +0.49686 | y21 +0.05598 |
| x22 +0.30438 | y22 -0.39668 | x22 +0.38526 | y22 -0.31871 | x22 +0.44273 | y22 -0.23236 | x22 +0.47899 | y22 -0.14340 | x22 +0.49686 | y22 -0.05598 |
| x23 +0.19134 | y23 -0.46194 | x23 +0.29389 | y23 -0.40451 | x23 +0.37426 | y23 -0.33156 | x23 +0.43301 | y23 -0.25000 | x23 +0.47194 | y23 -0.16514 |
| x24 +0.06526 | y24 -0.49572 | x24 +0.18406 | y24 -0.46489 | x24 +0.28403 | y24 -0.41149 | x24 +0.36369 | y24 -0.34312 | x24 +0.42336 | y24 -0.26602 |
|              |              | x25 +0.06267 | y25 -0.49606 | x25 +0.17730 | y25 -0.46751 | x25 +0.27475 | y25 -0.41774 | x25 +0.35355 | y25 -0.35355 |
|              |              |              |              | x26 +0.06027 | y26 -0.49635 | x26 +0.17101 | y26 -0.46985 | x26 +0.26602 | y26 -0.42336 |
|              |              |              |              |              |              | x27 +0.05805 | y27 -0.49662 | x27 +0.16514 | y27 -0.47194 |
|              |              |              |              |              |              |              |              | x28 +0.05598 | y28 -0.49686 |



The diagram shows a type "B" circle for a 5-hole circle. Coordinates x, y are given in the table for hole circles of from 3 to 28 holes. Dimensions are for holes numbered in a counterclockwise direction (as shown). Dimensions given are based upon a hole circle of unit diameter. For a hole circle of, say, 3-inch or 3-centimeter diameter, multiply table values by 3.

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## CUTTING SPEEDS AND FEEDS

### Introduction to Speeds and Feeds

**Work Materials.**—The large number of work materials that are commonly machined vary greatly in their basic structure and the ease with which they can be machined. Yet it is possible to group together certain materials having similar machining characteristics, for the purpose of recommending the cutting speed at which they can be cut. Most materials that are machined are metals and it has been found that the most important single factor influencing the ease with which a metal can be cut is its microstructure, followed by any cold work that may have been done to the metal, which increases its hardness. Metals that have a similar, but not necessarily the same microstructure, will tend to have similar machining characteristics. Thus, the grouping of the metals in the accompanying tables has been done on the basis of their microstructure.

With the exception of a few soft and gummy metals, experience has shown that harder metals are more difficult to cut than softer metals. Furthermore, any given metal is more difficult to cut when it is in a harder form than when it is softer. It is more difficult to penetrate the harder metal and more power is required to cut it. These factors in turn will generate a higher cutting temperature at any given cutting speed, thereby making it necessary to use a slower speed, for the cutting temperature must always be kept within the limits that can be sustained by the cutting tool without failure. Hardness, then, is an important property that must be considered when machining a given metal. Hardness alone, however, cannot be used as a measure of cutting speed. For example, if pieces of AISI 11L17 and AISI 1117 steel both have a hardness of 150 Bhn, their recommended cutting speeds for high-speed steel tools will be 140 fpm and 130 fpm, respectively. In some metals, two entirely different microstructures can produce the same hardness. As an example, a fine pearlite microstructure and a tempered martensite microstructure can result in the same hardness in a steel. These microstructures will not machine alike. For practical purposes, however, information on hardness is usually easier to obtain than information on microstructure; thus, hardness alone is usually used to differentiate between different cutting speeds for machining a metal. In some situations, the hardness of a metal to be machined is not known. When the hardness is not known, the material condition can be used as a guide.

The surface of ferrous metal castings has a scale that is more difficult to machine than the metal below. Some scale is more difficult to machine than others, depending on the foundry sand used, the casting process, the method of cleaning the casting, and the type of metal cast. Special electrochemical treatments sometimes can be used that almost entirely eliminate the effect of the scale on machining, although castings so treated are not frequently encountered. Usually, when casting scale is encountered, the cutting speed is reduced approximately 5 or 10 per cent. Difficult-to-machine surface scale can also be encountered when machining hot-rolled or forged steel bars.

Metallurgical differences that affect machining characteristics are often found within a single piece of metal. The occurrence of hard spots in castings is an example. Different microstructures and hardness levels may occur within a casting as a result of variations in the cooling rate in different parts of the casting. Such variations are less severe in castings that have been heat treated. Steel bar stock is usually harder toward the outside than toward the center of the bar. Sometimes there are slight metallurgical differences along the length of a bar that can affect its cutting characteristics.

**Cutting Tool Materials.**—The recommended cutting feeds and speeds in the accompanying tables are given for high-speed steel, coated and uncoated carbides, ceramics, cermets, and polycrystalline diamonds. More data are available for HSS and carbides because these materials are the most commonly used. Other materials that are used to make cutting tools are cemented oxides or ceramics, cermets, cast nonferrous alloys (Stellite), single-crystal diamonds, polycrystalline diamonds, and cubic boron nitride.

*Carbon Tool Steel:* It is used primarily to make the less expensive drills, taps, and reamers. It is seldom used to make single-point cutting tools. Hardening in carbon steels is very shallow, although some have a small amount of vanadium and chromium added to improve their hardening quality. The cutting speed to use for plain carbon tool steel should be approximately one-half of the recommended speed for high-speed steel.

*High-Speed Steel:* This designates a number of steels having several properties that enhance their value as cutting tool material. They can be hardened to a high initial or room-temperature hardness ranging from 63 Rc to 65 Rc for ordinary high-speed steels and up to 70 Rc for the so-called superhigh-speed steels. They can retain sufficient hardness at temperatures up to 1,000 to 1,100°F to enable them to cut at cutting speeds that will generate these tool temperatures, and they will return to their original hardness when cooled to room temperature. They harden very deeply, enabling high-speed steels to be ground to the tool shape from solid stock and to be reground many times without sacrificing hardness at the cutting edge. High-speed steels can be made soft by annealing so that they can be machined into complex cutting tools such as drills, reamers, and milling cutters and then hardened.

The principal alloying elements of high-speed steels are tungsten (W), molybdenum (Mo), chromium (Cr), vanadium (V), together with carbon (C). There are a number of grades of high-speed steel that are divided into two types: tungsten high-speed steels and molybdenum high-speed steels. Tungsten high-speed steels are designated by the prefix T before the number that designates the grade. Molybdenum high-speed steels are designated by the prefix letter M. There is little performance difference between comparable grades of tungsten or molybdenum high-speed steel.

The addition of 5 to 12 per cent cobalt to high-speed steel increases its hardness at the temperatures encountered in cutting, thereby improving its wear resistance and cutting efficiency. Cobalt slightly increases the brittleness of high-speed steel, making it susceptible to chipping at the cutting edge. For this reason, cobalt high-speed steels are primarily made into single-point cutting tools that are used to take heavy roughing cuts in abrasive materials and through rough abrasive surface scales.

The M40 series and T15 are a group of high-hardness or so-called super high-speed steels that can be hardened to 70 Rc; however, they tend to be brittle and difficult to grind. For cutting applications, they are usually heat treated to 67–68 Rc to reduce their brittleness and tendency to chip. The M40 series is appreciably easier to grind than T15. They are recommended for machining tough die steels and other difficult-to-cut materials; they are not recommended for applications where conventional high-speed steels perform well. High-speed steels made by the powder-metallurgy process are tougher and have an improved grindability when compared with similar grades made by the customary process. Tools made of these steels can be hardened about 1 Rc higher than comparable high-speed steels made by the customary process without a sacrifice in toughness. They are particularly useful in applications involving intermittent cutting and where tool life is limited by chipping. All these steels augment rather than replace the conventional high-speed steels.

*Cemented Carbides:* They are also called sintered carbides or simply carbides. They are harder than high-speed steels and have excellent wear resistance. Information on cemented carbides and other hard metal tools is included in the section *CEMENTED CARBIDES* starting on page 773.

Cemented carbides retain a very high degree of hardness at temperatures up to 1400°F and even higher; therefore, very fast cutting speeds can be used. When used at fast cutting speeds, they produce good surface finishes on the workpiece. Carbides are more brittle than high-speed steel and, therefore, must be used with more care.

Hundreds of grades of carbides are available and attempts to classify these grades by area of application have not been entirely successful.

There are four distinct types of carbides: 1) straight tungsten carbides; 2) crater-resistant carbides; 3) titanium carbides; and 4) coated carbides.

*Straight Tungsten Carbide:* This is the most abrasion-resistant cemented carbide and is used to machine gray cast iron, most nonferrous metals, and nonmetallic materials, where abrasion resistance is the primary criterion. Straight tungsten carbide will rapidly form a crater on the tool face when used to machine steel, which reduces the life of the tool. Titanium carbide is added to tungsten carbide in order to counteract the rapid formation of the crater. In addition, tantalum carbide is usually added to prevent the cutting edge from deforming when subjected to the intense heat and pressure generated in taking heavy cuts.

*Crater-Resistant Carbides:* These carbides, containing titanium and tantalum carbides in addition to tungsten carbide, are used to cut steels, alloy cast irons, and other materials that have a strong tendency to form a crater.

*Titanium Carbides:* These carbides are made entirely from titanium carbide and small amounts of nickel and molybdenum. They have an excellent resistance to cratering and to heat. Their high hot hardness enables them to operate at higher cutting speeds, but they are more brittle and less resistant to mechanical and thermal shock. Therefore, they are not recommended for taking heavy or interrupted cuts. Titanium carbides are less abrasion-resistant and not recommended for cutting through scale or oxide films on steel. Although the resistance to cratering of titanium carbides is excellent, failure caused by crater formation can sometimes occur because the chip tends to curl very close to the cutting edge, thereby forming a small crater in this region that may break through.

*Coated Carbides:* These are available only as indexable inserts because the coating would be removed by grinding. The principal coating materials are titanium carbide (TiC), titanium nitride (TiN), and aluminum oxide ( $Al_2O_3$ ). A very thin layer (approximately 0.0002 in.) of coating material is deposited over a cemented carbide insert; the material below the coating is called the substrate. The overall performance of the coated carbide is limited by the substrate, which provides the required toughness and resistance to deformation and thermal shock. With an equal tool life, coated carbides can operate at higher cutting speeds than uncoated carbides. The increase may be 20 to 30 per cent and sometimes up to 50 per cent faster. Titanium carbide and titanium nitride coated carbides usually operate in the medium (200–800 fpm) cutting speed range, and aluminum oxide coated carbides are used in the higher (800–1600 fpm) cutting speed range.

*Carbide Grade Selection:* The selection of the best grade of carbide for a particular application is very important. An improper grade of carbide will result in a poor performance—it may even cause the cutting edge to fail before any significant amount of cutting has been done. Because of the many grades and the many variables that are involved, the carbide producers should be consulted to obtain recommendations for the application of their grades of carbide. A few general guidelines can be given that are useful to form an orientation. Metal cutting carbides usually range in hardness from about 89.5 Ra (Rockwell A Scale) to 93.0 Ra with the exception of titanium carbide, which has a hardness range of 90.5 Ra to 93.5 Ra. Generally, the harder carbides are more wear-resistant and more brittle, whereas the softer carbides are less wear-resistant but tougher. A choice of hardness must be made to suit the given application. The very hard carbides are generally used for taking light finishing cuts. For other applications, select the carbide that has the highest hardness with sufficient strength to prevent chipping or breaking. Straight tungsten carbide grades should always be used unless cratering is encountered. Straight tungsten carbides are used to machine gray cast iron, ferritic malleable iron, austenitic stainless steel, high-temperature alloys, copper, brass, bronze, aluminum alloys, zinc alloy die castings, and plastics. Crater-resistant carbides should be used to machine plain carbon steel, alloy steel, tool steel, pearlitic malleable iron, nodular iron, other highly alloyed cast irons, ferritic stainless steel, martensitic stainless steel, and certain high-temperature alloys. Titanium carbides are recommended for taking high-speed finishing and semifinishing cuts on steel, especially the low-carbon, low-alloy steels, which are less abrasive and have a strong tendency to form a crater. They are also used to take light cuts on alloy cast iron and on



some high-nickel alloys. Nonferrous materials, such as some aluminum alloys and brass, that are essentially nonabrasive may also be machined with titanium carbides. Abrasive materials and others that should not be machined with titanium carbides include gray cast iron, titanium alloys, cobalt- and nickel-base superalloys, stainless steel, bronze, many aluminum alloys, fiberglass, plastics, and graphite. The feed used should not exceed about 0.020 inch per revolution.

Coated carbides can be used to take cuts ranging from light finishing to heavy roughing on most materials that can be cut with these carbides. The coated carbides are recommended for machining all free-machining steels, all plain carbon and alloy steels, tool steels, martensitic and ferritic stainless steels, precipitation-hardening stainless steels, alloy cast iron, pearlitic and martensitic malleable iron, and nodular iron. They are also recommended for taking light finishing and roughing cuts on austenitic stainless steels. Coated carbides should not be used to machine nickel- and cobalt-base superalloys, titanium and titanium alloys, brass, bronze, aluminum alloys, pure metals, refractory metals, and nonmetals such as fiberglass, graphite, and plastics.

*Ceramic Cutting Tool Materials:* These are made from finely powdered aluminum oxide particles sintered into a hard dense structure without a binder material. Aluminum oxide is also combined with titanium carbide to form a composite, which is called a cermet. These materials have a very high hot hardness enabling very high cutting speeds to be used. For example, ceramic cutting tools have been used to cut AISI 1040 steel at a cutting speed of 18,000 fpm with a satisfactory tool life. However, much lower cutting speeds, in the range of 1000 to 4000 fpm and lower, are more common because of limitations placed by the machine tool, cutters, and chucks. Although most applications of ceramic and cermet cutting tool materials are for turning, they have also been used successfully for milling. Ceramics and cermets are relatively brittle and a special cutting edge preparation is required to prevent chipping or edge breakage. This preparation consists of honing or grinding a narrow flat land, 0.002 to 0.006 inch wide, on the cutting edge that is made about 30 degrees with respect to the tool face. For some heavy-duty applications, a wider land is used. The setup should be as rigid as possible and the feed rate should not normally exceed 0.020 inch, although 0.030 inch has been used successfully. Ceramics and cermets are recommended for roughing and finishing operations on all cast irons, plain carbon and alloy steels, and stainless steels. Materials up to a hardness of 60 Rockwell C Scale can be cut with ceramic and cermet cutting tools. These tools should not be used to machine aluminum and aluminum alloys, magnesium alloys, titanium, and titanium alloys.

*Cast Nonferrous Alloy:* Cutting tools of this alloy are made from tungsten, tantalum, chromium, and cobalt plus carbon. Other alloying elements are also used to produce materials with high temperature and wear resistance. These alloys cannot be softened by heat treatment and must be cast and ground to shape. The room-temperature hardness of cast nonferrous alloys is lower than for high-speed steel, but the hardness and wear resistance is retained to a higher temperature. The alloys are generally marketed under trade names such as Stellite, Crobalt, and Tantung. The initial cutting speed for cast nonferrous tools can be 20 to 50 per cent greater than the recommended cutting speed for high-speed steel as given in the accompanying tables.

*Diamond Cutting Tools:* These are available in three forms: single-crystal natural diamonds shaped to a cutting edge and mounted on a tool holder on a boring bar; polycrystalline diamond indexable inserts made from synthetic or natural diamond powders that have been compacted and sintered into a solid mass, and chemically vapor-deposited diamond. Single-crystal and polycrystalline diamond cutting tools are very wear-resistant, and are recommended for machining abrasive materials that cause other cutting tool materials to wear rapidly. Typical of the abrasive materials machined with single-crystal and polycrystalline diamond tools and cutting speeds used are the following: fiberglass, 300 to 1000 fpm; fused silica, 900 to 950 fpm; reinforced melamine plastics, 350 to 1000 fpm; reinforced phenolic plastics, 350 to 1000 fpm; thermosetting plastics, 300 to 2000 fpm; Teflon,

600 fpm; nylon, 200 to 300 fpm; mica, 300 to 1000 fpm; graphite, 200 to 2000 fpm; babbitt bearing metal, 700 fpm; and aluminum-silicon alloys, 1000 to 2000 fpm. Another important application of diamond cutting tools is to produce fine surface finishes on soft nonferrous metals that are difficult to finish by other methods. Surface finishes of 1 to 2 microinches can be readily obtained with single-crystal diamond tools, and finishes down to 10 microinches can be obtained with polycrystalline diamond tools. In addition to babbitt and the aluminum-silicon alloys, other metals finished with diamond tools include: soft aluminum, 1000 to 2000 fpm; all wrought and cast aluminum alloys, 600 to 1500 fpm; copper, 1000 fpm; brass, 500 to 1000 fpm; bronze, 300 to 600 fpm; oilite bearing metal, 500 fpm; silver, gold, and platinum, 300 to 2500 fpm; and zinc, 1000 fpm. Ferrous alloys, such as cast iron and steel, should not be machined with diamond cutting tools because the high cutting temperatures generated will cause the diamond to transform into carbon.

*Chemically Vapor-Deposited (CVD) Diamond:* This is a new tool material offering performance characteristics well suited to highly abrasive or corrosive materials, and hard-to-machine composites. CVD diamond is available in two forms: thick-film tools, which are fabricated by brazing CVD diamond tips, approximately 0.020 inch (0.5 mm) thick, to carbide substrates; and thin-film tools, having a pure diamond coating over the rake and flank surfaces of a ceramic or carbide substrate.

CVD is pure diamond, made at low temperatures and pressures, with no metallic binder phase. This diamond purity gives CVD diamond tools extreme hardness, high abrasion resistance, low friction, high thermal conductivity, and chemical inertness. CVD tools are generally used as direct replacements for PCD (polycrystalline diamond) tools, primarily in finishing, semifinishing, and continuous turning applications of extremely wear-intensive materials. The small grain size of CVD diamond (ranging from less than 1  $\mu\text{m}$  to 50  $\mu\text{m}$ ) yields superior surface finishes compared with PCD, and the higher thermal conductivity and better thermal and chemical stability of pure diamond allow CVD tools to operate at faster speeds without generating harmful levels of heat. The extreme hardness of CVD tools may also result in significantly longer tool life.

CVD diamond cutting tools are recommended for the following materials: aluminum and other ductile; nonferrous alloys such as copper, brass, and bronze; and highly abrasive composite materials such as graphite, carbon-carbon, carbon-filled phenolic, fiberglass, and honeycomb materials.

*Cubic Boron Nitride (CBN):* Next to diamond, CBN is the hardest known material. It will retain its hardness at a temperature of 1800°F and higher, making it an ideal cutting tool material for machining very hard and tough materials at cutting speeds beyond those possible with other cutting tool materials. Indexable inserts and cutting tool blanks made from this material consist of a layer, approximately 0.020 inch thick, of polycrystalline cubic boron nitride firmly bonded to the top of a cemented carbide substrate. Cubic boron nitride is recommended for rough and finish turning hardened plain carbon and alloy steels, hardened tool steels, hard cast irons, all hardness grades of gray cast iron, and superalloys. As a class, the superalloys are not as hard as hardened steel; however, their combination of high strength and tendency to deform plastically under the pressure of the cut, or gumminess, places them in the class of hard-to-machine materials. Conventional materials that can be readily machined with other cutting tool materials should not be machined with cubic boron nitride. Round indexable CBN inserts are recommended when taking severe cuts in order to provide maximum strength to the insert. When using square or triangular inserts, a large lead angle should be used, normally 15°, and whenever possible, 45°. A negative rake angle should always be used, which for most applications is negative 5°. The relief angle should be 5° to 9°. Although cubic boron nitride cutting tools can be used without a coolant, flooding the tool with a water-soluble type coolant is recommended.

**Cutting Speed, Feed, Depth of Cut, Tool Wear, and Tool Life.**—The cutting conditions that determine the rate of metal removal are the cutting speed, the feed rate, and the depth of cut. These cutting conditions and the nature of the material to be cut determine the

power required to take the cut. The cutting conditions must be adjusted to stay within the power available on the machine tool to be used. Power requirements are discussed in Estimating Machining Power later in this section.

The cutting conditions must also be considered in relation to the tool life. Tool life is defined as the cutting time to reach a predetermined amount of wear, usually flank wear. Tool life is determined by assessing the time—the tool life—at which a given predetermined flank wear is reached (0.01, 0.015, 0.025, 0.03 inch, for example). This amount of wear is called the tool wear criterion, and its size depends on the tool grade used. Usually, a tougher grade can be used with a bigger flank wear, but for finishing operations, where close tolerances are required, the wear criterion is relatively small. Other wear criteria are a predetermined value of the machined surface roughness and the depth of the crater that develops on the rake face of the tool.

The ANSI standard, Specification For Tool Life Testing With Single-Point Tools (ANSI B94.55M-1985), defines the end of tool life as a given amount of wear on the flank of a tool. This standard is followed when making scientific machinability tests with single-point cutting tools in order to achieve uniformity in testing procedures so that results from different machinability laboratories can be readily compared. It is not practicable or necessary to follow this standard in the shop; however, it should be understood that the cutting conditions and tool life are related.

Tool life is influenced most by cutting speed, then by the feed rate, and least by the depth of cut. When the depth of cut is increased to about 10 times greater than the feed, a further increase in the depth of cut will have no significant effect on the tool life. This characteristic of the cutting tool performance is very important in determining the operating or cutting conditions for machining metals. Conversely, if the cutting speed or the feed is decreased, the increase in the tool life will be proportionately greater than the decrease in the cutting speed or the feed.

Tool life is reduced when either feed or cutting speed is increased. For example, the cutting speed and the feed may be increased if a shorter tool life is accepted; furthermore, the reduction in the tool life will be proportionately greater than the increase in the cutting speed or the feed. However, it is less well understood that a higher feed rate (feed/rev  $\times$  speed) may result in a longer tool life if a higher feed/rev is used in combination with a lower cutting speed. This principle is well illustrated in the speed tables of this section, where two sets of feed and speed data are given (labeled *optimum* and *average*) that result in the same tool life. The *optimum* set results in a greater feed rate (i.e., increased productivity) although the feed/rev is higher and cutting speed lower than the *average* set. Complete instructions for using the speed tables and for estimating tool life are given in *How to Use the Feeds and Speeds Tables* starting on page 1022.

**Selecting Cutting Conditions.**—The first step in establishing the cutting conditions is to select the depth of cut. The depth of cut will be limited by the amount of metal that is to be machined from the workpiece, by the power available on the machine tool, by the rigidity of the workpiece and the cutting tool, and by the rigidity of the setup. The depth of cut has the least effect upon the tool life, so the heaviest possible depth of cut should always be used.

The second step is to select the feed (feed/rev for turning, drilling, and reaming, or feed/tooth for milling). The available power must be sufficient to make the required depth of cut at the selected feed. The maximum feed possible that will produce an acceptable surface finish should be selected.

The third step is to select the cutting speed. Although the accompanying tables provide recommended cutting speeds and feeds for many materials, experience in machining a certain material may form the best basis for adjusting the given cutting speeds to a particular job. However, in general, the depth of cut should be selected first, followed by the feed, and last the cutting speed.

**Table 16. Tool Troubleshooting Check List**

| Problem                                  | Tool Material   | Remedy   |
|--|-----------------|--|
| Excessive flank wear—Tool life too short | Carbide         | <ol style="list-style-type: none"> <li>1. Change to harder, more wear-resistant grade</li> <li>2. Reduce the cutting speed</li> <li>3. Reduce the cutting speed and increase the feed to maintain production</li> <li>4. Reduce the feed</li> <li>5. For work-hardenable materials—increase the feed</li> <li>6. Increase the lead angle</li> <li>7. Increase the relief angles</li> </ol>                                       |
|  | HSS             | <ol style="list-style-type: none"> <li>1. Use a coolant</li> <li>2. Reduce the cutting speed</li> <li>3. Reduce the cutting speed and increase the feed to maintain production</li> <li>4. Reduce the feed</li> <li>5. For work-hardenable materials—increase the feed</li> <li>6. Increase the lead angle</li> <li>7. Increase the relief angle</li> </ol>  |
| Excessive cratering                      | Carbide         | <ol style="list-style-type: none"> <li>1. Use a crater-resistant grade</li> <li>2. Use a harder, more wear-resistant grade</li> <li>3. Reduce the cutting speed</li> <li>4. Reduce the feed</li> <li>5. Widen the chip breaker groove</li> </ol>   |
|  | HSS             | <ol style="list-style-type: none"> <li>1. Use a coolant</li> <li>2. Reduce the cutting speed</li> <li>3. Reduce the feed</li> <li>4. Widen the chip breaker groove</li> </ol>  |
| Cutting edge chipping                    | Carbide         | <ol style="list-style-type: none"> <li>1. Increase the cutting speed</li> <li>2. Lightly hone the cutting edge</li> <li>3. Change to a tougher grade</li> <li>4. Use negative-rake tools</li> <li>5. Increase the lead angle</li> <li>6. Reduce the feed</li> <li>7. Reduce the depth of cut</li> <li>8. Reduce the relief angles</li> <li>9. If low cutting speed must be used, use a high-additive EP cutting fluid</li> </ol> |
|  | HSS             | <ol style="list-style-type: none"> <li>1. Use a high additive EP cutting fluid</li> <li>2. Lightly hone the cutting edge before using</li> <li>3. Increase the lead angle</li> <li>4. Reduce the feed</li> <li>5. Reduce the depth of cut</li> <li>6. Use a negative rake angle</li> <li>7. Reduce the relief angles</li> </ol>  |
|  | Carbide and HSS | <ol style="list-style-type: none"> <li>1. Check the setup for cause if chatter occurs</li> <li>2. Check the grinding procedure for tool overheating</li> <li>3. Reduce the tool overhang</li> </ol>  |
| Cutting edge deformation                 | Carbide         | <ol style="list-style-type: none"> <li>1. Change to a grade containing more tantalum</li> <li>2. Reduce the cutting speed</li> <li>3. Reduce the feed</li> </ol>   |
| Poor surface finish                      | Carbide         | <ol style="list-style-type: none"> <li>1. Increase the cutting speed</li> <li>2. If low cutting speed must be used, use a high additive EP cutting fluid</li> <li>4. For light cuts, use straight titanium carbide grade</li> <li>5. Increase the nose radius</li> <li>6. Reduce the feed</li> <li>7. Increase the relief angles</li> <li>8. Use positive rake tools</li> </ol>  |

**Table 16. (Continued) Tool Troubleshooting Check List**

| Problem                            | Tool Material   | Remedy   |
|------------------------------------|-----------------|--|
| Poor surface finish<br>(Continued) | HSS             | 1. Use a high additive EP cutting fluid<br>2. Increase the nose radius<br>3. Reduce the feed<br>4. Increase the relief angles<br>5. Increase the rake angles |
|                                    | Diamond         | 1. Use diamond tool for soft materials   |
| Notching at the depth of cut line  | Carbide and HSS | 1. Increase the lead angle   |
|                                    |                 | 2. Reduce the feed   |

**Cutting Speed Formulas**

Most machining operations are conducted on machine tools having a rotating spindle. Cutting speeds are usually given in feet or meters per minute and these speeds must be converted to spindle speeds, in revolutions per minute, to operate the machine. Conversion is accomplished by use of the following formulas:

$$\begin{array}{ll} \text{For U.S. units:} & \text{For metric units:} \\ N = \frac{12V}{\pi D} = 3.82 \frac{V}{D} \text{ rpm} & N = \frac{1000V}{\pi D} = 318.3 \frac{V}{D} \text{ rpm} \end{array}$$

where  $N$  is the spindle speed in revolutions per minute (rpm);  $V$  is the cutting speed in feet per minute (fpm) for U.S. units and meters per minute (m/min) for metric units. In turning,  $D$  is the diameter of the workpiece; in milling, drilling, reaming, and other operations that use a rotating tool,  $D$  is the cutter diameter in inches for U.S. units and in millimeters for metric units.  $\pi = 3.1416$ .

*Example:* The cutting speed for turning a 4-inch (101.6-mm) diameter bar has been found to be 575 fpm (175.3 m/min). Using both the inch and metric formulas, calculate the lathe spindle speed.

$$N = \frac{12V}{\pi D} = \frac{12 \times 575}{3.1416 \times 4} = 549 \text{ rpm} \quad N = \frac{1000V}{\pi D} = \frac{1000 \times 175.3}{3.1416 \times 101.6} = 549 \text{ rpm}$$

When the cutting tool or workpiece diameter and the spindle speed in rpm are known, it is often necessary to calculate the cutting speed in feet or meters per minute. In this event, the following formulas are used.

$$\begin{array}{ll} \text{For U.S. units:} & \text{For metric units:} \\ V = \frac{\pi DN}{12} \text{ fpm} & V = \frac{\pi DN}{1000} \text{ m/min} \end{array}$$

As in the previous formulas,  $N$  is the rpm and  $D$  is the diameter in inches for the U.S. unit formula and in millimeters for the metric formula.

*Example:* Calculate the cutting speed in feet per minute and in meters per minute if the spindle speed of a  $\frac{3}{4}$ -inch (19.05-mm) drill is 400 rpm.

$$\begin{array}{l} V = \frac{\pi DN}{12} = \frac{\pi \times 0.75 \times 400}{12} = 78.5 \text{ fpm} \\ V = \frac{\pi DN}{1000} = \frac{\pi \times 19.05 \times 400}{1000} = 24.9 \text{ m/min} \end{array}$$

## Cutting Speeds and Equivalent RPM for Drills of Number and Letter Sizes

| Size No. | Cutting Speed, Feet per Minute          |      |      |      |      |      |      |      |      |      |       |
|----------|---|------|------|------|------|------|------|------|------|------|-------|
|          | 30'                                     | 40'  | 50'  | 60'  | 70'  | 80'  | 90'  | 100' | 110' | 130' | 150'  |
|          | Revolutions per Minute for Number Sizes |      |      |      |      |      |      |      |      |      |       |
| 1        | 503                                     | 670  | 838  | 1005 | 1173 | 1340 | 1508 | 1675 | 1843 | 2179 | 2513  |
| 2        | 518                                     | 691  | 864  | 1037 | 1210 | 1382 | 1555 | 1728 | 1901 | 2247 | 2593  |
| 4        | 548                                     | 731  | 914  | 1097 | 1280 | 1462 | 1645 | 1828 | 2010 | 2376 | 2741  |
| 6        | 562                                     | 749  | 936  | 1123 | 1310 | 1498 | 1685 | 1872 | 2060 | 2434 | 2809  |
| 8        | 576                                     | 768  | 960  | 1151 | 1343 | 1535 | 1727 | 1919 | 2111 | 2495 | 2879  |
| 10       | 592                                     | 790  | 987  | 1184 | 1382 | 1579 | 1777 | 1974 | 2171 | 2566 | 2961  |
| 12       | 606                                     | 808  | 1010 | 1213 | 1415 | 1617 | 1819 | 2021 | 2223 | 2627 | 3032  |
| 14       | 630                                     | 840  | 1050 | 1259 | 1469 | 1679 | 1889 | 2099 | 2309 | 2728 | 3148  |
| 16       | 647                                     | 863  | 1079 | 1295 | 1511 | 1726 | 1942 | 2158 | 2374 | 2806 | 3237  |
| 18       | 678                                     | 904  | 1130 | 1356 | 1582 | 1808 | 2034 | 2260 | 2479 | 2930 | 3380  |
| 20       | 712                                     | 949  | 1186 | 1423 | 1660 | 1898 | 2135 | 2372 | 2610 | 3084 | 3559  |
| 22       | 730                                     | 973  | 1217 | 1460 | 1703 | 1946 | 2190 | 2433 | 2676 | 3164 | 3649  |
| 24       | 754                                     | 1005 | 1257 | 1508 | 1759 | 2010 | 2262 | 2513 | 2764 | 3267 | 3769  |
| 26       | 779                                     | 1039 | 1299 | 1559 | 1819 | 2078 | 2338 | 2598 | 2858 | 3378 | 3898  |
| 28       | 816                                     | 1088 | 1360 | 1631 | 1903 | 2175 | 2447 | 2719 | 2990 | 3534 | 4078  |
| 30       | 892                                     | 1189 | 1487 | 1784 | 2081 | 2378 | 2676 | 2973 | 3270 | 3864 | 4459  |
| 32       | 988                                     | 1317 | 1647 | 1976 | 2305 | 2634 | 2964 | 3293 | 3622 | 4281 | 4939  |
| 34       | 1032                                    | 1376 | 1721 | 2065 | 2409 | 2753 | 3097 | 3442 | 3785 | 4474 | 5162  |
| 36       | 1076                                    | 1435 | 1794 | 2152 | 2511 | 2870 | 3228 | 3587 | 3945 | 4663 | 5380  |
| 38       | 1129                                    | 1505 | 1882 | 2258 | 2634 | 3010 | 3387 | 3763 | 4140 | 4892 | 5645  |
| 40       | 1169                                    | 1559 | 1949 | 2339 | 2729 | 3118 | 3508 | 3898 | 4287 | 5067 | 5846  |
| 42       | 1226                                    | 1634 | 2043 | 2451 | 2860 | 3268 | 3677 | 4085 | 4494 | 5311 | 6128  |
| 44       | 1333                                    | 1777 | 2221 | 2665 | 3109 | 3554 | 3999 | 4442 | 4886 | 5774 | 6662  |
| 46       | 1415                                    | 1886 | 2358 | 2830 | 3301 | 3773 | 4244 | 4716 | 5187 | 6130 | 7074  |
| 48       | 1508                                    | 2010 | 2513 | 3016 | 3518 | 4021 | 4523 | 5026 | 5528 | 6534 | 7539  |
| 50       | 1637                                    | 2183 | 2729 | 3274 | 3820 | 4366 | 4911 | 5457 | 6002 | 7094 | 8185  |
| 52       | 1805                                    | 2406 | 3008 | 3609 | 4211 | 4812 | 5414 | 6015 | 6619 | 7820 | 9023  |
| 54       | 2084                                    | 2778 | 3473 | 4167 | 4862 | 5556 | 6251 | 6945 | 7639 | 9028 | 10417 |
| Size     | Revolutions per Minute for Letter Sizes |      |      |      |      |      |      |      |      |      |       |
| A        | 491                                     | 654  | 818  | 982  | 1145 | 1309 | 1472 | 1636 | 1796 | 2122 | 2448  |
| B        | 482                                     | 642  | 803  | 963  | 1124 | 1284 | 1445 | 1605 | 1765 | 2086 | 2407  |
| C        | 473                                     | 631  | 789  | 947  | 1105 | 1262 | 1420 | 1578 | 1736 | 2052 | 2368  |
| D        | 467                                     | 622  | 778  | 934  | 1089 | 1245 | 1400 | 1556 | 1708 | 2018 | 2329  |
| E        | 458                                     | 611  | 764  | 917  | 1070 | 1222 | 1375 | 1528 | 1681 | 1968 | 2292  |
| F        | 446                                     | 594  | 743  | 892  | 1040 | 1189 | 1337 | 1486 | 1635 | 1932 | 2229  |
| G        | 440                                     | 585  | 732  | 878  | 1024 | 1170 | 1317 | 1463 | 1610 | 1903 | 2195  |
| H        | 430                                     | 574  | 718  | 862  | 1005 | 1149 | 1292 | 1436 | 1580 | 1867 | 2154  |
| I        | 421                                     | 562  | 702  | 842  | 983  | 1123 | 1264 | 1404 | 1545 | 1826 | 2106  |
| J        | 414                                     | 552  | 690  | 827  | 965  | 1103 | 1241 | 1379 | 1517 | 1793 | 2068  |
| K        | 408                                     | 544  | 680  | 815  | 951  | 1087 | 1223 | 1359 | 1495 | 1767 | 2039  |
| L        | 395                                     | 527  | 659  | 790  | 922  | 1054 | 1185 | 1317 | 1449 | 1712 | 1976  |
| M        | 389                                     | 518  | 648  | 777  | 907  | 1036 | 1166 | 1295 | 1424 | 1683 | 1942  |
| N        | 380                                     | 506  | 633  | 759  | 886  | 1012 | 1139 | 1265 | 1391 | 1644 | 1897  |
| O        | 363                                     | 484  | 605  | 725  | 846  | 967  | 1088 | 1209 | 1330 | 1571 | 1813  |
| P        | 355                                     | 473  | 592  | 710  | 828  | 946  | 1065 | 1183 | 1301 | 1537 | 1774  |
| Q        | 345                                     | 460  | 575  | 690  | 805  | 920  | 1035 | 1150 | 1266 | 1496 | 1726  |
| R        | 338                                     | 451  | 564  | 676  | 789  | 902  | 1014 | 1127 | 1239 | 1465 | 1690  |
| S        | 329                                     | 439  | 549  | 659  | 769  | 878  | 988  | 1098 | 1207 | 1427 | 1646  |
| T        | 320                                     | 426  | 533  | 640  | 746  | 853  | 959  | 1066 | 1173 | 1387 | 1600  |
| U        | 311                                     | 415  | 519  | 623  | 727  | 830  | 934  | 1038 | 1142 | 1349 | 1557  |
| V        | 304                                     | 405  | 507  | 608  | 709  | 810  | 912  | 1013 | 1114 | 1317 | 1520  |
| W        | 297                                     | 396  | 495  | 594  | 693  | 792  | 891  | 989  | 1088 | 1286 | 1484  |
| X        | 289                                     | 385  | 481  | 576  | 672  | 769  | 865  | 962  | 1058 | 1251 | 1443  |
| Y        | 284                                     | 378  | 473  | 567  | 662  | 756  | 851  | 945  | 1040 | 1229 | 1418  |
| Z        | 277                                     | 370  | 462  | 555  | 647  | 740  | 832  | 925  | 1017 | 1202 | 1387  |

For fractional drill sizes, use the following table.

## Revolutions per Minute for Various Cutting Speeds and Diameters

| Dia.,<br>Inches  | Cutting Speed, Feet per Minute |      |      |      |      |      |      |      |      |      |      |      |
|------------------|--------------------------------|------|------|------|------|------|------|------|------|------|------|------|
|                  | 40                             | 50   | 60   | 70   | 80   | 90   | 100  | 120  | 140  | 160  | 180  | 200  |
|                  | Revolutions per Minute         |      |      |      |      |      |      |      |      |      |      |      |
| $\frac{1}{4}$    | 611                            | 764  | 917  | 1070 | 1222 | 1376 | 1528 | 1834 | 2139 | 2445 | 2750 | 3056 |
| $\frac{5}{16}$   | 489                            | 611  | 733  | 856  | 978  | 1100 | 1222 | 1466 | 1711 | 1955 | 2200 | 2444 |
| $\frac{3}{8}$    | 408                            | 509  | 611  | 713  | 815  | 916  | 1018 | 1222 | 1425 | 1629 | 1832 | 2036 |
| $\frac{7}{16}$   | 349                            | 437  | 524  | 611  | 699  | 786  | 874  | 1049 | 1224 | 1398 | 1573 | 1748 |
| $\frac{1}{2}$    | 306                            | 382  | 459  | 535  | 611  | 688  | 764  | 917  | 1070 | 1222 | 1375 | 1528 |
| $\frac{9}{16}$   | 272                            | 340  | 407  | 475  | 543  | 611  | 679  | 813  | 951  | 1086 | 1222 | 1358 |
| $\frac{5}{8}$    | 245                            | 306  | 367  | 428  | 489  | 552  | 612  | 736  | 857  | 979  | 1102 | 1224 |
| $\frac{11}{16}$  | 222                            | 273  | 333  | 389  | 444  | 500  | 555  | 666  | 770  | 888  | 999  | 1101 |
| $\frac{3}{4}$    | 203                            | 254  | 306  | 357  | 408  | 458  | 508  | 610  | 711  | 813  | 914  | 1016 |
| $\frac{13}{16}$  | 190                            | 237  | 284  | 332  | 379  | 427  | 474  | 569  | 664  | 758  | 853  | 948  |
| $\frac{7}{8}$    | 175                            | 219  | 262  | 306  | 349  | 392  | 438  | 526  | 613  | 701  | 788  | 876  |
| $\frac{15}{16}$  | 163                            | 204  | 244  | 285  | 326  | 366  | 407  | 488  | 570  | 651  | 733  | 814  |
| 1                | 153                            | 191  | 229  | 267  | 306  | 344  | 382  | 458  | 535  | 611  | 688  | 764  |
| $1\frac{1}{16}$  | 144                            | 180  | 215  | 251  | 287  | 323  | 359  | 431  | 503  | 575  | 646  | 718  |
| $1\frac{1}{8}$   | 136                            | 170  | 204  | 238  | 272  | 306  | 340  | 408  | 476  | 544  | 612  | 680  |
| $1\frac{3}{16}$  | 129                            | 161  | 193  | 225  | 258  | 290  | 322  | 386  | 451  | 515  | 580  | 644  |
| $1\frac{1}{4}$   | 123                            | 153  | 183  | 214  | 245  | 274  | 306  | 367  | 428  | 490  | 551  | 612  |
| $1\frac{3}{16}$  | 116                            | 146  | 175  | 204  | 233  | 262  | 291  | 349  | 407  | 466  | 524  | 582  |
| $1\frac{5}{8}$   | 111                            | 139  | 167  | 195  | 222  | 250  | 278  | 334  | 389  | 445  | 500  | 556  |
| $1\frac{7}{16}$  | 106                            | 133  | 159  | 186  | 212  | 239  | 265  | 318  | 371  | 424  | 477  | 530  |
| $1\frac{1}{2}$   | 102                            | 127  | 153  | 178  | 204  | 230  | 254  | 305  | 356  | 406  | 457  | 508  |
| $1\frac{9}{16}$  | 97.6                           | 122  | 146  | 171  | 195  | 220  | 244  | 293  | 342  | 390  | 439  | 488  |
| $1\frac{5}{8}$   | 93.9                           | 117  | 141  | 165  | 188  | 212  | 234  | 281  | 328  | 374  | 421  | 468  |
| $1\frac{11}{16}$ | 90.4                           | 113  | 136  | 158  | 181  | 203  | 226  | 271  | 316  | 362  | 407  | 452  |
| $1\frac{3}{4}$   | 87.3                           | 109  | 131  | 153  | 175  | 196  | 218  | 262  | 305  | 349  | 392  | 436  |
| $1\frac{7}{8}$   | 81.5                           | 102  | 122  | 143  | 163  | 184  | 204  | 244  | 286  | 326  | 367  | 408  |
| 2                | 76.4                           | 95.5 | 115  | 134  | 153  | 172  | 191  | 229  | 267  | 306  | 344  | 382  |
| $2\frac{1}{16}$  | 72.0                           | 90.0 | 108  | 126  | 144  | 162  | 180  | 216  | 252  | 288  | 324  | 360  |
| $2\frac{1}{4}$   | 68.0                           | 85.5 | 102  | 119  | 136  | 153  | 170  | 204  | 238  | 272  | 306  | 340  |
| $2\frac{3}{8}$   | 64.4                           | 80.5 | 96.6 | 113  | 129  | 145  | 161  | 193  | 225  | 258  | 290  | 322  |
| $2\frac{1}{2}$   | 61.2                           | 76.3 | 91.7 | 107  | 122  | 138  | 153  | 184  | 213  | 245  | 275  | 306  |
| $2\frac{5}{8}$   | 58.0                           | 72.5 | 87.0 | 102  | 116  | 131  | 145  | 174  | 203  | 232  | 261  | 290  |
| $2\frac{3}{4}$   | 55.6                           | 69.5 | 83.4 | 97.2 | 111  | 125  | 139  | 167  | 195  | 222  | 250  | 278  |
| $2\frac{7}{8}$   | 52.8                           | 66.0 | 79.2 | 92.4 | 106  | 119  | 132  | 158  | 185  | 211  | 238  | 264  |
| 3                | 51.0                           | 63.7 | 76.4 | 89.1 | 102  | 114  | 127  | 152  | 178  | 203  | 228  | 254  |
| $3\frac{1}{8}$   | 48.8                           | 61.0 | 73.2 | 85.4 | 97.6 | 110  | 122  | 146  | 171  | 195  | 219  | 244  |
| $3\frac{1}{4}$   | 46.8                           | 58.5 | 70.2 | 81.9 | 93.6 | 105  | 117  | 140  | 164  | 188  | 211  | 234  |
| $3\frac{3}{8}$   | 45.2                           | 56.5 | 67.8 | 79.1 | 90.4 | 102  | 113  | 136  | 158  | 181  | 203  | 226  |
| $3\frac{1}{2}$   | 43.6                           | 54.5 | 65.5 | 76.4 | 87.4 | 98.1 | 109  | 131  | 153  | 174  | 196  | 218  |
| $3\frac{5}{8}$   | 42.0                           | 52.5 | 63.0 | 73.5 | 84.0 | 94.5 | 105  | 126  | 147  | 168  | 189  | 210  |
| $3\frac{3}{4}$   | 40.8                           | 51.0 | 61.2 | 71.4 | 81.6 | 91.8 | 102  | 122  | 143  | 163  | 184  | 205  |
| $3\frac{7}{8}$   | 39.4                           | 49.3 | 59.1 | 69.0 | 78.8 | 88.6 | 98.5 | 118  | 138  | 158  | 177  | 197  |
| 4                | 38.2                           | 47.8 | 57.3 | 66.9 | 76.4 | 86.0 | 95.6 | 115  | 134  | 153  | 172  | 191  |
| $4\frac{1}{4}$   | 35.9                           | 44.9 | 53.9 | 62.9 | 71.8 | 80.8 | 89.8 | 108  | 126  | 144  | 162  | 180  |
| $4\frac{1}{2}$   | 34.0                           | 42.4 | 51.0 | 59.4 | 67.9 | 76.3 | 84.8 | 102  | 119  | 136  | 153  | 170  |
| $4\frac{3}{4}$   | 32.2                           | 40.2 | 48.2 | 56.3 | 64.3 | 72.4 | 80.4 | 96.9 | 113  | 129  | 145  | 161  |
| 5                | 30.6                           | 38.2 | 45.9 | 53.5 | 61.1 | 68.8 | 76.4 | 91.7 | 107  | 122  | 138  | 153  |
| $5\frac{1}{8}$   | 29.1                           | 36.4 | 43.6 | 50.9 | 58.2 | 65.4 | 72.7 | 87.2 | 102  | 116  | 131  | 145  |
| $5\frac{1}{2}$   | 27.8                           | 34.7 | 41.7 | 48.6 | 55.6 | 62.5 | 69.4 | 83.3 | 97.2 | 111  | 125  | 139  |
| $5\frac{3}{4}$   | 26.6                           | 33.2 | 39.8 | 46.5 | 53.1 | 59.8 | 66.4 | 80.0 | 93.0 | 106  | 120  | 133  |
| 6                | 25.5                           | 31.8 | 38.2 | 44.6 | 51.0 | 57.2 | 63.6 | 76.3 | 89.0 | 102  | 114  | 127  |
| $6\frac{1}{8}$   | 24.4                           | 30.6 | 36.7 | 42.8 | 48.9 | 55.0 | 61.1 | 73.3 | 85.5 | 97.7 | 110  | 122  |
| $6\frac{1}{2}$   | 23.5                           | 29.4 | 35.2 | 41.1 | 47.0 | 52.8 | 58.7 | 70.4 | 82.2 | 93.9 | 106  | 117  |
| $6\frac{3}{4}$   | 22.6                           | 28.3 | 34.0 | 39.6 | 45.3 | 50.9 | 56.6 | 67.9 | 79.2 | 90.6 | 102  | 113  |
| 7                | 21.8                           | 27.3 | 32.7 | 38.2 | 43.7 | 49.1 | 54.6 | 65.5 | 76.4 | 87.4 | 98.3 | 109  |
| $7\frac{1}{8}$   | 21.1                           | 26.4 | 31.6 | 36.9 | 42.2 | 47.4 | 52.7 | 63.2 | 73.8 | 84.3 | 94.9 | 105  |
| $7\frac{1}{2}$   | 20.4                           | 25.4 | 30.5 | 35.6 | 40.7 | 45.8 | 50.9 | 61.1 | 71.0 | 81.4 | 91.6 | 102  |
| $7\frac{3}{4}$   | 19.7                           | 24.6 | 29.5 | 34.4 | 39.4 | 44.3 | 49.2 | 59.0 | 68.9 | 78.7 | 88.6 | 98.4 |
| 8                | 19.1                           | 23.9 | 28.7 | 33.4 | 38.2 | 43.0 | 47.8 | 57.4 | 66.9 | 76.5 | 86.0 | 95.6 |

## Revolutions per Minute for Various Cutting Speeds and Diameters

| Dia.,<br>Inches | Cutting Speed, Feet per Minute |      |      |      |      |      |      |      |      |      |      |      |
|-----------------|--------------------------------|------|------|------|------|------|------|------|------|------|------|------|
|                 | 225                            | 250  | 275  | 300  | 325  | 350  | 375  | 400  | 425  | 450  | 500  | 550  |
|                 | Revolutions per Minute         |      |      |      |      |      |      |      |      |      |      |      |
| 1/4             | 3438                           | 3820 | 4202 | 4584 | 4966 | 5348 | 5730 | 6112 | 6493 | 6875 | 7639 | 8403 |
| 3/16            | 2750                           | 3056 | 3362 | 3667 | 3973 | 4278 | 4584 | 4889 | 5195 | 5501 | 6112 | 6723 |
| 3/8             | 2292                           | 2546 | 2801 | 3056 | 3310 | 3565 | 3820 | 4074 | 4329 | 4584 | 5093 | 5602 |
| 7/16            | 1964                           | 2182 | 2401 | 2619 | 2837 | 3056 | 3274 | 3492 | 3710 | 3929 | 4365 | 4802 |
| 1/2             | 1719                           | 1910 | 2101 | 2292 | 2483 | 2675 | 2866 | 3057 | 3248 | 3439 | 3821 | 4203 |
| 9/16            | 1528                           | 1698 | 1868 | 2037 | 2207 | 2377 | 2547 | 2717 | 2887 | 3056 | 3396 | 3736 |
| 5/8             | 1375                           | 1528 | 1681 | 1834 | 1987 | 2139 | 2292 | 2445 | 2598 | 2751 | 3057 | 3362 |
| 11/16           | 1250                           | 1389 | 1528 | 1667 | 1806 | 1941 | 2084 | 2223 | 2362 | 2501 | 2779 | 3056 |
| 3/4             | 1146                           | 1273 | 1401 | 1528 | 1655 | 1783 | 1910 | 2038 | 2165 | 2292 | 2547 | 2802 |
| 13/16           | 1058                           | 1175 | 1293 | 1410 | 1528 | 1646 | 1763 | 1881 | 1998 | 2116 | 2351 | 2586 |
| 7/8             | 982                            | 1091 | 1200 | 1310 | 1419 | 1528 | 1637 | 1746 | 1855 | 1965 | 2183 | 2401 |
| 15/16           | 917                            | 1019 | 1120 | 1222 | 1324 | 1426 | 1528 | 1630 | 1732 | 1834 | 2038 | 2241 |
| 1               | 859                            | 955  | 1050 | 1146 | 1241 | 1337 | 1432 | 1528 | 1623 | 1719 | 1910 | 2101 |
| 1 1/16          | 809                            | 899  | 988  | 1078 | 1168 | 1258 | 1348 | 1438 | 1528 | 1618 | 1798 | 1977 |
| 1 1/8           | 764                            | 849  | 933  | 1018 | 1103 | 1188 | 1273 | 1358 | 1443 | 1528 | 1698 | 1867 |
| 1 1/4           | 724                            | 804  | 884  | 965  | 1045 | 1126 | 1206 | 1287 | 1367 | 1448 | 1609 | 1769 |
| 1 1/4           | 687                            | 764  | 840  | 917  | 993  | 1069 | 1146 | 1222 | 1299 | 1375 | 1528 | 1681 |
| 1 3/8           | 654                            | 727  | 800  | 873  | 946  | 1018 | 1091 | 1164 | 1237 | 1309 | 1455 | 1601 |
| 1 3/8           | 625                            | 694  | 764  | 833  | 903  | 972  | 1042 | 1111 | 1181 | 1250 | 1389 | 1528 |
| 1 7/8           | 598                            | 664  | 730  | 797  | 863  | 930  | 996  | 1063 | 1129 | 1196 | 1329 | 1461 |
| 1 1/2           | 573                            | 636  | 700  | 764  | 827  | 891  | 955  | 1018 | 1082 | 1146 | 1273 | 1400 |
| 1 9/16          | 550                            | 611  | 672  | 733  | 794  | 855  | 916  | 978  | 1039 | 1100 | 1222 | 1344 |
| 1 5/8           | 528                            | 587  | 646  | 705  | 764  | 822  | 881  | 940  | 999  | 1057 | 1175 | 1293 |
| 1 11/16         | 509                            | 566  | 622  | 679  | 735  | 792  | 849  | 905  | 962  | 1018 | 1132 | 1245 |
| 1 3/4           | 491                            | 545  | 600  | 654  | 709  | 764  | 818  | 873  | 927  | 982  | 1091 | 1200 |
| 1 13/16         | 474                            | 527  | 579  | 632  | 685  | 737  | 790  | 843  | 895  | 948  | 1054 | 1159 |
| 1 7/8           | 458                            | 509  | 560  | 611  | 662  | 713  | 764  | 815  | 866  | 917  | 1019 | 1120 |
| 1 15/16         | 443                            | 493  | 542  | 591  | 640  | 690  | 739  | 788  | 838  | 887  | 986  | 1084 |
| 2               | 429                            | 477  | 525  | 573  | 620  | 668  | 716  | 764  | 811  | 859  | 955  | 1050 |
| 2 1/8           | 404                            | 449  | 494  | 539  | 584  | 629  | 674  | 719  | 764  | 809  | 899  | 988  |
| 2 1/4           | 382                            | 424  | 468  | 509  | 551  | 594  | 636  | 679  | 721  | 764  | 849  | 933  |
| 2 3/8           | 362                            | 402  | 442  | 482  | 522  | 563  | 603  | 643  | 683  | 724  | 804  | 884  |
| 2 1/2           | 343                            | 382  | 420  | 458  | 496  | 534  | 573  | 611  | 649  | 687  | 764  | 840  |
| 2 5/8           | 327                            | 363  | 400  | 436  | 472  | 509  | 545  | 582  | 618  | 654  | 727  | 800  |
| 2 3/4           | 312                            | 347  | 381  | 416  | 451  | 486  | 520  | 555  | 590  | 625  | 694  | 763  |
| 2 7/8           | 299                            | 332  | 365  | 398  | 431  | 465  | 498  | 531  | 564  | 598  | 664  | 730  |
| 3               | 286                            | 318  | 350  | 381  | 413  | 445  | 477  | 509  | 541  | 572  | 636  | 700  |
| 3 1/8           | 274                            | 305  | 336  | 366  | 397  | 427  | 458  | 488  | 519  | 549  | 611  | 672  |
| 3 1/4           | 264                            | 293  | 323  | 352  | 381  | 411  | 440  | 470  | 499  | 528  | 587  | 646  |
| 3 3/8           | 254                            | 283  | 311  | 339  | 367  | 396  | 424  | 452  | 481  | 509  | 566  | 622  |
| 3 1/2           | 245                            | 272  | 300  | 327  | 354  | 381  | 409  | 436  | 463  | 490  | 545  | 600  |
| 3 5/8           | 237                            | 263  | 289  | 316  | 342  | 368  | 395  | 421  | 447  | 474  | 527  | 579  |
| 3 3/4           | 229                            | 254  | 280  | 305  | 331  | 356  | 382  | 407  | 433  | 458  | 509  | 560  |
| 3 7/8           | 221                            | 246  | 271  | 295  | 320  | 345  | 369  | 394  | 419  | 443  | 493  | 542  |
| 4               | 214                            | 238  | 262  | 286  | 310  | 334  | 358  | 382  | 405  | 429  | 477  | 525  |
| 4 1/4           | 202                            | 224  | 247  | 269  | 292  | 314  | 337  | 359  | 383  | 404  | 449  | 494  |
| 4 1/2           | 191                            | 212  | 233  | 254  | 275  | 297  | 318  | 339  | 360  | 382  | 424  | 466  |
| 4 3/4           | 180                            | 201  | 221  | 241  | 261  | 281  | 301  | 321  | 341  | 361  | 402  | 442  |
| 5               | 171                            | 191  | 210  | 229  | 248  | 267  | 286  | 305  | 324  | 343  | 382  | 420  |
| 5 1/4           | 163                            | 181  | 199  | 218  | 236  | 254  | 272  | 290  | 308  | 327  | 363  | 399  |
| 5 1/2           | 156                            | 173  | 190  | 208  | 225  | 242  | 260  | 277  | 294  | 312  | 347  | 381  |
| 5 3/4           | 149                            | 166  | 182  | 199  | 215  | 232  | 249  | 265  | 282  | 298  | 332  | 365  |
| 6               | 143                            | 159  | 174  | 190  | 206  | 222  | 238  | 254  | 270  | 286  | 318  | 349  |
| 6 1/4           | 137                            | 152  | 168  | 183  | 198  | 213  | 229  | 244  | 259  | 274  | 305  | 336  |
| 6 1/2           | 132                            | 146  | 161  | 176  | 190  | 205  | 220  | 234  | 249  | 264  | 293  | 322  |
| 6 3/4           | 127                            | 141  | 155  | 169  | 183  | 198  | 212  | 226  | 240  | 254  | 283  | 311  |
| 7               | 122                            | 136  | 149  | 163  | 177  | 190  | 204  | 218  | 231  | 245  | 272  | 299  |
| 7 1/4           | 118                            | 131  | 144  | 158  | 171  | 184  | 197  | 210  | 223  | 237  | 263  | 289  |
| 7 1/2           | 114                            | 127  | 139  | 152  | 165  | 178  | 190  | 203  | 216  | 229  | 254  | 279  |
| 7 3/4           | 111                            | 123  | 135  | 148  | 160  | 172  | 185  | 197  | 209  | 222  | 246  | 271  |
| 8               | 107                            | 119  | 131  | 143  | 155  | 167  | 179  | 191  | 203  | 215  | 238  | 262  |



**Revolutions per Minute for Various Cutting Speeds and Diameters (Metric Units)**

| Dia.,<br>mm | Cutting Speed, Meters per Minute |      |      |      |      |      |      |      |      |      |      |      |
|-------------|----------------------------------|------|------|------|------|------|------|------|------|------|------|------|
|             | 5                                | 6    | 8    | 10   | 12   | 16   | 20   | 25   | 30   | 35   | 40   | 45   |
|             | Revolutions per Minute           |      |      |      |      |      |      |      |      |      |      |      |
| 5           | 318                              | 382  | 509  | 637  | 764  | 1019 | 1273 | 1592 | 1910 | 2228 | 2546 | 2865 |
| 6           | 265                              | 318  | 424  | 530  | 637  | 849  | 1061 | 1326 | 1592 | 1857 | 2122 | 2387 |
| 8           | 199                              | 239  | 318  | 398  | 477  | 637  | 796  | 995  | 1194 | 1393 | 1592 | 1790 |
| 10          | 159                              | 191  | 255  | 318  | 382  | 509  | 637  | 796  | 955  | 1114 | 1273 | 1432 |
| 12          | 133                              | 159  | 212  | 265  | 318  | 424  | 531  | 663  | 796  | 928  | 1061 | 1194 |
| 16          | 99.5                             | 119  | 159  | 199  | 239  | 318  | 398  | 497  | 597  | 696  | 796  | 895  |
| 20          | 79.6                             | 95.5 | 127  | 159  | 191  | 255  | 318  | 398  | 477  | 557  | 637  | 716  |
| 25          | 63.7                             | 76.4 | 102  | 127  | 153  | 204  | 255  | 318  | 382  | 446  | 509  | 573  |
| 30          | 53.1                             | 63.7 | 84.9 | 106  | 127  | 170  | 212  | 265  | 318  | 371  | 424  | 477  |
| 35          | 45.5                             | 54.6 | 72.8 | 90.9 | 109  | 145  | 182  | 227  | 273  | 318  | 364  | 409  |
| 40          | 39.8                             | 47.7 | 63.7 | 79.6 | 95.5 | 127  | 159  | 199  | 239  | 279  | 318  | 358  |
| 45          | 35.4                             | 42.4 | 56.6 | 70.7 | 84.9 | 113  | 141  | 177  | 212  | 248  | 283  | 318  |
| 50          | 31.8                             | 38.2 | 51   | 63.7 | 76.4 | 102  | 127  | 159  | 191  | 223  | 255  | 286  |
| 55          | 28.9                             | 34.7 | 46.3 | 57.9 | 69.4 | 92.6 | 116  | 145  | 174  | 203  | 231  | 260  |
| 60          | 26.6                             | 31.8 | 42.4 | 53.1 | 63.7 | 84.9 | 106  | 133  | 159  | 186  | 212  | 239  |
| 65          | 24.5                             | 29.4 | 39.2 | 49   | 58.8 | 78.4 | 98   | 122  | 147  | 171  | 196  | 220  |
| 70          | 22.7                             | 27.3 | 36.4 | 45.5 | 54.6 | 72.8 | 90.9 | 114  | 136  | 159  | 182  | 205  |
| 75          | 21.2                             | 25.5 | 34   | 42.4 | 51   | 68   | 84.9 | 106  | 127  | 149  | 170  | 191  |
| 80          | 19.9                             | 23.9 | 31.8 | 39.8 | 47.7 | 63.7 | 79.6 | 99.5 | 119  | 139  | 159  | 179  |
| 90          | 17.7                             | 21.2 | 28.3 | 35.4 | 42.4 | 56.6 | 70.7 | 88.4 | 106  | 124  | 141  | 159  |
| 100         | 15.9                             | 19.1 | 25.5 | 31.8 | 38.2 | 51   | 63.7 | 79.6 | 95.5 | 111  | 127  | 143  |
| 110         | 14.5                             | 17.4 | 23.1 | 28.9 | 34.7 | 46.2 | 57.9 | 72.3 | 86.8 | 101  | 116  | 130  |
| 120         | 13.3                             | 15.9 | 21.2 | 26.5 | 31.8 | 42.4 | 53.1 | 66.3 | 79.6 | 92.8 | 106  | 119  |
| 130         | 12.2                             | 14.7 | 19.6 | 24.5 | 29.4 | 39.2 | 49   | 61.2 | 73.4 | 85.7 | 97.9 | 110  |
| 140         | 11.4                             | 13.6 | 18.2 | 22.7 | 27.3 | 36.4 | 45.5 | 56.8 | 68.2 | 79.6 | 90.9 | 102  |
| 150         | 10.6                             | 12.7 | 17   | 21.2 | 25.5 | 34   | 42.4 | 53.1 | 63.7 | 74.3 | 84.9 | 95.5 |
| 160         | 9.9                              | 11.9 | 15.9 | 19.9 | 23.9 | 31.8 | 39.8 | 49.7 | 59.7 | 69.6 | 79.6 | 89.5 |
| 170         | 9.4                              | 11.2 | 15   | 18.7 | 22.5 | 30   | 37.4 | 46.8 | 56.2 | 65.5 | 74.9 | 84.2 |
| 180         | 8.8                              | 10.6 | 14.1 | 17.7 | 21.2 | 28.3 | 35.4 | 44.2 | 53.1 | 61.9 | 70.7 | 79.6 |
| 190         | 8.3                              | 10   | 13.4 | 16.8 | 20.1 | 26.8 | 33.5 | 41.9 | 50.3 | 58.6 | 67   | 75.4 |
| 200         | 8                                | 39.5 | 12.7 | 15.9 | 19.1 | 25.5 | 31.8 | 39.8 | 47.7 | 55.7 | 63.7 | 71.6 |
| 220         | 7.2                              | 8.7  | 11.6 | 14.5 | 17.4 | 23.1 | 28.9 | 36.2 | 43.4 | 50.6 | 57.9 | 65.1 |
| 240         | 6.6                              | 8    | 10.6 | 13.3 | 15.9 | 21.2 | 26.5 | 33.2 | 39.8 | 46.4 | 53.1 | 59.7 |
| 260         | 6.1                              | 7.3  | 9.8  | 12.2 | 14.7 | 19.6 | 24.5 | 30.6 | 36.7 | 42.8 | 49   | 55.1 |
| 280         | 5.7                              | 6.8  | 9.1  | 11.4 | 13.6 | 18.2 | 22.7 | 28.4 | 34.1 | 39.8 | 45.5 | 51.1 |
| 300         | 5.3                              | 6.4  | 8.5  | 10.6 | 12.7 | 17   | 21.2 | 26.5 | 31.8 | 37.1 | 42.4 | 47.7 |
| 350         | 4.5                              | 5.4  | 7.3  | 9.1  | 10.9 | 14.6 | 18.2 | 22.7 | 27.3 | 31.8 | 36.4 | 40.9 |
| 400         | 4                                | 4.8  | 6.4  | 8    | 9.5  | 12.7 | 15.9 | 19.9 | 23.9 | 27.9 | 31.8 | 35.8 |
| 450         | 3.5                              | 4.2  | 5.7  | 7.1  | 8.5  | 11.3 | 14.1 | 17.7 | 21.2 | 24.8 | 28.3 | 31.8 |
| 500         | 3.2                              | 3.8  | 5.1  | 6.4  | 7.6  | 10.2 | 12.7 | 15.9 | 19.1 | 22.3 | 25.5 | 28.6 |

**Revolutions per Minute for Various Cutting Speeds and Diameters (Metric Units)**

| Dia.,<br>mm | Cutting Speed, Meters per Minute |      |      |      |      |      |      |      |      |      |      |        |
|-------------|----------------------------------|------|------|------|------|------|------|------|------|------|------|--------|
|             | 50                               | 55   | 60   | 65   | 70   | 75   | 80   | 85   | 90   | 95   | 100  | 200    |
|             | Revolutions per Minute           |      |      |      |      |      |      |      |      |      |      |        |
| 5           | 3183                             | 3501 | 3820 | 4138 | 4456 | 4775 | 5093 | 5411 | 5730 | 6048 | 6366 | 12,732 |
| 6           | 2653                             | 2918 | 3183 | 3448 | 3714 | 3979 | 4244 | 4509 | 4775 | 5039 | 5305 | 10,610 |
| 8           | 1989                             | 2188 | 2387 | 2586 | 2785 | 2984 | 3183 | 3382 | 3581 | 3780 | 3979 | 7958   |
| 10          | 1592                             | 1751 | 1910 | 2069 | 2228 | 2387 | 2546 | 2706 | 2865 | 3024 | 3183 | 6366   |
| 12          | 1326                             | 1459 | 1592 | 1724 | 1857 | 1989 | 2122 | 2255 | 2387 | 2520 | 2653 | 5305   |
| 16          | 995                              | 1094 | 1194 | 1293 | 1393 | 1492 | 1591 | 1691 | 1790 | 1890 | 1989 | 3979   |
| 20          | 796                              | 875  | 955  | 1034 | 1114 | 1194 | 1273 | 1353 | 1432 | 1512 | 1592 | 3183   |
| 25          | 637                              | 700  | 764  | 828  | 891  | 955  | 1019 | 1082 | 1146 | 1210 | 1273 | 2546   |
| 30          | 530                              | 584  | 637  | 690  | 743  | 796  | 849  | 902  | 955  | 1008 | 1061 | 2122   |
| 35          | 455                              | 500  | 546  | 591  | 637  | 682  | 728  | 773  | 819  | 864  | 909  | 1818   |
| 40          | 398                              | 438  | 477  | 517  | 557  | 597  | 637  | 676  | 716  | 756  | 796  | 1592   |
| 45          | 354                              | 389  | 424  | 460  | 495  | 531  | 566  | 601  | 637  | 672  | 707  | 1415   |
| 50          | 318                              | 350  | 382  | 414  | 446  | 477  | 509  | 541  | 573  | 605  | 637  | 1273   |
| 55          | 289                              | 318  | 347  | 376  | 405  | 434  | 463  | 492  | 521  | 550  | 579  | 1157   |
| 60          | 265                              | 292  | 318  | 345  | 371  | 398  | 424  | 451  | 477  | 504  | 530  | 1061   |
| 65          | 245                              | 269  | 294  | 318  | 343  | 367  | 392  | 416  | 441  | 465  | 490  | 979    |
| 70          | 227                              | 250  | 273  | 296  | 318  | 341  | 364  | 387  | 409  | 432  | 455  | 909    |
| 75          | 212                              | 233  | 255  | 276  | 297  | 318  | 340  | 361  | 382  | 403  | 424  | 849    |
| 80          | 199                              | 219  | 239  | 259  | 279  | 298  | 318  | 338  | 358  | 378  | 398  | 796    |
| 90          | 177                              | 195  | 212  | 230  | 248  | 265  | 283  | 301  | 318  | 336  | 354  | 707    |
| 100         | 159                              | 175  | 191  | 207  | 223  | 239  | 255  | 271  | 286  | 302  | 318  | 637    |
| 110         | 145                              | 159  | 174  | 188  | 203  | 217  | 231  | 246  | 260  | 275  | 289  | 579    |
| 120         | 133                              | 146  | 159  | 172  | 186  | 199  | 212  | 225  | 239  | 252  | 265  | 530    |
| 130         | 122                              | 135  | 147  | 159  | 171  | 184  | 196  | 208  | 220  | 233  | 245  | 490    |
| 140         | 114                              | 125  | 136  | 148  | 159  | 171  | 182  | 193  | 205  | 216  | 227  | 455    |
| 150         | 106                              | 117  | 127  | 138  | 149  | 159  | 170  | 180  | 191  | 202  | 212  | 424    |
| 160         | 99.5                             | 109  | 119  | 129  | 139  | 149  | 159  | 169  | 179  | 189  | 199  | 398    |
| 170         | 93.6                             | 103  | 112  | 122  | 131  | 140  | 150  | 159  | 169  | 178  | 187  | 374    |
| 180         | 88.4                             | 97.3 | 106  | 115  | 124  | 133  | 141  | 150  | 159  | 168  | 177  | 354    |
| 190         | 83.8                             | 92.1 | 101  | 109  | 117  | 126  | 134  | 142  | 151  | 159  | 167  | 335    |
| 200         | 79.6                             | 87.5 | 95.5 | 103  | 111  | 119  | 127  | 135  | 143  | 151  | 159  | 318    |
| 220         | 72.3                             | 79.6 | 86.8 | 94   | 101  | 109  | 116  | 123  | 130  | 137  | 145  | 289    |
| 240         | 66.3                             | 72.9 | 79.6 | 86.2 | 92.8 | 99.5 | 106  | 113  | 119  | 126  | 132  | 265    |
| 260         | 61.2                             | 67.3 | 73.4 | 79.6 | 85.7 | 91.8 | 97.9 | 104  | 110  | 116  | 122  | 245    |
| 280         | 56.8                             | 62.5 | 68.2 | 73.9 | 79.6 | 85.3 | 90.9 | 96.6 | 102  | 108  | 114  | 227    |
| 300         | 53.1                             | 58.3 | 63.7 | 69   | 74.3 | 79.6 | 84.9 | 90.2 | 95.5 | 101  | 106  | 212    |
| 350         | 45.5                             | 50   | 54.6 | 59.1 | 63.7 | 68.2 | 72.8 | 77.3 | 81.8 | 86.4 | 91   | 182    |
| 400         | 39.8                             | 43.8 | 47.7 | 51.7 | 55.7 | 59.7 | 63.7 | 67.6 | 71.6 | 75.6 | 79.6 | 159    |
| 450         | 35.4                             | 38.9 | 42.4 | 46   | 49.5 | 53.1 | 56.6 | 60.1 | 63.6 | 67.2 | 70.7 | 141    |
| 500         | 31.8                             | 35   | 38.2 | 41.4 | 44.6 | 47.7 | 50.9 | 54.1 | 57.3 | 60.5 | 63.6 | 127    |

## SPEED AND FEED TABLES

### How to Use the Feeds and Speeds Tables

**Introduction to the Feed and Speed Tables.**—The principal tables of feed and speed values are listed in the table below. In this section, [Tables 1](#) through [9](#) give data for turning, [Tables 10](#) through [15e](#) give data for milling, and [Tables 17](#) through [23](#) give data for reaming, drilling, threading.

The materials in these tables are categorized by description, and Brinell hardness number (Bhn) range or material condition. So far as possible, work materials are grouped by similar machining characteristics. The types of cutting tools (HSS end mill, for example) are identified in one or more rows across the tops of the tables. Other important details concerning the use of the tables are contained in the footnotes to [Tables 1](#), [10](#) and [17](#). Information concerning specific cutting tool grades is given in notes at the end of each table.

### Principal Speed and Feed Tables

| <b>Feeds and Speeds for Turning</b>  |
|--|
| <a href="#">Table 1.</a> Cutting Feeds and Speeds for Turning Plain Carbon and Alloy Steels                                |
| <a href="#">Table 2.</a> Cutting Feeds and Speeds for Turning Tool Steels  |
| <a href="#">Table 3.</a> Cutting Feeds and Speeds for Turning Stainless Steels   |
| <a href="#">Table 4a.</a> Cutting Feeds and Speeds for Turning Ferrous Cast Metals   |
| <a href="#">Table 4b.</a> Cutting Feeds and Speeds for Turning Ferrous Cast Metals   |
| <a href="#">Table 5c.</a> Cutting-Speed Adjustment Factors for Turning with HSS Tools                                      |
| <a href="#">Table 5a.</a> Turning-Speed Adjustment Factors for Feed, Depth of Cut, and Lead Angle                          |
| <a href="#">Table 5b.</a> Tool Life Factors for Turning with Carbides, Ceramics, Cermets, CBN, and Polycrystalline Diamond |
| <a href="#">Table 6.</a> Cutting Feeds and Speeds for Turning Copper Alloys  |
| <a href="#">Table 7.</a> Cutting Feeds and Speeds for Turning Titanium and Titanium Alloys                                 |
| <a href="#">Table 8.</a> Cutting Feeds and Speeds for Turning Light Metals   |
| <a href="#">Table 9.</a> Cutting Feeds and Speeds for Turning Superalloys  |
| <b>Feeds and Speeds for Milling</b>  |
| <a href="#">Table 10.</a> Cutting Feeds and Speeds for Milling Aluminum Alloys   |
| <a href="#">Table 11.</a> Cutting Feeds and Speeds for Milling Plain Carbon and Alloy Steels                               |
| <a href="#">Table 12.</a> Cutting Feeds and Speeds for Milling Tool Steels   |
| <a href="#">Table 13.</a> Cutting Feeds and Speeds for Milling Stainless Steels  |
| <a href="#">Table 14.</a> Cutting Feeds and Speeds for Milling Ferrous Cast Metals   |
| <a href="#">Table 15a.</a> Recommended Feed in Inches per Tooth (ft) for Milling with High Speed Steel Cutters             |
| <a href="#">Table 15b.</a> End Milling (Full Slot) Speed Adjustment Factors for Feed, Depth of Cut, and Lead Angle         |
| <a href="#">Table 15c.</a> End, Slit, and Side Milling Speed Adjustment Factors for Radial Depth of Cut                    |
| <a href="#">Table 15d.</a> Face Milling Speed Adjustment Factors for Feed, Depth of Cut, and Lead Angle                    |
| <a href="#">Table 15e.</a> Tool Life Adjustment Factors for Face Milling, End Milling, Drilling, and Reaming               |
| <a href="#">Table 16.</a> Cutting Tool Grade Descriptions and Common Vendor Equivalents                                    |
| <b>Feeds and Speeds for Drilling, Reaming, and Threading</b>   |
| <a href="#">Table 17.</a> Feeds and Speeds for Drilling, Reaming, and Threading Plain Carbon and Alloy Steels              |
| <a href="#">Table 18.</a> Feeds and Speeds for Drilling, Reaming, and Threading Tool Steels                                |
| <a href="#">Table 19.</a> Feeds and Speeds for Drilling, Reaming, and Threading Stainless Steels                           |
| <a href="#">Table 20.</a> Feeds and Speeds for Drilling, Reaming, and Threading Ferrous Cast Metals                        |
| <a href="#">Table 21.</a> Feeds and Speeds for Drilling, Reaming, and Threading Light Metals                               |
| <a href="#">Table 22.</a> Feed and Diameter Speed Adjustment Factors for HSS Twist Drills and Reamers                      |
| <a href="#">Table 23.</a> Feeds and Speeds for Drilling and Reaming Copper Alloys  |

Each of the cutting speed tables in this section contains two distinct types of cutting speed data. The speed columns at the left of each table contain traditional Handbook cutting speeds for use with high-speed steel (HSS) tools. For many years, this extensive collection of cutting data has been used successfully as starting speed values for turning, milling, drilling, and reaming operations. Instructions and adjustment factors for use with these speeds are given in Table 5c (feed and depth-of-cut factors) for turning, and in Table 15a (feed, depth of cut, and cutter diameter) for milling. Feeds for drilling and reaming are discussed in Using the Feed and Speed Tables for Drilling, Reaming, and Threading. With traditional speeds and feeds, tool life may vary greatly from material to material, making it very difficult to plan efficient cutting operations, in particular for setting up unattended jobs on CNC equipment where the tool life must exceed cutting time, or at least be predictable so that tool changes can be scheduled. This limitation is reduced by using the combined feed/speed data contained in the remaining columns of the speed tables.

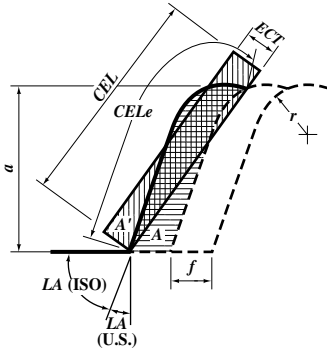
The combined feed/speed portion of the speed tables gives two sets of feed and speed data for each material represented. These feed/speed pairs are the *optimum* and *average* data (identified by *Opt.* and *Avg.*); the *optimum* set is always on the left side of the column and the *average* set is on the right. The *optimum* feed/speed data are approximate values of feed and speed that achieve minimum-cost machining by combining a high productivity rate with low tooling cost at a fixed tool life. The *average* feed/speed data are expected to achieve approximately the same tool life and tooling costs, but productivity is usually lower, so machining costs are higher. The data in this portion of the tables are given in the form of two numbers, of which the first is the feed in thousandths of an inch per revolution (or per tooth, for milling) and the second is the cutting speed in feet per minute. For example, the feed/speed set 15/215 represents a feed of 0.015 in./rev at a speed of 215 fpm. Blank cells in the data tables indicate that feed/speed data for these materials were not available at the time of publication.

Generally, the feed given in the *optimum* set should be interpreted as the maximum safe feed for the given work material and cutting tool grade, and the use of a greater feed may result in premature tool wear or tool failure before the end of the expected tool life. The primary exception to this rule occurs in milling, where the feed may be greater than the *optimum* feed if the radial depth of cut is less than the value established in the table footnote; this topic is covered later in the milling examples. Thus, except for milling, the speed and tool life adjustment tables, to be discussed later, do not permit feeds that are greater than the *optimum* feed. On the other hand, the speed and tool life adjustment factors often result in cutting speeds that are well outside the given *optimum* to *average* speed range.

The combined feed/speed data in this section were contributed by Dr. Colding of Colding International Corp., Ann Arbor, MI. The speed, feed, and tool life calculations were made by means of a special computer program and a large database of cutting speed and tool life testing data. The COMP computer program uses tool life equations that are extensions of the F. W. Taylor tool life equation, first proposed in the early 1900s. The Colding tool life equations use a concept called equivalent chip thickness (*ECT*), which simplifies cutting speed and tool life predictions, and the calculation of cutting forces, torque, and power requirements. *ECT* is a basic metal cutting parameter that combines the four basic turning variables (depth of cut, lead angle, nose radius, and feed per revolution) into one basic parameter. For other metal cutting operations (milling, drilling, and grinding, for example), *ECT* also includes additional variables such as the number of teeth, width of cut, and cutter diameter. The *ECT* concept was first presented in 1931 by Prof. R. Woxen, who showed that equivalent chip thickness is a basic metal cutting parameter for high-speed cutting tools. Dr. Colding later extended the theory to include other tool materials and metal cutting operations, including grinding.

The equivalent chip thickness is defined by  $ECT = A/CEL$ , where *A* is the cross-sectional area of the cut (approximately equal to the feed times the depth of cut), and *CEL* is the cutting edge length or tool contact rubbing length. *ECT* and several other terms related to tool

geometry are illustrated in Figs. 1 and 2. Many combinations of feed, lead angle, nose radius and cutter diameter, axial and radial depth of cut, and numbers of teeth can give the same value of *ECT*. However, for a constant cutting speed, no matter how the depth of cut, feed, or lead angle, etc., are varied, if a constant value of *ECT* is maintained, the tool life will also remain constant. A constant value of *ECT* means that a constant cutting speed gives a constant tool life and an increase in speed results in a reduced tool life. Likewise, if *ECT* were increased and cutting speed were held constant, as illustrated in the generalized cutting speed vs. *ECT* graph that follows, tool life would be reduced.



- $a$  = depth of cut
- $A = A'$  = chip cross-sectional area
- $CEL = CELe$  = engaged cutting edge length
- $ECT$  = equivalent chip thickness =  $A'/CEL$
- $f$  = feed/rev
- $r$  = nose radius
- $LA$  = lead angle (U.S.)
- $LA(ISO) = 90 - LA$

Fig. 1. Cutting Geometry, Equivalent Chip Thickness, and Cutting Edge Length

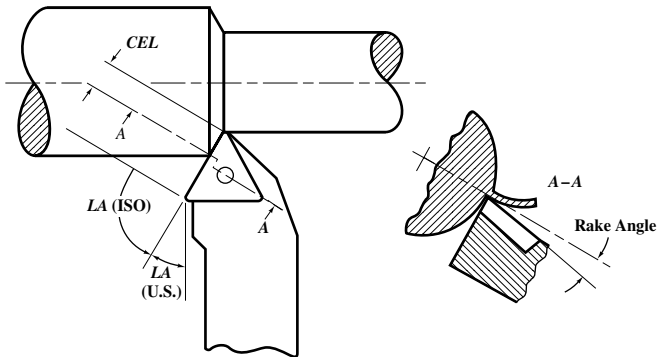


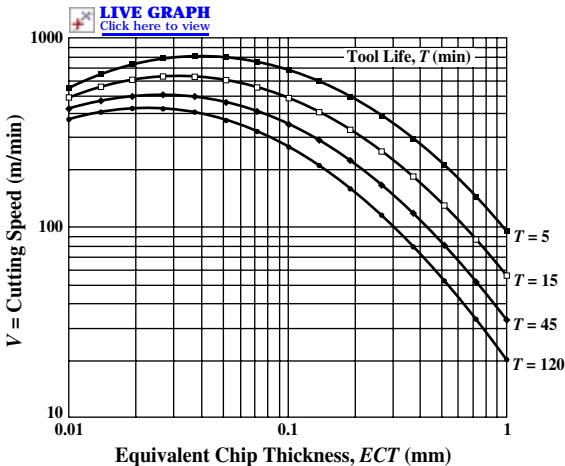
Fig. 2. Cutting Geometry for Turning

In the tables, the *optimum* feed/speed data have been calculated by COMP to achieve a fixed tool life based on the maximum *ECT* that will result in successful cutting, without premature tool wear or early tool failure. The same tool life is used to calculate the *average* feed/speed data, but these values are based on one-half of the maximum *ECT*. Because the data are not linear except over a small range of values, both *optimum* and *average* sets are required to adjust speeds for feed, lead angle, depth of cut, and other factors.

Tool life is the most important factor in a machining system, so feeds and speeds cannot be selected as simple numbers, but must be considered with respect to the many parameters that influence tool life. The accuracy of the combined feed/speed data presented is believed to be very high. However, machining is a variable and complicated process and use of the feed and speed tables requires the user to follow the instructions carefully to achieve good predictability. The results achieved, therefore, may vary due to material condition, tool material, machine setup, and other factors, and cannot be guaranteed.

The feed values given in the tables are valid for the standard tool geometries and fixed depths of cut that are identified in the table footnotes. If the cutting parameters and tool geometry established in the table footnotes are maintained, turning operations using either the *optimum* or *average* feed/speed data (Tables 1 through 9) should achieve a constant tool life of approximately 15 minutes; tool life for milling, drilling, reaming, and threading data (Tables 10 through 14 and Tables 17 through 22) should be approximately 45 minutes. The reason for the different economic tool lives is the higher tooling cost associated with milling-drilling operations than for turning. If the cutting parameters or tool geometry are different from those established in the table footnotes, the same tool life (15 or 45 minutes) still may be maintained by applying the appropriate speed adjustment factors, or tool life may be increased or decreased using tool life adjustment factors. The use of the speed and tool life adjustment factors is described in the examples that follow.

Both the *optimum* and *average* feed/speed data given are reasonable values for effective cutting. However, the *optimum* set with its higher feed and lower speed (always the left entry in each table cell) will usually achieve greater productivity. In Table 1, for example, the two entries for turning 1212 free-machining plain carbon steel with uncoated carbide are 17/805 and 8/1075. These values indicate that a feed of 0.017 in./rev and a speed of 805 ft/min, or a feed of 0.008 in./rev and a speed of 1075 ft/min can be used for this material. The tool life, in each case, will be approximately 15 minutes. If one of these feed and speed pairs is assigned an arbitrary cutting time of 1 minute, then the relative cutting time of the second pair to the first is equal to the ratio of their respective feed  $\times$  speed products. Here, the same amount of material that can be cut in 1 minute, at the higher feed and lower speed (17/805), will require 1.6 minutes at the lower feed and higher speed (8/1075) because  $17 \times 805 / (8 \times 1075) = 1.6$  minutes.



Cutting Speed versus Equivalent Chip Thickness with Tool Life as a Parameter

**Speed and Feed Tables for Turning.**—Speeds for HSS (high-speed steel) tools are based on a feed of 0.012 inch/rev and a depth of cut of 0.125 inch; use [Table 5c](#) to adjust the given speeds for other feeds and depths of cut. The combined feed/speed data in the remaining columns are based on a depth of cut of 0.1 inch, lead angle of 15 degrees, and nose radius of  $\frac{3}{64}$  inch. Use [Table 5a](#) to adjust given speeds for other feeds, depths of cut, and lead angles; use [Table 5b](#) to adjust given speeds for increased tool life up to 180 minutes. Examples are given in the text.

*Examples Using the Feed and Speed Tables for Turning:* The examples that follow give instructions for determining cutting speeds for turning. In general, the same methods are also used to find cutting speeds for milling, drilling, reaming, and threading, so reading through these examples may bring some additional insight to those other metalworking processes as well. The first step in determining cutting speeds is to locate the work material in the left column of the appropriate table for turning, milling, or drilling, reaming, and threading.

*Example 1, Turning:* Find the cutting speed for turning SAE 1074 plain carbon steel of 225 to 275 Brinell hardness, using an uncoated carbide insert, a feed of 0.015 in./rev, and a depth of cut of 0.1 inch.

In [Table 1](#), feed and speed data for two types of uncoated carbide tools are given, one for hard tool grades, the other for tough tool grades. In general, use the speed data from the tool category that most closely matches the tool to be used because there are often significant differences in the speeds and feeds for different tool grades. From the uncoated carbide hard grade values, the *optimum* and *average* feed/speed data given in [Table 1](#) are 17/615 and 8/815, or 0.017 in./rev at 615 ft/min and 0.008 in./rev at 815 ft/min. Because the selected feed (0.015 in./rev) is different from either of the feeds given in the table, the cutting speed must be adjusted to match the feed. The other cutting parameters to be used must also be compared with the general tool and cutting parameters given in the speed tables to determine if adjustments need to be made for these parameters as well. The general tool and cutting parameters for turning, given in the footnote to [Table 1](#), are depth of cut = 0.1 inch, lead angle =  $15^\circ$ , and tool nose radius =  $\frac{3}{64}$  inch.

[Table 5a](#) is used to adjust the cutting speeds for turning (from [Tables 1](#) through [9](#)) for changes in feed, depth of cut, and lead angle. The new cutting speed  $V$  is found from  $V = V_{opt} \times F_f \times F_d$ , where  $V_{opt}$  is the *optimum* speed from the table (always the lower of the two speeds given), and  $F_f$  and  $F_d$  are the adjustment factors from [Table 5a](#) for feed and depth of cut, respectively.

To determine the two factors  $F_f$  and  $F_d$ , calculate the ratio of the selected feed to the *optimum* feed,  $0.015/0.017 = 0.9$ , and the ratio of the two given speeds  $V_{avg}$  and  $V_{opt}$ ,  $815/615 = 1.35$  (approximately). The feed factor  $F_f = 1.07$  is found in [Table 5a](#) at the intersection of the feed ratio row and the speed ratio column. The depth-of-cut factor  $F_d = 1.0$  is found in the same row as the feed factor in the column for depth of cut = 0.1 inch and lead angle =  $15^\circ$ , or for a tool with a  $45^\circ$  lead angle,  $F_d = 1.18$ . The final cutting speed for a  $15^\circ$  lead angle is  $V = V_{opt} \times F_f \times F_d = 615 \times 1.07 \times 1.0 = 658$  fpm. Notice that increasing the lead angle tends to permit higher cutting speeds; such an increase is also the general effect of increasing the tool nose radius, although nose radius correction factors are not included in this table. Increasing lead angle also increases the radial pressure exerted by the cutting tool on the workpiece, which may cause unfavorable results on long, slender workpieces.

*Example 2, Turning:* For the same material and feed as the previous example, what is the cutting speed for a 0.4-inch depth of cut and a  $45^\circ$  lead angle?

As before, the feed is 0.015 in./rev, so  $F_f$  is 1.07, but  $F_d = 1.03$  for depth of cut equal to 0.4 inch and a  $45^\circ$  lead angle. Therefore,  $V = 615 \times 1.07 \times 1.03 = 676$  fpm. Increasing the lead angle from  $15^\circ$  to  $45^\circ$  permits a much greater (four times) depth of cut, at the same feed and nearly constant speed. Tool life remains constant at 15 minutes. (*Continued on page 1036*)

**Table 1. Cutting Feeds and Speeds for Turning Plain Carbon and Alloy Steels**

| Material<br>AISI/SAE Designation  | Brinell<br>Hardness | Tool Material  |  |           |           |           |                |            |            |           |            |            |           |            |           |           |           |
|---|---------------------|----------------|--|-----------|-----------|-----------|----------------|------------|------------|-----------|------------|------------|-----------|------------|-----------|-----------|-----------|
|   |                     | HSS            | Uncoated Carbide                             |           |           |           | Coated Carbide |            |            |           | Ceramic    |            |           |            | Cermets   |           |           |
|   |                     |                | Hard   |           | Tough     |           | Hard           |            | Tough      |           | Hard       |            | Tough     |            |           |           |           |
|   |                     | Speed<br>(fpm) | f = feed (0.001 in./rev), s = speed (ft/min) |           |           |           |                |            |            |           |            |            |           |            |           |           |           |
|   |                     | Opt.           | Avg.   | Opt.      | Avg.      | Opt.      | Avg.           | Opt.       | Avg.       | Opt.      | Avg.       | Opt.       | Avg.      | Opt.       | Avg.      |           |           |
| Free-machining plain carbon steels<br>(resulfurized): 1212, 1213, 1215  | 100-150             | 150            | f<br>s                                       | 17<br>805 | 8<br>1075 | 36<br>405 | 17<br>555      | 17<br>1165 | 8<br>1295  | 28<br>850 | 13<br>1200 | 15<br>3340 | 8<br>4985 | 15<br>1670 | 8<br>2500 | 7<br>1610 | 3<br>2055 |
|   | 150-200             | 160            | f<br>s                                       | 17<br>745 | 8<br>935  | 36<br>345 | 17<br>470      | 28<br>915  | 13<br>1130 | 28<br>785 | 13<br>1110 | 15<br>1795 | 8<br>2680 | 15<br>1485 | 8<br>2215 | 7<br>1490 | 3<br>1815 |
| 1108, 1109, 1115, 1117, 1118, 1120, 1126, 1211  | 100-150             | 130            | f<br>s                                       | 17<br>730 | 8<br>990  | 36<br>300 | 17<br>430      | 17<br>1090 | 8<br>1410  | 28<br>780 | 13<br>1105 | 15<br>1610 | 8<br>2780 | 15<br>1345 | 8<br>2005 | 7<br>1355 | 3<br>1695 |
|   | 150-200             | 120            | f<br>s                                       | 17<br>615 | 8<br>815  | 36<br>300 | 17<br>405      | 17<br>865  | 8<br>960   | 28<br>755 | 13<br>960  | 13<br>1400 | 7<br>1965 | 13<br>1170 | 7<br>1640 |           |           |
| 1132, 1137, 1139, 1140, 1144, 1146, 1151  | 275-325             | 75             |  |           |           |           |                |            |            |           |            |            |           |            |           |           |           |
|   | 325-375             | 50             | f<br>s                                       | 17<br>515 | 8<br>685  | 36<br>235 | 17<br>340      | 17<br>720  | 8<br>805   | 28<br>650 | 13<br>810  | 10<br>1430 | 5<br>1745 | 10<br>1070 | 5<br>1305 |           |           |
| (Leaded): 11L17, 11L18, 12L13, 12L14  | 100-150             | 140            | f<br>s                                       | 17<br>745 | 8<br>935  | 36<br>345 | 17<br>470      | 28<br>915  | 13<br>1130 | 28<br>785 | 13<br>1110 | 15<br>1795 | 8<br>2680 | 15<br>1485 | 8<br>2215 | 7<br>1490 | 3<br>1815 |
|   | 150-200             | 145            | f<br>s                                       | 17<br>615 | 8<br>815  | 36<br>300 | 17<br>405      | 17<br>865  | 8<br>960   | 28<br>755 | 13<br>960  | 13<br>1400 | 7<br>1965 | 13<br>1170 | 7<br>1640 |           |           |
| Plain carbon steels: 1006, 1008, 1009, 1010, 1012, 1015, 1016, 1017, 1018, 1019, 1020, 1021, 1022, 1023, 1024, 1025, 1026, 1513, 1514 | 100-125             | 120            | f<br>s                                       | 17<br>805 | 8<br>1075 | 36<br>405 | 17<br>555      | 17<br>1165 | 8<br>1295  | 28<br>850 | 13<br>1200 | 15<br>3340 | 8<br>4985 | 15<br>1670 | 8<br>2500 | 7<br>1610 | 3<br>2055 |
|   | 125-175             | 110            | f<br>s                                       | 17<br>745 | 8<br>935  | 36<br>345 | 17<br>470      | 28<br>915  | 13<br>1130 | 28<br>785 | 13<br>1110 | 15<br>1795 | 8<br>2680 | 15<br>1485 | 8<br>2215 | 7<br>1490 | 3<br>1815 |
|   | 175-225             | 90             |  |           |           |           |                |            |            |           |            |            |           |            |           |           |           |
|   | 225-275             | 70             | f<br>s                                       | 17<br>615 | 8<br>815  | 36<br>300 | 17<br>405      | 17<br>865  | 8<br>960   | 28<br>755 | 13<br>960  | 13<br>1400 | 7<br>1965 | 13<br>1170 | 7<br>1640 |           |           |



Table 1. (Continued) Cutting Feeds and Speeds for Turning Plain Carbon and Alloy Steels

| Material<br>AISI/SAE Designation  | Brinell<br>Hardness | Tool Material  |     |                  |     |       |     |                |      |       |      |         |      |       |      |        |      |
|---|---------------------|----------------|-----|------------------|-----|-------|-----|----------------|------|-------|------|---------|------|-------|------|--------|------|
|   |                     | HSS            |     | Uncoated Carbide |     |       |     | Coated Carbide |      |       |      | Ceramic |      |       |      |        |      |
|   |                     |                |     | Hard             |     | Tough |     | Hard           |      | Tough |      | Hard    |      | Tough |      | Cermet |      |
|   |                     | Speed<br>(fpm) |     | Opt.             |     | Avg.  |     | Opt.           |      | Avg.  |      | Opt.    |      | Avg.  |      | Opt.   |      |
| Plain carbon steels (continued): 1027, 1030, 1033, 1035, 1036, 1037, 1038, 1039, 1040, 1041, 1042, 1043, 1045, 1046, 1048, 1049, 1050, 1052, 1524, 1526, 1527, 1541 | 125-175             | 100            | f   | 17               | 8   | 36    | 17  | 28             | 13   | 28    | 13   | 15      | 8    | 15    | 8    | 7      | 3    |
|   | 175-225             | 85             | s   | 745              | 935 | 345   | 470 | 915            | 1130 | 785   | 1110 | 1795    | 2680 | 1485  | 2215 | 1490   | 1815 |
|   | 225-275             | 70             | f   | 17               | 8   | 36    | 17  | 17             | 8    | 28    | 13   | 13      | 7    | 13    | 7    |        |      |
|   | 275-325             | 60             | s   | 615              | 815 | 300   | 405 | 865            | 960  | 755   | 960  | 1400    | 1965 | 1170  | 1640 |        |      |
|   | 325-375             | 40             | f   | 17               | 8   | 36    | 17  | 17             | 8    | 28    | 13   | 10      | 5    | 10    | 5    |        |      |
| 375-425   | 30                  | s              | 515 | 685              | 235 | 340   | 720 | 805            | 650  | 810   | 1430 | 1745    | 1070 | 1305  |      |        |      |
| Plain carbon steels (continued): 1055, 1060, 1064, 1065, 1070, 1074, 1078, 1080, 1084, 1086, 1090, 1095, 1548, 1551, 1552, 1561, 1566                               | 125-175             | 100            | f   | 17               | 8   | 36    | 17  | 17             | 8    | 28    | 13   | 15      | 8    | 15    | 8    | 7      | 3    |
|   | 175-225             | 80             | s   | 730              | 990 | 300   | 430 | 1090           | 1410 | 780   | 1105 | 1610    | 2780 | 1345  | 2005 | 1355   | 1695 |
|   | 225-275             | 65             | f   | 17               | 8   | 36    | 17  | 17             | 8    | 28    | 13   | 13      | 7    | 13    | 7    | 7      | 3    |
|   | 275-325             | 50             | s   | 615              | 815 | 300   | 405 | 865            | 960  | 755   | 960  | 1400    | 1965 | 1170  | 1640 | 1365   | 1695 |
|   | 325-375             | 35             | f   | 17               | 8   | 36    | 17  | 17             | 8    | 28    | 13   | 10      | 5    | 10    | 5    |        |      |
| 375-425   | 30                  | s              | 515 | 685              | 235 | 340   | 720 | 805            | 650  | 810   | 1430 | 1745    | 1070 | 1305  |      |        |      |
| Free-machining alloy steels, (resulfurized): 4140, 4150   | 175-200             | 110            | f   | 17               | 8   | 36    | 17  | 17             | 8    | 28    | 13   | 15      | 8    | 15    | 8    | 7      | 3    |
|   | 200-250             | 90             | s   | 525              | 705 | 235   | 320 | 505            | 525  | 685   | 960  | 1490    | 2220 | 1190  | 1780 | 1040   | 1310 |
|   | 250-300             | 65             | f   | 17               | 8   | 36    | 17  | 17             | 8    | 28    | 13   | 10      | 5    | 10    | 5    | 7      | 3    |
|   | 300-375             | 50             | s   | 355              | 445 | 140   | 200 | 630            | 850  | 455   | 650  | 1230    | 1510 | 990   | 1210 | 715    | 915  |
| 375-425   | 40                  | f              | 17  | 8                | 36  | 17    | 17  | 8              | 28   | 13    | 8    | 4       | 8    | 4     | 7    | 3      |      |
|   |                     |                | s   | 330              | 440 | 125   | 175 | 585            | 790  | 125   | 220  | 1200    | 1320 | 960   | 1060 | 575    | 740  |

Table 1. (Continued) Cutting Feeds and Speeds for Turning Plain Carbon and Alloy Steels

| Material<br>AISI/SAE Designation   | Brinell<br>Hardness | Tool Material  |          |                  |     |             |     |                |      |             |      |             |      |             |      |             |      |
|--|---------------------|----------------|----------|------------------|-----|-------------|-----|----------------|------|-------------|------|-------------|------|-------------|------|-------------|------|
|  |                     | HSS            |          | Uncoated Carbide |     |             |     | Coated Carbide |      |             |      | Ceramic     |      |             |      |             |      |
|  |                     |                |          | Hard             |     | Tough       |     | Hard           |      | Tough       |      | Hard        |      | Tough       |      | Cermet      |      |
|  |                     | Speed<br>(fpm) |          | <i>Opt.</i>      |     | <i>Avg.</i> |     | <i>Opt.</i>    |      | <i>Avg.</i> |      | <i>Opt.</i> |      | <i>Avg.</i> |      | <i>Opt.</i> |      |
| Free-machining alloy steels: (leadeds): 41L30,<br>41L40, 41L47, 41L50, 43L47, 51L32, 52L100,<br>86L20, 86L40   | 150-200             | 120            | <b>f</b> | 17               | 8   | 36          | 17  | 17             | 8    | 28          | 13   | 15          | 8    | 15          | 8    | 7           | 3    |
|  |                     |                | <b>s</b> | 730              | 990 | 300         | 430 | 1090           | 1410 | 780         | 1105 | 1610        | 2780 | 1345        | 2005 | 1355        | 1695 |
|  | 200-250             | 100            | <b>f</b> | 17               | 8   | 36          | 17  | 17             | 8    | 28          | 13   | 13          | 7    | 13          | 7    | 7           | 3    |
|  |                     |                | <b>s</b> | 615              | 815 | 300         | 405 | 865            | 960  | 755         | 960  | 1400        | 1965 | 1170        | 1640 | 1355        | 1695 |
|  | 250-300             | 75             |          |                  |     |             |     |                |      |             |      |             |      |             |      |             |      |
| 300-375  | 55                  | <b>f</b>       | 17       | 8                | 36  | 17          | 17  | 8              | 28   | 13          | 10   | 5           | 10   | 5           |      |             |      |
|  |                     | <b>s</b>       | 515      | 685              | 235 | 340         | 720 | 805            | 650  | 810         | 1430 | 1745        | 1070 | 1305        |      |             |      |
| 375-425  | 50                  |                |          |                  |     |             |     |                |      |             |      |             |      |             |      |             |      |
| Alloy steels: 4012, 4023, 4024, 4028, 4118, 4320,<br>4419, 4422, 4427, 4615, 4620, 4621, 4626, 4718,<br>4720, 4815, 4817, 4820, 5015, 5117, 5120, 6118,<br>8115, 8615, 8617, 8620, 8622, 8625, 8627, 8720,<br>8822, 94B17  | 125-175             | 100            | <b>f</b> | 17               | 8   | 36          | 17  | 17             | 8    | 28          | 13   | 15          | 8    | 15          | 8    | 7           | 3    |
|  |                     |                | <b>s</b> | 525              | 705 | 235         | 320 | 505            | 525  | 685         | 960  | 1490        | 2220 | 1190        | 1780 | 1040        | 1310 |
|  | 175-225             | 90             | <b>f</b> | 17               | 8   | 36          | 1   | 17             | 8    | 28          | 13   | 10          | 5    | 10          | 5    | 7           | 3    |
|  |                     |                | <b>s</b> | 355              | 445 | 140         | 200 | 630            | 850  | 455         | 650  | 1230        | 1510 | 990         | 1210 | 715         | 915  |
|  | 225-275             | 70             | <b>f</b> | 17               | 8   | 36          | 17  | 17             | 8    | 28          | 13   | 9           | 5    | 8           | 5    | 7           | 3    |
|  |                     | <b>s</b>       | 330      | 440              | 135 | 190         | 585 | 790            | 240  | 350         | 1230 | 1430        | 990  | 1150        | 655  | 840         |      |
| 275-325  | 60                  | <b>f</b>       | 17       | 8                | 36  | 17          | 17  | 8              | 28   | 13          | 8    | 4           | 8    | 4           | 7    | 3           |      |
|  |                     | <b>s</b>       | 330      | 440              | 125 | 175         | 585 | 790            | 125  | 220         | 1200 | 1320        | 960  | 1060        | 575  | 740         |      |
| 325-35   | 50                  |                |          |                  |     |             |     |                |      |             |      |             |      |             |      |             |      |
| 375-425  | 30 (20)             |                |          |                  |     |             |     |                |      |             |      |             |      |             |      |             |      |
| Alloy steels: 1330, 1335, 1340, 1345, 4032, 4037,<br>4042, 4047, 4130, 4135, 4137, 4140, 4142, 4145,<br>4147, 4150, 4161, 4337, 4340, 50B44, 50B46,<br>50B50, 50B60, 5130, 5132, 5140, 5145, 5147,<br>5150, 5160, 51B60, 6150, 81B45, 8630, 8635,<br>8637, 8640, 8642, 8645, 8650, 8655, 8660, 8740,<br>9254, 9255, 9260, 9262, 94B30<br>E51100, E52100 use (HSS Speeds) | 175-225             | 85 (70)        | <b>f</b> | 17               | 8   | 36          | 17  | 17             | 8    | 28          | 13   | 15          | 8    | 15          | 8    | 7           | 3    |
|  |                     |                | <b>s</b> | 525              | 705 | 235         | 320 | 505            | 525  | 685         | 960  | 1490        | 2220 | 1190        | 1780 | 1020        | 1310 |
|  | 225-275             | 70 (65)        | <b>f</b> | 17               | 8   | 36          | 17  | 17             | 8    | 28          | 13   | 10          | 5    | 10          | 5    | 7           | 3    |
|  |                     |                | <b>s</b> | 355              | 445 | 140         | 200 | 630            | 850  | 455         | 650  | 1230        | 1510 | 990         | 1210 | 715         | 915  |
|  | 275-325             | 60 (50)        | <b>f</b> | 17               | 8   | 36          | 17  | 17             | 8    | 28          | 13   | 9           | 5    | 8           | 5    | 7           | 3    |
|  |                     | <b>s</b>       | 330      | 440              | 135 | 190         | 585 | 790            | 240  | 350         | 1230 | 1430        | 990  | 1150        | 655  | 840         |      |
| 325-375  | 40 (30)             |                |          |                  |     |             |     |                |      |             |      |             |      |             |      |             |      |
| 375-425  | 30 (20)             |                |          |                  |     |             |     |                |      |             |      |             |      |             |      |             |      |

Table 1. (Continued) Cutting Feeds and Speeds for Turning Plain Carbon and Alloy Steels

| Material<br>AISI/SAE Designation  | Brinell<br>Hardness | Tool Material  |        |                  |          |           |           |                |           |           |           |            |           |            |           |           |           |      |
|---|---------------------|----------------|--------|------------------|----------|-----------|-----------|----------------|-----------|-----------|-----------|------------|-----------|------------|-----------|-----------|-----------|------|
|   |                     | HSS            |        | Uncoated Carbide |          |           |           | Coated Carbide |           |           |           | Ceramic    |           |            |           | Cermet    |           |      |
|   |                     |                |        | Hard             |          | Tough     |           | Hard           |           | Tough     |           | Hard       |           | Tough      |           |           |           |      |
|   |                     | Speed<br>(fpm) |        | Opt.             |          | Avg.      |           | Opt.           |           | Avg.      |           | Opt.       |           | Avg.       |           | Opt.      |           | Avg. |
| Ultra-high-strength steels (not ASI): AMS alloys<br>6421 (98B37 Mod.), 6422 (98BV40), 6424,<br>6427, 6428, 6430, 6432, 6433, 6434, 6436, and<br>6442; 300M and D6ac | 220–300             | 65             |        |                  |          |           |           |                |           |           |           |            |           |            |           |           |           |      |
|   | 300–350             | 50             | f<br>s | 17<br>220        | 8<br>295 | 36<br>100 | 17<br>150 | 20<br>355      | 10<br>525 | 28<br>600 | 13<br>865 |            |           | 10<br>660  | 5<br>810  | 7<br>570  | 3<br>740  |      |
|   | 350–400             | 35             | f<br>s | 17<br>165        | 8<br>185 | 36<br>55  | 17<br>105 | 17<br>325      | 8<br>350  | 28<br>175 | 13<br>260 |            |           | 8<br>660   | 4<br>730  | 7<br>445  | 3<br>560  |      |
|   | 43–48 Rc            | 25             |        |                  |          |           |           |                |           |           |           |            |           |            |           |           |           |      |
|   | 48–52 Rc            | 10             | f<br>s |                  |          | 17<br>55† | 8<br>90   |                |           |           |           |            | 7<br>385  | 3<br>645   | 10<br>270 | 5<br>500  |           |      |
| Maraging steels (not AISI): 18% Ni, Grades 200,<br>250, 300, and 350  | 250–325             | 60             | f<br>s | 17<br>220        | 8<br>295 | 36<br>100 | 17<br>150 | 20<br>355      | 10<br>525 | 28<br>600 | 13<br>865 | 660        | 810       | 10<br>570  | 5<br>740  | 7         | 3         |      |
|   | 50–52 Rc            | 10             | f<br>s |                  |          | 17<br>55† | 8<br>90   |                |           |           |           | 7<br>385‡  | 3<br>645  | 10<br>270  | 5<br>500  |           |           |      |
| Nitriding steels (not AISI): Nitalloy 125, 135, 135<br>Mod., 225, and 230, Nitalloy N, Nitalloy EZ,<br>Nitrex 1   | 200–250             | 70             | f<br>s | 17<br>525        | 8<br>705 | 36<br>235 | 17<br>320 | 17<br>505      | 8<br>525  | 28<br>685 | 13<br>960 | 15<br>1490 | 8<br>2220 | 15<br>1190 | 8<br>1780 | 7<br>1040 | 3<br>1310 |      |
|   | 300–350             | 30             | f<br>s | 17<br>330        | 8<br>440 | 36<br>125 | 17<br>175 | 17<br>585      | 8<br>790  | 28<br>125 | 13<br>220 | 8<br>1200  | 4<br>1320 | 8<br>960   | 4<br>1060 | 7<br>575  | 3<br>740  |      |

Speeds for HSS (high-speed steel) tools are based on a feed of 0.012 inch/rev and a depth of cut of 0.125 inch; use Table 5c to adjust the given speeds for other feeds and depths of cut. The combined feed/speed data in the remaining columns are based on a depth of cut of 0.1 inch, lead angle of 15 degrees, and nose radius of  $\frac{3}{64}$  inch. Use Table 5a to adjust given speeds for other feeds, depths of cut, and lead angles; use Table 5b to adjust given speeds for increased tool life up to 180 minutes. Examples are given in the text.

The combined feed/speed data in this table are based on tool grades (identified in Table 16) as follows: uncoated carbides, hard = 17, tough = 19, † = 15; coated carbides, hard = 11, tough = 14; ceramics, hard = 2, tough = 3, ‡ = 4; cermet = 7.

Table 2. Cutting Feeds and Speeds for Turning Tool Steels

| Material<br>AISI Designation  | Brinell<br>Hardness | Tool Material   |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
|---|---------------------|-----------------|--|------|-------|------|----------------|------|-------|------|---------|------|-------|------|---------|--|
|   |                     | Uncoated<br>HSS | Uncoated Carbide                             |      |       |      | Coated Carbide |      |       |      | Ceramic |      |       |      | Cermets |  |
|   |                     |                 | Hard   |      | Tough |      | Hard           |      | Tough |      | Hard    |      | Tough |      |         |  |
|   |                     | Speed<br>(fpm)  | f = feed (0.001 in./rev), s = speed (ft/min) |      |       |      |                |      |       |      |         |      |       |      |         |  |
| Opt.  | Avg.                |                 | Opt.   | Avg. | Opt.  | Avg. | Opt.           | Avg. | Opt.  | Avg. | Opt.    | Avg. | Opt.  | Avg. |         |  |
| Water hardening: W1, W2, W5   | 150-200             | 100             |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
| Shock resisting: S1, S2, S5, S6, S7                                   | 175-225             | 70              |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
| Cold work, oil hardening: O1, O2, O6, O7                              | 175-225             | 70              | f  |      |       |      |                |      |       |      |         |      |       |      |         |  |
| Cold work, high carbon, high chromium: D2, D3, D4, D5, D7             | 200-250             | 45              | s  | 17   | 8     | 36   | 17             | 17   | 8     | 28   | 13      | 13   | 7     | 13   | 7       |  |
|   |                     |                 |  | 445  | 610   | 210  | 270            | 830  | 1110  | 575  | 805     | 935  | 1310  | 790  | 1110    |  |
|   |                     |                 |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
| Cold work, air hardening: A2, A3, A8, A9, A10                         | 200-250             | 70              |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
| A4, A6  | 200-250             | 55              | f  |      |       |      |                |      |       |      |         |      |       |      |         |  |
| A7  | 225-275             | 45              | s  | 17   | 8     | 36   | 17             | 17   | 8     | 28   | 13      | 13   | 7     | 13   | 7       |  |
|   |                     |                 |  | 445  | 490   | 170  | 235            | 705  | 940   | 515  | 770     | 660  | 925   | 750  | 1210    |  |
|   |                     |                 |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
|   | 150-200             | 80              |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
| Hot work, chromium type: H10, H11, H12, H13, H14, H19                 | 200-250             | 65              |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
|   | 325-375             | 50              | f  | 17   | 8     | 36   | 17             | 17   | 8     | 28   | 13      |      |       | 8    | 4       |  |
|   |                     |                 | s  | 165  | 185   | 55   | 105            | 325  | 350   | 175  | 260     |      |       | 660  | 730     |  |
|   |                     |                 |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
|   | 48-50 Rc            | 20              | f  |      |       | 17   | 8              |      |       |      |         | 7    | 3     | 10   | 5       |  |
|   | 50-52 Rc            | 10              | s  |      |       | 55†  | 90             |      |       |      |         | 385‡ | 645   | 270  | 500     |  |
|   | 52-56 Rc            | —               |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
| Hot work, tungsten type: H21, H22, H23, H24, H25, H26                 | 150-200             | 60              |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
|   | 200-250             | 50              | f  | 17   | 8     | 36   | 17             | 17   | 8     | 28   | 13      | 13   | 7     | 13   | 7       |  |
|   |                     |                 | s  | 445  | 490   | 170  | 235            | 705  | 940   | 515  | 770     | 660  | 925   | 750  | 1210    |  |
| Hot work, molybdenum type: H41, H42, H43                              | 150-200             | 55              |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
|   | 200-250             | 45              |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
| Special purpose, low alloy: L2, L3, L6                                | 150-200             | 75              | f  | 17   | 8     | 36   | 17             | 17   | 8     | 28   | 13      | 13   | 7     | 13   | 7       |  |
|   |                     |                 | s  | 445  | 610   | 210  | 270            | 830  | 1110  | 575  | 805     | 935  | 1310  | 790  | 1110    |  |
| Mold: P2, P3, P4, P5, P6, P26, P21                                    | 100-150             | 90              | f  | 17   | 8     | 36   | 17             | 17   | 8     | 28   | 13      | 13   | 7     | 13   | 7       |  |
|   | 150-200             | 80              | s  | 445  | 610   | 210  | 270            | 830  | 1110  | 575  | 805     | 935  | 1310  | 790  | 1110    |  |
| High-speed steel: M1, M2, M6, M10, T1, T2, T6                         | 200-250             | 65              |  |      |       |      |                |      |       |      |         |      |       |      |         |  |
| M3-1, M4 M7, M30, M33, M34, M36, M41, M42, M43, M44, M46, M47, T5, T8 | 225-275             | 55              | f  | 17   | 8     | 36   | 17             | 17   | 8     | 28   | 13      | 13   | 7     | 13   | 7       |  |
| T15, M3-2   | 225-275             | 45              | s  | 445  | 490   | 170  | 235            | 705  | 940   | 515  | 770     | 660  | 925   | 750  | 1210    |  |

Speeds for HSS (high-speed steel) tools are based on a feed of 0.012 inch/rev and a depth of cut of 0.125 inch; use Table 5c to adjust the given speeds for other feeds and depths of cut. The combined feed/speed data in the remaining columns are based on a depth of cut of 0.1 inch, lead angle of 15 degrees, and nose radius of  $\frac{3}{64}$  inch. Use Table 5a to adjust given speeds for other feeds, depths of cut, and lead angles; use Table 5b to adjust given speeds for increased tool life up to 180 minutes. Examples are given in the text. The combined feed/speed data in this table are based on tool grades (identified in Table 16) as follows: uncoated carbides, hard = 17, tough = 19, † = 15; coated carbides, hard = 11, tough = 14; ceramics, hard = 2, tough = 3, ‡ = 4; cermet = 7.

Table 3. Cutting Feeds and Speeds for Turning Stainless Steels

| Material  | Brinell Hardness   | Tool Material |  |           |           |           |                |           |          |           |           |            |          |
|---|--------------------|---------------|--|-----------|-----------|-----------|----------------|-----------|----------|-----------|-----------|------------|----------|
|   |                    | Uncoated HSS  | Uncoated Carbide                             |           |           |           | Coated Carbide |           |          |           | Cermets   |            |          |
|   |                    |               | Hard   |           | Tough     |           | Hard           |           | Tough    |           |           |            |          |
|   |                    | Speed (fpm)   | f = feed (0.001 in./rev), s = speed (ft/min) |           |           |           |                |           |          |           |           |            |          |
| Opt.  | Avg.               |               | Opt.   | Avg.      | Opt.      | Avg.      | Opt.           | Avg.      | Opt.     | Avg.      |           |            |          |
| Free-machining stainless steel<br>(Ferritic): 430F, 430FSe<br><br>(Austenitic): 203EZ, 303, 303Se, 303MA,<br>303Pb, 303Cu, 303 Plus X                                     | 135–185            | 110           | f<br>s                                       | 20<br>480 | 10<br>660 | 36<br>370 | 17<br>395      | 17<br>755 | 8<br>945 | 28<br>640 | 13<br>810 | 7<br>790   | 3<br>995 |
|   | 135–185<br>225–275 | 100<br>80     | f<br>s                                       | 13<br>520 | 7<br>640  | 36<br>310 | 17<br>345      |           |          | 28<br>625 | 13<br>815 | 7<br>695   | 3<br>875 |
| (Martensitic): 416, 416Se, 416 Plus X,<br>420F, 420FSe, 440F, 440FSe  | 135–185            | 110           | f<br>s                                       | 13<br>520 | 7<br>640  | 36<br>310 |                |           |          | 28<br>625 | 13<br>815 | 7<br>695   | 3<br>875 |
|   | 185–240            | 100           | f<br>s                                       | 13<br>520 | 7<br>640  | 36<br>310 |                |           |          | 28<br>625 | 13<br>815 | 7<br>695   | 3<br>875 |
|   | 275–325            | 60            | f<br>s                                       | 13<br>210 | 7<br>260  | 36<br>85  | 17<br>135      |           |          | 28<br>130 | 13<br>165 |            |          |
|   | 375–425            | 30            | f<br>s                                       | 13<br>210 | 7<br>260  | 36<br>85  | 17<br>135      |           |          | 28<br>130 | 13<br>165 |            |          |
| Stainless steels (Ferritic): 405, 409 429,<br>430, 434, 436, 442, 446, 502<br><br>(Austenitic): 201, 202, 301, 302, 304, 304L,<br>305, 308, 321, 347, 348                 | 135–185            | 90            | f<br>s                                       | 20<br>480 | 10<br>660 | 36<br>370 | 17<br>395      | 17<br>755 | 8<br>945 | 28<br>640 | 13<br>810 | 7<br>790   | 3<br>995 |
|   | 135–185<br>225–275 | 75<br>65      | f<br>s                                       | 13<br>520 | 7<br>640  | 36<br>310 | 17<br>345      |           |          | 28<br>625 | 13<br>165 | 7<br>695   | 3<br>875 |
| (Austenitic): 302B, 309, 309S, 310, 310S,<br>314, 316, 316L, 317, 330<br><br>(Martensitic): 403, 410, 420, 501  | 135–185            | 70            | f<br>s                                       | 13<br>520 | 7<br>640  | 36<br>310 | 17<br>345      |           |          | 28<br>625 | 13<br>165 | 7<br>695   | 3<br>875 |
|   | 135–175            | 95            |  |           |           |           |                |           |          |           |           |            |          |
|   | 175–225            | 85            |  |           |           |           |                |           |          |           |           |            |          |
|   | 275–325            | 55            |  |           |           |           |                |           |          |           |           |            |          |
| (Martensitic): 414, 431, Greek Ascoloy,<br>440A, 440B, 440C   | 375–425            | 35            | f<br>s                                       | 13<br>210 | 7<br>260  | 36<br>85  | 17<br>135      |           |          | 28<br>130 | 13<br>165 | 13<br>200† | 7<br>230 |
|   | 225–275            | 55–60         |  |           |           |           |                |           |          |           |           |            |          |
|   | 275–325            | 45–50         |  |           |           |           |                |           |          |           |           |            |          |
|   | 375–425            | 30            |  |           |           |           |                |           |          |           |           |            |          |
| (Precipitation hardening): 15-5PH, 17-4PH,<br>17-7PH, AF-71, 17-14CuMo, AFC-77,<br>AM-350, AM-355, AM-362, Custom 455,<br>HNM, PH13-8, PH14-8Mo, PH15-7Mo,<br>Stainless W | 150–200            | 60            | f<br>s                                       | 13<br>520 | 7<br>640  | 36<br>310 | 17<br>345      |           |          | 28<br>625 | 13<br>815 | 13<br>695  | 7<br>875 |
|   | 275–325            | 50            | f<br>s                                       | 13<br>520 | 7<br>640  | 36<br>310 | 17<br>345      |           |          | 28<br>625 | 13<br>815 | 13<br>695  | 7<br>875 |
|   | 325–375            | 40            | f<br>s                                       | 13<br>195 | 7<br>240  | 36<br>85  | 17<br>155      |           |          |           |           |            |          |
| 375–450   | 25                 | f<br>s        | 13<br>195                                    | 7<br>240  | 36<br>85  | 17<br>155 |                |           |          |           |           |            |          |

See footnote to Table 1 for more information. The combined feed/speed data in this table are based on tool grades (identified in Table 16) as follows: uncoated carbides, hard = 17, tough = 19; coated carbides, hard = 11, tough = 14; cermet = 7, † = 18.

Table 4a. Cutting Feeds and Speeds for Turning Ferrous Cast Metals

| Material  | Brinell Hardness | Tool Material                                |                  |     |      |     |                |     |      |      |         |      |      |     |        |      |       |  |
|---|------------------|--|------------------|-----|------|-----|----------------|-----|------|------|---------|------|------|-----|--------|------|-------|--|
|   |                  | HSS  | Uncoated Carbide |     |      |     | Coated Carbide |     |      |      | Ceramic |      |      |     | Cermet |      | CBN   |  |
|   |                  |  | Tough            |     | Hard |     | Tough          |     | Hard |      | Tough   |      |      |     |        |      |       |  |
|   |                  | f = feed (0.001 in./rev), s = speed (ft/min) |                  |     |      |     |                |     |      |      |         |      |      |     |        |      |       |  |
| Speed (fpm)   | Opt.             |  | Avg.             |     | Opt. |     | Avg.           |     | Opt. |      | Avg.    |      | Opt. |     | Avg.   |      |       |  |
| Gray Cast Iron  |                  |  |                  |     |      |     |                |     |      |      |         |      |      |     |        |      |       |  |
| ASTM Class 20   | 120–150          | 120  | f                | 28  | 13   | 28  | 13             | 28  | 13   | 15   | 8       | 15   | 8    | 8   | 4      | 24   | 11    |  |
| ASTM Class 25   | 160–200          | 90   | s                | 240 | 365  | 665 | 1040           | 585 | 945  | 1490 | 2220    | 1180 | 1880 | 395 | 510    | 8490 | 36380 |  |
| ASTM Class 30, 35, and 40                             | 190–220          | 80   |                  |     |      |     |                |     |      |      |         |      |      |     |        |      |       |  |
| ASTM Class 45 and 50                                  | 220–260          | 60   | f                | 28  | 13   | 28  | 13             | 28  | 13   | 11   | 6       | 11   | 6    | 8   | 4      | 24   | 11    |  |
| ASTM Class 55 and 60                                  | 250–320          | 35   | s                | 160 | 245  | 400 | 630            | 360 | 580  | 1440 | 1880    | 1200 | 1570 | 335 | 420    | 1590 | 2200  |  |
| ASTM Type 1, 1b, 5 (Ni resist)                        | 100–215          | 70   | f                | 28  | 13   |     |                | 28  | 13   | 15   | 8       | 15   | 8    | 8   | 4      |      |       |  |
| ASTM Type 2, 3, 6 (Ni resist)                         | 120–175          | 65   | s                | 110 | 175  |     |                | 410 | 575  | 1060 | 1590    | 885  | 1320 | 260 | 325    |      |       |  |
| ASTM Type 2b, 4 (Ni resist)                           | 150–250          | 50   |                  |     |      |     |                |     |      |      |         |      |      |     |        |      |       |  |
| Malleable Iron  |                  |  |                  |     |      |     |                |     |      |      |         |      |      |     |        |      |       |  |
| (Ferritic): 32510, 35018                              | 110–160          | 130  | f                | 28  | 13   | 28  | 13             | 28  | 13   | 15   | 8       | 15   | 8    |     |        |      |       |  |
|   |                  |  | s                | 180 | 280  | 730 | 940            | 660 | 885  | 1640 | 2450    | 1410 | 2110 |     |        |      |       |  |
| (Pearlitic): 40010, 43010, 45006, 45008, 48005, 50005 | 160–200          | 95   | f                | 28  | 13   | 28  | 13             | 28  | 13   | 13   | 7       | 13   | 7    |     |        |      |       |  |
|   | 200–240          | 75   | s                | 125 | 200  | 335 | 505            | 340 | 510  | 1640 | 2310    | 1400 | 1970 |     |        |      |       |  |
| (Martensitic): 53004, 60003, 60004                    | 200–255          | 70   |                  |     |      |     |                |     |      |      |         |      |      |     |        |      |       |  |
| (Martensitic): 70002, 70003                           | 220–260          | 60   | f                | 28  | 13   |     |                | 28  | 13   | 11   | 6       | 11   | 6    |     |        |      |       |  |
| (Martensitic): 80002                                  | 240–280          | 50   | s                | 100 | 120  |     |                | 205 | 250  | 1720 | 2240    | 1460 | 1910 |     |        |      |       |  |
| (Martensitic): 90001                                  | 250–320          | 30   |                  |     |      |     |                |     |      |      |         |      |      |     |        |      |       |  |

Speeds for HSS (high-speed steel) tools are based on a feed of 0.012 inch/rev and a depth of cut of 0.125 inch; use [Table 5c](#) to adjust the given speeds for other feeds and depths of cut. The combined feed/speed data in the remaining columns are based on a depth of cut of 0.1 inch, lead angle of 15 degrees, and nose radius of  $\frac{3}{64}$  inch. Use [Table 5a](#) to adjust the given speeds for other feeds, depths of cut, and lead angles; use [Table 5b](#) to adjust given speeds for increased tool life up to 180 minutes. Examples are given in the text.

The combined feed/speed data in this table are based on tool grades (identified in [Table 16](#)) as follows: uncoated carbides, tough = 15; Coated carbides, hard = 11, tough = 14; ceramics, hard = 2, tough = 3; cermet = 7; CBN = 1.

Table 4b. Cutting Feeds and Speeds for Turning Ferrous Cast Metals

| Material   | Brinell Hardness | Tool Material                                |                  |      |       |      |                |      |       |      |         |      |       |      |         |     |
|--|------------------|--|------------------|------|-------|------|----------------|------|-------|------|---------|------|-------|------|---------|-----|
|  |                  | Uncoated HSS                                 | Uncoated Carbide |      |       |      | Coated Carbide |      |       |      | Ceramic |      |       |      | Cermets |     |
|  |                  |  | Hard             |      | Tough |      | Hard           |      | Tough |      | Hard    |      | Tough |      |         |     |
|  |                  | f = feed (0.001 in./rev), s = speed (ft/min) |                  |      |       |      |                |      |       |      |         |      |       |      |         |     |
| Speed (fpm)  | Opt.             | Avg.   | Opt.             | Avg. | Opt.  | Avg. | Opt.           | Avg. | Opt.  | Avg. | Opt.    | Avg. | Opt.  | Avg. |         |     |
| Nodular (Ductile) Iron   |                  |  |                  |      |       |      |                |      |       |      |         |      |       |      |         |     |
| (Ferritic): 60-40-18, 65-45-12   | 140-190          | 100  | f                |      | 28    | 13   | 28             | 13   | 28    | 13   | 15      | 8    | 15    | 8    | 8       | 4   |
|  |                  |  | s                |      | 200   | 325  | 490            | 700  | 435   | 665  | 970     | 1450 | 845   | 1260 | 365     | 480 |
| (Ferritic-Pearlitic): 80-55-06   | 190-225          | 80   | f                |      | 28    | 13   | 28             | 13   | 28    | 13   | 11      | 6    | 11    | 6    | 8       | 4   |
|  | 225-260          | 65   | s                |      | 130   | 210  | 355            | 510  | 310   | 460  | 765     | 995  | 1260  | 1640 | 355     | 445 |
| (Pearlitic-Martensitic): 100-70-03   | 240-300          | 45   | f                |      |       |      |                |      |       |      |         |      |       |      |         |     |
|  |                  |  | s                |      |       |      |                |      |       |      |         |      |       |      |         |     |
| (Martensitic): 120-90-02   | 270-330          | 30   | f                |      | 28    | 13   |                |      | 28    | 13   | 10      | 5    | 10    | 5    | 8       | 4   |
|  | 300-400          | 15   | s                |      | 40    | 65   |                |      | 145   | 175  | 615     | 750  | 500   | 615  | 120     | 145 |
| Cast Steels  |                  |  |                  |      |       |      |                |      |       |      |         |      |       |      |         |     |
| (Low-carbon): 1010, 1020   | 100-150          | 110  | f                | 17   | 8     | 36   | 17             | 17   | 8     | 28   | 13      | 15   | 8     |      | 7       | 3   |
|  | 125-175          | 100  | s                | 370  | 490   | 230  | 285            | 665  | 815   | 495  | 675     | 2090 | 3120  |      | 625     | 790 |
| (Medium-carbon): 1030, 1040, 1050  | 175-225          | 90   | f                |      |       |      |                |      |       |      |         |      |       |      |         |     |
|  | 225-300          | 70   | s                |      |       |      |                |      |       |      |         |      |       |      |         |     |
| (Low-carbon alloy): 1320, 2315, 2320, 4110, 4120, 4320, 8020, 8620   | 150-200          | 90   | f                | 17   | 8     | 36   | 17             | 17   | 8     | 28   | 13      | 15   | 8     |      | 7       | 3   |
|  | 200-250          | 80   | s                | 370  | 490   | 150  | 200            | 595  | 815   | 410  | 590     | 1460 | 2170  |      | 625     | 790 |
|  | 250-300          | 60   | f                |      |       |      |                |      |       |      |         |      |       |      |         |     |
|  |                  |  | s                |      |       |      |                |      |       |      |         |      |       |      |         |     |
| (Medium-carbon alloy): 1330, 1340, 2325, 2330, 4125, 4130, 4140, 4330, 4340, 8030, 80B30, 8040, 8430, 8440, 8630, 8640, 9525, 9530, 9535 | 175-225          | 80   | f                | 17   | 8     | 36   | 17             | 17   | 8     |      |         | 15   | 8     |      |         |     |
|  | 225-250          | 70   | s                | 310  | 415   | 115  | 150            | 555  | 760   |      |         | 830  | 1240  |      |         |     |
|  | 250-300          | 55   | f                |      |       | 28   | 13             |      |       |      |         | 15   | 8     |      |         |     |
|  | 300-350          | 45   | s                |      |       | 70†  | 145            |      |       |      |         | 445  | 665   |      |         |     |
|  | 350-400          | 30   | f                |      |       | 28   | 13             |      |       | 28   | 13      |      |       | 15   | 8       |     |
|  |                  |  | s                |      |       | 115† | 355            |      |       | 335  | 345     |      |       | 955  | 1430    |     |

The combined feed/speed data in this table are based on tool grades (identified in Table 16) as shown: uncoated carbides, hard = 17; tough = 19, † = 15; coated carbides, hard = 11; tough = 14; ceramics, hard = 2; tough = 3; cermet = 7. Also, see footnote to Table 4a.

**Table 5a. Turning-Speed Adjustment Factors for Feed, Depth of Cut, and Lead Angle**

| Ratio of Chosen Feed to Optimum Feed | Ratio of the two cutting speeds given in the tables<br>$V_{avg}/V_{opt}$ |      |      |      |      |      |      | Depth of Cut and Lead Angle               |     |                   |      |                  |      |                  |      |                   |      |
|--------------------------------------|--|------|------|------|------|------|------|---|-----|-------------------|------|------------------|------|------------------|------|-------------------|------|
|                                      |  |      |      |      |      |      |      | 1 in. (25.4 mm)                           |     | 0.4 in. (10.2 mm) |      | 0.2 in. (5.1 mm) |      | 0.1 in. (2.5 mm) |      | 0.04 in. (1.0 mm) |      |
|                                      | 1.00   | 1.10 | 1.25 | 1.35 | 1.50 | 1.75 | 2.00 | 15°                                       | 45° | 15°               | 45°  | 15°              | 45°  | 15°              | 45°  | 15°               | 45°  |
|                                      | Feed Factor, $F_f$   |      |      |      |      |      |      | Depth of Cut and Lead Angle Factor, $F_d$ |     |                   |      |                  |      |                  |      |                   |      |
| 1.00                                 | 1.0  | 1.0  | 1.0  | 1.0  | 1.0  | 1.0  | 1.0  | 0.74                                      | 1.0 | 0.79              | 1.03 | 0.85             | 1.08 | 1.0              | 1.18 | 1.29              | 1.35 |
| 0.90                                 | 1.00   | 1.02 | 1.05 | 1.07 | 1.09 | 1.10 | 1.12 | 0.75                                      | 1.0 | 0.80              | 1.03 | 0.86             | 1.08 | 1.0              | 1.17 | 1.27              | 1.34 |
| 0.80                                 | 1.00   | 1.03 | 1.09 | 1.10 | 1.15 | 1.20 | 1.25 | 0.77                                      | 1.0 | 0.81              | 1.03 | 0.87             | 1.07 | 1.0              | 1.15 | 1.25              | 1.31 |
| 0.70                                 | 1.00   | 1.05 | 1.13 | 1.22 | 1.22 | 1.32 | 1.43 | 0.77                                      | 1.0 | 0.82              | 1.03 | 0.87             | 1.08 | 1.0              | 1.15 | 1.24              | 1.30 |
| 0.60                                 | 1.00   | 1.08 | 1.20 | 1.25 | 1.35 | 1.50 | 1.66 | 0.78                                      | 1.0 | 0.82              | 1.03 | 0.88             | 1.07 | 1.0              | 1.14 | 1.23              | 1.29 |
| 0.50                                 | 1.00   | 1.10 | 1.25 | 1.35 | 1.50 | 1.75 | 2.00 | 0.78                                      | 1.0 | 0.82              | 1.03 | 0.88             | 1.07 | 1.0              | 1.14 | 1.23              | 1.28 |
| 0.40                                 | 1.00   | 1.09 | 1.28 | 1.44 | 1.66 | 2.03 | 2.43 | 0.78                                      | 1.0 | 0.84              | 1.03 | 0.89             | 1.06 | 1.0              | 1.13 | 1.21              | 1.26 |
| 0.30                                 | 1.00   | 1.06 | 1.32 | 1.52 | 1.85 | 2.42 | 3.05 | 0.81                                      | 1.0 | 0.85              | 1.02 | 0.90             | 1.06 | 1.0              | 1.12 | 1.18              | 1.23 |
| 0.20                                 | 1.00   | 1.00 | 1.34 | 1.60 | 2.07 | 2.96 | 4.03 | 0.84                                      | 1.0 | 0.89              | 1.02 | 0.91             | 1.05 | 1.0              | 1.10 | 1.15              | 1.19 |
| 0.10                                 | 1.00   | 0.80 | 1.20 | 1.55 | 2.24 | 3.74 | 5.84 | 0.88                                      | 1.0 | 0.91              | 1.01 | 0.92             | 1.03 | 1.0              | 1.06 | 1.10              | 1.12 |

Use with Tables 1 through 9. Not for HSS tools. Tables 1 through 9 data, except for HSS tools, are based on depth of cut = 0.1 inch, lead angle = 15 degrees, and tool life = 15 minutes. For other depths of cut, lead angles, or feeds, use the two feed/speed pairs from the tables and calculate the ratio of desired (new) feed to optimum feed (largest of the two feeds given in the tables), and the ratio of the two cutting speeds ( $V_{avg}/V_{opt}$ ). Use the value of these ratios to find the feed factor  $F_f$  at the intersection of the feed ratio row and the speed ratio column in the left half of the table. The depth-of-cut factor  $F_d$  is found in the same row as the feed factor in the right half of the table under the column corresponding to the depth of cut and lead angle. The adjusted cutting speed can be calculated from  $V = V_{opt} \times F_f \times F_d$ , where  $V_{opt}$  is the smaller (optimum) of the two speeds from the speed table (from the left side of the column containing the two feed/speed pairs). See the text for examples.

**Table 5b. Tool Life Factors for Turning with Carbides, Ceramics, Cermet, CBN, and Polycrystalline Diamond**

| Tool Life, $T$<br>(minutes) | Turning with Carbides:<br>Workpiece < 300 Bhn |       |       | Turning with Carbides: Workpiece > 300 Bhn;<br>Turning with Ceramics: Any Hardness |       |       | Turning with Mixed Ceramics:<br>Any Workpiece Hardness |       |       |
|-----------------------------|---|-------|-------|--|-------|-------|--|-------|-------|
|                             | $f_s$   | $f_m$ | $f_l$ | $f_s$  | $f_m$ | $f_l$ | $f_s$  | $f_m$ | $f_l$ |
| 15                          | 1.0   | 1.0   | 1.0   | 1.0  | 1.0   | 1.0   | 1.0  | 1.0   | 1.0   |
| 45                          | 0.86  | 0.81  | 0.76  | 0.80   | 0.75  | 0.70  | 0.89   | 0.87  | 0.84  |
| 90                          | 0.78  | 0.71  | 0.64  | 0.70   | 0.63  | 0.56  | 0.82   | 0.79  | 0.75  |
| 180                         | 0.71  | 0.63  | 0.54  | 0.61   | 0.53  | 0.45  | 0.76   | 0.72  | 0.67  |

Except for HSS speed tools, feeds and speeds given in Tables 1 through 9 are based on 15-minute tool life. To adjust speeds for another tool life, multiply the cutting speed for 15-minute tool life  $V_{15}$  by the tool life factor from this table according to the following rules: for small feeds where feed  $\leq \frac{1}{2}f_{opt}$ , the cutting speed for desired tool life is  $V_T = f_s \times V_{15}$ ; for medium feeds where  $\frac{1}{2}f_{opt} < \text{feed} < \frac{3}{4}f_{opt}$ ,  $V_T = f_m \times V_{15}$ ; and for larger feeds where  $\frac{3}{4}f_{opt} \leq \text{feed} \leq f_{opt}$ ,  $V_T = f_l \times V_{15}$ . Here,  $f_{opt}$  is the largest (optimum) feed of the two feed/speed values given in the speed tables.



**Table 5c. Cutting-Speed Adjustment Factors for Turning with HSS Tools**

| Feed  |      | Feed Factor<br>$F_f$ | Depth of Cut |       | Depth-of-Cut<br>Factor<br>$F_d$ |
|-------|------|----------------------|--------------|-------|---------------------------------|
| in.   | mm   |                      | in.          | mm    |                                 |
| 0.002 | 0.05 | 1.50                 | 0.005        | 0.13  | 1.50                            |
| 0.003 | 0.08 | 1.50                 | 0.010        | 0.25  | 1.42                            |
| 0.004 | 0.10 | 1.50                 | 0.016        | 0.41  | 1.33                            |
| 0.005 | 0.13 | 1.44                 | 0.031        | 0.79  | 1.21                            |
| 0.006 | 0.15 | 1.34                 | 0.047        | 1.19  | 1.15                            |
| 0.007 | 0.18 | 1.25                 | 0.062        | 1.57  | 1.10                            |
| 0.008 | 0.20 | 1.18                 | 0.078        | 1.98  | 1.07                            |
| 0.009 | 0.23 | 1.12                 | 0.094        | 2.39  | 1.04                            |
| 0.010 | 0.25 | 1.08                 | 0.100        | 2.54  | 1.03                            |
| 0.011 | 0.28 | 1.04                 | 0.125        | 3.18  | 1.00                            |
| 0.012 | 0.30 | 1.00                 | 0.150        | 3.81  | 0.97                            |
| 0.013 | 0.33 | 0.97                 | 0.188        | 4.78  | 0.94                            |
| 0.014 | 0.36 | 0.94                 | 0.200        | 5.08  | 0.93                            |
| 0.015 | 0.38 | 0.91                 | 0.250        | 6.35  | 0.91                            |
| 0.016 | 0.41 | 0.88                 | 0.312        | 7.92  | 0.88                            |
| 0.018 | 0.46 | 0.84                 | 0.375        | 9.53  | 0.86                            |
| 0.020 | 0.51 | 0.80                 | 0.438        | 11.13 | 0.84                            |
| 0.022 | 0.56 | 0.77                 | 0.500        | 12.70 | 0.82                            |
| 0.025 | 0.64 | 0.73                 | 0.625        | 15.88 | 0.80                            |
| 0.028 | 0.71 | 0.70                 | 0.688        | 17.48 | 0.78                            |
| 0.030 | 0.76 | 0.68                 | 0.750        | 19.05 | 0.77                            |
| 0.032 | 0.81 | 0.66                 | 0.812        | 20.62 | 0.76                            |
| 0.035 | 0.89 | 0.64                 | 0.938        | 23.83 | 0.75                            |
| 0.040 | 1.02 | 0.60                 | 1.000        | 25.40 | 0.74                            |
| 0.045 | 1.14 | 0.57                 | 1.250        | 31.75 | 0.73                            |
| 0.050 | 1.27 | 0.55                 | 1.250        | 31.75 | 0.72                            |
| 0.060 | 1.52 | 0.50                 | 1.375        | 34.93 | 0.71                            |

For use with HSS tool data only from Tables 1 through 9. Adjusted cutting speed  $V = V_{HSS} \times F_f \times F_d$ , where  $V_{HSS}$  is the tabular speed for turning with high-speed tools.

**Example 3, Turning:** Determine the cutting speed for turning 1055 steel of 175 to 225 Brinell hardness using a hard ceramic insert, a  $15^\circ$  lead angle, a 0.04-inch depth of cut and 0.0075 in./rev feed.

The two feed/speed combinations given in Table 5a for 1055 steel are 15/1610 and 8/2780, corresponding to 0.015 in./rev at 1610 fpm and 0.008 in./rev at 2780 fpm, respectively. In Table 5a, the feed factor  $F_f = 1.75$  is found at the intersection of the row corresponding to  $feed/f_{opt} = 7.5/15 = 0.5$  and the column corresponding to  $V_{avg}/V_{opt} = 2780/1610 = 1.75$  (approximately). The depth-of-cut factor  $F_d = 1.23$  is found in the same row, under the column heading for a depth of cut = 0.04 inch and lead angle =  $15^\circ$ . The adjusted cutting speed is  $V = 1610 \times 1.75 \times 1.23 = 3466$  fpm.

**Example 4, Turning:** The cutting speed for 1055 steel calculated in Example 3 represents the speed required to obtain a 15-minute tool life. Estimate the cutting speed needed to obtain a tool life of 45, 90, and 180 minutes using the results of Example 3.

To estimate the cutting speed corresponding to another tool life, multiply the cutting speed for 15-minute tool life  $V_{15}$  by the adjustment factor from the Table 5b, Tool Life Factors for Turning. This table gives three factors for adjusting tool life based on the feed used,  $f_s$  for feeds less than or equal to  $\frac{1}{2}f_{opt}$ ,  $\frac{3}{4}f_m$  for midrange feeds between  $\frac{1}{2}$  and  $\frac{3}{4}f_{opt}$  and  $f_l$  for large feeds greater than or equal to  $\frac{3}{4}f_{opt}$  and less than  $f_{opt}$ . In Example 3,  $f_{opt}$  is 0.015 in./rev and the selected feed is 0.0075 in./rev =  $\frac{1}{2}f_{opt}$ . The new cutting speeds for the various tool lives are obtained by multiplying the cutting speed for 15-minute tool life  $V_{15}$  by the factor

for small feeds  $f_s$  from the column for turning with ceramics in Table 5b. These calculations, using the cutting speed obtained in Example 3, follow.

| Tool Life | Cutting Speed                             |
|-----------|---|
| 15 min    | $V_{15} = 3466$ fpm                       |
| 45 min    | $V_{45} = V_{15} \times 0.80 = 2773$ fpm  |
| 90 min    | $V_{90} = V_{15} \times 0.70 = 2426$ fpm  |
| 180 min   | $V_{180} = V_{15} \times 0.61 = 2114$ fpm |

Depth of cut, feed, and lead angle remain the same as in Example 3. Notice, increasing the tool life from 15 to 180 minutes, a factor of 12, reduces the cutting speed by only about one-third of the  $V_{15}$  speed.

**Table 6. Cutting Feeds and Speeds for Turning Copper Alloys**

| Group 1  |                       |                |   |                     |                            |      |      |
|--|-----------------------|----------------|---|---------------------|----------------------------|------|------|
| Architectural bronze (C38500); Extra-high-headed brass (C35600); Forging brass (C37700); Free-cutting phosphor bronze, B2 (C54400); Free-cutting brass (C36000); Free-cutting Muntz metal (C37000); High-leaded brass (C33200; C34200); High-leaded brass tube (C35300); Leaded commercial bronze (C31400); Leaded naval brass (C48500); Medium-leaded brass (C34000)  |                       |                |   |                     |                            |      |      |
| Group 2  |                       |                |   |                     |                            |      |      |
| Aluminum brass, arsenical (C68700); Cartridge brass, 70% (C26000); High-silicon bronze, B (C65500); Admiralty brass (inhibited) (C44300, C44500); Jewelry bronze, 87.5% (C22600); Leaded Muntz metal (C36500, C36800); Leaded nickel silver (C79600); Low brass, 80% (C24000); Low-leaded brass (C33500); Low-silicon bronze, B (C65100); Manganese bronze, A (C67500); Muntz metal, 60% (C28000); Nickel silver, 55-18 (C77000); Red brass, 85% (C23000); Yellow brass (C26800)   |                       |                |   |                     |                            |      |      |
| Group 3  |                       |                |   |                     |                            |      |      |
| Aluminum bronze, D (C61400); Beryllium copper (C17000, C17200, C17500); Commercial-bronze, 90% (C22000); Copper nickel, 10% (C70600); Copper nickel, 30% (C71500); Electrolytic tough pitch copper (C11000); Guilding, 95% (C21000); Nickel silver, 65-10 (C74500); Nickel silver, 65-12 (C75700); Nickel silver, 65-15 (C75400); Nickel silver, 65-18 (C75200); Oxygen-free copper (C10200); Phosphor bronze, 1.25% (C50200); Phosphor bronze, 10% D (C52400) Phosphor bronze, 5% A (C51000); Phosphor bronze, 8% C (C52100); Phosphorus deoxidized copper (C12200) |                       |                |   |                     |                            |      |      |
| Wrought Alloys<br>Description and UNS<br>Alloy Numbers   | Material<br>Condition | Speed<br>(fpm) | HSS   | Uncoated<br>Carbide | Polycrystalline<br>Diamond |      |      |
|  |                       |                | f = feed (0.001 in./rev),<br>s = speed (ft/min) |                     |                            |      |      |
|  |                       |                | Opt.  | Avg.                | Opt.                       | Avg. |      |
| Group 1  | A                     | 300            | f   | 28                  | 13                         |      |      |
|  | CD                    | 350            | s   | 1170                | 1680                       |      |      |
| Group 2  | A                     | 200            | f   | 28                  | 13                         |      |      |
|  | CD                    | 250            | s   | 715                 | 900                        |      |      |
| Group 3  | A                     | 100            | f   | 28                  | 13                         | 7    | 13   |
|  | CD                    | 110            | s   | 440                 | 610                        | 1780 | 2080 |

Abbreviations designate: A, annealed; CD, cold drawn.

The combined feed/speed data in this table are based on tool grades (identified in Table 16) as follows: uncoated carbide, 15; diamond, 9. See the footnote to Table 7.

**Table 7. Cutting Feeds and Speeds for Turning Titanium and Titanium Alloys**

| Material  | Brinell Hardness   | Tool Material |   |          |           |
|---|--------------------|---------------|---|----------|-----------|
|   |                    | HSS           | Uncoated Carbide (Tough)                        |          |           |
|   |                    | Speed (fpm)   | f = feed (0.001 in./rev),<br>s = speed (ft/min) |          | Avg.      |
| Opt.  | Avg.               |               |   |          |           |
| Commercially Pure and Low Alloyed   |                    |               |   |          |           |
| 99.5Ti, 99.5Ti-0.15Pd   | 110–150            | 100–105       | f<br>s  | 28<br>55 | 13<br>190 |
| 99.1Ti, 99.2Ti, 99.2Ti-0.15Pd,<br>98.9Ti-0.8Ni-0.3Mo  | 180–240            | 85–90         | f<br>s  | 28<br>50 | 13<br>170 |
| 99.0 Ti   | 250–275            | 70            | f<br>s  | 20<br>75 | 10<br>210 |
| Alpha Alloys and Alpha-Beta Alloys  |                    |               |   |          |           |
| 5Al-2.5Sn, 8Mn, 2Al-11Sn-5Zr-1Mo, 4Al-3Mo-1V, 5Al-6Sn-2Zr-1Mo, 6Al-2Sn-4Zr-2Mo, 6Al-2Sn-4Zr-6Mo, 6Al-2Sn-4Zr-2Mo-0.25Si | 300–350            | 50            | f<br>s  | 17<br>95 | 8<br>250  |
| 6Al-4V  | 310–350            | 40            |   |          |           |
| 6Al-6V-2Sn, Al-4Mo,<br>8V-5Fe-1Al   | 320–370<br>320–380 | 30<br>20      |   |          |           |
| 6Al-4V, 6Al-2Sn-4Zr-2Mo,<br>6Al-2Sn-4Zr-6Mo,<br>6Al-2Sn-4Zr-2Mo-0.25Si  | 320–380            | 40            |   |          |           |
| 4Al-3Mo-1V, 6Al-6V-2Sn, 7Al-4Mo<br>1 Al-8V-5Fe  | 375–420<br>375–440 | 20<br>20      |   |          |           |
| Beta Alloys   |                    |               |   |          |           |
| 13V-11Cr-3Al, 8Mo-8V-2Fe-3Al,<br>3Al-8V-6Cr-4Mo-4Zr,<br>11.5Mo-6Zr-4.5Sn  | 275–350<br>375–440 | 25<br>20      | f<br>s  | 17<br>55 | 8<br>150  |

The speed recommendations for turning with HSS (high-speed steel) tools may be used as starting speeds for milling titanium alloys, using Table 15a to estimate the feed required. Speeds for HSS (high-speed steel) tools are based on a feed of 0.012 inch/rev and a depth of cut of 0.125 inch; use Table 5c to adjust the given speeds for other feeds and depths of cut. The combined feed/speed data in the remaining columns are based on a depth of cut of 0.1 inch, lead angle of 15 degrees, and nose radius of 3/64 inch. Use Table 5a to adjust given speeds for other feeds, depths of cut, and lead angles; use Table 5b to adjust given speeds for increased tool life up to 180 minutes. Examples are given in the text. The combined feed/speed data in this table are based on tool grades (identified in Table 16) as follows: uncoated carbide, 15.

**Table 8. Cutting Feeds and Speeds for Turning Light Metals**

| Material Description  | Material Condition | Tool Material |  |            |                         |                         |           |
|---|--------------------|---------------|--|------------|-------------------------|-------------------------|-----------|
|   |                    | HSS           | Uncoated Carbide (Tough)                     |            | Polycrystalline Diamond |                         |           |
|   |                    | Speed (fpm)   | f = feed (0.001 in./rev), s = speed (ft/min) |            | Opt.                    | Avg.                    |           |
| Opt.  | Avg.               |               | Opt.   | Avg.       |                         |                         |           |
| All wrought and cast magnesium alloys   | A, CD, ST, and A   | 800           |  |            |                         |                         |           |
| All wrought aluminum alloys, including 6061-T651, 5000, 6000, and 7000 series | CD<br>ST and A     | 600<br>500    | f<br>s                                       | 36<br>2820 | 17<br>4570              |                         |           |
| All aluminum sand and permanent mold casting alloys                           | AC<br>ST and A     | 750<br>600    |  |            |                         |                         |           |
| Aluminum Die-Casting Alloys   |                    |               |  |            |                         |                         |           |
| Alloys 308.0 and 319.0  | —                  | —             | f<br>s                                       | 36<br>865  | 17<br>1280              | 11<br>5890 <sup>a</sup> | 8<br>8270 |
| Alloys 390.0 and 392.0  | AC<br>ST and A     | 80<br>60      | f<br>s                                       | 24<br>2010 | 11<br>2760              | 8<br>4765               | 4<br>5755 |
| Alloy 413   | —                  | —             | f<br>s                                       | 32<br>430  | 15<br>720               | 10<br>5085              | 5<br>6570 |
| All other aluminum die-casting alloys including alloys 360.0 and 380.0        | ST and A<br>AC     | 100<br>125    | f<br>s                                       | 36<br>630  | 17<br>1060              | 11<br>7560              | 6<br>9930 |

<sup>a</sup>The feeds and speeds for turning Al alloys 308.0 and 319.0 with (polycrystalline) diamond tooling represent an expected tool life  $T = 960$  minutes = 16 hours; corresponding feeds and speeds for 15-minute tool life are 11/28600 and 6/37500.

Abbreviations for material condition: A, annealed; AC, as cast; CD, cold drawn; and ST and A, solution treated and aged, respectively. Speeds for HSS (high-speed steel) tools are based on a feed of 0.012 inch/rev and a depth of cut of 0.125 inch; use Table 5c to adjust the HSS speeds for other feeds and depths of cut. The combined feed/speed data are based on a depth of cut of 0.1 inch, lead angle of 15 degrees, and nose radius of  $\frac{3}{64}$  inch. Use Table 5a to adjust given speeds for other feeds, depths of cut, and lead angles; use Table 5b to adjust given speeds for increased tool life up to 180 minutes. The data are based on tool grades (identified in Table 16) as follows: uncoated carbide, 15; diamond, 9.

**Table 9. Cutting Feeds and Speeds for Turning Superalloys**

| Material Description  | Tool Material |        |  |      |         |      |       |      |      |      |     |
|---|---------------|--------|--|------|---------|------|-------|------|------|------|-----|
|   | HSS Turning   |        | Uncoated Carbide                             |      | Ceramic |      |       |      | CBN  |      |     |
|   | Rough         | Finish | Tough  |      | Hard    |      | Tough |      |      |      |     |
|   | Speed (fpm)   |        | f = feed (0.001 in./rev), s = speed (ft/min) |      |         |      |       |      |      |      |     |
|   |               |        | Opt.   | Avg. | Opt.    | Avg. | Opt.  | Avg. | Opt. | Avg. |     |
| T-D Nickel  | 70-80         | 80-100 |  |      |         |      |       |      |      |      |     |
| Discalloy   | 15-35         | 35-40  |  |      |         |      |       |      |      |      |     |
| 19-9DL, W-545   | 25-35         | 30-40  | f  | 24   | 11      |      |       |      | 20   | 10   |     |
| 16-25-6, A-286, Incoloy 800, 801, and 802, V-57   | 30-35         | 35-40  | s  | 90   | 170     |      |       |      | 365  | 630  |     |
| Refractalloy 26   | 15-20         | 20-25  | f  | 20   | 10      |      |       |      | 20   | 10   |     |
| J1300   | 15-25         | 20-30  | s  | 75   | 135     |      |       |      | 245  | 420  |     |
| Inconel 700 and 702, Nimonic 90 and 95  | 10-12         | 12-15  |  |      |         |      |       |      |      |      |     |
| S-816, V-36   | 10-15         | 15-20  |  |      |         |      |       |      |      |      |     |
| S-590   | 10-20         | 15-30  |  |      |         |      |       |      |      |      |     |
| Udimet 630  |               | 20-25  |  |      |         |      |       |      |      |      |     |
| N-155   |               | 15-25  | f  | 20   | 10      |      |       |      | 20   | 10   |     |
| Air Resist 213; Hastelloy B, C, G and X (wrought); Haynes 25 and 188; J1570; M252 (wrought); Mar-M905 and M918; Nimonic 75 and 80 | 15-20         | 20-25  | s  | 75   | 125     | 11   | 6     | 11   | 6    | 230  | 400 |
| CW-12M; Hastelloy B and C (cast); N-12M   | 8-12          | 10-15  |  |      |         |      |       |      |      |      |     |
| Rene 95 (Hot Isostatic Pressed)   | —             | —      |  |      |         |      |       |      |      |      |     |
| HS 6, 21, 2, 31 (X 40), 36, and 151; Haynes 36 and 151; Mar-M302, M322, and M509, WI-52   | 10-12         | 10-15  |  |      |         |      |       |      |      |      |     |
| Rene 41   | 10-15         | 12-20  |  |      |         |      |       |      |      |      |     |
| Incoloy 901   | 10-20         | 20-35  |  |      |         |      |       |      |      |      |     |
| Waspaloy  | 10-30         | 25-35  | f  | 28   | 13      | 11   | 6     | 10   | 5    | 20   | 10  |
| Inconel 625, 702, 706, 718 (wrought), 721, 722, X750, 751, 901, 600, and 604  | 15-20         | 20-35  | s  | 20   | 40      | 895  | 2230  | 345  | 815  | 185  | 315 |
| AF2-1DA, Unitemp 1753   | 8-10          | 10-15  |  |      |         |      |       |      |      |      |     |
| Colmonoy, Inconel 600, 718, K-Monel, Stellite   | —             | —      |  |      |         |      |       |      |      |      |     |
| Air Resist 13 and 215, FSH-H14, Nasa C-W-Re, X-45   | 10-12         | 10-15  |  |      |         |      |       |      |      |      |     |
| Udimet 500, 700, and 710  | 10-15         | 12-20  |  |      |         |      |       |      |      |      |     |
| Astroloy  | 5-10          | 5-15   |  |      |         |      |       |      |      |      |     |
| Mar-M200, M246, M421, and Rene 77, 80, and 95 (forged)  |               | 10-12  | f  | 28   | 13      | 11   | 6     | 10   | 5    | 20   | 10  |
| B-1900, GMR-235 and 235D, IN 100 and 738, Inconel 713C and 718 (cast), M252 (cast)  | 8-10          | 10-15  | s  | 15   | 15      | 615  | 1720  | 290  | 700  | 165  | 280 |
|   |               | 8-10   |  |      |         |      |       |      |      |      |     |

The speed recommendations for rough turning may be used as starting values for milling and drilling with HSS tools. The combined feed/speed data in this table are based on tool grades (identified in Table 16) as follows: uncoated carbide = 15; ceramic, hard = 4, tough = 3; CBN = 1.

Speeds for HSS (high-speed steel) tools are based on a feed of 0.012 inch/rev and a depth of cut of 0.125 inch; use [Table 5c](#) to adjust the given speeds for other feeds and depths of cut. The combined feed/speed data in the remaining columns are based on a depth of cut of 0.1 inch, lead angle of 15 degrees, and nose radius of  $\frac{3}{64}$  inch. Use [Table 5a](#) to adjust given speeds for other feeds, depths of cut, and lead angles; use [Table 5b](#) to adjust given speeds for increased tool life up to 180 minutes. Examples are given in the text.

**Speed and Feed Tables for Milling.**—[Tables 10](#) through [14](#) give feeds and speeds for milling. The data in the first speed column can be used with high-speed steel tools using the feeds given in [Table 15a](#); these are the same speeds contained in previous editions of the Handbook. The remaining data in [Tables 10](#) through [14](#) are combined feeds and speeds for end, face, and slit, slot, and side milling that use the speed adjustment factors given in [Tables 15b, 15c, and 15d](#). Tool life for the combined feed/speed data can also be adjusted using the factors in [Table 15e](#). [Table 16](#) lists cutting tool grades and vendor equivalents.

*End Milling:* Table data for end milling are based on a 3-tooth, 20-degree helix angle tool with a diameter of 1.0 inch, an axial depth of cut of 0.2 inch, and a radial depth of cut of 1 inch (full slot). Use [Table 15b](#) to adjust speeds for other feeds and axial depths of cut, and [Table 15c](#) to adjust speeds if the radial depth of cut is less than the tool diameter. Speeds are valid for all tool diameters.

*Face Milling:* Table data for face milling are based on a 10-tooth, 8-inch diameter face mill, operating with a 15-degree lead angle,  $\frac{3}{64}$ -inch nose radius, axial depth of cut = 0.1 inch, and radial depth (width) of cut = 6 inches (i.e., width of cut to cutter diameter ratio =  $\frac{3}{4}$ ). These speeds are valid if the cutter axis is above or close to the center line of the workpiece (eccentricity is small). Under these conditions, use [Table 15d](#) to adjust speeds for other feeds and axial and radial depths of cut. For larger eccentricity (i.e., when the cutter axis to workpiece center line offset is one half the cutter diameter or more), use the end and side milling adjustment factors ([Tables 15b and 15c](#)) instead of the face milling factors.

*Slit and Slot Milling:* Table data for slit milling are based on an 8-tooth, 10-degree helix angle tool with a cutter width of 0.4 inch, diameter  $D$  of 4.0 inch, and a depth of cut of 0.6 inch. Speeds are valid for all tool diameters and widths. See the examples in the text for adjustments to the given speeds for other feeds and depths of cut.

Tool life for all tabulated values is approximately 45 minutes; use [Table 15e](#) to adjust tool life from 15 to 180 minutes.

*Using the Feed and Speed Tables for Milling:* The basic feed for milling cutters is the feed per tooth ( $f$ ), which is expressed in inches per tooth. There are many factors to consider in selecting the feed per tooth and no formula is available to resolve these factors. Among the factors to consider are the cutting tool material; the work material and its hardness; the width and the depth of the cut to be taken; the type of milling cutter to be used and its size; the surface finish to be produced; the power available on the milling machine; and the rigidity of the milling machine, the workpiece, the workpiece setup, the milling cutter, and the cutter mounting.

The cardinal principle is to always use the maximum feed that conditions will permit. Avoid, if possible, using a feed that is less than 0.001 inch per tooth because such low feeds reduce the tool life of the cutter. When milling hard materials with small-diameter end mills, such small feeds may be necessary, but otherwise use as much feed as possible. Harder materials in general will require lower feeds than softer materials. The width and the depth of cut also affect the feeds. Wider and deeper cuts must be fed somewhat more slowly than narrow and shallow cuts. A slower feed rate will result in a better surface finish; however, always use the heaviest feed that will produce the surface finish desired. Fine chips produced by fine feeds are dangerous when milling magnesium because spontaneous combustion can occur. Thus, when milling magnesium, a fast feed that will produce a relatively thick chip should be used. Cutting stainless steel produces a work-hardened layer on the surface that has been cut. Thus, when milling this material, the feed should be large enough to allow each cutting edge on the cutter to penetrate below the work-hardened

layer produced by the previous cutting edge. The heavy feeds recommended for face milling cutters are to be used primarily with larger cutters on milling machines having an adequate amount of power. For smaller face milling cutters, start with smaller feeds and increase as indicated by the performance of the cutter and the machine.

When planning a milling operation that requires a high cutting speed and a fast feed, always check to determine if the power required to take the cut is within the capacity of the milling machine. Excessive power requirements are often encountered when milling with cemented carbide cutters. The large metal removal rates that can be attained require a high horsepower output. An example of this type of calculation is given in the section on Machining Power that follows this section. If the size of the cut must be reduced in order to stay within the power capacity of the machine, start by reducing the cutting speed rather than the feed in inches per tooth.

The formula for calculating the table feed rate, when the feed in inches per tooth is known, is as follows:

$$f_m = f_t n_t N$$

where  $f_m$  = milling machine table feed rate in inches per minute (ipm)

$f_t$  = feed in inch per tooth (ipt)

$n_t$  = number of teeth in the milling cutter

$N$  = spindle speed of the milling machine in revolutions per minute (rpm)

*Example:* Calculate the feed rate for milling a piece of AISI 1040 steel having a hardness of 180 Bhn. The cutter is a 3-inch diameter high-speed steel plain or slab milling cutter with 8 teeth. The width of the cut is 2 inches, the depth of cut is 0.062 inch, and the cutting speed from Table 11 is 85 fpm. From Table 15a, the feed rate selected is 0.008 inch per tooth.

$$N = \frac{12V}{\pi D} = \frac{12 \times 85}{3.14 \times 3} = 108 \text{ rpm}$$

$$\begin{aligned} f_m &= f_t n_t N = 0.008 \times 8 \times 108 \\ &= 7 \text{ ipm (approximately)} \end{aligned}$$

*Example 1, Face Milling:* Determine the cutting speed and machine operating speed for face milling an aluminum die casting (alloy 413) using a 4-inch polycrystalline diamond cutter, a 3-inch width of cut, a 0.10-inch depth of cut, and a feed of 0.006 inch/tooth.

Table 10 gives the feeds and speeds for milling aluminum alloys. The feed/speed pairs for face milling die cast alloy 413 with polycrystalline diamond (PCD) are 8/2320 (0.008 in./tooth feed at 2320 fpm) and 4/4755 (0.004 in./tooth feed at 4755 fpm). These speeds are based on an axial depth of cut of 0.10 inch, an 8-inch cutter diameter  $D$ , a 6-inch radial depth (width) of cut  $ar$ , with the cutter approximately centered above the workpiece, i.e., eccentricity is low, as shown in Fig. 3. If the preceding conditions apply, the given feeds and speeds can be used without adjustment for a 45-minute tool life. The given speeds are valid for all cutter diameters if a radial depth of cut to cutter diameter ratio ( $ar/D$ ) of  $\frac{3}{4}$  is maintained (i.e.,  $\frac{9}{8} = \frac{3}{4}$ ). However, if a different feed or axial depth of cut is required, or if the  $ar/D$  ratio is not equal to  $\frac{3}{4}$ , the cutting speed must be adjusted for the conditions. The adjusted cutting speed  $V$  is calculated from  $V = V_{opt} \times F_f \times F_d \times F_{ar}$ , where  $V_{opt}$  is the lower of the two speeds given in the speed table, and  $F_f$ ,  $F_d$ , and  $F_{ar}$  are adjustment factors for feed, axial depth of cut, and radial depth of cut, respectively, obtained from Table 15d (face milling); except, when cutting near the end or edge of the workpiece as in Fig. 4, Table 15c (side milling) is used to obtain  $F_f$ .

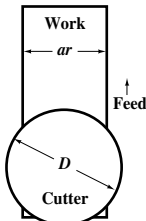


Fig. 3.

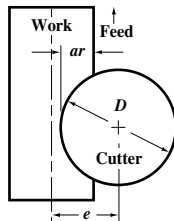


Fig. 4.

In this example, the cutting conditions match the standard conditions specified in the speed table for radial depth of cut to cutter diameter (3 in./4 in.), and depth of cut (0.01 in), but the desired feed of 0.006 in./tooth does not match either of the feeds given in the speed table (0.004 or 0.008). Therefore, the cutting speed must be adjusted for this feed. As with turning, the feed factor  $F_f$  is determined by calculating the ratio of the desired feed  $f$  to maximum feed  $f_{opt}$  from the speed table, and from the ratio  $V_{avg}/V_{opt}$  of the two speeds given in the speed table. The feed factor is found at the intersection of the feed ratio row and the speed ratio column in Table 15d. The speed is then obtained using the following equation:

$$\frac{\text{Chosen feed}}{\text{Optimum feed}} = \frac{f}{f_{opt}} = \frac{0.006}{0.008} = 0.75 \quad \frac{\text{Average speed}}{\text{Optimum speed}} = \frac{V_{avg}}{V_{opt}} = \frac{4755}{2320} \approx 2.0$$

$$F_f = (1.25 + 1.43)/2 = 1.34$$

$$F_d = 1.0$$

$$F_{ar} = 1.0$$

$$V = 2320 \times 1.34 \times 1.0 \times 1.0 = 3109 \text{ fpm, and } 3.82 \times 3109/4 = 2970 \text{ rpm}$$

**Example 2, End Milling:** What cutting speed should be used for cutting a full slot (i.e., a slot cut from the solid, in one pass, that is the same width as the cutter) in 5140 steel with hardness of 300 Bhn using a 1-inch diameter coated carbide (insert)  $0^\circ$  lead angle end mill, a feed of 0.003 in./tooth, and a 0.2-inch axial depth of cut?

The feed and speed data for end milling 5140 steel, Brinell hardness = 275–325, with a coated carbide tool are given in Table 11 as 15/80 and 8/240 for optimum and average sets, respectively. The speed adjustment factors for feed and depth of cut for full slot (end milling) are obtained from Table 15b. The calculations are the same as in the previous examples:  $ff_{opt} = 3/15 = 0.2$  and  $V_{avg}/V_{opt} = 240/80 = 3.0$ , therefore,  $F_f = 6.86$  and  $F_d = 1.0$ . The cutting speed for a 45-minute tool life is  $V = 80 \times 6.86 \times 1.0 = 548.8$ , approximately 550 ft/min.

**Example 3, End Milling:** What cutting speed should be used in Example 2 if the radial depth of cut  $ar$  is 0.02 inch and axial depth of cut is 1 inch?

In end milling, when the radial depth of cut is less than the cutter diameter (as in Fig. 4), first obtain the feed factor  $F_f$  from Table 15c, then the axial depth of cut and lead angle factor  $F_d$  from Table 15b. The radial depth of cut to cutter diameter ratio  $ar/D$  is used in Table 15c to determine the maximum and minimum feeds that guard against tool failure at high feeds and against premature tool wear caused by the tool rubbing against the work at very low feeds. The feed used should be selected so that it falls within the minimum to maximum feed range, and then the feed factor  $F_f$  can be determined from the feed factors at minimum and maximum feeds,  $F_{f1}$  and  $F_{f2}$  as explained below.

The maximum feed  $f_{max}$  is found in Table 15c by multiplying the optimum feed from the speed table by the maximum feed factor that corresponds to the  $ar/D$  ratio, which in this instance is  $0.02/1 = 0.02$ ; the minimum feed  $f_{min}$  is found by multiplying the optimum feed by the minimum feed factor. Thus,  $f_{max} = 4.5 \times 0.015 = 0.0675$  in./tooth and  $f_{min} = 3.1 \times 0.015 = 0.0465$  in./tooth. If a feed between these maximum and minimum values is selected, 0.050 in./tooth for example, then for  $ar/D = 0.02$  and  $V_{avg}/V_{opt} = 3.0$ , the feed factors at maximum and minimum feeds are  $F_{f1} = 7.90$  and  $F_{f2} = 7.01$ , respectively, and by interpolation,  $F_f = 7.01 + (0.050 - 0.0465)(0.0675 - 0.0465) \times (7.90 - 7.01) = 7.16$ , approximately 7.2.

The depth of cut factor  $F_d$  is obtained from Table 15b, using  $f_{max}$  from Table 15c instead of the optimum feed  $f_{opt}$  for calculating the feed ratio (chosen feed/optimum feed). In this example, the feed ratio = chosen feed/ $f_{max} = 0.050/0.0675 = 0.74$ , so the feed factor is  $F_d = 0.93$  for a depth of cut = 1.0 inch and  $0^\circ$  lead angle. Therefore, the final cutting speed is  $80 \times 7.2 \times 0.93 = 587$  ft/min. Notice that  $f_{max}$  obtained from Table 15c was used instead of the optimum feed from the speed table, in determining the feed ratio needed to find  $F_d$ .

**Slit Milling.**—The tabular data for slit milling is based on an 8-tooth, 10-degree helix angle cutter with a width of 0.4 inch, a diameter  $D$  of 4.0 inch, and a depth of cut of 0.6 inch. The given feeds and speeds are valid for any diameters and tool widths, as long as sufficient machine power is available. Adjustments to cutting speeds for other feeds and depths of cut are made using Table 15c or 15d, depending on the orientation of the cutter to the work, as illustrated in Case 1 and Case 2 of Fig. 5. The situation illustrated in Case 1 is approximately equivalent to that illustrated in Fig. 3, and Case 2 is approximately equivalent to that shown in Fig. 4.

*Case 1:* If the cutter is fed directly into the workpiece, i.e., the feed is perpendicular to the surface of the workpiece, as in cutting off, then Table 15d (face milling) is used to adjust speeds for other feeds. The depth of cut portion of Table 15d is not used in this case ( $F_d = 1.0$ ), so the adjusted cutting speed  $V = V_{opt} \times F_f \times F_{ar}$ . In determining the factor  $F_{ar}$  from Table 15d, the radial depth of cut  $ar$  is the length of cut created by the portion of the cutter engaged in the work.

*Case 2:* If the cutter feed is parallel to the surface of the workpiece, as in slotting or side milling, then Table 15c (side milling) is used to adjust the given speeds for other feeds. In Table 15c, the cutting depth (slot depth, for example) is the radial depth of cut  $ar$  that is used to determine maximum and minimum allowable feed/tooth and the feed factor  $F_f$ . These minimum and maximum feeds are determined in the manner described previously, however, the axial depth of cut factor  $F_d$  is not required. The adjusted cutting speed, valid for cutters of any thickness (width), is given by  $V = V_{opt} \times F_f$ .

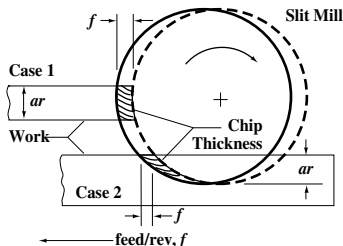


Fig. 5. Determination of Radial Depth of Cut in Slit Milling



**Table 10. Cutting Feeds and Speeds for Milling Aluminum Alloys**

| Material  | Material Condition* | End Milling                                    |           |                                   |           | Face Milling                      |           |                         |           | Slit Milling |            |                                   |           |            |
|---|---------------------|--|-----------|-----------------------------------|-----------|-----------------------------------|-----------|-------------------------|-----------|--------------|------------|-----------------------------------|-----------|------------|
|   |                     | HSS  |           | Indexable Insert Uncoated Carbide |           | Indexable Insert Uncoated Carbide |           | Polycrystalline Diamond |           | HSS          |            | Indexable Insert Uncoated Carbide |           |            |
|   |                     | f = feed (0.001 in./tooth), s = speed (ft/min) |           |                                   |           |                                   |           |                         |           |              |            |                                   |           |            |
|   |                     | Opt.   | Avg.      | Opt.                              | Avg.      | Opt.                              | Avg.      | Opt.                    | Avg.      | Opt.         | Avg.       | Opt.                              | Avg.      |            |
| All wrought aluminum alloys, 6061-T651, 5000, 6000, 7000 series | CD<br>ST and A      | f<br>s   | 15<br>8   | 8<br>100                          | 15<br>620 | 8<br>2020                         | 39<br>755 | 20<br>1720              | 8<br>3750 | 4<br>8430    | 16<br>1600 | 8<br>4680                         | 39<br>840 | 20<br>2390 |
| All aluminum sand and permanent mold casting alloys             | CD<br>ST and A      | f<br>s   | 15<br>165 | 8<br>850                          | 15<br>620 | 8<br>2020                         | 39<br>755 | 20<br>1720              | 8<br>3750 | 4<br>8430    | 16<br>1600 | 8<br>4680                         | 39<br>840 | 20<br>2390 |
| Aluminum Die-Casting Alloys                                     |                     |  |           |                                   |           |                                   |           |                         |           |              |            |                                   |           |            |
| Alloys 308.0 and 319.0  | —                   | f  | 15        | 8                                 | 15        | 8                                 | 39        | 20                      |           |              | 16         | 8                                 | 39        | 20         |
|   |                     | s  | 30        | 100                               | 620       | 2020                              | 755       | 1720                    |           |              | 160        | 375                               | 840       | 2390       |
| Alloys 360.0 and 380.0  | —                   | f  | 15        | 8                                 | 15        | 8                                 | 39        | 20                      | 8         | 4            | 16         | 8                                 | 39        | 20         |
|   |                     | s  | 30        | 90                                | 485       | 1905                              | 555       | 1380                    | 3105      | 7845         | 145        | 355                               | 690       | 2320       |
| Alloys 390.0 and 392.0  | —                   | f  |           |                                   |           |                                   | 39        | 20                      |           |              |            |                                   |           |            |
|   |                     | s  |           |                                   |           |                                   | 220       | 370                     |           |              |            |                                   |           |            |
| Alloy 413   | —                   | f  |           |                                   | 15        | 8                                 | 39        | 20                      | 8         | 4            |            |                                   | 39        | 20         |
|   |                     | s  |           |                                   | 355       | 1385                              | 405       | 665                     | 2320      | 4755         |            |                                   | 500       | 1680       |
| All other aluminum die-casting alloys                           | ST and A            | f  |           |                                   | 15        | 8                                 | 39        | 20                      | 8         | 4            |            |                                   | 39        | 20         |
|   |                     | s  |           |                                   | 355       | 1385                              | 405       | 665                     | 2320      | 4755         |            |                                   | 500       | 1680       |
| All other aluminum die-casting alloys                           | AC                  | f  | 15        | 8                                 | 15        | 8                                 | 39        | 20                      | 8         | 4            | 16         | 8                                 | 39        | 20         |
|   |                     | s  | 30        | 90                                | 485       | 1905                              | 555       | 1380                    | 3105      | 7845         | 145        | 335                               | 690       | 2320       |

Abbreviations designate: A, annealed; AC, as cast; CD, cold drawn; and ST and A, solution treated and aged, respectively.

**End Milling:** Table data for end milling are based on a 3-tooth, 20-degree helix angle tool with a diameter of 1.0 inch, an axial depth of cut of 0.2 inch, and a radial depth of cut of 1 inch (full slot). Use [Table 15b](#) to adjust speeds for other feeds and axial depths of cut, and [Table 15c](#) to adjust speeds if the radial depth of cut is less than the tool diameter. Speeds are valid for all tool diameters.

**Face Milling:** Table data for face milling are based on a 10-tooth, 8-inch diameter face mill, operating with a 15-degree lead angle,  $\frac{3}{4}$ -inch nose radius, axial depth of cut = 0.1 inch, and radial depth (width) of cut = 6 inches (i.e., width of cut to cutter diameter ratio =  $\frac{3}{4}$ ). These speeds are valid if the cutter axis is above or close to the center line of the workpiece (eccentricity is small). Under these conditions, use [Table 15d](#) to adjust speeds for other feeds and axial and radial depths of cut. For larger eccentricity (i.e., when the cutter axis to workpiece center line offset is one half the cutter diameter or more), use the end and side milling adjustment factors ([Tables 15b](#) and [15c](#)) instead of the face milling factors.

**Slit and Slot Milling:** Table data for slit milling are based on an 8-tooth, 10-degree helix angle tool with a cutter width of 0.4 inch, diameter  $D$  of 4.0 inch, and a depth of cut of 0.6 inch. Speeds are valid for all tool diameters and widths. See the examples in the text for adjustments to the given speeds for other feeds and depths of cut.

Tool life for all tabulated values is approximately 45 minutes; use [Table 15e](#) to adjust tool life from 15 to 180 minutes. The combined feed/speed data in this table are based on tool grades (identified in [Table 16](#)) as follows: uncoated carbide = 15; diamond = 9.

Table 11. Cutting Feeds and Speeds for Milling Plain Carbon and Alloy Steels

| Material  | Brinell Hardness | HSS         | End Milling |  |                  |          |                |          | Face Milling     |           |                |           | Slit Milling     |           |                |           |           |
|---|------------------|-------------|-------------|--|------------------|----------|----------------|----------|------------------|-----------|----------------|-----------|------------------|-----------|----------------|-----------|-----------|
|   |                  |             | HSS         |  | Uncoated Carbide |          | Coated Carbide |          | Uncoated Carbide |           | Coated Carbide |           | Uncoated Carbide |           | Coated Carbide |           |           |
|   |                  | Speed (fpm) | f<br>s      | Opt.   | Avg.             | Opt.     | Avg.           | Opt.     | Avg.             | Opt.      | Avg.           | Opt.      | Avg.             | Opt.      | Avg.           | Opt.      | Avg.      |
|   |                  |             |             | f = feed (0.001 in./tooth), s = speed (ft/min) |                  |          |                |          |                  |           |                |           |                  |           |                |           |           |
| Free-machining plain carbon steels (resulfurized): 1212, 1213, 1215   | 100–150          | 140         | f<br>s      | 7<br>45  | 4<br>125         | 7<br>465 | 4<br>735       | 7<br>800 | 4<br>1050        | 39<br>225 | 20<br>335      | 39<br>415 | 20<br>685        | 39<br>265 | 20<br>495      | 39<br>525 | 20<br>830 |
|   | 150–200          | 130         | f<br>s      | 7<br>35  | 4<br>100         |          |                |          |                  |           |                | 39<br>215 | 20<br>405        |           |                |           |           |
| (Resulfurized): 1108, 1109, 1115, 1117, 1118, 1120, 1126, 1211  | 100–150          | 130         | f<br>s      | 7<br>30  | 4<br>85          | 7<br>325 | 4<br>565       | 7<br>465 | 4<br>720         | 39<br>140 | 20<br>220      | 39<br>195 | 20<br>365        | 39<br>170 | 20<br>350      | 39<br>245 | 20<br>495 |
|   | 150–200          | 115         | f<br>s      | 7<br>30  | 4<br>85          |          |                |          |                  |           |                |           |                  | 39<br>185 | 20<br>350      |           |           |
|   | 175–225          | 115         | f<br>s      | 7<br>30  | 4<br>85          |          |                |          |                  |           |                |           |                  |           |                |           |           |
| (Resulfurized): 1132, 1137, 1139, 1140, 1144, 1146, 1151  | 275–325          | 70          |             |  |                  |          |                |          |                  |           |                |           |                  |           |                |           |           |
|   | 325–375          | 45          | f<br>s      | 7<br>25  | 4<br>70          | 7<br>210 | 4<br>435       | 7<br>300 | 4<br>560         | 39<br>90  | 20<br>170      | 39<br>175 | 20<br>330        | 39<br>90  | 20<br>235      | 39<br>135 | 20<br>325 |
|   | 375–425          | 35          |             |  |                  |          |                |          |                  |           |                |           |                  |           |                |           |           |
|   | 100–150          | 140         | f<br>s      | 7<br>35  | 4<br>100         |          |                |          |                  |           |                | 39<br>215 | 20<br>405        |           |                |           |           |
| (Leaded): 11L17, 11L18, 12L13, 12L14  | 150–200          | 130         | f<br>s      | 7<br>30  | 4<br>85          |          |                |          |                  |           |                | 39<br>185 | 20<br>350        |           |                |           |           |
|   | 200–250          | 110         | f<br>s      | 7<br>30  | 4<br>85          |          |                |          |                  |           |                |           |                  |           |                |           |           |
|   | 100–125          | 110         | f<br>s      | 7<br>45  | 4<br>125         | 7<br>465 | 4<br>735       | 7<br>800 | 4<br>1050        | 39<br>225 | 20<br>335      | 39<br>415 | 20<br>685        | 39<br>265 | 20<br>495      | 39<br>525 | 20<br>830 |
| Plain carbon steels: 1006, 1008, 1009, 1010, 1012, 1015, 1016, 1017, 1018, 1019, 1020, 1021, 1022, 1023, 1024, 1025, 1026, 1513, 1514 | 125–175          | 110         | f<br>s      | 7<br>35  | 4<br>100         |          |                |          |                  |           |                | 39<br>215 | 20<br>405        |           |                |           |           |
|   | 175–225          | 90          | f<br>s      | 7<br>30  | 4<br>85          |          |                |          |                  |           |                | 39<br>185 | 20<br>350        |           |                |           |           |
|   | 225–275          | 65          |             |  |                  |          |                |          |                  |           |                |           |                  |           |                |           |           |
|   |                  |             |             |  |                  |          |                |          |                  |           |                |           |                  |           |                |           |           |

**Table 11. (Continued) Cutting Feeds and Speeds for Milling Plain Carbon and Alloy Steels**

| Material  | Brinell Hardness | HSS<br>Speed (fpm) | End Milling  |          |                  |             |                |             | Face Milling     |             |                |             | Slit Milling     |             |                |             |           |
|---|------------------|--------------------|--|----------|------------------|-------------|----------------|-------------|------------------|-------------|----------------|-------------|------------------|-------------|----------------|-------------|-----------|
|   |                  |                    | HSS  |          | Uncoated Carbide |             | Coated Carbide |             | Uncoated Carbide |             | Coated Carbide |             | Uncoated Carbide |             | Coated Carbide |             |           |
|   |                  |                    | <i>f</i>   | <i>s</i> | <i>Opt.</i>      | <i>Avg.</i> | <i>Opt.</i>    | <i>Avg.</i> | <i>Opt.</i>      | <i>Avg.</i> | <i>Opt.</i>    | <i>Avg.</i> | <i>Opt.</i>      | <i>Avg.</i> | <i>Opt.</i>    | <i>Avg.</i> |           |
|   |                  |                    | <i>f</i> = feed (0.001 in./tooth), <i>s</i> = speed (ft/min) |          |                  |             |                |             |                  |             |                |             |                  |             |                |             |           |
| Plain carbon steels: 1027, 1030, 1033, 1035, 1036, 1037, 1038, 1039, 1040, 1041, 1042, 1043, 1045, 1046, 1048, 1049, 1050, 1052, 1524, 1526, 1527, 1541 | 125–175          | 100                | <i>f</i><br><i>s</i>   | 7<br>35  | 4<br>100         |             |                |             |                  |             |                | 39<br>215   | 20<br>405        |             |                |             |           |
|   | 175–225          | 85                 | <i>f</i><br><i>s</i>   | 7<br>30  | 4<br>85          |             |                |             |                  |             |                | 39<br>185   | 20<br>350        |             |                |             |           |
|   | 225–275          | 70                 |  |          |                  |             |                |             |                  |             |                |             |                  |             |                |             |           |
|   | 275–325          | 55                 | <i>f</i><br><i>s</i>   | 7<br>25  | 4<br>70          | 7<br>210    | 4<br>435       | 7<br>300    | 4<br>560         | 39<br>90    | 20<br>170      | 39<br>175   | 20<br>330        | 39<br>90    | 20<br>235      | 39<br>135   | 20<br>325 |
|   | 325–375          | 35                 |  |          |                  |             |                |             |                  |             |                |             |                  |             |                |             |           |
| 375–425   | 25               |                    |  |          |                  |             |                |             |                  |             |                |             |                  |             |                |             |           |
| Plain carbon steels: 1055, 1060, 1064, 1065, 1070, 1074, 1078, 1080, 1084, 1086, 1090, 1095, 1548, 1551, 1552, 1561, 1566                               | 125–175          | 90                 | <i>f</i><br><i>s</i>   | 7<br>30  | 4<br>85          | 7<br>325    | 4<br>565       | 7<br>465    | 4<br>720         | 39<br>140   | 20<br>220      | 39<br>195   | 20<br>365        | 39<br>170   | 20<br>350      | 39<br>245   | 20<br>495 |
|   | 175–225          | 75                 |  |          |                  |             |                |             |                  |             |                |             |                  |             |                |             |           |
|   | 225–275          | 60                 | <i>f</i><br><i>s</i>   | 7<br>30  | 4<br>85          |             |                |             |                  |             |                | 39<br>185   | 20<br>350        |             |                |             |           |
|   | 275–325          | 45                 |  |          |                  |             |                |             |                  |             |                |             |                  |             |                |             |           |
|   | 325–375          | 30                 | <i>f</i><br><i>s</i>   | 7<br>25  | 4<br>70          | 7<br>210    | 4<br>435       | 7<br>300    | 4<br>560         | 39<br>90    | 20<br>170      | 39<br>175   | 20<br>330        | 39<br>90    | 20<br>235      | 39<br>135   | 20<br>325 |
| 375–425   | 15               |                    |  |          |                  |             |                |             |                  |             |                |             |                  |             |                |             |           |
| Free-machining alloy steels (Resulfurized): 4140, 4150  | 175–200          | 100                | <i>f</i><br><i>s</i>   | 15<br>7  | 8<br>30          | 15<br>105   | 8<br>270       | 15<br>270   | 8<br>450         |             |                | 39<br>295   | 20<br>475        | 39<br>135   | 20<br>305      | 7<br>25     | 4<br>70   |
|   | 200–250          | 90                 |  |          |                  |             |                |             |                  |             |                |             |                  |             |                |             |           |
|   | 250–300          | 60                 | <i>f</i><br><i>s</i>   | 15<br>6  | 8<br>25          | 15<br>50    | 8<br>175       | 15<br>85    | 8<br>255         |             |                | 39<br>200   | 20<br>320        | 39<br>70    | 20<br>210      | 7<br>25     | 4<br>70   |
|   | 300–375          | 45                 | <i>f</i><br><i>s</i>   | 15<br>5  | 8<br>20          | 15<br>40    | 8<br>155       | 15<br>75    | 8<br>225         |             |                | 39<br>175   | 20<br>280        |             |                |             |           |
| 375–425   | 35               |                    |  |          |                  |             |                |             |                  |             |                |             |                  |             |                |             |           |

Table 11. (Continued) Cutting Feeds and Speeds for Milling Plain Carbon and Alloy Steels

| Material   | Brinell Hardness | HSS         | End Milling                                    |         |                  |           |                |           | Face Milling     |           |                |           | Slit Milling     |           |                |           |           |      |
|--|------------------|-------------|--|---------|------------------|-----------|----------------|-----------|------------------|-----------|----------------|-----------|------------------|-----------|----------------|-----------|-----------|------|
|  |                  |             | HSS  |         | Uncoated Carbide |           | Coated Carbide |           | Uncoated Carbide |           | Coated Carbide |           | Uncoated Carbide |           | Coated Carbide |           |           |      |
|  |                  | Speed (fpm) | f = feed (0.001 in./tooth), s = speed (ft/min) |         |                  |           |                |           |                  |           |                |           |                  |           |                |           |           |      |
|  |                  |             | Opt.   | Avg.    | Opt.             | Avg.      | Opt.           | Avg.      | Opt.             | Avg.      | Opt.           | Avg.      | Opt.             | Avg.      | Opt.           | Avg.      | Opt.      | Avg. |
| Free-machining alloy steels<br>(Leaded): 41L30, 41L40, 41L47,<br>41L50, 43L47, 51L32, 52L100,<br>86L20, 86L40  | 150–200          | 115         | <b>f</b><br><b>s</b>                           | 7<br>30 | 4<br>85          | 7<br>325  | 4<br>565       | 7<br>465  | 4<br>720         | 39<br>140 | 20<br>220      | 39<br>195 | 20<br>365        | 39<br>170 | 20<br>350      | 39<br>245 | 20<br>495 |      |
|  | 200–250          | 95          | <b>f</b><br><b>s</b>                           | 7<br>30 | 4<br>85          |           |                |           |                  |           |                | 39<br>185 | 20<br>350        |           |                |           |           |      |
|  | 250–300          | 70          |  |         |                  |           |                |           |                  |           |                |           |                  |           |                |           |           |      |
|  | 300–375          | 50          | <b>f</b><br><b>s</b>                           | 7<br>25 | 4<br>70          | 7<br>210  | 4<br>435       | 7<br>300  | 4<br>560         | 39<br>90  | 20<br>170      | 39<br>175 | 20<br>330        | 39<br>90  | 20<br>235      | 39<br>135 | 20<br>325 |      |
|  | 375–425          | 40          |  |         |                  |           |                |           |                  |           |                |           |                  |           |                |           |           |      |
| Alloy steels: 4012, 4023, 4024,<br>4028, 4118, 4320, 4419, 4422,<br>4427, 4615, 4620, 4621, 4626,<br>4718, 4720, 4815, 4817, 4820,<br>5015, 5117, 5120, 6118, 8115,<br>8615, 8617, 8620, 8622, 8625,<br>8627, 8720, 8822, 94B17  | 125–175          | 100         | <b>f</b><br><b>s</b>                           | 15<br>7 | 8<br>30          | 15<br>105 | 8<br>270       | 15<br>220 | 8<br>450         |           |                | 39<br>295 | 20<br>475        | 39<br>135 | 20<br>305      | 39<br>265 | 20<br>495 |      |
|  | 175–225          | 90          |  |         |                  |           |                |           |                  |           |                |           |                  |           |                |           |           |      |
|  | 225–275          | 60          | <b>f</b><br><b>s</b>                           | 15<br>6 | 8<br>25          | 15<br>50  | 8<br>175       | 15<br>85  | 8<br>255         |           |                | 39<br>200 | 20<br>320        | 39<br>70  | 20<br>210      | 39<br>115 | 20<br>290 |      |
|  | 275–325          | 50          | <b>f</b><br><b>s</b>                           | 15<br>5 | 8<br>20          | 15<br>45  | 8<br>170       | 15<br>80  | 8<br>240         |           |                | 39<br>190 | 20<br>305        |           |                |           |           |      |
|  | 325–375          | 40          | <b>f</b><br><b>s</b>                           | 15<br>5 | 8<br>20          | 15<br>40  | 8<br>155       | 15<br>75  | 8<br>225         |           |                | 39<br>175 | 20<br>280        |           |                |           |           |      |
| Alloy steels: 1330, 1335, 1340,<br>1345, 4032, 4037, 4042, 4047,<br>4130, 4135, 4137, 4140, 4142,<br>4145, 4147, 4150, 4161, 4337,<br>4340, 50B44, 50B46, 50B50,<br>50B60, 5130, 5132, 5140, 5145,<br>5147, 5150, 5160, 51B60, 6150,<br>81B45, 8630, 8635, 8637, 8640,<br>8642, 8645, 8650, 8655, 8660,<br>8740, 9254, 9255, 9260, 9262,<br>94B30<br>E51100, E52100: use (HSS<br>speeds) | 175–225          | 75 (65)     | <b>f</b><br><b>s</b>                           | 15<br>5 | 8<br>30          | 15<br>105 | 8<br>270       | 15<br>220 | 8<br>450         |           |                | 39<br>295 | 20<br>475        | 39<br>135 | 20<br>305      | 39<br>265 | 20<br>495 |      |
|  | 225–275          | 60          | <b>f</b><br><b>s</b>                           | 15<br>5 | 8<br>25          | 15<br>50  | 8<br>175       | 15<br>85  | 8<br>255         |           |                | 39<br>200 | 20<br>320        | 39<br>70  | 20<br>210      | 39<br>115 | 20<br>290 |      |
|  | 275–325          | 50 (40)     | <b>f</b><br><b>s</b>                           | 15<br>5 | 8<br>25          | 15<br>45  | 8<br>170       | 15<br>80  | 8<br>240         |           |                | 39<br>190 | 20<br>305        |           |                |           |           |      |
|  | 325–375          | 35 (30)     |  |         |                  |           |                |           |                  |           |                |           |                  |           |                |           |           |      |
|  | 375–425          | 20          | <b>f</b><br><b>s</b>                           | 15<br>5 | 8<br>20          | 15<br>40  | 8<br>155       | 15<br>75  | 8<br>225         |           |                | 39<br>175 | 20<br>280        |           |                |           |           |      |

**Table 11. (Continued) Cutting Feeds and Speeds for Milling Plain Carbon and Alloy Steels**

| Material  | Brinell Hardness | HSS | End Milling                                    |       |                  |         |                |      | Face Milling     |         |                |         | Slit Milling     |      |                |      |
|---|------------------|-----|--|-------|------------------|---------|----------------|------|------------------|---------|----------------|---------|------------------|------|----------------|------|
|   |                  |     | HSS  |       | Uncoated Carbide |         | Coated Carbide |      | Uncoated Carbide |         | Coated Carbide |         | Uncoated Carbide |      | Coated Carbide |      |
|   |                  |     | f = feed (0.001 in./tooth), s = speed (ft/min) |       |                  |         |                |      |                  |         |                |         |                  |      |                |      |
|   |                  |     | Speed (fpm)                                    | Opt.  | Avg.             | Opt.    | Avg.           | Opt. | Avg.             | Opt.    | Avg.           | Opt.    | Avg.             | Opt. | Avg.           | Opt. |
| Ultra-high-strength steels (not AISI): AMS 6421 (98B37 Mod.), 6422 (98BV40), 6424, 6427, 6428, 6430, 6432, 6433, 6434, 6436, and 6442; 300M, D6ac | 220–300          | 60  | f  |       | 8                | 4       | 8              | 4    |                  |         |                |         |                  |      |                |      |
|   | 300–350          | 45  | s  |       | 165              | 355     | 300            | 480  |                  |         |                |         |                  |      |                |      |
|   | 350–400          | 20  | f  | 8 4   | 8 4              | 8 4     |                |      |                  | 39 20   | 39 20          |         |                  |      |                |      |
|   |                  |     | s  | 15 45 | 150 320          |         |                |      |                  | 130 235 | 75 175         |         |                  |      |                |      |
|   | 43–52 Rc         | —   | f  |       | 5 3              |         |                |      |                  |         | 39 20          |         |                  |      |                |      |
|   |                  |     | s  |       | 20† 55           |         |                |      |                  |         | 5 15           |         |                  |      |                |      |
| Maraging steels (not AISI): 18% Ni Grades 200, 250, 300, and 350  | 250–325          | 50  | f  |       | 8 4              | 8 4     |                |      |                  |         |                |         |                  |      |                |      |
|   |                  |     | s  |       | 165 355          | 300 480 |                |      |                  |         |                |         |                  |      |                |      |
|   | 50–52 Rc         | —   | f  |       | 5 3              |         |                |      |                  |         | 39 20          |         |                  |      |                |      |
|   |                  |     | s  |       | 20† 55           |         |                |      |                  |         | 5 15           |         |                  |      |                |      |
| Nitriding steels (not AISI): Nitralloy 125, 135, 135 Mod., 225, and 230. Nitralloy N, Nitralloy EZ, Nitrex 1                                      | 200–250          | 60  | f  | 15 8  | 15 8             | 15 8    |                |      |                  | 39 20   | 39 20          | 39 20   |                  |      |                |      |
|   |                  |     | s  | 7 30  | 105 270          | 220 450 |                |      |                  | 295 475 | 135 305        | 265 495 |                  |      |                |      |
|   | 300–350          | 25  | f  | 15 8  | 15 8             | 15 8    |                |      |                  | 39 20   |                |         |                  |      |                |      |
|   |                  |     | s  | 5 20  | 40 155           | 75 225  |                |      |                  | 175 280 |                |         |                  |      |                |      |

For HSS (high-speed steel) tools in the first speed column only, use [Table 15a](#) for recommended feed in inches per tooth and depth of cut.

**End Milling:** Table data for end milling are based on a 3-tooth, 20-degree helix angle tool with a diameter of 1.0 inch, an axial depth of cut of 0.2 inch, and a radial depth of cut of 1 inch (full slot). Use [Table 15b](#) to adjust speeds for other feeds and axial depths of cut, and [Table 15c](#) to adjust speeds if the radial depth of cut is less than the tool diameter. Speeds are valid for all tool diameters.

**Face Milling:** Table data for face milling are based on a 10-tooth, 8-inch diameter face mill, operating with a 15-degree lead angle,  $\frac{3}{64}$ -inch nose radius, axial depth of cut = 0.1 inch, and radial depth (width) of cut = 6 inches (i.e., width of cut to cutter diameter ratio =  $\frac{3}{4}$ ). These speeds are valid if the cutter axis is above or close to the center line of the workpiece (eccentricity is small). Under these conditions, use [Table 15d](#) to adjust speeds for other feeds and axial and radial depths of cut. For larger eccentricity (i.e., when the cutter axis to workpiece center line offset is one half the cutter diameter or more), use the end and side milling adjustment factors ([Tables 15b](#) and [15c](#)) instead of the face milling factors.

**Slit and Slot Milling:** Table data for slit milling are based on an 8-tooth, 10-degree helix angle tool with a cutter width of 0.4 inch, diameter  $D$  of 4.0 inches, and a depth of cut of 0.6 inch. Speeds are valid for all tool diameters and widths. See the examples in the text for adjustments to the given speeds for other feeds and depths of cut.

Tool life for all tabulated values is approximately 45 minutes; use [Table 15e](#) to adjust tool life from 15 to 180 minutes. The combined feed/speed data in this table are based on tool grades (identified in [Table 16](#)) as follows: end and slit milling uncoated carbide = 20 except † = 15; face milling uncoated carbide = 19; end, face, and slit milling coated carbide = 10.

Table 12. Cutting Feeds and Speeds for Milling Tool Steels

| Material   | Brinell Hardness                 | HSS         | End Milling                                    |         |                  |          | Face Milling   |          |                  |           | Slit Milling |          |                  |           |                |           |           |
|--|----------------------------------|-------------|--|---------|------------------|----------|----------------|----------|------------------|-----------|--------------|----------|------------------|-----------|----------------|-----------|-----------|
|  |                                  |             | HSS  |         | Uncoated Carbide |          | Coated Carbide |          | Uncoated Carbide |           | CBN          |          | Uncoated Carbide |           | Coated Carbide |           |           |
|  |                                  | Speed (fpm) | f = feed (0.001 in./tooth), s = speed (ft/min) |         |                  |          |                |          |                  |           |              |          |                  |           |                |           |           |
|  |                                  |             | Opt.   | Avg.    | Opt.             | Avg.     | Opt.           | Avg.     | Opt.             | Avg.      | Opt.         | Avg.     | Opt.             | Avg.      | Opt.           | Avg.      |           |
| Water hardening: W1, W2, W5  | 150-200                          |             |  |         |                  |          |                |          |                  |           |              |          |                  |           |                |           |           |
| Shock resisting: S1, S2, S5, S6, S7  | 175-225                          |             |  |         |                  |          |                |          |                  |           |              |          |                  |           |                |           |           |
| Cold work, oil hardening: O1, O2, O6, O7   | 175-225                          | 50          | f<br>s   | 8<br>25 | 4<br>70          | 8<br>235 | 4<br>455       | 8<br>405 | 4<br>635         | 39<br>235 | 20<br>385    |          |                  | 39<br>115 | 20<br>265      | 39<br>245 | 20<br>445 |
| Cold work, high carbon, high chromium: D2, D3, D4, D5, D7  | 200-250                          | 40          |  |         |                  |          |                |          |                  |           |              |          |                  |           |                |           |           |
| Cold work, air hardening: A2, A3, A8, A9, A10<br>A4, A6<br>A7  | 200-250                          | 50          | f<br>s   |         |                  |          |                |          |                  | 39<br>255 | 20<br>385    |          |                  |           |                |           |           |
|  | 200-250                          | 45          |  |         |                  |          |                |          |                  |           |              |          |                  |           |                |           |           |
|  | 225-275                          | 40          |  |         |                  |          |                |          |                  |           |              |          |                  |           |                |           |           |
| Hot work, chromium type: H10, H11, H12, H13, H14, H19  | 150-200                          | 60          |  |         |                  |          |                |          |                  |           |              |          |                  |           |                |           |           |
|  | 200-250                          | 50          |  |         |                  |          |                |          |                  |           |              |          |                  |           |                |           |           |
|  | 325-375                          | 30          | f<br>s   | 8<br>15 | 4<br>45          | 8<br>150 | 4<br>320       |          |                  | 39<br>130 | 20<br>235    |          |                  | 39<br>75  | 20<br>175      |           |           |
|  | 48-50 Rc<br>50-52 Rc<br>52-56 Rc | —<br>—<br>— | f<br>s   |         |                  | 5<br>20† | 3<br>55        |          |                  |           |              | 39<br>50 | 20<br>135        | 39<br>5†  | 20<br>15       |           |           |
| Hot work, tungsten and molybdenum types: H21, H22, H23, H24, H25, H26, H41, H42, H43   | 150-200                          | 55          | f<br>s   |         |                  |          |                |          |                  | 39<br>255 | 20<br>385    |          |                  |           |                |           |           |
|  | 200-250                          | 45          |  |         |                  |          |                |          |                  |           |              |          |                  |           |                |           |           |
| Special-purpose, low alloy: L2, L3, L6   | 150-200                          | 65          | f<br>s   | 8<br>25 | 4<br>70          | 8<br>235 | 4<br>455       | 8<br>405 | 4<br>635         | 39<br>235 | 20<br>385    |          |                  | 39<br>115 | 20<br>265      | 39<br>245 | 20<br>445 |
| Mold: P2, P3, P4, P5, P6 P20, P21  | 100-150<br>150-200               | 75<br>60    |  |         |                  |          |                |          |                  |           |              |          |                  |           |                |           |           |
| High-speed steel: M1, M2, M6, M10, T1, T2, T6<br>M3-1, M4, M7, M30, M33, M34, M36, M41, M42, M43, M44, M46, M47, T5, T8<br>T15, M3-2 | 200-250                          | 50          |  |         |                  |          |                |          |                  |           |              |          |                  |           |                |           |           |
|  | 225-275                          | 40          | f<br>s   |         |                  |          |                |          |                  | 39<br>255 | 20<br>385    |          |                  |           |                |           |           |
|  | 225-275                          | 30          |  |         |                  |          |                |          |                  |           |              |          |                  |           |                |           |           |

For HSS (high-speed steel) tools in the first speed column only, use [Table 15a](#) for recommended feed in inches per tooth and depth of cut.

**End Milling:** Table data for end milling are based on a 3-tooth, 20-degree helix angle tool with a diameter of 1.0 inch, an axial depth of cut of 0.2 inch, and a radial depth of cut of 1 inch (full slot). Use [Table 15b](#) to adjust speeds for other feeds and axial depths of cut, and [Table 15c](#) to adjust speeds if the radial depth of cut is less than the tool diameter. Speeds are valid for all tool diameters.

**Face Milling:** Table data for face milling are based on a 10-tooth, 8-inch diameter face mill, operating with a 15-degree lead angle,  $\frac{3}{64}$ -inch nose radius, axial depth of cut = 0.1 inch, and radial depth (width) of cut = 6 inches (i.e., width of cut to cutter diameter ratio =  $\frac{3}{4}$ ). These speeds are valid if the cutter axis is above or close to the center line of the workpiece (eccentricity is small). Under these conditions, use [Table 15d](#) to adjust speeds for other feeds and axial and radial depths of cut. For larger eccentricity (i.e., when the cutter axis to workpiece center line offset is one half the cutter diameter or more), use the end and side milling adjustment factors ([Tables 15b](#) and [15c](#)) instead of the face milling factors.

**Slit and Slot Milling:** Table data for slit milling are based on an 8-tooth, 10-degree helix angle tool with a cutter width of 0.4 inch, diameter  $D$  of 4.0 inches, and a depth of cut of 0.6 inch. Speeds are valid for all tool diameters and widths. See the examples in the text for adjustments to the given speeds for other feeds and depths of cut.

Tool life for all tabulated values is approximately 45 minutes; use [Table 15e](#) to adjust tool life from 15 to 180 minutes. The combined feed/speed data in this table are based on tool grades (identified in [Table 16](#)) as follows: uncoated carbide = 20,  $\ddagger$  = 15; coated carbide = 10; CBN = 1.

**Table 13. Cutting Feeds and Speeds for Milling Stainless Steels**

| Material   | Brinell Hardness                  | HSS     | End Milling |      |                  |      |                |      | Face Milling   |      | Slit Milling     |      |                |      |
|--|-----------------------------------|---------|-------------|------|------------------|------|----------------|------|----------------|------|------------------|------|----------------|------|
|  |                                   |         | HSS         |      | Uncoated Carbide |      | Coated Carbide |      | Coated Carbide |      | Uncoated Carbide |      | Coated Carbide |      |
|  |                                   |         | Opt.        | Avg. | Opt.             | Avg. | Opt.           | Avg. | Opt.           | Avg. | Opt.             | Avg. | Opt.           | Avg. |
|  |                                   |         |             |      |                  |      |                |      |                |      |                  |      |                |      |
| Free-machining stainless steels (Ferritic): 430F, 430FSe                 | 135-185                           | 110     | f           | 7    | 4                | 7    | 4              | 7    | 4              | 39   | 20               | 39   | 20             |      |
|  |                                   |         | s           | 30   | 80               | 305  | 780            | 420  | 1240           | 210  | 385              | 120  | 345            | 155  |
| (Austenitic): 203EZ, 303, 303Se, 303MA, 303Pb, 303Cu, 303 Plus X         | 135-185                           | 100     | f           | 7    | 4                | 7    | 4              |      |                |      |                  | 39   | 20             |      |
|  | 225-275                           | 80      |             |      |                  |      |                |      |                |      |                  |      |                | s    |
| (Martensitic): 416, 416Se, 416 Plus X, 420F, 420FSe, 440F, 440FSe        | 135-185                           | 110     |             |      |                  |      |                |      |                |      |                  |      |                |      |
|  |                                   | 185-240 | 100         |      |                  |      |                |      |                |      |                  |      |                |      |
|  | 275-325                           | 60      |             |      |                  |      |                |      |                |      |                  |      |                |      |
|  | 375-425                           | 30      |             |      |                  |      |                |      |                |      |                  |      |                |      |
| Stainless steels (Ferritic): 405, 409, 429, 430, 434, 436, 442, 446, 502 | 135-185                           | 90      | f           | 7    | 4                | 7    | 4              | 7    | 4              | 39   | 20               | 39   | 20             |      |
|  |                                   |         | s           | 30   | 80               | 305  | 780            | 420  | 1240           | 210  | 385              | 120  | 345            | 155  |
| (Austenitic): 201, 202, 301, 302, 304, 304L, 305, 308, 321, 347, 348     | 135-185                           | 75      | f           | 7    | 4                | 7    | 4              |      |                |      |                  | 39   | 20             |      |
|  | 225-275                           | 65      |             |      |                  |      |                |      |                |      |                  |      |                | s    |
| (Austenitic): 302B, 309, 309S, 310, 310S, 314, 316, 316L, 317, 330       | 135-185                           | 70      |             |      |                  |      |                |      |                |      |                  |      |                |      |
|  | (Martensitic): 403, 410, 420, 501 | 135-175 | 95          |      |                  |      |                |      |                |      |                  |      |                |      |
| 175-225  |                                   | 85      |             |      |                  |      |                |      |                |      |                  |      |                |      |
| 275-325  |                                   | 55      |             |      |                  |      |                |      |                |      |                  |      |                |      |
| 375-425  |                                   | 35      |             |      |                  |      |                |      |                |      |                  |      |                |      |

**Table 13. (Continued) Cutting Feeds and Speeds for Milling Stainless Steels**

| Material  | Brinell Hardness | HSS   | End Milling                                    |         |                  |          |                |      | Face Milling   |      | Slit Milling     |          |                |      |
|---|------------------|-------|--|---------|------------------|----------|----------------|------|----------------|------|------------------|----------|----------------|------|
|   |                  |       | HSS  |         | Uncoated Carbide |          | Coated Carbide |      | Coated Carbide |      | Uncoated Carbide |          | Coated Carbide |      |
|   |                  |       | f = feed (0.001 in./tooth), s = speed (ft/min) |         |                  |          |                |      |                |      |                  |          |                |      |
|   |                  |       | Opt.   | Avg.    | Opt.             | Avg.     | Opt.           | Avg. | Opt.           | Avg. | Opt.             | Avg.     | Opt.           | Avg. |
| Stainless Steels (Martensitic): 414, 431, Greek Ascoloy, 440A, 440B, 440C   | 225–275          | 55–60 |  |         |                  |          |                |      |                |      |                  |          |                |      |
|   | 275–325          | 45–50 |  |         |                  |          |                |      |                |      |                  |          |                |      |
|   | 375–425          | 30    |  |         |                  |          |                |      |                |      |                  |          |                |      |
| (Precipitation hardening): 15-5PH, 17-4PH, 17-7PH, AF-71, 17-14CuMo, AFC-77, AM-350, AM-355, AM-362, Custom 455, HNM, PH13-8, PH14-8Mo, PH15-7Mo, Stainless W | 150–200          | 60    | f<br>s   | 7<br>20 | 4<br>55          | 7<br>210 | 4<br>585       |      |                |      |                  | 39<br>75 | 20<br>240      |      |
|   | 275–325          | 50    |  |         |                  |          |                |      |                |      |                  |          |                |      |
|   | 325–375          | 40    |  |         |                  |          |                |      |                |      |                  |          |                |      |
|   | 375–450          | 25    |  |         |                  |          |                |      |                |      |                  |          |                |      |

For HSS (high-speed steel) tools in the first speed column only, use [Table 15a](#) for recommended feed in inches per tooth and depth of cut.

**End Milling:** Table data for end milling are based on a 3-tooth, 20-degree helix angle tool with a diameter of 1.0 inch, an axial depth of cut of 0.2 inch, and a radial depth of cut of 1 inch (full slot). Use [Table 15b](#) to adjust speeds for other feeds and axial depths of cut, and [Table 15c](#) to adjust speeds if the radial depth of cut is less than the tool diameter. Speeds are valid for all tool diameters.

**Face Milling:** Table data for face milling are based on a 10-tooth, 8-inch diameter face mill, operating with a 15-degree lead angle,  $\frac{3}{4}$ -inch nose radius, axial depth of cut = 0.1 inch, and radial depth (width) of cut = 6 inches (i.e., width of cut to cutter diameter ratio =  $\frac{3}{4}$ ). These speeds are valid if the cutter axis is above or close to the center line of the workpiece (eccentricity is small). Under these conditions, use [Table 15d](#) to adjust speeds for other feeds and axial and radial depths of cut. For larger eccentricity (i.e., when the cutter axis to workpiece center line offset is one half the cutter diameter or more), use the end and side milling adjustment factors ([Tables 15b](#) and [15c](#)) instead of the face milling factors.

**Slit and Slot Milling:** Table data for slit milling are based on an 8-tooth, 10-degree helix angle tool with a cutter width of 0.4 inch, diameter  $D$  of 4.0 inch, and a depth of cut of 0.6 inch. Speeds are valid for all tool diameters and widths. See the examples in the text for adjustments to the given speeds for other feeds and depths of cut.

Tool life for all tabulated values is approximately 45 minutes; use [Table 15e](#) to adjust tool life from 15 to 180 minutes. The combined feed/speed data in this table are based on tool grades (identified in [Table 16](#)) as follows: uncoated carbide = 20; coated carbide = 10.



Table 14. Cutting Feeds and Speeds for Milling Ferrous Cast Metals

| Material  | Brinell Hardness | HSS | End Milling                                    |      |                  | Face Milling   |                  |                |         | Slit Milling |                  |                |      |      |     |     |     |     |
|---|------------------|-----|--|------|------------------|----------------|------------------|----------------|---------|--------------|------------------|----------------|------|------|-----|-----|-----|-----|
|   |                  |     | HSS  |      | Uncoated Carbide | Coated Carbide | Uncoated Carbide | Coated Carbide | Ceramic | CBN          | Uncoated Carbide | Coated Carbide |      |      |     |     |     |     |
|   |                  |     | f = feed (0.001 in./tooth), s = speed (ft/min) |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
|   |                  |     | Opt.   | Avg. | Opt.             | Avg.           | Opt.             | Avg.           | Opt.    | Avg.         | Opt.             | Avg.           | Opt. | Avg. |     |     |     |     |
| Gray Cast Iron  |                  |     |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
| ASTM Class 20   | 120-150          | 100 | f  | 5    | 3                | 5              | 3                |                | 39      | 20           | 39               | 20             | 39   | 20   | 39  | 20  |     |     |
| ASTM Class 25   | 160-200          | 80  | s  | 35   | 90               | 520            | 855              |                | 140     | 225          | 285              | 535            | 1130 | 1630 | 200 | 530 | 205 | 420 |
| ASTM Class 30, 35, and 40                             | 190-220          | 70  |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
| ASTM Class 45 and 50                                  | 220-260          | 50  | f  | 5    | 3                | 5              | 3                |                | 39      | 20           | 39               | 20             | 39   | 20   | 39  | 20  | 39  | 20  |
| ASTM Class 55 and 60                                  | 250-320          | 30  | s  | 30   | 70               | 515            | 1100             |                | 95      | 160          | 185              | 395            | 845  | 1220 | 150 | 400 | 145 | 380 |
| ASTM Type 1, 1b, 5 (Ni resist)                        | 100-215          | 50  |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
| ASTM Type 2, 3, 6 (Ni resist)                         | 120-175          | 40  |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
| ASTM Type 2b, 4 (Ni resist)                           | 150-250          | 30  |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
| Malleable Iron  |                  |     |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
| (Ferritic): 32510, 35018                              | 110-160          | 110 | f  | 5    | 3                | 5              | 3                |                | 39      | 20           | 39               | 20             | 39   | 20   |     |     | 39  | 20  |
|   |                  |     | s  | 30   | 70               | 180            | 250              |                | 120     | 195          | 225              | 520            | 490  | 925  |     |     | 85  | 150 |
| (Pearlitic): 40010, 43010, 45006, 45008, 48005, 50005 | 160-200          | 80  | f  | 5    | 3                | 5              | 3                |                | 39      | 20           | 39               | 20             | 39   | 20   |     |     | 39  | 20  |
|   | 200-240          | 65  | s  | 25   | 65               | 150            | 215              |                | 90      | 150          | 210              | 400            | 295  | 645  |     |     | 70  | 125 |
| (Martensitic): 53004, 60003, 60004                    | 200-255          | 55  |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
| (Martensitic): 70002, 70003                           | 220-260          | 50  |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
| (Martensitic): 80002                                  | 240-280          | 45  |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
| (Martensitic): 90001                                  | 250-320          | 25  |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
| Nodular (Ductile) Iron                                |                  |     |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
| (Ferritic): 60-40-18, 65-45-12                        | 140-190          | 75  | f  | 7    | 4                | 7              | 4                |                | 39      | 20           | 39               | 20             | 39   | 20   |     |     | 39  | 20  |
|   |                  |     | s  | 15   | 35               | 125            | 240              |                | 100     | 155          | 120              | 255            | 580  | 920  |     |     | 60  | 135 |
| (Ferritic-Pearlitic): 80-55-06                        | 190-225          | 60  | f  | 7    | 4                | 7              | 4                |                | 39      | 20           | 39               | 20             | 39   | 20   |     |     | 39  | 20  |
|   | 225-260          | 50  | s  | 10   | 30               | 90             | 210              |                | 95      | 145          | 150              | 275            | 170  | 415  |     |     | 40  | 100 |
| (Pearlitic-Martensitic): 100-70-03                    | 240-300          | 40  |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |
| (Martensitic): 120-90-02                              | 270-330          | 25  |  |      |                  |                |                  |                |         |              |                  |                |      |      |     |     |     |     |

Table 14. (Continued) Cutting Feeds and Speeds for Milling Ferrous Cast Metals

| Material   | Brinell Hardness | HSS<br>Speed<br>(fpm) | End Milling                                    |      |                  |      |                |      | Face Milling     |      |                |      | Slit Milling |      |                  |                |     |      |     |     |     |
|--|------------------|-----------------------|--|------|------------------|------|----------------|------|------------------|------|----------------|------|--------------|------|------------------|----------------|-----|------|-----|-----|-----|
|  |                  |                       | HSS  |      | Uncoated Carbide |      | Coated Carbide |      | Uncoated Carbide |      | Coated Carbide |      | Ceramic      | CBN  | Uncoated Carbide | Coated Carbide |     |      |     |     |     |
|  |                  |                       | Opt.   | Avg. | Opt.             | Avg. | Opt.           | Avg. | Opt.             | Avg. | Opt.           | Avg. | Opt.         | Avg. | Opt.             | Avg.           |     |      |     |     |     |
|  |                  |                       | f = feed (0.001 in./tooth), s = speed (ft/min) |      |                  |      |                |      |                  |      |                |      |              |      |                  |                |     |      |     |     |     |
| Cast Steels  |                  |                       |  |      |                  |      |                |      |                  |      |                |      |              |      |                  |                |     |      |     |     |     |
| (Low carbon): 1010, 1020   | 100–150          | 100                   | f  | 7    | 4                | 7    | 4              | 7    | 4                |      |                |      |              |      |                  | 39             | 20  | 39   | 20  |     |     |
|  | 125–175          | 95                    | s  | 25   | 70               | 245† | 410            | 420  | 650              |      |                |      |              |      |                  | 265‡           | 430 | 135† | 260 | 245 | 450 |
| (Medium carbon): 1030, 1040 1050   | 175–225          | 80                    |  |      |                  |      |                |      |                  |      |                |      |              |      |                  |                |     |      |     |     |     |
|  | 225–300          | 60                    | f  | 7    | 4                | 7    | 4              | 7    | 4                |      |                |      |              |      |                  | 39             | 20  | 39   | 20  |     |     |
|  | 150–200          | 85                    | s  | 20   | 55               | 160† | 400            | 345  | 560              |      |                |      |              |      |                  | 205‡           | 340 | 65†  | 180 | 180 | 370 |
| (Low-carbon alloy): 1320, 2315, 2320, 4110, 4120, 4320, 8020, 8620   | 200–250          | 75                    |  |      |                  |      |                |      |                  |      |                |      |              |      |                  |                |     |      |     |     |     |
|  | 250–300          | 50                    |  |      |                  |      |                |      |                  |      |                |      |              |      |                  |                |     |      |     |     |     |
| (Medium-carbon alloy): 1330, 1340, 2325, 2330, 4125, 4130, 4140, 4330, 4340, 8030, 80B30, 8040, 8430, 8440, 8630, 8640, 9525, 9530, 9535 | 175–225          | 70                    | f  | 7    | 4                | 7    | 4              |      |                  |      |                |      |              |      |                  |                |     | 39   | 20  |     |     |
|  | 225–250          | 65                    | s  | 15   | 45               | 120† | 310            |      |                  |      |                |      |              |      |                  |                |     | 45†  | 135 |     |     |
|  | 250–300          | 50                    | f  |      |                  |      |                |      |                  |      |                |      |              |      |                  | 39             | 20  |      |     |     |     |
|  | 300–350          | 30                    | s  |      |                  |      |                |      |                  |      |                |      |              |      | 25               | 40             |     |      |     |     |     |

For HSS (high-speed steel) tools in the first speed column only, use Table 15a for recommended feed in inches per tooth and depth of cut.

**End Milling:** Table data for end milling are based on a 3-tooth, 20-degree helix angle tool with a diameter of 1.0 inch, an axial depth of cut of 0.2 inch, and a radial depth of cut of 1 inch (full slot). Use Table 15b to adjust speeds for other feeds and axial depths of cut, and Table 15c to adjust speeds if the radial depth of cut is less than the tool diameter. Speeds are valid for all tool diameters.

**Face Milling:** Table data for face milling are based on a 10-tooth, 8-inch diameter face mill, operating with a 15-degree lead angle,  $\frac{3}{4}$ -inch nose radius, axial depth of cut = 0.1 inch, and radial depth (width) of cut = 6 inches (i.e., width of cut to cutter diameter ratio =  $\frac{3}{4}$ ). These speeds are valid if the cutter axis is above or close to the center line of the workpiece (eccentricity is small). Under these conditions, use Table 15d to adjust speeds for other feeds and axial and radial depths of cut. For larger eccentricity (i.e., when the cutter axis to workpiece center line offset is one half the cutter diameter or more), use the end and side milling adjustment factors (Tables 15b and 15c) instead of the face milling factors.

**Slit and Slot Milling:** Table data for slit milling are based on an 8-tooth, 10-degree helix angle tool with a cutter width of 0.4 inch, diameter  $D$  of 4.0 inches, and a depth of cut of 0.6 inch. Speeds are valid for all tool diameters and widths. See the examples in the text for adjustments to the given speeds for other feeds and depths of cut.

Tool life for all tabulated values is approximately 45 minutes; use Table 15e to adjust tool life from 15 to 180 minutes. The combined feed/speed data in this table are based on tool grades (identified in Table 16) as follows: uncoated carbide = 15 except † = 20; end and slit milling coated carbide = 10; face milling coated carbide = 11 except ‡ = 10. ceramic = 6; CBN = 1.

**Table 15a. Recommended Feed in Inches per Tooth ( $f_t$ ) for Milling with High Speed Steel Cutters**

| Material   | Hardness, HB  | End Mills             |      |          |                       |      |      |          | Plain or Slab Mills | Form Relieved Cutters | Face Mills and Shell End Mills | Slotting and Side Mills |
|--|---|-----------------------|------|----------|-----------------------|------|------|----------|---------------------|-----------------------|--------------------------------|-------------------------|
|  |   | Depth of Cut, .250 in |      |          | Depth of Cut, .050 in |      |      |          |                     |                       |                                |                         |
|  |   | Cutter Diam., in      |      |          | Cutter Diam., in      |      |      |          |                     |                       |                                |                         |
|  |   | ½                     | ¾    | 1 and up | ¼                     | ½    | ¾    | 1 and up |                     |                       |                                |                         |
| Feed per Tooth, inch   |   |                       |      |          |                       |      |      |          |                     |                       |                                |                         |
| Free-machining plain carbon steels   | 100–185   | .001                  | .003 | .004     | .001                  | .002 | .003 | .004     | .003–.008           | .005                  | .004–.012                      | .002–.008               |
| Plain carbon steels, AISI 1006 to 1030; 1513 to 1522   | 100–150   | .001                  | .003 | .003     | .001                  | .002 | .003 | .004     | .003–.008           | .004                  | .004–.012                      | .002–.008               |
|  | 150–200   | .001                  | .002 | .003     | .001                  | .002 | .002 | .003     | .003–.008           | .004                  | .003–.012                      | .002–.008               |
|  | 120–180   | .001                  | .003 | .003     | .001                  | .002 | .003 | .004     | .003–.008           | .004                  | .004–.012                      | .002–.008               |
|  | 180–220   | .001                  | .002 | .003     | .001                  | .002 | .002 | .003     | .003–.008           | .004                  | .003–.012                      | .002–.008               |
| AISI 1033 to 1095; 1524 to 1566  | 220–300   | .001                  | .002 | .002     | .001                  | .001 | .002 | .003     | .002–.006           | .003                  | .002–.008                      | .002–.006               |
|  | Alloy steels having less than 3% carbon. Typical examples: AISI 4012, 4023, 4027, 4118, 4320 4422, 4427, 4615, 4620, 4626, 4720, 4820, 5015, 5120, 6118, 8115, 8620 8627, 8720, 8820, 8822, 9310, 93B17 | 125–175               | .001 | .003     | .003                  | .001 | .002 | .003     | .004                | .003–.008             | .004                           | .004–.012               |
| Alloy steels having 3% carbon or more. Typical examples: AISI 1330, 1340, 4032, 4037, 4130, 4140, 4150, 4340, 50B40, 50B60, 5130, 51B60, 6150, 81B45, 8630, 8640, 86B45, 8660, 8740, 94B30 | 175–225   | .001                  | .002 | .003     | .001                  | .002 | .003 | .003     | .003–.008           | .004                  | .003–.012                      | .002–.008               |
|  | 225–275   | .001                  | .002 | .003     | .001                  | .001 | .002 | .003     | .002–.006           | .003                  | .003–.010                      | .002–.006               |
|  | 275–325   | .001                  | .002 | .002     | .001                  | .001 | .002 | .003     | .002–.005           | .003                  | .002–.008                      | .002–.005               |
|  | 325–375   | .001                  | .002 | .002     | .001                  | .001 | .002 | .002     | .002–.004           | .002                  | .002–.008                      | .002–.005               |
| Tool steel   | 150–200   | .001                  | .002 | .002     | .001                  | .002 | .003 | .003     | .003–.008           | .004                  | .003–.010                      | .002–.006               |
|  | 200–250   | .001                  | .002 | .002     | .001                  | .002 | .002 | .003     | .002–.006           | .003                  | .003–.008                      | .002–.005               |
| Gray cast iron   | 120–180   | .001                  | .003 | .004     | .002                  | .003 | .004 | .004     | .004–.012           | .005                  | .005–.016                      | .002–.010               |
|  | 180–225   | .001                  | .002 | .003     | .001                  | .002 | .003 | .003     | .003–.010           | .004                  | .004–.012                      | .002–.008               |
|  | 225–300   | .001                  | .002 | .002     | .001                  | .001 | .002 | .002     | .002–.006           | .003                  | .002–.008                      | .002–.005               |
| Free malleable iron  | 110–160   | .001                  | .003 | .004     | .002                  | .003 | .004 | .004     | .003–.010           | .005                  | .005–.016                      | .002–.010               |

Table 15a. (Continued) Recommended Feed in Inches per Tooth ( $f_t$ ) for Milling with High Speed Steel Cutters

| Material(Continued)                  | Hardness, HB | End Mills             |      |          |                       |      |      |          | Plain or Slab Mills | Form Relieved Cutters | Face Mills and Shell End Mills | Slotting and Side Mills |
|--------------------------------------|--------------|-----------------------|------|----------|-----------------------|------|------|----------|---------------------|-----------------------|--------------------------------|-------------------------|
|                                      |              | Depth of Cut, .250 in |      |          | Depth of Cut, .050 in |      |      |          |                     |                       |                                |                         |
|                                      |              | Cutter Diam., in      |      |          | Cutter Diam., in      |      |      |          |                     |                       |                                |                         |
|                                      |              | 1/2                   | 3/4  | 1 and up | 1/4                   | 1/2  | 3/4  | 1 and up |                     |                       |                                |                         |
| Feed per Tooth, inch                 |              |                       |      |          |                       |      |      |          |                     |                       |                                |                         |
| Pearlitic-Martensitic malleable iron | 160-200      | .001                  | .003 | .004     | .001                  | .002 | .003 | .004     | .003-.010           | .004                  | .004-.012                      | .002-.018               |
|                                      | 200-240      | .001                  | .002 | .003     | .001                  | .002 | .003 | .003     | .003-.007           | .004                  | .003-.010                      | .002-.006               |
|                                      | 240-300      | .001                  | .002 | .002     | .001                  | .001 | .002 | .002     | .002-.006           | .003                  | .002-.008                      | .002-.005               |
| Cast steel                           | 100-180      | .001                  | .003 | .003     | .001                  | .002 | .003 | .004     | .003-.008           | .004                  | .003-.012                      | .002-.008               |
|                                      | 180-240      | .001                  | .002 | .003     | .001                  | .002 | .003 | .003     | .003-.008           | .004                  | .003-.010                      | .002-.006               |
|                                      | 240-300      | .001                  | .002 | .002     | .005                  | .002 | .002 | .002     | .002-.006           | .003                  | .003-.008                      | .002-.005               |
| Zinc alloys (die castings)           | ...          | .002                  | .003 | .004     | .001                  | .003 | .004 | .006     | .003-.010           | .005                  | .004-.015                      | .002-.012               |
| Copper alloys (brasses & bronzes)    | 100-150      | .002                  | .004 | .005     | .002                  | .003 | .005 | .006     | .003-.015           | .004                  | .004-.020                      | .002-.010               |
|                                      | 150-250      | .002                  | .003 | .004     | .001                  | .003 | .004 | .005     | .003-.015           | .004                  | .003-.012                      | .002-.008               |
| Free cutting brasses & bronzes       | 80-100       | .002                  | .004 | .005     | .002                  | .003 | .005 | .006     | .003-.015           | .004                  | .004-.015                      | .002-.010               |
| Cast aluminum alloys—as cast         | ...          | .003                  | .004 | .005     | .002                  | .004 | .005 | .006     | .005-.016           | .006                  | .005-.020                      | .004-.012               |
| Cast aluminum alloys—hardened        | ...          | .003                  | .004 | .005     | .002                  | .003 | .004 | .005     | .004-.012           | .005                  | .005-.020                      | .004-.012               |
| Wrought aluminum alloys—cold drawn   | ...          | .003                  | .004 | .005     | .002                  | .003 | .004 | .005     | .004-.014           | .005                  | .005-.020                      | .004-.012               |
| Wrought aluminum alloys—hardened     | ...          | .002                  | .003 | .004     | .001                  | .002 | .003 | .004     | .003-.012           | .004                  | .005-.020                      | .004-.012               |
| Magnesium alloys                     | ...          | .003                  | .004 | .005     | .003                  | .004 | .005 | .007     | .005-.016           | .006                  | .008-.020                      | .005-.012               |
| Ferritic stainless steel             | 135-185      | .001                  | .002 | .003     | .001                  | .002 | .003 | .003     | .002-.006           | .004                  | .004-.008                      | .002-.007               |
| Austenitic stainless steel           | 135-185      | .001                  | .002 | .003     | .001                  | .002 | .003 | .003     | .003-.007           | .004                  | .005-.008                      | .002-.007               |
|                                      | 185-275      | .001                  | .002 | .003     | .001                  | .002 | .002 | .002     | .003-.006           | .003                  | .004-.006                      | .002-.007               |
| Martensitic stainless steel          | 135-185      | .001                  | .002 | .002     | .001                  | .002 | .003 | .003     | .003-.006           | .004                  | .004-.010                      | .002-.007               |
|                                      | 185-225      | .001                  | .002 | .002     | .001                  | .002 | .002 | .003     | .003-.006           | .004                  | .003-.008                      | .002-.007               |
|                                      | 225-300      | .0005                 | .002 | .002     | .0005                 | .001 | .002 | .002     | .002-.005           | .003                  | .002-.006                      | .002-.005               |
| Monel                                | 100-160      | .001                  | .003 | .004     | .001                  | .002 | .003 | .004     | .002-.006           | .004                  | .002-.008                      | .002-.006               |

**Table 15b. End Milling (Full Slot) Speed Adjustment Factors for Feed, Depth of Cut, and Lead Angle**

| Cutting Speed, $V = V_{opt} \times F_f \times F_d$ |   |      |      |      |      |      |   |                             |      |                  |      |                 |      |                 |      |                  |      |
|--|---|------|------|------|------|------|---|-----------------------------|------|------------------|------|-----------------|------|-----------------|------|------------------|------|
| Ratio of Chosen Feed to Optimum Feed               | Ratio of the two cutting speeds<br>(average/optimum) given in the tables<br>$V_{avg}/V_{opt}$ |      |      |      |      |      |   | Depth of Cut and Lead Angle |      |                  |      |                 |      |                 |      |                  |      |
|  | 1.00 1.25 1.50 2.00 2.50 3.00 4.00  |      |      |      |      |      |   | 1 in (25.4 mm)              |      | 0.4 in (10.2 mm) |      | 0.2 in (5.1 mm) |      | 0.1 in (2.4 mm) |      | 0.04 in (1.0 mm) |      |
|  |   |      |      |      |      |      |   | 0°                          | 45°  | 0°               | 45°  | 0°              | 45°  | 0°              | 45°  | 0°               | 45°  |
| Feed Factor, $F_f$                                 |   |      |      |      |      |      | Depth of Cut and Lead Angle Factor, $F_d$ |                             |      |                  |      |                 |      |                 |      |                  |      |
| 1.00   | 1.0   | 1.0  | 1.0  | 1.0  | 1.0  | 1.0  | 1.0                                       | 0.91                        | 1.36 | 0.94             | 1.38 | 1.00            | 0.71 | 1.29            | 1.48 | 1.44             | 1.66 |
| 0.90   | 1.00  | 1.06 | 1.09 | 1.14 | 1.18 | 1.21 | 1.27                                      | 0.91                        | 1.33 | 0.94             | 1.35 | 1.00            | 0.72 | 1.26            | 1.43 | 1.40             | 1.59 |
| 0.80   | 1.00  | 1.12 | 1.19 | 1.31 | 1.40 | 1.49 | 1.63                                      | 0.92                        | 1.30 | 0.95             | 1.32 | 1.00            | 0.74 | 1.24            | 1.39 | 1.35             | 1.53 |
| 0.70   | 1.00  | 1.18 | 1.30 | 1.50 | 1.69 | 1.85 | 2.15                                      | 0.93                        | 1.26 | 0.95             | 1.27 | 1.00            | 0.76 | 1.21            | 1.35 | 1.31             | 1.44 |
| 0.60   | 1.00  | 1.20 | 1.40 | 1.73 | 2.04 | 2.34 | 2.89                                      | 0.94                        | 1.22 | 0.96             | 1.25 | 1.00            | 0.79 | 1.18            | 1.28 | 1.26             | 1.26 |
| 0.50   | 1.00  | 1.25 | 1.50 | 2.00 | 2.50 | 3.00 | 4.00                                      | 0.95                        | 1.17 | 0.97             | 1.18 | 1.00            | 0.82 | 1.14            | 1.21 | 1.20             | 1.21 |
| 0.40   | 1.00  | 1.23 | 1.57 | 2.29 | 3.08 | 3.92 | 5.70                                      | 0.96                        | 1.11 | 0.97             | 1.12 | 1.00            | 0.86 | 1.09            | 1.14 | 1.13             | 1.16 |
| 0.30   | 1.00  | 1.14 | 1.56 | 2.57 | 3.78 | 5.19 | 8.56                                      | 0.98                        | 1.04 | 0.99             | 1.04 | 1.00            | 0.91 | 1.04            | 1.07 | 1.05             | 1.09 |
| 0.20   | 1.00  | 0.90 | 1.37 | 2.68 | 4.49 | 6.86 | 17.60                                     | 1.00                        | 0.85 | 1.00             | 0.95 | 1.00            | 0.99 | 0.97            | 0.93 | 0.94             | 0.88 |
| 0.10   | 1.00  | 0.44 | 0.80 | 2.08 | 4.26 | 8.00 | 20.80                                     | 1.05                        | 0.82 | 1.00             | 0.81 | 1.00            | 1.50 | 0.85            | 0.76 | 0.78             | 0.67 |

For HSS (high-speed steel) tool speeds in the first speed column of [Tables 10 through 14](#), use [Table 15a](#) to determine appropriate feeds and depths of cut.

Cutting feeds and speeds for end milling given in [Tables 11 through 14](#) (except those for high-speed steel in the first speed column) are based on milling a 0.20-inch deep full slot (i.e., radial depth of cut = end mill diameter) with a 1-inch diameter, 20-degree helix angle, 0-degree lead angle end mill. For other depths of cut (axial), lead angles, or feed, use the two feed/speed pairs from the tables and calculate the ratio of desired (new) feed to optimum feed (largest of the two feeds are given in the tables), and the ratio of the two cutting speeds ( $V_{avg}/V_{opt}$ ). Find the feed factor  $F_f$  at the intersection of the feed ratio row and the speed ratio column in the left half of the Table. The depth of cut factor  $F_d$  is found in the same row as the feed factor, in the right half of the table under the column corresponding to the depth of cut and lead angle. The adjusted cutting speed can be calculated from  $V = V_{opt} \times F_f \times F_d$ , where  $V_{opt}$  is the smaller (optimum) of the two speeds from the speed table (from the left side of the column containing the two feed/speed pairs). See the text for examples.

If the radial depth of cut is less than the cutter diameter (i.e., for cutting less than a full slot), the feed factor  $F_f$  in the previous equation and the maximum feed  $f_{max}$  must be obtained from [Table 15c](#). The axial depth of cut factor  $F_d$  can then be obtained from this table using  $f_{max}$  in place of the optimum feed in the feed ratio. Also see the footnote to [Table 15c](#).

Table 15c. End, Slit, and Side Milling Speed Adjustment Factors for Radial Depth of Cut

| Ratio of Radial Depth of Cut to Diameter | Cutting Speed, $V = V_{opt} \times F_f \times F_d$ |   |      |      |      |      |       |                           |   |      |      |      |      |       |
|--|--|---|------|------|------|------|-------|---------------------------|---|------|------|------|------|-------|
|  | Maximum Feed/Tooth Factor                          | $V_{avg}/V_{opt}$                                     |      |      |      |      |       | Maximum Feed/Tooth Factor | $V_{avg}/V_{opt}$                                     |      |      |      |      |       |
|  |  | 1.25  | 1.50 | 2.00 | 2.50 | 3.00 | 4.00  |                           | 1.25  | 1.50 | 2.00 | 2.50 | 3.00 | 4.00  |
|  |  | Feed Factor $F_f$ at Maximum Feed per Tooth, $F_{f1}$ |      |      |      |      |       |                           | Feed Factor $F_f$ at Minimum Feed per Tooth, $F_{f2}$ |      |      |      |      |       |
| 1.00                                     | 1.00   | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00  | 0.70                      | 1.18  | 1.30 | 1.50 | 1.69 | 1.85 | 2.15  |
| 0.75                                     | 1.00   | 1.15  | 1.24 | 1.46 | 1.54 | 1.66 | 1.87  | 0.70                      | 1.24  | 1.48 | 1.93 | 2.38 | 2.81 | 3.68  |
| 0.60                                     | 1.00   | 1.23  | 1.40 | 1.73 | 2.04 | 2.34 | 2.89  | 0.70                      | 1.24  | 1.56 | 2.23 | 2.95 | 3.71 | 5.32  |
| 0.50                                     | 1.00   | 1.25  | 1.50 | 2.00 | 2.50 | 3.00 | 4.00  | 0.70                      | 1.20  | 1.58 | 2.44 | 3.42 | 4.51 | 6.96  |
| 0.40                                     | 1.10   | 1.25  | 1.55 | 2.17 | 2.83 | 3.51 | 4.94  | 0.77                      | 1.25  | 1.55 | 2.55 | 3.72 | 5.08 | 8.30  |
| 0.30                                     | 1.35   | 1.20  | 1.57 | 2.28 | 3.05 | 3.86 | 5.62  | 0.88                      | 1.23  | 1.57 | 2.64 | 4.06 | 5.76 | 10.00 |
| 0.20                                     | 1.50   | 1.14  | 1.56 | 2.57 | 3.78 | 5.19 | 8.56  | 1.05                      | 1.40  | 1.56 | 2.68 | 4.43 | 6.37 | 11.80 |
| 0.10                                     | 2.05   | 0.92  | 1.39 | 2.68 | 4.46 | 6.77 | 13.10 | 1.44                      | 0.92  | 1.29 | 2.50 | 4.66 | 7.76 | 17.40 |
| 0.05                                     | 2.90   | 0.68  | 1.12 | 2.50 | 4.66 | 7.75 | 17.30 | 2.00                      | 0.68  | 1.12 | 2.08 | 4.36 | 8.00 | 20.80 |
| 0.02                                     | 4.50   | 0.38  | 0.71 | 1.93 | 4.19 | 7.90 | 21.50 | 3.10                      | 0.38  | 0.70 | 1.38 | 3.37 | 7.01 | 22.20 |

This table is for side milling, end milling when the radial depth of cut (width of cut) is less than the tool diameter (i.e., less than full slot milling), and slit milling when the feed is parallel to the work surface (slotting). The radial depth of cut to diameter ratio is used to determine the recommended maximum and minimum values of feed/tooth, which are found by multiplying the feed/tooth factor from the appropriate column above (maximum or minimum) by  $f_{opt}$  from the speed tables. For example, given two feed/speed pairs  $\frac{7}{15}$  and  $\frac{4}{45}$  for end milling cast, medium-carbon, alloy steel, and a radial depth of cut to diameter ratio  $ar/D$  of 0.10 (a 0.05-inch width of cut for a  $\frac{1}{2}$ -inch diameter end mill, for example), the maximum feed  $f_{max} = 2.05 \times 0.007 = 0.014$  in./tooth and the minimum feed  $f_{min} = 1.44 \times 0.007 = 0.010$  in./tooth. The feed selected should fall in the range between  $f_{min}$  and  $f_{max}$ . The feed factor  $F_f$  is determined by interpolating between the feed factors  $F_{f1}$  and  $F_{f2}$  corresponding to the maximum and minimum feed per tooth, at the appropriate  $ar/D$  and speed ratio. In the example given,  $ar/D = 0.10$  and  $V_{avg}/V_{opt} = 45/15 = 3$ , so the feed factor  $F_{f1}$  at the maximum feed per tooth is 6.77, and the feed factor  $F_{f2}$  at the minimum feed per tooth is 7.76. If a working feed of 0.012 in./tooth is chosen, the feed factor  $F_f$  is half way between 6.77 and 7.76 or by formula,  $F_f = F_{f1} + (\text{feed} - f_{min})/(f_{max} - f_{min}) \times (f_{f2} - f_{f1}) = 6.77 + (0.012 - 0.010)/(0.014 - 0.010) \times (7.76 - 6.77) = 7.27$ . The cutting speed is  $V = V_{opt} \times F_f \times F_d$ , where  $F_d$  is the depth of cut and lead angle factor from Table 15b that corresponds to the feed ratio (chosen feed)/ $f_{max}$ , not the ratio (chosen feed)/optimum feed. For a feed ratio =  $0.012/0.014 = 0.86$  (chosen feed/ $f_{max}$ ), depth of cut = 0.2 inch and lead angle =  $45^\circ$ , the depth of cut factor  $F_d$  in Table 15b is between 0.72 and 0.74. Therefore, the final cutting speed for this example is  $V = V_{opt} \times F_f \times F_d = 15 \times 7.27 \times 0.73 = 80$  ft/min.

**Slit and Side Milling:** This table only applies when feed is parallel to the work surface, as in slotting. If feed is perpendicular to the work surface, as in cutting off, obtain the required speed-correction factor from Table 15d (face milling). The minimum and maximum feeds/tooth for slit and side milling are determined in the manner described above, however, the axial depth of cut factor  $F_d$  is not required. The adjusted cutting speed, valid for cutters of any thickness (width), is given by  $V = V_{opt} \times F_f$ . Examples are given in the text.

**Table 15d. Face Milling Speed Adjustment Factors for Feed, Depth of Cut, and Lead Angle**

| Cutting Speed $V = V_{opt} \times F_f \times F_d \times F_{ar}$ |   |      |      |      |      |      |                            |   |      |                  |      |                 |      |                 |      |                  |                                      |  |      |      |      |      |      |      |
|---|---|------|------|------|------|------|----------------------------|---|------|------------------|------|-----------------|------|-----------------|------|------------------|--------------------------------------|--|------|------|------|------|------|------|
| Ratio of Chosen Feed to Optimum Feed                            | Ratio of the two cutting speeds (average/optimum) given in the tables |      |      |      |      |      |                            | Depth of Cut, inch (mm), and Lead Angle |      |                  |      |                 |      |                 |      |                  |                                      | Ratio of Radial Depth of Cut/Cutter Diameter, $ar/D$ |      |      |      |      |      |      |
|   |   |      |      |      |      |      |                            | 1 in (25.4 mm)                          |      | 0.4 in (10.2 mm) |      | 0.2 in (5.1 mm) |      | 0.1 in (2.4 mm) |      | 0.04 in (1.0 mm) |                                      |  |      |      |      |      |      |      |
|   | $V_{avg}/V_{opt}$   |      |      |      |      |      |                            | 15°                                     | 45°  | 15°              | 45°  | 15°             | 45°  | 15°             | 45°  | 15°              | 45°                                  | $F_{ar}$   |      |      |      |      |      |      |
| Feed Factor, $F_f$  |   |      |      |      |      |      | Depth of Cut Factor, $F_d$ |   |      |                  |      |                 |      |                 |      |                  | Radial Depth of Cut Factor, $F_{ar}$ |  |      |      |      |      |      |      |
| 1.00  | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00                       | 0.78                                    | 1.11 | 0.94             | 1.16 | 0.90            | 1.10 | 1.00            | 1.29 | 1.47             | 1.66                                 | 0.72   | 1.00 | 1.53 | 1.89 | 2.43 | 3.32 | 5.09 |
| 0.90  | 1.00  | 1.02 | 1.05 | 1.07 | 1.09 | 1.10 | 1.12                       | 0.78                                    | 1.10 | 0.94             | 1.16 | 0.90            | 1.09 | 1.00            | 1.27 | 1.45             | 1.58                                 | 0.73   | 1.00 | 1.50 | 1.84 | 2.24 | 3.16 | 4.69 |
| 0.80  | 1.00  | 1.03 | 1.09 | 1.10 | 1.15 | 1.20 | 1.25                       | 0.80                                    | 1.10 | 0.94             | 1.14 | 0.91            | 1.08 | 1.00            | 1.25 | 1.40             | 1.52                                 | 0.75   | 1.00 | 1.45 | 1.73 | 2.15 | 2.79 | 3.89 |
| 0.70  | 1.00  | 1.05 | 1.13 | 1.22 | 1.22 | 1.32 | 1.43                       | 0.81                                    | 1.09 | 0.95             | 1.14 | 0.91            | 1.08 | 1.00            | 1.24 | 1.39             | 1.50                                 | 0.75   | 1.00 | 1.44 | 1.72 | 2.12 | 2.73 | 3.77 |
| 0.60  | 1.00  | 1.08 | 1.20 | 1.25 | 1.35 | 1.50 | 1.66                       | 0.81                                    | 1.09 | 0.95             | 1.13 | 0.92            | 1.08 | 1.00            | 1.23 | 1.38             | 1.48                                 | 0.76   | 1.00 | 1.42 | 1.68 | 2.05 | 2.61 | 3.52 |
| 0.50  | 1.00  | 1.10 | 1.25 | 1.35 | 1.50 | 1.75 | 2.00                       | 0.81                                    | 1.09 | 0.95             | 1.13 | 0.92            | 1.08 | 1.00            | 1.23 | 1.37             | 1.47                                 | 0.76   | 1.00 | 1.41 | 1.66 | 2.02 | 2.54 | 3.39 |
| 0.40  | 1.00  | 1.09 | 1.28 | 1.44 | 1.66 | 2.03 | 2.43                       | 0.82                                    | 1.08 | 0.95             | 1.12 | 0.92            | 1.07 | 1.00            | 1.21 | 1.34             | 1.43                                 | 0.78   | 1.00 | 1.37 | 1.60 | 1.90 | 2.34 | 2.99 |
| 0.30  | 1.00  | 1.06 | 1.32 | 1.52 | 1.85 | 2.42 | 3.05                       | 0.84                                    | 1.07 | 0.96             | 1.11 | 0.93            | 1.06 | 1.00            | 1.18 | 1.30             | 1.37                                 | 0.80   | 1.00 | 1.32 | 1.51 | 1.76 | 2.10 | 2.52 |
| 0.20  | 1.00  | 1.00 | 1.34 | 1.60 | 2.07 | 2.96 | 4.03                       | 0.86                                    | 1.06 | 0.96             | 1.09 | 0.94            | 1.05 | 1.00            | 1.15 | 1.24             | 1.29                                 | 0.82   | 1.00 | 1.26 | 1.40 | 1.58 | 1.79 | 1.98 |
| 0.10  | 1.00  | 0.80 | 1.20 | 1.55 | 2.24 | 3.74 | 5.84                       | 0.90                                    | 1.04 | 0.97             | 1.06 | 0.96            | 1.04 | 1.00            | 1.10 | 1.15             | 1.18                                 | 0.87   | 1.00 | 1.16 | 1.24 | 1.31 | 1.37 | 1.32 |

For HSS (high-speed steel) tool speeds in the first speed column, use Table 15a to determine appropriate feeds and depths of cut.

Tabular feeds and speeds data for face milling in Tables 11 through 14 are based on a 10-tooth, 8-inch diameter face mill, operating with a 15-degree lead angle,  $\frac{3}{64}$ -inch cutter insert nose radius, axial depth of cut = 0.1 inch, and radial depth (width) of cut = 6 inches (i.e., width of cut to cutter diameter ratio =  $\frac{3}{8}$ ). For other depths of cut (radial or axial), lead angles, or feed, calculate the ratio of desired (new) feed to optimum feed (largest of the two feeds given in the speed table), and the ratio of the two cutting speeds ( $V_{avg}/V_{opt}$ ). Use these ratios to find the feed factor  $F_f$  at the intersection of the feed ratio row and the speed ratio column in the left third of the table. The depth of cut factor  $F_d$  is found in the same row as the feed factor, in the center third of the table, in the column corresponding to the depth of cut and lead angle. The radial depth of cut factor  $F_{ar}$  is found in the same row as the feed factor, in the right third of the table, in the column corresponding to the radial depth of cut to cutter diameter ratio  $ar/D$ . The adjusted cutting speed can be calculated from  $V = V_{opt} \times F_f \times F_d \times F_{ar}$ , where  $V_{opt}$  is the smaller (optimum) of the two speeds from the speed table (from the left side of the column containing the two feed/speed pairs).

The cutting speeds as calculated above are valid if the cutter axis is centered above or close to the center line of the workpiece (eccentricity is small). For larger eccentricity (i.e., the cutter axis is offset from the center line of the workpiece by about one-half the cutter diameter or more), use the adjustment factors from Tables 15b and 15c (end and side milling) instead of the factors from this table. Use Table 15e to adjust end and face milling speeds for increased tool life up to 180 minutes.

**Slit and Slot Milling:** Tabular speeds are valid for all tool diameters and widths. Adjustments to the given speeds for other feeds and depths of cut depend on the circumstances of the cut. *Case 1:* If the cutter is fed directly into the workpiece, i.e., the feed is perpendicular to the surface of the workpiece, as in cutting off, then this table (face milling) is used to adjust speeds for other feeds. The depth of cut factor is not used for slit milling ( $F_d = 1.0$ ), so the adjusted cutting speed  $V = V_{opt} \times F_f \times F_{ar}$ . For determining the factor  $F_{ar}$ , the radial depth of cut  $ar$  is the length of cut created by the portion of the cutter engaged in the work. *Case 2:* If the cutter is fed parallel to the surface of the workpiece, as in slotting, then Tables 15b and 15c are used to adjust the given speeds for other feeds. See Fig. 5.

**Table 15e. Tool Life Adjustment Factors for Face Milling, End Milling, Drilling, and Reaming**

| Tool Life, $T$<br>(minutes) | Face Milling with Carbides and Mixed Ceramics |       |       | End Milling with Carbides and HSS |       |       | Twist Drilling and Reaming with HSS |       |       |
|-----------------------------|---|-------|-------|-----------------------------------|-------|-------|-------------------------------------|-------|-------|
|                             | $f_s$   | $f_m$ | $f_l$ | $f_s$                             | $f_m$ | $f_l$ | $f_s$                               | $f_m$ | $f_l$ |
| 15                          | 1.69  | 1.78  | 1.87  | 1.10                              | 1.23  | 1.35  | 1.11                                | 1.21  | 1.30  |
| 45                          | 1.00  | 1.00  | 1.00  | 1.00                              | 1.00  | 1.00  | 1.00                                | 1.00  | 1.00  |
| 90                          | 0.72  | 0.70  | 0.67  | 0.94                              | 0.89  | 0.83  | 0.93                                | 0.89  | 0.85  |
| 180                         | 0.51  | 0.48  | 0.45  | 0.69                              | 0.69  | 0.69  | 0.87                                | 0.80  | 0.72  |

The feeds and speeds given in Tables 11 through 14 and Tables 17 through 23 (except for HSS speeds in the first speed column) are based on a 45-minute tool life. To adjust the given speeds to obtain another tool life, multiply the adjusted cutting speed for the 45-minute tool life  $V_{45}$  by the tool life factor from this table according to the following rules: for small feeds, where feed  $\leq \frac{1}{2}f_{opt}$ , the cutting speed for the desired tool life  $T$  is  $V_T = f_s \times V_{15}$ ; for medium feeds, where  $\frac{1}{2}f_{opt} < \text{feed} < \frac{3}{4}f_{opt}$ ,  $V_T = f_m \times V_{15}$ ; and for larger feeds, where  $\frac{3}{4}f_{opt} \leq \text{feed} \leq f_{opt}$ ,  $V_T = f_l \times V_{15}$ . Here,  $f_{opt}$  is the largest (optimum) feed of the two feed/speed values given in the speed tables or the maximum feed  $f_{max}$  obtained from Table 15c, if that table was used in calculating speed adjustment factors.

**Table 16. Cutting Tool Grade Descriptions and Common Vendor Equivalents**

| Grade Description   | Tool Identification Code | Approximate Vendor Equivalents |            |       |          |
|---------------------|--------------------------|--------------------------------|------------|-------|----------|
|                     |                          | Sandvik Coromant               | Kennametal | Seco  | Valenite |
| Cubic boron nitride | 1                        | CB50                           | KD050      | CBN20 | VC721    |
| Ceramics            | 2                        | CC620                          | K060       | 480   | —        |
|                     | 3                        | CC650                          | K090       | 480   | Q32      |
|                     | 4 (Whiskers)             | CC670                          | KYON2500   | —     | —        |
|                     | 5 (Sialon)               | CC680                          | KYON2000   | 480   | —        |
| Cermets             | 6                        | CC690                          | KYON3000   | —     | Q6       |
|                     | 7                        | CT515                          | KT125      | CM    | VC605    |
| Polycrystalline     | 8                        | CT525                          | KT150      | CR    | VC610    |
|                     | 9                        | CD10                           | KD100      | PAX20 | VC727    |
| Coated carbides     | 10                       | GC-A                           | —          | —     | —        |
|                     | 11                       | GC3015                         | KC910      | TP100 | SV310    |
|                     | 12                       | GC235                          | KC9045     | TP300 | SV235    |
|                     | 13                       | GC4025                         | KC9025     | TP200 | SV325    |
|                     | 14                       | GC415                          | KC950      | TP100 | SV315    |
| Uncoated carbides   | 15                       | H13A                           | K8, K4H    | 883   | VC2      |
|                     | 16                       | S10T                           | K420, K28  | CP20  | VC7      |
|                     | 17                       | S1P                            | K45        | CP20  | VC7      |
|                     | 18                       | S30T                           | —          | CP25  | VC5      |
|                     | 19                       | S6                             | K21, K25   | CP50  | VC56     |
|                     | 20                       | SM30                           | KC710      | CP25  | VC35M    |

See Table 2 on page 779 and the section *Cemented Carbides and Other Hard Materials* for more detailed information on cutting tool grades.

The identification codes in column two correspond to the grade numbers given in the footnotes to Tables 1 to 4b, 6 to 14, and 17 to 23.



**Using the Feed and Speed Tables for Drilling, Reaming, and Threading.**—The first two speed columns in [Tables 17](#) through [23](#) give traditional Handbook speeds for drilling and reaming. The following material can be used for selecting feeds for use with the traditional speeds.

The remaining columns in [Tables 17](#) through [23](#) contain combined feed/speed data for drilling, reaming, and threading, organized in the same manner as in the turning and milling tables. Operating at the given feeds and speeds is expected to result in a tool life of approximately 45 minutes, except for indexable insert drills, which have an expected tool life of approximately 15 minutes per edge. Examples of using this data follow.

Adjustments to HSS drilling speeds for feed and diameter are made using [Table 22](#); [Table 5a](#) is used for adjustments to indexable insert drilling speeds, where one-half the drill diameter  $D$  is used for the depth of cut. Tool life for HSS drills, reamers, and thread chasers and taps may be adjusted using [Table 15e](#) and for indexable insert drills using [Table 5b](#).

The feed for drilling is governed primarily by the size of the drill and by the material to be drilled. Other factors that also affect selection of the feed are the workpiece configuration, the rigidity of the machine tool and the workpiece setup, and the length of the chisel edge. A chisel edge that is too long will result in a very significant increase in the thrust force, which may cause large deflections to occur on the machine tool and drill breakage.

For ordinary twist drills, the feed rate used is 0.001 to 0.003 in./rev for drills smaller than  $\frac{1}{8}$  in, 0.002 to 0.006 in./rev for  $\frac{1}{8}$ - to  $\frac{1}{4}$ -in drills; 0.004 to 0.010 in./rev for  $\frac{1}{4}$ - to  $\frac{1}{2}$ -in drills; 0.007 to 0.015 in./rev for  $\frac{1}{2}$ - to 1-in drills; and, 0.010 to 0.025 in./rev for drills larger than 1 inch.

The lower values in the feed ranges should be used for hard materials such as tool steels, superalloys, and work-hardening stainless steels; the higher values in the feed ranges should be used to drill soft materials such as aluminum and brass.

*Example 1, Drilling:* Determine the cutting speed and feed for use with HSS drills in drilling 1120 steel.

[Table 15a](#) gives two sets of feed and speed parameters for drilling 1120 steel with HSS drills. These sets are 16/50 and 8/95, i.e., 0.016 in./rev feed at 50 ft/min and 0.008 in./rev at 95 fpm, respectively. These feed/speed sets are based on a 0.6-inch diameter drill. Tool life for either of the given feed/speed settings is expected to be approximately 45 minutes.

For different feeds or drill diameters, the cutting speeds must be adjusted and can be determined from  $V = V_{opt} \times F_f \times F_d$ , where  $V_{opt}$  is the minimum speed for this material given in the speed table (50 fpm in this example) and  $F_f$  and  $F_d$  are the adjustment factors for feed and diameter, respectively, found in [Table 22](#).

Table 17. Feeds and Speeds for Drilling, Reaming, and Threading Plain Carbon and Alloy Steels

| Material   | Brinell Hardness | Drilling    | Reaming | Drilling                                     |          |                                 |          | Reaming  |           | Threading |           |           |
|--|------------------|-------------|---------|--|----------|---------------------------------|----------|----------|-----------|-----------|-----------|-----------|
|  |                  | HSS         |         | HSS  |          | Indexable Insert Coated Carbide |          | HSS      |           | HSS       |           |           |
|  |                  | Speed (fpm) |         | f = feed (0.001 in./rev), s = speed (ft/min) |          |                                 |          |          |           |           |           |           |
|  |                  |             |         | Opt.   | Avg.     | Opt.                            | Avg.     | Opt.     | Avg.      | Opt.      | Avg.      |           |
| Free-machining plain carbon steels (Resulfurized):<br>1212, 1213, 1215   | 100–150          | 120         | 80      | f<br>s                                       | 21<br>55 | 11<br>125                       | 8<br>310 | 4<br>620 | 36<br>140 | 18<br>185 | 83<br>140 | 20<br>185 |
|  | 150–200          | 125         | 80      |  |          |                                 |          |          |           |           |           |           |
| (Resulfurized): 1108, 1109, 1115, 1117, 1118, 1120,<br>1126, 1211  | 100–150          | 110         | 75      | f<br>s                                       | 16<br>50 | 8<br>95                         | 8<br>370 | 4<br>740 | 27<br>105 | 14<br>115 | 83<br>90  | 20<br>115 |
|  | 150–200          | 120         | 80      |  |          |                                 |          |          |           |           |           |           |
| (Resulfurized): 1132, 1137, 1139, 1140, 1144, 1146,<br>1151  | 175–225          | 100         | 65      | f<br>s                                       |          |                                 | 8<br>365 | 4<br>735 |           |           |           |           |
|  | 275–325          | 70          | 45      |  |          |                                 |          |          |           |           |           |           |
|  | 325–375          | 45          | 30      |  |          |                                 |          |          |           |           |           |           |
|  | 375–425          | 35          | 20      |  |          |                                 |          |          |           |           |           |           |
| (Leaded): 11L17, 11L18, 12L13, 12L14   | 100–150          | 130         | 85      |  |          |                                 |          |          |           |           |           |           |
|  | 150–200          | 120         | 80      |  |          |                                 |          |          |           |           |           |           |
|  | 200–250          | 90          | 60      | f<br>s                                       |          |                                 | 8<br>365 | 4<br>735 |           |           |           |           |
| Plain carbon steels: 1006, 1008, 1009, 1010, 1012,<br>1015, 1016, 1017, 1018, 1019, 1020, 1021, 1022,<br>1023, 1024, 1025, 1026, 1513, 1514                      | 100–125          | 100         | 65      | f<br>s                                       | 21<br>55 | 11<br>125                       | 8<br>310 | 4<br>620 | 36<br>140 | 18<br>185 | 83<br>140 | 20<br>185 |
|  | 125–175          | 90          | 60      |  |          |                                 |          |          |           |           |           |           |
|  | 175–225          | 70          | 45      | f<br>s                                       |          |                                 | 8<br>365 | 4<br>735 |           |           |           |           |
|  | 225–275          | 60          | 40      |  |          |                                 |          |          |           |           |           |           |
| Plain carbon steels: 1027, 1030, 1033, 1035, 1036,<br>1037, 1038, 1039, 1040, 1041, 1042, 1043, 1045,<br>1046, 1048, 1049, 1050, 1052, 1524, 1526, 1527,<br>1541 | 125–175          | 90          | 60      |  |          |                                 |          |          |           |           |           |           |
|  | 175–225          | 75          | 50      |  |          |                                 |          |          |           |           |           |           |
|  | 225–275          | 60          | 40      | f<br>s                                       |          |                                 | 8<br>365 | 4<br>735 |           |           |           |           |
|  | 275–325          | 50          | 30      |  |          |                                 |          |          |           |           |           |           |
|  | 325–375          | 35          | 20      |  |          |                                 |          |          |           |           |           |           |
| 375–425  | 25               | 15          |         |  |          |                                 |          |          |           |           |           |           |

Table 17. (Continued) Feeds and Speeds for Drilling, Reaming, and Threading Plain Carbon and Alloy Steels

| Material  | Brinell Hardness | Drilling    | Reaming | Drilling                                     |      |                                 |      | Reaming |      | Threading |      |     |
|---|------------------|-------------|---------|--|------|---------------------------------|------|---------|------|-----------|------|-----|
|   |                  | HSS         |         | HSS  |      | Indexable Insert Coated Carbide |      | HSS     |      | HSS       |      |     |
|   |                  | Speed (fpm) |         | f = feed (0.001 in./rev), s = speed (ft/min) |      |                                 |      |         |      |           |      |     |
|   |                  | Opt.        | Avg.    | Opt.   | Avg. | Opt.                            | Avg. | Opt.    | Avg. | Opt.      | Avg. |     |
| Plain carbon steels (Continued): 1055, 1060, 1064, 1065, 1070, 1074, 1078, 1080, 1084, 1086, 1090, 1095, 1548, 1551, 1552, 1561, 1566   | 125-175          | 85          | 55      | f  | 16   | 8                               | 8    | 4       | 27   | 14        | 83   | 20  |
|   | 175-225          | 70          | 45      | s  | 50   | 95                              | 370  | 740     | 105  | 115       | 90   | 115 |
|   | 225-275          | 50          | 30      | f  |      |                                 | 8    | 4       |      |           |      |     |
|   |                  |             |         | s  |      |                                 | 365  | 735     |      |           |      |     |
|   | 275-325          | 40          | 25      |  |      |                                 |      |         |      |           |      |     |
| 325-375   | 30               | 20          |         |  |      |                                 |      |         |      |           |      |     |
| 375-425   | 15               | 10          |         |  |      |                                 |      |         |      |           |      |     |
| Free-machining alloy steels (Resulfurized): 4140, 4150  | 175-200          | 90          | 60      | f  | 16   | 8                               | 8    | 4       | 26   | 13        | 83   | 20  |
|   | 200-250          | 80          | 50      | s  | 75   | 140                             | 410  | 685     | 150  | 160       | 125  | 160 |
|   | 250-300          | 55          | 30      | f  |      |                                 | 8    | 4       |      |           |      |     |
|   |                  |             |         | s  |      |                                 | 355  | 600     |      |           |      |     |
|   | 300-375          | 40          | 25      | f  |      |                                 | 8    | 4       |      |           |      |     |
| 375-425   | 30               | 15          | s       |  |      | 310                             | 525  |         |      |           |      |     |
| (Leaded): 41L30, 41L40, 41L47, 41L50, 43L47, 51L32, 52L100, 86L20, 86L40  | 150-200          | 100         | 65      | f  | 16   | 8                               | 8    | 4       | 27   | 14        | 83   | 20  |
|   | 200-250          | 90          | 60      | s  | 50   | 95                              | 370  | 740     | 105  | 115       | 90   | 115 |
|   | 250-300          | 65          | 40      | f  |      |                                 | 8    | 4       |      |           |      |     |
|   |                  |             |         | s  |      |                                 | 365  | 735     |      |           |      |     |
|   | 300-375          | 45          | 30      |  |      |                                 |      |         |      |           |      |     |
| 375-425   | 30               | 15          |         |  |      |                                 |      |         |      |           |      |     |
| Alloy steels: 4012, 4023, 4024, 4028, 4118, 4320, 4419, 4422, 4427, 4615, 4620, 4621, 4626, 4718, 4720, 4815, 4817, 4820, 5015, 5117, 5120, 6118, 8115, 8615, 8617, 8620, 8622, 8625, 8627, 8720, 8822, 94B17 | 125-175          | 85          | 55      | f  | 16   | 8                               | 8    | 4       | 26   | 13        | 83   | 20  |
|   | 175-225          | 70          | 45      | s  | 75   | 140                             | 410  | 685     | 150  | 160       | 125  | 160 |
|   | 225-275          | 55          | 35      | f  |      |                                 | 8    | 4       |      |           |      |     |
|   |                  |             |         | s  |      |                                 | 355  | 600     |      |           |      |     |
|   | 275-325          | 50          | 30      | f  | 11   | 6                               | 8    | 4       | 19   | 10        | 83   | 20  |
|   |                  |             | s       | 50   | 85   | 335                             | 570  | 95      | 135  | 60        | 95   |     |
| 325-375   | 35               | 25          | f       |  |      | 8                               | 4    |         |      |           |      |     |
| 375-425   | 25               | 15          | s       |  |      | 310                             | 525  |         |      |           |      |     |

Table 17. (Continued) Feeds and Speeds for Drilling, Reaming, and Threading Plain Carbon and Alloy Steels

| Material  | Brinell Hardness   | Drilling           | Reaming            | Drilling                                     |          |                                 |          | Reaming  |           | Threading |           |           |
|---|--------------------|--------------------|--------------------|--|----------|---------------------------------|----------|----------|-----------|-----------|-----------|-----------|
|   |                    | HSS                |                    | HSS  |          | Indexable Insert Coated Carbide |          | HSS      |           | HSS       |           |           |
|   |                    | Speed (fpm)        |                    | f = feed (0.001 in./rev), s = speed (ft/min) |          |                                 |          |          |           |           |           |           |
|   |                    | Opt.               | Avg.               | Opt.   | Avg.     | Opt.                            | Avg.     | Opt.     | Avg.      | Opt.      | Avg.      |           |
| Alloy steels: 1330, 1335, 1340, 1345, 4032, 4037, 4042, 4047, 4130, 4135, 4137, 4140, 4142, 4145, 4147, 4150, 4161, 4337, 4340, 50B44, 50B46, 50B50, 50B60, 5130, 5132, 5140, 5145, 5147, 5150, 5160, 51B60, 6150, 81B45, 8630, 8635, 8637, 8640, 8642, 8645, 8650, 8655, 8660, 8740, 9254, 9255, 9260, 9262, 94B30<br>E51100, E52100: use (HSS speeds) | 175–225            | 75 (60)            | 50 (40)            | f<br>s                                       | 16<br>75 | 8<br>140                        | 8<br>410 | 4<br>685 | 26<br>150 | 13<br>160 | 83<br>125 | 20<br>160 |
|   | 225–275            | 60 (50)            | 40 (30)            | f<br>s                                       |          |                                 | 8<br>355 | 4<br>600 |           |           |           |           |
|   | 275–325            | 45 (35)            | 30 (25)            | f<br>s                                       | 11<br>50 | 6<br>85                         | 8<br>335 | 4<br>570 | 19<br>95  | 10<br>135 | 83<br>60  | 20<br>95  |
|   | 325–375<br>375–425 | 30 (30)<br>20 (20) | 15 (20)<br>15 (10) | f<br>s                                       |          |                                 | 8<br>310 | 4<br>525 |           |           |           |           |
| Ultra-high-strength steels (not AISI): AMS 6421 (98B37 Mod.), 6422 (98BV40), 6424, 6427, 6428, 6430, 6432, 6433, 6434, 6436, and 6442; 300M, D6ac   | 220–300            | 50                 | 30                 | f<br>s                                       |          |                                 | 8<br>325 | 4<br>545 |           |           |           |           |
|   | 300–350            | 35                 | 20                 | f<br>s                                       |          |                                 | 8<br>270 | 4<br>450 |           |           |           |           |
|   | 350–400            | 20                 | 10                 | f<br>s                                       |          |                                 | 8<br>325 | 4<br>545 |           |           |           |           |
| Maraging steels (not AISI): 18% Ni Grade 200, 250, 300, and 350   | 250–325            | 50                 | 30                 | f<br>s                                       |          |                                 | 8<br>325 | 4<br>545 |           |           |           |           |
| Nitriding steels (not AISI): Nitralloy 125, 135, 135 Mod., 225, and 230, Nitralloy N, Nitralloy EZ, Nitrex I  | 200–250            | 60                 | 40                 | f<br>s                                       | 16<br>75 | 8<br>140                        | 8<br>410 | 4<br>685 | 26<br>150 | 13<br>160 | 83<br>125 | 20<br>160 |
|   | 300–350            | 35                 | 20                 | f<br>s                                       |          |                                 | 8<br>310 | 4<br>525 |           |           |           |           |

The two leftmost speed columns in this table contain traditional Handbook speeds for drilling and reaming with HSS steel tools. The section Feed Rates for Drilling and Reaming contains useful information concerning feeds to use in conjunction with these speeds.

**HSS Drilling and Reaming:** The combined feed/speed data for drilling are based on a 0.60-inch diameter HSS drill with standard drill point geometry (2-flute with  $118^\circ$  tip angle). Speed adjustment factors in Table 22 are used to adjust drilling speeds for other feeds and drill diameters. Examples of using this data are given in the text. The given feeds and speeds for reaming are based on an 8-tooth,  $\frac{25}{32}$ -inch diameter,  $30^\circ$  lead angle reamer, and a 0.008-inch radial depth of cut. For other feeds, the correct speed can be obtained by interpolation using the given speeds if the desired feed lies in the recommended range (between the given values of *optimum* and *average* feed). If a feed lower than the given *average* value is chosen, the speed should be maintained at the corresponding *average* speed (i.e., the highest of the two speed values given). The cutting speeds for reaming do not require adjustment for tool diameters for standard ratios of radial depth of cut to reamer diameter (i.e.,  $f_d = 1.00$ ). Speed adjustment factors to modify tool life are found in Table 15c.

**Indexable Insert Drilling:** The feed/speed data for indexable insert drilling are based on a tool with two cutting edges, an insert nose radius of  $\frac{3}{64}$  inch, a 10-degree lead angle, and diameter  $D = 1$  inch. Adjustments to cutting speed for feed and depth of cut are made using Table 5a Adjustment Factors) using a depth of cut of  $D/2$ , or one-half the drill diameter. Expected tool life at the given feeds and speeds is approximately 15 minutes for short hole drilling (i.e., where maximum hole depth is about  $2D$  or less). Speed adjustment factors to increase tool life are found in Table 5b.

**Tapping and Threading:** The data in this column are intended for use with thread chasers and for tapping. The feed used for tapping and threading must be equal to the lead (feed = lead = pitch) of the thread being cut. The two feed/speed pairs given for each material, therefore, are representative speeds for two thread pitches, 12 and 50 threads per inch ( $1/0.083 = 12$ , and  $1/0.020 = 50$ ). Tool life is expected to be approximately 45 minutes at the given feeds and speeds. When cutting fewer than 12 threads per inch (pitch  $\geq 0.08$  inch), use the lower (*optimum*) speed; for cutting more than 50 threads per inch (pitch  $\leq 0.02$  inch), use the larger (*average*) speed; and, in the intermediate range between 12 and 50 threads per inch, interpolate between the given *average* and *optimum* speeds.

The combined feed/speed data in this table are based on tool grades (identified in Table 16) as follows: coated carbide = 10.

**Example 2, Drilling:** If the 1120 steel of Example 1 is to be drilled with a 0.60-inch drill at a feed of 0.012 in./rev, what is the cutting speed in ft/min? Also, what spindle rpm of the drilling machine is required to obtain this cutting speed?

To find the feed factor  $F_d$  in Table 22, calculate the ratio of the desired feed to the *optimum* feed and the ratio of the two cutting speeds given in the speed tables. The desired feed is 0.012 in./rev and the *optimum* feed, as explained above is 0.016 in./rev, therefore,  $\text{feed}/f_{opt} = 0.012/0.016 = 0.75$  and  $V_{avg}/V_{opt} = 95/50 = 1.9$ , approximately 2.

The feed factor  $F_f$  is found at the intersection of the feed ratio row and the speed ratio column.  $F_f = 1.40$  corresponds to about halfway between 1.31 and 1.50, which are the feed factors that correspond to  $V_{avg}/V_{opt} = 2.0$  and  $\text{feed}/f_{opt}$  ratios of 0.7 and 0.8, respectively.  $F_d$ , the diameter factor, is found on the same row as the feed factor (halfway between the 0.7 and 0.8 rows, for this example) under the column for drill diameter = 0.60 inch. Because the speed table values are based on a 0.60-inch drill diameter,  $F_d = 1.0$  for this example, and the cutting speed is  $V = V_{opt} \times F_f \times F_d = 50 \times 1.4 \times 1.0 = 70$  ft/min. The spindle speed in rpm is  $N = 12 \times V/(\pi \times D) = 12 \times 70/(3.14 \times 0.6) = 445$  rpm.

**Example 3, Drilling:** Using the same material and feed as in the previous example, what cutting speeds are required for 0.079-inch and 4-inch diameter drills? What machine rpm is required for each?

Because the feed is the same as in the previous example, the feed factor is  $F_f = 1.40$  and does not need to be recalculated. The diameter factors are found in Table 22 on the same row as the feed factor for the previous example (about halfway between the diameter factors corresponding to  $\text{feed}/f_{opt}$  values of 0.7 and 0.8) in the column corresponding to drill diameters 0.079 and 4.0 inches, respectively. Results of the calculations are summarized below.

| <i>Drill diameter = 0.079 inch</i>              | <i>Drill diameter = 4.0 inches</i>          |
|---|---|
| $F_f = 1.40$                                    | $F_f = 1.40$                                |
| $F_d = (0.34 + 0.38)/2 = 0.36$                  | $F_d = (1.95 + 1.73)/2 = 1.85$              |
| $V = 50 \times 1.4 \times 0.36 = 25.2$ fpm      | $V = 50 \times 1.4 \times 1.85 = 129.5$ fpm |
| $12 \times 25.2/(3.14 \times 0.079) = 1219$ rpm | $12 \times 129.5/(3.14 \times 4) = 124$ rpm |

*Drilling Difficulties:* A drill split at the web is evidence of too much feed or insufficient lip clearance at the center due to improper grinding. Rapid wearing away of the extreme outer corners of the cutting edges indicates that the speed is too high. A drill chipping or breaking out at the cutting edges indicates that either the feed is too heavy or the drill has been ground with too much lip clearance. Nothing will "check" a high-speed steel drill quicker than to turn a stream of cold water on it after it has been heated while in use. It is equally bad to plunge it in cold water after the point has been heated in grinding. The small checks or cracks resulting from this practice will eventually chip out and cause rapid wear or breakage. Insufficient speed in drilling small holes with hand feed greatly increases the risk of breakage, especially at the moment the drill is breaking through the farther side of the work, due to the operator's inability to gage the feed when the drill is running too slowly.

Small drills have heavier webs and smaller flutes in proportion to their size than do larger drills, so breakage due to clogging of chips in the flutes is more likely to occur. When drilling holes deeper than three times the diameter of the drill, it is advisable to withdraw the drill (peck feed) at intervals to remove the chips and permit coolant to reach the tip of the drill.

*Drilling Holes in Glass:* The simplest method of drilling holes in glass is to use a standard, tungsten-carbide-tipped masonry drill of the appropriate diameter, in a gun-drill. The edges of the carbide in contact with the glass should be sharp. Kerosene or other liquid may be used as a lubricant, and a light force is maintained on the drill until just before the point breaks through. The hole should then be started from the other side if possible, or a very light force applied for the remainder of the operation, to prevent excessive breaking of material from the sides of the hole. As the hard particles of glass are abraded, they accumulate and act to abrade the hole, so it may be advisable to use a slightly smaller drill than the required diameter of the finished hole.

Alternatively, for holes of medium and large size, use brass or copper tubing, having an outside diameter equal to the size of hole required. Revolve the tube at a peripheral speed of about 100 feet per minute, and use carborundum (80 to 100 grit) and light machine oil between the end of the pipe and the glass. Insert the abrasive under the drill with a thin piece of soft wood, to avoid scratching the glass. The glass should be supported by a felt or rubber cushion, not much larger than the hole to be drilled. If practicable, it is advisable to drill about halfway through, then turn the glass over, and drill down to meet the first cut. Any fin that may be left in the hole can be removed with a round second-cut file wetted with turpentine.

Smaller-diameter holes may also be drilled with triangular-shaped cemented carbide drills that can be purchased in standard sizes. The end of the drill is shaped into a long tapering triangular point. The other end of the cemented carbide bit is brazed onto a steel shank. A glass drill can be made to the same shape from hardened drill rod or an old three-cornered file. The location at which the hole is to be drilled is marked on the workpiece. A dam of putty or glazing compound is built up on the work surface to contain the cutting fluid, which can be either kerosene or turpentine mixed with camphor. Chipping on the back edge of the hole can be prevented by placing a scrap plate of glass behind the area to be drilled and drilling into the backup glass. This procedure also provides additional support to the workpiece and is essential for drilling very thin plates. The hole is usually drilled with an electric hand drill. When the hole is being produced, the drill should be given a small circular motion using the point as a fulcrum, thereby providing a clearance for the drill in the hole.

Very small round or intricately shaped holes and narrow slots can be cut in glass by the ultrasonic machining process or by the abrasive jet cutting process.

Table 18. Feeds and Speeds for Drilling, Reaming, and Threading Tool Steels

| Material   | Brinell Hardness   | Drilling       |          | Reaming                                      |          | Drilling                             |          |          |          | Reaming  |          | Threading |      |
|--|--------------------|----------------|----------|--|----------|--------------------------------------|----------|----------|----------|----------|----------|-----------|------|
|  |                    | HSS            |          | HSS  |          | Indexable Insert<br>Uncoated Carbide |          | HSS      |          | HSS      |          | HSS       |      |
|  |                    | Speed<br>(fpm) |          | f = feed (0.001 in./rev), s = speed (ft/min) |          |                                      |          |          |          |          |          |           |      |
|  |                    | Opt.           | Avg.     | Opt.   | Avg.     | Opt.                                 | Avg.     | Opt.     | Avg.     | Opt.     | Avg.     | Opt.      | Avg. |
| Water hardening: W1, W2, W5  | 150–200            | 85             | 55       |  |          |                                      |          |          |          |          |          |           |      |
| Shock resisting: S1, S2, S5, S6, S7                                    | 175–225            | 50             | 35       |  |          |                                      |          |          |          |          |          |           |      |
| Cold work (oil hardening): O1, O2, O6, O7                              | 175–225            | 45             | 30       |  |          |                                      |          |          |          |          |          |           |      |
| (High carbon, high chromium): D2, D3, D4, D5, D7                       | 200–250            | 30             | 20       | f<br>s                                       | 15<br>45 | 7<br>85                              | 8<br>360 | 4<br>605 | 24<br>90 | 12<br>95 | 83<br>75 | 20<br>95  |      |
| (Air hardening): A2, A3, A8, A9, A10                                   | 200–250            | 50             | 35       |  |          |                                      |          |          |          |          |          |           |      |
| A4, A6   | 200–250            | 45             | 30       |  |          |                                      |          |          |          |          |          |           |      |
| A7   | 225–275            | 30             | 20       |  |          |                                      |          |          |          |          |          |           |      |
|  |                    |                |          |  |          |                                      |          |          |          |          |          |           |      |
| Hot work (chromium type): H10, H11, H12, H13, H14, H19                 | 150–200<br>200–250 | 60<br>50       | 40<br>30 | f<br>s                                       |          |                                      | 8<br>270 | 4<br>450 |          |          |          |           |      |
| (Tungsten type): H21, H22, H23, H24, H25, H26                          | 150–200<br>200–250 | 55<br>40       | 35<br>25 | f<br>s                                       | 15<br>45 | 7<br>85                              | 8<br>360 | 4<br>605 | 24<br>90 | 12<br>95 | 83<br>75 | 20<br>95  |      |
| (Molybdenum type): H41, H42, H43                                       | 150–200<br>200–250 | 45<br>35       | 30<br>20 |  |          |                                      |          |          |          |          |          |           |      |
| Special-purpose, low alloy: L2, L3, L6                                 | 150–200            | 60             | 40       |  |          |                                      |          |          |          |          |          |           |      |
| Mold steel: P2, P3, P4, P5, P6P20, P21                                 | 100–150<br>150–200 | 75<br>60       | 50<br>40 | f<br>s                                       | 15<br>45 | 7<br>85                              | 8<br>360 | 4<br>605 | 24<br>90 | 12<br>95 | 83<br>75 | 20<br>95  |      |
| High-speed steel: M1, M2, M6, M10, T1, T2, T6                          | 200–250            | 45             | 30       | f<br>s                                       | 15<br>45 | 7<br>85                              | 8<br>360 | 4<br>605 | 24<br>90 | 12<br>95 | 83<br>75 | 20<br>95  |      |
| M3-1, M4, M7, M30, M33, M34, M36, M41, M42, M43, M44, M46, M47, T5, T8 | 225–275            | 35             | 20       |  |          |                                      |          |          |          |          |          |           |      |
| T15, M3-2  | 225–275            | 25             | 15       |  |          |                                      |          |          |          |          |          |           |      |

See the footnote to Table 17 for instructions concerning the use of this table. The combined feed/speed data in this table are based on tool grades (identified in Table 16) as follows: coated carbide = 10.

**Table 19. Feeds and Speeds for Drilling, Reaming, and Threading Stainless Steels**

| Material  | Brinell Hardness | Drilling    | Reaming | Drilling                                     |         |                                 |          | Reaming  |          | Threading |          |
|---|------------------|-------------|---------|--|---------|---------------------------------|----------|----------|----------|-----------|----------|
|   |                  | HSS         |         | HSS  |         | Indexable Insert Coated Carbide |          | HSS      |          | HSS       |          |
|   |                  | Speed (fpm) |         | f = feed (0.001 in./rev), s = speed (ft/min) |         |                                 |          |          |          |           |          |
|   |                  | Opt.        | Avg.    | Opt.   | Avg.    | Opt.                            | Avg.     | Opt.     | Avg.     | Opt.      | Avg.     |
| Free-machining stainless steels (Ferritic): 430F, 430FSe  | 135–185          | 90          | 60      | f 15<br>s 25                                 | 7<br>45 | 8<br>320                        | 4<br>540 | 24<br>50 | 12<br>50 | 83<br>40  | 20<br>51 |
| (Austenitic): 203EZ, 303, 303Se, 303MA, 303Pb, 303Cu, 303 Plus X  | 135–185          | 85          | 55      | f 15<br>s 20                                 | 7<br>40 | 8<br>250                        | 4<br>425 | 24<br>40 | 12<br>40 | 83<br>35  | 20<br>45 |
|   | 225–275          | 70          | 45      |  |         |                                 |          |          |          |           |          |
| (Martensitic): 416, 416Se, 416 Plus X, 420F, 420FSe, 440F, 440FSe   | 135–185          | 90          | 60      |  |         |                                 |          |          |          |           |          |
|   | 185–240          | 70          | 45      |  |         |                                 |          |          |          |           |          |
|   | 275–325          | 40          | 25      |  |         |                                 |          |          |          |           |          |
|   | 375–425          | 20          | 10      |  |         |                                 |          |          |          |           |          |
| Stainless steels (Ferritic): 405, 409, 429, 430, 434  | 135–185          | 65          | 45      | f 15<br>s 25                                 | 7<br>45 | 8<br>320                        | 4<br>540 | 24<br>50 | 12<br>50 | 83<br>40  | 20<br>51 |
| (Austenitic): 201, 202, 301, 302, 304, 304L, 305, 308, 321, 347, 348  | 135–185          | 55          | 35      | f 15<br>s 20                                 | 7<br>40 | 8<br>250                        | 4<br>425 | 24<br>40 | 12<br>40 | 83<br>35  | 20<br>45 |
|   | 225–275          | 50          | 30      |  |         |                                 |          |          |          |           |          |
| (Austenitic): 302B, 309, 309S, 310, 310S, 314, 316  | 135–185          | 50          | 30      |  |         |                                 |          |          |          |           |          |
|   | 135–175          | 75          | 50      |  |         |                                 |          |          |          |           |          |
|   | 175–225          | 65          | 45      |  |         |                                 |          |          |          |           |          |
|   | 275–325          | 40          | 25      |  |         |                                 |          |          |          |           |          |
| (Martensitic): 403, 410, 420, 501   | 375–425          | 25          | 15      |  |         |                                 |          |          |          |           |          |
|   | 225–275          | 50          | 30      |  |         |                                 |          |          |          |           |          |
|   | 275–325          | 40          | 25      |  |         |                                 |          |          |          |           |          |
| (Martensitic): 414, 431, Greek Ascoloy  | 375–425          | 25          | 15      |  |         |                                 |          |          |          |           |          |
|   | 225–275          | 45          | 30      |  |         |                                 |          |          |          |           |          |
|   | 275–325          | 40          | 25      |  |         |                                 |          |          |          |           |          |
| (Martensitic): 440A, 440B, 440C   | 375–425          | 25          | 15      |  |         |                                 |          |          |          |           |          |
|   | 225–275          | 45          | 30      |  |         |                                 |          |          |          |           |          |
|   | 275–325          | 40          | 25      |  |         |                                 |          |          |          |           |          |
| (Precipitation hardening): 15–5PH, 17–4PH, 17–7PH, AF–71, 17–14CuMo, AFC–77, AM–350, AM–355, AM–362, Custom 455, HNM, PH13–8, PH14–8Mo, PH15–7Mo, Stainless W | 150–200          | 50          | 30      | f 15<br>s 20                                 | 7<br>40 | 8<br>250                        | 4<br>425 | 24<br>40 | 12<br>40 | 83<br>35  | 20<br>45 |
|   | 275–325          | 45          | 25      |  |         |                                 |          |          |          |           |          |
|   | 325–375          | 35          | 20      |  |         |                                 |          |          |          |           |          |
|   | 375–450          | 20          | 10      |  |         |                                 |          |          |          |           |          |

See the footnote to [Table 17](#) for instructions concerning the use of this table. The combined feed/speed data in this table are based on tool grades (identified in [Table 16](#)) as follows: coated carbide = 10.



Table 20. Feeds and Speeds for Drilling, Reaming, and Threading Ferrous Cast Metals

| Material  | Brinell Hardness | Drilling    |      | Reaming                                      |      | Drilling                 |      |        |      | Reaming |      | Threading |      |    |
|---|------------------|-------------|------|--|------|--------------------------|------|--------|------|---------|------|-----------|------|----|
|   |                  | HSS         |      | HSS  |      | Indexable Carbide Insert |      |        |      | HSS     |      | HSS       |      |    |
|   |                  |             |      |  |      | Uncoated                 |      | Coated |      |         |      |           |      |    |
|   |                  | Speed (fpm) |      | f = feed (0.001 in./rev), s = speed (ft/min) |      |                          |      |        |      |         |      |           |      |    |
|   |                  | Opt.        | Avg. | Opt.   | Avg. | Opt.                     | Avg. | Opt.   | Avg. | Opt.    | Avg. | Opt.      | Avg. |    |
| ASTM Class 20   | 120–150          | 100         | 65   |  |      |                          |      |        |      |         |      |           |      |    |
| ASTM Class 25   | 160–200          | 90          | 60   | f  | 16   | 8                        | 11   | 6      | 11   | 6       | 26   | 13        | 83   | 20 |
| ASTM Class 30, 35, and 40                             | 190–220          | 80          | 55   | s  | 80   | 90                       | 85   | 180    | 235  | 485     | 85   | 65        | 90   | 80 |
| ASTM Class 45 and 50                                  | 220–260          | 60          | 40   | f  | 13   | 6                        | 11   | 6      | 11   | 6       | 21   | 10        | 83   | 20 |
| ASTM Class 55 and 60                                  | 250–320          | 30          | 20   | s  | 50   | 50                       | 70   | 150    | 195  | 405     | 50   | 30        | 55   | 45 |
| ASTM Type 1, 1b, 5 (Ni resist)                        | 100–215          | 50          | 30   |  |      |                          |      |        |      |         |      |           |      |    |
| ASTM Type 2, 3, 6 (Ni resist)                         | 120–175          | 40          | 25   |  |      |                          |      |        |      |         |      |           |      |    |
| ASTM Type 2b, 4 (Ni resist)                           | 150–250          | 30          | 20   |  |      |                          |      |        |      |         |      |           |      |    |
| Malleable Iron  |                  |             |      |  |      |                          |      |        |      |         |      |           |      |    |
| (Ferritic): 32510, 35018                              | 110–160          | 110         | 75   | f  | 19   | 10                       |      |        | 11   | 6       | 30   | 16        | 83   | 20 |
|   |                  |             |      | s  | 80   | 100                      |      |        | 270  | 555     | 95   | 80        | 100  | 85 |
| (Pearlitic): 40010, 43010, 45006, 45008, 48005, 50005 | 160–200          | 80          | 55   | f  | 14   | 7                        | 11   | 6      | 11   | 6       | 22   | 11        | 83   | 20 |
|   | 200–240          | 70          | 45   | s  | 65   | 65                       | 85   | 180    | 235  | 485     | 65   | 45        | 70   | 60 |
| (Martensitic): 53004, 60003, 60004                    | 200–255          | 55          | 35   |  |      |                          |      |        |      |         |      |           |      |    |
| (Martensitic): 70002, 70003                           | 220–260          | 50          | 30   |  |      |                          |      |        |      |         |      |           |      |    |
| (Martensitic): 80002                                  | 240–280          | 45          | 30   |  |      |                          |      |        |      |         |      |           |      |    |
| (Martensitic): 90001                                  | 250–320          | 25          | 15   |  |      |                          |      |        |      |         |      |           |      |    |
| Nodular (Ductile) Iron                                |                  |             |      |  |      |                          |      |        |      |         |      |           |      |    |
| (Ferritic): 60-40-18, 65-45-12                        | 140–190          | 100         | 65   | f  | 17   | 9                        | 11   | 6      | 11   | 6       | 28   | 14        | 83   | 20 |
|   |                  |             |      | s  | 70   | 80                       | 85   | 180    | 235  | 485     | 80   | 60        | 80   | 70 |

**Table 20. (Continued) Feeds and Speeds for Drilling, Reaming, and Threading Ferrous Cast Metals**

| Material  | Brinell Hardness | Drilling    | Reaming | Drilling                                     |      |                          |      |        |      | Reaming |      | Threading |      |    |
|---|------------------|-------------|---------|--|------|--------------------------|------|--------|------|---------|------|-----------|------|----|
|   |                  | HSS         |         | HSS  |      | Indexable Carbide Insert |      |        |      | HSS     |      | HSS       |      |    |
|   |                  |             |         |  |      | Uncoated                 |      | Coated |      |         |      |           |      |    |
|   |                  | Speed (fpm) |         | f = feed (0.001 in./rev), s = speed (ft/min) |      |                          |      |        |      |         |      |           |      |    |
|   |                  | Opt.        | Avg.    | Opt.   | Avg. | Opt.                     | Avg. | Opt.   | Avg. | Opt.    | Avg. | Opt.      | Avg. |    |
| (Martensitic): 120-90-02<br>(Ferritic-Pearlitic): 80-55-06<br>(Pearlitic-Martensitic): 100-70-03  | 270-330          | 25          | 15      |  |      |                          |      |        |      |         |      |           |      |    |
|   | 330-400          | 10          | 5       |  |      |                          |      |        |      |         |      |           |      |    |
|   | 190-225          | 70          | 45      | f  | 13   | 6                        | 11   | 6      | 11   | 6       | 21   | 11        | 83   | 20 |
|   | 225-260          | 50          | 30      | s  | 60   | 60                       | 70   | 150    | 195  | 405     | 55   | 40        | 60   | 55 |
|   | 240-300          | 40          | 25      |  |      |                          |      |        |      |         |      |           |      |    |
| Cast Steels   |                  |             |         |  |      |                          |      |        |      |         |      |           |      |    |
| (Low carbon): 1010, 1020<br>(Medium carbon): 1030, 1040, 1050<br>(Low-carbon alloy): 1320, 2315, 2320, 4110, 4120, 4320, 8020, 8620<br>(Medium-carbon alloy): 1330, 1340, 2325, 2330, 4125, 4130, 4140, 4330, 4340, 8030, 80B30, 8040, 8430, 8440, 8630, 8640, 9525, 9530, 9535 | 100-150          | 100         | 65      | f  | 18   | 9                        |      |        |      |         | 29   | 15        | 83   | 20 |
|   | 125-175          | 90          | 60      | s  | 35   | 70                       |      |        |      |         | 75   | 85        | 65   | 85 |
|   | 175-225          | 70          | 45      | f  | 15   | 7                        |      |        | 8    | 4       | 24   | 12        | 83   | 20 |
|   | 225-300          | 55          | 35      | s  | 35   | 60                       |      |        | 195† | 475     | 65   | 70        | 55   | 70 |
|   | 150-200          | 75          | 50      |  |      |                          |      |        |      |         |      |           |      |    |
|   | 200-250          | 65          | 40      |  |      |                          |      |        |      |         |      |           |      |    |
|   | 250-300          | 50          | 30      |  |      |                          |      |        |      |         |      |           |      |    |
|   | 175-225          | 70          | 45      | f  |      |                          |      | 8      | 4    |         |      |           |      |    |
|   | 225-250          | 60          | 35      | s  |      |                          |      | 130†   | 315  |         |      |           |      |    |
|   | 250-300          | 45          | 30      |  |      |                          |      |        |      |         |      |           |      |    |
|   | 300-350          | 30          | 20      |  |      |                          |      |        |      |         |      |           |      |    |
|   | 350-400          | 20          | 10      |  |      |                          |      |        |      |         |      |           |      |    |

See the footnote to Table 17 for instructions concerning the use of this table. The combined feed/speed data in this table are based on tool grades (identified in Table 16) as follows: uncoated = 15; coated carbide = 11, † = 10.

**Table 21. Feeds and Speeds for Drilling, Reaming, and Threading Light Metals**

| Material  | Brinell Hardness  | Drilling       |      | Reaming                                      |                        | Drilling                             |            |            |           | Reaming   |           | Threading |           |
|---|-------------------|----------------|------|--|------------------------|--------------------------------------|------------|------------|-----------|-----------|-----------|-----------|-----------|
|   |                   | HSS            |      | HSS  |                        | Indexable Insert<br>Uncoated Carbide |            | HSS        |           | HSS       |           | HSS       |           |
|   |                   | Speed<br>(fpm) |      | f = feed (0.001 in./rev), s = speed (ft/min) |                        |                                      |            |            |           |           |           |           |           |
|   |                   | Opt.           | Avg. | Opt.   | Avg.                   | Opt.                                 | Avg.       | Opt.       | Avg.      | Opt.      | Avg.      | Opt.      | Avg.      |
| All wrought aluminum alloys, 6061-T651, 5000, 6000, 7000 series | CD                | 400            | 400  | f<br>s                                       | 31<br>390              | 16<br>580                            | 11<br>3235 | 6<br>11370 | 52<br>610 | 26<br>615 | 83<br>635 | 20<br>565 |           |
|   | ST and A          | 350            | 350  |  |                        |                                      |            |            |           |           |           |           |           |
| All aluminum sand and permanent mold casting alloys             | AC                | 500            | 500  | f<br>s                                       | 31<br>390              | 16<br>580                            | 11<br>3235 | 6<br>11370 | 52<br>610 | 26<br>615 | 83<br>635 | 20<br>565 |           |
|   | ST and A          | 350            | 350  |  |                        |                                      |            |            |           |           |           |           |           |
| Aluminum Die-Casting Alloys                                     |                   |                |      |  |                        |                                      |            |            |           |           |           |           |           |
| Alloys 308.0 and 319.0  | —                 | —              | —    | f<br>s                                       | 23<br>110              | 11<br>145                            | 11<br>945  | 6<br>3325  | 38<br>145 | 19<br>130 | 83<br>145 | 20<br>130 |           |
|   |                   |                |      |  | Alloys 360.0 and 380.0 | 27<br>90                             | 14<br>125  | 11<br>855  | 6<br>3000 | 45<br>130 | 23<br>125 | 83<br>130 | 20<br>115 |
| Alloys 390.0 and 392.0  | AC                | 300            | 300  | f<br>s                                       | 24<br>65               | 12<br>85                             | 11<br>555  | 6<br>1955  | 40<br>85  | 20<br>80  | 83<br>85  | 20<br>80  |           |
|   | ST and A          | 70             | 70   |  |                        |                                      |            |            |           |           |           |           |           |
| Alloys 413  | —                 | —              | —    | f<br>s                                       | 24<br>65               | 12<br>85                             | 11<br>555  | 6<br>1955  | 40<br>85  | 20<br>80  | 83<br>85  | 20<br>80  |           |
| ST and A  | 45                | 40             |      |  |                        |                                      |            |            |           |           |           |           |           |
| All other aluminum die-casting alloys                           | AC                | 125            | 100  | f<br>s                                       | 27<br>90               | 14<br>125                            | 11<br>855  | 6<br>3000  | 45<br>130 | 23<br>125 | 83<br>130 | 20<br>115 |           |
| Magnesium Alloys  |                   |                |      |  |                        |                                      |            |            |           |           |           |           |           |
| All wrought magnesium alloys                                    | A,CD,ST<br>and A  | 500            | 500  | f<br>s                                       | 27<br>90               | 14<br>125                            | 11<br>855  | 6<br>3000  | 45<br>130 | 23<br>125 | 83<br>130 | 20<br>115 |           |
| All cast magnesium alloys                                       | A,AC, ST<br>and A | 450            | 450  | f<br>s                                       | 27<br>90               | 14<br>125                            | 11<br>855  | 6<br>3000  | 45<br>130 | 23<br>125 | 83<br>130 | 20<br>115 |           |

Abbreviations designate: A, annealed; AC, as cast; CD, cold drawn; and ST and A, solution treated and aged, respectively. See the footnote to Table 17 for instructions concerning the use of this table. The combined feed/speed data in this table are based on tool grades (identified in Table 16) as follows; uncoated carbide = 15.

**Table 22. Feed and Diameter Speed Adjustment Factors for HSS Twist Drills and Reamers**

| Cutting Speed, $V = V_{opt} \times F_f \times F_d$ |   |      |      |      |      |      |       |                        |                   |                   |                    |                    |                    |                    |                    |                     |
|--|---|------|------|------|------|------|-------|------------------------|-------------------|-------------------|--------------------|--------------------|--------------------|--------------------|--------------------|---------------------|
| Ratio of Chosen Feed to Optimum Feed               | Ratio of the two cutting speeds<br>(average/optimum) given in the tables<br>$V_{avg}/V_{opt}$ |      |      |      |      |      |       | Tool Diameter          |                   |                   |                    |                    |                    |                    |                    |                     |
|  |   |      |      |      |      |      |       | 0.08 in<br>(2 mm)      | 0.15 in<br>(4 mm) | 0.25 in<br>(6 mm) | 0.40 in<br>(10 mm) | 0.60 in<br>(15 mm) | 1.00 in<br>(25 mm) | 2.00 in<br>(50 mm) | 3.00 in<br>(75 mm) | 4.00 in<br>(100 mm) |
|  | Feed Factor, $F_f$  |      |      |      |      |      |       | Diameter Factor, $F_d$ |                   |                   |                    |                    |                    |                    |                    |                     |
| 1.00   | 1.00  | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00  | 0.30                   | 0.44              | 0.56              | 0.78               | 1.00               | 1.32               | 1.81               | 2.11               | 2.29                |
| 0.90   | 1.00  | 1.06 | 1.09 | 1.14 | 1.18 | 1.21 | 1.27  | 0.32                   | 0.46              | 0.59              | 0.79               | 1.00               | 1.30               | 1.72               | 1.97               | 2.10                |
| 0.80   | 1.00  | 1.12 | 1.19 | 1.31 | 1.40 | 1.49 | 1.63  | 0.34                   | 0.48              | 0.61              | 0.80               | 1.00               | 1.27               | 1.64               | 1.89               | 1.95                |
| 0.70   | 1.00  | 1.15 | 1.30 | 1.50 | 1.69 | 1.85 | 2.15  | 0.38                   | 0.52              | 0.64              | 0.82               | 1.00               | 1.25               | 1.52               | 1.67               | 1.73                |
| 0.60   | 1.00  | 1.23 | 1.40 | 1.73 | 2.04 | 2.34 | 2.89  | 0.42                   | 0.55              | 0.67              | 0.84               | 1.00               | 1.20               | 1.46               | 1.51               | 1.54                |
| 0.50   | 1.00  | 1.25 | 1.50 | 2.00 | 2.50 | 3.00 | 5.00  | 0.47                   | 0.60              | 0.71              | 0.87               | 1.00               | 1.15               | 1.30               | 1.34               | 1.94                |
| 0.40   | 1.00  | 1.23 | 1.57 | 2.29 | 3.08 | 3.92 | 5.70  | 0.53                   | 0.67              | 0.77              | 0.90               | 1.00               | 1.10               | 1.17               | 1.16               | 1.12                |
| 0.30   | 1.00  | 1.14 | 1.56 | 2.57 | 3.78 | 5.19 | 8.56  | 0.64                   | 0.76              | 0.84              | 0.94               | 1.00               | 1.04               | 1.02               | 0.96               | 0.90                |
| 0.20   | 1.00  | 0.90 | 1.37 | 2.68 | 4.49 | 6.86 | 17.60 | 0.83                   | 0.92              | 0.96              | 1.00               | 1.00               | 0.96               | 0.81               | 0.73               | 0.66                |
| 0.10   | 1.00  | 1.44 | 0.80 | 2.08 | 4.36 | 8.00 | 20.80 | 1.29                   | 1.26              | 1.21              | 1.11               | 1.00               | 0.84               | 0.60               | 0.46               | 0.38                |

This table is specifically for use with the combined feed/speed data for HSS twist drills in [Tables 17 through 23](#); use [Tables 5a and 5b](#) to adjust speed and tool life for indexable insert drilling with carbides. The combined feed/speed data for HSS twist drilling are based on a 0.60-inch diameter HSS drill with standard drill point geometry (2-flute with 118° tip angle). To adjust the given speeds for different feeds and drill diameters, use the two feed/speed pairs from the tables and calculate the ratio of desired (new) feed to optimum feed (largest of the two feeds from the speed table), and the ratio of the two cutting speeds  $V_{avg}/V_{opt}$ . Use the values of these ratios to find the feed factor  $F_f$  at the intersection of the feed ratio row and the speed ratio column in the left half of the table. The diameter factor  $F_d$  is found in the same row as the feed factor, in the right half of the table, under the column corresponding to the drill diameter. For diameters not given, interpolate between the nearest available sizes. The adjusted cutting speed can be calculated from  $V = V_{opt} \times F_f \times F_d$ , where  $V_{opt}$  is the smaller (optimum) of the two speeds from the speed table (from the left side of the column containing the two feed/speed pairs). Tool life using the selected feed and the adjusted speed should be approximately 45 minutes. Speed adjustment factors to modify tool life are found in [Table 15c](#).

**Table 23. Feeds and Speeds for Drilling and Reaming Copper Alloys**

| Group 1  |                    |             |         |  |      |                                   |      |         |      |     |
|--|--------------------|-------------|---------|--|------|-----------------------------------|------|---------|------|-----|
| Architectural bronze(C38500); Extra-high-leaded brass (C35600); Forging brass (C37700); Free-cutting phosphor bronze (B-2) (C54400); Free-cutting brass (C36000); Free-cutting Muntz metal (C37000); High-leaded brass (C33200, C34200); High-leaded brass tube (C35300); Leaded commercial bronze (C31400); Leaded naval brass (C48500); Medium-leaded brass (C34000)   |                    |             |         |  |      |                                   |      |         |      |     |
| Group 2  |                    |             |         |  |      |                                   |      |         |      |     |
| Aluminum brass, arsenical (C68700); Cartridge brass, 70% (C26000); High-silicon bronze, B (C65500); Admiralty brass (inhibited) (C44300, C44500); Jewelry bronze, 87.5% (C22600); Leaded Muntz metal (C36500, C36800); Leaded nickel silver (C79600); Low brass, 80% (C24000); Low-leaded brass (C33500); Low-silicon bronze, B (C65100); Manganese bronze, A (C67500); Muntz metal, 60% (C28000); Nickel silver, 55–18 (C77000); Red brass, 85% (C23000); Yellow brass (C26800)   |                    |             |         |  |      |                                   |      |         |      |     |
| Group 3  |                    |             |         |  |      |                                   |      |         |      |     |
| Aluminum bronze, D (C61400); Beryllium copper (C17000, C17200, C17500); Commercial bronze, 90% (C22000); Copper nickel, 10% (C70600); Copper nickel, 30% (C71500); Electrolytic tough-pitch copper (C11000); Gilding, 95% (C21000); Nickel silver, 65–10 (C74500); Nickel silver, 65–12 (C75700); Nickel silver, 65–15 (C75400); Nickel silver, 65–18 (C75200); Oxygen-free copper (C10200); Phosphor bronze, 1.25% (C50200); Phosphor bronze, 10% D (C52400); Phosphor bronze, 5% A (C51000); Phosphor bronze, 8% C (C52100); Phosphorus deoxidized copper (C12200) |                    |             |         |  |      |                                   |      |         |      |     |
| Alloy Description and UNS Alloy Numbers  | Material Condition | Drilling    | Reaming | Drilling                                     |      |                                   |      | Reaming |      |     |
|  |                    | HSS         |         | HSS  |      | Indexable Insert Uncoated Carbide |      | HSS     |      |     |
|  |                    | Speed (fpm) |         | f = feed (0.001 in./rev), s = speed (ft/min) |      |                                   |      |         |      |     |
|  |                    |             |         | Opt.   | Avg. | Opt.                              | Avg. | Opt.    | Avg. |     |
| Wrought Alloys   |                    |             |         |  |      |                                   |      |         |      |     |
| Group 1  | A                  | 160         | 160     | f  | 21   | 11                                | 11   | 6       | 36   | 18  |
|  | CD                 | 175         | 175     | s  | 210  | 265                               | 405  | 915     | 265  | 230 |
| Group 2  | A                  | 120         | 110     | f  | 24   | 12                                | 11   | 6       | 40   | 20  |
|  | CD                 | 140         | 120     | s  | 100  | 130                               | 205  | 455     | 130  | 120 |
| Group 3  | A                  | 60          | 50      | f  | 23   | 11                                | 11   | 6       | 38   | 19  |
|  | CD                 | 65          | 60      | s  | 155  | 195                               | 150  | 340     | 100  | 175 |

Abbreviations designate: A, annealed; CD, cold drawn. The two leftmost speed columns in this table contain traditional Handbook speeds for HSS steel tools. The text contains information concerning feeds to use in conjunction with these speeds.

**HSS Drilling and Reaming:** The combined feed/speed data for drilling and Table 22 are used to adjust drilling speeds for other feeds and drill diameters. Examples are given in the text. The given feeds and speeds for reaming are based on an 8-tooth,  $\frac{25}{32}$ -inch diameter, 30° lead angle reamer, and a 0.008-inch radial depth of cut. For other feeds, the correct speed can be obtained by interpolation using the given speeds if the desired feed lies in the recommended range (between the given values of optimum and average feed). The cutting speeds for reaming do not require adjustment for tool diameter as long as the radial depth of cut does not become too large. Speed adjustment factors to modify tool life are found in Table 15e.

**Indexable Insert Drilling:** The feed/speed data for indexable insert drilling are based on a tool with two cutting edges, an insert nose radius of  $\frac{3}{64}$  inch, a 10-degree lead angle, and diameter *D* of 1 inch. Adjustments for feed and depth of cut are made using Table 5a (Turning Speed Adjustment Factors) using a depth of cut of *D*/2, or one-half the drill diameter. Expected tool life at the given feeds and speeds is 15 minutes for short hole drilling (i.e., where hole depth is about 2*D* or less). Speed adjustment factors to increase tool life are found in Table 5b. The combined feed/speed data in this table are based on tool grades (identified in Table 16) as follows: uncoated carbide = 15.

**Using the Feed and Speed Tables for Tapping and Threading.**—The feed used in tapping and threading is always equal to the pitch of the screw thread being formed. The

threading data contained in the tables for drilling, reaming, and threading (Tables 17 through 23) are primarily for tapping and thread chasing, and do not apply to thread cutting with single-point tools.

The threading data in Tables 17 through 23 give two sets of feed (pitch) and speed values, for 12 and 50 threads/inch, but these values can be used to obtain the cutting speed for any other thread pitches. If the desired pitch falls between the values given in the tables, i.e., between 0.020 inch (50 tpi) and 0.083 inch (12 tpi), the required cutting speed is obtained by interpolation between the given speeds. If the pitch is less than 0.020 inch (more than 50 tpi), use the *average* speed, i.e., the largest of the two given speeds. For pitches greater than 0.083 inch (fewer than 12 tpi), the *optimum* speed should be used. Tool life using the given feed/speed data is intended to be approximately 45 minutes, and should be about the same for threads between 12 and 50 threads per inch.

*Example:* Determine the cutting speed required for tapping 303 stainless steel with a  $\frac{1}{2}$ -20 coated HSS tap.

The two feed/speed pairs for 303 stainless steel, in Table 19, are 83/35 (0.083 in./rev at 35 fpm) and 20/45 (0.020 in./rev at 45 fpm). The pitch of a  $\frac{1}{2}$ -20 thread is  $1/20 = 0.05$  inch, so the required feed is 0.05 in./rev. Because 0.05 is between the two given feeds (Table 19), the cutting speed can be obtained by interpolation between the two given speeds as follows:

$$V = 35 + \frac{0.05 - 0.02}{0.083 - 0.02}(45 - 35) = 40 \text{ fpm}$$

The cutting speed for coarse-pitch taps must be lower than for fine-pitch taps with the same diameter. Usually, the difference in pitch becomes more pronounced as the diameter of the tap becomes larger and slight differences in the pitch of smaller-diameter taps have little significant effect on the cutting speed. Unlike all other cutting tools, the feed per revolution of a tap cannot be independently adjusted—it is always equal to the lead of the thread and is always greater for coarse pitches than for fine pitches. Furthermore, the thread form of a coarse-pitch thread is larger than that of a fine-pitch thread; therefore, it is necessary to remove more metal when cutting a coarse-pitch thread.

Taps with a long chamfer, such as starting or taper taps, can cut faster in a short hole than short chamfer taps, such as plug taps. In deep holes, however, short chamfer or plug taps can run faster than long chamfer taps. Bottoming taps must be run more slowly than either starting or plug taps. The chamfer helps to start the tap in the hole. It also functions to involve more threads, or thread form cutting edges, on the tap in cutting the thread in the hole, thus reducing the cutting load on any one set of thread form cutting edges. In so doing, more chips and thinner chips are produced that are difficult to remove from deeper holes. Shortening the chamfer length causes fewer thread form cutting edges to cut, thereby producing fewer and thicker chips that can easily be disposed of. Only one or two sets of thread form cutting edges are cut on bottoming taps, causing these cutting edges to assume a heavy cutting load and produce very thick chips.

Spiral-pointed taps can operate at a faster cutting speed than taps with normal flutes. These taps are made with supplementary angular flutes on the end that push the chips ahead of the tap and prevent the tapped hole from becoming clogged with chips. They are used primarily to tap open or through holes although some are made with shorter supplementary flutes for tapping blind holes.

The tapping speed must be reduced as the percentage of full thread to be cut is increased. Experiments have shown that the torque required to cut a 100 per cent thread form is more than twice that required to cut a 50 per cent thread form. An increase in the percentage of full thread will also produce a greater volume of chips.

The tapping speed must be lowered as the length of the hole to be tapped is increased. More friction must be overcome in turning the tap and more chips accumulate in the hole.

It will be more difficult to apply the cutting fluid at the cutting edges and to lubricate the tap to reduce friction. This problem becomes greater when the hole is being tapped in a horizontal position.

Cutting fluids have a very great effect on the cutting speed for tapping. Although other operating conditions when tapping frequently cannot be changed, a free selection of the cutting fluid usually can be made. When planning the tapping operation, the selection of a cutting fluid warrants a very careful consideration and perhaps an investigation.

Taper threaded taps, such as pipe taps, must be operated at a slower speed than straight thread taps with a comparable diameter. All the thread form cutting edges of a taper threaded tap that are engaged in the work cut and produce a chip, but only those cutting edges along the chamfer length cut on straight thread taps. Pipe taps often are required to cut the tapered thread from a straight hole, adding to the cutting burden.

The machine tool used for the tapping operation must be considered in selecting the tapping speed. Tapping machines and other machines that are able to feed the tap at a rate of advance equal to the lead of the tap, and that have provisions for quickly reversing the spindle, can be operated at high cutting speeds. On machines where the feed of the tap is controlled manually—such as on drill presses and turret lathes—the tapping speed must be reduced to allow the operator to maintain safe control of the operation.

There are other special considerations in selecting the tapping speed. Very accurate threads are usually tapped more slowly than threads with a commercial grade of accuracy. Thread forms that require deep threads for which a large amount of metal must be removed, producing a large volume of chips, require special techniques and slower cutting speeds. Acme, buttress, and square threads, therefore, are generally cut at lower speeds.

**Cutting Speed for Broaching.**—Broaching offers many advantages in manufacturing metal parts, including high production rates, excellent surface finishes, and close dimensional tolerances. These advantages are not derived from the use of high cutting speeds; they are derived from the large number of cutting teeth that can be applied consecutively in a given period of time, from their configuration and precise dimensions, and from the width or diameter of the surface that can be machined in a single stroke. Most broaching cutters are expensive in their initial cost and are expensive to sharpen. For these reasons, a long tool life is desirable, and to obtain a long tool life, relatively slow cutting speeds are used. In many instances, slower cutting speeds are used because of the limitations of the machine in accelerating and stopping heavy broaching cutters. At other times, the available power on the machine places a limit on the cutting speed that can be used; i.e., the cubic inches of metal removed per minute must be within the power capacity of the machine.

The cutting speeds for high-speed steel broaches range from 3 to 50 feet per minute, although faster speeds have been used. In general, the harder and more difficult to machine materials are cut at a slower cutting speed and those that are easier to machine are cut at a faster speed. Some typical recommendations for high-speed steel broaches are: AISI 1040, 10 to 30 fpm; AISI 1060, 10 to 25 fpm; AISI 4140, 10 to 25 fpm; AISI 41L40, 20 to 30 fpm; 201 austenitic stainless steel, 10 to 20 fpm; Class 20 gray cast iron, 20 to 30 fpm; Class 40 gray cast iron, 15 to 25 fpm; aluminum and magnesium alloys, 30 to 50 fpm; copper alloys, 20 to 30 fpm; commercially pure titanium, 20 to 25 fpm; alpha and beta titanium alloys, 5 fpm; and the superalloys, 3 to 10 fpm. Surface broaching operations on gray iron castings have been conducted at a cutting speed of 150 fpm, using indexable insert cemented carbide broaching cutters. In selecting the speed for broaching, the cardinal principle of the performance of all metal cutting tools should be kept in mind; i.e., increasing the cutting speed may result in a proportionately larger reduction in tool life, and reducing the cutting speed may result in a proportionately larger increase in the tool life. When broaching most materials, a suitable cutting fluid should be used to obtain a good surface finish and a better tool life. Gray cast iron can be broached without using a cutting fluid although some shops prefer to use a soluble oil.

## Spade Drills

Spade drills are used to produce holes ranging in size from about 1 inch to 6 inches diameter, and even larger. Very deep holes can be drilled and blades are available for core drilling, counterboring, and for bottoming to a flat or contoured shape. There are two principal parts to a spade drill, the blade and the holder. The holder has a slot into which the blade fits; a wide slot at the back of the blade engages with a tongue in the holder slot to locate the blade accurately. A retaining screw holds the two parts together. The blade is usually made from high-speed steel, although cast nonferrous metal and cemented carbide-tipped blades are also available. Spade drill holders are classified by a letter symbol designating the range of blade sizes that can be held and by their length. Standard stub, short, long, and extra long holders are available; for very deep holes, special holders having wear strips to support and guide the drill are often used. Long, extra long, and many short length holders have coolant holes to direct cutting fluid, under pressure, to the cutting edges. In addition to its function in cooling and lubricating the tool, the cutting fluid also flushes the chips out of the hole. The shank of the holder may be straight or tapered; special automotive shanks are also used. A holder and different shank designs are shown in Fig. 1; Figs. 2a through Fig. 2f show some typical blades.

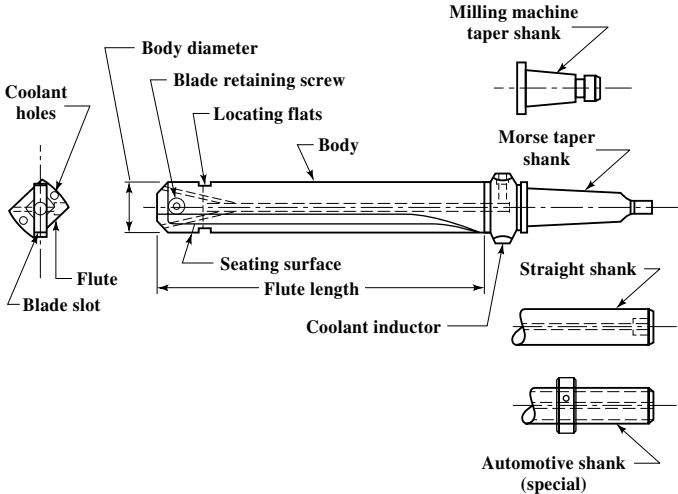


Fig. 1. Spade Drill Blade Holder

**Spade Drill Geometry.**—Metal separation from the work is accomplished in a like manner by both twist drills and spade drills, and the same mechanisms are involved for each. The two cutting lips separate the metal by a shearing action that is identical to that of chip formation by a single-point cutting tool. At the chisel edge, a much more complex condition exists. Here the metal is extruded sideways and at the same time is sheared by the rotation of the blunt wedge-formed chisel edge. This combination accounts for the very high thrust force required to penetrate the work. The chisel edge of a twist drill is slightly rounded, but on spade drills, it is a straight edge. Thus, it is likely that it is more difficult for the extruded metal to escape from the region of the chisel edge with spade drills. However, the chisel edge is shorter in length than on twist drills and the thrust for spade drilling is less.



## Typical Spade Drill Blades

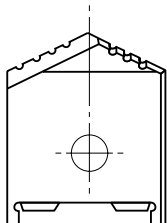


Fig. 2a. Standard blade

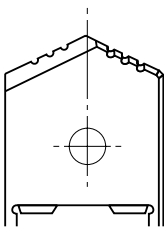


Fig. 2b. Standard blade with corner chamfer

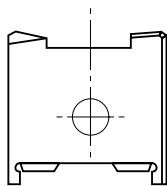


Fig. 2c. Core drilling blade

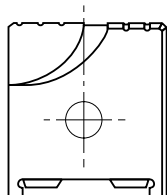


Fig. 2d. Center cutting facing or bottoming blade

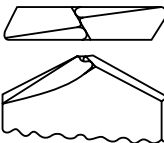


Fig. 2e. Standard blade with split point or crankshaft point

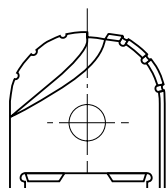


Fig. 2f. Center cutting radius blade

Basic spade drill geometry is shown in Fig. 3. Normally, the point angle of a standard tool is 130 degrees and the lip clearance angle is 18 degrees, resulting in a chisel edge angle of 108 degrees. The web thickness is usually about  $\frac{1}{4}$  to  $\frac{5}{16}$  as thick as the blade thickness. Usually, the cutting edge angle is selected to provide this web thickness and to provide the necessary strength along the entire length of the cutting lip. A further reduction of the chisel edge length is sometimes desirable to reduce the thrust force in drilling. This reduction can be accomplished by grinding a secondary rake surface at the center or by grinding a split point, or crankshaft point, on the point of the drill.

The larger point angle of a standard spade drill—130 degrees as compared with 118 degrees on a twist drill—causes the chips to flow more toward the periphery of the drill, thereby allowing the chips to enter the flutes of the holder more readily. The rake angle facilitates the formation of the chip along the cutting lips. For drilling materials of average hardness, the rake angle should be 10 to 12 degrees; for hard or tough steels, it should be 5 to 7 degrees; and for soft and ductile materials, it can be increased to 15 to 20 degrees. The rake surface may be flat or rounded, and the latter design is called radial rake. Radial rake is usually ground so that the rake angle is maximum at the periphery and decreases uniformly toward the center to provide greater cutting edge strength at the center. A flat rake surface is recommended for drilling hard and tough materials in order to reduce the tendency to chipping and to reduce heat damage.

A most important feature of the cutting edge is the chip splitters, which are also called chip breaker grooves. Functionally, these grooves are chip dividers; instead of forming a single wide chip along the entire length of the cutting edge, these grooves cause formation of several chips that can be readily disposed of through the flutes of the holder. Chip splitters must be carefully ground to prevent the chips from packing in the grooves, which greatly reduces their effectiveness. Splitters should be ground perpendicular to the cutting lip and parallel to the surface formed by the clearance angle. The grooves on the two cut-

ting lips must not overlap when measured radially along the cutting lip. Fig. 4 and the accompanying table show the groove form and dimensions.

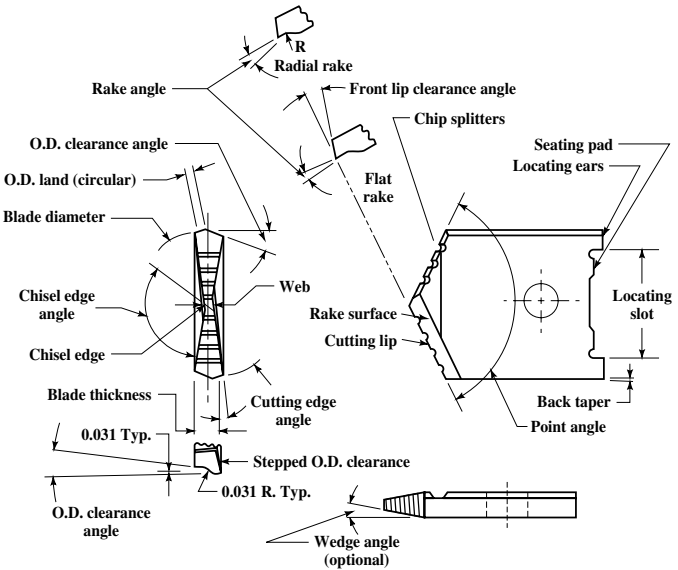


Fig. 3. Spade Drill Blade

On spade drills, the front lip clearance angle provides the relief. It may be ground on a drill grinding machine but usually it is ground flat. The normal front lip clearance angle is 8 degrees; in some instances, a secondary relief angle of about 14 degrees is ground below the primary clearance. The wedge angle on the blade is optional. It is generally ground on thicker blades having a larger diameter to prevent heel dragging below the cutting lip and to reduce the chisel edge length. The outside-diameter land is circular, serving to support and guide the blade in the hole. Usually it is ground to have a back taper of 0.001 to 0.002 inch per inch per side. The width of the land is approximately 20 to 25 per cent of the blade thickness. Normally, the outside-diameter clearance angle behind the land is 7 to 10 degrees. On many spade drill blades, the outside-diameter clearance surface is stepped about 0.030 inch below the land.

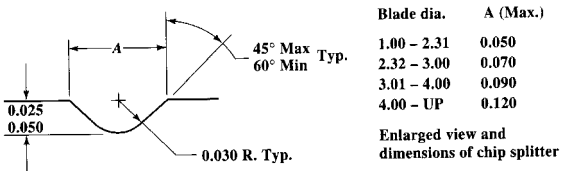


Fig. 4. Spade Drill Chip Splitter Dimensions

**Spade Drilling.**—Spade drills are used on drilling machines and other machine tools where the cutting tool rotates; they are also used on turning machines where the work

rotates and the tool is stationary. Although there are some slight operational differences, the methods of using spade drills are basically the same. An adequate supply of cutting fluid must be used, which serves to cool and lubricate the cutting edges; to cool the chips, thus making them brittle and more easily broken; and to flush chips out of the hole. Flood cooling from outside the hole can be used for drilling relatively shallow holes, of about one to two and one-half times the diameter in depth. For deeper holes, the cutting fluid should be injected through the holes in the drill. When drilling very deep holes, it is often helpful to blow compressed air through the drill in addition to the cutting fluid to facilitate ejection of the chips. Air at full shop pressure is throttled down to a pressure that provides the most efficient ejection. The cutting fluids used are light and medium cutting oils, water-soluble oils, and synthetics, and the type selected depends on the work material.

Starting a spade drill in the workpiece needs special attention. The straight chisel edge on the spade drill has a tendency to wander as it starts to enter the work, especially if the feed is too light. This wander can result in a mispositioned hole and possible breakage of the drill point. The best method of starting the hole is to use a stub or short-length spade drill holder and a blade of full size that should penetrate at least  $\frac{1}{8}$  inch at full diameter. The holder is then changed for a longer one as required to complete the hole to depth. Difficulties can be encountered if spotting with a center drill or starting drill is employed because the angles on these drills do not match the 130-degree point angle of the spade drill. Longer spade drills can be started without this starting procedure if the drill is guided by a jig bushing and if the holder is provided with wear strips.

Chip formation warrants the most careful attention as success in spade drilling is dependent on producing short, well-broken chips that can be easily ejected from the hole. Straight, stringy chips or chips that are wound like a clock spring cannot be ejected properly; they tend to pack around the blade, which may result in blade failure. The chip splitters must be functioning to produce a series of narrow chips along each cutting edge. Each chip must be broken, and for drilling ductile materials they should be formed into a "C" or "figure 9" shape. Such chips will readily enter the flutes on the holder and flow out of the hole.

Proper chip formation is dependent on the work material, the spade drill geometry, and the cutting conditions. Brittle materials such as gray cast iron seldom pose a problem because they produce a discontinuous chip, but austenitic stainless steels and very soft and ductile materials require much attention to obtain satisfactory chip control. Thinning the web or grinding a split point on the blade will sometimes be helpful in obtaining better chip control, as these modifications allow use of a heavier feed. Reducing the rake angle to obtain a tighter curl on the chip and grinding a corner chamfer on the tool will sometimes help to produce more manageable chips.

In most instances, it is not necessary to experiment with the spade drill blade geometry to obtain satisfactory chip control. Control usually can be accomplished by adjusting the cutting conditions; i.e., the cutting speed and the feed rate.

Normally, the cutting speed for spade drilling should be 10 to 15 per cent lower than that for an equivalent twist drill, although the same speed can be used if a lower tool life is acceptable. The recommended cutting speeds for twist drills on [Tables 17 through 23](#), starting on page [1061](#), can be used as a starting point; however, they should be decreased by the percentage just given. It is essential to use a heavy feed rate when spade drilling to produce a thick chip, and to force the chisel edge into the work. In ductile materials, a light feed will produce a thin chip that is very difficult to break. The thick chip on the other hand, which often contains many rupture planes, will curl and break readily. [Table 1](#) gives suggested feed rates for different spade drill sizes and materials. These rates should be used as a starting point and some adjustments may be necessary as experience is gained.

Table 1. Feed Rates for Spade Drilling

| Material                       | Hardness,<br>Bhn | Feed—Inches per Revolution  |       |       |       |       |       |
|--------------------------------|------------------|-----------------------------|-------|-------|-------|-------|-------|
|                                |                  | Spade Drill Diameter—Inches |       |       |       |       |       |
|                                |                  | 1-1¼                        | 1¼-2  | 2-3   | 3-4   | 4-5   | 5-8   |
| Free Machining Steel           | 100-240          | 0.014                       | 0.016 | 0.018 | 0.022 | 0.025 | 0.030 |
|                                | 240-325          | 0.010                       | 0.014 | 0.016 | 0.020 | 0.022 | 0.025 |
|                                | 100-225          | 0.012                       | 0.015 | 0.018 | 0.022 | 0.025 | 0.030 |
| Plain Carbon Steels            | 225-275          | 0.010                       | 0.013 | 0.015 | 0.018 | 0.020 | 0.025 |
|                                | 275-325          | 0.008                       | 0.010 | 0.013 | 0.015 | 0.018 | 0.020 |
|                                | 150-250          | 0.014                       | 0.016 | 0.018 | 0.022 | 0.025 | 0.030 |
| Free Machining Alloy Steels    | 250-325          | 0.012                       | 0.014 | 0.016 | 0.018 | 0.020 | 0.025 |
|                                | 325-375          | 0.010                       | 0.010 | 0.014 | 0.016 | 0.018 | 0.020 |
|                                | 125-180          | 0.012                       | 0.015 | 0.018 | 0.022 | 0.025 | 0.030 |
| Alloy Steels                   | 180-225          | 0.010                       | 0.012 | 0.016 | 0.018 | 0.022 | 0.025 |
|                                | 225-325          | 0.009                       | 0.010 | 0.013 | 0.015 | 0.018 | 0.020 |
|                                | 325-400          | 0.006                       | 0.008 | 0.010 | 0.012 | 0.014 | 0.016 |
| Tool Steels                    |                  |                             |       |       |       |       |       |
| Water Hardening                | 150-250          | 0.012                       | 0.014 | 0.016 | 0.018 | 0.020 | 0.022 |
| Shock Resisting                | 175-225          | 0.012                       | 0.014 | 0.015 | 0.016 | 0.017 | 0.018 |
| Cold Work                      | 200-250          | 0.007                       | 0.008 | 0.009 | 0.010 | 0.011 | 0.012 |
| Hot Work                       | 150-250          | 0.012                       | 0.013 | 0.015 | 0.016 | 0.018 | 0.020 |
| Mold                           | 150-200          | 0.010                       | 0.012 | 0.014 | 0.016 | 0.018 | 0.018 |
| Special-Purpose                | 150-225          | 0.010                       | 0.012 | 0.014 | 0.016 | 0.016 | 0.018 |
| High-Speed                     | 200-240          | 0.010                       | 0.012 | 0.013 | 0.015 | 0.017 | 0.018 |
|                                | 110-160          | 0.020                       | 0.022 | 0.026 | 0.028 | 0.030 | 0.034 |
| Gray Cast Iron                 | 160-190          | 0.015                       | 0.018 | 0.020 | 0.024 | 0.026 | 0.028 |
|                                | 190-240          | 0.012                       | 0.014 | 0.016 | 0.018 | 0.020 | 0.022 |
|                                | 240-320          | 0.010                       | 0.012 | 0.016 | 0.018 | 0.018 | 0.018 |
|                                | 140-190          | 0.014                       | 0.016 | 0.018 | 0.020 | 0.022 | 0.024 |
| Ductile or Nodular Iron        | 190-250          | 0.012                       | 0.014 | 0.016 | 0.018 | 0.018 | 0.020 |
|                                | 250-300          | 0.010                       | 0.012 | 0.016 | 0.018 | 0.018 | 0.018 |
| Malleable Iron                 |                  |                             |       |       |       |       |       |
| Ferritic                       | 110-160          | 0.014                       | 0.016 | 0.018 | 0.020 | 0.022 | 0.024 |
| Pearlitic                      | 160-220          | 0.012                       | 0.014 | 0.016 | 0.018 | 0.020 | 0.020 |
|                                | 220-280          | 0.010                       | 0.012 | 0.014 | 0.016 | 0.018 | 0.018 |
| Free Machining Stainless Steel |                  |                             |       |       |       |       |       |
| Ferritic                       | ...              | 0.016                       | 0.018 | 0.020 | 0.024 | 0.026 | 0.028 |
| Austenitic                     | ...              | 0.016                       | 0.018 | 0.020 | 0.022 | 0.024 | 0.026 |
| Martensitic                    | ...              | 0.012                       | 0.014 | 0.016 | 0.016 | 0.018 | 0.020 |
| Stainless Steel                |                  |                             |       |       |       |       |       |
| Ferritic                       | ...              | 0.012                       | 0.014 | 0.018 | 0.020 | 0.020 | 0.022 |
| Austenitic                     | ...              | 0.012                       | 0.014 | 0.016 | 0.018 | 0.020 | 0.020 |
| Martensitic                    | ...              | 0.010                       | 0.012 | 0.012 | 0.014 | 0.016 | 0.018 |
| Aluminum Alloys                | ...              | 0.020                       | 0.022 | 0.024 | 0.028 | 0.030 | 0.040 |
|                                | (Soft)           | 0.016                       | 0.018 | 0.020 | 0.026 | 0.028 | 0.030 |
| Copper Alloys                  | (Hard)           | 0.010                       | 0.012 | 0.014 | 0.016 | 0.018 | 0.018 |
| Titanium Alloys                | ...              | 0.008                       | 0.010 | 0.012 | 0.014 | 0.014 | 0.016 |
| High-Temperature Alloys        | ...              | 0.008                       | 0.010 | 0.012 | 0.012 | 0.014 | 0.014 |

**Power Consumption and Thrust for Spade Drilling.**—In each individual setup, there are factors and conditions influencing power consumption that cannot be accounted for in a simple equation; however, those given below will enable the user to estimate power consumption and thrust accurately enough for most practical purposes. They are based on experimentally derived values of unit horsepower, as given in Table 2. As a word of caution, these values are for sharp tools. In spade drilling, it is reasonable to estimate that a dull tool will increase the power consumption and the thrust by 25 to 50 per cent. The unit horsepower values in the table are for the power consumed at the cutting edge, to which must be added the power required to drive the machine tool itself, in order to obtain the horsepower required by the machine tool motor. An allowance for power to drive the machine is provided by dividing the horsepower at the cutter by a mechanical efficiency factor,  $e_m$ . This factor can be estimated to be 0.90 for a direct spindle drive with a belt, 0.75 for a back gear drive, and 0.70 to 0.80 for geared head drives. Thus, for spade drilling the formulas are

$$hp_c = uhp \left( \frac{\pi D^2}{4} \right) f N$$

$$B_s = 148,500 \text{ uhp} f D$$

$$hp_m = \frac{hp_c}{e_m}$$

$$f = \frac{f_m}{N}$$

where  $hp_c$  = horsepower at the cutter     $hp_m$  = horsepower at the motor

$B_s$  = thrust for spade drilling in pounds

$uhp$  = unit horsepower

$D$  = drill diameter in inches

$f$  = feed in inches per revolution

$f_m$  = feed in inches per minute

$N$  = spindle speed in revolutions per minute

$e_m$  = mechanical efficiency factor

**Table 2. Unit Horsepower for Spade Drilling**

| Material                     | Hardness    | uhp  | Material         | Hardness    | uhp  |
|------------------------------|-------------|------|------------------|-------------|------|
| Plain Carbon and Alloy Steel | 85–200 Bhn  | 0.79 | Titanium Alloys  | 250–375 Bhn | 0.72 |
|                              | 200–275     | 0.94 | High-Temp Alloys | 200–360 Bhn | 1.44 |
|                              | 275–375     | 1.00 | Aluminum Alloys  | ...         | 0.22 |
|                              | 375–425     | 1.15 | Magnesium Alloys | ...         | 0.16 |
|                              | 45–52 Rc    | 1.44 | Copper Alloys    | 20–80 Rb    | 0.43 |
| Cast Irons                   | 110–200 Bhn | 0.5  |                  | 80–100 Rb   | 0.72 |
|                              | 200–300     | 1.08 |                  |             |      |
| Stainless Steels             | 135–275 Bhn | 0.94 |                  |             |      |
|                              | 30–45 Rc    | 1.08 |                  |             |      |

*Example:* Estimate the horsepower and thrust required to drive a 2-inch diameter spade drill in AISI 1045 steel that is quenched and tempered to a hardness of 275 Bhn. From Table 17 on page 1061, the cutting speed,  $V$ , for drilling this material with a twist drill is 50 feet per minute. This value is reduced by 10 per cent for spade drilling and the speed selected is thus  $0.9 \times 50 = 45$  feet per minute. The feed rate (from Table 1, page 1079) is 0.015 in/rev. and the unit horsepower from Table 2 above is 0.94. The machine efficiency factor is estimated to be 0.80 and it will be assumed that a 50 per cent increase in the unit horsepower must be allowed for dull tools.

Step 1. Calculate the spindle speed from the following formula:

$$N = \frac{12V}{\pi D}$$

where:  $N$  = spindle speed in revolutions per minute

$V$  = cutting speed in feet per minute

$D$  = drill diameter in inches

$$\text{Thus, } N = \frac{12 \times 45}{\pi \times 2} = 86 \text{ revolutions per minute}$$

Step 2. Calculate the horsepower at the cutter:

$$\text{hp}_c = \text{uhp} \left( \frac{\pi D^2}{4} \right) f N = 0.94 \left( \frac{\pi \times 2^2}{4} \right) 0.015 \times 86 = 3.8$$

Step 3. Calculate the horsepower at the motor and provide for a 50 per cent power increase for the dull tool:

$$\text{hp}_m = \frac{\text{hp}_c}{e_m} = \frac{3.8}{0.80} = 4.75 \text{ horsepower}$$

$$\text{hp}_m \text{ (with dull tool)} = 1.5 \times 4.75 = 7.125 \text{ horsepower}$$

Step 4. Estimate the spade drill thrust:

$$B_s = 148,500 \times \text{uhp} \times f D = 148,500 \times 0.94 \times 0.015 \times 2 = 4188 \text{ lb (for sharp tool)}$$

$$B_s = 1.5 \times 4188 = 6282 \text{ lb (for dull tool)}$$

**Trepanning.**—Cutting a groove in the form of a circle or boring or cutting a hole by removing the center or core in one piece is called trepanning. Shallow trepanning, also called face grooving, can be performed on a lathe using a single-point tool that is similar to a grooving tool but has a curved blade. Generally, the minimum outside diameter that can be cut by this method is about 3 inches and the maximum groove depth is about 2 inches. Trepanning is probably the most economical method of producing deep holes that are 2 inches, and larger, in diameter. Fast production rates can be achieved. The tool consists of a hollow bar, or stem, and a hollow cylindrical head to which a carbide or high-speed steel, single-point cutting tool is attached. Usually, only one cutting tool is used although for some applications a multiple cutter head must be used; e.g., heads used to start the hole have multiple tools. In operation, the cutting tool produces a circular groove and a residue core that enters the hollow stem after passing through the head. On outside-diameter exhaust trepanning tools, the cutting fluid is applied through the stem and the chips are flushed around the outside of the tool; inside-diameter exhaust tools flush the chips out through the stem with the cutting fluid applied from the outside. For starting the cut, a tool that cuts a starting groove in the work must be used, or the trepanning tool must be guided by a bushing. For holes less than about five diameters deep, a machine that rotates the trepanning tool can be used. Often, an ordinary drill press is satisfactory; deeper holes should be machined on a lathe with the work rotating. A hole diameter tolerance of  $\pm 0.010$  inch can be obtained easily by trepanning and a tolerance of  $\pm 0.001$  inch has sometimes been held. Hole runout can be held to  $\pm 0.003$  inch per foot and, at times, to  $\pm 0.001$  inch per foot. On heat-treated metal, a surface finish of 125 to 150  $\mu\text{m}$  AA can be obtained and on annealed metals 100 to 250  $\mu\text{m}$  AA is common.

## ESTIMATING SPEEDS AND MACHINING POWER

**Estimating Planer Cutting Speeds.**—Whereas most planers of modern design have a means of indicating the speed at which the table is traveling, or cutting, many older planers do not. Thus, the following formulas are useful for planers that do not have a means of indicating the table or cutting speed. It is not practicable to provide a formula for calculating the exact cutting speed at which a planer is operating because the time to stop and start the table when reversing varies greatly. The formulas below will, however, provide a reasonable estimate.

$$V_c \cong S_c L$$

$$S_c \cong \frac{V_c}{L}$$

where  $V_c$  = cutting speed; fpm or m/min

$S_c$  = number of cutting strokes per minute of planer table

$L$  = length of table cutting stroke; ft or m

**Cutting Speed for Planing and Shaping.**—The traditional HSS cutting tool speeds in [Tables 1](#) through [4b](#) and [Tables 6](#) through [9](#) can be used for planing and shaping. The feed and depth of cut factors in [Tables 5c](#) should also be used, as explained previously. Very often, other factors relating to the machine or the setup will require a reduction in the cutting speed used on a specific job.

**Cutting Time for Turning, Boring, and Facing.**—The time required to turn a length of metal can be determined by the following formula in which  $T$  = time in minutes,  $L$  = length of cut in inches,  $f$  = feed in inches per revolution, and  $N$  = lathe spindle speed in revolutions per minute.

$$T = \frac{L}{fN}$$

When making job estimates, the time required to load and to unload the workpiece on the machine, and the machine handling time, must be added to the cutting time for each length cut to obtain the floor-to-floor time.

**Planing Time.**—The approximate time required to plane a surface can be determined from the following formula in which  $T$  = time in minutes,  $L$  = length of stroke in feet,  $V_c$  = cutting speed in feet per minute,  $V_r$  = return speed in feet per minute;  $W$  = width of surface to be planed in inches,  $F$  = feed in inches, and 0.025 = approximate reversal time factor per stroke in minutes for most planers:

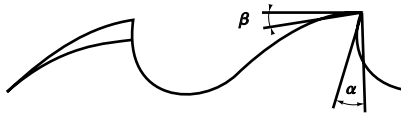
$$T = \frac{W}{F} \left[ L \times \left( \frac{1}{V_c} + \frac{1}{V_r} \right) + 0.025 \right]$$

**Speeds for Metal-Cutting Saws.**—The following speeds and feeds for solid-tooth, high-speed-steel, circular, metal-cutting saws are recommended by Saws International, Inc. (sfpm = surface feet per minute =  $3.142 \times$  blade diameter in inches  $\times$  rpm of saw shaft  $\div 12$ ).

**Speeds for Turning Unusual Materials.**—*Slate*, on account of its peculiarly stratified formation, is rather difficult to turn, but if handled carefully, can be machined in an ordinary lathe. The cutting speed should be about the same as for cast iron. A sheet of fiber or pressed paper should be interposed between the chuck or steadyrest jaws and the slate, to protect the latter. Slate rolls must not be centered and run on the tailstock. A satisfactory method of supporting a slate roll having journals at the ends is to bore a piece of lignum vitae to receive the turned end of the roll, and center it for the tailstock spindle.

*Rubber* can be turned at a peripheral speed of 200 feet per minute, although it is much easier to grind it with an abrasive wheel that is porous and soft. For cutting a rubber roll in

## Speeds, Feeds, and Tooth Angles for Sawing Various Materials



$\alpha$  = Cutting angle  
 $\beta$  = Relief angle

| Materials                        | Front Rake Angle $\alpha$ (deg) | Back Rake Angle $\beta$ (deg) | Stock Diameters (inches)      |                                |                                  |                                  |
|----------------------------------|---------------------------------|-------------------------------|-------------------------------|--------------------------------|----------------------------------|----------------------------------|
|                                  |                                 |                               | $\frac{1}{4}$ - $\frac{3}{4}$ | $\frac{3}{4}$ -1 $\frac{1}{2}$ | 1 $\frac{1}{2}$ -2 $\frac{1}{2}$ | 2 $\frac{1}{2}$ -3 $\frac{1}{2}$ |
| Aluminum                         | 24                              | 12                            | 6500 sfpm<br>100 in/min       | 6200 sfpm<br>85 in/min         | 6000 sfpm<br>80 in/min           | 5000 sfpm<br>75 in/min           |
| Light Alloys with Cu, Mg, and Zn | 22                              | 10                            | 3600 sfpm<br>70 in/min        | 3300 sfpm<br>65 in/min         | 3000 sfpm<br>63 in/min           | 2600 sfpm<br>60 in/min           |
| Light Alloys with High Si        | 20                              | 8                             | 650 sfpm<br>16 in/min         | 600 sfpm<br>16 in/min          | 550 sfpm<br>14 in/min            | 550 sfpm<br>12 in/min            |
| Copper                           | 20                              | 10                            | 1300 sfpm<br>24 in/min        | 1150 sfpm<br>24 in/min         | 1000 sfpm<br>22 in/min           | 800 sfpm<br>22 in/min            |
| Bronze                           | 15                              | 8                             | 1300 sfpm<br>24 in/min        | 1150 sfpm<br>24 in/min         | 1000 sfpm<br>22 in/min           | 800 sfpm<br>20 in/min            |
| Hard Bronze                      | 10                              | 8                             | 400 sfpm<br>6.3 in/min        | 360 sfpm<br>6 in/min           | 325 sfpm<br>5.5 in/min           | 300 sfpm<br>5.1 in/min           |
| Cu-Zn Brass                      | 16                              | 8                             | 2000 sfpm<br>43 in/min        | 2000 sfpm<br>43 in/min         | 1800 sfpm<br>39 in/min           | 1800 sfpm<br>35 in/min           |
| Gray Cast Iron                   | 12                              | 8                             | 82 sfpm<br>4 in/min           | 75 sfpm<br>4 in/min            | 72 sfpm<br>3.5 in/min            | 66 sfpm<br>3 in/min              |
| Carbon Steel                     | 20                              | 8                             | 160 sfpm<br>6.3 in/min        | 150 sfpm<br>5.9 in/min         | 150 sfpm<br>5.5 in/min           | 130 sfpm<br>5.1 in/min           |
| Medium Hard Steel                | 18                              | 8                             | 100 sfpm<br>5.1 in/min        | 100 sfpm<br>4.7 in/min         | 80 sfpm<br>4.3 in/min            | 80 sfpm<br>4.3 in/min            |
| Hard Steel                       | 15                              | 8                             | 66 sfpm<br>4.3 in/min         | 66 sfpm<br>4.3 in/min          | 60 sfpm<br>4 in/min              | 57 sfpm<br>3.5 in/min            |
| Stainless Steel                  | 15                              | 8                             | 66 sfpm<br>2 in/min           | 63 sfpm<br>1.75 in/min         | 60 sfpm<br>1.75 in/min           | 57 sfpm<br>1.5 in/min            |

two, the ordinary parting tool should not be used, but a tool shaped like a knife; such a tool severs the rubber without removing any material.

*Gutta percha* can be turned as easily as wood, but the tools must be sharp and a good soap-and-water lubricant used.

*Copper* can be turned easily at 200 feet per minute.

*Limestone* such as is used in the construction of pillars for balconies, etc., can be turned at 150 feet per minute, and the formation of ornamental contours is quite easy. *Marble* is a treacherous material to turn. It should be cut with a tool such as would be used for brass, but



at a speed suitable for cast iron. It must be handled very carefully to prevent flaws in the surface.

The foregoing speeds are for high-speed steel tools. Tools tipped with tungsten carbide are adapted for cutting various non-metallic products which cannot be machined readily with steel tools, such as slate, marble, synthetic plastic materials, etc. In drilling slate and marble, use flat drills; and for plastic materials, tungsten-carbide-tipped twist drills. Cutting speeds ranging from 75 to 150 feet per minute have been used for drilling slate (without coolant) and a feed of 0.025 inch per revolution for drills  $\frac{3}{4}$  and 1 inch in diameter.

**Estimating Machining Power.**—Knowledge of the power required to perform machining operations is useful when planning new machining operations, for optimizing existing machining operations, and to develop specifications for new machine tools that are to be acquired. The available power on any machine tool places a limit on the size of the cut that it can take. When much metal must be removed from the workpiece it is advisable to estimate the cutting conditions that will utilize the maximum power on the machine. Many machining operations require only light cuts to be taken for which the machine obviously has ample power; in this event, estimating the power required is a wasteful effort. Conditions in different shops may vary and machine tools are not all designed alike, so some variations between the estimated results and those obtained on the job are to be expected. However, by using the methods provided in this section a reasonable estimate of the power required can be made, which will suffice in most practical situations.

The measure of power in customary inch units is the horsepower; in SI metric units it is the kilowatt, which is used for both mechanical and electrical power. The power required to cut a material depends upon the rate at which the material is being cut and upon an experimentally determined power constant,  $K_p$ , which is also called the unit horsepower, unit power, or specific power consumption. The power constant is equal to the horsepower required to cut a material at a rate of one cubic inch per minute; in SI metric units the power constant is equal to the power in kilowatts required to cut a material at a rate of one cubic centimeter per second, or 1000 cubic millimeters per second ( $1 \text{ cm}^3 = 1000 \text{ mm}^3$ ). Different values of the power constant are required for inch and for metric units, which are related as follows: to obtain the SI metric power constant, multiply the inch power constant by 2.73; to obtain the inch power constant, divide the SI metric power constant by 2.73. Values of the power constant in [Tables 3a](#), and [3b](#) can be used for all machining operations except drilling and grinding. Values given are for sharp tools.

**Table 3a. Power Constants,  $K_p$ , Using Sharp Cutting Tools**

| Material                   | Brinell Hardness | $K_p$<br>Inch<br>Units | $K_p$<br>Metric<br>Units | Material       | Brinell Hardness | $K_p$<br>Inch<br>Units | $K_p$<br>Metric<br>Units |
|----------------------------|------------------|------------------------|--------------------------|----------------|------------------|------------------------|--------------------------|
| <b>Ferrous Cast Metals</b> |                  |                        |                          |                |                  |                        |                          |
| Gray Cast<br>Iron          | 100–120          | 0.28                   | 0.76                     | Malleable Iron |                  |                        |                          |
|                            | 120–140          | 0.35                   | 0.96                     | Ferritic       | 150–175          | 0.42                   | 1.15                     |
|                            | 140–160          | 0.38                   | 1.04                     | Pearlitic      | 175–200          | 0.57                   | 1.56                     |
|                            | 160–180          | 0.52                   | 1.42                     |                | 200–250          | 0.82                   | 2.24                     |
|                            | 180–200          | 0.60                   | 1.64                     |                | 250–300          | 1.18                   | 3.22                     |
|                            | 200–220          | 0.71                   | 1.94                     |                |                  |                        |                          |
|                            | 220–240          | 0.91                   | 2.48                     |                |                  |                        |                          |
| Alloy Cast<br>Iron         | 150–175          | 0.30                   | 0.82                     | Cast Steel     | 150–175          | 0.62                   | 1.69                     |
|                            | 175–200          | 0.63                   | 1.72                     |                | 175–200          | 0.78                   | 2.13                     |
|                            | 200–250          | 0.92                   | 2.51                     |                | 200–250          | 0.86                   | 2.35                     |
|                            |                  |                        |                          | ...            | ...              | ...                    | ...                      |

**Table 3a. (Continued) Power Constants,  $K_p$ , Using Sharp Cutting Tools**

| Material   | Brinell Hardness | $K_p$<br>Inch<br>Units | $K_p$<br>Metric<br>Units | Material             | Brinell<br>Hardness | $K_p$<br>Inch<br>Units | $K_p$<br>Metric<br>Units |
|--|------------------|------------------------|--------------------------|----------------------|---------------------|------------------------|--------------------------|
| <b>High-Temperature Alloys, Tool Steel, Stainless Steel, and Nonferrous Metals</b> |                  |                        |                          |                      |                     |                        |                          |
| High-Temperature Alloys  |                  |                        |                          |                      | 150-175             | 0.60                   | 1.64                     |
| A286   | 165              | 0.82                   | 2.24                     | Stainless Steel {    | 175-200             | 0.72                   | 1.97                     |
| A286   | 285              | 0.93                   | 2.54                     |                      | 200-250             | 0.88                   | 2.40                     |
| Chromoloy  | 200              | 0.78                   | 3.22                     | Zinc Die Cast Alloys | ...                 | 0.25                   | 0.68                     |
| Chromoloy  | 310              | 1.18                   | 3.00                     | Copper (pure)        | ...                 | 0.91                   | 2.48                     |
| Inco 700   | 330              | 1.12                   | 3.06                     | Brass                |                     |                        |                          |
| Inco 702   | 230              | 1.10                   | 3.00                     | Hard                 | ...                 | 0.83                   | 2.27                     |
| Hastelloy-B  | 230              | 1.10                   | 3.00                     | Medium               | ...                 | 0.50                   | 1.36                     |
| M-252  | 230              | 1.10                   | 3.00                     | Soft                 | ...                 | 0.25                   | 0.68                     |
| M-252  | 310              | 1.20                   | 3.28                     | Leaded               | ...                 | 0.30                   | 0.82                     |
| Ti-150A  | 340              | 0.65                   | 1.77                     |                      |                     |                        |                          |
| U-500  | 375              | 1.10                   | 3.00                     | Bronze               |                     |                        |                          |
|  |                  |                        |                          | Hard                 | ...                 | 0.91                   | 2.48                     |
| Monel Metal  | ...              | 1.00                   | 2.73                     | Medium               | ...                 | 0.50                   | 1.36                     |
|  | 175-200          | 0.75                   | 2.05                     | Aluminum             |                     |                        |                          |
|  | 200-250          | 0.88                   | 2.40                     | Cast                 | ...                 | 0.25                   | 0.68                     |
| Tool Steel {   | 250-300          | 0.98                   | 2.68                     | Rolled (hard)        | ...                 | 0.33                   | 0.90                     |
|  | 300-350          | 1.20                   | 3.28                     |                      |                     |                        |                          |
|  | 350-400          | 1.30                   | 3.55                     | Magnesium Alloys     | ...                 | 0.10                   | 0.27                     |

The value of the power constant is essentially unaffected by the cutting speed, the depth of cut, and the cutting tool material. Factors that do affect the value of the power constant, and thereby the power required to cut a material, include the hardness and microstructure of the work material, the feed rate, the rake angle of the cutting tool, and whether the cutting edge of the tool is sharp or dull. Values are given in the power constant tables for different material hardness levels, whenever this information is available. Feed factors for the power constant are given in [Table 4](#). All metal cutting tools wear but a worn cutting edge requires more power to cut than a sharp cutting edge.

Factors to provide for tool wear are given in [Table 5](#). In this table, the extra-heavy-duty category for milling and turning occurs only on operations where the tool is allowed to wear more than a normal amount before it is replaced, such as roll turning. The effect of the rake angle usually can be disregarded. The rake angle for which most of the data in the power constant tables are given is positive 14 degrees. Only when the deviation from this angle is large is it necessary to make an adjustment. Using a rake angle that is more positive reduces the power required approximately 1 per cent per degree; using a rake angle that is more negative increases the power required; again approximately 1 per cent per degree.

Many indexable insert cutting tools are formed with an integral chip breaker or other cutting edge modifications, which have the effect of reducing the power required to cut a material. The extent of this effect cannot be predicted without a test of each design. Cutting fluids will also usually reduce the power required, when operating in the lower range of cutting speeds. Again, the extent of this effect cannot be predicted because each cutting fluid exhibits its own characteristics.

**Table 3b. Power Constants,  $K_p$ , Using Sharp Cutting Tools**

| Material   | Brinell Hardness | $K_p$<br>Inch<br>Units | $K_p$<br>Metric<br>Units | Material   | Brinell<br>Hardness | $K_p$<br>Inch<br>Units | $K_p$<br>SI Metric<br>Units |
|--|------------------|------------------------|--------------------------|--|---------------------|------------------------|-----------------------------|
| <b>Wrought Steels</b>  |                  |                        |                          |  |                     |                        |                             |
| Plain Carbon Steels  |                  |                        |                          |  |                     |                        |                             |
| All Plain<br>Carbon Steels   | 80–100           | 0.63                   | 1.72                     | All Plain<br>Carbon Steels   | 220–240             | 0.89                   | 2.43                        |
|  | 100–120          | 0.66                   | 1.80                     |  | 240–260             | 0.92                   | 2.51                        |
|  | 120–140          | 0.69                   | 1.88                     |  | 260–280             | 0.95                   | 2.59                        |
|  | 140–160          | 0.74                   | 2.02                     |  | 280–300             | 1.00                   | 2.73                        |
|  | 160–180          | 0.78                   | 2.13                     |  | 300–320             | 1.03                   | 2.81                        |
|  | 180–200          | 0.82                   | 2.24                     |  | 320–340             | 1.06                   | 2.89                        |
|  | 200–220          | 0.85                   | 2.32                     |  | 340–360             | 1.14                   | 3.11                        |
| Free Machining Steels  |                  |                        |                          |  |                     |                        |                             |
| AISI 1108, 1109,<br>1110, 1115, 1116,<br>1117, 1118, 1119,<br>1120, 1125, 1126,<br>1132  | 100–120          | 0.41                   | 1.12                     | AISI 1137, 1138,<br>1139, 1140,<br>1141, 1144,<br>1145, 1146,<br>1148, 1151                      | 180–200             | 0.51                   | 1.39                        |
|  | 120–140          | 0.42                   | 1.15                     |  | 200–220             | 0.55                   | 1.50                        |
|  | 140–160          | 0.44                   | 1.20                     |  | 220–240             | 0.57                   | 1.56                        |
|  | 160–180          | 0.48                   | 1.31                     |  | 240–260             | 0.62                   | 1.69                        |
|  | 180–200          | 0.50                   | 1.36                     |  | ...                 | ...                    | ...                         |
| Alloy Steels   |                  |                        |                          |  |                     |                        |                             |
| AISI 4023, 4024,<br>4027, 4028, 4032,<br>4037, 4042, 4047,<br>4137, 4140, 4142,<br>4145, 4147, 4150,<br>4340, 4640, 4815,<br>4817, 4820, 5130,<br>5132, 5135, 5140,<br>5145, 5150, 6118,<br>6150, 8637, 8640,<br>8642, 8645, 8650,<br>8740 | 140–160          | 0.62                   | 1.69                     | AISI 4130, 4320,<br>4615, 4620,<br>4626, 5120,<br>8615, 8617,<br>8620, 8622,<br>8625, 8630, 8720 | 140–160             | 0.56                   | 1.53                        |
|  | 160–180          | 0.65                   | 1.77                     |  | 160–180             | 0.59                   | 1.61                        |
|  | 180–200          | 0.69                   | 1.88                     |  | 180–200             | 0.62                   | 1.69                        |
|  | 200–220          | 0.72                   | 1.97                     |  | 200–220             | 0.65                   | 1.77                        |
|  | 220–240          | 0.76                   | 2.07                     |  | 220–240             | 0.70                   | 1.91                        |
|  | 240–260          | 0.80                   | 2.18                     |  | 240–260             | 0.74                   | 2.02                        |
|  | 260–280          | 0.84                   | 2.29                     |  | 260–280             | 0.77                   | 2.10                        |
|  | 280–300          | 0.87                   | 2.38                     |  | 280–300             | 0.80                   | 2.18                        |
|  | 300–320          | 0.91                   | 2.48                     |  | 300–320             | 0.83                   | 2.27                        |
|  | 320–340          | 0.96                   | 2.62                     |  | 320–340             | 0.89                   | 2.43                        |
|  | 340–360          | 1.00                   | 2.73                     |  | ...                 | ...                    | ...                         |
| AISI 1330, 1335,<br>1340, E52100   | 160–180          | 0.79                   | 2.16                     | ...  | ...                 | ...                    |                             |
|  | 180–200          | 0.83                   | 2.27                     | ...  | ...                 | ...                    |                             |
|  | 200–220          | 0.87                   | 2.38                     | ...  | ...                 | ...                    |                             |

The machine tool transmits the power from the driving motor to the workpiece, where it is used to cut the material. The effectiveness of this transmission is measured by the machine tool efficiency factor,  $E$ . Average values of this factor are given in Table 6. Formulas for calculating the metal removal rate,  $Q$ , for different machining operations are given in Table 7. These formulas are used together with others given below. The following formulas can be used with either customary inch or with SI metric units.

$$P_c = K_p C Q W \quad (1)$$

$$P_m = \frac{P_c}{E} = \frac{K_p C Q W}{E} \quad (2)$$

where  $P_c$  = power at the cutting tool; hp, or kW

**Table 4. Feed Factors,  $C$ , for Power Constants**

| Inch Units               |      |                          |      | SI Metric Units         |      |                         |      |
|--------------------------|------|--------------------------|------|-------------------------|------|-------------------------|------|
| Feed<br>in. <sup>a</sup> | $C$  | Feed<br>in. <sup>a</sup> | $C$  | Feed<br>mm <sup>b</sup> | $C$  | Feed<br>mm <sup>b</sup> | $C$  |
| 0.001                    | 1.60 | 0.014                    | 0.97 | 0.02                    | 1.70 | 0.35                    | 0.97 |
| 0.002                    | 1.40 | 0.015                    | 0.96 | 0.05                    | 1.40 | 0.38                    | 0.95 |
| 0.003                    | 1.30 | 0.016                    | 0.94 | 0.07                    | 1.30 | 0.40                    | 0.94 |
| 0.004                    | 1.25 | 0.018                    | 0.92 | 0.10                    | 1.25 | 0.45                    | 0.92 |
| 0.005                    | 1.19 | 0.020                    | 0.90 | 0.12                    | 1.20 | 0.50                    | 0.90 |
| 0.006                    | 1.15 | 0.022                    | 0.88 | 0.15                    | 1.15 | 0.55                    | 0.88 |
| 0.007                    | 1.11 | 0.025                    | 0.86 | 0.18                    | 1.11 | 0.60                    | 0.87 |
| 0.008                    | 1.08 | 0.028                    | 0.84 | 0.20                    | 1.08 | 0.70                    | 0.84 |
| 0.009                    | 1.06 | 0.030                    | 0.83 | 0.22                    | 1.06 | 0.75                    | 0.83 |
| 0.010                    | 1.04 | 0.032                    | 0.82 | 0.25                    | 1.04 | 0.80                    | 0.82 |
| 0.011                    | 1.02 | 0.035                    | 0.80 | 0.28                    | 1.01 | 0.90                    | 0.80 |
| 0.012                    | 1.00 | 0.040                    | 0.78 | 0.30                    | 1.00 | 1.00                    | 0.78 |
| 0.013                    | 0.98 | 0.060                    | 0.72 | 0.33                    | 0.98 | 1.50                    | 0.72 |

<sup>a</sup>Turning, in/rev; milling, in/tooth; planing and shaping, in/stroke; broaching, in/tooth.

<sup>b</sup>Turning, mm/rev; milling, mm/tooth; planing and shaping, mm/stroke; broaching, mm/tooth.

**Table 5. Tool Wear Factors,  $W$** 

| Type of Operation                           |  | $W$       |
|---|--|-----------|
| For all operations with sharp cutting tools |  | 1.00      |
| Turning:                                    | Finish turning (light cuts)  | 1.10      |
|   | Normal rough and semifinish turning                                    | 1.30      |
|   | Extra-heavy-duty rough turning   | 1.60–2.00 |
| Milling:                                    | Slab milling   | 1.10      |
|   | End milling  | 1.10      |
|   | Light and medium face milling  | 1.10–1.25 |
|   | Extra-heavy-duty face milling  | 1.30–1.60 |
| Drilling:                                   | Normal drilling  | 1.30      |
|   | Drilling hard-to-machine materials and drilling with a very dull drill | 1.50      |
| Broaching:                                  | Normal broaching   | 1.05–1.10 |
|   | Heavy-duty surface broaching   | 1.20–1.30 |
| Planing and Shaping                         | Use values given for turning   |           |

$P_m$  = power at the motor; hp, or kW

$K_p$  = power constant (see Tables 3a and 3b)

$Q$  = metal removal rate; in<sup>3</sup>/min or cm<sup>3</sup>/s (see Table 7)

$C$  = feed factor for power constant (see Table 4)

$W$  = tool wear factor (see Table 5)

$E$  = machine tool efficiency factor (see Table 6)

$V$  = cutting speed, fpm, or m/min

$N$  = cutting speed, rpm

$f$  = feed rate for turning; in/rev or mm/rev

- $f$  = feed rate for planing and shaping; in/stroke, or mm/stroke  
 $f_t$  = feed per tooth; in/tooth, or mm/tooth  
 $f_m$  = feed rate; in/min or mm/min  
 $d_t$  = maximum depth of cut per tooth; inch, or mm  
 $d$  = depth of cut; inch, or mm  
 $n_t$  = number of teeth on milling cutter  
 $n_c$  = number of teeth engaged in work  
 $w$  = width of cut; inch, or mm

**Table 6. Machine Tool Efficiency Factors,  $E$** 

| Type of Drive     | $E$  | Type of Drive       | $E$       |
|-------------------|------|---------------------|-----------|
| Direct Belt Drive | 0.90 | Geared Head Drive   | 0.70–0.80 |
| Back Gear Drive   | 0.75 | Oil-Hydraulic Drive | 0.60–0.90 |

**Table 7. Formulas for Calculating the Metal Removal Rate,  $Q$** 

| Operation   | Metal Removal Rate                                  |  |
|---|---|--|
|   | For Inch Units Only<br>$Q = \text{in}^3/\text{min}$ | For SI Metric Units Only<br>$Q = \text{cm}^3/\text{s}$ |
| Single-Point Tools<br>(Turning, Planing, and Shaping) | $12Vfd$   | $\frac{V}{60}fd$                                       |
| Milling   | $f_m wd$  | $\frac{f_m wd}{60,000}$                                |
| Surface Broaching                                     | $12Vwn_c d_t$                                       | $\frac{V}{60}un_c d_t$                                 |

*Example:* A 180–200 Bhn AISI 4130 shaft is to be turned on a geared head lathe using a cutting speed of 350 fpm (107 m/min), a feed rate of 0.016 in/rev (0.40 mm/rev), and a depth of cut of 0.100 inch (2.54 mm). Estimate the power at the cutting tool and at the motor, using both the inch and metric data.

Inch units:

$$K_p = 0.62 \text{ (from Table 3b)}$$

$$C = 0.94 \text{ (from Table 4)}$$

$$W = 1.30 \text{ (from Table 5)}$$

$$E = 0.80 \text{ (from Table 6)}$$

$$Q = 12 Vfd = 12 \times 350 \times 0.016 \times 0.100 \text{ (from Table 7)}$$

$$Q = 6.72 \text{ in}^3/\text{min}$$

$$P_c = K_p C Q W = 0.62 \times 0.94 \times 6.72 \times 1.30 = 5.1 \text{ hp}$$

$$P_m = \frac{P_c}{E} = \frac{5}{0.80} = 6.4 \text{ hp}$$

SI metric units:

$$K_p = 1.69 \text{ (from Table 3b)}$$

$$C = 0.94 \text{ (from Table 4)}$$

$$W = 1.30 \text{ (from Table 5)}$$

$$E = 0.80 \text{ (from Table 6)}$$

$$Q = \frac{V}{60}fd = \frac{107}{60} \times 0.40 \times 2.54 = 1.81 \text{ cm}^3/\text{s} \text{ (from Table 7)}$$

$$P_c = K_p C Q W = 1.69 \times 0.94 \times 1.81 \times 1.30 = 3.74 \text{ kW}$$

$$P_m = \frac{P_c}{E} = \frac{3.74}{0.80} = 4.677 \text{ kW}$$

Whenever possible the maximum power available on a machine tool should be used when heavy cuts must be taken.

The cutting conditions for utilizing the maximum power should be selected in the following order: 1) select the maximum depth of cut that can be used; 2) select the maximum feed rate that can be used; and 3) estimate the cutting speed that will utilize the maximum power available on the machine. This sequence is based on obtaining the longest tool life of the cutting tool and at the same time obtaining as much production as possible from the machine.

*The life of a cutting tool is most affected by the cutting speed, then by the feed rate, and least of all by the depth of cut.* The maximum metal removal rate that a given machine is capable of machining from a given material is used as the basis for estimating the cutting speed that will utilize all the power available on the machine.

*Example:* A 0.125 inch deep cut is to be taken on a 200–210 Bhn AISI 1050 steel part using a 10 hp geared head lathe. The feed rate selected for this job is 018 in./rev. Estimate the cutting speed that will utilize the maximum power available on the lathe.

$$K_p = 0.85 \text{ (From Table 3b)}$$

$$C = 0.92 \text{ (From Table 4)}$$

$$W = 1.30 \text{ (From Table 5)}$$

$$E = 0.80 \text{ (From Table 6)}$$

$$Q_{max} = \frac{P_m E}{K_p C W} = \frac{10 \times 0.80}{0.85 \times 0.92 \times 1.30} \quad \left( P_m = \frac{K_p C Q W}{E} \right)$$

$$= 7.87 \text{ in}^3/\text{min}$$

$$V = \frac{Q_{max}}{12fd} = \frac{7.87}{12 \times 0.018 \times 0.125} \quad (Q = 12Vfd)$$

$$= 291 \text{ fpm}$$

*Example:* A 160–180 Bhn gray iron casting that is 6 inches wide is to have  $\frac{1}{8}$  inch stock removed on a 10 hp milling machine, using an 8 inch diameter, 10 tooth, indexable insert cemented carbide face milling cutter. The feed rate selected for this cutter is 0.012 in/tooth, and all the stock (0.125 inch) will be removed in one cut. Estimate the cutting speed that will utilize the maximum power available on the machine.

$$K_p = 0.52 \text{ (From Table 3a)}$$

$$C = 1.00 \text{ (From Table 4)}$$

$$W = 1.20 \text{ (From Table 5)}$$

$$E = 0.80 \text{ (From Table 6)}$$

$$Q_{max} = \frac{P_m E}{K_p C W} = \frac{10 \times 0.80}{0.52 \times 1.00 \times 1.20} = 12.82 \text{ in}^3/\text{min} \quad \left( P_m = \frac{K_p C Q W}{E} \right)$$

$$f_m = \frac{Q_{max}}{w d} = \frac{12.82}{6 \times 0.125} = 17.1 \text{ in/min} \quad (Q = f_m w d)$$

$$N = \frac{f_{max}}{f_t n_t} = \frac{17}{0.012 \times 10} = 142.4 \text{ rpm} \quad (f_m = f_t n_t N)$$

$$V = \frac{\pi D N}{12} = \frac{\pi \times 8 \times 142}{12} = 298.3 \text{ fpm} \quad \left( N = \frac{12 V}{\pi D} \right)$$

**Estimating Drilling Thrust, Torque, and Power.**—Although the lips of a drill cut metal and produce a chip in the same manner as the cutting edges of other metal cutting tools, the chisel edge removes the metal by means of a very complex combination of extrusion and cutting. For this reason a separate method must be used to estimate the power required for drilling. Also, it is often desirable to know the magnitude of the thrust and the torque required to drill a hole. The formulas and tabular data provided in this section are based on information supplied by the National Twist Drill Division of Regal-Beloit Corp. The values in Tables 8 through 11 are for sharp drills, and tool wear factors are given in Table 5. For most ordinary drilling operations 1.30 can be used as the tool wear factor. When drilling most difficult-to-machine materials and when the drill is allowed to become very dull, 1.50 should be used as the value of this factor. It is usually more convenient to measure the web thickness at the drill point than the length of the chisel edge; for this reason, the approximate  $w/d$  ratio corresponding to each  $c/d$  ratio for a correctly ground drill is provided in Table 9. For most standard twist drills the  $c/d$  ratio is 0.18, unless the drill has been ground short or the web has been thinned. The  $c/d$  ratio of split point drills is 0.03. The formulas given below can be used for spade drills, as well as for twist drills. Separate formulas are required for use with customary inch units and for SI metric units.

**Table 8. Work Material Factor,  $K_d$ , for Drilling with a Sharp Drill**

| Work Material                                      | Material Constant, $K_d$   |
|--|--|
| AISI 1117 (Resulfurized free machining mild steel) | 12,000   |
| Steel, 200 Bhn                                     | 24,000   |
| Steel, 300 Bhn                                     | 31,000   |
| Steel, 400 Bhn                                     | 34,000   |
| Cast Iron, 150 Bhn                                 | 14,000   |
| Most Aluminum Alloys                               | 7,000  |
| Most Magnesium Alloys                              | 4,000  |
| Most Brasses                                       | 14,000   |
| Leaded Brass                                       | 7,000  |
| Austenitic Stainless Steel (Type 316)              | 24,000 <sup>a</sup> for Torque<br>35,000 <sup>a</sup> for Thrust |
| Titanium Alloy Ti6Al4V 40R <sub>c</sub>            | 18,000 <sup>a</sup> for Torque<br>29,000 <sup>a</sup> for Thrust |
| René 41 40R <sub>c</sub>                           | 40,000 <sup>ab</sup> min.  |
| Hastelloy-C  | 30,000 <sup>a</sup> for Torque<br>37,000 <sup>a</sup> for Thrust |

<sup>a</sup> Values based upon a limited number of tests.

<sup>b</sup> Will increase with rapid wear.

**Table 9. Chisel Edge Factors for Torque and Thrust**

| <i>c/d</i> | Approx.<br><i>w/d</i> | Torque<br>Factor<br><i>A</i> | Thrust<br>Factor<br><i>B</i> | Thrust<br>Factor<br><i>J</i> | <i>c/d</i> | Approx.<br><i>w/d</i> | Torque<br>Factor<br><i>A</i> | Thrust<br>Factor<br><i>B</i> | Thrust<br>Factor<br><i>J</i> |
|------------|-----------------------|------------------------------|------------------------------|------------------------------|------------|-----------------------|------------------------------|------------------------------|------------------------------|
| 0.03       | 0.025                 | 1.000                        | 1.100                        | 0.001                        | 0.18       | 0.155                 | 1.085                        | 1.355                        | 0.030                        |
| 0.05       | 0.045                 | 1.005                        | 1.140                        | 0.003                        | 0.20       | 0.175                 | 1.105                        | 1.380                        | 0.040                        |
| 0.08       | 0.070                 | 1.015                        | 1.200                        | 0.006                        | 0.25       | 0.220                 | 1.155                        | 1.445                        | 0.065                        |
| 0.10       | 0.085                 | 1.020                        | 1.235                        | 0.010                        | 0.30       | 0.260                 | 1.235                        | 1.500                        | 0.090                        |
| 0.13       | 0.110                 | 1.040                        | 1.270                        | 0.017                        | 0.35       | 0.300                 | 1.310                        | 1.575                        | 0.120                        |
| 0.15       | 0.130                 | 1.080                        | 1.310                        | 0.022                        | 0.40       | 0.350                 | 1.395                        | 1.620                        | 0.160                        |

For drills of standard design, use  $c/d = 0.18$ ; for split point drills, use  $c/d = 0.03$

$c/d$  = Length of Chisel Edge  $\div$  Drill Diameter.

$w/d$  = Web Thickness at Drill Point  $\div$  Drill Diameter.

For inch units only:

$$T = 2K_d F_f F_T B W + K_d D^2 J W \quad (1)$$

$$M = K_d F_f F_M A W \quad (2)$$

$$P_c = MN / 63.025 \quad (3)$$

For SI metric units only:

$$T = 0.05 K_d F_f F_T B W + 0.007 K_d D^2 J W \quad (4)$$

$$M = \frac{K_d F_f F_M A W}{40,000} = 0.000025 K_d F_f F_M A W \quad (5)$$

$$P_c = MN / 9550 \quad (6)$$

Use with either inch or metric units:

$$P_m = \frac{P_c}{E} \quad (7)$$

where  $P_c$  = Power at the cutter; hp, or kW     $P_m$  = Power at the motor; hp, or kW

$M$  = Torque; in. lb, or N.m

$T$  = Thrust; lb, or N

$K_d$  = Work material factor (See Table 8)

$F_f$  = Feed factor (See Table 10)

$F_T$  = Thrust factor for drill diameter (See Table 11)

$F_M$  = Torque factor for drill diameter (See Table 11)

$A$  = Chisel edge factor for torque (See Table 9)

$B$  = Chisel edge factor for thrust (See Table 9)

$J$  = Chisel edge factor for thrust (See Table 9)

$W$  = Tool wear factor (See Table 5)

$N$  = Spindle speed; rpm

$E$  = Machine tool efficiency factor (See Table 6)

$D$  = Drill diameter; in., or mm

$c$  = Chisel edge length; in., or mm (See Table 9)

$w$  = Web thickness at drill point; in., or mm (See Table 9)

*Example:* A standard  $\frac{7}{8}$  inch drill is to drill steel parts having a hardness of 200 Bhn on a drilling machine having an efficiency of 0.80. The spindle speed to be used is 350 rpm and the feed rate will be 0.008 in./rev. Calculate the thrust, torque, and power required to drill these holes:

$$K_d = 24,000 \text{ (From Table 8)} \quad F_f = 0.021 \text{ (From Table 10)}$$

$$F_T = 0.899 \text{ (From Table 11)} \quad F_M = 0.786 \text{ (From Table 11)}$$

$$A = 1.085 \text{ (From Table 9)} \quad B = 1.355 \text{ (From Table 9)} \quad J = 0.030 \text{ (From Table 9)}$$



**Table 10. Feed Factors  $F_f$  for Drilling**

| Inch Units    |        |               |       | SI Metric Units |       |              |       |
|---------------|--------|---------------|-------|-----------------|-------|--------------|-------|
| Feed, in./rev | $F_f$  | Feed, in./rev | $F_f$ | Feed, mm/rev    | $F_f$ | Feed, mm/rev | $F_f$ |
| 0.0005        | 0.0023 | 0.012         | 0.029 | 0.01            | 0.025 | 0.30         | 0.382 |
| 0.001         | 0.004  | 0.013         | 0.031 | 0.03            | 0.060 | 0.35         | 0.432 |
| 0.002         | 0.007  | 0.015         | 0.035 | 0.05            | 0.091 | 0.40         | 0.480 |
| 0.003         | 0.010  | 0.018         | 0.040 | 0.08            | 0.133 | 0.45         | 0.528 |
| 0.004         | 0.012  | 0.020         | 0.044 | 0.10            | 0.158 | 0.50         | 0.574 |
| 0.005         | 0.014  | 0.022         | 0.047 | 0.12            | 0.183 | 0.55         | 0.620 |
| 0.006         | 0.017  | 0.025         | 0.052 | 0.15            | 0.219 | 0.65         | 0.708 |
| 0.007         | 0.019  | 0.030         | 0.060 | 0.18            | 0.254 | 0.75         | 0.794 |
| 0.008         | 0.021  | 0.035         | 0.068 | 0.20            | 0.276 | 0.90         | 0.919 |
| 0.009         | 0.023  | 0.040         | 0.076 | 0.22            | 0.298 | 1.00         | 1.000 |
| 0.010         | 0.025  | 0.050         | 0.091 | 0.25            | 0.330 | 1.25         | 1.195 |

**Table 11. Drill Diameter Factors:  $F_T$  for Thrust,  $F_M$  for Torque**

| Inch Units      |       |       |                 |       |       | SI Metric Units |       |       |                |       |       |
|-----------------|-------|-------|-----------------|-------|-------|-----------------|-------|-------|----------------|-------|-------|
| Drill Dia., in. | $F_T$ | $F_M$ | Drill Dia., in. | $F_T$ | $F_M$ | Drill Dia., mm  | $F_T$ | $F_M$ | Drill Dia., mm | $F_T$ | $F_M$ |
| 0.063           | 0.110 | 0.007 | 0.875           | 0.899 | 0.786 | 1.60            | 1.46  | 2.33  | 22.00          | 11.86 | 260.8 |
| 0.094           | 0.151 | 0.014 | 0.938           | 0.950 | 0.891 | 2.40            | 2.02  | 4.84  | 24.00          | 12.71 | 305.1 |
| 0.125           | 0.189 | 0.024 | 1.000           | 1.000 | 1.000 | 3.20            | 2.54  | 8.12  | 25.50          | 13.34 | 340.2 |
| 0.156           | 0.226 | 0.035 | 1.063           | 1.050 | 1.116 | 4.00            | 3.03  | 12.12 | 27.00          | 13.97 | 377.1 |
| 0.188           | 0.263 | 0.049 | 1.125           | 1.099 | 1.236 | 4.80            | 3.51  | 16.84 | 28.50          | 14.58 | 415.6 |
| 0.219           | 0.297 | 0.065 | 1.250           | 1.195 | 1.494 | 5.60            | 3.97  | 22.22 | 32.00          | 16.00 | 512.0 |
| 0.250           | 0.330 | 0.082 | 1.375           | 1.290 | 1.774 | 6.40            | 4.42  | 28.26 | 35.00          | 17.19 | 601.6 |
| 0.281           | 0.362 | 0.102 | 1.500           | 1.383 | 2.075 | 7.20            | 4.85  | 34.93 | 38.00          | 18.36 | 697.6 |
| 0.313           | 0.395 | 0.124 | 1.625           | 1.475 | 2.396 | 8.00            | 5.28  | 42.22 | 42.00          | 19.89 | 835.3 |
| 0.344           | 0.426 | 0.146 | 1.750           | 1.565 | 2.738 | 8.80            | 5.96  | 50.13 | 45.00          | 21.02 | 945.8 |
| 0.375           | 0.456 | 0.171 | 1.875           | 1.653 | 3.100 | 9.50            | 6.06  | 57.53 | 48.00          | 22.13 | 1062  |
| 0.438           | 0.517 | 0.226 | 2.000           | 1.741 | 3.482 | 11.00           | 6.81  | 74.90 | 50.00          | 22.86 | 1143  |
| 0.500           | 0.574 | 0.287 | 2.250           | 1.913 | 4.305 | 12.50           | 7.54  | 94.28 | 58.00          | 25.75 | 1493  |
| 0.563           | 0.632 | 0.355 | 2.500           | 2.081 | 5.203 | 14.50           | 8.49  | 123.1 | 64.00          | 27.86 | 1783  |
| 0.625           | 0.687 | 0.429 | 2.750           | 2.246 | 6.177 | 16.00           | 9.19  | 147.0 | 70.00          | 29.93 | 2095  |
| 0.688           | 0.741 | 0.510 | 3.000           | 2.408 | 7.225 | 17.50           | 9.87  | 172.8 | 76.00          | 31.96 | 2429  |
| 0.750           | 0.794 | 0.596 | 3.500           | 2.724 | 9.535 | 19.00           | 10.54 | 200.3 | 90.00          | 36.53 | 3293  |
| 0.813           | 0.847 | 0.689 | 4.000           | 3.031 | 12.13 | 20.00           | 10.98 | 219.7 | 100.00         | 39.81 | 3981  |

$W = 1.30$  (From Table 5)

$$T = 2K_d F_f F_T B W + K_d d^2 J W$$

$$= 2 \times 24,000 \times 0.21 \times 0.899 \times 1.355 \times 1.30 + 24,000 \times 0.875^2 \times 0.030 \times 1.30$$

$$= 2313 \text{ lb}$$

$$M = K_d F_f F_M A W$$

$$= 24,000 \times 0.021 \times 0.786 \times 1.085 \times 1.30 = 559 \text{ in. lb}$$

$$P_c = \frac{MN}{63,025} = \frac{559 \times 350}{63,025} = 3.1 \text{ hp} \quad P_m = \frac{P_c}{E} = \frac{3.1}{0.80} = 3.9 \text{ hp}$$

Twist drills are generally the most highly stressed of all metal cutting tools. They must not only resist the cutting forces on the lips, but also the drill torque resulting from these forces and the very large thrust force required to push the drill through the hole. Therefore, often when drilling smaller holes, the twist drill places a limit on the power used and for very large holes, the machine may limit the power.

## MACHINING ECONOMETRICS

## Tool Wear And Tool Life Relationships

**Tool wear.**—Tool-life is defined as the cutting time to reach a predetermined wear, called the tool wear criterion. The size of tool wear criterion depends on the grade used, usually a tougher grade can be used at bigger flank wear. For finishing operations, where close tolerances are required, the wear criterion is relatively small. Other alternative wear criteria are a predetermined value of the surface roughness, or a given depth of the crater which develops on the rake face of the tool. The most appropriate wear criteria depends on cutting geometry, grade, and materials.

Tool-life is determined by assessing the time — the tool-life — at which a given predetermined flank wear is reached, 0.25, 0.4, 0.6, 0.8 mm etc. Fig. 1 depicts how flank wear varies with cutting time (approximately straight lines in a semi-logarithmic graph) for three combinations of cutting speeds and feeds. Alternatively, these curves may represent how variations of machinability impact on tool-life, when cutting speed and feed are constant. All tool wear curves will sooner or later bend upwards abruptly and the cutting edge will break, i.e., catastrophic failure as indicated by the white arrows in Fig. 1.

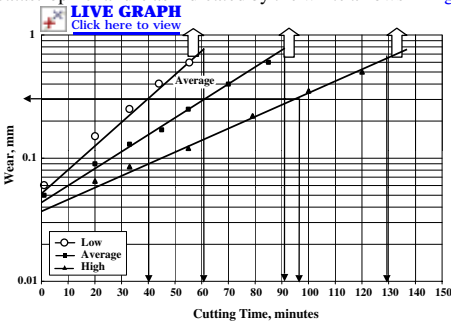


Fig. 1. Flank Wear as a Function of Cutting Time

The maximum deviation from the average tool-life 60 minutes in Fig. 1 is assumed to range between 40 and 95 minutes, i.e.  $-33\%$  and  $+58\%$  variation. The positive deviation from the average (longer than expected tool-life) is not important, but the negative one (shorter life) is, as the edge may break before the scheduled tool change after 60 minutes, when the flank wear is 0.6 mm.

It is therefore important to set the wear criterion at a safe level such that tool failures due to “normal” wear become negligible. This is the way machinability variations are mastered.

**Equivalent Chip Thickness (*ECT*).**—*ECT* combines the four basic turning variables, depth of cut, lead angle, nose radius and feed per revolution into one basic parameter. For all other metal cutting operations such as drilling, milling and grinding, additional variables such as number of teeth, width of cut, and cutter diameter are included in the parameter *ECT*. In turning, milling, and drilling, according to the *ECT* principle, when the product of feed times depth of cut is constant the tool-life is constant no matter how the depth of cut or feed is selected, provided that the cutting speed and cutting edge length are maintained constant. By replacing the geometric parameters with *ECT*, the number of tool-life tests to evaluate cutting parameters can be reduced considerably, by a factor of 4 in turning, and in milling by a factor of 7 because radial depth of cut, cutter diameter and number of teeth are additional parameters.

The introduction of the *ECT* concept constitutes a major simplification when predicting tool-life and calculating cutting forces, torque, and power. *ECT* was first presented in 1931 by Professor R. Woxen, who both theoretically and experimentally proved that *ECT* is a basic metal cutting parameter for high-speed cutting tools. Dr. Colding later proved that the concept also holds for carbide tools, and extended the calculation of *ECT* to be valid for cutting conditions when the depth of cut is smaller than the tool nose radius, or for round inserts. Colding later extended the concept to all other metal cutting operations, including the grinding process.

The definition of *ECT* is:

$$ECT = \frac{Area}{CEL} \text{ (mm or inch)}$$

where  $A$  = cross sectional area of cut (approximately = feed  $\times$  depth of cut), (mm<sup>2</sup> or inch<sup>2</sup>)

$CEL$  = cutting edge length (tool contact rubbing length), (mm or inch), see Fig. 9.

An exact value of  $A$  is obtained by the product of *ECT* and  $CEL$ . In turning, milling, and drilling, *ECT* varies between 0.05 and 1 mm, and is always less than the feed/rev or feed/tooth; its value is usually about 0.7 to 0.9 times the feed.

*Example 1:* For a feed of 0.8 mm/rev, depth of cut  $a = 3$  mm, and a cutting edge length  $CEL = 4$  mm<sup>2</sup>, the value of *ECT* is approximately  $ECT = 0.8 \times 3 \div 4 = 0.6$  mm.

The product of *ECT*,  $CEL$ , and cutting speed  $V$  (m/min or ft/min) is equal to the metal removal rate, *MRR*, which is measured in terms of the volume of chips removed per minute:

$$\begin{aligned} MRR &= 1000V \times Area = 1000V \times ECT \times CEL \text{ mm}^3/\text{min} \\ &= V \times Area \text{ cm}^3/\text{min or inch}^3/\text{min} \end{aligned}$$

The specific metal removal rate *SMRR* is the metal removal rate per mm cutting edge length  $CEL$ , thus:

$$\begin{aligned} SMMR &= 1000V \times ECT \text{ mm}^3/\text{min}/\text{mm} \\ &= V \times ECT \text{ cm}^3/\text{min}/\text{mm or inch}^3/\text{min}/\text{inch} \end{aligned}$$

*Example 2:* Using above data and a cutting speed of  $V = 250$  m/min specific metal removal rate becomes  $SMRR = 0.6 \times 250 = 150$  (cm<sup>3</sup>/min/mm).

*ECT in Grinding:* In grinding *ECT* is defined as in the other metal cutting processes, and is approximately equal to  $ECT = V_w \times ar \div V$ , where  $V_w$  is the work speed,  $ar$  is the depth of cut, and  $A = V_w \times ar$ . Wheel life is constant no matter how depth  $ar$ , or work speed  $V_w$ , is selected at  $V = \text{constant}$  (usually the influence of grinding contact width can be neglected). This translates into the same wheel life as long as the specific metal removal rate is constant, thus:

$$SMMR = 1000V_w \times ar \text{ mm}^3/\text{min}/\text{mm}$$

In grinding, *ECT* is much smaller than in the other cutting processes, ranging from about 0.0001 to 0.001 mm (0.000004 to 0.00004 inch). The grinding process is described in a separate chapter *GRINDING FEEDS AND SPEEDS* starting on page 1158.

**Tool-life Relationships.**—Plotting the cutting times to reach predetermined values of wear typically results in curves similar to those shown in Fig. 2 (cutting time versus cutting speed at constant feed per tooth) and Fig. 3 (cutting time versus feed per tooth at constant cutting speed). These tests were run in 1993 with mixed ceramics turn-milling hard steel, 82 R<sub>C</sub>, at the Technische Hochschule Darmstadt.

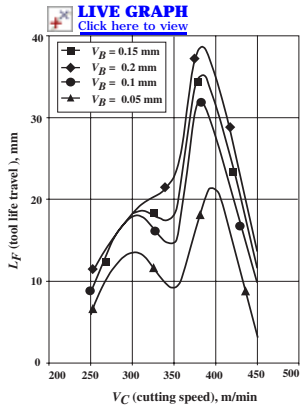
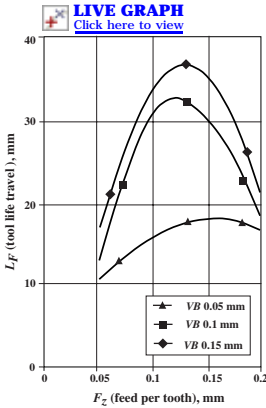


Fig. 2. Influence of feed per tooth on cutting time Fig. 3. Influence of cutting speed on tool-life

Tool-life has a maximum value at a particular setting of feed and speed. Economic and productive cutting speeds always occur on the right side of the curves in Figs. 2 and 4, which are called Taylor curves, represented by the so called Taylor's equation.

The variation of tool-life with feed and speed constitute complicated relationships, illustrated in Figs. 6a, 6b, and 6c.

**Taylor's Equation.**—Taylor's equation is the most commonly used relationship between tool-life  $T$ , and cutting speed  $V$ . It constitutes a straight line in a log-log plot, one line for each feed, nose radius, lead angle, or depth of cut, mathematically represented by:

$$V \times T^n = C \tag{1a}$$

where  $n$  = is the slope of the line

$C$  = is a constant equal to the cutting speed for  $T = 1$  minute

By transforming the equation to logarithmic axes, the Taylor lines become straight lines with slope =  $n$ . The constant  $C$  is the cutting speed on the horizontal ( $V$ ) axis at tool-life  $T = 1$  minute, expressed as follows

$$\ln V + n \times \ln T = \ln C \tag{1b}$$

For different values of feed or  $ECT$ , log-log plots of Equation (1a) form approximately straight lines in which the slope decreases slightly with a larger value of feed or  $ECT$ . In practice, the Taylor lines are usually drawn parallel to each other, i.e., the slope  $n$  is assumed to be constant.

Fig. 4 illustrates the Taylor equation, tool-life  $T$  versus cutting speed  $V$ , plotted in log-log coordinates, for four values of  $ECT = 0.1, 0.25, 0.5$  and  $0.7$  mm.

In Fig. 4, starting from the right, each  $T-V$  line forms a generally straight line that bends off and reaches its maximum tool-life, then drops off with decreasing speed (see also Figs. 2 and 3). When operating at short tool-lives, approximately when  $T$  is less than 5 minutes, each line bends a little so that the cutting speed for 1 minute life becomes less than the value calculated by constant  $C$ .

The Taylor equation is a very good approximation of the right hand side of the real tool-life curve (slightly bent). The portion of the curve to the left of the maximum tool-life gives shorter and shorter tool-lives when decreasing the cutting speed starting from the point of maximum tool-life. Operating at the maximum point of maximum tool-life, or to the left of it, causes poor surface finish, high cutting forces, and sometimes vibrations.

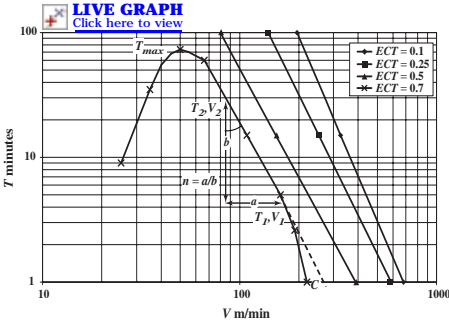


Fig. 4. Definition of slope  $n$  and constant  $C$  in Taylor's equation

**Evaluation of Slope  $n$ , and Constant  $C$ .**—When evaluating the value of the Taylor slope based on wear tests, care must be taken in selecting the tool-life range over which the slope is measured, as the lines are slightly curved.

The slope  $n$  can be found in three ways:

- Calculate  $n$  from the formula  $n = (\ln C - \ln V)/\ln T$ , reading the values of  $C$  and  $V$  for any value of  $T$  in the graph.
- Alternatively, using two points on the line,  $(V_1, T_1)$  and  $(V_2, T_2)$ , calculate  $n$  using the relationship  $V_1 \times T_1^n = V_2 \times T_2^n$ . Then, solving for  $n$ ,

$$n = \frac{\ln(V_1/V_2)}{\ln(T_2/T_1)}$$

- Graphically,  $n$  may be determined from the graph by measuring the distances “ $a$ ” and “ $b$ ” using a mm scale, and  $n$  is the ratio of  $a$  and  $b$ , thus,  $n = a/b$

*Example:* Using Fig. 4, and a given value of  $ECT=0.7$  mm, calculate the slope and constant of the Taylor line.

On the Taylor line for  $ECT=0.7$ , locate points corresponding to tool-lives  $T_1 = 15$  minutes and  $T_2 = 60$  minutes. Read off the associated cutting speeds as, approximately,  $V_1 = 110$  m/min and  $V_2 = 65$  m/min.

The slope  $n$  is then found to be  $n = \ln(110/65)/\ln(60/15) = 0.38$

The constant  $C$  can be then determined using the Taylor equation and either point  $(T_1, V_1)$  or point  $(T_2, V_2)$ , with equivalent results, as follows:

$$C = V \times T^n = 110 \times 15^{0.38} = 65 \times 60^{0.38} = 308 \text{ m/min (1027 fpm)}$$

**The Generalized Taylor Equation.**—The above calculated slope and constant  $C$  define tool-life at one particular value of feed  $f$ , depth of cut  $a$ , lead angle  $LA$ , nose radius  $r$ , and other relevant factors.

The generalized Taylor equation includes these parameters and is written

$$T^n = A \times f^m \times a^p \times LA^q \times r^s \quad (2)$$

where  $A$  = area; and,  $n, m, p, q,$  and  $s$  = constants.

There are two problems with the generalized equation: 1) a great number of tests have to be run in order to establish the constants  $n, m, p, q, s,$  etc.; and 2) the accuracy is not very good because Equation (2) yields straight lines when plotted versus  $f, a, LA,$  and  $r,$  when in reality, they are parabolic curves..

The Generalized Taylor Equation using Equivalent Chip Thickness (ECT): Due to the compression of the aforementioned geometrical variables ( $f, a, LA, r, \text{etc.}$ ) into ECT, Equation (2) can now be rewritten:

$$V \times T^n = A \times ECT^m \tag{3}$$

Experimental data confirms that the Equation (3) holds, approximately, within the range of the test data, but as soon as the equation is extended beyond the test results, the error can become very great because the  $V$ -ECT curves are represented as straight lines by Equation (3) and the real curves have a parabolic shape.

**The Colding Tool-life Relationship.**—This relationship contains 5 constants  $H, K, L, M,$  and  $N_0$ , which attain different values depending on tool grade, work material, and the type of operation, such as longitudinal turning versus grooving, face milling versus end milling, etc.

This tool-life relationship is proven to describe, with reasonable accuracy, how tool-life varies with ECT and cutting speed for any metal cutting and grinding operation. It is expressed mathematically as follows either as a generalized Taylor equation (4a), or, in logarithmic coordinates (4b):

$$V \times T^{(N_0 - L \times \ln ECT)} \times ECT^{\left(-\frac{H}{2M} + \frac{\ln ECT}{4M}\right)} = e^{\left(K - \frac{H}{4M}\right)} \tag{4a}$$

$$y = K - \frac{x - H}{4M} - z(N_0 - L_x) \tag{4b}$$

where  $x = \ln ECT$   $y = \ln V$   $z = \ln T$

$M$  = the vertical distance between the maximum point of cutting speed ( $ECT_H, V_H$ ) for  $T = 1$  minute and the speed  $V_G$ , at point ( $ECT_G, V_G$ ), as shown in Fig. 5.

$2M$  = the horizontal distance between point ( $ECT_H, V_G$ ) and point ( $V_G, ECT_G$ )

$H$  and  $K$  = the logarithms of the coordinates of the maximum speed point ( $ECT_H, V_H$ ) at tool-life  $T = 1$  minute, thus  $H = \ln(ECT_H)$  and  $K = \ln(V_H)$

$N_0$  and  $L$  = the variation of the Taylor slope  $n$  with ECT:  $n = N_0 - L \times \ln(ECT)$

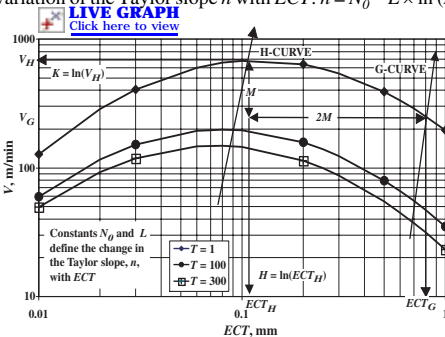


Fig. 5. Definitions of the constants  $H, K, L, M,$  and  $N_0$  for tool-life equation in the  $V$ -ECT plane with tool-life constant

The constants  $L$  and  $N_0$  are determined from the slopes  $n_1$  and  $n_2$  of two Taylor lines at  $ECT_1$  and  $ECT_2$ , and the constant  $M$  from 3  $V$ -ECT values at any constant tool-life. Constants  $H$  and  $K$  are then solved using the tool-life equation with the above-calculated values of  $L, N_0$  and  $M$ .

**The G- and H-curves.**—The *G*-curve defines the longest possible tool-life for any given metal removal rate, *MRR*, or specific metal removal rate, *SMRR*. It also defines the point where the total machining cost is minimum, after the economic tool-life  $T_E$ , or optimal tool-life  $T_O$ , has been calculated, see *Optimization Models, Economic Tool-life when Feed is Constant* starting on page 1110.

The tool-life relationship is depicted in the 3 planes:  $T-V$ , where *ECT* is the plotted parameter (the Taylor plane);  $T-ECT$ , where *V* is plotted; and,  $V-ECT$ , where *T* is a parameter. The latter plane is the most useful because the optimal cutting conditions are more readily understood when viewing in the  $V-ECT$  plane. Figs. 6a, 6b, and 6c show how the tool-life curves look in these 3 planes in log-log coordinates.

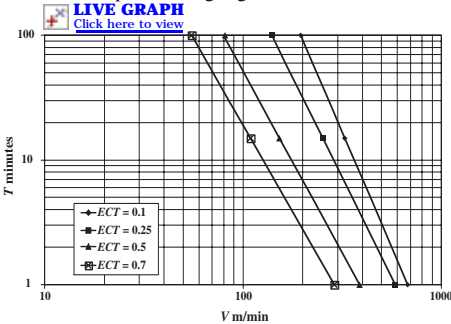


Fig. 6a. Tool-life vs. cutting speed  $T-V$ ,  $ECT$  plotted

Fig. 6a shows the Taylor lines, and Fig. 6b illustrates how tool-life varies with  $ECT$  at different values of cutting speed, and shows the *H*-curve. Fig. 6c illustrates how cutting speed varies with  $ECT$  at different values of tool-life. The *H*- and *G*-curves are also drawn in Fig. 6c.

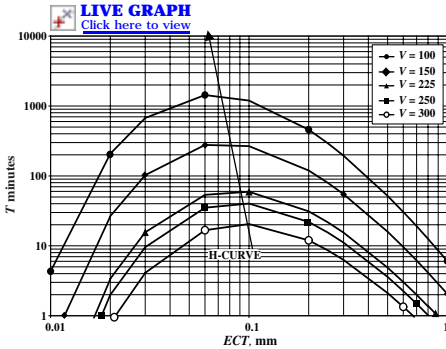


Fig. 6b. Tool-life vs.  $ECT$ ,  $T-ECT$ , cutting speed plotted

A simple and practical method to ascertain that machining is not done to the left of the *H*-curve is to examine the chips. When  $ECT$  is too small, about 0.03-0.05 mm, the chips tend to become irregular and show up more or less as dust.

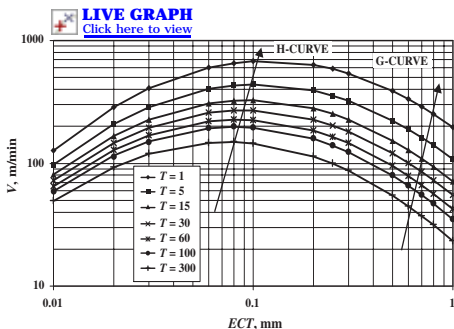


Fig. 6c. Cutting speed vs.  $ECT$ ,  $V-ECT$ , tool-life plotted

**The  $V-ECT-T$  Graph and the Tool-life Envelope.**— The tool-life envelope, in Fig. 7, is an area laid over the  $V-ECT-T$  graph, bounded by the points A, B, C, D, and E, within which successful cutting can be realized. The H- and G-curves represent two borders, lines AE and BC. The border curve, line AB, shows a lower limit of tool-life,  $T_{MIN} = 5$  minutes, and border curve, line DE, represents a maximum tool-life,  $T_{MAX} = 300$  minutes.

$T_{MIN}$  is usually 5 minutes due to the fact that tool-life versus cutting speed does not follow a straight line for short tool-lives; it decreases sharply towards one minute tool-life.  $T_{MAX}$  varies with tool grade, material, speed and  $ECT$  from 300 minutes for some carbide tools to 10000 minutes for diamond tools or diamond grinding wheels, although systematic studies of maximum tool-lives have not been conducted.

Sometimes the metal cutting system cannot utilize the maximum values of the  $V-ECT-T$  envelope, that is, cutting at optimum  $V-ECT$  values along the G-curve, due to machine power or fixture constraints, or vibrations. Maximum  $ECT$  values,  $ECT_{MAX}$ , are related to the strength of the tool material and the tool geometry, and depend on the tool grade and material selection, and require a relatively large nose radius.

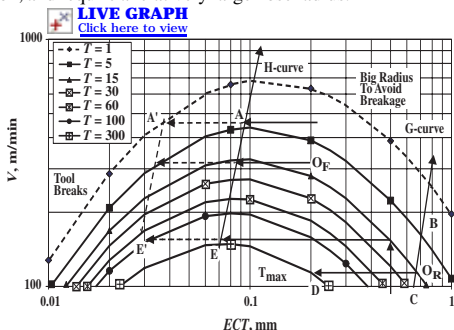


Fig. 7. Cutting speed vs.  $ECT$ ,  $V-ECT$ , tool-life plotted

Minimum  $ECT$  values,  $ECT_{MIN}$ , are defined by the conditions at which surface finish suddenly deteriorates and the cutting edge begins rubbing rather than cutting. These conditions begin left of the H-curve, and are often accompanied by vibrations and built-up edges on the tool. If feed or  $ECT$  is reduced still further, excessive tool wear with sparks and tool breakage, or melting of the edge occurs. For this reason, values of  $ECT$  lower than approx-



imately 0.03 mm should not be allowed. In Fig. 7, the  $ECT_{MIN}$  boundary is indicated by contour line  $A'E'$ .

In milling the minimum feed/tooth depends on the ratio  $ar/D$ , of radial depth of cut  $ar$ , and cutter diameter  $D$ . For small  $ar/D$  ratios, the chip thickness becomes so small that it is necessary to compensate by increasing the feed/tooth. See *High-speed Machining Econometrics* starting on page 1122 for more on this topic.

Fig. 7 demonstrates, in principle, minimum cost conditions for roughing at point  $O_R$ , and for finishing at point  $O_F$ , where surface finish or tolerances have set a limit. Maintaining the speed at  $O_R$ , 125 m/min, and decreasing feed reaches a maximum tool-life = 300 minutes at  $ECT = 0.2$ , and a further decrease of feed will result in shorter lives.

Similarly, starting at point X ( $V = 150$ ,  $ECT = 0.5$ ,  $T = 15$ ) and reducing feed, the  $H$ -curve will be reached at point E ( $ECT = 0.075$ ,  $T = 300$ ). Continuing to the left, tool-life will decrease and serious troubles occur at point E' ( $ECT = 0.03$ ).

Starting at point  $O_F$  ( $V = 300$ ,  $ECT = 0.2$ ,  $T = 15$ ) and reducing feed the  $H$ -curve will be reached at point E ( $ECT = 0.08$ ,  $T = 15$ ). Continuing to the left, life will decrease and serious troubles occur at  $ECT = 0.03$ .

Starting at point X ( $V = 400$ ,  $ECT = 0.2$ ,  $T = 5$ ) and reducing feed the  $H$ -curve will be reached at point E ( $ECT = 0.09$ ,  $T = 7$ ). Continuing to the left, life will decrease and serious troubles occur at point A' ( $ECT = 0.03$ ), where  $T = 1$  minute.

**Cutting Forces and Chip Flow Angle.**—There are three cutting forces, illustrated in Fig. 8, that are associated with the cutting edge with its nose radius  $r$ , depth of cut  $a$ , lead angle  $LA$ , and feed per revolution  $f$ , or in milling feed per tooth  $f_z$ . There is one drawing for roughing and one for finishing operations.

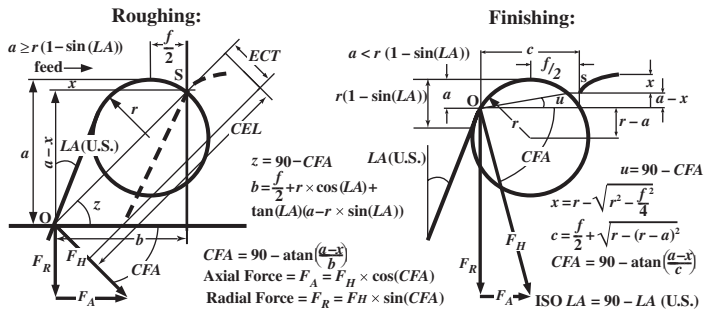


Fig. 8. Definitions of equivalent chip thickness,  $ECT$ , and chip flow angle,  $CFA$ .

The cutting force  $F_C$ , or tangential force, is perpendicular to the paper plane. The other two forces are the feed or axial force  $F_A$ , and the radial force  $F_R$  directed towards the work piece. The resultant of  $F_A$  and  $F_R$  is called  $F_H$ . When finishing,  $F_R$  is bigger than  $F_A$ , while in roughing  $F_A$  is usually bigger than  $F_R$ . The direction of  $F_H$ , measured by the chip flow angle  $CFA$ , is perpendicular to the rectangle formed by the cutting edge length  $CEL$  and  $ECT$  (the product of  $ECT$  and  $CEL$  constitutes the cross sectional area of cut,  $A$ ). The important task of determining the direction of  $F_H$ , and calculation of  $F_A$  and  $F_R$ , are shown in the formulas given in the Fig. 8.

The method for calculating the magnitudes of  $F_H$ ,  $F_A$ , and  $F_R$  is described in the following. The first thing is to determine the value of the cutting force  $F_C$ . Approximate formulas

to calculate the tangential cutting force, torque and required machining power are found in the section *ESTIMATING SPEEDS AND MACHINING POWER* starting on page 1082.

*Specific Cutting Force,  $K_c$* : The specific cutting force, or the specific energy to cut,  $K_c$ , is defined as the ratio between the cutting force  $F_C$  and the chip cross sectional area,  $A$ , thus,  $K_c = F_C \div A$  N/mm<sup>2</sup>.

The value of  $K_c$  decreases when  $ECT$  increases, and when the cutting speed  $V$  increases. Usually,  $K_c$  is written in terms of its value at  $ECT = 1$ , called  $K_{c1}$ , and neglecting the effect of cutting speed, thus  $K_c = K_{c1} \times ECT^B$ , where  $B$  = slope in log-log coordinates

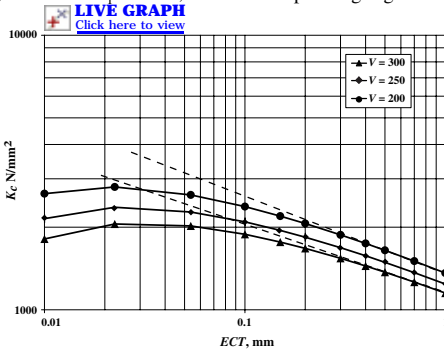


Fig. 9.  $K_c$  vs.  $ECT$ , cutting speed plotted

A more accurate relationship is illustrated in Fig. 9, where  $K_c$  is plotted versus  $ECT$  at 3 different cutting speeds. In Fig. 9, the two dashed lines represent the aforementioned equation, which each have different slopes,  $B$ . For the middle value of cutting speed,  $K_c$  varies with  $ECT$  from about 1900 to 1300 N/mm<sup>2</sup> when  $ECT$  increases from 0.1 to 0.7 mm. Generally the speed effect on the magnitude of  $K_c$  is approximately 5 to 15 percent when using economic speeds.

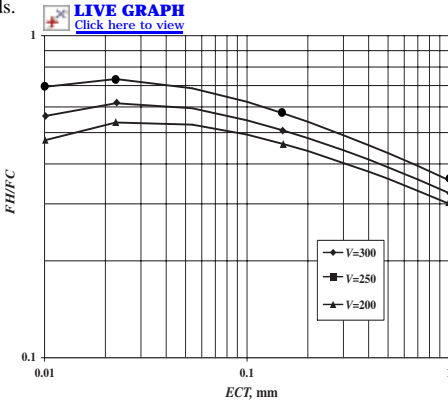


Fig. 10.  $F_H/F_C$  vs.  $ECT$ , cutting speed plotted

*Determination of Axial,  $F_A$ , and Radial,  $F_R$ , Forces*: This is done by first determining the resultant force  $F_H$  and then calculating  $F_A$  and  $F_R$  using the Fig. 8 formulas.  $F_H$  is derived

from the ratio  $F_H/F_C$ , which varies with  $ECT$  and speed in a fashion similar to  $Kc$ . Fig. 10 shows how this relationship may vary.

As seen in Fig. 10,  $F_H/F_C$  is in the range 0.3 to 0.6 when  $ECT$  varies from 0.1 to 1 mm, and speed varies from 200 to 250 m/min using modern insert designs and grades. Hence, using reasonable large feeds  $F_H/F_C$  is around 0.3–0.4 and when finishing about 0.5–0.6.

*Example:* Determine  $F_A$  and  $F_R$ , based on the chip flow angle and the cutting force  $F_C$ , in turning.

Using a value of  $Kc = 1500 \text{ N/mm}^2$  for roughing, when  $ECT = 0.4$ , and the cutting edge length  $CEL = 5 \text{ mm}$ , first calculate the area  $A = 0.4 \times 5 = 2 \text{ mm}^2$ . Then, determine the cutting force  $F_C = 2 \times 1500 = 3000 \text{ Newton}$ , and an approximate value of  $F_H = 0.5 \times 3000 = 1500 \text{ Newton}$ .

Using a value of  $Kc = 1700 \text{ N/mm}^2$  for finishing, when  $ECT = 0.2$ , and the cutting edge length  $CEL = 2 \text{ mm}$ , calculate the area  $A = 0.2 \times 2 = 0.4 \text{ mm}^2$ . The cutting force  $F_C = 0.4 \times 1700 = 680 \text{ Newton}$  and an approximate value of  $F_H = 0.35 \times 680 = 238 \text{ Newton}$ .

Fig. 8 can be used to estimate  $CFA$  for rough and finish turning. When the lead angle  $LA$  is 15 degrees and the nose radius is relatively large, an estimated value of the chip flow angle becomes about 30 degrees when roughing, and about 60 degrees in finishing. Using the formulas for  $F_A$  and  $F_R$  relative to  $F_H$  gives:

#### Roughing:

$$F_A = F_H \times \cos(CFA) = 1500 \times \cos 30 = 1299 \text{ Newton}$$

$$F_R = F_H \times \sin(CFA) = 1500 \times \sin 30 = 750 \text{ Newton}$$

#### Finishing:

$$F_A = F_H \times \cos(CFA) = 238 \times \cos 60 = 119 \text{ Newton}$$

$$F_R = F_H \times \sin(CFA) = 238 \times \sin 60 = 206 \text{ Newton}$$

The force ratio  $F_H/F_C$  also varies with the tool rake angle and increases with negative rakes. In grinding,  $F_H$  is much larger than the grinding cutting force  $F_C$ ; generally  $F_H/F_C$  is approximately 2 to 4, because grinding grits have negative rakes of the order  $-35$  to  $-45$  degrees.

**Forces and Tool-life.**—Forces and tool life are closely linked. The ratio  $F_H/F_C$  is of particular interest because of the unique relationship of  $F_H/F_C$  with tool-life.

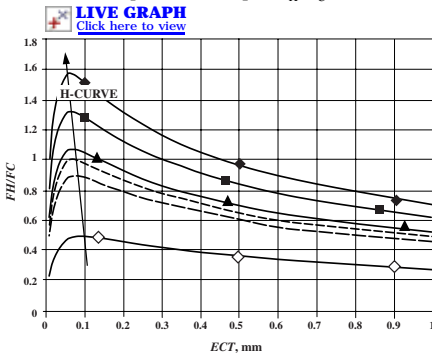


Fig. 11a.  $F_H/F_C$  vs.  $ECT$

The results of extensive tests at Ford Motor Company are shown in Figs. 11a and 11b, where  $F_H/F_C$  and tool-life  $T$  are plotted versus  $ECT$  at different values of cutting speed  $V$ .

For any constant speed, tool-life has a maximum at approximately the same values of  $ECT$  as has the function  $F_H/F_C$ . [LIVE GRAPH](#)  
[Click here to view](#)

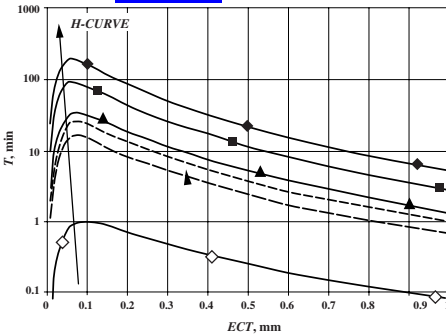


Fig. 11b. Tool-life vs.  $ECT$

*The Force Relationship:* Similar tests performed elsewhere confirm that the  $F_H/F_C$  function can be determined using the 5 tool-life constants ( $H, K, M, L, N_0$ ) introduced previously, and a new constant ( $L_F/L$ ).

$$\ln\left(\frac{1}{a} \cdot \frac{F_H}{F_C}\right) = \frac{K - y - \frac{(x - H)^2}{4M}}{\frac{L_F}{L}(N_0 - Lx)} \tag{5}$$

The constant  $a$  depends on the rake angle; in turning  $a$  is approximately 0.25 to 0.5 and  $L_F/L$  is 10 to 20.  $F_C$  attains its maximum values versus  $ECT$  along the  $H$ -curve, when the tool-life equation has maxima, and the relationships in the three force ratio planes look very similar to the tool-life functions shown in the tool-life planes in Figs. 6a, 6b, and 6c.

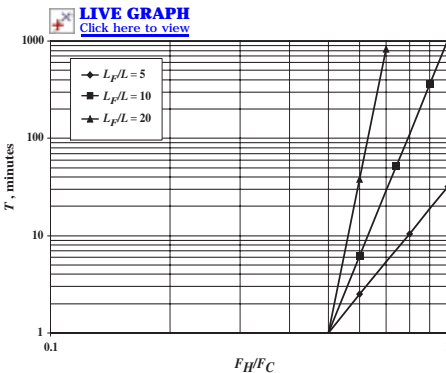


Fig. 12. Tool-life vs.  $F_H/F_C$

Tool-life varies with  $F_H/F_C$  with a simple formula according to Equation (5) as follows:

$$T = \left( \frac{F_H}{aF_C} \right)^{\frac{L_F}{L}}$$

where  $L$  is the constant in the tool-life equation, Equation (4a) or (4b), and  $L_F$  is the corresponding constant in the force ratio equation, Equation (5). In Fig. 12 this function is plotted for  $a = 0.5$  and for  $L_F/L = 5, 10, \text{ and } 20$ .

Accurate calculations of aforementioned relationships require elaborate laboratory tests, or better, the design of a special test and follow-up program for parts running in the ordinary production. A software machining program, such as Colding International Corp. *COMP* program can be used to generate the values of all 3 forces, torque and power requirements both for sharp and worn tools

**Surface Finish  $R_a$  and Tool-life.**—It is well known that the surface finish in turning decreases with a bigger tool nose radius and increases with feed; usually it is assumed that  $R_a$  increases with the square of the feed per revolution, and decreases inversely with increasing size of the nose radius. This formula, derived from simple geometry, gives rise to great errors. In reality, the relationship is more complicated because the tool geometry must taken into account, and the work material and the cutting conditions also have a significant influence.

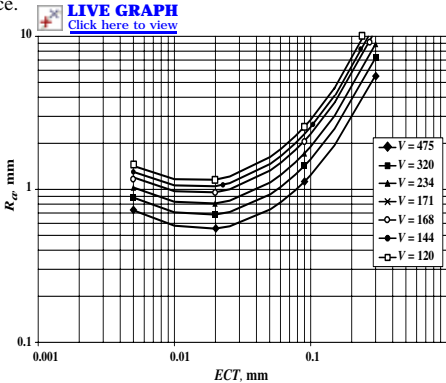


Fig. 13.  $R_a$  vs.  $ECT$ , nose radius  $r$  constant

Fig. 13 shows surface finish  $R_a$  versus  $ECT$  at various cutting speeds for turning cast iron with carbide tools and a nose radius  $r = 1.2$  mm. Increasing the cutting speed leads to a smaller  $R_a$  value.

Fig. 14 shows how the finish improves when the tool nose radius,  $r$ , increases at a constant cutting speed (168 m/min) in cutting nodular cast iron.

In Fig. 15,  $R_a$  is plotted versus  $ECT$  with cutting speed  $V$  for turning a 4310 steel with carbide tools, for a nose radius  $r = 1.2$  mm, illustrating that increasing the speed also leads to a smaller  $R_a$  value for steel machining.

A simple rule of thumb for the effect of increasing nose radius  $r$  on decreasing surface finish  $R_a$ , regardless of the ranges of  $ECT$  or speeds used, albeit within common practical values, is as follows. In finishing,

$$\frac{R_{a1}}{R_{a2}} = \left( \frac{r_2}{r_1} \right)^{0.5} \quad (6)$$

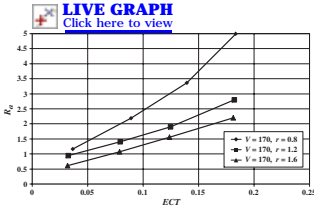


Fig. 14.  $R_a$  vs.  $ECT$   
cutting speed constant, nose radius  $r$  varies

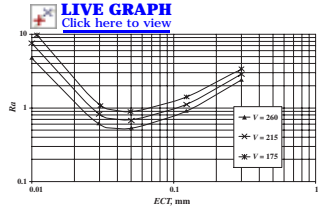


Fig. 15.  $R_a$  vs.  $ECT$ ,  
cutting speed and nose radius  $r$  constant

In roughing, multiply the finishing values found using Equation (6) by 1.5, thus,  $R_{a(Rough)} = 1.5 \times R_{a(Finish)}$  for each  $ECT$  and speed.

*Example 1:* Find the decrease in surface roughness resulting from a tool nose radius change from  $r = 0.8$  mm to  $r = 1.6$  mm in finishing. Also, find the comparable effect in roughing.

For finishing, using  $r_2 = 1.6$  and  $r_1 = 0.8$ ,  $R_{a1}/R_{a2} = (1.6/0.8)^{0.5} = 1.414$ , thus, the surface roughness using the larger tool radius is  $R_{a2} = R_{a1} \div 1.414 = 0.7R_{a1}$

In roughing, at the same  $ECT$  and speed,  $R_a = 1.5 \times R_{a2} = 1.5 \times 0.7R_{a1} = 1.05R_{a1}$

*Example 2:* Find the decrease in surface roughness resulting from a tool nose radius change from  $r = 0.8$  mm to  $r = 1.2$  mm

For finishing, using  $r_2 = 1.2$  and  $r_1 = 0.8$ ,  $R_{a1}/R_{a2} = (1.2/0.8)^{0.5} = 1.224$ , thus, the surface roughness using the larger tool radius is  $R_{a2} = R_{a1} \div 1.224 = 0.82R_{a1}$

In roughing, at the same  $ECT$  and speed,  $R_a = 1.5 \times R_{a2} = 1.5 \times 0.82R_{a1} = 1.23R_{a1}$

It is interesting to note that, at a given  $ECT$ , the  $R_a$  curves have a minimum, see Figs. 13 and 15, while tool-life shows a maximum, see Figs. 6b and 6c. As illustrated in Fig. 16,  $R_a$  increases with tool-life  $T$  when  $ECT$  is constant, in principle in the same way as does the force ratio.

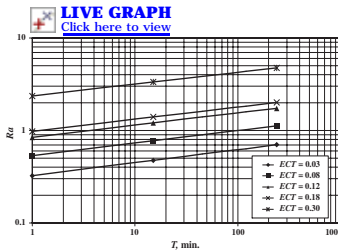


Fig. 16.  $R_a$  vs.  $T$ , holding  $ECT$  constant

*The Surface Finish Relationship:*  $R_a$  is determined using the same type of mathematical relationship as for tool-life and force calculations:

$$y = K_{Ra} - \frac{x - H_{Ra}}{4M_{Ra}} - (N_{ORa} - L_{Ra}) \ln(R_a)$$

where  $K_{Ra}$ ,  $H_{Ra}$ ,  $M_{Ra}$ ,  $N_{ORa}$ , and  $L_{Ra}$  are the 5 surface finish constants.

**Shape of Tool-life Relationships for Turning, Milling, Drilling and Grinding Operations—Overview.**—A summary of the general shapes of tool-life curves ( $V$ - $ECT$ - $T$  graphs) for the most common machining processes, including grinding, is shown in double logarithmic coordinates in Fig. 17a through Fig. 17h.

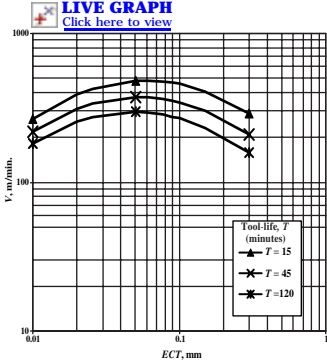


Fig. 17a. Tool-life for turning cast iron using coated carbide

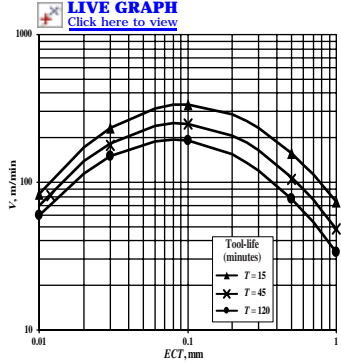


Fig. 17b. Tool-life for turning low-alloy steel using coated carbide

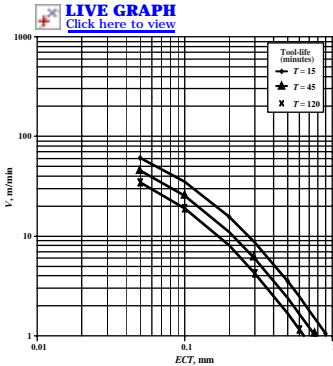


Fig. 17c. Tool-life for end-milling AISI4140 steel using high-speed steel

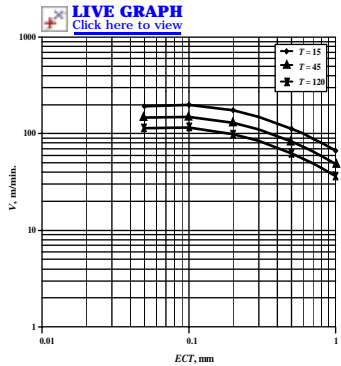


Fig. 17d. Tool-life for end-milling low-alloy steel using uncoated carbide

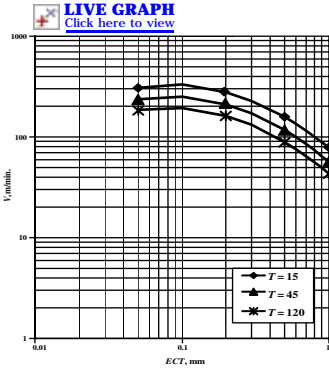


Fig. 17e. Tool-life for end-milling low-alloy steel using coated carbide

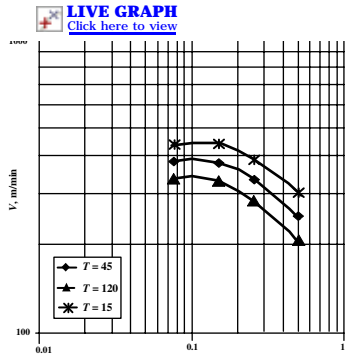


Fig. 17f. Tool-life for face-milling SAE 1045 steel using coated carbide

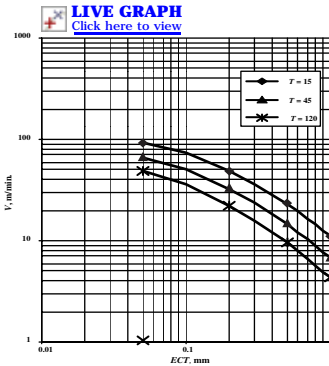


Fig. 17g. Tool-life for solid carbide drill

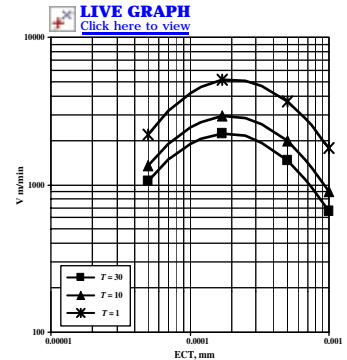


Fig. 17h. Wheel-life in grinding M4 tool-steel

**Calculation Of Optimized Values Of Tool-life, Feed And Cutting Speed**

**Minimum Cost.**—Global optimum is defined as the absolute minimum cost considering all alternative speeds, feeds and tool-lives, and refers to the determination of optimum tool-life  $T_O$ , feed  $f_O$ , and cutting speed  $V_O$ , for either minimum cost or maximum production rate. When using the tool-life equation,  $T = f(V, ECT)$ , determine the corresponding feed, for given values of depth of cut and operation geometry, from optimum equivalent chip thickness,  $ECT_O$ . Mathematically the task is to determine minimum cost, employing the cost function  $C_{TOT} = \text{cost of machining time} + \text{tool changing cost} + \text{tooling cost}$ . Minimum cost optima occur along the so-called *G*-curve, identified in Fig. 6c.

Another important factor when optimizing cutting conditions involves choosing the proper cost values for cost per edge  $C_E$ , replacement time per edge  $T_{RPL}$ , and not least, the hourly rate  $H_R$  that should be applied.  $H_R$  is defined as the portion of the hourly shop rate that is applied to the operations and machines in question. If optimizing all operations in the portion of the shop for which  $H_R$  is calculated, use the full rate; if only one machine is involved, apply a lower rate, as only a portion of the general overhead rate should be used, otherwise the optimum, and anticipated savings, are erroneous.



**Production Rate.**—The production rate is defined as the cutting time or the metal removal rate, corrected for the time required for tool changes, but neglecting the cost of tools.

The result of optimizing production rate is a shorter tool-life, higher cutting speed, and a higher feed compared to minimum cost optimization, and the tooling cost is considerably higher. Production rates optima also occur along the *G*-curve.

**The Cost Function.**—There are a number of ways the total machining cost  $C_{TOT}$  can be plotted, for example, versus feed, *ECT*, tool-life, cutting speed or other parameter. In Fig. 18a, cost for a face milling operation is plotted versus cutting time, holding feed constant, and using a range of tool-lives, *T*, varying from 1 to 240 minutes.

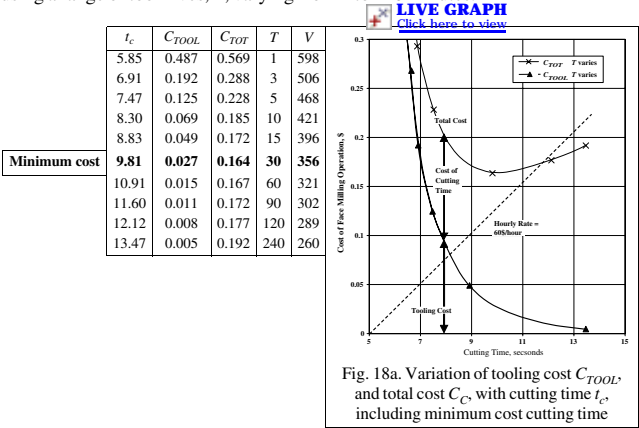


Fig. 18a. Variation of tooling cost  $C_{TOOL}$  and total cost  $C_C$  with cutting time  $t_c$ , including minimum cost cutting time

The tabulated values show the corresponding cutting speeds determined from the tool-life equation, and the influence of tooling on total cost. Tooling cost,  $C_{TOOL}$  = sum of tool cost + cost of replacing worn tools, decreases the longer the cutting time, while the total cost,  $C_{TOT}$ , has a minimum at around 10 seconds of cutting time. The dashed line in the graph represents the cost of machining time: the product of hourly rate  $H_R$ , and the cutting time  $t_c$  divided by 60. The slope of the line defines the value of  $H_R$ .

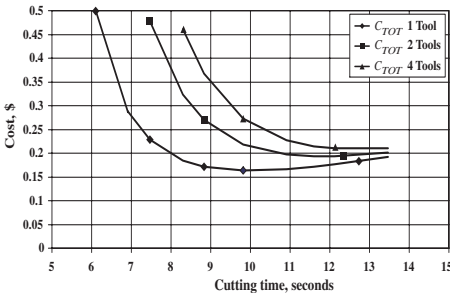


Fig. 18b. Total cost vs. cutting time for simultaneously cutting with 1, 2, and 4 tools

The cutting time for minimum cost varies with the ratio of tooling cost and  $H_R$ . Minimum cost moves towards a longer cutting time (longer tool-life) when either the price of the tooling increases, or when several tools cut simultaneously on the same part. In Fig. 18b, this is exemplified by running 2 and 4 cutters simultaneously on the same work piece, at the same feed and depth of cut, and with a similar tool as in Fig. 18a. As the tooling cost goes up 2 and 4 times, respectively, and  $H_R$  is the same, the total costs curves move up, but also moves to the right, as do the points of minimum cost and optimal cutting times. This means that going somewhat slower, with more simultaneously cutting tools, is advantageous.

**Global Optimum.**—Usually, global optimum occurs for large values of feed, heavy roughing, and in many cases the cutting edge will break trying to apply the large feeds required. Therefore, true optima cannot generally be achieved when roughing, in particular when using coated and wear resistant grades; instead, use the maximum values of feed,  $ECT_{max}$ , along the tool-life envelope, see Fig. 7.

As will be shown in the following, the first step is to determine the optimal tool-life  $T_O$ , and then determine the optimum values of feeds and speeds.

| Optimum Tool-life $T_O = 22$ minutes     |              |              |               |               |
|--|--------------|--------------|---------------|---------------|
| $f_z$                                    | $V_{22}$     | $t_c$ , sec. | $C_{TOOL}$    | $C_{TOT}$     |
| 0.03                                     | 416          | 28.067       | 0.1067        | 0.4965        |
| 0.08                                     | 397          | 11.017       | 0.0419        | 0.1949        |
| 0.10                                     | 374          | 9.357        | 0.0356        | 0.1655        |
| 0.17                                     | 301          | 6.831        | 0.0260        | 0.1208        |
| 0.20                                     | 276          | 6.334        | 0.0241        | 0.1120        |
| 0.40                                     | 171          | 5.117        | 0.0194        | 0.0905        |
| <b>0.60</b>                              | <b>119</b>   | <b>4.903</b> | <b>0.0186</b> | <b>0.0867</b> |
| 0.70                                     | 91           | 4.924        | 0.0187        | 0.0871        |
| Maximum Production Rate, $T = 5$ minutes |              |              |               |               |
| $f_z$                                    | $V_5$        | $t_c$        | $C_{TOOL}$    | $C_{TOT}$     |
| 0.7                                      | 163          | 3.569        | 0.059         | 0.109         |
| T Varies between 1 and 240 minutes       |              |              |               |               |
| $f_z = 0.10$                             |              | ECT=0.26     |               |               |
| $t_c$ secs.                              | $C_{TOOL}$   | $C_{TOT}$    | $T$           | $V$           |
| 5.850                                    | 0.487        | 0.569        | 1             | 598           |
| 6.914                                    | 0.192        | 0.288        | 3             | 506           |
| 7.473                                    | 0.125        | 0.228        | 5             | 468           |
| 8.304                                    | 0.069        | 0.185        | 10            | 421           |
| 8.832                                    | 0.049        | 0.172        | 15            | 396           |
| <b>9.815</b>                             | <b>0.027</b> | <b>0.164</b> | <b>30</b>     | <b>357</b>    |
| 10.906                                   | 0.015        | 0.167        | 60            | 321           |
| 11.600                                   | 0.011        | 0.172        | 90            | 302           |
| 12.119                                   | 0.008        | 0.177        | 120           | 289           |
| 13.467                                   | 0.005        | 0.192        | 240           | 260           |

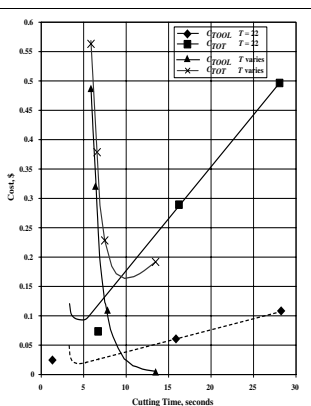


Fig. 19. Variation of tooling and total cost with cutting time, comparing global optimum with minimum cost at  $f_z = 0.1$  mm

The example in Fig. 19 assumes that  $T_O = 22$  minutes and the feed and speed optima were calculated as  $f_o = 0.6$  mm/tooth,  $V_o = 119$  m/min, and cutting time  $t_{cO} = 4.9$  secs.

The point of maximum production rate corresponds to  $f_o = 0.7$  mm/tooth,  $V_o = 163$  m/min, at tool-life  $T_O = 5$  minutes, and cutting time  $t_{cO} = 3.6$  secs. The tooling cost is approximately 3 times higher than at minimum cost (0.059 versus 0.0186), while the piece cost is only slightly higher: \$0.109 versus \$0.087.

When comparing the global optimum cost with the minimum at feed = 0.1 mm/tooth the graph shows it to be less than half (0.087 versus 0.164), but also the tooling cost is about 1/3 lower (0.0186 versus 0.027). The reason why tooling cost is lower depends on the tooling cost term  $t_c \times C_{E/T}$  (see *Calculation of Cost of Cutting and Grinding Operations* on page

1115). In this example, cutting times  $t_c = 4.9$  and  $9.81$  seconds, at  $T = 22$  and  $30$  minutes respectively, and the ratios are proportional to  $4.9/22 = 0.222$  and  $9.81/30 = 0.327$  respectively.

The portions of the total cost curve for shorter cutting times than at minimum corresponds to using feeds and speeds right of the  $G$ -curve, and those on the other side are left of this curve.

**Optimization Models, Economic Tool-life when Feed is Constant.**—Usually, optimization is performed versus the parameters tool-life and cutting speed, keeping feed at a constant value. The cost of cutting as function of cutting time is a straight line with the slope  $= H_R =$  hourly rate. This cost is independent of the values of tool change and tooling. Adding the cost of tool change and tooling, gives the variation of total cutting cost which shows a minimum with cutting time that corresponds to an economic tool-life,  $T_E$ . Economic tool-life represents a local optima (minimum cost) at a given constant value of feed, feed/tooth, or  $ECT$ .

Using the Taylor Equation:  $V \times T = C$  and differentiating  $C_{TOT}$  with respect to  $T$  yields:

**Economic tool-life:**

$$T_E = T_V \times (1/n - 1), \text{ minutes}$$

**Economic cutting speed:**

$$V_E = C/T_E^n, \text{ m/min, or sfm}$$

In these equations,  $n$  and  $C$  are constants in the Taylor equation for the given value of feed. Values of Taylor slopes,  $n$ , are estimated using the speed and feed Tables 1 through 23 starting on page 1027 and handbook Table 5b on page 1035 for turning, and Table 15e on page 1059 for milling and drilling; and  $T_V$  is the equivalent tooling-cost time.  $T_V = T_{RPL} + 60 \times C_E \div H_R$ , minutes, where  $T_{RPL}$  = time for replacing a worn insert, or a set of inserts in a milling cutter or inserted drill, or a twist drill, reamer, thread chaser, or tap.  $T_V$  is described in detail, later;  $C_E$  = cost per edge, or set of edges, or cost per regrind including amortized price of tool;

and  $H_R$  = hourly shop rate, or that rate that is impacted by the changes of cutting conditions.

In two dimensions, Fig. 20a shows how economic tool-life varies with feed per tooth. In this figure, the equivalent tooling-cost time  $T_V$  is constant, however the Taylor constant  $n$  varies with the feed per tooth.

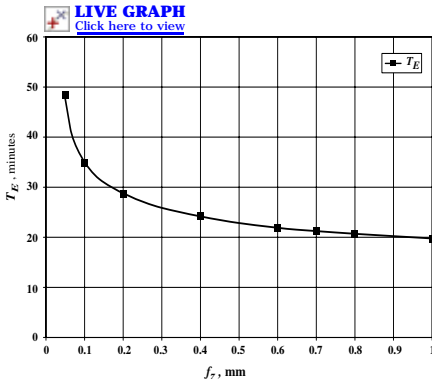


Fig. 20a. Economic tool-life,  $T_E$  vs. feed per tooth,  $f_z$

Economic tool-life increases with greater values of  $T_V$ , either when  $T_{RPL}$  is longer, or when cost per edge  $C_E$  is larger for constant  $H_R$ , or when  $H_R$  is smaller and  $T_{RPL}$  and  $C_E$  are unchanged. For example, when using an expensive machine (which makes  $H_R$  bigger) the value of  $T_V$  gets smaller, as does the economic tool-life,  $T_E = T_V \times (1/n - 1)$ . Reducing  $T_E$  results in an increase in the economic cutting speed,  $V_E$ . This means raising the cutting speed, and illustrates the importance, in an expensive system, of utilizing the equipment better by using more aggressive machining data.

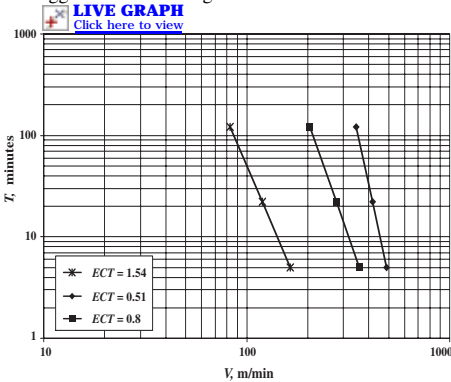


Fig. 20b. Tool-life vs. cutting speed, constant  $ECT$

As shown in Fig. 20a for a face milling operation, economic tool-life  $T_E$  varies considerably with feed/tooth  $f_z$ , in spite of the fact that the Taylor lines have only slightly different slopes ( $ECT = 0.51, 0.6, 1.54$ ), as shown in Fig. 20b. The calculation is based on the following cost data:  $T_V = 6$ , hourly shop rate  $H_R = \$60/\text{hour}$ , cutter diameter  $D = 125$  mm with number of teeth  $z = 10$ , and radial depth of cut  $ar = 40$  mm.

The conclusion relating to the determination of economic tool-life is that both hourly rate  $H_R$  and slope  $n$  must be evaluated with reasonable accuracy in order to arrive at good values. However, the method shown will aid in setting the trend for general machining economics evaluations.

**Global Optimum, Graphical Method.**—There are several ways to demonstrate in graphs how cost varies with the production parameters including optimal conditions. In all cases, tool-life is a crucial parameter.

Cutting time  $t_c$  is inversely proportional to the specific metal removal rate,  $SMRR = V \times ECT$ , thus,  $1/t_c = V \times ECT$ . Taking the log of both sides,

$$\ln V = -\ln ECT - \ln t_c + C \quad (7)$$

where  $C$  is a constant.

Equation (7) is a straight line with slope  $(-1)$  in the  $V-ECT$  graph when plotted in a log-log graph. This means that a constant cutting time is a straight 45-degree line in the  $V-ECT$  graph, when plotted in log-log coordinates with the same scale on both axis (a square graph).

The points at which the constant cutting time lines (at 45 degrees slope) are tangent to the tool-life curves define the  $G$ -curve, along which global optimum cutting occurs.

*Note:* If the ratio  $a/CEL$  is not constant when  $ECT$  varies, the constant cutting time lines are not straight, but the cutting time deviation is quite small in most cases.

In the  $V$ - $ECT$  graph, Fig. 21, 45-degree lines have been drawn tangent to each tool-life curve:  $T=1, 5, 15, 30, 60$  and 300 minutes. The tangential points define the  $G$ -curve, and the 45-degree lines represent different constant cutting times: 1, 2, 3, 10 minutes, etc. Following one of these lines and noting the intersection points with the tool-life curves  $T=1, 5, \text{etc.}$ , many different speed and feed combinations can be found that will give the same cutting time. As tool-life gets longer (tooling cost is reduced),  $ECT$  (feed) increases but the cutting speed has to be reduced.

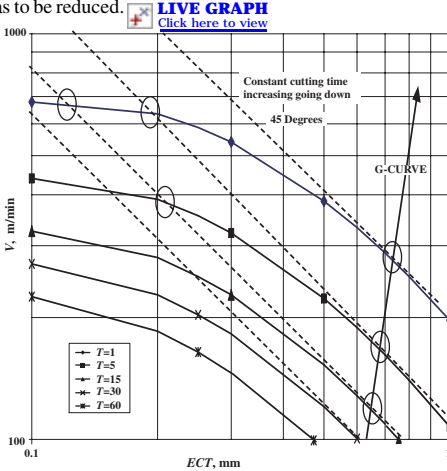


Fig. 21. Constant cutting time in the  $V$ - $ECT$  plane, tool-life constant

**Global Optimum, Mathematical Method.**—Global optimization is the search for extremum of  $C_{TOT}$  for the three parameters:  $T$ ,  $ECT$ , and  $V$ . The results, in terms of the tool-life equation constants, are:

**Optimum tool-life:**

$$T_O = T_V \times \left( \frac{1}{n_O} - 1 \right)$$

$$n_O = 2M \times (L \times \ln T_O)^2 + 1 - N_0 + L \times (2M + H)$$

where  $n_O$  = slope at optimum  $ECT$ .

The same approach is used when searching for maximum production rate, but without the term containing tooling cost.

**Optimum cutting speed:**

$$V_O = e^{-M + K + (H \times L - N_0) \times \ln T_O + M \times L^2 \times (\ln T_O)^2}$$

**Optimum  $ECT$ :**

$$ECT_O = e^{H + 2M \times (L \times \ln(T_O) + 1)}$$

Global optimum is not reached when face milling for very large feeds, and  $C_{TOT}$  decreases continually with increasing feed/tooth, but can be reached for a cutter with many teeth, say 20 to 30. In end milling, global optimum can often be achieved for big feeds and for 3 to 8 teeth.

### Determination Of Machine Settings And Calculation Of Costs

Based on the rules and knowledge presented in Chapters 1 and 2, this chapter demonstrates, with examples, how machining times and costs are calculated.

Additional formulas are given, and the speed and feed tables given in *SPEED AND FEED TABLES* starting on page 1022 should be used. Finally the selection of feeds, speeds and tool-lives for optimized conditions are described with examples related to turning, end milling, and face milling.

There are an infinite number of machine settings available in the machine tool power train producing widely different results. In practice only a limited number of available settings are utilized. Often, feed is generally selected independently of the material being cut, however, the influence of material is critical in the choice of cutting speed. The tool-life is normally not known or directly determined, but the number of pieces produced before the change of worn tools is better known, and tool-life can be calculated using the formula for piece cutting time  $t_c$  given in this chapter.

It is well known that increasing feeds or speeds reduces the number of pieces cut between tool changes, but not how big are the changes in the basic parameter tool-life. Therefore, there is a tendency to select "safe" data in order to get a long tool-life. Another common practice is to search for a tool grade yielding a longer life using the current speeds and feeds, or a 10–20% increase in cutting speed while maintaining the current tool-life. The reason for this old-fashioned approach is the lack of knowledge about the opportunities the metal cutting process offers for increased productivity.

For example, when somebody wants to calculate the cutting time, he/she can select a value of the feed rate (product of feed and rpm), and easily find the cutting time by dividing cutting distance by the feed rate. The number of pieces obtained out of a tool is a guess-work, however. This problem is very common and usually the engineers find desired tool-lives after a number of trial and error runs using a variety of feeds and speeds. If the user is not well familiar with the material cut, the tool-life obtained could be any number of seconds or minutes, or the cutting edge might break.

There are an infinite number of feeds and speeds, giving the same feed rate, producing equal cutting time. The same cutting time per piece  $t_c$  is obtained independent of the selection of feed/rev  $f$  and cutting speed  $V$ , (or rpm), as long as the feed rate  $F_R$  remains the same:  $F_R = f_1 \times \text{rpm}_1 = f_2 \times \text{rpm}_2 = f_3 \times \text{rpm}_3 \dots$ , etc. However, the number of parts before tool change  $N_{ch}$  will vary considerably including the tooling cost  $c_{tool}$  and the total cutting cost  $c_{tot}$ .

The dilemma confronting the machining-tool engineer or the process planner is how to set feeds and speeds for either desired cycle time, or number of parts between tool changes, while balancing the process versus other operations or balancing the total times in one cell with another. These problems are addressed in this section.

#### Nomenclature

$f$  = feed/rev or tooth, mm     $f_E$  = economic feed     $f_O$  = optimum feed  
 $T$  = tool-life, minutes     $T_E$  = economic tool-life     $T_O$  = optimum tool-life  
 $V$  = cutting speed, m/min     $V_E$  = economic cutting speed     $V_O$  = optimum cutting speed, m/min

Similarly, economic and optimum values of:

$c_{tool}$  = piece cost of tooling, \$     $C_{TOOL}$  = cost of tooling per batch, \$  
 $c_{tot}$  = piece total cost of cutting, \$     $C_{TOT}$  = total cost of cutting per batch, \$  
 $F_R$  = feed rate measured in the feeding direction, mm/rev  
 $N$  = batch size  
 $N_{ch}$  = number of parts before tool change  
 $t_c$  = piece cutting time, minutes     $T_C$  = cutting time per batch, minutes  
 $t_{cyc}$  = piece cycle time, minutes     $T_{CYC}$  = cycle time before tool change, minutes

$t_i$  = idle time (tool "air" motions during cycle), minutes

$z$  = cutter number of teeth

The following variables are used for calculating the per batch cost of cutting:

$C_C$  = cost of cutting time per batch, \$

$C_{CH}$  = cost of tool changes per batch, \$

$C_E$  = cost per edge, for replacing or regrinding, \$

$H_R$  = hourly rate, \$

$T_V$  = equivalent tooling-cost time, minutes

$T_{RPL}$  = time for replacing worn edge(s), or tool for regrinding, minutes

*Note:* In the list above, when two variables use the same name, one in capital letters and one lower case,  $T_C$  and  $t_c$  for example, the variable name in capital letters refers to batch processing and lowercase letters to per piece processing, such as  $T_C = N_{ch} \times t_c$ ,  $C_{TOT} = N_{ch} \times c_{tot}$ , etc.

### Formulas Valid For All Operation Types Including Grinding

#### Calculation of Cutting Time and Feed Rate

##### Feed Rate:

$F_R = f \times \text{rpm}$  (mm/min), where  $f$  is the feed in mm/rev along the feeding direction,

rpm is defined in terms of work piece or cutter diameter  $D$  in mm, and cutting speed  $V$  in m/min, as follows:

$$\text{rpm} = \frac{1000V}{\pi D} = \frac{318V}{D}$$

##### Cutting time per piece:

*Note:* Constant cutting time is a straight 45-degree line in the  $V$ - $ECT$  graph, along which tool-life varies considerably, as is shown in Chapter 2.

$$t_c = \frac{Dist}{F_R} = \frac{Dist}{f \times \text{rpm}} = \frac{Dist \times \pi D}{1000V \times f}$$

where the units of distance cut  $Dist$ , diameter  $D$ , and feed  $f$  are mm, and  $V$  is in m/min.

In terms of  $ECT$ , cutting time per piece,  $t_c$ , is as follows:

$$t_c = \frac{Dist \times \pi D}{1000V} \times \frac{a}{CEL \times ECT}$$

where  $a$  = depth of cut, because feed  $\times$  cross sectional chip area =  $f \times a = CEL \times ECT$ .

*Example 3, Cutting Time:* Given  $Dist = 105$  mm,  $D = 100$  mm,  $f = 0.3$  mm,  $V = 300$  m/min, rpm = 700,  $F_R = 210$  mm/min, find the cutting time.

Cutting time =  $t_c = 105 \times 3.1416 \times 100 \div (1000 \times 300 \times 0.3) = 0.366$  minutes = 22 seconds

#### Scheduling of Tool Changes

##### Number of parts before tool change:

$$N_{ch} = T \div t_c$$

##### Cycle time before tool change:

$T_{CYC} = N_{ch} \times (t_c + t_i)$ , where  $t_{CYC} = t_c + t_i$ , where  $t_c$  = cutting time per piece,  $t_i$  = idle time per piece

##### Tool-life:

$$T = N_{ch} \times t_c$$

*Example 4:* Given tool-life  $T = 90$  minutes, cutting time  $t_c = 3$  minutes, and idle time  $t_i = 3$  minutes, find the number of parts produced before a tool change is required and the time until a tool change is required.

Number of parts before tool change =  $N_{ch} = 90/3 = 30$  parts.

Cycle time before tool change =  $T_{CYC} = 30 \times (3 + 3) = 180$  minutes

*Example 5:* Given cutting time,  $t_c = 1$  minute, idle time  $t_i = 1$  minute,  $N_{ch} = 100$  parts, calculate the tool-life  $T$  required to complete the job without a tool change, and the cycle time before a tool change is required.

Tool-life =  $T = N_{ch} \times t_c = 100 \times 1 = 100$  minutes.

Cycle time before tool change =  $T_{CYC} = 100 \times (1 + 1) = 200$  minutes.

**Calculation of Cost of Cutting and Grinding Operations.**—When machining data varies, the cost of cutting, tool changing, and tooling will change, but the costs of idle and slack time are considered constant.

**Cost of Cutting per Batch:**

$$C_C = H_R \times T_C / 60$$

$T_C$  = cutting time per batch = (number of parts)  $\times t_c$ , minutes, or when determining time for tool change  $T_{Cch} = N_{ch} \times t_c$  minutes = cutting time before tool change.

$t_c$  = Cutting time/part, minutes

$H_R$  = Hourly Rate

**Cost of Tool Changes per Batch:**

$$C_{CH} = \frac{H_R}{60} \times T_C \times \frac{T_{RPL}}{T} \quad \frac{\$}{min} \cdot min = \$$$

where  $T$  = tool-life, minutes, and  $T_{RPL}$  = time for replacing a worn edge(s), or tool for regrinding, minutes

**Cost of Tooling per Batch:**

Including cutting tools and holders, but without tool changing costs,

$$C_{TOOL} = \frac{H_R}{60} \times T_C \times \frac{60C_E}{T} \quad \frac{\$}{min} \cdot min \cdot \frac{min}{hr} \cdot \frac{\$}{min} = \$$$

**Cost of Tooling + Tool Changes per Batch:**

Including cutting tools, holders, and tool changing costs,

$$(C_{TOOL} + C_{CH}) = \frac{H_R}{60} \times T_C \times \frac{T_{RPL} + \frac{60C_E}{H_R}}{T}$$

**Total Cost of Cutting per Batch:**

$$C_{TOT} = \frac{H_R}{60} \times T_C \left( 1 + \frac{T_{RPL} + \frac{60C_E}{H_R}}{T} \right)$$

**Equivalent Tooling-cost Time,  $T_V$ :**

The two previous expressions can be simplified by using  $T_V = T_{RPL} + \frac{60C_E}{H_R}$

thus:

$$(C_{TOOL} + C_{CH}) = \frac{H_R}{60} \times T_C \times \frac{T_V}{T}$$



$$C_{TOT} = \frac{H_R}{60} \times T_C \left( 1 + \frac{T_V}{T} \right)$$

$C_E$  = cost per edge(s) is determined using two alternate formulas, depending on whether tools are reground or inserts are replaced:

#### Cost per Edge, Tools for Regrinding

$$C_E = \frac{\text{cost of tool} + (\text{number of regrinds} \times \text{cost/regrind})}{1 + \text{number of regrinds}}$$

#### Cost per Edge, Tools with Inserts:

$$C_E = \frac{\text{cost of insert(s)}}{\text{number of edges per insert}} + \frac{\text{cost of cutter body}}{\text{cutter body life in number of edges}}$$

*Note:* In practice allow for insert failures by multiplying the insert cost by 4/3, that is, assuming only 3 out of 4 edges can be effectively used.

*Example 6, Cost per Edge—Tools for Regrinding:* Use the data in the table below to calculate the cost per edge(s)  $C_E$ , and the equivalent tooling-cost time  $T_V$ , for a drill.

| Time for cutter replacement $T_{RPL}$ , minute | Cutter Price, \$ | Cost per regrind, \$ | Number of regrinds | Hourly shop rate, \$ | Batch size | Taylor slope, $n$ | Economic cutting time, $t_{cE}$ minute |
|--|------------------|----------------------|--------------------|----------------------|------------|-------------------|--|
| 1  | 40               | 6                    | 5                  | 50                   | 1000       | 0.25              | 1.5                                    |

Using the cost per edge formula for reground tools,  $C_E = (40 + 5 \times 6) \div (1 + 5) = \$6.80$

When the hourly rate is \$50/hr,  $T_V = T_{RPL} + \frac{60C_E}{H_R} = 1 + \frac{60(6.8)}{50} = 9.16$  minutes

Calculate economic tool-life using  $T_E = T_V \times \left( \frac{1}{n} - 1 \right)$  thus,  $T_E = 9.17 \times (1/0.25 - 1) = 9.16 \times 3 = 27.48$  minutes.

Having determined, elsewhere, the economic cutting time per piece to be  $t_{cE} = 1.5$  minutes, for a batch size = 1000 calculate:

Cost of Tooling + Tool Change per Batch:

$$(C_{TOOL} + C_{CH}) = \frac{H_R}{60} \times T_C \times \frac{T_V}{T} = \frac{50}{60} \times 1000 \times 1.5 \times \frac{9.16}{27.48} = \$ 417$$

Total Cost of Cutting per Batch:

$$C_{TOT} = \frac{H_R}{60} \times T_C \left( 1 + \frac{T_V}{T} \right) = \frac{50}{60} \times 1000 \times 1.5 \times \left( 1 + \frac{9.16}{27.48} \right) = \$ 1617$$

*Example 7, Cost per Edge—Tools with Inserts:* Use data from the table below to calculate the cost of tooling and tool changes, and the total cost of cutting.

For face milling, multiply insert price by safety factor 4/3 then calculate the cost per edge:  $C_E = 10 \times (5/3) \times (4/3) + 750/500 = 23.72$  per set of edges

When the hourly rate is \$50, equivalent tooling-cost time is  $T_V = 2 + 23.72 \times 60/50 = 30.466$  minutes (first line in table below). The economic tool-life for Taylor slope  $n = 0.333$  would be  $T_E = 30.466 \times (1/0.333 - 1) = 30.466 \times 2 = 61$  minutes.

When the hourly rate is \$25, equivalent tooling-cost time is  $T_V = 2 + 23.72 \times 60/25 = 58.928$  minutes (second line in table below). The economic tool-life for Taylor slope  $n = 0.333$  would be  $T_E = 58.928 \times (1/0.333 - 1) = 58.928 \times 2 = 118$  minutes.

| Time for replacement of inserts<br>$T_{RPL}$ , minutes | Number of inserts | Price per insert | Edges per insert | Cutter Price | Edges per cutter | Cost per set of edges, $C_E$ | Hourly shop rate | $T_V$ minutes |
|--|-------------------|------------------|------------------|--------------|------------------|------------------------------|------------------|---------------|
| Face mill  |                   |                  |                  |              |                  |                              |                  |               |
| 2  | 10                | 5                | 3                | 750          | 500              | 23.72                        | 50               | 30.466        |
| 2  | 10                | 5                | 3                | 750          | 500              | 23.72                        | 25               | 58.928        |
| End mill   |                   |                  |                  |              |                  |                              |                  |               |
| 1  | 3                 | 6                | 2                | 75           | 200              | 4.375                        | 50               | 6.25          |
| Turning  |                   |                  |                  |              |                  |                              |                  |               |
| 1  | 1                 | 5                | 3                | 50           | 100              | 2.72                         | 30               | 6.44          |

With above data for the face mill, and after having determined the economic cutting time as  $t_{cE} = 1.5$  minutes, calculate for a batch size = 1000 and \$50 per hour rate:

Cost of Tooling + Tool Change per Batch:

$$(C_{TOOL} + C_{CH}) = \frac{H_R}{60} \times T_C \times \frac{T_V}{T} = \frac{50}{60} \times 1000 \times 1.5 \times \frac{30.466}{61} = \$ 624$$

Total Cost of Cutting per Batch:

$$C_{TOT} = \frac{H_R}{60} \times T_C \left(1 + \frac{T_V}{T}\right) = \frac{50}{60} \times 1000 \times 1.5 \times \left(1 + \frac{30.466}{61}\right) = \$ 1874$$

Similarly, at the \$25/hour shop rate,  $(C_{TOOL} + C_{CH})$  and  $C_{TOT}$  are \$312 and \$937, respectively.

*Example 8, Turning:* Production parts were run in the shop at feed/rev = 0.25 mm. One series was run with speed  $V_1 = 200$  m/min and tool-life was  $T_1 = 45$  minutes. Another was run with speed  $V_2 = 263$  m/min and tool-life was  $T_2 = 15$  minutes. Given idle time  $t_i = 1$  minute, cutting distance  $Dist = 1000$  mm, work diameter  $D = 50$  mm.

First, calculate Taylor slope,  $n$ , using Taylor's equation  $V_1 \times T_1^n = V_2 \times T_2^n$ , as follows:

$$n = \ln \frac{V_1}{V_2} \div \ln \frac{T_2}{T_1} = \ln \frac{200}{263} \div \ln \frac{15}{45} = 0.25$$

Economic tool-life  $T_E$  is next calculated using the equivalent tooling-cost time  $T_V$ , as described previously. Assuming a calculated value of  $T_V = 4$  minutes, then  $T_E$  can be calculated from

$$T_E = T_V \times \left(\frac{1}{n} - 1\right) = 4 \times \left(\frac{1}{0.25} - 1\right) = 12 \text{ minutes}$$

Economic cutting speed,  $V_E$  can be found using Taylor's equation again, this time using the economic tool-life, as follows,

$$V_{E1} \times (T_E)^n = V_2 \times (T_2)^n$$

$$V_{E1} = V_2 \times \left(\frac{T_2}{T_E}\right)^n = 263 \times \left(\frac{15}{12}\right)^{0.25} = 278 \text{ m/min}$$

Using the process data, the remaining economic parameters can be calculated as follows:

Economic spindle rpm,  $rpm_E = (1000V_E)/(\pi D) = (1000 \times 278)/(3.1416 \times 50) = 1770$  rpm

Economic feed rate,  $F_{RE} = f \times rpm_E = 0.25 \times 1770 = 443$  mm/min

Economic cutting time,  $t_{cE} = Dist / F_{RE} = 1000 / 443 = 2.259$  minutes

Economic number of parts before tool change,  $N_{chE} = T_E \div t_{cE} = 12 \div 2.259 = 5.31$  parts

Economic cycle time before tool change,  $T_{CYCE} = N_{chE} \times (t_c + t_i) = 5.31 \times (2.259 + 1) = 17.3$  minutes.

### Variation Of Tooling And Total Cost With The Selection Of Feeds And Speeds

It is a well-known fact that tool-life is reduced when either feed or cutting speed is increased. When a higher feed/rev is selected, the cutting speed must be decreased in order to maintain tool-life. However, a higher feed rate (feed rate = feed/rev  $\times$  rpm, mm/min) can result in a longer tool-life if proper cutting data are applied. Optimized cutting data require accurate machinability databases and a computer program to analyze the options. Reasonably accurate optimized results can be obtained by selecting a large feed/rev or tooth, and then calculating the economic tool-life  $T_E$ . Because the cost versus feed or  $ECT$  curve is shallow around the true minimum point, i.e., the global optimum, the error in applying a large feed is small compared with the exact solution.

Once a feed has been determined, the economic cutting speed  $V_E$  can be found by calculating the Taylor slope, and the time/cost calculations can be completed using the formulas described in last section.

The remainder of this section contains examples useful for demonstrating the required procedures. Global optimum may or may not be reached, and tooling cost may or may not be reduced, compared to currently used data. However, the following examples prove that significant time and cost reductions are achievable in today's industry.

*Note:* Starting values of reasonable feeds in mm/rev can be found in the Handbook speed and feed tables, see *Principal Speed and Feed Tables* on page 1022, by using the  $f_{avg}$  values converted to mm as follows: feed (mm/rev) = feed (inch/rev)  $\times$  25.4 (mm/inch), thus 0.001 inch/rev = 0.001  $\times$  25.4 = 0.0254 mm/rev. When using speed and feed [Tables 1](#) through [23](#), where feed values are given in thousandths of inch per revolution, simply multiply the given feed by 25.4/1000 = 0.0254, thus feed (mm/rev) = feed (0.001 inch/rev)  $\times$  0.0254 (mm/0.001inch).

*Example 9, Converting Handbook Feed Values From Inches to Millimeters:* Handbook tables give feed values  $f_{opt}$  and  $f_{avg}$  for 4140 steel as 17 and 8  $\times$  (0.001 inch/rev) = 0.017 and 0.009 inch/rev, respectively. Convert the given feeds to mm/rev.

$$\text{feed} = 0.017 \times 25.4 = 17 \times 0.0254 = 0.4318 \text{ mm/rev}$$

$$\text{feed} = 0.008 \times 25.4 = 8 \times 0.0254 = 0.2032 \text{ mm/rev}$$

*Example 10, Using Handbook Tables to Find the Taylor Slope and Constant:* Calculate the Taylor slope and constant, using cutting speed data for 4140 steel in [Table 1](#) starting on page [1027](#), and for ASTM Class 20 grey cast iron using data from [Table 4a](#) on page [1033](#), as follows:

For the 175–250 Brinell hardness range, and the hard tool grade,

$$n = \frac{\ln(V_1/V_2)}{\ln(T_2/T_1)} = \frac{\ln(525/705)}{\ln(15/45)} = 0.27 \quad C = V_1 \times (T_1)^n = 1458$$

For the 175–250 Brinell hardness range, and the tough tool grade,

$$n = \frac{\ln(V_1/V_2)}{\ln(T_2/T_1)} = \frac{\ln(235/320)}{\ln(15/45)} = 0.28 \quad C = V_1 \times (T_1)^n = 685$$

For the 300–425 Brinell hardness range, and the hard tool grade,

$$n = \frac{\ln(V_1/V_2)}{\ln(T_2/T_1)} = \frac{\ln(330/440)}{\ln(15/45)} = 0.26 \quad C = V_1 \times (T_1)^n = 894$$

For the 300–425 Brinell hardness range, and the tough tool grade,

$$n = \frac{\ln(V_1/V_2)}{\ln(T_2/T_1)} = \frac{\ln(125/175)}{\ln(15/45)} = 0.31 \quad C = V_1 \times (T_1)^n = 401$$

For ASTM Class 20 grey cast iron, using hard ceramic,

$$n = \frac{\ln(V_1/V_2)}{\ln(T_2/T_1)} = \frac{\ln(1490/2220)}{\ln(15/45)} = 0.36 \quad C = V_1 \times (T_1)^n = 5932$$

**Selection of Optimized Data.**—Fig. 22 illustrates cutting time, cycle time, number of parts before a tool change, tooling cost, and total cost, each plotted versus feed for a constant tool-life. Approximate minimum cost conditions can be determined using the formulas previously given in this section.

First, select a large feed/rev or tooth, and then calculate economic tool-life  $T_E$ , and the economic cutting speed  $V_E$ , and do all calculations using the time/cost formulas as described previously.

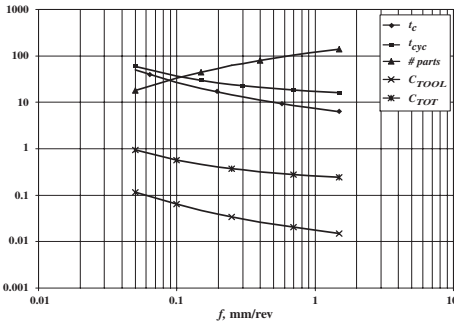


Fig. 22. Cutting time, cycle time, number of parts before tool change, tooling cost, and total cost vs. feed for tool-life = 15 minutes, idle time = 10 s, and batch size = 1000 parts

**Example 11, Step by Step Procedure: Turning – Facing out:** 1) Select a big feed/rev, in this case  $f = 0.9$  mm/rev (0.035 inch/rev). A Taylor slope  $n$  is first determined using the Handbook tables and the method described in Example 10. In this example, use  $n = 0.35$  and  $C = 280$ .

2) Calculate  $T_V$  from the tooling cost parameters:

If cost of insert = \$7.50; edges per insert = 2; cost of tool holder = \$100; life of holder = 100 insert sets; and for tools with inserts, allowance for insert failures = cost per insert by 4/3, assuming only 3 out of 4 edges can be effectively used.

Then, cost per edge =  $C_E$  is calculated as follows:

$$C_E = \frac{\text{cost of insert(s)}}{\text{number of edges per insert}} + \frac{\text{cost of cutter body}}{\text{cutter body life in number of edges}}$$

$$= \frac{7.50 \times 4/3}{2} + \frac{100}{100} = \$6.00$$

The time for replacing a worn edge of the facing insert =  $T_{RPL} = 2.24$  minutes. Assuming an hourly rate  $H_R = \$50/\text{hour}$ , calculate the equivalent tooling-cost time  $T_V$

$$T_V = T_{RPL} + 60 \times C_E/H_R = 2.24 + 60 \times 6/50 = 9.44 \text{ minutes}$$

3) Determine economic tool-life  $T_E$

$$T_E = T_V \times (1/n - 1) = 9.44 \times (1/0.35 - 1) = 17.5 \text{ minutes}$$

4) Determine economic cutting speed using the Handbook tables using the method shown in Example 10,

$$V_E = C/T_E^n \text{ m/min} = 280 / 17.5^{0.35} = 103 \text{ m/min}$$

5) Determine cost of tooling per batch (cutting tools, holders and tool changing) then total cost of cutting per batch:

$$C_{TOOL} = H_R \times T_C \times (C_E/T)/60$$

$$(C_{TOOL} + C_{CH}) = H_R \times T_C \times ((T_{RPL} + C_E/T)/60)$$

$$C_{TOT} = H_R \times T_C (1 + (T_{RPL} + C_E)/T)$$

*Example 12, Face Milling – Minimum Cost*: This example demonstrates how a modern firm, using the formulas previously described, can determine optimal data. It is here applied to a face mill with 10 teeth, milling a 1045 type steel, and the radial depth versus the cutter diameter is 0.8. The  $V-ECT-T$  curves for tool-lives 5, 22, and 120 minutes for this operation are shown in Fig. 23a. [LIVE GRAPH](#)  
[Click here to view](#)

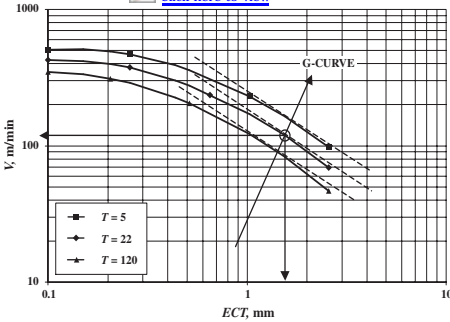


Fig. 23a. Cutting speed vs. ECT, tool-life constant

The global cost minimum occurs along the  $G$ -curve, see Fig. 6c and Fig. 23a, where the 45-degree lines defines this curve. Optimum  $ECT$  is in the range 1.5 to 2 mm.

For face and end milling operations,  $ECT = z \times f_z \times ar/D \times aa/CEL \div \pi$ . The ratio  $aa/CEL = 0.95$  for lead angle  $LA = 0$ , and for  $ar/D = 0.8$  and 10 teeth, using the formula to calculate the feed/tooth range gives for  $ECT = 1.5$ ,  $f_z = 0.62$  mm and for  $ECT = 2$ ,  $f_z = 0.83$  mm.

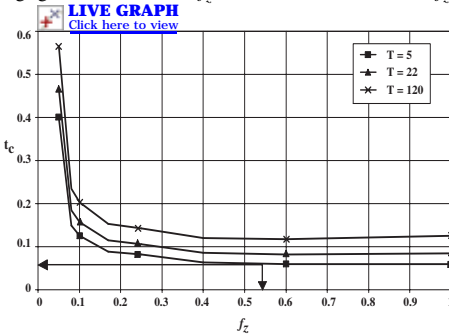


Fig. 23b. Cutting time per part vs. feed per tooth

Using computer simulation, the minimum cost occurs approximately where Fig. 23a indicates it should be. Total cost has a global minimum at  $f_z$  around 0.6 to 0.7 mm and a speed of around 110 m/min.  $ECT$  is about 1.9 mm and the optimal cutter life is  $T_O = 22$  minutes. Because it may be impossible to reach the optimum feed value due to tool breakage,

the maximum practical feed  $f_{max}$  is used as the optimal value. The difference in costs between a global optimum and a practical minimum cost condition is negligible, as shown in Figs. 23c and 23e. A summary of the results are shown in Figs. 23a through 23e, and Table 1.

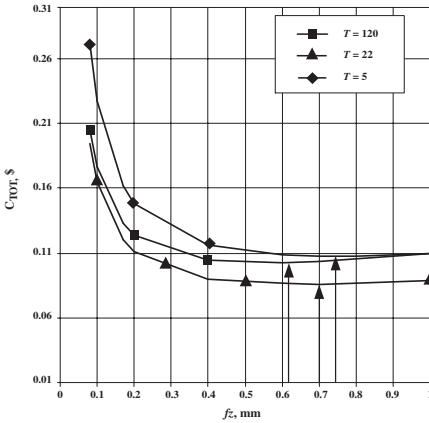


Fig. 23c. Total cost vs. feed/tooth

When plotting cutting time/part,  $t_c$ , versus feed/tooth,  $f_z$ , at  $T = 5, 22, 120$  in Figs. 23b, tool-life  $T = 5$  minutes yields the shortest cutting time, but total cost is the highest; the minimum occurs for  $f_z$  about 0.75 mm, see Figs. 23c. The minimum for  $T = 120$  minutes is about 0.6 mm and for  $T_O = 22$  minutes around 0.7 mm.

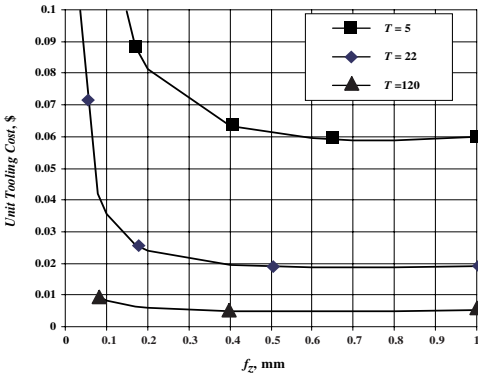


Fig. 23d. Tooling cost versus feed/tooth

Fig. 23d shows that tooling cost drop off quickly when increasing feed from 0.1 to 0.3 to 0.4 mm, and then diminishes slowly and is almost constant up to 0.7 to 0.8 mm/tooth. It is generally very high at the short tool-life 5 minutes, while tooling cost of optimal tool-life 22 minutes is about 3 times higher than when going slow at  $T=120$  minutes.

## MACHINING ECONOMETRICS

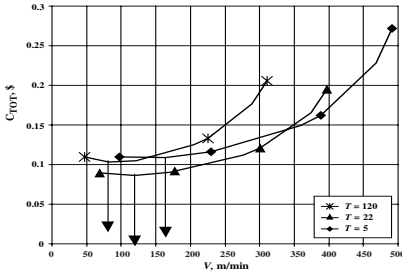


Fig. 23e. Total cost vs. cutting speed at 3 constant tool-lives, feed varies

The total cost curves in Fig. 23e. were obtained by varying feed and cutting speed in order to maintain constant tool-lives at 5, 22 and 120 minutes. Cost is plotted as a function of speed  $V$  instead of feed/tooth. Approximate optimum speeds are  $V = 150$  m/min at  $T = 5$  minutes,  $V = 180$  m/min at  $T = 120$  minutes, and the global optimum speed is  $V_0 = 110$  m/min for  $T_0 = 22$  minutes.

Table 1 displays the exact numerical values of cutting speed, tooling cost and total cost for the selected tool-lives of 5, 22, and 120 minutes, obtained from the software program.

**Table 1. Face Milling, Total and Tooling Cost versus  $ECT$ , Feed/tooth  $f_z$ , and Cutting Speed  $V$ , at Tool-lives 5, 22, and 120 minutes**

| $f_z$ | $ECT$ | $T = 5$ minutes |           |            | $T = 22$ minutes |           |            | $T = 120$ minutes |           |            |
|-------|-------|-----------------|-----------|------------|------------------|-----------|------------|-------------------|-----------|------------|
|       |       | $V$             | $C_{TOT}$ | $C_{TOOL}$ | $V$              | $C_{TOT}$ | $C_{TOOL}$ | $V$               | $C_{TOT}$ | $C_{TOOL}$ |
| 0.03  | 0.08  | 489             | 0.72891   | 0.39759    | 416              | 0.49650   | 0.10667    | 344               | 0.49378   | 0.02351    |
| 0.08  | 0.21  | 492             | 0.27196   | 0.14834    | 397              | 0.19489   | 0.04187    | 311               | 0.20534   | 0.00978    |
| 0.10  | 0.26  | 469             | 0.22834   | 0.12455    | 374              | 0.16553   | 0.03556    | 289               | 0.17674   | 0.00842    |
| 0.17  | 0.44  | 388             | 0.16218   | 0.08846    | 301              | 0.12084   | 0.02596    | 225               | 0.13316   | 0.00634    |
| 0.20  | 0.51  | 359             | 0.14911   | 0.08133    | 276              | 0.11204   | 0.02407    | 205               | 0.12466   | 0.00594    |
| 0.40  | 1.03  | 230             | 0.11622   | 0.06339    | 171              | 0.09051   | 0.01945    | 122               | 0.10495   | 0.00500    |
| 0.60  | 1.54  | 164             | 0.10904   | 0.05948    | 119              | 0.08672   | 0.01863    | 83                | 0.10301   | 0.00491    |
| 0.70  | 1.80  | 141             | 0.10802   | 0.05892    | 102              | 0.08665   | 0.01862    | 70                | 0.10393   | 0.00495    |
| 0.80  | 2.06  | 124             | 0.10800   | 0.05891    | 89               | 0.08723   | 0.01874    | 60                | 0.10547   | 0.00502    |
| 1.00  | 2.57  | 98              | 0.10968   | 0.05982    | 69               | 0.08957   | 0.01924    | 47                | 0.10967   | 0.00522    |

### High-speed Machining Econometrics

**High-speed Machining – No Mystery.**—This section describes the theory and gives the basic formulas for any milling operation and high-speed milling in particular, followed by several examples on high-speed milling econometrics. These rules constitute the basis on which selection of milling feed factors is done. Selection of cutting speeds for general milling is done using the Handbook Table 10 through 14, starting on page 1044.

High-speed machining is no mystery to those having a good knowledge of metal cutting. Machining materials with very good machinability, such as low-alloyed aluminum, have for ages been performed at cutting speeds well below the speed values at which these materials should be cut. Operating at these low speeds often results in built-up edges and poor surface finish, because the operating conditions selected are on the wrong side of the Taylor curve, i.e. to the left of the  $H$ -curve representing maximum tool-life values (see Fig. 4 on page 1096).

In the 1950's it was discovered that cutting speed could be raised by a factor of 5 to 10 when hobbing steel with HSS cutters. This is another example of being on the wrong side of the Taylor curve.

One of the first reports on high-speed end milling using high-speed steel (HSS) and carbide cutters for milling 6061-T651 and A356-T6 aluminum was reported in a study funded by Defense Advanced Research Project Agency (DARPA). Cutting speeds of up to 4400 m/min (14140 fpm) were used. Maximum tool-lives of 20 through 40 minutes were obtained when the feed/tooth was 0.2 through 0.25 mm (0.008 to 0.01 inch), or measured in terms of *ECT* around 0.07 to 0.09 mm. Lower or higher feed/tooth resulted in shorter cutter lives. The same types of previously described curves, namely *T-ECT* curves with maximum tool-life along the *H*-curve, were produced.

When examining the influence of *ECT*, or feed/rev, or feed/tooth, it is found that too small values cause chipping, vibrations, and poor surface finish. This is caused by inadequate (too small) chip thickness, and as a result the material is not cut but plowed away or scratched, due to the fact that operating conditions are on the wrong (left) side of the tool-life versus *ECT* curve (*T-ECT* with constant speed plotted).

There is a great difference in the thickness of chips produced by a tooth traveling through the cutting arc in the milling process, depending on how the center of the cutter is placed in relation to the workpiece centerline, in the feed direction. Although end and face milling cut in the same way, from a geometry and kinematics standpoint they are in practice distinguished by the cutter center placement away from, or close to, the work centerline, respectively, because of the effect of cutter placement on chip thickness. This is the criteria used to distinguishing between the end and face milling processes in the following.

*Depth of Cut/Cutter Diameter, ar/D* is the ratio of the radial depth of cut *ar* and the cutter diameter *D*. In face milling when the cutter axis points approximately to the middle of the work piece axis, eccentricity is close to zero, as illustrated in Figs. 3 and 4, page 1042, and Fig. 5 on page 1043. In end milling, *ar/D* = 1 for full slot milling.

*Mean Chip Thickness, hm* is a key parameter that is used to calculate forces and power requirements in high-speed milling. If the mean chip thickness *hm* is too small, which may occur when feed/tooth is too small (this holds for all milling operations), or when *ar/D* decreases (this holds for ball nose as well as for straight end mills), then cutting occurs on the left (wrong side) of the tool-life versus *ECT* curve, as illustrated in Figs. 6b and 6c.

In order to maintain a given chip thickness in end milling, the feed/tooth has to be increased, up to 10 times for very small *ar/D* values in an extreme case with no run out and otherwise perfect conditions. A 10 times increase in feed/tooth results in 10 times bigger feed rates ( $F_R$ ) compared to data for full slot milling (valid for *ar/D* = 1), yet maintain a given chip thickness. The cutter life at any given cutting speed will not be the same, however.

Increasing the number of teeth from say 2 to 6 increases equivalent chip thickness *ECT* by a factor of 3 while the mean chip thickness *hm* remains the same, but does not increase the feed rate to 30 ( $3 \times 10$ ) times bigger, because the cutting speed must be reduced. However, when the *ar/D* ratio matches the number of teeth, such that one tooth enters when the second tooth leaves the cutting arc, then  $ECT = hm$ . Hence, *ECT* is proportional to the number of teeth. Under ideal conditions, an increase in number of teeth *z* from 2 to 6 increases the feed rate by, say, 20 times, maintaining tool-life at a reduced speed. In practice about 5 times greater feed rates can be expected for small *ar/D* ratios (0.01 to 0.02), and up to 10 times with 3 times as many teeth. So, high-speed end milling is no mystery.

**Chip Geometry in End and Face Milling.**—Fig. 24 illustrates how the chip forming process develops differently in face and end milling, and how mean chip thickness *hm* varies with the angle of engagement *AE*, which depends on the *ar/D* ratio. The pertinent chip geometry formulas are given in the text that follows.



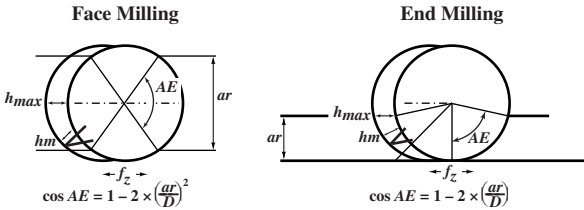


Fig. 24.

Comparison of face milling and end milling geometry

High-speed end milling refers to values of  $ar/D$  that are less than 0.5, in particular to  $ar/D$  ratios which are considerably smaller. When  $ar/D = 0.5$  ( $AE = 90$  degrees) and diminishing in end milling, the chip thickness gets so small that poor cutting action develops, including plowing or scratching. This situation is remedied by increasing the feed/tooth, as shown in Table 2a as an increasing  $f_z/f_{z0}$  ratio with decreasing  $ar/D$ . For end milling, the  $f_z/f_{z0}$  feed ratio is 1.0 for  $ar/D = 1$  and also for  $ar/D = 0.5$ . In order to maintain the same  $hm$  as at  $ar/D = 1$ , the feed/tooth should be increased, by a factor of 6.38 when  $ar/D$  is 0.01 and by more than 10 when  $ar/D$  is less than 0.01. Hence high-speed end milling could be said to begin when  $ar/D$  is less than 0.5

In end milling, the ratio  $f_z/f_{z0} = 1$  is set at  $ar/D = 1.0$  (full slot), a common value in vendor catalogs and handbooks, for  $hm = 0.108$  mm.

The face milling chip making process is exactly the same as end milling when face milling the side of a work piece and  $ar/D = 0.5$  or less. However, when face milling close to and along the work centerline (eccentricity is close to zero) chip making is quite different, as shown in Fig. 24. When  $ar/D = 0.74$  ( $AE = 95$  degrees) in face milling, the  $f_z/f_{z0}$  ratio = 1 and increases up to 1.4 when the work width is equal to the cutter diameter ( $ar/D = 1$ ). The face milling  $f_z/f_{z0}$  ratio continues to diminish when the  $ar/D$  ratio decreases below  $ar/D = 0.74$ , but very insignificantly, only about 11 percent when  $ar/D = 0.01$ .

In face milling  $f_z/f_{z0} = 1$  is set at  $ar/D = 0.74$ , a common value recommended in vendor catalogs and handbooks, for  $hm = 0.151$  mm.

Fig. 25 shows the variation of the feed/tooth-ratio in a graph for end and face milling.

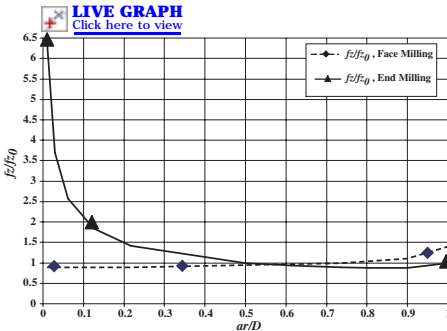


Fig. 25. Feed/tooth versus  $ar/D$  for face and end milling

**Table 2a. Variation of Chip Thickness and  $f_z/f_{z0}$  with  $ar/D$**

| $ar/D$ | Face Milling   |         |       |          |              | End Milling (straight)   |         |       |          |              |
|--------|--|---------|-------|----------|--------------|--|---------|-------|----------|--------------|
|        | eccentricity $e = 0$<br>$z = 8$<br>$f_{z0} = 0.017$<br>$\cos AE = 1 - 2 \times (ar/D)^2$ |         |       |          |              | $z = 2$<br>$f_{z0} = 0.017$<br>$\cos AE = 1 - 2 \times (ar/D)$ |         |       |          |              |
|        | $AE$   | $hmf_z$ | $hm$  | $ECT/hm$ | $f_z/f_{z0}$ | $AE$   | $hmf_z$ | $hm$  | $ECT/hm$ | $f_z/f_{z0}$ |
| 1.0000 | 180.000  | 0.637   | 0.108 | 5.000    | 1.398        | 180.000  | 0.637   | 0.108 | 1.000    | 1.000        |
| 0.9000 | 128.316  | 0.804   | 0.137 | 3.564    | 1.107        | 143.130  | 0.721   | 0.122 | 0.795    | 0.884        |
| 0.8000 | 106.260  | 0.863   | 0.147 | 2.952    | 1.032        | 126.870  | 0.723   | 0.123 | 0.711    | 0.881        |
| 0.7355 | 94.702   | 0.890   | 0.151 | 2.631    | 1.000        | 118.102  | 0.714   | 0.122 | 0.667    | 0.892        |
| 0.6137 | 75.715   | 0.929   | 0.158 | 1.683    | 0.958        | 103.144  | 0.682   | 0.116 | 0.573    | 0.934        |
| 0.5000 | 60.000   | 0.162   | 0.932 | 0.216    | 0.202        | 90.000   | 0.674   | 0.115 | 0.558    | 1.000        |
| 0.3930 | 46.282   | 0.973   | 0.165 | 1.028    | 0.915        | 77.643   | 0.580   | 0.099 | 0.431    | 1.098        |
| 0.2170 | 25.066   | 0.992   | 0.169 | 0.557    | 0.897        | 55.528   | 0.448   | 0.076 | 0.308    | 1.422        |
| 0.1250 | 14.361   | 0.997   | 0.170 | 0.319    | 0.892        | 41.410   | 0.346   | 0.059 | 0.230    | 1.840        |
| 0.0625 | 7.167  | 0.999   | 0.170 | 0.159    | 0.891        | 28.955   | 0.247   | 0.042 | 0.161    | 2.574        |
| 0.0300 | 3.438  | 1.000   | 0.170 | 0.076    | 0.890        | 19.948   | 0.172   | 0.029 | 0.111    | 3.694        |
| 0.0100 | 1.146  | 1.000   | 0.170 | 0.025    | 0.890        | 11.478   | 0.100   | 0.017 | 0.064    | 6.377        |
| 0.0010 | 0.115  | 1.000   | 0.000 | 0.000    | 0.890        | 3.624  | 0.000   | 0.000 | 0.000    | 20.135       |

In Table 2a, a standard value  $f_{z0} = 0.17$  mm/tooth (commonly recommended average feed) was used, but the  $f_z/f_{z0}$  values are independent of the value of feed/tooth, and the previously mentioned relationships are valid whether  $f_{z0} = 0.17$  or any other value.

In both end and face milling,  $hm = 0.108$  mm for  $f_{z0} = 0.17$  mm when  $ar/D = 1$ . When the  $f_z/f_{z0}$  ratio = 1,  $hm = 0.15$  for face milling, and 0.108 in end milling both at  $ar/D = 1$  and 0.5. The tabulated data hold for perfect milling conditions, such as, zero run-out and accurate sharpening of all teeth and edges.

**Mean Chip Thickness  $hm$  and Equivalent Chip Thickness  $ECT$ .**—The basic formula for equivalent chip thickness  $ECT$  for any milling process is:

$ECT = f_z \times z/\pi \times (ar/D) \times aa/CEL$ , where  $f_z$  = feed/tooth,  $z$  = number of teeth,  $D$  = cutter diameter,  $ar$  = radial depth of cut,  $aa$  = axial depth of cut, and  $CEL$  = cutting edge length. As a function of mean chip thickness  $hm$ :

$ECT = hm \times (z/2) \times (AE/180)$ , where  $AE$  = angle of engagement.

Both terms are exactly equal when one tooth engages as soon as the preceding tooth leaves the cutting section. Mathematically,  $hm = ECT$  when  $z = 360/AE$ ; thus:

for face milling,  $AE = \arccos(1 - 2 \times (ar/D)^2)$

for end milling,  $AE = \arccos(1 - 2 \times (ar/D))$

*Calculation of Equivalent Chip Thickness (ECT) versus Feed/tooth and Number of teeth.*: Table 2b is a continuation of Table 2a, showing the values of  $ECT$  for face and end milling for decreasing values  $ar/D$ , and the resulting  $ECT$  when multiplied by the  $f_z/f_{z0}$  ratio  $f_{z0} = 0.17$  (based on  $hm = 0.108$ ).

Small  $ar/D$  ratios produce too small mean chip thickness for cutting chips. In practice, minimum values of  $hm$  are approximately 0.02 through 0.04 mm for both end and face milling.

**Formulas.**— Equivalent chip thickness can be calculated for other values of  $f_z$  and  $z$  by means of the following formulas:

Face milling:  $ECT_F = ECT_{0F} \times (z/8) \times (f_z/0.17) \times (aa/CEL)$

or, if  $ECT_F$  is known calculate  $f_z$  using:

$f_z = 0.17 \times (ECT_F/ECT_{0F}) \times (8/z) \times (CEL/aa)$

**Table 2b. Variation of  $ECT$ , Chip Thickness and  $f_z/f_{z0}$  with  $ar/D$** 

| $ar/D$ | Face Milling |              |       |  | End Milling (straight) |              |       |  |
|--------|--------------|--------------|-------|--|------------------------|--------------|-------|--|
|        | $hm$         | $f_z/f_{z0}$ | $ECT$ | $ECT_0$<br>corrected<br>for $f_z/f_{z0}$ | $hm$                   | $f_z/f_{z0}$ | $ECT$ | $ECT_0$<br>corrected<br>for $f_z/f_{z0}$ |
| 1.0000 | 0.108        | 1.398        | 0.411 | 0.575                                    | 0.108                  | 1.000        | 0.103 | 0.103                                    |
| 0.9000 | 0.137        | 1.107        | 0.370 | 0.410                                    | 0.122                  | 0.884        | 0.093 | 0.082                                    |
| 0.8080 | 0.146        | 1.036        | 0.332 | 0.344                                    | 0.123                  | 0.880        | 0.083 | 0.073                                    |
| 0.7360 | 0.151        | 1.000        | 0.303 | 0.303                                    | 0.121                  | 0.892        | 0.076 | 0.067                                    |
| 0.6137 | 0.158        | 0.958        | 0.252 | 0.242                                    | 0.116                  | 0.934        | 0.063 | 0.059                                    |
| 0.5900 | 0.159        | 0.952        | 0.243 | 0.231                                    | 0.115                  | 0.945        | 0.061 | 0.057                                    |
| 0.5000 | 0.162        | 0.932        | 0.206 | 0.192                                    | 0.108                  | 1.000        | 0.051 | 0.051                                    |
| 0.2170 | 0.169        | 0.897        | 0.089 | 0.080                                    | 0.076                  | 1.422        | 0.022 | 0.032                                    |
| 0.1250 | 0.170        | 0.892        | 0.051 | 0.046                                    | 0.059                  | 1.840        | 0.013 | 0.024                                    |
| 0.0625 | 0.170        | 0.891        | 0.026 | 0.023                                    | 0.042                  | 2.574        | 0.006 | 0.017                                    |
| 0.0300 | 0.170        | 0.890        | 0.012 | 0.011                                    | 0.029                  | 3.694        | 0.003 | 0.011                                    |
| 0.0100 | 0.170        | 0.890        | 0.004 | 0.004                                    | 0.017                  | 6.377        | 0.001 | 0.007                                    |
| 0.0010 | 0.170        | 0.890        | 0.002 | 0.002                                    | 0.005                  | 20.135       | 0.001 | 0.005                                    |

In face milling, the approximate values of  $aa/CEL = 0.95$  for lead angle  $LA = 0^\circ$  ( $90^\circ$  in the metric system); for other values of  $LA$ ,  $aa/CEL = 0.95 \times \sin(LA)$ , and  $0.95 \times \cos(LA)$  in the metric system.

*Example, Face Milling:* For a cutter with  $D = 250$  mm and  $ar = 125$  mm, calculate  $ECT_F$  for  $f_z = 0.1$ ,  $z = 12$ , and  $LA = 30$  degrees. First calculate  $ar/D = 0.5$ , and then use [Table 2b](#) and find  $ECT_{0F} = 0.2$ .

Calculate  $ECT_F$  with above formula:

$$ECT_F = 0.2 \times (12/8) \times (0.1/0.17) \times 0.95 \times \sin 30 = 0.084 \text{ mm.}$$

*End milling:*  $ECT_E = ECT_{0E} \times (z/2) \times (f_z/0.17) \times (aa/CEL)$ ,

or if  $ECT_E$  is known calculate  $f_z$  from:

$$f_z = 0.17 \times (ECT_E/ECT_{0E}) \times (2/z) \times (CEL/aa)$$

The approximate values of  $aa/CEL = 0.95$  for lead angle  $LA = 0^\circ$  ( $90^\circ$  in the metric system).

*Example, High-speed End Milling:* For a cutter with  $D = 25$  mm and  $ar = 3.125$  mm, calculate  $ECT_E$  for  $f_z = 0.1$  and  $z = 6$ . First calculate  $ar/D = 0.125$ , and then use [Table 2b](#) and find  $ECT_{0E} = 0.0249$ .

Calculate  $ECT_E$  with above formula:

$$ECT_E = 0.0249 \times (6/2) \times (0.1/0.17) \times 0.95 \times 1 = 0.042 \text{ mm.}$$

*Example, High-speed End Milling:* For a cutter with  $D = 25$  mm and  $ar = 0.75$  mm, calculate  $ECT_E$  for  $f_z = 0.17$  and  $z = 2$  and  $6$ . First calculate  $ar/D = 0.03$ , and then use [Table 2b](#) and find  $f_z/f_{z0} = 3.694$

Then,  $f_z = 3.694 \times 0.17 = 0.58$  mm/tooth and  $ECT_E = 0.0119 \times 0.95 = 0.0113$  mm and  $0.0357 \times 0.95 = 0.0339$  mm for 2 and 6 teeth respectively. These cutters are marked HS2 and HS6 in [Figs. 26a, 26d, and 26e](#).

*Example, High-speed End Milling:* For a cutter with  $D = 25$  mm and  $ar = 0.25$  mm, calculate  $ECT_E$  for  $f_z = 0.17$  and  $z = 2$  and  $6$ . First calculate  $ar/D = 0.01$ , and then use [Table 2b](#) and find  $ECT_{0E} = 0.0069$  and  $0.0207$  for 2 and 6 teeth respectively. When obtaining such small values of  $ECT$ , there is a great danger to be far on the left side of the  $H$ -curve, at least when there are only 2 teeth. Doubling the feed would be the solution if cutter design and material permit.

*Example, Full Slot Milling:* For a cutter with  $D = 25$  mm and  $ar = 25$  mm, calculate  $ECT_E$  for  $f_z = 0.17$  and  $z = 2$  and  $6$ . First calculate  $ar/D = 1$ , and then use [Table 2b](#) and find  $ECT_E =$

$0.108 \times 0.95 = 0.103$  and  $3 \times 0.108 \times 0.95 = 0.308$  for 2 and 6 teeth, respectively. These cutters are marked SL2 and SL6 in Figs. 26a, 26d, and 26e.

**Physics behind  $hm$  and  $ECT$ , Forces and Tool-life ( $T$ ).**—The  $ECT$  concept for all metal cutting and grinding operations says that the more energy put into the process, by increasing feed/rev, feed/tooth, or cutting speed, the life of the edge decreases. When increasing the number of teeth (keeping everything else constant) the work and the process are subjected to a higher energy input resulting in a higher rate of tool wear.

In high-speed milling when the angle of engagement  $AE$  is small the contact time is shorter compared to slot milling ( $ar/D = 1$ ) but the chip becomes shorter as well. Maintaining the same chip thickness as in slot milling has the effect that the energy consumption to remove the chip will be different. Hence, maintaining a constant chip thickness is a good measure when calculating cutting forces (keeping speed constant), but not when determining tool wear. Depending on cutting conditions the wear rate can either increase or decrease, this depends on whether cutting occurs on the left or right side of the  $H$ -curve.

Fig. 26a shows an example of end milling of steel with coated carbide inserts, where cutting speed  $V$  is plotted versus  $ECT$  at 5, 15, 45 and 180 minutes tool-lives. Notice that the  $ECT$  values are independent of  $ar/D$  or number of teeth or feed/tooth, or whether  $f_z$  or  $f_{z0}$  is used, as long as the corresponding  $f_z/f_{z0}$ -ratio is applied to determine  $ECT_E$ . The result is one single curve per tool-life. Had cutting speed been plotted versus  $f_{z0}$ ,  $ar/D$ , or  $z$  values (number of teeth), several curves would be required at each constant tool-life, one for each of these parameters. This illustrates the advantage of using the basic parameter  $ECT$  rather than  $f_z$ , or  $hm$ , or  $ar/D$  on the horizontal axis.

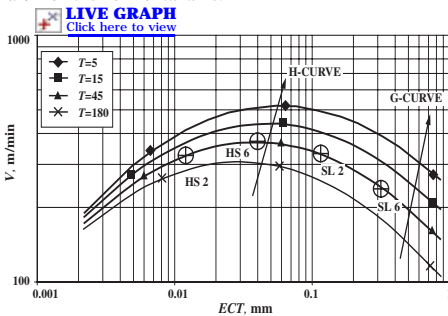


Fig. 26a. Cutting speed vs.  $ECT$ , tool-life plotted, for end milling

*Example:* The points (HS2, HS6) and (SL2, SL6) on the 45-minute curve in Fig. 26a relate to the previous high-speed and full slot milling examples for 2 and 6 teeth, respectively.

Running a slot at  $f_{z0} = 0.17$  mm/tooth ( $hm = 0.108$ ,  $ECT_E = 0.103$  mm) with 2 teeth and for a tool-life 45 minutes, the cutting speed should be selected at  $V = 340$  m/min at point SL2 and for six teeth ( $hm = 0.108$  mm,  $ECT_E = 0.308$ ) at  $V = 240$  m/min at point SL6.

When high-speed milling for  $ar/D = 0.03$  at  $f_z = 3.394 \times 0.17 = 0.58$  mm/tooth = 0.58 mm/tooth,  $ECT$  is reduced to 0.011 mm ( $hm = 0.108$ ) the cutting speed is 290 m/min to maintain  $T = 45$  minutes, point HS2. This point is far to the left of the  $H$ -curve in Fig. 26b, but if the number of teeth is increased to 6 ( $ECT_E = 3 \times 0.103 = 0.3090$ ), the cutting speed is 360 m/min at  $T = 45$  minutes and is close to the  $H$ -curve, point HS6. Slotting data using 6 teeth are on the right of this curve at point SL6, approaching the  $G$ -curve, but at a lower slotting speed of 240 m/min.

Depending on the starting  $f_z$  value and on the combination of cutter grade - work material, the location of the  $H$ -curve plays an important role when selecting high-speed end milling data.

**Feed Rate and Tool-life in High-speed Milling, Effect of ECT and Number of Teeth.**—Calculation of feed rate is done using the formulas in previously given:

Feed Rate:

$$F_R = z \times f_z \times \text{rpm}, \text{ where } z \times f_z = f \text{ (feed/rev of cutter). Feed is measured along the feeding direction.}$$

$$\text{rpm} = 1000 \times V/3.1416/D, \text{ where } D \text{ is diameter of cutter.}$$

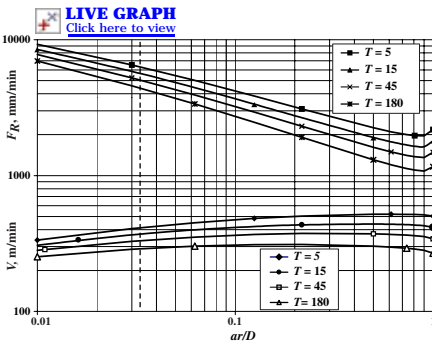


Fig. 26b. High speed feed rate and cutting speed versus  $ar/D$  at  $T = 5, 15, 45,$  and  $180$  minutes

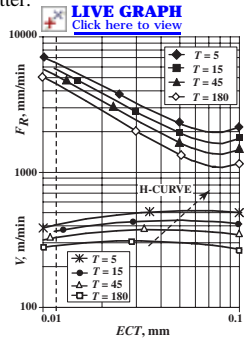


Fig. 26c. High speed feed rate and cutting speed versus  $ECT, ar/D$  plotted at  $T = 5, 15, 45,$  and  $180$  minutes

Fig. 26b shows the variation of feed rate  $F_R$  plotted versus  $ar/D$  for tool-lives 5, 15, 45 and 180 minutes with a 25 mm diameter cutter and 2 teeth. Fig. 26c shows the variation of feed rate  $F_R$  when plotted versus  $ECT$ . In both graphs the corresponding cutting speeds are also plotted. The values for  $ar/D = 0.03$  in Fig. 26b correspond to  $ECT = 0.011$  in Fig. 26c.

Feed rates have minimum around values of  $ar/D = 0.8$  and  $ECT = 0.75$  and not along the  $H$ -curve. This is due to the fact that the  $f_z/f_{z=0}$  ratio to maintain a mean chip thickness = 0.108 mm changes  $F_R$  in a different proportion than the cutting speed.

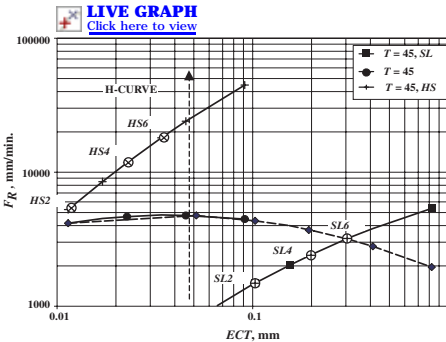


Fig. 26d. Feed rate versus  $ECT$  comparison of slot milling ( $ar/D = 1$ ) and high-speed milling (at  $ar/D = 0.03$ ) for 2, 4, and 6 teeth at  $T = 45$  minutes

A comparison of feed rates for full slot ( $ar/D = 1$ ) and high-speed end milling ( $ar/D = 0.03$  and  $f_z = 3.69 \times f_{z0} = 0.628$  mm) for tool-life 45 minutes is shown in Fig. 26d. The points SL2, SL4, SL6 and HS2, HS4, HS6, refer to 2, 4, and 6 teeth (2 to 6 teeth are commonly used in practice). Feed rate is also plotted versus number of teeth  $z$  in Fig. 26e, for up to 16 teeth, still at  $f_z = 0.628$  mm.

Comparing the effect of using 2 versus 6 teeth in high-speed milling shows that feed rates increase from 5250 mm/min (413 ipm) up to 18000 mm/min (1417 ipm) at 45 minutes tool-life. The effect of using 2 versus 6 teeth in full slot milling is that feed rate increases from 1480 mm/min (58 ipm) up to 3230 mm/min (127 ipm) at tool-life 45 minutes. If 16 teeth could be used at  $ar/D = 0.03$ , the feed rate increases to  $F_R = 44700$  mm/min (1760 ipm), and for full slot milling  $F_R = 5350$  mm/min (210 ipm).

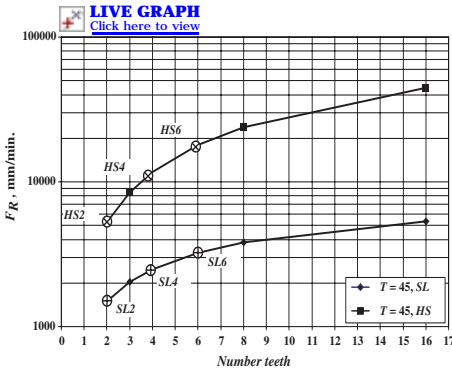


Fig. 26e. Feed rate versus number of teeth comparison of slot milling ( $ar/D = 1$ ) and high-speed milling at ( $ar/D = 0.03$ ) for 2, 4, and 6 teeth at  $T = 45$  minutes

Comparing the feed rates that can be obtained in steel cutting with the one achieved in the earlier referred DARPA investigation, using HSS and carbide cutters milling 6061-T651 and A356-T6 aluminum, it is obvious that aluminium end milling can be run at 3 to 6 times higher feed rates. This requires 3 to 6 times higher spindle speeds (cutter diameter 25 mm, radial depth of cut  $ar = 12.5$  mm, 2 teeth). Had these tests been run with 6 teeth, the feed rates would increase up to 150000-300000 mm/min, when feed/tooth =  $3.4 \times 0.25 = 0.8$  mm/tooth at  $ar/D = 0.03$ .

**Process Econometrics Comparison of High-speed and Slot End Milling.**—When making a process econometrics comparison of high-speed milling and slot end milling use the formulas for total cost  $c_{tot}$  (*Determination Of Machine Settings And Calculation Of Costs* starting on page 1113). Total cost is the sum of the cost of cutting, tool changing, and tooling:

$$c_{tot} = H_R \times (Dist/F_R) \times (1 + T_V/T)/60$$

where  $T_V = T_{RPL} + 60 \times C_E/H_R =$  equivalent tooling-cost time, minutes

$T_{RPL}$  = replacement time for a set of edges or tool for regrinding

$C_E$  = cost per edge(s)

$H_R$  = hourly rate, \$

Fig. 27. compares total cost  $c_{tot}$ , using the end milling cutters of the previous examples, for full slot milling with high-speed milling at  $ar/D=0.03$ , and versus  $ECT$  at  $T=45$  minutes.

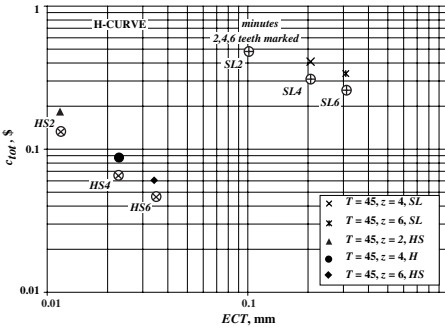


Fig. 27. Cost comparison of slot milling ( $ar/D = 1$ ) and high-speed milling at  $ar/D = 0.03$  for 2, 4, and 6 teeth at  $T = 45$  minutes

The feed/tooth for slot milling is  $f_{z0} = 0.17$  and for high-speed milling at  $ar/D = 0.03$  the feed is  $f_z = 3.69 \times f_{z0} = 0.628$  mm.

The calculations for total cost are done according to above formula using tooling cost at  $T_V = 6, 10,$  and  $14$  minutes, for  $z = 2, 4,$  and  $6$  teeth respectively. The distance cut is  $Dist = 1000$  mm. Full slot milling costs are,

at feed rate  $F_R = 3230$  and  $z = 6$

$$c_{tot} = 50 \times (1000/3230) \times (1 + 14/45)/60 = \$0.338 \text{ per part}$$

at feed rate  $F_R = 1480$  and  $z = 2$

$$c_{tot} = 50 \times (1000/1480) \times (1 + 6/45)/60 = \$0.638 \text{ per part}$$

High-speed milling costs,

at  $F_R = 18000, z = 6$

$$c_{tot} = 50 \times (1000/18000) \times (1 + 14/45)/60 = \$0.0606 \text{ per part}$$

at  $F_R = 5250, z = 2$

$$c_{tot} = 50 \times (1000/5250) \times (1 + 6/45)/60 = \$0.180 \text{ per part}$$

The cost reduction using high-speed milling compared to slotting is enormous. For high-speed milling with 2 teeth, the cost for high-speed milling with 2 teeth is 61 percent ( $0.208/0.338$ ) of full slot milling with 6 teeth ( $z = 6$ ). The cost for high-speed milling with 6 teeth is 19 percent ( $0.0638/0.338$ ) of full slot for  $z = 6$ .

Aluminium end milling can be run at 3 to 6 times lower costs than when cutting steel. Costs of idle (non-machining) and slack time (waste) are not considered in the example. These data hold for perfect milling conditions such as zero run-out and accurate sharpening of all teeth and edges.

## SCREW MACHINE FEEDS AND SPEEDS

**Feeds and Speeds for Automatic Screw Machine Tools.**—Approximate feeds and speeds for standard screw machine tools are given in the accompanying table.

**Knurling in Automatic Screw Machines.**—When knurling is done from the cross slide, it is good practice to feed the knurl gradually to the center of the work, starting to feed when the knurl touches the work and then passing off the center of the work with a quick rise of the cam. The knurl should also dwell for a certain number of revolutions, depending on the pitch of the knurl and the kind of material being knurled. See also *KNURLS AND KNURLING* starting on page 1240.

When two knurls are employed for spiral and diamond knurling from the turret, the knurls can be operated at a higher rate of feed for producing a spiral than they can for producing a diamond pattern. The reason for this is that in the first case the knurls work in the same groove, whereas in the latter case they work independently of each other.

**Revolutions Required for Top Knurling.**—The depth of the teeth and the feed per revolution govern the number of revolutions required for top knurling from the cross slide. If  $R$  is the radius of the stock,  $d$  is the depth of the teeth,  $c$  is the distance the knurl travels from the point of contact to the center of the work at the feed required for knurling, and  $r$  is the radius of the knurl; then

$$c = \sqrt{(R+r)^2 - (R+r-d)^2}$$

For example, if the stock radius  $R$  is  $\frac{5}{32}$  inch, depth of teeth  $d$  is 0.0156 inch, and radius of knurl  $r$  is 0.3125 inch, then

$$\begin{aligned} c &= \sqrt{(0.1562 + 0.3125)^2 - (0.1562 + 0.3125 - 0.0156)^2} \\ &= 0.120 \text{ inch} = \text{cam rise required} \end{aligned}$$

Assume that it is required to find the number of revolutions to knurl a piece of brass  $\frac{5}{16}$  inch in diameter using a 32 pitch knurl. The included angle of the teeth for brass is 90 degrees, the circular pitch is 0.03125 inch, and the calculated tooth depth is 0.0156 inch. The distance  $c$  (as determined in the previous example) is 0.120 inch. Referring to the accompanying table of feeds and speeds, the feed for top knurling brass is 0.005 inch per revolution. The number of revolutions required for knurling is, therefore,  $0.120 \div 0.005 = 24$  revolutions. If conditions permit, the higher feed of 0.008 inch per revolution given in the table may be used, and 15 revolutions are then required for knurling.

**Cams for Threading.**—The table *Spindle Revolutions and Cam Rise for Threading* on page 1134 gives the revolutions required for threading various lengths and pitches and the corresponding rise for the cam lobe. To illustrate the use of this table, suppose a set of cams is required for threading a screw to the length of  $\frac{3}{8}$  inch in a Brown & Sharpe machine. Assume that the spindle speed is 2400 revolutions per minute; the number of revolutions to complete one piece, 400; time required to make one piece, 10 seconds; pitch of the thread,  $\frac{1}{32}$  inch or 32 threads per inch. By referring to the table, under 32 threads per inch, and opposite  $\frac{3}{8}$  inch (length of threaded part), the number of revolutions required is found to be 15 and the rise required for the cam, 0.413 inch.



Approximate Cutting Speeds and Feeds for Standard Automatic Screw Machine Tools—Brown and Sharpe

| Tool  | Cut                             |                                | Material to be Machined     |                             |                              |                          |                             |                              |                 |
|---|---------------------------------|--------------------------------|-----------------------------|-----------------------------|------------------------------|--------------------------|-----------------------------|------------------------------|-----------------|
|   | Width<br>or<br>Depth,<br>Inches | Dia.<br>of<br>Hole,<br>Inches  | Brass <sup>a</sup>          | Mild or Soft Steel          |                              | Tool Steel, 0.80–1.00% C |                             |                              |                 |
|   |                                 |                                | Feed,<br>Inches<br>per Rev. | Feed,<br>Inches<br>per Rev. | Surface Speed, Feet per Min. |                          | Feed,<br>Inches<br>per Rev. | Surface Speed, Feet per Min. |                 |
|   |                                 |                                |                             |                             | Carbon<br>Tools              | H.S.S.<br>Tools          |                             | Carbon<br>Tools              | H.S.S.<br>Tools |
| Boring tools                                    | 0.005                           | ...                            | ...                         | 0.008                       | 50                           | 110                      | 0.004                       | 30                           | 60              |
| Box tools, roller rest<br>Single chip finishing | $\frac{1}{32}$                  | ...                            | 0.012                       | 0.010                       | 70                           | 150                      | 0.005                       | 40                           | 75              |
|   | $\frac{1}{16}$                  | ...                            | 0.010                       | 0.008                       | 70                           | 150                      | 0.004                       | 40                           | 75              |
|   | $\frac{1}{8}$                   | ...                            | 0.008                       | 0.007                       | 70                           | 150                      | 0.003                       | 40                           | 75              |
|   | $\frac{3}{16}$                  | ...                            | 0.008                       | 0.006                       | 70                           | 150                      | 0.002                       | 40                           | 75              |
|   | $\frac{1}{4}$                   | ...                            | 0.006                       | 0.005                       | 70                           | 150                      | 0.0015                      | 40                           | 75              |
| Finishing                                       | 0.005                           | ...                            | 0.010                       | 0.010                       | 70                           | 150                      | 0.006                       | 40                           | 75              |
| Center drills                                   | ...                             | Under $\frac{1}{8}$            | 0.003                       | 0.0015                      | 50                           | 110                      | 0.001                       | 30                           | 75              |
|   | ...                             | Over $\frac{1}{8}$             | 0.006                       | 0.0035                      | 50                           | 110                      | 0.002                       | 30                           | 75              |
| Cutoff tools {                                  | Angular                         | ...                            | 0.0015                      | 0.0006                      | 80                           | 150                      | 0.0004                      | 50                           | 85              |
|   | Circular                        | $\frac{3}{64}$ – $\frac{1}{8}$ | 0.0035                      | 0.0015                      | 80                           | 150                      | 0.001                       | 50                           | 85              |
|   | Straight                        | $\frac{1}{16}$ – $\frac{1}{8}$ | 0.0035                      | 0.0015                      | 80                           | 150                      | 0.001                       | 50                           | 85              |
| Stock diameter under $\frac{1}{4}$ in.          | ...                             | ...                            | 0.002                       | 0.0008                      | 80                           | 150                      | 0.0005                      | 50                           | 85              |
| Dies {  | Button                          | ...                            | ...                         | ...                         | 30                           | ...                      | ...                         | 14                           | ...             |
|   | Chaser                          | ...                            | ...                         | ...                         | 30                           | 40                       | ...                         | 16                           | 20              |
| Drills, twist cut                               | ...                             | 0.02                           | 0.0014                      | 0.001                       | 40                           | 60                       | 0.0006                      | 30                           | 45              |
|   | ...                             | 0.04                           | 0.002                       | 0.0014                      | 40                           | 60                       | 0.0008                      | 30                           | 45              |
|   | ...                             | $\frac{1}{16}$                 | 0.004                       | 0.002                       | 40                           | 60                       | 0.0012                      | 30                           | 45              |
|   | ...                             | $\frac{3}{32}$                 | 0.006                       | 0.0025                      | 40                           | 60                       | 0.0016                      | 30                           | 45              |
|   | ...                             | $\frac{1}{8}$                  | 0.009                       | 0.0035                      | 40                           | 75                       | 0.002                       | 30                           | 60              |
|   | ...                             | $\frac{3}{16}$                 | 0.012                       | 0.004                       | 40                           | 75                       | 0.003                       | 30                           | 60              |
|   | ...                             | $\frac{1}{4}$                  | 0.014                       | 0.005                       | 40                           | 75                       | 0.003                       | 30                           | 60              |
|   | ...                             | $\frac{5}{16}$                 | 0.016                       | 0.005                       | 40                           | 75                       | 0.0035                      | 30                           | 60              |
|   | ...                             | $\frac{3}{8}$ – $\frac{5}{8}$  | 0.016                       | 0.006                       | 40                           | 85                       | 0.004                       | 30                           | 60              |
| Form tools, circular                            | $\frac{1}{8}$                   | ...                            | 0.002                       | 0.0009                      | 80                           | 150                      | 0.0006                      | 50                           | 85              |
|   | $\frac{1}{4}$                   | ...                            | 0.002                       | 0.0008                      | 80                           | 150                      | 0.0005                      | 50                           | 85              |
|   | $\frac{3}{8}$                   | ...                            | 0.0015                      | 0.0007                      | 80                           | 150                      | 0.0004                      | 50                           | 85              |
|   | $\frac{1}{2}$                   | ...                            | 0.0012                      | 0.0006                      | 80                           | 150                      | 0.0004                      | 50                           | 85              |
|   | $\frac{5}{8}$                   | ...                            | 0.001                       | 0.0005                      | 80                           | 150                      | 0.0003                      | 50                           | 85              |
|   | $\frac{3}{4}$                   | ...                            | 0.001                       | 0.0005                      | 80                           | 150                      | 0.0003                      | 50                           | 85              |
|   | 1                               | ...                            | 0.001                       | 0.0004                      | 80                           | 150                      | ...                         | ...                          | ...             |

## Approximate Cutting Speeds and Feeds for Standard Automatic Screw Machine Tools—Brown and Sharpe (Continued)

| Tool                                     | Cut                                     |                                | Material to be Machined |                       |                              |              |                          |                              |              |
|--|---|--------------------------------|-------------------------|-----------------------|------------------------------|--------------|--------------------------|------------------------------|--------------|
|  | Width or Depth, Inches                  | Dia. of Hole, Inches           | Brass <sup>a</sup>      | Mild or Soft Steel    |                              |              | Tool Steel, 0.80–1.00% C |                              |              |
|  |   |                                | Feed, Inches per Rev.   | Feed, Inches per Rev. | Surface Speed, Feet per Min. |              | Feed, Inches per Rev.    | Surface Speed, Feet per Min. |              |
|  |   |                                |                         |                       | Carbon Tools                 | H.S.S. Tools |                          | Carbon Tools                 | H.S.S. Tools |
| Hollow mills and balance turning tools { | Turned diam. under $\frac{5}{32}$ in. { | $\frac{1}{32}$                 | 0.012                   | 0.010                 | 70                           | 150          | 0.008                    | 40                           | 85           |
|  |   | $\frac{1}{16}$                 | 0.010                   | 0.009                 | 70                           | 150          | 0.006                    | 40                           | 85           |
|  |   | $\frac{1}{8}$                  | 0.017                   | 0.014                 | 70                           | 150          | 0.010                    | 40                           | 85           |
|  | Turned diam. over $\frac{5}{32}$ in. {  | $\frac{1}{16}$                 | 0.015                   | 0.012                 | 70                           | 150          | 0.008                    | 40                           | 85           |
|  |   | $\frac{1}{8}$                  | 0.012                   | 0.010                 | 70                           | 150          | 0.008                    | 40                           | 85           |
|  |   | $\frac{3}{16}$                 | 0.010                   | 0.008                 | 70                           | 150          | 0.006                    | 40                           | 85           |
| Knee tools                               |   | $\frac{1}{4}$                  | 0.009                   | 0.007                 | 70                           | 150          | 0.0045                   | 40                           | 85           |
| Knurling tools {                         | Turret {                                | On                             | 0.020                   | 0.015                 | 150                          | ...          | 0.010                    | 105                          | ...          |
|  |   | Off                            | 0.040                   | 0.030                 | 150                          | ...          | 0.025                    | 105                          | ...          |
|  | Side or swing {                         | ...                            | 0.004                   | 0.002                 | 150                          | ...          | 0.002                    | 105                          | ...          |
|  |   | ...                            | 0.006                   | 0.004                 | 150                          | ...          | 0.003                    | 105                          | ...          |
|  |   | ...                            | 0.005                   | 0.003                 | 150                          | ...          | 0.002                    | 105                          | ...          |
| Top {                                    | ...                                     | 0.008                          | 0.006                   | 150                   | ...                          | 0.004        | 105                      | ...                          |              |
| Pointing and facing tools                | ...                                     | ...                            | 0.001                   | 0.0008                | 70                           | 150          | 0.0005                   | 40                           | 80           |
|  | ...                                     | ...                            | 0.0025                  | 0.002                 | 70                           | 150          | 0.0008                   | 40                           | 80           |
| Reamers and bits                         | 0.003 – 0.004                           | $\frac{1}{8}$ or less          | 0.010 – 0.007           | 0.008 – 0.006         | 70                           | 105          | 0.006 – 0.004            | 40                           | 60           |
|  | 0.004 – 0.008                           | $\frac{1}{8}$ or over          | 0.010                   | 0.010                 | 70                           | 105          | 0.006 – 0.008            | 40                           | 60           |
| Recessing tools {                        | End cut {                               | ...                            | 0.001                   | 0.0006                | 70                           | 150          | 0.0004                   | 40                           | 75           |
|  |   | ...                            | 0.005                   | 0.003                 | 70                           | 150          | 0.002                    | 40                           | 75           |
|  | Inside cut {                            | ...                            | 0.0025                  | 0.002                 | 70                           | 105          | 0.0015                   | 40                           | 60           |
|  |   | $\frac{1}{16}$ – $\frac{1}{8}$ | ...                     | 0.0008                | 0.0006                       | 70           | 105                      | 0.0004                       | 40           |
| Swing tools, forming                     | $\frac{1}{8}$                           | ...                            | 0.002                   | 0.0007                | 70                           | 150          | 0.0005                   | 40                           | 85           |
|  | $\frac{1}{4}$                           | ...                            | 0.0012                  | 0.0005                | 70                           | 150          | 0.0003                   | 40                           | 85           |
|  | $\frac{3}{8}$                           | ...                            | 0.001                   | 0.0004                | 70                           | 150          | 0.0002                   | 40                           | 85           |
|  | $\frac{1}{2}$                           | ...                            | 0.0008                  | 0.0003                | 70                           | 150          | 0.0002                   | 40                           | 85           |
| Turning, straight and taper <sup>b</sup> | $\frac{1}{32}$                          | ...                            | 0.008                   | 0.006                 | 70                           | 150          | 0.0035                   | 40                           | 85           |
|  | $\frac{1}{16}$                          | ...                            | 0.006                   | 0.004                 | 70                           | 150          | 0.003                    | 40                           | 85           |
|  | $\frac{1}{8}$                           | ...                            | 0.005                   | 0.003                 | 70                           | 150          | 0.002                    | 40                           | 85           |
|  | $\frac{3}{16}$                          | ...                            | 0.004                   | 0.0025                | 70                           | 150          | 0.0015                   | 40                           | 85           |
| Taps                                     | ...                                     | ...                            | ...                     | ...                   | 25                           | 30           | ...                      | 12                           | 15           |

<sup>a</sup> Use maximum spindle speed on machine.<sup>b</sup> For taper turning use feed slow enough for greatest depth of cut.

## Spindle Revolutions and Cam Rise for Threading

| Length of Threaded Portion, Inch | Number of Threads per Inch   |        |       |       |       |       |       |       |       |       |       |       |       |       |       |
|----------------------------------|--|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                                  | 80   | 72     | 64    | 56    | 48    | 40    | 36    | 32    | 30    | 28    | 24    | 20    | 18    | 16    | 14    |
|                                  | First Line: Revolutions of Spindle for Threading. Second Line: Rise on Cam for Threading, Inch |        |       |       |       |       |       |       |       |       |       |       |       |       |       |
| $\frac{1}{16}$                   | 9.50   | 9.00   | 8.50  | 8.00  | 6.00  | 5.50  | 5.50  | 5.00  | 5.00  | 5.00  | 3.00  | ...   | ...   | ...   | ...   |
|                                  | 0.107  | 0.113  | 0.120 | 0.129 | 0.110 | 0.121 | 0.134 | 0.138 | 0.147 | 0.157 | 0.106 | ...   | ...   | ...   | ...   |
| $\frac{1}{8}$                    | 14.50  | 13.50  | 12.50 | 11.50 | 9.00  | 8.00  | 7.00  | 7.00  | 7.00  | 6.50  | 4.50  | 4.00  | 3.50  | 3.50  | ...   |
|                                  | 0.163  | 0.169  | 0.176 | 0.185 | 0.165 | 0.176 | 0.171 | 0.193 | 0.205 | 0.204 | 0.159 | 0.170 | 0.165 | 0.186 | ...   |
| $\frac{3}{16}$                   | 19.50  | 18.00  | 16.50 | 15.00 | 12.00 | 10.50 | 10.00 | 9.00  | 8.50  | 8.50  | 6.00  | 5.50  | 5.00  | 4.50  | 4.00  |
|                                  | 0.219  | 0.225  | 0.232 | 0.241 | 0.220 | 0.231 | 0.244 | 0.248 | 0.249 | 0.267 | 0.213 | 0.234 | 0.236 | 0.239 | 0.243 |
| $\frac{1}{4}$                    | 24.50  | 23.508 | 20.50 | 18.50 | 15.00 | 13.00 | 12.00 | 11.00 | 10.50 | 10.00 | 7.50  | 6.50  | 6.00  | 5.50  | 5.00  |
|                                  | 0.276  | 0.294  | 0.288 | 0.297 | 0.275 | 0.286 | 0.293 | 0.303 | 0.308 | 0.314 | 0.266 | 0.276 | 0.283 | 0.292 | 0.304 |
| $\frac{5}{16}$                   | 29.50  | 27.00  | 24.50 | 22.00 | 18.00 | 15.50 | 14.50 | 13.00 | 12.50 | 12.00 | 9.00  | 8.00  | 7.00  | 6.50  | 6.00  |
|                                  | 0.332  | 0.338  | 0.345 | 0.354 | 0.340 | 0.341 | 0.354 | 0.358 | 0.367 | 0.377 | 0.319 | 0.340 | 0.330 | 0.345 | 0.364 |
| $\frac{3}{8}$                    | 34.50  | 31.50  | 28.50 | 25.50 | 21.00 | 18.00 | 16.50 | 15.00 | 14.50 | 13.50 | 10.50 | 9.00  | 8.50  | 7.50  | 7.00  |
|                                  | 0.388  | 0.394  | 0.401 | 0.410 | 0.385 | 0.396 | 0.403 | 0.413 | 0.425 | 0.424 | 0.372 | 0.383 | 0.401 | 0.398 | 0.425 |
| $\frac{7}{16}$                   | 39.50  | 36.00  | 32.50 | 29.00 | 24.00 | 20.50 | 19.00 | 17.00 | 16.00 | 15.50 | 12.00 | 10.50 | 9.50  | 8.50  | 7.50  |
|                                  | 0.444  | 0.450  | 0.457 | 0.466 | 0.440 | 0.451 | 0.464 | 0.468 | 0.469 | 0.487 | 0.425 | 0.446 | 0.448 | 0.451 | 0.455 |
| $\frac{1}{2}$                    | 44.50  | 40.50  | 36.50 | 32.50 | 27.00 | 23.00 | 21.00 | 19.00 | 18.00 | 17.00 | 13.50 | 11.50 | 10.50 | 9.50  | 8.50  |
|                                  | 0.501  | 0.506  | 0.513 | 0.522 | 0.495 | 0.506 | 0.513 | 0.523 | 0.528 | 0.534 | 0.478 | 0.489 | 0.496 | 0.504 | 0.516 |
| $\frac{9}{16}$                   | 49.50  | 45.00  | 40.50 | 36.00 | 30.00 | 25.50 | 23.50 | 21.00 | 20.00 | 19.00 | 15.00 | 13.00 | 11.50 | 10.50 | 9.50  |
|                                  | 0.559  | 0.563  | 0.570 | 0.579 | 0.550 | 0.561 | 0.574 | 0.578 | 0.587 | 0.597 | 0.531 | 0.553 | 0.543 | 0.558 | 0.577 |
| $\frac{5}{8}$                    | 54.50  | 49.50  | 44.50 | 39.50 | 33.00 | 28.00 | 25.50 | 23.00 | 22.00 | 20.50 | 16.50 | 14.00 | 13.00 | 11.50 | 10.50 |
|                                  | 0.613  | 0.619  | 0.626 | 0.635 | 0.605 | 0.616 | 0.623 | 0.633 | 0.645 | 0.644 | 0.584 | 0.595 | 0.614 | 0.611 | 0.637 |
| $\frac{11}{16}$                  | 59.50  | 54.00  | 48.50 | 43.00 | 36.00 | 30.50 | 28.00 | 25.00 | 23.50 | 22.50 | 18.00 | 15.50 | 14.00 | 12.50 | 11.00 |
|                                  | 0.679  | 0.675  | 0.682 | 0.691 | 0.660 | 0.671 | 0.684 | 0.688 | 0.689 | 0.707 | 0.638 | 0.659 | 0.661 | 0.664 | 0.668 |
| $\frac{3}{4}$                    | 64.50  | 58.50  | 52.50 | 46.50 | 39.00 | 33.00 | 30.00 | 27.00 | 25.50 | 24.00 | 19.50 | 16.50 | 15.00 | 13.50 | 12.00 |
|                                  | 0.726  | 0.731  | 0.738 | 0.747 | 0.715 | 0.726 | 0.733 | 0.743 | 0.748 | 0.754 | 0.691 | 0.701 | 0.708 | 0.717 | 0.728 |

Threading cams are often cut on a circular milling attachment. When this method is employed, the number of minutes the attachment should be revolved for each 0.001 inch rise, is first determined. As 15 spindle revolutions are required for threading and 400 for completing one piece, that part of the cam surface required for the actual threading operation equals  $15 \div 400 = 0.0375$ , which is equivalent to 810 minutes of the circumference. The total rise, through an arc of 810 minutes is 0.413 inch, so the number of minutes for each 0.001 inch rise equals  $810 \div 413 = 1.96$  or, approximately, two minutes. If the attachment is graduated to read to five minutes, the cam will be fed laterally 0.0025 inch each time it is turned through five minutes of arc.

**Practical Points on Cam and Tool Design.**—The following general rules are given to aid in designing cams and special tools for automatic screw machines, and apply particularly to Brown and Sharpe machines:

- 1) Use the highest speeds recommended for the material used that the various tools will stand.
- 2) Use the arrangement of circular tools best suited for the class of work.
- 3) Decide on the quickest and best method of arranging the operations before designing the cams.
- 4) Do not use turret tools for forming when the cross-slide tools can be used to better advantage.
- 5) Make the shoulder on the circular cutoff tool large enough so that the clamping screw will grip firmly.
- 6) Do not use too narrow a cutoff blade.
- 7) Allow 0.005 to 0.010 inch for the circular tools to approach the work and 0.003 to 0.005 inch for the cutoff tool to pass the center.
- 8) When cutting off work, the feed of the cutoff tool should be decreased near the end of the cut where the piece breaks off.
- 9) When a thread is cut up to a shoulder, the piece should be grooved or necked to make allowance for the lead on the die. An extra projection on the forming tool and an extra amount of rise on the cam will be needed.
- 10) Allow sufficient clearance for tools to pass one another.
- 11) Always make a diagram of the cross-slide tools in position on the work when difficult operations are to be performed; do the same for the tools held in the turret.
- 12) Do not drill a hole the depth of which is more than 3 times the diameter of the drill, but rather use two or more drills as required. If there are not enough turret positions for the extra drills needed, make provision for withdrawing the drill clear of the hole and then advancing it into the hole again.
- 13) Do not run drills at low speeds. Feeds and speeds recommended in the table starting on page 1132 should be followed as far as is practicable.
- 14) When the turret tools operate farther in than the face of the chuck, see that they will clear the chuck when the turret is revolved.
- 15) See that the bodies of all turret tools will clear the side of the chute when the turret is revolved.
- 16) Use a balance turning tool or a hollow mill for roughing cuts.
- 17) The rise on the thread lobe should be reduced so that the spindle will reverse when the tap or die holder is drawn out.
- 18) When bringing another tool into position after a threading operation, allow clearance before revolving the turret.
- 19) Make provision to revolve the turret rapidly, especially when pieces are being made in from three to five seconds and when only a few tools are used in the turret. It is sometimes desirable to use two sets of tools.
- 20) When using a belt-shifting attachment for threading, clearance should be allowed, as it requires extra time to shift the belt.

21) When laying out a set of cams for operating on a piece that requires to be slotted, cross-drilled or burred, allowance should be made on the lead cam so that the transferring arm can descend and ascend to and from the work without coming in contact with any of the turret tools.

22) Always provide a vacant hole in the turret when it is necessary to use the transferring arm.

23) When designing special tools allow as much clearance as possible. Do not make them so that they will just clear each other, as a slight inaccuracy in the dimensions will often cause trouble.

24) When designing special tools having intricate movements, avoid springs as much as possible, and use positive actions.

**Stock for Screw Machine Products.**—The amount of stock required for the production of 1000 pieces on the automatic screw machine can be obtained directly from the table *Stock Required for Screw Machine Products*. To use this table, add to the length of the work the width of the cut-off tool blade; then the number of feet of material required for 1000 pieces can be found opposite the figure thus obtained, in the column headed "Feet per 1000 Parts." Screw machine stock usually comes in bars 10 feet long, and in compiling this table an allowance was made for chucking on each bar.

The table can be extended by using the following formula, in which

$F$  = number of feet required for 1000 pieces

$L$  = length of piece in inches

$W$  = width of cut-off tool blade in inches

$$F = (L + W) \times 84$$

The amount to add to the length of the work, or the width of the cut-off tool, is given in the following, which is standard in a number of machine shops:

| Diameter of Stock, Inches | Width of Cut-off Tool Blade, Inches |
|---------------------------|-------------------------------------|
| 0.000–0.250               | 0.045                               |
| 0.251–0.375               | 0.062                               |
| 0.376–0.625               | 0.093                               |
| 0.626–1.000               | 0.125                               |
| 1.001–1.500               | 0.156                               |

It is sometimes convenient to know the weight of a certain number of pieces, when estimating the price. The weight of round bar stock can be found by means of the following formulas, in which

$W$  = weight in pounds

$D$  = diameter of stock in inches

$F$  = length in feet

For brass stock:  $W = D^2 \times 2.86 \times F$

For steel stock:  $W = D^2 \times 2.675 \times F$

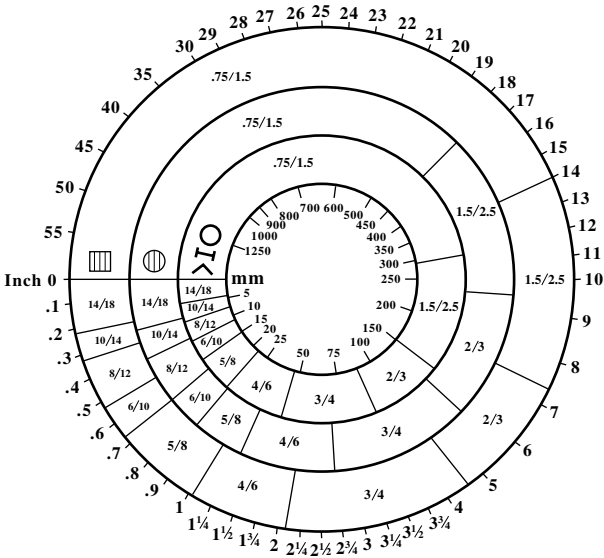
For iron stock:  $W = D^2 \times 2.65 \times F$

**Stock Required for Screw Machine Products**

The table gives the amount of stock, in feet, required for 1000 pieces, when the length of the finished part plus the thickness of the cut-off tool blade is known. Allowance has been made for chucking. To illustrate, if length of cut-off tool and work equals 0.140 inch, 11.8 feet of stock is required for the production of 1000 parts.

| Length of Piece and Cut-Off Tool | Feet per 1000 Parts | Length of Piece and Cut-Off Tool | Feet per 1000 Parts | Length of Piece and Cut-Off Tool | Feet per 1000 Parts | Length of Piece and Cut-Off Tool | Feet per 1000 Parts |
|----------------------------------|---------------------|----------------------------------|---------------------|----------------------------------|---------------------|----------------------------------|---------------------|
| 0.050                            | 4.2                 | 0.430                            | 36.1                | 0.810                            | 68.1                | 1.380                            | 116.0               |
| 0.060                            | 5.0                 | 0.440                            | 37.0                | 0.820                            | 68.9                | 1.400                            | 117.6               |
| 0.070                            | 5.9                 | 0.450                            | 37.8                | 0.830                            | 69.7                | 1.420                            | 119.3               |
| 0.080                            | 6.7                 | 0.460                            | 38.7                | 0.840                            | 70.6                | 1.440                            | 121.0               |
| 0.090                            | 7.6                 | 0.470                            | 39.5                | 0.850                            | 71.4                | 1.460                            | 122.7               |
| 0.100                            | 8.4                 | 0.480                            | 40.3                | 0.860                            | 72.3                | 1.480                            | 124.4               |
| 0.110                            | 9.2                 | 0.490                            | 41.2                | 0.870                            | 73.1                | 1.500                            | 126.1               |
| 0.120                            | 10.1                | 0.500                            | 42.0                | 0.880                            | 73.9                | 1.520                            | 127.7               |
| 0.130                            | 10.9                | 0.510                            | 42.9                | 0.890                            | 74.8                | 1.540                            | 129.4               |
| 0.140                            | 11.8                | 0.520                            | 43.7                | 0.900                            | 75.6                | 1.560                            | 131.1               |
| 0.150                            | 12.6                | 0.530                            | 44.5                | 0.910                            | 76.5                | 1.580                            | 132.8               |
| 0.160                            | 13.4                | 0.540                            | 45.4                | 0.920                            | 77.3                | 1.600                            | 134.5               |
| 0.170                            | 14.3                | 0.550                            | 46.2                | 0.930                            | 78.2                | 1.620                            | 136.1               |
| 0.180                            | 15.1                | 0.560                            | 47.1                | 0.940                            | 79.0                | 1.640                            | 137.8               |
| 0.190                            | 16.0                | 0.570                            | 47.9                | 0.950                            | 79.8                | 1.660                            | 139.5               |
| 0.200                            | 16.8                | 0.580                            | 48.7                | 0.960                            | 80.7                | 1.680                            | 141.2               |
| 0.210                            | 17.6                | 0.590                            | 49.6                | 0.970                            | 81.5                | 1.700                            | 142.9               |
| 0.220                            | 18.5                | 0.600                            | 50.4                | 0.980                            | 82.4                | 1.720                            | 144.5               |
| 0.230                            | 19.3                | 0.610                            | 51.3                | 0.990                            | 83.2                | 1.740                            | 146.2               |
| 0.240                            | 20.2                | 0.620                            | 52.1                | 1.000                            | 84.0                | 1.760                            | 147.9               |
| 0.250                            | 21.0                | 0.630                            | 52.9                | 1.020                            | 85.7                | 1.780                            | 149.6               |
| 0.260                            | 21.8                | 0.640                            | 53.8                | 1.040                            | 87.4                | 1.800                            | 151.3               |
| 0.270                            | 22.7                | 0.650                            | 54.6                | 1.060                            | 89.1                | 1.820                            | 152.9               |
| 0.280                            | 23.5                | 0.660                            | 55.5                | 1.080                            | 90.8                | 1.840                            | 154.6               |
| 0.290                            | 24.4                | 0.670                            | 56.3                | 1.100                            | 92.4                | 1.860                            | 156.3               |
| 0.300                            | 25.2                | 0.680                            | 57.1                | 1.120                            | 94.1                | 1.880                            | 158.0               |
| 0.310                            | 26.1                | 0.690                            | 58.0                | 1.140                            | 95.8                | 1.900                            | 159.7               |
| 0.320                            | 26.9                | 0.700                            | 58.8                | 1.160                            | 97.5                | 1.920                            | 161.3               |
| 0.330                            | 27.7                | 0.710                            | 59.7                | 1.180                            | 99.2                | 1.940                            | 163.0               |
| 0.340                            | 28.6                | 0.720                            | 60.5                | 1.200                            | 100.8               | 1.960                            | 164.7               |
| 0.350                            | 29.4                | 0.730                            | 61.3                | 1.220                            | 102.5               | 1.980                            | 166.4               |
| 0.360                            | 30.3                | 0.740                            | 62.2                | 1.240                            | 104.2               | 2.000                            | 168.1               |
| 0.370                            | 31.1                | 0.750                            | 63.0                | 1.260                            | 105.9               | 2.100                            | 176.5               |
| 0.380                            | 31.9                | 0.760                            | 63.9                | 1.280                            | 107.6               | 2.200                            | 184.9               |
| 0.390                            | 32.8                | 0.770                            | 64.7                | 1.300                            | 109.2               | 2.300                            | 193.3               |
| 0.400                            | 33.6                | 0.780                            | 65.5                | 1.320                            | 110.9               | 2.400                            | 201.7               |
| 0.410                            | 34.5                | 0.790                            | 66.4                | 1.340                            | 112.6               | 2.500                            | 210.1               |
| 0.420                            | 35.3                | 0.800                            | 67.2                | 1.360                            | 114.3               | 2.600                            | 218.5               |

**Band Saw Blade Selection.**—The primary factors to consider in choosing a saw blade are: the pitch, or the number of teeth per inch of blade; the tooth form; and the blade type (material and construction). Tooth pitch selection depends on the size and shape of the work, whereas tooth form and blade type depend on material properties of the workpiece and on economic considerations of the job.



*Courtesy of American Saw and Manufacturing Company*

The tooth selection chart above is a guide to help determine the best blade pitch for a particular job. The tooth specifications in the chart are standard variable-pitch blade sizes as specified by the Hack and Band Saw Association. The variable-pitch blades listed are designated by two numbers that refer to the approximate maximum and minimum tooth pitch. A 4/6 blade, for example, has a maximum tooth spacing of approximately  $\frac{1}{4}$  inch and a minimum tooth spacing of about  $\frac{1}{6}$  inch. Blades are available, from most manufacturers, in sizes within about  $\pm 10$  per cent of the sizes listed.

To use the chart, locate the length of cut in inches on the outside circle of the table (for millimeters use the inside circle) and then find the tooth specification that aligns with the length, on the ring corresponding to the material shape. The length of cut is the distance that any tooth of the blade is in contact with the work as it passes once through the cut. For cutting solid round stock, use the diameter as the length of cut and select a blade from the ring with the solid circle. When cutting angles, channels, I-beams, tubular pieces, pipe, and hollow or irregular shapes, the length of cut is found by dividing the cross-sectional area of the cut by the distance the blade needs to travel to finish the cut. Locate the length of cut on the outer ring (inner ring for mm) and select a blade from the ring marked with the angle, I-beam, and pipe sections.

*Example:* A 4-inch pipe with a 3-inch inside diameter is to be cut. Select a variable pitch blade for cutting this material.

The area of the pipe is  $\pi/4 \times (4^2 - 3^2) = 5.5 \text{ in.}^2$ . The blade has to travel 4 inches to cut through the pipe, so the average length of cut is  $5.5/4 = 1.4$  inches. On the tooth selection wheel, estimate the location of 1.4 inches on the outer ring, and read the tooth specification from the ring marked with the pipe, angle, and I-beam symbols. The chart indicates that a 4/6 variable-pitch blade is the preferred blade for this cut.

**Tooth Forms.**—Band saw teeth are characterized by a tooth form that includes the shape, spacing (pitch), rake angle, and gullet capacity of the tooth. Tooth form affects the cutting efficiency, noise level, blade life, chip-carrying capacity, and the surface finish quality of the cut. The rake angle, which is the angle between the face of the tooth and a line perpendicular to the direction of blade travel, influences the cutting speed. In general, positive rake angles cut faster. The *standard tooth* form has conventional shape teeth, evenly spaced with deep gullets and a  $0^\circ$  rake angle. Standard tooth blades are used for general-purpose cutting on a wide variety of materials. The *skip tooth* form has shallow, widely spaced teeth arranged in narrow bands and a  $0^\circ$  rake angle. Skip tooth blades are used for cutting soft metals, wood, plastics, and composite materials. The *hook tooth* form is similar to the skip tooth, but has a positive rake angle and is used for faster cutting of large sections of soft metal, wood, and plastics, as well as for cutting some metals, such as cast iron, that form a discontinuous chip. The *variable-tooth* (variable-pitch) form has a conventional tooth shape, but the tips of the teeth are spaced a variable distance (pitch) apart. The variable pitch reduces vibration of the blade and gives smoother cutting, better surface finish, and longer blade life. The *variable positive tooth* form is a variable-pitch tooth with a positive rake angle that causes the blade to penetrate the work faster. The variable positive tooth blade increases production and gives the longest blade life.

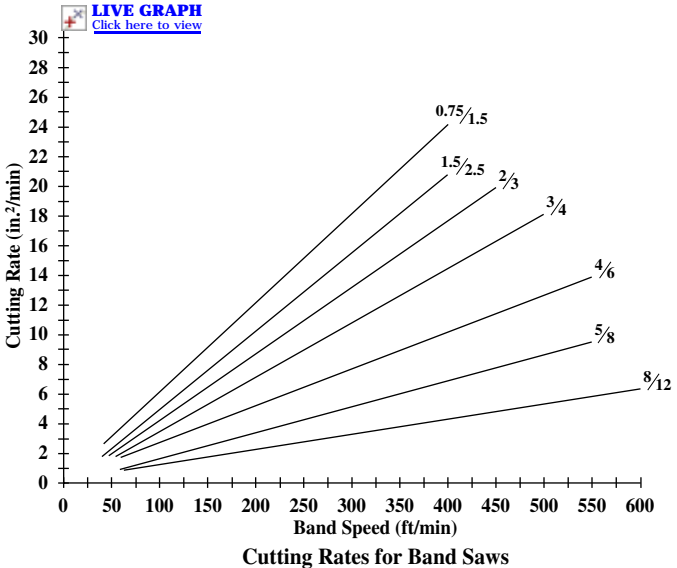
*Set* is the angle that the teeth are offset from the straight line of a blade. The set affects the blade efficiency (i.e., cutting rate), chip-carrying ability, and quality of the surface finish. *Alternate set* blades have adjacent teeth set alternately one to each side. Alternate set blades, which cut faster but with a poorer finish than other blades, are especially useful for rapid rough cutting. A *raker set* is similar to the alternate set, but every few teeth, one of the teeth is set to the center, not to the side (typically every third tooth, but sometimes every fifth or seventh tooth). The raker set pattern cuts rapidly and produces a good surface finish. The *vari-raker set*, or variable raker, is a variable-tooth blade with a raker set. The vari-raker is quieter and produces a better surface finish than a raker set standard tooth blade. *Wavy set* teeth are set in groups, alternately to one side, then to the other. Both wavy set and vari-raker set blades are used for cutting tubing and other interrupted cuts, but the blade efficiency and surface finish produced are better with a vari-raker set blade.

**Types of Blades.**—The most important band saw blade types are carbon steel, bimetal, carbide tooth, and grit blades made with embedded carbide or diamond. *Carbon steel blades* have the lowest initial cost, but they may wear out faster. Carbon steel blades are used for cutting a wide variety of materials, including mild steels, aluminum, brass, bronze, cast iron, copper, lead, and zinc, as well as some abrasive materials such as cork, fiberglass, graphite, and plastics. *Bimetal blades* are made with a high-speed steel cutting edge that is welded to a spring steel blade back. Bimetal blades are stronger and last longer, and they tend to produce straighter cuts because the blade can be tensioned higher than carbon steel blades. Because bimetal blades last longer, the cost per cut is frequently lower than when using carbon steel blades. Bimetal blades are used for cutting all ferrous and nonferrous metals, a wide range of shapes of easy to moderately machinable material, and solids and heavy wall tubing with moderate to difficult machinability. *Tungsten carbide blades* are similar to bimetal blades but have tungsten carbide teeth welded to the blade back. The welded teeth of carbide blades have greater wear and high-temperature resistance than either carbon steel or bimetal blades and produce less tooth vibration, while giving smoother, straighter, faster, and quieter cuts requiring less feed force. Carbide blades are used on tough alloys such as cobalt, nickel- and titanium-based alloys, and for nonferrous materials such as aluminum castings, fiberglass, and graphite. The *carbide grit blade*



has tungsten carbide grit metallurgically bonded to either a gulletted (serrated) or toothless steel band. The blades are made in several styles and grit sizes. Both carbide grit and diamond grit blades are used to cut materials that conventional (carbon and bimetal) blades are unable to cut such as: fiberglass, reinforced plastics, composite materials, carbon and graphite, aramid fibers, plastics, cast iron, stellites, high-hardness tool steels, and superalloys.

**Band Saw Speed and Feed Rate.**—The band speed necessary to cut a particular material is measured in feet per minute (fpm) or in meters per minute (m/min), and depends on material characteristics and size of the workpiece. Typical speeds for a bimetal blade cutting 4-inch material with coolant are given in the speed selection table that follows. For other size materials or when cutting without coolant, adjust speeds according to the instructions at the bottom of the table.



The feed or cutting rate, usually measured in square inches or square meters per minute, indicates how fast material is being removed and depends on the speed and pitch of the blade, not on the workpiece material. The graph above, based on material provided by American Saw and Mfg., gives approximate cutting rates (in.<sup>2</sup>/min) for various variable-pitch blades and cutting speeds. Use the value from the graph as an initial starting value and then adjust the feed based on the performance of the saw. The size and character of the chips being produced are the best indicators of the correct feed force. Chips that are curly, silvery, and warm indicate the best feed rate and band speed. If the chips appear burned and heavy, the feed is too great, so reduce the feed rate, the band speed, or both. If the chips are thin or powdery, the feed rate is too low, so increase the feed rate or reduce the band speed. The actual cutting rate achieved during a cut is equal to the area of the cut divided by the time required to finish the cut. The time required to make a cut is equal to the area of the cut divided by the cutting rate in square inches per minute.

**Bimetal Band Saw Speeds for Cutting 4-Inch Material with Coolant**

| Material  | Category (AISI/SAE)   | Speed (fpm) | Speed (m/min) |
|---|---|-------------|---------------|
| Aluminum Alloys   | 1100, 2011, 2017, 2024, 3003, 5052, 5086, 6061, 6063, 6101, 6262, 7075  | 500         | 152           |
| Cast Iron   | A536 (60-40-18)   | 360         | 110           |
|   | A47   | 300         | 91            |
|   | A220 (50005), A536 (80-55-06)   | 240         | 73            |
|   | A48 (20 ksi)  | 230         | 70            |
|   | A536 (100-70-03)  | 185         | 56            |
|   | A48 (40 ksi)  | 180         | 55            |
|   | A220 (60004)  | 170         | 52            |
|   | A436 (1B)   | 150         | 46            |
|   | A220 (70003)  | 145         | 44            |
|   | A436 (2)  | 140         | 43            |
|   | A220 (80002), A436 (2B)   | 125         | 38            |
|   | A536 (120-90-02)  | 120         | 37            |
|   | A220 (90001), A48 (60 ksi)  | 100         | 30            |
|   | A439 (D-2)  | 80          | 24            |
|   | A439 (D-2B)   | 60          | 18            |
| Cobalt  | WF-11   | 65          | 20            |
|   | Astroloy M  | 60          | 18            |
| Copper  | 356, 360  | 450         | 137           |
|   | 353   | 400         | 122           |
|   | 187, 1452   | 375         | 114           |
|   | 380, 544  | 350         | 107           |
|   | 173, 932, 934   | 315         | 96            |
|   | 330, 365  | 285         | 87            |
|   | 623, 624  | 265         | 81            |
|   | 230, 260, 272, 280, 464, 632, 655   | 245         | 75            |
|   | 101, 102, 110, 122, 172, 17510, 182, 220, 510, 625, 706, 715  | 235         | 72            |
|   | 630   | 230         | 70            |
|   | 811   | 215         | 66            |
| Iron Base Super Alloy   | Pyromet X-15  | 120         | 37            |
|   | A286, Incoloy 800 and 801   | 90          | 27            |
| Magnesium   | AZ31B   | 900         | 274           |
| Nickel  | Nickel 200, 201, 205  | 85          | 26            |
| Nickel Alloy  | Inconel 625   | 100         | 30            |
|   | Incoloy 802, 804  | 90          | 27            |
|   | Monel R405  | 85          | 26            |
|   | 20CB3   | 80          | 24            |
|   | Monel 400, 401  | 75          | 23            |
|   | Hastelloy B, B2, C, C4, C22, C276, F, G, G2, G3, G30, N, S, W, X, Incoloy 825, 926, Inconel 751, X750, Waspaloy | 70          | 21            |
|   | Monel K500  | 65          | 20            |
|   | Incoloy 901, 903, Inconel 600, 718, Ni-Span-C902, Nimonic 263, Rene 41, Udimet 500                              | 60          | 18            |
|   | Nimonic 75  | 50          | 15            |
|   | Stainless Steel   | 416, 420    | 190           |
| 203EZ, 430, 430F, 4302  |   | 150         | 46            |
| 303, 303PB, 303SE, 410, 440F, 30323   |   | 140         | 43            |
| 304   |   | 120         | 37            |
| 414, 30403  |   | 115         | 35            |
| 347   |   | 110         | 34            |
| 316, 31603  |   | 100         | 30            |
| Greek Ascology  |   | 95          | 29            |
| 18-18-2, 309, Ferralium   |   | 90          | 27            |
| 15-5PH, 17-4PH, 17-7PH, 2205, 310, AM350, AM355, Custom 450, Custom 455, PH13-8Mo, PH14-8Mo, PH15-7Mo |   | 80          | 24            |
| 22-13-5, Nitronic 50, 60  |   | 60          | 18            |

**Bimetal Band Saw Speeds for Cutting 4-Inch Material with Coolant (Continued)**

| Material  | Category (AISI/SAE)                          | Speed (fpm)                                    | Speed (m/min) |
|---|--|--|---------------|
| Steel   | 12L14  | 425  | 130           |
|   | 1213, 1215                                   | 400  | 122           |
|   | 1117   | 340  | 104           |
|   | 1030   | 330  | 101           |
|   | 1008, 1015, 1020, 1025                       | 320  | 98            |
|   | 1035   | 310  | 94            |
|   | 1018, 1021, 1022, 1026, 1513, A242 Cor-Ten A | 300  | 91            |
|   | 1137   | 290  | 88            |
|   | 1141, 1144, 1144 Hi Stress                   | 280  | 85            |
|   | 41L40  | 275  | 84            |
|   | 1040, 4130, A242 Cor-Ten B, (A36 Shapes)     | 270  | 82            |
|   | 1042, 1541, 4140, 4142                       | 250  | 76            |
|   | 8615, 8620, 8622                             | 240  | 73            |
|   | W-1  | 225  | 69            |
|   | 1044, 1045, 1330, 4340, E4340, 5160, 8630    | 220  | 67            |
|   | 1345, 4145, 6150                             | 210  | 64            |
|   | 1060, 4150, 8640, A-6, O-1, S-1              | 200  | 61            |
|   | H-11, H-12, H-13, L-6, O-6                   | 190  | 58            |
|   | 1095   | 185  | 56            |
|   | A-2  | 180  | 55            |
|   | E9310  | 175  | 53            |
|   | 300M, A-10, E52100, HY-80, HY-100            | 160  | 49            |
|   | S-5  | 140  | 43            |
|   | S-7  | 125  | 38            |
|   | M-1  | 110  | 34            |
|   | HP 9-4-20, HP 9-4-25                         | 105  | 32            |
|   | M-2, M-42, T1                                | 100  | 30            |
|   | D-2  | 90   | 27            |
|   | T-15   | 70   | 21            |
|   | Titanium                                     | Pure, Ti-3Al-8V-6Cr-4Mo-4Zr, Ti-8Mo-8V-2Fe-3Al | 80            |
| Ti-2Al-11Sn-5Zr-1Mo, Ti-5Al-2.5Sn, Ti-6Al-2Sn-4Zr-2Mo |  | 75   | 23            |
| Ti-6Al-4V   |  | 70   | 21            |
| Ti-7Al-4Mo, Ti-8Al-1Mo-1V                             |  | 65   | 20            |

The speed figures given are for 4-in. material (length of cut) using a 3/4 variable-tooth bimetal blade and cutting fluid. For cutting dry, reduce speed 30–50%; for carbon steel band saw blades, reduce speed 50%. For other cutting lengths: increase speed 15% for 1/4-in. material (10/14 blade); increase speed 12% for 3/4-in. material (6/10 blade); increase speed 10% for 1 1/4-in. material (4/6 blade); decrease speed 12% for 8-in. material (2/3 blade).

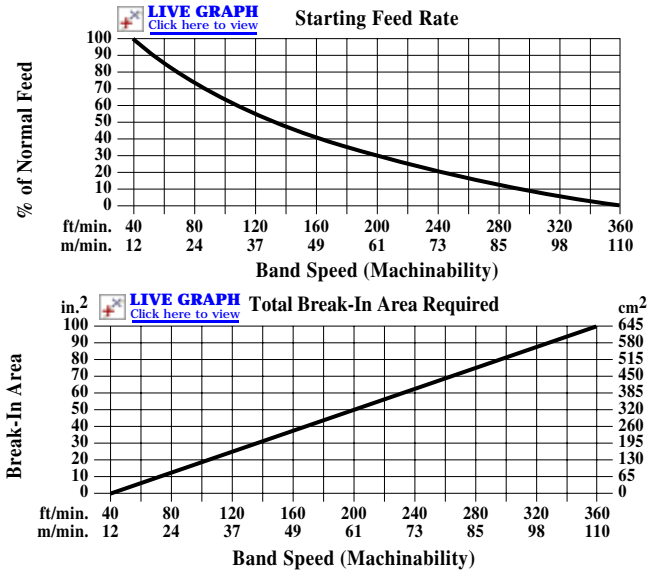
Table data are based on material provided by LENOX Blades, American Saw & Manufacturing Co.

*Example:* Find the band speed, the cutting rate, and the cutting time if the 4-inch pipe of the previous example is made of 304 stainless steel.

The preceding blade speed table gives the band speed for 4-inch 304 stainless steel as 120 fpm (feet per minute). The average length of cut for this pipe (see the previous example) is 1.4 inches, so increase the band saw speed by about 10 per cent (see footnote on ) to 130 fpm to account for the size of the piece. On the cutting rate graph above, locate the point on the 4/6 blade line that corresponds to the band speed of 130 fpm and then read the cutting rate from the left axis of the graph. The cutting rate for this example is approximately 4 in. <sup>2</sup>/min. The cutting time is equal to the area of the cut divided by the cutting rate, so cutting time = 5.5/4 = 1.375 minutes.

**Band Saw Blade Break-In.**—A new band saw blade must be broken in gradually before it is allowed to operate at its full recommended feed rate. Break-in relieves the blade of residual stresses caused by the manufacturing process so that the blade retains its cutting ability longer. Break-in requires starting the cut at the material cutting speed with a low feed rate and then gradually increasing the feed rate over time until enough material has been cut. A blade should be broken in with the material to be cut.

To break in a new blade, first set the band saw speed at the recommended cutting speed for the material and start the first cut at the feed indicated on the starting feed rate graph below. After the saw has penetrated the work to a distance equal to the width of the blade, increase the feed slowly. When the blade is about halfway through the cut, increase the feed again slightly and finish the cut without increasing the feed again. Start the next and each successive cut with the same feed rate that ended the previous cut, and increase the feed rate slightly again before the blade reaches the center of the cut. Repeat this procedure until the area cut by the new blade is equal to the total area required as indicated on the graph below. At the end of the break-in period, the blade should be cutting at the recommended feed rate, otherwise adjusted to that rate.



### Cutting Fluids for Machining

The goal in all conventional metal-removal operations is to raise productivity and reduce costs by machining at the highest practical speed consistent with long tool life, fewest rejects, and minimum downtime, and with the production of surfaces of satisfactory accuracy and finish. Many machining operations can be performed "dry," but the proper application of a cutting fluid generally makes possible: higher cutting speeds, higher feed rates, greater depths of cut, lengthened tool life, decreased surface roughness, increased dimensional accuracy, and reduced power consumption. Selecting the proper cutting fluid for a specific machining situation requires knowledge of fluid functions, properties, and limitations. Cutting fluid selection deserves as much attention as the choice of machine tool, tooling, speeds, and feeds.

To understand the action of a cutting fluid it is important to realize that almost all the energy expended in cutting metal is transformed into heat, primarily by the deformation of the metal into the chip and, to a lesser degree, by the friction of the chip sliding against the tool face. With these factors in mind it becomes clear that the primary functions of any cut-

ting fluid are: cooling of the tool, workpiece, and chip; reducing friction at the sliding contacts; and reducing or preventing welding or adhesion at the contact surfaces, which forms the "built-up edge" on the tool. Two other functions of cutting fluids are flushing away chips from the cutting zone and protecting the workpiece and tool from corrosion.

The relative importance of the functions is dependent on the material being machined, the cutting tool and conditions, and the finish and accuracy required on the part. For example, cutting fluids with greater lubricity are generally used in low-speed machining and on most difficult-to-cut materials. Cutting fluids with greater cooling ability are generally used in high-speed machining on easier-to-cut materials.

**Types of Cutting and Grinding Fluids.**—In recent years a wide range of cutting fluids has been developed to satisfy the requirements of new materials of construction and new tool materials and coatings.

There are four basic types of cutting fluids; each has distinctive features, as well as advantages and limitations. Selection of the right fluid is made more complex because the dividing line between types is not always clear. Most machine shops try to use as few different fluids as possible and prefer fluids that have long life, do not require constant changing or modifying, have reasonably pleasant odors, do not smoke or fog in use, and, most important, are neither toxic nor cause irritation to the skin. Other issues in selection are the cost and ease of disposal.

The major divisions and subdivisions used in classifying cutting fluids are:

*Cutting Oils*, including straight and compounded mineral oils plus additives.

*Water-Miscible Fluids*, including emulsifiable oils; chemical or synthetic fluids; and semichemical fluids.

*Gases*.

*Paste and Solid Lubricants*.

Since the cutting oils and water-miscible types are the most commonly used cutting fluids in machine shops, discussion will be limited primarily to these types. It should be noted, however, that compressed air and inert gases, such as carbon dioxide, nitrogen, and Freon, are sometimes used in machining. Paste, waxes, soaps, graphite, and molybdenum disulfide may also be used, either applied directly to the workpiece or as an impregnant in the tool, such as in a grinding wheel.

**Cutting Oils.**—Cutting oils are generally compounds of mineral oil with the addition of animal, vegetable, or marine oils to improve the wetting and lubricating properties. Sulfur, chlorine, and phosphorous compounds, sometimes called extreme pressure (EP) additives, provide for even greater lubricity. In general, these cutting oils do not cool as well as water-miscible fluids.

**Water-Miscible Fluids.**—*Emulsions or soluble oils* are a suspension of oil droplets in water. These suspensions are made by blending the oil with emulsifying agents (soap and soaplike materials) and other materials. These fluids combine the lubricating and rust-prevention properties of oil with water's excellent cooling properties. Their properties are affected by the emulsion concentration, with "lean" concentrations providing better cooling but poorer lubrication, and with "rich" concentrations having the opposite effect. Additions of sulfur, chlorine, and phosphorus, as with cutting oils, yield "extreme pressure" (EP) grades.

*Chemical fluids* are true solutions composed of organic and inorganic materials dissolved in water. Inactive types are usually clear fluids combining high rust inhibition, high cooling, and low lubricity characteristics with high surface tension. Surface-active types include wetting agents and possess moderate rust inhibition, high cooling, and moderate lubricating properties with low surface tension. They may also contain chlorine and/or sulfur compounds for extreme pressure properties.

*Semichemical fluids* are combinations of chemical fluids and emulsions. These fluids have a lower oil content but a higher emulsifier and surface-active-agent content than

emulsions, producing oil droplets of much smaller diameter. They possess low surface tension, moderate lubricity and cooling properties, and very good rust inhibition. Sulfur, chlorine, and phosphorus also are sometimes added.

**Selection of Cutting Fluids for Different Materials and Operations.**—The choice of a cutting fluid depends on many complex interactions including the machinability of the metal; the severity of the operation; the cutting tool material; metallurgical, chemical, and human compatibility; fluid properties, reliability, and stability; and finally cost. Other factors affect results. Some shops standardize on a few cutting fluids which have to serve all purposes. In other shops, one cutting fluid must be used for all the operations performed on a machine. Sometimes, a very severe operating condition may be alleviated by applying the “right” cutting fluid manually while the machine supplies the cutting fluid for other operations through its coolant system. Several voluminous textbooks are available with specific recommendations for the use of particular cutting fluids for almost every combination of machining operation and workpiece and tool material. In general, when experience is lacking, it is wise to consult the material supplier and/or any of the many suppliers of different cutting fluids for advice and recommendations. Another excellent source is the Machinability Data Center, one of the many information centers supported by the U.S. Department of Defense. While the following recommendations represent good practice, they are to serve as a guide only, and it is not intended to say that other cutting fluids will not, in certain specific cases, also be effective.

**Steels:** Caution should be used when using a cutting fluid on steel that is being turned at a high cutting speed with cemented carbide cutting tools. See *Application of Cutting Fluids to Carbides* later. Frequently this operation is performed dry. If a cutting fluid is used, it should be a soluble oil mixed to a consistency of about 1 part oil to 20 to 30 parts water. A sulfurized mineral oil is recommended for reaming with carbide tipped reamers although a heavy-duty soluble oil has also been used successfully.

The cutting fluid recommended for machining steel with high speed cutting tools depends largely on the severity of the operation. For ordinary turning, boring, drilling, and milling on medium and low strength steels, use a soluble oil having a consistency of 1 part oil to 10 to 20 parts water. For tool steels and tough alloy steels, a heavy-duty soluble oil having a consistency of 1 part oil to 10 parts water is recommended for turning and milling. For drilling and reaming these materials, a light sulfurized mineral-fatty oil is used. For tough operations such as tapping, threading, and broaching, a sulfochlorinated mineral-fatty oil is recommended for tool steels and high-strength steels, and a heavy sulfurized mineral-fatty oil or a sulfochlorinated mineral oil can be used for medium- and low-strength steels. Straight sulfurized mineral oils are often recommended for machining tough, stringy low carbon steels to reduce tearing and produce smooth surface finishes.

**Stainless Steel:** For ordinary turning and milling a heavy-duty soluble oil mixed to a consistency of 1 part oil to 5 parts water is recommended. Broaching, threading, drilling, and reaming produce best results using a sulfochlorinated mineral-fatty oil.

**Copper Alloys:** Most brasses, bronzes, and copper are stained when exposed to cutting oils containing active sulfur and chlorine; thus, sulfurized and sulfochlorinated oils should not be used. For most operations a straight soluble oil, mixed to 1 part oil and 20 to 25 parts water is satisfactory. For very severe operations and for automatic screw machine work a mineral-fatty oil is used. A typical mineral-fatty oil might contain 5 to 10 per cent lard oil with the remainder mineral oil.

**Monel Metal:** When turning this material, an emulsion gives a slightly longer tool life than a sulfurized mineral oil, but the latter aids in chip breakage, which is frequently desirable.

**Aluminum Alloys:** Aluminum and aluminum alloys are frequently machined dry. When a cutting fluid is used it should be selected for its ability to act as a coolant. Soluble oils mixed to a consistency of 1 part oil to 20 to 30 parts water can be used. Mineral oil-base

cutting fluids, when used to machine aluminum alloys, are frequently cut back to increase their viscosity so as to obtain good cooling characteristics and to make them flow easily to cover the tool and the work. For example, a mineral-fatty oil or a mineral plus a sulfurized fatty oil can be cut back by the addition of as much as 50 per cent kerosene.

*Cast Iron:* Ordinarily, cast iron is machined dry. Some increase in tool life can be obtained or a faster cutting speed can be used with a chemical cutting fluid or a soluble oil mixed to consistency of 1 part oil and 20 to 40 parts water. A soluble oil is sometimes used to reduce the amount of dust around the machine.

*Magnesium:* Magnesium may be machined dry, or with an air blast for cooling. A light mineral oil of low acid content may be used on difficult cuts. Coolants containing water should not be used on magnesium because of the danger of releasing hydrogen caused by reaction of the chips with water. Proprietary water-soluble oil emulsions containing inhibitors that reduce the rate of hydrogen generation are available.

*Grinding:* Soluble oil emulsions or emulsions made from paste compounds are used extensively in precision grinding operations. For cylindrical grinding, 1 part oil to 40 to 50 parts water is used. Solution type fluids and translucent grinding emulsions are particularly suited for many fine-finish grinding applications. Mineral oil-base grinding fluids are recommended for many applications where a fine surface finish is required on the ground surface. Mineral oils are used with vitrified wheels but are not recommended for wheels with rubber or shellac bonds. Under certain conditions the oil vapor mist caused by the action of the grinding wheel can be ignited by the grinding sparks and explode. To quench the grinding spark a secondary coolant line to direct a flow of grinding oil below the grinding wheel is recommended.

*Broaching:* For steel, a heavy mineral oil such as sulfurized oil of 300 to 500 Saybolt viscosity at 100 degrees F can be used to provide both adequate lubricating effect and a dampening of the shock loads. Soluble oil emulsions may be used for the lighter broaching operations.

**Cutting Fluids for Turning, Milling, Drilling and Tapping.**—The following table, *Cutting Fluids Recommended for Machining Operations*, gives specific cutting oil recommendations for common machining operations.

*Soluble Oils:* Types of oils paste compounds that form emulsions when mixed with water: Soluble oils are used extensively in machining both ferrous and non-ferrous metals when the cooling quality is paramount and the chip-bearing pressure is not excessive. Care should be taken in selecting the proper soluble oil for precision grinding operations. Grinding coolants should be free from fatty materials that tend to load the wheel, thus affecting the finish on the machined part. Soluble coolants should contain rust preventive constituents to prevent corrosion.

*Base Oils:* Various types of highly sulfurized and chlorinated oils containing inorganic, animal, or fatty materials. This "base stock" usually is "cut back" or blended with a lighter oil, unless the chip-bearing pressures are high, as when cutting alloy steel. Base oils usually have a viscosity range of from 300 to 900 seconds at 100 degrees F.

*Mineral Oils:* This group includes all types of oils extracted from petroleum such as paraffin oil, mineral seal oil, and kerosene. Mineral oils are often blended with base stocks, but they are generally used in the original form for light machining operations on both free-machining steels and non-ferrous metals. The coolants in this class should be of a type that has a relatively high flash point. Care should be taken to see that they are nontoxic, so that they will not be injurious to the operator. The heavier mineral oils (paraffin oils) usually have a viscosity of about 100 seconds at 100 degrees F. Mineral seal oil and kerosene have a viscosity of 35 to 60 seconds at 100 degrees F.

## Cutting Fluids Recommended for Machining Operations

| Material to be Cut                     | Turning  | Milling  |
|--|--|--|
| Aluminum <sup>a</sup>                  | Mineral Oil with 10 Per cent Fat<br>(or)<br>Soluble Oil  | Soluble Oil (96 Per Cent Water)<br>(or)<br>Mineral Seal Oil<br>(or)<br>Mineral Oil   |
| Alloy Steels <sup>b</sup>              | 25 Per Cent Sulfur base Oil <sup>b</sup> with<br>75 Per Cent Mineral Oil                                 | 10 Per Cent Lard Oil with 90 Per<br>Cent Mineral Oil   |
| Brass                                  | Mineral Oil with 10 Per Cent Fat   | Soluble Oil (96 Per Cent Water)  |
| Tool Steels and Low-car-<br>bon Steels | 25 Per Cent Lard Oil with 75 Per<br>Cent Mineral Oil   | Soluble Oil  |
| Copper                                 | Soluble Oil  | Soluble Oil  |
| Monel Metal                            | Soluble Oil  | Soluble Oil  |
| Cast Iron <sup>c</sup>                 | Dry  | Dry  |
| Malleable Iron                         | Soluble Oil  | Soluble Oil  |
| Bronze                                 | Soluble Oil  | Soluble Oil  |
| Magnesium <sup>d</sup>                 | 10 Per Cent Lard Oil with 90 Per<br>Cent Mineral Oil   | Mineral Seal Oil   |
| Material to be Cut                     | Drilling   | Tapping  |
| Aluminum <sup>c</sup>                  | Soluble Oil (75 to 90 Per Cent<br>Water)<br>(or)<br>10 Per Cent Lard Oil with 90 Per<br>Cent Mineral Oil | Lard Oil<br>(or)<br>Sperm Oil<br>(or)<br>Wool Grease<br>(or)<br>25 Per Cent Sulfur-base Oil <sup>b</sup><br>Mixed with Mineral Oil |
| Alloy Steels <sup>b</sup>              | Soluble Oil  | 30 Per Cent Lard Oil with 70 Per<br>Cent Mineral Oil   |
| Brass                                  | Soluble Oil (75 to 90 Per Cent<br>Water)<br>(or)<br>30 Per Cent Lard Oil with 70 Per<br>Cent Mineral Oil | 10 to 20 Per Cent Lard Oil with<br>Mineral Oil   |
| Tool Steels and Low-car-<br>bon Steels | Soluble Oil  | 25 to 40 Per Cent Lard Oil with<br>Mineral Oil<br>(or)<br>25 Per Cent Sulfur-base Oil <sup>b</sup> with<br>75 Per Cent Mineral Oil |
| Copper                                 | Soluble Oil  | Soluble Oil  |
| Monel Metal                            | Soluble Oil  | 25 to 40 Per Cent Lard Oil Mixed<br>with Mineral Oil<br>(or)<br>Sulfur-base Oil <sup>b</sup> Mixed with Min-<br>eral Oil           |
| Cast Iron <sup>c</sup>                 | Dry  | Dry<br>(or)<br>25 Per Cent Lard Oil with 75 Per<br>Cent Mineral Oil  |
| Malleable Iron                         | Soluble Oil  | Soluble Oil  |
| Bronze                                 | Soluble Oil  | 20 Per Cent Lard Oil with 80 Per<br>Cent Mineral Oil   |
| Magnesium <sup>d</sup>                 | 60-second Mineral Oil  | 20 Per Cent Lard Oil with 80 Per<br>Cent Mineral Oil   |

<sup>a</sup> In machining aluminum, several varieties of coolants may be used. For rough machining, where the stock removal is sufficient to produce heat, water soluble mixtures can be used with good results to dissipate the heat. Other oils that may be recommended are straight mineral seal oil; a 50–50 mixture of mineral seal oil and kerosene; a mixture of 10 per cent lard oil with 90 per cent kerosene; and a 100-second mineral oil cut back with mineral seal oil or kerosene.

<sup>b</sup> The sulfur-base oil referred to contains 4½ per cent sulfur compound. Base oils are usually dark in color. As a rule, they contain sulfur compounds resulting from a thermal or catalytic refinery process. When so processed, they are more suitable for industrial coolants than when they have had such compounds as flowers of sulfur added by hand. The adding of sulfur compounds by hand to the coolant reservoir is of temporary value only, and the non-uniformity of the solution may affect the machining operation.

<sup>c</sup> A soluble oil or low-viscosity mineral oil may be used in machining cast iron to prevent excessive metal dust.



<sup>d</sup>When a cutting fluid is needed for machining magnesium, low or nonacid mineral seal or lard oils are recommended. Coolants containing water should not be used because of the fire danger when magnesium chips react with water, forming hydrogen gas.

<sup>e</sup>Sulfurized oils ordinarily are not recommended for tapping aluminum; however, for some tapping operations they have proved very satisfactory, although the work should be rinsed in a solvent right after machining to prevent discoloration.

**Application of Cutting Fluids to Carbides.**—Turning, boring, and similar operations on lathes using carbides are performed dry or with the help of soluble oil or chemical cutting fluids. The effectiveness of cutting fluids in improving tool life or by permitting higher cutting speeds to be used, is less with carbides than with high-speed steel tools. Furthermore, the effectiveness of the cutting fluid is reduced as the cutting speed is increased. Cemented carbides are very sensitive to sudden changes in temperature and to temperature gradients within the carbide. Thermal shocks to the carbide will cause thermal cracks to form near the cutting edge, which are a prelude to tool failure. An unsteady or interrupted flow of the coolant reaching the cutting edge will generally cause these thermal cracks. The flow of the chip over the face of the tool can cause an interruption to the flow of the coolant reaching the cutting edge even though a steady stream of coolant is directed at the tool. When a cutting fluid is used and frequent tool breakage is encountered, it is often best to cut dry. When a cutting fluid must be used to keep the workpiece cool for size control or to allow it to be handled by the operator, special precautions must be used. Sometimes applying the coolant from the front and the side of the tool simultaneously is helpful. On lathes equipped with overhead shields, it is very effective to apply the coolant from below the tool into the space between the shoulder of the work and the tool flank, in addition to applying the coolant from the top. Another method is not to direct the coolant stream at the cutting tool at all but to direct it at the workpiece above or behind the cutting tool.

The danger of thermal cracking is great when milling with carbide cutters. The nature of the milling operation itself tends to promote thermal cracking because the cutting edge is constantly heated to a high temperature and rapidly cooled as it enters and leaves the workpiece. For this reason, carbide milling operations should be performed dry.

Lower cutting-edge temperatures diminish the danger of thermal cracking. The cutting-edge temperatures usually encountered when reaming with solid carbide or carbide-tipped reamers are generally such that thermal cracking is not apt to occur except when reaming certain difficult-to-machine metals. Therefore, cutting fluids are very effective when used on carbide reamers. Practically every kind of cutting fluid has been used, depending on the job material encountered. For difficult surface-finish problems in holes, heavy duty soluble oils, sulfurized mineral-fatty oils, and sulfochlorinated mineral-fatty oils have been used successfully. On some work, the grade and the hardness of the carbide also have an effect on the surface finish of the hole.

Cutting fluids should be applied where the cutting action is taking place and at the highest possible velocity without causing splashing. As a general rule, it is preferable to supply from 3 to 5 gallons per minute for each single-point tool on a machine such as a turret lathe or automatic. The temperature of the cutting fluid should be kept below 110 degrees F. If the volume of fluid used is not sufficient to maintain the proper temperature, means of cooling the fluid should be provided.

**Cutting Fluids for Machining Magnesium.**—In machining magnesium, it is the general but not invariable practice in the United States to use a cutting fluid. In other places, magnesium usually is machined dry except where heat generated by high cutting speeds would not be dissipated rapidly enough without a cutting fluid. This condition may exist when, for example, small tools without much heat-conducting capacity are employed on automatics.

The cutting fluid for magnesium should be an anhydrous oil having, at most, a very low acid content. Various mineral-oil cutting fluids are used for magnesium.

**Occupational Exposure To Metal working Fluids**

The term *metalworking fluids* (MWFs) describes coolants and lubricants used during the fabrication of products from metals and metal substitutes. These fluids are used to prolong the life of machine tools, carry away debris, and protect or treat the surfaces of the material being processed. MWFs reduce friction between the cutting tool and work surfaces, reduce wear and galling, protect surface characteristics, reduce surface adhesion or welding, carry away generated heat, and flush away swarf, chips, fines, and residues. Table 1 describes the four different classes of metal working fluids:

**Table 1. Classes of Metalworking Fluids (MWFs)**

| MWF  | Description   | Dilution factor                            |
|--|---|--|
| <b>Straight oil</b><br>(neat oil or cutting oil) | Highly refined petroleum oils (lubricant-base oils) or other animal, marine, vegetable, or synthetic oils used singly or in combination with or without additives. These are lubricants, or function to improve the finish on the metal cut, and prevent corrosion.   | none                                       |
| <b>Soluble oil</b><br>(emulsifiable oil)         | Combinations of 30% to 85% highly refined, high-viscosity lubricant-base oils and emulsifiers that may include other performance additives. Soluble oils are diluted with water before use at ratios of parts water.  | 1 part concentrate to 5 to 40 parts water  |
| <b>Semisynthetic</b>                             | Contain smaller amounts of severely refined lubricant-base oil (5 to 30% in the concentrate), a higher proportion of emulsifiers that may include other performance additives, and 30 to 50% water.   | 1 part concentrate to 10 to 40 parts water |
| <b>Synthetic<sup>a</sup></b>                     | Contain no petroleum oils and may be water soluble or water dispersible. The simplest synthetics are made with organic and inorganic salts dissolved in water. Offer good rust protection and heat removal but usually have poor lubricating ability. May be formulated with other performance additives. Stable, can be made bioresistant. | 1 part concentrate to 10 to 40 parts water |

<sup>a</sup> Over the last several decades major changes in the U.S. machine tool industry have increased the consumption of MWFs. Specifically, the use of synthetic MWFs increased as tool and cutting speeds increased.

**Occupational Exposures to Metal Working Fluids (MWFs).—**Workers can be exposed to MWFs by inhalation of aerosols (mists) or by skin contact resulting in an increased risk of respiratory (lung) and skin disease. Health effects vary based on the type of MWF, route of exposure, concentration, and length of exposure.

Skin contact usually occurs when the worker dips his/her hands into the fluid, floods the machine tool, or handling parts, tools, equipment or workpieces coated with the fluid, without the use of personal protective equipment such as gloves and apron. Skin contact can also result from fluid splashing onto worker from the machine if guarding is absent or inadequate.

Inhalation exposures result from breathing MWF mist or aerosol. The amount of mist generated (and the severity of the exposure) depends on a variety of factors: the type of MWF and its application process; the MWF temperature; the specific machining or grinding operation; the presence of splash guarding; and the effectiveness of the ventilation system. In general, the exposure will be higher if the worker is in close proximity to the machine, the operation involves high tool speeds and deep cuts, the machine is not enclosed, or if ventilation equipment was improperly selected or poorly maintained. In addition, high-pressure and/or excessive fluid application, contamination of the fluid with tramp oils, and improper fluid selection and maintenance will tend to result in higher exposure.

Each MWF class consists of a wide variety of chemicals used in different combinations and the risk these chemicals pose to workers may vary because of different manufacturing processes, various degrees of refining, recycling, improperly reclaimed chemicals, different degrees of chemical purity, and potential chemical reactions between components.

Exposure to hazardous contaminants in MWFs may present health risks to workers. Contamination may occur from: process chemicals and ancillary lubricants inadvertently introduced; contaminants, metals, and alloys from parts being machined; water and cleaning agents used for routine housekeeping; and, contaminants from other environmental sources at the worksite. In addition, bacterial and fungal contaminants may metabolize and degrade the MWFs to hazardous end-products as well as produce endotoxins.

The improper use of biocides to manage microbial growth may result in potential health risks. Attempts to manage microbial growth solely with biocides may result in the emergence of biocide-resistant strains from complex interactions that may occur among different member species or groups within the population. For example, the growth of one species, or the elimination of one group of organisms may permit the overgrowth of another. Studies also suggest that exposure to certain biocides can cause either allergic or contact dermatitis.

**Fluid Selection, Use, and Application.**—The MWFs selected should be as nonirritating and nonsensitizing as possible while remaining consistent with operational requirements. Petroleum-containing MWFs should be evaluated for potential carcinogenicity using ASTM Standard E1687-98, “Determining Carcinogenic Potential of Virgin Base Oils in Metalworking Fluids”. If soluble oil or synthetic MWFs are used, ASTM Standard E1497-94, “Safe Use of Water-Miscible Metalworking Fluids” should be consulted for safe use guidelines, including those for product selection, storage, dispensing, and maintenance. To minimize the potential for nitrosamine formation, nitrate-containing materials should not be added to MWFs containing ethanolamines.

Many factors influence the generation of MWF mists, which can be minimized through the proper design and operation of the MWF delivery system. ANSI Technical Report B11 TR2-1997, “Mist Control Considerations for the Design, Installation and Use of Machine Tools Using Metalworking Fluids” provides directives for minimizing mist and vapor generation. These include minimizing fluid delivery pressure, matching the fluid to the application, using MWF formulations with low oil concentrations, avoiding contamination with tramp oils, minimizing the MWF flow rate, covering fluid reservoirs and return systems where possible, and maintaining control of the MWF chemistry. Also, proper application of MWFs can minimize splashing and mist generation. Proper application includes: applying MWFs at the lowest possible pressure and flow volume consistent with provisions for adequate part cooling, chip removal, and lubrication; applying MWFs at the tool/workpiece interface to minimize contact with other rotating equipment; ceasing fluid delivery when not performing machining; not allowing MWFs to flow over the unprotected hands of workers loading or unloading parts; and using mist collectors engineered for the operation and specific machine enclosures.

Properly maintained filtration and delivery systems provide cleaner MWFs, reduce mist, and minimize splashing and emissions. Proper maintenance of the filtration and delivery systems includes: the selection of appropriate filters; ancillary equipment such as chip handling operations, dissolved air-flotation devices, belt-skimmers, chillers or plate and frame heat exchangers, and decantation tanks; guard coolant return trenches to prevent dumping of floor wash water and other waste fluids; covering sumps or coolant tanks to prevent contamination with waste or garbage (e.g., cigarette butts, food, etc.); and, keeping the machine(s) clean of debris. Parts washing before machining can be an important part of maintaining cleaner MWFs.

Since all additives will be depleted with time, the MWF and additives concentrations should be monitored frequently so that components and additives can be made up as needed. The MWF should be maintained within the pH and concentration ranges recom-

mended by the formulator or supplier. MWF temperature should be maintained at the lowest practical level to slow the growth of microorganisms, reduce water losses and changes in viscosity, and—in the case of straight oils—reduce fire hazards.

**Fluid Maintenance.**—Drums, tanks, or other containers of MWF concentrates should be stored appropriately to protect them from outdoor weather conditions and exposure to low or high temperatures. Extreme temperature changes may destabilize the fluid concentrates, especially in the case of concentrates mixed with water, and cause water to seep into unopened drums encouraging bacterial growth. MWFs should be maintained at as low a temperature as is practical. Low temperatures slow the growth of microorganisms, reduce water losses and change in viscosity, and in the case of straight oils, reduce the fire hazard risks.

To maintain proper MWF concentrations, neither water nor concentrate should be used to top off the system. The MWF mixture should be prepared by first adding the concentrate to the clean water (in a clean container) and then adding the emulsion to that mixture in the coolant tank. MWFs should be mixed just before use; large amounts should not be stored, as they may deteriorate before use.

*Personal Protective Clothing:* Personal protective clothing and equipment should always be worn when removing MWF concentrates from the original container, mixing and diluting concentrate, preparing additives (including biocides), and adding MWF emulsions, biocides, or other potentially hazardous ingredients to the coolant reservoir. Personal protective clothing includes eye protection or face shields, gloves, and aprons which do not react with but shed MWF ingredients and additives.

*System Service:* Coolant systems should be regularly serviced, and the machines should be rigorously maintained to prevent contamination of the fluids by tramp oils (e.g., hydraulic oils, gear box oils, and machine lubricants leaking from the machines or total loss slide-way lubrication). Tramp oils can destabilize emulsions, cause pumping problems, and clog filters. Tramp oils can also float to the top of MWFs, effectively sealing the fluids from the air, allowing metabolic products such as volatile fatty acids, mercaptols, scatols, ammonia, and hydrogen sulfide are produced by the anaerobic and facultative anaerobic species growing within the biofilm to accumulate in the reduced state.

When replacing the fluids, thoroughly clean all parts of the system to inhibit the growth of microorganisms growing on surfaces. Some bacteria secrete layers of slime that may grow in stringy configurations that resemble fungal growth. Many bacteria secrete polymers of polysaccharide and/or protein, forming a glycocalyx which cements cells together much as mortar holds bricks. Fungi may grow as masses of hyphae forming mycelial mats. The attached community of microorganisms is called a biofilm and may be very difficult to remove by ordinary cleaning procedures.

*Biocide Treatment:* Biocides are used to maintain the functionality and efficacy of MWFs by preventing microbial overgrowth. These compounds are often added to the stock fluids as they are formulated, but over time the biocides are consumed by chemical and biological demands. Biocides with a wide spectrum of biocidal activity should be used to suppress the growth of the widely diverse contaminant population. Only the concentration of biocide needed to meet fluid specifications should be used since overdosing could lead to skin or respiratory irritation in workers, and under-dosing could lead to an inadequate level of microbial control.

*Ventilation Systems:* The ventilation system should be designed and operated to prevent the accumulation or recirculation of airborne contaminants in the workplace. The ventilation system should include a positive means of bringing in at least an equal volume of air from the outside, conditioning it, and evenly distributing it throughout the exhausted area.

Exhaust ventilation systems function through suction openings placed near a source of contamination. The suction opening or exhaust hood creates an air motion sufficient to overcome room air currents and any airflow generated by the process. This airflow cap-

tures the contaminants and conveys them to a point where they can either be discharged or removed from the airstream. Exhaust hoods are classified by their position relative to the process as canopy, side draft, down draft or enclosure. ANSI Technical Report B11 TR 2-1997 contains guidelines for exhaust ventilation of machining and grinding operations. Enclosures are the only type of exhaust hood recommended by the ANSI committee. They consist of physical barriers between the process and the worker's environment. Enclosures can be further classified by the extent of the enclosure: close capture (enclosure of the point of operation, total enclosure (enclosure of the entire machine), or tunnel enclosure (continuous enclosure over several machines).

If no fresh make up air is introduced into the plant, air will enter the building through open doors and windows, potentially causing cross-contamination of all process areas. Ideally, all air exhausted from the building should be replaced by tempered air from an uncontaminated location. By providing a slight excess of make up air in relatively clean areas and a slight deficit of make up air in dirty areas, cross-contamination can be reduced. In addition, this air can be channeled directly to operator work areas, providing the cleanest possible work environment. Ideally, this fresh air should be supplied in the form of a low-velocity air shower (<100 ft/min to prevent interference with the exhaust hoods) directly above the worker.

*Protective Clothing and Equipment:* Engineering controls are used to reduce worker exposure to MWFs. But in the event of airborne exposures that exceed the NIOSH REL or dermal contact with the MWFs, the added protection of chemical protective clothing (CPC) and respirators should be provided. Maintenance staff may also need CPC because their work requires contact with MWFs during certain operations. All workers should be trained in the proper use and care of CPC. After any item of CPC has been in routine use, it should be examined to ensure that its effectiveness has not been compromised.

Selection of the appropriate respirator depends on the operation, chemical components, and airborne concentrations in the worker's breathing zone. Table 2. lists the NIOSH- recommended respiratory protection for workers exposed to MWF aerosol.

**Table 2. Respiratory Protection for Workers Exposed to MWF Aerosols\***

| Concentration of MWF aerosol (mg/m <sup>3</sup> ) | Minimum respiratory protection <sup>a</sup>   |
|---|---|
| #0.5 mg/m <sup>3</sup> (1 × REL) <sup>b</sup>     | No respiratory protection required for healthy workers <sup>c</sup>   |
| #5.0 mg/m <sup>3</sup> (10 × REL)                 | Any air-purifying, half-mask respirator including a disposable respirator <sup>d,e</sup> equipped with any P- or R-series particulate filter (P95, P99, P100, R95, R99, or R100) number |
| #12.5 mg/m <sup>3</sup> (25 × REL)                | Any powered, air-purifying respirator equipped with a hood or helmet and a HEPA filter <sup>f</sup>   |

<sup>a</sup> Respirators with higher assigned protection factors (APFs) may be substituted for those with lower APFs [NIOSH 1987a].

<sup>b</sup> APF times the NIOSH REL for total particulate mass. The APF [NIOSH 1987b] is the minimum anticipated level of protection provided by each type of respirator.

<sup>c</sup> See text for recommendations regarding workers with asthma and for other workers affected by MWF aerosols.

<sup>d</sup> A respirator that should be discarded after the end of the manufacturer's recommended period of use or after a noticeable increase in breathing resistance or when physical damage, hygiene considerations, or other warning indicators render the respirator unsuitable for further use.

<sup>e</sup> An APF of 10 is assigned to disposable particulate respirators if they have been properly fitted.

<sup>f</sup> High-efficiency particulate air filter. When organic vapors are a potential hazard during metalworking operations, a combination particulate and organic vapor filter is necessary.

\* Only NIOSH/MSHA-approved or NIOSH-approved (effective date July 10, 1995) respiratory equipment should be used.

**MACHINING NONFERROUS METALS  
AND NON-METALLIC MATERIALS****Nonferrous Metals**

**Machining Aluminum.**—Some of the alloys of aluminum have been machined successfully without any lubricant or cutting compound, but some form of lubricant is desirable to obtain the best results. For many purposes, a soluble cutting oil is good.

Tools for aluminum and aluminum alloys should have larger relief and rake angles than tools for cutting steel. For high-speed steel turning tools the following angles are recommended: relief angles, 14 to 16 degrees; back rake angle, 5 to 20 degrees; side rake angle, 15 to 35 degrees. For very soft alloys even larger side rake angles are sometimes used. High silicon aluminum alloys and some others have a very abrasive effect on the cutting tool. While these alloys can be cut successfully with high-speed-steel tools, cemented carbides are recommended because of their superior abrasion resistance. The tool angles recommended for cemented carbide turning tools are: relief angles, 12 to 14 degrees; back rake angle, 0 to 15 degrees; side rake angle, 8 to 30 degrees.

Cut-off tools and necking tools for machining aluminum and its alloys should have from 12 to 20 degrees back rake angle and the end relief angle should be from 8 to 12 degrees. Excellent threads can be cut with single-point tools in even the softest aluminum. Experience seems to vary somewhat regarding the rake angle for single-point thread cutting tools. Some prefer to use a rather large back and side rake angle although this requires a modification in the included angle of the tool to produce the correct thread contour. When both rake angles are zero, the included angle of the tool is ground equal to the included angle of the thread. Excellent threads have been cut in aluminum with zero rake angle thread-cutting tools using large relief angles, which are 16 to 18 degrees opposite the front side of the thread and 12 to 14 degrees opposite the back side of the thread. In either case, the cutting edges should be ground and honed to a keen edge. It is sometimes advisable to give the face of the tool a few strokes with a hone between cuts when chasing the thread to remove any built-up edge on the cutting edge.

Fine surface finishes are often difficult to obtain on aluminum and aluminum alloys, particularly the softer metals. When a fine finish is required, the cutting tool should be honed to a keen edge and the surfaces of the face and the flank will also benefit by being honed smooth. Tool wear is inevitable, but it should not be allowed to progress too far before the tool is changed or sharpened. A sulphurized mineral oil or a heavy-duty soluble oil will sometimes be helpful in obtaining a satisfactory surface finish. For best results, however, a diamond cutting tool is recommended. Excellent surface finishes can be obtained on even the softest aluminum and aluminum alloys with these tools.

Although ordinary milling cutters can be used successfully in shops where aluminum parts are only machined occasionally, the best results are obtained with coarse-tooth, large helix-angle cutters having large rake and clearance angles. Clearance angles up to 10 to 12 degrees are recommended. When slab milling and end milling a profile, using the peripheral teeth on the end mill, climb milling (also called down milling) will generally produce a better finish on the machined surface than conventional (or up) milling. Face milling cutters should have a large axial rake angle. Standard twist drills can be used without difficulty in drilling aluminum and aluminum alloys although high helix-angle drills are preferred. The wide flutes and high helix-angle in these drills helps to clear the chips. Sometimes split-point drills are preferred. Carbide tipped twist drills can be used for drilling aluminum and its alloys and may afford advantages in some production applications. Ordinary hand and machine taps can be used to tap aluminum and its alloys although spiral-fluted ground thread taps give superior results. Experience has shown that such taps should have a right-hand ground flute when intended to cut right-hand threads and the helix angle should be similar to that used in an ordinary twist drill.

**Machining Magnesium.**—Magnesium alloys are readily machined and with relatively low power consumption per cubic inch of metal removed. The usual practice is to employ high cutting speeds with relatively coarse feeds and deep cuts. Exceptionally fine finishes can be obtained so that grinding to improve the finish usually is unnecessary. The horsepower normally required in machining magnesium varies from 0.15 to 0.30 per cubic inch per minute. While this value is low, especially in comparison with power required for cast iron and steel, the total amount of power for machining magnesium usually is high because of the exceptionally rapid rate at which metal is removed.

Carbide tools are recommended for maximum efficiency, although high-speed steel frequently is employed. Tools should be designed so as to dispose of chips readily or without excessive friction, by employing polished chip-bearing surfaces, ample chip spaces, large clearances, and small contact areas. *Keen-edged tools should always be used.*

*Feeds and Speeds for Magnesium:* Speeds ordinarily range up to 5000 feet per minute for rough- and finish-turning, up to 3000 feet per minute for rough-milling, and up to 9000 feet per minute for finish-milling. For rough-turning, the following combinations of speed in feet per minute, feed per revolution, and depth of cut are recommended: Speed 300 to 600 feet per minute — feed 0.030 to 0.100 inch, depth of cut 0.5 inch; speed 600 to 1000 — feed 0.020 to 0.080, depth of cut 0.4; speed 1000 to 1500 — feed 0.010 to 0.060, depth of cut 0.3; speed 1500 to 2000 — feed 0.010 to 0.040, depth of cut 0.2; speed 2000 to 5000 — feed 0.010 to 0.030, depth of cut 0.15.

*Lathe Tool Angles for Magnesium:* The true or actual rake angle resulting from back and side rakes usually varies from 10 to 15 degrees. Back rake varies from 10 to 20, and side rake from 0 to 10 degrees. Reduced back rake may be employed to obtain better chip breakage. The back rake may also be reduced to from 2 to 8 degrees on form tools or other broad tools to prevent chatter.

*Parting Tools:* For parting tools, the back rake varies from 15 to 20 degrees, the front end relief 8 to 10 degrees, the side relief measured perpendicular to the top face 8 degrees, the side relief measured in the plane of the top face from 3 to 5 degrees.

*Milling Magnesium:* In general, the coarse-tooth type of cutter is recommended. The number of teeth or cutting blades may be one-third to one-half the number normally used; however, the two-blade fly-cutter has proved to be very satisfactory. As a rule, the land relief or primary peripheral clearance is 10 degrees followed by secondary clearance of 20 degrees. The lands should be narrow, the width being about  $\frac{3}{64}$  to  $\frac{1}{16}$  inch. The rake, which is positive, is about 15 degrees.

For rough-milling and speeds in feet per minute up to 900 — feed, inch per tooth, 0.005 to 0.025, depth of cut up to 0.5; for speeds 900 to 1500 — feed 0.005 to 0.020, depth of cut up to 0.375; for speeds 1500 to 3000 — feed 0.005 to 0.010, depth of cut up to 0.2.

*Drilling Magnesium:* If the depth of a hole is less than five times the drill diameter, an ordinary twist drill with highly polished flutes may be used. The included angle of the point may vary from 70 degrees to the usual angle of 118 degrees. The relief angle is about 12 degrees. The drill should be kept sharp and the outer corners rounded to produce a smooth finish and prevent burr formation. For deep hole drilling, use a drill having a helix angle of 40 to 45 degrees with large polished flutes of uniform cross-section throughout the drill length to facilitate the flow of chips. A pyramid-shaped “spur” or “pilot point” at the tip of the drill will reduce the “spiraling or run-off.”

Drilling speeds vary from 300 to 2000 feet per minute with feeds per revolution ranging from 0.015 to 0.050 inch.

*Reaming Magnesium:* Reamers up to 1 inch in diameter should have four flutes; larger sizes, six flutes. These flutes may be either parallel with the axis or have a negative helix angle of 10 degrees. The positive rake angle varies from 5 to 8 degrees, the relief angle from 4 to 7 degrees, and the clearance angle from 15 to 20 degrees.

*Tapping Magnesium:* Standard taps may be used unless Class 3B tolerances are required, in which case the tap should be designed for use in magnesium. A high-speed steel concentric type with a ground thread is recommended. The concentric form, which eliminates the radial thread relief, prevents jamming of chips while the tap is being backed out of the hole. The positive rake angle at the front may vary from 10 to 25 degrees and the "heel rake angle" at the back of the tooth from 3 to 5 degrees. The chamfer extends over two to three threads. For holes up to  $\frac{1}{4}$  inch in diameter, two-fluted taps are recommended; for sizes from  $\frac{1}{2}$  to  $\frac{3}{4}$  inch, three flutes; and for larger holes, four flutes. Tapping speeds ordinarily range from 75 to 200 feet per minute, and mineral oil cutting fluid should be used.

*Threading Dies for Magnesium:* Threading dies for use on magnesium should have about the same cutting angles as taps. Narrow lands should be used to provide ample chip space. Either solid or self-opening dies may be used. The latter type is recommended when maximum smoothness is required. Threads may be cut at speeds up to 1000 feet per minute.

*Grinding Magnesium:* As a general rule, magnesium is ground dry. The highly inflammable dust should be formed into a sludge by means of a spray of water or low-viscosity mineral oil. Accumulations of dust or sludge should be avoided. For surface grinding, when a fine finish is desirable, a low-viscosity mineral oil may be used.

**Machining Zinc Alloy Die-Castings.**—Machining of zinc alloy die-castings is mostly done without a lubricant. For particular work, especially deep drilling and tapping, a lubricant such as lard oil and kerosene (about half and half) or a 50-50 mixture of kerosene and machine oil may be used to advantage. A mixture of turpentine and kerosene has been found effective on certain difficult jobs.

*Reaming:* In reaming, tools with six straight flutes are commonly used, although tools with eight flutes irregularly spaced have been found to yield better results by one manufacturer. Many standard reamers have a land that is too wide for best results. A land about 0.015 inch wide is recommended but this may often be ground down to around 0.007 or even 0.005 inch to obtain freer cutting, less tendency to loading, and reduced heating.

*Turning:* Tools of high-speed steel are commonly employed although the application of Stellite and carbide tools, even on short runs, is feasible. For steel or Stellite, a positive top rake of from 0 to 20 degrees and an end clearance of about 15 degrees are commonly recommended. Where side cutting is involved, a side clearance of about 4 degrees minimum is recommended. With carbide tools, the end clearance should not exceed 6 to 8 degrees and the top rake should be from 5 to 10 degrees positive. For boring, facing, and other lathe operations, rake and clearance angles are about the same as for tools used in turning.

**Machining Monel and Nickel Alloys.**—These alloys are machined with high-speed steel and with cemented carbide cutting tools. High-speed steel lathe tools usually have a back rake of 6 to 8 degrees, a side rake of 10 to 15 degrees, and relief angles of 8 to 12 degrees. Broad-nose finishing tools have a back rake of 20 to 25 degrees and an end relief angle of 12 to 15 degrees. In most instances, standard commercial cemented-carbide tool holders and tool shanks can be used which provide an acceptable tool geometry. Honing the cutting edge lightly will help if chipping is encountered.

The most satisfactory tool materials for machining Monel and the softer nickel alloys, such as Nickel 200 and Nickel 230, are M2 and T5 for high-speed steel and crater resistant grades of cemented carbides. For the harder nickel alloys such as K Monel, Permanickel, Duranickel, and Nitinol alloys, the recommended tool materials are T15, M41, M42, M43, and for high-speed steel, M42. For carbides, a grade of crater resistant carbide is recommended when the hardness is less than 300 Bhn, and when the hardness is more than 300 Bhn, a grade of straight tungsten carbide will often work best, although some crater resistant grades will also work well.



A sulfurized oil or a water-soluble oil is recommended for rough and finish turning. A sulfurized oil is also recommended for milling, threading, tapping, reaming, and broaching. Recommended cutting speeds for Monel and the softer nickel alloys are 70 to 100 fpm for high-speed steel tools and 200 to 300 fpm for cemented carbide tools. For the harder nickel alloys, the recommended speed for high-speed steel is 40 to 70 fpm for a hardness up to 300 Bhn and for a higher hardness, 10 to 20 fpm; for cemented carbides, 175 to 225 fpm when the hardness is less than 300 Bhn and for a higher hardness, 30 to 70 fpm.

Nickel alloys have a high tendency to work harden. To minimize work hardening caused by machining, the cutting tools should be provided with adequate relief angles and positive rake angles. Furthermore, the cutting edges should be kept sharp and replaced when dull to prevent burnishing of the work surface. The depth of cut and feed should be sufficiently large to ensure that the tool penetrates the work without rubbing.

**Machining Copper Alloys.**—Copper alloys can be machined by tooling and methods similar to those used for steel, but at higher surface speeds. Machinability of copper alloys is discussed in [Table 2](#) on page 556 and [Table 3](#) on page 560. Machinability is based on a rating of 100 per cent for the free-cutting alloy C35000, which machines with small, easily broken chips. As with steels, copper alloys containing lead have the best machining properties, with alloys containing tin, and lead, having machinability ratings of 80 and 70 per cent. Tellurium and sulphur are added to copper alloys to increase machinability with minimum effect on conductivity. Lead additions are made to facilitate machining, as their effect is to produce easily broken chips.

Copper alloys containing silicon, aluminum, manganese and nickel become progressively more difficult to machine, and produce long, stringy chips, the latter alloys having only 20 per cent of the machinability of the free-cutting alloys. Although copper is frequently machined dry, a cooling compound is recommended. Other lubricants that have been used include tallow for drilling, gasoline for turning, and beeswax for threading.

### Machining Non-metals

**Machining Hard Rubber.**—Tools suitable for steel may be used for hard rubber, with no top or side rake angles and 10 to 20 degree clearance angles, of high speed steel or tungsten carbide. Without coolant, surface speeds of about 200 ft/min. are recommended for turning, boring and facing, and may be increased to 300 surface ft/min. with coolant.

*Drilling of hard rubber* requires high speed steel drills of 35 to 40 degree helix angle to obtain maximum cutting speeds and drill life. Feed rates for drilling range up to 0.015 in/rev. Deep-fluted taps are best for threading hard rubber, and should be 0.002 to 0.005 in. oversize if close tolerances are to be held. Machine oil is used for a lubricant. Hard rubber may be sawn with band saws having 5 to 10 teeth per inch, running at about 3000 ft/min. or cut with abrasive wheels. Use of coolant in grinding rubber gives a smoother finish.

*Piercing and blanking* of sheet rubber is best performed with the rubber or dies heated. Straightening of the often-distorted blanks may be carried out by dropping them into a pan of hot water.

**Formica Machining.**—Blanks can be cut from sheets of "Formica" either by a band saw or by trepanning tools in a boring mill or a drill press. To saw blanks, first describe a circle as a guide line, then use a 21-gage 3½-point saw running at a speed of 5000 feet per minute. The saw should be sharp, with a ¼-inch set on both sides. In drilling, use an ordinary high-speed drill whose point is ground to an included angle of 55 to 60 degrees. Another method is to grind the drill point slightly off center. The feed must be rapid and caution used to prevent the drill from lagging in its work, and the speed must be 1200 revolutions per minute. For all machining operations on "Formica" gear material, provision must be made in grinding for the tools to clear themselves. For reaming, the entry of the reamer and the reaming process must be rapid. There must not be a lag between the end of the reaming operation and the withdrawal of the reamer. In turning the outside diameter and the sides of blanks,

## MACHINING MICARTA

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the tools must be sharp and have 3 to 5 degrees more rake than is common practice for metal. A cutting speed of 750 feet per minute, which is equal to 720 revolutions per minute on a 4-inch diameter blank, is recommended. The depth of the cut can be  $\frac{1}{16}$  to  $\frac{1}{8}$  inch, but the feed should be 0.010 inch, regardless of the depth of the cut. Teeth may be cut on a hobbing machine, shaper, or milling machine. The speed of the cutter should be 150 feet per minute, and the feed from 0.023 to 0.040 inch per revolution. It is advisable to back up the blank to prevent fraying or breaking out of the material as the cutter comes through. The backing plates can be economically made from hard wood.

**Micarta Machining.**—In cutting blanks from sheets of “micarta” a band saw running at a speed of 350 revolutions per minute has been found suitable. The saw should be of the bevel-tooth type, seven teeth to the inch. For large quantities a trepanning tool should be used. In trepanning blanks, the tool should be fed so as to cut part way through all of the “layouts”; then the micarta plate should be turned over, and the cutting completed from the reverse side.

Turning tools should be of high-speed steel cutting at speeds similar to those used for bronze or cast iron. If two cuts are taken, about 0.010 inch of stock should be left for the finishing cut.

Drilling at right angles to the layers is done with a standard drill, which should be backed off sufficiently to provide plenty of clearance. When drilling parallel to layers, a “flat” or “bottom” drill should be used. In rough-drilling, the hole should preferably be drilled partly through the material from each side to prevent possible splitting as the tool protrudes. If this is impracticable, the hole can be drilled all the way through the material, provided the material is “backed up” with wood, stiff cardboard, or any other material that is sufficiently rigid to support the under surface at the point where the drill comes through.

The methods described for drilling apply as well to tapping, except that when the tapping is done parallel to the layers, it is advisable to clamp the material to equalize the stress on the layers and prevent possible splitting.

In milling, a standard tool may be used at a speed and feed corresponding to that used in working bronze or soft steel. The cutting angle of the cutter will give better results if ground with a slight rake.

While there is a wide range of practice as to feeds and speeds in cutting gears on hobbing machines, a hob speed of not less than 140 revolutions per minute, has given satisfaction. In machining gear teeth on a gear shaper, a speed of about 100 to 130 strokes per minute with a fairly fine feed has given good results. Backing-up plates should be used in machining micarta gears.

**Ultrasonic Machining.**—This method of cutting and engraving hard materials such as glass, precious stones, and carbides uses a transducer (vibratory unit) to obtain the necessary mechanical vibrations needed. The transducer converts the input energy, in this case electrical, into another form of energy, in this case mechanical.

A tool of the required size and shape is made of brass or other soft material and is attached to the transducer. The tool is lowered until it just barely touches the work, and current is applied. At the same time, a slurry of water and fine abrasive, usually boron carbide, is pumped over the work. The tool does not actually touch the work, but the vibrations literally hammer the particles of abrasive into the surface and chip off tiny fragments. Some wear does take place in the tool, but it is very slight and, as it is equally distributed, it does not change the shape. The method is quite commonly applied to cutting designs in the stones of signet rings, but it is also applied to cutting intricately shaped holes in carbide or hardened steel.

## GRINDING FEEDS AND SPEEDS

Grinding data are scarcely available in handbooks, which usually recommend a small range of depths and work speeds at constant wheel speed, including small variations in wheel and work material composition. Wheel life or grinding stiffness are seldom considered.

Grinding parameter recommendations typically range as follows:

- Wheel speeds are usually recommended in the 1200 to 1800 m/min (4000 to 6000 fpm) range, or in rare cases up to 3600 m/min (12000 fpm)
- Work speeds are in the range 20 to 40 m/min (70 to 140 fpm); and, depths of cut of 0.01 to 0.025 mm (0.0004 to 0.001 inch) for roughing, and around 0.005 mm (.0002 in.) for finish grinding.
- Grit sizes for roughing are around 46 to 60 for easy-to-grind materials, and for difficult-to-grind materials higher such as 80 grit. In finishing, a smaller grit size (higher grit number) is recommended. Internal grinding grit sizes for small holes are approximately 100 to 320.
- Specific metal removal rate,  $SMRR$ , represents the rate of material removal per unit of wheel contact width and are commonly recommended from 200 to 500 mm<sup>3</sup>/mm width/min (0.3 to 0.75 in<sup>3</sup>/inch width/min).
- Grinding stiffness is a major variable in determining wheel-life and spark-out time. A typical value of system stiffness in outside-diameter grinding, for 10:1 length/diameter ratio, is approximately  $K_{ST} = 30\text{--}50 \text{ N}/\mu\text{m}$ . System stiffness  $K_{ST}$  is calculated from the stiffness of the part,  $K_w$  and the machine and fixtures,  $K_m$ . Machine values can be obtained from manufacturers, or can be measured using simple equipment along with the part stiffness.
- Generally a lower wheel hardness (soft wheel) is recommended when the system stiffness is poor or when a better finish is desired.

### Basic Rules

The wheel speed  $V$  and *equivalent chip thickness*  $ECT = SMRR \div V \div 1000$  are the primary parameters that determine wheel-life, forces and surface finish in grinding. The following general rules and recommendations, using  $ECT$ , are based on extensive laboratory and industry tests both in Europe and USA. The relationships and shapes of curves pertaining to grinding tool-life, grinding time, and cost are similar to those of any metal cutting operation such as turning, milling and drilling.

In turning and milling, the  $ECT$  theory says that if the product of feed times depth of cut is constant, the tool-life is constant no matter how the depth of cut or feed is varied, provided that the cutting speed and cutting edge length are maintained constant.

In grinding, wheel-life  $T$  remains constant for constant cutting speed  $V$ , regardless of how depth of cut  $a_r$  or work speed  $V_w$  are selected as long as the specific metal removal rate  $SMRR = V_w \times a_r$  is held constant (neglecting the influence of grinding contact width).

$ECT$  is much smaller in grinding than in milling, ranging from about 0.0001 to 0.001 mm (0.000004 to 0.00004 inch). See the section *MACHINING ECONOMETRICS* starting on page 1093 for a detailed explanation of the role of  $ECT$  in conventional machining.

**Wheel life  $T$  and Grinding Ratio.**—A commonly used measure of relative wheel-life in grinding is the *grinding ratio* that is used to compare grindability when varying grinding wheel composition and work material properties under otherwise constant cutting conditions.

The *grinding ratio* is defined as the slope of the wear curve versus metal removal rate:  $\text{grinding ratio} = MRR \div W^*$ , where  $MRR$  is the metal removal rate, and  $W^*$  is the volume wheel wear at which the wheel has to be dressed. The grinding ratio is not a measure of wheel-life, but a relationship between *grinding ratio* and wheel-life  $T$  can be obtained from

the formula  $\text{grinding ratio} = SMRR \times T \div W^*$ , where  $SMRR$  (specific metal removal rate) is determined from  $MRR = SMRR \times T$  or from  $ECT = SMRR \div V \div 1000$ .

Thus,  $\text{grinding ratio} = 1000 \times ECT \times V \times T \div W^*$ , and  $T = \text{grinding ratio} \times W^* \div (1000 \times ECT \times V)$ , provided that the wheel wear criterion  $W^*$  is valid for all data combinations.

*Example 1:* If  $W^*$  in one test is found to be  $500 \text{ mm}^3$  for  $ECT = 0.00033 \text{ mm}$  and  $V = 3600 \text{ m/min}$ , and  $\text{grinding ratio} = 10$ , then wheel-life will vary with measured grinding ratios, wheel speed, and  $ECT$  as follows:  $T = 500 \times \text{grinding ratio} \div (V \times ECT) = 4.2$  minutes.

In the remainder of this section the  $\text{grinding ratio}$  will not be used, and wheel-life is expressed in terms of  $ECT$  or  $SMRR$  and wheel speed  $V$ .

**ECT in Grinding.**—In turning and milling,  $ECT$  is defined as the volume of chips removed per unit cutting edge length per revolution of the work or cutter. In milling specifically,  $ECT$  is defined as the ratio of (number of teeth  $z \times$  feed per tooth  $f_z \times$  radial depth of cut  $a_r \times$  and axial depth of cut  $a_a$ ) and (cutting edge length  $CEL$  divided by  $\pi D$ ), where  $D$  is the cutter diameter, thus,

$$ECT = \frac{\pi D z f_z a_r a_a}{CEL}$$

In grinding, the same definition of  $ECT$  applies if we replace the number of teeth with the average number of grits along the wheel periphery, and replace the feed per tooth by the average feed per grit. This definition is not very practical, however, and  $ECT$  is better defined by the ratio of the specific metal removal rate  $SMRR$ , and the wheel speed  $V$ . Thus,  $ECT = 1000 \times SMRR \div V$ . Keeping  $ECT$  constant when varying  $SMRR$  requires that the wheel speed must be changed proportionally.

In milling and turning  $ECT$  can also be redefined in terms of  $SMRR$  divided by the work and the cutter speeds, respectively, because  $SMRR$  is proportional to the feed rate  $F_R$ .

**Work Speed and Depth of Cut Selection:** Work speed  $V_w$  is determined by dividing  $SMRR$  by the depth of cut  $a_r$ , or by using the graph in Fig. 1.

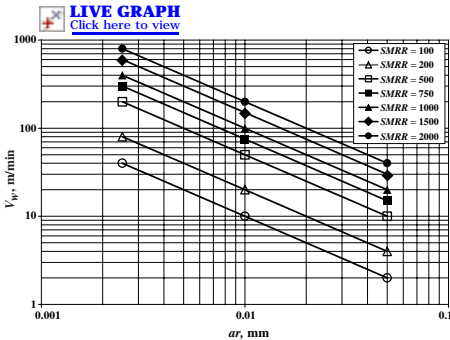


Fig. 1. Work speed  $V_w$  vs. depth of cut  $a_r$ .

Referring to Fig. 1, for depths of cuts of 0.01 and 0.0025 mm, a specific metal removal rate  $SMRR = 1000 \text{ mm}^3/\text{mm width/min}$  is achieved at work speeds of 100 and 400 m/min, respectively, and for  $SMRR = 100 \text{ mm}^3/\text{mm width/min}$  at work speeds of 10 and 40 m/min, respectively.

Unfortunately, the common use of low values of work speed (20 to 40 m/min) in finishing cause thermal surface damage, disastrous in critical parts such as aircraft components. As the grains slide across the work they generate surface heat and fatigue-type loading may cause residual tensile stresses and severe surface cracks. Proper finish grinding conditions

are obtained by increasing the work speed 5 to 10 times higher than the above recommendations indicate. These higher work speeds will create compressive stresses that are not detrimental to the surface. The by-product of higher work speeds is much higher *SMRR* values and thereby much shorter grinding times. Compressive stresses are also obtained by reducing the depth of cut  $a_r$ .

**Wheel Life Relationships and Optimum Grinding Data.**—Figs. 2a, 2b, and 2c show, in three planes, the 3-dimensional variation of wheel-life  $T$  with wheel speed  $V$  and  $ECT$  when grinding a hardened tool steel. Fig. 2a depicts wheel-life versus wheel speed (the  $T$ - $V$  plane) with constant  $ECT$  appearing as approximately straight lines when plotted in log-log coordinates.

In grinding, the wheel-life variation follows curves similar to those obtained for conventional metal cutting processes, including a bend-off of the Taylor lines ( $T$ - $V$  graph) towards shorter life and lower cutting speeds when a certain maximum life is achieved for each value of  $ECT$ . In the two other planes ( $T$ - $ECT$ , and  $V$ - $ECT$ ) we usually find smooth curves in which the maximum values of wheel-life are defined by points along a curve called the  $H$ -curve.

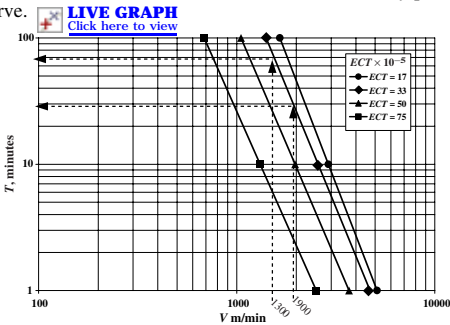


Fig. 2a. Taylor lines:  $T$  vs.  $V$ ,  $ECT$  plotted for grinding M4 tool steel, hardness Rc 64

**Example 2:** The variation of  $SMRR = V \times ECT \times 1000$  and wheel-life at various wheel speeds can be obtained from Fig. 2a. Using sample values of  $ECT = 33 \times 10^{-5}$  mm and  $V = 1300$  and  $1900$  m/min,  $SMRR = 1300 \times 33 \times 10^{-5} \times 1000 = 429$ , and  $1900 \times 33 \times 10^{-5} \times 1000 = 627$  mm<sup>3</sup>/mm width/min, respectively; the corresponding wheel lives are read off as approximately 70 and 30 minutes, respectively.

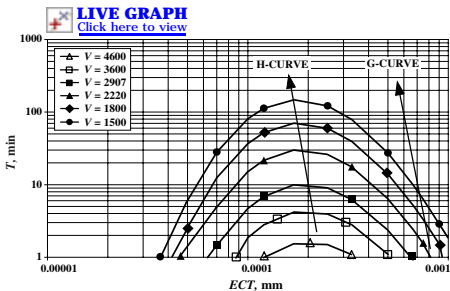


Fig. 2b.  $T$  vs.  $ECT$ ,  $V$  plotted

Fig. 2b depicts wheel-life  $T$  versus  $ECT$  with constant wheel speed  $V$  shown as curves plotted in log-log coordinates, similar to those for the other cutting operations.

*Example 3:* Fig. 2b shows that maximum values of wheel-life occur along the *H*-curve. For the 3 speeds 1800, 2700, and 3600 m/min, maximum wheel lives are approximately 70, 14 and 4 minutes, respectively, at *ECT* around  $17 \times 10^{-5}$  through  $20 \times 10^{-5}$  mm along the *H*-curve. Left and right of the *H*-curve wheel-life is shorter.

Fig. 2c depicts wheel speed *V* versus *ECT* with wheel-life *T* parameter shown as curves in log-log coordinates, similar to those for the other cutting operations, with the characteristic *H*- and *G*-curves.

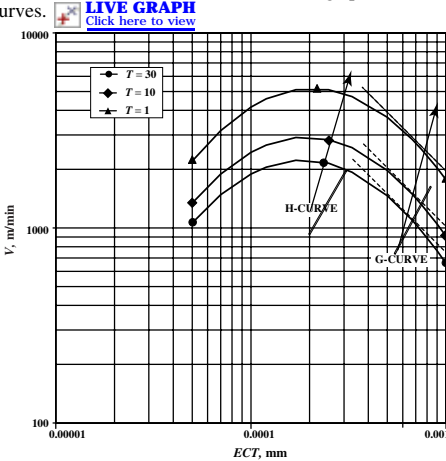


Fig. 2c. *V* vs. *ECT*, *T* plotted

*Optimum grinding data for roughing* occur along the *G*-curve, which is determined from the *V-ECT* graph by drawing 45-degree lines tangent to the *T*-curves, as shown in Fig. 2c, and drawing a line (the *G*-curve) through the points of tangency on the respective *T*-curves, thus the location and direction of the *G*-curve is determined. Globally optimum data correspond to the *T*-curve for which wheel-life is calculated using the corresponding equivalent tooling-cost time,  $T_v$ , calculated from  $T_v = T_{RPL} + 60 \times C_E \div H_R$ , minutes, where  $T_{RPL}$  is the time required to replace wheel,  $C_E$  = cost per wheel dressing = wheel cost + cost per dressing, and  $H_R$  is the hourly rate.

*Minimum cost conditions* occur along the *G*-curve; if optimum life  $T_O$  was determined at either 10 or 30 minutes then  $V_O = 1500$  and 1100 m/min, respectively, and *ECT* is around  $65 - 70 \times 10^{-5}$  mm in both cases. The corresponding optimum values of *SMRR* are  $1000 \times 1500 \times 67 \times 10^{-5} = 1000$  and  $1000 \times 1100 \times 67 \times 10^{-5} = 740$  mm<sup>3</sup>/min/mm wheel contact width (1.5 to 1.1 in<sup>3</sup>/in/min).

Using Fig. 1 we find optimum work speeds for depths of cut  $a_r = 0.01$  and 0.005 mm to be  $V_w = 100$  and 75 m/min, and 200 and 150 m/min (330 and 250 fpm, and 660 and 500 fpm) respectively for 10- and 30-minute wheel-life.

These high work speeds are possible using proper dressing conditions, high system stiffness, good grinding fluid quality and wheel composition.

Fig. 3 shows the variation of specific metal removal rate with wheel speed for several materials and a range of *ECT*s at 10- and 30-minutes wheel-life. *ECT* decreases when moving to the left and down along each curve. The two curves for unhardened 1020 steel have the largest values of *SMRR*, and represent the most productive grinding conditions, while the heat resistant alloy Inconel yields the least productive grinding conditions. Each

branch attains a maximum  $SMRR$  along the  $G$ -curve (compare with the same curve in the  $V$ - $ECT$  graph, Fig. 2c) and a maximum speed region along the  $H$ -curve. When the  $SMRR$ -values are lower than the  $H$ -curve the  $ECT$  values for each branch decrease towards the bottom of the graph, then the speed for constant wheel-life must be reduced due to the fact that the  $ECT$  values are to the left of their respective  $H$ -curves in  $V$ - $ECT$  graphs.

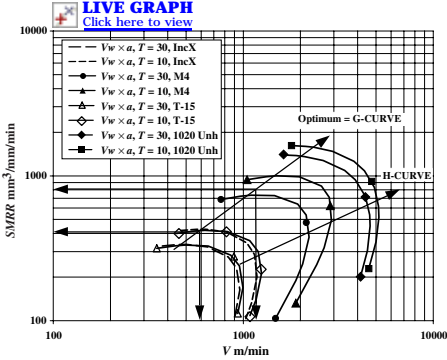


Fig. 3. Specific metal removal rate vs. cutting speed at  $T=10$  and 30 minutes wheel life

In the figure, IncX is Inconel; M4, and T-15 are tool steels; and 1020 Unh is unhardened 1020 steel.

**Surface Finish,  $R_a$ .**—The finish is improved by decreasing the value of  $ECT$  as shown in Fig. 4, where  $R_a$  is plotted versus  $ECT$  at 3 different wheel lives 1, 10 and 30 minutes at constant wheel speed. Because  $ECT$  is proportional to the depth of cut, a smaller depth of cut is favorable for reducing surface roughness when the work speed is constant.

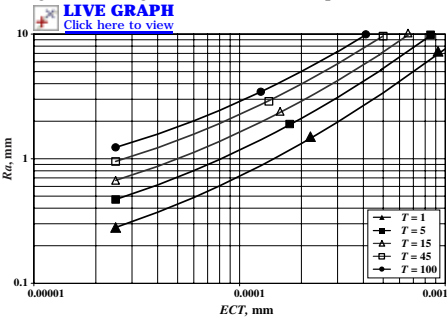


Fig. 4. Surface finish,  $R_a$  vs.  $ECT$ , wheel-life  $T$  plotted

In Fig. 5,  $R_a$  is plotted versus wheel-life at 5 different  $ECT$ 's. Both Figs. 4 and 5 illustrate that a shorter life improves the surface finish, which means that either an increased wheel speed (wheel-life decreases) at constant  $ECT$ , or a smaller  $ECT$  at constant speed (wheel-life increases), will result in an improved finish. For a required surface finish,  $ECT$  and wheel-life have to be selected appropriately in order to also achieve an optimum grinding time or cost. In cylindrical grinding a reduction of side feed  $f_s$  improves  $R_a$  as well.

In terms of specific metal removal rate, reducing  $SMRR$  will improve the surface finish  $R_a$ .

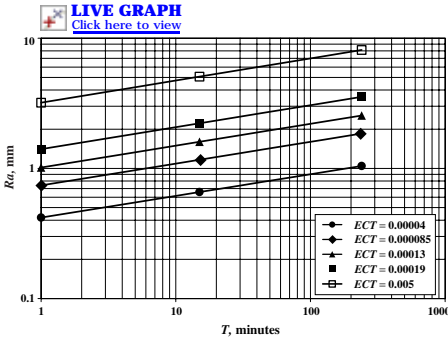


Fig. 5. Surface roughness,  $R_a$  vs. wheel life  $T$ ,  $ECT$  plotted

*Example 4, Specific Metal Removal Rates and Work Speeds in Rough and Finish Grinding:* The tabulated values in the following table indicate that a decreasing  $ECT$  combined with a higher wheel speed for 10 minutes wheel-life will decrease the metal removal rate and thereby increasing the grinding time. This change is accompanied by a better finish in both roughing and finishing operations. Note the high work speeds when finishing.

| $ECT$ mm | Tool Life $T = 10$ minutes    |  | Roughing Depth<br>$a_r = 0.025$ mm | Finishing Depth<br>$a_f = 0.0025$ mm |
|----------|-------------------------------|--|------------------------------------|--------------------------------------|
|          | Wheel speed<br>$V_{10}$ m/min | Removal Rate<br>$SMRR_{10}$ mm <sup>3</sup> /mm/ min | Work speed $V_w$ m/min             |                                      |
| 0.00050  | 1970                          | 985  | 39                                 | 390                                  |
| 0.00033  | 2580                          | 850  | 34                                 | 340                                  |
| 0.00017  | 2910                          | 500  | 20                                 | 200                                  |

The grit size, however, is a major parameter. Fig. 6, shows that a high wheel speed, combined with a small grit size, say 320 Mesh, can achieve  $R_A$  values as small as 0.03 microns.

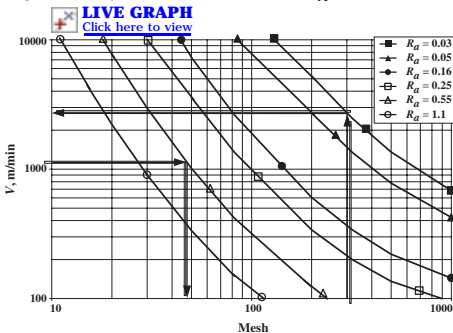


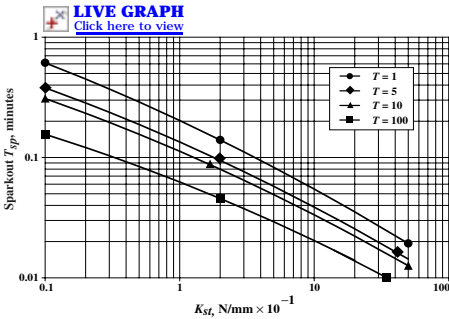
Fig. 6. Wheel speed vs. wheel mesh,  $R_a$  plotted

**Spark-out Time.**— Fig. 7 shows how spark-out time varies with system stiffness. As with surface finish, when wheel-life is short (high wear rate) the spark-out time decreases.

*Equivalent Diameter (Work Conformity) Factor:* The difference in curvature of the work and wheel in the contact region, determined by the equivalent diameter or work conformity formula, is an important factor for calculating spark-out time and forces, but has a

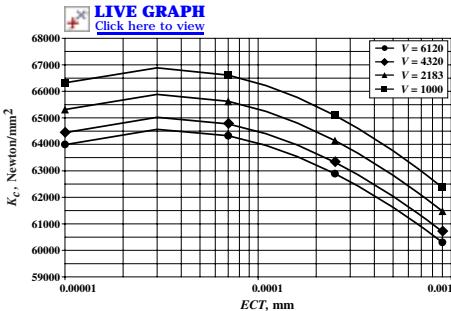


## GRINDING FEEDS AND SPEEDS

Fig. 7. Sparkout time vs. system stiffness, wheel-life  $T$  plotted

negligible influence on wheel-life. Therefore, an equivalent diameter,  $D_e = D/(1 \pm (D/D_w))$ , with the minus sign for internal grinding and the plus sign for external grinding operations, is used to consider the effect of conformity when using internal and external grinding with varying work and wheel diameters.  $D_e$  is equal to the wheel diameter in surface grinding (work flat); in internal grinding, the wheel conforms closely to the work and  $D_e$  is therefore larger than in external grinding.

**Grinding Cutting Forces, Torque and Power.**—Formulas to calculate the tangential cutting force, torque and required machining power are found in *Estimating Machining Power* on page 1084, but the values of  $K_c$ , specific cutting force or specific energy, are approximately 30 to 40 times higher in grinding than in turning, milling and drilling. This is primarily due to the fact that the  $ECT$  values in grinding are 1000 to 10000 times smaller, and also due to the negative rake angles of the grit. Average grinding rake angles are around  $-35$  to  $-45$  degrees.  $K_c$  for grinding unhardened steel is around 50000 to 70000  $N/mm^2$  and up to 150000 to 200000  $N/mm^2$  for hardened steels and heat resistant alloys. The grinding cutting forces are relatively small because the chip area is very small.

Fig. 8. Specific grinding force  $K_c$  vs.  $ECT$ ;  $V$  plotted

As in the other metal cutting operations, the forces vary with  $ECT$  and to a smaller extent with the wheel speed  $V$ . An example is shown in Fig. 8, where  $K_c$ , specific cutting force, is plotted versus  $ECT$  at wheel speeds between 1000 and 6000 m/min. The material is medium unhardened carbon steel ground by an aluminum oxide wheel. The impact of wheel speed is relatively small (2 to 5% lower with increasing speed).

*Example 5:* Find the cutting force when  $ECT = 0.00017$  mm, the cutting edge length (width of cut)  $CEL$  is 10 mm, and  $K_c = 150000$  N/mm<sup>2</sup>.

The chip area is  $ECT \times CEL = 0.0017$  mm<sup>2</sup>. For  $K_c = 150000$ , the cutting force is  $0.0017 \times 150000 = 255$  Newton.

Another difference compared to turning is the influence of the negative rake angles, illustrated by the ratio of  $F_H/F_C$ , where  $F_H$  is the normal force and  $F_C$  the tangential grinding force acting in the wheel speed direction.  $F_H$  is much larger than the grinding cutting force, generally  $F_H/F_C$  ratio is approximately 2 to 4. An example is shown in Fig. 9, where  $F_H/F_C$  is plotted versus  $ECT$  at wheel speeds between 1000 and 6000 m/min, under the same conditions as in Fig. 8.

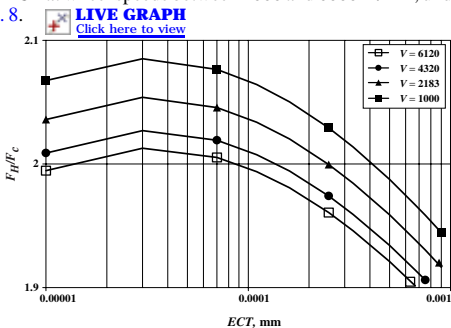


Fig. 9.  $F_H/F_C$  vs.  $ECT$ ; cutting speed plotted

In both Fig. 8 and Fig. 9, it is apparent that both  $K_c$  and  $F_H/F_C$  attain maximum values for given small values of  $ECT$ , in this case approximately  $ECT = 0.00005$  mm. This fact illustrates that forces and wheel-life are closely linked; for example, wheel speed has a maximum for constant wheel-life at approximately the same values of  $ECT$  shown in the two graphs (compare with the trends illustrated in Figs. 2a, 2b, 2c, and 3). As a matter of fact, force relationships obey the same type of relationships as those of wheel-life. Colding's force relationship uses the same 5 constants as the tool life equation, but requires values for the specific cutting force at  $ECT = 0.001$  and an additional constant, obtained by a special data base generator. This requires more elaborate laboratory tests, or better, the design of a special test and follow-up program for parts running in the ordinary production.

### Grinding Data Selection Including Wheel Life

The first estimate of machine settings is based on dividing work materials into 10 groups, based on grindability, as given in Table 1. Compositions of these work materials are found in the Handbook in the section *STANDARD STEELS* starting on page 438.

Grinding wheel nomenclature is described in *American National Standard Grinding Wheel Markings* starting on page 1179. The wheel compositions are selected according to the grade recommendations in the section *The Selection of Grinding Wheels* starting on page 1180. Grinding fluid recommendations are given in *Cutting Fluids for Machining* starting on page 1143.

*Note:* Maximum wheel speeds should always be checked using the safety standards in the section *Safe Operating Speeds* starting on page 1209, because the recommendations will sometimes lead to speeds above safety levels.

The material in this section is based on the use of a typical standard wheel composition such as 51-A-46-L-5-V-23, with wheel grade (wheel hardness) = L or above, and mesh (grit size) = 46 or above.

**Table 1. Grindability Groups**

| Group                         | Examples                               |
|-------------------------------|--|
| Group 1 Unhardened Steels     |  |
| Group 2 Stainless Steels      | SAE 30201–30347, 51409–51501           |
| Group 3 Cast Iron             |  |
| Group 4 Tool Steels           | M1, M8, T1, H, O, L, F, 52100          |
| Group 5 Tool Steels           | M2, T2, T5, T6, D2, H41, H42, H43, M50 |
| Group 6 Tool Steels           | M3, M4, T3, D7                         |
| Group 7 Tool Steels           | T15, M15                               |
| Group 8 Heat Resistant Steels | Inconel, Rene etc.                     |
| Group 9 Carbide Materials     | P30 Diamond Wheel                      |
| Group 10 Ceramic Materials    |  |

For each grindability group there is one table and 2 graphs (one with Taylor lines and the other with  $SMRR$  versus wheel speed  $V$ ) that are used to get a first estimate of standardized machine settings, assuming a good system stiffness ( $K_{ST} > 30 \text{ N}/\mu\text{m}$ ). These data are then calibrated with the users own data in order to refine the estimate and optimize the grinding process, as discussed in *User Calibration of Recommendations*. The recommendations are valid for all grinding processes such as plunge grinding, cylindrical, and surface grinding with periphery or side of wheel, as well as for creep feed grinding.

The grinding data machinability system is based on the basic parameters equivalent chip thickness  $ECT$ , and wheel speed  $V$ , and is used to determine specific metal removal rates  $SMRR$  and wheel-life  $T$ , including the work speed  $V_w$  after the grinding depths for roughing and finishing are specified.

For each material group, the grinding data machinability system consists of  $T$ - $V$  Taylor lines in log-log coordinates for 3 wheel speeds at wheel lives of 1, 10 and 100 minutes wheel-life with 4 different values of equivalent chip thickness  $ECT$ . The wheel speeds are designated  $V_1$ ,  $V_{10}$ , and  $V_{100}$  respectively. In each table the corresponding specific metal removal rates  $SMRR$  are also tabulated and designated as  $SMRR_1$ ,  $SMRR_{10}$  and  $SMRR_{100}$  respectively. The user can select any value of  $ECT$  and interpolate between the Taylor lines. These curves look the same in grinding as in the other metal cutting processes and the slope is set at  $n = 0.26$ , so each Taylor line is formulated by  $V \times T^{0.26} = C$ , where  $C$  is a constant tabulated at four  $ECT$  values,  $ECT = 17, 33, 50$  and  $75 \times 10^{-5} \text{ mm}$ , for each material group. Hence, for each value of  $ECT$ ,  $V_1 \times 1^{0.26} = V_{10} \times 10^{0.26} = V_{100} \times 100^{0.26} = C$ .

**Side Feed, Roughing and Finishing.**—In cylindrical grinding, the side feed,  $f_s = C \times \text{Width}$ , does not impact on the values in the tables, but on the feed rate  $F_R$ , where the fraction of the wheel width  $C$  is usually selected for roughing and in finishing operations, as shown in the following table.

| Work Material    | Roughing, C | Finishing, C |
|------------------|-------------|--------------|
| Unhardened Steel | 2/3–3/4     | 1/3–3/8      |
| Stainless Steel  | 1/2         | 1/4          |
| Cast Iron        | 3/4         | 3/8          |
| Hardened Steel   | 1/2         | 1/4          |

**Finishing:** The depth of cut in rough grinding is determined by the allowance and usually set at  $a_r = 0.01$  to  $0.025 \text{ mm}$ . The depth of cut for finishing is usually set at  $a_f = 0.0025 \text{ mm}$  and accompanied by higher wheel speeds in order to improve surface finish. However, the most important criterion for critical parts is to increase the work speed in order to avoid thermal damage and surface cracks. In cylindrical grinding, a reduction of side feed  $f_s$

improves  $R_a$  as well. Small grit sizes are very important when very small finishes are required. See Figs. 4, 5, and 6 for reference.

#### Terms and Definitions

$a_a$  = depth of cut

$a_r$  = radial depth of cut, mm

$C$  = fraction of grinding wheel width

$CEL$  = cutting edge length, mm

$C_U$  = Taylor constant

$D$  = wheel diameter, mm

$DIST$  = grinding distance, mm

$d_w$  = work diameter, mm

$ECT$  = equivalent chip thickness =  $f(a_r, V, V_w, f_s)$ , mm

$$= 1 \div (V \div V_w \div a_r + 1 \div f_s) = \frac{V_w f_s (a_r + 1)}{V}$$

= approximately  $V_w \times a_r \div V = SMRR \div V \div 1000$

=  $z \times f_z \times a_r \times a_a \div CEL \div (\pi D)$  mm

$F_R$  = feed rate, mm/min

=  $f_s \times RPM_w$  for cylindrical grinding

=  $f_i \times RPM_w$  for plunge (in-feed) grinding

$f_i$  = in-feed in plunge grinding, mm/rev of work

$f_s$  = side feed or engaged wheel width in cylindrical grinding =  $C \times Width = a_a$  approximately equal to the cutting edge length  $CEL$

*Grinding ratio* =  $MRR \div W^* = SMRR \times T \div W^* = 1000 \times ECT \times V \times T \div W^*$

$MRR$  = metal removal rate =  $SMRR \times T = 1000 \times f_s \times a_r \times V_w$  mm<sup>3</sup>/min

$SMRR$  = specific metal removal rate obtained by dividing  $MRR$  by the engaged wheel width ( $C \times Width$ ) =  $1000 \times a_r \times V_w$  mm<sup>3</sup>/mm width/min

*Note:* 100 mm<sup>3</sup>/mm/min = 0.155 in<sup>3</sup>/in/min, and 1 in<sup>3</sup>/in/min = 645.16 mm<sup>3</sup>/mm/min

$T, T_U$  = wheel-life = *Grinding ratio*  $\times W \div (1000 \times ECT \times V)$  minutes

$t_c$  = grinding time per pass =  $DIST \div F_R$  min

=  $DIST \div F_R + t_{sp}$  (min) when spark-out time is included

= # Strokes  $\times (DIST \div F_R + t_{sp})$  (min) when spark-out time and strokes are included

$t_{sp}$  = spark-out time, minutes

$V, V_U$  = wheel speed, m/min

$V_w, V_{wU}$  = work speed =  $SMRR \div 1000 \div a_r$  m/min

$W^*$  = volume wheel wear, mm<sup>3</sup>

$Width$  = wheel width (mm)

$RPM$  = wheel speed =  $1000 \times V \div D \div \pi$  rpm

$RPM_w$  = work speed =  $1000 \times V_w \div D_w \div \pi$  rpm

**Relative Grindability.**—An overview of grindability of the data base, which must be based on a constant wheel wear rate, or wheel-life, is demonstrated using 10 minutes wheel-life shown in Table 2.

**Table 2. Grindability Overview**

| Material Group                    | $ECT \times 10^{-5}$ | $V_{10}$         | $SMRR_{10}$       | $V_w$                           |                                   |
|-----------------------------------|----------------------|------------------|-------------------|---------------------------------|-----------------------------------|
|                                   |                      |                  |                   | Roughing Depth<br>$a_r = 0.025$ | Finishing Depth<br>$a_r = 0.0025$ |
| 1 Unhardened                      | 33                   | 3827             | 1263              | 50                              | 500                               |
| 2 Stainless                       | 33                   | 1080             | 360               | 15                              | 150                               |
| 3 Cast Iron                       | 33                   | 4000             | 1320              | 53                              | 530                               |
| 4 Tool Steel                      | 33                   | 3190             | 1050              | 42                              | 420                               |
| 5 Tool Steel                      | 33                   | 2870             | 950               | 38                              | 380                               |
| 6 Tool Steel                      | 33                   | 2580             | 850               | 35                              | 350                               |
| 7 Tool Steel                      | 33                   | 1080             | 360               | 15                              | 150                               |
| 8 Heat resistant                  | 33                   | 1045             | 345               | 14                              | 140                               |
| 9 Carbide with<br>Diamond Wheel   | 5                    | $V_{600} = 1200$ | $SMRR_{600} = 50$ | 2                               | 20                                |
| 10 Ceramics with<br>Diamond Wheel | 5                    | $V_{600} = 411$  | $SMRR_{600} = 21$ | 0.84                            | 84                                |

**Procedure to Determine Data.**—The following wheel-life recommendations are designed for 4 values of  $ECT = 0.00017, 0.00033, 0.00050$  and  $0.00075$  mm (shown as 17, 33, 50 and 75 in the tables). Lower values of  $ECT$  than  $0.00010$  mm ( $0.000004$  in.) are not recommended as these may lie to the left of the  $H$ -curve.

The user selects any one of the  $ECT$  values, or interpolates between these, and selects the wheel speed for 10 or 100 minutes life, denoted by  $V_{10}$  and  $V_{100}$ , respectively. For other desired wheel lives the wheel speed can be calculated from the tabulated Taylor constants  $C$  and  $n = 0.26$  as follows:

$$(V \times T_{(desired)})^{0.26} = C, \text{ the value of which is tabulated for each } ECT \text{ value. } C \text{ is the value of cutting speed } V \text{ at } T = 1 \text{ minute, hence is the same as for the speed } V_I \\ (V_I \times 1^{0.26} = C)$$

$$V_{10}$$

$$C \div 10^{0.26} = C \div 1.82$$

$$V_{100}$$

$$C \div 100^{0.26} = C \div 3.31.$$

**Example 6:** A tool steel in material group 6 with  $ECT = 0.00033$ , has constant  $C = 4690$ ,  $V_{10} = 2578$  m/min, and  $V_{100} = 1417$  m/min. From this information, find the wheel speed for desired wheel-life of  $T = 15$  minutes and  $T = 45$  minutes

For  $T = 15$  minutes we get  $V_{15} = 4690 \div 15^{0.26} = 2319$  m/min (7730 fpm) and for  $T = 45$  minutes  $V_{45} = 4690 \div 45^{0.26} = 1743$  m/min (5810 fpm).

### The Tables are arranged in 3 sections:

1. Speeds  $V_{10}$  and  $V_I = \text{Constant CST (standard)}$  for 4  $ECT$  values  $0.00017, 0.00033, 0.00050$  and  $0.00075$  mm. Values  $C_U$  and  $V_{10U}$  refer to user calibration of the standard values in each material group, explained in the following.

2. Speeds  $V_{100}$  (first row of 3),  $V_{10}$  and  $V_I$  (last in row) corresponding to wheel lives 100, 10 and 1 minutes, for 4  $ECT$  values  $0.00017, 0.00033, 0.00050$  and  $0.00075$  mm.

3. Specific metal removal rates  $SMRR_{100}$ ,  $SMRR_{10}$  and  $SMRR_I$  corresponding to wheel lives 100, 10 and 1 minutes, for the 4  $ECT$  values  $0.00017, 0.00033, 0.00050$ , and  $0.00075$  mm

The 2 Graphs show: wheel life versus wheel speed in double logarithmic coordinates (Taylor lines); and, *SMRR* versus wheel speed in double logarithmic coordinates for 4 *ECT* values: 0.00017, 0.00033, 0.00050 and 0.00075 mm.

**Table 1. Group 1—Unhardened Steels**

| Tool Life<br><i>T</i> (min) | <i>ECT</i> = 0.00017 mm  |             | <i>ECT</i> = 0.00033 mm  |             | <i>ECT</i> = 0.00050 mm  |             | <i>ECT</i> = 0.00075 mm  |             |
|-----------------------------|--------------------------|-------------|--------------------------|-------------|--------------------------|-------------|--------------------------|-------------|
|                             | Constant <i>C</i> = 8925 |             | Constant <i>C</i> = 6965 |             | Constant <i>C</i> = 5385 |             | Constant <i>C</i> = 3885 |             |
|                             | <i>V<sub>T</sub></i>     | <i>SMRR</i> | <i>V<sub>T</sub></i>     | <i>SMRR</i> | <i>V<sub>T</sub></i>     | <i>SMRR</i> | <i>V<sub>T</sub></i>     | <i>SMRR</i> |
| 100                         | 2695                     | 460         | 2105                     | 695         | 1625                     | 815         | 1175                     | 880         |
| <b>10</b>                   | <b>4905</b>              | <b>835</b>  | <b>3830</b>              | <b>1265</b> | <b>2960</b>              | <b>1480</b> | <b>2135</b>              | <b>1600</b> |
| 1                           | 8925                     | 1520        | 6965                     | 2300        | 5385                     | 2695        | 3885                     | 2915        |

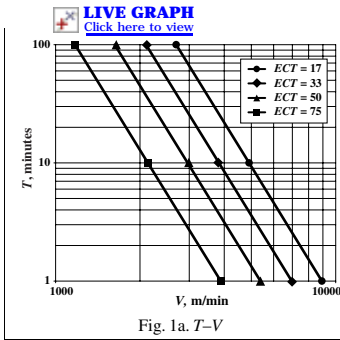


Fig. 1a. *T-V*

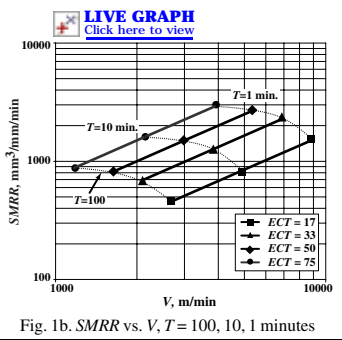


Fig. 1b. *SMRR vs. V, T* = 100, 10, 1 minutes

**Table 2. Group 2—Stainless Steels SAE 30201 – 30347, SAE 51409 – 51501**

| Tool Life<br><i>T</i> (min) | <i>ECT</i> = 0.00017 mm  |             | <i>ECT</i> = 0.00033 mm  |             | <i>ECT</i> = 0.00050 mm  |             | <i>ECT</i> = 0.00075 mm  |             |
|-----------------------------|--------------------------|-------------|--------------------------|-------------|--------------------------|-------------|--------------------------|-------------|
|                             | Constant <i>C</i> = 2270 |             | Constant <i>C</i> = 1970 |             | Constant <i>C</i> = 1505 |             | Constant <i>C</i> = 1010 |             |
|                             | <i>V<sub>T</sub></i>     | <i>SMRR</i> | <i>V<sub>T</sub></i>     | <i>SMRR</i> | <i>V<sub>T</sub></i>     | <i>SMRR</i> | <i>V<sub>T</sub></i>     | <i>SMRR</i> |
| 100                         | 685                      | 115         | 595                      | 195         | 455                      | 225         | 305                      | 230         |
| <b>10</b>                   | <b>1250</b>              | <b>210</b>  | <b>1080</b>              | <b>355</b>  | <b>825</b>               | <b>415</b>  | <b>555</b>               | <b>415</b>  |
| 1                           | 2270                     | 385         | 1970                     | 650         | 1505                     | 750         | 1010                     | 760         |

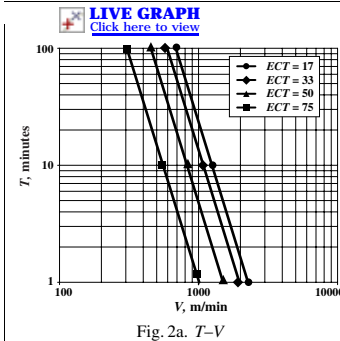


Fig. 2a. *T-V*

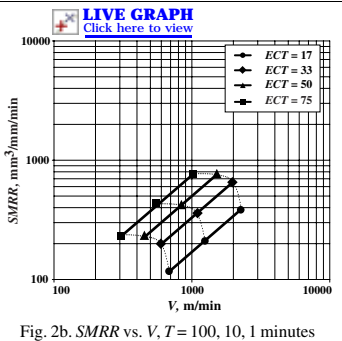


Fig. 2b. *SMRR vs. V, T* = 100, 10, 1 minutes

**Table 3. Group 3—Cast Iron**

| Tool Life<br>$T$ (min) | $ECT = 0.00017$ mm   |             | $ECT = 0.00033$ mm  |             | $ECT = 0.00050$ mm  |             | $ECT = 0.00075$ mm  |             |
|------------------------|----------------------|-------------|---------------------|-------------|---------------------|-------------|---------------------|-------------|
|                        | Constant $C = 10710$ |             | Constant $C = 8360$ |             | Constant $C = 6465$ |             | Constant $C = 4665$ |             |
|                        | $V_T$                | $SMRR$      | $V_T$               | $SMRR$      | $V_T$               | $SMRR$      | $V_T$               | $SMRR$      |
| 100                    | 3235                 | 550         | 2525                | 835         | 1950                | 975         | 1410                | 1055        |
| <b>10</b>              | <b>5885</b>          | <b>1000</b> | <b>4595</b>         | <b>1515</b> | <b>3550</b>         | <b>1775</b> | <b>2565</b>         | <b>1920</b> |
| 1                      | 10710                | 1820        | 8360                | 2760        | 6465                | 3230        | 4665                | 3500        |

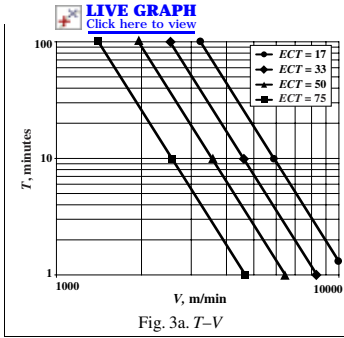


Fig. 3a.  $T$ - $V$

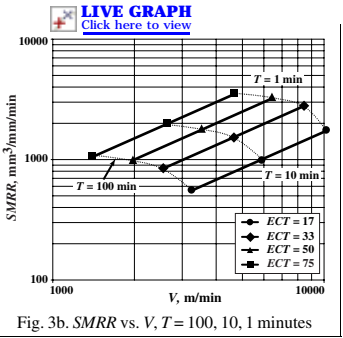


Fig. 3b.  $SMRR$  vs.  $V$ ,  $T = 100, 10, 1$  minutes

**Table 4. Group 4—Tool Steels, M1, M8, T1, H, O, L, F, 52100**

| Tool Life<br>$T$ (min) | $ECT = 0.00017$ mm  |            | $ECT = 0.00033$ mm  |             | $ECT = 0.00050$ mm  |             | $ECT = 0.00075$ mm  |             |
|------------------------|---------------------|------------|---------------------|-------------|---------------------|-------------|---------------------|-------------|
|                        | Constant $C = 7440$ |            | Constant $C = 5805$ |             | Constant $C = 4490$ |             | Constant $C = 3240$ |             |
|                        | $V_T$               | $SMRR$     | $V_T$               | $SMRR$      | $V_T$               | $SMRR$      | $V_T$               | $SMRR$      |
| 100                    | 2245                | 380        | 1755                | 580         | 1355                | 680         | 980                 | 735         |
| <b>10</b>              | <b>4090</b>         | <b>695</b> | <b>3190</b>         | <b>1055</b> | <b>2465</b>         | <b>1235</b> | <b>1780</b>         | <b>1335</b> |
| 1                      | 7440                | 1265       | 5805                | 1915        | 4490                | 2245        | 3240                | 2430        |

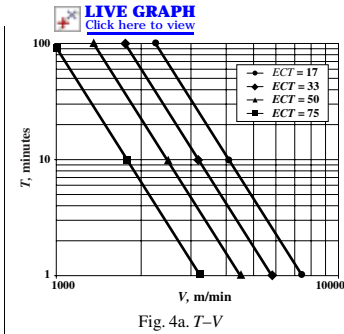


Fig. 4a.  $T$ - $V$

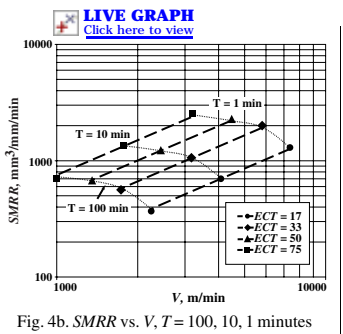


Fig. 4b.  $SMRR$  vs.  $V$ ,  $T = 100, 10, 1$  minutes

**Table 5. Group 5—Tool Steels, M2, T2, T5, T6, D2, D5, H41, H42, H43, M50**

| Tool Life<br>$T$ , (min) | $ECT = 0.00017$ mm  |            | $ECT = 0.00033$ mm  |            | $ECT = 0.00050$ mm  |             | $ECT = 0.00075$ mm  |             |
|--------------------------|---------------------|------------|---------------------|------------|---------------------|-------------|---------------------|-------------|
|                          | Constant $C = 6695$ |            | Constant $C = 5224$ |            | Constant $C = 4040$ |             | Constant $C = 2915$ |             |
|                          | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     | $V_T$               | $SMRR$      | $V_T$               | $SMRR$      |
| 100                      | 2020                | 345        | 1580                | 520        | 1220                | 610         | 880                 | 660         |
| <b>10</b>                | <b>3680</b>         | <b>625</b> | <b>2870</b>         | <b>945</b> | <b>2220</b>         | <b>1110</b> | <b>1600</b>         | <b>1200</b> |
| 1                        | 6695                | 1140       | 5225                | 1725       | 4040                | 2020        | 2915                | 2185        |

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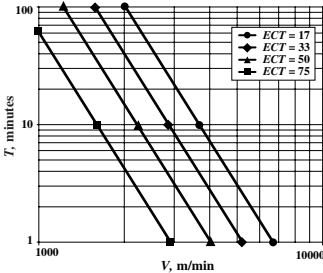


Fig. 5a.  $T$ - $V$

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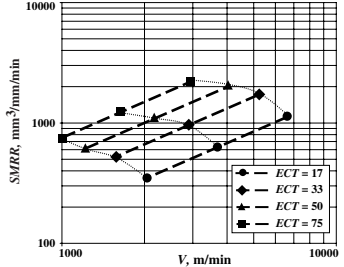


Fig. 5b.  $SMRR$  vs.  $V$ ,  $T = 100, 10, 1$  minutes

**Table 6. Group 6—Tool Steels, M3, M4, T3, D7**

| Tool Life<br>$T$ , (min) | $ECT = 0.00017$ mm  |            | $ECT = 0.00033$ mm  |            | $ECT = 0.00050$ mm  |            | $ECT = 0.00075$ mm  |            |
|--------------------------|---------------------|------------|---------------------|------------|---------------------|------------|---------------------|------------|
|                          | Constant $C = 5290$ |            | Constant $C = 4690$ |            | Constant $C = 3585$ |            | Constant $C = 2395$ |            |
|                          | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     |
| 100                      | 1600                | 270        | 1415                | 465        | 1085                | 540        | 725                 | 540        |
| <b>10</b>                | <b>2910</b>         | <b>495</b> | <b>2580</b>         | <b>850</b> | <b>1970</b>         | <b>985</b> | <b>1315</b>         | <b>985</b> |
| 1                        | 5290                | 900        | 4690                | 1550       | 3585                | 1795       | 2395                | 1795       |

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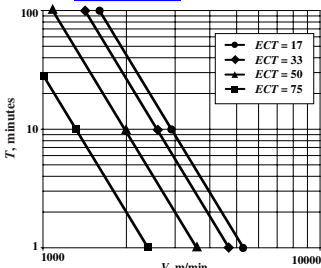


Fig. 6a. Group 6 Tool Steels  $T$ - $V$

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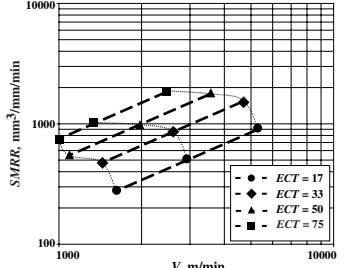


Fig. 6b.  $SMRR$  vs.  $V$ ,  $T = 100, 10, 1$  minutes



GRINDING FEEDS AND SPEEDS

Table 7. Group 7—Tool Steels, T15, M15

| Tool Life<br>$T$ (min) | $ECT = 0.00017$ mm  |            | $ECT = 0.00033$ mm  |            | $ECT = 0.00050$ mm  |            | $ECT = 0.00075$ mm  |            |
|------------------------|---------------------|------------|---------------------|------------|---------------------|------------|---------------------|------------|
|                        | Constant $C = 2270$ |            | Constant $C = 1970$ |            | Constant $C = 1505$ |            | Constant $C = 1010$ |            |
|                        | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     |
| 100                    | 685                 | 115        | 595                 | 195        | 455                 | 225        | 305                 | 230        |
| <b>10</b>              | <b>1250</b>         | <b>210</b> | <b>1080</b>         | <b>355</b> | <b>825</b>          | <b>415</b> | <b>555</b>          | <b>415</b> |
| 1                      | 2270                | 385        | 1970                | 650        | 1505                | 750        | 1010                | 760        |

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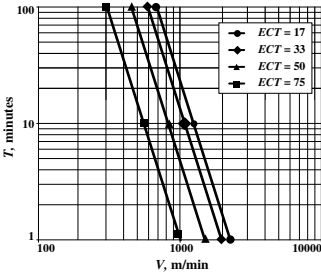


Fig. 7a.  $T$ - $V$

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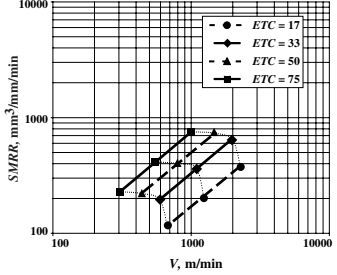


Fig. 7b.  $SMRR$  vs.  $V, T = 100, 10, 1$  minutes

Table 8. Group 8—Heat Resistant Alloys, Inconel, Rene, etc.

| Tool Life<br>$T$ (min) | $ECT = 0.00017$ mm  |            | $ECT = 0.00033$ mm  |            | $ECT = 0.00050$ mm  |            | $ECT = 0.00075$ mm  |            |
|------------------------|---------------------|------------|---------------------|------------|---------------------|------------|---------------------|------------|
|                        | Constant $C = 2150$ |            | Constant $C = 1900$ |            | Constant $C = 1490$ |            | Constant $C = 1035$ |            |
|                        | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     |
| 100                    | 650                 | 110        | 575                 | 190        | 450                 | 225        | 315                 | 235        |
| <b>10</b>              | <b>1185</b>         | <b>200</b> | <b>1045</b>         | <b>345</b> | <b>820</b>          | <b>410</b> | <b>570</b>          | <b>425</b> |
| 1                      | 2150                | 365        | 1900                | 625        | 1490                | 745        | 1035                | 780        |

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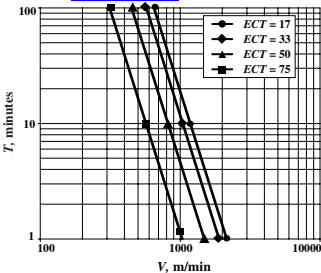


Fig. 8a.  $T$ - $V$

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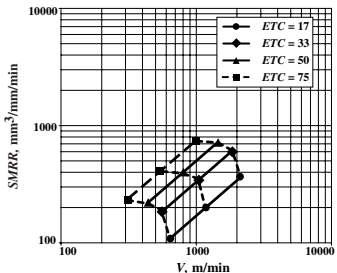


Fig. 8b.  $SMRR$  vs.  $V, T = 100, 10, 1$  minutes

**Table 9. Group 9—Carbide Materials, Diamond Wheel**

| Tool Life<br>$T$ (min) | $ECT = 0.00002$ mm  |        | $ECT = 0.00003$ mm  |        | $ECT = 0.00005$ mm  |        | $ECT = 0.00008$ mm  |        |
|------------------------|---------------------|--------|---------------------|--------|---------------------|--------|---------------------|--------|
|                        | Constant $C = 9030$ |        | Constant $C = 8030$ |        | Constant $C = 5365$ |        | Constant $C = 2880$ |        |
|                        | $V_T$               | $SMRR$ | $V_T$               | $SMRR$ | $V_T$               | $SMRR$ | $V_T$               | $SMRR$ |
| 4800                   | 1395                | 30     | 1195                | 35     | 760                 | 40     | 390                 | 30     |
| 600                    | 2140                | 45     | 1855                | 55     | 1200                | 60     | 625                 | 50     |
| 10                     | 4960                | 100    | 4415                | 130    | 2950                | 145    | 1580                | 125    |

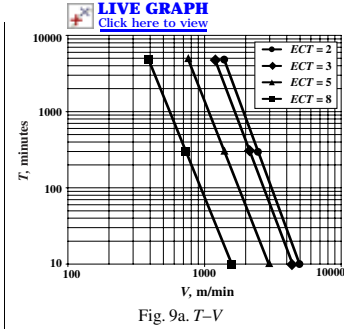


Fig. 9a.  $T$ - $V$

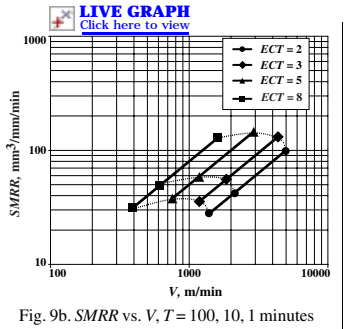


Fig. 9b.  $SMRR$  vs.  $V$ ,  $T = 100, 10, 1$  minutes

**Table 10. Group 10 — Ceramic Materials  $Al_2O_3$ ,  $ZrO_2$ ,  $SiC$ ,  $Si_3N_4$ , Diamond Wheel**

| Tool Life<br>$T$ (min) | $ECT = 0.00002$ mm  |        | $ECT = 0.00003$ mm  |        | $ECT = 0.00005$ mm  |        | $ECT = 0.00008$ mm  |        |
|------------------------|---------------------|--------|---------------------|--------|---------------------|--------|---------------------|--------|
|                        | Constant $C = 2460$ |        | Constant $C = 2130$ |        | Constant $C = 1740$ |        | Constant $C = 1420$ |        |
|                        | $V_T$               | $SMRR$ | $V_T$               | $SMRR$ | $V_T$               | $SMRR$ | $V_T$               | $SMRR$ |
| 4800                   | 395                 | 8      | 335                 | 10     | 265                 | 13     | 210                 | 17     |
| 600                    | 595                 | 12     | 510                 | 15     | 410                 | 20     | 330                 | 25     |
| 10                     | 1355                | 25     | 1170                | 35     | 955                 | 50     | 780                 | 60     |

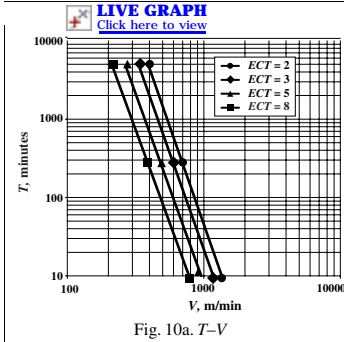


Fig. 10a.  $T$ - $V$

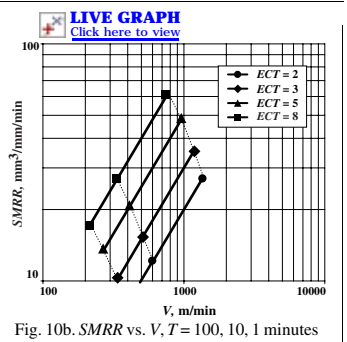


Fig. 10b.  $SMRR$  vs.  $V$ ,  $T = 100, 10, 1$  minutes

**User Calibration of Recommendations**

It is recommended to copy or redraw the standard graph for any of the material groups before applying the data calibration method described below. The method is based on the user's own experience and data. The procedure is described in the following and illustrated in Table 11 and Fig. 12.

Only one shop data set is needed to adjust all four Taylor lines as shown below. The required shop data is the user's wheel-life  $T_U$  obtained at the user's wheel speed  $V_U$ , the user's work speed  $V_{wU}$ , and depth of cut  $a_r$ .

1) First the user finds out which wheel-life  $T_U$  was obtained in the shop, and the corresponding wheel speed  $V_U$ , depth of cut  $a_r$  and work speed  $V_{wU}$ .

2) Second, calculate:

a)  $ECT = V_{wU} \times ar \div V_U$

b) the user Taylor constant  $C_U = V_U \times T_U^{0.26}$

$V_{10U} = C_U \div 10^{0.26}$

$V_{100U} = C_U \div 100^{0.26}$

3) Thirdly, the user Taylor line is drawn in the pertinent graph. If the user wheel-life  $T_U$  is longer than that in the standard graph the speed values will be higher, or if the user wheel-life is shorter the speeds  $C_U, V_{10U}, V_{100U}$  will be lower than the standard values  $C, V_{10}$  and  $V_{100}$ .

The results are a series of lines moved to the right or to the left of the standard Taylor lines for  $ECT = 17, 33, 50$  and  $75 \times 10^{-5}$  mm. Each standard table contains the values  $C = V_U, V_{10}, V_{100}$  and empty spaces for filling out the calculated user values:  $C_U = V_U \times T_U^{0.26}, V_{10U} = C_U \div 10^{0.26}$  and  $V_{100U} = C_U \div 100^{0.26}$ .

*Example 7:* Assume the following test results on a Group 6 material: user speed is  $V_U = 1800$  m/min, wheel-life  $T_U = 7$  minutes, and  $ECT = 0.00017$  mm. The Group 6 data is repeated below for convenience.

**Standard Table Data, Group 6 Material**

| Tool Life<br>$T$ (min) | $ECT = 0.00017$ mm  |            | $ECT = 0.00033$ mm  |            | $ECT = 0.00050$ mm  |            | $ECT = 0.00075$ mm  |            |
|------------------------|---------------------|------------|---------------------|------------|---------------------|------------|---------------------|------------|
|                        | Constant $C = 5290$ |            | Constant $C = 4690$ |            | Constant $C = 3585$ |            | Constant $C = 2395$ |            |
|                        | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     | $V_T$               | $SMRR$     |
| 100                    | 1600                | 270        | 1415                | 465        | 1085                | 540        | 725                 | 540        |
| <b>10</b>              | <b>2910</b>         | <b>495</b> | <b>2580</b>         | <b>850</b> | <b>1970</b>         | <b>985</b> | <b>1315</b>         | <b>985</b> |
| 1                      | 5290                | 900        | 4690                | 1550       | 3585                | 1795       | 2395                | 1795       |

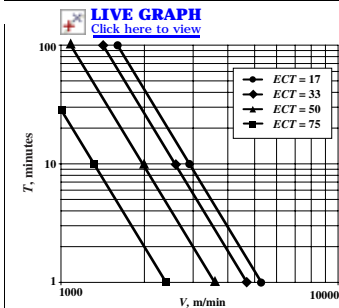


Fig. 11a. Group 6 Tool Steels,  $T-V$

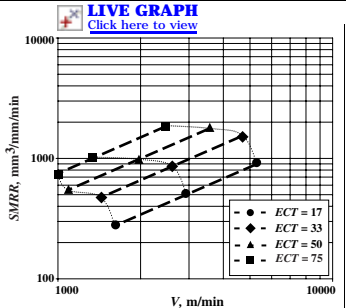


Fig. 11b.  $SMRR$  vs.  $V, T = 100, 10, 1$  minutes

*Calculation Procedure*

- 1) Calculate  $V_{IU}$ ,  $V_{10U}$ ,  $V_{100U}$  and  $SMRR_{IU}$ ,  $SMRR_{10U}$ ,  $SMRR_{100U}$  for  $ECT = 0.00017$  mm
- a)  $V_{IU} =$  the user Taylor constant  $C_U = V_U \times T_U^{0.26} = 1800 \times 7^{0.26} = 2985$  m/min, and  
 $SMRR_{IU} = 1000 \times 2985 \times 0.00017 = 507$  mm<sup>3</sup>/mm width/min
- $V_{10U} = C_U \div 10^{0.26} = 2985 \div 10^{0.26} = 1640$  m/min, and  $SMRR_{10U} = 1000 \times 1640 \times 0.00017 = 279$  mm<sup>3</sup>/mm width/min
- $V_{100U} = C_U \div 100^{0.26} = 2985 \div 100^{0.26} = 900$  m/min, and  $SMRR_{100U} = 1000 \times 900 \times 0.00017 = 153$  mm<sup>3</sup>/mm width/min
- 2) For  $ECT = 0.00017$  mm, calculate the ratio of user Taylor constant to standard Taylor constant from the tables  $= C_U \div C_{ST} = C_U \div V_I = 2985 \div 5290 = 0.564$  (see Table 6 for the value of  $C_{ST} = V_I$  at  $ECT = 0.00017$  mm).
- 3) For  $ECT = 0.00033$ ,  $0.00050$ , and  $0.00075$  mm calculate the user Taylor constants from  $C_U = C_{ST} \times$  (the ratio calculated in step 2)  $= V_I \times 0.564 = V_{IU}$ . Then, calculate  $V_{10U}$  and  $V_{100U}$  and  $SMRR_{IU}$ ,  $SMRR_{10U}$ ,  $SMRR_{100U}$  using the method in items 1b) and 1c) above.
- a) For  $ECT = 0.00033$  mm
- $V_{IU} = C_U = 4690 \times 0.564 = 2645$  m/min
- $V_{10U} = C_U \div 10^{0.26} = 2645 \div 10^{0.26} = 1455$  m/min
- $V_{100U} = C_U \div 100^{0.26} = 2645 \div 100^{0.26} = 800$  m/min
- $SMRR_{IU}$ ,  $SMRR_{10U}$ , and  $SMRR_{100U} = 876, 480,$  and  $264$  mm<sup>3</sup>/mm width/min
- b) For  $ECT = 0.00050$  mm
- $V_{IU} = C_U = 3590 \times 0.564 = 2025$  m/min
- $V_{10U} = C_U \div 10^{0.26} = 2025 \div 10^{0.26} = 1110$  m/min
- $V_{100U} = C_U \div 100^{0.26} = 2025 \div 100^{0.26} = 610$  m/min
- $SMRR_{IU}$ ,  $SMRR_{10U}$ , and  $SMRR_{100U} = 1013, 555,$  and  $305$  mm<sup>3</sup>/mm width/min
- c) For  $ECT = 0.00075$  mm
- $V_{IU} = C_U = 2395 \times 0.564 = 1350$  m/min
- $V_{10U} = C_U \div 10^{0.26} = 1350 \div 10^{0.26} = 740$  m/min
- $V_{100U} = C_U \div 100^{0.26} = 1350 \div 100^{0.26} = 405$  m/min
- $SMRR_{IU}$ ,  $SMRR_{10U}$ , and  $SMRR_{100U} = 1013, 555,$  and  $305$  mm<sup>3</sup>/mm width/min

Thus, the wheel speed for any desired wheel-life at a given  $ECT$  can be calculated from  $V = C_U \div T^{0.26}$ . For example, at  $ECT = 0.00050$  mm and desired tool-life  $T = 9$ ,  $V_9 = 2025 \div 9^{0.26} = 1144$  m/min. The corresponding specific metal removal rate is  $SMRR = 1000 \times 1144 \times 0.0005 = 572$  mm<sup>3</sup>/mm width/min (0.886 in<sup>3</sup>/inch width/min).

**Table 11. User Calculated Data, Group 6 Material**

| Tool Life<br>$T$ (min) | $ECT = 0.00017$ mm            |            | $ECT = 0.00033$ mm            |            | $ECT = 0.00050$ mm            |            | $ECT = 0.00075$ mm            |            |
|------------------------|-------------------------------|------------|-------------------------------|------------|-------------------------------|------------|-------------------------------|------------|
|                        | User Constant<br>$C_U = 2985$ |            | User Constant<br>$C_U = 2645$ |            | User Constant<br>$C_U = 2025$ |            | User Constant<br>$C_U = 1350$ |            |
|                        | $V_T$                         | $SMRR$     | $V_T$                         | $SMRR$     | $V_T$                         | $SMRR$     | $V_T$                         | $SMRR$     |
| 100                    | 900                           | 153        | 800                           | 264        | 610                           | 305        | 405                           | 305        |
| <b>10</b>              | <b>1640</b>                   | <b>279</b> | <b>1455</b>                   | <b>480</b> | <b>1110</b>                   | <b>555</b> | <b>740</b>                    | <b>555</b> |
| 1                      | 2985                          | 507        | 2645                          | 876        | 2025                          | 1013       | 1350                          | 1013       |

## GRINDING FEEDS AND SPEEDS

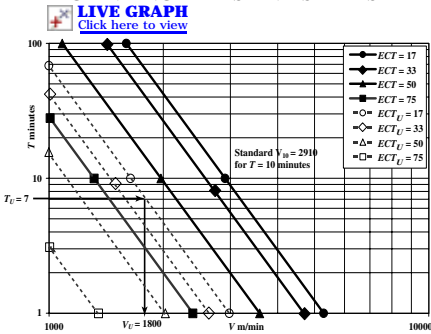


Fig. 12. Calibration of user grinding data to standard Taylor Lines  
User Input:  $V_U = 1800$  m/min,  $T_U = 7$  minutes,  $ECT = 0.00017$  mm

**Optimization.**— As shown, a global optimum occurs along the  $G$ -curve, in selected cases for values of  $ECT$  around 0.00075, i.e. at high metal removal rates as in other machining operations. It is recommended to use the simple formula for economic life:  $T_E = 3 \times T_V$  minutes.  $T_V = T_{RPL} + 60 \times C_E \div H_R$ , minutes, where  $T_{RPL}$  is the time required to replace wheel,  $C_E = \text{cost per wheel dressing} = \text{wheel cost} + \text{cost per dressing}$ , and  $H_R$  is the hourly rate.

In grinding, values of  $T_V$  range between 2 and 5 minutes in conventional grinders, which means that the economic wheel lives range between 6 and 15 minutes indicating higher metal removal rates than are commonly used. When wheels are sharpened automatically after each stroke as in internal grinding, or when grits are continually replaced as in abrasive grinding (machining),  $T_V$  may be less than one minute. This translates into wheel lives around one minute in order to achieve minimum cost grinding.

*Grinding Cost, Optimization and Process Planning:* More accurate results are obtained when the firm collects and systemizes the information on wheel lives, wheel and work speeds, and depths of cut from production runs. A computer program can be used to plan the grinding process and apply the rules and formulas presented in this chapter. A complete grinding process planning program, such as that developed by Colding International Corporation, can be used to optimize machine settings for various feed-speed preferences corresponding wheel-life requirements, minimum cost or maximum production rate grinding, required surface finish and sparkout time; machine and fixture requirements based on the grinding forces, torque and power for sharp and worn grinding wheels; and, detailed time and cost analysis per part and per batch including wheel dressing and wheel changing schedules.

Table 12 summarizes the time and cost savings per batch as it relates to tool life. The sensitivity of how grinding parameters are selected is obvious. Minimum cost conditions yield a 51% reduction of time and 44% reduction of cost, while maximum production rate reduces total time by 65% but, at the expense of heavy wheel consumption (continuous dressing), cost by only 18%.

Table 12. Wheel Life vs. Cost

| Preferences         | Time per Batch, minutes | Cost per Batch, \$ |            | Reduction from Long Life, % |      |
|---------------------|-------------------------|--------------------|------------|-----------------------------|------|
|                     |                         | Tooling            | Total Cost | Time                        | Cost |
| Long Life           | 2995                    | 39                 | 2412       | —                           | —    |
| Economic Life       | 2433                    | 252                | 2211       | 19                          | 8    |
| Minimum Cost        | 1465                    | 199                | 1344       | 51                          | 44   |
| Max Production Rate | 1041                    | 1244               | 1980       | 65                          | 18   |

## GRINDING AND OTHER ABRASIVE PROCESSES

Processes and equipment discussed under this heading use abrasive grains for shaping workpieces by means of machining or related methods. Abrasive grains are hard crystals either found in nature or manufactured. The most commonly used materials are aluminum oxide, silicon carbide, cubic boron nitride and diamond. Other materials such as garnet, zirconia, glass and even walnut shells are used for some applications. Abrasive products are used in three basic forms by industry:

a) *Bonded* to form a solid shaped tool such as disks (the basic shape of grinding wheels), cylinders, rings, cups, segments, or sticks to name a few.

b) *Coated* on backings made of paper or cloth, in the form of sheets, strips, or belts.

c) *Loose*, held in some liquid or solid carrier (for lapping, polishing, tumbling), or propelled by centrifugal force, air, or water pressure against the work surface (blast cleaning).

The applications for abrasive processes are multiple and varied. They include:

a) *Cleaning* of surfaces, also the coarse removal of excess material—such as rough off-hand grinding in foundries to remove gates and risers.

b) *Shaping*, such as in form grinding and tool sharpening.

c) *Sizing*, a general objective, but of primary importance in precision grinding.

d) *Surface finish improvement*, either primarily as in lapping, honing, and polishing or as a secondary objective in other types of abrasive processes.

e) *Separating*, as in cut-off or slicing operations.

The main field of application of abrasive processes is in metalworking, because of the capacity of abrasive grains to penetrate into even the hardest metals and alloys. However, the great hardness of the abrasive grains also makes the process preferred for working other hard materials, such as stones, glass, and certain types of plastics. Abrasive processes are also chosen for working relatively soft materials, such as wood, rubber, etc., for such reasons as high stock removal rates, long-lasting cutting ability, good form control, and fine finish of the worked surface.

### Grinding Wheels

**Abrasive Materials.**—In earlier times, only natural abrasives were available. From about the beginning of this century, however, manufactured abrasives, primarily silicon carbide and aluminum oxide, have replaced the natural materials; even natural diamonds have been almost completely supplanted by synthetics. Superior and controllable properties, and dependable uniformity characterize the manufactured abrasives.

Both silicon carbide and aluminum oxide abrasives are very hard and brittle. This brittleness, called friability, is controllable for different applications. Friable abrasives break easily, thus forming sharp edges. This decreases the force needed to penetrate into the work material and the heat generated during cutting. Friable abrasives are most commonly used for precision and finish grinding. Tough abrasives resist fracture and last longer. They are used for rough grinding, snagging, and off-hand grinding.

As a general rule, although subject to variation:

1) Aluminum oxide abrasives are used for grinding plain and alloyed steel in a soft or hardened condition.

2) Silicon carbide abrasives are selected for cast iron, nonferrous metals, and nonmetallic materials.

3) Diamond is the best type of abrasive for grinding cemented carbides. It is also used for grinding glass, ceramics, and hardened tool steel.

4) Cubic Boron Nitride (CBN) is known by several trade names including Borazon (General Electric Co.), ABN (De Beers), Sho-bon (Showa-Denko), and Elbor (USSR). CBN is a synthetic superabrasive used for grinding hardened steels and wear-resistant superalloys. (See *Cubic Boron Nitride (CBN)* starting on page 1013.) CBN grinding wheels have long lives and can maintain close tolerances with superior surface finishes.

**Bond Properties and Grinding Wheel Grades.**—The four main types of bonds used for grinding wheels are the vitrified, resinoid, rubber, and metal.

*Vitrified bonds* are used for more than half of all grinding wheels made, and are preferred because of their strength and other desirable qualities. Being inert, glass-like materials, vitrified bonds are not affected by water or by the chemical composition of different grinding fluids. Vitrified bonds also withstand the high temperatures generated during normal grinding operations. The structure of vitrified wheels can be controlled over a wide range of strength and porosity. Vitrified wheels, however, are more sensitive to impact than those made with organic bonds.

*Resinoid bonds* are selected for wheels subjected to impact, or sudden loads, or very high operating speeds. They are preferred for snagging, portable grinder uses, or roughing operations. The higher flexibility of this type of bond—essentially a filled thermosetting plastic—helps it withstand rough treatment.

*Rubber bonds* are even more flexible than the resinoid type, and for that reason are used for producing a high finish and for resisting sudden rises in load. Rubber bonded wheels are commonly used for wet cut-off wheels because of the nearly burr-free cuts they produce, and for centerless grinder regulating wheels to provide a stronger grip and more reliable workpiece control.

*Metal bonds* are used in CBN and diamond wheels. In metal bonds produced by electrodeposition, a single layer of superabrasive material (diamond or CBN) is bonded to a metal core by a matrix of metal, usually nickel. The process is so controlled that about 30–40 per cent of each abrasive particle projects above the deposited surface, giving the wheel a very aggressive and free-cutting action. With proper use, such wheels have remarkably long lives. When dulled, or worn down, the abrasive can be stripped off and the wheel renewed by a further deposit process. These wheels are also used in electrical discharge grinding and electrochemical grinding where an electrically conductive wheel is needed.

In addition to the basic properties of the various bond materials, each can also be applied in different proportions, thereby controlling the grade of the grinding wheel.

*Grinding wheel grades* commonly associated with hardness, express the amount of bond material in a grinding wheel, and hence the strength by which the bond retains the individual grains.

During grinding, the forces generated when cutting the work material tend to dislodge the abrasive grains. As the grains get dull and if they don't fracture to resharpen themselves, the cutting forces will eventually tear the grains from their supporting bond. For a "soft" wheel the cutting forces will dislodge the abrasive grains before they have an opportunity to fracture. When a "hard" wheel is used, the situation is reversed. Because of the extra bond in the wheel the grains are so firmly held that they never break loose and the wheel becomes glazed. During most grinding operations it is desirable to have an intermediate wheel where there is a continual slow wearing process composed of both grain fracture and dislodgement.

The grades of the grinding wheels are designated by capital letters used in alphabetical order to express increasing "hardness" from A to Z.

**Grinding Wheel Structure.**—The individual grains, which are encased and held together by the bond material, do not fill the entire volume of the grinding wheel; the intermediate open space is needed for several functional purposes such as heat dissipation, coolant application, and particularly, for the temporary storage of chips. It follows that the

spacing of the grains must be greater for coarse grains which cut thicker chips and for large contact areas within which the chips have to be retained on the surface of the wheel before being disposed of. On the other hand, a wide spacing reduces the number of grains that contact the work surface within a given advance distance, thereby producing a coarser finish.

In general, denser structures are specified for grinding hard materials, for high-speed grinding operations, when the contact area is narrow, and for producing fine finishes and/or accurate forms. Wheels with open structure are used for tough materials, high stock removal rates, and extended contact areas, such as grinding with the face of the wheel. There are, however, several exceptions to these basic rules, an important one being the grinding of parts made by powder metallurgy, such as cemented carbides; although they represent one of the hardest industrial materials, grinding carbides requires wheels with an open structure.

Most kinds of general grinding operations, when carried out with the periphery of the wheel, call for medium spacing of the grains. The structure of the grinding wheels is expressed by numerals from 1 to 16, ranging from dense to open. Sometimes, "induced porosity" is used with open structure wheels. This term means that the grinding wheel manufacturer has placed filler material (which later burns out when the wheel is fired to vitrify the bond) in the grinding wheel mix. These fillers create large "pores" between grain clusters without changing the total volume of the "pores" in the grinding wheel. Thus, an A46-H12V wheel and an A46H12VP wheel will contain the same amounts of bond, abrasive, and air space. In the former, a large number of relatively small pores will be distributed throughout the wheel. The latter will have a smaller number of larger pores.

**American National Standard Grinding Wheel Markings.**—ANSI Standard B74.13-1990 "Markings for Identifying Grinding Wheels and Other Bonded Abrasives," applies to grinding wheels and other bonded abrasives, segments, bricks, sticks, hones, rubs, and other shapes that are for removing material, or producing a desired surface or dimension. It does not apply to specialties such as sharpening stones and provides only a standard system of markings. Wheels having the same standard markings but made by different wheel manufacturers may not—and probably will not—produce exactly the same grinding action. This desirable result cannot be obtained because of the impossibility of closely correlating any measurable physical properties of bonded abrasive products in terms of their grinding action.

Symbols for designating diamond and cubic boron wheel compositions are given on page 1204.

**Sequence of Markings.**—The accompanying illustration taken from ANSI B74.13-1990 shows the makeup of a typical wheel or bonded abrasive marking.

| Prefix | 1<br>Abrasive<br>Type | 2<br>Grain<br>Size | 3<br>Grade | 4<br>Structure | 5<br>Bond<br>Type | 6<br>Manufacturer's<br>Record |
|--------|-----------------------|--------------------|------------|----------------|-------------------|-------------------------------|
| 51     | A                     | 36                 | L          | 5              | V                 | 23                            |

The meaning of each letter and number in this or other markings is indicated by the following complete list.

1) *Abrasive Letters:* The letter (A) is used for aluminum oxide, (C) for silicon carbide, and (Z) for aluminum zirconium. The manufacturer may designate some particular type in any one of these broad classes, by using his own symbol as a prefix (example, 51).

2) *Grain Size:* The grain sizes commonly used and varying from coarse to very fine are indicated by the following numbers: 8, 10, 12, 14, 16, 20, 24, 30, 36, 46, 54, 60, 70, 80, 90, 100, 120, 150, 180, and 220. The following additional sizes are used occasionally: 240, 280, 320, 400, 500, and 600. The wheel manufacturer may add to the regular grain number an additional symbol to indicate a special grain combination.



3) *Grade*: Grades are indicated by letters of the alphabet from A to Z in all bonds or processes. Wheel grades from A to Z range from soft to hard.

4) *Structure*: The use of a structure symbol is optional. The structure is indicated by Nos. 1 to 16 (or higher, if necessary) with progressively higher numbers indicating a progressively wider grain spacing (more open structure).

5) *Bond or Process*: Bonds are indicated by the following letters: V, vitrified; S, silicate; E, shellac or elastic; R, rubber; RF, rubber reinforced; B, resinoid (synthetic resins); BF, resinoid reinforced; O, oxychloride.

6) *Manufacturer's Record*: The sixth position may be used for manufacturer's private factory records; this is optional.

**American National Standard Shapes and Sizes of Grinding Wheels.**—The ANSI Standard B74.2-1982 which includes shapes and sizes of grinding wheels, gives a wide variety of grinding wheel shape and size combinations. These are suitable for the majority of applications. Although grinding wheels can be manufactured to shapes and dimensions different from those listed, it is advisable, for reasons of cost and inventory control, to avoid using special shapes and sizes, unless technically warranted.

Standard shapes and size ranges as given in this Standard together with typical applications are shown in [Table 1a](#) for inch dimensions and in [Table 1b](#) for metric dimensions.

The operating surface of the grinding wheel is often referred to as the wheel face. In the majority of cases it is the periphery of the grinding wheel which, when not specified otherwise, has a straight profile. However, other face shapes can also be supplied by the grinding wheel manufacturers, and also reproduced during usage by appropriate truing. ANSI B74.2-1982 standard offers 13 different shapes for grinding wheel faces, which are shown in [Table 2](#).

**The Selection of Grinding Wheels.**—In selecting a grinding wheel, the determining factors are the composition of the work material, the type of grinding machine, the size range of the wheels used, and the expected grinding results, in this approximate order.

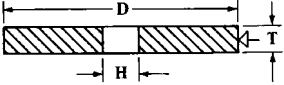
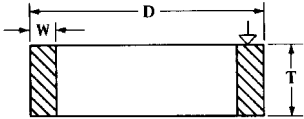
The Norton Company has developed, as the result of extensive test series, a method of grinding wheel recommendation that is more flexible and also better adapted to taking into consideration pertinent factors of the job, than are listings based solely on workpiece categories. This approach is the basis for [Tables 3](#) through [6](#), inclusive. Tool steels and constructional steels are considered in the detailed recommendations presented in these tables.

[Table 3](#) assigns most of the standardized tool steels to five different grindability groups. The AISI-SAE tool steel designations are used.

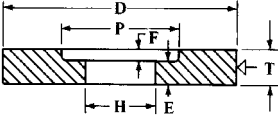
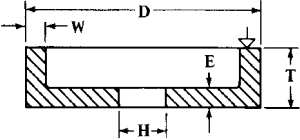
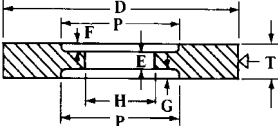
After having defined the grindability group of the tool steel to be ground, the operation to be carried out is found in the first column of [Table 4](#). The second column in this table distinguishes between different grinding wheel size ranges, because wheel size is a factor in determining the contact area between wheel and work, thus affecting the apparent hardness of the grinding wheel. Distinction is also made between wet and dry grinding.

Finally, the last two columns define the essential characteristics of the recommended types of grinding wheels under the headings of first and second choice, respectively. Where letters are used *preceding* A, the standard designation for aluminum oxide, they indicate a degree of friability different from the regular, thus: SF = semi friable (Norton equivalent 16A) and F = friable (Norton equivalent 33A and 38A). The suffix P, where applied, expresses a degree of porosity that is more open than the regular.

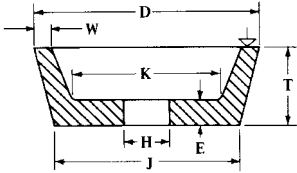
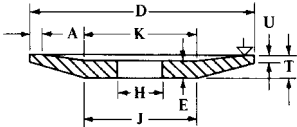
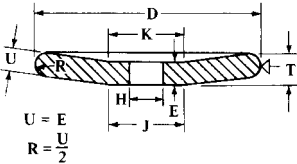
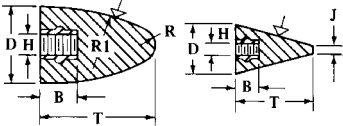
**Table 1a. Standard Shapes and Inch Size Ranges of Grinding Wheels**  
ANSI B74.2-1982

| Applications   | Size Ranges of Principal Dimensions, Inches |                                 |                                  |
|--|---|---------------------------------|----------------------------------|
|  | $D = \text{Dia.}$                           | $T = \text{Thick.}$             | $H = \text{Hole}$                |
|  <p><b>Type 1. Straight Wheel</b> For peripheral grinding.</p>  |   |                                 |                                  |
| CUTTING OFF (Organic bonds only)   | 1 to 48                                     | $\frac{1}{64}$ to $\frac{3}{8}$ | $\frac{1}{16}$ to 6              |
| CYLINDRICAL GRINDING<br>Between centers  | 12 to 48                                    | $\frac{1}{2}$ to 6              | 5 to 20                          |
| CYLINDRICAL GRINDING<br>Centerless grinding wheels   | 14 to 30                                    | 1 to 20                         | 5 or 12                          |
| CYLINDRICAL GRINDING<br>Centerless regulating wheels   | 8 to 14                                     | 1 to 12                         | 3 to 6                           |
| INTERNAL GRINDING  | $\frac{1}{4}$ to 4                          | $\frac{1}{4}$ to 2              | $\frac{3}{32}$ to $\frac{7}{8}$  |
| OFFHAND GRINDING<br>Grinding on the periphery  |   |                                 |                                  |
| General purpose  | 6 to 36                                     | $\frac{1}{2}$ to 4              | $\frac{1}{2}$ to 3               |
| For wet tool grinding only   | 30 or 36                                    | 3 or 4                          | 20                               |
| SAW GUMMING (F-type face)  | 6 to 12                                     | $\frac{1}{4}$ to $1\frac{1}{2}$ | $\frac{1}{2}$ to $1\frac{1}{4}$  |
| SNAGGING<br>Floor stand machines   | 12 to 24                                    | 1 to 3                          | $1\frac{1}{4}$ to $2\frac{1}{2}$ |
| SNAGGING<br>Floor stand machines (Organic bond, wheel speed over 6500 sfpm)  | 20 to 36                                    | 2 to 4                          | 6 or 12                          |
| SNAGGING<br>Mechanical grinders (Organic bond, wheel speed up to 16,500 sfpm)  | 24  | 2 to 3                          | 12                               |
| SNAGGING<br>Portable machines  | 3 to 8                                      | $\frac{1}{4}$ to 1              | $\frac{3}{8}$ to $\frac{5}{8}$   |
| SNAGGING<br>Portable machines (Reinforced organic bond, 17,000 sfpm)   | 6 or 8                                      | $\frac{3}{4}$ or 1              | 1                                |
| SNAGGING<br>Swing frame machines   | 12 to 24                                    | 2 to 3                          | $3\frac{1}{2}$ to 12             |
| SURFACE GRINDING<br>Horizontal spindle machines  | 6 to 24                                     | $\frac{1}{2}$ to 6              | $1\frac{1}{4}$ to 12             |
| TOOL GRINDING<br>Broaches, cutters, mills, reamers, taps, etc.   | 6 to 10                                     | $\frac{1}{4}$ to $\frac{1}{2}$  | $\frac{5}{8}$ to 5               |
|  <p><b>Type 2. Cylindrical Wheel</b> Side grinding wheel — mounted on the diameter; may also be mounted in a chuck or on a plate.</p> |   |                                 |                                  |
|  |   |                                 | $W = \text{Wall}$                |
| SURFACE GRINDING<br>Vertical spindle machines  | 8 to 20                                     | 4 or 5                          | 1 to 4                           |

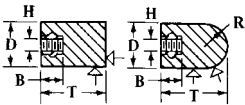
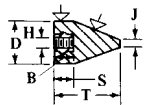
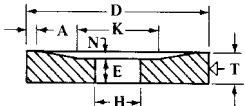
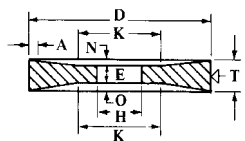
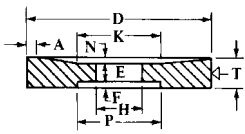
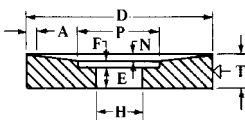
**Table 1a. (Continued) Standard Shapes and Inch Size Ranges of Grinding Wheels**  
ANSI B74.2-1982

| Applications   | Size Ranges of Principal Dimensions, Inches |            |          |
|--|---|------------|----------|
|  | D = Dia.                                    | T = Thick. | H = Hole |
|  <p><b>Type 5. Wheel</b>, recessed one side For peripheral grinding. Allows wider faced wheels than the available mounting thickness, also grinding clearance for the nut and flange.</p>   |   |            |          |
| CYLINDRICAL GRINDING<br>Between centers  | 12 to 36                                    | 1½ to 4    | 5 or 12  |
| CYLINDRICAL GRINDING<br>Centerless regulating wheel  | 8 to 14                                     | 3 to 6     | 3 or 5   |
| INTERNAL GRINDING  | ⅜ to 4                                      | ⅜ to 2     | ⅛ to ⅞   |
| SURFACE GRINDING<br>Horizontal spindle machines  | 7 to 24                                     | ¾ to 6     | 1¼ to 12 |
|  <p><b>Type 6. Straight-Cup Wheel</b> Side grinding wheel, in whose dimensioning the wall thickness (W) takes precedence over the diameter of the recess. Hole is ⅝-11UNC-2B threaded for the snagging wheels and ½ or ¼" for the tool grinding wheels.</p> |   |            |          |
|  |   |            | W = Wall |
| SNAGGING<br>Portable machines, organic bond only.  | 4 to 6                                      | 2          | ¾ to 1½  |
| TOOL GRINDING<br>Broaches, cutters, mills, reamers, taps, etc.   | 2 to 6                                      | 1¼ to 2    | ⅝ or ⅜   |
|  <p><b>Type 7. Wheel</b>, recessed two sides Peripheral grinding. Recesses allow grinding clearance for both flanges and also narrower mounting thickness than overall thickness.</p>   |   |            |          |
| CYLINDRICAL GRINDING<br>Between centers  | 12 to 36                                    | 1½ to 4    | 5 or 12  |
| CYLINDRICAL GRINDING<br>Centerless regulating wheel  | 8 to 14                                     | 4 to 20    | 3 to 6   |
| SURFACE GRINDING<br>Horizontal spindle machines  | 12 to 24                                    | 2 to 6     | 5 to 12  |

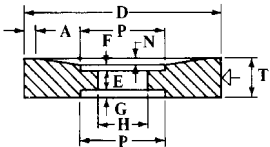
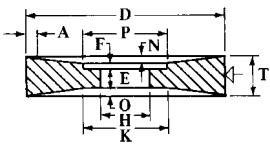
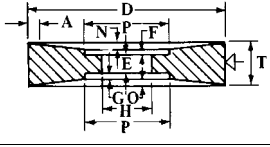
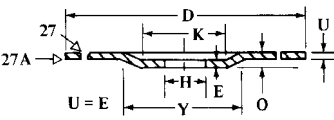
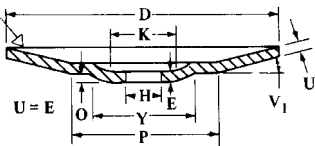
**Table 1a. (Continued) Standard Shapes and Inch Size Ranges of Grinding Wheels**  
ANSI B74.2-1982

| Applications   | Size Ranges of Principal Dimensions, Inches |   |  |
|--|---|---|--|
|  | D = Dia.                                    | T = Thick.  | H = Hole   |
|  <p><b>Type 11. Flaring-Cup Wheel</b> Side grinding wheel with wall tapered outward from the back; wall generally thicker in the back.</p>  |   |   |  |
| <p>SNAGGING<br/>Portable machines, organic bonds only, threaded hole</p> <p>TOOL GRINDING<br/>Broaches, cutters, mills, reamers, taps, etc.</p>  | 4 to 6                                      | 2   | $\frac{5}{8}$ -11 UNC-2B                                 |
|  <p><b>Type 12. Dish Wheel</b> Grinding on the side or on the U-face of the wheel, the U-face being always present in this type.</p>  |   |   |  |
| <p>TOOL GRINDING<br/>Broaches, cutters, mills, reamers, taps, etc.</p>   | 3 to 8                                      | $\frac{1}{2}$ or $\frac{3}{4}$  | $\frac{1}{2}$ to 1 $\frac{1}{4}$                         |
|  <p><b>Type 13. Saucer Wheel</b> Peripheral grinding wheel, resembling the shape of a saucer, with cross section equal throughout.</p> <p><math>U = E</math><br/><math>R = \frac{U}{2}</math></p> |   |   |  |
| <p>SAW GUMMING<br/>Saw tooth shaping and sharpening</p>  | 8 to 12                                     | $\frac{1}{2}$ to 1 $\frac{3}{4}$<br>U & E<br>$\frac{1}{4}$ to 1 $\frac{1}{2}$ | $\frac{3}{4}$ to 1 $\frac{1}{4}$                         |
|  <p><b>Type 16. Cone, Curved Side</b><br/><b>Type 17. Cone, Straight Side, Square Tip</b><br/><b>Type 17R. Cone, Straight Side, Round Tip</b> (Tip Radius <math>R = J/2</math>)</p>                |   |   |  |
| <p>SNAGGING<br/>Portable machine, threaded holes</p>   | 1 $\frac{1}{4}$ to 3                        | 2 to 3 $\frac{1}{2}$  | $\frac{3}{8}$ -24UNF-2B<br>to<br>$\frac{5}{8}$ -11UNC-2B |

**Table 1a. (Continued) Standard Shapes and Inch Size Ranges of Grinding Wheels**  
ANSI B74.2-1982

| Applications  | Size Ranges of Principal Dimensions, Inches |            |                                |
|---|---|------------|--------------------------------|
|   | D = Dia.                                    | T = Thick. | H = Hole                       |
|  <p style="text-align: right;"> <b>Type 18. Plug, Square End</b><br/> <b>Type 18R. Plug, Round End <math>R = D/2</math></b> </p>   |   |            |                                |
|  <p style="text-align: right;"> <b>Type 19. Plugs, Conical End, Square Tip</b><br/> <b>Type 19R. Plugs, Conical End, Round Tip</b><br/>                     (Tip Radius <math>R = J/2</math>)                 </p> |   |            |                                |
| SNAGGING<br>Portable machine, threaded holes  | 1 ¼ to 3                                    | 2 to 3 ½   | ⅜-24UNF-2B<br>to<br>⅝-11UNC-2B |
|  <p style="text-align: right;"> <b>Type 20. Wheel, Relieved One Side</b> Peripheral grinding wheel, one side flat, the other side relieved to a flat.                 </p>   |   |            |                                |
| CYLINDRICAL GRINDING<br>Between centers   | 12 to 36                                    | ¾ to 4     | 5 to 20                        |
|  <p style="text-align: right;"> <b>Type 21. Wheel, Relieved Two Sides</b> Both sides relieved to a flat.                 </p>   |   |            |                                |
|  <p style="text-align: right;"> <b>Type 22. Wheel, Relieved One Side, Recessed Other Side</b> One side relieved to a flat.                 </p>  |   |            |                                |
|  <p style="text-align: right;"> <b>Type 23. Wheel, Relieved and Recessed Same Side</b><br/>                     The other side is straight.                 </p>   |   |            |                                |
| CYLINDRICAL GRINDING<br>Between centers, with wheel periphery   | 20 to 36                                    | 2 to 4     | 12 or 20                       |

**Table 1a. (Continued) Standard Shapes and Inch Size Ranges of Grinding Wheels**  
ANSI B74.2-1982

| Applications  | Size Ranges of Principal Dimensions, Inches   |   |                                |
|---|---|---|--------------------------------|
|   | D = Dia.  | T = Thick.  | H = Hole                       |
|    | <p><b>Type 24. Wheel, Relieved and Recessed One Side, Recessed Other Side</b> One side recessed, the other side is relieved to a recess.</p>  |   |                                |
|    | <p><b>Type 25. Wheel, Relieved and Recessed One Side, Relieved Other Side</b> One side relieved to a flat, the other side relieved to a recess.</p>   |   |                                |
|    | <p><b>Type 26. Wheel, Relieved and Recessed Both Sides</b></p>  |   |                                |
| <p>CYLINDRICAL GRINDING<br/>Between centers, with the periphery of the wheel</p>    | 20 to 36  | 2 to 4  | 12 or 20                       |
|    | <p><b>TYPES 27 &amp; 27A. Wheel, Depressed Center</b><br/> <b>27. Portable Grinding:</b> Grinding normally done by contact with work at approx. a 15° angle with face of the wheel.<br/> <b>27A. Cutting-off:</b> Using the periphery as grinding face.</p> |   |                                |
| <p>CUTTING OFF<br/>Reinforced organic bonds only</p>                                | 16 to 30  | $U = E = \frac{5}{32}$ to $\frac{1}{4}$             | 1 or 1 $\frac{1}{2}$           |
| <p>SNAGGING<br/>Portable machine</p>  | 3 to 9  | $U =$ Uniform thick. $\frac{1}{8}$ to $\frac{3}{8}$ | $\frac{3}{8}$ or $\frac{7}{8}$ |
|  | <p><b>Type 28. Wheel, Depressed Center (Saucer Shaped Grinding Face)</b> Grinding at approx. 15° angle with wheel face.</p>   |   |                                |
| <p>SNAGGING<br/>Portable machine</p>  | 7 or 9  | $U =$ Uniform thickness $\frac{1}{4}$               | $\frac{7}{8}$                  |

Throughout table large open-head arrows indicate grinding surfaces.

**Table 1b. Standard Shapes and Metric Size Ranges of Grinding Wheels**  
ANSI B74.2-1982

| Applications  | Size Ranges of Principal Dimensions,<br>Millimeters |                   |                 |
|---|---|-------------------|-----------------|
|   | <i>D</i> = Diam.                                    | <i>T</i> = Thick. | <i>H</i> = Hole |
| <b>Type 1. Straight Wheel<sup>a</sup></b>   |   |                   |                 |
| CUTTING OFF<br>(nonreinforced and reinforced organic bonds only)                          | 150 to 1250   | 0.8 to 10         | 16 to 152.4     |
| CYLINDRICAL GRINDING<br>Between centers   | 300 to 1250   | 20 to 160         | 127 to 508      |
| CYLINDRICAL GRINDING<br>Centerless grinding wheels  | 350 to 750  | 25 to 500         | 127 or 304.8    |
| CYLINDRICAL GRINDING<br>Centerless regulating wheels                                      | 200 to 350  | 25 to 315         | 76.2 to 152.4   |
| INTERNAL GRINDING   | 6 to 100  | 6 to 50           | 2.5 to 25       |
| OFFHAND GRINDING<br>Grinding on the periphery   |   |                   |                 |
| General purpose   | 150 to 900  | 13 to 100         | 20 to 76.2      |
| For wet tool grinding only  | 750 or 900  | 80 or 100         | 508             |
| SAW GUMMING (F-type face)   | 150 to 300  | 6 to 40           | 32              |
| SNAGGING<br>Floor stand machines  | 300 to 600  | 25 to 80          | 32 to 76.2      |
| SNAGGING<br>Floor stand machines(organic bond, wheel speed over 33<br>meters per second)  | 500 to 900  | 50 to 100         | 152.4 or 304.8  |
| SNAGGING<br>Mechanical grinders (organic bond, wheel speed up to 84<br>meters per second) | 600   | 50 to 80          | 304.8           |
| SNAGGING<br>Portable machines   | 80 to 200   | 6 to 25           | 10 to 16        |
| SNAGGING<br>Swing frame machines (organic bond)   | 300 to 600  | 50 to 80          | 88.9 to 304.8   |
| SURFACE GRINDING<br>Horizontal spindle machines   | 150 to 600  | 13 to 160         | 32 to 304.8     |
| TOOL GRINDING<br>Broaches, cutters, mills, reamers, taps, etc.                            | 150 to 250  | 6 to 20           | 32 to 127       |
| <b>Type 2. Cylindrical Wheel<sup>a</sup></b>  |   |                   |                 |
|   |   |                   | <i>W</i> = Wall |
| SURFACE GRINDING<br>Vertical spindle machines   | 200 to 500  | 100 or 125        | 25 to 100       |

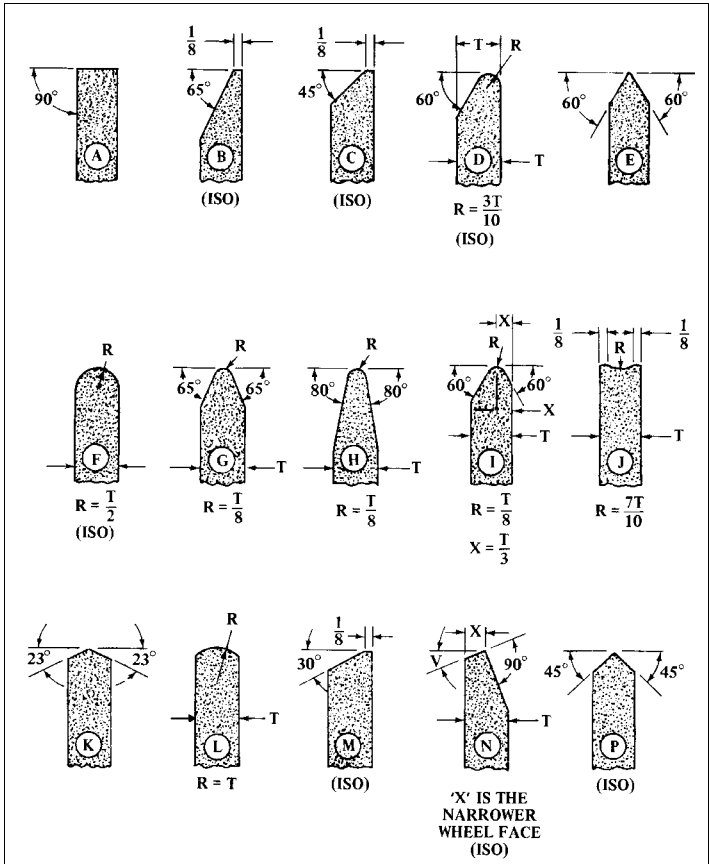
**Table 1b. (Continued) Standard Shapes and Metric Size Ranges of Grinding Wheels  
ANSI B74.2-1982**

| Applications  | Size Ranges of Principal Dimensions,<br>Millimeters |                     |                          |
|---|---|---------------------|--------------------------|
|   | $D$ = Diam.   | $T$ = Thick.        | $H$ = Hole               |
| <b>Type 5. Wheel, recessed one side<sup>a</sup></b>                                     |   |                     |                          |
| CYLINDRICAL GRINDING<br>Between centers   | 300 to 900  | 40 to 100           | 127 or 304.8             |
| CYLINDRICAL GRINDING<br>Centerless regulating wheels                                    | 200 to 350  | 80 to 160           | 76.2 or 127              |
| INTERNAL GRINDING   | 10 to 100   | 10 to 50            | 3.18 to 25               |
| <b>Type 6. Straight-Cup Wheel<sup>a</sup></b>   |   |                     |                          |
|   |   |                     | $W$ = Wall               |
| SNAGGING<br>Portable machines, organic bond only<br>(hole is $\frac{5}{8}$ -11 UNC-2B)  | 100 to 150  | 50                  | 20 to 40                 |
| TOOL GRINDING<br>Broaches, cutters, mills, reamers, taps, etc.<br>(Hole is 13 to 32 mm) | 50 to 150   | 32 to 50            | 8 or 10                  |
| <b>Type 7. Wheel, recessed two sides<sup>a</sup></b>                                    |   |                     |                          |
| CYLINDRICAL GRINDING<br>Between centers   | 300 to 900  | 40 to 100           | 127 or 304.8             |
| CYLINDRICAL GRINDING<br>Centerless regulating wheels                                    | 200 to 350  | 100 to 500          | 76.2 to 152.4            |
| <b>Type 11. Flaring-Cup Wheel<sup>a</sup></b>   |   |                     |                          |
| SNAGGING<br>Portable machines, organic bonds only, threaded hole                        | 100 to 150  | 50                  | $\frac{5}{8}$ -11 UNC-2B |
| TOOL GRINDING<br>Broaches, cutters, mills, reamers, taps, etc.                          | 50 to 125   | 32 to 50            | 13 to 32                 |
| <b>Type 12. Dish Wheel<sup>a</sup></b>  |   |                     |                          |
| TOOL GRINDING<br>Broaches, cutters, mills, reamers, taps, etc.                          | 80 to 200   | 13 or 20            | 13 to 32                 |
| <b>Type 27 and 27A. Wheel, depressed center<sup>a</sup></b>                             |   |                     |                          |
| CUTTING OFF<br>Reinforced organic bonds only  | 400 to 750  | $U = E = 6$         | 25.4 or 38.1             |
| SNAGGING<br>Portable machines   | 80 to 230   | $U = E = 3.2$ to 10 | 9.53 or 22.23            |

<sup>a</sup> See Table 1a for diagrams and descriptions of each wheel type.  
All dimensions in millimeters.



Table 2. Standard Shapes of Grinding Wheel Faces ANSI B74.2-1982



Recommendations, similar in principle, yet somewhat less discriminating have been developed by the Norton Company for *constructional steels*. These materials can be ground either in their original state (soft) or in their after-hardened state (directly or following carburization). Constructional steels must be distinguished from structural steels which are used primarily by the building industry in mill shapes, without or with a minimum of machining.

Constructional steels are either plain carbon or alloy type steels assigned in the AISI-SAE specifications to different groups, according to the predominant types of alloying elements. In the following recommendations no distinction is made because of different compositions since that factor generally, has a minor effect on grinding wheel choice in constructional steels. However, separate recommendations are made for soft (Table 5) and

hardened (Table 6) constructional steels. For the relatively rare instance where the use of a single type of wheel for both soft and hardened steel materials is considered more important than the selection of the best suited types for each condition of the work materials, Table 5 lists "All Around" wheels in its last column.

For applications where cool cutting properties of the wheel are particularly important, Table 6 lists, as a second alternative, porous-type wheels. The sequence of choices as presented in these tables does not necessarily represent a second, or third best; it can also apply to conditions where the first choice did not provide optimum results and by varying slightly the composition of the grinding wheel, as indicated in the subsequent choices, the performance experience of the first choice might be improved.

**Table 3. Classification of Tool Steels by their Relative Grindability**

| Relative Grindability Group  | AISI-SAE Designation of Tool Steels   |
|--|---|
| <p><i>GROUP 1—Any area of work surface</i></p> <p>High grindability tool and die steels<br/>(Grindability index greater than 12)</p>                                       | <p>W1, W2, W5<br/>S1, S2, S4, S5, S6, S7<br/>O1, O2, O6, O7<br/>H10, H11, H12, H13, H14<br/>L2, L6</p>  |
| <p><i>GROUP 2—Small area of work surface<br/>(as found in tools)</i></p> <p>Medium grindability tool and die steels<br/>(Grindability index 3 to 12)</p>                   | <p>H19, H20, H21, H22, H23, H24, H26<br/>P6, P20, P21<br/>T1, T7, T8<br/>M1, M2, M8, M10, M33, M50<br/>D1, D2, D3, D4, D5, D6<br/>A2, A4, A6, A8, A9, A10</p> |
| <p><i>GROUP 3—Small area of work surface<br/>(as found in tools)</i></p> <p>Low grindability tool and die steels<br/>(Grindability index between 1.0 and 3)</p>            | <p>T4, T5, T6, T8<br/>M3, M6, M7, M34, M36, M41, M42, M46,<br/>M48, M52, M62<br/>D2, D5<br/>A11</p>   |
| <p><i>GROUP 4—Large area of work surface<br/>(as found in dies)</i></p> <p>Medium and low grindability tool and die steels<br/>(Grindability index between 1.0 and 12)</p> | <p>All steels found in Groups 2 and 3</p>   |
| <p><i>GROUP 5—Any area of work surface</i></p> <p>Very low grindability tool and die steels<br/>(Grindability index less than 1.0)</p>                                     | <p>D3, D4, D7<br/>M4<br/>A7<br/>T15</p>   |

**Table 4. Grinding Wheel Recommendations for Hardened Tool Steels According to their Grindability**

| Operation  | Wheel or Rim Diameter, Inches                        | First-Choice Specifications  | Second-Choice Specifications                                    |
|--|--|--|---|
| <b>Group 1 Steels</b>  |  |  |   |
| Surfacing<br>Surfacing wheels  | 14 and smaller<br>14 and smaller<br>Over 14          | Wet FA46-I8V<br>Dry FA46-H8V<br>Wet FA36-I8V                                       | SFA46-G12VP<br>FA46-F12VP<br>SFA36-I8V                          |
| Segments or Cylinders  | 1½ rim or less                                       | Wet FA30-H8V   | FA30-F12VP  |
| Cups   | ¾ rim or less  | Wet FA36-H8V   | FA46-F12VP  |
| (for rims wider than 1½ inches, go one grade softer in available specifications) |  |  |   |
| Cutter sharpening<br>Straight wheel  | ...  | Wet FA46-K8V<br>Dry FA46-J8V   | FA60-K8V<br>FA46-H12VP  |
| Dish shape   | ...  | Dry FA60-J8V   | FA60-H12VP  |
| Cup shape  | ...  | Dry FA46-L8V<br>Wet SFA46-L5V  | FA60-H12VP<br>SFA60-L5V   |
| Form tool grinding   | 8 and smaller<br>8 and smaller<br>10 and larger      | Wet FA60-L8V to FA100-M7V<br>Dry FA60-K8V to FA100-L8V<br>Wet FA60-L8V to FA80-M6V |   |
| Cylindrical  | 14 and smaller<br>16 and larger                      | Wet SFA60-L5V<br>Wet SFA60-M5V   | ...<br>...  |
| Centerless   | ...  | Wet SFA60-M5V  | ...   |
| Internal<br>Production grinding  | Under ½<br>½ to 1<br>Over 1 to 3                     | Wet SPA80-N6V<br>Wet SFA60-M5V<br>Wet SFA54-L5V                                    | SFA80-N7V<br>SFA60-M6V<br>SFA54-L6V                             |
| Tool room grinding   | Over 3<br>Under ½<br>½ to 1<br>Over 1 to 3<br>Over 3 | Wet SFA46-L5V<br>Dry FA80-L6V<br>Dry FA70-K7V<br>Dry FA60-J8V<br>Dry FA46-J8V      | SFA46-K5V<br>SFA80-L7V<br>SFA70-K7V<br>FA60-H12VP<br>FA54-H12VP |
| <b>Group 2 Steels</b>  |  |  |   |
| Surfacing<br>Straight wheels   | 14 and smaller<br>14 and smaller<br>Over 14          | Wet FA46-I8V<br>Dry FA46-H8V<br>Wet FA46-H8V                                       | FA46-G12VP<br>FA46-F12VP<br>SFA46-I8V                           |
| Segments or Cylinders  | 1½ rim or less                                       | Wet FA30-G8V   | FA36-E12VP  |
| Cups   | ¾ rim or less  | Wet FA36-H8V   | FA46-F12VP  |
| (for rims wider than 1½ inches, go one grade softer in available specifications) |  |  |   |

**Table 4. (Continued) Grinding Wheel Recommendations for Hardened Tool Steels According to their Grindability**

| Operation  | Wheel or Rim Diameter, Inches                   | First-Choice Specifications  | Second-Choice Specifications          |
|--|---|--|---------------------------------------|
| Cutter sharpening<br>Straight wheel<br><br>Dish shape<br>Cup shape               | ...   | Wet FA46-L5V   | FA60-K8V                              |
|  | ...   | Dry FA46-J8V   | FA60-H12VP                            |
|  | ...   | Dry FA60-J5V   | FA60-G12VP                            |
|  | ...   | Dry FA46-K5V   | FA60-G12VP                            |
|  | ...   | Wet FA46-L5V   | FA60-J8V                              |
| Form tool grinding   | 8 and smaller<br>8 and smaller<br>10 and larger | Wet FA60-K8V to FA120-L8V<br>Dry FA80-K8V to FA150-K8V<br>Wet FA60-K8V to FA120-L8V  |                                       |
| Cylindrical<br><br>Centerless  | 14 and less<br>16 and larger                    | Wet FA60-L5V<br>Wet FA60-K5V   | SFA60-L5V<br>SFA60-K5V                |
|  | ...   | Wet FA60-M5V   | SFA60-M5V                             |
| Internal<br>Production grinding  | Under ½   | Wet FA80-L6V   | SFA80-L6V                             |
|  | ½ to 1  | Wet FA70-K5V   | SFA70-K5V                             |
|  | Over 1 to 3                                     | Wet FA60-J8V   | SFA60-J7V                             |
|  | Over 3  | Wet FA54-J8V   | SFA54-J8V                             |
| Tool room grinding   | Under ½   | Dry FA80-I8V   | SFA80-K7V                             |
|  | ½ to 1  | Dry FA70-J8V   | SFA70-J7V                             |
|  | Over 1 to 3                                     | Dry FA60-I8V   | FA60-G12VP                            |
|  | Over 3  | Dry FA54-I8V   | FA54-G12VP                            |
| Group 3 Steels   |   |  |                                       |
| Surfacing<br>Straight wheels<br><br>Segments or Cylinders<br><br>Cups            | 14 and smaller<br>14 and smaller<br>Over 14     | Wet FA60-I8V<br>Dry FA60-H8V<br>Wet FA60-H8V   | FA60-G12VP<br>FA60-F12VP<br>SFA60-I8V |
|  | 1½ rim or less                                  | Wet FA46-G8V   | FA46-E12VP                            |
|  | ¾ rim or less                                   | Wet FA46-G8V   | FA46-E12VP                            |
| (for rims wider than 1½ inches, go one grade softer in available specifications) |   |  |                                       |
| Cutter grinding<br>Straight wheel<br><br>Dish shape<br>Cup shape                 | ...   | Wet FA46-J8V   | FA60-J8V                              |
|  | ...   | Dry FA46-I8V   | FA46-G12VP                            |
|  | ...   | Dry FA60-H8V   | FA60-F12VP                            |
|  | ...   | Dry FA46-I8V   | FA60-F12VP                            |
|  | ...   | Wet FA46-J8V   | FA60-J8V                              |
| Form tool grinding   | 8 and smaller<br>8 and smaller<br>10 and larger | Wet FA80-K8V to FA150-L9V<br>Dry FA100-J8V to FA150-K8V<br>Wet FA80-J8V to FA150-J8V |                                       |

**Table 4. (Continued) Grinding Wheel Recommendations for Hardened Tool Steels According to their Grindability**

| Operation   | Wheel or Rim Diameter, Inches | First-Choice Specifications | Second-Choice Specifications |
|---|-------------------------------|-----------------------------|------------------------------|
| Cylindrical   | 14 and less                   | Wet FA80-L5V                | SFA80-L6V                    |
|   | 16 and larger                 | Wet FA60-L6V                | SFA60-K5V                    |
| Centerless  | ...                           | Wet FA60-L5V                | SFA60-L5V                    |
| Internal  |                               |                             |                              |
| Production grinding   | Under ½                       | Wet FA90-L6V                | SFA90-L6V                    |
|   | ½ to 1                        | Wet FA80-L6V                | SFA80-L6V                    |
|   | Over 1 to 3                   | Wet FA70-K5V                | SFA70-K5V                    |
|   | Over 3                        | Wet FA60-J5V                | SFA60-J5V                    |
| Tool room grinding  | Under ½                       | Dry FA90-K8V                | SFA90-K7V                    |
|   | ½ to 1                        | Dry FA80-J8V                | SFA80-J7V                    |
|   | Over 1 to 3                   | Dry FA70-I8V                | SFA70-G12VP                  |
|   | Over 3                        | Dry FA60-I8V                | SFA60-G12VP                  |
| Group 4 Steels  |                               |                             |                              |
| Surfacing   |                               |                             |                              |
| Straight wheels   | 14 and smaller                | Wet FA60-I8V                | C60-JV                       |
|   | 14 and smaller                | Wet FA60-H8V                | C60-IV                       |
|   | Over 14                       | Wet FA46-H8V                | C60-HV                       |
| Segments  | 1 ½ rim or less               | Wet FA46-G8V                | C46-HV                       |
| Cylinders   | 1 ½ rim or less               | Wet FA46-G8V                | C60-HV                       |
| Cups  | ¾ rim or less                 | Wet FA46-G6V                | C60-IV                       |
| (for rims wider than 1 ½ inches, go one grade softer in available specifications) |                               |                             |                              |
| Form tool grinding  | 8 and smaller                 | Wet FA60-J8V to FA150-K8V   |                              |
|   | 8 and smaller                 | Dry FA80-I8V to FA180-J8V   |                              |
|   | 10 and larger                 | Wet FA60-J8V to FA150-K8V   |                              |
| Cylindrical   | 14 and less                   | Wet FA80-K8V                | C60-KV                       |
|   | 16 and larger                 | Wet FA60-J8V                | C60-KV                       |
| Internal  |                               |                             |                              |
| Production grinding   | Under ½                       | Wet FA90-L8V                | C90-LV                       |
|   | ½ to 1                        | Wet FA80-K5V                | C80-KV                       |
|   | Over 1 to 3                   | Wet FA70-J8V                | C70-JV                       |
|   | Over 3                        | Wet FA60-I8V                | C60-IV                       |
| Tool room grinding  | Under ½                       | Dry FA90-K8V                | C90-KV                       |
|   | ½ to 1                        | Dry FA80-J8V                | C80-JV                       |
|   | Over 1 to 3                   | Dry FA70-I8V                | C70-IV                       |
|   | Over 3                        | Dry FA60-H8V                | C60-HV                       |

**Table 4. (Continued) Grinding Wheel Recommendations for Hardened Tool Steels According to their Grindability**

| Operation   | Wheel or Rim Diameter, Inches | First-Choice Specifications | Second-Choice Specifications | Third-Choice Specifications |
|---|-------------------------------|-----------------------------|------------------------------|-----------------------------|
| Group 5 Steels  |                               |                             |                              |                             |
| Surfacing   |                               |                             |                              |                             |
| Straight wheels   | 14 and smaller                | Wet SFA60-H8V               | FA60-E12VP                   | C60-IV                      |
|   | 14 and smaller                | Dry SFA80-H8V               | FA80-E12VP                   | C80-HV                      |
| Segments or Cylinders   | Over 14                       | Wet SFA60-H8V               | FA60-E12VP                   | C60-HV                      |
|   | 1 ½ rim or less               | Wet SFA46-G8V               | FA46-E12VP                   | C46-GV                      |
| Cups  | ¾ rim or less                 | Wet SFA60-G8V               | FA60-E12VP                   | C60-GV                      |
| (for rims wider than 1 ½ inches, go one grade softer in available specifications) |                               |                             |                              |                             |
| Cutter grinding   |                               |                             |                              |                             |
| Straight wheels   | ...                           | Wet SFA60-I8V               | SFA60-G12VP                  | ...                         |
|   | ...                           | Dry SFA60-H8V               | SFA80-F12VP                  | ...                         |
| Dish shape  | ...                           | Dry SFA80-H8V               | SFA80-F12VP                  | ...                         |
| Cup shape   | ...                           | Dry SFA60-I8V               | SFA60-G12VP                  | ...                         |
|   | ...                           | Wet SFA60-J8V               | SFA60-H12VP                  | ...                         |
| Form tool grinding  |                               |                             |                              |                             |
|   | 8 and smaller                 | Wet FA80-J8V to FA180-J9V   |                              | ...                         |
|   | 8 and smaller                 | Dry FA100-I8V to FA220-J9V  |                              | ...                         |
|   | 10 and larger                 | Wet FA80-J8V to FA180-J9V   |                              | ...                         |
| Cylindrical   | 14 and less                   | Wet FA80-J8V                | C80-KV                       | FA80-H12VP                  |
| Centerless  | 16 and larger                 | Wet FA80-I8V                | C80-KV                       | FA80-G12VP                  |
|   | ...                           | Wet FA80-J5V                | C80-LV                       | ...                         |
| Internal  |                               |                             |                              |                             |
| Production grinding   | Under ½                       | Wet FA100-L8V               | C90-MV                       | ...                         |
|   | ½ to 1                        | Wet FA90-K8V                | C80-LV                       | ...                         |
|   | Over 1 to 3                   | Wet FA80-J8V                | C70-KV                       | FA80-H12VP                  |
|   | Over 3                        | Wet FA70-I8V                | C60-JV                       | FA70-G12VP                  |
| Tool room grinding  | Under ½                       | Dry FA100-K8V               | C90-KV                       | ...                         |
|   | ½ to 1                        | Dry FA90-J8V                | C80-JV                       | ...                         |
|   | Over 1 to 3                   | Dry FA80-I8V                | C70-IV                       | FA80-G12VP                  |
|   | Over 3                        | Dry FA70-I8V                | C60-IV                       | FA70-G12VP                  |

**Table 5. Grinding Wheel Recommendations for Constructional Steels (Soft)**

| Grinding Operation                    | Wheel or Rim Diameter, Inches | First Choice                 | Alternate Choice (Porous type) | All-Around Wheel     |
|---------------------------------------|-------------------------------|------------------------------|--------------------------------|----------------------|
| Surfacing<br>Straight wheels          | 14 and smaller                | Wet FA46-J8V                 | FA46-H12VP                     | FA46-J8V             |
|                                       | 14 and smaller<br>Over 14     | Dry FA46-I8V<br>Wet FA36-J8V | FA46-H12VP<br>FA36-H12VP       | FA46-I8V<br>FA36-J8V |
| Segments                              | 1½ rim or less                | Wet FA24-H8V                 | FA30-F12VP                     | FA24-H8V             |
| Cylinders                             | 1½ rim or less                | Wet FA24-I8V                 | FA30-G12VP                     | FA24-H8V             |
| Cups                                  | ¾ rim or less                 | Wet FA24-H8V                 | FA30-F12VP                     | FA30-H8V             |
| (for wider rims, go one grade softer) |                               |                              |                                |                      |
| Cylindrical                           | 14 and smaller                | Wet SFA60-M5V                | ...                            | SFA60-L5V            |
| Centerless                            | 16 and larger                 | Wet SFA54-M5V                | ...                            | SFA54-L5V            |
|                                       | ...                           | Wet SFA54-N5V                | ...                            | SFA60-M5V            |
| Internal                              | Under ½                       | Wet SFA60-M5V                | ...                            | SFA80-L6V            |
|                                       | ½ to 1                        | Wet SFA60-L5V                | ...                            | SFA60-K5V            |
|                                       | Over 1 to 3                   | Wet SFA54-K5V                | ...                            | SFA54-J5V            |
|                                       | Over 3                        | Wet SFA46-K5V                | ...                            | SFA46-J5V            |

**Table 6. Grinding Wheel Recommendations for Constructional Steels (Hardened or Carburized)**

| Grinding Operation                    | Wheel or Rim Diameter, Inches | First Choice                 | Alternate Choice (Porous Type) |
|---------------------------------------|-------------------------------|------------------------------|--------------------------------|
| Surfacing<br>Straight wheels          | 14 and smaller                | Wet FA46-I8V                 | FA46-G12VP                     |
|                                       | 14 and smaller<br>Over 14     | Dry FA46-H8V<br>Wet FA36-I8V | FA46-F12VP<br>FA36-G12VP       |
| Segments or Cylinders                 | 1½ rim or less                | Wet FA30-H8V                 | FA36-F12VP                     |
| Cups                                  | ¾ rim or less                 | Wet FA36-H8V                 | FA46-F12VP                     |
| (for wider rims, go one grade softer) |                               |                              |                                |
| Forms and Radius                      | 8 and smaller                 | Wet FA60-L7V to FA100-M8V    |                                |
| Grinding                              | 8 and smaller                 | Dry FA60-K8V to FA100-L8V    |                                |
|                                       | 10 and larger                 | Wet FA60-L7V to FA80-M7V     |                                |
| Cylindrical                           |                               |                              |                                |
| Work diameter                         |                               |                              |                                |
| 1 inch and smaller                    | 14 and smaller                | Wet SFA80-L6V                | ...                            |
| Over 1 inch                           | 14 and smaller                | Wet SFA80-K5V                | ...                            |
| 1 inch and smaller                    | 16 and larger                 | Wet SFA60-L5V                | ...                            |
| Over 1 inch                           | 16 and larger                 | Wet SFA60-L5V                | ...                            |
| Centerless                            | ...                           | Wet SFA80-M6V                | ...                            |
| Internal                              | Under ½                       | Wet SFA80-N6V                | ...                            |
|                                       | ½ to 1                        | Wet SFA60-M5V                | ...                            |
|                                       | Over 1 to 3                   | Wet SFA54-L5V                | ...                            |
|                                       | Over 3                        | Wet SFA46-K5V                | ...                            |
|                                       | Under ½                       | Dry FA80-L6V                 | ...                            |
|                                       | ½ to 1                        | Dry FA70-K8V                 | ...                            |
|                                       | Over 1 to 3                   | Dry FA60-J8V                 | FA60-H12VP                     |
|                                       | Over 3                        | Dry FA46-J8V                 | FA54-H12VP                     |

**Cubic Boron Nitride (CBN) Grinding Wheels.**—Although CBN is not quite as hard, strong, and wear-resistant as a diamond, it is far harder, stronger, and more resistant to wear than aluminum oxide and silicon carbide. As with diamond, CBN materials are available in different types for grinding workpieces of 50 Rc and above, and for superalloys of 35 Rc and harder. Microcrystalline CBN grinding wheels are suitable for grinding mild steels, medium-hard alloy steels, stainless steels, cast irons, and forged steels. Wheels with larger mesh size grains (up to 20/30), now available, provide for higher rates of metal removal.

Special types of CBN are produced for resin, vitrified, and electrodeposited bonds. Wheel standards and nomenclature generally conform to those used for diamond wheels (page 1201), except that the letter **B** instead of **D** is used to denote the type of abrasive. Grinding machines for CBN wheels are generally designed to take full advantage of the ability of CBN to operate at high surface speeds of 9,000–25,000 sfm. CBN is very responsive to changes in grinding conditions, and an increase in wheel speed from 5,000 to 10,000 sfm can increase wheel life by a factor of 6 or more. A change from a water-based coolant to a coolant such as a sulfochlorinated or sulfurized straight grinding oil can increase wheel life by a factor of 10 or more.

Machines designed specifically for use with CBN grinding wheels generally use either electrodeposited wheels or have special truing systems for other CBN bond wheels, and are totally enclosed so they can use oil as a coolant. Numerical control systems are used, often running fully automatically, including loading and unloading. Machines designed for CBN grinding with electrodeposited wheels are extensively used for form and gear grinding, special systems being used to ensure rapid mounting to exact concentricity and truth in running, no truing or dressing being required. CBN wheels can produce workpieces having excellent accuracy and finish, with no truing or dressing for the life of the wheel, even over many hours or days of production grinding of hardened steel components.

Resin-, metal-, and vitrified-bond wheels are used extensively in production grinding, in standard and special machines. Resin-bonded wheels are used widely for dry tool and cutter resharpening on conventional hand-operated tool and cutter grinders. A typical wheel for such work would be designated 11V9 cup type, 100/120 mesh, 75 concentration, with a  $\frac{1}{16}$  or  $\frac{1}{8}$  in. rim section. Special shapes of resin-bonded wheels are used on dedicated machines for cutting tool manufacture. These types of wheels are usually self-dressing, and allow full machine control of the operation without the need for an operator to see, hear, or feel the action.

Metal-bonded CBN wheels are usually somewhat cheaper than those using other types of bond because only a thin layer of abrasive is present. Metal bonding is also used in manufacture of CBN honing stones. Vitrified-bond CBN wheels are a recent innovation, and high-performance bonds are still being developed. These wheels are used for grinding cams, internal diameters, and bearing components, and can be easily redressed.

An important aspect of grinding with CBN and diamond wheels is reduced heating of the workpiece, thought to result from their superior thermal conductivity compared with aluminum oxide, for instance. CBN and diamond grains also are harder, which means that they stay sharp longer than aluminum oxide grains. The superior ability to absorb heat from the workpiece during the grinding process reduces formation of untempered martensite in the ground surface, caused by overheating followed by rapid quenching. At the same time, a higher compressive residual stress is induced in the surface, giving increased fatigue resistance, compared with the tensile stresses found in surfaces ground with aluminum oxide abrasives. Increased fatigue resistance is of particular importance for gear grinding, especially in the root area.

**Variations from General Grinding Wheel Recommendations.**—Recommendations for the selection of grinding wheels are usually based on average values with regard to both operational conditions and process objectives. With variations from such average values,



the composition of the grinding wheels must be adjusted to obtain optimum results. Although it is impossible to list and to appraise all possible variations and to define their effects on the selection of the best suited grinding wheels, some guidance is obtained from experience. The following tabulation indicates the general directions in which the characteristics of the initially selected grinding wheel may have to be altered in order to approach optimum performance. Variations in a sense opposite to those shown will call for wheel characteristic changes in reverse.

| Conditions or Objectives                  | Direction of Change   |
|---|---|
| To increase cutting rate                  | Coarser grain, softer bond, higher porosity   |
| To retain wheel size and/or form          | Finer grain, harder bond  |
| For small or narrow work surface          | Finer grain, harder bond  |
| For larger wheel diameter                 | Coarser grain   |
| To improve finish on work                 | Finer grain, harder bond, or resilient bond   |
| For increased work speed or feed rate     | Harder bond   |
| For increased wheel speed                 | Generally, softer bond, except for high-speed grinding, which requires a harder bond for added wheel strength |
| For interrupted or coarse work surface    | Harder bond   |
| For thin walled parts                     | Softer bond   |
| To reduce load on the machine drive motor | Softer bond   |

**Dressing and Truing Grinding Wheels.**—The perfect grinding wheel operating under ideal conditions will be self sharpening, i.e., as the abrasive grains become dull, they will tend to fracture and be dislodged from the wheel by the grinding forces, thereby exposing new, sharp abrasive grains. Although in precision machine grinding this ideal sometimes may be partially attained, it is almost never attained completely. Usually, the grinding wheel must be dressed and trued after mounting on the precision grinding machine spindle and periodically thereafter.

Dressing may be defined as any operation performed on the face of a grinding wheel that improves its cutting action. Truing is a dressing operation but is more precise, i.e., the face of the wheel may be made parallel to the spindle or made into a radius or special shape. Regularly applied truing is also needed for accurate size control of the work, particularly in automatic grinding. The tools and processes generally used in grinding wheel dressing and truing are listed and described in [Table 1](#).

**Table 1. Tools and Methods for Grinding Wheel Dressing and Truing**

| Designation            | Description   | Application   |
|------------------------|---|---|
| Rotating Hand Dressers | Freely rotating discs, either star-shaped with protruding points or discs with corrugated or twisted perimeter, supported in a fork-type handle, the lugs of which can lean on the tool rest of the grinding machine. | Preferred for bench- or floor-type grinding machines; also for use on heavy portable grinders (snagging grinders) where free-cutting properties of the grinding wheel are primarily sought and the accuracy of the trued profile is not critical. |
| Abrasive Sticks        | Made of silicon carbide grains with a hard bond. Applied directly or supported in a handle. Less frequently abrasive sticks are also made of boron carbide.   | Usually hand held and use limited to smaller-size wheels. Because it also shears the grains of the grinding wheel, or preshaping, prior to final dressing with, e.g., a diamond.  |

**Table 1. (Continued) Tools and Methods for Grinding Wheel Dressing and Truing**

| Designation                              | Description   | Application  |
|--|---|--|
| Abrasive Wheels (Rolls)                  | Silicon carbide grains in a hard vitrified bond are cemented on ball-bearing mounted spindles. Use either as hand tools with handles or rigidly held in a supporting member of the grinding machine. Generally freely rotating; also available with adjustable brake for diamond wheel dressing.                | Preferred for large grinding wheels as a diamond saver, but also for improved control of the dressed surface characteristics. By skewing the abrasive dresser wheel by a few degrees out of parallel with the grinding wheel axis, the basic crushing action is supplemented with wiping and shearing, thus producing the desired degree of wheel surface smoothness.                              |
| Single-Point Diamonds                    | A diamond stone of selected size is mounted in a steel nib of cylindrical shape with or without head, dimensioned to fit the truing spindle of specific grinding machines. Proper orientation and retainment of the diamond point in the setting is an important requirement.                                   | The most widely used tool for dressing and truing grinding wheels in precision grinding. Permits precisely controlled dressing action by regulating infeed and cross feed rate of the truing spindle when the latter is guided by cams or templates for accurate form truing.  |
| Single-Point Form Truing Diamonds        | Selected diamonds having symmetrically located natural edges with precisely lapped diamond points, controlled cone angles and vertex radius, and the axis coinciding with that of the nib.  | Used for truing operations requiring very accurately controlled, and often steeply inclined wheel profiles, such as are needed for thread and gear grinding, where one or more diamond points participate in generating the resulting wheel periphery form. Dependent on specially designed and made truing diamonds and nibs.   |
| Cluster-Type Diamond Dresser             | Several, usually seven, smaller diamond stones are mounted in spaced relationship across the working surface of the nib. In some tools, more than a single layer of such clusters is set at parallel levels in the matrix, the deeper positioned layer becoming active after the preceding layer has worn away. | Intended for straight-face dressing and permits the utilization of smaller, less expensive diamond stones. In use, the holder is canted at a 3° to 10° angle, bringing two to five points into contact with the wheel. The multiple-point contact permits faster cross feed rates during truing than may be used with single-point diamonds for generating a specific degree of wheel-face finish. |
| Impregnated Matrix-Type Diamond Dressers | The operating surface consists of a layer of small, randomly distributed, yet rather uniformly spaced diamonds that are retained in a bond holding the points in an essentially common plane. Supplied either with straight or canted shaft, the latter being used to cancel the tilt of angular truing posts.  | For the truing of wheel surfaces consisting of a single or several flat elements. The nib face should be held tangent to the grinding wheel periphery or parallel with a flat working surface. Offers economic advantages where technically applicable because of using less expensive diamond splinters presented in a manner permitting efficient utilization.                                   |
| Form-Generating Truing Devices           | Swiveling diamond holder post with adjustable pivot location, arm length, and swivel arc, mounted on angularly adjustable cross slides with controlled traverse movement, permits the generation of various straight and circular profile elements, kept in specific mutual locations.                          | Such devices are made in various degrees of complexity for the positionally controlled interrelation of several different profile elements. Limited to regular straight and circular sections, yet offers great flexibility of setup, very accurate adjustment, and unique versatility for handling a large variety of frequently changing profiles.   |

**Table 1. (Continued) Tools and Methods for Grinding Wheel Dressing and Truing**

| Designation                                      | Description   | Application   |
|--|---|---|
| Contour-Duplicating Truing Devices               | The form of a master, called cam or template, shaped to match the profile to be produced on the wheel, or its magnified version, is translated into the path of the diamond point by means of mechanical linkage, a fluid actuator, or a pantograph device.   | Preferred single-point truing method for profiles to be produced in quantities warranting the making of special profile bars or templates. Used also in small- and medium-volume production when the complexity of the profile to be produced excludes alternate methods of form generation.  |
| Grinding Wheel Contouring by Crush Truing        | A hardened steel or carbide roll, which is free to rotate and has the desired form of the workpiece, is fed gradually into the grinding wheel, which runs at slow speed. The roll will, by crushing action, produce its reverse form in the wheel. Crushing produces a free-cutting wheel face with sharp grains. | Requires grinding machines designed for crush truing, having stiff spindle bearings, rigid construction, slow wheel speed for truing, etc. Due to the cost of crush rolls and equipment, the process is used for repetitive work only. It is one of the most efficient methods for precisely duplicating complex wheel profiles that are capable of grinding in the 8-microinch AA range. Applicable for both surface and cylindrical grinding. |
| Rotating Diamond Roll-Type Grinding Wheel Truing | Special rolls made to agree with specific profile specifications have their periphery coated with a large number of uniformly distributed diamonds, held in a matrix into which the individual stones are set by hand (for larger diamonds) or bonded by a plating process (for smaller elements).                | The diamond rolls must be rotated by an air, hydraulic, or electric motor at about one-fourth of the grinding wheel surface speed and in opposite direction to the wheel rotation. Whereas the initial costs are substantially higher than for single-point diamond truing the savings in truing time warrants the method's application in large-volume production of profile-ground components.  |
| Diamond Dressing Blocks                          | Made as flat blocks for straight wheel surfaces, are also available for radius dressing and profile truing. The working surface consists of a layer of electroplated diamond grains, uniformly distributed and capable of truing even closely toleranced profiles.  | For straight wheels, dressing blocks can reduce dressing time and offer easy installation on surface grinders, where the blocks mount on the magnetic plate. Recommended for small- and medium-volume production for truing intricate profiles on regular surface grinders, because the higher pressure developed in crush dressing is avoided.   |

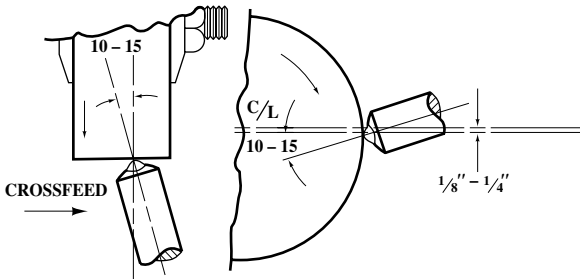
**Guidelines for Truing and Dressing with Single-Point Diamonds.**—The diamond nib should be canted at an angle of 10 to 15 degrees in the direction of the wheel rotation and also, if possible, by the same amount in the direction of the cross feed traverse during the truing (see diagram). The dragging effect resulting from this “angling,” combined with the occasional rotation of the diamond nib in its holder, will prolong the diamond life by limiting the extent of wear facets and will also tend to produce a pyramid shape of the diamond tip. The diamond may also be set to contact the wheel at about  $\frac{1}{8}$  to  $\frac{1}{4}$  inch below its centerline.

*Depth of Cut:* This amount should not exceed 0.001 inch per pass for general work, and will have to be reduced to 0.0002 to 0.0004 inch per pass for wheels with fine grains used for precise finishing work.

*Diamond crossfeed rate:* This value may be varied to some extent depending on the required wheel surface: faster crossfeed for free cutting, and slower crossfeed for produc-

ing fine finishes. Such variations, however, must always stay within the limits set by the grain size of the wheel. Thus, the advance rate of the truing diamond per wheel revolution should not exceed the diameter of a grain or be less than half of that rate. Consequently, the diamond crossfeed must be slower for a large wheel than for a smaller wheel having the same grain size number.

Typical crossfeed values for frequently used grain sizes are given in Table 2.



**Table 2. Typical Diamond Truing and Crossfeeds**

|                               |             |             |              |             |
|-------------------------------|-------------|-------------|--------------|-------------|
| Grain Size                    | 30          | 36          | 46           | 50          |
| Crossfeed per Wheel Rev., in. | 0.014–0.024 | 0.012–0.019 | 0.008–0.014  | 0.007–0.012 |
| Grain Size                    | 60          | 80          | 120          | ...         |
| Crossfeed per Wheel Rev., in. | 0.006–0.010 | 0.004–0.007 | 0.0025–0.004 | ...         |

These values can be easily converted into the more conveniently used inch-per-minute units, simply by multiplying them by the rpm of the grinding wheel.

*Example:* For a 20-inch diameter wheel, Grain No. 46, running at 1200 rpm: Crossfeed rate for roughing-cut truing—approximately 17 ipm, for finishing-cut truing—approximately 10 ipm

*Coolant* should be applied before the diamond comes into contact with the wheel and must be continued in generous supply while truing.

*The speed of the grinding wheel* should be at the regular grinding rate, or not much lower. For that reason, the feed wheels of centerless grinding machines usually have an additional speed rate higher than functionally needed, that speed being provided for wheel truing only.

*The initial approach of the diamond* to the wheel surface must be carried out carefully to prevent sudden contact with the diamond, resulting in penetration in excess of the selected depth of cut. It should be noted that the highest point of a worn wheel is often in its center portion and not at the edge from which the crossfeed of the diamond starts.

*The general conditions* of the truing device are important for best truing results and for assuring extended diamond life. A rigid truing spindle, well-seated diamond nib, and firmly set diamond point are mandatory. Sensitive infeed and smooth traverse movement at uniform speed also must be maintained.

*Resetting of the diamond point:* Never let the diamond point wear to a degree where the grinding wheel is in contact with the steel nib. Such contact can damage the setting of the diamond point and result in its loss. Expert resetting of a worn diamond can repeatedly add to its useful life, even when applied to lighter work because of reduced size.

**Size Selection Guide for Single-Point Truing Diamonds.**—There are no rigid rules for determining the proper size of the diamond for any particular truing application because of the very large number of factors affecting that choice. Several of these factors are related to the condition, particularly the rigidity, of the grinding machine and truing device, as well as to such characteristics of the diamond itself as purity, crystalline structure, etc. Although these factors are difficult to evaluate in a generally applicable manner, the expected effects of several other conditions can be appraised and should be considered in the selection of the proper diamond size.

The recommended sizes in [Table 3](#) must be considered as informative only and as representing minimum values for generally favorable conditions. Factors calling for larger diamond sizes than listed are the following:

Silicon carbide wheels ([Table 3](#) refers to aluminum oxide wheels)

Dry truing

Grain sizes coarser than No. 46

Bonds harder than M

Wheel speed substantially higher than 6500 sfm.

It is advisable to consider any single or pair of these factors as justifying the selection of one size larger diamond. As an example: for truing an SiC wheel, with grain size No. 36 and hardness P, select a diamond that is two sizes larger than that shown in [Table 3](#) for the wheel size in use.

**Table 3. Recommended Minimum Sizes for Single-Point Truing Diamonds**

| Diamond Size<br>in Carats <sup>a</sup> | Index Number<br>(Wheel Dia. × Width<br>in Inches) | Examples of Max. Grinding Wheel<br>Dimensions |       |
|--|---|---|-------|
|  |   | Diameter                                      | Width |
| 0.25                                   | 3   | 4   | 0.75  |
| 0.35                                   | 6   | 6   | 1     |
| 0.50                                   | 10  | 8   | 1.25  |
| 0.60                                   | 15  | 10  | 1.50  |
| 0.75                                   | 21  | 12  | 1.75  |
| 1.00                                   | 30  | 12  | 2.50  |
| 1.25                                   | 48  | 14  | 3.50  |
| 1.50                                   | 65  | 16  | 4.00  |
| 1.75                                   | 80  | 20  | 4.00  |
| 2.00                                   | 100   | 20  | 5.00  |
| 2.50                                   | 150   | 24  | 6.00  |
| 3.00                                   | 200   | 24  | 8.00  |
| 3.50                                   | 260   | 30  | 8.00  |
| 4.00                                   | 350   | 36  | 10.00 |

<sup>a</sup> One carat equals 0.2 gram.

Single-point diamonds are available as loose stones, but are preferably procured from specialized manufacturers supplying the diamonds set into steel nibs. Expert setting, comprising both the optimum orientation of the stone and its firm retainment, is mandatory for assuring adequate diamond life and satisfactory truing. Because the holding devices for truing diamonds are not yet standardized, the required nib dimensions vary depending on the make and type of different grinding machines. Some nibs are made with angular heads, usually hexagonal, to permit occasional rotation of the nib either manually, with a wrench, or automatically.

### Diamond Wheels

**Diamond Wheels.**—A diamond wheel is a special type of grinding wheel in which the abrasive elements are diamond grains held in a bond and applied to form a layer on the operating face of a non-abrasive core. Diamond wheels are used for grinding very hard or highly abrasive materials. Primary applications are the grinding of cemented carbides, such as the sharpening of carbide cutting tools; the grinding of glass, ceramics, asbestos, and cement products; and the cutting and slicing of germanium and silicon.

**Shapes of Diamond Wheels.**—The industry-wide accepted Standard (ANSI B74.3-1974) specifies ten basic diamond wheel core shapes which are shown in Table 1 with the applicable designation symbols. The applied diamond abrasive layer may have different cross-sectional shapes. Those standardized are shown in Table 2. The third aspect which is standardized is the location of the diamond section on the wheel as shown by the diagrams in Table 3. Finally, modifications of the general core shape together with pertinent designation letters are given in Table 4.

The characteristics of the wheel shape listed in these four tables make up the components of the standard designation symbol for diamond wheel shapes. An example of that symbol with arbitrarily selected components is shown in Fig. 1.

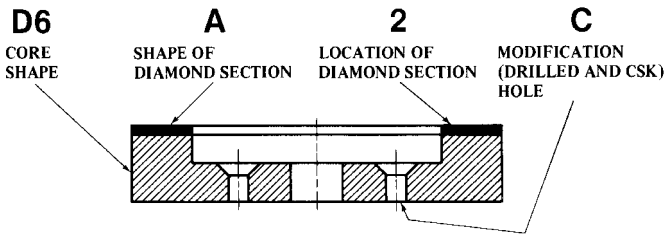


Fig. 1. A Typical Diamond Wheel Shape Designation Symbol

An explanation of these components is as follows:

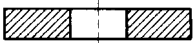
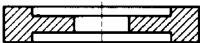

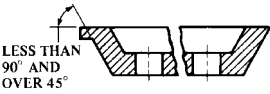

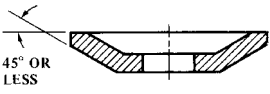
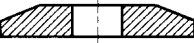
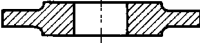
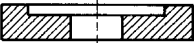
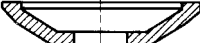
**Basic Core Shape:** This portion of the symbol indicates the basic shape of the core on which the diamond abrasive section is mounted. The shape is actually designated by a number. The various core shapes and their designations are given in Table 1.

**Diamond Cross-Section Shape:** This, the second component, consisting of one or two letters, denotes the cross-sectional shape of the diamond abrasive section. The various shapes and their corresponding letter designations are given in Table 2.






























**Diamond Section Location:** The third component of the symbol consists of a number which gives the location of the diamond section, i.e., periphery, side, corner, etc. An explanation of these numbers is shown in Table 3.

**Modification:** The fourth component of the symbol is a letter designating some modification, such as drilled and counterbored holes for mounting or special relieving of diamond section or core. This modification position of the symbol is used only when required. The modifications and their designations are given in Table 4.

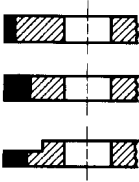
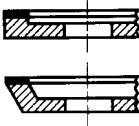


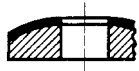
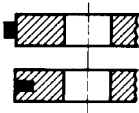

**Table 1. Diamond Wheel Core Shapes and Designations** *ANSI B74.3-1974*

|   |   |   |    |
|---|---|---|----|
|  | 1 |  | 9  |
|  | 2 |  | 11 |
|  | 3 |  | 12 |
|  | 4 |  | 14 |
|  | 6 |  | 15 |

**Table 2. Diamond Cross-sections and Designations**  
*ANSI B74.3-1974*


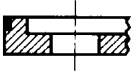

|  |    |   |    |   |    |   |    |   |    |   |   |
|--|----|---|----|---|----|---|----|---|----|---|---|
|   | A  |    | CH |    | ER |    | GN |    | LL |    | S |
|  | AH |  | D  |  | ET |  | H  |  | M  |  | U |
|  | B  |  | DD |  | F  |  | J  |  | P  |  | V |
|  | BT |  | E  |  | FF |  | K  |  | Q  |  | Y |
|  | C  |  | EE |  | G  |  | L  |  | QQ |   |   |

**Table 3. Designations for Location of Diamond Section on Diamond Wheel** *ANSI B74.3-1974*

| Designation No. and Location | Description   | Illustration  |
|------------------------------|---|---|
| 1 — Periphery                | The diamond section shall be placed on the periphery of the core and shall extend the full thickness of the wheel. The axial length of this section may be greater than, equal to, or less than the depth of diamond, measured radially. A hub or hubs shall not be considered as part of the wheel thickness for this definition.                |    |
| 2 — Side                     | The diamond section shall be placed on the side of the wheel and the length of the diamond section shall extend from the periphery toward the center. It may or may not include the entire side and shall be greater than the diamond depth measured axially. It shall be on that side of the wheel which is commonly used for grinding purposes. |    |
| 3 — Both Sides               | The diamond sections shall be placed on both sides of the wheel and shall extend from the periphery toward the center. They may or may not include the entire sides, and the radial length of the diamond section shall exceed the axial diamond depth.   |    |
| 4 — Inside Bevel or Arc      | This designation shall apply to the general wheel types 2, 6, 11, 12, and 15 and shall locate the diamond section on the side wall. This wall shall have an angle or arc extending from a higher point at the wheel periphery to a lower point toward the wheel center.   |   |
| 5 — Outside Bevel or Arc     | This designation shall apply to the general wheel types, 2, 6, 11, and 15 and shall locate the diamond section on the side wall. This wall shall have an angle or arc extending from a lower point at the wheel periphery to a higher point toward the wheel center.  |  |
| 6 — Part of Periphery        | The diamond section shall be placed on the periphery of the core but shall not extend the full thickness of the wheel and shall not reach to either side.   |  |
| 7 — Part of Side             | The diamond section shall be placed on the side of the core and shall not extend to the wheel periphery. It may or may not extend to the center.  |  |



**Table 3. (Continued) Designations for Location of Diamond Section on Diamond Wheel ANSI B74.3-1974**

| Designation No. and Location | Description  | Illustration  |
|------------------------------|--|---|
| 8 — Throughout               | Designates wheels of solid diamond abrasive section without cores.   |  |
| 9 — Corner                   | Designates a location which would commonly be considered to be on the periphery except that the diamond section shall be on the corner but shall not extend to the other corner. |  |
| 10 — Annular                 | Designates a location of the diamond abrasive section on the inner annular surface of the wheel.   |  |

**Composition of Diamond and Cubic Boron Nitride Wheels.**—According to American National Standard ANSI B74.13-1990, a series of symbols is used to designate the composition of these wheels. An example is shown below.

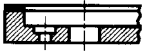
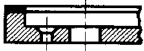
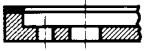
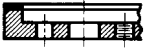






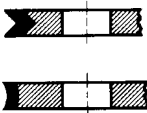
| Prefix   | Abrasive | Grain Size | Grade    | Concentration | Bond Type | Bond Modification | Depth of Abrasive | Manufacturer's Identification Symbol |
|----------|----------|------------|----------|---------------|-----------|-------------------|-------------------|--------------------------------------|
| <b>M</b> | <b>D</b> | <b>120</b> | <b>R</b> | <b>100</b>    | <b>B</b>  | <b>56</b>         | $\frac{1}{8}$     | <b>*</b>                             |

Fig. 2. Designation Symbols for Composition of Diamond and Cubic Boron Nitride Wheels

The meaning of each symbol is indicated by the following list:

- 1) *Prefix*: The prefix is a manufacturer's symbol indicating the exact kind of abrasive. Its use is optional.
- 2) *Abrasive Type*: The letter (B) is used for cubic boron nitride and (D) for diamond.
- 3) *Grain Size*: The grain sizes commonly used and varying from coarse to very fine are indicated by the following numbers: 8, 10, 12, 14, 16, 20, 24, 30, 36, 46, 54, 60, 70, 80, 90, 100, 120, 150, 180, and 220. The following additional sizes are used occasionally: 240, 280, 320, 400, 500, and 600. The wheel manufacturer may add to the regular grain number an additional symbol to indicate a special grain combination.
- 4) *Grade*: Grades are indicated by letters of the alphabet from A to Z in all bonds or processes. Wheel grades from A to Z range from soft to hard.
- 5) *Concentration*: The concentration symbol is a manufacturer's designation. It may be a number or a symbol.
- 6) *Bond*: Bonds are indicated by the following letters: B, resinoid; V, vitrified; M, metal.
- 7) *Bond Modification*: Within each bond type a manufacturer may have modifications to tailor the bond to a specific application. These modifications may be identified by either letters or numbers.
- 8) *Abrasive Depth*: Abrasive section depth, in inches or millimeters (inches illustrated), is indicated by a number or letter which is the amount of total dimensional wear a user may expect from the abrasive portion of the product. Most diamond and CBN wheels are made with a depth of coating on the order of  $\frac{1}{16}$  in.,  $\frac{1}{8}$  in., or more as specified. In some cases the diamond is applied in thinner layers, as thin as one thickness of diamond grains. The L is included in the marking system to identify a layered type product.
- 9) *Manufacturer's Identification Symbol*: The use of this symbol is optional.

**Table 4. Designation Letters for Modifications of Diamond Wheels**  
ANSI B74.3-1974

| Designation Letter <sup>a</sup> | Description   | Illustration  |
|---------------------------------|---|---|
| B — Drilled and Counterbored    | Holes drilled and counterbored in core.   |    |
| C — Drilled and Countersunk     | Holes drilled and countersunk in core.  |    |
| H — Plain Hole                  | Straight hole drilled in core.  |    |
| M — Holes Plain and Threaded    | Mixed holes, some plain, some threaded, are in core.  |    |
| P — Relieved One Side           | Core relieved on one side of wheel. Thickness of core is less than wheel thickness.   |    |
| R — Relieved Two Sides          | Core relieved on both sides of wheel. Thickness of core is less than wheel thickness.   |    |
| S — Segmented-Diamond Section   | Wheel has segmental diamond section mounted on core. (Clearance between segments has no bearing on definition.)   |   |
| SS — Segmental and Slotted      | Wheel has separated segments mounted on a slotted core.   |  |
| T — Threaded Holes              | Threaded holes are in core.   |  |
| Q — Diamond Inserted            | Three surfaces of the diamond section are partially or completely enclosed by the core.   |  |
| V — Diamond Inverted            | Any diamond cross section, which is mounted on the core so that the interior point of any angle, or the concave side of any arc, is exposed shall be considered inverted.<br><i>Exception:</i> Diamond cross section AH shall be placed on the core with the concave side of the arc exposed. |  |

<sup>a</sup> Y — Diamond Inserted and Inverted. See definitions for Q and V.

**The Selection of Diamond Wheels.**—Two general aspects must be defined: (a) The shape of the wheel, also referred to as the basic wheel type and (b) The specification of the abrasive portion.

**Table 5. General Diamond Wheel Recommendations for Wheel Type and Abrasive Specification**

| Typical Applications or Operation   | Basic Wheel Type | Abrasive Specification  |
|---|------------------|---|
| Single Point Tools (offhand grinding)   | D6A2C            | <i>Rough:</i> MD100-N100-B $\frac{1}{8}$<br><i>Finish:</i> MD220-P75-B $\frac{1}{8}$  |
| Single Point Tools (machine ground)   | D6A2H            | <i>Rough:</i> MD180-J100-B $\frac{1}{8}$<br><i>Finish:</i> MD320-L75-B $\frac{1}{8}$  |
| Chip Breakers   | D1A1             | MD150-R100-B $\frac{1}{8}$  |
| Multitooth Tools and Cutters (face mills, end mills, reamers, broaches, etc.) | D11V9            | <i>Rough:</i> MD100-R100-B $\frac{1}{8}$<br><i>Combination:</i> MD150-R100-B $\frac{1}{8}$<br><i>Finish:</i> MD220-R100-B $\frac{1}{8}$ |
| Sharpening and Backing off  |                  |   |
| Fluting   |                  | D12A2   |
| Saw Sharpening  | D12A2            | MD180-R100-B $\frac{1}{8}$  |
| Surface Grinding (horizontal spindle)   | D1A1             | <i>Rough:</i> MD120-N100-B $\frac{1}{8}$<br><i>Finish:</i> MD240-P100-B $\frac{1}{8}$   |
| Surface Grinding (vertical spindle)   | D2A2T            | MD80-R75-B $\frac{1}{8}$  |
| Cylindrical or Centertype Grinding  | D1A1             | MD120-P100-B $\frac{1}{8}$  |
| Internal Grinding   | D1A1             | MD150-N100-B $\frac{1}{8}$  |
| Slotting and Cutoff   | D1A1R            | MD150-R100-B $\frac{1}{4}$  |
| Lapping   | Disc             | MD400-L50-B $\frac{1}{16}$  |
| Hand Honing   | DH1, DH2         | <i>Rough:</i> MD220-B $\frac{1}{16}$<br><i>Finish:</i> MD320-B $\frac{1}{6}$  |

General recommendations for the dry grinding, with resin bond diamond wheels, of most grades of cemented carbides of average surface to ordinary finishes at normal rates of metal removal with average size wheels, as published by Cincinnati Milacron, are listed in [Table 5](#).

A further set of variables are *the dimensions of the wheel*, which must be adapted to the available grinding machine and, in some cases, to the configuration of the work.

The general abrasive specifications in [Table 5](#) may be modified to suit operating conditions by the following suggestions:

Use softer wheel grades for harder grades of carbides, for grinding larger areas or larger or wider wheel faces.

Use harder wheel grades for softer grades of carbides, for grinding smaller areas, for using smaller and narrower face wheels and for light cuts.

Use fine grit sizes for harder grades of carbides and to obtain better finishes.

Use coarser grit sizes for softer grades of carbides and for roughing cuts.

Use higher diamond concentration for harder grades of carbides, for larger diameter or wider face wheels, for heavier cuts, and for obtaining better finish.

**Guidelines for the Handling and Operation of Diamond Wheels.**—Grinding machines used for grinding with diamond wheels should be of the precision type, in good service condition, with true running spindles and smooth slide movements.

*Mounting of Diamond Wheels:* Wheel mounts should be used which permit the precise centering of the wheel, resulting in a runout of less than 0.001 inch axially and 0.0005 inch radially. These conditions should be checked with a 0.0001-inch type dial indicator. Once mounted and centered, the diamond wheel should be retained on its mount and stored in that condition when temporarily removed from the machine.

*Truing and Dressing:* Resinoid bonded diamond wheels seldom require dressing, but when necessary a soft silicon carbide stick may be hand-held against the wheel. Peripheral and cup type wheels may be sharpened by grinding the cutting face with a 60 to 80 grit silicon carbide wheel. This can be done with the diamond wheel mounted on the spindle of the machine, and with the silicon carbide wheel driven at a relatively slow speed by a specially designed table-mounted grinder or by a small table-mounted tool post grinder. The diamond wheel can be mounted on a special arbor and ground on a lathe with a tool post grinder; peripheral wheels can be ground on a cylindrical grinder or with a special brake-controlled truing device with the wheel mounted on the machine on which it is used. Cup and face type wheels are often lapped on a cast iron or glass plate using a 100 grit silicon carbide abrasive. Care must be used to lap the face parallel to the back, otherwise they must be ground to restore parallelism. Peripheral diamond wheels can be trued and dressed by grinding a silicon carbide block or a special diamond impregnated bronze block in a manner similar to surface grinding. Conventional diamonds must not be used for truing and dressing diamond wheels.

**Speeds and Feeds in Diamond Grinding.**—General recommendations are as follows:

*Wheel Speeds:* The generally recommended wheel speeds for diamond grinding are in the range of 5000 to 6000 surface feet per minute, with this upper limit as a maximum to avoid harmful "overspeeding." Exceptions from that general rule are diamond wheels with coarse grains and high concentration (100 per cent) where the wheel wear in dry surface grinding can be reduced by lowering the speed to 2500–3000 sfpm. However, this lower speed range can cause rapid wheel breakdown in finer grit wheels or in those with reduced diamond concentration.

*Work Speeds:* In diamond grinding, work rotation and table traverse are usually established by experience, adjusting these values to the selected infeed so as to avoid excessive wheel wear.

*Infeed per Pass:* Often referred to as downfeed and usually a function of the grit size of the wheel. The following are general values which may be increased for raising the productivity, or lowered to improve finish or to reduce wheel wear.

| Wheel Grit Size Range | Infeed per Pass |
|-----------------------|-----------------|
| 100 to 120            | 0.001 inch      |
| 150 to 220            | 0.0005 inch     |
| 250 and finer         | 0.00025 inch    |

### Grinding Wheel Safety

**Safety in Operating Grinding Wheels.**—Grinding wheels, although capable of exceptional cutting performance due to hardness and wear resistance, are prone to damage caused by improper handling and operation. Vitrified wheels, comprising the major part of grinding wheels used in industry, are held together by an inorganic bond which is actually

a type of pottery product and therefore brittle and breakable. Although most of the organic bond types are somewhat more resistant to shocks, it must be realized that all grinding wheels are conglomerates of individual grains joined by a bond material whose strength is limited by the need of releasing the dull, abrasive grains during use.

It must also be understood that during the grinding process very substantial forces act on the grinding wheel, including the centrifugal force due to rotation, the grinding forces resulting from the resistance of the work material, and shocks caused by sudden contact with the work. To be able to resist these forces, the grinding wheel must have a substantial minimum strength throughout that is well beyond that needed to hold the wheel together under static conditions.

Finally, a damaged grinding wheel can disintegrate during grinding, liberating dormant forces which normally are constrained by the resistance of the bond, thus presenting great hazards to both operator and equipment.

To avoid breakage of the operating wheel and, should such a mishap occur, to prevent damage or injury, specific precautions must be applied. These safeguards have been formulated into rules and regulations and are set forth in the American National Standard ANSI B7.1-1988, entitled the American National Standard Safety Requirements for the Use, Care, and Protection of Abrasive Wheels.

**Handling, Storage and Inspection.**—Grinding wheels should be hand carried, or transported, with proper support, by truck or conveyor. A grinding wheel must not be rolled around on its periphery.

The storage area, positioned not far from the location of the grinding machines, should be free from excessive temperature variations and humidity. Specially built racks are recommended on which the smaller or thin wheels are stacked lying on their sides and the larger wheels in an upright position on two-point cradle supports consisting of appropriately spaced wooden bars. Partitions should separate either the individual wheels, or a small group of identical wheels. Good accessibility to the stored wheels reduces the need of undesirable handling.

Inspection will primarily be directed at detecting visible damage, mostly originating from handling and shipping. Cracks which are not obvious can usually be detected by “ring testing,” which consists of suspending the wheel from its hole and tapping it with a non-metallic implement. Heavy wheels may be allowed to rest vertically on a clean, hard floor while performing this test. A clear metallic tone, a “ring”, should be heard; a dead sound being indicative of a possible crack or cracks in the wheel.

**Machine Conditions.**—The general design of the grinding machines must ensure safe operation under normal conditions. The bearings and grinding wheel spindle must be dimensioned to withstand the expected forces and ample driving power should be provided to ensure maintenance of the rated spindle speed. For the protection of the operator, stationary machines used for dry grinding should have a provision made for connection to an exhaust system and when used for off-hand grinding, a work support must be available.

Wheel guards are particularly important protection elements and their material specifications, wall thicknesses and construction principles should agree with the Standard's specifications. The exposure of the wheel should be just enough to avoid interference with the grinding operation. The need for access of the work to the grinding wheel will define the boundary of guard opening, particularly in the direction of the operator.

**Grinding Wheel Mounting.**—The mass and speed of the operating grinding wheel makes it particularly sensitive to imbalance. Vibrations that result from such conditions are harmful to the machine, particularly the spindle bearings, and they also affect the ground surface, i.e., wheel imbalance causes chatter marks and interferes with size control. Grinding wheels are shipped from the manufacturer's plant in a balanced condition, but retaining the balanced state after mounting the wheel is quite uncertain. Balancing of the mounted wheel is thus required, and is particularly important for medium and large size

wheels, as well as for producing accurate and smooth surfaces. The most common way of balancing mounted wheels is by using balancing flanges with adjustable weights. The wheel and balancing flanges are mounted on a short balancing arbor, the two concentric and round stub ends of which are supported in a balancing stand.

Such stands are of two types: 1) the parallel straight-edged, which must be set up precisely level; and 2) the disk type having two pairs of ball bearing mounted overlapping disks, which form a V for containing the arbor ends without hindering the free rotation of the wheel mounted on that arbor.

The wheel will then rotate only when it is out of balance and its heavy spot is not in the lowest position. Rotating the wheel by hand to different positions will move the heavy spot, should such exist, from the bottom to a higher location where it can reveal its presence by causing the wheel to turn. Having detected the presence and location of the heavy spot, its effect can be cancelled by displacing the weights in the circular groove of the flange until a balanced condition is accomplished.

Flanges are commonly used means for holding grinding wheels on the machine spindle. For that purpose, the wheel can either be mounted directly through its hole or by means of a sleeve which slips over a tapered section of the machine spindle. Either way, the flanges must be of equal diameter, usually not less than one-third of the new wheel's diameter. The purpose is to securely hold the wheel between the flanges without interfering with the grinding operation even when the wheel becomes worn down to the point where it is ready to be discarded. Blotters or flange facings of compressible material should cover the entire contact area of the flanges.

One of the flanges is usually fixed while the other is loose and can be removed and adjusted along the machine spindle. The movable flange is held against the mounted grinding wheel by means of a nut engaging a threaded section of the machine spindle. The sense of that thread should be such that the nut will tend to tighten as the spindle revolves. In other words, to remove the nut, it must be turned in the direction that the spindle revolves when the wheel is in operation.

**Safe Operating Speeds.**—Safe grinding processes are predicated on the proper use of the previously discussed equipment and procedures, and are greatly dependent on the application of adequate operating speeds.

The Standard establishes maximum speeds at which grinding wheels can be operated, assigning the various types of wheels to several classification groups. Different values are listed according to bond type and to wheel strength, distinguishing between low, medium and high strength wheels.

For the purpose of general information, the accompanying table shows an abbreviated version of the Standard's specification. However, for the governing limits, the authoritative source is the manufacturer's tag on the wheel which, particularly for wheels of lower strength, might specify speeds below those of the table.

All grinding wheels of 6 inches or greater diameter must be test run in the wheel manufacturer's plant at a speed that for all wheels having operating speeds in excess of 5000 sfpm is 1.5 times the maximum speed marked on the tag of the wheel.

The table shows the permissible wheel speeds in surface feet per minute (sfpm) units, whereas the tags on the grinding wheels state, for the convenience of the user, the maximum operating speed in revolutions per minute (rpm). The sfpm unit has the advantage of remaining valid for worn wheels whose rotational speed may be increased to the applicable sfpm value. The conversion from either one to the other of these two kinds of units is a matter of simple calculation using the formulas:

$$\text{sfpm} = \text{rpm} \times \frac{D}{12} \times \pi \quad \text{or} \quad \text{rpm} = \frac{\text{sfpm} \times 12}{D \times \pi}$$

where  $D$  = maximum diameter of the grinding wheel, in inches. **Table 2**, showing the conversion values from surface speed into rotational speed, can be used for the direct reading of the rpm values corresponding to several different wheel diameters and surface speeds.

**Special Speeds:** Continuing progress in grinding methods has led to the recognition of certain advantages that can result from operating grinding wheels above, sometimes even higher than twice, the speeds considered earlier as the safe limits of grinding wheel operations. Advantages from the application of high speed grinding are limited to specific processes, but the Standard admits, and offers code regulations for the use of wheels at special high speeds. These regulations define the structural requirements of the grinding machine and the responsibilities of the grinding wheel manufacturers, as well as of the users. High speed grinding should not be applied unless the machines, particularly guards, spindle assemblies, and drive motors, are suitable for such methods. Also, appropriate grinding wheels expressly made for special high speeds must be used and, of course, the maximum operating speeds indicated on the wheel's tag must never be exceeded.

**Portable Grinders.**—The above discussed rules and regulations, devised primarily for stationary grinding machines apply also to portable grinders. In addition, the details of various other regulations, specially applicable to different types of portable grinders are discussed in the Standard, which should be consulted, particularly for safe applications of portable grinding machines.

**Table 1. Maximum Peripheral Speeds for Grinding Wheels  
Based on ANSI B7.1–1988**

| Classification No. | Types of Wheels <sup>a</sup>  | Maximum Operating Speeds, sfpm,<br>Depending on Strength of Bond |                              |
|--------------------|---|--|------------------------------|
|                    |   | Inorganic Bonds  | Organic Bonds                |
| 1                  | Straight wheels — Type 1, except classifications 6, 7, 9, 10, 11, and 12 below<br>Taper Side Wheels — Type 4 <sup>b</sup><br>Types 5, 7, 20, 21, 22, 23, 24, 25, 26<br>Dish wheels — Type 12<br>Saucer wheels — Type 13<br>Cones and plugs — Types 16, 17, 18, 19 | 5,500 to 6,500   | 6,500 to 9,500               |
| 2                  | Cylinder wheels — Type 2<br>Segments  | 5,000 to 6,000   | 5,000 to 7,000               |
| 3                  | Cup shape tool grinding wheels — Types 6 and 11 (for fixed base machines)   | 4,500 to 6,000   | 6,000 to 8,500               |
| 4                  | Cup shape snagging wheels — Types 6 and 11 (for portable machines)  | 4,500 to 6,500   | 6,000 to 9,500               |
| 5                  | Abrasive disks  | 5,500 to 6,500   | 5,500 to 8,500               |
| 6                  | Reinforced wheels — except cutting-off wheels (depending on diameter and thickness)   | ...  | 9,500 to 16,000              |
| 7                  | Type 1 wheels for bench and pedestal grinders, Types 1 and 5 also in certain sizes for surface grinders   | 5,500 to 7,550   | 6,500 to 9,500               |
| 8                  | Diamond and cubic boron nitride wheels<br>Metal bond<br>Steel centered cutting off  | to 6,500<br>to 12,000<br>to 16,000                               | to 9,500<br>...<br>to 16,000 |
| 9                  | Cutting-off wheels — Larger than 16-inch diameter (incl. reinforced organic)  | ...  | 9,500 to 14,200              |
| 10                 | Cutting-off wheels — 16-inch diameter and smaller (incl. reinforced organic)  | ...  | 9,500 to 16,000              |
| 11                 | Thread and flute grinding wheels  | 8,000 to 12,000  | 8,000 to 12,000              |
| 12                 | Crankshaft and camshaft grinding wheels   | 5,500 to 8,500   | 6,500 to 9,500               |

<sup>a</sup> See **Tables 1a** and **1b** starting on page 1181.

<sup>b</sup> Non-standard shape. For snagging wheels, 16 inches and larger — Type 1, internal wheels — Types 1 and 5, and mounted wheels, see ANSI B7.1–1988. Under no conditions should a wheel be operated faster than the maximum operating speed established by the manufacturer.

Values in this table are for general information only.

**Table 2. Revolutions per Minute for Various Grinding Speeds and Wheel Diameters (Based on ANSI B7.1-1988)**

| Wheel Diameter, Inch | Peripheral (Surface) Speed, Feet per Minute |        |        |        |        |        |        |        |        |        |        |        |        |        |        | Wheel Diameter, Inch |        |
|----------------------|---|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|----------------------|--------|
|                      | 4,000                                       | 4,500  | 5,000  | 5,500  | 6,000  | 6,500  | 7,000  | 7,500  | 8,000  | 8,500  | 9,000  | 9,500  | 10,000 | 12,000 | 14,000 |                      | 16,000 |
|                      | Revolutions per Minute                      |        |        |        |        |        |        |        |        |        |        |        |        |        |        |                      |        |
| 1                    | 15,279                                      | 17,189 | 19,099 | 21,008 | 22,918 | 24,828 | 26,738 | 28,648 | 30,558 | 32,468 | 34,377 | 36,287 | 38,197 | 45,837 | 53,476 | 61,115               | 1      |
| 2                    | 7,639                                       | 8,594  | 9,549  | 10,504 | 11,459 | 12,414 | 13,369 | 14,324 | 15,279 | 16,234 | 17,189 | 18,144 | 19,099 | 22,918 | 26,738 | 30,558               | 2      |
| 3                    | 5,093                                       | 5,730  | 6,366  | 7,003  | 7,639  | 8,276  | 8,913  | 9,549  | 10,186 | 10,823 | 11,459 | 12,096 | 12,732 | 15,279 | 17,825 | 20,372               | 3      |
| 4                    | 3,820                                       | 4,297  | 4,775  | 5,252  | 5,730  | 6,207  | 6,685  | 7,162  | 7,639  | 8,117  | 8,594  | 9,072  | 9,549  | 11,459 | 13,369 | 15,279               | 4      |
| 5                    | 3,056                                       | 3,438  | 3,820  | 4,202  | 4,584  | 4,966  | 5,348  | 5,730  | 6,112  | 6,494  | 6,875  | 7,257  | 7,639  | 9,167  | 10,695 | 12,223               | 5      |
| 6                    | 2,546                                       | 2,865  | 3,183  | 3,501  | 3,820  | 4,138  | 4,456  | 4,775  | 5,093  | 5,411  | 5,730  | 6,048  | 6,366  | 7,639  | 8,913  | 10,186               | 6      |
| 7                    | 2,183                                       | 2,456  | 2,728  | 3,001  | 3,274  | 3,547  | 3,820  | 4,093  | 4,365  | 4,638  | 4,911  | 5,184  | 5,457  | 6,548  | 7,639  | 8,731                | 7      |
| 8                    | 1,910                                       | 2,149  | 2,387  | 2,626  | 2,865  | 3,104  | 3,342  | 3,581  | 3,820  | 4,058  | 4,297  | 4,536  | 4,775  | 5,730  | 6,685  | 7,639                | 8      |
| 9                    | 1,698                                       | 1,910  | 2,122  | 2,334  | 2,546  | 2,759  | 2,971  | 3,183  | 3,395  | 3,608  | 3,820  | 4,032  | 4,244  | 5,093  | 5,942  | 6,791                | 9      |
| 10                   | 1,528                                       | 1,719  | 1,910  | 2,101  | 2,292  | 2,483  | 2,674  | 2,865  | 3,056  | 3,247  | 3,438  | 3,629  | 3,820  | 4,584  | 5,348  | 6,112                | 10     |
| 12                   | 1,273                                       | 1,432  | 1,592  | 1,751  | 1,910  | 2,069  | 2,228  | 2,387  | 2,546  | 2,706  | 2,865  | 3,024  | 3,183  | 3,820  | 4,456  | 5,093                | 12     |
| 14                   | 1,091                                       | 1,228  | 1,364  | 1,501  | 1,637  | 1,773  | 1,910  | 2,046  | 2,183  | 2,319  | 2,456  | 2,592  | 2,728  | 3,274  | 3,820  | 4,365                | 14     |
| 16                   | 955   | 1,074  | 1,194  | 1,313  | 1,432  | 1,552  | 1,671  | 1,790  | 1,910  | 2,029  | 2,149  | 2,268  | 2,387  | 2,865  | 3,342  | 3,820                | 16     |
| 18                   | 849   | 955    | 1,061  | 1,167  | 1,273  | 1,379  | 1,485  | 1,592  | 1,698  | 1,804  | 1,910  | 2,016  | 2,122  | 2,546  | 2,971  | 3,395                | 18     |
| 20                   | 764   | 859    | 955    | 1,050  | 1,146  | 1,241  | 1,337  | 1,432  | 1,528  | 1,623  | 1,719  | 1,814  | 1,910  | 2,292  | 2,674  | 3,056                | 20     |
| 22                   | 694   | 781    | 868    | 955    | 1,042  | 1,129  | 1,215  | 1,302  | 1,389  | 1,476  | 1,563  | 1,649  | 1,736  | 2,083  | 2,431  | 2,778                | 22     |
| 24                   | 637   | 716    | 796    | 875    | 955    | 1,035  | 1,114  | 1,194  | 1,273  | 1,353  | 1,432  | 1,512  | 1,592  | 1,910  | 2,228  | 2,546                | 24     |
| 26                   | 588   | 661    | 735    | 808    | 881    | 955    | 1,028  | 1,102  | 1,175  | 1,249  | 1,322  | 1,396  | 1,469  | 1,763  | 2,057  | 2,351                | 26     |
| 28                   | 546   | 614    | 682    | 750    | 819    | 887    | 955    | 1,023  | 1,091  | 1,160  | 1,228  | 1,296  | 1,364  | 1,637  | 1,910  | 2,183                | 28     |
| 30                   | 509   | 573    | 637    | 700    | 764    | 828    | 891    | 955    | 1,019  | 1,082  | 1,146  | 1,210  | 1,273  | 1,528  | 1,783  | 2,037                | 30     |
| 32                   | 477   | 537    | 597    | 657    | 716    | 776    | 836    | 895    | 955    | 1,015  | 1,074  | 1,134  | 1,194  | 1,432  | 1,671  | 1,910                | 32     |
| 34                   | 449   | 506    | 562    | 618    | 674    | 730    | 786    | 843    | 899    | 955    | 1,011  | 1,067  | 1,123  | 1,348  | 1,573  | 1,798                | 34     |
| 36                   | 424   | 477    | 531    | 584    | 637    | 690    | 743    | 796    | 849    | 902    | 955    | 1,008  | 1,061  | 1,273  | 1,485  | 1,698                | 36     |
| 38                   | 402   | 452    | 503    | 553    | 603    | 653    | 704    | 754    | 804    | 854    | 905    | 955    | 1,005  | 1,206  | 1,407  | 1,608                | 38     |
| 40                   | 382   | 430    | 477    | 525    | 573    | 621    | 668    | 716    | 764    | 812    | 859    | 907    | 955    | 1,146  | 1,337  | 1,528                | 40     |
| 42                   | 364   | 409    | 455    | 500    | 546    | 591    | 637    | 682    | 728    | 773    | 819    | 864    | 909    | 1,091  | 1,273  | 1,455                | 42     |
| 44                   | 347   | 391    | 434    | 477    | 521    | 564    | 608    | 651    | 694    | 738    | 781    | 825    | 868    | 1,042  | 1,215  | 1,389                | 44     |
| 46                   | 332   | 374    | 415    | 457    | 498    | 540    | 581    | 623    | 664    | 706    | 747    | 789    | 830    | 996    | 1,163  | 1,329                | 46     |
| 48                   | 318   | 358    | 398    | 438    | 477    | 517    | 557    | 597    | 637    | 676    | 716    | 756    | 796    | 955    | 1,114  | 1,273                | 48     |
| 53                   | 288   | 324    | 360    | 396    | 432    | 468    | 504    | 541    | 577    | 613    | 649    | 685    | 721    | 865    | 1,009  | 1,153                | 53     |
| 60                   | 255   | 286    | 318    | 350    | 382    | 414    | 446    | 477    | 509    | 541    | 573    | 605    | 637    | 764    | 891    | 1,019                | 60     |
| 72                   | 212   | 239    | 265    | 292    | 318    | 345    | 371    | 398    | 424    | 451    | 477    | 504    | 531    | 637    | 743    | 849                  | 72     |



### Cylindrical Grinding

Cylindrical grinding designates a general category of various grinding methods that have the common characteristic of rotating the workpiece around a fixed axis while grinding outside surface sections in controlled relation to that axis of rotation.

The form of the part or section being ground in this process is frequently cylindrical, hence the designation of the general category. However, the shape of the part may be tapered or of curvilinear profile; the position of the ground surface may also be perpendicular to the axis; and it is possible to grind concurrently several surface sections, adjacent or separated, of equal or different diameters, located in parallel or mutually inclined planes, etc., as long as the condition of a common axis of rotation is satisfied.

*Size Range of Workpieces and Machines:* Cylindrical grinding is applied in the manufacture of miniature parts, such as instrument components and, at the opposite extreme, for grinding rolling mill rolls weighing several tons. Accordingly, there are cylindrical grinding machines of many different types, each adapted to a specific work-size range. Machine capacities are usually expressed by such factors as maximum work diameter, work length and weight, complemented, of course, by many other significant data.

**Plain, Universal, and Limited-Purpose Cylindrical Grinding Machines.**—The plain cylindrical grinding machine is considered the basic type of this general category, and is used for grinding parts with cylindrical or slightly tapered form.

The universal cylindrical grinder can be used, in addition to grinding the basic cylindrical forms, for the grinding of parts with steep tapers, of surfaces normal to the part axis, including the entire face of the workpiece, and for internal grinding independently or in conjunction with the grinding of the part's outer surfaces. Such variety of part configurations requiring grinding is typical of work in the tool room, which constitutes the major area of application for universal cylindrical grinding machines.

Limited-purpose cylindrical grinders are needed for special work configurations and for high-volume production, where productivity is more important than flexibility of adaptation. Examples of limited-purpose cylindrical grinding machines are crankshaft and camshaft grinders, polygonal grinding machines, roll grinders, etc.

**Traverse or Plunge Grinding.**—In traverse grinding, the machine table carrying the work performs a reciprocating movement of specific travel length for transporting the rotating workpiece along the face of the grinding wheel. At each or at alternate stroke ends, the wheel slide advances for the gradual feeding of the wheel into the work. The length of the surface that can be ground by this method is generally limited only by the stroke length of the machine table. In large roll grinders, the relative movement between work and wheel is accomplished by the traverse of the wheel slide along a stationary machine table.

In plunge grinding, the machine table, after having been set, is locked and, while the part is rotating, the wheel slide continually advances at a preset rate, until the finish size of the part is reached. The width of the grinding wheel is a limiting factor of the section length that can be ground in this process. Plunge grinding is required for profiled surfaces and for the simultaneous grinding of multiple surfaces of different diameters or located in different planes.

When the configuration of the part does not make use of either method mandatory, the choice may be made on the basis of the following general considerations: traverse grinding usually produces a better finish, and the productivity of plunge grinding is generally higher.

**Work Holding on Cylindrical Grinding Machines.**—The manner in which the work is located and held in the machine during the grinding process determines the configuration of the part that can be adapted for cylindrical grinding and affects the resulting accuracy of the ground surface. The method of work holding also affects the attainable production rate, because the mounting and dismounting of the part can represent a substantial portion of the total operating time.

Whatever method is used for holding the part on cylindrical types of grinding machines, two basic conditions must be satisfied: 1) the part should be located with respect to its correct axis of rotation; and 2) the work drive must cause the part to rotate, at a specific speed, around the established axis.

The lengthwise location of the part, although controlled, is not too critical in traverse grinding; however, in plunge grinding, particularly when shoulder sections are also involved, it must be assured with great accuracy.

Table 1 presents a listing, with brief discussions, of work-holding methods and devices that are most frequently used in cylindrical grinding.

**Table 1. Work-Holding Methods and Devices for Cylindrical Grinding**

| Designation                                     | Description  | Discussion   |
|---|--|--|
| Centers, nonrotating ("dead"), with drive plate | Headstock with nonrotating spindle holds the center. Around the spindle, an independently supported sleeve carries the drive plate for rotating the work. Tailstock for opposite center. | The simplest method of holding the work between two opposite centers is also the potentially most accurate, as long as correctly prepared and located center holes are used in the work.                           |
| Centers, driving type                           | Work held between two centers obtains its rotation from the concurrently applied drive by the live headstock spindle and live tailstock spindle.   | Eliminates the drawback of the common center-type grinding with driver plate, which requires a dog attached to the workpiece. Driven spindles permit the grinding of the work up to both ends.                     |
| Chuck, geared, or cam-actuated                  | Two, three, or four jaws moved radially through mechanical elements, hand-, or power-operated, exert concentrically acting clamping force on the workpiece.                              | Adaptable to workpieces of different configurations and within a generally wide capacity of the chuck. Flexible in uses that, however, do not include high-precision work.   |
| Chuck, diaphragm                                | Force applied by hand or power of a flexible diaphragm causes the attached jaws to deflect temporarily for accepting the work, which is held when force is released.                     | Rapid action and flexible adaptation to different work configurations by means of special jaws offer varied uses for the grinding of disk-shaped and similar parts.  |
| Collets   | Holding devices with externally or internally acting clamping force, easily adaptable to power actuation, assuring high centering accuracy.  | Limited to parts with previously machined or ground holding surfaces, because of the small range of clamping movement of the collet jaws.  |
| Face plate                                      | Has four independently actuated jaws, any or several of which may be used, or entirely removed, using the base plate for supporting special clamps.                                      | Used for holding bulky parts, or those of awkward shape, which are ground in small quantities not warranting special fixtures.   |
| Magnetic plate                                  | Flat plates, with pole distribution adapted to the work, are mounted on the spindle like chucks and may be used for work with the locating face normal to the axis.                      | Applicable for light cuts such as are frequent in tool making, where the rapid clamping action and easy access to both the O.D. and the exposed face are sometimes of advantage.                                   |
| Steady rests                                    | Two basic types are used: (a) the two-jaw type supporting the work from the back (back rest), leaving access by the wheel; (b) the three-jaw type (center rest).                         | A complementary work-holding device, used in conjunction with primary work holders, to provide additional support, particularly to long and/or slender parts.  |
| Special fixtures                                | Single-purpose devices, designed for a particular workpiece, primarily for providing special locating elements.  | Typical workpieces requiring special fixturing are, as examples, crankshafts where the holding is combined with balancing functions; or internal gears located on the pitch circle of the teeth for O.D. grinding. |

**Selection of Grinding Wheels for Cylindrical Grinding.**—For cylindrical grinding, as for grinding in general, the primary factor to be considered in wheel selection is the work material. Other factors are the amount of excess stock and its rate of removal (speeds and feeds), the desired accuracy and surface finish, the ratio of wheel and work diameter, wet or dry grinding, etc. In view of these many variables, it is not practical to set up a complete

list of grinding wheel recommendations with general validity. Instead, examples of recommendations embracing a wide range of typical applications and assuming common practices are presented in Table 2. This is intended as a guide for the starting selection of grinding-wheel specifications which, in case of a not entirely satisfactory performance, can be refined subsequently. The content of the table is a version of the grinding-wheel recommendations for cylindrical grinding by the Norton Company using, however, non-proprietary designations for the abrasive types and bonds.

**Table 2. Wheel Recommendations for Cylindrical Grinding**

| Material                   | Wheel Marking | Material                 | Wheel Marking |
|----------------------------|---------------|--------------------------|---------------|
| Aluminum                   | SFA46-18V     | Forgings                 | A46-M5V       |
| Armatures (laminated)      | SFA100-18V    | Gages (plug)             | SFA80-K8V     |
| Axles (auto & railway)     | A54-M5V       | General-purpose grinding | SFA54-L5V     |
| Brass                      | C36-KV        | Glass                    | BFA220-011V   |
| Bronze                     |               | Gun barrels              |               |
| Soft                       | C36-KV        | Spotting and O.D.        | BFA60-M5V     |
| Hard                       | A46-M5V       | Nitralloy                |               |
| Bushings (hardened steel)  | BFA60-L5V     | Before nitriding         | A60-K5V       |
| Bushings (cast iron)       | C36-JV        | After nitriding          |               |
| Cam lobes (cast alloy)     |               | Commercial finish        | SFA60-18V     |
| Roughing                   | BFA54-N5V     | High finish              | C100-1V       |
| Finishing                  | A70-P6B       | Reflective finish        | C500-19E      |
| Cam lobes (hardened steel) |               | Pistons (aluminum)       | SFA46-18V     |
| Roughing                   | BFA54-L5V     | (cast iron)              | C36-KV        |
| Finishing                  | BFA80-T8B     | Plastics                 | C46-JV        |
| Cast iron                  | C36-JV        | Rubber                   |               |
| Chromium plating           |               | Soft                     | SFA20-K5B     |
| Commercial finish          | SFA60-J8V     | Hard                     | C36-KB        |
| High finish                | A150-K5E      | Spline shafts            | SFA60-N5V     |
| Reflective finish          | C500-19E      | Sprayed metal            | C60-JV        |
| Commutators (copper)       | C60-M4E       | Steel                    |               |
| Crankshafts (airplane)     |               | Soft                     |               |
| Pins                       | BFA46-K5V     | 1 in. dia. and smaller   | SFA60-M5V     |
| Bearings                   | A46-L5V       | over 1 in. dia.          | SFA46-L5V     |
| Crankshafts (automotive    |               | Hardened                 |               |
| pins and bearings)         |               | 1 in. dia. and smaller   | SFA80-L8V     |
| Finishing                  | A54-N5V       | over 1 in. dia.          | SFA60-K5V     |
| Roughing & finishing       | A54-O5V       | 300 series stainless     | SFA46-K8V     |
| Regrinding                 | A54-M5V       | Stellite                 | BFA46-M5V     |
| Regrinding, sprayed        |               | Titanium                 | C60-JV        |
| metal                      | C60-JV        | Valve stems (automotive) | BFA54-N5V     |
| Drills                     | BFA54-N5V     | Valve tappets            | BFA54-M5V     |

Note: Prefixes to the standard designation "A" of aluminum oxide indicate modified abrasives as follows: BFA = Blended friable (a blend of regular and friable), SFA = Semifriable.

**Operational Data for Cylindrical Grinding.**—In cylindrical grinding, similarly to other metalcutting processes, the applied speed and feed rates must be adjusted to the operational conditions as well as to the objectives of the process. Grinding differs, however, from other types of metalcutting methods in regard to the cutting speed of the tool which, in grinding, is generally not a variable; it should be maintained at, or close to the optimum rate, commonly 6500 feet per minute peripheral speed.

In establishing the proper process values for grinding, of prime consideration are the work material, its condition (hardened or soft), and the type of operation (roughing or finishing). Other influencing factors are the characteristics of the grinding machine (stability, power), the specifications of the grinding wheel, the material allowance, the rigidity and

balance of the workpiece, as well as several grinding process conditions, such as wet or dry grinding, the manner of wheel truing, etc.

Variables of the cylindrical grinding process, often referred to as *grinding data*, comprise the speed of work rotation (measured as the surface speed of the work); the infeed (in inches per pass for traverse grinding, or in inches per minute for plunge grinding); and, in the case of traverse grinding, the speed of the reciprocating table movement (expressed either in feet per minute, or as a fraction of the wheel width for each revolution of the work).

For the purpose of starting values in setting up a cylindrical grinding process, a brief listing of basic data for common cylindrical grinding conditions and involving frequently used materials, is presented in [Table 3](#).

**Table 3. Basic Process Data for Cylindrical Grinding**

| Traverse Grinding  |                                |                         |                   |               |  |               |
|--------------------|--------------------------------|-------------------------|-------------------|---------------|--|---------------|
| Work Material      | Material Condition             | Work Surface Speed, fpm | Infeed, Inch/Pass |               | Traverse for Each Work Revolution, In Fractions of the Wheel Width |               |
|                    |                                |                         | Roughing          | Finishing     | Roughing   | Finishing     |
| Plain Carbon Steel | Annealed                       | 100                     | 0.002             | 0.0005        | $\frac{1}{2}$  | $\frac{1}{6}$ |
|                    | Hardened                       | 70                      | 0.002             | 0.0003–0.0005 | $\frac{1}{4}$  | $\frac{1}{8}$ |
| Alloy Steel        | Annealed                       | 100                     | 0.002             | 0.0005        | $\frac{1}{2}$  | $\frac{1}{6}$ |
|                    | Hardened                       | 70                      | 0.002             | 0.0002–0.0005 | $\frac{1}{4}$  | $\frac{1}{8}$ |
| Tool Steel         | Annealed                       | 60                      | 0.002             | 0.0005 max.   | $\frac{1}{2}$  | $\frac{1}{6}$ |
|                    | Hardened                       | 50                      | 0.002             | 0.0001–0.0005 | $\frac{1}{4}$  | $\frac{1}{8}$ |
| Copper Alloys      | Annealed or Cold Drawn         | 100                     | 0.002             | 0.0005 max.   | $\frac{1}{3}$  | $\frac{1}{6}$ |
| Aluminum Alloys    | Cold Drawn or Solution Treated | 150                     | 0.002             | 0.0005 max.   | $\frac{1}{3}$  | $\frac{1}{6}$ |

| Plunge Grinding                |   |           |
|--------------------------------|---|-----------|
| Work Material                  | Infeed per Revolution of the Work, Inch |           |
|                                | Roughing                                | Finishing |
| Steel, soft                    | 0.0005                                  | 0.0002    |
| Plain carbon steel, hardened   | 0.0002                                  | 0.000050  |
| Alloy and tool steel, hardened | 0.0001                                  | 0.000025  |

These data, which are, in general, considered conservative, are based on average operating conditions and may be modified subsequently by: a) reducing the values in case of unsatisfactory quality of the grinding or the occurrence of failures; and b) increasing the rates for raising the productivity of the process, particularly for rigid workpieces, substantial stock allowance, etc.

**High-Speed Cylindrical Grinding.**—The maximum peripheral speed of the wheels in regular cylindrical grinding is generally 6500 feet per minute; the commonly used grinding wheels and machines are designed to operate efficiently at this speed. Recently, efforts were made to raise the productivity of different grinding methods, including cylindrical grinding, by increasing the peripheral speed of the grinding wheel to a substantially higher than traditional level, such as 12,000 feet per minute or more. Such methods are designated by the distinguishing term of high-speed grinding.

For high-speed grinding, special grinding machines have been built with high dynamic stiffness and static rigidity, equipped with powerful drive motors, extra-strong spindles and bearings, reinforced wheel guards, etc., and using grinding wheels expressly made and tested for operating at high peripheral speeds. The higher stock-removal rate accomplished by high-speed grinding represents an advantage when the work configuration and material permit, and the removable stock allowance warrants its application.

**CAUTION:** High-speed grinding must *not* be applied on standard types of equipment, such as general types of grinding machines and regular grinding wheels. Operating grinding wheels, even temporarily, at higher than approved speed constitutes a grave safety hazard.

**Areas and Degrees of Automation in Cylindrical Grinding.**—Power drive for the work rotation and for the reciprocating table traverse are fundamental machine movements that, once set for a certain rate, will function without requiring additional attention. Loading and removing the work, starting and stopping the main movements, and applying infeed by hand wheel are carried out by the operator on cylindrical grinding machines in their basic degree of mechanization. Such equipment is still frequently used in tool room and jobbing-type work.

More advanced levels of automation have been developed for cylindrical grinders and are being applied in different degrees, particularly in the following principal respects:

a) *Infeed*, in which different rates are provided for rapid approach, roughing and finishing, followed by a spark-out period, with presetting of the advance rates, the cutoff points, and the duration of time-related functions.

b) *Automatic cycling* actuated by a single lever to start work rotation, table reciprocation, grinding-fluid supply, and infeed, followed at the end of the operation by wheel slide retraction, the successive stopping of the table movement, the work rotation, and the fluid supply.

c) *Table traverse dwells* (tarry) in the extreme positions of the travel, over preset periods, to assure uniform exposure to the wheel contact of the entire work section.

d) *Mechanized work loading*, clamping, and, after termination of the operation, unloading, combined with appropriate work-feeding devices such as indexing-type drums.

e) *Size control* by in-process or post-process measurements. Signals originated by the gage will control the advance movement or cause automatic compensation of size variations by adjusting the cutoff points of the infeed.

f) *Automatic wheel dressing* at preset frequency, combined with appropriate compensation in the infeed movement.

g) *Numerical control* obviates the time-consuming setups for repetitive work performed on small- or medium-size lots. As an application example: shafts with several sections of different lengths and diameters can be ground automatically in a single operation, grinding the sections in consecutive order to close dimensional limits, controlled by an in-process gage, which is also automatically set by means of the program.

The choice of the grinding machine functions to be automated and the extent of automation will generally be guided by economic considerations, after a thorough review of the available standard and optional equipment. Numerical control of partial or complete cycles is being applied to modern cylindrical and other grinding machines.

**Cylindrical Grinding Troubles and Their Correction.**—Troubles that may be encountered in cylindrical grinding may be classified as work defects (chatter, checking, burning, scratching, and inaccuracies), improperly operating machines (jumpy infeed or traverse), and wheel defects (too hard or soft action, loading, glazing, and breakage). The Landis Tool Company has listed some of these troubles, their causes, and corrections as follows:

*Chatter:* Sources of chatter include: 1) faulty coolant; 2) wheel out of balance; 3) wheel out of round; 4) wheel too hard; 5) improper dressing; 6) faulty work support or rotation; 7) improper operation; 8) faulty traverse; 9) work vibration; 10) outside vibration transmitted to machine; 11) interference; 12) wheel base; and 13) headstock.

Suggested procedures for correction of these troubles are:

1) *Faulty coolant:* Clean tanks and lines. Replace dirty or heavy coolant with correct mixture.

2) *Wheel out of balance:* Rebalance on mounting before and after dressing. Run wheel without coolant to remove excess water. Store a removed wheel on its side to keep retained

water from causing a false heavy side. Tighten wheel mounting flanges. Make sure wheel center fits spindle.

3) *Wheel out of round*: True before and after balancing. True sides to face.

4) *Wheel too hard*: Use coarser grit, softer grade, more open bond. See *Wheel Defects* on page 1219.

5) *Improper dressing*: Use sharp diamond and hold rigidly close to wheel. It must not overhang excessively. Check diamond in mounting.

6) *Faulty work support or rotation*: Use sufficient number of work rests and adjust them more carefully. Use proper angles in centers of work. Clean dirt from footstock spindle and be sure spindle is tight. Make certain that work centers fit properly in spindles.

7) *Improper operation*: Reduce rate of wheel feed.

8) *Faulty traverse*: See *Uneven Traverse or Infeed of Wheel Head* on page 1219.

9) *Work vibration*: Reduce work speed. Check workpiece for balance.

10) *Outside vibration transmitted to machine*: Check and make sure that machine is level and sitting solidly on foundation. Isolate machine or foundation.

11) *Interference*: Check all guards for clearance.

12) *Wheel base*: Check spindle bearing clearance. Use belts of equal lengths or uniform cross-section on motor drive. Check drive motor for unbalance. Check balance and fit of pulleys. Check wheel feed mechanism to see that all parts are tight.

13) *Headstock*: Put belts of same length and cross-section on motor drive; check for correct work speeds. Check drive motor for unbalance. Make certain that headstock spindle is not loose. Check work center fit in spindle. Check wear of face plate and jackshaft bearings.

*Spirals on Work (traverse lines with same lead on work as rate of traverse)*: Sources of spirals include: 1) machine parts out of line; and 2) truing.

Suggested procedures for correction of these troubles are:

1) *Machine parts out of line*: Check wheel base, headstock, and footstock for proper alignment.

2) *Truing*: Point truing tool down 3 degrees at the workwheel contact line. Round off wheel edges.

*Check Marks on Work*: Sources of check marks include: 1) improper operation; 2) improper heat treatment; 3) improper size control; 4) improper wheel; and 5) improper dressing.

Suggested procedures for correction of these troubles are:

1) *Improper operation*: Make wheel act softer. See *Wheel Defects*. Do not force wheel into work. Use greater volume of coolant and a more even flow. Check the correct positioning of coolant nozzles to direct a copious flow of clean coolant at the proper location.

2) *Improper heat treatment*: Take corrective measures in heat-treating operations.

3) *Improper size control*: Make sure that engineering establishes reasonable size limits. See that they are maintained.

4) *Improper wheel*: Make wheel act softer. Use softer-grade wheel. Review the grain size and type of abrasive. A finer grit or more friable abrasive or both may be called for.

5) *Improper dressing*: Check that the diamond is sharp, of good quality, and well set. Increase speed of the dressing cycle. Make sure diamond is not cracked.

*Burning and Discoloration of Work*: Sources of burning and discoloration are: improper operation and improper wheel.

Suggested procedures for correction of these troubles are:

1) *Improper operation*: Decrease rate of infeed. Don't stop work while in contact with wheel.

2) *Improper wheel*: Use softer wheel or obtain softer effect. See *Wheel Defects*. Use greater volume of coolant.

*Isolated Deep Marks on Work:* Source of trouble is an unsuitable wheel. Use a finer wheel and consider a change in abrasive type.

*Fine Spiral or Thread on Work:* Sources of this trouble are: 1) improper operation; and 2) faulty wheel dressing.

Suggested procedures for corrections of these troubles are:

1) *Improper operation:* Reduce wheel pressure. Use more work rests. Reduce traverse with respect to work rotation. Use different traverse rates to break up pattern when making numerous passes. Prevent edge of wheel from penetrating by dressing wheel face parallel to work.

2) *Faulty wheel dressing:* Use slower or more even dressing traverse. Set dressing tool at least 3 degrees down and 30 degrees to the side from time to time. Tighten holder. Don't take too deep a cut. Round off wheel edges. Start dressing cut from wheel edge.

*Narrow and Deep Regular Marks on Work:* Source of trouble is that the wheel is too coarse. Use finer grain size.

*Wide, Irregular Marks of Varying Depth on Work:* Source of trouble is too soft a wheel. Use a harder grade wheel. See *Wheel Defects*.

*Widely Spaced Spots on Work:* Sources of trouble are oil spots or glazed areas on wheel face. Balance and true wheel. Keep oil from wheel face.

*Irregular "Fish-tail" Marks of Various Lengths and Widths on Work:* Source of trouble is dirty coolant. Clean tank frequently. Use filter for fine finish grinding. Flush wheel guards after dressing or when changing to finer wheel.

*Wavy Traverse Lines on Work:* Source of trouble is wheel edges. Round off. Check for loose thrust on spindle and correct if necessary.

*Irregular Marks on Work:* Cause is loose dirt. Keep machine clean.

*Deep, Irregular Marks on Work:* Source of trouble is loose wheel flanges. Tighten and make sure blotters are used.

*Isolated Deep Marks on Work:* Sources of trouble are: 1) grains pull out; coolant too strong; 2) coarse grains or foreign matter in wheel face; and 3) improper dressing.

Respective suggested procedures for corrections of these troubles are: 1) decrease soda content in coolant mixture; 2) dress wheel; and 3) use sharper dressing tool.

Brush wheel after dressing with stiff bristle brush.

*Grain Marks on Work:* Sources of trouble are: 1) improper finishing cut; 2) grain sizes of roughing and finishing wheels differ too much; 3) dressing too coarse; and 4) wheel too coarse or too soft.

Respective suggested procedures for corrections of these troubles are: start with high work and traverse speeds; finish with high work speed and slow traverse, letting wheel "spark-out" completely; finish out better with roughing wheel or use finer roughing wheel; use shallower and slower cut; and use finer grain size or harder-grade wheel.

*Inaccuracies in Work:* Work out-of-round, out-of-parallel, or tapered.

Sources of trouble are: 1) misalignment of machine parts; 2) work centers; 3) improper operation; 4) coolant; 5) wheel; 6) improper dressing; 7) spindle bearings; and 8) work.

Suggested procedures for corrections of these troubles are:

1) *Misalignment of machine parts:* Check headstock and tailstock for alignment and proper clamping.

2) *Work centers:* Centers in work must be deep enough to clear center point. Keep work centers clean and lubricated. Check play of footstock spindle and see that footstock spindle is clean and tightly seated. Regrind work centers if worn. Work centers must fit taper of work-center holes. Footstock must be checked for proper tension.

3) *Improper operation:* Don't let wheel traverse beyond end of work. Decrease wheel pressure so work won't spring. Use harder wheel or change feeds and speeds to make

wheel act harder. Allow work to “spark-out.” Decrease feed rate. Use proper number of work rests. Allow proper amount of tarry. Workpiece must be balanced if it is an odd shape.

4) *Coolant*: Use greater volume of coolant.

5) *Wheel*: Rebalance wheel on mounting before and after truing.

6) *Improper dressing*: Use same positions and machine conditions for dressing as in grinding.

7) *Spindle bearings*: Check clearance.

8) *Work*: Work must come to machine in reasonably accurate form.

*Inaccurate Work Sizing (when wheel is fed to same position, it grinds one piece to correct size, another oversize, and still another undersize)*: Sources of trouble are: 1) improper work support or rotation; 2) wheel out of balance; 3) loaded wheel; 4) improper infeed; 5) improper traverse; 6) coolant; 7) misalignment; and 8) work.

Suggested procedures for corrections of these troubles are:

1) *Improper work support or rotation*: Keep work centers clean and lubricated. Regrind work-center tips to proper angle. Be sure footstock spindle is tight. Use sufficient work rests, properly spaced.

2) *Wheel out of balance*: Balance wheel on mounting before and after truing.

3) *Loaded wheel*: See *Wheel Defects*.

4) *Improper infeed*: Check forward stops of rapid feed and slow feed. When readjusting position of wheel base by means of the fine feed, move the wheel base back after making the adjustment and then bring it forward again to take up backlash and relieve strain in feed-up parts. Check wheel spindle bearings. Don't let excessive lubrication of wheel base slide cause “floating.” Check and tighten wheel feed mechanism. Check parts for wear. Check pressure in hydraulic system. Set infeed cushion properly. Check to see that pistons are not sticking.

5) *Improper traverse*: Check traverse hydraulic system and the operating pressure. Prevent excessive lubrication of carriage ways with resultant “floating” condition. Check to see if carriage traverse piston rods are binding. Carriage rack and driving gear must not bind. Change length of tarry period.

6) *Coolant*: Use greater volume of clean coolant.

7) *Misalignment*: Check level and alignment of machine.

8) *Work*: Workpieces may vary too much in length, permitting uneven center pressure.

*Uneven Traverse or Infeed of Wheel Head*: Sources of uneven traverse or infeed of wheel head are: carriage and wheel head, hydraulic system, interference, unbalanced conditions, and wheel out of balance. Suggested procedures for correction of these troubles are:

1) *Carriage and wheel head*: Ways may be scored. Be sure to use recommended oil for both lubrication and hydraulic system. Make sure ways are not so smooth that they press out oil film. Check lubrication of ways. Check wheel feed mechanism, traverse gear, and carriage rack clearance. Prevent binding of carriage traverse cylinder rods.

2) *Hydraulic systems*: Remove air and check pressure of hydraulic oil. Check pistons and valves for oil leakage and for gumminess caused by incorrect oil. Check worn valves or pistons that permit leakage.

3) *Interference*: Make sure guard strips do not interfere.

4) *Unbalanced conditions*: Eliminate loose pulleys, unbalanced wheel drive motor, uneven belts, or high spindle keys.

5) *Wheel out of balance*: Balance wheel on mounting before and after truing.

*Wheel Defects*: When *wheel is acting too hard*, such defects as glazing, some loading, lack of cut, chatter, and burning of work result.



Suggested procedures for correction of these faults are: 1) Increase work and traverse speeds as well as rate of in-feed; 2) decrease wheel speed, diameter, or width; 3) dress more sharply; 4) use thinner coolant; 5) don't tarry at end of traverse; 6) select softer wheel grade and coarser grain size; 7) avoid gummy coolant; and 8) on hardened work select finer grit, more fragile abrasive or both to get penetration. Use softer grade.

When *wheel is acting too soft*, such defects as wheel marks, tapered work, short wheel life, and not-holding-cut result.

Suggested procedures for correction of these faults are: 1) Decrease work and traverse speeds as well as rate of in-feed; 2) increase wheel speed, diameter, or width; 3) dress with little in-feed and slow traverse; 4) use heavier coolants; 5) don't let wheel run off work at end of traverse; and 6) select harder wheel or less fragile grain or both.

*Wheel Loading and Glazing:* Sources of the trouble of wheel loading or glazing are: 1) Incorrect wheel; 2) improper dress; 3) faulty operation; 4) faulty coolant; and 5) gummy coolant.

Suggested procedures for correction of these faults are:

- 1) *Incorrect wheel:* Use coarser grain size, more open bond, or softer grade.
- 2) *Improper dressing:* Keep wheel sharp with sharp dresser, clean wheel after dressing, use faster dressing traverse, and deeper dressing cut.
- 3) *Faulty operation:* Control speeds and feeds to soften action of wheel. Use less in-feed to prevent loading; more in-feed to stop glazing.
- 4) *Faulty coolant:* Use more, cleaner and thinner coolant, and less oily coolant.
- 5) *Gummy coolant:* To stop wheel glazing, increase soda content and avoid the use of soluble oils if water is hard. In using soluble oil coolant with hard water a suitable conditioner or "softener" should be added.

*Wheel Breakage:* Suggested procedures for the correction of a radial break with three or more pieces are: 1) Reduce wheel speed to or below rated speed; 2) mount wheel properly, use blotters, tight arbors, even flange pressure and be sure to keep out dirt between flange and wheel; 3) use plenty of coolant to prevent over-heating; 4) use less in-feed; and 5) don't allow wheel to become jammed on work.

A radial break with two pieces may be caused by excessive side strain. To prevent an irregular wheel break, don't let wheel become jammed on work; don't allow striking of wheel; and never use wheels that have been damaged in handling. In general, do not use a wheel that is too tight on the arbor since the wheel is apt to break when started. Prevent excessive hammering action of wheel. Follow rules of the American National Standard Safety Requirements for the Use, Care, and Protection of Abrasive Wheels (ANSI B7.1-1988).

### Centerless Grinding

In centerless grinding the work is supported on a work rest blade and is between the grinding wheel and a regulating wheel. The regulating wheel generally is a rubber bonded abrasive wheel. In the normal grinding position the grinding wheel forces the work downward against the work rest blade and also against the regulating wheel. The latter imparts a uniform rotation to the work giving it its same peripheral speed which is adjustable.

The higher the work center is placed above the line joining the centers of the grinding and regulating wheels the quicker the rounding action. Rounding action is also increased by a high work speed and a slow rate of traverse (if a through-feed operation). It is possible to have a higher work center when using softer wheels, as their use gives decreased contact pressures and the tendency of the workpiece to lift off the work rest blade is lessened.

Long rods or bars are sometimes ground with their centers below the line-of-centers of the wheels to eliminate the whipping and chattering due to slight bends or kinks in the rods or bars, as they are held more firmly down on the blade by the wheels.

There are three general methods of centerless grinding which may be described as through-feed, in-feed, and end-feed methods.

**Through-feed Method of Grinding.**—The through-feed method is applied to straight cylindrical parts. The work is given an axial movement by the regulating wheel and passes between the grinding and regulating wheels from one side to the other. The rate of feed depends upon the diameter and speed of the regulating wheel and its inclination which is adjustable. It may be necessary to pass the work between the wheels more than once, the number of passes depending upon such factors as the amount of stock to be removed, the roundness and straightness of the unground work, and the limits of accuracy required.

The work rest fixture also contains adjustable guides on either side of the wheels that directs the work to and from the wheels in a straight line.

**In-feed Method of Centerless Grinding.**—When parts have shoulders, heads or some part larger than the ground diameter, the in-feed method usually is employed. This method is similar to “plungecut” form grinding on a center type of grinder. The length or sections to be ground in any one operation are limited by the width of the wheel. As there is no axial feeding movement, the regulating wheel is set with its axis approximately parallel to that of the grinding wheel, there being a slight inclination to keep the work tight against the end stop.

**End-feed Method of Grinding.**—The end-feed method is applied only to taper work. The grinding wheel, regulating wheel, and the work rest blade are set in a fixed relation to each other and the work is fed in from the front mechanically or manually to a fixed end stop. Either the grinding or regulating wheel, or both, are dressed to the proper taper.

**Automatic Centerless Grinding.**—The grinding of relatively small parts may be done automatically by equipping the machine with a magazine, gravity chute, or hopper feed, provided the shape of the part will permit using these feed mechanisms.

**Internal Centerless Grinding.**—Internal grinding machines based upon the centerless principle utilize the outside diameter of the work as a guide for grinding the bore which is concentric with the outer surface. In addition to straight and tapered bores, interrupted and “blind” holes can be ground by the centerless method. When two or more grinding operations such as roughing and finishing must be performed on the same part, the work can be reucked in the same location as often as required.

**Centerless Grinding Troubles.**—A number of troubles and some corrective measures compiled by a manufacturer are listed here for the through-feed and in-feed methods of centerless grinding.

*Chattermarks* are caused by having the work center too high above the line joining the centers of the grinding and regulating wheels; using too hard or too fine a grinding wheel; using too steep an angle on the work support blade; using too thin a work support blade; “play” in the set-up due to loosely clamped members; having the grinding wheel fit loosely on the spindle; having vibration either transmitted to the machine or caused by a defective drive in the machine; having the grinding wheel out-of-balance; using too heavy a stock removal; and having the grinding wheel or the regulating wheel spindles not properly adjusted.

*Feed lines or spiral marks* in through-feed grinding are caused by too sharp a corner on the exit side of the grinding wheel which may be alleviated by dressing the grinding wheel to a slight taper about  $\frac{1}{2}$  inch from the edge, dressing the edge to a slight radius, or swiveling the regulating wheel a bit.

*Scored work* is caused by burrs, abrasive grains, or removed material being imbedded in or fused to the work support blade. This condition may be alleviated by using a coolant with increased lubricating properties and if this does not help a softer grade wheel should be used.

*Work not ground round* may be due to the work center not being high enough above the line joining the centers of the grinding and regulating wheels. Placing the work center higher and using a softer grade wheel should help to alleviate this condition.

*Work not ground straight* in through-feed grinding may be due to an incorrect setting of the guides used in introducing and removing the work from the wheels, and the existence of convex or concave faces on the regulating wheel. For example, if the work is tapered on the front end, the work guide on the entering side is deflected toward the regulating wheel. If tapered on the back end, then the work guide on the exit side is deflected toward the regulating wheel. If both ends are tapered, then both work guides are deflected toward the regulating wheel. The same barrel-shaped pieces are also obtained if the face of the regulating wheel is convex at the line of contact with the work. Conversely, the work would be ground with hollow shapes if the work guides were deflected toward the grinding wheel or if the face of the regulating wheel were concave at the line of contact with the work. The use of a warped work rest blade may also result in the work not being ground straight and the blade should be removed and checked with a straight edge.

In in-feed grinding, in order to keep the wheel faces straight which will insure straightness of the cylindrical pieces being ground, the first item to be checked is the straightness and the angle of inclination of the work rest blade. If this is satisfactory then one of three corrective measures may be taken: the first might be to swivel the regulating wheel to compensate for the taper, the second might be to true the grinding wheel to that angle that will give a perfectly straight workpiece, and the third might be to change the inclination of the regulating wheel (this is true only for correcting very slight tapers up to 0.0005 inch).

*Difficulties in sizing* the work in in-feed grinding are generally due to a worn in-feed mechanism and may be overcome by adjusting the in-feed nut.

*Flat spots* on the workpiece in in-feed grinding usually occur when grinding heavy work and generally when the stock removal is light. This condition is due to insufficient driving power between the work and the regulating wheel which may be alleviated by equipping the work rest with a roller that exerts a force against the workpiece; and by feeding the workpiece to the end stop using the upper slide.

### Surface Grinding

The term surface grinding implies, in current technical usage, the grinding of surfaces which are essentially flat. Several methods of surface grinding, however, are adapted and used to produce surfaces characterized by parallel straight line elements in one direction, while normal to that direction the contour of the surface may consist of several straight line sections at different angles to each other (e.g., the guideways of a lathe bed); in other cases the contour may be curved or profiled (e.g., a thread cutting chaser).

**Advantages of Surface Grinding.**—Alternate methods for machining work surfaces similar to those produced by surface grinding are milling and, to a much more limited degree, planing. Surface grinding, however, has several advantages over alternate methods that are carried out with metal-cutting tools. Examples of such potential advantages are as follows:

- 1) Grinding is applicable to very hard and/or abrasive work materials, without significant effect on the efficiency of the stock removal.
- 2) The desired form and dimensional accuracy of the work surface can be obtained to a much higher degree and in a more consistent manner.
- 3) Surface textures of very high finish and—when the appropriate system is utilized—with the required lay, are generally produced.
- 4) Tooling for surface grinding as a rule is substantially less expensive, particularly for producing profiled surfaces, the shapes of which may be dressed into the wheel, often with simple devices, in processes that are much more economical than the making and the maintenance of form cutters.

5) Fixturing for work holding is generally very simple in surface grinding, particularly when magnetic chucks are applicable, although the mechanical holding fixture can also be simpler, because of the smaller clamping force required than in milling or planing.

6) Parallel surfaces on opposite sides of the work are produced accurately, either in consecutive operations using the first ground surface as a dependable reference plane or, simultaneously, in double face grinding, which usually operates without the need for holding the parts by clamping.

7) Surface grinding is well adapted to process automation, particularly for size control, but also for mechanized work handling in the large volume production of a wide range of component parts.

**Principal Systems of Surface Grinding.**—Flat surfaces can be ground with different surface portions of the wheel, by different arrangements of the work and wheel, as well as by different interrelated movements. The various systems of surface grinding, with their respective capabilities, can best be reviewed by considering two major distinguishing characteristics:

1) *The operating surface of the grinding wheel*, which may be the periphery or the face (the side);

2) *The movement of the work during the process*, which may be traverse (generally reciprocating) or rotary (continuous), depending on the design of a particular category of surface grinders.

The accompanying [Table 1](#) and the text that follows provides a concise review of the principal surface grinding systems, defined by the preceding characteristics. It should be noted that many surface grinders are built for specific applications, and do not fit exactly into any one of these major categories.

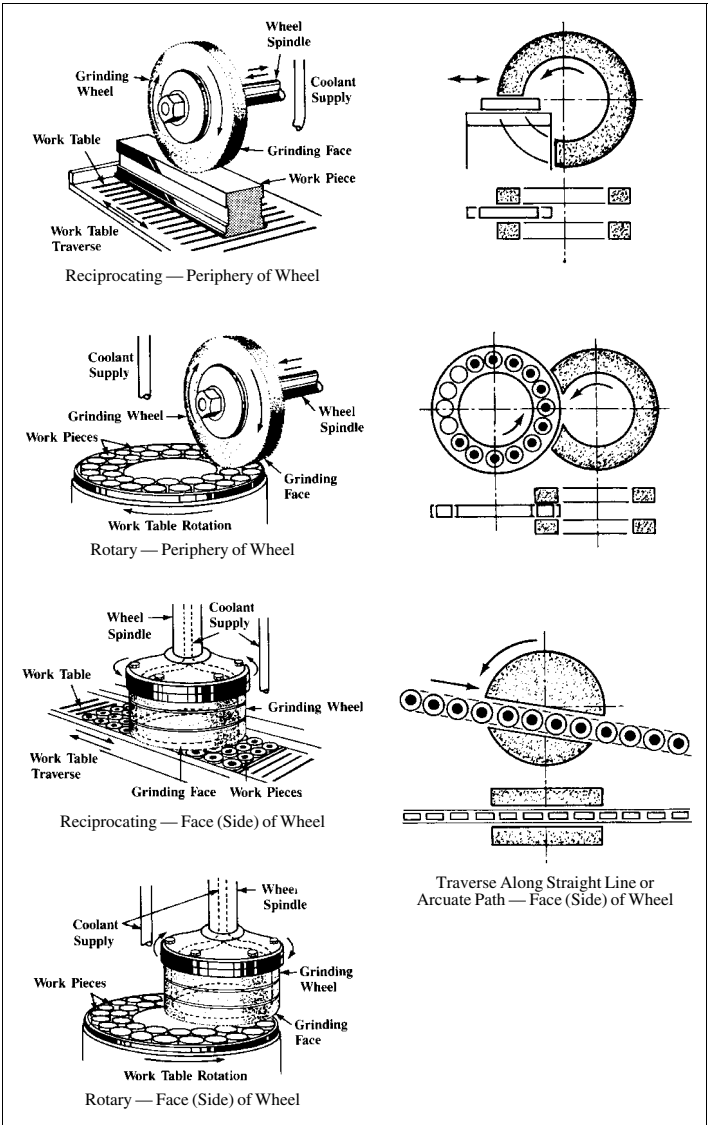
*Operating Surface, Periphery of Wheel: Movement of Work, Reciprocating:* Work is mounted on the horizontal machine table that is traversed in a reciprocating movement at a speed generally selected from a steplessly variable range. The transverse movement, called cross feed of the table or of the wheel slide, operates at the end of the reciprocating stroke and assures the gradual exposure of the entire work surface, which commonly exceeds the width of the wheel. The depth of the cut is controlled by the downfeed of the wheel, applied in increments at the reversal of the transverse movement.

*Operating Surface, Periphery of Wheel: Movement of Work, Rotary:* Work is mounted, usually on the full-diameter magnetic chuck of the circular machine table that rotates at a preset constant or automatically varying speed, the latter maintaining an approximately equal peripheral speed of the work surface area being ground. The wheelhead, installed on a cross slide, traverses over the table along a radial path, moving in alternating directions, toward and away from the center of the table. Infeed is by vertical movement of the saddle along the guideways of the vertical column, at the end of the radial wheelhead stroke. The saddle contains the guideways along which the wheelhead slide reciprocates.

*Operating Surface, Face of Wheel: Movement of Work, Reciprocating:* Operation is similar to the reciprocating table-type peripheral surface grinder, but grinding is with the face, usually with the rim of a cup-shaped wheel, or a segmental wheel for large machines. Capable of covering a much wider area of the work surface than the peripheral grinder, thus frequently no need for cross feed. Provides efficient stock removal, but is less adaptable than the reciprocating table-type peripheral grinder.

*Operating Surface, Face of Wheel: Movement of Work, Rotary:* The grinding wheel, usually of segmental type, is set in a position to cover either an annular area near the periphery of the table or, more commonly, to reach beyond the table center. A large circular magnetic chuck generally covers the entire table surface and facilitates the mounting of workpieces, even of fixtures, when needed. The uninterrupted passage of the work in contact with the large wheel face permits a very high rate of stock removal and the machine,

Table 1. Principal Systems of Surface Grinding — Diagrams



with single or double wheelhead, can be adapted also to automatic operation with continuous part feed by mechanized work handling.

*Operating Surface, Face of Wheel: Movement of Work, Traverse Along Straight or Arcuate Path:* The grinding wheel, usually of segmental type, is set in a position to cover either an annular area near the periphery of the table or, more commonly, to reach beyond the table center. A large circular magnetic chuck generally covers the entire table surface and facilitates the mounting of workpieces, even of fixtures, when needed. The uninterrupted passage of the work in contact with the large wheel face permits a very high rate of stock removal and the machine, with single or double wheelhead, can be adapted also to automatic operation with continuous part feed by mechanized work handling.

**Selection of Grinding Wheels for Surface Grinding.**—The most practical way to select a grinding wheel for surface grinding is to base the selection on the work material. [Table 2a](#) gives the grinding wheel recommendations for Types 1, 5, and 7 straight wheels used on reciprocating and rotary table surface grinders with horizontal spindles. [Table 2b](#) gives the grinding wheel recommendations for Type 2 cylinder wheels, Type 6 cup wheels, and wheel segments used on vertical spindle surface grinders.

The last letters (two or three) that may follow the bond designation V (vitrified) or B (resinoid) refer to: 1) bond modification, “BE” being especially suitable for surface grinding; 2) special structure, “P” type being distinctively porous; and 3) for segments made of 23A type abrasives, the term 12VSM implies porous structure, and the letter “P” is not needed.

The wheel markings in [Tables 2a](#) and [2b](#) are those used by the Norton Co., complementing the basic standard markings with Norton symbols. The complementary symbols used in these tables, that is, those preceding the letter designating A (aluminum oxide) or C (silicon carbide), indicate the special type of basic abrasive that has the friability best suited for particular work materials. Those preceding A (aluminum oxide) are

57—a versatile abrasive suitable for grinding steel in either a hard or soft state.

38—the most friable abrasive.

32—the abrasive suited for tool steel grinding.

23—an abrasive with intermediate grinding action, and

19—the abrasive produced for less heat-sensitive steels.

Those preceding C (silicon carbide) are

37—a general application abrasive, and

39—an abrasive for grinding hard cemented carbide.

**Table 2a. Grinding Wheel Recommendations for Surface Grinding—  
Using Straight Wheel Types 1, 5, and 7**

| Material  | Horizontal-spindle, reciprocating-table surface grinders |                                    | Horizontal-spindle, rotary-table surface grinders |
|---|--|------------------------------------|---|
|   | Wheels less than 16 inches diameter                      | Wheels 16 inches diameter and over | Wheels of any diameter                            |
| Cast iron   | 37C36-K8V or 23A46-I8VBE                                 | 23A36-I8VBE                        | 37C36-K8V or 23A46-I8VBE                          |
| Nonferrous metal                                  | 37C36-K8V  | 37C36-K8V                          | 37C36-K8V   |
| Soft steel  | 23A46-J8VBE  | 23A36-J8VBE                        | 23A46-J8VBE                                       |
| Hardened steel, broad contact                     | 32A46-H8VBE or 32A60-F12VBEP                             | 32A36-H8VBE or 32A36-F12VBEP       | 32A46-I8VBE                                       |
| Hardened steel, narrow contact or interrupted cut | 32A46-I8VBE  | 32A36-J8VBE                        | 32A46-J8VBE                                       |
| General-purpose wheel                             | 23A46-H8VBE  | 23A36-I8VBE                        | 23A46-I8VBE                                       |
| Cemented carbides                                 | Diamond wheels <sup>a</sup>                              | Diamond wheels <sup>a</sup>        | Diamond wheels <sup>a</sup>                       |

<sup>a</sup> General diamond wheel recommendations are listed in [Table 5](#) on page 1206.

**Table 2b. Grinding Wheel Recommendations for Surface Grinding—Using Type 2 Cylinder Wheels, Type 6 Cup Wheels, and Wheel Segments**

| Material  | Type 2<br>Cylinder Wheels       | Type 6<br>Cup Wheels            | Wheel<br>Segments               |
|---|---------------------------------|---------------------------------|---------------------------------|
| High tensile cast iron and non-ferrous metals                 | 37C24-HKV                       | 37C24-HVK                       | 37C24-HVK                       |
| Soft steel, malleable cast iron, steel castings, boiler plate | 23A24-I8VBE or<br>23A30-G12VBEP | 23A24-I8VBE                     | 23A24-I8VSM or<br>23A30-H12VSM  |
| Hardened steel—broad contact                                  | 32A46-G8VBE or<br>32A36-E12VBEP | 32A46-G8VBE or<br>32A60-E12VBEP | 32A36-G8VBE or<br>32A46-E12VBEP |
| Hardened steel—narrow contact or interrupt cut                | 32A46-H8VBE                     | 32A60-H8VBE                     | 32A46-G8VBE or<br>32A60-G12VBEP |
| General-purpose use   | 23A30-H8VBE or<br>23A30-E12VBEP | ...                             | 23A30-H8VSM or<br>23A30-G12VSM  |

**Process Data for Surface Grinding.**—In surface grinding, similarly to other metal-cutting processes, the speed and feed rates that are applied must be adjusted to the operational conditions as well as to the objectives of the process. Grinding differs, however, from other types of metal cutting methods in regard to the cutting speed of the tool; the peripheral speed of the grinding wheel is maintained within a narrow range, generally 5500 to 6500 surface feet per minute. Speed ranges different from the common one are used in particular processes which require special wheels and equipment.

**Table 3. Basic Process Data for Peripheral Surface Grinding on Reciprocating Table Surface Grinders**

| Work<br>Material                 | Hardness     | Material<br>Condition                              | Wheel<br>Speed,<br>fpm | Table<br>Speed,<br>fpm | Downfeed,<br>in. per pass |                 | Crossfeed<br>per pass,<br>fraction of<br>wheel width |
|----------------------------------|--------------|--|------------------------|------------------------|---------------------------|-----------------|--|
|                                  |              |  |                        |                        | Rough                     | Finish,<br>max. |  |
| Plain carbon<br>steel            | 52 Rc max.   | Annealed, cold drawn                               | 5500–6500              | 50–100                 | 0.003                     | 0.0005          | $\frac{1}{4}$  |
|                                  | 52–65 Rc     | Carburized and/or<br>quenched and tempered         | 5500–6500              | 50–100                 | 0.003                     | 0.0005          | $\frac{1}{10}$                                       |
| Alloy steels                     | 52 Rc max.   | Annealed or<br>quenched and tempered               | 5500–6500              | 50–100                 | 0.003                     | 0.001           | $\frac{1}{4}$  |
|                                  | 52–65 Rc     | Carburized and/or<br>quenched and tempered         | 5500–6500              | 50–100                 | 0.003                     | 0.0005          | $\frac{1}{10}$                                       |
| Tool steels                      | 150–275 Bhn  | Annealed   | 5500–6500              | 50–100                 | 0.002                     | 0.0005          | $\frac{1}{5}$  |
|                                  | 56–65 Rc     | Quenched and tempered                              | 5500–6500              | 50–100                 | 0.002                     | 0.0005          | $\frac{1}{10}$                                       |
| Nitriding steels                 | 200–350 Bhn  | Normalized, annealed                               | 5500–6500              | 50–100                 | 0.003                     | 0.001           | $\frac{1}{4}$  |
|                                  | 60–65 Rc     | Nitrided   | 5500–6500              | 50–100                 | 0.003                     | 0.0005          | $\frac{1}{10}$                                       |
| Cast steels                      | 52 Rc max.   | Normalized, annealed                               | 5500–6500              | 50–100                 | 0.003                     | 0.001           | $\frac{1}{4}$  |
|                                  | Over 52 Rc   | Carburized and/or<br>quenched and tempered         | 5500–6500              | 50–100                 | 0.003                     | 0.0005          | $\frac{1}{10}$                                       |
| Gray irons                       | 52 Rc max.   | As cast, annealed, and/or<br>quenched and tempered | 5000–6500              | 50–100                 | 0.003                     | 0.001           | $\frac{1}{3}$  |
| Ductile irons                    | 52 Rc max.   | As cast, annealed or<br>quenched and tempered      | 5500–6500              | 50–100                 | 0.003                     | 0.001           | $\frac{1}{5}$  |
| Stainless steels,<br>martensitic | 135–235 Bhn  | Annealed or cold drawn                             | 5500–6500              | 50–100                 | 0.002                     | 0.0005          | $\frac{1}{4}$  |
|                                  | Over 275 Bhn | Quenched and tempered                              | 5500–6500              | 50–100                 | 0.001                     | 0.0005          | $\frac{1}{8}$  |
| Aluminum<br>alloys               | 30–150 Bhn   | As cast, cold drawn<br>or treated                  | 5500–6500              | 50–100                 | 0.003                     | 0.001           | $\frac{1}{3}$  |

In establishing the proper process values for grinding, of prime consideration are the work material, its condition, and the type of operation (roughing or finishing). [Table 3](#) gives basic process data for peripheral surface grinding on reciprocating table surface

grinders. For different work materials and hardness ranges data are given regarding table speeds, downfeed (infeed) rates and cross feed, the latter as a function of the wheel width.

**Common Faults and Possible Causes in Surface Grinding.**—Approaching the ideal performance with regard to both the quality of the ground surface and the efficiency of surface grinding, requires the monitoring of the process and the correction of conditions adverse to the attainment of that goal.

Defective, or just not entirely satisfactory surface grinding may have any one or more of several causes. Exploring and determining the cause for eliminating its harmful effects is facilitated by knowing the possible sources of the experienced undesirable performance. Table 4, associating the common faults with their possible causes, is intended to aid in determining the actual cause, the correction of which should restore the desired performance level.

While the table lists the more common faults in surface grinding, and points out their frequent causes, other types of improper performance and/or other causes, in addition to those indicated, are not excluded.

**Vitrified Grinding Wheels.**—The term “vitrified” denotes the type of bond used in these grinding wheels. The bond in a grinding wheel is the material which holds the abrasive grains together and supports them while they cut. With a given type of bond, it is the amount of bond that determines the “hardness” or softness” of wheels. The abrasive itself is extremely hard in all wheels, and the terms “hard” and “soft” refer to the *strength of bonding*; the greater the percentage of bond with respect to the abrasive, the heavier the coating of bond around the abrasive grains and the stronger the bond posts, the “harder” the wheel.

Most wheels are made with a vitrified bond composed of clays and feldspar selected for their fusibility. During the “burning” process in grinding wheel manufacture, the clays are fused into a molten glass condition. Upon cooling, a span or post of this glass connects each abrasive grain to its neighbors to make a rigid, strong, grinding wheel. These wheels are porous, free cutting and unaffected by water, acids, oils, heat, or cold. Vitrified wheels are extensively used for cylindrical grinding, surface grinding, internal grinding and cutter grinding.

**Silicate Bonding Process.**—Silicate grinding wheels derive their name from the fact that silicate of soda or water glass is the principal ingredient used in the bond. These wheels are also sometimes referred to as *semi-vitrified* wheels. Ordinarily, they cut smoothly and with comparatively little heat, and for grinding operations requiring the lowest wheel wear, compatible with cool cutting, silicate wheels are often used. Their grade is also dependable and much larger wheels can be made by this bonding process than by the vitrified process. Some of the grinding operations for which silicate wheels have been found to be especially adapted are as follows: for grinding high-speed steel machine shop tools, such as reamers, milling cutters, etc.; for hand-grinding lathe and planer tools; for surface grinding with machines of the vertical ring-wheel type; and for operations requiring dish-shaped wheels and cool cutting. These wheels are unequalled for wet grinding on hardened steel and for wet tool grinding. They are easily recognized by their light gray color.

**Oilstones.**—The natural oilstones commonly used are the *Washita* and *Arkansas*. The Washita is a coarser and more rapidly cutting stone, and is generally considered the most satisfactory for sharpening woodworkers' tools. There are various grades of Washita rock, varying from the perfect crystallized and porous whetstone grit, to vitreous flint and hard sandstone. The best whetstones are porous and uniform in texture and are composed entirely of silica crystals. The poorer grades are less porous, making them vitreous or “glassy.” They may also have hard spots or sand holes, or contain grains of sand among the crystals. For general work, a soft, free-grit, quick-cutting stone is required, although a fine-grit medium-hard stone is sometimes preferable. These are commonly furnished in three grits: fine, medium, and coarse, and in all required shapes.



**Table 4. Common Faults and Possible Causes in Surface Grinding**

| CAUSES                       | FAULTS                            | WORK DIMENSION |                   |                   | METALLURGICAL DEFECTS |                     | SURFACE QUALITY |               |                      |             | WHEEL CONDITION |               |                  | WORK RETAINMENT   |                       |
|------------------------------|-----------------------------------|----------------|-------------------|-------------------|-----------------------|---------------------|-----------------|---------------|----------------------|-------------|-----------------|---------------|------------------|-------------------|-----------------------|
|                              |                                   | Work not flat  | Work not parallel | Poor size holding | Burnishing of work    | Burning or checking | Feed lines      | Chatter marks | Scratches on surface | Poor finish | Wheel loading   | Wheel glazing | Rapid wheel wear | Not firmly seated | Work sliding on chuck |
| WORK CONDITION               | Heat treat stresses               | ●              | ..                | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ..              | ..            | ..               | ..                | ..                    |
|                              | Work too thin                     | ●              | ●                 | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ..              | ..            | ..               | ..                | ..                    |
|                              | Work warped                       | ●              | ..                | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ..              | ..            | ●                | ..                | ..                    |
|                              | Abrupt section changes            | ●              | ●                 | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ..              | ..            | ..               | ..                | ..                    |
| GRINDING WHEEL               | Grit too fine                     | ..             | ..                | ..                | ●                     | ●                   | ..              | ..            | ..                   | ..          | ●               | ●             | ..               | ..                | ..                    |
|                              | Grit too coarse                   | ..             | ..                | ..                | ..                    | ..                  | ..              | ..            | ..                   | ●           | ..              | ..            | ..               | ..                | ..                    |
|                              | Grade too hard                    | ●              | ..                | ..                | ●                     | ●                   | ..              | ●             | ..                   | ..          | ●               | ●             | ..               | ..                | ..                    |
|                              | Grade too soft                    | ..             | ..                | ●                 | ..                    | ..                  | ..              | ●             | ..                   | ..          | ..              | ..            | ●                | ..                | ..                    |
|                              | Wheel not balanced                | ..             | ..                | ..                | ..                    | ..                  | ..              | ●             | ..                   | ..          | ..              | ..            | ..               | ..                | ..                    |
| Dense structure              | ..                                | ..             | ..                | ..                | ..                    | ..                  | ..              | ..            | ..                   | ●           | ●               | ..            | ..               | ..                |                       |
| TOOLING AND COOLANT          | Improper coolant                  | ..             | ..                | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ●               | ..            | ..               | ..                | ..                    |
|                              | Insufficient coolant              | ●              | ●                 | ..                | ●                     | ●                   | ..              | ..            | ..                   | ..          | ●               | ●             | ..               | ..                | ..                    |
|                              | Dirty coolant                     | ..             | ..                | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ●               | ●             | ..               | ..                | ..                    |
|                              | Diamond loose or chipped          | ●              | ●                 | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ●               | ●             | ..               | ..                | ..                    |
|                              | Diamond dull                      | ..             | ..                | ●                 | ..                    | ..                  | ..              | ..            | ..                   | ..          | ●               | ●             | ..               | ..                | ..                    |
|                              | No or poor magnetic force         | ..             | ..                | ●                 | ..                    | ..                  | ..              | ..            | ..                   | ..          | ..              | ..            | ..               | ●                 | ●                     |
| Chuck surface worn or burred | ●                                 | ●              | ..                | ..                | ..                    | ..                  | ..              | ..            | ..                   | ●           | ●               | ..            | ●                | ●                 |                       |
| MACHINE AND SETUP            | Chuck not aligned                 | ..             | ●                 | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ..              | ..            | ..               | ..                | ..                    |
|                              | Vibrations in machine             | ..             | ..                | ..                | ..                    | ..                  | ..              | ●             | ..                   | ..          | ..              | ..            | ..               | ..                | ..                    |
|                              | Plane of movement out of parallel | ●              | ●                 | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ..              | ..            | ..               | ..                | ..                    |
| OPERATIONAL CONDITIONS       | Too low work speed                | ..             | ..                | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ●               | ..            | ..               | ..                | ..                    |
|                              | Too light feed                    | ..             | ..                | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ..              | ..            | ..               | ..                | ..                    |
|                              | Too heavy cut                     | ●              | ..                | ..                | ●                     | ..                  | ..              | ..            | ..                   | ..          | ●               | ..            | ..               | ..                | ..                    |
|                              | Chuck retained swarf              | ●              | ●                 | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ..              | ..            | ..               | ..                | ●                     |
|                              | Chuck loading improper            | ●              | ●                 | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ..              | ..            | ..               | ..                | ●                     |
|                              | Insufficient blocking of parts    | ..             | ..                | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ..              | ..            | ..               | ..                | ●                     |
|                              | Wheel runs off the work           | ..             | ●                 | ●                 | ..                    | ●                   | ..              | ..            | ..                   | ..          | ..              | ..            | ..               | ..                | ..                    |
|                              | Wheel dressing too fine           | ●              | ..                | ..                | ..                    | ..                  | ..              | ..            | ..                   | ..          | ..              | ..            | ..               | ..                | ..                    |
|                              | Wheel edge not chamfered          | ..             | ..                | ..                | ..                    | ..                  | ●               | ..            | ..                   | ..          | ..              | ..            | ..               | ..                | ..                    |
|                              | Loose dirt under guard            | ..             | ..                | ..                | ..                    | ..                  | ..              | ..            | ●                    | ..          | ..              | ..            | ..               | ..                | ..                    |

### Offhand Grinding

Offhand grinding consists of holding the wheel to the work or the work to the wheel and grinding to broad tolerances and includes such operations as certain types of tool sharpening, weld grinding, snagging castings and other rough grinding. Types of machines that are used for rough grinding in foundries are floor- and bench-stand machines. Wheels for these machines vary from 6 to 30 inches in diameter. Portable grinding machines (electric, flexible shaft, or air-driven) are used for cleaning and smoothing castings.

Many rough grinding operations on castings can be best done with shaped wheels, such as cup wheels (including plate mounted) or cone wheels, and it is advisable to have a good assortment of such wheels on hand to do the odd jobs the best way.

**Floor- and Bench-Stand Grinding.**—The most common method of rough grinding is on double-end floor and bench stands. In machine shops, welding shops, and automotive repair shops, these grinders are usually provided with a fairly coarse grit wheel on one end for miscellaneous rough grinding and a finer grit wheel on the other end for sharpening tools. The pressure exerted is a very important factor in selecting the proper grinding wheel. If grinding is to be done mostly on hard sharp fins, then durable, coarse and hard wheels are required, but if grinding is mostly on large gate and riser pads, then finer and softer wheels should be used for best cutting action.

**Portable Grinding.**—Portable grinding machines are usually classified as air grinders, flexible shaft grinders, and electric grinders. The electric grinders are of two types; namely, those driven by standard 60 cycle current and so-called high-cycle grinders. Portable grinders are used for grinding down and smoothing weld seams; cleaning metal before welding; grinding out imperfections, fins and parting lines in castings and smoothing castings; grinding punch press dies and patterns to proper size and shape; and grinding manganese steel castings.

Wheels used on portable grinders are of three bond types; namely, resinoid, rubber, and vitrified. By far the largest percentage is resinoid. Rubber bond is used for relatively thin wheels and where a good finish is required. Some of the smaller wheels such as cone and plug wheels are vitrified bonded.

Grit sizes most generally used in wheels from 4 to 8 inches in diameter are 16, 20, and 24. In the still smaller diameters, finer sizes are used, such as 30, 36, and 46.

The particular grit size to use depends chiefly on the kind of grinding to be done. If the work consists of sharp fins and the machine has ample power, a coarse grain size combined with a fairly hard grade should be used. If the job is more in the nature of smoothing or surfacing and a fairly good finish is required, then finer and softer wheels are called for.

**Swing-Frame Grinding.**—This type of grinding is employed where a considerable amount of material is to be removed as on snagging large castings. It may be possible to remove 10 times as much material from steel castings using swing-frame grinders as with portable grinders; and 3 times as much material as with high-speed floor-stand grinders.

The largest field of application for swing-frame machines is on castings which are too heavy to handle on a floor stand; but often it is found that comparatively large gates and risers on smaller castings can be ground more quickly with swing-frame grinders, even if fins and parting lines have to be ground on floor stands as a second operation.

In foundries, the swing-frame machines are usually suspended from a trolley on a jib that can be swung out of the way when placing the work on the floor with the help of an overhead crane. In steel mills when grinding billets, a number of swing-frame machines are usually suspended from trolleys on a line of beams which facilitate their use as required.

The grinding wheels used on swing-frame machines are made with coarser grit sizes and harder grades than wheels used on floor stands for the same work. The reason is that greater grinding pressures can be obtained on the swing-frame machines.

**Abrasive Belt Grinding**

Abrasive belts are used in the metalworking industry for removing stock, light cleaning up of metal surfaces, grinding welds, deburring, breaking and polishing hole edges, and finish grinding of sheet steel. The types of belts that are used may be coated with aluminum oxide (the most common coating) for stock removal and finishing of all alloy steels, high-carbon steel, and tough bronzes; and silicon carbide for use on hard, brittle, and low-tensile strength metals which would include aluminum and cast irons.

**Table 1** is a guide to the selection of the proper abrasive belt, lubricant, and contact wheel. This table is entered on the basis of the material used and type of operation to be done and gives the abrasive belt specifications (type of bonding and abrasive grain size and material), the range of speeds at which the belt may best be operated, the type of lubricant to use, and the type and hardness of the contact wheel to use. **Table 2** serves as a guide in the selection of contact wheels. This table is entered on the basis of the type of contact wheel surface and the contact wheel material. The table gives the hardness and/or density, the type of abrasive belt grinding for which the contact wheel is intended, the character of the wheel action and such comments as the uses, and hints for best use. Both tables are intended only as guides for general shop practice; selections may be altered to suit individual requirements.

There are three types of abrasive belt grinding machines. One type employs a contact wheel behind the belt at the point of contact of the workpiece to the belt and facilitates a high rate of stock removal. Another type uses an accurate parallel ground platen over which the abrasive belt passes and facilitates the finishing of precision parts. A third type which has no platens or contact wheel is used for finishing parts having uneven surfaces or contours. In this type there is no support behind the belt at the point of contact of the belt with the workpiece. Some machines are so constructed that besides grinding against a platen or a contact wheel the workpiece may be moved and ground against an unsupported portion of the belt, thereby in effect making it a dual machine.

Although abrasive belts at the time of their introduction were used dry, since the advent of the improved waterproof abrasive belts, they have been used with coolants, oil-mists, and greases to aid the cutting action. The application of a coolant to the area of contact retards loading, resulting in a cool, free cutting action, a good finish and a long belt life.

**Abrasive Cutting**

Abrasive cut-off wheels are used for cutting steel, brass and aluminum bars and tubes of all shapes and hardnesses, ceramics, plastics, insulating materials, glass and cemented carbides. Originally a tool or stock room procedure, this method has developed into a high-speed production operation. While the abrasive cut-off machine and cut-off wheel can be said to have revolutionized the practice of cutting-off materials, the metal saw continues to be the more economical method for cutting-off large cross-sections of certain materials. However, there are innumerable materials and shapes that can be cut with much greater speed and economy by the abrasive wheel method. On conventional chop-stroke abrasive cutting machines using 16-inch diameter wheels, 2-inch diameter bar stock is the maximum size that can be cut with satisfactory wheel efficiency, but bar stock up to 6 inches in diameter can be cut efficiently on oscillating-stroke machines. Tubing up to 3½ inches in diameter can also be cut efficiently.

Abrasive wheels are commonly available in four types of bonds: Resinoid, rubber, shellac and fiber or fabric reinforced. In general, resinoid bonded cut-off wheels are used for dry cutting where burrs and some burn are not objectionable and rubber bonded wheels are used for wet cutting where cuts are to be smooth, clean and free from burrs. Shellac bonded wheels have a soft, free cutting quality which makes them particularly useful in the tool room where tool steels are to be cut without discoloration. Fiber reinforced bonded wheels are able to withstand severe flexing and side pressures and fabric reinforced bonded

Table 1. Guide to the Selection and Application of Abrasive Belts

| Material                     | Type of Operation | Abrasive Belt <sup>a</sup>  | Grit    | Belt Speed, fpm | Type of Grease Lubricant        | Contact Wheel   |                    |
|------------------------------|-------------------|---|---------|-----------------|---------------------------------|---|--------------------|
|                              |                   |   |         |                 |                                 | Type  | Durometer Hardness |
| Hot and Cold-Rolled Steel    | Roughing          | R/R Al <sub>2</sub> O <sub>3</sub>  | 24-60   | 4000-65000      | Light-body or none              | Cog-tooth, serrated rubber  | 70-90              |
|                              | Polishing         | R/G or R/R Al <sub>2</sub> O <sub>3</sub>   | 80-150  | 4500-7000       | Light-body or none              | Plain or serrated rubber, sectional or finger-type cloth wheel, free belt | 20-60              |
|                              | Fine Polishing    | R/G or electro-coated Al <sub>2</sub> O <sub>3</sub> cloth  | 180-500 | 4500-7000       | Heavy or with abrasive compound | Smooth-faced rubber or cloth  | 20-40              |
| Stainless Steel              | Roughing          | R/R Al <sub>2</sub> O <sub>3</sub>  | 50-80   | 3500-5000       | Light-body or none              | Cog-tooth, serrated rubber  | 70-90              |
|                              | Polishing         | R/G or R/R Al <sub>2</sub> O <sub>3</sub>   | 80-120  | 4000-5500       | Light-body or none              | Plain or serrated rubber, sectional or finger-type cloth wheel, free belt | 30-60              |
|                              | Fine Polishing    | Closed-coat SiC   | 150-280 | 4500-5500       | Heavy or oil mist               | Smooth-faced rubber or cloth  | 20-40              |
| Aluminum, Cast or Fabricated | Roughing          | R/R SiC or Al <sub>2</sub> O <sub>3</sub>   | 24-80   | 5000-6500       | Light                           | Cog-tooth, serrated rubber  | 70-90              |
|                              | Polishing         | R/G SiC or Al <sub>2</sub> O <sub>3</sub>   | 100-180 | 4500-6500       | Light                           | Plain or serrated rubber, sectional or finger-type cloth wheel, free belt | 30-50              |
|                              | Fine Polishing    | Closed-coat SiC or electro-coated Al <sub>2</sub> O <sub>3</sub>  | 220-320 | 4500-6500       | Heavy or with abrasive compound | Plain faced rubber, finger-type cloth or free belt                        | 20-50              |
| Copper Alloys or Brass       | Roughing          | R/R SiC or Al <sub>2</sub> O <sub>3</sub>   | 36-80   | 2200-4500       | Light-body                      | Cog-tooth, serrated rubber  | 70-90              |
|                              | Polishing         | Closed-coat SiC or electro-coated Al <sub>2</sub> O <sub>3</sub> or R/G SiC or Al <sub>2</sub> O <sub>3</sub> | 100-150 | 4000-6500       | Light-body                      | Plain or serrated rubber, sectional or finger-type cloth wheel, free belt | 30-50              |
|                              | Fine Polishing    | Closed-coat SiC or electro-coated Al <sub>2</sub> O <sub>3</sub>  | 180-320 | 4000-6500       | Light or with abrasive compound | Same as for polishing   | 20-30              |
| Non-ferrous Die-castings     | Roughing          | R/R SiC or Al <sub>2</sub> O <sub>3</sub>   | 24-80   | 4500-6500       | Light-body                      | Hard wheel depending on application                                       | 50-70              |
|                              | Polishing         | R/G SiC or Al <sub>2</sub> O <sub>3</sub>   | 100-180 | 4500-6500       | Light-body                      | Plain rubber, cloth or free belt  | 30-50              |
|                              | Fine Polishing    | Electro-coated Al <sub>2</sub> O <sub>3</sub> or closed-coat SiC  | 220-320 | 4500-6500       | Heavy or with abrasive compound | Plain or finger-type cloth wheel, or free belt                            | 20-30              |
| Cast Iron                    | Roughing          | R/R Al <sub>2</sub> O <sub>3</sub>  | 24-60   | 2000-4000       | None                            | Cog-tooth, serrated rubber  | 70-90              |
|                              | Polishing         | R/R Al <sub>2</sub> O <sub>3</sub>  | 80-150  | 4000-5500       | None                            | Serrated rubber   | 30-70              |
|                              | Fine Polishing    | R/R Al <sub>2</sub> O <sub>3</sub>  | 120-240 | 4000-5500       | Light-body                      | Smooth-faced rubber   | 30-40              |
| Titanium                     | Roughing          | R/R SiC or Al <sub>2</sub> O <sub>3</sub>   | 36-50   | 700-1500        | Sulfur-chlorinated              | Small-diameter, cog-tooth serrated rubber                                 | 70-80              |
|                              | Polishing         | R/R SiC   | 60-120  | 1200-2000       | Light-body                      | Standard serrated rubber  | 50                 |
|                              | Fine Polishing    | R/R SiC   | 120-240 | 1200-2000       | Light-body                      | Smooth-faced rubber or cloth  | 20-40              |

<sup>a</sup>R/R indicates that both the making and sizing bond coats are resin. R/G indicates that the making coat is glue and the sizing coat is resin. The abbreviations Al<sub>2</sub>O<sub>3</sub> for aluminum oxide and SiC for silicon carbide are used. Almost all R/R and R/G Al<sub>2</sub>O<sub>3</sub> and SiC belts have a heavy-drill weight cloth backing. Most electro-coated Al<sub>2</sub>O<sub>3</sub> and closed-coat SiC belts have a jeans weight cloth backing.

**Table 2. Guide to the Selection and Application of Contact Wheels**

| Surface             | Material                          | Hardness and Density                             | Purposes               | Wheel Action  | Comments   |
|---------------------|-----------------------------------|--|------------------------|---|--|
| Cog-tooth           | Rubber                            | 70 to 90 durometer                               | Roughing               | Fast cutting, allows long belt life.  | For cutting down projections on castings and weld beads.   |
| Standard serrated   | Rubber                            | 40 to 50 durometer, medium density               | Roughing               | Leaves rough- to medium-ground surface.   | For smoothing projections and face defects.  |
| X-shaped serrations | Rubber                            | 20 to 50 durometer                               | Roughing and polishing | Flexibility of rubber allows entry into contours. Medium polishing, light removal.                      | Same as for standard serrated wheels but preferred for soft non-ferrous metals.                      |
| Plain face          | Rubber                            | 20 to 70 durometer                               | Roughing and polishing | Plain wheel face allows controlled penetration of abrasive grain. Softer wheels give better finishes.   | For large or small flat faces.   |
| Flat flexible       | Compressed canvas                 | About nine densities from very hard to very soft | Roughing and polishing | Hard wheels can remove metal, but not as quickly as cog-tooth rubber wheels. Softer wheels polish well. | Good for medium-range grinding and polishing.  |
| Flat flexible       | Solid sectional canvas            | Soft, medium, and hard                           | Polishing              | Uniform polishing. Avoids abrasive pattern on work. Adjusts to contours. Can be performed for contours. | A low-cost wheel with uniform density at the face. Handles all types of polishing.                   |
| Flat flexible       | Buff sectional canvas             | Soft   | Contour polishing      | For fine polishing and finishing.   | Can be widened or narrowed by adding or removing sections. Low cost.                                 |
| Flat flexible       | Sponge rubber inserts             | 5 to 10 durometer, soft                          | Polishing              | Uniform polishing and finishing. Polishes and blends contours.  | Has replaceable segments. Polishes and blends contours. Segments allow density changes.              |
| Flexible            | Fingers of canvas attached to hub | Soft   | Polishing              | Uniform polishing and finishing.  | For polishing and finishing.   |
| Flat flexible       | Rubber segments                   | Varies in hardness                               | Roughing and polishing | Grinds or polishes depending on density and hardness of inserts.  | For portable machines. Uses replaceable segments that save on wheel costs and allow density changes. |
| Flat flexible       | Inflated rubber                   | Air pressure controls hardness                   | Roughing and polishing | Uniform finishing.  | Adjusts to contours.   |

wheels which are highly resistant to breakage caused by extreme side pressures, are fast cutting and have a low rate of wear.

The types of abrasives available in cut-off wheels are: Aluminum oxide, for cutting steel and most other metals; silicon carbide, for cutting non-metallic materials such as carbon, tile, slate, ceramics, etc.; and diamond, for cutting cemented carbides. The method of denoting abrasive type, grain size, grade, structure and bond type by using a system of markings is the same as for grinding wheels (see page 1179). Maximum wheel speeds given in the American National Standard "Safety Requirements for The Use, Care, and Protection of Abrasive Wheels" (ANSI B7.1-1988) range from 9500 to 14,200 surface feet per minute for organic bonded cut-off wheels larger than 16 inches in diameter and from 9500 to 16,000 surface feet per minute for organic bonded cut-off wheels 16 inches in diameter and smaller. Maximum wheel speeds specified by the manufacturer should never be exceeded even though they may be lower than those given in the B7.1 Standard.

There are four basic types of abrasive cutting machines: Chop-stroke, oscillating stroke, horizontal stroke and work rotating. Each of these four types may be designed for dry cutting or for wet cutting (includes submerged cutting).

The accompanying table based upon information made available by The Carborundum Co. gives some of the probable causes of cutting off difficulties that might be experienced when using abrasive cut-off wheels.

**Probable Causes of Cutting-Off Difficulties**

| Difficulty                      | Probable Cause  |
|---------------------------------|---|
| Angular Cuts and Wheel Breakage | (1) Inadequate clamping which allows movement of work while the wheel is in the cut. The work should be clamped on both sides of the cut.<br>(2) Work vise higher on one side than the other causing wheel to be pinched.<br>(3) Wheel vibration resulting from worn spindle bearings.<br>(4) Too fast feeding into the cut when cutting wet. |
| Burning of Stock                | (1) Insufficient power or drive allowing wheel to stall.<br>(2) Cuts too heavy for grade of wheel being used.<br>(3) Wheel fed through the work too slowly. This causes a heating up of the material being cut. This difficulty encountered chiefly in dry cutting.   |
| Excessive Wheel Wear            | (1) Too rapid cutting when cutting wet.<br>(2) Grade of wheel too hard for work, resulting in excessive heating and burning out of bond.<br>(3) Inadequate coolant supply in wet cutting.<br>(4) Grade of wheel too soft for work.<br>(5) Worn spindle bearings allowing wheel vibration.   |
| Excessive Burring               | (1) Feeding too slowly when cutting dry.<br>(2) Grit size in wheel too coarse.<br>(3) Grade of wheel too hard.<br>(4) Wheel too thick for job.  |

### Honing Process

The hone-abrading process for obtaining cylindrical forms with precise dimensions and surfaces can be applied to internal cylindrical surfaces with a wide range of diameters such as engine cylinders, bearing bores, pin holes, etc. and also to some external cylindrical surfaces.

The process is used to: 1) eliminate inaccuracies resulting from previous operations by generating a true cylindrical form with respect to roundness and straightness within minimum dimensional limits; 2) generate final dimensional size accuracy within low tolerances, as may be required for interchangeability of parts; 3) provide rapid and economical stock removal consistent with accomplishment of the other results; and 4) generate surface finishes of a specified degree of surface smoothness with high surface quality.

**Amount and Rate of Stock Removal.**—Honing may be employed to increase bore diameters by as much as 0.100 inch or as little as 0.001 inch. The amount of stock removed by the honing process is entirely a question of processing economy. If other operations are performed before honing then the bulk of the stock should be taken off by the operation that can do it most economically. In large diameter bores that have been distorted in heat treating, it may be necessary to remove as much as 0.030 to 0.040 inch from the diameter to make the bore round and straight. For out-of-round or tapered bores, a good "rule of thumb" is to leave twice as much stock (on the diameter) for honing as there is error in the bore. Another general rule is: For bores over one inch in diameter, leave 0.001 to 0.0015 inch stock per inch of diameter. For example, 0.002 to 0.003 inch of stock is left in two-inch bores and 0.010 to 0.015 inch in ten-inch bores. Where parts are to be honed for finish only, the amount of metal to be left for removing tool marks may be as little as 0.0002 to 0.015 inch on the diameter.

In general, the honing process can be employed to remove stock from bore diameters at the rate of 0.009 to 0.012 inch per minute on cast-iron parts and from 0.005 to 0.008 inch per minute on steel parts having a hardness of 60 to 65 Rockwell C. These rates are based on parts having a length equal to three or four times the diameter. Stock has been removed

from long parts such as gun barrels, at the rate of 65 cubic inches per hour. Recommended honing speeds for cast iron range from 110 to 200 surface feet per minute of rotation and from 50 to 110 lineal feet per minute of reciprocation. For steel, rotating surface speeds range from 50 to 110 feet per minute and reciprocation speeds from 20 to 90 lineal feet per minute. The exact rotation and reciprocation speeds to be used depend upon the size of the work, the amount and characteristics of the material to be removed and the quality of the finish desired. In general, the harder the material to be honed, the lower the speed. Interrupted bores are usually honed at faster speeds than plain bores.

**Formula for Rotative Speeds.**—Empirical formulas for determining rotative speeds for honing have been developed by the Micromatic Hone Corp. These formulas take into consideration the type of material being honed, its hardness and its surface characteristics; the abrasive area; and the type of surface pattern and degree of surface roughness desired. Because of the wide variations in material characteristics, abrasives available, and types of finishes specified, these formulas should be considered as a guide only in determining which of the available speeds (pulley or gear combinations) should be used for any particular application.

The formula for rotative speed,  $S$ , in surface feet per minute is: 
$$S = \frac{K \times D}{W \times N}$$

The formula for rotative speed in revolutions per minute is: 
$$\text{R.P.M.} = \frac{R}{W \times N}$$

where,  $K$  and  $R$  are factors taken from the table on the following page,  $D$  is the diameter of the bore in inches,  $W$  is the width of the abrasive stone or stock in inches, and  $N$  is the number of stones.

Although the actual speed of the abrasive is the resultant of both the rotative speed and the reciprocation speed, this latter quantity is seldom solved for or used. The reciprocation speed is not determined empirically but by testing under operating conditions. Changing the reciprocation speed affects the dressing action of the abrasive stones, therefore, the reciprocation speed is adjusted to provide for a desired surface finish which is usually a well lubricated bearing surface that will not scuff.

**Table of Factors for Use in Rotative Speed Formulas**

| Character of Surface <sup>a</sup> | Material  | Hardness <sup>b</sup> |     |        |     |      |     |
|-----------------------------------|-----------|-----------------------|-----|--------|-----|------|-----|
|                                   |           | Soft                  |     | Medium |     | Hard |     |
|                                   |           | $K$                   | $R$ | $K$    | $R$ | $K$  | $R$ |
| Base Metal                        | Cast Iron | 110                   | 420 | 80     | 300 | 60   | 230 |
|                                   | Steel     | 80                    | 300 | 60     | 230 | 50   | 190 |
| Dressing Surface                  | Cast Iron | 150                   | 570 | 110    | 420 | 80   | 300 |
|                                   | Steel     | 110                   | 420 | 80     | 300 | 60   | 230 |
| Severe Dressing                   | Cast Iron | 200                   | 760 | 150    | 570 | 110  | 420 |
|                                   | Steel     | 150                   | 570 | 110    | 420 | 80   | 300 |

<sup>a</sup>The character of the surface is classified according to its effect on the abrasive; *Base Metal* being a honed, ground or fine bored section that has little dressing action on the grit; *Dressing Surface* being a rough bored, reamed or broached surface or any surface broken by cross holes or ports; *Severe Dressing* being a surface interrupted by keyways, undercuts or burrs that dress the stones severely. If over half of the stock is to be removed after the surface is cleaned up, the speed should be computed using the *Base Metal* factors for  $K$  and  $R$ .

<sup>b</sup>Hardness designations of soft, medium and hard cover the following ranges on the Rockwell "C" hardness scale, respectively: 15 to 45, 45 to 60 and 60 to 70.

**Possible Adjustments for Eliminating Undesirable Honing Conditions**

| Undesirable Condition     | Adjustment Required to Correct Condition <sup>a</sup> |            |          |           |               |               |        |             |               |
|---------------------------|---|------------|----------|-----------|---------------|---------------|--------|-------------|---------------|
|                           | Abrasive <sup>b</sup>                                 |            |          |           | Other         |               |        |             |               |
|                           | Friability  | Grain Size | Hardness | Structure | Feed Pressure | Reciprocation | R.P.M. | Runout Time | Stroke Length |
| Abrasive Glazing          | +   | --         | --       | +         | ++            | ++            | --     | -           | 0             |
| Abrasive Loading          | 0   | --         | -        | -         | ++            | +             | --     | 0           | 0             |
| Too Rough Surface Finish  | 0   | ++         | ++       | -         | -             | -             | ++     | +           | 0             |
| Too Smooth Surface Finish | 0   | --         | --       | +         | +             | +             | --     | -           | 0             |
| Poor Stone Life           | -   | +          | ++       | -         | -             | -             | +      | 0           | 0             |
| Slow Stock Removal        | +   | --         | -        | +         | ++            | ++            | --     | 0           | 0             |
| Taper — Large at Ends     | 0   | 0          | 0        | 0         | 0             | 0             | 0      | 0           | -             |
| Taper — Small at Ends     | 0   | 0          | 0        | 0         | 0             | 0             | 0      | 0           | +             |

<sup>a</sup> The + and ++ symbols generally indicate that there should be an increase or addition while the - and -- symbols indicate that there should be a reduction or elimination. In each case, the double symbol indicates that the contemplated change would have the greatest effect. The 0 symbol means that a change would have no effect.

<sup>b</sup> For the abrasive adjustments the + and ++ symbols indicate a more friable grain, a finer grain, a harder grade or a more open structure and the - and -- symbols just the reverse.

Compiled by Micromatic Hone Corp.

**Abrasive Stones for Honing.**—Honing stones consist of aluminum oxide, silicon carbide, CBN or diamond abrasive grits, held together in stick form by a vitrified clay, resinoid or metal bond. CBN metal-bond stones are particularly suitable and widely used for honing. The grain and grade of abrasive to be used in any particular honing operation depend upon the quality of finish desired, the amount of stock to be removed, the material being honed and other factors.

The following general rules may be followed in the application of abrasive for honing: 1) Silicon-carbide abrasive is commonly used for honing cast iron, while aluminum-oxide abrasive is generally used on steel; 2) The harder the material being honed, the softer the abrasive stick used; 3) A rapid reciprocating speed will tend to make the abrasive cut fast because the dressing action on the grits will be severe; and 4) To improve the finish, use a finer abrasive grit, incorporate more multi-direction action, allow more "run-out" time after honing to size, or increase the speed of rotation.

Surface roughnesses ranging from less than 1 micro-inch r.m.s. to a relatively coarse roughness can be obtained by judicious choice of abrasive and honing time but the most common range is from 3 to 50 micro-inches r.m.s.

**Adjustments for Eliminating Undesirable Honing Conditions.**—The accompanying table indicates adjustments that may be made to correct certain undesirable conditions encountered in honing. Only one change should be made at a time and its effect noted before making other adjustments.

**Tolerances.**—For bore diameters above 4 inches the tolerance of honed surfaces with respect to roundness and straightness ranges from 0.0005 to 0.001 inch; for bore diameters from 1 to 4 inches, 0.0003 to 0.0005 inch; and for bore diameters below 1 inch, 0.00005 to 0.0003 inch.

**Laps and Lapping**

**Material for Laps.**—Laps are usually made of soft cast iron, copper, brass or lead. In general, the best material for laps to be used on very accurate work is soft, close-grained cast iron. If the grinding, prior to lapping, is of inferior quality, or an excessive allowance has been left for lapping, copper laps may be preferable. They can be charged more easily and cut more rapidly than cast iron, but do not produce as good a finish. Whatever material is



used, the lap should be softer than the work, as, otherwise, the latter will become charged with the abrasive and cut the lap, the order of the operation being reversed. A common and inexpensive form of lap for holes is made of lead which is cast around a tapering steel arbor. The arbor usually has a groove or keyway extending lengthwise, into which the lead flows, thus forming a key that prevents the lap from turning. When the lap has worn slightly smaller than the hole and ceases to cut, the lead is expanded or stretched a little by the driving in of the arbor. When this expanding operation has been repeated two or three times, the lap usually must be trued or replaced with a new one, owing to distortion.

The tendency of lead laps to lose their form is an objectionable feature. They are, however, easily molded, inexpensive, and quickly charged with the cutting abrasive. A more elaborate form for holes is composed of a steel arbor and a split cast-iron or copper shell which is sometimes prevented from turning by a small dowel pin. The lap is split so that it can be expanded to accurately fit the hole being operated upon. For hardened work, some toolmakers prefer copper to either cast iron or lead. For holes varying from  $\frac{1}{4}$  to  $\frac{1}{2}$  inch in diameter, copper or brass is sometimes used; cast iron is used for holes larger than  $\frac{1}{2}$  inch in diameter. The arbors for these laps should have a taper of about  $\frac{1}{4}$  or  $\frac{3}{8}$  inch per foot. The length of the lap should be somewhat greater than the length of the hole, and the thickness of the shell or lap proper should be from  $\frac{1}{8}$  to  $\frac{1}{6}$  its diameter.

External laps are commonly made in the form of a ring, there being an outer ring or holder and an inner shell which forms the lap proper. This inner shell is made of cast iron, copper, brass or lead. Ordinarily the lap is split and screws are provided in the holder for adjustment. The length of an external lap should at least equal the diameter of the work, and might well be longer. Large ring laps usually have a handle for moving them across the work.

**Laps for Flat Surfaces.**—Laps for producing plane surfaces are made of cast iron. In order to secure accurate results, the lapping surface must be a true plane. A flat lap that is used for roughing or "blocking down" will cut better if the surface is scored by narrow grooves. These are usually located about  $\frac{1}{2}$  inch apart and extend both lengthwise and crosswise, thus forming a series of squares similar to those on a checker-board. An abrasive of No. 100 or 120 emery and lard oil can be used for charging the roughing lap. For finer work, a lap having an unscored surface is used, and the lap is charged with a finer abrasive. After a lap is charged, all loose abrasive should be washed off with gasoline, for fine work, and when lapping, the surface should be kept moist, preferably with kerosene. Gasoline will cause the lap to cut a little faster, but it evaporates so rapidly that the lap soon becomes dry and the surface caked and glossy in spots. Loose emery should not be applied while lapping, for if the lap is well charged with abrasive in the beginning, is kept well moistened and not crowded too hard, it will cut for a considerable time. The pressure upon the work should be just enough to insure constant contact. The lap can be made to cut only so fast, and if excessive pressure is applied it will become "stripped" in places. The causes of scratches are: Loose abrasive on the lap; too much pressure on the work, and poorly graded abrasive. To produce a perfectly smooth surface free from scratches, the lap should be charged with a very fine abrasive.

**Grading Abrasives for Lapping.**—For high-grade lapping, abrasives can be evenly graded as follows: A quantity of flour-emery or other abrasive is placed in a heavy cloth bag, which is gently tapped, causing very fine particles to be sifted through. When a sufficient quantity has been obtained in this way, it is placed in a dish of lard or sperm oil. The largest particles will then sink to the bottom and in about one hour the oil should be poured into another dish, care being taken not to disturb the sediment at the bottom. The oil is then allowed to stand for several hours, after which it is poured again, and so on, until the desired grade is obtained.

**Charging Laps.**—To charge a flat cast-iron lap, spread a very thin coating of the prepared abrasive over the surface and press the small cutting particles into the lap with a hard steel block. There should be as little rubbing as possible. When the entire surface is apparently charged, clean and examine for bright spots; if any are visible, continue charging until the entire surface has a uniform gray appearance. When the lap is once charged, it should be used without applying more abrasive until it ceases to cut. If a lap is over-charged and an excessive amount of abrasive is used, there is a rolling action between the work and lap which results in inaccuracy. The surface of a flat lap is usually finished true, prior to charging, by scraping and testing with a standard surface-plate, or by the well-known method of scraping-in three plates together, in order to secure a plane surface. In any case, the bearing marks or spots should be uniform and close together. These spots can be blended by covering the plates evenly with a fine abrasive and rubbing them together. While the plates are being ground in, they should be carefully tested and any high spots which may form should be reduced by rubbing them down with a smaller block.

To charge cylindrical laps for internal work, spread a thin coating of prepared abrasive over the surface of a hard steel block, preferably by rubbing lightly with a cast-iron or copper block; then insert an arbor through the lap and roll the latter over the steel block, pressing it down firmly to embed the abrasive into the surface of the lap. For external cylindrical laps, the inner surface can be charged by rolling-in the abrasive with a hard steel roller that is somewhat smaller in diameter than the lap. The taper cast-iron blocks which are sometimes used for lapping taper holes can also be charged by rolling-in the abrasive, as previously described; there is usually one roughing and one finishing lap, and when charging the former, it may be necessary to vary the charge in accordance with any error which might exist in the taper.

**Rotary Diamond Lap.**—This style of lap is used for accurately finishing very small holes, which, because of their size, cannot be ground. While the operation is referred to as lapping, it is, in reality, a grinding process, the lap being used the same as a grinding wheel. Laps employed for this work are made of mild steel, soft material being desirable because it can be charged readily. Charging is usually done by rolling the lap between two hardened steel plates. The diamond dust and a little oil is placed on the lower plate, and as the lap revolves, the diamond is forced into its surface. After charging, the lap should be washed in benzine. The rolling plates should also be cleaned before charging with dust of a finer grade. It is very important not to force the lap when in use, especially if it is a small size. The lap should just make contact with the high spots and gradually grind them off. If a diamond lap is lubricated with kerosene, it will cut freer and faster. These small laps are run at very high speeds, the rate depending upon the lap diameter. Soft work should never be ground with diamond dust because the dust will leave the lap and charge the work.

When using a diamond lap, it should be remembered that such a lap will not produce sparks like a regular grinding wheel; hence, it is easy to crowd the lap and "strip" some of the diamond dust. To prevent this, a sound intensifier or "harker" should be used. This is placed against some stationary part of the grinder spindle, and indicates when the lap touches the work, the sound produced by the slightest contact being intensified.

**Grading Diamond Dust.**—The grades of diamond dust used for charging laps are designated by numbers, the fineness of the dust increasing as the numbers increase. The diamond, after being crushed to powder in a mortar, is thoroughly mixed with high-grade olive oil. This mixture is allowed to stand five minutes and then the oil is poured into another receptacle. The coarse sediment which is left is removed and labeled No. 0, according to one system. The oil poured from No. 0 is again stirred and allowed to stand ten minutes, after which it is poured into another receptacle and the sediment remaining is labeled No. 1. This operation is repeated until practically all of the dust has been recovered from the oil, the time that the oil is allowed to stand being increased as shown by the following table. This is done in order to obtain the smaller particles that require a longer time for precipitation:

|                              |                                      |
|------------------------------|--------------------------------------|
| To obtain No. 1 — 10 minutes | To obtain No. 4 — 2 hours            |
| To obtain No. 2 — 30 minutes | To obtain No. 5 — 10 hours           |
| To obtain No. 3 — 1 hour     | To obtain No. 6 — until oil is clear |

The No. 0 or coarse diamond which is obtained from the first settling is usually washed in benzine, and re-crushed unless very coarse dust is required. This No. 0 grade is sometimes known as "ungraded" dust. In some places the time for settling, in order to obtain the various numbers, is greater than that given in the table.

**Cutting Properties of Laps and Abrasives.**—In order to determine the cutting properties of abrasives when used with different lapping materials and lubricants, a series of tests was conducted, the results of which were given in a paper by W. A. Knight and A. A. Case, presented before the American Society of Mechanical Engineers. In connection with these tests, a special machine was used, the construction being such that quantitative results could be obtained with various combinations of abrasive, lubricant, and lap material. These tests were confined to surface lapping.

It was not the intention to test a large variety of abrasives, three being selected as representative; namely, Naxos emery, carborundum, and alundum. Abrasive No. 150 was used in each case, and seven different lubricants, five different pressures, and three different lap materials were employed. The lubricants were lard oil, machine oil, kerosene, gasoline, turpentine, alcohol, and soda water.

These tests indicated throughout that there is, for each different combination of lap and lubricant, a definite size of grain that will give the maximum amount of cutting. With all the tests, except when using the two heavier lubricants, some reduction in the size of the grain below that used in the tests (No. 150) seemed necessary before the maximum rate of cutting was reached. This reduction, however, was continuous and soon passed below that which gave the maximum cutting rate.

**Cutting Qualities with Different Laps.**—The surfaces of the steel and cast-iron laps were finished by grinding. The hardness of the different laps, as determined by the scleroscope was, for cast-iron, 28; steel, 18; copper, 5. The total amount ground from the test-pieces with each of the three laps showed that, taking the whole number of tests as a standard, there is scarcely any difference between the steel and cast iron, but that copper has somewhat better cutting qualities, although, when comparing the laps on the basis of the highest and lowest values obtained with each lap, steel and cast iron are as good for all practical purposes as copper, when the proper abrasive and lubricant are used.

**Wear of Laps.**—The wear of laps depends upon the material from which they are made and the abrasive used. The wear on all laps was about twice as fast with carborundum as with emery, while with alundum the wear was about one and one-fourth times that with emery. On an average, the wear of the copper lap was about three times that of the cast-iron lap. This is not absolute wear, but wear in proportion to the amount ground from the test-pieces.

**Lapping Abrasives.**—As to the qualities of the three abrasives tested, it was found that carborundum usually began at a lower rate than the other abrasives, but, when once started, its rate was better maintained. The performance gave a curve that was more nearly a straight line. The charge or residue as the grinding proceeded remained cleaner and sharper and did not tend to become pasty or mucklike, as is so frequently the case with emery. When using a copper lap, carborundum shows but little gain over the cast-iron and steel laps, whereas, with emery and alundum, the gain is considerable.

**Effect of Different Lapping Lubricants.**—The action of the different lubricants, when tested, was found to depend upon the kind of abrasive and the lap material.

*Lard and Machine Oil:* The test showed that lard oil, without exception, gave the higher rate of cutting, and that, in general, the initial rate of cutting is higher with the lighter lubri-

cants, but falls off more rapidly as the test continues. The lowest results were obtained with machine oil, when using an emery-charged, cast-iron lap. When using lard oil and a carborundum-charged steel lap, the highest results were obtained.

*Gasoline and Kerosene:* On the cast-iron lap, gasoline was superior to any of the lubricants tested. Considering all three abrasives, the relative value of gasoline, when applied to the different laps, is as follows: Cast iron, 127; copper, 115; steel, 106. Kerosene, like gasoline, gives the best results on cast iron and the poorest on steel. The values obtained by carborundum were invariably higher than those obtained with emery, except when using gasoline and kerosene on a copper lap.

*Turpentine and Alcohol:* Turpentine was found to do good work with carborundum on any lap. With emery, turpentine did fair work on the copper lap, but, with the emery on cast-iron and steel laps, it was distinctly inferior. Alcohol gives the lowest results with emery on the cast-iron and steel laps.

*Soda Water:* Soda water gives medium results with almost any combination of lap and abrasives, the best work being on the copper lap and the poorest on the steel lap. On the cast-iron lap, soda water is better than machine or lard oil, but not so good as gasoline or kerosene. Soda water when used with alundum on the copper lap, gave the highest results of any of the lubricants used with that particular combination.

**Lapping Pressures.**—Within the limits of the pressures used, that is, up to 25 pounds per square inch, the rate of cutting was found to be practically proportional to the pressure. The higher pressures of 20 and 25 pounds per square inch are not so effective on the copper lap as on the other materials.

**Wet and Dry Lapping.**—With the “wet method” of using a surface lap, there is a surplus of oil and abrasive on the surface of the lap. As the specimen being lapped is moved over it, there is more or less movement or shifting of the abrasive particles. With the “dry method,” the lap is first charged by rubbing or rolling the abrasive into its surface. All surplus oil and abrasive are then washed off, leaving a clean surface, but one that has embedded uniformly over it small particles of the abrasive. It is then like the surface of a very fine oilstone and will cut away hardened steel that is rubbed over it. While this has been termed the dry method, in practice, the lap surface is kept moistened with kerosene or gasoline.

Experiments on dry lapping were carried out on the cast-iron, steel, and copper laps used in the previous tests, and also on one of tin made expressly for the purpose. Carborundum alone was used as the abrasive and a uniform pressure of 15 pounds per square inch was applied to the specimen throughout the tests. In dry lapping, much depends upon the manner of charging the lap. The rate of cutting decreased much more rapidly after the first 100 revolutions than with the wet method. Considering the amounts ground off during the first 100 revolutions, and the best result obtained with each lap taken as the basis of comparison, it was found that with a tin lap, charged by rolling No. 150 carborundum into the surface, the rate of cutting, when dry, approached that obtained with the wet method. With the other lap materials, the rate with the dry method was about one-half that of the wet method.

**Summary of Lapping Tests.**—The initial rate of cutting does not greatly differ for different abrasives. There is no advantage in using an abrasive coarser than No. 150. The rate of cutting is practically proportional to the pressure. The wear of the laps is in the following proportions: cast iron, 1.00; steel, 1.27; copper, 2.62. In general, copper and steel cut faster than cast iron, but, where permanence of form is a consideration, cast iron is the superior metal. Gasoline and kerosene are the best lubricants to use with a cast-iron lap. Machine and lard oil are the best lubricants to use with copper or steel laps. They are, however, least effective on a cast-iron lap. In general, wet lapping is from 1.2 to 6 times as fast as dry lapping, depending upon the material of the lap and the manner of charging.

## KNURLS AND KNURLING

**ANSI Standard Knurls and Knurling.**—The ANSI/ASME Standard B94.6-1984 covers knurling tools with standardized diametral pitches and their dimensional relations with respect to the work in the production of straight, diagonal, and diamond knurling on cylindrical surfaces having teeth of uniform pitch parallel to the cylinder axis or at a helix angle not exceeding 45 degrees with the work axis.

These knurling tools and the recommendations for their use are equally applicable to general purpose and precision knurling. The advantage of this ANSI Standard system is the provision by which good tracking (the ability of teeth to mesh as the tool penetrates the work blank in successive revolutions) is obtained by tools designed on the basis of diametral pitch instead of TPI (teeth per inch) when used with work blank diameters that are multiples of  $\frac{1}{64}$  inch for 64 and 128 diametral pitch or  $\frac{1}{32}$  inch for 96 and 160 diametral pitch. The use of knurls and work blank diameters which will permit good tracking should improve the uniformity and appearance of knurling, eliminate the costly trial and error methods, reduce the failure of knurling tools and production of defective work, and decrease the number of tools required. Preferred sizes for cylindrical knurls are given in Table 1 and detailed specifications appear in Table 2.

**Table 1. ANSI Standard Preferred Sizes for Cylindrical Type Knurls**  
ANSI/ASME B94.6-1984

| Nominal Outside Diameter $D_{nr}$                        | Width of Face $F$ | Diameter of Hole $A$ | Standard Diametral Pitches, $P$               |    |     |     |
|--|-------------------|----------------------|---|----|-----|-----|
|  |                   |                      | 64  | 96 | 128 | 160 |
|  |                   |                      | Number of Teeth, $N_r$ , for Standard Pitches |    |     |     |
| $\frac{1}{2}$  | $\frac{3}{16}$    | $\frac{3}{16}$       | 32  | 48 | 64  | 80  |
| $\frac{5}{8}$  | $\frac{1}{4}$     | $\frac{1}{4}$        | 40  | 60 | 80  | 100 |
| $\frac{3}{4}$  | $\frac{3}{8}$     | $\frac{1}{4}$        | 48  | 72 | 96  | 120 |
| $\frac{7}{8}$  | $\frac{3}{8}$     | $\frac{1}{4}$        | 56  | 84 | 112 | 140 |
| Additional Sizes for Bench and Engine Lathe Tool Holders |                   |                      |   |    |     |     |
| $\frac{5}{8}$  | $\frac{5}{16}$    | $\frac{7}{32}$       | 40  | 60 | 80  | 100 |
| $\frac{3}{4}$  | $\frac{5}{8}$     | $\frac{1}{4}$        | 48  | 72 | 96  | 120 |
| 1  | $\frac{3}{8}$     | $\frac{5}{16}$       | 64  | 96 | 128 | 160 |

The 96 diametral pitch knurl should be given preference in the interest of tool simplification. Dimensions  $D_{nr}$ ,  $F$ , and  $A$  are in inches.

**Table 2. ANSI Standard Specifications for Cylindrical Knurls with Straight or Diagonal Teeth**  
ANSI/ASME B94.6-1984

| Diametral Pitch $P$ | Nominal Diameter, $D_{nr}$                          |               |               |               |        | Tracking Correction Factor $Q$ | Tooth Depth, $h$ ,<br>+ 0.0015,<br>- 0.0000 |          | Radius at Root $R$ |
|---------------------|---|---------------|---------------|---------------|--------|--------------------------------|---|----------|--------------------|
|                     | $\frac{1}{2}$                                       | $\frac{5}{8}$ | $\frac{3}{4}$ | $\frac{7}{8}$ | 1      |                                | Straight                                    | Diagonal |                    |
|                     | Major Diameter of Knurl, $D_{nr} + 0.0000, -0.0015$ |               |               |               |        |                                |   |          |                    |
| 64                  | 0.4932  | 0.6165        | 0.7398        | 0.8631        | 0.9864 | 0.0006676                      | 0.024                                       | 0.021    | 0.0070<br>0.0050   |
| 96                  | 0.4960  | 0.6200        | 0.7440        | 0.8680        | 0.9920 | 0.0002618                      | 0.016                                       | 0.014    | 0.0060<br>0.0040   |
| 128                 | 0.4972  | 0.6215        | 0.7458        | 0.8701        | 0.9944 | 0.0001374                      | 0.012                                       | 0.010    | 0.0045<br>0.0030   |
| 160                 | 0.4976  | 0.6220        | 0.7464        | 0.8708        | 0.9952 | 0.00009425                     | 0.009                                       | 0.008    | 0.0040<br>0.0025   |

All dimensions except diametral pitch are in inches.

Approximate angle of space between sides of adjacent teeth for both straight and diagonal teeth is 80 degrees. The permissible eccentricity of teeth for all knurls is 0.002 inch maximum (total indicator reading).

Number of teeth in a knurl equals diametral pitch multiplied by nominal diameter.

Diagonal teeth have 30-degree helix angle,  $\psi$ .

The term *Diametral Pitch* applies to the quotient obtained by dividing the total number of teeth in the circumference of the work by the basic blank diameter; in the case of the knurling tool it would be the total number of teeth in the circumference divided by the *nominal* diameter. In the Standard the diametral pitch and number of teeth are always measured in a transverse plane which is perpendicular to the axis of rotation for diagonal as well as straight knurls and knurling.

**Cylindrical Knurling Tools.**—The cylindrical type of knurling tool comprises a tool holder and one or more knurls. The knurl has a centrally located mounting hole and is provided with straight or diagonal teeth on its periphery. The knurl is used to reproduce this tooth pattern on the work blank as the knurl and work blank rotate together.

*\*Formulas for Cylindrical Knurls*

$$P = \text{diametral pitch of knurl} = N_t \div D_{nt} \quad (1)$$

$$D_{nt} = \text{nominal diameter of knurl} = N_t \div P \quad (2)$$

$$N_t = \text{no. of teeth on knurl} = P \times D_{nt} \quad (3)$$

$$*P_{nt} = \text{circular pitch on nominal diameter} = \pi \div P \quad (4)$$

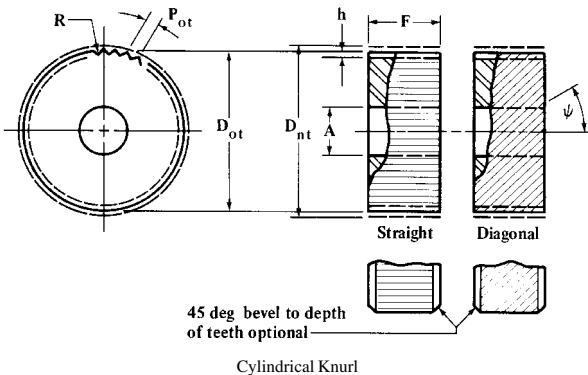
$$*P_{ot} = \text{circular pitch on major diameter} = \pi D_{ot} \div N_t \quad (5)$$

$$D_{ot} = \text{major diameter of knurl} = D_{nt} - (N_t Q \div \pi) \quad (6)$$

$$Q = P_{nt} - P_{ot} = \text{tracking correction factor in Formula} \quad (7)$$

*Tracking Correction Factor Q:* Use of the preferred pitches for cylindrical knurls, [Table 2](#), results in good tracking on all fractional work-blank diameters which are multiples of  $\frac{1}{64}$  inch for 64 and 128 diametral pitch, and  $\frac{1}{32}$  inch for 96 and 160 diametral pitch; an indication of good tracking is evenness of marking on the work surface during the first revolution of the work.

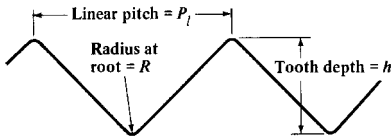
The many variables involved in knurling practice require that an empirical correction method be used to determine what actual circular pitch is needed at the major diameter of the knurl to produce good tracking and the required circular pitch on the workpiece. The empirical tracking correction factor,  $Q$ , in [Table 2](#) is used in the calculation of the major diameter of the knurl, Formula (6).



\*Note: For diagonal knurls,  $P_{nt}$  and  $P_{ot}$  are the transverse circular pitches which are measured in the plane perpendicular to the axis of rotation.

**Flat Knurling Tools.**—The flat type of tool is a knurling die, commonly used in reciprocating types of rolling machines. Dies may be made with either single or duplex faces having either straight or diagonal teeth. No preferred sizes are established for flat dies.

*Flat Knurling Die with Straight Teeth:*



$R$  = radius at root

$P$  = diametral pitch =  $N_w \div D_w$  (8)

$D_w$  = work blank (pitch) diameter =  $N_w \div P$  (9)

$N_w$  = number of teeth on work =  $P \times D_w$  (10)

$h$  = tooth depth

$Q$  = tracking correction factor (see Table 2)

$P_l$  = linear pitch on die

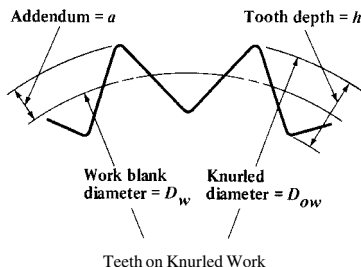
= circular pitch on work pitch diameter =  $P - Q$  (11)

**Table 3. ANSI Standard Specifications for Flat Knurling Dies**  
ANSI/ASME B94.6-1984

| Diametral Pitch, $P$ | Linear Pitch, <sup>a</sup> $P_l$ | Tooth Depth, $h$ |          | Radius at Root, $R$ | Diametral Pitch, $P$ | Linear Pitch, <sup>a</sup> $P_l$ | Tooth Depth, $h$ |          | Radius at Root, $R$ |
|----------------------|----------------------------------|------------------|----------|---------------------|----------------------|----------------------------------|------------------|----------|---------------------|
|                      |                                  | Straight         | Diagonal |                     |                      |                                  | Straight         | Diagonal |                     |
| 64                   | 0.0484                           | 0.024            | 0.021    | 0.0070<br>0.0050    | 128                  | 0.0244                           | 0.012            | 0.010    | 0.0045<br>0.0030    |
| 96                   | 0.0325                           | 0.016            | 0.014    | 0.0060<br>0.0040    | 160                  | 0.0195                           | 0.009            | 0.008    | 0.0040<br>0.0025    |

<sup>a</sup>The linear pitches are theoretical. The exact linear pitch produced by a flat knurling die may vary slightly from those shown depending upon the rolling condition and the material being rolled.

All dimensions except diametral pitch are in inches.



**Formulas Applicable to Knurled Work.**—The following formulas are applicable to knurled work with straight, diagonal, and diamond knurling.

*Formulas for Straight or Diagonal Knurling with Straight or Diagonal Tooth Cylindrical Knurling Tools Set with Knurl Axis Parallel with Work Axis:*

$$P = \text{diametral pitch} = N_w \div D_w \quad (12)$$

$$D_w = \text{work blank diameter} = N_w \div P \quad (13)$$

$$N_w = \text{no. of teeth on work} = P \times D_w \quad (14)$$

$$a = \text{"addendum" of tooth on work} = (D_{ow} - D_w) \div 2 \quad (15)$$

$h$  = tooth depth (see Table 2)

$$D_{ow} = \text{knurled diameter (outside diameter after knurling)} = D_w + 2a \quad (16)$$

*Formulas for Diagonal and Diamond Knurling with Straight Tooth Knurling Tools Set at an Angle to the Work Axis:*

If,  $\psi$  = angle between tool axis and work axis

$P$  = diametral pitch on tool

$P_\psi$  = diametral pitch produced on work blank (as measured in the transverse plane) by setting tool axis at an angle  $\psi$  with respect to work blank axis

$D_w$  = diameter of work blank; and

$N_w$  = number of teeth produced on work blank (as measured in the transverse plane)

then,  $P_\psi = P \cos \psi$  (17)

and,  $N = D_w P \cos \psi$  (18)

For example, if 30 degree diagonal knurling were to be produced on 1-inch diameter stock with a 160 pitch straight knurl:

$$N_w = D_w P \cos 30^\circ = 1.000 \times 160 \times 0.86603 = 138.56 \text{ teeth}$$

Good tracking is theoretically possible by changing the helix angle as follows to correspond to a whole number of teeth (138):

$$\cos \psi = N_w \div D_w P = 138 \div (1 \times 160) = 0.8625$$

$$\psi = 30\frac{1}{2} \text{ degrees, approximately}$$

Whenever it is more practical to machine the stock, good tracking can be obtained by reducing the work blank diameter as follows to correspond to a whole number of teeth (138):

$$D_w = \frac{N_w}{P \cos \psi} = \frac{138}{160 \times 0.866} = 0.996 \text{ inch}$$

**Table 4. ANSI Standard Recommended Tolerances on Knurled Diameters**  
ANSI/ASME B94.6-1984

| Tolerance Class | Diametral Pitch                       |                    |                    |                    |  |                      |                     |                      |
|-----------------|---------------------------------------|--------------------|--------------------|--------------------|--|----------------------|---------------------|----------------------|
|                 | 64                                    | 96                 | 128                | 160                | 64   | 96                   | 128                 | 160                  |
|                 | Tolerance on Knurled Outside Diameter |                    |                    |                    | Tolerance on Work-Blank Diameter Before Knurling |                      |                     |                      |
| I               | + 0.005<br>- 0.012                    | + 0.004<br>- 0.010 | + 0.003<br>- 0.008 | + 0.002<br>- 0.006 | ± 0.0015   | ± 0.0010             | ± 0.0007            | ± 0.0005             |
| II              | + 0.000<br>- 0.010                    | + 0.000<br>- 0.009 | + 0.000<br>- 0.008 | + 0.000<br>- 0.006 | ± 0.0015   | ± 0.0010             | ± 0.0007            | ± 0.0005             |
| III             | + 0.000<br>- 0.006                    | + 0.000<br>- 0.005 | + 0.000<br>- 0.004 | + 0.000<br>- 0.003 | + 0.000<br>- 0.0015                              | + 0.0000<br>- 0.0010 | + 0.000<br>- 0.0007 | + 0.0000<br>- 0.0005 |



**Recommended Tolerances on Knurled Outside Diameters.**—The recommended applications of the tolerance classes shown in Table 4 are as follows:

*Class I:* Tolerances in this classification may be applied to straight, diagonal and raised diamond knurling where the knurled outside diameter of the work need not be held to close dimensional tolerances. Such applications include knurling for decorative effect, grip on thumb screws, and inserts for moldings and castings.

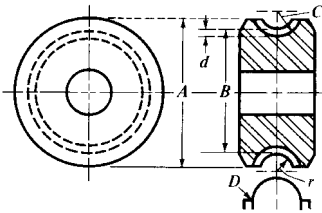
*Class II:* Tolerances in this classification may be applied to straight knurling only and are recommended for applications requiring closer dimensional control of the knurled outside diameter than provided for by Class I tolerances.

*Class III:* Tolerances in this classification may be applied to straight knurling only and are recommended for applications requiring closest possible dimensional control of the knurled outside diameter. Such applications include knurling for close fits.

*Note:* The width of the knurling should not exceed the diameter of the blank, and knurling wider than the knurling tool cannot be produced unless the knurl starts at the end of the work.

**Marking on Knurls and Dies.**—Each knurl and die should be marked as follows: *a.* when straight to indicate its diametral pitch; *b.* when diagonal, to indicate its diametral pitch, helix angle, and hand of angle.

**Concave Knurls.**—The radius of a concave knurl should not be the same as the radius of the piece to be knurled. If the knurl and the work are of the same radius, the material compressed by the knurl will be forced down on the shoulder *D* and spoil the appearance of the work. A design of concave knurl is shown in the accompanying illustration, and all the important dimensions are designated by letters. To find these dimensions, the pitch of the knurl required must be known, and also, approximately, the throat diameter *B*. This diameter must suit the knurl holder used, and be such that the circumference contains an even number of teeth with the required pitch. When these dimensions have been decided upon, all the other unknown factors can be found by the following formulas: Let *R* = radius of piece to be knurled; *r* = radius of concave part of knurl; *C* = radius of cutter or hob for cutting the teeth in the knurl; *B* = diameter over concave part of knurl (throat diameter); *A* = outside diameter of knurl; *d* = depth of tooth in knurl; *P* = pitch of knurl (number of teeth per inch circumference); *p* = circular pitch of knurl; then  $r = R + \frac{1}{2}d$ ;  $C = r + d$ ;  $A = B + 2r - (3d + 0.010 \text{ inch})$ ; and  $d = 0.5 \times p \times \cot \alpha/2$ , where  $\alpha$  is the included angle of the teeth.



As the depth of the tooth is usually very slight, the throat diameter *B* will be accurate enough for all practical purposes for calculating the pitch, and it is not necessary to take into consideration the pitch circle. For example, assume that the pitch of a knurl is 32, that the throat diameter *B* is 0.5561 inch, that the radius *R* of the piece to be knurled is  $\frac{1}{16}$  inch, and that the angle of the teeth is 90 degrees; find the dimensions of the knurl. Using the notation given:

$$p = \frac{1}{P} = \frac{1}{32} = 0.03125 \text{ inch}$$

$$d = 0.5 \times 0.03125 \times \cot 45^\circ = 0.0156 \text{ inch}$$

$$r = \frac{1}{16} + \frac{0.0156}{2} = 0.0703 \text{ inch}$$

$$C = 0.0703 + 0.0156 = 0.0859 \text{ inch}$$

$$A = 0.5561 + 0.1406 - (0.0468 + 0.010) = 0.6399 \text{ inch}$$

## MACHINE TOOL ACCURACY

**Accuracy, Repeatability, and Resolution:** In machine tools, accuracy is the maximum spread in measurements made of slide movements during successive runs at a number of target points, as discussed below. Repeatability is the spread of the normal curve at the target point that has the largest spread. A rule of thumb says that repeatability is approximately half the accuracy value, or twice as good as the accuracy, but this rule is somewhat nullified due to the introduction of error-compensation features on NC machines. Resolution refers to the smallest units of measurement that the system (controller plus servo) can recognize. Resolution is an electronic/electrical term and the unit is usually smaller than either the accuracy or the repeatability. Low values for resolution are usually, though not necessarily, applied to machines of high accuracy. In addition to high cost, a low-resolution-value design usually has a low maximum feed rate and the use of such designs is usually restricted to applications requiring high accuracy.

**Positioning Accuracy:** The positioning accuracy of a numerically controlled machine tool refers to the ability of an NC machine to place the tip of a tool at a preprogrammed target. Although no metal cutting is involved, this test is very significant for a machine tool and the cost of an NC machine will rise almost geometrically with respect to its positioning accuracy. Care, therefore, should be taken when deciding on the purchase of such a machine, to avoid paying the premium for unneeded accuracy but instead to obtain a machine that will meet the tolerance requirements for the parts to be produced.

Accuracy can be measured in many ways. A tool tip on an NC machine could be moved, for example, to a target point whose  $X$ -coordinate is 10.0000 inches. If the move is along the  $X$ -axis, and the tool tip arrives at a point that measures 10.0001 inches, does this mean that the machine has an accuracy of 0.0001 inch? What if a repetition of this move brought the tool tip to a point measuring 10.0003 inches, and another repetition moved the tool to a point that measured 9.9998 inches? In practice, it is expected that there would be a scattering or distribution of measurements and some kind of averaging is normally used.

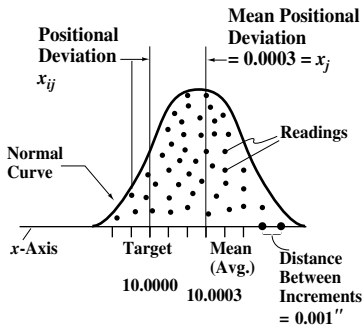


Fig. 1. In a Normal Distribution, Plotted Points Cluster Around the Mean.

Although averaging the results of several runs is an improvement over a single run, the main problem with averaging is that it does not consider the extent or width of the spread of readings. For example, if one measurement to the 10.0000-inch target is 9.9000 inches and another is 10.1000 inches, the difference of the two readings is 0.2000 inch, and the accuracy is poor. However, the readings average a perfect 10 inches. Therefore, the average and the spread of several readings must both be considered in determining the accuracy.

Plotting the results of a large number of runs generates a *normal distribution curve*, as shown in Fig. 1. In this example, the readings are plotted along the  $X$ -axis in increments of

0.0001 inch (0.0025 mm). Usually, five to ten such readings are sufficient. The distance of any one reading from the target is called the *positional deviation* of the point. The distance of the mean, or average, for the normal distribution from the target is called the *mean positional deviation*.

The spread for the normal curve is determined by a mathematical formula that calculates the distance from the mean that a certain percentage of the readings fall into. The mathematical formula used calculates one *standard deviation*, which represents approximately 32 per cent of the points that will fall within the normal curve, as shown in Fig. 2. One standard deviation is also called one sigma, or  $1\sigma$ . Plus or minus one sigma ( $\pm 1\sigma$ ) represents 64 per cent of all the points under the normal curve. A wider range on the curve,  $\pm 2\sigma$ , means that 95.44 per cent of the points are within the normal curve, and  $\pm 3\sigma$  means that 99.74 per cent of the points are within the normal curve. If an infinite number of runs were made, almost all the measurements would fall within the  $\pm 3\sigma$  range.

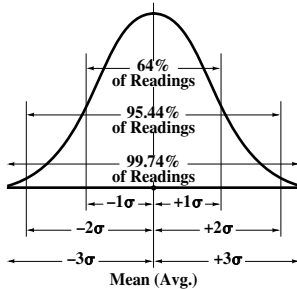


Fig. 2. Percentages of Points Falling in the  $\pm 1\sigma$  (64%),  $\pm 2\sigma$  (95.44%), and  $\pm 3\sigma$  (99.74%) Ranges  
The formula for calculating one standard deviation is

$$1\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (X_{ij} - \bar{X}_j)^2}$$

where  $n$  = number of runs to the target;  $i$  = identification for any one run;  $X_{ij}$  = positional deviation for any one run (see Fig. 1); and,  $\bar{X}_j$  = mean positional deviation (see Fig. 1).

The bar over the  $\bar{X}$  in the formula indicates that the value is the mean or average for the normal distribution.

*Example:* From Fig. 3, five runs were made at a target point that is 10.0000 inches along the X-axis and the positional deviations for each run were:

$x_{1j} = -0.0002$ ,  $x_{2j} = +0.0002$ ,  $x_{3j} = +0.0005$ ,  $x_{4j} = +0.0007$ , and  $x_{5j} = +0.0008$  inch. The algebraic total of these five runs is +0.0020, and the mean positional deviation =  $\bar{X}_j = 0.0020/5 = 0.0004$ .

The calculations for one standard deviation are:

$$\begin{aligned} 1\sigma &= \sqrt{\frac{1}{n-1} [(X_{1j} - \bar{X}_j)^2 + (X_{2j} - \bar{X}_j)^2 + (X_{3j} - \bar{X}_j)^2 + (X_{4j} - \bar{X}_j)^2 + (X_{5j} - \bar{X}_j)^2]} \\ 1\sigma &= \sqrt{\frac{1}{5-1} [(-0.0002 - 0.0004)^2 + (0.0002 - 0.0004)^2 + \\ &\quad (0.0005 - 0.0004)^2 + (0.0007 - 0.0004)^2 + (0.0008 - 0.0004)^2]} \\ &= \sqrt{\frac{1}{4}(0.0000066)} = \sqrt{0.17 \times 10^{-6}} = 0.0004 \end{aligned}$$

Three sigma variations or  $3\sigma$ , is 3 times sigma, equal to 0.0012 for the example.

If an infinite number of trials were made to the target position of 10.0000 inches for the ongoing example, 99.74 per cent of the points would fall between 9.9992 and 10.0016 inches, giving a spread of  $\pm 3\sigma$ , or 0.0024 inch. This spread alone is not considered as the accuracy but rather the repeatability for the target point 10.0000.

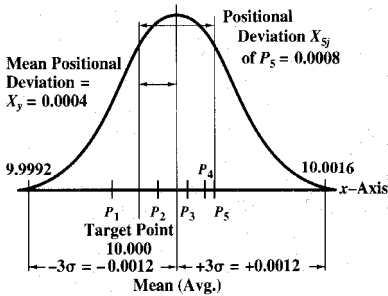


Fig. 3. Readings for Five Runs to Target Points  $P_1, P_2, P_3, P_4,$  and  $P_5$  Result in a Mean Positional Deviation of 0.0004

To calculate the accuracy, it is not sufficient to make a number of runs to one target point along a particular axis, but rather to a number of points along the axis, the number depending on the length of axis travel provided. For example, a travel of about 3 ft requires 5, and a travel of 6 ft requires 10 target points. The standard deviation and spread for the normal curve must be determined at each target point, as shown in Fig. 4. The accuracy for the axis would then be the spread between the normal curve with the most negative position and the normal curve with the most positive position. Technically, the accuracy is a spread rather than a  $\pm$  figure, but it is often referred to as a  $\pm$  figure and it may be assumed that a  $\pm 0.003$ , for expediency, is equal to a spread of 0.006.

The above description for measuring accuracy considers unidirectional approaches to target points. Bidirectional movements (additional movements to the same target point from either direction) will give different results, mostly due to backlash in the lead-screw, though backlash is small with ballnut leadscrews. Measurements made with bidirectional movements will show greater spreads and somewhat less accuracy than will unidirectional movements.

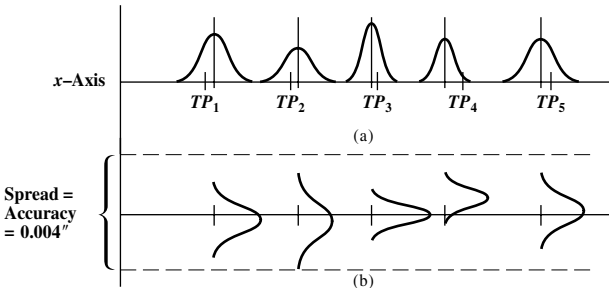


Fig. 4. Two Ways of Plotting Five Target Point Spreads

Rules for determining accuracy were standardized in guidelines last revised by the Association for Manufacturing Technology (AMT) in 1972. Some European machine tool builders use the VDI/DGQ 3441 (German) guidelines, which are similar to those of the

AMT in that normal distributions are used and a number of target points are selected along an axis. Japanese standards JIS B6201, JIS B6336, and JIS B6338 are somewhat simpler and consider only the spread of the readings, so that the final accuracy figure may be almost double that given by the AMT or VDI methods. The International Standards Organization (ISO), in 1988, issued ISO 230-2, which follows the procedures discussed above, but is somewhat less strict than the AMT recommendations. Table 1 lists some types of NC machines and the degree of accuracy that they normally provide.

**Table 1. Degrees of Accuracy Expected with NC Machine Tools**

| Type of NC Machine                                   | Accuracy       |              |
|--|----------------|--------------|
|  | inches         | mm           |
| Large boring machines or boring mills                | 0.0010–0.0020  | 0.025–0.050  |
| Small milling machines                               | 0.0006–0.0010  | 0.015–0.025  |
| Large machining centers                              | 0.0005–0.0008  | 0.012–0.020  |
| Small and medium-sized machining centers             | 0.0003–0.0006  | 0.008–0.015  |
| Lathes, slant bed, small and medium sizes            | 0.0002–0.0005  | 0.006–0.012  |
| Lathes, small precision                              | 0.0002–0.0003  | 0.004–0.008  |
| Horizontal jigmill                                   | 0.0002–0.0004  | 0.004–0.010  |
| Vertical jig boring machines                         | 0.0001–0.0002  | 0.002–0.005  |
| Vertical jig grinding machines                       | 0.0001–0.0002  | 0.002–0.005  |
| Cylindrical grinding machines, small to medium sizes | 0.00004–0.0003 | 0.001–0.007  |
| Diamond turning lathes                               | 0.00002–0.0001 | 0.0005–0.003 |

*Significance of Accuracy:* Numerically controlled machines are generally considered to be more accurate and more consistent in their movements than their conventional counterparts. CNC controllers have improved the accuracy by providing the ability to compensate for mechanical inaccuracies. Thus, compensation for errors in the lead-screw, parallelism and squareness of the machine ways, and for the effects of heating can be made automatically on NC machines. Some machine tool types are expected to be more accurate than others; for instance, grinding machines are more accurate than milling machines, and lathes for diamond turning are more accurate than normal slant-bed lathes.

Accuracy of machine tools depends on temperature, air pressure, local vibrations, and humidity. ISO standard 230-2 requires that, where possible, the ambient temperature for conducting such tests be held between 67.1 and 68.9 degrees F (19.5 and 20.5 degrees C).

*Autocollimation:* Checks on movements of slides and spindles, and alignment and other characteristics of machine tools are performed with great accuracy by means of an autocollimator, which is an optical, noncontact, angle-measuring instrument. Flatness, straightness, perpendicularity, and runout can also be checked by autocollimation. The instrument is designed to project a beam of light from a laser or an incandescent bulb onto an optically flat mirror. When the light beam is reflected back to the instrument, the distance traveled by the beam, also deviations from a straight line, can be detected by the projector and calculated electronically or measured by the scale.

Autocollimators have a small angular measuring range and are usually calibrated in arc-seconds. One arc-second is an angle of 4.85 millionths of an inch (0.00000485 in.) per inch of distance from the vertex, and is often rounded to 5 millionths of an inch per inch. Angles can also be described in terms of radians and 1 arc-second is equal to 4.85 microradians, or 0.0000573 deg.

In practice, the interferometer or autocollimator is fixed to a rigid structure and the optical mirror, which should have a flatness of one-quarter wavelength of the light used (see page 723), is fixed to the workpiece to be measured. The initial reading is taken, and then

the workpiece is moved to another position. Readings of movement can be made to within a few millionths of an inch. Angular displacements, corresponding to successive positions, of about 1 arc-second can be taken from most autocollimators, in azimuth or elevation or a combination of the two. Generally, the line width of the reticle limits the accuracy of reading such instruments.

Laser interferometers are designed to allow autocollimation readings to be taken by a photodetector instead of the eye, and some designs can measure angles to 0.001 arc-second, closer than is required for most machine shop applications. Output from an electronic autocollimator is usually transferred to a computer for recording or analysis if required. The computer calculates, lists, and plots the readings for the target points automatically, under control of the inspection program.

A typical plot from such a setup is seen in Fig. 5, where the central line connects the averages for the normal distributions at each target point. The upper line connects the positive outer limits and the lower line the negative outer limits for the normal distributions. The normal spread, indicating the accuracy of positioning, is 0.00065 inch (0.016 mm), for the Y-axis along which the measurements were taken.

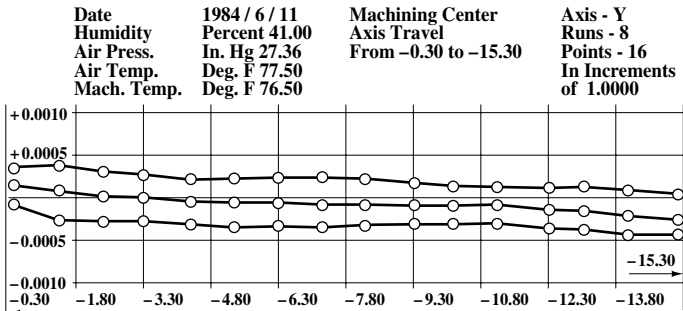



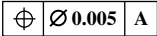
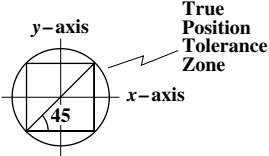
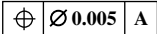
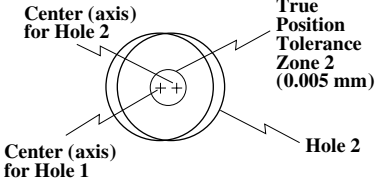
Fig. 5. Laser Interferometer Plots of Movements of Slides on a Large Horizontal Machining Center Showing an Accuracy of 0.00065 inch (0.016 mm) for the y Axis

### Effect of Machine Accuracy on Part Tolerances





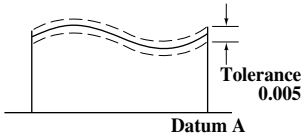
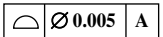
Part tolerances are usually shown on prints, usually in a control block to ANSI Standard 14.5M-1994 (see *Geometric Dimensioning and Tolerancing* starting on page 630.) Table 2 shows some part tolerance symbols that relate to machine tool positioning accuracy. The accuracy of a part is affected by machine and cutting tool dynamics, alignment, fixture accuracy, operator settings, and accuracies of the cutting tools, holders, and collets, but the positioning accuracy of the machine probably has the greatest influence. Spindle rotation accuracy, or runout, also has a large influence on part accuracy.

The ratio of the attainable part accuracy to the no-load positioning accuracy can vary from 1.7:1 to 8.31:1, depending on the type of cutting operation. For instance, making a hole by drilling, followed by a light boring or reaming operation, produces a quite accurate result in about the 1.7:1 range, whereas contour milling on hard material could be at the higher end of the range. A good average for part accuracy versus machine positioning accuracy is 3.3:1, which means that the part accuracy is 3.3 times the positioning accuracy.

**Table 2. Symbols and Feature Control Frames ANSI Y14.5M-1994**

| Symbol  | Characteristic | Meaning of Characteristic   | Relationship to the Machine Tool   |
|---|----------------|---|--|
|  | Position       | <p>The allowable true position tolerance of a feature from a datum (assume feature to be a drilled hole).<br/>Feature control block might appear as:</p> <div style="text-align: center;">  </div> <p>A is the datum, which can be another surface, another hole, or other feature</p> | <p>Assume tolerance is 0.005 mm. Machine positioning accuracy would be at least <math>0.005 \times 0.707 = 0.0035</math> mm even if it is assumed that the hole accuracy is the same as the positioning accuracy. Machine could be milling, drilling, or machining center.</p> <div style="text-align: center;">  </div> |
|   | Position       | <p>Assume feature to be a turned circumference, the axis of which has to be within a tolerance to another feature.<br/>Feature control block would appear as follows if feature A were the axis of hole 1:</p> <div style="text-align: center;">  </div>                               | <div style="text-align: center;">  </div>  |

**Table 2. Symbols and Feature Control Frames ANSI Y14.5M-1994**

| Symbol   | Characteristic       | Meaning of Characteristic  | Relationship to the Machine Tool  |
|--|----------------------|--|---|
|  | Roundness            | <p>The roundness tolerance establishes a band.</p>    | <p>This tolerance would apply to turning and would be the result of radial spindle runout.</p>  |
|  | Diameter             | <p>Usually expressed as a <math>\pm</math> tolerance attached to the dimension.</p>  | <p>Diametral accuracy of the part would depend on the positioning accuracy of the cross-slide of lathe or grinder. Positioning accuracy would be from <math>\frac{1}{2}</math> to <math>\frac{1}{4}</math> of part accuracy, depending chiefly on the rigidity of the tool, depth of cut, and material being cut.</p> |
|  | Profile of a surface | <p>Specifies a uniform boundary, along a true profile.</p>  <p>Feature control block might appear as:</p>  | <p>Affected by positioning accuracy of machine. There would be side and/or end forces on the tool so expect part to machine positioning accuracy to be high, say, 5:1</p>   |



**Table 2. Symbols and Feature Control Frames** ANSI Y14.5M-1994

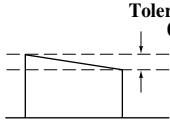

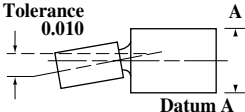

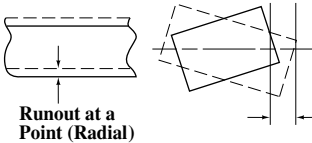
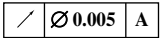

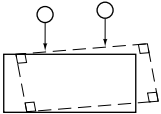

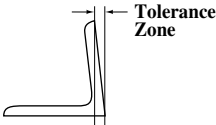
| Symbol   | Characteristic | Meaning of Characteristic  | Relationship to the Machine Tool                                    |
|--|----------------|--|---|
| //   | Parallelism    | <p>A feature (surface) parallel to a datum plane or datum axis.</p>  <p style="text-align: center;"><b>Datum A</b></p> <p>Feature control block might appear as:</p> <div style="text-align: center; border: 1px solid black; padding: 5px; display: inline-block;"> <span style="font-size: 1.2em;">//</span> <span style="font-size: 1.2em;">Ø 0.010</span> <span style="font-size: 1.2em;">A</span> </div>   | Affected by positioning accuracy, machine alignment, and fixturing. |
|  | Concentricity  | <p>Applies to turning. The axis of the feature must lie within the tolerance zone of another axis.</p>  <p style="text-align: center;"><b>Datum A</b></p> <p>Feature control block might appear as follows:</p> <div style="text-align: center; border: 1px solid black; padding: 5px; display: inline-block;"> <span style="font-size: 1.2em;">⊙</span> <span style="font-size: 1.2em;">Ø 0.005</span> <span style="font-size: 1.2em;">A</span> </div> | Affected by positioning accuracy, most likely along Z axis.         |

Table 2. Symbols and Feature Control Frames ANSI Y14.5M-1994

| Symbol   | Characteristic   | Meaning of Characteristic  | Relationship to the Machine Tool  |
|--|------------------|--|---|
|  | Runout           | <p>Applies to the runout (both radial and axial) of a circular feature at any one position around the circumference or flat, perpendicular to the axis.</p>  <p><b>Runout at a Point (Radial)</b>      <b>Runout at a Point (Axial)</b></p> <p>Runout at a Point (Radial)</p> | <p>Radial runout on part is not affected by spindle radial runout unless whole machine is untrue.</p> <p>Axial runout on part is affected by axial runout on machine. Feature would normally be perpendicular to datum.</p> <p>Feature control block might appear as:</p>  |
|  | Total runout     | <p>Similar to runout but applies to total surface and therefore consider both radial and axial runout.</p>    | <p>Would be affected by either radial or axial runout, or both, machine misalignment, or setup.</p>   |
|  | Perpendicularity | <p>A feature is perpendicular to a datum plane or axis.</p>  <p><b>Tolerance Zone</b></p>   | <p>Affected principally by misalignment of machine or fixturing.</p>  |

## NUMERICAL CONTROL

**Introduction.**—The Electronic Industries Association (EIA) defines numerical control as “a system in which actions are controlled by the direct insertion of numerical data at some point.” More specifically, numerical control, or NC as it will be called here, involves machines controlled by electronic systems designed to accept numerical data and other instructions, usually in a coded form. These instructions may come directly from some source such as a punched tape, a floppy disk, directly from a computer, or from an operator.

The key to the success of numerical control lies in its flexibility. To machine a different part, it is only necessary to “play” a different tape. NC machines are more productive than conventional equipment and consequently produce parts at less cost even when the higher investment is considered. NC machines also are more accurate and produce far less scrap than their conventional counterparts. By 1985, over 110,000 NC machine tools were operating in the United States. Over 80 per cent of the dollars being spent on the most common types of machine tools, namely, drilling, milling, boring, and turning machines, are going into NC equipment.

NC is a generic term for the whole field of numerical control and encompasses a complete field of endeavor. Sometimes CNC, which stands for Computer Numerical Control and applies only to the control system, is used erroneously as a replacement term for NC. Albeit a monumental development, use of the term CNC should be confined to installations where the older hardware control systems have been replaced.

Metal cutting is the most popular application, but NC is being applied successfully to other equipment, including punch presses, EDM wire cutting machines, inspection machines, laser and other cutting and torching machines, tube bending machines, and sheet metal cutting and forming machines.

**State of the CNC Technology Today.**—Early numerical control machines were ordinary machines retrofitted with controls and motors to drive tools and tables. The operations performed were the same as the operations were on the machines replaced. Over the years, NC machines began to combine additional operations such as automatically changing tools and workpieces. The structure of the machines has been strengthened to provide more rigid platforms. These changes have resulted in a class of machine that can outperform its predecessors in both speed and accuracy. Typical capabilities of a modern machining center are accuracy better than  $\pm 0.00035$  inch; spindle speeds in the range up to 25,000 rpm or more, and increasing; feed rates up to 400 inches per minute and increasing; tool change times hovering between 2 and 4 seconds and decreasing. Specialized machines have been built that can achieve accuracy better than one millionth (0.000001) of an inch.

Computer numerical control of machines has undergone a great deal of change in the last decade, largely as a result of rapid increases in computer capability. Development of new and improved materials for tooling and bearings, improvements in tool geometry, and the added structural stiffness of the new machines have made it possible to perform cutting operations at speeds and feeds that were formerly impossible to attain.

**Numerical Control vs. Manual Operations.**—The initial cost of a CNC machine is generally much higher than a manual machine of the same nominal capacity, and the higher initial cost leads to a higher overall cost of the machine per hour of its useful life. However, the additional cost of a CNC machine has to be considered against potential savings that the machine may make possible. Some of the individual factors that make NC and CNC machining attractive are considered below.

Labor is usually one of the highest costs in the production of a part, but the labor rate paid to a CNC machine operator may be lower than the rate paid to the operator of conventional machines. This statement is particularly true when there is a shortage of operators with specialized skills necessary for setting up and operating a manual machine. However, it should not be assumed that skilled CNC machine operators are not needed because most CNCs have manual overrides that allow the operator to adjust feeds and speeds and to manually edit or enter programs as necessary. Also, skilled setup personnel and operators are

likely to promote better production rates and higher efficiency in the shop. In addition, the labor rate for setting up and operating a CNC machine can sometimes be divided between two or more machines, further reducing the labor costs and cost per part produced.

The quantity and quality requirements for an order of parts often determines what manufacturing process will be used to produce them. CNC machines are probably most effective when the jobs call for a small to medium number of components that require a wide range of operations to be performed. For example, if a large number of parts are to be machined and the allowable tolerances are large, then manual or automatic fixed-cycle machines may be the most viable process. But, if a large quantity of high quality parts with strict tolerances are required, then a CNC machine will probably be able to produce the parts for the lowest cost per piece because of the speed and accuracy of CNC machines. Moreover, if the production run requires designing and making a lot of specialized form tools, cams, fixtures, or jigs, then the economics of CNC machining improves even more because much of the preproduction work is not required by the nature of the CNC process.

CNC machines can be effective for producing one-of-a-kind jobs if the part is complicated and requires a lot of different operations that, if done manually, would require specialized setups, jigs, fixtures, etc. On the other hand, a single component requiring only one or two setups might be more practical to produce on a manual machine, depending on the tolerances required. When a job calls for a small to medium number of components that require a wide range of operations, CNC is usually preferable. CNC machines are also especially well suited for batch jobs where small numbers of components are produced from an existing part program, as inventory is needed. Once the part program has been tested, a batch of the parts can be run whenever necessary. Design changes can be incorporated by changing the part program as required. The ability to process batches also has an additional benefit of eliminating large inventories of finished components.

CNC machining can help reduce machine idle time. Surveys have indicated that when machining on manual machines, the average time spent on material removal is only about 40 per cent of the time required to complete a part. On particularly complicated pieces, this ratio can drop to as low as 10 per cent or even less. The balance of the time is spent on positioning the tool or work, changing tools, and similar activities. On numerically controlled machines, the metal removal time frequently has been found to be in excess of 70 per cent of the total time spent on the part. CNC nonmachining time is lower because CNC machines perform quicker tool changes and tool or work positioning than manual machines. CNC part programs require a skilled programmer and cost additional preproduction time, but specialized jigs and fixtures that are frequently required with manual machines are not usually required with CNC machines, thereby reducing setup time and cost considerably.

Additional advantages of CNC machining are reduced lead time; improved cutting efficiency and longer tool life, as a result of better control over the feeds and speeds; improved quality and consistently accurate parts, reduced scrap, and less rework; lower inspection costs after the first part is produced and proven correct; reduced handling of parts because more operations can be performed per setup; and faster response to design changes because most part changes can be made by editing the CNC program.

**Numerical Control Standards.**—Standards for NC hardware and software have been developed by many organizations, and copies of the latest standards may be obtained from the following: Electronic Industries Association (EIA), 2001 Pennsylvania Avenue NW, Washington, DC 20006 (EIA and ANSI/EIA); American Society of Mechanical Engineers (ASME), 345 East 47th Street, New York, NY 10017 (ANSI/ASME); American National Standards Institute (ANSI), 25 West 43rd Street, New York, NY 10036 (ANSI, ANSI/EIA, ANSI/ASME, and ISO); National Standards Association, Inc. (NSA), 1200 Quince Orchard Boulevard, Gaithersburg, MD 20878; NMTBA The Association for Manufacturing Technology, 7901 Westpark Drive, McLean, VA 22102. Some of the standards and their contents are listed briefly in the accompanying table.

## Numerical Control Standards

| Standard Title          | Description   |
|-------------------------|---|
| ANSI/CAM-I<br>101-1990  | Dimensional Measuring Interface Specification   |
| ANSI/ASME B5.50         | V-Flange Tool Shanks for Machining Centers with Automatic Tool Changers   |
| ANSI/ASME<br>B5.54-1992 | Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers   |
| ANSI/ASME<br>B89.1.12M  | Methods for Performance Evaluation of Coordinate Measuring Machines   |
| ANSI/EIA 227-A          | 1-inch Perforated Tape  |
| ANSI/EIA 232-D          | Interface Between Data Terminal Equipment and Data Circuit-Terminating Equipment Employing Serial Binary Data Interchange   |
| ANSI/EIA 267-B          | Axis and Motion Nomenclature for Numerically Controlled Machines  |
| ANSI/EIA 274-D          | Interchangeable Variable Block Data Format for Positioning, Contouring and Contouring/Positioning Numerically Controlled Machines   |
| ANSI/EIA 358-B          | Subset of American National Standard Code for Information Interchange for Numerical Machine Control Perforated Tape   |
| ANSI/EIA 408            | Interface Between NC Equipment and Data Terminal Equipment Employing Parallel Binary Data Interchange   |
| ANSI/EIA 423-A          | Electrical Characteristics of Unbalanced Voltage Digital Interface Circuits   |
| ANSI/EIA 431            | Electrical Interface Between Numerical Control and Machine Tools  |
| ANSI/EIA 441            | Operator Interface Function of Numerical Controls   |
| ANSI/EIA 449            | General Purpose 37-position and 9-position Interface for Data Terminal Equipment and Data Circuit-Terminating Equipment Employing Serial Binary Data Interchange  |
| ANSI/EIA 484            | Electrical and Mechanical Interface Characteristics and Line Control Protocol Using Communication Control Characters for Serial Data Link between a Direct Numerical Control System and Numerical Control Equipment Employing Asynchronous Full Duplex Transmission |
| ANSI/EIA 491-A<br>-1990 | Interface between a Numerical Control Unit and Peripheral Equipment Employing Asynchronous Binary Data Interchange over Circuits having EIA-423-A Electrical Characteristics  |
| ANSI/EIA 494            | 32-bit Binary CL Interchange (BCL) Input Format for Numerically Controlled Machines   |
| EIA AB3-D               | Glossary of Terms for Numerically Controlled Machines   |
| EIA Bulletin 12         | Application Notes on Interconnection between Interface Circuits Using RS-449 and RS-232-C   |
| ANSI X 3.94             | Programming Aid for Numerically Controlled Manufacturing  |
| ANSI X 3.37             | Programming Language APT  |
| ANSI X 3.20             | 1-inch Perforated Tape Take-up Reels for Information Interchange  |
| ANSI X 3.82             | One-sided Single Density Unformatted 5.25 inch Flexible Disc Cartridges   |

**Numerical Control Standards (Continued)**

| Standard Title | Description  |
|----------------|--|
| ISO 841        | Numerical Control of Machines—Axis and Motion Nomenclature   |
| ISO 2806       | Numerical Control of Machines—Bilingual Vocabulary   |
| ISO 2972       | Numerical Control of Machines—Symbols  |
| ISO 3592       | Numerical Control of Machines—Numerical Control Processor Output, Logical Structure and Major Words  |
| ISO 4336       | Numerical Control of Machines—Specification of Interface Signals between the Numerical Control Unit and the Electrical Equipment of a Numerically Controlled Machine |
| ISO 4343       | Numerical Control of Machines—NC Processor Output— Minor Elements of 2000-type Records (Post Processor Commands)   |
| ISO TR 6132    | Numerical Control of Machines—Program Format and Definition of Address Words—Part 1: Data Format for Positioning, Line Motion and Contouring Control Systems         |
| ISO 230-1      | Geometric Accuracy of Machines Operating Under No-Load or Finishing Conditions   |
| ISO 230-2      | Determination of Accuracy and Repeatability of Positioning of Numerically Controlled Machine Tools   |
| NAS 911        | Numerically Controlled Skin/Profile Milling Machines   |
| NAS 912        | Numerically Controlled Spar Milling Machines   |
| NAS 913        | Numerically Controlled Profiling and Contouring Milling Machines   |
| NAS 914        | Numerically Controlled Horizontal Boring, Drilling and Milling Machines  |
| NAS 960        | Numerically Controlled Drilling Machines   |
| NAS 963        | Computer Numerically Controlled Vertical and Horizontal Jig Boring Machines  |
| NAS 970        | Basic Tool Holders for Numerically Controlled Machine Tools  |
| NAS 971        | Precision Numerically Controlled Measuring/Inspection Machines   |
| NAS 978        | Numerically Controlled Machining Centers   |
| NAS 990        | Numerically Controlled Composite Filament Tape Laying Machines   |
| NAS 993        | Direct Numerical Control System  |
| NAS 994        | Adaptive Control System for Numerically Controlled Milling Machines  |
| NAS 995        | Specification for Computerized Numerical Control (CNC)   |
| NMTBA          | Common Words as They Relate to Numerical Control Software  |
| NMTBA          | Definition and Evaluation of Accuracy and Repeatability of Numerically Controlled Machine Tools  |
| NMTBA          | Numerical Control Character Code Cross Reference Chart   |
| NMTBA          | Selecting an Appropriate Numerical Control Programming Method  |
| NEMA 1A1       | Industrial Cell Controller Classification Concepts and Selection Guide   |

**Programmable Controller.**—Frequently referred to as a PC or PLC (the latter term meaning Programmable Logic Controller), a programmable controller is an electronic unit or small computer. PLCs are used to control machinery, equipment, and complete processes, and to assist CNC systems in the control of complex NC machine tools and flexible manufacturing modules and cells. In effect, PLCs are the technological replacements for electrical relay systems.

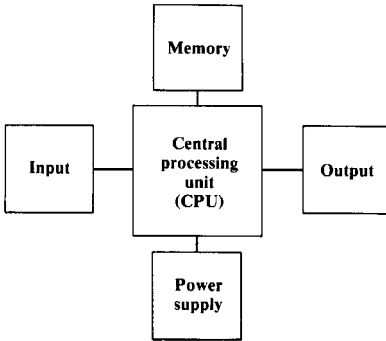


Fig. 1. Programmable Controllers' Four Basic Elements

As shown in Fig. 1, a PLC is composed of four basic elements: the equipment for handling input and output (I/O) signals, the central processing unit (CPU), the power supply, and the memory. Generally, the CPU is a microprocessor and the brain of the PLC. Early PLCs used hardwired special-purpose electronic logic circuits, but most PLCs now being offered are based on microprocessors and have far more logic and control capabilities than was possible with hardwired systems. The CPU scans the status of the input devices continuously, correlates these inputs with the control logic in the memory, and produces the appropriate output responses needed to control the machine or equipment.

Input to a PLC is either discrete or continuous. Discrete inputs may come from push buttons, micro switches, limit switches, photocells, proximity switches or pressure switches, for instance. Continuous inputs may come from sources such as thermocouples, potentiometers, or voltmeters. Outputs from a PLC normally are directed to actuating hardware such as solenoids, solenoid valves, and motor starters. The function of a PLC is to examine the status of an input or set of inputs and, based on this status, actuate or regulate an output or set of outputs.

Digital control logic and sensor input signals are stored in the memory as a series of binary numbers (zeros and ones). Each memory location holds only one "bit" (either 0 or 1) of binary information; however, most of the data in a PLC are used in groups of 8 bits, or bytes. A word is a group of bytes that is operated on at one time by the PLC. The word size in modern PLCs ranges from 8 to 32 bits (1 to 4 bytes), depending on the design of the PLC. In general, the larger the word size that a system is able to operate on (that is, to work on at one time), the faster the system is going to perform. New systems are now beginning to appear that can operate on 64 bits of information at a time.

There are two basic categories of memory: volatile and nonvolatile. Volatile memory loses the stored information when the power is turned off, but nonvolatile memory retains its logic even when power is cut off. A backup battery must be used if the information stored in volatile memory is to be retained. There are six commonly used types of memory. Of these six, random-access memory (RAM) is the most common type because it is the easiest to program and edit. RAM is also the only one of the six common types that is vola-

tile memory. The five nonvolatile memory types are: core memory, read-only memory (ROM), programmable read-only memory (PROM), electronically alterable programmable read-only memory (EAPROM), and electronically erasable programmable read-only memory (EEPROM). EEPROMs are becoming more popular due to their relative ease of programming and their nonvolatile characteristic. ROM is often used as a generic term to refer to the general class of read-only memory types and to indicate that this type of memory is not usually reprogrammed.

More than 90 per cent of the microprocessor PLCs now in the field use RAM memory. RAM is primarily used to store data, which are collected or generated by a process, and to store programs that are likely to change frequently. For example, a part program for machining a workpiece on a CNC machining center is loaded into and stored in RAM. When a different part is to be made, a different program can be loaded in its place. The nonvolatile memory types are usually used to store programs and data that are not expected to be changed. Programs that directly control a specific piece of equipment and contain specific instructions that allow other programs (such as a part program stored in RAM) to access and operate the hardware are usually stored in nonvolatile memory or ROM. The benefit of ROM is that stored programs and data do not have to be reloaded into the memory after the power has been turned off.

PLCs are used primarily with handling systems such as conveyors, automatic retrieval and storage systems, robots, and automatic guided vehicles (AGV), such as are used in flexible manufacturing cells, modules, and systems (see *Flexible Manufacturing Systems (FMS)*, *Flexible Manufacturing Cell*, and *Flexible Manufacturing Module*). PLCs are also to be found in applications as diverse as combustion chamber control, chemical process control, and printed-circuit-board manufacturing.

#### Types of Programmable Controllers

| Type   | No. of I/Os | General Applications  | Math Capability |
|--------|-------------|---|-----------------|
| Mini   | 32          | Replaces relays, timers, and counters.  | Yes             |
| Micro  | 32–64       | Replaces relays, timers, and counters.  | Yes             |
| Small  | 64–128      | Replaces relays, timers, and counters. Used for materials handling, and some process control.   | Yes             |
| Medium | 128–512     | Replaces relays, timers, and counters. Used for materials handling, process control, and data collection.                                   | Yes             |
| Large  | 512+        | Replaces relays, timers, and counters. Master control for other PLCs and cells and for generation of reports. High-level network capability | Yes             |

Types of PLCs may be divided into five groups consisting of micro, mini, small, medium, and large according to the number of I/Os, functional capabilities, and memory capacity. The smaller the number of I/Os and memory capacity, and the fewer the functions, the simpler the PLC. Micro and mini PLCs are usually little more than replacements for relay systems, but larger units may have the functional capabilities of a small computer and be able to handle mathematical functions, generate reports, and maintain high-level communications.



The preceding guidelines have some gray areas because mini, micro, and small PLCs are now available with large memory sizes and functional capacities normally reserved for medium and large PLCs. The accompanying table compares the various types of PLCs and their applications.

Instructions that are input to a PLC are called programs. Four major programming languages are used with PLCs, comprising ladder diagrams, Boolean mnemonics, functional blocks, and English statements. Some PLC systems even support high-level programming languages such as BASIC and PASCAL. Ladder diagrams and Boolean mnemonics are the basic control-level languages. Functional blocks and English statements are considered high-level languages. Ladder diagrams were used with electrical relay systems before these systems were replaced by PLCs and are still the most popular programming method, so they will be discussed further.

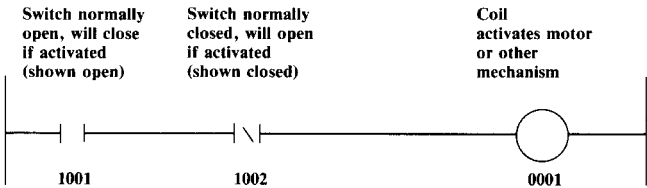


Fig. 2. One Rung on a Ladder Diagram

A ladder diagram consists of symbols, or ladder logic elements, that represent relay contacts or switches and other elements in the control system. One of the more basic symbols represents a normally open switch and is described by the symbol  $\text{—}| \text{—}$ . Another symbol is the normally closed switch, described by the symbol  $\text{—}| \text{—} / \text{—}$ . When the normally open switch is activated, it will close, and when the normally closed switch is activated, it will open. Fig. 2 shows one rung (line) on a ladder diagram. Switch 1001 is normally open and switch 1002 is closed. A symbol for a coil (0001) is shown at the right. If switch 1001 is actuated, it will close. If switch 1002 is not activated, it will stay closed. With the two switches closed, current will flow through the line and energize coil 0001. The coil will activate some mechanism such as an electric motor, a robot, or an NC machine tool, for instance.

As an example, Fig. 3 shows a flexible manufacturing module (FMM), consisting of a turning center (NC lathe), an infeed conveyor, an outfeed conveyor, a robot that moves workpieces between the infeed conveyor, the turning center, and the outfeed conveyor, and a PLC. The arrowed lines show the signals going to and coming from the PLC.

Fig. 4 shows a ladder diagram for a PLC that would control the operations of the FMM by:

- 1) Activating the infeed conveyor to move the workpiece to a position where the robot can pick it up
- 2) Activating the robot to pick up the workpiece and load it into the chuck on the NC lathe
- 3) Activating the robot to remove the finished workpiece and place it on the outfeed conveyor
- 4) Activating the outfeed conveyor to move the workpiece to the next operation

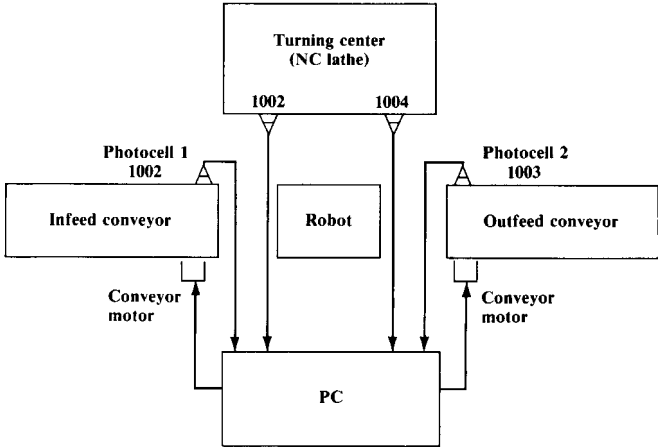


Fig. 3. Layout of a Flexible Manufacturing Module

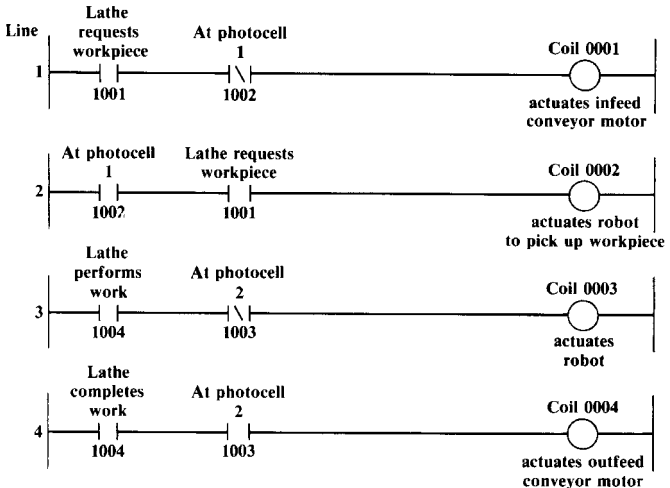


Fig. 4. Portion of a Typical Ladder Diagram for Control of a Flexible Manufacturing Module Including a Turning Center, Conveyors, a Robot, and a Programmable Controller

In Rung 1 of Fig. 4, a request signal for a workpiece from the NC lathe closes the normally open switch 1001. Switch 1002 will remain closed if photocell 1 is not activated, i.e., if it does not detect a workpiece. The signal therefore closes the circuit, energizes the coil, and starts the conveyor motor to bring the next workpiece into position for the robot to grasp.

In Rung 2, switch 1002 (which has been changed in the program of the PLC from a normally closed to a normally open switch) closes when it is activated as photocell 1 detects the workpiece. The signal thus produced, together with the closing of the now normally open switch 1001, energizes the coil, causing the robot to pick up the workpiece from the infeed conveyor.

In Rung 3, switch 1004 on the lathe closes when processing of the part is completed and it is ready to be removed by the robot. Photocell 2 checks to see if there is a space on the conveyor to accept the completed part. If no part is seen by photocell 2, switch 1003 will remain closed, and with switch 1004 closed, the coil will be energized, activating the robot to transfer the completed part to the outfeed conveyor.

Rung 4 shows activation of the output conveyor when a part is to be transferred. Normally open switch 1004 was closed when processing of the part was completed. Switch 1003 (which also was changed from a normally closed to a normally open switch by the program) closes if photocell 2 detects a workpiece. The circuit is then closed and the coil is energized, starting the conveyor motor to move the workpiece clear to make way for the succeeding workpiece.

**Closed-Loop System.**—Also referred to as a servo or feedback system, a closed-loop system is a control system that issues commands to the drive motors of an NC machine. The system then compares the results of these commands as measured by the movement or location of the machine component, such as the table or spindlehead. The feedback devices normally used for measuring movement or location of the component are called resolvers, encoders, Inductosyns, or optical scales. The resolver, which is a rotary analog mechanism, is the least expensive, and has been the most popular since the first NC machines were developed. Resolvers are normally connected to the lead-screws of NC machines. Linear measurement is derived from monitoring the angle of rotation of the leadscrew and is quite accurate.

Encoders also are normally connected to the leadscrew of the NC machine, and measurements are in digital form. Pulses, or a binary code in digital form, are generated by rotation of the encoder, and represent turns or partial turns of the leadscrew. These pulses are well suited to the digital NC system, and encoders have therefore become very popular with such systems. Encoders generally are somewhat more expensive than resolvers.

The Inductosyn (a trade name of Farrand Controls, Inc.) also produces analog signals, but is attached to the slide or fixed part of a machine to measure the position of the table, spindlehead, or other component. The Inductosyn provides almost twice the measurement accuracy of the resolver, but is considerably more expensive, depending on the length of travel to be measured.

Optical scales generally produce information in digital form and, like the Inductosyn, are attached to the slide or fixed part of the machine. Optical scale measurements are more accurate than either resolvers or encoders and, because of their digital nature, are well suited to the digital computer in a CNC system. Like the Inductosyn, optical scales are more costly than either resolvers or encoders.

**Open-Loop System.**—A control system that issues commands to the drive motors of an NC machine and has no means of assessing the results of these commands is known as an open-loop system. In such a system, no provision is made for feedback of information concerning movement of the slide(s), or rotation of the leadscrew(s). Stepping motors are popular as drives for open-loop systems.

**Adaptive Control.**—Measuring performance of a process and then adjusting the process to obtain optimum performance is called adaptive control. In the machine tool field, adaptive control is a means of adjusting the feed and/or speed of the cutting tool, based on sensor feedback information, to maintain optimum cutting conditions. A typical arrangement is seen in Fig. 5. Adaptive control is used primarily for cutting higher-strength materials

such as titanium, although the concept is applicable to the cutting of any material. The costs of the sensors and software have restricted wider use of the feature.

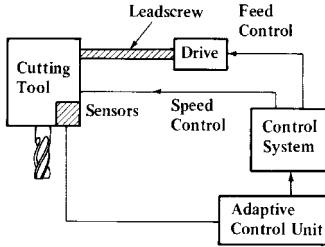


Fig. 5.

The sensors used for adaptive control are generally mounted on the machine drive shafts, tools, or even built into the drive motor. Typically, sensors are used to provide information such as the temperature at the tip of the cutting tool and the cutting force exerted by the tool. The information measured by the sensors is used by the control system computer to analyze the cutting process and adjust the feeds and speeds of the machine to maximize the material removal rate or to optimize another process variable such as surface finish. For the computer to effectively evaluate the process in real time (i.e., while cutting is in progress), details such as maximum allowable tool temperature, maximum allowable cutting force, and information about the drive system need to be integrated into the computer program monitoring the cutting process.

Adaptive control can be used to detect worn, broken, or dull tooling. Ordinarily, the adaptive control system monitors the cutting process to keep the process variables (cutting speed and feed rate, for example) within the proper range. Because the force required to machine a workpiece is lowest when the tool is new or recently resharpened, a steady increase in cutting force during a machining operation, assuming that the feed remains the same, is an indication that the tool is becoming dull (temperature may increase as well). Upon detecting cutting forces that are greater than a predetermined maximum allowable force, the control system causes the feed rate, the cutting speed, or both to be adjusted to maintain the cutting force within allowable limits. If the cutting force cannot be maintained without causing the speed and/or feed rate to be adjusted outside its allowable limits, the machine will be stopped, indicating that the tool is too dull and must be resharpened or replaced.

On some systems, the process monitoring equipment can interface directly with the machine control system, as discussed above. On other systems, the adaptive control is implemented by a separate monitoring system that is independent of the machine control system. These systems include instrumentation to monitor the operations of the machine tool, but do not have the capability to directly change operating parameters, such as feeds and speeds. In addition, this type of control does not require any modification of the existing part programs for control of the machine.

**Flexible Manufacturing Systems (FMS).**—A flexible manufacturing system (FMS) is a computer-controlled machining arrangement that can perform a variety of continuous metal-cutting operations on a range of components without manual intervention. The objective of such a system is to produce components at the lowest possible cost, especially components of which only small quantities are required. Flexibility, or the ability to switch from manufacture of one type of component to another, or from one type of machining to another, without interrupting production, is the prime requirement of such a system. In general, FMS are used for production of numbers of similar parts between 200 and 2000,

although larger quantities are not uncommon. An FMS involves almost all the departments in a company, including engineering, methods, tooling and part programming, planning and scheduling, purchasing, sales and customer service, accounting, maintenance, and quality control. Initial costs of an FMS are estimated as being borne (percentages in parentheses) by machine tools (46.2), materials handling systems (7.7), tooling and fixtures (5.9), pallets (1.9), computer hardware (3.7), computer software (2.2), wash stations (2.8), automatic storage and retrieval systems (6.8), coolant and chip systems (2.4), spares (2), and others (18.4).

FMS are claimed to bring reductions in direct labor (80–90), production planning and control (65), and inspection (70). Materials handling and shop supervision are reduced, and individual productivity is raised. In the materials field, savings are made in tooling (35), scrap and rework (65), and floor space (50). Inventory is reduced and many other costs are avoided. Intangible savings claimed to result from FMS include reduced tooling changeover time, ability to produce complex parts, to incorporate engineering changes more quickly and efficiently than with other approaches, and to make special designs, so that a company can adapt quickly to changing market conditions. Requirements for spare parts with good fit are easily met, and the lower costs combine with higher quality to improve market share. FMS also are claimed to improve morale among workers, leading to higher productivity, with less paper work and more orderly shop operations. Better control of costs and improved cost data help to produce more accurate forecasts of sales and manpower requirements. Response to surges in demand and more economical materials ordering are other advantages claimed with FMS.

Completion of an FMS project is said to average 57 months, including 20 months from the time of starting investigations to the placing of the purchase order. A further 13 months are needed for delivery and a similar period for installation. Debugging and building of production takes about another 11 months before production is running smoothly. FMS are expensive, requiring large capital outlays and investments in management time, software, engineering, and shop support. Efficient operation of FMS also require constant workflow because gaps in the production cycle are very costly.

**Flexible Manufacturing Cell.**—A flexible manufacturing cell usually consists of two or three NC machines with some form of pallet-changing equipment or an industrial robot. Prismatic-type parts, such as would be processed on a machining center, are usually handled on pallets. Cylindrical parts, such as would be machined on an NC lathe, usually are handled with an overhead type of robot. The cell may be controlled by a computer, but is often run by programmable controllers. The systems can be operated without attendants, but the mixture of parts usually must be less than with a flexible manufacturing system (FMS).

**Flexible Manufacturing Module.**—A flexible manufacturing module is defined as a single machining center (or turning center) with some type of automatic materials handling equipment such as multiple pallets for machining centers, or robots for manipulating cylindrical parts and chucks for turning centers. The entire module is usually controlled by one or more programmable logic controllers.

**Axis Nomenclature.**—To distinguish among the different motions, or axes, of a machine tool, a system of letter addresses has been developed. A letter is assigned, for example, to the table of the machine, another to the saddle, and still another to the spindle head. These letter addresses, or axis designations, are necessary for the electronic control system to assign movement instructions to the proper machine element. The assignment of these letter addresses has been standardized on a worldwide basis and is contained in three standards, all of which are in agreement. These standards are EIA RS-267-B, issued by the Electronics Industries Association; AIA NAS-938, issued by the Aerospace Industries Association; and ISO/R 841, issued by the International Organization for Standardization.

The standards are based on a "right-hand rule," which describes the orientation of the motions as well as whether the motions are positive or negative. If a right hand is laid palm up on the table of a vertical milling machine, as shown in Fig. 1, for example, the thumb will point in the positive  $X$ -direction, the forefinger in the positive  $Y$ -direction, and the erect middle finger in the positive  $Z$ -direction, or up. The direction signs are based on the motion of the cutter relative to the workpiece. The movement of the table shown in Fig. 2 is therefore positive, even though the table is moving to the left, because the motion of the cutter relative to the workpiece is to the right, or in the positive direction. The motions are considered from the part programmer's viewpoint, which assumes that the cutter always moves around the part, regardless of whether the cutter or the part moves. The right-hand rule also holds with a horizontal-spindle machine and a vertical table, or angle plate, as shown in Fig. 3. Here, spindle movement back and away from the angle plate, or workpiece, is a positive  $Z$ -motion, and movement toward the angle plate is a negative  $Z$ -motion.

Rotary motions also are governed by a right-hand rule, but the fingers are joined and the thumb is pointed in the positive direction of the axis. Fig. 4 shows the designations of the rotary motions about the three linear axes,  $X$ ,  $Y$ , and  $Z$ . Rotary motion about the  $X$ -axis is designated as  $A$ ; rotary motion about the  $Y$ -axis is  $B$ ; and rotary motion about the  $Z$ -axis is  $C$ . The fingers point in the positive rotary directions. Movement of the rotary table around the  $Y$ -axis shown in Fig. 4 is a  $B$  motion and is common with horizontal machining centers. Here, the view is from the spindle face looking toward the rotary table. Referring, again, to linear motions, if the spindle is withdrawn axially from the work, the motion is a positive  $Z$ . A move toward the work is a negative  $Z$ .

When a second linear motion is parallel to another linear motion, as with the horizontal boring mill seen in Fig. 5, the horizontal motion of the spindle, or quill, is designated as  $Z$  and a parallel motion of the angle plate is  $W$ . A movement parallel to the  $X$ -axis is  $U$  and a movement parallel to the  $Y$ -axis is  $V$ . Corresponding motions are summarized as follows:

| Linear | Rotary | Linear and Parallel |
|--------|--------|---------------------|
| $X$    | $A$    | $U$                 |
| $Y$    | $B$    | $V$                 |
| $Z$    | $C$    | $W$                 |

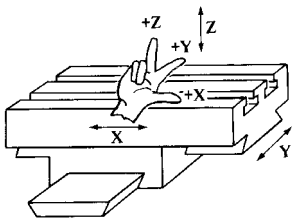


Fig. 1.

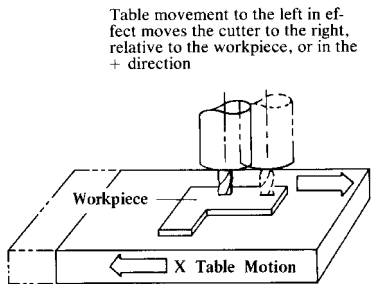


Fig. 2.

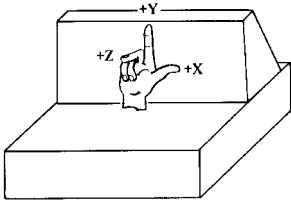


Fig. 3.

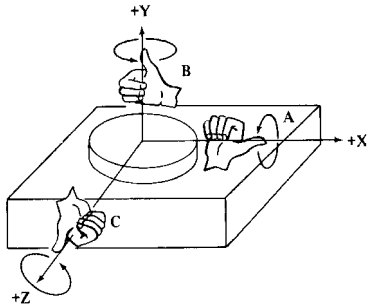


Fig. 4.

Axis designations for a lathe are shown in Fig. 6. Movement of the cross-slide away from the workpiece, or the centerline of the spindle, is noted as a plus  $X$ . Movement toward the workpiece is a minus  $X$ . The middle finger points in the positive  $Z$ -direction; therefore, movement away from the headstock is positive and movement toward the headstock is negative. Generally, there is no  $Y$ -movement.

The machine shown in Fig. 6 is of conventional design, but most NC lathes look more like that shown in Fig. 7. The same right-hand rule applies to this four-axis lathe, on which each turret moves along its own two independent axes. Movement of the outside-diameter or upper turret, up and away from the workpiece, or spindle centerline, is a positive  $X$ -motion, and movement toward the workpiece is a negative  $X$ -motion. The same rules apply to the  $U$ -movement of the inside-diameter, or boring, turret. Movement of the lower turret parallel to the  $Z$ -motion of the outside-diameter turret is called the  $W$ -motion. A popular lathe configuration is to have both turrets on one slide, giving a two-axis system rather than the four-axis system shown.  $X$ - and  $Z$ -motions may be addressed for either of the two heads. Upward movement of the boring head therefore is a positive  $X$ -motion.

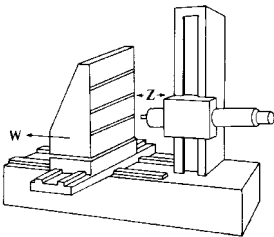


Fig. 5.

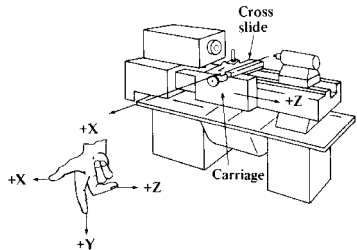
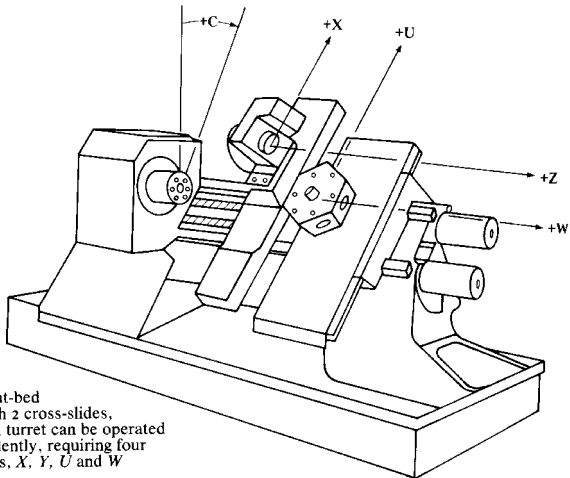


Fig. 6.



On a slant-bed lathe with 2 cross-slides, each tool turret can be operated independently, requiring four addresses,  $X$ ,  $Y$ ,  $U$  and  $W$

Fig. 7.

Axis nomenclature for other machine configurations is shown in Fig. 9. The letters with the prime notation (e.g.,  $X'$ ,  $Y'$ ,  $Z'$ ,  $W'$ ,  $A'$ , and  $B'$ ) mean that the motion shown is positive, because the movement of the cutter with respect to the work is in a positive direction. In these instances, the workpiece is moving rather than the cutter.

**Total Indicator Reading (TIR).**—Total indicator reading is used as a measure of the range of machine tool error. TIR is particularly useful for describing the error in a machine tool spindle, referred to as runout. As shown in Fig. 8, there are two types of runout: axial and radial, which can be measured with a dial indicator. Axial runout refers to the wobble of a spindle and is measured at the spindle face. Radial runout is the range of movement of the spindle centerline and is measured on the side of the spindle or quill.

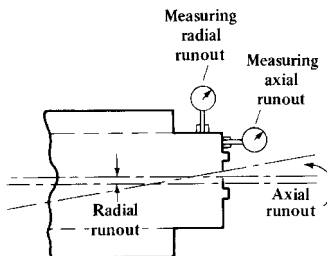


Fig. 8.



NUMERICAL CONTROL

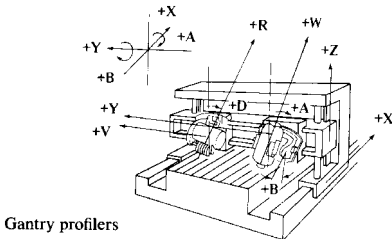
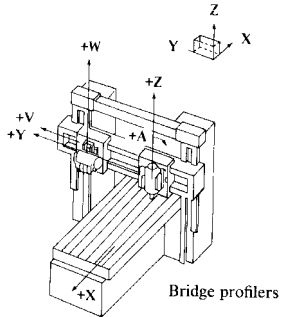
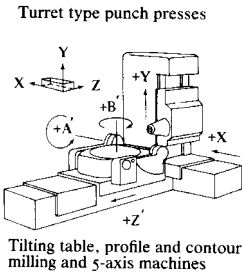
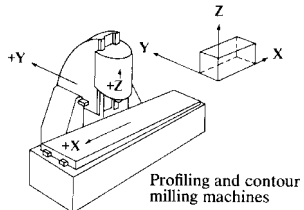
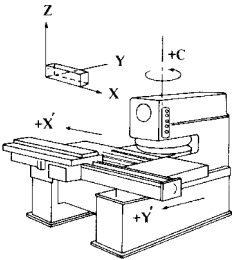
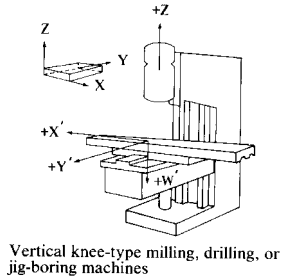
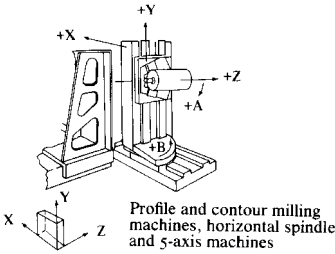


Fig. 9.

## NUMERICAL CONTROL PROGRAMMING

**Programming.**—A numerical control (NC) program is a list of instructions (commands) that completely describes, in sequence, every operation to be carried out by a machine. When a program is run, each instruction is interpreted by the machine controller, which causes an action such as starting or stopping of a spindle or coolant, changing of spindle speed or rotation, or moving a table or slide a specified direction, distance, or speed. The form that program instructions can take, and how programs are stored and/or loaded into the machine, depends on the individual machine/control system. However, program instructions must be in a form (language) that the machine controller can understand.

A programming language is a system of symbols, codes, and rules that describes the manner in which program instructions can be written. One of the earliest and most widely recognized numerical control programming languages is based on the Standard ANSI/EIA RS-274-D-1980. The standard defines a recommended data format and codes for sending instructions to machine controllers. Although adherence to the standard is not mandatory, most controller manufacturers support it and most NC machine controllers (especially controllers on older NC machines using tape input) can accept data in a format that conforms, at least in part, with the recommended codes described in the RS-274-D standard. Most newer controllers also accept instructions written in proprietary formats offered (specified) by the controller's manufacturer.

One of the primary benefits of a standardized programming format is easy transfer of programs from one machine to another, but even standardized code formats such as RS-274-D are implemented differently on different machines. Consequently, a program written for one machine may not operate correctly on another machine without some modification of the program. On the other hand, proprietary formats are attractive because of features that are not available using the standardized code formats. For example, a proprietary format may make available certain codes that allow a programmer, with only a few lines of code, to program complex motions that would be difficult or even impossible to do in the standard language. The disadvantage of proprietary formats is that transferring programs to another machine may require a great deal of program modification or even complete rewriting. Generally, with programs written in a standardized format, the modifications required to get a program written for one machine to work on another machine are not extensive.

In programming, before describing the movement of any machine part, it is necessary to establish a coordinate system(s) as a reference frame for identifying the type and direction of the motion. A description of accepted terminology used worldwide to indicate the types of motion and the orientation of machine axes is contained in a separate section (Axis Nomenclature). Part geometry is programmed with reference to the same axes as are used to describe motion.

*Manual data input* (MDI) permits the machine operator to insert machining instructions directly into the NC machine control system via push buttons, pressure pads, knobs, or other arrangements. MDI has been available since the earliest NC machines were designed, but the method was less efficient than tape for machining operations and was used primarily for setting up the NC machine. Computer numerical control (CNC) systems, with their canned cycles and other computing capabilities, have now made the MDI concept more feasible and for some work MDI may be more practical than preparing a program. The choice depends very much on the complexity of the machining work to be done and, to a lesser degree, on the skill of the person who prepares the program.

*Conversational part programming* is a form of MDI that requires the operator or programmer to answer a series of questions displayed on the control panel of the CNC. The operator replies to questions that describe the part, material, tool and machine settings, and machining operations by entering numbers that identify the material, blank size and thickness or diameter, tool definitions, and other required data. Depending on capability, some

controls can select the required spindle speed and feed rate automatically by using a materials look-up table; other systems request the appropriate feed and speed data. Tool motions needed to machine a part are described by selecting a linear or circular motion programming mode and entering endpoint and intersection coordinates of lines and radius, diameter, tangent points, and directions of arcs and circles (with some controllers, intersection and tangent points are calculated automatically). Machined elements such as holes, slots, and bolt circles are entered by selecting the appropriate tool and describing its action, or with "canned routines" built into the CNC to perform specific machining operations. On some systems, if a feature is once described, it can be copied and/or moved by: translation (copy and/or move), rotation about a point, mirror image (copy and rotate about an axis), and scaling (copy and change size). On many systems, as each command is entered, a graphic image of the part or operation gives a visual check that the program is producing the intended results. When all the necessary data have been entered, the program is constructed and can be run immediately or saved on tape, floppy disk, or other storage media for later use.

Conversational programming gives complete control of machine operations to the shop personnel, taking advantage of the experience and practical skills of the machine operator/programmer. Control systems that provide conversational programming usually include many built-in routines (fixed or canned cycles) for commonly used machining operations and may also have routines for specialized operations. Built-in routines speed programming because one command may replace many lines of program code that would take considerable time to write. Some built-in cycles allow complex machining operations to be programmed simply by specifying the final component profile and the starting stock size, handling such details as developing tool paths, depth of cut, number of roughing passes, and cutter speed automatically. On turning machines, built-in cycles for reducing diameters, chamfer and radius turning, and cutting threads automatically are common. Although many CNC machines have a conversational programming mode, the programming methods used and the features available are not standardized. Some control systems cannot be programmed from the control panel while another program is running (i.e., while a part is being machined), but those systems that can be thus programmed are more productive because programming does not require the machine to be idle. Conversational programming is especially beneficial in reducing programming time in shops that do most of their part programming from the control panel of the machine.

*Manual part programming* describes the preparation of a part program by manually writing the part program in word addressed format. In the past, this method implied programming without using a computer to determine tool paths, speeds and feeds, or any of the calculations normally required to describe the geometry of a part. Today, however, computers are frequently used for writing and storing the program on disk, as well as for calculations required to program the part. Manual part programming consists of writing codes, in a format appropriate to the machine controller, that instruct the controller to perform a specific action. The most widely accepted form of coding the instructions for numerically controlled machines uses the codes and formats suggested in the ANSI/EIA RS-274-D-1980, standard. This type of programming is sometimes called G-code programming, referring to a commonly used word address used in the RS-274-D standard. Basic details of programming in this format, using the various codes available, are discussed in the next section (G-Code Programming).

*Computer-assisted part programming* (CAPP) uses a computer to help in the preparation of the detailed instructions for operating an NC machine. In the past, defining a curve or complicated surface profile required a series of complex calculations to describe the features in intimate detail. However, with the introduction of the microprocessor as an integral part of the CNC machine, the process of defining many complex shapes has been reduced to the simple task of calling up a canned cycle to calculate the path of the cutter. Most new CNC systems have some graphic programming capability, and many use

graphic images of the part “drawn” on a computer screen. The part programmer moves a cutter about the part to generate the part program or the detailed block format instructions required by the control system. Machining instructions, such as the speed and feed rate, are entered via the keyboard. Using the computer as an assistant is faster and far more accurate than the manual part programming method.

Computer-assisted part programming methods generally can be characterized as either language-based or graphics-based, the distinction between the two methods being primarily in the manner by which the tool paths are developed. Some modern-language-based programming systems, such as Compact II, use interactive alphanumeric input so that programming errors are detected as soon as they are entered. Many of these programming systems are completely integrated with computer graphics and display an image of the part or operation as soon as an instruction is entered. The language-based programming systems are usually based on, or are a variation of, the APT programming language, which is discussed separately within this section (APT Programming).

The choice between computer-assisted part programming and manual part programming depends on the complexity of the part (particularly its geometry) and how many parts need to be programmed. The more complicated the part, the more benefit to be gained by CAPP, and if many parts are to be programmed, even if they are simple ones, the benefits of a computer-aided system are substantial. If the parts are not difficult to program but involve much repetition, computer-assisted part programming may also be preferred. If parts are to be programmed for several different control systems, a high-level part programming language such as APT will make writing the part programs easier. Because almost all machines have some deviations from standard practices, and few control systems use exactly the same programming format, a higher-level language allows the programmer to concentrate primarily on part geometry and machining considerations. The postprocessors (see *Postprocessors* below) for the individual control systems accommodate most of the variations in the programming required. The programmer only needs to write the program; the postprocessor deals with the machine specifics.

*Graphical programming* involves building a two- or three-dimensional model of a part on a computer screen by graphically defining the geometric shapes and surfaces of the part using the facilities of a CAD program. In many cases, depending on features of the CAD software package, the same computer drawing used in the design and drafting stage of a project can also be used to generate the program to produce the part. The graphical entities, such as holes, slots, and surfaces, are linked with additional information required for the specific machining operations needed. Most of the cutter movements (path of the cutter), such as those needed for the generation of pockets and lathe roughing cuts, are handled automatically by the computer. The program may then sort the various machining operations into an efficient sequence so that all operations that can be performed with a particular tool are done together, if possible. The output of graphical part programming is generally an alphanumeric part programming language output file, in a format such as an APT or Compact II file.

The part programming language file can be manually checked, and modified, as necessary before being run, and to help detect errors, many graphics programming systems also include some form of part verification software that simulates machining the part on the computer screen. Nongraphic data, such as feed rates, spindle speeds and coolant on/off, must be typed in by the part programmer or entered from a computer data base at the appropriate points in the program, although some programs prompt for this information when needed. When the part program language file is run or compiled, the result is a center line data (CL data) file describing the part. With most computer-aided part programming output files, the CL data file needs to be processed through a postprocessor (see *Postprocessors* below) to tailor the final code produced to the actual machine being used. Postprocessor output is in a form that can be sent directly to the control system, or can be saved on tape or magnetic media and transferred to the machine tool when necessary. The

graphic image of the part and the alphanumeric output files are saved in separate files so that either can be edited in the future if changes in the part become necessary. Revised files must be run and processed again for the part modifications to be included in the part program. Software for producing part programs is discussed further in the CAD/CAM section.

**Postprocessors.**—A postprocessor is computer software that contains a set of computer instructions designed to tailor the cutter center line location data (CL data), developed by a computerized part programming language, to meet the requirements of a particular machine tool/system combination. Generally, when a machine tool is programmed in a graphical programming environment or any high-level language such as APT, a file is created that describes all movements required of a cutting tool to make the part. The file thus created is run, or compiled, and the result is a list of coordinates (CL data) that describes the successive positions of the cutter relative to the origin of the machine's coordinate system. The output of the program must be customized to fit the input requirements of the machine controller that will receive the instructions. Cutter location data must be converted into a format recognized by the control system, such as G codes and M codes, or into another language or proprietary format recognized by the controller. Generally, some instructions are also added or changed by the programmer at this point.

The lack of standardization among machine tool control systems means that almost all computerized part programming languages require a postprocessor to translate the computer-generated language instructions into a form that the machine controller recognizes. Postprocessors are software and are generally prepared for a fee by the machine tool builder, the control system builder, a third party vendor, or by the user.

### G-Code Programming

Programs written to operate numerical control (NC) machines with control systems that comply with the ANSI/EIA RS-274-D-1980, Standard consist of a series of data blocks, each of which is treated as a unit by the controller and contains enough information for a complete command to be carried out by the machine. Each block is made up of one or more words that indicate to the control system how its corresponding action is to be performed. A word is an ordered set of characters, consisting of a letter plus some numerical digits, that triggers a specific action of a machine tool. The first letter of the word is called the letter address of the word, and is used to identify the word to the control system. For example, X is the letter address of a dimension word that requires a move in the direction of the X-axis, Y is the letter address of another dimension word; and F is the letter address of the feed rate. The assigned letter addresses and their meanings, as listed in ANSI/EIA RS-274-D, are shown in [Table 1](#).

**Format Classification.**—The *format classification sheet* completely describes the format requirements of a control system and gives other important information required to program a particular control including: the type of machine, the format classification shorthand and format detail, a listing of specific letter address codes recognized by the system (for example, G-codes: G01, G02, G17, etc.) and the range of values the available codes may take (S range: 10 to 1800 rpm, for example), an explanation of any codes not specifically assigned by the Standard, and any other unique features of the system.

The *format classification shorthand* is a nine- or ten-digit code that gives the type of system, the number of motion and other words available, the type and format of dimensional data required by the system, the number of motion control channels, and the number of numerically controlled axes of the system. The *format detail* very succinctly summarizes details of the machine and control system. This NC shorthand gives the letter address words and word lengths that can be used to make up a block. The format detail defines the basic features of the control system and the type of machine tool to which it refers. For example, the format detail

**Table 1. Letter Addresses Used in Numerical Control**

| Letter Address | Description   | Refers to                            |
|----------------|---|--------------------------------------|
| A              | Angular dimension about the <i>X</i> -axis. Measured in decimal parts of a degree   | Axis nomenclature                    |
| B              | Angular dimension about the <i>Y</i> -axis. Measured in decimal parts of a degree   | Axis nomenclature                    |
| C              | Angular dimension about the <i>Z</i> -axis. Measured in decimal parts of a degree   | Axis nomenclature                    |
| D              | Angular dimension about a special axis, or third feed function, or tool function for selection of tool compensation               | Axis nomenclature                    |
| E              | Angular dimension about a special axis or second feed function  | Axis nomenclature                    |
| F              | Feed word (code)  | Feed words                           |
| G              | Preparatory word (code)   | Preparatory words                    |
| H              | Unassigned  |                                      |
| I              | Interpolation parameter or thread lead parallel to the <i>X</i> -axis   | Circular interpolation and threading |
| J              | Interpolation parameter or thread lead parallel to the <i>Y</i> -axis   | Circular interpolation and threading |
| K              | Interpolation parameter or thread lead parallel to the <i>Z</i> -axis   | Circular interpolation and threading |
| L              | Unassigned  |                                      |
| M              | Miscellaneous or auxiliary function   | Miscellaneous functions              |
| N              | Sequence number   | Sequence number                      |
| O              | Sequence number for secondary head only   | Sequence number                      |
| P              | Third rapid-traverse dimension or tertiary-motion dimension parallel to <i>X</i>  | Axis nomenclature                    |
| Q              | Second rapid-traverse dimension or tertiary-motion dimension parallel to <i>Y</i>   | Axis nomenclature                    |
| R              | First rapid-traverse dimension or tertiary-motion dimension parallel to <i>Z</i> or radius for constant surface-speed calculation | Axis nomenclature                    |
| S              | Spindle-speed function  | Spindle speed                        |
| T              | Tool function   | Tool function                        |
| U              | Secondary-motion dimension parallel to <i>X</i>   | Axis nomenclature                    |
| V              | Secondary-motion dimension parallel to <i>Y</i>   | Axis nomenclature                    |
| W              | Secondary-motion dimension parallel to <i>Z</i>   | Axis nomenclature                    |
| X              | Primary <i>X</i> -motion dimension  | Axis nomenclature                    |
| Y              | Primary <i>Y</i> -motion dimension  | Axis nomenclature                    |
| Z              | Primary <i>Z</i> -motion dimension  | Axis nomenclature                    |

N4G2X + 24Y + 24Z + 24B24I24J24F31T4M2

specifies that the NC machine is a machining center (has *X*-, *Y*-, and *Z*-axes) and a tool changer with a four-digit tool selection code (T4); the three linear axes are programmed with two digits before the decimal point and four after the decimal point (X + 24Y + 24Z + 24) and can be positive or negative; probably has a horizontal spindle and rotary table (B24

= rotary motion about the Y-axis); has circular interpolation (I24J24); has a feed rate range in which there are three digits before and one after the decimal point (F31); and can handle a four-digit sequence number (N4), two-digit G-words (G2), and two-digit miscellaneous words (M2). The sequence of letter addresses in the format detail is also the sequence in which words with those addresses should appear when used in a block.

The information given in the format shorthand and format detail is especially useful when programs written for one machine are to be used on different machines. Programs that use the variable block data format described in RS-274-D can be used interchangeably on systems that have the same format classification, but for complete program compatibility between machines, other features of the machine and control system must also be compatible, such as the relationships of the axes and the availability of features and control functions.

Control systems differ in the way that the numbers may be written. Most newer CNC machines accept numbers written in a decimal-point format, however, some systems require numbers to be in a fixed-length format that does not use an explicit decimal point. In the latter case, the control system evaluates a number based on the number of digits it has, including zeros. *Zero suppression* in a control system is an arrangement that allows zeros before the first significant figure to be dropped (leading zero suppression) or allows zeros after the last significant figure to be dropped (trailing zero suppression). An X-axis movement of 05.3400, for example, could be expressed as 053400 if represented in the full field format, 53400 (leading zero suppression), or 0534 (trailing zero suppression). With decimal-point programming, the above number is expressed simply as 5.34. To ensure program compatibility between machines, all leading and trailing zeros should be included in numbers unless decimal-point programming is used.

**Sequence Number (N-Word).**—A block normally starts with a sequence number that identifies the block within the part program. Most control systems use a four-digit sequence number allowing step numbers up to N9999. The numbers are usually advanced by fives or tens in order to leave spaces for additional blocks to be inserted later if required. For example, the first block in a program would be N0000, the next block N0005; the next N0010; and so on. The slash character, /, placed in a block, before the sequence number, is called an *optional stop* and causes the block to be skipped over when actuated by the operator. The block that is being worked on by the machine is often displayed on a digital read-out so that the operator may know the precise operation being performed.

**Preparatory Word (G-Word).**—A preparatory word (also referred to as a preparatory function or G-code) consists of the letter address G and usually two digits. The preparatory word is placed at the beginning of a block, normally following the sequence number. Most newer CNC machines allow more than one G-code to be used in a single block, although many of the older systems do not. To ensure compatibility with older machines and with the RS-274-D Standard, only one G-code per block should be used.

The G-word indicates to the control system how to interpret the remainder of the block. For example, G01 refers to linear interpolation and indicates that the words following in the block will move the cutter in a straight line. The G02 code indicates that the words following in the block will move the cutter in a clockwise circular path. A G-word can completely change the normal meaning of other words in a block. For example, X is normally a dimension word that describes a distance or position in the X-direction. However, if a block contains the G04 word, which is the code for a dwell, the X word represents the time, in seconds, that the machine is to dwell.

The majority of G-codes are designated as modal, which means that once used, the code remains in effect for succeeding blocks unless it is specifically changed or canceled. Therefore, it is not necessary to include modal G-codes in succeeding blocks except to change or cancel them. Unless a G-code is modal, it is only effective within its designated block for the operation it defines. [Table 2](#), G-Code Addresses, lists standardized G-code addresses and modality.

Table 2. G-Code Addresses

| Code                            | Description   | Code                     | Description   |
|---------------------------------|---|--------------------------|---|
| G00                             | <sup>abs</sup> Rapid traverse, point to point (M,L)   | G34                      | <sup>abs</sup> Thread cutting, increasing lead (L)  |
| G01                             | <sup>abc</sup> Linear interpolation (M,L)   | G35                      | <sup>abc</sup> Thread cutting, decreasing lead (L)  |
| G02                             | <sup>abc</sup> Circular interpolation—clockwise movement (M,L)  | G36-G39                  | <sup>ab</sup> Permanently unassigned  |
| G03                             | <sup>abc</sup> Circular interpolation—counter-clockwise movement (M,L)  | G36                      | <sup>c</sup> Used for automatic acceleration and deceleration when the blocks are short (M,L)                           |
| G04                             | <sup>ab</sup> Dwell—a programmed time delay (M,L)   | G37, G37.1, G37.2, G37.3 | Used for tool gaging (M,L)  |
| G05                             | <sup>ab</sup> Unassigned  | G37.4                    |   |
| G06                             | <sup>abc</sup> Parabolic interpolation (M,L)  | G38                      | Used for probing to measure the diameter and center of a hole (M)   |
| G07                             | <sup>c</sup> Used for programming with cylindrical diameter values (L)  | G38.1                    | Used with a probe to measure the parallelness of a part with respect to an axis (M)                                     |
| G08                             | <sup>ab</sup> Programmed acceleration (M,L). <sup>d</sup> Also for lathe programming with cylindrical diameter values | G39, G39.1               | Generates a nonprogrammed block to improve cycle time and corner cutting quality when used with cutter compensation (M) |
| G09                             | <sup>ab</sup> Programmed deceleration (M,L). <sup>d</sup> Used to stop the axis movement at a precise location (M,L)  | G39                      | Tool tip radius compensation used with linear generated block (L)   |
| G10-G12                         | <sup>ab</sup> Unassigned. <sup>d</sup> Sometimes used for machine lock and unlock devices                             | G39.1                    | Tool tip radius compensation used with circular generated block (L)   |
| G13-G16                         | <sup>ac</sup> Axis selection (M,L)  | G40                      | <sup>abc</sup> Cancel cutter compensation/offset (M)  |
| G13-G16                         | <sup>b</sup> Unassigned   | G41                      | <sup>abc</sup> Cutter compensation, left (M)  |
| G13                             | Used for computing lines and circle intersections (M,L)   | G42                      | <sup>abc</sup> Cutter compensation, right (M)   |
| G14, G14.1                      | <sup>c</sup> Used for scaling (M,L)   | G43                      | <sup>abc</sup> Cutter offset, inside corner (M,L)   |
| G15-G16                         | <sup>c</sup> Polar coordinate programming (M)   | G44                      | <sup>abc</sup> Cutter offset, outside corner (M,L)  |
| G15, G16.1                      | <sup>c</sup> Cylindrical interpolation—C axis (L)   | G45-G49                  | <sup>ab</sup> Unassigned  |
| G16.2                           | <sup>c</sup> End face milling—C axis (L)  | G50-G59                  | <sup>a</sup> Reserved for adaptive control (M,L)  |
| G17-G19                         | <sup>abc</sup> X-Y, X-Z, Y-Z plane selection, respectively (M,L)  | G50                      | <sup>bb</sup> Unassigned  |
| G20                             | Unassigned  | G50.1                    | <sup>c</sup> Cancel mirror image (M,L)  |
| G22-G32                         | <sup>ab</sup> Unassigned  | G51.1                    | <sup>c</sup> Program mirror image (M,L)   |
| G22-G23                         | <sup>c</sup> Defines safety zones in which the machine axis may not enter (M,L)                                       | G52                      | <sup>b</sup> Unassigned   |
| G22.1, G233.1                   | <sup>c</sup> Defines safety zones in which the cutting tool may not exit (M,L)  | G52                      | Used to offset the axes with respect to the coordinate zero point (see G92) (M,L)                                       |
| G24                             | <sup>c</sup> Single-pass rough-facing cycle (L)   | G53                      | <sup>bc</sup> Datum shift cancel  |
| G27-G29                         | Used for automatically moving to and returning from home position (M,L)   | G53                      | <sup>c</sup> Call for motion in the machine coordinate system (M,L)   |
| G30                             | Return to an alternate home position (M,L)  | G54-G59                  | <sup>bc</sup> Datum shifts (M,L)  |
| G31, G31.1, G31.2, G31.3, G31.4 | External skip function, moves an axis on a linear path until an external signal aborts the move (M,L)                 | G54-G59.3                | <sup>c</sup> Allows for presetting of work coordinate systems (M,L)   |
| G33                             | <sup>abc</sup> Thread cutting, constant lead (L)  | G60-G62                  | <sup>abc</sup> Unassigned   |



Table 2. (Continued) G-Code Addresses

| Code    | Description   | Code   | Description  |
|---------|---|--------|--|
| G61     | c Modal equivalent of G09 except that rapid moves are not taken to a complete stop before the next motion block is executed (M,L)     | G80    | abc Cancel fixed cycles  |
| G62     | c Automatic corner override, reduces the feed rate on an inside corner cut (M,L)  | G81    | abc Drill cycle, no dwell and rapid out (M,L)  |
| G63     | a Unassigned  | G82    | abc Drill cycle, dwell and rapid out (M,L)   |
| G63     | bc Tapping mode (M,L)   | G83    | abc Deep hole peck drilling cycle (M,L)  |
| G64–G69 | abc Unassigned  | G84    | abc Right-hand tapping cycle (M,L)   |
| G64     | c Cutting mode, usually set by the system installer (M,L)   | G84.1  | c Left-hand tapping cycle (M,L)  |
| G65     | c Calls for a parametric macro (M,L)  | G85    | abc Boring cycle, no dwell, feed out (M,L)   |
| G66     | c Calls for a parametric macro. Applies to motion blocks only (M,L)   | G86    | abc Boring cycle, spindle stop, rapid out (M,L)  |
| G66.1   | c Same as G66 but applies to all blocks (M,L)   | G87    | abc Boring cycle, manual retraction (M,L)  |
| G67     | c Stop the modal parametric macro (see G65, G66, G66.1) (M,L)   | G88    | abc Boring cycle, spindle stop, manual retraction (M,L)  |
| G68     | c Rotates the coordinate system (i.e., the axes) (M)  | G88.1  | Pocket milling (rectangular and circular), roughing cycle (M)  |
| G69     | c Cancel axes rotation (M)  | G88.2  | Pocket milling (rectangular and circular), finish cycle (M)  |
| G70     | abc Inch programming (M,L)  | G88.3  | Post milling, roughs out material around a specified area (M)  |
| G71     | abc Metric programming (M,L)  | G88.4  | Post milling, finish cuts material around a post (M)   |
| G72     | ac Circular interpolation CW (three-dimensional) (M)  | G88.5  | Hemisphere milling, roughing cycle (M)   |
| G72     | b Unassigned  | G88.6  | Hemisphere milling, finishing cycle (M)  |
| G72     | c Used to perform the finish cut on a turned part along the Z-axis after the roughing cuts initiated under G73, G74, or G75 codes (L) | G89    | abc Boring cycle, dwell and feed out (M,L)   |
| G73     | b Unassigned  | G89.1  | Irregular pocket milling, roughing cycle (M)   |
| G73     | c Deep hole peck drilling cycle (M); OD and ID roughing cycle, running parallel to the Z-axis (L)                                     | G89.2  | Irregular pocket milling, finishing cycle (M)  |
| G74     | ac Cancel multiquadrant circular interpolation (M,L)  | G90    | abc Absolute dimension input (M,L)   |
| G74     | bc Move to home position (M,L)  | G91    | abc Incremental dimension input (M,L)  |
| G74     | c Left-hand tapping cycle (M)   | G92    | abc Preload registers, used to shift the coordinate axes relative to the current tool position (M,L) |
| G74     | Rough facing cycle (L)  | G93    | abc Inverse time feed rate (velocity/distance) (M,L)   |
| G75     | ac Multiquadrant circular interpolation (M,L)   | G94    | c Feed rate in inches or millimeters per minute (ipm or mpm) (M,L)                                   |
| G75     | b Unassigned  | G95    | abc Feed rate given directly in inches or millimeters per revolution (ipr or mpr) (M,L)              |
| G75     | Roughing routine for castings or forgings (L)   | G96    | abc Maintains a constant surface speed, feet (meters) per minute (L)                                 |
| G76–G79 | ab Unassigned   | G97    | abc Spindle speed programmed in rpm (M,L)  |
|         |   | G98–99 | ab Unassigned  |

<sup>a</sup> Adheres to ANSI/EIA RS-274-D;

<sup>b</sup> Adheres to ISO 6983/1,2,3 Standards; where both symbols appear together, the ANSI/EIA and ISO standard codes are comparable;

<sup>c</sup> This code is modal. All codes that are not identified as modal are nonmodal, when used according to the corresponding definition.

<sup>d</sup> Indicates a use of the code that does not conform with the Standard.

Symbols following a description: (M) indicates that the code applies to a mill or machining center; (L) indicates that the code applies to turning machines; (M,L) indicates that the code applies to both milling and turning machines.

Codes that appear more than once in the table are codes that are in common use, but are not defined by the Standard or are used in a manner that is different than that designated by the Standard (e.g., see G61).

Most systems that support the RS-274-D Standard codes do not use all the codes available in the Standard. Unassigned G-words in the Standard are often used by builders of machine tool control systems for a variety of special purposes, sometimes leading to confusion as to the meanings of unassigned codes. Even more confusing, some builders of systems and machine tools use the less popular standardized codes for other than the meaning listed in the Standard. For these reasons, machine code written specifically for one machine/controller will not necessarily work correctly on another machine controller without modification.

*Dimension words* contain numerical data that indicate either a distance or a position. The dimension units are selected by using G70 (inch programming) or G71 (metric programming) code. G71 is canceled by a G70 command, by miscellaneous functions M02 (end of program), or by M30 (end of data). The dimension words immediately follow the G-word in a block and on multiaxis machines should be placed in the following order: X, Y, Z, U, V, W, P, Q, R, A, B, C, D, and E.

*Absolute programming* (G90) is a method of defining the coordinate locations of points to which the cutter (or workpiece) is to move based on the fixed machine zero point. In Fig. 1, the X–Y coordinates of P1 are  $X = 1.0$ ,  $Y = 0.5$  and the coordinates of P2 are  $X = 2.0$ ,  $Y = 1.1$ . To indicate the movement of the cutter from one point to another when using the absolute coordinate system, only the coordinates of the destination point P2 are needed.

*Incremental programming* (G91) is a method of identifying the coordinates of a particular location in terms of the distance of the new location from the current location. In the example shown in Fig. 2, a move from P1 to P2 is written as  $X + 1.0$ ,  $Y + 0.6$ . If there is no movement along the Z-axis, Z is zero and normally is not noted. An X–Y incremental move from P2 to P3 in Fig. 2 is written as  $X + 1.0$ ,  $Y - 0.7$ .

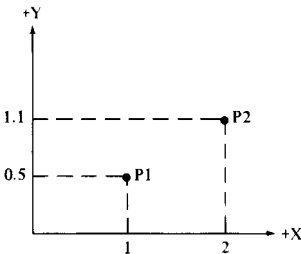


Fig. 1.

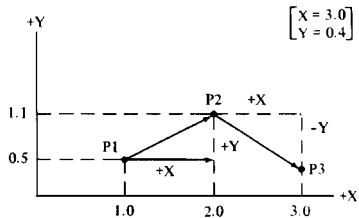


Fig. 2.

Most CNC systems offer both absolute and incremental part programming. The choice is handled by G-code G90 for absolute programming and G91 for incremental programming. G90 and G91 are both modal, so they remain in effect until canceled.

The G92 word is used to preload the registers in the control system with desired values. A common example is the loading of the axis-position registers in the control system for a lathe. Fig. 3 shows a typical home position of the tool tip with respect to the zero point on the machine. The tool tip here is registered as being 15.0000 inches in the Z-direction and 4.5000 inches in the X-direction from machine zero. No movement of the tool is required. Although it will vary with different control system manufacturers, the block to accomplish the registration shown in Fig. 3 will be approximately:

N0050 G92 X4.5 Z15.0

**Miscellaneous Functions (M-Words).**—Miscellaneous functions, or M-codes, also referred to as auxiliary functions, constitute on-off type commands. M functions are used to control actions such as starting and stopping of motors, turning coolant on and off, changing tools, and clamping and unclamping parts. M functions are made up of the letter M followed by a two-digit code. Table 3 lists the standardized M-codes, however, the functions available will vary from one control system to another. Most systems provide fewer M functions than the complete list and may use some of the unassigned codes to provide additional functions that are not covered by the Standard. If an M-code is used in a block, it follows the T-word and is normally the last word in the block.

**Table 3. Miscellaneous Function Words from ANSI/EIA RS-274-D**

| Code       | Description  |
|------------|--|
| M00        | Automatically <i>stops</i> the machine. The operator must push a button to continue with the remainder of the program.   |
| M01        | An <i>optional stop</i> acted upon only when the operator has previously signaled for this command by pushing a button. The machine will automatically stop when the control system senses the M01 code. |
| M02        | This <i>end-of-program</i> code stops the machine when all commands in the block are completed. May include rewinding of tape.   |
| M03        | Start <i>spindle rotation</i> in a <i>clockwise</i> direction—looking out from the spindle face.   |
| M04        | Start <i>spindle rotation</i> in a <i>counterclockwise</i> direction—looking out from the spindle face.  |
| M05        | <i>Stop</i> the spindle in a normal and efficient manner.  |
| M06        | Command to <i>change a tool</i> (or tools) manually or automatically. Does not cover tool selection, as is possible with the T-words.  |
| M07 to M08 | M07 (coolant 2) and M08 (coolant 1) are codes to <i>turn on coolant</i> . M07 may control <i>flood</i> coolant and M08 <i>mist</i> coolant.  |
| M09        | Shuts off the coolant.   |
| M10 to M11 | M10 applies to automatic <i>clamping</i> of the machine slides, workpiece, fixture spindle, etc. M11 is an unclamping code.  |
| M12        | An inhibiting code used to synchronize multiple sets of axes, such as a four-axis lathe having two independently operated heads (turrets).   |
| M13        | Starts <i>CCW spindle</i> motion and <i>coolant on</i> in the same command.  |
| M14        | Starts <i>CCW spindle</i> motion and <i>coolant on</i> in the same command.  |
| M15 to M16 | Rapid traverse of feed motion in either the +(M15) or -(M16) direction.  |
| M17 to M18 | Unassigned.  |
| M19        | Oriented spindle stop. Causes the spindle to stop at a predetermined angular position.   |
| M20 to M29 | Permanently unassigned.  |
| M30        | An <i>end-of-tape</i> code similar to M02, but M30 will also rewind the tape; also may switch automatically to a second tape reader.   |
| M31        | A command known as <i>interlock bypass</i> for temporarily circumventing a normally provided interlock.  |

**Table 3. (Continued) Miscellaneous Function Words from ANSI/EIA RS-274-D**

| Code       | Description   |
|------------|---|
| M32 to M35 | Unassigned.   |
| M36 to M39 | Permanently unassigned.   |
| M40 to M46 | Used to signal gear changes if required at the machine; otherwise, unassigned.  |
| M47        | Continues program execution from the start of the program unless inhibited by an interlock signal.                    |
| M48 to M49 | M49 deactivates a manual spindle or feed override and returns the parameter to the programmed value; M48 cancels M49. |
| M50 to M57 | Unassigned.   |
| M58 to M59 | Holds the rpm constant at the value in use when M59 is initiated; M58 cancels M59.                                    |
| M60 to M89 | Unassigned.   |
| M90 to M99 | Reserved for use by the machine user.   |

**Feed Function (F-Word).**—F-word stands for feed-rate word or feed rate. The meaning of the feed word depends on the system of units in use and the feed mode. For example, F15 could indicate a feed rate of 0.15 inch (or millimeter) per revolution or 15 inches (or millimeters) per minute, depending on whether G70 or G71 is used to indicate inch or metric programming and whether G94 or G95 is used to specify feed rate expressed as inches (or mm) per minute or revolution. The G94 word is used to indicate inches/minute (ipm) or millimeters/minute (mmpm) and G95 is used for inches/revolution (ipr) or millimeters/revolution (mmpr). The default system of units is selected by G70 (inch programming) or G71 (metric programming) prior to using the feed function. The feed function is modal, so it stays in effect until it is changed by setting a new feed rate. In a block, the feed function is placed immediately following the dimension word of the axis to which it applies or immediately following the last dimension word to which it applies if it is used for more than one axis.

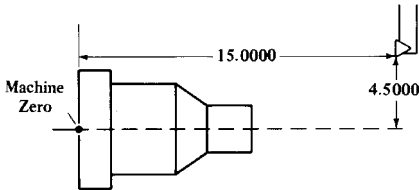


Fig. 3.

In turning operations, when G95 is used to set a constant feed rate per revolution, the spindle speed is varied to compensate for the changing diameter of the work — the spindle speed increases as the working diameter decreases. To prevent the spindle speed from increasing beyond a maximum value, the S-word, see *Spindle Function (S-Word)*, is used to specify the maximum allowable spindle speed before issuing the G95 command. If the spindle speed is changed after the G95 is used, the feed rate is also changed accordingly. If G94 is used to set a constant feed per unit of time (inches or millimeters per minute), changes in the spindle speed do not affect the feed rate.

Feed rates expressed in inches or millimeters per revolution can be converted to feed rates in inches or millimeters per minute by multiplying the feed rate by the spindle speed in revolutions per minute:  $\text{feed/minute} = \text{feed/revolution} \times \text{spindle speed in rpm}$ . Feed rates for milling cutters are sometimes given in inches or millimeters per tooth. To convert feed

per tooth to feed per revolution, multiply the feed rate per tooth by the number of cutter teeth: feed/revolution = feed/tooth  $\times$  number of teeth.

For certain types of cuts, some systems require an inverse-time *feed command* that is the reciprocal of the time in minutes required to complete the block of instructions. The feed command is indicated by a G93 code followed by an F-word value found by dividing the feed rate, in inches (millimeters) or degrees per minute, by the distance moved in the block: feed command = feed rate/distance = (distance/time)/distance = 1/time.

*Feed-rate override* refers to a control, usually a rotary dial on the control system panel, that allows the programmer or operator to override the programmed feed rate. Feed-rate override does not change the program; permanent changes can only be made by modifying the program. The range of override typically extends from 0 to 150 per cent of the programmed feed rate on CNC machines; older hardwired systems are more restrictive and most cannot be set to exceed 100 per cent of the preset rate.

**Spindle Function (S-Word).**—An S-word specifies the speed of rotation of the spindle. The spindle function is programmed by the address S followed by the number of digits specified in the format detail (usually a four-digit number). Two G-codes control the selection of spindle speed input: G96 selects a constant cutting speed in surface feet per minute (sfm) or meters per minute (mpm) and G97 selects a constant spindle speed in revolutions per minute (rpm).

In turning, a constant spindle speed (G97) is applied for threading cycles and for machining parts in which the diameter remains constant. Feed rate can be programmed with either G94 (inches or millimeters per minute) or G95 (inches or millimeters per revolution) because each will result in a constant cutting speed to feed relationship.

G96 is used to select a constant cutting speed (i.e., a constant surface speed) for facing and other cutting operations in which the diameter of the workpiece changes. The spindle speed is set to an initial value specified by the S-word and then automatically adjusted as the diameter changes so that a constant surface speed is maintained. The control system adjusts spindle speed automatically, as the working diameter of the cutting tool changes, decreasing spindle speed as the working diameter increases or increasing spindle speed as the working diameter decreases. When G96 is used for a constant cutting speed, G95 in a succeeding block maintains a constant feed rate per revolution.

Speeds given in surface feet or meters per minute can be converted to speeds in revolutions per minute (rpm) by the formulas:

$$\text{rpm} = \frac{\text{sfm} \times 12}{\pi \times d} \qquad \text{rpm} = \frac{\text{mpm} \times 1000}{\pi \times d}$$

where  $d$  is the diameter, in inches or millimeters, of the part on a lathe or of the cutter on a milling machine; and  $\pi$  is equal to 3.14159.

**Tool Function (T-Word).**—The T-word calls out the tool that is to be selected on a machining center or lathe having an automatic tool changer or indexing turret. On machines without a tool changer, this word causes the machine to stop and request a tool change. This word also specifies the proper turret face on a lathe. The word usually is accompanied by several numbers, as in T0101, where the first pair of numbers refers to the tool number (and carrier or turret if more than one) and the second pair of numbers refers to the tool offset number. Therefore, T0101 refers to tool 1, offset 1.

Information about the tools and the tool setups is input to the CNC system in the form of a *tool data table*. Details of specific tools are transferred from the table to the part program via the T-word. The tool nose radius of a lathe tool, for example, is recorded in the tool data table so that the necessary tool path calculations can be made by the CNC system. The miscellaneous code M06 can also be used to signal a tool change, either manually or automatically.

Compensation for variations in the tool nose radius, particularly on turning machines, allows the programmer to program the part geometry from the drawing and have the tool follow the correct path in spite of variations in the tool nose shape. Typical of the data required, as shown in Fig. 4, are the nose radius of the cutter, the X and Z distances from the gage point to some fixed reference point on the turret, and the orientation of the cutter (tool tip orientation code), as shown in Fig. 5. Details of nose radius compensation for numerical control is given in a separate section (Indexable Insert Holders for NC).

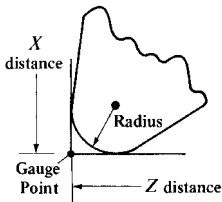
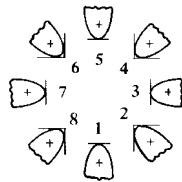


Fig. 4.



Tool tip orientation codes

Fig. 5.

*Tool offset*, also called cutter offset, is the amount of cutter adjustment in a direction parallel to the axis of a tool. Tool offset allows the programmer to accommodate the varying dimensions of different tooling by assuming (for the sake of the programming) that all the tools are identical. The actual size of the tool is totally ignored by the programmer who programs the movement of the tools to exactly follow the profile of the workpiece shape. Once tool geometry is loaded into the tool data table and the cutter compensation controls of the machine activated, the machine automatically compensates for the size of the tools in the programmed movements of the slide. In gage length programming, the tool length and tool radius or diameter are included in the program calculations. Compensation is then used only to account for minor variations in the setup dimensions and tool size.

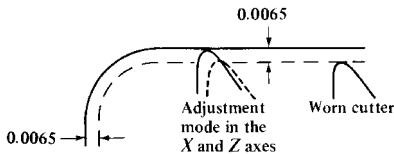


Fig. 6.

Customarily, the tool offset is used in the beginning of a program to initialize each individual tool. Tool offset also allows the machinist to correct for conditions, such as tool wear, that would cause the location of the cutting edge to be different from the programmed location. For example, owing to wear, the tool tip in Fig. 6 is positioned a distance of 0.0065 inch from the location required for the work to be done. To compensate for this wear, the operator (or part programmer), by means of the CNC control panel, adjusts the tool tip with reference to the X- and Z-axes, moving the tool closer to the work by

0.0065 inch throughout its traverse. The tool offset number causes the position of the cutter to be displaced by the value assigned to that offset number.

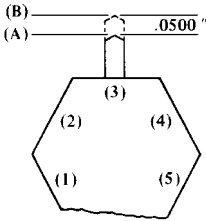


Fig. 7.

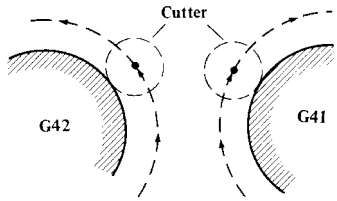


Fig. 8.

Changes to the programmed positions of cutting tool tip(s) can be made by *tool length offset* programs included in the control system. A dial or other means is generally provided on milling, drilling, and boring machines, and machining centers, allowing the operator or part programmer to override the programmed axial, or Z-axis, position. This feature is particularly helpful when setting the lengths of tools in their holders or setting a tool in a turret, as shown in Fig. 7, because an exact setting is not necessary. The tool can be set to an approximate length and the discrepancy eliminated by the control system.

The amount of offset may be determined by noting the amount by which the cutter is moved manually to a fixed point on the fixture or on the part, from the programmed Z-axis location. For example, in Fig. 7, the programmed Z-axis motion results in the cutter being moved to position A, whereas the required location for the tool is at B. Rather than resetting the tool or changing the part program, the tool length offset amount of 0.0500 inch is keyed into the control system. The 0.0500-inch amount is measured by moving the cutter tip manually to position B and reading the distance moved on the readout panel. Thereafter, every time that cutter is brought into the machining position, the programmed Z-axis location will be overridden by 0.0500 inch.

Manual adjustment of the cutter center path to correct for any variance between nominal and actual cutter radius is called *cutter compensation*. The net effect is to move the path of the center of the cutter closer to, or away from, the edge of the workpiece, as shown in Fig. 8. The compensation may also be handled via a tool data table.

When cutter compensation is used, it is necessary to include in the program a G41 code if the cutter is to be to the left of the part and a G42 code if to the right of the part, as shown in Fig. 8. A G40 code cancels cutter compensation. Cutter compensation with earlier hardware systems was expensive, very limited, and usually held to  $\pm 0.0999$  inch. The range for cutter compensation with CNC control systems can go as high as  $\pm 999.9999$  inches, although adjustments of this magnitude are unlikely to be required.

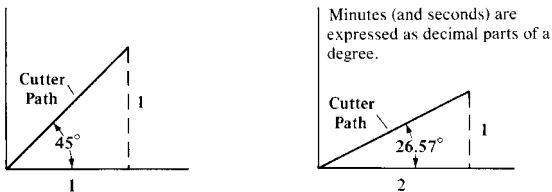


Fig. 9.

**Linear Interpolation.**—The ability of the control system to guide the workpiece along a straight-line path at an angle to the slide movements is called linear interpolation. Move-

ments of the slides are controlled through simultaneous monitoring of pulses by the control system. For example, if monitoring of the pulses for the  $X$ -axis of a milling machine is at the same rate as for the  $Y$ -axis, the cutting tool will move at a 45-degree angle relative to the  $X$ -axis. However, if the pulses are monitored at twice the rate for the  $X$ -axis as for the  $Y$ -axis, the angle that the line of travel will make with the  $X$ -axis will be 26.57 degrees (tangent of 26.57 degrees =  $\frac{1}{2}$ ), as shown in Fig. 9. The data required are the distances traveled in the  $X$ - and  $Y$ -directions, and from these data, the control system will generate the straight line automatically. This monitoring concept also holds for linear motions along three axes. The required G-code for linear interpolation blocks is G01. The code is modal, which means that it will hold for succeeding blocks until it is changed.

**Circular Interpolation.**—A simplified means of programming circular arcs in one plane, using one block of data, is called circular interpolation. This procedure eliminates the need to break the arc into straight-line segments. Circular interpolation is usually handled in one plane, or two dimensions, although three-dimensional circular interpolation is described in the Standards. The plane to be used is selected by a G or preparatory code. In Fig. 10, G17 is used if the circle is to be formed in the  $X$ - $Y$  plane,

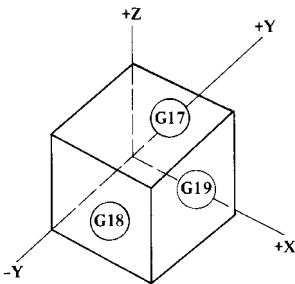


Fig. 10.

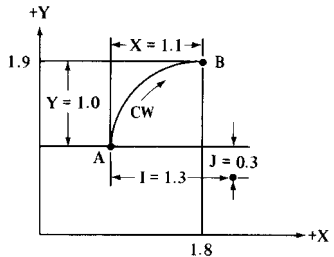


Fig. 11.

G18 if in the  $X$ - $Z$  plane, and G19 if in the  $Y$ - $Z$  plane. Often the control system is preset for the circular interpolation feature to operate in only one plane (e.g., the  $X$ - $Y$  plane for milling machines or machining centers or the  $X$ - $Z$  plane for lathes), and for these machines, the G-codes are not necessary.

A circular arc may be described in several ways. Originally, the RS-274 Standard specified that, with incremental programming, the block should contain:

1) A G-code describing the direction of the arc, G02 for clockwise (CW), and G03 for counterclockwise (CCW).

2) Directions for the component movements around the arc parallel to the axes. In the example shown in Fig. 11, the directions are  $X = +1.1$  inches and  $Y = +1.0$  inch. The signs are determined by the direction in which the arc is being generated. Here, both  $X$  and  $Y$  are positive.

3) The  $I$  dimension, which is parallel to the  $X$ -axis with a value of 1.3 inches, and the  $J$  dimension, which is parallel to the  $Y$ -axis with a value of 0.3 inch. These values, which locate point A with reference to the center of the arc, are called offset dimensions. The block for this work would appear as follows:

```
N0025 G02 X011000 Y010000 I013000 J003000
```

(The sequence number, N0025, is arbitrary.)

The block would also contain the plane selection (i.e., G17, G18, or G19), if this selection is not preset in the system. Most of the newer control systems allow duplicate words in the



same block, but most of the older systems do not. In these older systems, it is necessary to insert the plane selection code in a separate and prior block, for example, N0020 G17.

Another stipulation in the Standard is that the arc is limited to one quadrant. Therefore, four blocks would be required to complete a circle. Four blocks would also be required to complete the arc shown in Fig. 12, which extends into all four quadrants.

When utilizing absolute programming, the coordinates of the end point are described. Again from Fig. 11, the block, expressed in absolute coordinates, appears as:

N0055 G02 X01800 Y019000 I013000 J003000

where the arc is continued from a previous block; the starting point for the arc in this block would be the end point of the previous block.

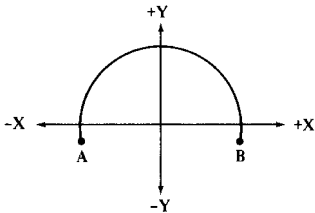


Fig. 12.

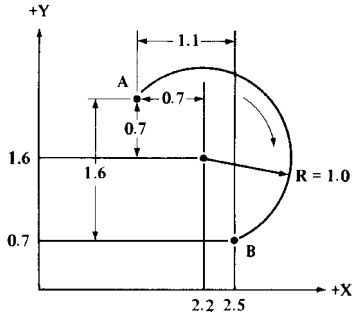


Fig. 13.

The Standard still contains the format discussed, but simpler alternatives have been developed. The latest version of the Standard (RS-274-D) allows *multiple quadrant programming* in one block, by inclusion of a G75 word. In the absolute-dimension mode (G90), the coordinates of the arc center are specified. In the incremental-dimension mode (G91), the signed (plus or minus) incremental distances from the beginning point of the arc to the arc center are given. Most system builders have introduced some variations on this format. One system builder utilizes the center and the end point of the arc when in an absolute mode, and might describe the block for going from A to B in Fig. 13 as:

N0065 G75 G02 X2.5 Y0.7 I2.2 J1.6

The I and the J words are used to describe the coordinates of the arc center. Decimal-point programming is also used here. A block for the same motion when programmed incrementally might appear as:

N0075 G75 G02 X1.1 Y - 1.6 I0.7 J0.7

This approach is more in conformance with the RS-274-D Standard in that the X and Y values describe the displacement between the starting and ending points (points A and B), and the I and J indicate the offsets of the starting point from the center. Another and even more convenient way of formulating a circular motion block is to note the coordinates of the ending point and the radius of the arc. Using absolute programming, the block for the motion in Fig. 13 might appear as:

N0085 G75 G02 X2.5 Y0.7 R10.0

The starting point is derived from the previous motion block. Multi-quadrant circular interpolation is canceled by a G74 code.

**Helical and Parabolic Interpolation.**—Helical interpolation is used primarily for milling large threads and lubrication grooves, as shown in Fig. 14. Generally, helical interpolation involves motion in all three axes (X, Y, Z) and is accomplished by using circular

interpolation (G02 or G03) while changing the third dimension. Parabolic interpolation (G06) is simultaneous and coordinated control of motion—such that the resulting cutter path describes part of a parabola. The RS-274-D Standard provides further details.

**Subroutine.**—A subroutine is a set of instructions or blocks that can be inserted into a program and repeated whenever required. Parametric subroutines permit letters or symbols to be inserted into the program in place of numerical values (see *Parametric Expressions and Macros*). Parametric subroutines can be called during part programming and values assigned to the letters or symbols. This facility is particularly helpful when dealing with families of parts.

A subprogram is similar to a subroutine except that a subprogram is not wholly contained within another program, as is a subroutine. Subprograms are used when it is necessary to perform the same task frequently, in different programs. The advantage of subprograms over subroutines is that subprograms may be called by any other program, whereas the subroutine can only be called by the program that contains the subroutine.

There is no standard subroutine format; however, the example below is typical of a program that might be used for milling the three pockets shown in Fig. 15. In the example, the beginning and end of the subroutine are indicated by the codes M92 and M93, respectively, and M94 is the code that is used to call the subroutine. The codes M92, M93, and M94 are not standardized (M-codes M90 through M99 are reserved for the user) and may be different from control system to control system. The subroutine functions may use different codes or may not be available at all on other systems.

|                      |   |
|----------------------|---|
| N0010 G00 X.6 Y.85   | Cutter is moved at a rapid traverse rate to a position over the corner of the first pocket to be cut. |
| N0020 M92            | Tells the system that the subroutine is to start in the next block.                                   |
| N0030 G01 Z-.25 F2.0 | Cutter is moved axially into the workpiece 0.25 inch at 2.0 ipm.                                      |
| N0040 X.8            | Cutter is moved to the right 0.8 inch.  |
| N0050 Y.2            | Cutter is moved laterally up 0.2 inch.  |
| N0060 X-.8           | Cutter is moved to the left 0.8 inch.   |
| N0070 Y.2            | Cutter is moved laterally up 0.2 inch.  |

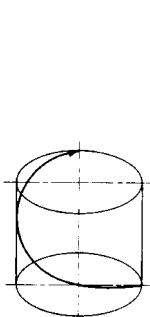


Fig. 14.

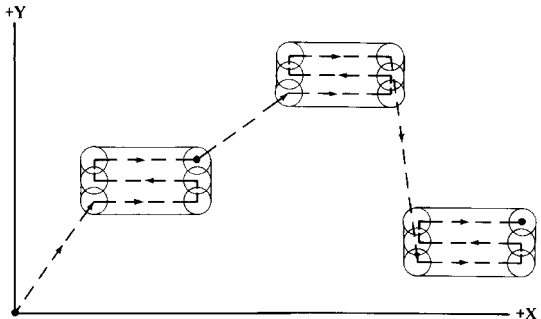


Fig. 15.

|                     |  |
|---------------------|--|
| N0080 X.8           | Cutter is moved to the right 0.8 inch.   |
| N0090 G00 Z.25 M93  | Cutter is moved axially out of pocket at rapid traverse rate. Last block of subroutine is signaled by word M93.                      |
| N0100 X.75 Y.5      | Cutter is moved to bottom left-hand corner of second pocket at rapid traverse rate.  |
| N0110 M94 N0030     | Word M94 calls for repetition of the subroutine that starts at sequence number N0030 and ends at sequence number N0090.              |
| N0120 G00 X.2 Y-1.3 | After the second pocket is cut by repetition of sequence numbers N0030 through N0090, the cutter is moved to start the third pocket. |
| N0130 M94 N0030     | Repetition of subroutine is called for by word M94 and the third pocket is cut.  |

**Parametric Expressions and Macros.**—Parametric programming is a method whereby a variable or replaceable parameter representing a value is placed in the machining code instead of using the actual value. In this manner, a section of code can be used several or many times with different numerical values, thereby simplifying the programming and reducing the size of the program. For example, if the values of X and Y in lines N0040 to N0080 of the previous example are replaced as follows:

N0040 X#1

N0050 Y#2

N0060 X#3

N0070 Y#4

then the subroutine starting at line N0030 is a parametric subroutine. That is, the numbers following the # signs are the variables or parameters that will be replaced with actual values when the program is run. In this example, the effect of the program changes is to allow the same group of code to be used for milling pockets of different sizes. If on the other hand, lines N0010, N0100, and N0120 of the original example were changed in a similar manner, the effect would be to move the starting location of each of the slots to the location specified by the replaceable parameters.

Before the program is run, the values that are to be assigned to each of the parameters or variables are entered as a list at the start of the part program in this manner:

#1 = .8

#2 = .2

#3 = .8

#4 = .2

All that is required to repeat the same milling process again, but this time creating a different size pocket, is to change the values assigned to each of the parameters #1, #2, #3, and #4 as necessary. Techniques for using parametric programming are not standardized and are not recognized by all control systems. For this reason, consult the programming manual of the particular system for specific details.

As with a parametric subroutine, macro describes a type of program that can be recalled to allow insertion of finite values for letter variables. The difference between a macro and a parametric subroutine is minor. The term macro normally applies to a source program that is used with computer-assisted part programming; the parametric subroutine is a feature of the CNC system and can be input directly into that system.

**Conditional Expressions.**—It is often useful for a program to make a choice between two or more options, depending on whether or not a certain condition exists. A program can contain one or more blocks of code that are not needed every time the program is run, but are needed some of the time. For example, refer to the previous program for milling three slots. An occasion arises that requires that the first and third slots be milled, but not the second one. If the program contained the following block of code, the machine could be easily instructed to skip the milling of the second slot:

```
N0095 IF [#5 EQ 0] GO TO N0120
```

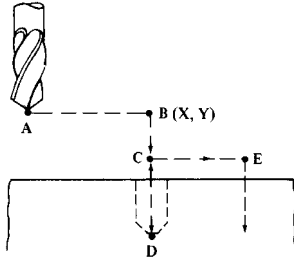
In this block, #5 is the name of a variable; EQ is a conditional expression meaning *equals*; and GO TO is a branch statement meaning resume execution of the program at the following line number. The block causes steps N0100 and N0110 of the program to be skipped if the value of #5 (a dummy variable) is set equal to zero. If the value assigned to #5 is any number other than zero, the expression (#5 EQ 0) is not true and the remaining instructions in block N0095 are not executed. Program execution continues with the next step, N0100, and the second pocket is milled. For the second pocket to be milled, parameter #5 is initialized at the beginning of the program with a statement such as #5 = 1 or #5 = 2. Initializing #5 = 0 guarantees that the pocket is not machined. On control systems that automatically initialize all variables to zero whenever the system is reset or a program is loaded, the second slot will not be machined unless the #5 is assigned a nonzero value each time the program is run.

Other conditional expressions are: NE = not equal to; GT = greater than; LT = less than; GE = greater than or equal to; and LE = less than or equal to. As with parametric expressions, conditional expressions may not be featured on all machines and techniques and implementation will vary. Therefore, consult the control system programming manual for the specific command syntax.

**Fixed (Canned) Cycles.**—Fixed (canned) cycles comprise sets of instructions providing for a preset sequence of events initiated by a single command or a block of data. Fixed cycles generally are offered by the builder of the control system or machine tool as part of the software package that accompanies the CNC system. Limited numbers of canned cycles began to appear on hardware control systems shortly before their demise. The canned cycles offered generally consist of the standard G-codes covering drilling, boring, and tapping operations, plus options that have been developed by the system builder such as thread cutting and turning cycles. (See *Thread Cutting* and *Turning Cycles*.) Some standard canned cycles included in RS-274-D are shown herewith. A block of data that might be used to generate the cycle functions is also shown above each illustration. Although the G-codes for the functions are standardized, the other words in the block and the block format are not, and different control system builders have different arrangements. The blocks shown are reasonable examples of fixed cycles and do not represent those of any particular system builder.

The G81 block for a simple drilling cycle is:

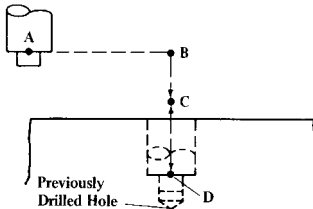
N\_\_\_G81 X\_\_\_Y\_\_\_C\_\_\_D\_\_\_F\_\_\_EOB  
 N\_\_\_X\_\_\_Y\_\_\_EOB



This G81 drilling cycle will move the drill point from position A to position B and then down to C at a rapid traverse rate; the drill point will next be fed from C to D at the programmed feed rate, then returned to C at the rapid traverse rate. If the cycle is to be repeated at a subsequent point, such as point E in the illustration, it is necessary Only to give the required X and Y coordinates. This repetition capability is typical of canned cycles.

The G82 block for a spotfacing or drilling cycle with a dwell is:

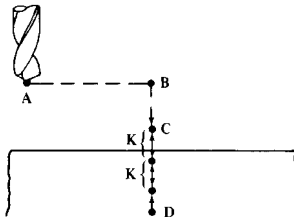
N\_\_\_G82 X\_\_\_Y\_\_\_C\_\_\_D\_\_\_T\_\_\_F\_\_\_EOB



This G82 code produces a cycle that is very similar to the cycle of the G81 code except for the dwell period at point D. The dwell period allows the tool to smooth out the bottom of the counterbore or spotface. The time for the dwell, in seconds, is noted as a T-word.

The G83 block for a peck-drilling cycle is:

N\_\_\_G83 X\_\_\_Y\_\_\_C\_\_\_D\_\_\_K\_\_\_F\_\_\_EOB

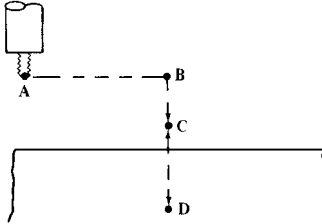


In the G83 peck-drilling cycle, the drill is moved from point A to point B and then to point C at the rapid traverse rate; the drill is then fed the incremental distance K, followed by

rapid return to C. Down feed again at the rapid traverse rate through the distance K is next, after which the drill is fed another distance K. The drill is then rapid traversed back to C, followed by rapid traverse for a distance of  $K + K$ ; down feed to D follows before the drill is rapid traversed back to C, to end the cycle.

The G84 block for a tapping cycle is:

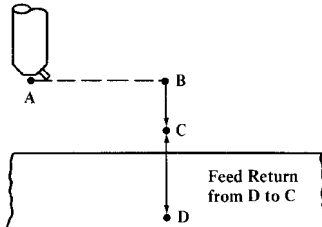
N \_\_\_\_\_ G84 X \_\_\_\_\_ Y \_\_\_\_\_ C \_\_\_\_\_ D \_\_\_\_\_ F \_\_\_\_\_ EOB



The G84 canned tapping cycle starts with the end of the tap being moved from point A to point B and then to point C at the rapid traverse rate. The tap is then fed to point D, reversed, and moved back to point C.

The G85 block for a boring cycle with tool retraction at the feed rate is:

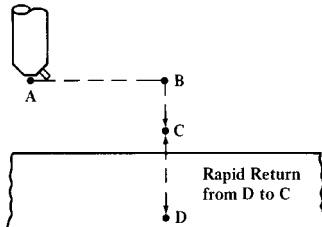
N \_\_\_\_\_ G85 X \_\_\_\_\_ Y \_\_\_\_\_ C \_\_\_\_\_ D \_\_\_\_\_ F \_\_\_\_\_ EOB



In the G85 boring cycle, the tool is moved from point A to point B and then to point C at the rapid traverse rate. The tool is next fed to point D and then, while still rotating, is moved back to point C at the same feed rate.

The G86 block for a boring cycle with rapid traverse retraction is:

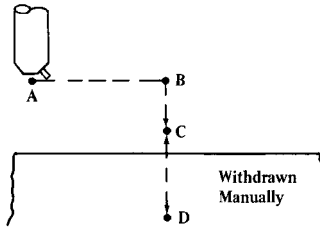
N \_\_\_\_\_ G86 X \_\_\_\_\_ Y \_\_\_\_\_ C \_\_\_\_\_ D \_\_\_\_\_ F \_\_\_\_\_ EOB



The G86 boring cycle is similar to the G85 cycle except that the tool is withdrawn at the rapid traverse rate.

The G87 block for a boring cycle with manual withdrawal of the tool is:

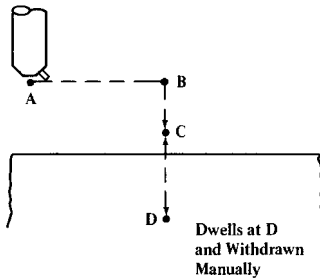
N \_\_\_ G87 X \_\_\_ Y \_\_\_ C \_\_\_ D \_\_\_ F \_\_\_ EOB



In the G87 canned boring cycle, the cutting tool is moved from A to B and then to C at the rapid traverse rate. The tool is then fed to D. The cycle is identical to the other boring cycles except that the tool is withdrawn manually.

The G88 block for a boring cycle with dwell and manual withdrawal is:

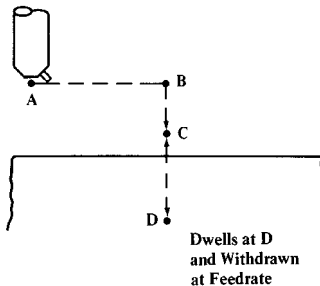
N \_\_\_ G88 X \_\_\_ Y \_\_\_ C \_\_\_ D \_\_\_ T \_\_\_ F \_\_\_ EOB



In the G88 dwell cycle, the tool is moved from A to B to C at the rapid traverse rate and then fed at the prescribed feed rate to D. The tool dwells at D, then stops rotating and is withdrawn manually.

The G89 block for a boring cycle with dwell and withdrawal at the feed rate is:

N \_\_\_ G89 X \_\_\_ Y \_\_\_ C \_\_\_ D \_\_\_ T \_\_\_ F \_\_\_ EOB



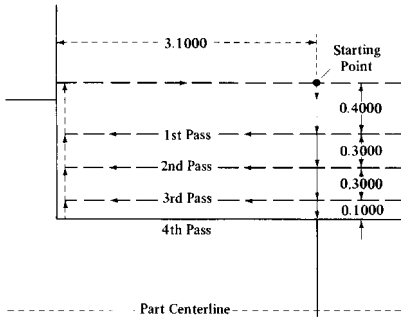


Fig. 16.

**Turning Cycles.**—Canned turning cycles are available from most system builders and are designed to allow the programmer to describe a complete turning operation in one or a few blocks. There is no standard for this type of operation, so a wide variety of programs have developed. Fig. 16 shows a hypothetical sequence in which the cutter is moved from the start point to depth for the first pass. If incremental programming is in effect, this distance is specified as D1. The depths of the other cuts will also be programmed as D2, D3, and so on. The length of the cut will be set by the W-word, and will remain the same with each pass. The preparatory word that calls for the roughing cycle is G77. The roughing feed rate is 0.03 ipr (inch per revolution), and the finishing feed rate (last pass) is 0.005 ipr. The block appears as follows:

```
N0054 G77 W=3.1 D1=.4 D2=.3 D3=.3 D4=.1 F1=.03 F2=.005
```

**Thread Cutting.**—Most NC lathes can produce a variety of thread types including constant-lead threads, variable-lead threads (increasing), variable-lead threads (decreasing), multiple threads, taper threads, threads running parallel to the spindle axis, threads (spiral groove) perpendicular to the spindle axis, and threads containing a combination of the preceding. Instead of the feed rate, the lead is specified in the threading instruction block, so that the feed rate is made consistent with, and dependent upon, the selected speed (rpm) of the spindle.

The thread lead is generally noted by either an I- or a K-word. The I-word is used if the thread is parallel to the X-axis and the K-word if the thread is parallel to the Z-axis, the latter being by far the most common. The G-word for a constant-lead thread is G33, for an increasing variable-lead thread is G34, and for a decreasing variable-lead thread is G35. Taper threads are obtained by noting the X- and Z-coordinates of the beginning and end points of the thread if the G90 code is in effect (absolute programming), or the incremental movement from the beginning point to the end point of the thread if the G91 code (incremental programming) is in effect.

|                           |   |
|---------------------------|---|
| N0001 G91                 | (Incremental programming)                             |
| N0002 G00 X-.1000         | (Rapid traverse to depth)                             |
| N0003 G33 Z-1.0000 K.0625 | (Produce a thread with a constant lead of 0.625 inch) |
| N0004 G00 X.1000          | (Withdraw at rapid traverse)                          |
| N0005 Z1.0000             | (Move back to start point)                            |



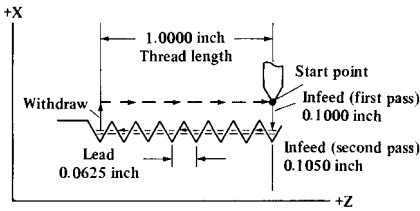


Fig. 17.

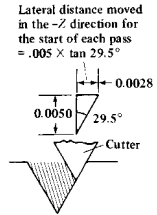


Fig. 18.

Multiple threads are specified by a code in the block that spaces the start of the threads equally around the cylinder being threaded. For example, if a triple thread is to be cut, the threads will start 120 degrees apart. Typical single-block thread cutting utilizing a plunge cut is illustrated in Fig. 17 and shows two passes. The passes are identical except for the distance of the plunge cut. Builders of control systems and machine tools use different code-words for threading, but those shown below can be considered typical. For clarity, both zeros and decimal points are shown.

The only changes in the second pass are the depth of the plunge cut and the withdrawal. The blocks will appear as follows:

```
N0006 X - .1050
N0007 G33 Z - 1.0000 K.0625
N0008 G00 X.1050
N0009 Z1.000
```

Compound thread cutting, rather than straight plunge thread cutting, is possible also, and is usually used on harder materials. As illustrated in Fig. 18, the starting point for the thread is moved laterally in the  $-Z$  direction by an amount equal to the depth of the cut times the tangent of an angle that is slightly less than 30 degrees. The program for the second pass of the example shown in Fig. 18 is as follows:

```
N0006 X - .1050 Z - .0028
N0007 G33 Z - 1.0000 K.0625
N0008 G00 X.1050
N0009 Z1.0000
```

Fixed (canned), one-block cycles also have been developed for CNC systems to produce the passes needed to complete a thread. These cycles may be offered by the builder of the control system or machine tool as standard or optional features. Subroutines also can generally be prepared by the user to accomplish the same purpose (see Subroutine). A one-block fixed threading cycle might look something like:

```
N0048 G98 X - .2000 Z - 1.0000 D.0050 F.0010
```

where G98 = preparatory code for the threading cycle

X-.2000 = total distance from the starting point to the bottom of the thread

Z-1.0000 = length of the thread

D.0050 = depths of successive cuts

F.0010 = depth(s) of the finish cut(s)

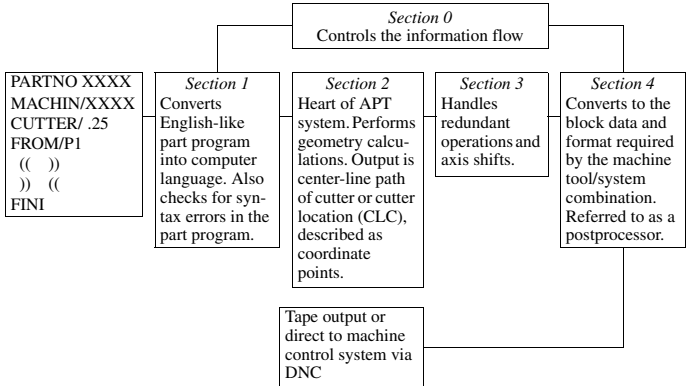
### APT Programming

**APT.**—APT stands for Automatically Programmed Tool and is one of many computer languages designed for use with NC machine tools. The selection of a computer-assisted part-programming language depends on the type and complexity of the parts being machined more than on any other factor. Although some of the other languages may be easier to use, APT has been chosen to be covered in this book because it is a nonproprietary

language in the public domain, has the broadest range of capability, and is one of the most advanced and universally accepted NC programming languages available. APT (or a variation thereof) is also one of the languages that is output by many computer programs that produce CNC part programs directly from drawings produced with CAD systems.

APT is suitable for use in programming part geometry from simple to exceptionally complex shapes. APT was originally designed and used on mainframe computers, however, it is now available, in many forms, on mini- and microcomputers as well. APT has also been adopted as ANSI Standard X3.37 and by the International Organization for Standardization (ISO) as a standardized language for NC programming. APT is a very dynamic program and is continually being updated. APT is being used as a processor for part-programming graphic systems, some of which have the capability of producing an APT program from a graphic screen display or CAD drawing and of producing a graphic display on the CAD system from an APT program.

APT is a high-level programming language. One difference between APT and the ANSI/EIA RS-274-D (G-codes) programming format discussed in the last section is that APT uses English like words and expressions to describe the motion of the tool or work-piece. APT has the capability of programming the machining of parts in up to five axes, and also allows computations and variables to be included in the programming statements so that a whole family of similar parts can be programmed easily. This section describes the general capabilities of the APT language and includes a ready reference guide to the basic geometry and motion statements of APT, which is suitable for use in programming the machining of the majority of cubic type parts involving two-dimensional movements. Some of the three-dimensional geometry capability of APT and a description of its five-dimensional capability are also included.



As shown above, the APT system can be thought of comprising the input program, the five sections 0 through IV, and the output program. The input program shown on the left progresses through the first four sections and all four are controlled by the fifth, section 0. Section IV, the postprocessor, is the software package that is added to sections II and III to customize the output and produce the necessary program format (including the G-words, M-words, etc.) so that the coded instructions will be recognizable by the control system. The postprocessor is software that is separate from the main body of the APT program, but for purposes of discussion, it may be easier to consider it as a unit within the APT program.

**APT Computational Statements.**—Algebraic and trigonometric functions and computations can be performed with the APT system as follows:

| Arithmetic Form | APT Form | Arithmetic Form | APT Form         | Arithmetic Form | APT Form         |
|-----------------|----------|-----------------|------------------|-----------------|------------------|
| $25 \times 25$  | 25*25    | $25^2$          | 25**2            | $\cos \theta$   | COSF( $\theta$ ) |
| $25 \div 25$    | 25/25    | $25^n$          | 25**n            | $\tan \theta$   | TANF( $\theta$ ) |
| $25 + 25$       | 25 + 25  | $\sqrt{25}$     | SQRTF (25)       | $\arctan .5000$ | ATANF(.5)        |
| $25 - 25$       | 25 - 25  | $\sin \theta$   | SINF( $\theta$ ) |                 |                  |

Computations may be used in the APT system in two ways. One way is to let a factor equal the computation and then substitute the factor in a statement; the other is to put the computation directly into the statement. The following is a series of APT statements illustrating the first approach.

P1 =POINT/0,0,1

T=(25\*2/3 + (3\*\*2 - 1))

P2 =POINT/T,0,0

The second way would be as follows;

P1 =POINT/0,0,1

P2 =POINT/(25\*2/3 + (3\*\*2 - 1)),0,0

*Note:* The parentheses have been used as they would be in an algebraic formula so that the calculations will be carried out in proper sequence. The operations within the inner parentheses would be carried out first. It is important for the total number of left-hand parentheses to equal the total number of right-hand parentheses; otherwise, the program will fail.

**APT Geometry Statements.**—Before movements around the geometry of a part can be described, the geometry must be defined. For example, in the statement GOTO/P1, the computer must know where P1 is located before the statement can be effective. P1 therefore must be described in a geometry statement, prior to its use in the motion statement GOTO/P1. The simplest and most direct geometry statement for a point is

P1 =POINT/X ordinate, Y ordinate, Z ordinate

If the Z ordinate is zero and the point lies on the X–Y plane, the Z location need not be noted. There are other ways of defining the position of a point, such as at the intersection of two lines or where a line is tangent to a circular arc. These alternatives are described below, together with ways to define lines and circles. Referring to the preceding statement, P1 is known as a symbol. Any combination of letters and numbers may be used as a symbol providing the total does not exceed six characters and at least one of them is a letter. MOUSE2 would be an acceptable symbol, as would CAT3 or FRISBE. However, it is sensible to use symbols that help define the geometry. For example, C1 or CIR3 would be good symbols for a circle. A good symbol for a vertical line would be VL5.

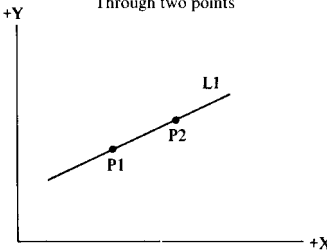
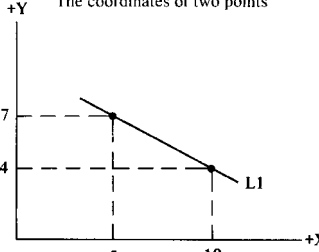
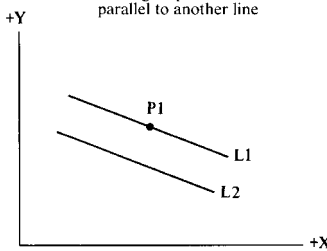
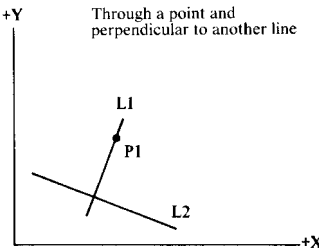
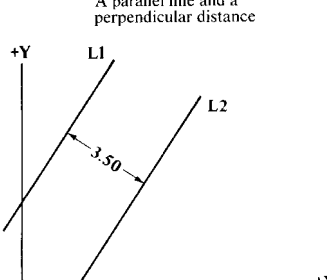
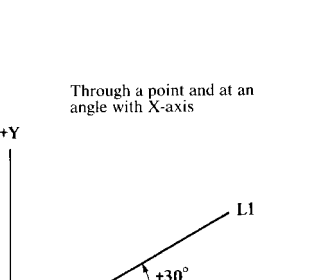
Next, and after the equal sign, the particular geometry is noted. Here, it is a POINT. This word is a vocabulary word and must be spelled exactly as prescribed. Throughout, the designers of APT have tried to use words that are as close to English as possible. A slash follows the vocabulary word and is followed by a specific description of the particular geometry, such as the coordinates of the point P1. A usable statement for P1 might appear as P1 = POINT/1,5,4. The 1 would be the X ordinate; the 5, the Y ordinate; and the 4, the Z ordinate.

Lines as calculated by the computer are infinitely long, and circles consist of 360 degrees. As the cutter is moved about the geometry under control of the motion statements, the lengths of the lines and the amounts of the arcs are “cut” to their proper size. (Some of the geometry statements shown in the accompanying illustrations for defining POINTS, LINES, CIRCLES, TABULATED CYLINDERS, CYLINDERS, CONES, and SPHERES, in the APT language, may not be included in some two-dimensional [ADAPT] systems.)

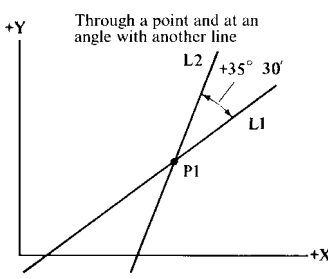
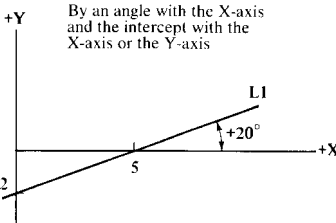
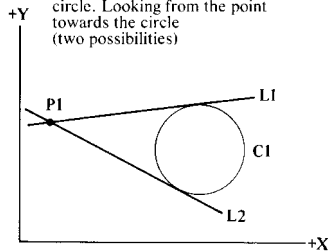
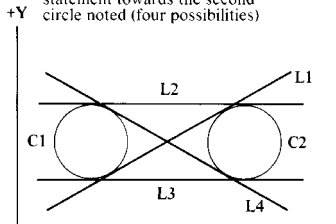
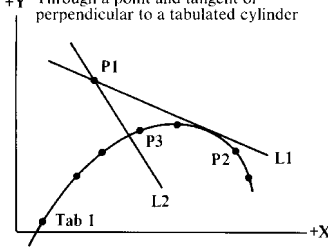
## Points

|  |   |
|--|---|
| <p><b>Point in space</b></p> <p><math>P_1 = \text{POINT}/4, 5, 2</math><br/> <math>P_2 = \text{POINT}/2, 2</math></p>  | <p><b>Intersection of two lines</b></p> <p><math>P_3 = \text{POINT}/\text{INTOF}, L_1, L_2</math></p>   |
| <p><b>Intersection of line and circle (two possibilities)</b></p> <p><math>P_1 = \text{POINT}/\text{XLARGE}, \text{INTOF}, L_1, C_1</math><br/> <math>P_1 = \text{POINT}/\text{YLARGE}, \text{INTOF}, L_1, C_1</math><br/> <math>P_2 = \text{POINT}/\text{XSMALL}, \text{INTOF}, L_1, C_1</math><br/> <math>P_2 = \text{POINT}/\text{YSMALL}, \text{INTOF}, L_1, C_1</math></p> <p>The <math>X</math> and <math>Y</math> ordinates of <math>P_1</math> are larger than the <math>X</math> and <math>Y</math> ordinates of <math>P_2</math></p> | <p><b>Intersection of two circles (two possibilities)</b></p> <p><math>P_1 = \text{POINT}/\text{XSMALL}, \text{INTOF}, C_1, C_2</math><br/> <math>P_1 = \text{POINT}/\text{YLARGE}, \text{INTOF}, C_1, C_2</math><br/> <math>P_2 = \text{POINT}/\text{XLARGE}, \text{INTOF}, C_1, C_2</math><br/> <math>P_2 = \text{POINT}/\text{YSMALL}, \text{INTOF}, C_1, C_2</math></p> |
| <p><b>Intersection of a radial line and a circle</b></p> <p><math>P_1 = \text{POINT}/C_1, \text{ATANGL}, 20</math></p>   | <p><b>Center of a circle</b></p> <p><math>P_1 = \text{POINT}/\text{CENTER}, C_1</math></p>  |

**Lines**

|  |   |
|--|---|
| <p>Through two points</p>  <p><math>L1 = \text{LINE}/P1, P2</math></p>   | <p>The coordinates of two points</p>  <p><math>L1 = \text{LINE}/5, 7, 10, 4</math></p>                               |
| <p>Through a point and parallel to another line</p>  <p><math>L1 = \text{LINE}/P1, \text{PARLEL}, L2</math></p>  | <p>Through a point and perpendicular to another line</p>  <p><math>L1 = \text{LINE}/P1, \text{PERPTO}, L2</math></p> |
| <p>A parallel line and a perpendicular distance</p>  <p><math>L1 = \text{LINE}/\text{PARLEL}, L2, \text{XSMALL}, 3,50</math><br/> or<br/> <math>L1 = \text{LINE}/\text{PARLEL}, L2, \text{YLARGE}, 3,50</math><br/> <math>L2 = \text{LINE}/\text{PARLEL}, L1, \text{XLARGE}, 3,50</math><br/> or<br/> <math>L2 = \text{LINE}/\text{PARLEL}, L1, \text{YSMALL}, 3,50</math></p> | <p>Through a point and at an angle with X-axis</p>  <p><math>L1 = \text{LINE}/P1, \text{ATANGL}, 30</math></p>     |

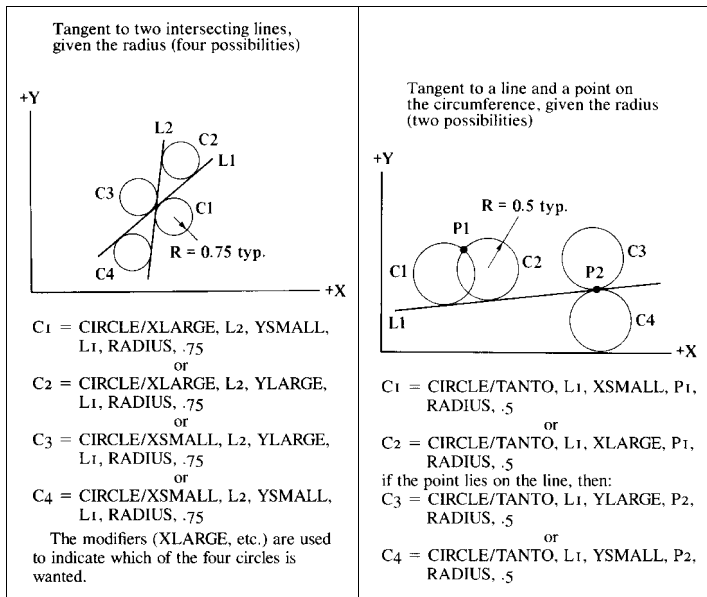
Lines (Continued)

|  |  |
|--|--|
| <p>Through a point and at an angle with another line</p>  <p>L2 = LINE/P1, ATANGL, 35.5, L1</p>  | <p>By an angle with the X-axis and the intercept with the X-axis or the Y-axis</p>  <p>L1 = LINE/ATANGL, 20, INTERC, XAXIS, 5<br/>L1 = LINE/ATANGL, 20, INTERC, YAXIS, 2</p>  |
| <p>Through a point and tangent to a circle. Looking from the point towards the circle (two possibilities)</p>  <p>L1 = LINE/P1, LEFT, TANTO, C1<br/>L2 = LINE/P1, RIGHT, TANTO, C1</p>   | <p>Tangent to two circles. Looking from the first circle noted in the statement towards the second circle noted (four possibilities)</p>  <p>L1 = LINE/RIGHT, TANTO, C2,<br/>LEFT, TANTO, C1<br/>or<br/>L1 = LINE/RIGHT, TANTO, C1,<br/>LEFT, TANTO, C2<br/>L2 = LINE/LEFT, TANTO, C1,<br/>LEFT, TANTO, C2<br/>or<br/>L2 = LINE/RIGHT, TANTO, C2,<br/>RIGHT, TANTO, C1<br/>L3 = LINE/RIGHT, TANTO, C1,<br/>RIGHT, TANTO, C2<br/>or<br/>L3 = LINE/LEFT, TANTO, C2,<br/>LEFT, TANTO, C1<br/>L4 = LINE/LEFT, TANTO, C2,<br/>RIGHT, TANTO, C1<br/>or<br/>L4 = LINE/LEFT, TANTO, C1,<br/>RIGHT, TANTO, C2</p> |
| <p>Through a point and tangent or perpendicular to a tabulated cylinder</p>  <p>L1 = LINE/P1, TANTO, TAB1, P3<br/>L1 = LINE/P1, PERPTO, TAB1, P3<br/>P2 and P3 are points close to the tangent points of L1 and the intersection point of L2, therefore cannot be end points of the tabulated cylinder</p> |  |

Circles

|   |  |
|---|--|
| <p>The center of the circle and the radius</p> <p><math>C1 = \text{CIRCLE}/5, 6, 2</math><br/> or<br/> <math>C1 = \text{CIRCLE}/5, 6, 0, 2</math><br/> <small>(where 0 = Z ordinate)</small><br/> or<br/> <math>C1 = \text{CIRCLE}/\text{CENTER}, P1, \text{RADIUS}, 2</math></p> | <p>The center of a circle and a tangent line</p> <p><math>C1 = \text{CIRCLE}/\text{CENTER}, P1, \text{TANTO}, L1</math></p>  |
| <p>The center of a circle and a point on the circumference</p> <p><math>C1 = \text{CIRCLE}/\text{CENTER}, P1, P2</math></p>   | <p>Three points on a circle</p> <p><math>C1 = \text{CIRCLE}/P1, P2, P3</math></p>  |
| <p>The center and a tangent circle (two possibilities)</p> <p><math>C1 = \text{CIRCLE}/\text{CENTER}, P1, \text{SMALL}, \text{TANTO}, C2</math><br/> or<br/> <math>C3 = \text{CIRCLE}/\text{CENTER}, P1, \text{LARGE}, \text{TANTO}, C2</math></p>                                | <p>The center and a tangent circle (two possibilities)</p> <p><math>C1 = \text{CIRCLE}/\text{CENTER}, P1, \text{SMALL}, \text{TANTO}, C2</math><br/> or<br/> <math>C3 = \text{CIRCLE}/\text{CENTER}, \text{LARGE}, \text{TANTO}, C2</math></p> |

## Circles



**APT Motion Statements.**—APT is based on the concept that a milling cutter is guided by two surfaces when in a contouring mode. Examples of these surfaces are shown in Fig. 1, and they are called the “part” and the “drive” surfaces. Usually, the part surface guides the bottom of the cutter and the drive surface guides the side of the cutter. These surfaces may or may not be actual surfaces on the part, and although they may be imaginary to the part programmer, they are very real to the computer. The cutter is either stopped or redirected by a third surface called a check surface. If one were to look directly down on these surfaces, they would appear as lines, as shown in Figs. 2a through 2c.

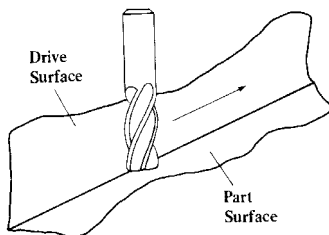


Fig. 1. Contouring Mode Surfaces

When the cutter is moving toward the check surface, it may move to it, onto it, or past it, as illustrated in Fig. 2a. When the cutter meets the check surface, it may go right, denoted by the APT command GORGT, or go left, denoted by the command GOLFT, in Fig. 2b.



Alternatively, the cutter may go forward, instructed by the command GOFWD, as in Fig. 2c. The command GOFWD is used when the cutter is moving either onto or off a tangent circular arc. These code instructions are part of what are called motion commands. Fig. 3 shows a cutter moving along a drive surface, L1, toward a check surface, L2. When it arrives at L2, the cutter will make a right turn and move along L2 and past the new check surface L3. Note that L2 changes from a check surface to a drive surface the moment the cutter begins to move along it. The APT motion statement for this move is:

GORGT/L2,PAST,L3

### Contouring Cutter Movements

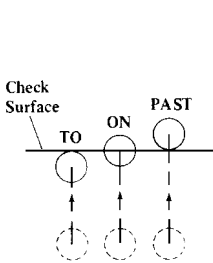


Fig. 2a.

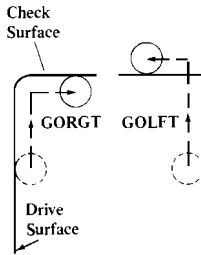


Fig. 2b.

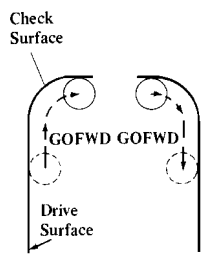


Fig. 2c.

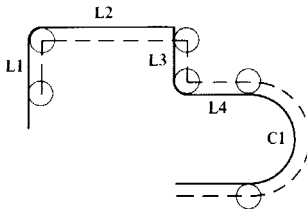


Fig. 3. Motion Statements for Movements Around a Workpiece

Still referring to Fig. 3, the cutter moves along L3 until it comes to L4. L3 now becomes the drive surface and L4 the check surface. The APT statement is:

GORGT/L3,TO,L4

The next statement is:

GOLFT/L4,TANTO,C1

Even though the cutter is moving to the right, it makes a left turn if one is looking in the direction of travel of the cutter. In writing the motion statements, the part programmers must imagine they are steering the cutter. The drive surface now becomes L4 and the check surface, C1. The next statement will therefore be:

GOFWD/C1,TANTO,L5

This movement could continue indefinitely, with the cutter being guided by the drive, part, and check surfaces.

**Start-Up Statements:** For the cutter to move along them, it must first be brought into contact with the three guiding surfaces by means of a start-up statement. There are three different start-up statements, depending on how many surfaces are involved.

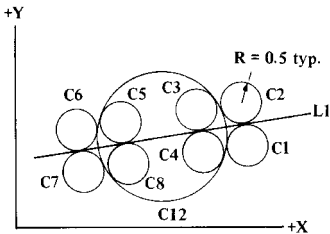
A three-surface start-up statement is one in which the cutter is moved to the drive, part, and check surfaces, as seen in Fig. 4a. A two-surface start-up is one in which the cutter is

moved to the drive and part surfaces, as in Fig. 4b. A one-surface start-up is one in which the cutter is moved to the drive surface and the X-Y plane, where  $Z = 0$ , as in Fig. 4c. With the two- and one-surface start-up statements, the cutter moves in the most direct path, or perpendicular to the surfaces. Referring to Fig. 4a (three-surface start-up), the move is initiated from a point P1. The two statements that will move the cutter from P1 to the three surfaces are:

FROM/P1  
GO/TO,DS,TO,PS,TO,CS

### Circles

Tangent to a line and a circle, given the radius (eight possibilities)

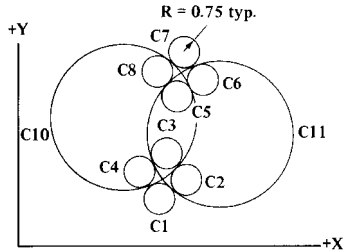


C1 = CIRCLE/YSMALL, L1, XLARGE, OUT, C12, RADIUS, .5  
 C2 = CIRCLE/YLARGE, L1, XLARGE, OUT, C12, RADIUS, .5  
 C3 = CIRCLE/YLARGE, L1, XLARGE, IN, C12, RADIUS, .5  
 C4 = CIRCLE/YSMALL, L1, XLARGE, IN, C12, RADIUS, .5  
 C5 = CIRCLE/YLARGE, L1, XSMALL, OUT, C12, RADIUS, .5  
 C6 = CIRCLE/XLARGE, L1, XSMALL, OUT, C12, RADIUS, .5  
 C7 = CIRCLE/YSMALL, L1, XSMALL, OUT, C12, RADIUS, .5  
 C8 = CIRCLE/YSMALL, L1, XSMALL, IN, C12, RADIUS, .5

#### Recommendations:

- Note which side of line circle is on (e.g., YSMALL, L1).
- Note whether the circle being defined is inside (IN), or outside (OUT), the known circle.
- Of the two remaining circles, note whether the circle to be defined is XLARGE, XSMALL, or YLARGE or YSMALL, to arrive at the second modifier in the statement.

Tangent to two circles, given the radius (eight possibilities)



C1 = CIRCLE/YSMALL, OUT, C10, OUT, C11, RADIUS, .75  
 C2 = CIRCLE/YSMALL, OUT, C10, IN, C11, RADIUS, .75  
 C3 = CIRCLE/YSMALL, IN, C10, IN, C11, RADIUS, .75  
 C4 = CIRCLE/YSMALL, IN, C10, OUT, C11, RADIUS, .75  
 C5 = CIRCLE/YLARGE, IN, C10, IN, C11, RADIUS, .75  
 C6 = CIRCLE/YLARGE, OUT, C10, IN, C11, RADIUS, .75  
 C7 = CIRCLE/YLARGE, OUT, C10, OUT, C11, RADIUS, .75  
 C8 = CIRCLE/YLARGE, IN, C10, OUT, C11, RADIUS, .75

#### Recommendations

- Apply IN, OUT modifiers.
- Apply XLARGE, etc., modifiers.

DS is used as the symbol for the Drive Surface; PS as the symbol for the Part Surface; and CS as the symbol for the Check Surface. The surfaces must be denoted in this sequence. The drive surface is the surface that the cutter will move along after coming in contact with the three surfaces. The two statements applicable to the two-surface start-up (Fig. 4b) are:

FROM/P1  
GO/TO,DS,TO,PS

The one-surface start-up (Fig. 4c) is:

FROM/P1  
GO/TO,DS

**Planes**

Planes are often used as the part surface, and are defined by three points not lying in a straight line

$PL1 = PLANE/P1, P2, P3$

A plane that is horizontal, or parallel to the X-Y plane, may be defined as:

$PL1 = PLANE/0, 0, 1, 5$  (0, 0, 1 does not change)

Alternatively, PL2 may be defined as a plane parallel to PL1

$PL2 = PLANE/PARLEL, PL1, ZLARGE, 10$

**Cutter Movement Surfaces**

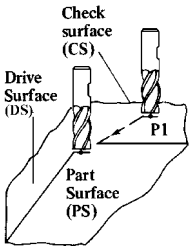


Fig. 4a.

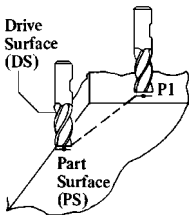


Fig. 4b.

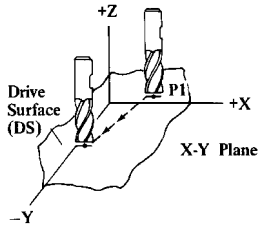
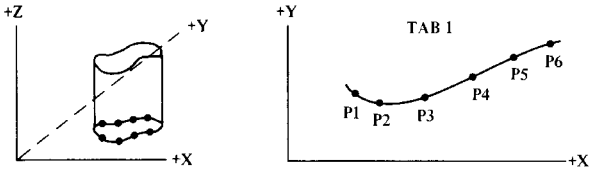


Fig. 4c.

**Tabulated Cylinder**



A tabulated cylinder is the line that is formed when an irregular cylinder intersects a plane. The plane intersected in the figure at the left is the  $X$ - $Y$  plane.

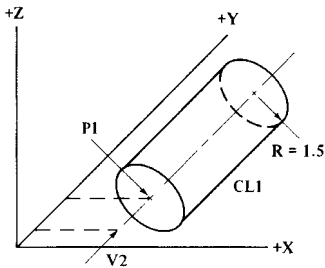
A section of the line can be defined by a series of points on the line, as seen at the right. This line is called a TABCYL. The line must pass through all the points, therefore, it is best not to use too many. The statement to the computer would read:

TAB1 = TABCYL/NOZ, SPLINE, P1, P2, P3, P4, P5, P6

TAB1 = TABCYL/NOZ, SPLINE, X., Y., X2, Y2, X3, Y3, X4, Y4, X5, Y5, X6, Y6  
 (where  $X$  and  $Y$  are the coordinates of the points)

**3-D Geometry**

**Cylinder**



Length of vector = 1

A cylinder is defined by a vector, a point on the centerline, and the radius

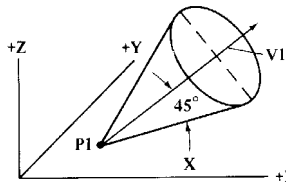
CL1 = CYLNDR/P1, V2, 1.5

where V2 is a unit vector in line with the cylinder centerline, and is described by the  $X$ ,  $Y$ , and  $Z$  components. The cylinder centerline lies on the  $X$ - $Y$  plane and is parallel to the  $Y$ -axis. The statement for the vector is therefore:

V2 = VECTOR/ $X$  component,  $Y$  component,  $Z$  component

V2 = VECTOR/0, 1, 0

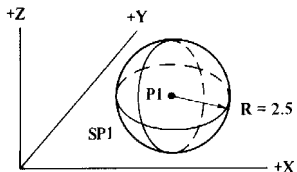
**Cone**



A cone is defined by its vertex, its axis as a unit vector, and the half angle (refer to cylinder for an example of a vector statement)

CON1 = CONE/P1,V1,45

**Sphere**



A sphere is defined by the center and the radius  
 SP1 = SPHERE/P1, RADIUS, 2.5

or  
 SP1 = SPHERE/5, 5, 3, 2.5 (where 5, 5, and 3 are the  $X$ ,  $Y$ , and  $Z$  coordinates or P1, and 2.5 is the radius)

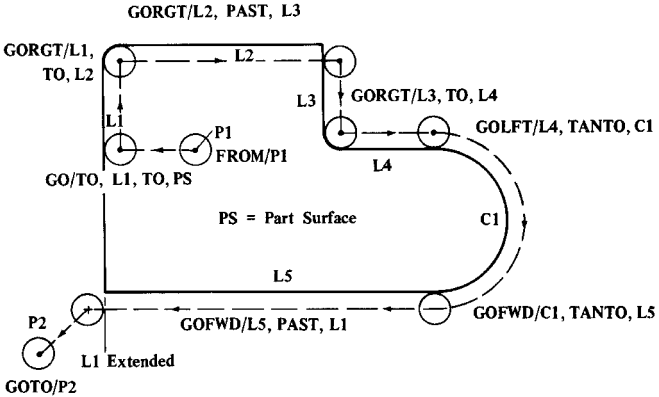


Fig. 5. A Completed Two-Surface Start-Up

Note that, in all three motion statements, the slash mark (/) lies between the GO and the TO. When the cutter is moving to a point rather than to surfaces, such as in a start-up, the statement is GOTO/ rather than GO/TO. A two-surface start-up, Fig. 3, when completed, might appear as shown in Fig. 5, which includes the motion statements needed. The motion statements, as they would appear in a part program, are shown at the left, below:

|                   |         |
|-------------------|---------|
| FROM/P1           | FROM/P1 |
| GO/TO,L1,TO,PS    | GOTO/P2 |
| GORGT/L1,TO,L2    | GOTO/P3 |
| GORGT/L2,PAST,L3  | GOTO/P4 |
| GORGT/L3,TO,L4    | GOTO/P5 |
| GOLFT/L4,TANTO,C1 | GOTO/P6 |
| GOFWD/C1,TANTO,L5 | GOTO/P7 |
| GOFWD/L5,PAST,L1  |         |
| GOTO/P2           |         |

GOTO statements can move the cutter throughout the range of the machine, as shown in Fig. 6. APT statements for such movements are shown at the right in the preceding example. The cutter may also be moved incrementally, as shown in Fig. 7. Here, the cutter is to move 2 inches in the + X direction, 1 inch in the + Y direction, and 1.5 inches in the + Z direction. The incremental move statement (indicated by DLTA) is:

GODLTA/2,1,1.5

The first position after the slash is the X movement; the second the Y movement, and the third, the Z movement.

**Five-Axis Machining:** Machining on five axes is achieved by causing the APT program to generate automatically a unit vector that is normal to the surface being machined, as shown in Fig. 8. The vector would be described by its X, Y, and Z components. These components, along with the X, Y, and Z coordinate positions of the tool tip, are fed into the post-processor, which determines the locations and angles for the machine tool head and/or table.

**APT Postprocessor Statements.**—Statements that refer to the operation of the machine rather than to the geometry of the part or the motion of the cutter about the part are called postprocessor statements. APT postprocessor statements have been standardized internationally. Some common statements and an explanation of their meaning follow:

**MACHIN/**Specifies the postprocessor that is to be used. Every postprocessor has an identity code, and this code must follow the slash mark (/). For example: MACHIN/LATH,82

**FEDRATE/**Denotes the feed rate. If in inches per minute (ipm), only the number

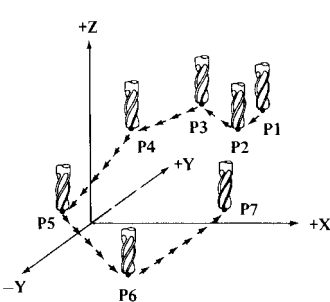


Fig. 6. A Series of GOTO Statements

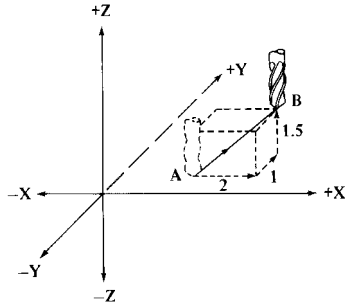


Fig. 7. Incremental Cutter Movements

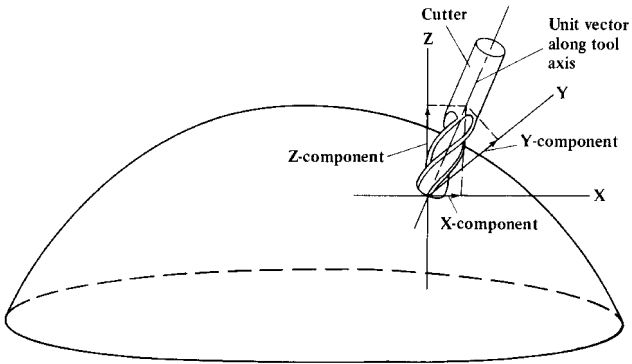


Fig. 8. Five-Axis Machining

need be shown. If in inches per revolution (ipr), IPR must be shown, for example: FED-RAT/.005,IPR

**RAPID** Means rapid traverse and applies only to the statement that immediately follows it

**SPINDL/**Refers to spindle speed. If in revolutions per minute (rpm), only the number need be shown. If in surface feet per minute (sfm), the letters SFM need to be shown, for example: SPINDL/ 100SFM

**COOLNT/**Means cutting fluid and can be subdivided into: COOLNT/ON, COOLNT/MIST, COOLNT/FLOOD, COOLNT/OFF

**TURRET/**Used to call for a selected tool or turret position

**CYCLE/**Specifies a cycle operation such as a drilling or boring cycle. An example of a drilling cycle is: CYCLE/DRILL,RAPTO.,45,FEDTO,0,IPR.,.004. The next statement might be GOTO/PI and the drill will then move to P1 and perform the cycle operation. The cycle will repeat until the CYCLE/OFF statement is read

END Stops the machine but does not turn off the control system

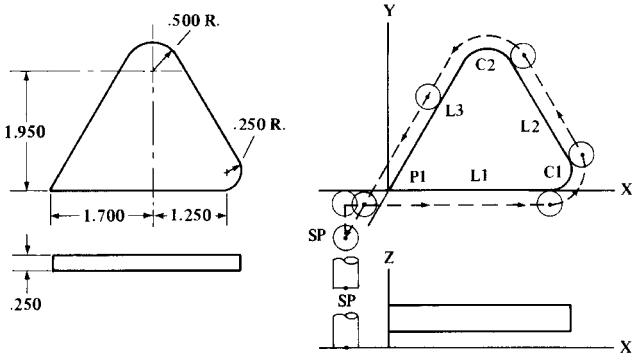


Fig. 9. Symbols for Geometrical Elements

**APT Example Program.**—A dimensioned drawing of a part and a drawing with the symbols for the geometry elements are shown in Fig. 9. A complete APT program for this part, starting with the statement PARTNO 47F36542 and ending with FINI, is shown at the left below.

The numbers at the left of the statements are for reference purposes only, and are not part of the program. The cutter is set initially at a point represented by the symbol SP, having coordinates  $X = -0.5$ ,  $Y = -0.5$ ,  $Z = 0.75$ , and moves to L1 (extended) with a one-surface start-up so that the bottom of the cutter rests on the  $X$ - $Y$  plane. The cutter then moves counterclockwise around the part, past L1 (extended), and returns to SP. The coordinates of P1 are  $X = 0$ ,  $Y = 0$ , and  $Z = 1$ .

|  |  |
|--|--|
| (1) PARTNO                                       | (1) PARTNO                                       |
| (2) CUTTER/.25                                   | (2) CUTTER/.25                                   |
| (3) FEDRAT/5                                     | (3) FEDRAT/5                                     |
| (4) SP = POINT/-0.5, -0.5, .75                   | (4) SP = POINT/-0.5, -0.5, .75                   |
| (5) P1 = POINT/0, 0, 1                           | (5) P1 = POINT/0, 0, 1                           |
| (6) L1 = LINE/P1, ATANGL, 0                      | (6) L1 = LINE/P1, ATANGL, 0                      |
| (7) C1 = CIRCLE/(1.700 + 1.250), .250, .250      | (7) C1 = CIRCLE/(1.700 + 1.250), .250, .250      |
| (8) C2 = CIRCLE/1.700, 1.950, .5                 | (8) C2 = CIRCLE/1.700, 1.950, .5                 |
| (9) L2 = LINE/RIGHT, TANTO, C1, RIGHT, TANTO, C2 | (9) L2 = LINE/RIGHT, TANTO, C1, RIGHT, TANTO, C2 |
| (10) L3 = LINE/P1, LEFT, TANTO, C2               | (10) L3 = LINE/P1, LEFT, TANTO, C2               |
| (11) FROM/SP                                     | (11) FROM/SP                                     |
| (12) GO/TO, L1                                   | (12) FRO -0.500 -0.5000 .7500<br>M               |
| (13) GORGT/L1, TANTO, C1                         | (13) GO/TO, L1                                   |
| (14) GOFWD/C1, TANTO, L2                         | (14) GT -0.5000 -0.1250 .0000                    |
| (15) GOFWD/L2, TANTO, C2                         | (15) GORGT/L1, TANTO, C1                         |
| (16) GOFWD/C2, TANTO, L3                         | (16) GT 2.9500 -0.1250 .0000                     |
| (17) GOFWD/L3, PAST, L1                          | (17) GOFWD/C1, TANTO, L2                         |
| (18) GOTO/SP                                     | (18) CIR 2.9500 .2500 .3750 CCLW                 |

## NUMERICAL CONTROL

1307

|           |      |                     |        |            |
|-----------|------|---------------------|--------|------------|
| (19) FINI | (19) | 3.2763              | .4348  | .0000      |
|           | (20) | GOFWD/L2, TANTO, C2 |        |            |
|           | (21) | GT                  | 2.2439 | 2.2580     |
|           | (22) | GOFWD/C2, TANTO, L3 |        | .0000      |
|           | (23) | CIR                 | 1.700  | 1.9500     |
|           | (24) |                     | 1.1584 | 2.2619     |
|           | (25) | GOFWD/L3, PAST, L1  |        | .6250 CCLW |
|           | (26) | GT                  | -.2162 | -.1250     |
|           | (27) | GOTO/SP             |        | .0000      |
|           | (28) | GT                  | -.5000 | -.5000     |
|           | (29) | FINI                |        | .7500      |

Referring to the numbers at the left of the program:

- (1) PARTNO must begin every program. Any identification can follow.
- (2) The diameter of the cutter is specified. Here it is 0.25 inch.
- (3) The feed rate is given as 5 inches per minute, which is contained in a postprocessor statement.
- (4)–(10) Geometry statements.
- (11)–(18) Motion statements.
- (19) All APT programs end with FINI.

A computer printout from section II of the APT program is shown at the right, above. This program was run on a desktop personal computer. Lines (1) through (10) repeat the geometry statements from the original program. The motion statements are also repeated, and below each motion statement are shown the  $X$ ,  $Y$ , and  $Z$  coordinates of the end points of the center-line (CL) movements for the cutter. Two lines of data follow those for the circular movements. For example, Line (18), which follows Line (17), GOFWD/C1,TANTO,L2, describes the  $X$  coordinate of the center of the arc, 2.9500, the  $Y$  coordinate of the center of the arc, 0.2500, and the radius of the arc required to be traversed by the cutter.

This radius is that of the arc shown on the part print, plus the radius of the cutter ( $0.2500 + 0.1250 = 0.3750$ ). Line (18) also shows that the cutter is traveling in a counterclockwise (CCLW) motion. A circular motion is described in Lines (22), (23), and (24). Finally, the cutter is directed to return to the starting point, SP, and this command is noted in Line (27). The  $X$ ,  $Y$ , and  $Z$  coordinates of SP are shown in Line (28).

**APT for Turning.**—In its basic form, APT is not a good program for turning. Although APT is probably the most suitable program for three-, four-, and five-axis machining, it is awkward for the simple two-axis geometry required for lathe operations. To overcome this problem, preprocessors have been developed especially for lathe part programming. The statements in the lathe program are automatically converted to basic APT statements in the computer and processed by the regular APT processor. An example of a lathe program, based on the APT processor and made available by the McDonnell Douglas Automation Co., is shown below. The numbers in parentheses are not part of the program, but are used only for reference. Fig. 10 shows the general set-up for the part, and Fig. 11 shows an enlarged view of the part profile with dimensions expressed along what would be the  $X$ - and  $Y$ -axes on the part print.



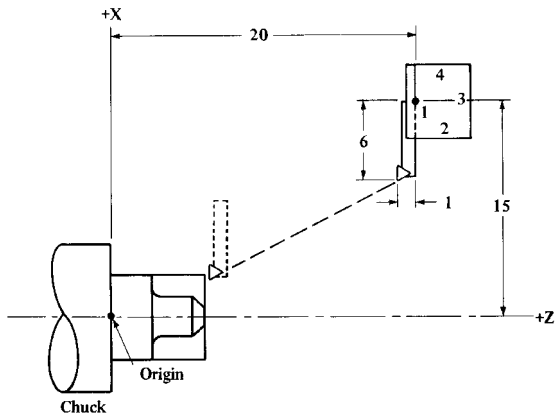


Fig. 10. Setup for APT Turning

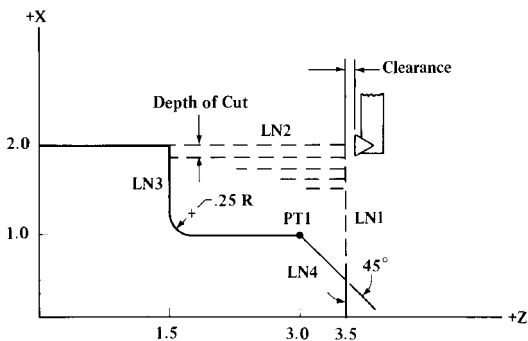


Fig. 11.

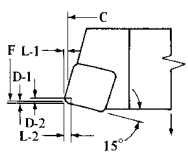
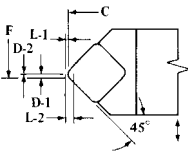
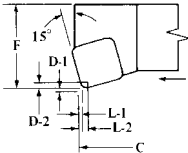
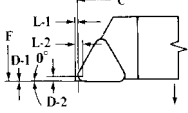
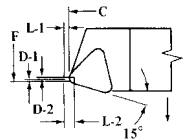
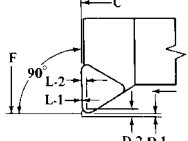
- (1) PARTNO LATHE EXAMPLE
- (2) MACHIN/MODEL LATHE
- (3) T1 = TOOL/FACE, 1, XOFF, -1, YOFF, -6, RADIUS, .031
- (4) BLANK1 = SHAPE/FACE, 3.5, TURN, 2
- (5) PART1 = SHAPE/FACE, 3.5, TAPER, 3.5, .5, ATANGL, -45, TURN, 1, \$  
FILLET, .25 FACE, 1.5 TURN, 2
- (6) FROM/(20-1), (15-6)
- (7) LATHE/ROUGH, BLANK1, PART1, STEP, .1, STOCK, .05, \$  
SFM, 300, IPR, .01, T1
- (8) LATHE/FINISH, PART1, SFM, 400, IPR, .005, T1
- (9) END
- (10) FINI

Line (3) describes the tool. Here, the tool is located on face 1 of the turret and its tip is -1 inch "off" (offset) in the  $X$  direction and -6 inches "off" in the  $Y$  direction, when considering  $X$ - $Y$  rather than  $X$ - $Z$  axes. The cutting tool tip radius is also noted in this statement. Line (4) describes the dimensions of the rough material, or blank. Lines parallel to the  $X$ -axis are noted as FACE lines, and lines parallel to the  $Z$ -axis are noted as TURN lines. The FACE line (LN1) is located 3.5 inches along the  $Z$ -axis and parallel to the  $X$ -axis. The TURN line (LN2) is located 2 inches above the  $Z$ -axis and parallel to it. Note that in Figs. 10 and 11, the  $X$ -axis is shown in a vertical position and the  $Z$ -axis in a horizontal position. Line (5) describes the shape of the finished part. The term FILLET is used in this statement to describe a circle that is tangent to the line described by TURN, 1 and the line that is described by FACE, 1.5. The \$ sign means that the statement is continued on the next line. These geometry elements must be contiguous and must be described in sequence. Line (6) specifies the position of the tool tip at the start of the operation, relative to the point of origin. Line (7) describes the roughing operation and notes that the material to be roughed out lies between BLANK1 and PART1; that the STEP, or depth of roughing cuts, is to be 0.1 inch; that 0.05 inch is to be left for the finish cut; that the speed is to be 300 sfm and the feed rate is to be 0.01 ipr; and that the tool to be used is identified by the symbol T1. Line (8) describes the finish cut, which is to be along the contour described by PART1.

**Indexable Insert Holders for NC.**—Indexable insert holders for numerical control lathes are usually made to more precise standards than ordinary holders. Where applicable, reference should be made to American National Standard B212.3-1986, Precision Holders for Indexable Inserts. This standard covers the dimensional specifications, styles, and designations of precision holders for indexable inserts, which are defined as tool holders that locate the gage insert (a combination of shim and insert thicknesses) from the back or front and end surfaces to a specified dimension with a  $\pm 0.003$  inch ( $\pm 0.08$  mm) tolerance. In NC programming, the programmed path is that followed by the center of the tool tip, which is the center of the point, or nose radius, of the insert. The surfaces produced are the result of the path of the nose and the major cutting edge, so it is necessary to compensate for the nose or point radius and the lead angle when writing the program. Table 1, from B212.3, gives the compensating dimensions for different holder styles. The reference point is determined by the intersection of extensions from the major and minor cutting edges, which would be the location of the point of a sharp pointed tool. The distances from this point to the nose radius are  $L1$  and  $D1$ ;  $L2$  and  $D2$  are the distances from the sharp point to the center of the nose radius. Threading tools have sharp corners and do not require a radius compensation. Other dimensions of importance in programming threading tools are also given in Table 2; the data were developed by Kennametal, Inc.

The  $C$  and  $F$  characters are tool holder dimensions other than the shank size. In all instances, the  $C$  dimension is parallel to the length of the shank and the  $F$  dimension is parallel to the side dimension; actual dimensions must be obtained from the manufacturer. For all  $K$  style holders, the  $C$  dimension is the distance from the end of the shank to the tangent point of the nose radius and the end cutting edge of the insert. For all other holders, the  $C$  dimension is from the end of the shank to a tangent to the nose radius of the insert. The  $F$  dimension on all B, D, E, M, P, and V style holders is measured from the back side of the shank to the tangent point of the nose radius and the side cutting edge of the insert. For all A, F, G, J, K, and L style holders, the  $F$  dimension is the distance from the back side of the shank to the tangent of the nose radius of the insert. In all these designs, the nose radius is the standard radius corresponding to those given in the paragraph *Cutting Point Configuration* on page 758.

**Table 1. Insert Radius Compensation ANSI B212.3-1986**

| Square Profile                                     |   |                                   |       |       |       |       |
|--|---|-----------------------------------|-------|-------|-------|-------|
| B Style <sup>a</sup><br>Also applies<br>to R Style |    | Turning 15° Lead Angle            |       |       |       |       |
|  |   | Rad.                              | L-1   | L-2   | D-1   | D-2   |
|  |   | 1/64                              | .0035 | .0191 | .0009 | .0110 |
|  |   | 1/32                              | .0070 | .0383 | .0019 | .0221 |
|  |   | 3/64                              | .0105 | .0574 | .0028 | .0331 |
|  |   | 1/16                              | .0140 | .0765 | .0038 | .0442 |
| D Style <sup>a</sup><br>Also applies<br>to S Style |    | Turning 45° Lead Angle            |       |       |       |       |
|  |   | Rad.                              | L-1   | L-2   | D-1   | D-2   |
|  |   | 1/64                              | .0065 | .0221 | .0065 | 0     |
|  |   | 1/32                              | .0129 | .0442 | .0129 | 0     |
|  |   | 3/64                              | .0194 | .0663 | .0194 | 0     |
|  |   | 1/16                              | .0259 | .0884 | .0259 | 0     |
| K Style <sup>a</sup>                               |    | Facing 15° Lead Angle             |       |       |       |       |
|  |   | Rad.                              | L-1   | L-2   | D-1   | D-2   |
|  |   | 1/64                              | .0009 | .0110 | .0035 | .0191 |
|  |   | 1/32                              | .0019 | .0221 | .0070 | .0383 |
|  |   | 3/64                              | .0028 | .0331 | .0105 | .0574 |
|  |   | 1/16                              | .0038 | .0442 | .0140 | .0765 |
| Triangle Profile                                   |   |                                   |       |       |       |       |
| G Style <sup>a</sup>                               |   | Turning 0° Lead Angle             |       |       |       |       |
|  |   | Rad.                              | L-1   | L-2   | D-1   | D-2   |
|  |   | 1/64                              | .0114 | .0271 | 0     | .0156 |
|  |   | 1/32                              | .0229 | .0541 | 0     | .0312 |
|  |   | 3/64                              | .0343 | .0812 | 0     | .0469 |
|  |   | 1/16                              | .0458 | .1082 | 0     | .0625 |
| B Style <sup>a</sup><br>Also applies<br>to R Style |  | Turning and Facing 15° Lead Angle |       |       |       |       |
|  |   | Rad.                              | L-1   | L-2   | D-1   | D-2   |
|  |   | 1/64                              | .0146 | .0302 | .0039 | .0081 |
|  |   | 1/32                              | .0291 | .0604 | .0078 | .0162 |
|  |   | 3/64                              | .0437 | .0906 | .0117 | .0243 |
|  |   | 1/16                              | .0582 | .1207 | .0156 | .0324 |
| F Style <sup>a</sup>                               |  | Facing 90° Lead Angle             |       |       |       |       |
|  |   | Rad.                              | L-1   | L-2   | D-1   | D-2   |
|  |   | 1/64                              | 0     | .0156 | .0114 | .0271 |
|  |   | 1/32                              | 0     | .0312 | .0229 | .0541 |
|  |   | 3/64                              | 0     | .0469 | .0343 | .0812 |
|  |   | 1/16                              | 0     | .0625 | .0458 | .1082 |

**Table 1. (Continued) Insert Radius Compensation ANSI B212.3-1986**

| Triangle Profile (continued) |       |  |       |       |       |       |
|------------------------------|-------|--|-------|-------|-------|-------|
| J Style <sup>a</sup>         |       | Turning & Facing 3° Lead Angle         |       |       |       |       |
|                              |       | Rad.                                   | L-1   | L-2   | D-1   | D-2   |
|                              |       | 1/64                                   | .0106 | .0262 | .0014 | .0170 |
|                              |       | 1/32                                   | .0212 | .0524 | .0028 | .0340 |
|                              |       | 3/64                                   | .0318 | .0786 | .0042 | .0511 |
| 1/16                         | .0423 | .1048                                  | .0056 | .0681 |       |       |
| 80° Diamond Profile          |       |  |       |       |       |       |
| G Style <sup>a</sup>         |       | Turning & Facing 0° Lead Angle         |       |       |       |       |
|                              |       | Rad.                                   | L-1   | L-2   | D-1   | D-2   |
|                              |       | 1/64                                   | .0030 | .0186 | 0     | .0156 |
|                              |       | 1/32                                   | .0060 | .0312 | 0     | .0312 |
|                              |       | 3/64                                   | .0090 | .0559 | 0     | .0469 |
| 1/16                         | .0120 | .0745                                  | 0     | .0625 |       |       |
| L Style <sup>a</sup>         |       | Turning & Facing 5° Reverse Lead Angle |       |       |       |       |
|                              |       | Rad.                                   | L-1   | L-2   | D-1   | D-2   |
|                              |       | 1/64                                   | .0016 | .0172 | .0016 | .0172 |
|                              |       | 1/32                                   | .0031 | .0344 | .0031 | .0344 |
|                              |       | 3/64                                   | .0047 | .0516 | .0047 | .0516 |
| 1/16                         | .0062 | .0688                                  | .0062 | .0688 |       |       |
| F Style <sup>a</sup>         |       | Facing 0° Lead Angle                   |       |       |       |       |
|                              |       | Rad.                                   | L-1   | L-2   | D-1   | D-2   |
|                              |       | 1/64                                   | 0     | .0156 | .0030 | .0186 |
|                              |       | 1/32                                   | 0     | .0312 | .0060 | .0372 |
|                              |       | 3/64                                   | 0     | .0469 | .0090 | .0559 |
| 1/16                         | 0     | .0625                                  | .0120 | .0745 |       |       |
| R Style <sup>a</sup>         |       | Turning 15° Lead Angle                 |       |       |       |       |
|                              |       | Rad.                                   | L-1   | L-2   | D-1   | D-2   |
|                              |       | 1/64                                   | .0011 | .0167 | .0003 | .0117 |
|                              |       | 1/32                                   | .0022 | .0384 | .0006 | .0234 |
|                              |       | 3/64                                   | .0032 | .0501 | .0009 | .0351 |
| 1/16                         | .0043 | .0668                                  | .0012 | .0468 |       |       |
| K Style <sup>a</sup>         |       | Facing 15° Lead Angle                  |       |       |       |       |
|                              |       | Rad.                                   | L-1   | L-2   | D-1   | D-2   |
|                              |       | 1/64                                   | .0003 | .0117 | .0011 | .0167 |
|                              |       | 1/32                                   | .0006 | .0234 | .0022 | .0334 |
|                              |       | 3/64                                   | .0009 | .0351 | .0032 | .0501 |
| 1/16                         | .0012 | .0468                                  | .0043 | .0668 |       |       |

**Table 1. (Continued) Insert Radius Compensation ANSI B212.3-1986**

| 55° Profile  |       |                                 |       |       |       |       |
|--|-------|---------------------------------|-------|-------|-------|-------|
| J Style <sup>a</sup>   |       | Profiling 3° Reverse Lead Angle |       |       |       |       |
|  |       | Rad.                            | L-1   | L-2   | D-1   | D-2   |
|  |       | 1/64                            | .0135 | .0292 | .0015 | .0172 |
|  |       | 1/32                            | .0271 | .0583 | .0031 | .0343 |
|  |       | 3/64                            | .0406 | .0875 | .0046 | .0519 |
| 1/16   | .0541 | .1166                           | .0062 | .0687 |       |       |
| 35° Profile  |       |                                 |       |       |       |       |
| J Style <sup>a</sup><br>Negative rake holders have 6° back rake and 6° side rake |       | Profiling 3° Reverse Lead Angle |       |       |       |       |
|  |       | Rad.                            | L-1   | L-2   | D-1   | D-2   |
|  |       | 1/64                            | .0330 | .0487 | .0026 | .0182 |
|  |       | 1/32                            | .0661 | .0973 | .0051 | .0364 |
|  |       | 3/64                            | .0991 | .1460 | .0077 | .0546 |
| 1/16   | .1322 | .1947                           | .0103 | .0728 |       |       |
| L Style <sup>a</sup>   |       | Profiling 5° Lead Angle         |       |       |       |       |
|  |       | Rad.                            | L-1   | L-2   | D-1   | D-2   |
|  |       | 1/64                            | .0324 | .0480 | .0042 | .0198 |
|  |       | 1/32                            | .0648 | .0360 | .0086 | .0398 |
|  |       | 3/64                            | .0971 | .1440 | .0128 | .0597 |
| 1/16   | .1205 | .1920                           | .0170 | .0795 |       |       |

<sup>a</sup> L-1 and D-1 over sharp point to nose radius; and L-2 and D-2 over sharp point to center of nose radius. The D-1 dimension for the B, E, D, M, P, S, T, and V style tools are over the sharp point of insert to a sharp point at the intersection of a line on the lead angle on the cutting edge of the insert and the C dimension. The L-1 dimensions on K style tools are over the sharp point of insert to sharp point intersection of lead angle and F dimensions.

All dimensions are in inches.

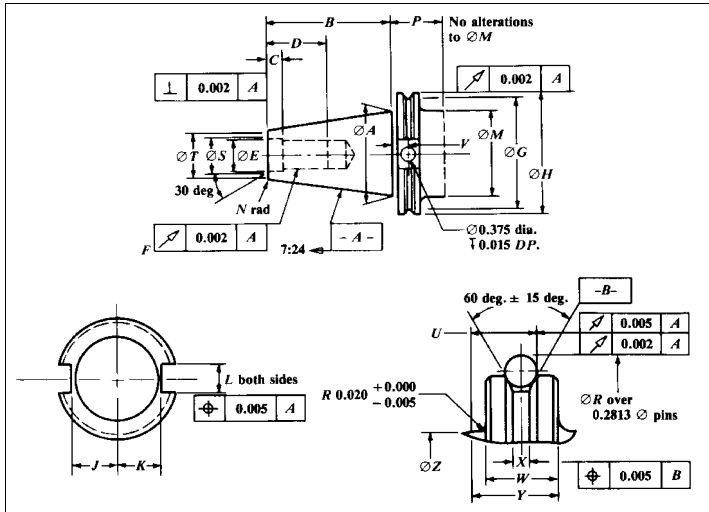
**Table 2. Threading Tool Insert Radius Compensation for NC Programming**

| Threading          |           |          |      |                 |      |      |
|--------------------|-----------|----------|------|-----------------|------|------|
| Insert Size        | T         | R        | U    | Y               | X    | Z    |
| 2                  | 5/32 Wide | .040     | .075 | .040            | .024 | .140 |
| 3                  | 3/16 Wide | .046     | .098 | .054            | .031 | .183 |
| 4                  | 1/4 Wide  | .053     | .128 | .054            | .049 | .239 |
| 5                  | 3/8 Wide  | .099     | .190 | ...             | ...  | ...  |
| Buttress Threading |           | 29° Acme |      | 60° V-Threading |      |      |
|                    |           |          |      |                 |      |      |
| NTB-B              | NTB-A     | NA       | NTF  | NT              |      |      |

All dimensions are given in inches. Courtesy of Kennametal, Inc.

**V-Flange Tool Shanks and Retention Knobs.**—Dimensions of ANSI B5.18-1972 (R1998) standard tool shanks and corresponding spindle noses are detailed on pages 940 through 944, and are suitable for spindles used in milling and associated machines. Corresponding equipment for higher-precision numerically controlled machines, using retention knobs instead of drawbars, is usually made to the ANSI/ASME B5.50-1985 standard.

**Essential Dimensions of V-Flange Tool Shanks** *ANSI/ASME B5.50-1985*



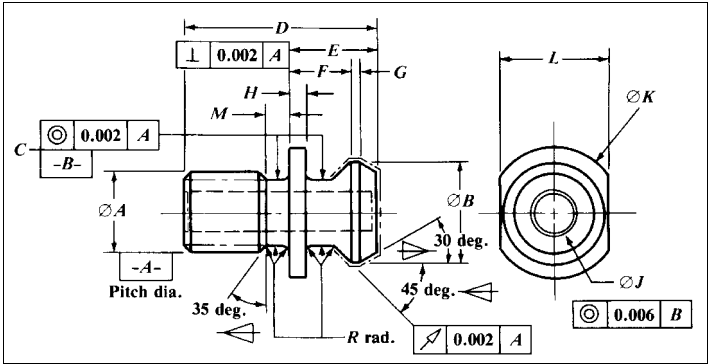
| A         |           | B      | C      | D    | E                | F        | G      | H      | J                | K                |
|-----------|-----------|--------|--------|------|------------------|----------|--------|--------|------------------|------------------|
| Tolerance |           | ±0.005 | ±0.010 | Min. | +0.015<br>-0.000 | UNC 2B   | ±0.010 | ±0.002 | +0.000<br>-0.015 | +0.000<br>-0.015 |
| Size      | Gage Dia. |        |        |      |                  |          |        |        |                  |                  |
| 30        | 1.250     | 1.875  | 0.188  | 1.00 | 0.516            | 0.500-13 | 1.531  | 1.812  | 0.735            | 0.640            |
| 40        | 1.750     | 2.687  | 0.188  | 1.12 | 0.641            | 0.625-11 | 2.219  | 2.500  | 0.985            | 0.890            |
| 45        | 2.250     | 3.250  | 0.188  | 1.50 | 0.766            | 0.750-10 | 2.969  | 3.250  | 1.235            | 1.140            |
| 50        | 2.750     | 4.000  | 0.250  | 1.75 | 1.031            | 1.000-8  | 3.594  | 3.875  | 1.485            | 1.390            |
| 60        | 4.250     | 6.375  | 0.312  | 2.25 | 1.281            | 1.250-7  | 5.219  | 5.500  | 2.235            | 2.140            |

| A         |           | L      | M      | N                | P     | R      | S      | T            | Z                |
|-----------|-----------|--------|--------|------------------|-------|--------|--------|--------------|------------------|
| Tolerance |           | ±0.001 | ±0.005 | +0.000<br>-0.015 | Min.  | ±0.002 | ±0.010 | Min.<br>Flat | +0.000<br>-0.005 |
| Size      | Gage Dia. |        |        |                  |       |        |        |              |                  |
| 30        | 1.250     | 0.645  | 1.250  | 0.030            | 1.38  | 2.176  | 0.590  | 0.650        | 1.250            |
| 40        | 1.750     | 0.645  | 1.750  | 0.060            | 1.38  | 2.863  | 0.720  | 0.860        | 1.750            |
| 45        | 2.250     | 0.770  | 2.250  | 0.090            | 1.38  | 3.613  | 0.850  | 1.090        | 2.250            |
| 50        | 2.750     | 1.020  | 2.750  | 0.090            | 1.38  | 4.238  | 1.125  | 1.380        | 2.750            |
| 60        | 4.250     | 1.020  | 4.250  | 0.120<br>0.200   | 1.500 | 5.683  | 1.375  | 2.04         | 4.250            |

Notes: Taper tolerance to be 0.001 in. in 12 in. applied in direction that increases rate of taper. Geometric dimension symbols are to ANSI Y14.5M-1982. Dimensions are in inches. Deburr all sharp edges. Unspecified fillets and radii to be  $0.03 \pm 0.010R$ , or  $0.03 \pm 0.010 \times 45$  degrees. Data for size 60 are not part of Standard. For all sizes, the values for dimensions  $U$  (tol.  $\pm 0.005$ ) are 0.579; for  $V$  (tol.  $\pm 0.010$ ), 0.440; for  $W$  (tol.  $\pm 0.002$ ), 0.625; for  $X$  (tol.  $\pm 0.005$ ), 0.151; and for  $Y$  (tol.  $\pm 0.002$ ), 0.750.

**Essential Dimensions of V-Flange Tool Shank Retention Knobs**  
ANSI/ASME B5.50-1985



| Size       | A        | B      | C      | D      | E      | F      |
|------------|----------|--------|--------|--------|--------|--------|
| 30         | 0.500-13 | 0.520  | 0.385  | 1.10   | 0.460  | 0.320  |
| 40         | 0.625-11 | 0.740  | 0.490  | 1.50   | 0.640  | 0.440  |
| 45         | 0.750-10 | 0.940  | 0.605  | 1.80   | 0.820  | 0.580  |
| 50         | 1.000-8  | 1.140  | 0.820  | 2.30   | 1.000  | 0.700  |
| 60         | 1.250-7  | 1.460  | 1.045  | 3.20   | 1.500  | 1.080  |
| Tolerances | UNC-2A   | ±0.005 | ±0.005 | ±0.040 | ±0.005 | ±0.005 |

| Size       | G      | H      | J      | K            | L                | M      | R                |
|------------|--------|--------|--------|--------------|------------------|--------|------------------|
| 30         | 0.04   | 0.10   | 0.187  | 0.65<br>0.64 | 0.53             | 0.19   | 0.094            |
| 40         | 0.06   | 0.12   | 0.281  | 0.94<br>0.92 | 0.75             | 0.22   | 0.094            |
| 45         | 0.08   | 0.16   | 0.375  | 1.20<br>1.18 | 1.00             | 0.22   | 0.094            |
| 50         | 0.10   | 0.20   | 0.468  | 1.44<br>1.42 | 1.25             | 0.25   | 0.125            |
| 60         | 0.14   | 0.30   | 0.500  | 2.14<br>2.06 | 1.50             | 0.31   | 0.125            |
| Tolerances | ±0.010 | ±0.010 | ±0.010 |              | +0.000<br>-0.010 | ±0.040 | +0.010<br>-0.005 |

Notes: Dimensions are in inches. Material: low-carbon steel. Heat treatment: carburize and harden to 0.016 to 0.028 in. effective case depth. Hardness of noted surfaces to be Rockwell 56-60; core hardness Rockwell C35-45. Hole *J* shall not be carburized. Surfaces *C* and *R* to be free from tool marks. Deburr all sharp edges. Geometric dimension symbols are to ANSI Y14.5M-1982.

Data for size 60 are not part of Standard.

**CAD/CAM**

**CAD/CAM.**—CAD in engineering means computer-aided design using a computer graphics system to develop mechanical, electrical/electronic, and architectural designs. A second D (CADD) is sometimes added (computer-aided drafting and design) and simply indicates a mechanical drafting or drawing program. CAD technology is the foundation for a wide variety of engineering, design, drafting, analysis, and manufacturing activities. Often a set of drawings initially developed in the design phase of a project is also used for analyzing and optimizing the design, creating mechanical drawings of parts and assemblies and for generating NC/CNC part programs that control machining operations. Formerly, after a component had been designed with CAD, the design was passed to a part programmer who developed a program for machining the components, either manually or directly on the computer (graphic) screen, but the process often required redefining and reentering part geometry. This procedure is often regarded as the CAM part of CAD/CAM, although CAM (for computer-aided manufacturing) has a much broader meaning and involves the computer in many other manufacturing activities such as factory simulation and planning analyses. Improvements in the speed and capability of computers, operating systems, and programs (including, but not limited to CAD) have simplified the process of integrating the manufacturing process and passing drawings (revised, modified, and translated, as necessary) through the design, analysis, simulation, and manufacturing stages.

A CAD drawing is a graphic representation of part geometry data stored in a drawing database file. The drawing database generally contains the complete list of entity (line, arc, etc.) and coordinate information required to build the CAD drawing, and additional information that may be required to define solid surfaces and other model characteristics. The format of data in a drawing file depends on the CAD program used to create the file. Generally, drawings are not directly interchangeable between drawing programs, however, drawings created in one system can usually be translated into an intermediate format or file type, such as DXF, that allows some of the drawing information to be exchanged between different programs. Translation frequently results in some loss of detail or loss of other drawing information because the various drawing programs do not all have the same features. The section Drawing Exchange Standards covers some of the available methods of transferring drawing data between different CAD programs.

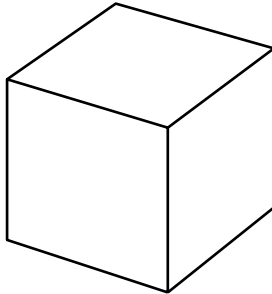


Fig. 1. Simple Wireframe Cube with Hidden Lines Automatically Removed

The simplest CAD drawings are two-dimensional and conform to normal engineering drafting practice showing orthographic (front, top, and side views, for example), exploded, isometric, or other views of a component. Depending on the complexity of the part and machining requirements, two-dimensional drawings are often sufficient for use in developing NC/CNC part programs. If a part can be programmed within a two-dimensional



CAD framework, a significant cost saving may be realized because 3-D drawings require considerably more time, drawing skill, and experience to produce than 2-D drawings.

*Wireframes* are the simplest two- and three-dimensional forms of drawing images and are created by defining all edges of a part and, where required, lines defining surfaces. Wireframe drawing elements consist primarily of lines and arcs that can be used in practically any combination. A wireframe drawing of a cube, as in Fig. 1, consists of 12 lines of equal length (some are hidden and thus not shown), each perpendicular to the others. Information about the interior of the cube and the character of the surfaces is not included in the drawing. With such a system, if a 1-inch cube is drawn and a 0.5-inch cylinder is required to intersect the cube's surface at the center of one of its faces, the intersection points cannot be determined because nothing is known about the area between the edges. A wireframe model of this type is ambiguous if the edges overlap or do not meet where they should. Hidden-line removal can be used to indicate the relative elevations of the drawing elements, but normally a drawing cannot be edited when hidden lines have been removed. Hidden lines can be shown dashed or can be omitted from the view.

Two-dimensional drawing elements, such as lines, arcs, and circles, are constructed by directly or indirectly specifying point coordinates, usually  $x$  and  $y$ , that identify the location, size, and orientation of the entities. Three-dimensional drawings are also made up of a collection of lines, arcs, circles, and other drawing elements and are stored in a similar manner. A third point coordinate,  $z$ , indicates the elevation of a point in 3-D drawings. On the drawing screen, working in the  $x$ - $y$  plane, the elevation is commonly thought of as the distance of a point or object into the screen (away from the observer) or out of the viewing screen (toward the observer). Coordinate axes are oriented according to the right-hand rule: If the fingers of the right hand point in the direction from the positive  $x$ -axis to the positive  $y$ -axis, the thumb of the right hand points in the direction of the positive  $z$ -axis.

Assigning a thickness (or extruding) to objects drawn in two dimensions quickly gives some 3-D characteristics to an object and can be used to create simple prismatic 3-D shapes, such as cubes and cylinders. Usually, the greatest difficulty in creating 3-D drawings is in picking and visualizing the three-dimensional points in a two-dimensional workspace (the computer display screen). To assist in the selection of 3-D points, many CAD programs use a split or windowed screen drawing area that can simultaneously show different views of a drawing. Changes made in the current or active window are reflected in each of the other windows. A typical window setup might show three orthogonal (mutually perpendicular) views of the drawing and a perspective or 3-D view. Usually, the views shown can be changed as required to suit the needs of the operator.

If carefully constructed, wireframe images may contain enough information to completely define the external geometry of simple plane figures. Wireframe images are especially useful for visualization of 3-D objects and are effectively used during the design process to check fits, clearances, and dimensional accuracy. Parts designed to be used together can be checked for accuracy of fit by bringing them together in a drawing, superimposing the images, and graphically measuring clearances. If the parts have been designed or drawn incorrectly, the errors will frequently be obvious and appropriate corrections can be made.

A more complicated level of 3-D drawing involves solids, with sections of the part being depicted on the screen as solid geometrical structures called primitives, such as cylinders, spheres, and cubes. Primitives can be assembled on a drawing to show more complex parts. Three distinct forms of image may be generated by 3-D systems, although not all systems make use of all three.

*Surface Images:* A surface image defines not only the edges of the part, but also the "skin" of each face or surface. For the example mentioned previously, the intersection for the 0.5-inch cylinder would be calculated and drawn in position. Surface models are necessary for designing free-form objects such as automotive body panels and plastics injection moldings used in consumer goods. For a surface model, the computer must be provided

with much more information about the part in addition to the  $x$ ,  $y$ ,  $z$  coordinates defining each point, as in a wireframe. This information may include tangent vectors, surface normals, and weighting that determines how much influence one point has on another, twists, and other mathematical data that define abstract curves, for instance. Fig. 2 shows a typical 3-D surface patch.

*Shaded images* may be constructed using simulated light sources, reflections, colors, and textures to make renderings more lifelike. Surface images are sometimes ambiguous, with surfaces that overlap or miss each other entirely. Information about the interior of the part, such as the center of gravity or the volume, also may not be available, depending on the CAD package.

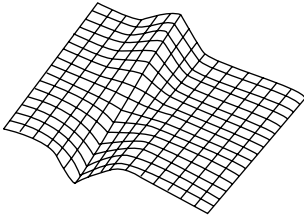


Fig. 2. A 3-D Surface Patch

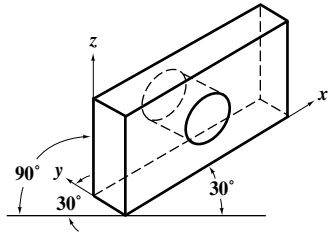


Fig. 3. Isometric Drawing Showing Orientation of Principle Drawing Axes

*Solid Images:* A solid image is the ultimate electronic representation of a part, containing all the necessary information about edges, surfaces, and the interior. Most solid-imaging programs can calculate volume, center of mass, centroid, and moment of inertia. Several methods are available for building a solid model. One method is to perform Boolean operations on simple shapes such as cylinders, cones, cubes, and blocks. Boolean operations are used to union (join), difference (subtract one from another), and intersect (find the common volume between two objects). Thus, making a hole in a part requires subtracting a cylinder from a rectangular block. This type of program is called constructive solid geometry (CSG).

The boundary representation type of imaging program uses profiles of 2-D shapes that it extrudes, rotates, and otherwise translates in 3-D space to create the required solid. Sometimes combinations of the above two programs are used to attain a blend of flexibility, accuracy, and performance. For more precision, greatly increased time is needed for calculations, so compromises sometimes are needed to maintain reasonable productivity. Solid images may be sliced or sectioned on the screen to provide a view of the interior. This type of image is also useful for checking fit and assembly of one part with another.

Solid images provide complete, unambiguous representation of a part, but the programs require large amounts of computer memory. Each time a Boolean operation is performed, the list of calculations that must be done to define the model becomes longer, so that computation time increases.

**Drawing Projections.**—Several different techniques are used to display objects on paper or a computer screen to give an accurate three-dimensional appearance. Several of these methods are commonly used in CAD drawings.

*Isometric drawings*, as in Fig. 3, can be used to good effect for visualizing a part because they give the impression of a 3-D view and are often much faster to create. Isometric drawings are created in 2-D space, with the  $x$ - and  $y$ -axes being inclined at 30 degrees to the horizontal, as shown in Fig. 3, and the  $z$ -axis as vertical. Holes and cylinders in isometric drawings become elliptical. Because of the orientation of the  $x$ -,  $y$ -, and  $z$ -axes, the true length of lines may not be accurately represented in isometric drawings and dimensions

should not be taken directly from a print. Some CAD programs have a special set of pre-defined drawing axes to facilitate creating isometric drawings.

In *parallel projections*, lines that are parallel in an object, assembly, or part being portrayed remain parallel in the drawing. Parallel projections show 3-D objects in a dimensionally correct manner, so that relative and scaled dimensions may be taken directly from a drawing. However, drawings may not appear as realistic as isometric or perspective drawings.

A characteristic of *perspective drawings* is that parallel lines converge (see Fig. 4) so that objects that are farther away from the observer appear smaller. Perspective drawing techniques are used in some three-dimensional drawings to convey the true look of an object, or group of objects. Because objects in perspective drawings are not drawn to scale, dimensional information cannot be extracted from the drawings of a part. Some 3-D drawing packages have a true perspective drawing capability, and others use a simulation technique to portray a 3-D perspective.

An *axonometric projection* is a 3-D perpendicular projection of an object onto a surface, such that the object is tilted relative to its normal orientation. An axonometric projection of a cube, as in Fig. 1, shows three faces of the cube. CAD systems are adept at using this type of view, making it easy to see an object from any angle.

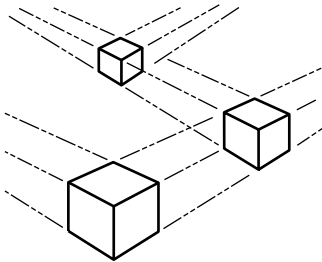


Fig. 4. Perspective Drawing of Three Equal-Size Cubes and Construction Lines

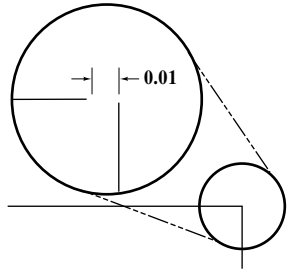


Fig. 5. A Common Positioning Error

**Drawing Tips and Traps.**—Images sometimes appear correct on the screen but contain errors that show up when the drawing is printed or used to produce NC/CNC part programs. In Fig. 5, the two lines within the smaller circle appear to intersect at a corner, but when the view of the intersection is magnified, as in the larger circle, it is clear that the lines actually do not touch. Although an error of this type may not be easily visible, other parts placed in the drawing relative to this part will be out of position.

A common problem that shows up in plotting, but is difficult to detect on the screen, comes from placing lines in the same spot. When two or more lines occupy exactly the same location on the screen, there is usually no noticeable effect on the display. However, when the drawing is plotted, each line is plotted separately, causing the single line visible to become thicker and darker. Likewise, if a line that appears continuous on the screen is actually made up of several segments, plotting the line will frequently result in a broken, marred, or blotted appearance to the line because the individual segments are plotted separately, and at different times. To avoid these problems and to get cleaner looking plots, replace segmented lines with single lines and avoid constructions that place one line directly on top of another.

Exact decimal values should be used when entering point coordinates from the keyboard, if possible; fractional sizes should be entered as fractions, not truncated decimals. For example,  $\frac{5}{16}$  should be entered as 0.3125 or  $\frac{5}{16}$ , not 0.313. Accumulated rounding errors and surprises later on when parts do not fit are thus reduced. Drawing dimensions, on the

other hand, should not have more significant digits or be more precise than necessary. Unnecessary precision in dimensioning leads to increased difficulty in the production stage because the part has to be made according to the accuracy indicated on the drawing.

*Snap* and *object snap* commands make selecting lines, arcs, circles, or other drawing entities faster, easier, and more accurate when picking and placing objects on the screen. Snap permits only points that are even multiples of the snap increment to be selected by the pointer. A  $\frac{1}{8}$ -inch snap setting, for example, will allow points to be picked at exactly  $\frac{1}{8}$ -inch intervals. Set the *snap increment* to the smallest distance increment (1 in.,  $\frac{1}{4}$  in., 1 ft., etc.) being used in the area of the drawing under construction and reset the snap increment frequently, if necessary. The snap feature can be turned off during a command to override the setting or to select points at a smaller interval than the snap increment allows. Some systems permit setting a different snap value for each coordinate axis.

The *object snap* selection mode is designed to select points on a drawing entity according to predefined characteristics of the entity. For example, if end-point snap is in effect, picking a point anywhere along a line will select the end point of the line nearest the point picked. Object snap modes include point, intersection, midpoint, center and quadrants of circles, tangency point (allows picking a point on an arc or circle that creates a tangent to a line), and perpendicular point (picks a point that makes a perpendicular from the base point to the object selected). When two or more object snap modes are used together, the nearest point that meets the selection criteria will be chosen. Using object snap will greatly reduce the frequency of the type of problem shown in Fig. 5.

*Copy*: Once drawn, avoid redrawing the same object. It is almost always faster to copy and modify a drawing than to draw it again. The basic copy commands are: copy, array, offset, and mirror. Use these, along with move and rotate and the basic editing commands, to modify existing objects. Copy and move should be the most frequently used commands. If possible, create just one instance of a drawing object and then copy and move it to create others.

To create multiple copies of an object, use the *copy, multiple* feature to copy selected objects as many times as required simply by indicating the destination points. The *array* command makes multiple copies of an object according to a regular pattern. The rectangular array produces rows and columns, and the polar array puts the objects into a circular pattern, such as in a bolt circle. *Offset* copies an entity and places the new entity a specified distance from the original and is particularly effective at placing parallel lines and curves, and for creating concentric copies of closed shapes. *Mirror* creates a mirror image copy of an object, and is useful for making right- and left-hand variations of an object as well as for copying objects from one side of an assembly to the other. In some CAD programs, a system variable controls whether text is mirrored along with other objects.

Many manufacturers distribute drawings of their product lines in libraries of CAD drawings, usually as DXF files, that can be incorporated into existing drawings. The suitability of such drawings depends on the CAD program and drawing format being used, the skill of the technician who created the drawings, and the accuracy of the drawings. A typical example, Fig. 6, shows a magnetically coupled actuator drawing distributed by Tol-O-Matic, Inc. Libraries of frequently used drawing symbols and blocks are also available from commercial sources.

*Create Blocks of Frequently Used Objects*: Once created, complete drawings or parts of drawings can be saved and later recalled, as needed, into another drawing. Such objects can be scaled, copied, stretched, mirrored, rotated, or otherwise modified without changing the original. When shapes are initially drawn in unit size (i.e., fitting within a  $1 \times 1$  square) and saved, they can be inserted into any drawing and scaled very easily. One or more individual drawing elements can be saved as a group element, or *block*, that can be manipulated in a drawing as a single element. Block properties vary, depending on the drawing program, but are among the most powerful features of CAD. Typically, blocks are uniquely named

and, as with simple objects, may be saved in a file on the disk. Blocks are ideal for creating libraries of frequently used drawing symbols. Blocks can be copied, moved, scaled very easily, rotated, arrayed, and inserted as many times as is required in a drawing and manipulated as one object. When scaled, each object within the block is also scaled to the same degree.

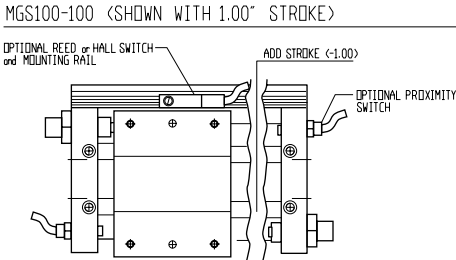


Fig. 6. Manufacturer's Drawing of a Magnetically Coupled Actuator (Courtesy of Tol-O-Matic, Inc.)

When a family of parts is to be drawn, create and block a single drawing of the part that fits within a unit cube of convenient size, such as  $1 \times 1 \times 1$ . When the block is inserted in a drawing, it is scaled appropriately in the  $x$ -,  $y$ -, and  $z$ -directions. For example,  $\frac{3}{8}$ -inch bolts can be drawn 1 inch long in the  $x$ -direction and  $\frac{3}{8}$ -inch in diameter in the  $y$ - $z$  plane. If a 5-inch bolt is needed, insert the "bolt" block with a scale of 5 in the  $x$ -direction and a scale of 1 in the  $y$ - and  $z$ -directions.

Once blocked, the individual components of a block (lines, arcs, circles, surfaces, and text, for example) cannot be individually changed or edited. To edit a block, a copy (instance) of the block must be *exploded* (unblocked) to divide it into its original components. Once exploded, all the individual elements of the block (except other blocks) can be edited. When the required changes have been made, the block must be redefined (redeclared as a block by giving it a name and identifying its components). If the block is redefined using the same name, any previous references to the block in the drawing will be updated to match the redefined block. For example, an assembly drawing is needed that shows a mechanical frame with 24 similar control panels attached to it. Once one of the panels is drawn and defined as a block (using the name *PANEL*, for instance), the block can be inserted (or copied) into the drawing 24 times. Later, if changes need to be made to the panel design, one instance of the block *PANEL* can be exploded, modified, and redefined with the name *PANEL*. When *PANEL* is redefined, every other copy of the *PANEL* block in the drawing is also redefined, so every copy of *PANEL* in the drawing is updated. On the other hand, if the block was redefined with a different name, say, *PANEL1*, existing copies of *PANEL* remain unchanged. When redefining a block that already exists in the drawing, be sure to use the same insertion point that was used for the original definition of the block; otherwise, the positions of existing blocks with the same name will be changed.

*Use of Text Attributes to Request Drawing Information Automatically:* Text attributes are a useful method for attaching textual information to a particular part or feature of a drawing. An attribute is basically a text variable that has a name and can be assigned a value. Attributes are created by defining attribute characteristics such as a name, location in the drawing, text size and style, and default value. The attribute value is assigned when the attribute is inserted into a drawing as part of a block.

Fig. 7 shows two views of a title block for size A to C drawing sheets. The upper figure includes the title block dimensions (included only for reference) and the names and locations of the attributes (COMPANY, TITLE1, TITLE2, etc.). When a block containing text

attributes is inserted in a drawing, the operator is asked to enter the value of each attribute. To create this title block, first draw the frame of the title block and define the attributes (name, location and default value for: company name and address, drawing titles [2 lines], drawing size, drawing number, revision number, scale, and sheet number). Finally, create and name a block containing the title frame and all the attribute definitions (do not include the dimensions).

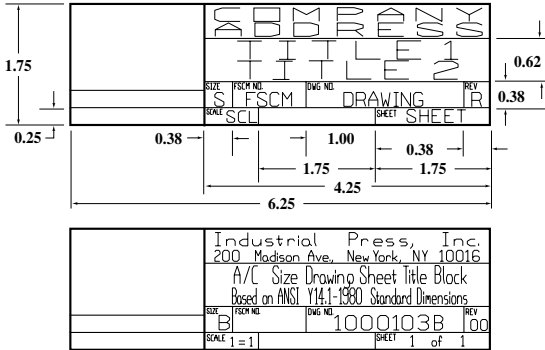


Fig. 7. Title Block for A to C Size Drawing Sheets Showing the Placement of Text Attributes. The Lower Figure Shows the Completed Block

When the block is inserted into a drawing, the operator is asked to enter the attribute values (such as company name, drawing title, etc.), which are placed into the title block at the predetermined location. The lower part of Fig. 7 shows a completed title block as it might appear inserted in a drawing. A complete drawing sheet could include several additional blocks, such as a sheet frame, a revision block, a parts list block, and any other supplementary blocks needed. Some of these blocks, such as the sheet frame, title, and parts list blocks, might be combined into a single block that could be inserted into a drawing at one time.

**Define a Default Drawing Configuration:** Drawing features that are commonly used in a particular type of drawing can be set up in a template file so that frequently used settings, such as text and dimension styles, text size, drawing limits, initial view, and other default settings, are automatically set up when a new drawing is started. Different configurations can be defined for each frequently used drawing type, such as assembly, parts, or printed circuit drawings. When creating a new drawing, use one of the template files as a pattern or open a template file and use it to create the new drawing, saving it with a new name.

**Scaling Drawings:** Normally, for fast and accurate drawing, it is easiest to draw most objects full scale, or with a 1:1 scale. This procedure greatly simplifies creation of the initial drawing, and ensures accuracy, because scale factors do not need to be calculated. If it becomes necessary to fit a large drawing onto a small drawing sheet (for example, to fit a 15 × 30 inch assembly onto a 11 × 17 inch, B-sized, drawing sheet), the drawing sheet can be scaled larger to fit the assembly size. Likewise, large drawing sheets can be scaled down to fit small drawings. The technique takes some practice, but it permits the drawing assembly to be treated full scale. If editing is required at a later date (to move something or add a hole in a particular location, for example), changes can be made without rescaling and dimensions can be taken directly from the unscaled drawing on the computer.

**Scaling Text on Drawing Sheets:** It is usually desirable that text, dimensions, and a few other features on drawings stay a consistent size on each sheet, even when the drawing size is very different. The following procedure ensures that text and dimensions (other features

as well, if desired) will be the same size, from drawing to drawing without resorting to scaling the drawing to fit onto the drawing sheet.

Create a drawing sheet having the exact dimensions of the actual sheet to be output (A, B, C, D, or E size, for example). Use text attributes, such as the title block illustrated in Fig. 7, to include any text that needs to be entered each time the drawing sheet is used. Create a block of the drawing sheet, including the text attributes, and save the block to disk. Repeat for each size drawing sheet required.

Establish the nominal text and dimension size requirements for the drawing sheet when it is plotted full size (1:1 scale). This is the size text that will appear on a completed drawing. Use Table 1 as a guide to recommended text sizes of various drawing features.

**Table 1. Standard Sizes of Mechanical Drawing Lettering ANSI Y14.2M-1992**

| Use For  | Inch                      |                  | Metric                    |              |
|--|---------------------------|------------------|---------------------------|--------------|
|  | Min. Letter Heights, (in) | Drawing Size     | Min. Letter Heights, (mm) | Drawing Size |
| Drawing title, drawing size, CAGE Code, drawing number, and revision letter <sup>a</sup> | 0.24                      | D, E, F, H, J, K | 6                         | A0, A1       |
|  | 0.12                      | A, B, C, G       | 3                         | A2, A3, A4   |
| Section and view letters   | 0.24                      | All              | 6                         | All          |
| Zone letters and numerals in borders   | 0.24                      | All              | 6                         | All          |
| Drawing block headings   | 0.10                      | All              | 2.5                       | All          |
| All other characters   | 0.12                      | All              | 3                         | All          |

<sup>a</sup> When used within the title block.

Test the sheet by setting the text size and dimension scale variables to their nominal values (established above) and place some text and dimensions onto the drawing sheet. Plot a copy of the drawing sheet and check that text and dimensions are the expected size.

To use the drawing sheet, open a drawing to be placed on the sheet and insert the sheet block into the drawing. Scale and move the sheet block to locate the sheet relative to the drawing contents. When scaling the sheet, try to use whole-number scale factors (3:1, 4:1, etc.), if possible; this will make setting text size and dimension scale easier later on. Set the text-size variable equal to the nominal text size multiplied by the drawing sheet insertion scale (for example, for 0.24 text height on a drawing sheet scaled 3:1, the text-size variable will be set to  $3 \times 0.24 = 0.72$ ). Likewise, set the dimension-scale variable equal to the nominal dimension size multiplied by the drawing sheet insertion scale.

Once the text size and dimensions scale variables have been set, enter all the text and dimensions into the drawing. If text of another size is needed, multiply the *new* nominal text size by the sheet scale to get the actual size of the text to use in the drawing.

*Use Appropriate Detail:* Excessive detail may reduce the effectiveness of the drawing, increase the drawing time on individual commands and the overall time spent on a drawing, and reduce performance and speed of the CAD program. Whenever possible, symbolic drawing elements should be used to represent more complicated parts of a drawing unless the appearance of that particular component is essential to the drawing.

Drawing everything to scale often serves no purpose but to complicate a drawing and increase drawing time. The importance of detail depends on the purpose of a drawing, but detail in one drawing is unnecessary in another. For example, the slot size of a screw head (length and width) varies with almost every size of screw. If the purpose of a drawing is to show the type and location of the hardware, a symbolic representation of a screw is usually all that is required. The same is generally true of other screw heads, bolt threads, bolt head diameters and width across the flats, wire diameters, and many other hardware features.

**Drawing Exchange Standards.**—The ability to transfer working data between different CAD, CAD/CAM, design analysis, and NC/CNC programs is one of the most important requirements of engineering drawing programs. Once an engineer, designer, draftsman, or machinist enters relevant product data into his or her machine (computer or machine tool), the information defining the characteristics of the product should be available to the others

involved in the project without recreating or reentering it. In view of manufacturing goals of reducing lead time and increasing productivity, concurrent engineering, and improved product performance, interchangeable data are a critical component in a CAD/CAM program. Depending on the requirements of a project, it may be entirely possible to transfer most if not all of the necessary product drawings from one drawing system to another.

*IGES* stands for Initial Graphics Exchange Specification and is a means of exchanging or converting drawings and CAD files for use in a different computer graphics system. The concept is shown diagrammatically in Fig. 8. Normally, a drawing prepared on the computer graphics system supplied by company A would have to be redrawn before it would operate on the computer graphics system supplied by company B. However, with IGES, the drawing can be passed through a software package called a preprocessor that converts it into a standardized IGES format that can be stored on a magnetic disk. A postprocessor at company B is then used to convert the standard IGES format to that required for their graphics system. Both firms would be responsible for purchasing or developing their own preprocessors and postprocessors, to suit their own machines and control systems. Almost all the major graphics systems manufacturing companies today either have or are developing IGES preprocessor and postprocessor programs to convert software from one system to another.

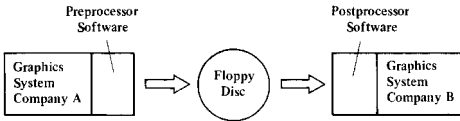


Fig. 8.

*DXF* stands for Drawing Exchange Format and is a pseudo-standard file format used for exchanging drawings and associated information between different CAD and design analysis programs. Nearly all two- and three-dimensional CAD programs support some sort of drawing exchange through the use of DXF files, and most can read and export DXF files. There are, however, differences in the drawing features supported and the manner in which the DXF files are handled by each program. For example, if a 3-D drawing is exported in the DXF format and imported into a 2-D CAD program, some loss of information results because all the 3-D features are not supported by the 2-D program, so that most attempts to make a transfer between such programs fail completely. Most common drawing entities (lines, arcs, etc.) will transfer successfully, although other problems may occur. For example, drawing entities that are treated as a single object in an original drawing (such as blocks, hatch patterns, and symbols) may be divided into hundreds of individual components when converted into a DXF file. Consequently, such a drawing may become much more difficult to edit after it is transferred to another drawing program.

*ASCII* stands for American Standard Code for Information Interchange. ASCII is a code system that describes the manner in which character-based information is stored in a computer system. Files stored in the ASCII format can be transferred easily between computers, even those using different operating systems. Although ASCII is not a drawing file format, many CAD drawing formats (DXF and IGES, for example) are ASCII files. In these files, the drawing information is stored according to a specific format using ASCII characters. ASCII files are often referred to as pure text files because they can be read and edited by simple text editors.

*HPGL*, for Hewlett-Packard Graphics Language, is a format that was first developed for sending vector- (line-) based drawing information to pen plotters. The format is commonly used for sending drawing files to printers and plotters for printing. Because HPGL is a character-based format (ASCII), it can be transferred between computers easily. Normally, devices that recognize the HPGL format can print the files without using the program on which the file (a drawing, for example) was created.



*STL* is a CAD drawing format that is primarily used to send CAD drawings to *rapid automated prototyping* machines. *STL* is a mnemonic abbreviation for stereo-lithography, the technique that is used to create three-dimensional solid models directly from computer-generated drawings and for which the drawing format was originally developed. Most prototyping machines use 3-D CAD drawing files in *STL* format to create a solid model of the part represented by a drawing.

*STEP* stands for Standard for Exchange of Product Model Data and is a series of existing and proposed ISO standards written to allow access to all the data that surround a product. It extends the *IGES* idea of providing a geometric data transfer to include all the other data that would need to be communicated about a product over its lifetime, and facilitates the use and accessibility of the product data. Although *STEP* is a new standard, software tools have been developed for converting data from the *IGES* to *STEP* format and from *STEP* to *IGES*.

**Rapid Automated Prototyping.**—Rapid automated prototyping is a method of quickly creating an accurate three-dimensional physical model directly from a computerized conception of the part. The process is accomplished without machining or the removal of any material, but rather is a method of building up the model in three-dimensional space. The process makes it possible to easily and automatically create shapes that would be difficult or impossible to produce by any other method. Currently, production methods are able to produce models with an accuracy tolerance of  $\pm 0.005$  inch. Models are typically constructed of photoreactive polymer resins, nylon, polycarbonate or other thermoplastics, and investment casting wax. The model size is limited by the capability of the modeling machines to about 1 cubic foot at the present, however, large models can be built in sections and glued or otherwise fastened together.

Much of the work and a large part of the cost associated with creating a physical model by rapid prototyping are in the initial creation of the CAD model. The model needs to be a 3-D design model, built using wireframe, surface, or solid CAD modeling techniques. Many full-featured CAD systems support translation of drawing files into the *STL* format, which is the preferred file format for downloading CAD models to rapid prototyping machines. CAD programs without *STL* file format capability can use the *IGES* or *DXF* file format. This process can be time-consuming and expensive because additional steps may have to be taken by the service bureau to recreate features lost in converting the *IGES* or *DXF* file into *STL* format. If the design file has to be edited by a service bureau to recreate surfaces lost in the translation, unwanted changes to the model may occur, unnoticed. The safest route is to create a CAD model and export it directly into the *STL* format, leaving little chance for unexpected errors. Reverse *STL* generators are also available that will display a file saved in *STL* format or convert it into a form that can be imported into a CAD program.

**DNC.**—*DNC* stands for Direct Numerical Control and refers to a method of controlling numerical control machines from a remote location by means of a link to a computer or computer network. In its simplest form, *DNC* consists of one *NC* or *CNC* machine linked by its serial port to a computer. The computer may be used to develop and store *CNC* part programs and to transfer part programs to the machine as required. *DNC* links are normally two-directional, meaning that the *NC/CNC* can be operated from a computer terminal and the computer can be operated or ordered to supply data to the *NC/CNC* from the machine's control panel.

The number of machines that can be connected to a *DNC* network depends on the network's capability; in theory, any number of machines can be attached, and controlled. The type of network depends on the individual *DNC* system, but most industry standard network protocols are supported, so *DNC* nodes can be connected to existing networks very easily. Individual *NC/CNC* machines on a network can be controlled locally, from a network terminal in another building, or even from a remote location miles away through phone or leased lines.

**Machinery Noise.**—Noise from machinery or mechanical systems can be controlled to some degree in the design or development stage if quantified noise criteria are provided the designer. Manufacturers and consumers may also use the same information in deciding whether the noise generated by a machine will be acceptable for a specific purpose.

Noise criteria for may be classified as follows: 1) relating to the degree of interference with speech communications; 2) relating to physiological damage to humans, especially hearing; and 3) those relating to psychological disturbances in people exposed to noise.

*Sound Level Specifications:* Noise criteria generally are specified in some system of units representing sound levels. One commonly used system specifies sound levels in units called decibels on the "A" scale, written dBA. The dBA scale designates a sound level system weighted to match human hearing responses to various frequencies and loudness. For example, to permit effective speech communication, typical criteria for indoor maximum noise levels are: meeting and conference rooms, 42 dBA; private offices and small meeting rooms, 38 to 47 dBA; supervisors' offices and reception rooms, 38 to 52 dBA; large offices and cafeterias, 42 to 52 dBA; laboratories, drafting rooms, and general office areas, 47 to 56 dBA; maintenance shops, computer rooms, and washrooms, 52 to 61 dBA; control and electrical equipment rooms, 56 to 66 dBA; and manufacturing areas and foremen's offices, 66 dBA. Similarly, there are standards and recommendations for daily permissible times of exposure at various steady sound levels to avoid hearing damage. For a working shift of 8 hours, a steady sound level of 90 dBA is the maximum generally permitted, with marked reduction in allowable exposure times for higher sound levels.\*

**Measuring Machinery Noise.**—The noise level produced by a single machine can be measured by using a standard sound level meter of the handheld type set to the dBA scale. However, when other machines are running at the same time, or when there are other background noises, the noise of the machine cannot be measured directly. In such cases, two measurements, taken as follows, can be used to calculate the noise level of the individual machine. The meter should be held at arm's length and well away from any bystanders to avoid possible significant error up to 5 dBA.

Step 1. At the point of interest, measure the total noise,  $T$ , in decibels; that is, measure the noise of the shop and the machine in question when all machines are running; Step 2. Turn off the machine in question and measure  $B$ , the remaining background noise level; Step 3. Calculate  $M$ , the noise of the machine alone,  $M = 10\log_{10}[10^{(T/10)} - 10^{(B/10)}]$ .

$$M = 10\log\left(10^{\frac{T}{10}} - 10^{\frac{B}{10}}\right)$$

*Example 1:* With a machine running, the sound level meter reads 51 decibels as the total shop noise  $T$ ; and with the machine shut off the meter reads 49 decibels as the remaining background noise  $B$ . What is the noise level  $M$  of the machine alone?

$$M = 10\log\left(10^{\frac{51}{10}} - 10^{\frac{49}{10}}\right) = 46.7 \text{ decibels dBA}$$

*Example 2:* If in [Example 1](#) the remaining background noise level  $B$  was 41 decibels instead of 49, what is the noise level of the machine alone?

$$M = 10\log\left(10^{\frac{51}{10}} - 10^{\frac{41}{10}}\right) = 50.5 \text{ decibels dBA}$$

*Note:* From this example it is evident that when the background noise level  $B$  is approximately 10 or more decibels lower than the total noise level  $T$  measured at the machine in question, then the background noise does not contribute significantly to the sound level at the machine and, for practical purposes,  $M = T$  and no calculation is required.

\* After April 1983, if employee noise exposures equal or exceed an 8-hour, time-weighted average sound level of 85 dB, OSHA requires employers to administer an effective hearing conservation program.

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## PUNCHES, DIES, AND PRESS WORK

**Clearance between Punches and Dies.**—The amount of clearance between a punch and die for blanking and perforating is governed by the thickness and kind of stock to be operated upon. For thin material, the punch should be a close sliding fit to prevent ragged edges, but for heavier stock, there should be some clearance. The clearance between the punch and die in cutting heavy material reduces the pressure required for the punching operation and the danger of breaking the punch.

**Meaning of the Term "Clearance".**—There is a difference of opinion among diemakers as to the method of designating clearance. The prevailing practice of fifteen firms specializing in die work is as follows: Ten of these firms define clearance as the space between the punch and die on *one side*, or one-half the difference between the punch and die sizes. The remaining five firms consider clearance as the total difference between the punch and die sizes; for example, if the die is round, clearance equals die diameter minus punch diameter. The advantage of designating clearance as the space on each side is particularly evident with dies of irregular form or of angular shape. Although the practice of designating clearance as the difference between the punch and die diameters may be satisfactory for round dies, it leads to confusion when the dies are of unsymmetrical forms. The term "clearance" should not be used in specifications without indicating clearly just what it means. According to one die manufacturer, the term "cutting clearance" is used to indicate the space between the punch and die on each side, and the term "die clearance" refers to the angular clearance provided below the cutting edge so that the parts will fall easily through the die. The term "clearance" as here used means the space on one side only; hence, for round dies, clearance equals die radius minus punch radius.

**Clearances Generally Allowed.**—For brass and soft steel, most dies are given a clearance on one side equal to the stock thickness multiplied by 0.05 or 0.06; but one-half of this clearance is preferred for some classes of work, and a clearance equal to the stock thickness multiplied by 0.10 may give the cleanest fracture for certain other operations such as punching holes in ductile steel boiler plate.

**Where Clearance Is Applied.**—Whether clearance is deducted from the diameter of the punch or added to the diameter of the die depends upon the nature of the work. If a blank of given size is required, the die is made to that size and the punch is made smaller. Inversely, when holes of a given size are required, the punch is made to the diameter wanted and the die is made larger. Therefore, for blanking to a given size, the clearance is deducted from the size of the punch, and for perforating, the clearance is added to the size of the die.

**Effect of Clearance on Working Pressure.**—Clearance affects not only the smoothness of the fracture, but also the pressure required for punching or blanking. This pressure is greatest when the punch diameter is small compared to the thickness of the stock. In one test, for example, a punching pressure of about 32,000 pounds was required to punch  $\frac{3}{4}$ -inch holes into  $\frac{5}{16}$ -inch mild steel plate when the clearance was about 10 per cent. With a clearance of about 4.5 per cent, the pressure increased to 33,000 pounds and a clearance of 2.75 per cent resulted in a pressure of 34,500 pounds.

Soft ductile metal requires more clearance than hard metal, although it has been common practice to increase the clearance for harder metals. In punching holes in fairly hard steel, a clean fracture was obtained with a clearance of only 0.03 times stock thickness.

**Angular Clearance for Dies.**—The angular clearance ordinarily used in a blanking die varies from 1 to 2 degrees, although dies intended for producing a comparatively small number of blanks are sometimes given a clearance angle of 4 or 5 degrees to facilitate making the die quickly. When large numbers of blanks are required, a clearance of about 1 degree is used.

There are two methods of giving clearance to dies: In one method, the clearance extends to the top face of the die; and in the other, there is a space about  $\frac{1}{8}$  inch below the cutting edge that is left practically straight, or having a very small amount of clearance.

For very soft metal, such as soft, thin brass, the first method is employed, but for harder material, such as hard brass, steel, etc., it is better to have a very small clearance for a short distance below the cutting edge. When a die is made in this way, thousands of blanks can be cut with little variation in their size, as grinding the die face will not enlarge the hole to any appreciable extent.

**Lubricants for Press Work.**—Blanking dies used for carbon and low-alloy steels are often run with only residual mill lubricant, but will last longer if lightly oiled. Higher alloy and stainless steels require thicker lubricants. Kerosene is usually used with aluminum. Lubricant thickness needs to be about 0.0001 in. and can be obtained with about 1 pint of fluid to cover 500 sq. ft of material. During successive strokes, metal debris adheres to the punch and may accelerate wear, but damage may be reduced by application of the lubricant to the sheet or strip by means of rollers or spray. High-speed blanking may require heavier applications or a continuous airless spraying of oil. For sheet thicker than  $\frac{1}{8}$  in. and for stainless steel, high-pressure lubricants containing sulfurs and chlorines are often used.

Shallow drawing and forming of steel can be done with low-viscosity oils and soap solutions, but deeper draws require light- to medium-viscosity oils containing fats and such active elements as sulfur or phosphorus, and mineral fillers such as chalk or mica. Deep drawing often involves ironing or thinning of the walls by up to 35 per cent, and thick oils containing high proportions of chemically active compounds are used. Additives used in drawing compounds are selected for their ability to maintain a physical barrier between the tool surfaces and the metal being shaped. Dry soaps and polymer films are frequently used for these purposes. Aluminum can be shallow drawn with oils of low to medium viscosity, and for deep drawing, tallow may be added, also wax or soap suspensions for very large reductions.

**Annealing Drawn Shells.**—When drawing steel, iron, brass, or copper, annealing is necessary after two or three draws have been made, because the metal is hardened by the drawing process. For steel and brass, anneal between alternate reductions, at least. Tin plate or stock that cannot be annealed without spoiling the finish must ordinarily be drawn to size in one or two operations. Aluminum can be drawn deeper and with less annealing than the other commercial metals, provided the proper grade is used. If it is necessary to anneal aluminum, it should be heated in a muffle furnace, care being taken to see that the temperature does not exceed 700 degrees F.

**Drawing Brass.**—When drawing brass shells or cup-shaped articles, it is usually possible to make the depth of the first draw equal to the diameter of the shell. By heating brass to a temperature just below what would show a dull red in a dark room, it is possible to draw difficult shapes, otherwise almost impossible, and to produce shapes with square corners.

**Drawing Rectangular Shapes.**—When square or rectangular shapes are to be drawn, the radius of the corners should be as large as possible, because defects usually occur in the corners when drawing. Moreover, the smaller the radius, the less the depth that can be obtained in the first draw.

The maximum depths that can be drawn with corners of a given radii are approximately as follows: With a radius of  $\frac{3}{32}$  to  $\frac{3}{16}$  inch, depth of draw, 1 inch; radius  $\frac{3}{16}$  to  $\frac{3}{8}$  inch, depth  $1\frac{1}{2}$  inches; radius  $\frac{3}{8}$  to  $\frac{1}{2}$  inch, depth 2 inches; and radius  $\frac{1}{2}$  to  $\frac{3}{4}$  inch, depth 3 inches.

These figures are taken from actual practice and can doubtless be exceeded slightly when using metal prepared for the process. If the box needs to be quite deep and the radius is quite small, two or more drawing operations will be necessary.

**Speeds and Pressures for Presses.**—The speeds for presses equipped with cutting dies depend largely upon the kind of material being worked, and its thickness. For punching

and shearing ordinary metals not over  $\frac{1}{4}$  inch thick, the speeds usually range between 50 and 200 strokes per minute, 100 strokes per minute being a fair average. For punching metal over  $\frac{1}{4}$  inch thick, geared presses with speeds ranging from 25 to 75 strokes per minute are commonly employed.

The cutting pressures required depend upon the shearing strength of the material, and the actual area of the surface being severed. For round holes, the pressure required equals the circumference of the hole  $\times$  the thickness of the stock  $\times$  the shearing strength.

To allow for some excess pressure, the tensile strength may be substituted for the shearing strength; the tensile strength for these calculations may be roughly assumed as follows: Mild steel, 60,000; wrought iron, 50,000; bronze, 40,000; copper, 30,000; aluminum, 20,000; zinc, 10,000; and tin and lead, 5,000 pounds per square inch.

**Pressure Required for Punching.**—The formula for the force in tons required to punch a circular hole in sheet steel is  $\pi DST/2000$ , where  $S$  = the shearing strength of the material in lb/in.<sup>2</sup>,  $T$  = thickness of the steel in inches, and 2000 is the number of lb in 1 ton. An approximate formula is  $DT \times 80$ , where  $D$  and  $T$  are the diameter of the hole and the thickness of the steel, respectively, both in inches, and 80 is a factor for steel. The result is the force in tons.

*Example:* Find the pressure required to punch a hole, 2 inches in diameter, through  $\frac{1}{4}$ -in. thick steel. By applying the approximate formula,  $2 \times \frac{1}{4} \times 80 = 40$  tons.

If the hole is not circular, replace the hole diameter with the value of one-third of the perimeter of the hole to be punched.

*Example:* Find the pressure required to punch a 1-inch square hole in  $\frac{1}{4}$ -in. thick steel. The total length of the hole perimeter is 4 in. and one-third of 4 in. is  $1\frac{1}{3}$  in., so the force is  $1\frac{1}{3} \times \frac{1}{4} \times 80 = 26\frac{2}{3}$  tons.

The corresponding factor for punching holes in brass is 65 instead of 80. So, to punch a hole measuring 1 by 2 inches in  $\frac{1}{4}$ -in. thick brass sheet, the factor for hole size is the perimeter length  $6 \div 3 = 2$ , and the formula is  $2 \times \frac{1}{4} \times 65 = 32\frac{1}{2}$  tons.

**Shut Height of Press.**—The term “shut height,” as applied to power presses, indicates the die space when the slide is at the bottom of its stroke and the slide connection has been adjusted upward as far as possible. The “shut height” is the distance from the lower face of the slide, either to the top of the bed or to the top of the bolster plate, there being two methods of determining it; hence, this term should always be accompanied by a definition explaining its meaning. According to one press manufacturer, the safest plan is to define “shut height” as the distance from the top of the bolster to the bottom of the slide, with the stroke down and the adjustment up, because most dies are mounted on bolster plates of standard thickness, and a misunderstanding that results in providing too much die space is less serious than having insufficient die space. It is believed that the expression “shut height” was applied first to dies rather than to presses, the shut height of a die being the distance from the bottom of the lower section to the top of the upper section or punch, excluding the shank, and measured when the punch is in the lowest working position.

**Diameters of Shell Blanks.**—The diameters of blanks for drawing plain cylindrical shells can be obtained from Table 1 on the following pages, which gives a very close approximation for thin stock. The blank diameters given in this table are for sharp-cornered shells and are found by the following formula in which  $D$  = diameter of flat blank;  $d$  = diameter of finished shell; and  $h$  = height of finished shell.

$$D = \sqrt{d^2 + 4dh} \quad (1)$$

*Example:* If the diameter of the finished shell is to be 1.5 inches, and the height, 2 inches, the trial diameter of the blank would be found as follows:



$$D = \sqrt{1.5^2 + 4 \times 1.5 \times 2} = \sqrt{14.25} = 3.78 \text{ inches}$$

For a round-cornered cup, the following formula, in which  $r$  equals the radius of the corner, will give fairly accurate diameters, provided the radius does not exceed, say,  $\frac{1}{4}$  the height of the shell:

$$D = \sqrt{d^2 + 4dh} - r \quad (2)$$

These formulas are based on the assumption that the thickness of the drawn shell is the same as the original thickness of the stock, and that the blank is so proportioned that its area will equal the area of the drawn shell. This method of calculating the blank diameter is quite accurate for thin material, when there is only a slight reduction in the thickness of the metal incident to drawing; but when heavy stock is drawn and the thickness of the finished shell is much less than the original thickness of the stock, the blank diameter obtained from [Formula \(1\)](#) or [\(2\)](#) will be too large, because when the stock is drawn thinner, there is an increase in area. When an appreciable reduction in thickness is to be made, the blank diameter can be obtained by first determining the "mean height" of the drawn shell by the following formula. This formula is only approximately correct, but will give results sufficiently accurate for most work:

$$M = \frac{ht}{T} \quad (3)$$

where  $M$  = approximate mean height of drawn shell;  $h$  = height of drawn shell;  $t$  = thickness of shell; and  $T$  = thickness of metal before drawing.

After determining the mean height, the blank diameter for the required shell diameter is obtained from the table previously referred to, the mean height being used instead of the actual height.

*Example:* Suppose a shell 2 inches in diameter and  $3\frac{3}{4}$  inches high is to be drawn, and that the original thickness of the stock is 0.050 inch, and the thickness of drawn shell, 0.040 inch. To what diameter should the blank be cut? Obtain the mean height from [Formula \(3\)](#):

$$M = \frac{ht}{T} = \frac{3.75 \times 0.040}{0.050} = 3 \text{ inches}$$

According to the table, the blank diameter for a shell 2 inches in diameter and 3 inches high is 5.29 inches. [Formula \(3\)](#) is accurate enough for all practical purposes, unless the reduction in the thickness of the metal is greater than about one-fifth the original thickness. When there is considerable reduction, a blank calculated by this formula produces a shell that is too long. However, the error is in the right direction, as the edges of drawn shells are ordinarily trimmed.

If the shell has a rounded corner, the radius of the corner should be deducted from the figures given in the table. For example, if the shell referred to in the foregoing example had a corner of  $\frac{1}{4}$ -inch radius, the blank diameter would equal  $5.29 - 0.25 = 5.04$  inches.

Another formula that is sometimes used for obtaining blank diameters for shells, when there is a reduction in the thickness of the stock, is as follows:

$$D = \sqrt{a^2 + (a^2 - b^2)\frac{h}{t}} \quad (4)$$

Table 1. Diameters of Blanks for Drawn Cylindrical Shells

| Diam.<br>of<br>Shell | Height of Shell |               |               |      |                |                |                |      |                |                |                |       |                |                |                |       |                |       |                |       |
|----------------------|-----------------|---------------|---------------|------|----------------|----------------|----------------|------|----------------|----------------|----------------|-------|----------------|----------------|----------------|-------|----------------|-------|----------------|-------|
|                      | $\frac{1}{4}$   | $\frac{1}{2}$ | $\frac{3}{4}$ | 1    | $1\frac{1}{4}$ | $1\frac{1}{2}$ | $1\frac{3}{4}$ | 2    | $2\frac{1}{4}$ | $2\frac{1}{2}$ | $2\frac{3}{4}$ | 3     | $3\frac{1}{4}$ | $3\frac{1}{2}$ | $3\frac{3}{4}$ | 4     | $4\frac{1}{2}$ | 5     | $5\frac{1}{2}$ | 6     |
| $\frac{1}{4}$        | 0.56            | 0.75          | 0.90          | 1.03 | 1.14           | 1.25           | 1.35           | 1.44 | 1.52           | 1.60           | 1.68           | 1.75  | 1.82           | 1.89           | 1.95           | 2.01  | 2.14           | 2.25  | 2.36           | 2.46  |
| $\frac{1}{2}$        | 0.87            | 1.12          | 1.32          | 1.50 | 1.66           | 1.80           | 1.94           | 2.06 | 2.18           | 2.29           | 2.40           | 2.50  | 2.60           | 2.69           | 2.78           | 2.87  | 3.04           | 3.21  | 3.36           | 3.50  |
| $\frac{3}{4}$        | 1.14            | 1.44          | 1.68          | 1.89 | 2.08           | 2.25           | 2.41           | 2.56 | 2.70           | 2.84           | 2.97           | 3.09  | 3.21           | 3.33           | 3.44           | 3.54  | 3.75           | 3.95  | 4.13           | 4.31  |
| 1                    | 1.41            | 1.73          | 2.00          | 2.24 | 2.45           | 2.65           | 2.83           | 3.00 | 3.16           | 3.32           | 3.46           | 3.61  | 3.74           | 3.87           | 4.00           | 4.12  | 4.36           | 4.58  | 4.80           | 5.00  |
| $1\frac{1}{4}$       | 1.68            | 2.01          | 2.30          | 2.56 | 2.79           | 3.01           | 3.21           | 3.40 | 3.58           | 3.75           | 3.91           | 4.07  | 4.22           | 4.37           | 4.51           | 4.64  | 4.91           | 5.15  | 5.39           | 5.62  |
| $1\frac{1}{2}$       | 1.94            | 2.29          | 2.60          | 2.87 | 3.12           | 3.36           | 3.57           | 3.78 | 3.97           | 4.15           | 4.33           | 4.50  | 4.66           | 4.82           | 4.98           | 5.12  | 5.41           | 5.68  | 5.94           | 6.18  |
| $1\frac{3}{4}$       | 2.19            | 2.56          | 2.88          | 3.17 | 3.44           | 3.68           | 3.91           | 4.13 | 4.34           | 4.53           | 4.72           | 4.91  | 5.08           | 5.26           | 5.41           | 5.58  | 5.88           | 6.17  | 6.45           | 6.71  |
| 2                    | 2.45            | 2.83          | 3.16          | 3.46 | 3.74           | 4.00           | 4.24           | 4.47 | 4.69           | 4.90           | 5.10           | 5.29  | 5.48           | 5.66           | 5.83           | 6.00  | 6.32           | 6.63  | 6.93           | 7.21  |
| $2\frac{1}{4}$       | 2.70            | 3.09          | 3.44          | 3.75 | 4.04           | 4.31           | 4.56           | 4.80 | 5.03           | 5.25           | 5.46           | 5.66  | 5.86           | 6.05           | 6.23           | 6.41  | 6.75           | 7.07  | 7.39           | 7.69  |
| $2\frac{1}{2}$       | 2.96            | 3.36          | 3.71          | 4.03 | 4.33           | 4.61           | 4.87           | 5.12 | 5.36           | 5.59           | 5.81           | 6.02  | 6.22           | 6.42           | 6.61           | 6.80  | 7.16           | 7.50  | 7.82           | 8.14  |
| $2\frac{3}{4}$       | 3.21            | 3.61          | 3.98          | 4.31 | 4.62           | 4.91           | 5.18           | 5.44 | 5.68           | 5.92           | 6.15           | 6.37  | 6.58           | 6.79           | 6.99           | 7.18  | 7.55           | 7.91  | 8.25           | 8.58  |
| 3                    | 3.46            | 3.87          | 4.24          | 4.58 | 4.90           | 5.20           | 5.48           | 5.74 | 6.00           | 6.25           | 6.48           | 6.71  | 6.93           | 7.14           | 7.35           | 7.55  | 7.94           | 8.31  | 8.66           | 9.00  |
| $3\frac{1}{4}$       | 3.71            | 4.13          | 4.51          | 4.85 | 5.18           | 5.48           | 5.77           | 6.04 | 6.31           | 6.56           | 6.80           | 7.04  | 7.27           | 7.49           | 7.70           | 7.91  | 8.31           | 8.69  | 9.06           | 9.41  |
| $3\frac{1}{2}$       | 3.97            | 4.39          | 4.77          | 5.12 | 5.45           | 5.77           | 6.06           | 6.34 | 6.61           | 6.87           | 7.12           | 7.36  | 7.60           | 7.83           | 8.05           | 8.26  | 8.67           | 9.07  | 9.45           | 9.81  |
| $3\frac{3}{4}$       | 4.22            | 4.64          | 5.03          | 5.39 | 5.73           | 6.05           | 6.35           | 6.64 | 6.91           | 7.18           | 7.44           | 7.69  | 7.92           | 8.16           | 8.38           | 8.61  | 9.03           | 9.44  | 9.83           | 10.20 |
| 4                    | 4.47            | 4.90          | 5.29          | 5.66 | 6.00           | 6.32           | 6.63           | 6.93 | 7.21           | 7.48           | 7.75           | 8.00  | 8.25           | 8.49           | 8.72           | 8.94  | 9.38           | 9.80  | 10.20          | 10.58 |
| $4\frac{1}{4}$       | 4.72            | 5.15          | 5.55          | 5.92 | 6.27           | 6.60           | 6.91           | 7.22 | 7.50           | 7.78           | 8.05           | 8.31  | 8.56           | 8.81           | 9.04           | 9.28  | 9.72           | 10.15 | 10.56          | 10.96 |
| $4\frac{1}{2}$       | 4.98            | 5.41          | 5.81          | 6.19 | 6.54           | 6.87           | 7.19           | 7.50 | 7.79           | 8.08           | 8.35           | 8.62  | 8.87           | 9.12           | 9.37           | 9.60  | 10.06          | 10.50 | 10.92          | 11.32 |
| $4\frac{3}{4}$       | 5.22            | 5.66          | 6.07          | 6.45 | 6.80           | 7.15           | 7.47           | 7.78 | 8.08           | 8.37           | 8.65           | 8.92  | 9.18           | 9.44           | 9.69           | 9.93  | 10.40          | 10.84 | 11.27          | 11.69 |
| 5                    | 5.48            | 5.92          | 6.32          | 6.71 | 7.07           | 7.42           | 7.75           | 8.06 | 8.37           | 8.66           | 8.94           | 9.22  | 9.49           | 9.75           | 10.00          | 10.25 | 10.72          | 11.18 | 11.62          | 12.04 |
| $5\frac{1}{4}$       | 5.73            | 6.17          | 6.58          | 6.97 | 7.33           | 7.68           | 8.02           | 8.34 | 8.65           | 8.95           | 9.24           | 9.52  | 9.79           | 10.05          | 10.31          | 10.56 | 11.05          | 11.51 | 11.96          | 12.39 |
| $5\frac{1}{2}$       | 5.98            | 6.42          | 6.84          | 7.23 | 7.60           | 7.95           | 8.29           | 8.62 | 8.93           | 9.23           | 9.53           | 9.81  | 10.08          | 10.36          | 10.62          | 10.87 | 11.37          | 11.84 | 12.30          | 12.74 |
| $5\frac{3}{4}$       | 6.23            | 6.68          | 7.09          | 7.49 | 7.86           | 8.22           | 8.56           | 8.89 | 9.21           | 9.52           | 9.81           | 10.10 | 10.38          | 10.66          | 10.92          | 11.18 | 11.69          | 12.17 | 12.63          | 13.08 |
| 6                    | 6.48            | 6.93          | 7.35          | 7.75 | 8.12           | 8.49           | 8.83           | 9.17 | 9.49           | 9.80           | 10.10          | 10.39 | 10.68          | 10.95          | 11.23          | 11.49 | 12.00          | 12.49 | 12.96          | 13.42 |

In this formula,  $D$  = blank diameter;  $a$  = outside diameter;  $b$  = inside diameter;  $t$  = thickness of shell at bottom; and  $h$  = depth of shell. This formula is based on the volume of the metal in the drawn shell. It is assumed that the shells are cylindrical, and no allowance is made for a rounded corner at the bottom, or for trimming the shell after drawing. To allow for trimming, add the required amount to depth  $h$ . When a shell is of irregular cross-section, if its weight is known, the blank diameter can be determined by the following formula:

$$D = 1.1284 \sqrt{\frac{W}{wt}} \quad (5)$$

where  $D$  = blank diameter in inches;  $W$  = weight of shell;  $w$  = weight of metal per cubic inch; and  $t$  = thickness of the shell.

In the construction of dies for producing shells, especially of irregular form, a common method to be used is to make the drawing tool first. The actual blank diameter then can be determined by trial. One method is to cut a trial blank as near to size and shape as can be estimated. The outline of this blank is then scribed on a flat sheet, after which the blank is drawn. If the finished shell shows that the blank is not of the right diameter or shape, a new trial blank is cut either larger or smaller than the size indicated by the line previously scribed, this line acting as a guide. If a model shell is available, the blank diameter can also be determined as follows:

First, cut a blank somewhat large, and from the same material used for making the model; then, reduce the size of the blank until its weight equals the weight of the model.

**Depth and Diameter Reductions of Drawn Cylindrical Shells.**—The depth to which metal can be drawn in one operation depends upon the quality and kind of material, its thickness, the slant or angle of the dies, and the amount that the stock is thinned or “ironed” in drawing. A general rule for determining the depth to which cylindrical shells can be drawn in one operation is as follows: The depth or length of the first draw should never be greater than the diameter of the shell. If the shell is to have a flange at the top, it may not be practicable to draw as deeply as is indicated by this rule, unless the metal is extra good, because the stock is subjected to a higher tensile stress, owing to the larger blank needed to form the flange. According to another rule, the depth given the shell on the first draw should equal one-third the diameter of the blank. Ordinarily, it is possible to draw sheet steel of any thickness up to  $\frac{1}{4}$  inch, so that the diameter of the first shell equals about six-tenths of the blank diameter. When drawing plain shells, the amount that the diameter is reduced for each draw must be governed by the quality of the metal and its susceptibility to drawing. The reduction for various thicknesses of metal is about as follows:

|   |                |               |                |               |                |
|---|----------------|---------------|----------------|---------------|----------------|
| Approximate thickness of sheet steel                              | $\frac{1}{16}$ | $\frac{1}{8}$ | $\frac{3}{16}$ | $\frac{1}{4}$ | $\frac{5}{16}$ |
| Possible reduction in diameter for each succeeding step, per cent | 20             | 15            | 12             | 10            | 8              |

For example, if a shell made of  $\frac{1}{16}$ -inch stock is 3 inches in diameter after the first draw, it can be reduced 20 per cent on the next draw, and so on until the required diameter is obtained. These figures are based upon the assumption that the shell is annealed after the first drawing operation, and at least between every two of the following operations. Necking operations—that is, the drawing out of a short portion of the lower part of the cup into a long neck—may be done without such frequent annealings. In double-action presses, where the inside of the cup is supported by a bushing during drawing, the reductions possible may be increased to 30, 24, 18, 15, and 12 per cent, respectively. (The latter figures may also be used for brass in single-action presses.)

When a hole is to be pierced at the bottom of a cup and the remaining metal is to be drawn after the hole has been pierced or punched, always pierce from the opposite direction to

that in which the stock is to be drawn after piercing. It may be necessary to machine the metal around the pierced hole to prevent the starting of cracks or flaws in the subsequent drawing operations.

The foregoing figures represent conservative practice and it is often possible to make greater reductions than are indicated by these figures, especially when using a good drawing metal. Taper shells require smaller reductions than cylindrical shells, because the metal tends to wrinkle if the shell to be drawn is much larger than the punch. The amount that the stock is "ironed" or thinned out while being drawn must also be considered, because a reduction in gage or thickness means greater force will be exerted by the punch against the bottom of the shell; hence the amount that the shell diameter is reduced for each drawing operation must be smaller when much ironing is necessary. The extent to which a shell can be ironed in one drawing operation ranges between 0.002 and 0.004 inch per side, and should not exceed 0.001 inch on the final draw, if a good finish is required.

**Allowances for Bending Sheet Metal.**—In bending steel, brass, bronze, or other metals, the problem is to find the length of straight stock required for each bend; these lengths are added to the lengths of the straight sections to obtain the total length of the material before bending.

If  $L$  = length in inches, of straight stock required before bending;  $T$  = thickness in inches; and  $R$  = inside radius of bend in inches:

For 90° bends in soft brass and soft copper see [Table 2](#) or:

$$L = (0.55 \times T) + (1.57 \times R) \quad (1)$$

For 90° bends in half-hard copper and brass, soft steel, and aluminum see [Table 3](#) or:

$$L = (0.64 \times T) + (1.57 \times R) \quad (2)$$

For 90° bends in bronze, hard copper, cold-rolled steel, and spring steel see [Table 4](#) or:

$$L = (0.71 \times T) + (1.57 \times R) \quad (3)$$

*Angle of Bend Other Than 90 Degrees:* For angles other than 90 degrees, find length  $L$ , using tables or formulas, and multiply  $L$  by angle of bend, in degrees, divided by 90 to find length of stock before bending. In using this rule, note that *angle of bend* is the angle through which the material has actually been bent; hence, it is not always the angle as given on a drawing. To illustrate, in [Fig. 1](#), the angle on the drawing is 60 degrees, but the angle of bend  $A$  is 120 degrees ( $180 - 60 = 120$ ); in [Fig. 2](#), the angle of bend  $A$  is 60 degrees; in [Fig. 3](#), angle  $A$  is  $90 - 30 = 60$  degrees. [Formulas \(1\), \(2\), and \(3\)](#) are based on extensive experiments of the Westinghouse Electric Co. They apply to parts bent with simple tools or on the bench, where limits of  $\pm \frac{1}{64}$  inch are specified. If a part has two or more bends of the same radius, it is, of course, only necessary to obtain the length required for one of the bends and then multiply by the number of bends, to obtain the total allowance for the bent sections.



Fig. 1.

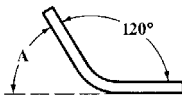


Fig. 2.



Fig. 3.

*Example, Showing Application of Formulas:* Find the length before bending of the part illustrated by [Fig. 4](#). Soft steel is to be used.

For bend at left-hand end (180-degree bend)

$$L = [(0.64 \times 0.125) + (1.57 \times 0.375)] \times \frac{180}{90} = 1.338$$

Table 2. Lengths of Straight Stock Required for 90-Degree Bends in Soft Copper and Soft Brass

| Radius <i>R</i><br>of Bend,<br>Inches | Thickness <i>T</i> of Material, Inch |                |                |                |                |                |               |                |                |                |               |                |                |
|---------------------------------------|--------------------------------------|----------------|----------------|----------------|----------------|----------------|---------------|----------------|----------------|----------------|---------------|----------------|----------------|
|                                       | $\frac{1}{64}$                       | $\frac{1}{32}$ | $\frac{3}{64}$ | $\frac{1}{16}$ | $\frac{5}{64}$ | $\frac{3}{32}$ | $\frac{1}{8}$ | $\frac{5}{32}$ | $\frac{1}{16}$ | $\frac{7}{32}$ | $\frac{1}{4}$ | $\frac{9}{32}$ | $\frac{5}{16}$ |
| $\frac{1}{32}$                        | 0.058                                | 0.066          | 0.075          | 0.083          | 0.092          | 0.101          | 0.118         | 0.135          | 0.152          | 0.169          | 0.187         | 0.204          | 0.221          |
| $\frac{3}{64}$                        | 0.083                                | 0.091          | 0.100          | 0.108          | 0.117          | 0.126          | 0.143         | 0.160          | 0.177          | 0.194          | 0.212         | 0.229          | 0.246          |
| $\frac{1}{16}$                        | 0.107                                | 0.115          | 0.124          | 0.132          | 0.141          | 0.150          | 0.167         | 0.184          | 0.201          | 0.218          | 0.236         | 0.253          | 0.270          |
| $\frac{3}{32}$                        | 0.156                                | 0.164          | 0.173          | 0.181          | 0.190          | 0.199          | 0.216         | 0.233          | 0.250          | 0.267          | 0.285         | 0.302          | 0.319          |
| $\frac{1}{8}$                         | 0.205                                | 0.213          | 0.222          | 0.230          | 0.239          | 0.248          | 0.265         | 0.282          | 0.299          | 0.316          | 0.334         | 0.351          | 0.368          |
| $\frac{5}{32}$                        | 0.254                                | 0.262          | 0.271          | 0.279          | 0.288          | 0.297          | 0.314         | 0.331          | 0.348          | 0.365          | 0.383         | 0.400          | 0.417          |
| $\frac{3}{16}$                        | 0.303                                | 0.311          | 0.320          | 0.328          | 0.337          | 0.346          | 0.363         | 0.380          | 0.397          | 0.414          | 0.432         | 0.449          | 0.466          |
| $\frac{7}{32}$                        | 0.353                                | 0.361          | 0.370          | 0.378          | 0.387          | 0.396          | 0.413         | 0.430          | 0.447          | 0.464          | 0.482         | 0.499          | 0.516          |
| $\frac{1}{4}$                         | 0.401                                | 0.409          | 0.418          | 0.426          | 0.435          | 0.444          | 0.461         | 0.478          | 0.495          | 0.512          | 0.530         | 0.547          | 0.564          |
| $\frac{5}{16}$                        | 0.450                                | 0.458          | 0.467          | 0.475          | 0.484          | 0.493          | 0.510         | 0.527          | 0.544          | 0.561          | 0.579         | 0.596          | 0.613          |
| $\frac{3}{8}$                         | 0.499                                | 0.507          | 0.516          | 0.524          | 0.533          | 0.542          | 0.559         | 0.576          | 0.593          | 0.610          | 0.628         | 0.645          | 0.662          |
| $\frac{7}{16}$                        | 0.549                                | 0.557          | 0.566          | 0.574          | 0.583          | 0.592          | 0.609         | 0.626          | 0.643          | 0.660          | 0.678         | 0.695          | 0.712          |
| $\frac{1}{2}$                         | 0.598                                | 0.606          | 0.615          | 0.623          | 0.632          | 0.641          | 0.658         | 0.675          | 0.692          | 0.709          | 0.727         | 0.744          | 0.761          |
| $\frac{3}{4}$                         | 0.646                                | 0.654          | 0.663          | 0.671          | 0.680          | 0.689          | 0.706         | 0.723          | 0.740          | 0.757          | 0.775         | 0.792          | 0.809          |
| $\frac{7}{8}$                         | 0.695                                | 0.703          | 0.712          | 0.720          | 0.729          | 0.738          | 0.755         | 0.772          | 0.789          | 0.806          | 0.824         | 0.841          | 0.858          |
| $\frac{15}{16}$                       | 0.734                                | 0.742          | 0.751          | 0.759          | 0.768          | 0.777          | 0.794         | 0.811          | 0.828          | 0.845          | 0.863         | 0.880          | 0.897          |
| 1                                     | 0.794                                | 0.802          | 0.811          | 0.819          | 0.828          | 0.837          | 0.854         | 0.871          | 0.888          | 0.905          | 0.923         | 0.940          | 0.957          |
| $\frac{1 1}{16}$                      | 0.892                                | 0.900          | 0.909          | 0.917          | 0.926          | 0.935          | 0.952         | 0.969          | 0.986          | 1.003          | 1.021         | 1.038          | 1.055          |
| $\frac{1 1}{8}$                       | 0.990                                | 0.998          | 1.007          | 1.015          | 1.024          | 1.033          | 1.050         | 1.067          | 1.084          | 1.101          | 1.119         | 1.136          | 1.153          |
| $\frac{1 1}{4}$                       | 1.089                                | 1.097          | 1.106          | 1.114          | 1.123          | 1.132          | 1.149         | 1.166          | 1.183          | 1.200          | 1.218         | 1.235          | 1.252          |
| $\frac{1 3}{8}$                       | 1.187                                | 1.195          | 1.204          | 1.212          | 1.221          | 1.230          | 1.247         | 1.264          | 1.281          | 1.298          | 1.316         | 1.333          | 1.350          |
| $\frac{1 1}{2}$                       | 1.286                                | 1.294          | 1.303          | 1.311          | 1.320          | 1.329          | 1.346         | 1.363          | 1.380          | 1.397          | 1.415         | 1.432          | 1.449          |
| $\frac{1 3}{4}$                       | 1.384                                | 1.392          | 1.401          | 1.409          | 1.418          | 1.427          | 1.444         | 1.461          | 1.478          | 1.495          | 1.513         | 1.530          | 1.547          |
| $\frac{1 7}{8}$                       | 1.481                                | 1.489          | 1.498          | 1.506          | 1.515          | 1.524          | 1.541         | 1.558          | 1.575          | 1.592          | 1.610         | 1.627          | 1.644          |
| 1 1/8                                 | 1.580                                | 1.588          | 1.597          | 1.605          | 1.614          | 1.623          | 1.640         | 1.657          | 1.674          | 1.691          | 1.709         | 1.726          | 1.743          |
| 1 1/4                                 | 1.678                                | 1.686          | 1.695          | 1.703          | 1.712          | 1.721          | 1.738         | 1.755          | 1.772          | 1.789          | 1.807         | 1.824          | 1.841          |
| 1 3/8                                 | 1.777                                | 1.785          | 1.794          | 1.802          | 1.811          | 1.820          | 1.837         | 1.854          | 1.871          | 1.888          | 1.906         | 1.923          | 1.940          |
| 1 3/4                                 | 1.875                                | 1.883          | 1.892          | 1.900          | 1.909          | 1.918          | 1.935         | 1.952          | 1.969          | 1.986          | 2.004         | 2.021          | 2.038          |
| 1 7/8                                 | 1.972                                | 1.980          | 1.989          | 1.997          | 2.006          | 2.015          | 2.032         | 2.049          | 2.066          | 2.083          | 2.101         | 2.118          | 2.135          |

Table 3. Lengths of Straight Stock Required for 90-Degree Bends in Half-Hard Brass and Sheet Copper, Soft Steel, and Aluminum

| Radius <i>R</i> of Bend, Inches | Thickness <i>T</i> of Material, Inch |                |                |                |                |                |               |                |               |                |                |               |                |
|---------------------------------|--------------------------------------|----------------|----------------|----------------|----------------|----------------|---------------|----------------|---------------|----------------|----------------|---------------|----------------|
|                                 | $\frac{1}{64}$                       | $\frac{1}{32}$ | $\frac{3}{64}$ | $\frac{1}{16}$ | $\frac{5}{64}$ | $\frac{3}{32}$ | $\frac{1}{8}$ | $\frac{7}{32}$ | $\frac{1}{2}$ | $\frac{3}{16}$ | $\frac{7}{32}$ | $\frac{1}{4}$ | $\frac{5}{16}$ |
| $\frac{1}{32}$                  | 0.059                                | 0.069          | 0.079          | 0.089          | 0.099          | 0.109          | 0.129         | 0.149          | 0.169         | 0.189          | 0.209          | 0.229         | 0.249          |
| $\frac{3}{64}$                  | 0.084                                | 0.094          | 0.104          | 0.114          | 0.124          | 0.134          | 0.154         | 0.174          | 0.194         | 0.214          | 0.234          | 0.254         | 0.274          |
| $\frac{1}{16}$                  | 0.108                                | 0.118          | 0.128          | 0.138          | 0.148          | 0.158          | 0.178         | 0.198          | 0.218         | 0.238          | 0.258          | 0.278         | 0.298          |
| $\frac{3}{32}$                  | 0.157                                | 0.167          | 0.177          | 0.187          | 0.197          | 0.207          | 0.227         | 0.247          | 0.267         | 0.287          | 0.307          | 0.327         | 0.347          |
| $\frac{1}{8}$                   | 0.206                                | 0.216          | 0.226          | 0.236          | 0.246          | 0.256          | 0.276         | 0.296          | 0.316         | 0.336          | 0.356          | 0.376         | 0.396          |
| $\frac{5}{32}$                  | 0.255                                | 0.265          | 0.275          | 0.285          | 0.295          | 0.305          | 0.325         | 0.345          | 0.365         | 0.385          | 0.405          | 0.425         | 0.445          |
| $\frac{3}{16}$                  | 0.305                                | 0.315          | 0.325          | 0.335          | 0.345          | 0.355          | 0.375         | 0.395          | 0.415         | 0.435          | 0.455          | 0.475         | 0.495          |
| $\frac{7}{32}$                  | 0.354                                | 0.364          | 0.374          | 0.384          | 0.394          | 0.404          | 0.424         | 0.444          | 0.464         | 0.484          | 0.504          | 0.524         | 0.544          |
| $\frac{1}{4}$                   | 0.403                                | 0.413          | 0.423          | 0.433          | 0.443          | 0.453          | 0.473         | 0.493          | 0.513         | 0.533          | 0.553          | 0.573         | 0.593          |
| $\frac{9}{32}$                  | 0.452                                | 0.462          | 0.472          | 0.482          | 0.492          | 0.502          | 0.522         | 0.542          | 0.562         | 0.582          | 0.602          | 0.622         | 0.642          |
| $\frac{5}{16}$                  | 0.501                                | 0.511          | 0.521          | 0.531          | 0.541          | 0.551          | 0.571         | 0.591          | 0.611         | 0.631          | 0.651          | 0.671         | 0.691          |
| $\frac{11}{32}$                 | 0.550                                | 0.560          | 0.570          | 0.580          | 0.590          | 0.600          | 0.620         | 0.640          | 0.660         | 0.680          | 0.700          | 0.720         | 0.740          |
| $\frac{3}{8}$                   | 0.599                                | 0.609          | 0.619          | 0.629          | 0.639          | 0.649          | 0.669         | 0.689          | 0.709         | 0.729          | 0.749          | 0.769         | 0.789          |
| $\frac{13}{32}$                 | 0.648                                | 0.658          | 0.668          | 0.678          | 0.688          | 0.698          | 0.718         | 0.738          | 0.758         | 0.778          | 0.798          | 0.818         | 0.838          |
| $\frac{7}{16}$                  | 0.697                                | 0.707          | 0.717          | 0.727          | 0.737          | 0.747          | 0.767         | 0.787          | 0.807         | 0.827          | 0.847          | 0.867         | 0.887          |
| $\frac{15}{32}$                 | 0.746                                | 0.756          | 0.766          | 0.776          | 0.786          | 0.796          | 0.816         | 0.836          | 0.856         | 0.876          | 0.896          | 0.916         | 0.936          |
| $\frac{1}{2}$                   | 0.795                                | 0.805          | 0.815          | 0.825          | 0.835          | 0.845          | 0.865         | 0.885          | 0.905         | 0.925          | 0.945          | 0.965         | 0.985          |
| $\frac{17}{32}$                 | 0.844                                | 0.854          | 0.864          | 0.874          | 0.884          | 0.894          | 0.914         | 0.934          | 0.954         | 0.974          | 0.994          | 1.014         | 1.034          |
| $\frac{9}{16}$                  | 0.894                                | 0.904          | 0.914          | 0.924          | 0.934          | 0.944          | 0.964         | 0.984          | 1.004         | 1.024          | 1.044          | 1.064         | 1.084          |
| $\frac{5}{8}$                   | 0.992                                | 1.002          | 1.012          | 1.022          | 1.032          | 1.042          | 1.062         | 1.082          | 1.102         | 1.122          | 1.142          | 1.162         | 1.182          |
| $\frac{11}{16}$                 | 1.090                                | 1.100          | 1.110          | 1.120          | 1.130          | 1.140          | 1.160         | 1.180          | 1.200         | 1.220          | 1.240          | 1.260         | 1.280          |
| $\frac{3}{4}$                   | 1.188                                | 1.198          | 1.208          | 1.218          | 1.228          | 1.238          | 1.258         | 1.278          | 1.298         | 1.318          | 1.338          | 1.358         | 1.378          |
| $\frac{13}{16}$                 | 1.286                                | 1.296          | 1.306          | 1.316          | 1.326          | 1.336          | 1.356         | 1.376          | 1.396         | 1.416          | 1.436          | 1.456         | 1.476          |
| $\frac{7}{8}$                   | 1.384                                | 1.394          | 1.404          | 1.414          | 1.424          | 1.434          | 1.454         | 1.474          | 1.494         | 1.514          | 1.534          | 1.554         | 1.574          |
| $\frac{15}{16}$                 | 1.483                                | 1.493          | 1.503          | 1.513          | 1.523          | 1.533          | 1.553         | 1.573          | 1.593         | 1.613          | 1.633          | 1.653         | 1.673          |
| 1                               | 1.581                                | 1.591          | 1.601          | 1.611          | 1.621          | 1.631          | 1.651         | 1.671          | 1.691         | 1.711          | 1.731          | 1.751         | 1.771          |
| 1 $\frac{1}{16}$                | 1.697                                | 1.689          | 1.699          | 1.709          | 1.719          | 1.729          | 1.749         | 1.769          | 1.789         | 1.809          | 1.829          | 1.849         | 1.869          |
| 1 $\frac{1}{8}$                 | 1.777                                | 1.787          | 1.797          | 1.807          | 1.817          | 1.827          | 1.847         | 1.867          | 1.887         | 1.907          | 1.927          | 1.947         | 1.967          |
| 1 $\frac{3}{16}$                | 1.875                                | 1.885          | 1.895          | 1.905          | 1.915          | 1.925          | 1.945         | 1.965          | 1.985         | 2.005          | 2.025          | 2.045         | 2.065          |
| 1 $\frac{1}{4}$                 | 1.973                                | 1.983          | 1.993          | 2.003          | 2.013          | 2.023          | 2.043         | 2.063          | 2.083         | 2.103          | 2.123          | 2.143         | 2.163          |

Table 4. Lengths of Straight Stock Required for 90-Degree Bends in Hard Copper, Bronze, Cold-Rolled Steel, and Spring Steel

| Radius <i>R</i><br>of Bend,<br>Inches | Thickness <i>T</i> of Material, Inch |                |                |                |                |                |               |                |                |                |               |                |                |
|---------------------------------------|--------------------------------------|----------------|----------------|----------------|----------------|----------------|---------------|----------------|----------------|----------------|---------------|----------------|----------------|
|                                       | $\frac{1}{64}$                       | $\frac{1}{32}$ | $\frac{3}{64}$ | $\frac{1}{16}$ | $\frac{5}{64}$ | $\frac{3}{32}$ | $\frac{1}{8}$ | $\frac{5}{32}$ | $\frac{3}{16}$ | $\frac{7}{32}$ | $\frac{1}{4}$ | $\frac{9}{32}$ | $\frac{5}{16}$ |
| $\frac{1}{32}$                        | 0.060                                | 0.071          | 0.082          | 0.093          | 0.104          | 0.116          | 0.138         | 0.160          | 0.182          | 0.204          | 0.227         | 0.249          | 0.271          |
| $\frac{3}{64}$                        | 0.085                                | 0.096          | 0.107          | 0.118          | 0.129          | 0.141          | 0.163         | 0.185          | 0.207          | 0.229          | 0.252         | 0.274          | 0.296          |
| $\frac{1}{16}$                        | 0.109                                | 0.120          | 0.131          | 0.142          | 0.153          | 0.165          | 0.187         | 0.209          | 0.231          | 0.253          | 0.276         | 0.298          | 0.320          |
| $\frac{3}{32}$                        | 0.158                                | 0.169          | 0.180          | 0.191          | 0.202          | 0.214          | 0.236         | 0.258          | 0.280          | 0.302          | 0.325         | 0.347          | 0.369          |
| $\frac{1}{8}$                         | 0.207                                | 0.218          | 0.229          | 0.240          | 0.251          | 0.263          | 0.285         | 0.307          | 0.329          | 0.351          | 0.374         | 0.396          | 0.418          |
| $\frac{5}{32}$                        | 0.256                                | 0.267          | 0.278          | 0.289          | 0.300          | 0.312          | 0.334         | 0.356          | 0.378          | 0.400          | 0.423         | 0.445          | 0.467          |
| $\frac{3}{16}$                        | 0.305                                | 0.316          | 0.327          | 0.338          | 0.349          | 0.361          | 0.383         | 0.405          | 0.427          | 0.449          | 0.472         | 0.494          | 0.516          |
| $\frac{7}{32}$                        | 0.355                                | 0.366          | 0.377          | 0.388          | 0.399          | 0.411          | 0.433         | 0.455          | 0.477          | 0.499          | 0.522         | 0.544          | 0.566          |
| $\frac{1}{4}$                         | 0.403                                | 0.414          | 0.425          | 0.436          | 0.447          | 0.459          | 0.481         | 0.503          | 0.525          | 0.547          | 0.570         | 0.592          | 0.614          |
| $\frac{9}{32}$                        | 0.452                                | 0.463          | 0.474          | 0.485          | 0.496          | 0.508          | 0.530         | 0.552          | 0.574          | 0.596          | 0.619         | 0.641          | 0.663          |
| $\frac{5}{16}$                        | 0.501                                | 0.512          | 0.523          | 0.534          | 0.545          | 0.557          | 0.579         | 0.601          | 0.623          | 0.645          | 0.668         | 0.690          | 0.712          |
| $\frac{11}{32}$                       | 0.551                                | 0.562          | 0.573          | 0.584          | 0.595          | 0.607          | 0.629         | 0.651          | 0.673          | 0.695          | 0.718         | 0.740          | 0.762          |
| $\frac{3}{8}$                         | 0.600                                | 0.611          | 0.622          | 0.633          | 0.644          | 0.656          | 0.678         | 0.700          | 0.722          | 0.744          | 0.767         | 0.789          | 0.811          |
| $\frac{13}{32}$                       | 0.648                                | 0.659          | 0.670          | 0.681          | 0.692          | 0.704          | 0.726         | 0.748          | 0.770          | 0.792          | 0.815         | 0.837          | 0.859          |
| $\frac{7}{16}$                        | 0.697                                | 0.708          | 0.719          | 0.730          | 0.741          | 0.753          | 0.775         | 0.797          | 0.819          | 0.841          | 0.864         | 0.886          | 0.908          |
| $\frac{15}{32}$                       | 0.736                                | 0.747          | 0.758          | 0.769          | 0.780          | 0.792          | 0.814         | 0.836          | 0.858          | 0.880          | 0.903         | 0.925          | 0.947          |
| $\frac{1}{2}$                         | 0.796                                | 0.807          | 0.818          | 0.829          | 0.840          | 0.852          | 0.874         | 0.896          | 0.918          | 0.940          | 0.963         | 0.985          | 1.007          |
| $\frac{9}{16}$                        | 0.894                                | 0.905          | 0.916          | 0.927          | 0.938          | 0.950          | 0.972         | 0.994          | 1.016          | 1.038          | 1.061         | 1.083          | 1.105          |
| $\frac{5}{8}$                         | 0.992                                | 1.003          | 1.014          | 1.025          | 1.036          | 1.048          | 1.070         | 1.092          | 1.114          | 1.136          | 1.159         | 1.181          | 1.203          |
| $\frac{11}{16}$                       | 1.091                                | 1.102          | 1.113          | 1.124          | 1.135          | 1.147          | 1.169         | 1.191          | 1.213          | 1.235          | 1.258         | 1.280          | 1.302          |
| $\frac{3}{4}$                         | 1.189                                | 1.200          | 1.211          | 1.222          | 1.233          | 1.245          | 1.267         | 1.289          | 1.311          | 1.333          | 1.356         | 1.378          | 1.400          |
| $\frac{13}{16}$                       | 1.288                                | 1.299          | 1.310          | 1.321          | 1.332          | 1.344          | 1.366         | 1.388          | 1.410          | 1.432          | 1.455         | 1.477          | 1.499          |
| $\frac{7}{8}$                         | 1.386                                | 1.397          | 1.408          | 1.419          | 1.430          | 1.442          | 1.464         | 1.486          | 1.508          | 1.530          | 1.553         | 1.575          | 1.597          |
| $\frac{15}{16}$                       | 1.483                                | 1.494          | 1.505          | 1.516          | 1.527          | 1.539          | 1.561         | 1.583          | 1.605          | 1.627          | 1.650         | 1.672          | 1.694          |
| 1                                     | 1.582                                | 1.593          | 1.604          | 1.615          | 1.626          | 1.638          | 1.660         | 1.682          | 1.704          | 1.726          | 1.749         | 1.771          | 1.793          |
| 1 $\frac{1}{16}$                      | 1.680                                | 1.691          | 1.702          | 1.713          | 1.724          | 1.736          | 1.758         | 1.780          | 1.802          | 1.824          | 1.847         | 1.869          | 1.891          |
| 1 $\frac{1}{8}$                       | 1.779                                | 1.790          | 1.801          | 1.812          | 1.823          | 1.835          | 1.857         | 1.879          | 1.901          | 1.923          | 1.946         | 1.968          | 1.990          |
| 1 $\frac{3}{16}$                      | 1.877                                | 1.888          | 1.899          | 1.910          | 1.921          | 1.933          | 1.955         | 1.977          | 1.999          | 2.021          | 2.044         | 2.066          | 2.088          |
| 1 $\frac{1}{4}$                       | 1.974                                | 1.985          | 1.996          | 2.007          | 2.018          | 2.030          | 2.052         | 2.074          | 2.096          | 2.118          | 2.141         | 2.163          | 2.185          |

For bend at right-hand end (60-degree bend)

$$L = [(0.64 \times 0.125) + (1.57 \times 0.625)] \times \frac{60}{90} = 0.707$$

Total length before bending =  $3.5 + 1.338 + 0.707 = 5.545$  inches

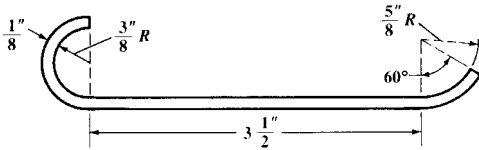


Fig. 4.

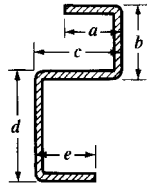


Fig. 5.

**Other Bending Allowance Formulas.**—When bending sheet steel or brass, add from  $\frac{1}{3}$  to  $\frac{1}{2}$  of the thickness of the stock, for *each bend*, to the sum of the inside dimensions of the finished piece, to get the length of the straight blank. The harder the material the greater the allowance ( $\frac{1}{3}$  of the thickness is added for soft stock and  $\frac{1}{2}$  of the thickness for hard material). The data given in the table, *Allowances for Bends in Sheet Metal* on page 1340, refer more particularly to the bending of sheet metal for counters, bank fittings and general office fixtures, for which purpose it is not absolutely essential to have the sections of the bends within very close limits. Absolutely accurate data for this work cannot be deduced, as the stock varies considerably as to hardness, etc. The figures given apply to sheet steel, aluminum, brass and bronze. Experience has demonstrated that for the semisquare corners, such as are formed in a V-die, the amount to be deducted from the sum of the outside bend dimensions, as shown in Fig. 5 by the sum of the letters from *a* to *e*, is as follows:  $X = 1.67 BG$ , where  $X$  = the amount to be deducted;  $B$  = the number of bends; and  $G$  = the decimal equivalent of the gage. The values of  $X$  for different gages and numbers of bends are given in the table. Its application may be illustrated by an example: A strip having two bends is to have outside dimensions of 2,  $1\frac{1}{2}$  and 2 inches, and is made of stock 0.125 inch thick. The sum of the outside dimensions is thus  $5\frac{1}{2}$  inches, and from the table the amount to be deducted is found to be 0.416; hence the blank will be  $5.5 - 0.416 = 5.084$  inches long.

The lower part of the table applies to square bends which are either drawn through a block of steel made to the required shape, or else drawn through rollers in a drawbench. The pressure applied not only gives a much sharper corner, but it also elongates the material more than in the V-die process. In this case, the deduction is  $X = 1.33 BG$ .

### Joining and Edging

A duct system is an assembly whose main function is to convey air. Elements of the duct system are sheets, transverse joints, longitudinal seams, and reinforcements. The sheets must be able to withstand deflection caused by both internal pressure and vibration due to turbulent air flow. Transverse joints must be able to withstand 1.5 times the maximum operating pressure without failure. Transverse joint designs should be consistent with the static pressure class, sealing requirements, materials involved, and support interval distances. Notching, bending, folding, and fit up tolerances shall be appropriate for the proper class. Longitudinal seams also must be able to withstand 1.5 times the operating pressure without deformation. Seams shall be formed and assembled with proper dimension and proportion for tight and secure fit up. Seams may be a butt, corner, plug, or spot weld design. Seams shall be selected based on material and pressure. A duct section between adjacent hangers must be able to carry its own weight and to resist external loads for which



## Allowances for Bends in Sheet Metal

| Square Bends                    | Gage | Thickness Inches | Amount to be Deducted from the Sum of the Outside Bend Dimensions, Inches |         |         |         |         |         |         |
|---------------------------------|------|------------------|---|---------|---------|---------|---------|---------|---------|
|                                 |      |                  | 1 Bend  | 2 Bends | 3 Bends | 4 Bends | 5 Bends | 6 Bends | 7 Bends |
| Formed in a Press by a V-die    | 18   | 0.0500           | 0.083   | 0.166   | 0.250   | 0.333   | 0.416   | 0.500   | 0.583   |
|                                 | 16   | 0.0625           | 0.104   | 0.208   | 0.312   | 0.416   | 0.520   | 0.625   | 0.729   |
|                                 | 14   | 0.0781           | 0.130   | 0.260   | 0.390   | 0.520   | 0.651   | 0.781   | 0.911   |
|                                 | 13   | 0.0937           | 0.156   | 0.312   | 0.468   | 0.625   | 0.781   | 0.937   | 1.093   |
|                                 | 12   | 0.1093           | 0.182   | 0.364   | 0.546   | 0.729   | 0.911   | 1.093   | 1.276   |
|                                 | 11   | 0.1250           | 0.208   | 0.416   | 0.625   | 0.833   | 1.041   | 1.250   | 1.458   |
|                                 | 10   | 0.1406           | 0.234   | 0.468   | 0.703   | 0.937   | 1.171   | 1.406   | 1.643   |
| Rolled or Drawn in a Draw-bench | 18   | 0.0500           | 0.066   | 0.133   | 0.200   | 0.266   | 0.333   | 0.400   | 0.466   |
|                                 | 16   | 0.0625           | 0.083   | 0.166   | 0.250   | 0.333   | 0.416   | 0.500   | 0.583   |
|                                 | 14   | 0.0781           | 0.104   | 0.208   | 0.312   | 0.416   | 0.521   | 0.625   | 0.729   |
|                                 | 13   | 0.0937           | 0.125   | 0.250   | 0.375   | 0.500   | 0.625   | 0.750   | 0.875   |
|                                 | 12   | 0.1093           | 0.145   | 0.291   | 0.437   | 0.583   | 0.729   | 0.875   | 1.020   |
|                                 | 11   | 0.1250           | 0.166   | 0.333   | 0.500   | 0.666   | 0.833   | 1.000   | 1.166   |
|                                 | 10   | 0.1406           | 0.187   | 0.375   | 0.562   | 0.750   | 0.937   | 1.125   | 1.312   |



it is constructed. The reinforcing members must be able to resist the deflection of the sheet, and its own deflection.

There is a relationship between duct width, reinforcement spacing, reinforcement size, pressure, and sheet thickness. For constant pressure and constant duct size, the thicker sheet allows more distance between reinforcements. The higher the pressure the shorter the spacing between reinforcements. Joints and intermediate reinforcements are labor intensive and may be more costly than the savings gained by a reduction in wall thickness. Thicker duct wall and stronger joints are more cost effective than using more reinforcement.

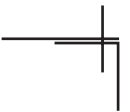
The following material illustrates various joint designs, used both in duct work and other sheet metal assemblies.

## Sheet Metal Joints

## Plain Lap and Flush Lap:

|   |  |
|---|--|
|  <p>Fig. 6. Plain Lap</p> | <p>The <i>plain lap</i> (Fig. 6) and <i>flush lap</i> (Fig. 7) are both used for various materials such as galvanized or black iron, copper, stainless steel, aluminum, or other metals, and may be soldered, and/or riveted, as well as spot, tack, or solid-welded. Lap dimensions vary with the particular application, and since it is the duty of the draftsman to specify straight joints in lengths that use full-sheet sizes, transverse lap dimensions must be known.</p> |
|  <p>Fig. 7. Flush Lap</p> |  |

## Raw and Flange Corner:

|  |   |
|--|---|
|  <p>Fig. 8. Raw and Flange Corner</p> | <p>The <i>raw and flange corner</i> (Fig. 8) is generally spot-welded, but may be riveted or soldered. For heavy gages it is tack-welded or solid-welded.</p> |
|--|---|

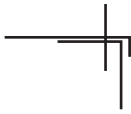
*Flange and Flange Corner:*

Fig. 9. Flange and Flange Corner

The *flange and flange corner* (Fig. 9) is a refinement of the raw and flange corner. It is particularly useful for heavy-gage duct sections which require flush outside corners and must be field-erected.

*Standing Seam:*

Fig. 10. Standing Seam

The *standing seam* (Fig. 10) is often used for large plenums, or casings. Before the draftsman is able to lay out a casing drawing, one of the items of information needed is seam allowance measurements, so that panel sizes can be detailed for economical use of standard sheets. Considering velocity levels, standing seams are considered for duct interiors: 1" seam is normally applied for duct widths up to 42", and 1½" for bigger ducts.

*Groove Seam:*

Fig. 11. Groove Seam

The *groove seam* (Fig. 11) is often used for rectangular or round duct straight joints, or to join some sheets for fittings that are too large to be cut out from standard sheets. It is also known as the pipelock, or flat lock seam.

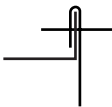
*Corner Standing Seam:*

Fig. 12. Corner Standing Seam

The *corner standing seam* (Fig. 12) has similar usage to the standing seam, and also can be used for straight-duct sections. This type of seams are mostly applied at the ends at 8" intervals.

*Double Seam:*

Fig. 13. Double Corner Seam

The *double corner seam* (Fig. 13) at one time was the most commonly used method for duct fitting fabrication. However, although it is seldom used because of the hand operations required for assembly, the double seam can be used advantageously for duct fittings with compound curves. It is called the slide lock seam. Machines are available to automatically close this seam.

*Slide-Corner:*

Fig. 14. Slide Corner

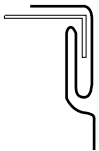
The *slide-corner* (Fig. 14) is a large version of the double seam. It is often used for field assembly of straight joints, such as in an existing ceiling space, or other restricted working area where ducts must be built in place. To assemble the duct segments, opposite ends of each seam are merely "entered" and then pushed into position. Ducts are sent to job sites "knocked-down" for more efficient use of shipping space.

*Button Punch Snap Lock:*


Fig. 15. Button Punch Snap Lock

The *button punch snap lock* (Fig. 15) is a flush-type seam which may be soldered or caulked. This seam can be modified slightly for use as a "snap lock". This types of seam is not applicable for aluminum or other soft metals. This seam may be used up to 4" w.g. by using screws at the ends. The pocket depth should not be smaller than ⅜" for 20, 22 and 26 gage.


*Pittsburg:*

|  |  |
|--|--|
|  <p>Fig. 16. Pittsburgh</p> | <p>The <i>Pittsburg</i> (Fig. 16) is the most commonly used seam for standard gage duct construction. The common pocket depths are <math>\frac{5}{16}</math>" and <math>\frac{5}{8}</math>" depending on the thickness of sheet.</p> |
|--|--|


*Flange:*

|  |  |
|--|--|
|  <p>Fig. 17. Flange</p> | <p>The <i>flange</i> (Fig. 17) is an end edge stiffener. The draftsman must indicate size of the flange, direction of bend, degree of bend (if other than 90°) and when full corners are desired. Full corners are generally advisable for collar connections to concrete or masonry wall openings at louvers.</p> |
|--|--|

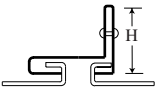
*Hem:*

|   |   |
|---|---|
|  <p>Fig. 18. Hem</p> | <p>The <i>hem edge</i> (Fig. 18) is a flat, finished edge. As with the flange, this must be designated by the draftsman. For example, drawing should show: <math>\frac{3}{4}</math>" hem out.</p> |
|---|---|


*Flat Drive Slip:*

|  |   |
|--|---|
|  <p>Fig. 19. Drive Slip</p> | <p>This is one of the simplest transverse joints. It is applicable where pressure is less than 2" w.g. This is a slide type connection generally used on small ducts in combination of "S" slips. Service above 2" inches w.g. is not applicable.</p> |
|--|---|

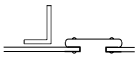
*Standing Drive Slip:*

|  |  |
|--|--|
|  <p>Fig. 20. Standing Drive Slip</p> | <p>This is also a slide type connection. It is made by elongating flat drive slip, fasten standing portions 2" from each end. It is applicable for any length in 2" w.g., 36" for 3" inch w.g., and 30" inches at 4" w.g. service.</p> |
|--|--|


*Flat Drive Slip Reinforced:*

|   |  |
|---|--|
|  <p>Fig. 21. Drive Slip Reinforced</p> | <p>This is the reinforcement on flat drive slip by adding a transverse angle section after a fixed interval.</p> |
|---|--|

*Double "S" Slip Reinforced:*

|   |   |
|---|---|
|  <p>Fig. 22. Double "S" Slip</p> | <p>The double "S" slip is applied, to eliminate the problem of notching and bending, especially for large ducts. Apply 24 gage sheet for 30" width or less, 22 gage sheet over 30" width.</p> |
|---|---|

*Flat "S" Slip:*

|  |  |
|--|--|
|  <p>Fig. 23. Plain "S" Slip</p> | <p>Normally the "S" slip is used for small ducts. However, it is also useful if the connection of a large duct is tight to a beam, column or other object, and an "S" slip is substituted for the shop standard slip. Service above 2" inches w.g. is not applicable. Gage shall not be less than 24, and shall not 2 gage less than the duct gage. When it is applied on all four edges, fasten within 2" of the corners and at 12" maximum interval.</p> |
|--|--|

*Hemmed "S" Slip:*

Fig. 24. Hemmed "S" Slip

This is the modified "S" slip, by adding hem and an angle for reinforcing. The hem edge is a flat, and finished edge. Hemmed "S" slip is mostly applied with angle. The drive is generally 16 gage, formed a 1 inch height slip pocket and screws at the end. Notching and bending operations on an "S" slip joints can be cumbersome and costly, especially for large sizes. Tied each section of the duct within 2" from the corner at maximum 6-inch interval.

**Other Types of Duct Connections***Clinch-bar Slip and Flange:*

Fig. 25. Clinch-bar Slip and Flange

The *clinch-bar slip and flange* (Fig. 25), uses the principle of the standing seam, but with a duct lap in the direction of airflow. These slips are generally assembled as a framed unit with full corners either riveted or spot-welded, which adds to the duct cross-section rigidity. Reinforcement may be accomplished by spot welding the flat-bar to the flange of the large end. Accessibility to all four sides of the duct is required because the flange of the slip must be folded over the flange on the large end after the ducts are connected.

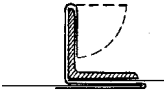
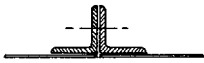
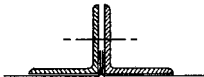
*Clinch-bar Slip and Angle :*

Fig. 26. Clinch-bar Slip and Angle

The *clinch bar slip and angle* (Fig. 26), is similar to clinch bar slip (Fig. 25), but it has a riveted or spot-welded angle on the large end. This connection can also have a raw large end which is inserted into the space between the angle and the shop-fabricated slip. Matched angles (minimum of 16 ga) are riveted or spot welded to the smaller sides of the ducts, to pull the connection "home."

**Flanged Duct Connections***Angle Frame, or Ring:*Fig. 27. Raw Ends and Matched  $\angle$ 

Any of the following flanged connections may have gaskets. The draftsman should not allow for gasket thicknesses in calculations for running length dimensions, nor should he indicate angle sizes, bolt centers, etc., as these items are established in job specifications and approved shop standards. Generally, angles are fastened to the duct sections in the shop. If conditions at the job site require consideration for length contingencies, the draftsman should specify "loose angles" such as at a connection to equipment which may be located later. The most common matched angle connection is the *angle frame, or ring* (Fig. 27). The angles are fastened flush to the end of the duct.

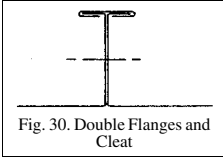
*Flanged End and Angle:*Fig. 28. Flanged Ends and Matched  $\angle$ s

The *flanged end and angle* (Fig. 28), is often used for ducts 16 ga or lighter, as the flange provides a metal-to-metal gasket and holds the angle frame or ring on the duct without additional fastening. The draftsman may indicate in a field note that a round-duct fitting is to be "rotated as required". This type of angle-ring-connection is convenient for such a condition.

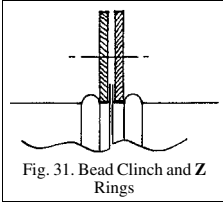
*Formed Flanges:*

Fig. 29. Formed Flanges

*Double flanges* (Fig. 29), are similar to Fig. 21, except that the connecting flange has a series of matched bolt holes. This connection, caulked airtight, is ideal for single-wall apparatus casings or plenums. The flanges are formed at the ends of the duct, after assembly they will form a T shape. Mating flanges shall be locked together by long clips. In order to form effective seal, gasket is used with suitable density and resiliency. At the corners 16 gage thickness steel corner are used with  $\frac{3}{8}$ " diameter bolts.

*Double Flanges and Cleat:*

*Double Flanges and Cleat* (Fig. 30) is identical to (Fig. 29), but has an air seal cleat. The reinforcements is attached to the duct wall on both sides of the joint.

*Clinch-type Flanged Connections:*

*Clinch-type flanged connections* for round ducts, 16 ga or lighter, are shown in Fig. 31. The angles or rings can be loose, as explained in *Flanged End and Angle*, (Fig. 28). The draftsman should indicate flange sizes, bend direction, and type of assembly. An example such as the flange lap for a field assembly of a 10-gage casing corner would be written:  $1\frac{1}{2}$ " flange out square on side with  $\frac{9}{32}$ "  $\varnothing$  bolt holes 12" CC. At the beginning and ending angles are connected by rivets or welding. The bolt will be  $\frac{3}{16}$ "  $\varnothing$  at 6" maximum spacing 4" w.g..

**Fine Blanking**

The process called fine blanking uses special presses and tooling to produce flat components from sheet metal or plate, with high dimensional accuracy. According to Hydrel A. G., Romanshorn, Switzerland, fine-blanking presses can be powered hydraulically or mechanically, or by a combination of these methods, but they must have three separate and distinct movements. These movements serve to clamp the work material, to perform the blanking operation, and to eject the finished part from the tool. Forces of 1.5–2.5 times those used in conventional stamping are needed for fine blanking, so machines and tools must be designed and constructed accordingly. In mechanical fine-blanking presses the clamping and ejection forces are exerted hydraulically. Such presses generally are of toggle-type design and are limited to total forces of up to about 280 tons. Higher forces generally require all-hydraulic designs. These presses are also suited to embossing, coining, and impact extrusion work.

Cutting elements of tooling for fine blanking generally are made from 12 per cent chromium steel, although high speed steel and tungsten carbide also are used for long runs or improved quality. Cutting clearances between the intermediate punch and die are usually held between 0.0001 and 0.0003 in. The clamping elements are sharp projections of 90-degree V-section that follow the outline of the workpiece and that are incorporated into each tool as part of the stripper plate with thin material and also as part of the die plate when material thicker than 0.15 in. is to be blanked. Pressure applied to the elements containing the V-projections prior to the blanking operation causes the sharp edges to enter the material surface, preventing sideways movement of the blank. The pressure applied as the projections bite into the work surface near the contour edges also squeezes the material, causing it to flow toward the cutting edges, reducing the usual rounding effect at the cut edge. When small details such as gear teeth are to be produced, V-projections are often used on both sides of the work, even with thin materials, to enhance the flow effect. With suitable tooling, workpieces can be produced with edges that are perpendicular to top and bottom surfaces within 0.004 in. on thicknesses of 0.2 in., for instance. V-projection dimensions for various material thicknesses are shown in the table *Dimensions for V-projections Used in Fine-Blanking Tools*.

Fine-blanked edges are free from the fractures that result from conventional tooling, and can have surface finishes down to 80  $\mu\text{in. Ra}$  with suitable tooling. Close tolerances can be

## Dimensions for V-projections Used in Fine-Blanking Tools

V-Projections On Stripper Plate Only

V-Projections On Both Stripper and Die Plate

| Material Thickness                           | A     | h     | r     | H     | R     |
|--|-------|-------|-------|-------|-------|
| V-Projections On Stripper Plate Only         |       |       |       |       |       |
| 0.040-0.063                                  | 0.040 | 0.012 | 0.008 | ...   | ...   |
| 0.063-0.098                                  | 0.055 | 0.015 | 0.008 | ...   | ...   |
| 0.098-0.125                                  | 0.083 | 0.024 | 0.012 | ...   | ...   |
| 0.125-0.157                                  | 0.098 | 0.028 | 0.012 | ...   | ...   |
| 0.157-0.197                                  | 0.110 | 0.032 | 0.012 | ...   | ...   |
| V-Projections On Both Stripper and Die Plate |       |       |       |       |       |
| 0.157-0.197                                  | 0.098 | 0.020 | 0.008 | 0.032 | 0.032 |
| 0.197-0.248                                  | 0.118 | 0.028 | 0.008 | 0.040 | 0.040 |
| 0.248-0.315                                  | 0.138 | 0.032 | 0.008 | 0.047 | 0.047 |
| 0.315-0.394                                  | 0.177 | 0.040 | 0.020 | 0.060 | 0.060 |
| 0.394-0.492                                  | 0.217 | 0.047 | 0.020 | 0.070 | 0.080 |
| 0.492-0.630                                  | 0.276 | 0.063 | 0.020 | 0.087 | 0.118 |

All units are in inches.

held on inner and outer forms, and on hole center distances. Flatness of fine-blanked components is better than that of parts made by conventional methods, but distortion may occur with thin materials due to release of internal stresses. Widths must be slightly greater than are required for conventional press working. Generally, the strip width must be 2-3 times the thickness, plus the width of the part measured transverse to the feed direction. Other factors to be considered are shape, material quality, size and shape of the V-projection in relation to the die outline, and spacing between adjacent blanked parts. Holes and slots can be produced with ratios of width to material thickness down to 0.7, compared with the 1:1 ratio normally specified for conventional tooling. Operations such as countersinking, coining, and bending up to 60 degrees can be incorporated in fine-blanking tooling.

The cutting force in lb exerted in fine blanking is 0.9 times the length of the cut in inches times the material thickness in inches, times the tensile strength in  $\text{lb}_f/\text{in}^2$ . Pressure in lb exerted by the clamping element(s) carrying the V-projections is calculated by multiplying the length of the V-projection, which depends on its shape, in inches by its height ( $h$ ), times the material tensile strength in  $\text{lb}_f/\text{in}^2$ , times an empirical factor  $f$ . Factor  $f$  has been determined to be 2.4-4.4 for a tensile strength of 28,000-113,000  $\text{lb}_f/\text{in}^2$ . The clamping pressure is approximately 30 per cent of the cutting force, calculated as above. Dimensions and positioning of the V-projection(s) are related to the material thickness, quality, and tensile strength. A small V-projection close to the line of cut has about the same effect as a large V-projection spaced away from the cut. However, if the V-projection is too close to the cut, it may move out of the material at the start of the cutting process, reducing its effectiveness.

Positioning the V-projection at a distance from the line of cut increases both material and blanking force requirements. Location of the V-projection relative to the line of cut also affects tool life.

### Steel Rule Dies

Steel rule dies (or knife dies) were patented by Robert Gair in 1879, and, as the name implies, have cutting edges made from steel strips of about the same proportions as the steel strips used in making graduated rules for measuring purposes. According to J. A. Richards, Sr., of the J. A. Richards Co., Kalamazoo, MI, a pioneer in the field, these dies were first used in the printing and shoemaking industries for cutting out shapes in paper, cardboard, leather, rubber, cork, felt, and similar soft materials. Steel rule dies were later adopted for cutting upholstery material for the automotive and other industries, and for cutting out simple to intricate shapes in sheet metal, including copper, brass, and aluminum. A typical steel rule die, partially cut away to show the construction, is shown in Fig. 1, and is designed for cutting a simple circular shape. Such dies generally cost 25 to 35 per cent of the cost of conventional blanking dies, and can be produced in much less time. The die shown also cuts a rectangular opening in the workpiece, and pierces four holes, all in one press stroke.

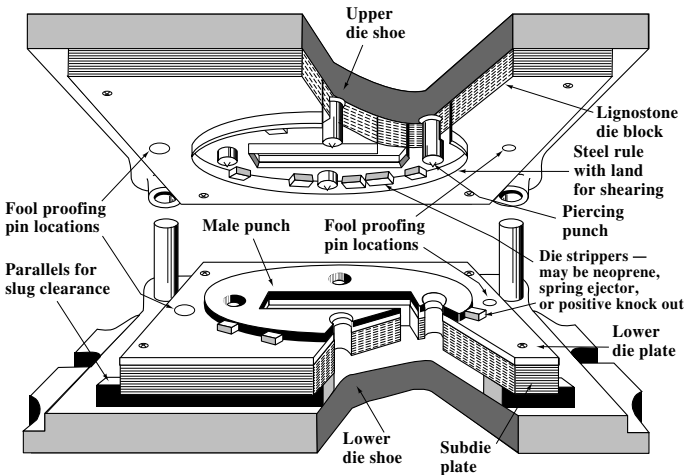


Fig. 1. Steel Rule Die for Cutting a Circular Shape, Sectioned to Show the Construction

The die blocks that hold the steel strips on edge on the press platen or in the die set may be made from plaster, hot lead or type metal, or epoxy resin, all of which can be poured to shape. However, the material most widely used for light work is  $\frac{3}{4}$ -in. thick, five- or seven-ply maple or birch wood. Narrow slots are cut in this wood with a jig saw to hold the strips vertically. Where greater forces are involved, as with operations on metal sheets, the blocks usually are made from Lignostone densified wood or from metal. In the  $\frac{3}{4}$ -in. thickness mostly used, medium- and high-density grades of Lignostone are available. The  $\frac{3}{4}$ -in. thickness is made from about 35 plies of highly compressed lignite wood, bonded with

phenolformaldehyde resin, which imparts great density and strength. The material is made in thicknesses up to 6 in., and in various widths and lengths.

Steel rule die blocks can carry punches of various shapes to pierce holes in the stock, also projections designed to form strengthening ribs and other shapes in material such as aluminum, at the same time as the die cuts the component to shape. Several dies can be combined or nested, and operated together in a large press, to produce various shapes simultaneously from one sheet of material.

As shown in Fig. 1, the die steel is held in the die block slot on its edge, usually against the flat platen of a die set attached to the moving slide of the press. The sharp, free end of the rule faces toward the workpiece, which is supported by the face of the other die half. This other die half may be flat or may have a punch attached to it, as shown, and it withstands the pressure exerted in the cutting or forming action when the press is operated. The closed height of the die is adjusted to permit the cutting edge to penetrate into the material to the extent needed, or, if there is a punch, to carry the cutting edges just past the punch edges for the cutting operation. After the sharp edge has penetrated it, the material often clings to the sides of the knife. Ejector inserts made from rubber, combinations of cork and rubber, and specially compounded plastics material, or purpose-made ejectors, either spring- or positively actuated, are installed in various positions alongside the steel rules and the punch. These ejectors are compressed as the dies close, and when the dies open, they expand, pushing the material clear of the knives or the punch.

The cutting edges of the steel rules can be of several shapes, as shown in profile in Fig. 2, to suit the material to be cut, or the type of cutting operation. Shape *A* is used for shearing in the punch in making tools for blanking and piercing operations, the sharp edge later being modified to a flat, producing a 90° cutting edge, *B*. The other shapes in Fig. 2 are used for cutting various soft materials that are pressed against a flat surface for cutting. The shape at *C* is used for thin, and the shape at *D* for thicker materials.

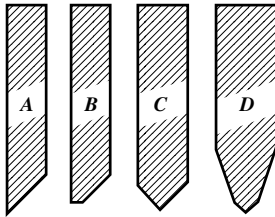


Fig. 2. Cutting Edges for Steel Rule Dies

Steel rule die steel is supplied in lengths of 30 and 50 in., or in coils of any length, with the edges ground to the desired shape, and heat treated, ready for use. The rule material width is usually referred to as the height, and material can be obtained in heights of 0.95, 1, 1 $\frac{1}{8}$ , 1 $\frac{1}{4}$ , and 1 $\frac{1}{2}$  in. Rules are available in thicknesses of 0.055, 0.083, 0.11, 0.138, 0.166, and 0.25 in. (4 to 18 points in printers' measure of 72 points = 1 in.). Generally, stock thicknesses of 0.138 or 0.166 in. (10 and 12 points) are preferred, the thinner rules being used mainly for dies requiring intricate outlines. The stock can be obtained in soft or hard temper. The standard edge bevel is 46°, but bevels of 40 to 50° can be used. Thinner rule stock is easiest to form to shape and is often used for short runs of 50 pieces or thereabouts. The thickness and hardness of the material to be blanked also must be considered when choosing rule thickness.

**Making of Steel Rule Dies.**—Die making begins with a drawing of the shape required. Saw cutting lines may be marked directly on the face of the die block in a conventional layout procedure using a height gage, or a paper drawing may be pasted to or drawn on the die



board. Because paper stretches and shrinks, Mylar or other nonshrink plastics sheets may be preferred for the drawing. A hole is drilled off the line to allow a jig saw to be inserted, and jig saw or circular saw cuts are then made under manual control along the drawing lines to produce the slots for the rules. Jig saw blades are available in a range of sizes to suit various thicknesses of rule and for sawing medium-density Lignostone, a speed of 300 strokes/min is recommended, the saw having a stroke of about 2 in. To make sure the rule thickness to be used will be a tight fit in the slot, trials are usually carried out on scrap pieces of die block before cuts are made on a new block.

During slot cutting, the saw blade must always be maintained vertical to the board being cut, and magnifying lenses are often used to keep the blade close to the line. Carbide or carbide-tipped saw blades are recommended for clean cuts as well as for long life. To keep any "islands" (such as the center of a circle) in position, various places in the sawn line are cut to less than full depth for lengths of  $\frac{1}{4}$  to  $\frac{1}{2}$  in., and to heights of  $\frac{3}{8}$  to  $\frac{3}{4}$  in. to bridge the gaps. Slots of suitable proportions must be provided in the steel rules, on the sides away from the cutting edges, to accommodate these die block bridges.

Rules for steel rule dies are bent to shape to fit the contours called for on the drawing by means of small, purpose-built bending machines, fitted with suitable tooling. For bends of small radius, the tooling on these machines is arranged to perform a peening or hammering action to force the steel rule into close contact with the radius-forming component of the machine so that quite small radii, as required for jig saw puzzles, for instance, can be produced with good accuracy. Some forms are best made in two or more pieces, then joined by welding or brazing. The edges to be joined are mitered for a perfect fit, and are clamped securely in place for joining. Electrical resistance or a gas heating torch is used to heat the joint. Wet rags are applied to the steel at each side of the joint to keep the material cool and the hardness at the preset level, as long as possible.

When shapes are to be blanked from sheet metal, the steel rule die is arranged with flat, 90° edges (*B*, in Fig. 2), which cut by pushing the work past a close-fitting counter-punch. This counterpunch, shown in Fig. 1, may be simply a pad of steel or other material, and has an outline corresponding to the shape of the part to be cut. Sometimes the pad may be given a gradual, slight reduction in height to provide a shearing action as the moving tool pushes the work material past the pad edges. As shown in Fig. 1, punches can be incorporated in the die to pierce holes, cut slots, or form ribs and other details during the blanking operation. These punches are preferably made from high-carbon, high-vanadium, alloy steel, heat treated to Rc 61 to 63, with the head end tempered to Rc 45 to 50.

Heat treatment of the high-carbon-steel rules is designed to produce a hardness suited to the application. Rules in dies for cutting cartons and similar purposes, with mostly straight cuts, are hardened to Rc 51 to 58. For dies requiring many intricate bends, lower-carbon material is used, and is hardened to Rc 38 to 45. And for dies to cut very intricate shapes, a steel in dead-soft condition with hardness of about Rb 95 is recommended. After the intricate bends are made, this steel must be carburized before it is hardened and tempered. For this material, heat treatment uses an automatic cycle furnace, and consists of carburizing in a liquid compound heated to 1500°F and quenching in oil, followed by "tough" tempering at 550°F and cooling in the furnace.

After the hardened rule has been reinstalled in the die block, the tool is loaded into the press and the sharp die is used with care to shear the sides of the pad to match the die contours exactly. A close fit, with clearances of about half those used in conventional blanking dies, is thus ensured between the steel rule and the punch. Adjustments to the clearances can be made at this point by grinding the die steel or the punch. After the adjustment work is done, the sharp edges of the rule steel are ground flat to produce a land of about  $\frac{1}{64}$  in. wide (*A* in Fig. 2), for the working edges of the die. Clearances for piercing punches should be similar to those used on conventional piercing dies.

## ELECTRICAL DISCHARGE MACHINING

Generally called EDM, electrical discharge machining uses an electrode to remove metal from a workpiece by generating electric sparks between conducting surfaces. The two main types of EDM are termed sinker or plunge, used for making mold or die cavities, and wire, used to cut shapes such as are needed for stamping dies. For die sinking, the electrode usually is made from copper or graphite and is shaped as a positive replica of the shape to be formed on or in the workpiece. A typical EDM sinker machine, shown diagrammatically in Fig. 1, resembles a vertical milling machine, with the electrode attached to the vertical slide. The slide is moved down and up by an electronic, servo-controlled drive unit that controls the spacing between the electrode and the workpiece on the table. The table can be adjusted in three directions, often under numerical control, to positions that bring a workpiece surface to within 0.0005 to 0.030 in. from the electrode surface, where a spark is generated.

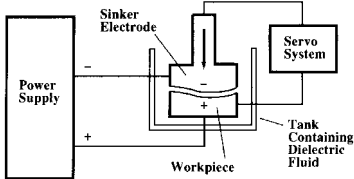


Fig. 1. Sinker or Plunge Type EDM Machines Are Used to Sink Cavities in Molds and Dies

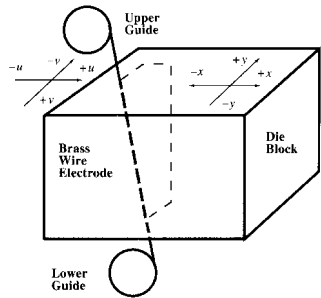


Fig. 2. Wire Type EDM Machines Are Used to Cut Stamping Die Profiles.

Wire EDM, shown diagrammatically in Fig. 2, are numerically controlled and somewhat resemble a bandsaw with the saw blade replaced by a fine brass or copper wire, which forms the electrode. This wire is wound off one reel, passed through tensioning and guide rollers, then through the workpiece and through lower guide rollers before being wound onto another reel for storage and eventual recycling. One set of guide rollers, usually the lower, can be moved on two axes at 90 degrees apart under numerical control to adjust the angle of the wire when profiles of varying angles are to be produced. The table also is movable in two directions under numerical control to adjust the position of the workpiece relative to the wire. Provision must be made for the cut-out part to be supported when it is freed from the workpiece so that it does not pinch and break the wire.

EDM applied to grinding machines is termed EDG. The process uses a graphite wheel as an electrode, and wheels can be up to 12 in. in diameter by 6 in. wide. The wheel periphery is dressed to the profile required on the workpiece and the wheel profile can then be transferred to the workpiece as it is traversed past the wheel, which rotates but does not touch the work. EDG machines are highly specialized and are mainly used for producing complex profiles on polycrystalline diamond cutting tools and for shaping carbide tooling such as form tools, thread chasers, dies, and crushing rolls.

**EDM Terms\***.—*Anode*: The positive terminal of an electrolytic cell or battery. In EDM, incorrectly applied to the tool or electrode.

\* Source: Hansvedt Industries

*Barrel effect:* In wire EDM, a condition where the center of the cut is wider than the entry and exit points of the wire, due to secondary discharges caused by particles being pushed to the center by flushing pressure from above and beneath the workpiece.

*Capacitor:* An electrical component that stores an electric charge. In some EDM power supplies, several capacitors are connected across the machining gap and the current for the spark comes directly from the capacitors when they are discharged.

*Cathode:* The negative terminal in an electrolytic cell or battery. In EDM incorrectly applied to the workpiece.

*Colloidal suspension:* Particles suspended in a liquid that are too fine to settle out. In EDM, the tiny particles produced in the sparking action form a colloidal suspension in the dielectric fluid.

*Craters:* Small cavities left on an EDM surface by the sparking action, also known as pits.

*Dielectric filter:* A filter that removes particles from 5  $\mu\text{m}$  (0.00020 in.) down to as fine as 1  $\mu\text{m}$  (0.00004 in) in size, from dielectric fluid.

*Dielectric fluid:* The non-conductive fluid that circulates between the electrode and the workpiece to provide the dielectric strength across which an arc can occur, to act as a coolant to solidify particles melted by the arc, and to flush away the solidified particles.

*Dielectric strength:* In EDM, the electrical potential (voltage) needed to break down (ionize) the dielectric fluid in the gap between the electrode and the workpiece.

*Discharge channel:* The conductive pathway formed by ionized dielectric and vapor between the electrode and the workpiece.

*Dither:* A slight up and down movement of the machine ram and attached electrode, used to improve cutting stability.

*Duty cycle:* The percentage of a pulse cycle during which the current is turned on (on time), relative to the total duration of the cycle.

*EDG:* Electrical discharge grinding using a machine that resembles a surface grinder but has a wheel made from electrode material. Metal is removed by an EDM process rather than by grinding.

*Electrode growth:* A plating action that occurs at certain low-power settings, whereby workpiece material builds up on the electrode, causing an increase in size.

*Electrode wear:* Amount of material removed from the electrode during the EDM process. This removal can be end wear or corner wear, and is measured linearly or volumetrically but is most often expressed as end wear per cent, measured linearly.

*Electro-forming:* An electro-plating process used to make metal EDM electrodes.

*Energy:* Measured in joules, is the equivalent of volt-coulombs or volt-ampere-seconds.

*Farad:* Unit of electrical capacitance, or the energy-storing capacity of a capacitor.

*Gap:* The closest point between the electrode and the workpiece where an electrical discharge will occur. (See *Overcut*)

*Gap current:* The average amperage flowing across the machining gap.

*Gap voltage:* The voltage across the gap while current is flowing. The voltage across the electrode/workpiece before current flows is called the open gap voltage. Heat-affected zone. The layer below the recast layer, which has been subjected to elevated temperatures that have altered the properties of the workpiece metal.

*Ion:* An atom or group of atoms that has lost or gained one or more electrons and is therefore carrying a positive or negative electrical charge, and is described as being ionized.

*Ionization:* The change in the dielectric fluid that is subjected to a voltage potential whereby it becomes electrically conductive, allowing it to conduct the arc.

*Low-wear:* An EDM process in which the volume of electrode wear is between 2 and 15 per cent of the volume of workpiece wear. Normal negative polarity wear ratios are 15 to 40 per cent.

*Negative electrode:* The electrode voltage potential is negative relative to the workpiece.

*No-wear:* An EDM process in which electrode wear is virtually eliminated and the wear ratio is usually less than 2 per cent by volume.

*Orbit:* A programmable motion between the electrode and the workpiece, produced by a feature built in to the machine, or an accessory, that produces a cavity or hole larger than the electrode. The path can be planetary (circular), vectorial, or polygonal (trace). These motions can often be performed in sequence, and combined with x-axis movement of the electrode.

*Overcut:* The distance between one side of an electrode and the adjacent wall of the workpiece cavity.

*Overcut taper:* The difference between the overcut dimensions at the top (entrance) and at the bottom of the cavity.

*Plasma:* A superheated, highly ionized gas that forms in the discharge channel due to the applied voltage.

*Positive electrode:* The electrode voltage potential is positive with respect to the workpiece. is the opposite of this condition.

*Power parameters:* A set of power supply, servo, electrode material, workpiece material, and flushing settings that are selected to produce a desired metal removal rate and surface finish.

*Quench:* The rapid cooling of the EDM surface by the dielectric fluid, which is partially responsible for metallurgical changes in the recast layer and in the heat-affected zone.

*Recast layer:* A layer created by the solidification of molten metal on the workpiece surface after it has been melted by the EDM process.

*Secondary discharge:* A discharge that occurs as conductive particles are carried out along the side of the electrode by the dielectric fluid.

*Spark in:* A method of locating an electrode with respect to the workpiece, using high frequency, low amperage settings so that there is no cutting action. The electrode is advanced toward the workpiece until contact is indicated and this point is used as the basis for setting up the job.

*Spark out:* A technique used in orbiting, which moves the electrode in the same path until sparking ceases.

*Square wave:* An electrical wave shape generated by a solid state power supply.

*Stroke:* The distance the ram travels under servo control.

*UV axis:* A mechanism that provides for movement of the upper head of a wire EDM machine to allow inclined surfaces to be generated.

*White layer:* The surface layer of an EDM cut that is affected by the heat generated during the process. The characteristics of the layer depend on the material, and may be extremely hard martensite or an annealed layer.

*Wire EDM:* An EDM machine or process in which the electrode is a continuously unspooling, conducting wire that moves in preset patterns in relation to the workpiece.

*Wire guide:* A replaceable precision round diamond insert, sized to match the wire, that guides the wire at the entrance and exit points of a wire cut.

*Wire speed:* The rate at which the wire is fed axially through the workpiece (not the rate at which cutting takes place), adjusted so that clean wire is maintained in the cut but slow enough to minimize waste.

**The EDM Process.**—During the EDM process, energy from the sparks created between the electrode and the workpiece is dissipated by the melting and vaporizing of the workpiece material preferentially, only small amounts of material being lost from the electrode. When current starts to flow between the electrode and the work, the dielectric fluid in the small area in which the gap is smallest, and in which the spark will occur, is transformed into a plasma of hydrogen, carbon, and various oxides. This plasma forms a conducting passageway, consisting of ionized or electrically charged particles, through which the spark can form between the electrode and the workpiece. After current starts to flow, to heat and vaporize a tiny area, the striking voltage is reached, the voltage drops, and the field of ionized particles loses its energy, so that the spark can no longer be sustained. As the voltage then begins to rise again with the increase in resistance, the electrical supply is

cut off by the control, causing the plasma to implode and creating a low-pressure pulse that draws in dielectric fluid to flush away metallic debris and cool the impinging area. Such a cycle typically lasts a few microseconds (millionths of a second, or  $\mu\text{s}$ ), and is repeated continuously in various places on the workpiece as the electrode is moved into the work by the control system.

*Flushing:* An insulating dielectric fluid is made to flow in the space between the workpiece and the electrode to prevent premature spark discharge, cool the workpiece and the electrode, and flush away the debris. For sinker machines, this fluid is paraffin, kerosene, or a silicon-based dielectric fluid, and for wire machines, the dielectric fluid is usually deionized water. The dielectric fluid can be cooled in a heat exchanger to prevent it from rising above about 100°F, at which cooling efficiency may be reduced. The fluid must also be filtered to remove workpiece particles that would prevent efficient flushing of the spark gaps. Care must be taken to avoid the possibility of entrapment of gases generated by sparking. These gases may explode, causing danger to life, breaking a valuable electrode or workpiece, or causing a fire.

Flushing away of particles generated during the process is vital to successful EDM operations. A secondary consideration is the heat transferred to the side walls of a cavity, which may cause the workpiece material to expand and close in around the electrode, leading to formation of dc arcs where conductive particles are trapped. Flushing can be done by forcing the fluid to pass through the spark gap under pressure, by sucking it through the gap, or by directing a side nozzle to move the fluid in the tank surrounding the workpiece. In pressure flushing, fluid is usually pumped through strategically placed holes in the electrode or in the workpiece. Vacuum flushing is used when side walls must be accurately formed and straight, and is seldom needed on numerically controlled machines because the table can be programmed to move the workpiece sideways.

Flushing needs careful consideration because of the forces involved, especially where fluid is pumped or sucked through narrow passageways, and large hydraulic forces can easily be generated. Excessively high pressures can lead to displacement of the electrode, the workpiece, or both, causing inaccuracy in the finished product. Many low-pressure flushing holes are preferable to a few high-pressure holes. Pressure-relief valves in the system are recommended.

*Electronic Controls:* The electrical circuit that produces the sparks between the electrode and the workpiece is controlled electronically, the length of the extremely short on and off periods being matched by the operator or the programmer to the materials of the electrode and the workpiece, the dielectric, the rate of flushing, the speed of metal removal, and the quality of surface finish required. The average current flowing between the electrode and the workpiece is shown on an ammeter on the power source, and is the determining factor in machining time for a specific operation. The average spark gap voltage is shown on a voltmeter.

EDM machines can incorporate provision for orbiting the electrode so that flushing is easier, and cutting is faster and increased on one side. Numerical control can also be used to move the workpiece in relation to the electrode with the same results. Numerical control can also be used for checking dimensions and changing electrodes when necessary. The clearance on all sides between the electrode and the workpiece, after the machining operation, is called the overcut or overburn. The overcut becomes greater with increases in the on time, the spark energy, or the amperage applied, but its size is little affected by voltage changes. Allowances must be made for overcut in the dimensioning of electrodes. Side-wall encroachment and secondary discharge can take up parts of these allowances, and electrodes must always be made smaller to avoid making a cavity or hole too large.

*Polarity:* Polarity can affect processing speed, finish, wear, and stability of the EDM operation. On sinker machines, the electrode is generally, made positive to protect the electrode from excessive wear and preserve its dimensional accuracy. This arrangement

removes metal at a slower rate than electrode negative, which is mostly used for high-speed metal removal with graphite electrodes. Negative polarity is also used for machining carbides, titanium, and refractory alloys using metallic electrodes. Metal removal with graphite electrodes can be as much as 50 per cent faster with electrode negative polarity than with electrode positive, but negative polarity results in much faster electrode wear, so it is generally restricted to electrode shapes that can be redressed easily.

Newer generators can provide less than 1 per cent wear with either copper or graphite electrodes during roughing operations. Roughing is typically done with a positive-polarity electrode using elevated on times. Some electrodes, particularly micrograin graphites, have a high resistance to wear. Fine-grain, high-density graphites provide better wear characteristics than coarser, less dense grades, and copper-tungsten resists wear better than pure copper electrodes.

*Machine Settings:* For vertical machines, a rule of thumb for power selection on graphite and copper electrodes is 50 to 65 amps per square inch of electrode engagement. For example, an electrode that is  $\frac{1}{2}$  in. square might use  $0.5 \times 0.5 \times 50 = 12.5$  amps. Although each square inch of electrode surface may be able to withstand higher currents, lower settings should be used with very large jobs or the workpiece may become overheated and it may be difficult to clean up the recast layer. Lower amperage settings are required for electrodes that are thin or have sharp details. The voltage applied across the arc gap between the electrode and the workpiece is ideally about 35 volts, but should be as small as possible to maintain stability of the process.

*Spark Frequency:* Spark frequency is the number of times per second that the current is switched on and off. Higher frequencies are used for finishing operations and for work on cemented carbide, titanium, and copper alloys. The frequency of sparking affects the surface finish produced, low frequencies being used with large spark gaps for rapid metal removal with a rough finish, and higher frequencies with small gaps for finer finishes. High frequency usually increases, and low frequency reduces electrode wear.

*The Duty Cycle:* Electronic units on modern EDM machines provide extremely close control of each stage in the sparking cycle, down to millionths of a second ( $\mu$ s). A typical EDM cycle might last 100  $\mu$ s. Of this time, the current might be on for 40  $\mu$ s and off for 60  $\mu$ s. The relationship between the lengths of the on and off times is called the duty cycle and it indicates the degree of efficiency of the operation. The duty cycle states the on time as a percentage of the total cycle time and in the previous example it is 40 per cent. Although reducing the off time will increase the duty cycle, factors such as flushing efficiency, electrode and workpiece material, and dielectric condition control the minimum off time. Some EDM units incorporate sensors and fuzzy logic circuits that provide for adaptive control of cutting conditions for unattended operation. Efficiency is also reported as the amount of metal removed, expressed as in.<sup>3</sup>/hr.

In the EDM process, work is done only during the on time, and the longer the on time, the more material is removed in each sparking cycle. Roughing operations use extended on time for high metal-removal rates, resulting in fewer cycles per second, or lower frequency. The resulting craters are broader and deeper so that the surface is rougher and the heat-affected zone (HAZ) on the workpiece is deeper. With positively charged electrodes, the spark moves from the electrode toward the workpiece and the maximum material is removed from the workpiece. However, every spark takes a minute particle from the electrode so that the electrode also is worn away. Finishing electrodes tend to wear much faster than roughing electrodes because more sparks are generated in unit time.

The part of the cycle needed for reionizing the dielectric (the off time) greatly affects the operating speed. Although increasing the off time slows the process, longer off times can increase stability by providing more time for the ejected material to be swept away by the flow of the dielectric fluid, and for deionization of the fluid, so that erratic cycling of the servo-mechanisms that advance and retract the electrode is avoided. In any vertical EDM

operation, if the overcut, wear, and finish are satisfactory, machining speed can best be adjusted by slowly decreasing the off time setting in small increments of 1 to 5  $\mu\text{s}$  until machining becomes erratic, then returning to the previous stable setting. As the off time is decreased, the machining gap or gap voltage will slowly fall and the working current will rise. The gap voltage should not be allowed to drop below 35 to 40 volts.

**Metal Removal Rates (MRR):** Amounts of metal removed in any EDM process depend largely on the length of the on time, the energy/spark, and the number of sparks/second. The following data were provided by Poco Graphite, Inc., in their *EDM Technical Manual*. For a typical roughing operation using electrode positive polarity on high-carbon steel, a 67 per cent duty cycle removed 0.28 in.<sup>3</sup>/hr. For the same material, a 50 per cent duty cycle removed 0.15 in.<sup>3</sup>/hr, and a 33 per cent duty cycle for finishing removed 0.075 in.<sup>3</sup>/hr.

In another example, shown in the top data row in Table 1, a 40 per cent duty cycle with a frequency of 10 kHz and peak current of 50 amps was run for 5 minutes of cutting time. Metal was removed at the rate of 0.8 in.<sup>3</sup>/hr with electrode wear of 2.5 per cent and a surface finish of 400  $\mu\text{in. } R_a$ . When the on and off times in this cycle were halved, as shown in the second data row in Table 1, the duty cycle remained at 40 per cent, but the frequency doubled to 20 kHz. The result was that the peak current remained unaltered, but with only half the on time the MRR was reduced to 0.7 in.<sup>3</sup>/hr, the electrode wear increased to 6.3 per cent, and the surface finish improved to 300  $\mu\text{in. } R_a$ . The third and fourth rows in Table 1 show other variations in the basic cycle and the results.

**Table 1. Effect of Electrical Control Adjustments on EDM Operations**

| On Time ( $\mu\text{s}$ ) | Off Time ( $\mu\text{s}$ ) | Frequency (kHz) | Peak Current (Amps) | Metal Removal Rate (in. <sup>3</sup> /hr) | Electrode Wear (%) | Surface Finish ( $\mu\text{in. } R_a$ ) |
|---------------------------|----------------------------|-----------------|---------------------|---|--------------------|---|
| 40                        | 60                         | 10              | 50                  | 0.08                                      | 2.5                | 400                                     |
| 20                        | 30                         | 20              | 50                  | 0.7                                       | 6.3                | 300                                     |
| 40                        | 10                         | 20              | 50                  | 1.2                                       | 1.4                | 430                                     |
| 40                        | 60                         | 10              | 25                  | 0.28                                      | 2.5                | 350                                     |

**The Recast Layer:** One drawback of the EDM process when used for steel is the recast layer, which is created wherever sparking occurs. The oil used as a dielectric fluid causes the EDM operation to become a random heat-treatment process in which the metal surface is heated to a very high temperature, then quenched in oil. The heat breaks down the oil into hydrocarbons, tars, and resins, and the molten metal draws out the carbon atoms and traps them in the resolidified metal to form the very thin, hard, brittle surface called the recast layer that covers the heat-affected zone (HAZ). This recast layer has a white appearance and consists of particles of material that have been melted by the sparks, enriched with carbon, and drawn back to the surface or retained by surface tension. The recast layer is harder than the parent metal and can be as hard as glass, and must be reduced or removed by vapor blasting with glass beads, polishing, electrochemical or abrasive flow machining, after the shaping process is completed, to avoid cracking or flaking of surface layers that may cause failure of the part in service.

Beneath the thin recast layer, the HAZ, in steel, consists of martensite that usually has been hardened by the heating and cooling sequences coupled with the heat-sink cooling effect of a thick steel workpiece. This martensite is hard and its rates of expansion and contraction are different from those of the parent metal. If the workpiece is subjected to heating and cooling cycles in use, the two layers are constantly stressed and these stresses may cause formation of surface cracks. The HAZ is usually much deeper in a workpiece cut on a sinker than on a wire machine, especially after roughing, because of the increased heating effect caused by the higher amounts of energy applied.

The depth of the HAZ depends on the amperage and the length of the on time, increasing as these values increase, to about 0.012 to 0.015 in. deep. Residual stress in the HAZ can range up to 650 N/mm<sup>2</sup>. The HAZ cannot be removed easily, so it is best avoided by programming the series of cuts taken on the machine so that most of the HAZ produced by one cut is removed by the following cut. If time is available, cut depth can be reduced gradually until the finishing cuts produce an HAZ having a thickness of less than 0.0001 in.

**Workpiece Materials.**—Most homogeneous materials used in metalworking can be shaped by the EDM process. Some data on typical workpiece materials are given in Table 2. Sintered materials present some difficulties caused by the use of a cobalt or other binder used to hold the carbide or other particles in the matrix. The binder usually melts at a lower temperature than the tungsten, molybdenum, titanium, or other carbides, so it is preferentially removed by the sparking sequence and the carbide particles are thus loosened and freed from the matrix. The structures of sintered materials based on tungsten, cobalt, and molybdenum require higher EDM frequencies with very short on times, so that there is less danger of excessive heat buildup, leading to melting. Copper-tungsten electrodes are recommended for EDM of tungsten carbides. When used with high frequencies for powdered metals, graphite electrodes often suffer from excessive wear.

Workpieces of aluminum, brass, and copper should be processed with metallic electrodes of low melting points such as copper or copper-tungsten. Workpieces of carbon and stainless steel that have high melting points should be processed with graphite electrodes. The melting points and specific gravities of the electrode material and of the workpiece should preferably be similar.

**Table 2. Characteristics of Common Workpiece Materials for EDM**

| Material        | Specific Gravity | Melting Point |      | Vaporization Temperature |      | Conductivity (Silver = 100) |
|-----------------|------------------|---------------|------|--------------------------|------|-----------------------------|
|                 |                  | °F            | °C   | °F                       | °C   |                             |
| Aluminum        | 2.70             | 1220          | 660  | 4442                     | 2450 | 63.00                       |
| Brass           | 8.40             | 1710          | 930  | ...                      | ...  | ...                         |
| Cobalt          | 8.71             | 2696          | 1480 | 5520                     | 2900 | 16.93                       |
| Copper          | 8.89             | 1980          | 1082 | 4710                     | 2595 | 97.61                       |
| Graphite        | 2.07             | N/A           |      | 6330                     | 3500 | 70.00                       |
| Inconel         | ...              | 2350          | 1285 | ...                      | ...  | ...                         |
| Magnesium       | 1.83             | 1202          | 650  | 2025                     | 1110 | 39.40                       |
| Manganese       | 7.30             | 2300          | 1260 | 3870                     | 2150 | 15.75                       |
| Molybdenum      | 10.20            | 4748          | 2620 | 10,040                   | 5560 | 17.60                       |
| Nickel          | 8.80             | 2651          | 1455 | 4900                     | 2730 | 12.89                       |
| Carbon Steel    | 7.80             | 2500          | 1371 | ...                      | ...  | 12.00                       |
| Tool Steel      | ...              | 2730          | 1500 | ...                      | ...  | ...                         |
| Stainless Steel | ...              | 2750          | 1510 | ...                      | ...  | ...                         |
| Titanium        | 4.50             | 3200          | 1700 | 5900                     | 3260 | 13.73                       |
| Tungsten        | 18.85            | 6098          | 3370 | 10,670                   | 5930 | 14.00                       |
| Zinc            | 6.40             | 790           | 420  | 1663                     | 906  | 26.00                       |

**Electrode Materials.**—Most EDM electrodes are made from graphite, which provides a much superior rate of metal removal than copper because of the ability of graphite to resist thermal damage. Graphite has a density of 1.55 to 1.85 g/cm<sup>3</sup>, lower than most metals. Instead of melting when heated, graphite sublimates, that is, it changes directly from a solid to a gas without passing through the liquid stage. Sublimation of graphite occurs at a temperature of 3350°C (6062°F). EDM graphite is made by sintering a compressed mixture of fine graphite powder (1 to 100 micron particle size) and coal tar pitch in a furnace. The open structure of graphite means that it is eroded more rapidly than metal in the EDM process. The electrode surface is also reproduced on the surface of the workpiece. The sizes of individual surface recesses may be reduced during sparking when the work is moved under numerical control of workpiece table movements.



The fine grain sizes and high densities of graphite materials that are specially made for high-quality EDM finishing provide high wear resistance, better finish, and good reproduction of fine details, but these fine grades cost more than graphite of larger grain sizes and lower densities. Premium grades of graphite cost up to five times as much as the least expensive and about three times as much as copper, but the extra cost often can be justified by savings during machining or shaping of the electrode.

Graphite has a high resistance to heat and wear at lower frequencies, but will wear more rapidly when used with high frequencies or with negative polarity. Infiltrated graphites for EDM electrodes are also available as a mixture of copper particles in a graphite matrix, for applications where good machinability of the electrode is required. This material presents a trade-off between lower arcing and greater wear with a slower metal-removal rate, but costs more than plain graphite.

EDM electrodes are also made from copper, tungsten, silver-tungsten, brass, and zinc, which all have good electrical and thermal conductivity. However, all these metals have melting points below those encountered in the spark gap, so they wear rapidly. Copper with 5 per cent tellurium, added for better machining properties, is the most commonly used metal alloy. Tungsten resists wear better than brass or copper and is more rigid when used for thin electrodes but is expensive and difficult to machine. Metal electrodes, with their more even surfaces and slower wear rates, are often preferred for finishing operations on work that requires a smooth finish. In fine-finishing operations, the arc gap between the surfaces of the electrode and the workpiece is very small and there is a danger of dc arcs being struck, causing pitting of the surface. This pitting is caused when particles dislodged from a graphite electrode during fine-finishing cuts are not flushed from the gap. If struck by a spark, such a particle may provide a path for a continuous discharge of current that will mar the almost completed work surface.

Some combinations of electrode and workpiece material, electrode polarity, and likely amounts of corner wear are listed in Table 3. Corner wear rates indicate the ability of the electrode to maintain its shape and reproduce fine detail. The column headed Capacitance refers to the use of capacitors in the control circuits to increase the impact of the spark without increasing the amperage. Such circuits can accomplish more work in a given time, at the expense of surface-finish quality and increased electrode wear.

**Table 3. Types of Electrodes Used for Various Workpiece Materials**

| Electrode       | Electrode Polarity | Workpiece Material | Corner Wear (%) | Capacitance |
|-----------------|--------------------|--------------------|-----------------|-------------|
| Copper          | +                  | Steel              | 2-10            | No          |
| Copper          | +                  | Inconel            | 2-10            | No          |
| Copper          | +                  | Aluminum           | <3              | No          |
| Copper          | -                  | Titanium           | 20-40           | Yes         |
| Copper          | -                  | Carbide            | 35-60           | Yes         |
| Copper          | -                  | Copper             | 34-45           | Yes         |
| Copper          | -                  | Copper-tungsten    | 40-60           | Yes         |
| Copper-tungsten | +                  | Steel              | 1-10            | No          |
| Copper-tungsten | -                  | Copper             | 20-40           | Yes         |
| Copper-tungsten | -                  | Copper-tungsten    | 30-50           | Yes         |
| Copper-tungsten | -                  | Titanium           | 15-25           | Yes         |
| Copper-tungsten | -                  | Carbide            | 35-50           | Yes         |
| Graphite        | +                  | Steel              | <1              | No          |
| Graphite        | -                  | Steel              | 30-40           | No          |
| Graphite        | +                  | Inconel            | <1              | No          |
| Graphite        | -                  | Inconel            | 30-40           | No          |
| Graphite        | +                  | Aluminum           | <1              | No          |
| Graphite        | -                  | Aluminum           | 10-20           | No          |
| Graphite        | -                  | Titanium           | 40-70           | No          |
| Graphite        | -                  | Copper             | N/A             | Yes         |

*Electrode Wear:* Wear of electrodes can be reduced by leaving the smallest amounts of finishing stock possible on the workpiece and using no-wear or low-wear settings to remove most of the remaining material so that only a thin layer remains for finishing with the redressed electrode. The material left for removal in the finishing step should be only slightly more than the maximum depth of the craters left by the previous cut. Finishing operations should be regarded as only changing the quality of the finish, not removing metal or sizing. Low power with very high frequencies and minimal amounts of offset for each finishing cut are recommended.

On manually adjusted machines, fine finishing is usually carried out by several passes of a full-size finishing electrode. Removal of a few thousandths of an inch from a cavity with such an arrangement requires the leading edge of the electrode to recut the cavity over the entire vertical depth. By the time the electrode has been sunk to full depth, it is so worn that precision is lost. This problem sometimes can be avoided on a manual machine by use of an orbiting attachment that will cause the electrode to traverse the cavity walls, providing improved speed, finish, and flushing, and reducing corner wear on the electrode.

*Selection of Electrode Material:* Factors that affect selection of electrode material include metal-removal rate, wear resistance (including volumetric, corner, end, and side, with corner wear being the greatest concern), desired surface finish, costs of electrode manufacture and material, and characteristics of the material to be machined. A major factor is the ability of the electrode material to resist thermal damage, but the electrode's density, the polarity, and the frequencies used are all important factors in wear rates. Copper melts at about 1085°C (1985°F) and spark-gap temperatures must generally exceed 3800°C (6872°F), so use of copper may be made unacceptable because of its rapid wear rates. Graphites have good resistance to heat and wear at low frequencies, but will wear more with high frequency, negative polarity, or a combination of these.

**Making Electrodes.**—Electrodes made from copper and its alloys can be machined conventionally by lathes, and milling and grinding machines, but copper acquires a burr on run-off edges during turning and milling operations. For grinding copper, the wheel must often be charged with beeswax or similar material to prevent loading of the surface. Flat grinding of copper is done with wheels having open grain structures (46-J, for instance) to contain the wax and to allow room for the soft, gummy, copper chips. For finish grinding, wheels of at least 60 and up to 80 grit should be used for electrodes requiring sharp corners and fine detail. These wheels will cut hot and load up much faster, but are necessary to avoid rapid breakdown of sharp corners.

Factors to be considered in selection of electrode materials are: the electrode material cost/in<sup>3</sup>; the time to manufacture electrodes; difficulty of flushing; the number of electrodes needed to complete the job; speed of the EDM; amount of electrode wear during EDM; and workpiece surface-finish requirements.

Copper electrodes have the advantage over graphite in their ability to be discharge-dressed in the EDM, usually under computer numerical control (CNC). The worn electrode is engaged with a premachined dressing block made from copper-tungsten or carbide. The process renews the original electrode shape, and can provide sharp, burr-free edges. Because of its higher vaporization temperature and wear resistance, discharge dressing of graphite is slow, but graphite has the advantage that it can be machined conventionally with ease.

*Machining Graphite:* Graphites used for EDM are very abrasive, so carbide tools are required for machining them. The graphite does not shear away and flow across the face of the tool as metal does, but fractures or is crushed by the tool pressure and floats away as a fine powder or dust. Graphite particles have sharp edges and, if allowed to mix with the machine lubricant, will form an abrasive slurry that will cause rapid wear of machine guiding surfaces. The dust may also cause respiratory problems and allergic reactions, espe-

cially if the graphite is infiltrated with copper, so an efficient exhaust system is needed for machining.

Compressed air can be used to flush out the graphite dust from blind holes, for instance, but provision must be made for vacuum removal of the dust to avoid hazards to health and problems with wear caused by the hard, sharp-edged particles. Air velocities of at least 500 ft/min are recommended for flushing, and of 2000 ft/min in collector ducts to prevent settling out. Fluids can also be used, but small-pore filters are needed to keep the fluid clean. High-strength graphite can be clamped or chucked tightly but care must be taken to avoid crushing. Collets are preferred for turning because of the uniform pressure they apply to the workpiece. Sharp corners on electrodes made from less dense graphite are liable to chip or break away during machining.

For conventional machining of graphite, tools of high-quality tungsten carbide or polycrystalline diamond are preferred and must be kept sharp. Recommended cutting speeds for high-speed steel tools are 100 to 300, tungsten carbide 500 to 750, and polycrystalline diamond, 500 to 2000 surface ft/min. Tools for turning should have positive rake angles and nose radii of  $\frac{1}{64}$  to  $\frac{1}{32}$  in. Depths of cut of 0.015 to 0.020 in. produce a better finish than light cuts such as 0.005 in. because of the tendency of graphite to chip away rather than flow across the tool face. Low feed rates of 0.005 in./rev for rough- and 0.001 to 0.003 in./rev for finish-turning are preferred. Cutting off is best done with a tool having an angle of  $20^\circ$ .

For bandsawing graphite, standard carbon steel blades can be run at 2100 to 3100 surface ft/min. Use low power feed rates to avoid overloading the teeth and the feed rate should be adjusted until the saw has a very slight speed up at the breakthrough point. Milling operations require rigid machines, short tool extensions, and firm clamping of parts. Milling cutters will chip the exit side of the cut, but chipping can be reduced by use of sharp tools, positive rake angles, and low feed rates to reduce tool pressure. Feed/tooth for two-flute end mills is 0.003 to 0.005 in. for roughing and 0.001 to 0.003 in. for finishing.

Standard high-speed steel drills can be used for drilling holes but will wear rapidly, causing holes that are tapered or undersized, or both. High-spiral, tungsten carbide drills should be used for large numbers of holes over  $\frac{1}{16}$  in. diameter, but diamond-tipped drills will last longer. Pecking cycles should be used to clear dust from the holes. Compressed air can be passed through drills with through coolant holes to clear dust. Feed rates for drilling are 0.0015 to 0.002 in./rev for drills up to  $\frac{1}{32}$ , 0.001 to 0.003 in./rev for  $\frac{1}{32}$ - to  $\frac{1}{8}$ -in. drills, and 0.002 to 0.005 in./rev for larger drills. Standard taps without fluid are best used for through holes, and for blind holes, tapping should be completed as far as possible with a taper tap before the bottoming tap is used.

For surface grinding of graphite, a medium (60) grade, medium-open structure, vitreous-bond, green-grit, silicon-carbide wheel is most commonly used. The wheel speed should be 5300 to 6000 surface ft/min, with traversing feed rates at about 56 ft/min. Roughing cuts are taken at 0.005 to 0.010 in./pass, and finishing cuts at 0.001 to 0.003 in./pass. Surface finishes in the range of 18 to 32  $\mu\text{in}$ .  $R_a$  are normal, and can be improved by longer spark-out times and finer grit wheels, or by lapping. Graphite can be centerless ground using a silicon-carbide, resinoid-bond work wheel and a regulating wheel speed of 195 ft/min.

Wire EDM, orbital abrading, and ultrasonic machining are also used to shape graphite electrodes. Orbital abrading uses a die containing hard particles to remove graphite, and can produce a fine surface finish. In ultrasonic machining, a water-based abrasive slurry is pumped between the die attached to the ultrasonic transducer and the graphite workpiece on the machine table. Ultrasonic machining is rapid and can reproduce small details down to 0.002 in. in size, with surface finishes down to 8  $\mu\text{in}$ .  $R_a$ . If coolants are used, the graphite should be dried for 1 hour at over  $400^\circ\text{F}$  (but not in a microwave oven) to remove liquids before used.

**Wire EDM.**—In the wire EDM process, with deionized water as the dielectric fluid, carbon is extracted from the recast layer, rather than added to it. When copper-base wire is used, copper atoms migrate into the recast layer, softening the surface slightly so that wire-cut surfaces are sometimes softer than the parent metal. On wire EDM machines, very high amperages are used with very short on times, so that the heat-affected zone (HAZ) is quite shallow. With proper adjustment of the on and off times, the depth of the HAZ can be held below 1 micron (0.00004 in.).

The cutting wire is used only once, so that the portion in the cut is always cylindrical and has no spark-eroded sections that might affect the cut accuracy. The power source controls the electrical supply to the wire and to the drive motors on the table to maintain the preset arc gap within 0.1 micron (0.000004 in.) of the programmed position. On wire EDM machines, the water used as a dielectric fluid is deionized by a deionizer included in the cooling system, to improve its properties as an insulator. Chemical balance of the water is also important for good dielectric properties.

*Drilling Holes for Wire EDM:* Before an aperture can be cut in a die plate, a hole must be provided in the workpiece. Such holes are often “drilled” by EDM, and the wire threaded through the workpiece before starting the cut. The “EDM drill” does not need to be rotated, but rotation will help in flushing and reduce electrode wear. The EDM process can drill a hole 0.04 in. in diameter through 4-in. thick steel in about 3 minutes, using an electrode made from brass or copper tubing. Holes of smaller diameter can be drilled, but the practical limit is 0.012 in. because of the overcut, the lack of rigidity of tubing in small sizes, and the excessive wear on such small electrodes. The practical upper size limit on holes is about 0.12 in. because of the comparatively large amounts of material that must be eroded away for larger sizes. However, EDM is commonly used for making large or deep holes in such hard materials as tungsten carbide. For instance, a 0.2-in. hole has been made in carbide 2.9 in. thick in 49 minutes by EDM. Blind holes are difficult to produce with accuracy, and must often be made with cut-and-try methods.

Deionized water is usually used for drilling and is directed through the axial hole in the tubular electrode to flush away the debris created by the sparking sequence. Because of the need to keep the extremely small cutting area clear of metal particles, the dielectric fluid is often not filtered but is replaced continuously by clean fluid that is pumped from a supply tank to a disposal tank on the machine.

*Wire Electrodes:* Wire for EDM generally is made from yellow brass containing copper 63 and zinc 37 per cent, with a tensile strength of 50,000 to 145,000 lb<sub>f</sub>/in.<sup>2</sup>, and may be from 0.002 to 0.012 in. diameter.

In addition to yellow brass, electrode wires are also made from brass alloyed with aluminum or titanium for tensile strengths of 140,000 to 160,000 lb<sub>f</sub>/in.<sup>2</sup>. Wires with homogeneous, uniform electrolytic coatings of alloys such as brass or zinc are also used. Zinc is favored as a coating on brass wires because it gives faster cutting and reduced wire breakage due to its low melting temperature of 419°C, and vaporization temperature of 906°C. The layer of zinc can boil off while the brass core, which melts at 930°C, continues to deliver current.

Some wires for EDM are made from steel for strength, with a coating of brass, copper, or other metal. Most wire machines use wire negative polarity (the wire is negative) because the wire is constantly renewed and is used only once, so wear is not important. Important qualities of wire for EDM include smooth surfaces, free from nicks, scratches and cracks, precise diameters to  $\pm 0.00004$  in. for drawn and  $\pm 0.00006$  in. for plated, high tensile strength, consistently good ductility, uniform spooling, and good protective packaging.

## IRON AND STEEL CASTINGS

### Material Properties

Cast irons and cast steels encompass a large family of ferrous alloys, which, as the name implies, are cast to shape rather than being formed by working in the solid state. In general, cast irons contain more than 2 per cent carbon and from 1 to 3 per cent silicon. Varying the balance between carbon and silicon, alloying with different elements, and changing melting, casting, and heat-treating practices can produce a broad range of properties. In most cases, the carbon exists in two forms: free carbon in the form of graphite and combined carbon in the form of iron carbide (cementite). Mechanical and physical properties depend strongly on the shape and distribution of the free graphite and the type of matrix surrounding the graphite particles.

The four basic types of cast iron are white iron, gray iron, malleable iron, and ductile iron. In addition to these basic types, there are other specific forms of cast iron to which special names have been applied, such as chilled iron, alloy iron, and compacted graphite cast iron.

**Gray Cast Iron.**—Gray cast iron may easily be cast into any desirable form and it may also be machined readily. It usually contains from 1.7 to 4.5 per cent carbon, and from 1 to 3 per cent silicon. The excess carbon is in the form of graphite flakes and these flakes impart to the material the dark-colored fracture which gives it its name. Gray iron castings are widely used for such applications as machine tools, automotive cylinder blocks, cast-iron pipe and fittings and agricultural implements.

The American National Standard Specifications for Gray Iron Castings—ANSI/ASTM A48-76 groups the castings into two categories. Gray iron castings in Classes 20A, 20B, 20C, 25A, 25B, 25C, 30A, 30B, 30C, 35A, 35B, and 35C are characterized by excellent machinability, high damping capacity, low modulus of elasticity, and comparative ease of manufacture. Castings in Classes 40B, 40C, 45B, 45C, 50B, 50C, 60B, and 60C are usually more difficult to machine, have lower damping capacity, a higher modulus of elasticity, and are more difficult to manufacture. The prefix number is indicative of the minimum tensile strength in pounds per square inch, i.e., 20 is 20,000 psi, 25 is 25,000 psi, 30 is 30,000 psi, etc.

High-strength iron castings produced by the Meehanite-controlled process may have various combinations of physical properties to meet different requirements. In addition to a number of general engineering types, there are heat-resisting, wear-resisting and corrosion-resisting Meehanite castings.

**White Cast Iron.**—When nearly all of the carbon in a casting is in the combined or cementite form, it is known as white cast iron. It is so named because it has a silvery-white fracture. White cast iron is very hard and also brittle; its ductility is practically zero. Castings of this material need particular attention with respect to design since sharp corners and thin sections result in material failures at the foundry. These castings are less resistant to impact loading than gray iron castings, but they have a compressive strength that is usually higher than 200,000 pounds per square inch as compared to 65,000 to 160,000 pounds per square inch for gray iron castings. Some white iron castings are used for applications that require maximum wear resistance but most of them are used in the production of malleable iron castings.

**Chilled Cast Iron.**—Many gray iron castings have wear-resisting surfaces of white cast iron. These surfaces are designated by the term "chilled cast iron" since they are produced in molds having metal chills for cooling the molten metal rapidly. This rapid cooling results in the formation of cementite and white cast iron.

**Alloy Cast Iron.**—This term designates castings containing alloying elements such as nickel, chromium, molybdenum, copper, and manganese in sufficient amounts to appreciably change the physical properties. These elements may be added either to increase the strength or to obtain special properties such as higher wear resistance, corrosion resistance,

or heat resistance. Alloy cast irons are used extensively for such parts as automotive cylinders, pistons, piston rings, crankcases, brake drums; for certain machine tool castings, for certain types of dies, for parts of crushing and grinding machinery, and for application where the casting must resist scaling at high temperatures. Machinable alloy cast irons having tensile strengths up to 70,000 pounds per square inch or even higher may be produced.

**Malleable-iron Castings.**—Malleable iron is produced by the annealing or graphitization of white iron castings. The graphitization in this case produces temper carbon which is graphite in the form of compact rounded aggregates. Malleable castings are used for many industrial applications where strength, ductility, machinability, and resistance to shock are important factors. In manufacturing these castings, the usual procedure is to first produce a hard, brittle white iron from a charge of pig iron and scrap. These hard white-iron castings are then placed in stationary batch-type furnaces or car-bottom furnaces and the graphitization (malleablizing) of the castings is accomplished by means of a suitable annealing heat treatment. During this annealing period the temperature is slowly (50 hours) increased to as much as 1650 or 1700 degrees F, after which time it is slowly (60 hours) cooled. The American National Standard Specifications for Malleable Iron Castings—ANSI/ASTM A47-77 specifies the following grades and their properties: No. 32520, having a minimum tensile strength of 50,000 pounds per square inch, a minimum yield strength of 32,500 psi., and a minimum elongation in 2 inches of 10 per cent; and No. 35018, having a minimum tensile strength of 53,000 psi., a minimum yield strength of 35,000 psi., and a minimum elongation in 2 inches of 18 per cent.

**Cupola Malleable Iron:** Another method of producing malleable iron involves initially the use of a cupola or a cupola in conjunction with an air furnace. This type of malleable iron, called cupola malleable iron, exhibits good fluidity and will produce sound castings. It is used in the making of pipe fittings, valves, and similar parts and possesses the useful property of being well suited to galvanizing. The American National Standard Specifications for Cupola Malleable Iron — ANSI/ASTM 197-79 calls for a minimum tensile strength of 40,000 pounds per square inch; a minimum yield strength of 30,000 psi.; and a minimum elongation in 2 inches of 5 per cent.

**Pearlitic Malleable Iron:** This type of malleable iron contains some combined carbon in various forms. It may be produced either by stopping the heat treatment of regular malleable iron during production before the combined carbon contained therein has all been transformed to graphite or by reheating regular malleable iron above the transformation range. Pearlitic malleable irons exhibit a wide range of properties and are used in place of steel castings or forgings or to replace malleable iron when a greater strength or wear resistance is required. Some forms are made rigid to resist deformation while others will undergo considerable deformation before breaking. This material has been used in axle housings, differential housings, camshafts, and crankshafts for automobiles; machine parts; ordnance equipment; and tools. Tension test requirements of pearlitic malleable iron castings called for in ASTM Specification A 220-79 are given in the accompanying table.

#### Tension Test Requirements of Pearlitic Malleable Iron Castings ASTM A220-79

| Casting Grade Numbers          |                              | 40010 | 45008 | 45006 | 50005 | 60004 | 70003 | 80002 | 90001 |
|--------------------------------|------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Min. Tensile Strength          | 1000s<br>Lbs. per<br>Sq. In. | 60    | 65    | 65    | 70    | 80    | 85    | 95    | 105   |
| Min. Yield Strength            |                              | 40    | 45    | 45    | 50    | 60    | 70    | 80    | 90    |
| Min. Elong. in 2 In., Per Cent |                              | 10    | 8     | 6     | 5     | 4     | 3     | 2     | 1     |

**Ductile Cast Iron.**—A distinguishing feature of this widely used type of cast iron, also known as spheroidal graphite iron or nodular iron, is that the graphite is present in ball-like form instead of in flakes as in ordinary gray cast iron. The addition of small amounts of magnesium- or cerium-bearing alloys together with special processing produces this spher-

roidal graphite structure and results in a casting of high strength and appreciable ductility. Its toughness is intermediate between that of cast iron and steel, and its shock resistance is comparable to ordinary grades of mild carbon steel. Melting point and fluidity are similar to those of the high-carbon cast irons. It exhibits good pressure tightness under high stress and can be welded and brazed. It can be softened by annealing or hardened by normalizing and air cooling or oil quenching and drawing.

Five grades of this iron are specified in ASTM A 536-80—Standard Specification for Ductile Iron Castings. The grades and their corresponding matrix microstructures and heat treatments are as follows: Grade 60-40-18, ferritic, may be annealed; Grade 65-45-12, mostly ferritic, as-cast or annealed; Grade 80-55-06, ferritic/pearlitic, as-cast; Grade 100-70-03, mostly pearlitic, may be normalized; Grade 120-90-02, martensitic, oil quenched and tempered. The grade nomenclature identifies the minimum tensile strength, on per cent yield strength, and per cent elongation in 2 inches. Thus, Grade 60-40-18 has a minimum tensile strength of 60,000 psi, a minimum 0.2 per cent yield strength of 40,000 psi, and minimum elongation in 2 inches of 18 per cent. Several other types are commercially available to meet specific needs. The common grades of ductile iron can also be specified by only Brinell hardness, although the appropriate microstructure for the indicated hardness is also a requirement. This method is used in SAE Specification J434C for automotive castings and similar applications. Other specifications not only specify tensile properties, but also have limitations in composition. Austenitic types with high nickel content, high corrosion resistance, and good strength at elevated temperatures, are specified in ASTM A439-80.

Ductile cast iron can be cast in molds containing metal chills if wear-resisting surfaces are desired. Hard carbide areas will form in a manner similar to the forming of areas of chilled cast iron in gray iron castings. Surface hardening by flame or induction methods is also feasible. Ductile cast iron can be machined with the same ease as gray cast iron. It finds use as crankshafts, pistons, and cylinder heads in the automotive industry; forging hammer anvils, cylinders, guides, and control levers in the heavy machinery field; and wrenches, clamp frames, face-plates, chuck bodies, and dies for forming metals in the tool and die field. The production of ductile iron castings involves complex metallurgy, the use of special melting stock, and close process control. The majority of applications of ductile iron have been made to utilize its excellent mechanical properties in combination with the castability, machinability, and corrosion resistance of gray iron.

**Steel Castings.**—Steel castings are especially adapted for machine parts that must withstand shocks or heavy loads. They are stronger than either wrought iron, cast iron, or malleable iron and are very tough. The steel used for making steel castings may be produced either by the open-hearth, electric arc, side-blow converter, or electric induction methods. The raw materials used are steel scrap, pig iron, and iron ore, the materials and their proportions varying according to the process and the type of furnace used. The open-hearth method is used when large tonnages are continually required while a small electric furnace might be used for steels of widely differing analyses, which are required in small lot production. The high frequency induction furnace is used for small quantity production of expensive steels of special composition such as high-alloy steels. Steel castings are used for such parts as hydroelectric turbine wheels, forging presses, gears, railroad car frames, valve bodies, pump casings, mining machinery, marine equipment, engine casings, etc.

Steel castings can generally be made from any of the many types of carbon and alloy steels produced in wrought form and respond similarly to heat treatment; they also do not exhibit directionality effects that are typical of wrought steel. Steel castings are classified into two general groups: carbon steel and alloy steel.

**Carbon Steel Castings.**—Carbon steel castings may be designated as low-carbon, medium-carbon, and high-carbon. Low-carbon steel castings have a carbon content of less than 0.20 per cent (most are produced in the 0.16 to 0.19 per cent range). Other elements present are: manganese, 0.50 to 0.85 per cent; silicon, 0.25 to 0.70 per cent; phosphorus,

0.05 per cent max.; and sulfur, 0.06 per cent max. Their tensile strengths (annealed condition) range from 40,000 to 70,000 pounds per square inch. Medium-carbon steel castings have a carbon content of from 0.20 to 0.50 per cent. Other elements present are: manganese, 0.50 to 1.00 per cent; silicon, 0.20 to 0.80 per cent; phosphorus, 0.05 per cent max.; and sulfur, 0.06 per cent max. Their tensile strengths range from 65,000 to 105,000 pounds per square inch depending, in part, upon heat treatment. High-carbon steel castings have a carbon content of more than 0.50 per cent and also contain: manganese, 0.50 to 1.00 per cent; silicon, 0.20 to 0.70 per cent; and phosphorus and sulfur, 0.05 per cent max. each. Fully annealed high-carbon steel castings exhibit tensile strengths of from 95,000 to 125,000 pounds per square inch. See [Table 1](#) for grades and properties of carbon steel castings.

**Table 1. Mechanical Properties of Steel Castings**

| Tensile Strength, Lbs. per Sq. In.             | Yield Point, Lbs. per Sq. In. | Elongation in 2 In., Per Cent | Brinell Hardness Number | Type of Heat Treatment   | Application Indicating Properties  |
|--|-------------------------------|-------------------------------|-------------------------|--------------------------|--|
| Structural Grades of Carbon Steel Castings     |                               |                               |                         |                          |  |
| 60,000   | 30,000                        | 32                            | 120                     | Annealed                 | Low electric resistivity. Desirable magnetic properties. Carburizing and case hardening grades. Weldability.                       |
| 65,000<br>70,000                               | 35,000<br>38,000              | 30<br>28                      | 130<br>140              | Normalized<br>Normalized | Good weldability. Medium strength with good machinability and high ductility.  |
| 80,000<br>85,000                               | 45,000<br>50,000              | 26<br>24                      | 160<br>175              | Normalized and tempered  | High strength carbon steels with good machinability, toughness and good fatigue resistance.  |
| 100,000  | 70,000                        | 20                            | 200                     |                          |  |
| Engineering Grades of Low Alloy Steel Castings |                               |                               |                         |                          |  |
| 70,000<br>80,000                               | 45,000<br>50,000              | 26<br>24                      | 150<br>170              | Normalized and tempered  | Good weldability. Medium strength with high toughness and good machinability. For high temperature service.                        |
| 90,000<br>100,000                              | 60,000<br>68,000              | 22<br>20                      | 190<br>209              |                          |  |
| 110,000<br>120,000                             | 85,000<br>95,000              | 20<br>16                      | 235<br>245              | Quenched and tempered    | Impact resistance. Good low temperature properties for certain steels. Deep hardening. Good combination of strength and toughness. |
| 150,000  | 125,000                       | 12                            | 300                     |                          |  |
| 175,000<br>200,000                             | 148,000<br>170,000            | 8<br>5                        | 340<br>400              | Quenched and tempered    | High strength and hardness. Wear resistance. High fatigue resistance.  |

For general information only. Not for use as design or specification limit values. The values listed above have been compiled by the Steel Founders' Society of America as those normally expected in the production of steel castings. The castings are classified according to tensile strength values which are given in the first column. Specifications covering steel castings are prepared by the American Society for Testing and Materials, the Association of American Railroads, the Society of Automotive Engineers, the United States Government (Federal and Military Specifications), etc. These specifications appear in publications issued by these organizations.

<sup>a</sup> Quench and temper heat treatments may also be employed for these classes.

**Alloy Steel Castings.**—Alloy cast steels are those in which special alloying elements such as manganese, chromium, nickel, molybdenum, vanadium have been added in sufficient quantities to obtain or increase certain desirable properties. Alloy cast steels are comprised of two groups—the low-alloy steels with their alloy content totaling less than 8 per cent and the high-alloy steels with their alloy content totaling 8 per cent or more. The addition of these various alloying elements in conjunction with suitable heat-treatments, makes it possible to secure steel castings having a wide range of properties. The three accompanying tables give information on these steels. The lower portion of [Table 1](#) gives the engi-



neering grades of low-alloy cast steels grouped according to tensile strengths and gives properties normally expected in the production of steel castings. Tables 2 and 3 give the standard designations and nominal chemical composition ranges of high-alloy castings which may be classified according to heat or corrosion resistance. The grades given in these tables are recognized in whole or in part by the Alloy Casting Institute (ACI), the American Society for Testing and Materials (ASTM), and the Society of Automotive Engineers (SAE).

**Table 2. Nominal Chemical Composition and Mechanical Properties of Heat-Resistant Steel Castings ASTM A297-81**

| Grade | Nominal Chemical Composition, Per Cent <sup>a</sup> | Tensile Strength, min |     | 0.2 Per Cent Yield Strength, min |     | Per Cent Elongation in 2 in., or 50 mm, min. |
|-------|---|-----------------------|-----|----------------------------------|-----|--|
|       |   | ksi                   | MPa | ksi                              | MPa |  |
| HF    | 19 Chromium, 9 Nickel                               | 70                    | 485 | 35                               | 240 | 25   |
| HH    | 25 Chromium, 12 Nickel                              | 75                    | 515 | 35                               | 240 | 10   |
| HI    | 28 Chromium, 15 Nickel                              | 70                    | 485 | 35                               | 240 | 10   |
| HK    | 25 Chromium, 20 Nickel                              | 65                    | 450 | 35                               | 240 | 10   |
| HE    | 29 Chromium, 9 Nickel                               | 85                    | 585 | 40                               | 275 | 9  |
| HT    | 15 Chromium, 35 Nickel                              | 65                    | 450 | ...                              | ... | 4  |
| HU    | 19 Chromium, 39 Nickel                              | 65                    | 450 | ...                              | ... | 4  |
| HW    | 12 Chromium, 60 Nickel                              | 60                    | 415 | ...                              | ... | ...  |
| HX    | 17 Chromium, 66 Nickel                              | 60                    | 415 | ...                              | ... | ...  |
| HC    | 28 Chromium   | 55                    | 380 | ...                              | ... | ...  |
| HD    | 28 Chromium, 5 Nickel                               | 75                    | 515 | 35                               | 240 | 8  |
| HL    | 29 Chromium, 20 Nickel                              | 65                    | 450 | 35                               | 240 | 10   |
| HN    | 20 Chromium, 25 Nickel                              | 63                    | 435 | ...                              | ... | 8  |
| HP    | 26 Chromium, 35 Nickel                              | 62.5                  | 430 | 34                               | 235 | 4.5  |

ksi = kips per square inch = 1000s of pounds per square inch; MPa = megapascals.

<sup>a</sup> Remainder is iron.

The specifications committee of the Steel Founders Society issues a *Steel Castings Handbook* with supplements. Supplement 1 provides design rules and data based on the fluidity and solidification of steel, mechanical principles involved in production of molds and cores, cleaning of castings, machining, and functionality and weight aspects. Data and examples are included to show how these rules are applied. Supplement 2 summarizes the standard steel castings specification issued by the ASTM SAE, Assoc. of Am. Railroads (AAR), Am. Bur of Shipping (ABS), and Federal authorities, and provides guidance as to their applications. Information is included for carbon and alloy cast steels, high alloy cast steels, and centrifugally cast steel pipe. Details are also given of standard test methods for steel castings, including mechanical, non-destructive (visual, liquid penetrant, magnetic particle, radiographic, and ultrasonic), and testing of qualifications of welding procedures and personnel. Other supplements cover such subjects as tolerances, drafting practices, properties, repair and fabrication welding, of carbon, low alloy and high alloy castings, foundry terms, and hardenability and heat treatment.

*Austenitic Manganese Cast Steel:* Austenitic manganese cast steel is an important high-alloy cast steel which provides a high degree of shock and wear resistance. Its composition normally falls within the following ranges: carbon, 1.00 to 1.40 per cent; manganese, 10.00 to 14.00 per cent; silicon, 0.30 to 1.00 per cent; sulfur, 0.06 per cent max.; phosphorus, 0.10 per cent, max. In the as-cast condition, austenitic manganese steel is quite brittle. In order to strengthen and toughen the steel, it is heated to between 1830 and 1940 degrees F and quenched in cold water. Physical properties of quenched austenitic manganese steel that has been cast to size are as follows: tensile strength, 80,000 to 100,000 pounds per square inch; shear strength (single shear), 84,000 pounds per square inch; elongation in 2 inches, 15 to 35 per cent; reduction in area, 15 to 35 per cent; and Brinell hardness number,

**Table 3. Nominal Chemical Composition and Mechanical Properties of Corrosion-Resistant Steel Castings ASTM A743-81a**

| Grade          | Nominal Chemical Composition, Per Cent <sup>a</sup> | Tensile Strength, min |                  | 0.2% Yield Strength, min |                  | Per Cent Elongation in 2 in., or 50 mm, min | Per Cent Reduction of Area, min |
|----------------|---|-----------------------|------------------|--------------------------|------------------|---|---------------------------------|
|                |   | ksi                   | MPa              | ksi                      | MPa              |   |                                 |
| CF-8           | 9 Chromium, 9 Nickel                                | 70 <sup>b</sup>       | 485 <sup>b</sup> | 30 <sup>b</sup>          | 205 <sup>b</sup> | 35  | ...                             |
| CG-12          | 22 Chromium, 12 Nickel                              | 70                    | 485              | 28                       | 195              | 35  | ...                             |
| CF-20          | 19 Chromium, 9 Nickel                               | 70                    | 485              | 30                       | 205              | 30  | ...                             |
| CF-8M          | 19 Chromium, 10 Nickel, with Molybdenum             | 70                    | 485              | 30                       | 205              | 30  | ...                             |
| CF-8C          | 19 Chromium, 10 Nickel with Niobium                 | 70                    | 485              | 30                       | 205              | 30  | ...                             |
| CF-16, CF-16Fa | 19 Chromium, 9 Nickel, Free Machining               | 70                    | 485              | 30                       | 205              | 25  | ...                             |
| CH-20, CH-10   | 25 Chromium, 12 Nickel                              | 70                    | 485              | 30                       | 205              | 30  | ...                             |
| CK-20          | 25 Chromium, 20 Nickel                              | 65                    | 450              | 28                       | 195              | 30  | ...                             |
| CE-30          | 29 Chromium, 9 Nickel                               | 80                    | 550              | 40                       | 275              | 10  | ...                             |
| CA-15, CA-15M  | 12 Chromium   | 90                    | 620              | 65                       | 450              | 18  | 30                              |
| CB-30          | 20 Chromium   | 65                    | 450              | 30                       | 205              | ...   | ...                             |
| CC-50          | 28 Chromium   | 55                    | 380              | ...                      | ...              | ...   | ...                             |
| CA-40          | 12 Chromium   | 100                   | 690              | 70                       | 485              | 15  | 25                              |
| CF-3           | 19 Chromium, 9 Nickel                               | 70                    | 485              | 30                       | 205              | 35  | ...                             |
| CF-3M          | 19 Chromium, 10 Nickel, with Molybdenum             | 70                    | 485              | 30                       | 205              | 30  | ...                             |
| CG6MMN         | Chromium-Nickel-Manganese -Molybdenum               | 75                    | 515              | 35                       | 240              | 30  | ...                             |
| CG-8M          | 19 Chromium, 11 Nickel, with Molybdenum             | 75                    | 520              | 35                       | 240              | 25  | ...                             |
| CN-7M          | 20 Chromium, 29 Nickel, with Copper and Molybdenum  | 62                    | 425              | 25                       | 170              | 35  | ...                             |
| CN-7MS         | 19 Chromium, 24 Nickel, with Copper and Molybdenum  | 70                    | 485              | 30                       | 205              | 35  | ...                             |
| CW-12M         | Nickel, Molybdenum, Chromium                        | 72                    | 495              | 46                       | 315              | 4.0   | ...                             |
| CY-40          | Nickel, Chromium, Iron                              | 70                    | 485              | 28                       | 195              | 30  | ...                             |
| CZ-100         | Nickel Alloy  | 50                    | 345              | 18                       | 125              | 10  | ...                             |
| M-35-1         | Nickel-Copper Alloy                                 | 65                    | 450              | 25                       | 170              | 25  | ...                             |
| M-35-2         | Nickel-Copper Alloy                                 | 65                    | 450              | 30                       | 205              | 25  | ...                             |
| CA-6NM         | 12 Chromium, 4 Nickel                               | 110                   | 755              | 80                       | 550              | 15  | 35                              |
| CD-4MCu        | 25 Chromium, 5 Nickel, 2 Molybdenum, 3 Copper       | 100                   | 690              | 70                       | 485              | 16  | ...                             |
| CA-6N          | 11 Chromium, 7 Nickel                               | 140                   | 965              | 135                      | 930              | 15  | 50                              |

<sup>a</sup> Remainder is iron.

<sup>b</sup> For low ferrite or non-magnetic castings of this grade, the following values shall apply: tensile strength, min, 65 ksi (450 MPa); yield point, min, 28 ksi (195 MPa).

180 to 220. When cold worked, the surface of such a casting increases to a Brinell hardness of from 450 to 550. In many cases the surfaces are cold worked to maximum hardness to assure immediate hardness in use. Heat-treated austenitic manganese steel is machined only with great difficulty since it hardens at and slightly ahead of the point of contact of the cutting tool. Grinding wheels mounted on specially adapted machines are used for boring, planing, keyway cutting, and similar operations on this steel. Where grinding cannot be employed and machining must be resorted to, high-speed tool steel or cemented carbide tools are used with heavy, rigid equipment and slow, steady operation. In any event, this procedure tends to be both tedious and expensive. Austenitic manganese cast steel can be arc-welded with manganese-nickel steel welding rods containing from 3 to 5 per cent nickel, 10 to 15 per cent manganese, and, usually, 0.60 to 0.80 per cent carbon.

### Casting of Metals

Molten metals are shaped by pouring (casting) into a mold of the required form, which they enter under gravity, centrifugal force, or various degrees of pressure. Molds are made of refractory materials like sand, plaster, graphite, or metal. Sand molds are formed around a pattern or replica of the part to be made, usually of wood though plastics or metal may be used when large numbers of molds for similar parts are to be made.

*Green-sand molding* is used for most sand castings, sand mixed with a binder being packed around the pattern by hand, with power tools, or in a vibrating machine which may also exert a compressive force to pack the grains more closely. The term "green-sand" implies that the binder is not cured by heating or chemical reactions. The pattern is made in two "halves," which usually are attached to opposite sides of a flat plate. Shaped bars and other projections are fastened to the plate to form connecting channels and funnels in the sand for entry of the molten metal into the casting cavities. The sand is supported at the plate edges by a box-shaped frame or flask, with locating tabs that align the two mold halves when they are later assembled for the pouring operation.

Hollows and undercut surfaces in the casting are produced by cores, also made from sand, that are placed in position before the mold is closed, and held in place by tenons in grooves (called prints) formed in the sand by pattern projections. An *undercut surface* is one from which the pattern cannot be withdrawn in a straight line, so must be formed by a core in the mold. When the poured metal has solidified, the frame is removed and the sand falls or is cleaned off, leaving the finished casting(s) ready to be cut from the runners.

*Gray iron* is easily cast in complex shapes in green-sand and other molds and can be machined readily. The iron usually contains carbon, 1.7–4.5, and silicon, 1–3 per cent by weight. Excess carbon in the form of graphite flakes produces the gray surface from which the name is derived, when a casting is fractured.

*Shell molding*: invented by a German engineer, Croning, uses a resin binder to lock the grains of sand in a  $\frac{1}{4}$  to  $\frac{3}{8}$ -in.-thick layer of sand/resin mixture, which adheres to a heated pattern plate after the mass of the mixture has been dumped back into the container. The hot resin quickly hardens enough to make the shell thus formed sufficiently rigid to be removed from the pattern, producing a half mold. The other half mold is produced on another plate by the same method. Pattern projections form runner channels, basins, core prints, and locating tenons in each mold half. Cores are inserted to form internal passages and undercuts. The shell assembly is placed in a molding box and supported with some other material such as steel shot or a coarse sand, when the molten metal is to be poured in. Some shell molds are strong enough to be filled without backup, and the two mold halves are merely clamped together for metal to be poured in to make the casting(s).

*V-Process* is a method whereby dry, unbonded sand is held to the shape of a pattern by a vacuum. The pattern is provided with multiple vent passages that terminate in various positions all over its surface, and are connected to a common plenum chamber. A heat-softened, 0.002–0.005-in.-thick plastics film is draped over the pattern and a vacuum of 200–400 mm of mercury is applied to the chamber, sucking out the air beneath the film so that the plastics is drawn into close contact with the pattern. A sand box or flask with walls that also contain hollow chambers and a flat grid that spans the central area is placed on the pattern plate to confine the dry unbonded sand that is allowed to fall through the grid on to the pattern.

After vibration to compact the sand around the pattern, a former is used to shape a sprue cup into the upper surface of the sand, connecting with a riser on the pattern, and the top surface of the sand is covered with a plastics film that extends over the flask sides. The hollow chambers in the flask walls are then connected to the vacuum source. The vacuum is sufficient to hold the sand grains in their packed condition between the plastics films above and beneath, firmly in the shape defined by the pattern, so that the flask and the sand half-mold can be lifted from the pattern plate. Matching half molds made by these procedures are assembled into a complete mold, with cores inserted if needed. With both mold halves still held by vacuum, molten metal is poured through the sprue cup into the mold, the plastics film between the mold surfaces being melted and evaporated by the hot metal. After solidification, the vacuum is released and the sand, together with the casting(s), falls from the mold flasks. The castings emerge cleanly, and the sand needs only to be cooled before reuse.

*Permanent mold, or gravity die, casting* is mainly used for nonferrous metals and alloys. The mold (or die) is usually iron or steel, or graphite, and is cooled by water channels or by air jets on the outer surfaces. Cavity surfaces in metal dies are coated with a thin layer of heat-resistant material. The mold or die design is usually in two halves, although many multiple-part molds are in use, with loose sand or metal cores to form undercut surfaces. The cast metal is simply poured into a funnel formed in the top of the mold, although elaborate tilting mechanisms are often used to control the passage of metal into (and emergence of air from) the remote portions of die cavities.

Because the die temperature varies during the casting cycle, its dimensions vary correspondingly. The die is opened and ejectors push the casting(s) out as soon as its temperature is low enough for sufficient strength to build up. During the period after solidification and before ejection, cooling continues but shrinkage of the casting(s) is restricted by the die. The alloy being cast must be sufficiently ductile to accommodate these restrictions without fracturing. An alloy that tears or splits during cooling in the die is said to be *hot short* and cannot be cast in rigid molds. Dimensions of the casting(s) at shop temperatures will be related to the die temperature and the dimensions at ejection. Rules for casting shrinkage that apply to friable (sand) molds do not hold for rigid molds. Designers of metal molds and dies rely on temperature-based calculations and experience in evolving shrinkage allowances.

*Low-pressure casting* uses mold or die designs similar to those for gravity casting. The container (crucible) for the molten metal has provision for an airtight seal with the mold, and when gas or air pressure (6–10 lb/in.<sup>2</sup>) is applied to the bath surface inside the crucible, the metal is forced up a hollow refractory tube (stalk) projecting from the die underside. This stalk extends below the bath level so that metal entering the die is free from oxides and impurities floating on the surface. The rate of filling is controlled so that air can be expelled from the die by the entering metal. With good design and control, high-quality, nonporous castings are made by both gravity and low-pressure methods, though the extra pressure in low-pressure die casting may increase the density and improve the reproduction of fine detail in the die.

*Squeeze casting* uses a metal die, of which one half is clamped to the bed of a large (usually) hydraulic press and the other to the vertically moving ram of the press. Molten metal is poured into the lower die and the upper die is brought down until the die is closed. The amount of metal in the die is controlled to produce a slight overflow as the die closes to ensure complete filling of the cavity. The heated dies are lubricated with graphite and pressures up to 25 tons per square inch may be applied by the press to squeeze the molten metal into the tiniest recesses in the die. When the press is opened, the solidified casting is pushed out by ejectors.

### Finishing Operations for Castings

**Removal of Gates and Risers from Castings.**—After the molten iron or steel has solidified and cooled, the castings are removed from their molds, either manually or by placing them on vibratory machines and shaking the sand loose from the castings. The gates and risers that are not broken off in the shake-out are removed by impact, sawing, shearing, or burning-off methods. In the impact method, a hammer is used to knock off the gates and risers. Where the possibility exists that the fracture would extend into the casting itself, the gates or risers are first notched to assure fracture in the proper place. Some risers have a necked-down section at which the riser breaks off when struck. Sprue-cutter machines are also used to shear off gates. These machines facilitate the removal of a number of small castings from a central runner. Band saws, power saws, and abrasive cut-off wheel machines are also used to remove gates and risers. The use of band saws permits following the contour of the casting when removing unwanted appendages. Abrasive cut-off wheels are used when the castings are too hard or difficult to saw. Oxyacetylene cutting torches are used to cut off gates and risers and to gouge out or remove surface defects on castings.

These torches are used on steel castings where the gates and risers are of a relatively large size. Surface defects are subsequently repaired by conventional welding methods.

Any unwanted material in the form of fins, gates, and riser pads that come above the casting surface, chaplets, parting-line flash, etc., is removed by chipping with pneumatic hammers, or by grinding with such equipment as floor or bench-stand grinders, portable grinders, and swing-frame grinders.

**Blast Cleaning of Castings.**—Blast cleaning of castings is performed to remove adhering sand, to remove cores, to improve the casting appearance, and to prepare the castings for their final finishing operation, which includes painting, machining, or assembling. Scale produced as a result of heat treating can also be removed. A variety of machines are used to handle all sizes of casting. The methods employed include blasting with sand, metal shot, or grit; and hydraulic cleaning or tumbling. In blasting, sharp sand, shot, or grit is carried by a stream of compressed air or water or by centrifugal force (gained as a result of whirling in a rapidly rotating machine) and directed against the casting surface by means of nozzles. The operation is usually performed in cabinets or enclosed booths. In some setups the castings are placed on a revolving table and the abrasive from the nozzles that are either mechanically or hand-held is directed against all the casting surfaces. Tumbling machines are also employed for cleaning, the castings being placed in large revolving drums together with slugs, balls, pins, metal punchings, or some abrasive, such as sandstone or granite chips, slag, silica, sand, or pumice. Quite frequently, the tumbling and blasting methods are used together, the parts then being tumbled and blasted simultaneously. Castings may also be cleaned by hydroblasting. This method uses a water-tight room in which a mixture of water and sand under high pressure is directed at the castings by means of nozzles. The action of the water and sand mixture cleans the castings very effectively.

**Heat Treatment of Steel Castings.**—Steel castings can be heat treated to bring about diffusion of carbon or alloying elements, softening, hardening, stress-relieving, toughening, improved machinability, increased wear resistance, and removal of hydrogen entrapped at the surface of the casting. Heat treatment of steel castings of a given composition follows closely that of wrought steel of similar composition. For discussion of types of heat treatment refer to the "Heat Treatment of Steel" section of this Handbook.

**Estimating Casting Weight.**—Where no pattern or die has yet been made, as when preparing a quotation for making a casting, the weight of a cast component can be estimated with fair accuracy by calculating the volume of each of the casting features, such as box- or rectangular-section features, cylindrical bosses, housings, ribs, and other parts, and adding them together. Several computer programs, also measuring mechanisms that can be applied to a drawing, are available to assist with these calculations. When the volume of metal has been determined it is necessary only to multiply by the unit weight of the alloy to be used, to arrive at the weight of the finished casting. The cost of the metal in the finished casting can then be estimated by multiplying the weight in lb by the cost/lb of the alloy. Allowances for melting losses, and for the extra metal used in risers and runners, and the cost of melting and machining may also be added to the cost/lb. Estimates of the costs of pattern- or die-making, molding, pouring and finishing of the casting(s), may also be added, to complete the quotation estimate.

#### **Pattern Materials—Shrinkage, Draft, and Finish Allowances**

**Woods for Patterns.**—Woods commonly used for patterns are white pine, mahogany, cherry, maple, birch, white wood, and fir. For most patterns, white pine is considered superior because it is easily worked, readily takes glue and varnish, and is fairly durable. For medium- and small-sized patterns, especially if they are to be used extensively, a harder wood is preferable. Mahogany is often used for patterns of this class, although many prefer cherry. As mahogany has a close grain, it is not as susceptible to atmospheric changes as a wood of coarser grain. Mahogany is superior in this respect to cherry, but is more expen-

sive. In selecting cherry, never use young timber. Maple and birch are employed quite extensively, especially for turned parts, as they take a good finish. White wood is sometimes substituted for pine, but it is inferior to the latter in being more susceptible to atmospheric changes.

**Selection of Wood.**—It is very important to select well-seasoned wood for patterns; that is, it should either be kiln-dried or kept 1 or 2 years before using, the time depending upon the size of the lumber. During the seasoning or drying process, the moisture leaves the wood cells and the wood shrinks, the shrinkage being almost entirely across the grain rather than in a lengthwise direction. Naturally, after this change takes place, the wood is less liable to warp, although it will absorb moisture in damp weather. Patterns also tend to absorb moisture from the damp sand of molds, and to minimize troubles from this source they are covered with varnish. Green or water-soaked lumber should not be put in a drying room, because the ends will dry out faster than the rest of the log, thus causing cracks. In a log, there is what is called “sap wood” and “heart wood.” The outer layers form the sap wood, which is not as firm as the heart wood and is more likely to warp; hence, it should be avoided, if possible.

**Pattern Varnish.**—Patterns intended for repeated use are varnished to protect them against moisture, especially when in the damp molding sand. The varnish used should dry quickly to give a smooth surface that readily draws from the sand. Yellow shellac varnish is generally used. It is made by dissolving gum shellac in grain alcohol. Wood alcohol is sometimes substituted, but is inferior. The color of the varnish is commonly changed for covering core prints, in order that the prints may be readily distinguished from the body of the pattern. Black shellac varnish is generally used. At least three coats of varnish should be applied to patterns, the surfaces being rubbed down with sandpaper after applying the preliminary coats, in order to obtain a smooth surface.

**Shrinkage Allowances.**—The shrinkage allowances ordinarily specified for patterns to compensate for the contraction of castings in cooling are as follows: cast iron,  $\frac{3}{32}$  to  $\frac{1}{8}$  inch per foot; common brass,  $\frac{3}{16}$  inch per foot; yellow brass,  $\frac{7}{32}$  inch per foot; bronze,  $\frac{5}{32}$  inch per foot; aluminum,  $\frac{1}{8}$  to  $\frac{5}{32}$  inch per foot; magnesium,  $\frac{1}{8}$  to  $\frac{1}{64}$  inch per foot; steel,  $\frac{3}{16}$  inch per foot. These shrinkage allowances are approximate values only because the exact allowance depends upon the size and shape of the casting and the resistance of the mold to the normal contraction of the casting during cooling. It is, therefore, possible that more than one shrinkage allowance will be required for different parts of the same pattern. Another factor that affects shrinkage allowance is the molding method, which may vary to such an extent from one foundry to another, that different shrinkage allowances for each would have to be used for the same pattern. For these reasons it is recommended that patterns be made at the foundry where the castings are to be produced to eliminate difficulties due to lack of accurate knowledge of shrinkage requirements.

An example of how casting shape can affect shrinkage allowance is given in the Steel Castings Handbook. In this example a straight round steel bar required a shrinkage allowance of approximately  $\frac{5}{32}$  inch per foot. The same bar but with a large knob on each end required a shrinkage allowance of only  $\frac{3}{16}$  inch per foot. A third steel bar with large flanges at each end required a shrinkage allowance of only  $\frac{3}{64}$  inch per foot. This example would seem to indicate that the best practice in designing castings and making patterns is to obtain shrinkage values from the foundry that is to make the casting because there can be no fixed allowances.

**Metal Patterns.**—Metal patterns are especially adapted to molding machine practice, owing to their durability and superiority in retaining the required shape. The original master pattern is generally made of wood, the casting obtained from the wood pattern being finished to make the metal pattern. The materials commonly used are brass, cast iron, aluminum, and steel. Brass patterns should have a rather large percentage of tin, to improve

the casting surface. Cast iron is generally used for large patterns because it is cheaper than brass and more durable. Cast-iron patterns are largely used on molding machines. Aluminum patterns are light but they require large shrinkage allowances. White metal is sometimes used when it is necessary to avoid shrinkage. The gates for the mold may be cast or made of sheet brass. Some patterns are made of vulcanized rubber, especially for light match-board work.

**Obtaining Weight of Casting from Pattern Weight.**—To obtain the approximate weight of a casting, multiply the weight of the pattern by the factor given in the accompanying table. For example, if the weight of a white-pine pattern is 4 pounds what is the weight of a solid cast-iron casting obtained from that pattern? Casting weight =  $4 \times 16 = 64$  pounds. If the casting is cored, fill the core-boxes with dry sand, and multiply the weight of the sand by one of the following factors: For cast iron, 4; for brass, 4.65; for aluminum, 1.4. Then subtract the product of the sand weight and the factor just given from the weight of the solid casting, to obtain the weight of the cored casting. The weight of wood varies considerably, so the results obtained by the use of the table are only approximate, the factors being based on the average weight of the woods listed. For metal patterns, the results may be more accurate.

**Factors for Obtaining Weight of Casting from Pattern Weight**

| Pattern Material   | Factors   |          |        |       |                                   |
|--------------------|-----------|----------|--------|-------|-----------------------------------|
|                    | Cast Iron | Aluminum | Copper | Zinc  | Brass, 70%<br>Copper,<br>30% Zinc |
| White pine         | 16.00     | 5.70     | 19.60  | 15.00 | 19.00                             |
| Mahogany, Honduras | 12.00     | 4.50     | 14.70  | 11.50 | 14.00                             |
| Cherry             | 10.50     | 3.80     | 13.00  | 10.00 | 12.50                             |
| Cast Iron          | 1.00      | 0.35     | 1.22   | 0.95  | 1.17                              |
| Aluminum           | 2.85      | 1.00     | 3.44   | 2.70  | 3.30                              |

### Die Casting

Die casting is a method of producing finished castings by forcing molten metal into a hard metal die, which is arranged to open after the metal has solidified so that the casting can be removed. The die-casting process makes it possible to secure accuracy and uniformity in castings, and machining costs are either eliminated altogether or are greatly reduced. The greatest advantage of the die-casting process is that parts are accurately and often completely finished when taken from the die. When the dies are properly made, castings may be accurate within 0.001 inch or even less and a limit of 0.002 or 0.003 inch per inch of casting dimension can be maintained on many classes of work.

Die castings are used extensively in the manufacture of such products as cash registers, meters, time-controlling devices, small housings, washing machines, and parts for a great variety of mechanisms. Lugs and gear teeth are cast in place and both external and internal screw threads can be cast. Holes can be formed within about 0.001 inch of size and the most accurate bearings require only a finish-reaming operation. Figures and letters may be cast sunken or in relief on wheels for counting or printing devices, and with ingenious die designs, many shapes that formerly were believed too intricate for die casting are now produced successfully by this process.

Die casting uses hardened steel molds (dies) into which the molten metal is injected at high speed, reaching pressures up to 10 tons/in.<sup>2</sup>, force being applied by a hydraulically actuated plunger moving in a cylindrical pressure chamber connected to the die cavity(s). If the plan area of the casting and its runner system cover 50 in.<sup>2</sup>, the total power applied is 10 tons/in.<sup>2</sup> of pressure on the metal  $\times$  50 in.<sup>2</sup> of projected area, producing a force of 500

tons, and the die-casting machine must hold the die shut against this force. Massive toggle mechanisms stretch the heavy (6-in. diameter) steel tie bars through about 0.045 in. on a typical (500-ton) machine to generate this force. Although the die is hot, metal entering the die cavity is cooled quickly, producing layers of rapidly chilled, dense material about 0.015 in. thick in the metal having direct contact with the die cavity surfaces. Because the high injection forces allow castings to be made with thin walls, these dense layers form a large proportion of the total wall thickness, producing high casting strength. This phenomenon is known as the skin effect, and should be taken into account when considering the tensile strengths and other properties measured in (usually thicker) test bars.

As to the limitations of the die-casting process it may be mentioned that the cost of dies is high, and, therefore, die casting is economical only when large numbers of duplicate parts are required. The stronger and harder metals cannot be die cast, so that the process is not applicable for casting parts that must necessarily be made of iron or steel, although special alloys have been developed for die casting that have considerable tensile and compressive strength.

Many die castings are produced by the hot-chamber method in which the pressure chamber connected to the die cavity is immersed permanently in the molten metal and is automatically refilled through a hole that is uncovered as the (vertical) pressure plunger moves back after filling the die. This method can be used for alloys of low melting point and high fluidity such as zinc, lead, tin, and magnesium. Other alloys requiring higher pressure, such as brass, or that can attack and dissolve the ferrous pressure chamber material, such as aluminum, must use the slower cold-chamber method with a water-cooled (horizontal) pressure chamber outside the molten metal.

**Porosity.**—Molten metal injected into a die cavity displaces most of the air, but some of the air is trapped and is mixed with the metal. The high pressure applied to the metal squeezes the pores containing the air to very small size, but subsequent heating will soften the casting so that air in the surface pores can expand and cause blisters. Die castings are seldom solution heat treated or welded because of this blistering problem. The chilling effect of the comparatively cold die causes the outer layers of a die casting to be dense and relatively free of porosity. Vacuum die casting, in which the cavity atmosphere is evacuated before metal is injected, is sometimes used to reduce porosity. Another method is to displace the air by filling the cavity with oxygen just prior to injection. The oxygen is burned by the hot metal so that porosity does not occur.

When these special methods are not used, machining depths must be limited to 0.020–0.035 inch if pores are not to be exposed, but as-cast accuracy is usually good enough for only light finishing cuts to be needed. Special pore-sealing techniques must be used if pressure tightness is required.

**Designing Die Castings.**—Die castings are best designed with uniform wall thicknesses (to reduce cooling stresses) and cores of simple shapes (to facilitate extraction from the die). Heavy sections should be avoided or cored out to reduce metal concentrations that may attract trapped gases and cause porosity concentrations. Designs should aim at arranging for metal to travel through thick sections to reach thin ones if possible. Because of the high metal injection pressures, conventional sand cores cannot be used, so cored holes and apertures are made by metal cores that form part of the die. Small and slender cores are easily bent or broken, so should be avoided in favor of piercing or drilling operations on the finished castings. Ribbing adds strength to thin sections, and fillets should be used on all inside corners to avoid high stress concentrations in the castings. Sharp outside corners should be avoided. Draft allowances on a die casting are usually from 0.5 to 1.5 degrees per side to permit the castings to be pushed off cores or out of the cavity.

**Alloys Used for Die Casting.**—The alloys used in modern die-casting practice are based on aluminum, zinc, and copper, with small numbers of castings also being made from magnesium-, tin-, and lead-based alloys.



**Aluminum-Base Alloys.**—Aluminum-base die-casting alloys are used more extensively than any other base metal alloy because of their superior strength combined with ease of castability. Linear shrinkage of aluminum alloys on cooling is about  $12.9$  to  $15.5 \times 10^{-6}$  in./in.-°F. Casting temperatures are of the order of 1200 deg. F. Most aluminum die castings are produced in aluminum-silicon-copper alloys such as the Aluminum Association (AA) No. 380 (ASTM SC84A; UNS A038000), containing silicon 7.5 to 9.5 and copper 3 to 4 per cent. Silicon increases fluidity for complete die filling, but reduces machinability, and copper adds hardness but reduces ductility in aluminum alloys. A less-used alloy having slightly greater fluidity is AA No. 384 (ASTM SC114A; UNS A03840) containing silicon 10.5 to 12.0 and copper 3.0 to 4.5 per cent. For marine applications, AA 360 (ASTM 100A; UNS A03600) containing silicon 9 to 10 and copper 0.6 per cent is recommended, the copper content being kept low to reduce susceptibility to corrosion in salt atmospheres. The tensile strengths of AA 380, 384, and 360 alloys are 47,000, 48,000, and 46,000 lb/in.<sup>2</sup>, respectively. Although 380, 384, and 360 are the most widely used die-castable alloys, several other aluminum alloys are used for special applications. For instance, the AA 390 alloy, with its high silicon content (16 to 18 per cent), is used for internal combustion engine cylinder castings, to take advantage of the good wear resistance provided by the hard silicon grains. No. 390 alloy also contains 4 to 5 per cent copper, and has a hardness of 120 Brinell with low ductility, and a tensile strength of 41,000 lb/in.<sup>2</sup>.

**Zinc-Base Alloys.**—In the molten state, zinc is extremely fluid and can therefore be cast into very intricate shapes. The metal also is plentiful and has good mechanical properties. Zinc die castings can be made to closer dimensional limits and with thinner walls than aluminum. Linear shrinkage of these alloys on cooling is about  $9$  to  $13 \times 10^{-6}$  in./in.-°F. The low casting temperatures (750–800 deg. F) and the hot-chamber process allow high production rates with simple automation. Zinc die castings can be produced with extremely smooth surfaces, lending themselves well to plating and other finishing methods. The established zinc alloys numbered 3, 5 and 7 [ASTM B86 (AG40A; UNS Z33520), AG41A (UNS Z35531), and AG40B (UNS Z33522)] each contains 3.5 to 4.3 per cent of aluminum, which adds strength and hardness, plus carefully controlled amounts of other elements. Recent research has brought forward three new alloys of zinc containing 8, 12, and 27 per cent of aluminum, which confer tensile strength of 50,000–62,000 lb/in.<sup>2</sup> and hardness approaching that of cast iron (105–125 Brinell). These alloys can be used for gears and racks, for instance, and as housings for shafts that run directly in reamed or bored holes, with no need for bearing bushes.

**Copper-Base Alloys.**—Brass alloys are used for plumbing, electrical, and marine components where resistance to corrosion must be combined with strength and wear resistance. With the development of the cold-chamber casting process, it became possible to make die castings from several standard alloys of copper and zinc such as yellow brass (ASTM B176-Z30A; UNS C85800) containing copper 58, zinc 40, tin 1, and lead 1 per cent. Tin and lead are included to improve corrosion resistance and machinability, respectively, and this alloy has a tensile strength of 45,000 lb/in.<sup>2</sup>. Silicon brass (ASTM B176-ZS331A; UNS C87800) with copper 65 and zinc 34 per cent also contains 1 per cent silicon, giving it more fluidity for castability and with higher tensile strength (58,000 psi) and better resistance to corrosion. High silicon brass or tombasil (ASTM B176-ZS144A), containing copper 82, zinc 14, and silicon 4 per cent, has a tensile strength of 70,000 lb/in.<sup>2</sup> and good wear resistance, but at the expense of machinability.

**Magnesium-Base Alloys.**—Light weight combined with good mechanical properties and excellent damping characteristics are principal reasons for using magnesium die castings. Magnesium has a low specific heat and does not dissolve iron so it may be die cast by the cold- or hot-chamber methods. For the same reasons, die life is usually much longer than for aluminum. The lower specific heat and more rapid solidification make production about 50 per cent faster than with aluminum. To prevent oxidation, an atmosphere of CO<sub>2</sub>

and air, containing about 0.5 per cent of SF<sub>6</sub> gas, is used to exclude oxygen from the surface of the molten metal. The most widely used alloy is AZ91D (ASTM B94; UNS 11916), a high-purity alloy containing aluminum 9 and zinc 0.7 per cent, and having a yield strength of 23,000 lb/in.<sup>2</sup> (Table 8a on page 587). AZ91D has a corrosion rate similar to that of 380 aluminum (see *Aluminum-Base Alloys* on page 1372).

**Tin-Base Alloys.**—In this group tin is alloyed with copper, antimony, and lead. SAE Alloy No. 10 contains, as the principal ingredients, in percentages, tin, 90; copper, 4 to 5; antimony, 4 to 5; lead, maximum, 0.35. This high-quality babbitt mixture is used for main-shaft and connecting-rod bearings or bronze-backed bearings in the automotive and aircraft industries. SAE No. 110 contains tin, 87.75; antimony, 7.0 to 8.5; copper, maximum, 2.25 to 3.75 per cent and other constituents the same as No. 10. SAE No. 11, which contains a little more copper and antimony and about 4 per cent less tin than No. 10, is also used for bearings or other applications requiring a high-class tin-base alloy. These tin-base compositions are used chiefly for automotive bearings but they are also used for milking machines, soda fountains, syrup pumps, and similar apparatus requiring resistance against the action of acids, alkalies, and moisture.

**Lead-Base Alloys.**—These alloys are employed usually where a cheap noncorrosive metal is needed and strength is relatively unimportant. Such alloys are used for parts of lead-acid batteries, for automobile wheel balancing weights, for parts that must withstand the action of strong mineral acids and for parts of X-ray apparatus. SAE Composition No. 13 contains (in percentages) lead, 86; antimony, 9.25 to 10.75; tin, 4.5 to 5.5 per cent. SAE Specification No. 14 contains less lead and more antimony and copper. The lead content is 76; antimony, 14 to 16; and tin, 9.25 to 10.75 per cent. Alloys Nos. 13 and 14 are inexpensive owing to the high lead content and may be used for bearings that are large and subjected to light service.

**Dies for Die-Casting Machines.**—Dies for die-casting machines are generally made of steel although cast iron and nonmetallic materials of a refractory nature have been used, the latter being intended especially for bronze or brass castings, which, owing to their comparatively high melting temperatures, would damage ordinary steel dies. The steel most generally used is a low-carbon steel. Chromium-vanadium and tungsten steels are used for aluminum, magnesium, and brass alloys, when dies must withstand relatively high temperatures.

Making die-casting dies requires considerable skill and experience. Dies must be so designed that the metal will rapidly flow to all parts of the impression and at the same time allow the air to escape through shallow vent channels, 0.003 to 0.005 inch deep, cut into the parting of the die. To secure solid castings, the gates and vents must be located with reference to the particular shape to be cast. Shrinkage is another important feature, especially on accurate work. The amount usually varies from 0.002 to 0.007 inch per inch, but to determine the exact shrinkage allowance for an alloy containing three or four elements is difficult except by experiment.

**Die-Casting Bearing Metals in Place.**—Practically all the metals that are suitable for bearings can be die cast in place. Automobile connecting rods are an example of work to which this process has been applied successfully. After the bearings are cast in place, they are finished by boring or reaming. The best metals for the bearings, and those that also can be die cast most readily, are the babbitts containing about 85 per cent tin with the remainder copper and antimony. These metals should not contain over 9 per cent copper. The copper constitutes the hardening element in the bearing. A recommended composition for a high-class bearing metal is 85 per cent tin, 10 per cent antimony, and 5 per cent copper. The antimony may vary from 7 to 10 per cent and the copper from 5 to 8 per cent. To reduce costs, some bearing metals use lead instead of tin. One bearing alloy contains from 95 to 98 per cent lead. The die-cast metal becomes harder upon seasoning a few days. In die-casting bearings, the work is located from the bolt holes that are drilled previous to die casting. It is

important that the bolt holes be drilled accurately with relation to the remainder of the machined surfaces.

**Injection Molding of Metal.**—The die casting and injection molding processes have been combined to make possible the injection molding of many metal alloys by mixing powdered metal, of 5 to 10  $\mu\text{m}$  (0.0002 to 0.0004 in.) particle size with thermoplastic binders. These binders are chosen for maximum flow characteristics to ensure that the mixture can penetrate to the most remote parts of the die/mold cavities. Moderate pressures and temperatures are used for the injection molding of these mixtures, and the molded parts harden as they cool so that they can be removed as solids from the mold. Shrinkage allowances for the cavities are greater than are required for the die casting process, because the injection molded parts are subject to a larger shrinkage (10 to 35 per cent) after removal from the die, due to evaporation of the binder and consolidation of the powder.

Binder removal may take several days because of the need to avoid distortion, and when it is almost complete the molded parts are sintered in a controlled atmosphere furnace at high temperatures to remove the remaining binder and consolidate the powdered metal component that remains. Density can thus be increased to about 95 per cent of the density of similar material produced by other processes. Tolerances are similar to those in die casting, and some parts are sized by a coining process for greater accuracy. The main limitation of the process is size, parts being restricted to about a 1.5-in. cube.

### Precision Investment Casting

Investment casting is a highly developed process that is capable of great casting accuracy and can form extremely intricate contours. The process may be utilized when metals are too hard to machine or otherwise fabricate; when it is the only practical method of producing a part; or when it is more economical than any other method of obtaining work of the quality required. Precision investment casting is especially applicable in producing either exterior or interior contours of intricate form with surfaces so located that they could not be machined readily if at all. The process provides efficient, accurate means of producing such parts as turbine blades, airplane, or other parts made from alloys that have high melting points and must withstand exceptionally high temperatures, and many other products. The accuracy and finish of precision investment castings may either eliminate machining entirely or reduce it to a minimum. The quantity that may be produced economically may range from a few to thousands of duplicate parts.

Investment casting uses an expendable pattern, usually of wax or injection-molded plastics. Several wax replicas or patterns are usually joined together or to bars of wax that are shaped to form runner channels in the mold. Wax shapes that will produce pouring funnels also are fastened to the runner bars. The mold is formed by dipping the wax assembly (tree) into a thick slurry containing refractory particles. This process is known as investing. After the coating has dried, the process is repeated until a sufficient thickness of material has been built up to form a one-piece mold shell. Because the mold is in one piece, undercuts, apertures, and hollows can be produced easily. As in shell molding, this invested shell is baked to increase its strength, and the wax or plastics pattern melts and runs out or evaporates (lost-wax casting). Some molds are backed up with solid refractory material that is also dried and baked to increase the strength. Molds for lighter castings are often treated similarly to shell molds described before. Filling of the molds may take place in the atmosphere, in a chamber filled with inert gas or under vacuum, to suit the metal being cast.

**Materials That May Be Cast.**—The precision investment process may be applied to a wide range of both ferrous and nonferrous alloys. In industrial applications, these include alloys of aluminum and bronze, Stellite, Hastelloys, stainless and other alloy steels, and iron castings, especially where thick and thin sections are encountered. In producing investment castings, it is possible to control the process in various ways so as to change the porosity or density of castings, obtain hardness variations in different sections, and vary the corrosion resistance and strength by special alloying.

**General Procedure in Making Investment Castings.**—Precision investment casting is similar in principle to the “lost-wax” process that has long been used in manufacturing jewelry, ornamental pieces, and individual dentures, inlays, and other items required in dentistry, which is not discussed here. When this process is employed, both the pattern and mold used in producing the casting are destroyed after each casting operation, but they may both be replaced readily. The “dispensable patterns” (or cluster of duplicate patterns) is first formed in a permanent mold or die and is then used to form the cavity in the mold or “investment” in which the casting (or castings) is made. The investment or casting mold consists of a refractory material contained within a reinforcing steel flask. The pattern is made of wax, plastics, or a mixture of the two. The material used is evacuated from the investment to form a cavity (without parting lines) for receiving the metal to be cast. Evacuation of the pattern (by the application of sufficient heat to melt and vaporize it) and the use of a master mold or die for reproducing it quickly and accurately in making duplicate castings are distinguishing features of this casting process. Modern applications of the process include many developments such as variations in the preparation of molds, patterns, investments, etc., as well as in the casting procedure. Application of the process requires specialized knowledge and experience.

**Master Mold for Making Dispensable Patterns.**—Duplicate patterns for each casting operation are made by injecting the wax, plastics, or other pattern material into a master mold or die that usually is made either of carbon steel or of a soft metal alloy. Rubber, alloy steels, and other materials may also be used. The mold cavity commonly is designed to form a cluster of patterns for multiple castings. The mold cavity is not, as a rule, an exact duplicate of the part to be cast because it is necessary to allow for shrinkage and perhaps to compensate for distortion that might affect the accuracy of the cast product. In producing master pattern molds there is considerable variation in practice. One general method is to form the cavity by machining; another is by pouring a molten alloy around a master pattern that usually is made of monel metal or of a high-alloy stainless steel. If the cavity is not machined, a master pattern is required. Sometimes, a sample of the product itself may be used as a master pattern, when, for example, a slight reduction in size due to shrinkage is not objectionable. The dispensable pattern material, which may consist of waxes, plastics, or a combination of these materials, is injected into the mold by pressure, by gravity, or by the centrifugal method. The mold is made in sections to permit removal of the dispensable pattern. The mold while in use may be kept at the correct temperature by electrical means, by steam heating, or by a water jacket.

**Shrinkage Allowances for Patterns.**—The shrinkage allowance varies considerably for different materials. In casting accurate parts, experimental preliminary casting operations may be necessary to determine the required shrinkage allowance and possible effects of distortion. Shrinkage allowances, in inches per inch, usually average about 0.022 for steel, 0.012 for gray iron, 0.016 for brass, 0.012 to 0.022 for bronze, 0.014 for aluminum and magnesium alloys. (See also *Shrinkage Allowances* on page 1369.)

**Casting Dimensions and Tolerances.**—Generally, dimensions on investment castings can be held to  $\pm 0.005$  in. and on specified dimensions to as low as  $\pm 0.002$  in. Many factors, such as the grade of refractory used for the initial coating on the pattern, the alloy composition, and the pouring temperature, affect the cast surface finish. Surface discontinuities on the as-cast products therefore can range from 30 to 300 microinches in height.

**Investment Materials.**—For investment casting of materials having low melting points, a mixture of plaster of Paris and powdered silica in water may be used to make the molds, the silica forming the refractory and the plaster acting as the binder. To cast materials having high melting points, the refractory may be changed to sillimanite, an alumina-silicate material having a low coefficient of expansion that is mixed with powdered silica as the binder. Powdered silica is then used as the binder. The interior surfaces of the mold are reproduced on the casting so, when fine finishes are needed, a first coating of fine sillimanite sand and a silicon ester such as ethyl silicate with a small amount of piperidine, is

applied and built up to a thickness of about 0.06 in. This investment is covered with a coarser grade of refractory that acts to improve bonding with the main refractory coatings, before the back up coatings are applied.

With light castings, the invested material may be used as a shell, without further reinforcement. With heavy castings the shell is placed in a larger container which may be of thick waxed paper or card, and further slurry is poured around it to form a thicker mold of whatever proportions are needed to withstand the forces generated during pouring and solidification. After drying in air for several hours, the invested mold is passed through an oven where it is heated to a temperature high enough to cause the wax to run out. When pouring is to take place, the mold is pre-heated to between 700 and 1000°C, to get rid of any remaining wax, to harden the binder and prepare for pouring the molten alloy. Pouring metal into a hot mold helps to ensure complete filling of intricate details in the castings. Pouring may be done under gravity, under a vacuum under pressure, or with a centrifuge. When pressure is used, attention must be paid to mold permeability to ensure gases can escape as the metal enters the cavities.

**Casting Operations.**—The temperature of the flask for casting may range all the way from a chilled condition up to 2000 degrees F or higher, depending upon the metal to be cast, the size and shape of the casting or cluster, and the desired metallurgical conditions. During casting, metals are nearly always subjected to centrifugal force vacuum, or other pressure. The procedure is governed by the kind of alloy, the size of the investment cavity, and its contours or shape.

**Investment Removal.**—When the casting has solidified, the investment material is removed by destroying it. Some investments are soluble in water, but those used for ferrous castings are broken by using pneumatic tools, hammers, or by shot or abrasive blasting and tumbling to remove all particles. Gates, sprues, and runners may be removed from the castings by an abrasive cutting wheel or a band saw according to the shape of the cluster and machinability of the material.

**Accuracy of Investment Castings.**—The accuracy of precision investment castings may, in general, compare favorably with that of many machined parts. The overall tolerance varies with the size of the work, the kind of metal and the skill and experience of the operators. Under normal conditions, tolerances may vary from  $\pm 0.005$  or  $\pm 0.006$  inch per inch, down to  $\pm 0.0015$  to  $\pm 0.002$  inch per inch, and even smaller tolerances are possible on very small dimensions. Where tolerances applying to a lengthwise dimension must be smaller than would be normal for the casting process, the casting gate may be placed at one end to permit controlling the length by a grinding operation when the gate is removed.

**Casting Weights and Sizes.**—Investment castings may vary in weight from a fractional part of an ounce up to 75 pounds or more. Although the range of weights representing the practice of different firms specializing in investment casting may vary from about  $\frac{1}{2}$  pound up to 10 or 20 pounds, a practical limit of 10 or 15 pounds is common. The length of investment castings ordinarily does not exceed 12 or 15 inches, but much longer parts may be cast. It is possible to cast sections having a thickness of only a few thousandths of an inch, but the preferred minimum thickness, as a general rule, is about 0.020 inch for alloys of high castability and 0.040 inch for alloys of low castability.

**Design for Investment Casting.**—As with most casting processes, best results from investment casting are achieved when uniform wall thicknesses between 0.040 and 0.375 in. are used for both cast components and channels forming runners in the mold. Gradual transition from thick to thin sections is also desirable. It is important that molten metal should not have to pass through a thin section to fill a thick part of the casting. Thin edges should be avoided because of the difficulty of producing them in the wax pattern. Fillets should be used in all internal corners to avoid stress concentrations that usually accompany sharp angles. Thermal contraction usually causes distortion of the casting, and should be allowed for if machining is to be minimized. Machining allowances vary from 0.010 in. on

small, to 0.040 in. on large parts. With proper arrangement of castings in the mold, grain size and orientation can be controlled and directional solidification can often be used to advantage to ensure desired physical properties in the finished components.

**Casting Milling Cutters by Investment Method.**—Possible applications of precision investment casting in tool manufacture and in other industrial applications are indicated by its use in producing high-speed steel milling cutters of various forms and sizes. Removal of the risers, sand blasting to improve the appearance, and grinding the cutting edges are the only machining operations required. The bore is used as cast. Numerous tests have shown that the life of these cutters compares favorably with high-speed steel cutters made in the usual way.

### Extrusion of Metals

**The Basic Process.**—Extrusion is a metalworking process used to produce long, straight semifinished products such as bars, tubes, solid and hollow sections, wire and strips by squeezing a solid slug of metal, either cast or wrought, from a closed container through a die. An analogy to the process is the dispensing of toothpaste from a collapsible tube.

During extrusion, compressive and shear, but no tensile, forces are developed in the stock, thus allowing the material to be heavily deformed without fracturing. The extrusion process can be performed at either room or high temperature, depending on the alloy and method. Cross sections of varying complexity can also be produced, depending on the materials and dies used.

In the specially constructed presses used for extrusion, the load is transmitted by a ram through an intermediate dummy block to the stock. The press container is usually fitted with a wear-resistant liner and is constructed to withstand high radial loads. The die stack consists of the die, die holder, and die backer, all of which are supported in the press end housing or platen, which resists the axial loads.

The following are characteristics of different extrusion methods and presses: 1) The movement of the extrusion relative to the ram. In "direct extrusion," the ram is advanced toward the die stack; in "indirect extrusion," the die moves down the container bore; 2) The position of the press axis, which is either horizontal or vertical; 3) The type of drive, which is either hydraulic or mechanical; and 4) The method of load application, which is either conventional or hydrostatic.

In forming a hollow extrusion, such as a tube, a mandrel integral with the ram is pushed through the previously pierced raw billet.

**Cold Extrusion:** Cold extrusion has often been considered a separate process from hot extrusion; however, the only real difference is that cold or only slightly warm billets are used as starting stock. Cold extrusion is not limited to certain materials; the only limiting factor is the stresses in the tooling. In addition to the soft metals such as lead and tin, aluminum alloys, copper, zirconium, titanium, molybdenum, beryllium, vanadium, niobium, and steel can be extruded cold or at low deformation temperatures. Cold extrusion has many advantages, such as no oxidation or gas/metal reactions; high mechanical properties due to cold working if the heat of deformation does not initiate recrystallization; narrow tolerances; good surface finish if optimum lubrication is used; fast extrusion speeds can be used with alloys subject to hot shortness.

Examples of cold extruded parts are collapsible tubes, aluminum cans, fire extinguisher cases, shock absorber cylinders, automotive pistons, and gear blanks.

**Hot Extrusion:** Most hot extrusion is performed in horizontal hydraulic presses rated in size from 250 to 12,000 tons. The extrusions are long pieces of uniform cross sections, but complex cross sections are also produced. Most types of alloys can be hot extruded.

Owing to the temperatures and pressures encountered in hot extrusion, the major problems are the construction and the preservation of the equipment. The following are approximate temperature ranges used to extrude various types of alloys: magnesium, 650–850

degrees F; aluminum, 650–900 degrees F; copper, 1200–2000 degrees F; steel, 2200–2400 degrees F; titanium, 1300–2100 degrees F; nickel 1900–2200 degrees F; refractory alloys, up to 4000 degrees F. In addition, pressures range from as low as 5000 to over 100,000 psi. Therefore, lubrication and protection of the chamber, ram, and die are generally required. The use of oil and graphite mixtures is often sufficient at the lower temperatures; while at higher temperatures, glass powder, which becomes a molten lubricant, is used.

*Extrusion Applications:* The stress conditions in extrusion make it possible to work materials that are brittle and tend to crack when deformed by other primary metalworking processes. The most outstanding feature of the extrusion process, however, is its ability to produce a wide variety of cross-sectional configurations; shapes can be extruded that have complex, nonuniform, and nonsymmetrical sections that would be difficult or impossible to roll or forge. Extrusions in many instances can take the place of bulkier, more costly assemblies made by welding, bolting, or riveting. Many machining operations may also be reduced through the use of extruded sections. However, as extrusion temperatures increase, processing costs also increase, and the range of shapes and section sizes that can be obtained becomes narrower.

While many asymmetrical shapes are produced, symmetry is the most important factor in determining extrudability. Adjacent sections should be as nearly equal as possible to permit uniform metal flow through the die. The length of their protruding legs should not exceed 10 times their thickness.

The size and weight of extruded shapes are limited by the section configuration and properties of the material extruded. The maximum size that can be extruded on a press of a given capacity is determined by the "circumscribing circle," which is defined as the smallest diameter circle that will enclose the shape. This diameter controls the die size, which in turn is limited by the press size. For instance, the larger presses are generally capable of extruding aluminum shapes with a 25-in.-diameter circumscribing circle and steel and titanium shapes with about 22-in.-diameter circle.

The minimum cross-sectional area and minimum thickness that can be extruded on a given size press are dependent on the properties of the material, the extrusion ratio (ratio of the cross-sectional area of the billet to the extruded section), and the complexity of shape. As a rule thicker sections are required with increased section size.

The following table gives the approximate minimum cross section and minimum thickness of some commonly extruded metals.

| Material                | Minimum Cross Section (sq in.) | Minimum Thickness (in.) |
|-------------------------|--------------------------------|-------------------------|
| Carbon and alloy steels | 0.40                           | 0.120                   |
| Stainless steels        | 0.45-0.70                      | 0.120-0.187             |
| Titanium                | 0.50                           | 0.150                   |
| Aluminum                | <0.40                          | 0.040                   |
| Magnesium               | <0.40                          | 0.040                   |

Extruded shapes minimize and sometimes eliminate the need for machining; however, they do not have the dimensional accuracy of machined parts. Smooth surfaces with finishes better than 30  $\mu\text{in. rms}$  are attainable in magnesium and aluminum; an extruded finish of 125  $\mu\text{in. rms}$  is generally obtained with most steels and titanium alloys. Minimum corner and fillet radii of  $\frac{1}{64}$  in. are preferred for aluminum and magnesium alloys; while for steel, minimum corner radii of 0.030 in. and fillet radii of 0.125 in. are typical.

*Extrusion of Tubes:* In tube extrusion, the metal passes through a die, which determines its outer diameter, and around a central mandrel, which determines its inner diameter. Either solid or hollow billets may be used, with the solid billet being used most often. When a solid billet is extruded, the mandrel must pierce the billet by pushing axially through it before the metal can pass through the annular gap between the die and the man-

drel. Special presses are used in tube extrusion to increase the output and improve the quality compared to what is obtained using ordinary extrusion presses. These special hydraulic presses independently control ram and mandrel positioning and movement.

### **Powder Metallurgy**

Powder metallurgy is a process whereby metal parts in large quantities can be made by the compressing and sintering of various powdered metals such as brass, bronze, aluminum, and iron. Compressing of the metal powder into the shape of the part to be made is done by accurately formed dies and punches in special types of hydraulic or mechanical presses. The "green" compressed pieces are then sintered in an atmosphere controlled furnace at high temperatures, causing the metal powder to be bonded together into a solid mass. A subsequent sizing or pressing operation and supplementary heat treatments may also be employed. The physical properties of the final product are usually comparable to those of cast or wrought products of the same composition. Using closely controlled conditions, steel of high hardness and tensile strength has also been made by this process.

Any desired porosity from 5 to 50 per cent can be obtained in the final product. Large quantities of porous bronze and iron bearings, which are impregnated with oil for self-lubrication, have been made by this process. Other porous powder metal products are used for filtering liquids and gases. Where continuous porosity is desired in the final product, the voids between particles are kept connected or open by mixing one per cent of zinc stearate or other finely powdered metallic soap throughout the metal powder before briquetting and then boiling this out in a low temperature baking before the piece is sintered.

The dense type of powdered metal products include refractory metal wire and sheet, cemented carbide tools, and electrical contact materials (products which could not be made as satisfactorily by other processes) and gears or other complex shapes which might also have been made by die casting or the precise machining of wrought or cast metal.

**Advantages of Powder Metallurgy.**—Parts requiring irregular curves, eccentrics, radial projections, or recesses often can be produced only by powder metallurgy. Parts that require irregular holes, keyways, flat sides, splines or square holes that are not easily machined, can usually be made by this process. Tapered holes and counter-bores are easily produced. Axial projections can be formed but the permissible size depends on the extent to which the powder will flow into the die recesses. Projections not more than one-quarter the length of the part are practicable. Slots, grooves, blind holes, and recesses of varied depths are also obtainable.

**Limiting Factors in Powdered Metal Process.**—The number and variety of shapes that may be obtained are limited by lack of plastic flow of powders, i.e., the difficulty with which they can be made to flow around corners. Tolerances in diameter usually cannot be held closer than 0.001 inch and tolerances in length are limited to 0.005 inch. This difference in diameter and length tolerances may be due to the elasticity of the powder and spring of the press.

**Factors Affecting Design of Briquetting Tools.**—High-speed steel is recommended for dies and punches and oil-hardening steel for strippers and knock-outs. One manufacturer specifies dimensional tolerances of 0.0002 inch and super-finished surfaces for these tools. Because of the high pressures employed and the abrasive character of certain refractory materials used in some powdered metal composition, there is frequently a tendency toward severe wear of dies and punches. In such instances, carbide inserts, chrome plating, or highly resistant die steels are employed. With regard to the shape of the die, corner radii, fillets, and bevels should be used to avoid sharp corners. Feather edges, threads, and reentrant angles are usually impracticable. The making of punches and dies is particularly exacting because allowances must be made for changes in dimensions due to growth after pressing and shrinkage or growth during sintering.



## SOLDERING AND BRAZING

Metals may be joined without using fasteners by employing soldering, brazing, and welding. Soldering involves the use of a non-ferrous metal whose melting point is below that of the base metal and in all cases below 800 degrees F. Brazing entails the use of a non-ferrous filler metal with a melting point below that of the base metal but above 800 degrees F. In fusion welding, abutting metal surfaces are made molten, are joined in the molten state, and then allowed to cool. The use of a filler metal and the application of pressure are considered to be optional in the practice of fusion welding.

### Soldering

Soldering employs lead- or tin-base alloys with melting points below 800 degrees F and is commonly referred to as soft soldering. Use of hard solders, silver solders and spelter solders which have silver, copper, or nickel bases and have melting points above 800 degrees F is known as brazing. Soldering is used to provide a convenient joint that does not require any great mechanical strength. It is used in a great many instances in combination with mechanical staking, crimping or folding, the solder being used only to seal against leakage or to assure electrical contact. The accompanying table, page 1381, gives some of the properties and uses of various solders that are generally available.

**Forms Available.**—Soft solders can be obtained in bar, cake, wire, pig, slab ingot, ribbon, segment, powder, and foil-form for various uses to which they are put. In bar form they are commonly used for hand soldering. The pigs, ingots, and slabs are used in operations that employ melting kettles. The ribbon, segment, powder and foil forms are used for special applications and the cake form is used for wiping. Wire forms are either solid or they contain acid or rosin cores for fluxing. These wire forms, both solid and core containing, are used in hand and automatic machine applications. Prealloyed powders, suspended in a fluxing medium, are frequently applied by brush and, upon heating, consistently wet the solderable surfaces to produce a satisfactory joint.

**Fluxes for Soldering.**—The surfaces of the metals being joined in the soldering operation must be clean in order to obtain an efficient joint. Fluxes clean the surfaces of the metal in the joint area by removing the oxide coating present, keep the area clean by preventing formation of oxide films, and lower the surface tension of the solder thereby increasing its wetting properties. Rosin, tallow, and stearin are mild fluxes which prevent oxidation but are not too effective in removing oxides present. Rosin is used for electrical applications since the residue is non-corrosive and non-conductive. Zinc chloride and ammonium chloride (sal ammoniac), used separately or in combination, are common fluxes that remove oxide films readily. The residue from these fluxes may in time cause trouble, due to their corrosive effects, if they are not removed or neutralized. Washing with water containing about 5 ounces of sodium citrate (for non-ferrous soldering) or 1 ounce of trisodium phosphate (for ferrous and non-ferrous soldering) per gallon followed by a clear water rinse or washing with commercial water-soluble detergents are methods of inactivating and removing this residue.

**Methods of Application.**—Solder is applied using a soldering iron, a torch, a solder bath, electric induction or resistance heating, a stream of hot neutral gas or by wiping. Clean surfaces which are hot enough to melt the solder being applied or accept molten solder are necessary to obtain a good clean bond. Parts being soldered should be free of oxides, dirt, oil, and scale. Scraping and the use of abrasives as well as fluxes are resorted to for preparing surfaces for soldering. The procedures followed in soldering aluminum, magnesium and stainless steel differ somewhat from conventional soldering techniques and are indicated in the material which follows

*Soldering Aluminum:* Two properties of aluminum which tend to make it more difficult to solder are its high thermal conductivity and the tenacity of its ever-present oxide film.

## Properties of Soft Solder Alloys Appendix, ASTM:B 32-70

| Nominal Composition <sup>a</sup><br>Per Cent |      |     |     | Specific<br>Gravity <sup>b</sup> | Melting Ranges, <sup>c</sup><br>Degrees Fahrenheit |          | Uses   |
|--|------|-----|-----|----------------------------------|--|----------|--|
| Sn   | Pb   | Sb  | Ag  |                                  | Solidus  | Liquidus |  |
| 70   | 30   | ... | ... | 8.32                             | 361  | 378      | For coating metals.  |
| 63   | 37   | ... | ... | 8.40                             | 361  | 361      | As lowest melting solder for dip and hand soldering methods.   |
| 60   | 40   | ... | ... | 8.65                             | 361  | 374      | "Fine Solder." For general purposes, but particularly where the temperature requirements are critical.   |
| 50   | 50   | ... | ... | 8.85                             | 361  | 421      | For general purposes. Most popular of all.   |
| 45   | 55   | ... | ... | 8.97                             | 361  | 441      | For automobile radiator cores and roofing seams.   |
| 40   | 60   | ... | ... | 9.30                             | 361  | 460      | Wiping solder for joining lead pipes and cable sheaths. For automobile radiator cores and heating units.   |
| 35   | 65   | ... | ... | 9.50                             | 361  | 477      | General purpose and wiping solder.   |
| 30   | 70   | ... | ... | 9.70                             | 361  | 491      | For machine and torch soldering.   |
| 25   | 75   | ... | ... | 10.00                            | 361  | 511      | For machine and torch soldering.   |
| 20   | 80   | ... | ... | 10.20                            | 361  | 531      | For coating and joining metals. For filling dents or seams in automobile bodies.   |
| 15   | 85   | ... | ... | 10.50                            | 440 <sup>d</sup>                                   | 550      | For coating and joining metals.  |
| 10   | 90   | ... | ... | 10.80                            | 514 <sup>d</sup>                                   | 570      | For coating and joining metals.  |
| 5  | 95   | ... | ... | 11.30                            | 518  | 594      | For coating and joining metals.  |
| 40   | 58   | 2   | ... | 9.23                             | 365  | 448      | Same uses as (50-50) tin-lead but not recommended for use on galvanized iron.  |
| 35   | 63.2 | 1.8 | ... | 9.44                             | 365  | 470      | For wiping and all uses except on galvanized iron.   |
| 30   | 68.4 | 1.6 | ... | 9.65                             | 364  | 482      | For torch soldering or machine soldering, except on galvanized iron.   |
| 25   | 73.7 | 1.3 | ... | 9.96                             | 364  | 504      | For torch and machine soldering, except on galvanized iron.  |
| 20   | 79   | 1   | ... | 10.17                            | 363  | 517      | For machine soldering and coating of metals, tipping, and like uses, but not recommended for use on galvanized iron.                                 |
| 95   | ...  | 5   | ... | 7.25                             | 452  | 464      | For joints on copper in electrical, plumbing and heating work.   |
| ...  | 97.5 | ... | 2.5 | 11.35                            | 579  | 579      | For use on copper, brass, and similar metals with torch heating. Not recommended in humid environments due to its known susceptibility to corrosion. |
| 1  | 97.5 | ... | 1.5 | 11.28                            | 588  | 588      | For use on copper, brass, and similar metals with torch heating.   |

<sup>a</sup> Abbreviations of alloying elements are as follows: Sn, tin; Pb, lead; Sb, antimony; and Ag, silver.

<sup>b</sup> The specific gravity multiplied by 0.0361 equals the density in pounds per cubic inch.

<sup>c</sup> The alloys are completely solid below the lower point given, designated "solidus," and completely liquid above the higher point given, designated "liquidus." In the range of temperatures between these two points the alloys are partly solid and partly liquid.

<sup>d</sup> For some engineering design purposes, it is well to consider these alloys as having practically no mechanical strength above 360 degrees F.

Aluminum soldering is performed in a temperature range of from 550 to 770 degrees F, compared to 375 to 400 degrees F temperature range for ordinary metals, because of the metal's high thermal conductivity. Two methods can be used, one using flux and one using abrasion. The method employing flux is most widely used and is known as flow soldering. In this method flux dissolves the aluminum oxide and keeps it from re-forming. The flux should be fluid at soldering temperatures so that the solder can displace it in the joint. In the friction method the oxide film is mechanically abraded with a soldering iron, wire brush, or multi-toothed tool while being covered with molten solder. The molten solder keeps the oxygen in the atmosphere from reacting with the newly-exposed aluminum surface; thus wetting of the surface can take place.

The alloys that are used in soldering aluminum generally contain from 50 to 75 per cent tin with the remainder zinc.

The following aluminum alloys are listed in order of ease of soldering: commercial and high-purity aluminum; wrought alloys containing not more than 1 per cent manganese or magnesium; and finally the heat-treatable alloys which are the most difficult.

Cast and forged aluminum parts are not generally soldered.

**Soldering Magnesium:** Magnesium is not ordinarily soldered to itself or other metals. Soldering is generally used for filling small surface defects, voids or dents in castings or sheets where the soldered area is not to be subjected to any load. Two solders can be used: one with a composition of 60 per cent cadmium, 30 per cent zinc, and 10 per cent tin has a melting point of 315 degrees F; the other has a melting point of 500 degrees F and has a nominal composition of 90 per cent cadmium and 10 per cent zinc.

The surfaces to be soldered are cleaned to a bright metallic luster by abrasive methods before soldering. The parts are preheated with a torch to the approximate melting temperature of the solder being used. The solder is applied and the surface under the molten solder is rubbed vigorously with a sharp pointed tool or wire brush. This action results in the wetting of the magnesium surface. To completely wet the surface, the solder is kept molten and the rubbing action continued. The use of flux is not recommended.

**Soldering Stainless Steel:** Stainless steel is somewhat more difficult to solder than other common metals. This is true because of a tightly adhering oxide film on the surface of the metal and because of its low thermal conductivity. The surface of the stainless steel must be thoroughly cleaned. This can be done by abrasion or by clean white pickling with acid. Muriatic (hydrochloric) acid saturated with zinc or combinations of this mixture and 25 per cent additional muriatic acid, or 10 per cent additional acetic acid, or 10 to 20 per cent additional water solution of orthophosphoric acid may all be used as fluxes for soldering stainless steel. Tin-lead solder can be used successfully. Because of the low thermal conductivity of stainless steel, a large soldering iron is needed to bring the surfaces to the proper temperature. The proper temperature is reached when the solder flows freely into the area of the joint. Removal of the corrosive flux is important in order to prevent joint failure. Soap and water or a commercial detergent may be used to remove the flux residue.

**Ultrasonic Fluxless Soldering.**—This more recently introduced method of soldering makes use of ultrasonic vibrations which facilitates the penetration of surface films by the molten solder thus eliminating the need for flux. The equipment offered by one manufacturer consists of an ultrasonic generator, ultrasonic soldering head which includes a transducer coupling, soldering tip, tip heater, and heating platen. Metals that can be soldered by this method include aluminum, copper, brass, silver, magnesium, germanium, and silicon.

### Brazing

Brazing is a metal joining process which uses a non-ferrous filler metal with a melting point below that of the base metals but above 800 degrees F. The filler metal wets the base metal when molten in a manner similar to that of a solder and its base metal. There is a slight diffusion of the filler metal into the hot, solid base metal or a surface alloying of the base and filler metal. The molten metal flows between the close-fitting metals because of capillary forces.

**Filler Metals for Brazing Applications.**—Brazing filler metals have melting points that are lower than those of the base metals being joined and have the ability when molten to flow readily into closely fitted surfaces by capillary action. The commonly used brazing metals may be considered as grouped into the seven standard classifications shown in [Tables 1a](#) and [1b](#). These are aluminum-silicon; copper-phosphorus; silver; nickel; copper and copper-zinc; magnesium; and precious metals.

The solidus and liquidus are given in [Tables 1a](#) and [1b](#) instead of the melting and flow points in order to avoid confusion. The solidus is the highest temperature at which the metal is completely solid or, in other words, the temperature above which the melting starts. The liquidus is the lowest temperature at which the metal is completely liquid, that is, the temperature below which the solidification starts.

**Table 1a. Brazing Filler Metals [ Based on Specification and Appendix of American Welding Society AWS A5.8-81 ]**

| AWS Classification <sup>a</sup> | Nominal Composition, <sup>b</sup> Per Cent |      |      |      |     |                         | Temperature, Degrees F |          |               | Standard Form <sup>c</sup> | Uses  |
|---------------------------------|--|------|------|------|-----|-------------------------|------------------------|----------|---------------|----------------------------|---|
|                                 | Ag   | Cu   | Zn   | Al   | Ni  | Other                   | Solidus                | Liquidus | Brazing Range |                            |   |
| BAISi-2                         | ...  | ...  | ...  | 92.5 | ... | Si, 7.5                 | 1070                   | 1135     | 1110-1150     | 7                          | For joining the following aluminum alloys: 1060, EC, 1100, 3003, 3004, 5005, 5050, 6053, 6061, 6062, 6063, 6951 and cast alloys A612 and C612. All of these filler metals are suitable for furnace and dip brazing. BAISi-3, -4 and -5 are suitable for torch brazing. Used with lap and tee joints rather than butt joints. Joint clearances run from .006 to .025 inch.                                   |
| BAISi-3                         | ...  | 4    | ...  | 86   | ... | Si, 10                  | 970                    | 1085     | 1160-1120     | 2, 3, 5                    |   |
| BAISi-4                         | ...  | ...  | ...  | 88   | ... | Si, 12                  | 1070                   | 1080     | 1080-1120     | 2, 3, 4, 5                 |   |
| BAISi-5                         | ...  | ...  | ...  | 90   | ... | Si, 10                  | 1070                   | 1095     | 1090-1120     | 7                          |   |
| BAISi-6                         | ...  | ...  | ...  | 90   | ... | Si, 7.5; Mg, 2.5        | 1038                   | 1125     | 1110-1150     | 7                          |   |
| BAISi-7                         | ...  | ...  | ...  | 88.5 | ... | Si, 10; Mg, 1.5         | 1038                   | 1105     | 1090-1120     | 7                          | BAISi-6 through -11 are vacuum brazing filler metals. Magnesium is present as an O <sub>2</sub> getter. When used in vacuum, solidus & liquidus temperatures are different from those shown.  |
| BAISi-8                         | ...  | ...  | ...  | 86.5 | ... | Si, 12; Mg, 1.5         | 1038                   | 1075     | 1080-1120     | 2, 7                       |   |
| BAISi-9                         | ...  | ...  | ...  | 87   | ... | Si, 12; Mg, 0.3         | 1044                   | 1080     | 1080-1120     | 7                          |   |
| BAISi-10                        | ...  | ...  | ...  | 86.5 | ... | Si, 11; Mg, 2.5         | 1038                   | 1086     | 1080-1120     | 2                          |   |
| BAISi-11                        | ...  | ...  | ...  | 88.4 | ... | Si, 10 Mg, 1.5; Bi, 0.1 | 1038                   | 1105     | 1090-1120     | 7                          |   |
| BCuP-1                          | ...  | 95   | ...  | ...  | ... | P, 5                    | 1310                   | 1465     | 1450-1700     | 1                          | For joining copper and its alloys with some limited use on silver, tungsten and molybdenum. Not for use on ferrous or nickel-base alloys. Are used for cupro-nickels but caution should be exercised when nickel content is greater than 30 per cent. Suitable for all brazing processes. Lap joints recommended but butt joints may be used. Clearances used range from .001 to .005 inch.                 |
| BCuP-2                          | ...  | 93   | ...  | ...  | ... | P, 7                    | 1310                   | 1460     | 1350-1550     | 2, 3, 4                    |   |
| BCuP-3                          | 5  | 89   | ...  | ...  | ... | P, 6                    | 1190                   | 1485     | 1300-1500     | 2, 3, 4                    |   |
| BCuP-4                          | 6  | 87   | ...  | ...  | ... | P, 7                    | 1190                   | 1335     | 1300-1450     | 2, 3, 4                    |   |
| BCuP-5                          | 15   | 80   | ...  | ...  | ... | P, 5                    | 1190                   | 1475     | 1300-1500     | 1, 2, 3, 4                 |   |
| BCuP-6                          | 2  | 91   | ...  | ...  | ... | P, 7                    | 1190                   | 1450     | 1350-1500     | 2, 3, 4                    |   |
| BCuP-7                          | 5  | 88   | ...  | ...  | ... | P, 6.8                  | 1190                   | 1420     | 1300-1500     | 2, 3, 4                    |   |
| BAG-1                           | 45   | 15   | 16   | ...  | ... | Cd, 24                  | 1125                   | 1145     | 1145-1400     | 1, 2, 4                    | For joining most ferrous and nonferrous metals except aluminum and magnesium. These filler metals have good brazing properties and are suitable for preplacement in the joint or for manual feeding into the joint. All methods of heating may be used. Lap joints are generally used; however, butt joints may be used. Joint clearances of .002 to .005 inch are recommended. Flux is generally required. |
| BAG-1a                          | 50   | 15.5 | 16.5 | ...  | ... | Cd, 18                  | 1160                   | 1175     | 1175-1400     | 1, 2, 4                    |   |
| BAG-2                           | 35   | 26   | 21   | ...  | ... | Cd, 18                  | 1125                   | 1295     | 1295-1550     | 1, 2, 4, 7                 |   |

**Table 1a. (Continued) Brazing Filler Metals [ Based on Specification and Appendix of American Welding Society AWS A5.8–81]**

| AWS Classification <sup>a</sup> | Nominal Composition, <sup>b</sup> Per Cent |      |      |     |     |          | Temperature, Degrees F |           |               | Standard Form <sup>c</sup> | Uses   |
|---------------------------------|--|------|------|-----|-----|----------|------------------------|-----------|---------------|----------------------------|--|
|                                 | Ag   | Cu   | Zn   | Al  | Ni  | Other    | Sol-idus               | Liq-uidus | Brazing Range |                            |  |
| BAG-2a                          | 30   | 27   | 23   | ... | ... | Cd, 20   | 1125                   | 1310      | 1310–1550     | 1, 2, 4                    | <p>For joining most ferrous and nonferrous metals except aluminum and magnesium. These filler metals have good brazing properties and are suitable for preplacement in the joint or for manual feeding into the joint. All methods of heating may be used. Lap joints are generally used; however, butt joints may be used. Joint clearances of .002 to .005 inch are recommended. Flux is generally required.</p> |
| BAG-3                           | 50   | 15.5 | 15.5 | ... | 3   | Cd, 16   | 1170                   | 1270      | 1270–1500     | 1, 2, 4, 7                 |  |
| BAG-4                           | 40   | 30   | 28   | ... | 2   | ...      | 1240                   | 1435      | 1435–1650     | 1, 2                       |  |
| BAG-5                           | 45   | 30   | 25   | ... | ... | ...      | 1250                   | 1370      | 1370–1550     | 1, 2                       |  |
| BAG-6                           | 50   | 34   | 16   | ... | ... | ...      | 1270                   | 1425      | 1425–1600     | 1, 2                       |  |
| BAG-7                           | 56   | 22   | 17   | ... | ... | Sn, 5    | 1145                   | 1205      | 1205–1400     | 1, 2                       |  |
| BAG-8                           | 72   | 28   | ...  | ... | ... | ...      | 1435                   | 1435      | 1435–1650     | 1, 2, 4                    |  |
| BAG-8a                          | 72   | 27.8 | ...  | ... | ... | Li, 2.   | 1410                   | 1410      | 1410–1600     | 1, 2                       |  |
| BAG-13                          | 54   | 40   | 5    | ... | 1   | ...      | 1325                   | 1575      | 1575–1775     | 1, 2                       |  |
| BAG-13a                         | 56   | 42   | ...  | ... | 2   | ...      | 1420                   | 1640      | 1600–1800     | 1, 2                       |  |
| BAG-18                          | 60   | 30   | ...  | ... | ... | Sn, 10   | 1115                   | 1325      | 1325–1550     | 1, 2                       |  |
| BAG-19                          | 92.5                                       | 7.3  | ...  | ... | ... | Li, 2    | 1435                   | 1635      | 1610–1800     | 1, 2                       |  |
| BAG-20                          | 30   | 38   | 32   | ... | ... | ...      | 1250                   | 1410      | 1410–1600     | 1, 2, 4                    |  |
| BAG-21                          | 63   | 28.5 | ...  | ... | 2.5 | Sn, 6    | 1275                   | 1475      | 1475–1650     | 1, 2, 4                    |  |
| BAG-22                          | 49   | 16   | 23   | ... | 4.5 | Mn, 7.5  | 1260                   | 1290      | 1290–1525     | 1, 2, 4, 7                 |  |
| BAG-23                          | 85   | ...  | ...  | ... | ... | Mn, 15   | 1760                   | 1780      | 1780–1900     | 1, 2, 4                    |  |
| BAG-24                          | 50   | 20   | 28   | ... | 2   | ...      | 1220                   | 1305      | 1305–1550     | 1, 2                       |  |
| BAG-25                          | 20   | 40   | 35   | ... | ... | Mn, 5    | 1360                   | 1455      | 1455–1555     | 2, 4                       |  |
| BAG-26                          | 25   | 38   | 33   | ... | 2   | Mn, 2    | 1305                   | 1475      | 1475–1600     | 1, 2, 4, 7                 |  |
| BAG-27                          | 25   | 35   | 26.5 | ... | ... | Cd, 13.5 | 1125                   | 1375      | 1375–1575     | 1, 2, 4                    |  |
| BAG-28                          | 40   | 30   | 28   | ... | ... | Sn, 2    | 1200                   | 1310      | 1310–1550     | 1, 2, 4                    |  |

<sup>a</sup>These classifications contain chemical symbols preceded by "B" which stands for brazing filler metal.

<sup>b</sup>These are nominal compositions. Trace elements may be present in small amounts and are not shown. Abbreviations used are: Ag, silver; Cu, copper; Zn, zinc; Al, aluminum; Ni, nickel; Ot, other; Si, silicon; P, phosphorus; Cd, cadmium; Sn, tin; Li, lithium; Cr, chromium; B, boron; Fe, iron; O, oxygen; Mg, magnesium; W, tungsten; Pd, palladium; and Au, gold.

<sup>c</sup>Numbers specify standard forms as follows: 1, strip; 2, wire; 3, rod; 4, powder; 5, sheet; 6, paste; 7, clad sheet or strip; and 8, transfer tape.

**Table 1b. Brazing Filler Metals [ Based on Specification and Appendix of American Welding Society AWS A5.8-81]**

| AWS Classification <sup>a</sup> | Nominal Composition, <sup>b</sup> Per Cent |      |     |     |     |                                      | Temperature, Degrees F |          |               | Standard Form <sup>c</sup> | Uses  |
|---------------------------------|--|------|-----|-----|-----|--------------------------------------|------------------------|----------|---------------|----------------------------|---|
|                                 | Ni   | Cu   | Cr  | B   | Si  | Other                                | Solidus                | Liquidus | Brazing Range |                            |   |
| BNi-1                           | 74   | ...  | 14  | 3.5 | 4   | Fe, 4.5                              | 1790                   | 1900     | 1950-2200     | 1, 2, 3, 4, 8              | For brazing AISI 300 and 400 series stainless steels, and nickel- and cobalt-base alloys. Particularly suited to vacuum systems and vacuum tube applications because of their very low vapor pressure. The limiting element is chromium in those alloys in which it is employed. Special brazing procedures required with filler metal containing manganese.    |
| BNi-2                           | 82.5                                       | ...  | 7   | 3   | 4.5 | Fe, 3                                | 1780                   | 1830     | 1850-2150     | 1, 2, 3, 4, 8              |   |
| BNi-3                           | 91   | ...  | ... | 3   | 4.5 | Fe, 1.5                              | 1800                   | 1900     | 1850-2150     | 1, 2, 3, 4, 8              |   |
| BNi-4                           | 93.5                                       | ...  | ... | 1.5 | 3.5 | Fe, 1.5                              | 1800                   | 1950     | 1850-2150     | 1, 2, 3, 4, 8              |   |
| BNi-5                           | 71   | ...  | 19  | ... | 10  | ...                                  | 1975                   | 2075     | 2100-2200     | 1, 2, 3, 4, 8              |   |
| BNi-6                           | 89   | ...  | ... | ... | ... | P, 11                                | 1610                   | 1610     | 1700-1875     | 1, 2, 3, 4, 8              |   |
| BNi-7                           | 77   | ...  | 13  | ... | ... | P, 10                                | 1630                   | 1630     | 1700-1900     | 1, 2, 3, 4, 8              |   |
| BNi-8                           | 65.5                                       | 4.5  | ... | ... | 7   | Mn, 23                               | 1800                   | 1850     | 1850-2000     | 1, 2, 3, 4, 8              |   |
| BCu-1                           | ...  | 100  | ... | ... | ... | ...                                  | 1980                   | 1980     | 2000-2100     | 1, 2                       | For joining various ferrous and nonferrous metals. They can also be used with various brazing processes. Avoid overheating the Cu-Zn alloys. Lap and butt joints are commonly used.   |
| BCu-1a                          | ...  | 99   | ... | ... | ... | Ot, 1                                | 1980                   | 1980     | 2000-2100     | 4                          |   |
| BCu-2                           | ...  | 86.5 | ... | ... | ... | O, 13.5                              | 1980                   | 1980     | 2000-2100     | 6                          |   |
| RBCuZn-A                        | ...  | 59   | ... | ... | ... | Zn, 41                               | 1630                   | 1650     | 1670-1750     | 1, 2, 3                    |   |
| RBCuZn-C                        | ...  | 58   | ... | ... | 0.1 | Zn, 40; Fe, 0.7; Mn, 0.3; Sn, 1      | 1590                   | 1630     | 1670-1750     | 2                          |   |
| RBCuZn-D                        | 10   | 48   | ... | ... | 0.2 | Zn, 42                               | 1690                   | 1715     | 1720-1800     | 1, 2, 3                    |   |
| BCuZn-E                         | ...  | 50   | ... | ... | ... | Zn, 50                               | 1595                   | 1610     | 1610-1725     | 1, 2, 3, 4, 5              |   |
| BCuZn-F                         | ...  | 50   | ... | ... | ... | Zn, 46.5; Sn, 3.5                    | 1570                   | 1580     | 1580-1700     | 1, 2, 3, 4, 5              |   |
| BCuZn-G                         | ...  | 70   | ... | ... | ... | Zn, 30                               | 1680                   | 1750     | 1750-1850     | 1, 2, 3, 4, 5              |   |
| BCuZn-H                         | ...  | 80   | ... | ... | ... | Zn, 20                               | 1770                   | 1830     | 1830-1950     | 1, 2, 3, 4, 5              |   |
| BMg-1                           | ...  | ...  | ... | ... | ... | <sup>a</sup>                         | 830                    | 1100     | 1120-1160     | 2, 3                       | BMg-1 is used for joining AZ10A, K1A, and M1A magnesium-base metals.  |
| BAu-1                           | ...  | 63   | ... | ... | ... | Au, 37                               | 1815                   | 1860     | 1860-2000     | 1, 2, 4                    | For brazing of iron, nickel, and cobalt-base metals where resistance to oxidation or corrosion is required. Low rate of interaction with base metal facilitates use on thin base metals. Used with induction, furnace, or resistance heating in a reducing atmosphere or in a vacuum and with no flux. For other applications, a borax-boric acid flux is used. |
| BAu-2                           | ...  | 20.5 | ... | ... | ... | Au, 79.5                             | 1635                   | 1635     | 1635-1850     | 1, 2, 4                    |   |
| BAu-3                           | 3  | 62.5 | ... | ... | ... | Au, 34.5                             | 1785                   | 1885     | 1885-1995     | 1, 2, 4                    |   |
| BAu-4                           | 18.5                                       | ...  | ... | ... | ... | Au, 81.5                             | 1740                   | 1740     | 1740-1840     | 1, 2, 4                    |   |
| BAu-5                           | 36   | ...  | ... | ... | ... | Au, 30; Pd, 34                       | 2075                   | 2130     | 2130-2250     | 1, 2, 4                    |   |
| BAu-6                           | 22   | ...  | ... | ... | ... | Au, 70; Pd, 8                        | 1845                   | 1915     | 1915-2050     | 1, 2, 4                    |   |
| BCo-1                           | 17   | ...  | ... | ... | 8   | Cr, 19; W, 4; B, 0.8; C, 0.4; Co, 59 | 2050                   | 2100     | 2100-2250     | 1, 3, 4, 8                 | Generally used for high temperature properties and compatibility with cobalt-base metals.   |

<sup>a</sup> Al, 9; Zn, 2; Mg, 89.

**Table 2. Guide to Selection of Brazing Filler Metals and Fluxes**

| Base Metals Being Brazed  | Filler Metals Recommended <sup>a</sup>                               | AWS Brazing Flux Type No. | Effective Temperature Range, Degrees F | Flux Ingredients   | Flux Supplied As         | Flux Method of Use <sup>b</sup> |
|---|--|---------------------------|--|--|--------------------------|---------------------------------|
| All brazeable aluminum alloys   | BA1Si  | 1                         | 700 to 1190                            | Chlorides, Fluorides   | Powder                   | 1, 2, 3, 4                      |
| All brazeable magnesium alloys  | BMg  | 2                         | 900 to 1200                            | Chlorides, Fluorides   | Powder                   | 3, 4                            |
| Alloys such as aluminum-bronze; aluminum-brass containing additions of aluminum of 0.5 per cent or more | BCuZn, BCuP  | 4 <sup>c</sup>            | 1050 to 1800                           | Chlorides, Fluorides, Borates, Wetting agent   | Paste or Powder          | 1, 2, 3                         |
| Titanium and zirconium in base alloys   | BAG  | 6                         | 700 to 1600                            | Chlorides, Fluorides, Wetting agent  | Paste or Powder          | 1, 2, 3                         |
| Any other brazeable alloys not listed above   | All brazing filler metals except BA1Si and BMg                       | 3                         | 700 to 2000                            | Boric acid, Borates, Fluorides, Fluoroates, Wetting agent<br><i>Must contain fluorine compound</i> | Paste, Powder, or Liquid | 1, 2, 3                         |
|   | All brazing filler metals except BA1Si, BMg, and BAG 1 through BAG 7 | 5                         | 1000 to 2200                           | Borax, Boric acid<br>Borates, Wetting agent<br><i>No fluorine in any form</i>                      | Paste, Powder, or Liquid | 1, 2, 3                         |

<sup>a</sup> Abbreviations used in this column are as follows: B, brazing filler metal; Al, aluminum; Si, silicon; Mg, magnesium; Cu, copper; Zn, zinc; P, phosphorus; and Ag, silver.

<sup>b</sup> Explanation of numbering system used is as follows: 1—dry powder is sprinkled in joint region; 2—heated metal filler rod is dipped into powder or paste; 3—flux is mixed with alcohol, water, monochlorobenzene, etc., to form a paste or slurry; 4—flux is used molten in a bath.

<sup>c</sup> Types 1 and 3 fluxes, alone or in combination, may be used with some of these base metals also.

**Fluxes for Brazing.**—In order to obtain a sound joint the surfaces in and adjacent to the joint must be free from dirt, oil, and oxides or other foreign matter at the time of brazing. Cleaning may be achieved by chemical or mechanical means. Some of the mechanical means employed are filing, grinding, scratch brushing and machining. The chemical means include the use of trisodium phosphate, carbon tetrachloride, and trichloroethylene for removing oils and greases.

Fluxes are used mainly to prevent the formation of oxides and to remove any oxides on the base and filler metals. They also promote free flow of the filler metal during the course of the brazing operation.

They are made available in the following forms: powders; pastes or solutions; gases or vapors; and as coatings on the brazing rods.

In the powder form a flux can be sprinkled along the joint, provided that the joint has been preheated sufficiently to permit the sprinkled flux to adhere and not be blown away by the torch flame during brazing. A thin paste or solution is easily applied and when spread on evenly, with no bare spots, gives a very satisfactory flux coating. Gases or vapors are used in controlled atmosphere furnace brazing where large amounts of assemblies are mass-brazed. Coatings on the brazing rods protect the filler metal from becoming oxidized and eliminate the need for dipping rods into the flux, but it is recommended that flux be applied to the base metal since it may become oxidized in the heating operation. No matter which flux is used, it performs its task only if it is chemically active at the brazing temperature.

Chemical compounds incorporated into brazing fluxes include borates (sodium, potassium, lithium, etc.), fused borax, fluoborates (potassium, sodium, etc.), fluorides (sodium,

potassium, lithium, etc.), chlorides (sodium, potassium, lithium), acids (boric, calcined boric acid), alkalis (potassium hydroxide, sodium hydroxide), wetting agents, and water (either as water of crystallization or as an addition for paste fluxes). [Table 2](#) provides a guide which will aid in the selection of brazing fluxes that are available commercially.

**Methods of Steadying Work for Brazing.**—Pieces to be joined by brazing after being properly jointed may be held in a stable position by means of clamping devices, spot welds, or mechanical means such as crimping, staking, or spinning. When using clamping devices care must be taken to avoid the use of devices containing springs for applying pressure because springs tend to lose their properties under the influence of heat. Care must also be taken to be sure that the clamping devices are no larger than is necessary for strength considerations, because a large metal mass in contact with the base metal near the brazing area would tend to conduct heat away from the area too quickly and result in an inefficient braze. Thin sections that are to be brazed are frequently held together by spot welds. It must be remembered that these spot welds may interfere with the flow of the molten brazing alloy and appropriate steps must be taken to be sure that the alloy is placed where it can flow into all portions of the joint.

**Methods of Supplying Heat for Brazing.**—The methods of supplying heat for brazing form the basis of the classification of the different brazing methods and are as follows.

*Torch or Blowpipe Brazing:* Air-gas, oxy-acetylene, air-acetylene, and oxy-other fuel gas blowpipes are used to bring the areas of the joint and the filler material to the proper heat for brazing. The flames should generally be neutral or slightly reducing but in some instances some types of bronze welding require a slightly oxidizing flame.

*Dip Brazing:* Baths of molten alloy, covered with flux, or baths of molten salts are used for dip brazing. The parts to be brazed are first assembled, usually with the aid of jigs, and are dipped into the molten metal, then raised and allowed to drain. The molten alloy enters the joint by capillary action. When the salt bath is used, the filler metal is first inserted between the parts being joined, or, in the form of wire, is wrapped around the area of the joint. The brazing metal melts and flows into the joint, again by capillary action.

*Furnace Brazing:* Furnaces that are heated electrically or by gas or oil with auxiliary equipment that maintains a reducing or protective atmosphere and controlled temperatures therein are used for brazing large numbers of units, usually without flux.

*Resistance Brazing:* Heat is supplied by means of hot or incandescent electrodes. The heat is produced by the resistance of the electrodes to the flow of electricity and the filler metal is frequently used as an insert between the parts being joined.

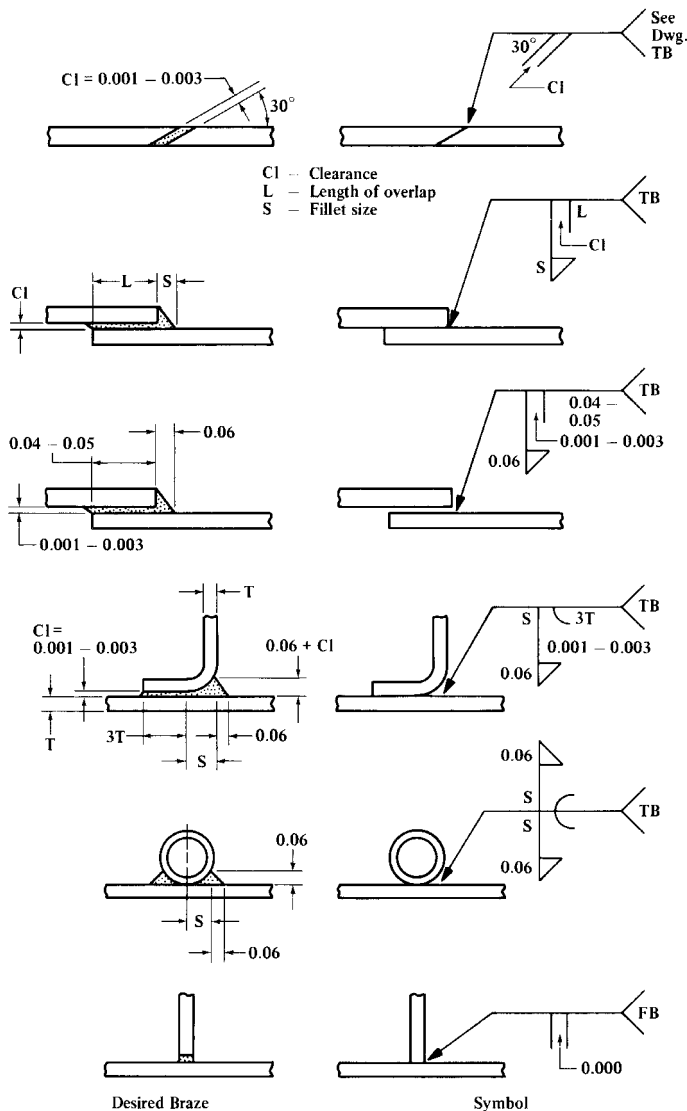
*Induction Brazing:* Parts to be joined are heated by being placed near a coil carrying an electric current. Eddy current losses of the induced electric current are dissipated in the form of heat raising the temperature of the work to a point higher than the melting point of the brazing alloy. This method is both quick and clean.

*Vacuum Furnace Brazing:* Cold-wall vacuum furnaces, with electrical-resistance radiant heaters, and pumping systems capable of evacuating a conditioned chamber to moderate vacuum (about 0.01 micron) in 5 minutes are recommended for vacuum brazing. Metals commonly brazed in vacuum are the stainless steels, heat-resistant alloys, titanium, refractory metals, and aluminum. Fluxes and filler metals containing alloying elements with low boiling points or high vapor pressure are not used.

**Brazing Symbol Application.**—ANSI/AWS A2.4-79 symbols for brazing are also used for welding with the exception of the symbol for a scarf joint (see the diagram at the top of page [1388](#), and the symbol for a scarf joint in the table *Basic Weld Symbols* on page [1433](#), for applications of brazing symbols). The second, third and fourth figures from the top of the next page show how joint clearances are indicated. If no special joint preparation is required, only the arrow is used with the brazing process indicated in the tail.



BRAZING



Typical Applications of Standard Brazing Symbols

## WELDING

Welding of metals requires that they be heated to a molten state so that they fuse together. A filler wire or rod is held in the heated zone to add material that will replace metal consumed by the process and to produce a slightly raised area that can be dressed down to make a level surface if needed. Most welding operations today use an electric arc, though the autogenous method using a torch that burns a mixture of (usually) acetylene and oxygen gases to heat the components is still used for certain work. Lasers are also used as the heating medium for some welding operations. In arc welding, a low-voltage, high-current arc is struck between the end of an electrode in a holder and the work, generating intense heat that immediately melts the surface.

### Welding Electrodes, Fluxes, and Processes

Electrodes for welding may be made of a tungsten or other alloy that does not melt at welding temperatures (nonconsumable) or of an alloy similar to that of the work so that it melts and acts as the filler wire (consumable). In welding with a nonconsumable electrode, filler metal is added to the pool as welding proceeds. Filler metals that will produce welds having strength properties similar to those of the work are used where high-strength welds are specified.

Briefly, the effects of the main alloying elements in welding filler wires and electrodes are: carbon adds strength but may cause brittle weld metal if cooling is rapid, so low-carbon wire is preferred; silicon adds strength and reduces oxidation, changes fluidity, and gives a flatter weld bead; manganese strengthens and assists deoxidation, plus it reduces effects of sulfur, lowering the risk of hot cracking; sulfur may help form iron sulfide, which increases the risk of hot cracking; and phosphorus, may contribute to hot cracking.

*Fluxes* in (usually) granular form are added to the weld zone, as coatings on the filler wire or as a core in the tube that forms the (consumable) electrode. The flux melts and flows in the weld zone, shielding the arc from the oxygen in the atmosphere, and often contains materials that clean impurities from the molten metal and prevent grain growth during recrystallization.

**Processes.**—There are approximately 100 welding and allied welding processes but the four manual arc welding processes: gas metal arc welding (GMAW) (which is also commonly known as MIG for metal inert gas), flux-cored arc (FCAW), shielded metal arc (SMAW), gas tungsten arc welding (GTAW), account for over 90 per cent of the arc welding used in production, fabrication, structural, and repair applications. FCAW and SMAW use fluxes to shield the arc and FCAW uses fluxes and gases to protect the weld from oxygen and nitrogen. GMAW and GTAW use mixtures of gases to protect the weld.

There are two groups of weld types, groove and fillet, which are self-explanatory. Each type of weld may be made with the work at any angle from horizontal (flat) to inverted (overhead). In a vertical orientation, the electrode tip may move down the groove or fillet (vertical down), or up (vertical up). In any weld other than flat, skill is needed to prevent the molten metal falling from the weld area.

Because of the many variables, such as material to be welded and its thickness, equipment, fluxes, gases, electrodes, degree of skill, and strength requirements for the finished welds, it is not practicable to set up a complete list of welding recommendations that would have general validity. Instead, examples embracing a wide range of typical applications, and assuming common practices, are presented here for the most-used welding processes. The recommendations given are intended as a guide to finding the best approach to any welding job, and are to be varied by the user to fit the conditions encountered in the specific welding situation.

**Gas Metal Arc Welding (GMAW)**

The two most cost-effective manual arc welding processes are GMAW and FCAW. These two welding processes are used with more than 50 per cent of the arc welding consumable electrodes purchased. Gas metal arc welding modes extend from short-circuit welding, where the consumable electrode wire is melted into the molten pool in a rapid succession of short circuits during which the arc is extinguished, to pulsed and regular spray transfer, where a stream of fine drops and vaporized weld metal is propelled across the continuous arc gap by electromagnetic forces in the arc.

GMAW is the most-used welding process and the two most common GMAW low-carbon steel electrodes used for production welding in North America are the E70S-3 and E70S-6 from the ANSI/AWS Standard A5 series of specifications for arc welding. The E70S-3 contains manganese and silicon as deoxidants and is mainly used for welding low-carbon steels, using argon mixtures as shielding gases. The wire used in the E70S-6 electrodes has more silicon than wire used for the E70S-3 electrodes, and is preferred where straight CO<sub>2</sub> or argon mixes are used as the shielding gas or if the metal to be welded is contaminated. The deoxidizing properties of the E70S-6 electrode also may be beneficial for high-current, deep-penetration welds, and welds in which higher than normal impact-strength properties are required.

E80S-D2 wire contains more manganese and silicon, plus 0.5 per cent molybdenum for welding such steels as AISI 4130, and steels for high-temperature service. The argon + CO<sub>2</sub> mixture is preferred to exert the influence of argon's inertness over the oxidizing action of CO<sub>2</sub>. E70S-2 electrodes contain aluminum, titanium, and zirconium to provide greater deoxidation action and are valuable for welding contaminated steel plate.

When the GMAW welding process is used for galvanized steels, minute welding cracks may be caused by the reaction of the zinc coating on the work with silicon in the electrode. Galvanized steel should be welded with an electrode having the lowest possible silicon content such as the E70S-3. For welding low-carbon and low-alloy steels with conventional argon mixture shielding gases, there is little difference between the E70S-3 and E70S-6.

**Electrode Diameters.**—One of the most important welding decisions is selecting the optimum GMAW electrode diameter. Selection of electrode diameters should be based on the material thickness, as shown for carbon and stainless steels in Table 1, the compatibility of the electrode current requirements with the material thickness, the mode of weld metal transfer, and the deposition rate potential shown in Table 2. The two most popular GMAW electrode sizes are 0.035 in. (1.0 mm) and 0.045 in. (1.2 mm). Diameters of electrodes used for GMAW exert a strong influence on cost of welding. Table 2 also shows how the weld deposition rate varies in short-circuit and spray transfer modes in welding carbon and stainless steels.

**Table 1. GMAW Electrode Sizes for Welding Carbon and Stainless Steels**

| Material Thickness                   | Electrode Diameter    |                       |                       |                       |
|--------------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|
|                                      | 0.030 in.<br>(0.8 mm) | 0.035 in.<br>(1.0 mm) | 0.045 in.<br>(1.2 mm) | 0.062 in.<br>(1.6 mm) |
| 25 to 21 gage (0.020 to 0.032 in.)   | yes                   | ...                   | ...                   | ...                   |
| 20 gage to ¼ in. (0.036 to 0.25 in.) | ...                   | yes                   | ...                   | ...                   |
| ⅜ to ⅞ in. flat and horizontal       | ...                   | ...                   | yes                   | ...                   |
| ½ in. and up                         | ...                   | ...                   | ...                   | yes                   |

The table is based on suitability of the electrode size to mode of weld transfer, material thickness, and cost effectiveness. If a smaller electrode size is selected, the lower deposition rates could increase welding costs by 20 to 60 per cent.

**Table 2. Typical Maximum GMAW Deposition Rates for Carbon and Stainless Steels. Constant-Voltage 450-amp Power Source and Standard Wire Feeder**

| Weld transfer mode | Electrode Diameter    |                       |                       |                       |
|--------------------|-----------------------|-----------------------|-----------------------|-----------------------|
|                    | 0.030 in.<br>(0.8 mm) | 0.035 in.<br>(1.0 mm) | 0.045 in.<br>(1.2 mm) | 0.062 in.<br>(1.6 mm) |
| Short circuit      | 5 lb/h<br>(2.3 kg/h)  | 7 lb/h<br>(3.2 kg/h)  | 9 lb/h<br>(4 kg/h)    | ...                   |
| Spray transfer     | 9 lb/h<br>(4 kg/h)    | 11 lb/h<br>(5 kg/h)   | 19 lb/h<br>(8.6 kg/h) | 21 lb/h<br>(9.5 kg/h) |

For the lowest-cost welds with GMAW electrodes larger than 0.030 in. in diameter, the power source should provide a minimum of 350 amps. The compatibility of the optimum current range of the 0.035-in. (1.0-mm) electrode and its deposition potential make it the first choice for welding of 20 gage to  $\frac{1}{4}$  in. (0.88 to 6.4 mm) thicknesses. For welding thinner sheet metals of 25 to 21 gage, the optimum electrode diameter is 0.030 in. (0.8 mm). The 0.045-in. (1.2-mm) electrode is the most practical choice for spray transfer applications on materials over  $\frac{1}{4}$  in. (6.4 mm) thick and thicker.

As an example, when welding  $\frac{1}{4}$ -in. (6.4-mm) thick steel, with 100 per cent arc-on time and a labor cost of \$15/h, the deposition rate with a 0.035-in. (0.9-mm) electrode is approximately 11 lb/h (5 kg/h). The labor cost per lb at \$15/h  $\div$  11 lb/h = \$1.36/lb (\$3.00/kg). If an electrode of 0.045-in. (1.2-mm) diameter is used for the same application, the deposition rate is 16 lb/h (7.2 kg/h) and at a \$15/h labor rate, the cost of weld metal deposited = \$15/h  $\div$  16 lb/h = \$0.93/lb (\$2.00/kg). The 0.045-in. diameter electrode would also cost less per pound than a smaller wire, and the weld time with the 0.045-in. electrode would be reduced, so less shielding gas also would be consumed.

**GMAW Welding of Sheet Steel.**—In GMAW, the short-circuit transfer mode is used to weld carbon steel, low-alloy steel, and stainless steel sheet of 24 gage (0.023 in., or 0.6 mm) to 11 gage (0.12 in., or 3 mm). The most common gage sizes welded with short-circuit transfer are 20 gage to 11 gage (0.88 to 3 mm) and the best GMAW electrode for these thin, sheet metal gages is the 0.035-in. (1-mm) diameter electrode. The short-circuit current requirements for these operations are typically 50 to 200 amps with voltages in the range of 14 to 22 volts. The optimum short-circuit voltage for the majority of applications is 16 to 18 volts.

**Shielding Gases for Welding Carbon and Low-Alloy Steels.**—With more than 40 GMAW gas mixtures available for welding carbon steels, low-alloy steels, and stainless steels, selection is often confusing. Reactive oxygen and carbon dioxide (CO<sub>2</sub>) are added to argon to stabilize the arc and add energy to the weld. CO<sub>2</sub> can provide more energy to the weld than oxygen. As the CO<sub>2</sub> content in a shielding gas mixture is increased to certain levels, the voltage requirements are increased. Argon + oxygen mixtures will require lower voltages than mixtures containing argon with 10 to 25 per cent CO<sub>2</sub>. Helium may also be added to argon if increased weld energy is required.

**Shielding Gases for Short-Circuit Welding of Carbon Steels.**—GMAW short-circuit transfer (SCT) is used mainly for welding thin metals of less than 10 gage, and gaps. With the SCT mode of weld metal transfer, the arc short circuits many times each second. The numerous short circuits switch the arc energy on and off. The short circuits and low current cause the transferred weld to freeze rapidly. Short-circuit transfer on carbon steel gage metals thicker than  $\frac{1}{16}$  in. (1.6 mm) requires a shielding gas that will provide substantial weld energy. For these applications, argon with 15–25 per cent CO<sub>2</sub> is recommended.

If short-circuit transfer is used on metals thinner than 18 gage (0.047 in., 1.2 mm), melt-through and distortion often occur. Melt-through and distortion can be reduced on very thin-gage carbon and low-alloy steels by using a shielding gas that provides less weld energy than argon + 15 to 25 per cent CO<sub>2</sub> mixes. Argon + oxygen mixtures can utilize

lower voltages to sustain the arc. Argon mixed with 2 to 5 per cent oxygen is a practical mixture for thin carbon steel of less than 16 gage, where there is sensitivity to heat.

**Shielding Gases for Spray Transfer Welding of Carbon Steels.**—With GMAW spray transfer, all traditional argon gas mixtures will provide spatter-free spray weld transfer, depending on the electrode diameter and welding parameters used. The electrode diameter and the electrode current density influence the formation of the weld metal to be transferred. For example, with a 0.035-in. diameter electrode using a mixture containing argon 75 + CO<sub>2</sub> 25 per cent, a small globular weld droplet is formed on the end of the electrode tip in the conventional spray transfer parameter range. With the same gas mixture, a 0.045-in. (1.2-mm) diameter electrode, and current above 330 amps, the globular formation disappears and the metal transfers in the spray mode.

Spatter potential stemming from shielding gas, with 0.035-in. (1.0-mm) and smaller diameter electrodes can be controlled by reducing the CO<sub>2</sub> content in the argon mixture to less than 21 per cent. Each different shielding gas will primarily influence the open arc spray transfer mode by variations in the weld energy provided through the welding voltage requirements.

Gas selection in spray transfer must be given careful consideration. In welding of clean cold-rolled carbon steel or low-alloy steel less than  $\frac{3}{8}$  in. (9.5 mm) thick, the energy potential of the arc is less important than it is for welding of steels thicker than  $\frac{1}{4}$  in. (13 mm) or steels with mill scale. The energy level of the arc is also a key factor in welding steels for which higher than normal impact properties are specified.

A simple, practical multipurpose gas mixture for carbon and low-alloy steels is argon + 15 to 20 per cent CO<sub>2</sub>, and a mixture of argon + 17 per cent CO<sub>2</sub> would be ideal. This two-part argon/CO<sub>2</sub> mixture provides higher weld energy than two-component argon + CO<sub>2</sub> mixtures having less than 10 per cent CO<sub>2</sub>, argon + oxygen mixtures, or argon + CO<sub>2</sub> + oxygen tri-component mixtures. The argon + 17 per cent CO<sub>2</sub> mixture will provide an arc slightly less sensitive to mill scale than the other mixtures mentioned.

The argon + 17 per cent CO<sub>2</sub> mixture also has practical benefits in that it provides sufficient weld energy for all GMAW short-circuit and spray transfer applications with cylinder or bulk gases. The argon + 17 per cent CO<sub>2</sub> mixture may also be used for all-position FCAW electrodes in welding carbon steels, low-alloy steels, and stainless steels.

**Shielding Gases for GMAW Welding of Stainless Steels.**—The major problems encountered when using GMAW on stainless steels of thinner than 14 gage include controlling potential melt-through, controlling distortion, and black oxidation on the weld surface. These three welding problems have a common denominator, which is heat. The key to welding thin stainless steel is to minimize the potential heat when welding, by appropriate choice of gas mixture.

A popular gas mixture that is often recommended for GMAW welding of thin-gage stainless steel is the three-part helium gas mixture containing helium 90 + argon 7.5 + CO<sub>2</sub> 2.5 per cent. In contrast to gas mixtures without helium, the helium tri-mixture requires the use of higher voltages to sustain the arc, which adds unnecessary heat to the heat-sensitive thin-gage welds.

A practical and lower-cost alternative for GMAW short-circuit transfer on stainless steels is an argon mixture with 2 to 4 per cent CO<sub>2</sub>. The argon + CO<sub>2</sub> mixture allows use of lower voltages than is practical with argon/helium mixtures, and the lower voltages resulting from the argon + CO<sub>2</sub> mixture will help to reduce distortion and oxidation, and decrease the melt-through potential. The mixture that works with short-circuit transfer is also a logical practical choice for spray transfer welding of stainless steel because it is less oxidizing than argon/oxygen mixtures. [Table 3](#) provides practical gas mixture recommendations for specific applications.

**Table 3. Shielding Gases for Welding Carbon Steels and Stainless Steels**

| Application  | Gas mixtures   |                                  |                              |                               |                                |                             |
|--|----------------|----------------------------------|------------------------------|-------------------------------|--------------------------------|-----------------------------|
|  | Argon + Oxygen | Argon + CO <sub>2</sub> + Oxygen | Argon + 2-4% CO <sub>2</sub> | Argon + 6-10% CO <sub>2</sub> | Argon + 13-20% CO <sub>2</sub> | Argon + 25% CO <sub>2</sub> |
| Short-circuit melt-through problems; less than 20 gage       | 1              | 1                                | 1                            | 1                             | 2                              | 3                           |
| Short-circuit 18 to 11 gage                                  | ...            | ...                              | ...                          | ...                           | 1                              | 1                           |
| Spray if mill scale or surface problems; carbon steels       | ...            | ...                              | ...                          | ...                           | 1                              | 2                           |
| Spray if low energy required; carbon steel                   | 1              | 1                                | 1                            | 1                             | ...                            | ...                         |
| Spray, best impact strengths, lowest porosity; carbon steels | ...            | ...                              | ...                          | ...                           | 1                              | ...                         |
| Best single gas mixture for carbon steels                    | ...            | ...                              | ...                          | ...                           | 1                              | ...                         |
| Short-circuit; stainless steels                              | ...            | ...                              | 1                            | ...                           | ...                            | ...                         |
| Spray; stainless steels                                      | 2              | ...                              | 1                            | ...                           | ...                            | ...                         |
| Best single gas mixture for stainless and duplex steels      | ...            | ...                              | 1                            | ...                           | ...                            | ...                         |

Preferred choice of shielding gas is 1, followed by 2 and 3.

For GMAW spray transfer welding of stainless steels thicker than 11 gage, the traditional GMAW shielding gas has been argon 98 + oxygen 2 per cent. The argon + oxygen mixture provides excellent, stable, spray transfer, but the oxygen promotes oxidation, leaving the weld with a black surface. To reduce the oxidation, the 2 per cent oxygen can be replaced with the less oxidizing 2-4 per cent CO<sub>2</sub>.

**Shielding Gases for GMAW Welding of Aluminum.**—For GMAW welding of aluminum, helium is added to argon to provide additional weld energy, increasing penetration width, and reducing porosity potential. A gas mixture that has worked well in practice and can be used on the majority of aluminum applications is argon + 25 to 35 per cent helium. Mixtures with higher helium content, of 50 to 90 per cent, require voltages and flow rates that may be excessive for many established aluminum applications.

**Welding Controls.**—The two primary controls for welding with GMAW are the electrode wire feed control on the wire feeder and the voltage control on the power source. As shown in Fig. 1, these controls typically consist of switches and knobs but do not have the scales, seen enlarged at the upper left, that indicate combinations of wire feed rate, wire gage, volts, and amps. These scales have been added here to allow clearer explanation of the functioning of the wire feed control.

The typical wire feed unit provides maximum feed rates of 600 to 800 in./min. The scale surrounding the setting knob on a wire feed control unit usually has only 10 unnumbered graduations, somewhat like the hour markers on a clock face. On most machines, each of these graduations represents an adjustment of the feed rate of approximately 70 in./min.

For each increase in the wire feed rate of 70 in./min, depending on the voltage, the welding current increases by approximately 20 to 40 amps, depending on the wire diameter and wire feed positions.

In Fig. 1, a black sector has been drawn in on the wire feed rate adjustment knob to indicate the range of wire feed rates usable with the gas mixture and the electrode diameter (gage) specified. The wire feed and voltage settings shown are for welding thin-gage carbon, low-alloy, or stainless steels with a 0.030- or 0.035-in. (0.8- or 1-mm) diameter electrode. The left edge of the sector on the wire feed knob is set to the eight o'clock position, corresponding to 70 in./min. The optimum voltage for this wire feed rate is 15. If a setting is too low, the knob is turned to the second (nine o'clock) or third (ten o'clock) position to increase the current. The voltage typically increases or decreases by 1 volt for each graduation of the wire feed quadrant.

The short-circuit transfer current range of 50 to 200 amps corresponds to a wire feed rate of 70 to 420 in./min, and is typically found between the eight and one o'clock positions on the scale, as indicated by the black sector on the knob in Fig. 1.

Diagrammatic quadrants have been added at the left in Fig. 1, to show the material thickness, voltage, and current that correspond to the setting of the wire feed rate adjustment knob. Optimum settings are easily made for short-circuit welding of sheet metals. When using a 0.030-in. (0.8-mm) or 0.035-in. (1-mm) diameter GMAW electrode, for instance, to weld 16-gage carbon or stainless steel with a conventional 200-to 450-amp constant-voltage power source and wire feeder, the wire feed control is set to the ten o'clock position for a feed rate of 210 in./min. With digital wire feed units, the short-circuit current range is typically between 100 and 400 in./min, so a good starting point is to set the wire feeder at 210 in./min. The welding voltage is set to 17.

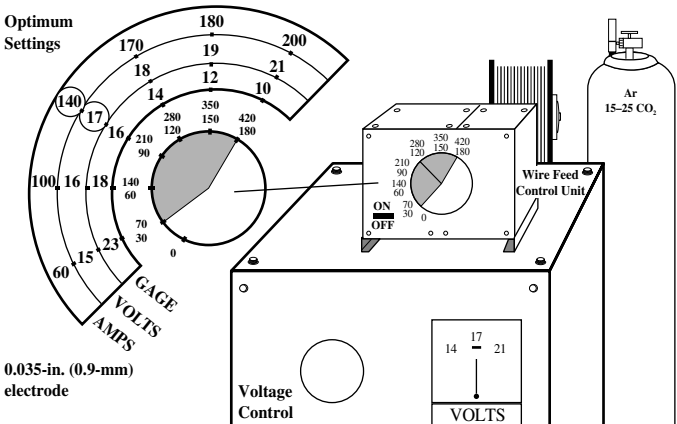


Fig. 1. Wire Feed Settings for Short-Circuit Welding of Carbon, Low-Alloy, and Stainless Steel Sheet.

Many welders set their parameters by an established mark on the equipment or by the sound of the arc as the weld is being made. The sound of the arc, influenced by the optimum current and voltage set, should be a consistent, smooth, crackling noise. If the SCT sound is harsh, the voltage should be increased slightly. If the sound is soft, the voltage should be decreased in volt increments until the sound becomes a smooth crackle. For welding metals thicker than 16 gage but less than 10 gage, the wire feed control should be moved to the eleven o'clock position (280 in./min), and the voltage reset to 18.

Welding of thicknesses less than 16 gage should be started with the wire feed control at the nine o'clock position (140 in./min) and the voltage control set to 16. The parameters discussed above apply when using argon mixtures containing 15 to 25 per cent CO<sub>2</sub>.

**GMAW Spray Transfer.**—In the spray transfer mode, spatter is often caused by the voltage being set so low that the electrode runs into the weld, resulting in expulsion of molten metal from the weld pool. GMAW spray transfer is normally used for welding carbon, low-alloy, and stainless steels of a minimum thickness of  $\frac{1}{8}$  in. (3.2 mm).

In Table 4, typical deposition rates with a 0.045-in. (1.2-mm) carbon steel electrode are compared with rates for larger carbon steel GMAW and flux-cored electrodes. These welds are typically carried out in the flat and horizontal positions. The practical GMAW electrode diameters commonly used for spray transfer are 0.035-in. (1-mm), 0.045-in. (1.2-mm), and 0.062-in. (1.6-mm) diameter. The most cost-effective GMAW electrode that also has the greatest range of applications on metals over  $\frac{3}{16}$  in. thick is the 0.045-in. (1.2-mm) diameter size.

**Table 4. Typical Deposition Rates for Carbon Steel Welding Electrodes**

| Electrode Diameter |       | Electrode Type | Amperage <sup>a</sup> | Deposit Rates |        |
|--------------------|-------|----------------|-----------------------|---------------|--------|
| in.                | (mm)  |                |                       | lb/h          | (kg/h) |
| 0.035              | (1.0) | GMAW           | 350                   | 11            | (5)    |
| 0.045              | (1.2) | GMAW           | 380                   | 13            | (6)    |
| 0.062              | (1.6) | GMAW           | 400                   | 14            | (6.4)  |
| $\frac{1}{16}$     | (1.6) | FCAW           | 350                   | 15            | (7)    |
| $\frac{3}{32}$     | (2.4) | FCAW           | 450                   | 16            | (7.3)  |

<sup>a</sup>The optimum ampere value for the electrode type is shown. The 0.045 GMAW electrode is the most versatile and cost-effective electrode for welding material of 14 gage to 1 in. thick.

**GMAW Spray Transfer Welding of Metal Thicknesses Less than  $\frac{1}{4}$  in. (6.4 mm).—**

The most versatile GMAW electrode for a welding shop that welds carbon, low-alloy, and stainless steels from 20 gage to  $\frac{1}{4}$  in. (6.4 mm) thick is the 0.035-in. (1.0-mm) diameter electrode. The traditional practical spray transfer current range of between 200 and 350 amps for the 0.035-in. electrode is well suited for welding thicknesses from 10 gage to  $\frac{1}{4}$  in. (6.4 mm).

The correct parameters for a 0.035-in. (1-mm) electrode and spray transfer welding are found on the wire feed unit between the one and five o'clock positions, or, on a digital wire feeder, between 420 and 700 in./min. In the drawing at the left in Fig. 2, the spray transfer wire feed range is shaded. When the wire feed rate has been set, the voltage should be fine-tuned so that the electrode wire tip is just touching the weld and a smooth crackling sound without spatter is produced.

An optimum single spray transfer mode current setting for a 0.035-in. (1-mm) diameter electrode for most welding applications is approximately 280 amps with the wire feed set at the three o'clock position for 560 in./min. Manual or high-speed mechanized welds on material of 10 gage to  $\frac{1}{4}$  in. thick can be made at the three o'clock wire feed position with only an adjustment for voltage, which should be set initially at 31 volts, when using an argon + CO<sub>2</sub> mixture.

**GMAW Spray Transfer for Metal Thicknesses  $\frac{1}{4}$  in. (6.4 mm) and Up.**—The 0.045-in. (1.2-mm) diameter is the most cost-effective GMAW electrode for spray transfer welding of carbon, low-alloy, and stainless steels  $\frac{1}{4}$  in. and thicker. A  $\frac{7}{16}$ -in. (11.2-mm) single-pass, no-weave, fillet weld can be produced with this electrode. If larger single-pass welds are required, use of flux-cored electrodes should be considered.



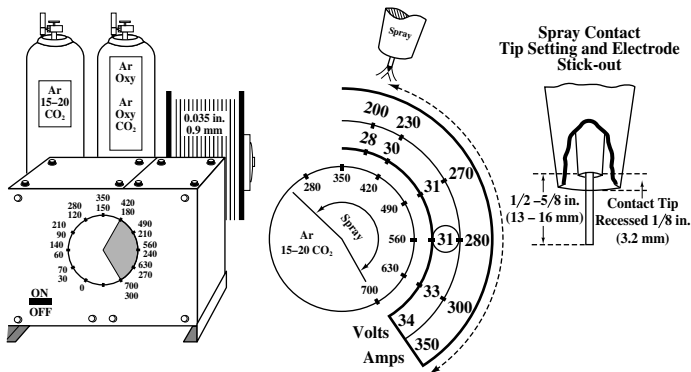


Fig. 2. GMAW Spray Transfer Parameters with 0.035-in. (0.9-mm) Diameter Electrodes

A 400-amp power source is a practical cost-effective unit to use with the 0.045-in. diameter electrode. Globular spray transfer, obtained at the ten o'clock position on the wire feed adjustment knob, starts at current levels of approximately 230 amps and requires a wire feed rate of approximately 210 in./min (90 mm/s). Most spray applications are carried out in the higher-energy, deeper-penetrating 270- to 380-amp range, or between twelve and two o'clock wire feed positions giving 350 to 490 in./min (150 to 210 mm/s). In this range, in which there is minimum weld spatter, the weld deposits are in the form of minute droplets and vaporized weld metal.

The quadrants at the top in Fig. 3 show some typical settings for feed rate, voltage, and current, with different shielding gases. An ideal starting point with a 0.045-in. (1.2-mm) diameter electrode is to set the wire feed rate knob at the one o'clock position, or 420 in./min, at which rate the current drawn, depending on the power source used, should be about 320 to 350 amps. The best starting voltage for the 0.045-in. (1.2-mm) electrode is 30 volts. The arc length should then be set as indicated in Fig. 4. With current over 400 amps at 560 in./min, the 0.045-in. diameter electrode may produce a turbulent weld puddle and a digging arc, which can lead to lack of fusion, porosity, and cracks.

**GMAW Spray Transfer with 0.062-in. (1.6-mm) Diameter Electrodes.**—Electrode wire of 0.062-in. (1.6-mm) diameter is the largest size in normal use and is often chosen for its high deposition rates. Due to the high-current requirements for the spray transfer mode, use of these thicker electrodes is generally restricted to metal thicknesses of  $\frac{1}{2}$  in. (13 mm) and thicker. The high-current requirement reduces ease of welding. This electrode size is suitable for mechanized welding in which fillet welds greater than  $\frac{3}{8}$  in. (9.6 mm) are required.

As indicated at the lower left in Fig. 3, the current range for 0.062-in. (1.6-mm) electrodes is narrow and most welds are made in the range of 360 to 420 amps, or between the ten and eleven o'clock positions on the wire feed control unit for 210 to 280 in./min (90 to 120 mm/s). The quadrants at the lower center and lower right in Fig. 3 show deposition rates in lb/h and kg/h for 0.045-in. (1.2-mm) and 0.062-in. (1.6-mm) diameter electrodes.

Some optimum settings for GMAW welding with a mixture of argon + 15 to 20 per cent  $\text{CO}_2$  gases are given in Table 5.

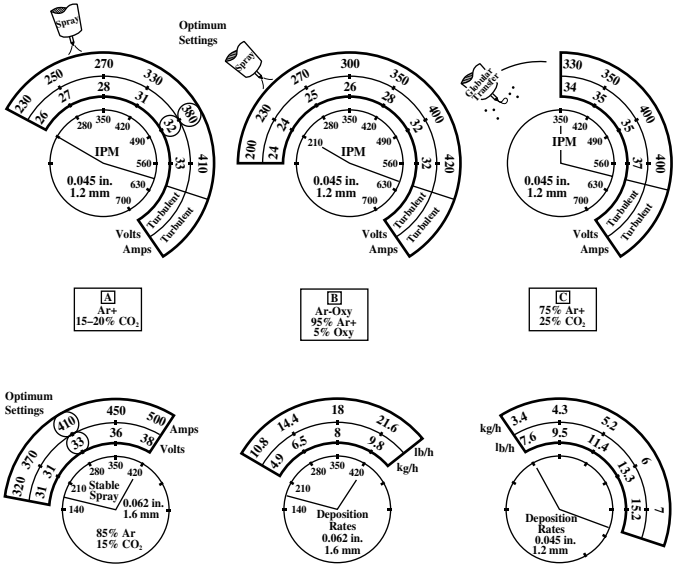


Fig. 3. GMAW Spray Transfer Parameters for Various Electrodes and Gases.

Table 5. Optimum Settings for GMAW with Argon + 15-20 per cent CO<sub>2</sub>

| Diameters |     | Mode           | Wire Feed Rates |       | Amps | Volts |
|-----------|-----|----------------|-----------------|-------|------|-------|
| in.       | mm  |                | in./min         | m/min |      |       |
| 0.035     | 1.0 | short circuit  | 210             | 5.3   | 140  | 17    |
|           |     | spray transfer | 560             | 14.2  | 280  | 29-30 |
| 0.045     | 1.2 | short circuit  | 210             | 5.3   | 190  | 18    |
|           |     | spray transfer | 420             | 10.7  | 380  | 30-31 |
| 0.052     | 1.4 | spray transfer | 280             | 7.1   | 370  | 31-32 |
| 0.062     | 1.6 | spray transfer | 280             | 7.1   | 410  | 31-32 |

*Note:* If argon + oxygen gas mixtures are used, voltage should be lowered by 1 to 4 volts for the spray transfer mode. The faster the weld travel speed, the lower the voltage required.

**Spray Transfer Voltage.**—The usual setting for spray transfer welding with commonly used electrode diameters is between 25 and 35 volts (see Fig. 4A). To set the optimum voltage for GMAW spray transfer, set the voltage initially so that it is too high, usually between 30 and 35 volts. With excess voltage, there should be a visible gap between the tip of the electrode and the weld, and the arc sound should be free from crackle. With the sequence shown in Fig. 4, the voltage should now be reduced until a consistent smooth crackle sound is produced. If the voltage is lowered too much, the electrode will run into the weld, making a harsh crackling sound, and the resulting weld expulsion will cause spatter.

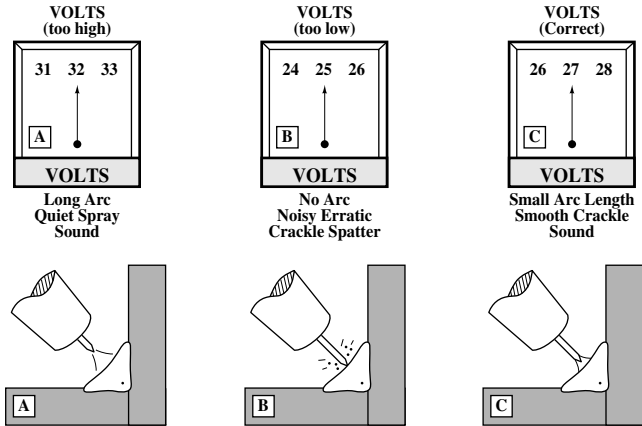


Fig. 4. Setting Optimum Voltage for GMAW Spray Transfer Welding.

### Flux-Cored Arc Welding

FCAW welding offers unique benefits for specific applications, but flux-cored consumable electrodes cost more than the solid electrodes used in gas metal arc welding, so users need to be aware of FCAW benefits and disadvantages compared with those of GMAW welding. Generally, flux-cored electrodes designed for use without a shielding gas are intended for welding outdoors. Most indoor FCAW welding is done with gas-shielded FCAW welding electrode wire. Some Standards for gas-shielded FCAW electrodes for various countries are listed in [Table 6](#).

**Table 6. Standards for Gas-Shielded, Flux-Cored Welding Electrodes**

| Steel Type        | Country        | Standard    |
|-------------------|----------------|-------------|
| Low-Carbon Steels | USA            | AWS A5.20   |
|                   | Canada         | CSA W48.5   |
|                   | Japan          | JIS Z3313   |
|                   | Germany        | DIN 8559    |
| Low-Alloy Steels  | USA            | AWS A5.29   |
|                   | Canada         | CSA W48.3-M |
|                   | United Kingdom | BS 639-2492 |
| Stainless Steels  | USA            | AWS A5.22   |

**All-Position, Gas-Shielded Electrodes.**—The term “all-position” does not necessarily mean that these electrodes are the best choice for all positions. Also, flux-cored electrodes may meet all standard specifications, but there will inevitably be subtle differences in weld transfer characteristics and recommended current, voltage, and other settings between electrodes made by different manufacturers. The chemistry and slag of the electrodes developed for welding in the flat and horizontal positions (E70T-X) typically provide superior results when they are used for flat and horizontal applications where the surface conditions of the plate are suspect or large, deep-penetrating welds are required. All-posi-

tion electrodes are intended for, and best used in, vertical and overhead welds. For extensive welding in flat or horizontal positions, the welder is better served with the electrodes designed for these specific positions.

All-position, gas-shielded FCAW electrodes provide unique benefits and potential for cost savings. In contrast with short-circuit GMAW, or pulsed GMAW, the all-position FCAW electrodes used for vertical up welding of carbon, low-alloy, or stainless steels are simpler to operate, are capable of greater weld quality, and will provide two to three times the rate of weld deposition. The electrode most commonly used in the USA for vertical up welding on carbon steels is the type E71T-1. The equivalent to the E71T-1 standardized electrode specification now in use in other countries include: Canada, E4801T9; Germany, SGR1; and Japan, YFW 24.

If the end user selects the correct all-position electrode diameter, the routine weaving of the electrode during vertical up and overhead applications may be minimized. Keeping the weld weave to a minimum reduces the skill level needed by the welder and increases the potential for consistent side-wall fusion and minimum porosity. If weaving is necessary, a straight-line oscillation technique is often preferred. Typical settings for welding with various sizes of gas-shielded FCAW electrodes are shown in [Table 7](#).

**Table 7. Typical Settings for Welding with Gas-Shielded FCAW Electrodes**

| Electrode Diameter |       | Vertical Up Welds               |                                 | Flat and Horizontal Welds       |                                 |
|--------------------|-------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| in.                | (mm)  |                                 |                                 |                                 |                                 |
| 0.035              | (1)   | Feed rate<br>Current<br>Voltage | 450 ipm<br>165 amps<br>28 volts | Feed rate<br>Current<br>Voltage | 630 ipm<br>250 amps<br>30 volts |
| 0.045              | (1.2) | Feed rate<br>Current<br>Voltage | 350 ipm<br>200 amps<br>25 volts | Feed rate<br>Current<br>Voltage | 560 ipm<br>280 amps<br>26 Volts |
| 0.052              | (1.4) | Feed rate<br>Current<br>Voltage | 240 ipm<br>200 amps<br>25 volts | Feed rate<br>Current<br>Voltage | 520 ipm<br>300 amps<br>30 volts |
| 0.062              | (1.6) | Feed rate<br>Current<br>Voltage | 210 ipm<br>240 amps<br>25 volts | Feed rate<br>Current<br>Voltage | 350 ipm<br>340 amps<br>29 volts |
| $\frac{3}{32}$     | (2.4) | ...                             |                                 | Feed rate<br>Current<br>Voltage | 210 ipm<br>460 amps<br>32 volts |

**Material Condition and Weld Requirements.**—Practical considerations for selecting a gas-shielded, flux-cored electrode depend on the material condition and weld requirements. FCAW electrodes are beneficial if the surface of the material to be welded is contaminated with mill scale, rust, oil, or paint; the fillet weld size is to be over  $\frac{3}{8}$  in. (9.6 mm) wide (a GMAW single-pass fillet weld with an electrode size of 0.045 in. is typically  $\frac{3}{8}$  in. wide); the weld is vertical up, or overhead; the required impact strengths and other mechanical properties are above normal levels; crack resistance needs to be high; and increased penetration is required.

**Selecting an FCAW Electrode.**—Selection of FCAW electrodes is simplified by matching the characteristics of flux-cored types with the material and weld requirements listed above. Once the correct electrode type is selected, the next step is to choose the optimum size. In selecting an all-position, flux-cored electrode for vertical up or overhead welding, the steel thickness is the prime consideration. Selecting the optimum electrode diameter allows the high current capability of the electrode to be fully used to attain maximum deposition rates and allows use of the highest penetrating current without concern for excessive heat-related problems during welding. When used in the optimum current range, the

deposited filler metal matches the required amount of filler metal for the specific size of the weld, determined by the plate thickness.

The following suggestions and recommendations are made for FCAW welding of carbon, low-alloy, and stainless steels having flat surfaces. For vertical up welds on steels of thicknesses from  $\frac{1}{8}$  to  $\frac{3}{16}$  in. (3.2 to 4.8 mm) and for vertical up welds on pipe in the thickness range of  $\frac{1}{4}$  to  $\frac{1}{2}$  in. (6.4 to 13 mm), consider the 0.035-in. (1.0-mm) diameter E71T-1 electrode. For vertical up welds on steels in the range of  $\frac{1}{4}$  to  $\frac{3}{8}$  in. (6.4 to 9.6 mm) thickness, consider the 0.045-in. (1.2-mm) diameter E71T-1 electrode or, in nonheat-sensitive applications, the 0.062-in. (1.6-mm) diameter E71T-1 electrode. For vertical up welds on steels of over  $\frac{3}{8}$  in. (9.6 mm) thickness, consider the 0.062-in. (1.6-mm) diameter E71T-1 electrodes for optimum deposition rates. For flat and horizontal welds on steels of  $\frac{3}{8}$  to  $\frac{3}{4}$  in. (9.6 to 19 mm) thickness, consider the  $\frac{1}{16}$ -in. (1.6-mm) diameter E70T-X electrodes. For flat and horizontal welds on steels over  $\frac{3}{4}$  in. (19 mm) in thickness, consider the  $\frac{3}{32}$ -in. (2.4-mm) E70T-X electrodes.

**FCAW Welding of Low-Carbon Steels.**—Low-carbon steel is usually called carbon steel or mild steel. The most-used FCAW electrode for welding carbon steels in the flat or horizontal welding positions is the type E70T-1, which is suited to welding of reasonably clean steel using single-pass or multi-pass welds. Type E70T-2 has added deoxidizers and is suited to surfaces with mill scale or other contamination. This type is used when no more than two layers of weld are to be applied. Type E70T-5 is used for single-pass or multi-pass welds where superior impact properties or improved crack resistance are required. The E70T-X electrodes typically range in size from 0.045 to  $\frac{3}{32}$  in. (1.2 to 2.4 mm) in diameter. Type E71T-1 all-position electrodes are available in diameters of 0.035 in. (1 mm) to 0.062 in. (1.6 mm). With the FCAW process, multi-pass welds are defined as a condition where three or more weld passes are placed on top of each other.

**Settings for Gas-Shielded, All-Position, FCAW Electrodes.**—The optimum setting range (volts and amps) for vertical up welding with all-position FCAW electrodes is rather narrow. The welder usually obtains the greatest degree of weld puddle control at the recommended low to medium current settings. The electrode manufacturers' recommended current range for an E71T-1 electrode of 0.045-in. (1.2-mm) diameter for vertical up welding may be approximately 130 to 250 amps. Using the 0.045-in. (1.2-mm) diameter electrode at 250 amps for a vertical up weld in  $\frac{1}{4}$ -in. (6.4-mm) thick steel, the welder may find that after 3 to 4 inches (75–100 mm) of weld, the weld heat built up in the steel being welded is sufficient to make the weld puddle fluidity increasingly difficult to control. Reducing the current to 160–220 amps will make it possible to maintain control over the weld puddle.

A typical optimum setting for a vertical up weld with an E71T-1, 0.035-in. (1.2-mm) diameter, all-position electrode is as follows. First, set the wire feed rate. If the wire feeder maximum rate is 650 to 750 in./min, the setting mark on the adjustment knob should be set between the one and two o'clock positions on the dial to obtain a feed rate of 450 in./min. If the wire feeder has a digital readout, the rate setting should be the same. At the 450-in./min setting, the welding current with the 0.035-in. all-position electrode should be optimized at between 160 and 170 amps. The welding voltage should be set at 27 to 28 volts with the electrode tip just touching the weld. If there is a gap causing the weld puddle to become too fluid, the voltage should be lowered. If the electrode runs into the weld, causing spatter, the voltage needs to be increased.

With the above conditions, welding steel of  $\frac{1}{8}$  to  $\frac{1}{4}$  in. thickness will deposit 5 to 7 lb/h (2.2 to 3 kg/h). The 0.035-in. electrode is also ideal for welding steel pipe with wall thicknesses of less than  $\frac{1}{2}$  in. (13 mm). The thickness of the pipe after bevelling controls the size

of electrode to be used. The 0.035-in. (6.4-mm) electrode can produce a  $\frac{1}{4}$ -in. (6.4-mm) vertical up fillet weld on such a pipe without weaving.

**Contact Tip Recess.**—The dimension labeled contact tip recess in Fig. 2, and indicated as  $\frac{1}{8}$  in., should be about  $\frac{1}{2}$  in. (13 mm) for a minimum electrode extension of  $\frac{3}{4}$  in. (19 mm), for FCAW welding. This dimension is critical for obtaining high-quality welds with all-position electrodes because they have a fast-freezing slag and operate with low to medium current and voltage. If the recess dimension is less than the optimum, the voltage may be lower than the minimum recommended, and if the settings are less than the minimum, the fast-freezing slag may solidify too rapidly, causing excess porosity or “worm tracks” on the weld surface.

The recommended length of electrode extension for all-position FCAW, E71T-1 electrodes is  $\frac{3}{4}$  to 1 in. (19 to 25 mm). The size of this extension not only affects the minimum required parameters, but a long electrode extension also ensures preheating of the electrode and allows lower current to be used. Preheating the electrode is further beneficial as it reduces moisture on the electrode surface, and in the electrode flux. When a change is made from the GMAW to the FCAW process, welders must be aware of the influence on weld quality of the electrode extension in the FCAW process.

**Porosity and Worm Tracks.**—As mentioned above, porosity and worm tracks typically result from a combination of incorrect electrode extension, incorrect welding settings, humidity, electrode moisture, refill scale, rust, paint, oils, or poor welding technique. Where humidity levels are high, potential for porosity and worm tracks increases. The FCAW process is less sensitive to mill scale than the GMAW spray transfer mode but mill scale will often cause excess weld porosity. The best way to avoid the effects of mill scale, rust, oil, and surface contaminants is to grind the area to be welded.

Another way to reduce porosity is to keep weaving to a minimum. If the correct size flux-cored electrode is used, weaving can be kept to a minimum for most flux-cored applications. The forehand technique produces the best weld bead surface on fillet weld beads up to  $\frac{3}{4}$  in. (19 mm) steel thickness in the flat and horizontal weld positions. On larger single-pass fillet welds, the backhand technique is beneficial because the voltage directed at the weld provides additional weld puddle control to the fluid welds. The backhand technique used for flat and horizontal welds produces a more convex weld bead, reduces potential for porosity, and increases penetration.

If porosity or worm tracks occur, the prime solution is in weld practices that increase heat at the weld, but the following remedies can also be tried. Grind clean the surface to be welded; use recommended electrode extensions; increase current (wire feed rate) decrease voltage; use the backhand welding technique; slow down travel speed, consider use of a different electrode formulation containing increased deoxidizers, avoid weaving; change from argon + CO<sub>2</sub> mixture to straight CO<sub>2</sub>; and provide a protective cover to keep the electrode spool clean and dry.

**Welding with 0.045-in. (1.2-mm) Diameter All-Position Electrodes.**—Fig. 5 shows wire feed settings for welding of steel with 0.045-in. (1.2-mm) diameter, E71T-1 all-position electrodes using a mixture of argon + 15 to 25 per cent CO<sub>2</sub> as the shielding gas, and an electrode extension of  $\frac{3}{4}$  in. (18 mm). Parameters for vertical up welding, shown at the left in Fig. 5, include setting the wire feed rate at the twelve o'clock position, or about 350 in./min, using 200 to 190 amps, and setting the voltage between 24 and 25 volts. Optimum parameters for flat welding, shown at the right in Fig. 5 include setting the wire feed rate at three o'clock position, or 560 in./min (240 mm/s), and 270 amps at 25 to 27 volts.

**Welding with 0.052-in. (1.3-mm) Diameter All-Position Electrodes.**—Settings for vertical up and flat welding with all-position E71T-1 electrodes of 0.052-in. (1.3-mm) diameter are seen at the left in Fig. 6. These electrodes are suited to welding steel having

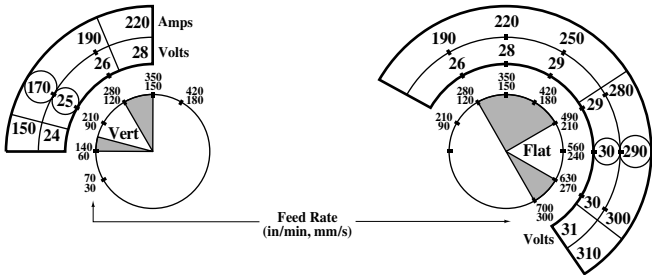


Fig. 5. Wire Feed and Voltage Settings for FCAW Welding with 0.045-in. (1.2-mm) Diameter E71T-1 Electrodes. Optimum settings are circled.

thicknesses of  $\frac{1}{4}$  in. (6 mm) and thicker. For vertical up welding, the wire feed rate is set between the ten and eleven o'clock positions, or 250 in./min (106 mm/s), with about 200 amps at 25 volts. Flat welding with these electrodes is best done with the wire feed rate set between the two and three o'clock positions, or 490 to 560 in./min (207 to 237 mm/s), giving approximately 300 amps at 28 volts.

Settings for all-position E71T-1 electrodes of 0.062-in. (1.6-mm) diameter, shown at the right in Fig. 6, for vertical up welding are just before the ten o'clock position, or 190 in./min, giving 230 to 240 amps with voltage adjusted to 24–25 volts. For flat welding, the wire feed is set to the twelve o'clock position, giving 340–350 amps with a voltage of 29–30 volts.

**High-Deposition, All-Position Electrodes.**—Vertical up weld deposition rates of 10 to 14 lb/h can be achieved with the E71T-1, 0.062-in. (1.6-mm) and 0.045-in. (1.2-mm) flux-cored electrodes. Settings are shown in Fig. 6 for E71T-1, FCAW electrodes of 0.052- and 0.062-in. (1.4- and 1.6-mm) diameter. These electrodes are suited to applications in which the steel thickness is  $\frac{1}{4}$  in. and thicker, and are the most cost-effective diameter for all-position welds on carbon and stainless steels of  $\frac{1}{4}$  in. (6.35 mm) thickness and thicker. In contrast, vertical up welds, using GMAW or SMAW, may deposit an average of 2 to 4 lb/h (1 to 2 kg/h). Deposition rates are based on welding 60 minutes of each hour. Pulsed GMAW provides deposition rates of 3 to 6 lb/h (1.3-2.7 kg/h). Average rates for vertical up welding with all-position, flux-cored electrodes are shown in Table 8.

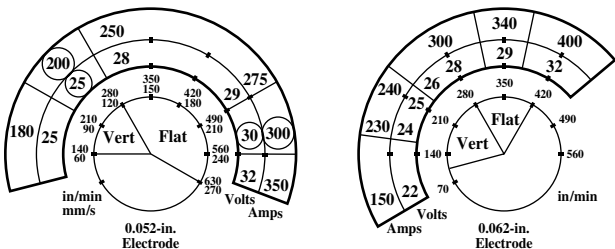


Fig. 6. Wire Feed and Voltage Settings for Vertical Up Welding with 0.052- and 0.062-in. Diameter Electrodes

The average deposition rates in Table 9 are to be expected with FCAW electrodes available today. Special electrodes are also available that are specifically designed to provide higher deposition rates. A typical manual welder, welding on steel of  $\frac{1}{4}$  to  $\frac{3}{8}$  in. thickness for 30 minutes of each hour with an all-position flux-cored 0.062-in. (1.6-mm) or 0.045-in. (1.2-mm) diameter electrode would deposit about 4–5 lb/h.

**Table 8. Deposition Rates for Vertical Up Welding with All-Position, Flux-Cored Electrodes (ET71T-1)**

| Electrode Diameter |       | Typical Deposition Rate Range |           | Average Deposition Rate |        |
|--------------------|-------|-------------------------------|-----------|-------------------------|--------|
| in.                | (mm)  | lb/h                          | (kg/h)    | lb/h                    | (kg/h) |
| 0.035              | (1)   | 2.7–6.5                       | (1.2–3)   | 5                       | (2.3)  |
| 0.045              | (1.2) | 5–11                          | (2.3–5)   | 8                       | (3.6)  |
| 0.052              | (1.4) | 4–8                           | (1.8–3.6) | 6.5                     | (3)    |
| 0.062              | (1.6) | 4–11                          | (1.8–5)   | 8.5                     | (4)    |

**Table 9. Average Deposition Rates for Flat and Horizontal Welds**

| Process             | Electrode Size |       | Cost-Effective Current Range (amps) | Optimum Current (amps) | Deposition Rate |        |
|---------------------|----------------|-------|-------------------------------------|------------------------|-----------------|--------|
|                     | in.            | (mm)  |                                     |                        | lb/h            | (kg/h) |
| GMAW spray transfer | 0.035          | (1)   | 250–350                             | 285                    | 9               | (4)    |
|                     | 0.045          | (1.2) | 300–400                             | 385                    | 13              | (5.9)  |
|                     | 0.052          | (1.4) | 350–470                             | 410                    | 11              | (5)    |
|                     | 0.062          | (1.6) | 375–500                             | 450                    | 17              | (7.7)  |
| FCAW                | 0.045          | (1.2) | 225–310                             | 300                    | 14              | (6.4)  |
|                     | 0.052          | (1.4) | 260–350                             | 310                    | 15              | (6.8)  |
|                     | 0.062          | (1.6) | 300–400                             | 340                    | 15              | (6.8)  |
|                     | $\frac{3}{32}$ | (2.4) | 380–560                             | 460                    | 17              | (7.7)  |

The average deposition rates of pulsed GMAW and FCAW for vertical up welds are similar for applications where the steel thickness is  $\frac{1}{8}$  in. (3.2 mm) or less. On steels thicker than  $\frac{1}{8}$  in., where the current may be increased, and larger-diameter all-position FCAW electrodes may be used, deposition rates will be much greater than with pulsed GMAW. Compared with GMAW electrodes for pulsed welding, FCAW all-position electrodes require less costly equipment, less welding skill, and have potential for increased weld fusion with less porosity than with GMAW pulsed techniques.

**Electrode Diameters and Deposition Rates.**—A cost-effective welding shop can achieve deposition rates on flat and horizontal welds of 12 to 15 lb/h (5 to 7 kg/h) with both the GMAW 0.045-in. wire and the 0.062-in. flux-cored wire electrodes, without welder discomfort, and with welds of consistent quality.

The first consideration in selecting the optimum size of gas-shielded FCAW E70T-X electrode for manual flat and horizontal welds on steels thicker than  $\frac{1}{4}$  in. (6.4 mm) is the current requirements needed to achieve deposition rates of 12 to 15 lb/h (5 to 7 kg/h). Large-size electrodes of  $\frac{3}{32}$ -in. (2.4-mm) diameter require 500 amps or more to attain optimum deposition rates. These  $\frac{3}{32}$ -in. diameter electrodes are often used with power sources in the 300–400 amp range, but even when the power source provides 500 to 600 amps, welding is often performed at the low end of the electrode's current requirements. With the large,  $\frac{3}{32}$ -in. diameter electrodes, welder appeal is low, smoke is often excessive, and deposition rates are often only comparable with smaller, easier-to-operate FCAW electrodes.



Typical deposition rates for flat and horizontal welds with various electrode sizes and weld settings are shown in [Table 9](#). In connection with this table, it may be noted that high deposition rates in welding steel plate thicker than  $\frac{1}{4}$  in. require use of currents above the minimum shown for the various sizes of electrodes. The optimum current requirements for the most popular electrode sizes indicate that a 450-amp power source is the most suitable for welding steel of more than  $\frac{1}{4}$  in. thickness. The two most cost-effective and versatile consumables for thin and thick steel sections are the 0.045 in. for GMAW and the 0.062 in. for FCAW electrodes.

The approach to a welding application is critical to achievement of optimum weld quality at minimum cost. In many applications, minimal consideration is given to weld costs. Half of every man-hour of welding in many shops could be saved with selection of the correct electrode diameter used with optimum parameter settings. A practical point that is often overlooked in selection of FCAW electrodes is that the larger the electrode diameter, the more restricted is the application thickness range. Large FCAW electrodes such as the  $\frac{3}{32}$  in. (2.4 mm) are neither suitable nor cost-effective for the common steel thickness range of  $\frac{1}{4}$  to  $\frac{1}{2}$  in. (6.4 to 13 mm). Smaller FCAW electrodes such as the  $\frac{1}{16}$ -in. (1.6-mm) diameter, are suitable for both thin and thick applications. A  $\frac{1}{16}$ -in. diameter FCAW electrode used in the 300- to 350-amp range provides excellent deposition rates with superior welder appeal and negligible smoke.

Large-diameter  $\frac{3}{32}$ -in. (2.4-mm) electrodes are popular for manual applications. However, from a practical point of view, this electrode size is often better suited to mechanized high-current welding in which the high currents required for optimum deposition rates may be safely used without health risks. Use of an electrode at 60 to 80 per cent of its welding current capability indicates that the correct diameter electrode has been selected for the application. When an electrode is used at its maximum-current capability, it shows that the next size larger electrode should be preferred, and when the low end of the current capability is in use, the electrode selected is typically too large.

**The 0.062-in. (1.6-mm) Diameter, E70T-X Electrode.**—The 0.062-in. (1.6-mm) diameter FCAW electrode is the most practical size of its type and will provide excellent deposition rate potential with a practical current range and the broadest application range. Settings for the common  $\frac{1}{16}$ -in. diameter E70T-1 electrode are shown in [Fig. 7](#). With the GMAW process, a  $\frac{3}{8}$ - to  $\frac{1}{16}$ -in. (9.6- to 11-mm) minimum-weave fillet weld is typically the maximum size that can be made in a single pass. The 0.062-in. ( $\frac{1}{16}$ -in., 1.6-mm) FCAW electrode can easily produce a  $\frac{3}{4}$ -in. (19-mm), nonweave, single-pass fillet weld. This size of electrode is also a practical choice for welding steel of  $\frac{1}{4}$  in. (6.4 mm) or greater thickness. From a cost perspective, FCAW consumable electrodes should be used whenever the GMAW process is not suitable.

The average deposition efficiency of a flux-cored electrode is 85 per cent, which means that for every 100 lb or kg of electrode material used, 85 lb or kg ends up as weld material. In contrast, the average deposition efficiency of a GMAW electrode used with argon mixtures and correct equipment settings should be a minimum of 99 per cent.

**Shielding Gases and FCAW Electrodes.**—The E70T-X flux-cored electrodes that are recommended for flat and horizontal welds use  $\text{CO}_2$  gas shielding. Because of new OSHA welding smoke restrictions, manufacturers of FCAW electrodes now provide E70T-X consumable electrodes that can be used with less reactive argon +  $\text{CO}_2$  mixtures to reduce smoke levels. The fast-freezing slag, all-position, E71T-1 flux-cored electrodes can use either  $\text{CO}_2$  or argon + 15 to 25 per cent  $\text{CO}_2$  mixtures for welding carbon, low-alloy, or stainless steels. The argon +  $\text{CO}_2$  mixture is often selected because it provides the highest energy from a reactive gas mixture with a compatible voltage range.

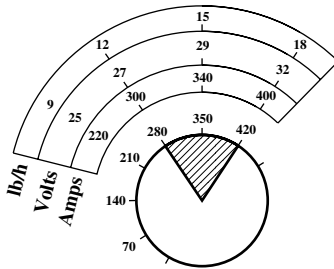


Fig. 7. Settings for  $\frac{1}{16}$ -in. (1.6-mm) FCAW, E70T-X Electrodes.

Instead of  $\text{CO}_2$ , welders often prefer the arc characteristics, lower smoke levels, and lower voltage requirements of the argon +  $\text{CO}_2$  mixtures for all-position welding. However, if lower reactive argon mixtures such as argon + oxygen, or argon with less than 13 per cent  $\text{CO}_2$ , are used, the weld voltage requirements and the arc plasma energy are reduced, adding to the possibility of changing the mechanical properties significantly, increasing the porosity, and raising the potential for forming worm tracks.

### Shielded Metal Arc Welding

With the shielded metal arc welding (SMAW) process, commonly known as stick welding, it is most important to select an electrode that is suited to the application. For welding austenitic stainless or high-alloy steels, the electrode is first selected to match the mechanical and chemical requirements of the metal to be welded. Secondary requirements such as the welding position, penetration potential, deposition capabilities, and ease of slag removal are then considered. Many electrodes for SMAW welding of low- to medium-carbon steels have unique characteristics making them the most suitable and cost-effective for a specific welding application.

In interpreting the ANSI/AWS Standard specification code for SMAW electrodes shown in Table 10, for example, E60XX, the E stands for a low-carbon steel, metal arc welding electrode. The next two digits, such as 60 or 70, indicate the approximate tensile strength of the weld deposit in thousands of psi.

Of the last two digits, the first indicates the usability as follows: 1 = usable in all welding positions; 2 = usable for flat or horizontal positions; and 3 = usable in flat position only.

The final digit, combined with the above, indicates the type of flux coating, as shown in Table 10.

British Standard BS 639:1986 defines requirements for covered carbon- and carbon-manganese-steel electrodes for manual metal arc welding, depositing weld metal having a tensile strength of not more than  $650 \text{ N/mm}^2$ . Appendix A of this standard lists minimum mandatory and optional characteristics of these electrodes. The extensive classifications provide for electrodes to be rated for strength, toughness, and covering (STC), with codes such as E 51 5 4 BB [160 3 0 H]. In this series, E indicates that the electrode is covered and is for manual metal arc welding. The next two digits (51) indicate the strength (tensile, yield, and elongation) properties. The next digits (5 and 4) give the temperatures at which minimum average impact strengths of 28J (at  $-40^\circ\text{C}$ ) and 47J (at  $-30^\circ\text{C}$ ), using Charpy V-notch test specimens, are required. The next group is for the covering and the BB stands for basic, high efficiency. Other letters are B for basic; C for cellulosic; R for rutile, RR for rutile, heavy coated; and S for other.

**Table 10. Significance of Digits in ANSI/AWS A5.18-1979 Standard**

| Third and Fourth Digits | Flux Type and Characteristics, SMAW Electrodes  |
|-------------------------|---|
| 10                      | High-cellulose coating bonded with sodium silicate. Deep penetration, energetic spray-type arc. All-positional, DCEP <sup>a</sup> only                              |
| 11                      | Similar to 10 but bonded with potassium silicate to permit use with AC or DCEP  |
| 12                      | High-rutile coating, bonded with sodium silicate. Quiet arc, medium penetration, all-positional, AC or DCEN   |
| 13                      | Similar to 12 but bonded with sodium silicate and with easily ionized materials added. Gives steady arc on low voltage. All-positional, AC or DCEN                  |
| 14                      | Similar to 12 with addition of medium amount of iron powder. All-positional, AC or DC   |
| 15                      | Lime-fluoride coating (basic low-hydrogen) bonded with sodium silicate. All-positional. For welding high-tensile steels. DCEP only                                  |
| 16                      | Similar to 15 but bonded with potassium silicate. AC or DCEP  |
| 18                      | Similar to 15 but with addition of iron powder. All-positional, AC or DC  |
| 20                      | High iron-oxide coating bonded with sodium silicate. Flat or HV positions. Good X-ray quality. AC or DC   |
| 24                      | Heavy coating containing high percentage of iron powder for fast deposition rates. Flat and horizontal positions only. AC or DC                                     |
| 27                      | Very heavy coating with ingredients similar to 20 and high percentage of iron powder. Flat or horizontal positions. High X-ray quality. AC or DC                    |
| 28                      | Similar to 18 but heavier coating and suited for use in flat and HV positions only. AC or DC  |
| 30                      | High-iron-oxide-type coating but produces less fluid slag than 20. For use in flat position only (primarily narrow-groove butt welds). Good X-ray quality. AC or DC |

<sup>a</sup> DC = direct current, AC = alternating current, EP = electrode positive, EN = electrode negative.

The letters in brackets are optional, and the first group indicates the efficiency, which is the ratio of the mass of weld metal to the mass of nominal diameter core wire consumed with the largest diameter electrode, rounded up to the nearest multiple of 10. The next digit (3) is the maker's advice for the position(s) to be used. Codes for this category include 1, all positions; 2, all positions except vertical down; 3, flat, and for fillet welds, horizontal/vertical; 4, flat; 5, flat, vertical/down; and for fillet welds, horizontal/vertical; and 9, other. The digit at (0), which may have numbers from 0 to 9, shows the polarity, and the minimum open-circuit voltage to be used for that electrode. A 0 here indicates that the electrode is not suited for use with AC. The (H) is included only for hydrogen-controlled electrodes that will deposit not more than 15 ml of diffusible hydrogen for each 100 g of deposited weld metal. The corresponding ISO Standard for BS 639 is ISO 2560. Low-alloy steel electrodes and chromium and chromium nickel steel electrodes are covered in BS 2493 and BS 2926.

The most common electrodes used for the SMAW process are the AWS types E60XX and E70XX. SMAW welding electrode Standards are issued by the American Welding Society (AWS), the British Standards Institute (BS), Canada (CSA), Germany (DIN), and Japan (JIS) and are shown in [Table 11](#).

**AWS E60XX Electrodes.**—Characteristics of the E60XX electrodes influence the weld position capability, ease of slag removal, penetration potential, weld travel speed capability, and weld deposition rates. These electrodes are designed for welding low-carbon steels and they provide welds with typical tensile strength in the range of 58,000 to 65,000 lb/in<sup>2</sup>,

depending on the specific electrode utilized, the base metal condition and chemistry, and the amount of weld dilution. In selecting an electrode for SMAW welding, knowing that the mechanical and chemical requirements have been matched, it is necessary to choose electrodes with characteristics that influence the features required, as shown in Table 11.

**Table 11. Characteristics of SMAW Welding Electrodes Made to Standards of Various Countries**

| Standard  | Description  |
|---|--|
| AWS E6010<br>CSA E41010<br>BS E4343C10<br>DIN E4343C4<br>JIS        | Designed for welding pipe and general structures. Excellent for all-position and vertical down welding. Slag is light and easy to remove. Deep, penetrating arc. Low deposition rates. Polarity DC + (electrode positive).   |
| AWS E6011<br>CSA E41011<br>BS E4343C13<br>DIN E4343C4<br>JIS D4311  | Similar to E6010 but modified to allow use of AC. Excellent for welding sheet metal corner joints vertical down. Polarity AC or DC + (electrode positive).   |
| AWS 6012<br>CSA E41012<br>BS E4332R12<br>DIN E4332R(C)<br>JIS D4313 | Designed for welding sheet metal and light structural steels. Medium penetration suitable for gaps or where minimum weld dilution is needed. Ideal for flat, horizontal, or vertical down welding. Will weld faster than the E6010-11 electrode. Polarity AC or DC—(electrode negative). |
| AWS E6013<br>CSA E41013<br>BS E4332R21<br>DIN E4332R3<br>JIS D4313  | Excellent AC or DC—performance. All-position. Shallow penetration. Good choice for low open-circuit welding machines. AC or DC both excellent on thin structural applications. Polarity AC or DC (DC both polarities).   |
| AWS 6027<br>CSA 41027<br>BSE4343A13035<br>DIN 4343AR11<br>JIS D4327 | Iron powder is added to the flux to provide higher deposition rates. Ideal for multipass groove and fillet welding in flat and horizontal positions. Polarity AC or DC (both polarities).  |

Table 12 shows approximate current requirements for AWS E60XX electrodes for welding sheet metal carbon steels. The current ranges specified vary slightly with different electrode manufacturers. For welding sheet metal start at the low end of the given current requirements with electrodes of  $\frac{3}{16}$ -in (5-mm) diameter or smaller. For metals thicker than 10 gage (0.134 in.), start in the center of the current range, then adjust to suit. A high DC current may result in arc blow, and improved results may then be obtained with AC.

**Table 12. Diameters of AWS E6010/E6011 SMAW Electrodes for Welding Low-Carbon Steel Sheet Metal**

| SWG of Sheet Metal to be Welded | Electrode Diameter |       | Current Starting Level (amps) |
|---------------------------------|--------------------|-------|-------------------------------|
|                                 | in.                | (mm)  |                               |
| 18                              | $\frac{3}{32}$     | (2.5) | 45–60                         |
| 16–14                           | $\frac{1}{8}$      | (3.2) | 80–110                        |
| 12                              | $\frac{5}{32}$     | (4)   | 125–135                       |
| 10                              | $\frac{3}{16}$     | (5)   | 135–150                       |

For welding thicker materials, a good starting setting is in the middle of the current range shown in Table 12. In welding material less than  $\frac{1}{4}$ -in. (6.4-mm) thick, vertically, with an E6010 electrode, try a  $\frac{1}{8}$ -in. (3.2-mm) electrode at 90 to 100 amps. For welding thicknesses between  $\frac{3}{16}$  and  $\frac{5}{16}$  in. (5 and 8 mm) with the E6010 electrode, vertically, try the  $\frac{5}{16}$ -in. (8-mm) diameter electrode at 100 to 125 amps. For thicknesses of  $\frac{3}{8}$  to 1 in. (9.5 to 25 mm), try a  $\frac{3}{16}$ -in. (5-mm) diameter electrode at 155 to 165 amps.

Recommended current ranges, shown in Table 13 for the various sizes of AWS E60XX electrodes most commonly used for welding carbon steel, will give optimum results with SMAW electrodes. An ideal starting point for the current setting for any SMAW electrode diameter is in the middle of the range. The current ranges shown are average values taken from literature of electrode manufacturers in three different countries.

**Table 13. Current Ranges for AWS E60XX SMAW Electrodes**

| Electrode Diameter |       | E6010/E6011 | E6012   | E6013   | E6027   |
|--------------------|-------|-------------|---------|---------|---------|
| in.                | (mm)  | (amps)      | (amps)  | (amps)  | (amps)  |
| $\frac{1}{16}$     | (1.6) | ...         | 25–50   | 20–40   | ...     |
| $\frac{3}{32}$     | (2.5) | 40–75       | 40–100  | 50–100  | ...     |
| $\frac{1}{8}$      | (3.2) | 75–130      | 85–140  | 75–135  | 120–180 |
| $\frac{5}{32}$     | (4)   | 90–170      | 115–185 | 110–185 | 155–245 |
| $\frac{3}{16}$     | (5)   | 135–220     | 145–240 | 150–235 | 200–300 |
| $\frac{1}{4}$      | (6.4) | 205–325     | 250–390 | 240–340 | 300–410 |
| $\frac{5}{16}$     | (8)   | 260–420     | 290–480 | 310–425 | 370–480 |

**AWS E70XX Electrodes.**—Information on the most commonly used AWS E70XX electrodes is given in Table 15. For critical welding applications, low-hydrogen electrodes are typically used. It is most important that manufacturers' instructions regarding storage requirements for keeping low-hydrogen electrodes free from moisture are followed. Current ranges for welding low-carbon steel sheet metal with E70XX electrodes of diameters from  $\frac{3}{32}$  to  $\frac{3}{16}$  in. (2.5 to 5 mm) are shown in Table 14. The optimum starting point is in the middle of the current range indicated.

**Table 14. Current Ranges for SMAW E70XX Welding Electrodes**

| Electrode Diameter |       | E7014   | E7018   | E7024   |
|--------------------|-------|---------|---------|---------|
| in.                | (mm)  | (amps)  | (amps)  | (amps)  |
| $\frac{3}{32}$     | (2.5) | 75–120  | 70–105  | 85–135  |
| $\frac{1}{8}$      | (3.2) | 110–155 | 110–160 | 130–180 |
| $\frac{5}{32}$     | (4)   | 145–210 | 150–215 | 175–240 |
| $\frac{3}{16}$     | (5)   | 190–280 | 180–275 | 230–315 |
| $\frac{7}{32}$     | (5.5) | 255–335 | 255–350 | 280–370 |
| $\frac{1}{4}$      | (6.4) | 330–415 | 295–360 | 325–450 |
| $\frac{5}{16}$     | (8)   | 380–490 | 370–480 | 390–530 |

In using AWS E7018 electrodes for vertical up welding of plate thicknesses of  $\frac{3}{16}$  to  $\frac{5}{16}$  in. (5 to 8 mm), try a  $\frac{1}{8}$ -in. (3.2-mm) diameter electrode. For vertical up welding of thicknesses greater than  $\frac{5}{16}$  in. (8 mm), try a  $\frac{5}{32}$ -in. (4-mm) electrode. With AWS E7018 electrodes, to make horizontal fillet welds in plate thicknesses of 10 swg (0.135 in., 3.4 mm), try a  $\frac{3}{16}$ -in. (5-mm) electrode, for  $\frac{1}{4}$ -in. (6.4-mm) plate, try the  $\frac{7}{32}$ -in. (5.5-mm) electrode, and for steel plate thicker than  $\frac{1}{4}$  in., try the  $\frac{1}{4}$ -in. (6.4-mm) diameter electrode.

**Table 15. Characteristics of AWS Electrodes for SMAW Welding**

| Standard   | Description   |
|--|---|
| AWS E7014<br>CSA E48014<br>BS E5121RR11011<br>DIN E5121RR8<br>JIS D4313      | An iron-powder, all-position electrode for shallow penetration. Excellent for vertical down and applications with poor fit. Similar to AWS E6012-E6013 with added iron powder. For welding mild and low-alloy steels. Polarity AC or DC, + or -.                              |
| AWS E7018<br>CSA E48018<br>BS E5154B11026(H)<br>DIN E5154B(R)10<br>JIS D5016 | An iron-powder, low-hydrogen, all-position electrode. Excellent for rigid, highly stressed structures of low- to medium-carbon steel. Can also be used for welding mild and high-strength steels, high-carbon steels, and alloy steels. Polarity AC or DC + reverse polarity. |
| AWS 7024<br>CSA E48024<br>BS E5122RR13034<br>DIN E5122RR11<br>JIS D4324      | An iron-powder electrode with low hydrogen, usable in all positions. Excellent for high-amperage, large, fillet welds in flat and horizontal positions. Polarity AC or DC, + or -.  |
| AWS E7028<br>CSA E48028<br>BS E514B12036(H)<br>DIN E5143B(R)12<br>JIS D5026  | An iron-powder, low-hydrogen electrode suitable for horizontal fillets and grooved flat position welding. Higher deposition rates. More cost-effective than the AWS E7018 electrode. Polarity AC or DC + reverse polarity.  |

The E7024 electrode is suggested for horizontal fillet welds. For 10-gage (0.135-in, 3.4-mm) material, try the  $\frac{1}{8}$ -in. (3.2-mm) diameter electrode; for above 10-gage to  $\frac{3}{16}$ -in. (5-mm) material, try the  $\frac{5}{32}$ -in. (4-mm) diameter electrode. For plate of  $\frac{3}{16}$ - to  $\frac{1}{4}$ -in. thickness, try the  $\frac{3}{16}$ -in. size, and for plate thicker than  $\frac{1}{4}$  in., try the  $\frac{1}{4}$ -in. (6.4-mm) electrode.

### Gas Tungsten Arc Welding

Often called TIG (for tungsten inert gas) welding, gas tungsten arc welding (GTAW) uses a nonconsumable tungsten electrode with a gas shield, and was, until the development of plasma arc welding (PAW), the most versatile of all common manual welding processes. Plasma arc welding is a modified GTAW process. In contrast to GTAW, plasma arc welding has less sensitivity to arc length variations, superior low-current arc stability, greater potential tungsten life, and the capability for single-pass, full-penetration welds on thick sections.

In examining a potential welding application, the three primary considerations are: achieving a quality weld, ease of welding, and cost. Selecting the optimum weld process becomes more complex as sophisticated electronic technology is applied to conventional welding equipment and consumable electrodes. Rapid advances in gas metal arc and PAW welding power source technology, and the development of many new flux-cored electrodes, have made selection of the optimum welding process or weld consumable more difficult. When several manual welding processes are available, the logical approach in considering GTAW for production welding is to first examine whether the job can be welded by gas metal arc or flux-cored methods.

**GTAW Welding Current.**—A major benefit offered by GTAW, compared with GMAW, FCAW, or SMAW, is the highly concentrated, spatter-free, inert heat from the tungsten arc, which is beneficial for many applications. The GTAW process can use any of three types of welding current, including: direct-current straight polarity, electrode negative (DC-), direct-current reverse polarity, electrode positive (DC+), alternating current with high frequency for arc stabilization (ACHF). Each of the different current types provides benefits that can be used for a specific application.

**GTAW Direct-Current Straight Polarity (DC-):** The most common GTAW current is straight polarity, where the electrode is connected to the negative terminal on the power source and the ground is connected to the positive terminal. Gas tungsten arc welding is used with inert gases such as argon, and argon + helium to weld most metals. During a DC- straight-polarity weld, electrons flow from the negative tungsten electrode tip and pass through the electric field in the arc plasma to the positive workpiece, as shown in Fig. 8.

Plasma is a high-temperature, ionized, gaseous column that is formed when electrons in the arc collide with the shielding gas molecules. The gas atoms lose one or more electrons, leaving them positively charged. The electrons and the resulting plasma are concentrated at the electrode tip, where they cause the plasma pressure to be at its greatest. The electron density thins out as the electrons travel from the straight-polarity, negatively charged, tungsten electrode across the open arc. As the electrons traverse the arc to the work, the resulting arc column width increases slightly, controlled in part by the electromagnetic forces generated by the current. With the increase in the arc column width, the density and pressure of the plasma decrease. The electrons collide with the work, liberating much heat. The downward pressure of the plasma is exerted against the surface of the weld pool. The gas ions in the plasma are positively charged and greater in mass than the electrons.

In DC-, straight-polarity welding, the positive gas ions are drawn to the negative electrode. The electron flow to the weld ensures that most of the arc heat is generated at the positive work side of the arc. This current setup provides maximum penetration potential, as indicated in Fig. 8. With DC-, straight polarity, the tungsten electrode can carry a higher current and operate at lower temperatures than with the other current arrangements.

**Direct-Current Reverse Polarity (DC+):** With direct-current positive polarity (DC+), the tungsten electrode is connected to the power-source positive terminal so that the electrons flow from the negative work to the positive electrode. As illustrated in Fig. 9, the electrons impinging on the electrode tip reverse the direction of the heat concentration that occurs with straight polarity, as described above. Approximately two-thirds of the heat generated with DC+ reverse polarity is at the electrode tip, and the electrode becomes very hot, even with low current levels. DC+ reverse polarity requires large-diameter electrodes.

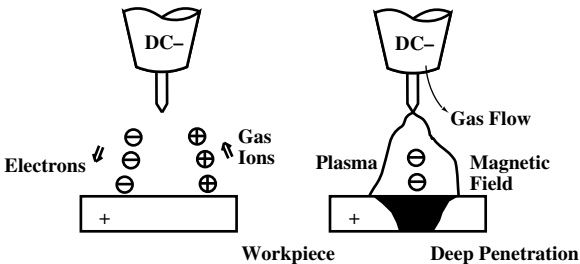


Fig. 8. Straight Polarity (DC-) Provides Highest Electrode Current Capacity and Deepest Penetration Potential.

In the current range of 100 to 150 amps, DC+ reverse polarity requires a  $\frac{1}{4}$ -in. (6.4-mm) diameter electrode. This larger electrode produces a weld puddle almost twice as wide as that produced by a 120-amp,  $\frac{1}{16}$ -in. (1.6-mm) diameter, DC- straight polarity electrode. Most of the heat is generated at the electrode tip with DC+ reverse polarity, so penetration is much less than with DC- straight polarity. With DC+ reverse polarity, the positive gas ions in the arc plasma are drawn to the negative workpiece where they bombard and break up the surface oxides that form on metals such as aluminum and magnesium. However, the best welding method for aluminum and magnesium is to use alternating current (AC), which combines the benefits of DC- straight and DC+ reverse polarity.

**Alternating Current (AC):** The surface oxides formed on metals such as aluminum and magnesium disturb the arc and reduce the weld quality. Welding of these metals requires DC+ reverse or AC polarity to break up the surface oxides. An alternating current (AC) cycle consists of one-half cycle of straight polarity and one-half cycle of reverse polarity. With alternating current, the cleaning action benefits of the reverse-polarity arc can be combined with the electrode current-carrying capacity of the straight-polarity arc. In welding aluminum and magnesium, the half cycles of AC polarity may become unbalanced. During the AC cycle, the reverse electrode-positive portion of the cycle is restricted by the oxides on the surfaces of these materials. The surface oxides are poor conductors and make it difficult for the electrons generated by the reverse-polarity part of the cycle to flow from the work to the electrode tip, but they do not upset the straight polarity in which the electrons flow from the electrode to the work.

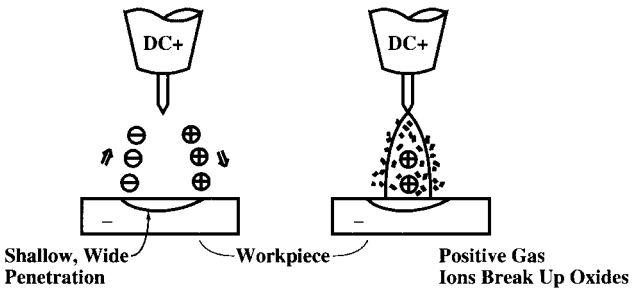


Fig. 9. Direct-Current (DC+) Reverse Polarity Provides a Shallow, Wide, Weld Pool.

**DC Component:** The part of the reverse-polarity cycle of alternating current (AC) that is upset by the poor conductivity of the oxides is changed into direct-current, straight polarity (DC-) and is directed back to the power source where it may cause overheating. The feedback is referred to as the DC component and its characteristics are important in deciding which process to use because, if an AC power source designed for shielded metal arc welding is to be used to weld aluminum by the GTAW process, the power source must be derated to protect the equipment. The power-source manufacturer will provide information on the level of derating required.

Power sources are available for GTAW that provide a balanced AC wave, and manufacturers will provide information about the benefits of balanced wave versus unbalanced wave, GTAW power sources, and equipment to protect against the DC component.

**High Frequency and AC:** To maintain the stability of the alternating-current (AC) arc when the positive cycle of the arc is upset by the aluminum oxide, and to avoid contamination of the tungsten electrode, high-frequency current is used to assist in arc ignition during each AC cycle. In direct-current, straight-polarity (DC-) welding of carbon and stainless steels, the high-frequency current is typically selected by the HF arc start-only switch. During AC welding of steels without oxide problems, the HF switch may be left on the arc start-only setting. When AC is used on aluminum, magnesium, or other metals with poor electron-conductive oxides, the HF switch should be moved to the continuous setting.

High-frequency current is also beneficial in that it promotes gas ionization. The more positively charged molecules produced, the more cleaning action takes place in the direct-current, reverse-polarity (DCRP) cycle.

**Selecting the Tungsten Electrode Type.**—Use of the correct tungsten electrode composition is vital to producing good-quality GTAW welds. Tungsten has the highest melting temperature of all metals. Pure tungsten provides a low-current capacity and requires addi-



tion of such alloying elements as thorium or zirconium to increase the current-carrying capability. The electrode diameter and the electrode tip configuration also require consideration as both have a great influence on the performance and application potential of GTAW welding.

Table 17 shows typical compositions of commonly used GTAW tungsten electrode materials from the American Welding Society AWS A5.12 Standard. New electrode compositions have been designed that utilize other alloys and rare-earth metals. These electrodes are designed for longer lives in both GTAW and plasma welding.

*Pure Tungsten:* Pure tungsten electrode material provides good arc stability with alternating current (AC). Tungsten has low current capacity and low resistance to electrode contamination. Pure tungsten is good for low-amperage welding of aluminum and magnesium alloys. On medium- to high-current ferrous applications, there is a potential for tungsten inclusions in the weld.

With DC, the current capacity of pure tungsten is lower than with the alloyed tungsten electrodes. During AC welding, a molten ball shape forms at the pure tungsten electrode tip, and this formation is desirable for welding aluminum.

**Table 16. Selection of Gas Tungsten Arc Welding (GTAW) Electrodes**

| Base Metal                                      | Electrode                  | Current | Recommendations                                       |
|---|----------------------------|---------|---|
| Carbon, low-alloy, stainless, and nickel steels | Thoriated                  | DCEN    | Use EWZr electrodes with AC on thin materials         |
| Aluminum  | Zirconium or pure tungsten | AC      | Use EWZr on critical applications                     |
| Aluminum  | Thoriated zirconium        | DCEP    | Use EWZr or EWP electrodes with DCEP on thin sections |
| Copper and copper alloys                        | Thoriated                  | DCEN    | Use EWZr or EWP with AC on thin sections              |
| Magnesium                                       | Zirconium                  | AC      | Use DCEP with same electrode on thin sections         |
| Titanium  | Thoriated                  | DCEN    | ...   |

**Table 17. Common Tungsten Electrode Compositions**

| Classification | Color  | Tungsten (%) | Thorium Oxide (%) | Zirconium Oxide (%) |
|----------------|--------|--------------|-------------------|---------------------|
| EWP            | Green  | 99.50        | ...               | ...                 |
| EWTh-1         | Yellow | 98.50        | 0.8-1.2           | ...                 |
| EWTh-2         | Red    | 97.50        | 1.7-2.2           | ...                 |
| EWTh-3         | Blue   | 98.95        | 0.35-0.55         | ...                 |
| EWZr           | Brown  | 99.20        | ...               | 0.15-0.4            |

In the classification column, E = electrode; W = tungsten; P = pure; Th = thoriated (thorium oxide); Zr = zirconiated (zirconium oxide). The colors are codes used by manufacturers to identify the material. Tungsten percentages are minimum requirements. The EWTh-3 is also called striped tungsten because it is made with a strip of thoriated material along the length. This electrode needs to be preheated by striking an arc to melt the tip, providing for the thorium and the tungsten to combine before welding is started.

The electrode recommendations in Table 16 are a guide to attaining good-quality GTAW welds from the venous types of polarities available.

**Electrode and Current Selection.**—Tables 18 and 19 show approximate current recommendations for common electrode types and diameters. The GTAW electrode size should be selected so that its midrange current provides the energy required for the intended application. If the electrode is too thin, excess current may be required, causing the electrode to wear too quickly or melt and contaminate the weld. If the electrodes used are found to be constantly at the top end of the current range, a change should be made to the next larger size. Tables 20 and 21 show recommended sizes of electrodes and filler metal rods or wires for welding various thicknesses of carbon, low-alloy, and stainless steels and aluminum.

**Table 18. Recommended Current Ranges for Thoriated GTAW Electrodes**

| Electrode          |          | Current Range (amps) |
|--------------------|----------|----------------------|
| $\frac{1}{16}$ in. | (1.6 mm) | 60–150               |
| $\frac{3}{32}$ in. | (2.4 mm) | 150–250              |
| $\frac{1}{8}$ in.  | (3.2 mm) | 250–400              |
| $\frac{5}{32}$ in. | (4 mm)   | 400–500              |

The electrode selected must suit the application and the current capacity of the power source.

**Table 19. Current Ranges for EWP and EWZr GTAW Electrodes**

| Electrode      |       | Ampere Range<br>AC Balanced |         | Ampere Range<br>AC Unbalanced |         |
|----------------|-------|-----------------------------|---------|-------------------------------|---------|
|                |       | EWP                         | EWZr    | EWP                           | EWZr    |
| in.            | (mm)  |                             |         |                               |         |
| $\frac{1}{16}$ | (1.6) | 30–80                       | 60–120  | 50–100                        | 70–150  |
| $\frac{3}{32}$ | (2.4) | 60–130                      | 100–180 | 100–160                       | 140–235 |
| $\frac{1}{8}$  | (3.2) | 100–180                     | 160–250 | 150–210                       | 225–325 |
| $\frac{5}{32}$ | (4)   | 160–240                     | 200–320 | 200–275                       | 300–400 |

**Table 20. Electrode and Current Recommendations for Carbon, Low-Alloy, and Stainless Steels**

| Material Thickness |       | Electrode Diameter |       | Filler Rod Diameter |       | Current Range (amps) |      |
|--------------------|-------|--------------------|-------|---------------------|-------|----------------------|------|
| in.                | (mm)  | in.                | (mm)  | in.                 | (mm)  | DCEN                 | EWTh |
| $\frac{1}{16}$     | (1.6) | $\frac{1}{16}$     | (1.6) | $\frac{1}{16}$      | (1.6) | 60–100               |      |
| $\frac{1}{8}$      | (3.2) | $\frac{3}{32}$     | (2.4) | $\frac{3}{32}$      | (2.4) | 150–170              |      |
| $\frac{3}{16}$     | (4.8) | $\frac{3}{32}$     | (2.4) | $\frac{1}{8}$       | (3.2) | 180–220              |      |
| $\frac{1}{4}$      | (6.4) | $\frac{1}{8}$      | (3.2) | $\frac{5}{32}$      | (7.2) | 260–300              |      |

Note: The shielding gas is argon at 15 to 20 cu ft/h (CFH). For stainless steel, reduce the current by approximately 10 per cent.

**Table 21. Recommendations for GTAW Welding of Aluminum with EWP Electrodes Using AC and High-Frequency Current**

| Material Thickness |       | Electrode Diameter |       | Filler Rod Diameter |       | AC Current Range |
|--------------------|-------|--------------------|-------|---------------------|-------|------------------|
| in.                | (mm)  | in.                | (mm)  | in.                 | (mm)  | (amps)           |
| $\frac{1}{16}$     | (1.6) | $\frac{1}{16}$     | (1.6) | $\frac{1}{16}$      | (1.6) | 40–70            |
| $\frac{1}{8}$      | (3.2) | $\frac{3}{32}$     | (2.4) | $\frac{3}{32}$      | (2.4) | 70–125           |
| $\frac{3}{16}$     | (4.8) | $\frac{1}{8}$      | (3.2) | $\frac{1}{8}$       | (3.2) | 110–170          |
| $\frac{1}{4}$      | (6.4) | $\frac{5}{32}$     | (4)   | $\frac{3}{16}$      | (4.8) | 170–220          |

**Thoriated Electrodes:** In contrast with the pure EWP electrodes, thoriated electrodes have a higher melting temperature and up to about 50 per cent more current-carrying capacity, with superior arc starting and arc stability. These electrodes are typically the first choice for critical DC welding applications, but do not have the potential to maintain a rounded ball shape at the tip. The best welding mode for these electrodes is with the tip ground to a tapered or fine point.

**Zirconiated Electrodes:** Tungsten electrodes with zirconium are practical for critical applications and have less sensitivity to contamination and superior current capacity than pure tungsten electrodes.

**Protecting and Prolonging Electrode Life:** To improve tungsten electrode life, the tip should be tapered in accordance with the manufacturer's recommendations. There must also be preflow, postflow shielding gas coverage to protect the electrode before and after

the weld. When possible, high frequency should be used to avoid scratch starts, which contaminate the electrode. The shortest possible electrode extension should be employed, to avoid the possibility of the electrode touching the filler or weld metal. The grinding wheel used to sharpen the tungsten must not be contaminated from grinding other metals or with dirt.

**Filler Metals.**—Specifications covering composition and mechanical properties for GTAW filler metal are published by the American Welding Society under the following classifications: A5.7, copper and copper alloys; A5.9, chromium and chromium nickel; A5.10, aluminum; A5.14, nickel; A5.16, titanium; A5.18, carbon steels; A5.19, magnesium; and A5.28, low-alloy steels.

Filler metals must be kept dry and clean if they are to be used satisfactorily.

**Shielding Gases.**—Inert gases such as argon, and argon + helium mixtures are most commonly used for GTAW. Helium provides greater thermal conductivity and additional arc voltage potential than argon, and is normally added to argon when more weld energy is required for improved penetration and increased mechanized welding travel speeds. Argon gas mixtures containing 30 to 75 per cent helium provide benefits for manual welding of aluminum over  $\frac{3}{8}$  in. (9.6 mm) thick; mechanized welding of aluminum where high speeds are required; mechanized welding of carbon and stainless steels where good penetration is needed; mechanized welding of stainless steel where good penetration and faster speeds are required; and for copper of  $\frac{1}{4}$  in. (6.4 mm) thickness and thicker.

Shielding gas purity for GTAW welding is important. Welding-grade argon is supplied at a purity of at least 99.996 per cent and helium is produced to a minimum purity of 99.995 per cent. However, shielding gases may be contaminated due to poor cylinder filling practices. If impure gas is suspected, the following test is suggested. With the HF and power on, create an arc without welding and hold the arc for about 30 seconds. Examine the electrode tip for signs of unusual coloration, oxidation, or contamination, which result from impurities in the shielding gas.

### Plasma Arc Welding (PAW)

When an electric current passes between two electrodes through certain gases, the energy of the gas molecules is increased so that they accelerate and collide with each other more often. With increases in energy, the binding forces between the nuclei and the electrons are exceeded, and electrons are released from the nuclei. The gas now consists of neutral molecules, positively charged atoms, and negatively charged electrons. The plasma gas is said to be ionized, so that it is capable of conducting electric current. Plasma forms in all welding arcs but in plasma arc welding it is generated by a series of events that begins with inert gas passing through the welding torch nozzle. High-frequency current is then generated between the tungsten electrode (cathode) and the torch nozzle (anode), forming a low-current pilot arc. The ionized path of this nontransferred arc is then transferred from the tungsten electrode to the work, and a preset plasma current is generated.

The above sequence of events provides the ionized path for the plasma current between the electrode and the work so that arcing between the electrode and the nozzle ceases. (Nontransferred arcs may be used for metal spraying or nonmetallic welds.) Forcing the ionized gas through the small orifice in the nozzle increases both the level of ionization and the arc velocity, and arc temperatures between 30,000 and 50,000°F (16,650 and 27,770°C) are generated.

**Gases for Plasma Arc Welding.**—Argon is the preferred gas for plasma arc welding (PAW) as it is easily ionized and the plasma column formed by argon can be sustained by a low voltage. The low thermal conductivity of argon produces a plasma column with a narrow, concentrated hot core surrounded by a cooler outer zone. Argon plasmas are suited to welding steel up to  $\frac{1}{8}$  in. (3.2 mm). For thicker materials, requiring a hotter arc and using

higher current melt-in technique, a mixture of argon 25 + helium 75 per cent may be used. Additions of helium and hydrogen to the gas mixture improve heat transfer, reduce porosity, and increase weld travel speed. For welding materials thinner than  $\frac{1}{8}$  in. thick by the plasma gas keyhole method (full penetration welds), gases may contain up to 15 per cent hydrogen with the remainder argon. Good results are obtained with argon + 5 per cent hydrogen in welding stainless and nickel steels over  $\frac{1}{8}$  in. thick.

**Shielding Gases.**—A shielding gas is needed to protect the narrow plasma arc column and the weld pool, and generally is provided by mixtures of argon, argon + hydrogen, argon + helium, or argon +  $O_2$  +  $CO_2$ , depending on compatibility with the material being welded. Shielding gas flow rates vary from 5 to 35 cu ft/h (2.4 to 17 l/min). However, if argon is used for both plasma and shielding, the plasma gas will become less concentrated. The normally tight plasma arc column will expand in contact with the colder shielding gas, reducing ionization and thus concentration and intensity of the plasma column. With no shielding gas, the tight column is unaffected by the surrounding oxygen and nitrogen of the atmosphere, which are not easily ionized.

*Hydrogen* is added to the shielding gas when welding low-alloy steels of less than  $\frac{1}{16}$  in. (1.6 mm) thickness, or stainless and nickel steels, with many benefits. The hydrogen molecules dissociate in contact with the arc at temperatures of about 7,000°F (3,870°C) and the energy thus created is released when the hydrogen molecules recombine on contact with the work surface. The diatomic molecular action creates a barrier around the plasma, maintaining column stiffness. Hydrogen in the shielding gas combines with oxygen in the weld zone, releasing it into the atmosphere and keeping the weld clean. Hydrogen reduces the surface tension of the weld pool, increasing fluidity, and the added energy increases penetration.

*Helium* mixed with the argon shielding gas is beneficial for all metals as it increases the ionization potential, allowing use of higher voltages that give increased welding temperatures. Flow rates are in the range of 15 to 50 cu ft/h (7 to 24 l/min). Arc-starting efficiency is reduced with pure helium, but adding 25 per cent of argon helps both arc starting and stability. Helium additions of 25 to 75 per cent are made to obtain increased thermal benefits.

Argon +  $CO_2$  shielding gas mixtures are beneficial in fusion welding of carbon steels. A mixture of argon with 20 to 30 per cent  $CO_2$  improves weld fluidity. Shielding gas mixtures of argon +  $CO_2$  with an argon + 5 per cent hydrogen plasma should be considered for welding carbon steel of  $\frac{1}{16}$  to  $\frac{1}{4}$  in. thickness. Steels with higher amounts of carbon have higher heat conductivity and need application of more heat than is needed with stainless steels. Manufacturers usually make recommendations on types of gas mixtures to use with their equipment.

**PAW Welding Equipment.**—The PAW process uses electrode negative (DCEN) polarity in a current range from 25 to 400 amps, and equipment is offered by many manufacturers. Solid-state inverter units are available with nonmechanical contactors. Most PAW units contain a high-frequency generator, a small DC power supply, controls for welding and shielding gas mixtures, and a torch coolant control. A weld sequencer is recommended, especially for keyhole mode welding, but it is also useful in automated fusion welding. The sequencer provides control of up-slope and down-slope conditions for gas mixtures and current, so that it is possible to make welds without run-on and run-off tabs, as is necessary with circumferential welds.

Generally, plasma arc torches are liquid-cooled using deionized water in the coolant lines to the torch to avoid effects of electrolysis. Electrodes are usually tungsten with 2 per cent thorium. If the welding shop already has a constant-current power supply and a coolant recirculator, plasma arc welding may be used by addition of a pilot arc welding console and a torch.

**Applications.**—Fusion welding is the main use for plasma arc welding. The process is used for high-volume, repetitive, high-duty cycle, manual and automated operations on lap, flange, butt, and corner fusion welds, in all positions. Joint design for materials less than 0.01 in. (0.254 mm) thick may require a flange type joint for rigidity and to allow use of extra, weld metal reinforcement. Filler metal may be added during fusion welding, and automated hot or cold wire feeders can be used. Fusion welding uses a soft, less-restricted arc with low gas flows, and the current level may vary from approximately 25 to 200 amps. The soft arc is obtained by setting the end of the tungsten electrode level with the face of the torch nozzle, in which position lower currents and gas flows are required. With these conditions, the weld bead is slightly wider than a bead produced with a recessed electrode.

*Low-Current Plasma Fusion Welding:* With the reduced consumption of gas and electric current, the low-current plasma fusion welding method is ideal for welding metals down to 0.001 in. (0.025 mm) in thickness, as the low-current plasma pilot arc allows arcs to be started consistently with currents of less than 1 amp. With currents below 1 amp, the pilot arc is usually left in the continuous mode to maintain the arc. In the conditions described, arc stability is improved and the process is much less sensitive to variations in the distance of the torch from the workpiece. Given this height tolerance, setting up is simplified, and with the smaller torches required, it is often easier to see the weld pool than with the GTAW process. Some plasma welding units incorporate gas flow meters that are designed for low flow rates, and currents in the range of 0.1 to 15 amps can be selected.

Low-current plasma arc welding is more economical than other gas tungsten arc welding methods, especially with solid-state inverter systems and smaller torches. The process is useful for sealing type welds where joint access is good, and for welding components of office furniture, household items, electronic and aerospace parts, metallic screening, and thin-wall tubing.

*Keyhole mode welding* describes a method whereby abutting edges of two plates are melted simultaneously, forming a vapor capillary (or keyhole) and the resulting molten-walled hole moves along the joint line. This method requires the end of the tungsten electrode to be positioned well back inside the torch nozzle to produce a high-velocity, restricted arc column with sufficient energy to pierce the workpiece. This mode is also used for the plasma cutting process, but the major difference is that welding uses very low plasma flow rates of the order of 1 to 3 cu ft/h (0.5 to 1.4 l/min) for work thicknesses of  $\frac{1}{16}$  to  $\frac{3}{32}$  in. (1.6 to 4 mm). These low rates avoid unwanted displacement of the weld metal. After the arc pierces the workpiece, the torch moves along the weld line and the thin layer of molten metal is supported by surface tension as it flows to the rear of the line of movement, where it solidifies and forms the weld.

As it passes through the keyhole, the high-velocity plasma gas column flushes the molten weld pool and carries away trapped gases and contaminants that otherwise would be trapped in the weld. Plasma arc keyhole welding is affected less by surface and internal defects in the work material than is the GTAW process. Most metals that can be welded by the gas tungsten arc method can be plasma arc welded with the conventional DC electrode, negative keyhole method, except aluminum, which requires a variable polarity keyhole method.

Plasma keyhole welding is usually automated because it requires consistent travel speed and torch height above the work. A typical operation is welding steel with square abutting edges (no bevels) in thicknesses of 0.09 to 0.375 in. (2.3 to 9 mm), where 100 per cent penetration in a single pass is required. Producing square-groove butt welds in materials thicker than  $\frac{1}{2}$  in. by the plasma arc keyhole process requires some edge preparation and several filler passes. The finished weld is uniformly narrow and the even distribution of heat means that distortion is minimized.

**Welding Aluminum.**—The variable polarity plasma arc (VPPA) process was developed for welding metals that form an oxide skin, such as aluminum. Electrode negative

(straight) polarity is necessary for the plasma arc to provide sufficient heat to the workpiece and minimize heat buildup in the tungsten electrode. With electrode negative polarity, electrons move rapidly from the negative cathode tungsten electrode to the positive anode workpiece, generating most of the heat in the workpiece. Because of the oxide skin on aluminum, however, straight polarity produces an erratic arc, poor weld fluidity, and an irregularly shaped weld bead. The oxide skin must be broken up if the metal flow is to be controlled, and this breakup is effected by a power supply that constantly switches from negative to positive polarity.

A typical cycle uses a 20-ms pulse of electrode negative polarity and a 3-ms pulse of electrode positive polarity. The pulses are generated as square waves and the positive (cleaning) pulse is set at 30 to 80 amps higher than the negative pulse for greater oxide-breaking action. The tenacious oxide skin is thus broken constantly and the rapid cycle changes result in optimum cathode cleaning with minimum deterioration of the tungsten electrode and consistent arc stability. Varying polarity has advantages in both gas metal arc and plasma arc welding, but with the keyhole process it allows single-pass, square-groove, full-penetration welds in materials up to  $\frac{1}{2}$  in. (12.7 mm) thick.

The VPPA process ensures extremely low levels of porosity in weld areas in aluminum. VPPA welding is often used in the vertical up position for aluminum because it provides superior control of root reinforcement, which tends to be excessive when welding is done in the flat position. Pulsing in the VPPA process when welding aluminum of  $\frac{1}{8}$  to  $\frac{1}{4}$  in. thickness in the flat position gives satisfactory root profiles. Pulsing gives improved arc control in keyhole welds in both ferrous and nonferrous metals and is beneficial with melt-in fusion welding of thin materials as it provides better control of heat input to the workpiece.

### Plasma Arc Surface Coating

*Plasma Arc Surfacing* uses an arc struck between the electrode and the workpiece, or transferred arc, to apply coatings of other metals or alloys to the workpiece surface. This high-temperature process produces homogeneous welds in which the ionized plasma gas stream melts both the work surface and a stream of powdered alloy or filler wire fed into the arc. Dilution of the base metal can be held below 5 per cent if required. With arc temperatures between 25,000 and 50,000°F (14,000 and 28,000°C), deposition occurs rapidly, and a rate of 15 lb/h (6.8 kg/h) of powdered alloy is not unusual. Deposition from wire can be performed at rates up to 28 lb/h (12.7 kg/h), much higher than with oxygen/fuel or gas metal/arc methods.

In the nontransferred arc process used for coating of surfaces, the arc is struck between the electrode and the torch nozzle, so that it does not attach to the work surface. This process is sometimes called metal spraying, and is used for building up surfaces for hard facing, and for application of anticorrosion and barrier layers. Argon is frequently used as the plasma gas. As the coating material in the form of powder or wire enters the plasma, it is melted thoroughly by the plasma column and is propelled toward the work at high velocity to form a mechanical bond with the work surface. Some 500 different powder combinations are available for this process, so that a variety of requirements can be fulfilled, and deposition rates up to 100 lb/h (45 kg/h) can be achieved.

The plasma arc process allows parts to be modified or recovered if worn, and surfaces with unique properties can be provided on new or existing components. Low levels of porosity in the deposited metal can be achieved. Metal spraying can be performed manually or automatically, and its use depends primarily on whether a mechanical bond is acceptable. Other factors include the volume of parts to be treated, the time needed for the process and for subsequent finishing, the quality requirements for the finished parts, rejection rates, and costs of consumable materials and energy.

Some systems are available that can use either metal powder or wire as the spray material, and can be operated at higher voltage settings that result in longer plasma arc lengths at temperatures over 10,000°F (5,537°C). With these systems, the plasma velocity is increased to about 12,000 ft/s (3,658 m/s), giving an extremely dense coating with less than 1 per cent porosity. Current ranges of 30 to 500 amps are available, and nitrogen is frequently used as the plasma gas, coupled with CO<sub>2</sub>, nitrogen, or compressed air as the shielding gas. Gas flow rates are between 50 and 350 cu ft/h (24 and 165 l/min). Large or small surface areas can be coated at low cost, with minimum heat input, if other aspects of the process are compatible with the product being made.

### Plasma Arc Cutting of Metals

**Plasma Arc Cutting.**—Higher current and gas flow rates than for plasma arc welding are used for the plasma arc cutting (PAC) process, which operates on DC straight polarity, and uses a transferred arc to melt through the material to be cut. The nozzle is positioned close to the work surface and the velocity of the plasma jet is greatly increased by a restricting nozzle orifice so that it blows away the metal as it is melted to make the cut. The higher energy level makes the process much faster than cutting with an oxygen/fuel torch on cutting steel of less than ½ in. thick, but the process produces kerfs with some variation in the width and in the bevel angle, affecting the precision of the part. Some of the molten metal may recast itself on the edges of the cut and may be difficult to remove.

Factors that affect plasma cutting include the type and pressure of the gas, its flow pattern, the current, the size and shape of the nozzle orifice, and its closeness to the work surface. To reduce noise and fumes, mechanized plasma arc cutting is often performed with the workpiece submerged in water. Oxidation of cut surfaces is almost nonexistent with the underwater method.

**Precision Plasma Arc Cutting.**—A later development of the above process uses a magnetic field in the cutter head to stabilize the plasma arc by means of Lorentz forces that cause it to spin faster and tighter on the electrode tip. The magnetic field also confines the spinning plasma so that a narrower kerf is produced without adverse effect on cutting speed. Results from this process are somewhat comparable with those from laser cutting and, with numerical control of machine movements, it is used for production of small batches of blanks for stamping and similar applications. With galvanized and aluminized steel, edges are clean and free from burrs, but some slag may cling to edges of mild-steel parts.

### Cutting Metals with an Oxidizing Flame

The oxyhydrogen and oxyacetylene flames are especially adapted to cutting metals. When iron or steel is heated to a high temperature, it has a great affinity for oxygen and readily combines with it to form various oxides, and causing the metal to be disintegrated and burned with great rapidity. The metal-cutting or burning torch operates on this principle. A torch tip is designed to preheat the metal, which is then burned or oxidized by a jet of pure oxygen. The kerf or path left by the flame is suggestive of a saw cut when the cutting torch has been properly adjusted and used. The traversing motion of the torch along the work may be controlled either by hand or mechanically.

**Arc Cutting.**—According to the *Procedure Handbook of Arc-Welding Design & Practice*, published by The Lincoln Electric Co., a steel may be cut easily, and with great accuracy by means of the oxyacetylene torch. All metals, however, do not cut as easily as steel. Cast iron, stainless steels, manganese steels, and nonferrous materials are not as readily cut and shaped with the oxyacetylene cutting process because of their reluctance to oxidize. For these materials, arc cutting is often used to good advantage.

The cutting of steel is a chemical action. The oxygen combines readily with the iron to form iron oxide. In cast iron, this action is hindered by the presence of carbon in graphite

form. Thus, cast iron cannot be cut as readily as steel; higher temperatures are necessary and cutting is slower. In steel, the action starts at bright red heat, whereas in cast iron, the temperature must be nearer to the melting point to obtain a sufficient reaction.

**The Cutting Torch.**—The ordinary cutting torch consists of a heating jet using oxygen and acetylene, oxygen and hydrogen, or, in fact, any other gas that, when combined with oxygen, will produce sufficient heat. By the use of this heating jet, the metal is first brought to a sufficiently high temperature, and an auxiliary jet of pure oxygen is then turned onto the red-hot metal, and the action just referred to takes place. Some cutting torches have a number of preheating flame ports surrounding the central oxygen port, so that a preheating flame will precede the oxygen regardless of the direction in which the torch is moved. This arrangement has been used to advantage in mechanically guided torches. The rate of cutting varies with the thickness of the steel, the size of the tip, and the oxygen pressure.

**Adjustment and Use of Cutting Torch.**—When using the cutting torch for the cutting of steel plate, the preheating flame first comes into contact with the edge of the plate and quickly raises it to a white-hot temperature. The oxygen valve is then opened, and as the pure oxygen comes into contact with the heated metal, the latter is burned or oxidized.

**Metals That Can Be Cut.**—Metals such as wrought iron and steels of comparatively low-carbon content can be cut readily with the cutting torch. High-carbon steels may be cut successfully if preheated to a temperature that depends somewhat on the carbon content. The higher the carbon content, the greater the degree of preheating required. A black heat is sufficient for ordinary tool steel, but a low red heat may be required for some alloy tool steels. Brass and bronze plates have been cut by interposing them between steel plates.

**Cutting Stainless Steel.**—Stainless steel can be cut readily by the flux-injection method. The elements that give stainless steels their desirable properties produce oxides that reduce the flame cutting operation to a slow melting-away process when the conventional oxy-acetylene cutting equipment is used. By injecting a suitable flux directly into the stream of cutting oxygen before it enters the torch, the obstructing oxides can be removed. Portable flux feeding units are designed to inject a predetermined amount of the flux powder. The rate of flux flow is accurately regulated by a vibrator type of dispenser with rheostat control. The flux-injection method is applicable either to machine cutting or to a hand-controlled torch. The operating procedure and speed of cutting are practically the same as in cutting mild steel.

**Cutting Cast Iron.**—The cutting of cast iron with the oxyacetylene torch is practicable, although it cannot be cut as readily as steel. The ease of cutting seems to depend largely on the physical character of the cast iron, very soft cast iron being more difficult to cut than harder varieties. The cost is much higher than that for cutting the same thickness of steel, because of the larger preheating flame necessary and the larger oxygen consumption. In spite of this extra cost, however, this method is often economical. The slag from a cast-iron cut contains considerable melted cast iron, whereas in steel, the slag is practically free from particles of the metal, indicating that cast-iron cutting is partly a melting operation. Increased speed and decreased cost often can be obtained by feeding a steel rod, about  $\frac{1}{4}$  inch in diameter, into the top of the cut, beneath the torch tip. This rod furnishes a large amount of slag that flows over the cut and increases the temperature of the cast iron. Special tips are used because of the larger amounts of heat and oxygen required.

**Mechanically Guided Torches.**—Cutting torches used for cutting openings in plates or blocks or for cutting parts to some definite outline are often guided mechanically or by numerical control. Torches guided by pantograph mechanisms are especially adapted for tracing the outline to be cut from a pattern or drawing. Other designs are preferable for straight-line cutting and one type is designed for circular cutting.

**Cutting Steel Castings.**—When cutting steel castings, care should be taken to prevent burning pockets in the metal when the flame strikes a blowhole. If a blowhole is pene-



trated, the molten oxide will splash into the cavity and the flame will be diverted. The presence of the blowhole is generally indicated by excessive sparks. The operator should immediately move the torch back along the cut and direct it at an angle so as to strike the metal beneath the blowhole and burn it away if possible beyond the cavity. Cutting in the normal position then may be resumed.

**Thickness of Metal That Can Be Cut.**—The maximum thickness of metal that can be cut by these high-temperature flames depends largely upon the gases used and the pressure of the oxygen, which may be as high as 150 lb/in.<sup>2</sup> The thicker the metal, the higher the pressure required. When using an oxyacetylene flame, it might be practicable to cut iron or steel up to 12 or 14 inches in thickness, whereas an oxyhydrogen flame has been used to cut steel plates 24 inches thick. The oxyhydrogen flame will cut thicker material principally because it is longer than the oxyacetylene flame and can penetrate to the full depth of the cut, thus keeping all the oxide in a molten condition so that it can be easily blown out by the oxygen cutting jet. A mechanically guided torch will cut thick material more satisfactorily than a hand-guided torch, because the flame is directed straight into the cut and does not wobble, as it tends to do when the torch is held by hand. With any flame, the cut is less accurate and the kerf wider, as the thickness of the metal increases. When cutting light material, the kerf might be  $\frac{1}{16}$  inch wide, whereas for heavy stock, it might be  $\frac{1}{4}$  or  $\frac{3}{8}$  inch wide.

### Hard Facing

Hard facing is a method of adding a coating, edge, or point, of a metal or alloy capable of resisting abrasion, corrosion, heat, or impact, to a metal component. The process can be applied equally well to new parts or old worn parts. The most common welding methods used to apply hard-facing materials include the oxyacetylene gas, shielded-metal arc, submerged arc, plasma arc, and inert-gas-shielded arc (consuming and nonconsuming electrode). Such coatings can also be applied by a spraying process, using equipment designed to handle the coating material in the form of a wire or a powder.

**Hard-Facing Materials.**—The first thing to be considered in the selection of a hard-facing material is the type of service the part in question is to undergo. Other considerations include machinability, cost of hard-facing material, porosity of the deposit, appearance in use, and ease of application. Only generalized information can be given here to guide the selection of a material as the choice is dependent upon experience with a particular type of service. Generally, the greater the hardness of the facing material, the greater is its resistance to abrasion and shock or impact wear. Many hardenable materials may be used for hard facing such as carbon steels, low-alloy steels, medium-alloy steels, and medium-high alloys but none of these is outstanding. Some of the materials that might be considered to be preferable are high-speed steel, austenitic manganese steel, austenitic high-chromium iron, cobalt-chromium alloy, copper-base alloy, and nickel-chromium-boron alloy.

**High-Speed Steels.**—These steels are available in the form of welding rods (RFe5) and electrodes (EFe5) for hard facing where hardness is required at service temperatures up to 1100 degrees F and where wear resistance and toughness are also required. Typical surfacing operations are done on cutting tools, shear blades, reamers, forming dies, shearing dies, guides, ingot tongs, and broaches using these metals.

**Hardness:** These steels have a hardness of 55 to 60 on the Rockwell C scale in the as-welded condition and a hardness of 30 Rockwell C in the annealed condition. At a temperature of 1100 degrees F, the as-deposited hardness of 60 Rockwell C falls off very slowly to 47 Rockwell C. At about 1200 degrees F, the maximum Rockwell C hardness is 30.

**Resistance Properties:** As deposited, the alloys can withstand only medium impact, but when tempered, the impact resistance is increased appreciably. Deposits of these alloys will oxidize readily because of their high molybdenum content but can withstand atmospheric corrosion. They do not withstand liquid corrosives.

*Other Properties or Characteristics:* The metals are well suited for metal-to-metal wear especially at elevated temperatures. They retain their hardness at elevated temperatures and can take a high polish. For machining, these alloys must first be annealed. Full hardness may be regained by a subsequent heat treatment of the metal.

**Austenitic Manganese Steels.**—These metals are available in the form of electrodes (EFeMn) for hard facing when dealing with metal-to-metal wear and impact. Uses include facing rock-crushing equipment and railway frogs and crossings.

*Hardness:* Hardness of the as-deposited metals are 170 to 230 Bhn, but they can be work-hardened to 450 to 550 Bhn very readily. For all practical purposes, these metals have no hot hardness as they become brittle when reheated above 500 to 600 degrees F.

*Resistance Properties:* These metals have high impact resistance. Their corrosion and oxidation resistance are similar to those of ordinary carbon steels. Their resistance to abrasion is only mediocre compared with hard abrasives like quartz.

*Other Properties or Characteristics:* The yield strength of the deposited metal in compression is low, but any compressive deformation rapidly raises it until plastic flow ceases. This property is an asset in impact wear situations. Machining is difficult with ordinary tools and equipment; finished surfaces are usually ground.

**Austenitic High-Chromium Irons.**—These metals are available in rod (RFeCr-A) and electrode (EFeCr-A) form and are used for facing agricultural machinery parts, coke chutes, steel mill guides, sand-blasting equipment, and brick-making machinery.

*Hardness:* The as-welded deposit ranges in hardness from 51 to 62 Rockwell C. Under impact, the deposit work hardens somewhat, but the resulting deformation also leads to cracking and impact service is therefore avoided. Hot hardness decreases slowly at temperatures up to 800 and 900 degrees F. At 900 degrees F, the instantaneous hardness is 43 Rockwell C. In 3 minutes under load, the hardness drops to 37 Rockwell C. At 1200 degrees F, the instantaneous hardness is 5 Rockwell C. The decrease in hardness during hot testing is practically recovered on cooling to ambient temperatures.

*Resistance Properties:* Deposits will withstand only light impact without cracking. Dynamic compression stresses above 60,000 pounds per square inch should be avoided. These metals exhibit good oxidation resistance up to 1800 degrees F and can be considered for hot wear applications where hot plasticity is not objectionable. They are not very resistant to corrosion from liquids and will rust in moist air, but are more stable than ordinary iron and steel. Resistance to low-stress scratching is outstanding and is related to the amount of hard carbides present. However, under high-stress grinding abrasion, performance is only mediocre and they are not deemed suitable for such service.

*Other Properties or Characteristics:* The deposited metals have a yield strength (0.1 per cent offset) of between 80,000 and 140,000 pounds per square inch in compression and an ultimate strength of from 150,000 to 280,000 pounds per square inch. Their tensile strength is low and therefore tension uses are avoided in design. These deposits are considered to be commercially unmachinable and are also very difficult to grind. When ground, a grinding wheel of aluminum oxide abrasive with a 24-grit size and a hard (Q) and medium-spaced resinoid bond is recommended for off-hand high-speed work and a slightly softer (P) vitrified bond for off-hand low-speed work.

**Cobalt-Base Alloys.**—These metals are available in both rod (RCoCr) and electrode (ECoCr) form and are frequently used to surface the contact surfaces of exhaust valves in aircraft, truck, and bus engines. Other uses include parts such as valve trim in steam engines, and on pump shafts, where conditions of corrosion and erosion are encountered. Several metals with a greater carbon content are available (CoCr-B, CoCr-C) and are used in applications requiring greater hardness and abrasion resistance but where impact resistance is not mandatory or expected to be a factor.

**Hardness:** Hardness ranges on the Rockwell C scale for gas-welded deposits are as follows: CoCr-A, 38 to 47; CoCr-B, 45 to 49; and CoCr-C, 48 to 58. For arc-welded deposits, hardness ranges (Rockwell C) as follows: CoCr-A, 23 to 47; CoCr-B, 34 to 47; and CoCr-C, 43 to 58. The values for arc-weld deposits depend for the most part on the base metal dilution. The greater the dilution, the lower the hardness. Many surfacing alloys are softened permanently by heating to elevated temperatures, however, these metals are exceptional. They do exhibit lower hardness values when hot but return to their approximate original hardness values upon cooling. Elevated-temperature strength and hardness are outstanding properties of this group. Their use at 1200 degrees F and above is considered advantageous but between 1000 and 1200 degrees F, their advantages are not definitely established, and at temperatures below 1000 degrees F, other surfacing metals may prove better.

**Resistance Properties:** In the temperature range from 1000 to 1200 degrees F, weld deposits of these metals have a great resistance to creep. Tough martensitic steel deposits are considered superior to cobalt-base deposits in both flow resistance and toughness. The chromium in the deposited metal promotes the formation of a thin, tightly adherent scale that provides a scaling resistance to combustion products of internal combustion engines, including deposits from leaded fuels. These metals are corrosion-resistant in such media as air, food, and certain acids. It is advisable to conduct field tests to determine specific corrosion resistance for the application being considered.

**Other Properties or Characteristics:** Deposits are able to take a high polish and have a low coefficient of friction and therefore are well suited for metal-to-metal wear resistance. Machining of these deposits is difficult; the difficulty increases in proportion to the increase in carbon content. CoCr-A alloys are preferably machined with sintered carbide tools. CoCr-C deposits are finished by grinding.

**Copper-Base Alloys.**—These metals are available in rod (RCuA1-A2, RCuA1-B, RCuA1-C, RCuA1-D, RCuA1-E, RCuSi-A, RCuSn, RCuSn-D, RCuSn-E, and RCuZn-E) and electrode (ECuA1-A2, ECuA1-B, ECuA1-C, ECuA1-D, ECuA1-E, ECuSi, ECuSn-A, ECuSn-C, ECuSn-E, and ECuZn-E) forms and are used in depositing overlays and inlays for bearing, corrosion-resistant, and wear-resistant surfaces. The CuA1-A2 rods and electrodes are used for surfacing bearing surfaces between the hardness ranges of 130 to 190 Bhn as well as for corrosion-resistant surfaces. The CuA1-B and CuA1-C rods and electrodes are used for surfacing bearing surfaces of hardness ranges 140 to 290 Bhn. The CuA1-D and CuA1-E rods and electrodes are used on bearing and wear-resistant surfaces requiring the higher hardnesses of 230 to 390 Bhn such as are found on gears, cams, wear plates, and dies. The copper-tin (CuSn) metals are used where a lower hardness is required for surfacing, for corrosion-resistant surfaces, and sometimes for wear-resistant applications.

**Hardness:** Hardness of a deposit depends upon the welding process employed and the manner of depositing the metal. Deposits made by the inert-gas metal-arc process (both consumable and nonconsumable electrode) will be higher in hardness than deposits made with the gas, metal-arc, and carbon-arc processes because lower losses of aluminum, tin, silicon, and zinc are achieved due to the better shielding from oxidation. Copper-base alloys are not recommended for use at elevated temperatures because their hardness and mechanical properties decrease consistently as the temperature goes above 400 degrees F.

**Resistance Properties:** The highest impact resistance of the copper-base alloy metals is exhibited by CuA1-A2 deposits. As the aluminum content increases, the impact resistance decreases markedly. CuSi weld deposits have good impact properties. CuSn metals as deposited have low impact resistance and CuZn-E deposits have a very low impact resistance. Deposits of the CuA1 filler metals form a protective oxide coating upon exposure to the atmosphere. Oxidation resistance of CuSi deposits is fair and that of CuSn deposits are comparable to pure copper. With the exception of the CuSn-E and CuZn-E alloys, these

metals are widely used to resist many acids, mild alkalies, and salt water. Copper-base alloy deposits are not recommended for use where severe abrasion is encountered in service. CuAl filler metals are used to overlay surfaces subjected to excessive wear from metal-to-metal contact such as gears, cams, sheaves, wear plates, and dies.

*Other Properties or Characteristics:* All copper-base alloy metals are used for overlays and inlays for bearing surfaces with the exception of the CuSi metals. Metals selected for bearing surfaces should have a Brinell hardness of 50 to 75 units below that of the mating metal surface. Slight porosity is generally acceptable in bearing service as a porous deposit is able to retain oil for lubricating purposes. CuAl deposits in compression have elastic limits ranging from 25,000 TO 65,000 lb/in.<sup>2</sup> and ultimate strengths of 120,000 to 171,000 lb/in.<sup>2</sup> The elastic limit and ultimate strength of CuSi deposits in compression are 22,000 lb/in.<sup>2</sup> and 60,000 lb/in.<sup>2</sup>, respectively. CuZn-E deposits in compression have an elastic limit of only about 5000 lb/in.<sup>2</sup> and an ultimate strength of 20,000 lb/in.<sup>2</sup> All copper-base alloy deposits can be machined.

**Nickel-Chromium-Boron Alloys.**—These metals are available in both rod (RNiCr) and electrode (ENiCr) form and their deposits have good metal-to-metal wear resistance, good low-stress, scratch-abrasion resistance, corrosion resistance, and retention of hardness at elevated temperatures. These properties make the alloys suitable for use on seal rings, cement pump screws, valves, screw conveyors, and cams. Three different formulations of these metals are recognized (NiCr-A, NiCr-B, and NiCr-C).

*Hardness:* Hardness of the deposited NiCr-A from rods range from 35 to 40 Rockwell C; of NiCr-B rods, 45 to 50 Rockwell C; of NiCr-C rods, 56 to 62 Rockwell C. Hardness of the deposited NiCr-A from electrodes ranges from 24 to 35 Rockwell C; of NiCr-B from electrodes, 30 to 45 Rockwell C; and of NiCr-C electrodes, 35 to 56. The lower hardness values and greater ranges of hardness values of the electrode deposits are attributed to the dilution of deposit and base metals. Hot Rockwell C hardness values of NiCr-A electrode deposits range from 30 to 19 in the temperature range from 600 to 1000 degrees F from instantaneous loading to a 3-minute loading interval. NiCr-A rod deposits range from 34 to 24 in the same temperature range and under the same load conditions. Hot Rockwell C hardness values of NiCr-B electrode deposits range from 41 to 26 in the temperature range from 600 to 1000 degrees F from instantaneous loading to a 3-minute loading interval. NiCr-B rod deposits range from 46 to 37 in the same temperature range and under the same load conditions. Hot Rockwell C hardness values of NiCr-C electrode deposits range from 49 to 31 in the temperature range from 600 to 1000 degrees F from instantaneous loading to a 3-minute loading interval. NiCr-C rod deposits range from 55 to 40 in the same temperature range and under the same load conditions.

*Resistance Properties:* Deposits of these metal alloys will withstand light impact fairly well. When plastic deformation occurs, cracks are more likely to appear in the NiCr-C deposit than in the NiCr-A and NiCr-B deposits. NiCr deposits are oxidation-resistant up to 1800 degrees F. Their use above 1750 degrees F is not recommended because fusion may begin near this temperature. NiCr deposits are completely resistant to atmospheric, steam, salt water, and salt spray corrosion and to the milder acids and many common corrosive chemicals. It is advisable to conduct field tests when a corrosion application is contemplated. These metals are not recommended for high-stress grinding abrasion. NiCr deposits have good metal-to-metal wear resistance, take a high polish under wearing conditions, and are particularly resistant to galling. These properties are especially evident in the NiCr-C alloy.

*Other Properties or Characteristics:* In compression, these alloys have an elastic limit of 42,000 lb/in.<sup>2</sup> Their yield strength in compression is 92,000 lb/in.<sup>2</sup> (0.01 per cent offset), 150,000 lb/in.<sup>2</sup> (0.10 per cent offset), and 210,000 lb/in.<sup>2</sup> (0.20 per cent offset). Deposits of NiCr filler metals may be machined with tungsten carbide tools using slow speeds, light

feeds, and heavy tool shanks. They are also finished by grinding using a soft-to-medium vitrified silicon carbide wheel.

**Chromium Plating.**—Chromium plating is an electrolytic process of depositing chromium on metals either as a protection against corrosion or to increase the surface-wearing qualities. The value of chromium-plating plug and ring gages has probably been more thoroughly demonstrated than any other single application of this treatment. Chromium-plated gages not only wear longer, but when worn, the chromium may be removed and the gage replated and reground to size.

In general, chromium-plated tools have operated well, giving greatly improved performance on nearly all classes of materials such as brass, bronze, copper, nickel, aluminum, cast iron, steel, plastics, asbestos compositions, and similar materials. Increased cutting life has been obtained with chromium-plated drills, taps, reamers, files, broaches, tool tips, saws, thread chasers, and the like. Dies for stamping, drawing, hot forging, die casting, and for molding plastics materials have shown greatly increased life after being plated with hard chromium.

Special care is essential in grinding and lapping tools preparatory to plating the cutting edges, because the chromium deposit is influenced materially by the grain structure and hardness of the base metal. The thickness of the plating may vary from 0.0001 to 0.001 or 0.002 inch, the thicker platings being used to build up undersize tools such as taps and reamers. A common procedure in the hard chromium plating of tools, as well as for parts to be salvaged by depositing chromium to increase diameters, is as follows:

- 1) Degrease with solvent; 2) Mount the tools on racks; 3) Clean in an anodic alkali bath held at a temperature of 82 degrees C for from 3 to 5 minutes; 4) Rinse in boiling water; 5) Immerse in a 20 per cent hydrochloric acid solution for 2 to 3 seconds; 6) Rinse in cold water; 7) Rinse in hot water; 8) Etch in a reverse-current chromic acid bath for 2 to 5 minutes; 9) Place work immediately in the chromium plating bath; and 10) Remove hydrogen embrittlement, if necessary, by immersing the plated tools for 2 hours in an oil bath maintained at 177 degrees C.

Chromium has a very low coefficient of friction. The static coefficient of friction for steel on chromium-plated steel is 0.17, and the sliding coefficient of friction is 0.16. This value may be compared with the static coefficient of friction for steel on steel of 0.30 and a sliding coefficient of friction of 0.20. The static coefficient of friction for steel on babbitt is 0.25, and the sliding coefficient of friction 0.20, whereas for chromium-plated steel on babbitt, the static coefficient of friction is 0.15, and the sliding coefficient of friction is 0.13. These figures apply to highly polished bearing surfaces. Articles that are to be chromium plated in order to resist frictional wear should be highly polished before plating so that full advantage can be taken of the low coefficient of friction that is characteristic of chromium. Chromium resists attack by almost all organic and inorganic compounds, except muriatic and sulfuric acids. The melting point of chromium is 2930 degrees F, and it remains bright up to 1200 degrees F. Above 1200 degrees F, a light adherent oxide forms and does not readily become detached. For this reason, chromium has been used successfully for protecting articles that must resist high temperatures, even above 2000 degrees F.

### **Electron-Beam (EB) Welding**

Heat for melting of metals in electron-beam welding is obtained by generating electrons, concentrating them into a beam, and accelerating them to between 30 and 70 per cent of the speed of light, using voltages between 25 and 200 kV. The apparatus used is called an electron-beam gun, and it is provided with electrical coils to focus and deflect the beam as needed for the welding operation. Energy input depends on the number of electrons impinging on the work in unit time, their velocity, the degree of concentration of the beam, and the traveling speed of the workpiece being welded. Some  $6.3 \times 10^{15}$  electrons/s are generated in a 1-mA current stream. With beam diameters of 0.01 to 0.03 in. (0.25 to 0.76

mm), beam power can reach 100 kW and power density can be as high as  $10^7$  W/in<sup>2</sup> ( $1.55 \times 10^4$  W/mm<sup>2</sup>), higher than most arc welding levels.

At these power densities, an electron beam can penetrate steel up to 4 in thick and form a vapor capillary or keyhole, as described earlier. Although patterns can be traced by deflecting the beam, the method used in welding is to move the electron gun or the workpiece. A numerical control, or computer numerical control, program is used because of the accuracy required to position the narrow beam in relation to the weld line.

Equipment is available for electron-beam welding under atmospheric pressure or at various degrees of vacuum. The process is most efficient (produces the narrowest width and deepest penetration welds) at high levels of vacuum, of the order of  $10^{-6}$  to  $10^{-3}$  torr or lower (standard atmospheric pressure is about 760 torr, or 760 mm of mercury), so that a vacuum chamber large enough to enclose the work is needed. Operation in a vacuum minimizes contamination of the molten weld material by oxygen and nitrogen. Gases produced during welding are also extracted rapidly by the vacuum pump so that welding of reactive metals is eased. However, the pumping time and the size of many workpieces restrict the use of high-vacuum enclosures.

At atmospheric pressures, scattering of the beam electrons by gas molecules is increased in relation to the number of stray molecules and the distance traveled, so that penetration depth is less and the beam spread is greater. In the atmosphere, the gun-to-work distance must be less than about 1.5 in. (38 mm). Electron-beam welding at atmospheric pressure requires beam-accelerating voltages above 150 kV, but lower values can be used with a protective gas. Helium is preferred because it is lighter than air and permits greater penetration. Argon, which is heavier than air and allows less penetration, can also be used to prevent contamination.

Required safety precautions, such as radiation shields to guard workers against the effects of X-rays when the electron beam strikes the work, are essential when electron-beam welding is done at atmospheric pressure. Such barriers are usually built into enclosures that are designed specifically for electron-beam welding in a partial vacuum. Adequate ventilation is also required to remove ozone and other gases generated when the process is used in the atmosphere.

Carbon, low-alloy, and stainless steels; high-temperature and refractory alloys; copper and aluminum alloys can be electron-beam welded, and single-pass, reasonably square, butt welds can be made in materials up to 1 in. (25.4 mm) thick at good speeds with nonvacuum equipment rated at 60 kW. Edges of thick material to be electron-beam welded require precision machining to provide good joint alignment and minimize the joint gap. Dissimilar metals usually may be welded without problems.

Because of the heat-sink effect, electron-beam welds solidify and cool very rapidly, causing cracking in certain materials such as low-ferrite stainless steel. Although capital costs for electron-beam welding are generally higher than for other methods, welding of large numbers of parts and the high welding travel rates make the process competitive.

### Pipe Welding

**Pipe Welding.**—Welding of (usually steel) pipe is commonly performed manually, with the pipe joint stationary, or held in a fixture whereby rotation can be used to keep the weld location in a fixed, downhand, position. Alternatively, pipe may need to be welded on site, without rotation, and the welder then has to exert considerable skill to produce a satisfactory, pressure-tight joint. Before welding stationary pipe, a welder must be proficient in welding in the four basic positions: 1G flat, 2G horizontal, 3G vertical and 4G overhead, depicted at the top in [Figs. 1a, 1b, 1c, and 1d](#).

## Positioning of Joint Components in Pipe Welding

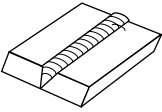


Fig. 1a. Flat Position 1G

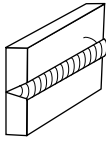


Fig. 1b. Horizontal Position 2G

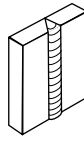


Fig. 1c. Vertical Position 3G

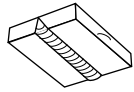
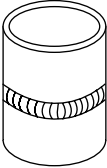
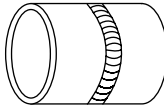
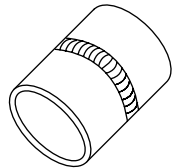


Fig. 1d. Overhead Position 4G

Fig. 1e. Horizontal position 2G  
Pipe Axis VerticalFig. 1f. Position 5G  
Pipe Fixed, Axis HorizontalFig. 1g. Position 6G  
Pipe Fixed, Axis Inclined

At the bottom are shown pipe joints in three positions, the first of which, Fig. 1e, corresponds to the 2G horizontal (non-rotational) position in the upper row. The remaining two are respectively 5G, Fig. 1f, that represents pipe with the weld in a fixed vertical (non-rotational) position; and 6G, Fig. 1g, that typifies pipe to be welded at an angle and not rotated during welding.

For satisfactory pipe welding, consideration must be given to the chemical composition and thickness of the metal to be welded; selection of a suitable electrode material composition and size; determination of the current, voltage and wire feed rate to be used; preparation of the joint or edges of the pipes; and ways of holding the pipes in the positions needed while welding is carried out. High-quality tack welds, each about 1.5 inches (38 mm) long, and projecting about  $\frac{1}{16}$  inch (1.6 mm) beyond the inner wall of the pipe, are usually made to hold the parts of the assembly in position during welding.

SMAW (stick) welding was used almost exclusively for pipe welding until the advent of MIG welding with its potential for much greater rates of deposition. It cannot be emphasized too strongly that practices suitable for SMAW cannot be transferred to MIG welding, for which greater expertise is required if satisfactory welds are to be produced. MIG short-circuit, globular, and spray transfer, and pulsed MIG, with flux or metal-cored consumables (electrodes) can now all be used for pipe welding. Use of all-position, flux-cored, MIG consumables in particular, can reduce skill requirements, improve weld quality, and hold down costs in pipe welding.

Among the important items involved in the change to the MIG process is the automatic wire feeder. With today's wire feeding equipment, an increase of one increment on the dial, say from the 9 to the 10 o'clock position, can increase the wire feed rate by 70 in/min. As an example, such an increase could raise the weld current from 110 to 145 amps and the weld voltage from 16 to 17, resulting in an increase of 40 per cent in the energy supplied to the weld. Another vital parameter is the amount that the wire sticks out from the contact tip. In low-parameter, short-circuit welding, a small change in the wire stick-out can alter the energy supplied to the weld by 20 to 30 per cent.

*Root passes:* Whatever welding process is selected, the most important step in pipe welding, as in other types of welding, is the root pass, which helps to determine the degree of penetration of the weld metal, and affects the amount of lack of fusion in the finished weld. During the root pass, the action of the arc in the weld area should reshape the gap between

the adjacent sides of the joint into a pear-shaped opening, often called a "keyhole." As the work proceeds, this keyhole opening is continuously being filled, on the trailing side of the weld, by the metal being deposited from the electrode. The keyhole travels along with the weld so that the root pass produces a weld that penetrates slightly through the inner wall of the pipe.

MIG short-circuit root welding of carbon steel pipe requires a gap of  $\frac{5}{32} \pm \frac{1}{32}$  ( $4 \pm 0.8$  mm), between the ends of the pipe, and the width of the root faces (at the base of the bevels) should be  $\frac{1}{16}$  to  $\frac{3}{32}$  inch (1.6 to 2.4 mm). The recommended bevel angle for MIG pipe welding is 40E (80E included angle) and the maximum root gap is  $\frac{3}{16}$  inch (4.8 mm). The root pass in 1G welds should be made in the vertical-down direction with the electrode held between the 2 and 3 o'clock positions. When an 0.035-inch (0.9-mm) diameter E70S-3 MIG wire is used with the above root dimensions, weaving is not needed for the root pass except when welding over tack welds.

*Fill passes:* In welding carbon steel pipe in the 1G position with an 0.035-inch diameter electrode wire, MIG short circuit fill passes should use a minimum of 135 amps and be done in the vertical-up position. Fill passes should deposit a maximum thickness of no more than  $\frac{1}{8}$  inch (3.2 mm). Inclusion of CO<sub>2</sub> gas in the mixture will improve weld fusion. With flux-cored electrodes, the minimum amount of wire stick out is  $\frac{3}{4}$  inch (19 mm). Weld fusion can be improved in welding pipe of 0.4 inch (10 mm) wall thickness and thicker by preheating the work to a temperature between 400 and 500°F.

*Horizontal Pipe Welding:* In 1G welds (see Fig. 1a), the pipe should be rotated in the direction that moves the solidifying area away from the wire tip, to minimize penetration and resulting breakthrough. Welding of pipe in the 2G, horizontal position is made more difficult by the tendency for the molten metal to drip from the weld pool. Such dripping may cause an excessively large keyhole to form during the root-welding pass, and in subsequent passes electrode metal may be lost. Metal may also be lost from the edge of the upper pipe, causing an undercut at that side of the weld.

*Vertical-down welding:* With the pipe axis horizontal (as in the 5G position in Fig. 1f), vertical-down welding is usually started at the top or 12 o'clock location, and proceeds until the 6 o'clock location is reached. Welding then starts again at the 12 o'clock location and continues in the opposite direction until the 6 o'clock location is reached. Vertical-down welding is mainly used for thin-walled, low-carbon steel pipe of  $\frac{1}{8}$  to  $\frac{5}{16}$  inch (3.2 to 7.9 mm) wall thickness, which has low heat-retaining capacity so that the weld metal cools slowly, producing a soft and ductile structure. The slow rate of cooling also permits faster weld deposition, and, when several beads are deposited, causes an annealing effect that may refine the entire weld structure.

*Vertical-up welding:* In the 5G position, vertical-up welding normally begins at the 6 o'clock location and continues up to the 12 o'clock location, the weld then being completed by starting at the 6 o'clock location on the other side of the pipe and traversing up to the 12 o'clock location again. Vertical-up welding is more suited to pipe with thick walls and to alloy steels. However, the greater heat sink effect of the heavy-walled pipe may result in a faster cooling rate and embrittlement of the material, especially in alloy steels. The cooling rate can be reduced by slowing the rate of traverse and depositing a heavier bead of metal, both facilitated by welding in the vertical-up direction.

Using a thicker electrode and higher current for thicker-walled pipe to reduce the number of beads required may result in dripping from the molten puddle of metal. Defects such as pin holes, lack of fusion, and cold lap, may then appear in the weld. Vertical-up welding of pipe in the 5G, fixed, horizontal position, Fig. 1f, used for thick-walled pipe, is probably the most difficult for a welder, but once mastered will form the basis for other methods of pipe welding. Starting at the 6 o'clock location, the arc for the root pass is struck overhead, with the electrode at an angle of 5 to 10° from the vertical, on the joint, not on the tack weld.



A long arc should be maintained for a short-period while weaving the electrode to pre-heat the area ahead of the weld. Only small amounts of filler metal will be transferred while this long arc is maintained in the overhead position. The electrode tip is then advanced to establish the correct arc length and held in position long enough for the keyhole to form before starting to lay down the root bead, moving up toward the 12 o'clock location.

*Thin-wall pipe:* The optimum globular/spray parameters for welding rotated, (1G position) thin-wall pipe of less than 12 inch diameter are 0.035-inch electrode wire fed at 380 to 420 in/min with a protective gas mixture of argon 80 to 85, CO<sub>2</sub> 15 to 20 per cent, and current of 190 to 210 amps. These conditions will provide deposition rates of about 6 lb/hr (3 kg/hr).

**Use of Flux-cored Electrodes.**—Small diameter, flux cored electrodes developed in the eighties are still a rarity in many pipe welding shops, but flux cored welding can produce consistent, high-quality, low-cost welds on carbon steel or stainless pipe. Flux cored E71T-1, 0.035-inch (1 mm) diameter wire provides a continuous, medium energy, open arc, with a practical current range of 135 to 165 amps for welding pipe. This current range is similar to the optimum MIG short-circuit current range, and is 25 to 30 percent less current than the minimum open arc spray transfer current for an 0.035-inch diameter MIG wire.

In contrast to MIG short circuit welding, FCAW works with an open arc and no short circuits. The FCAW arc energy is continuous, and, in contrast to short-circuit transfer, provides increased weld fusion potential. The weld metal from the flux-cored tubular wire is transferred from the periphery and the center of the wire, resulting in broad coverage of the weld. The plasma in the flux cored arc is wider than MIG plasma, and the flux-cored arc is less focused and easier to control than the MIG spray arc.

Open arc, gas shielded, flux-cored welding can produce spray type transfer at lower currents than open arc MIG spray transfer. With FCAW, the current density is high because the electrode wire cross-sectional area is less than that of the same size MIG solid wire due to the central core of flux. This higher density provides for improved weld penetration potential. The FCAW process produces slag, which serves as a mold to hold the fluid molten metal in place, an ideal arrangement for vertical-up and overhead welds.

All position, flux-cored wires require less operator skill for vertical-up and overhead welds than MIG, SMAW, and TIG processes. Fill passes can also be completed in 30 to 50 percent less time with all-position, flux-cored wires than with MIG short circuit and SMAW wires.

For good quality FCAW, welders need to know the best root and bevel dimensions, and the importance of maintaining those dimensions for continuous weld fusion; the preferred direction of pipe rotation; the diameter of flux cored electrode best suited for welding thin wall pipe; the optimum parameter range for that electrode on 1G and 5G welds; the preferred amount of wire stick out (typically 0.7 inch or 18 mm); and how to fine tune the voltage. When flux-cored welding is to be used for the fill passes, MIG short circuit welding is recommended for the root welds to reduce the possibility of slag from the flux being trapped in the weld. Higher weld deposit rates are provided with flux-cored, vertical-up welding, and there is the temptation to weld faster with a process that's easy to use. Conservative wire feed settings are recommended unless the high deposition rates are shown to provide consistent weld fusion. Wire feed settings should allow the welder time to control and direct the weave into the critical groove locations.

**Complete Weld Fusion.**—It is essential that new weld metal deposits be completely fused with the pipe components, and with metal laid down in successive passes. Factors that can prevent complete fusing are too numerous to list here. Some basic rules that, if followed, will improve weld fusion and quality in MIG welding in the 1G and 5G positions are:

- 1) The maximum gap at the root should be  $\frac{3}{16}$  inch (5 mm)
- 2) The root land should be  $\frac{1}{16}$  to  $\frac{3}{32}$  inch (1.6 to 2.4 mm) wide

- 3) A bevel angle of 80° inclusive should be used for MIG and flux-cored welding of pipe to provide width for weaving and improve fusion.
- 4) An 0.035-in MIG electrode should have a minimum short circuit current of 135 amps for fill passes
- 5) Tack and root welds should be made in the vertical-down position.
- 6) Tack welds should be about 1.5 in (38 mm) long by  $\frac{1}{16}$  to  $\frac{3}{32}$  inch (1.6 to 2.4 mm) thick.
- 7) Short circuit fill passes should be made in the vertical-up position.
- 8) With flux-cored electrodes, a minimum of 0.7 inch (18 mm) wire stick out from the contact tip must be maintained.
- 9) Current and voltage must be related to the pipe wall thickness
- 10) Argon+25 per cent CO<sub>2</sub> is recommended for short circuit welding of pipe roots.
- 11) Use of undiluted CO<sub>2</sub> gas will improve MIG weld fusion in fill passes because of the "digging" action of the arc, and the increased weld energy
- 12) With pipe wall thicknesses of 0.4 in (10 mm) or greater, preheating to between 400 and 500° F (205 and 260°C), will help make fusion complete

**Other Methods.**—Pulsed MIG is a viable alternative to flux-cored for all-position welds on 5G pipe, but requires more costly equipment. The pulsed MIG process however, has few advantages over conventional MIG and flux-cored when the latter are used correctly. Pulsed MIG may have some advantage on mechanized 5G welds, and on welding of stainless steel, pipe in the 5G position.

Metal-cored electrode wire also has few advantages for pipe welds because they work best with low-energy gas welds, which cancels out the increased current density claimed for them.

On most manual pipe welds, the welder needs time to control and direct the weave to ensure even heating and avoid lack of fusion. Satisfactory welds are often performed at travel speeds of 4 to 12 in/min giving deposit rates of 3 to 5 lb/hr.

### Pipe Welding Procedure

Because of the variety of parameter combinations that can be used in pipe welding, it is suggested that charts be prepared and displayed in welding booths to remind welders of the basic settings to be used. Examples of such charts for tack, root, fill and cover passes, are included in what follows:

**FCAW 5G (Non-rotated) MIG Welding of Thick-Walled, Carbon-steel Pipes, Procedure for Root Welding.**—This procedure can be applied to most pipe sizes, and should be given special consideration for 5G (non-rotated) welds on carbon steel pipe with  $\frac{3}{8}$  inch (10 mm) wall thickness and thicker.

#### Pipe and Weld Data

Pipe bevel included angle = 80°

Root face land =  $\frac{3}{32} \pm \frac{1}{32}$  inch (2.4 ± 0.8 mm)

Root gap between faces =  $\frac{5}{32} \pm \frac{1}{32}$  inch (4 ± 0.8 mm)

Electrode for root weld = 0.035-inch (0.9 mm) diameter, E70S-3 flux-cored.

Gas = argon with 15–25% CO<sub>2</sub>

Gas flow rates = 30 to 40 cubic ft/hr

Set wire feeder to 210–280 in/min (10 to 11 o'clock position on many feeders) for current of 140–170 amps, 17–18 volts.

**Wire extension:** For MIG root weld, set contact tip to stick outside the nozzle,  $\frac{1}{16}$  to  $\frac{1}{8}$  inch (1.6 to 3 mm). Maintain  $\frac{3}{8}$  to  $\frac{5}{8}$  inch (10 to 16 mm) maximum wire stick out from contact tip.

*Tack Welding Procedures for FCAW 5G Pipe Welds:* Make tack welds 1.5 to 2 inches (38 to 50 mm) long. After welding, grind full length of tack to thickness of approximately  $\frac{1}{16}$  inch (1.6 mm). Feather tack ends back  $\frac{3}{8}$  to  $\frac{1}{2}$  inches (9.5 to 13 mm).

On pipes of less than 6 inches (15 cm) outside diameter, use three tack welds, equally spaced, starting at 12 o'clock.

On pipes over 6 inches outside diameter use 4 tack welds. Locate tack welds at 12, 3, 6, and 9 o'clock.

*Root Welding Procedures for FCAW 5G Pipe Welds:* Root weld MIG vertical-down. Weld sequence: 12 to 3, 9 to 6, 3 to 6, and 12 to 9 o'clock positions.

Start and finish MIG root welds at tack centers. Use slight weave oscillation over tacks. No weave necessary if  $\frac{1}{8}$ - to  $\frac{5}{32}$ -inch root gap is maintained. Weaving may be required if root gap is less than  $\frac{1}{8}$  inch (3 mm). Weaving is also beneficial for root welds between 7 and 6 o'clock, and between 5 and 6 o'clock. After each root pass, blend the starts and stops back to the original tack thickness.

To complete the root, ensure that the weld stops and starts on the last tack, and that the root weld center is ground flat or slightly concave. Remove any slag islands.

**FCAW 5G (Non-rotated) MIG Welding of Thick-Walled, Carbon-steel Pipes, Procedure for Fill and Cover Welds.**—This procedure can be applied to most common pipe sizes, and should be given special consideration for 5G (non-rotated) welds on carbon steel pipe with  $\frac{3}{8}$  inch (10 mm) wall thickness and thicker.

#### *Pipe and Weld Data*

*Electrode for fill and cover passes* = 0.035 inch (0.9 mm) diameter, 71T-1 flux-cored

*Gas* = argon with 15–25% CO<sub>2</sub>

*Gas flow rates* = 30 to 40 cubic ft/hr

Set an initial wire feed rate of 350 to 450 in/min (12 to 1 o'clock position on typical wire feed unit), 135–165 amps, 25–28 volts. Alternatively, use a wire feed setting of 350 in/min (12 o'clock on wire feed unit), which should result in about 135–145 amps, 25–26 volts. If the weld pool and weld heat build up permit, increase the wire feed rate to 380 in/min (between the 12 and 1 o'clock positions), 150 amps, 27 volts. Try also a wire feed setting of 420 in/min (1 o'clock on the wire feeder), 165 amps, 28 volts. Determine the low and maximum wire feed rates to be used by examination of the weld fusion obtained in sectioned test samples.

*Wire extension:* Adjust contact tip so it is recessed  $\frac{1}{2}$  inch within the nozzle to provide a total wire stick out from the contact tip of 0.7 to 1 inch (18 to 25 mm).

*Fill and Cover Pass Procedures for FCAW 5G Pipe Welds:* Weld vertical-up. If the pipe diameter allows the fill pass to be made in two passes, start at the 7 o'clock position and weld to the 1 o'clock position. This approach is preferable to starting and finishing on the root tacks. Starting at the 7 o'clock position will ensure that optimum weld energy is achieved as the first pass welds over the initial 6 o'clock root tack location. Use the grinder to feather the first 1 inch (25 mm) of the weld start and stop of the first pass, before applying the second vertical-up weld pass. Use a slight weave action for the fill pass.

Remove all flux-cored slag between weld passes. Make sure no fill pass is greater in depth than  $\frac{1}{8}$  inch (3 mm). Use a straight weave across the root face. At the bevel edge use a slight upward motion with the gun. The motion should be no greater than the wire diameter. Then use a slight back step for added bevel fusion and to avoid undercuts.

Leave  $\frac{1}{32}$  to  $\frac{1}{16}$  inch (0.8 to 1.6 mm) of the groove depth to provide for the optimum cover pass profile. The bevel edge will act as a guide for the cover pass weld. If more weld fusion is required for pipe thicker than  $\frac{3}{8}$  inch (10 mm), after the root weld is complete, preheat the

pipe to between 400 and 600°F (200–300°C) before welding. Preheating is typically not necessary for a cover pass.

For pipe diameters on which the welder needs more than two passes for the vertical-up welds, the recommended sequence for vertical-up welding is:

- 1) First pass, weld from the 7 to the 4 o'clock position. Start with a slight forehand nozzle angle. At the 4 o'clock position, the gun should be at the same angle as the pipe.
- 2) Second pass, weld from the 10 to the 1 o'clock position, then grind all stops and start again at the 1-inch (25 mm) position.
- 3) Third pass, weld from the 4 to the 1 o'clock position.
- 4) Fourth pass, weld from the 7 to the 10 o'clock position.

**FCAW 5G (Non-rotated) Welding of Thin-Walled Carbon Steel Pipes, Procedure for Root, Fill and Cover Pass Welding.**—This procedure can be applied to most common pipe sizes, and should be given special consideration for 5G (non-rotated) welding of carbon steel pipe with wall thicknesses up to  $\frac{3}{8}$  inch (10 mm).

*Pipe and Weld Data*

*Electrode for root weld* = 0.035 inch diameter, E70S-6 flux cored.

*Gas* = argon with 15–25% CO<sub>2</sub>

*Gas flow rates* = 30 to 40 cubic ft/hr

*Root Welding Procedure for 5G Welds:* Use root welding data from *Root Welding Procedures for FCAW 5G Pipe Welds*, above.

*Fill and Cover Pass Procedures for 5G Welds:* Use MIG short-circuit, vertical-up for fill and cover passes. Electrode wire and gas, same as for root weld.

Weld vertical-up. If the vertical-up fill pass can be made in two passes, weld from the 7 to the 1 o'clock position, to avoid starting and finishing on the root tacks. Starting just past 6 o'clock ensures that optimum weld energy is achieved as the first pass welds over the initial 6 o'clock root tack location. Feather 1 inch (25 mm) of the weld start and stop on the first pass with the grinder before applying the second vertical-up weld pass. Use a slight weave action.

Use MIG short-circuit wire feed, 200–230 in/min 125–135 amps, 19–22 volts. Start at optimum 210 in/min (10 o'clock on the wire feeder) for 130 amps, 21–22 volts. Fine tune voltage by listening to arc sound to obtain a consistent rapid crackle sound.

Electrode sticks out  $\frac{1}{2}$  to  $\frac{5}{8}$  inch, contact tip flush with nozzle end.

Remove MIG surface slag islands between weld passes. No fill pass should be thicker than  $\frac{1}{8}$  inch (3 mm). Use straight weave across the root face. At the bevel, use a slight upward motion with the gun. The motion should be no greater than the wire diameter. Then use a slight back step for added bevel fusion and to avoid possibility of undercut.

For the cover pass, leave  $\frac{1}{32}$  to  $\frac{1}{16}$  inch of the groove depth for the optimum cover pass profile. The bevel edge will act as a guide for the cover pass weld.

If more weld fusion is required after the root is complete and between fill passes, pre-heat pipe to 200 to 400°F.

For pipe diameters on which more than two passes are required for the circumference the weld sequence is:

- 1) First pass, weld from the 7 to the 4 o'clock position. Start with a slight forehand nozzle angle. At the 4 o'clock position the gun should point straight at the joint;
- 2) Second pass, weld from the 10 to the 1 o'clock position, then grind all stops and starts for at least 1 inch (25 mm);
- 3) Third pass, weld from the 4 to the 1 o'clock position; and
- 4) Fourth pass, weld from the 7 to the 10 o'clock position.

## Weld and Welding Symbols

**American National Standard Weld and Welding Symbols.**—Graphical symbols for welding provide a means of conveying complete welding information from the designer to the welder by means of drawings. The symbols and their method of use (examples of which are given in the table following this section) are part of the American National Standard ANSI/AWS A2.4-79 sponsored by the American Welding Society.

In the Standard a distinction is made between the terms *weld symbol* and *welding symbol*. Weld symbols, shown in the table *Basic Weld Symbols*, are ideographs used to indicate the type of weld desired, whereas welding symbol denotes a symbol made up of as many as eight elements conveying explicit welding instructions.

The eight elements which may appear in a welding symbol are: reference line; arrow; basic weld symbols; dimensions and other data; supplementary symbols; finish symbols; tail and specification; and process or other reference.

The standard location of elements of a welding symbol are shown in Fig. 1.

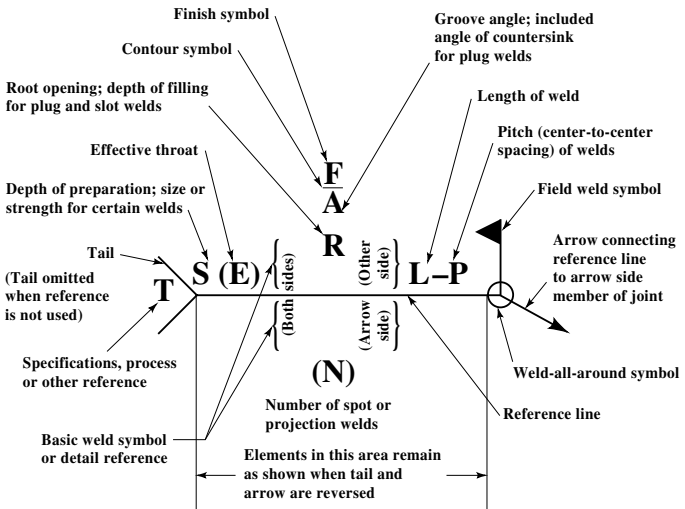


Fig. 1. Standard Location of Elements of a Welding Symbol

**Reference Line:** This is the basis of the welding symbol. All other elements are oriented with respect to this line. The arrow is affixed to one end and a tail, when necessary, is affixed to the other.

**Arrow:** This connects the reference line to one side of the joint in the case of groove, fillet, flange, and flash or upset welding symbols. This side of the joint is known as the *arrow side* of the joint. The opposite side is known as the *other side* of the joint. In the case of plug, slot, projection, and seam welding symbols, the arrow connects the reference line to the outer surface of one of the members of the joint at the center line of the weld. In this case the member to which the arrow points is the *arrow side* member; the other member is the *other side* member. In the case of bevel and J-groove weld symbols, a two-directional arrow pointing toward a member indicates that the member is to be chamfered.

**Basic Weld Symbols:** These designate the type of welding to be performed. The basic symbols which are shown in the table *Basic Weld Symbols* are placed approximately in the

center of the reference line, either above or below it or on both sides of it as shown in Fig. 1. Welds on the arrow side of the joint are shown by placing the weld symbols on the side of the reference line towards the reader (lower side). Welds on the other side of the joint are shown by placing the weld symbols on the side of the reference line away from the reader (upper side).

**Supplementary Symbols:** These convey additional information relative to the extent of the welding, where the welding is to be performed, and the contour of the weld bead. The “weld-all-around” and “field” symbols are placed at the end of the reference line at the base of the arrow as shown in Fig. 1 and the table *Supplementary Weld Symbols*.

**Dimensions:** These include the size, length, spacing, etc., of the weld or welds. The size of the weld is given to the left of the basic weld symbol and the length to the right. If the length is followed by a dash and another number, this number indicates the center-to-center spacing of intermittent welds. Other pertinent information such as groove angles, included angle of countersink for plug welds and the designation of the number of spot or projection welds are also located above or below the weld symbol. The number designating the number of spot or projection welds is always enclosed in parentheses.

**Contour and Finish Symbols:** The contour symbol is placed above or below the weld symbol. The finish symbol always appears above or below the contour symbol (see Fig. 1).

The following finish symbols indicate the method, not the degrees of finish: C—chipping; G—grinding; M—machining; R—rolling; and H—hammering.

For indication of surface finish refer to the section *SURFACE TEXTURE* starting on page 724.

**Tail:** The tail which appears on the end of the reference line opposite to the arrow end is used when a specification, process, or other reference is made in the welding symbol. When no specification, process, or other reference is used with a welding symbol, the tail may be omitted.

**Table 1. Basic Weld Symbols**

| Groove Weld Symbols |                    |                    |       |                 |           |         |             |
|---------------------|--------------------|--------------------|-------|-----------------|-----------|---------|-------------|
| Square              | Scarf <sup>a</sup> | V                  | Bevel | U               | J         | Flare V | Flare bevel |
|                     |                    |                    |       |                 |           |         |             |
| Other Weld Symbols  |                    |                    |       |                 |           |         |             |
| Fillet              | Plug or slot       | Spot or projection | Seam  | Back or backing | Surfacing | Flange  |             |
|                     |                    |                    |       |                 |           | Edge    | Corner      |
|                     |                    |                    |       |                 |           |         |             |

<sup>a</sup>This scarf symbol used for brazing only (see page 1388).

For examples of basic weld symbol applications see starting on page 1436.

Table 2. Supplementary Weld Symbols

| Weld all around | Field weld | Melt-thru | Backing or spacer material | Countour |        |         |
|-----------------|------------|-----------|----------------------------|----------|--------|---------|
|                 |            |           |                            | Flush    | Convex | Concave |
|                 |            |           |                            |          |        |         |

**Melt-Thru Symbol:** The melt-thru symbol is used only where 100 per cent joint or member penetration plus reinforcement are required.

**Specification, Process, or Other Designation:** These are placed in the tail of the welding symbol and are in accordance with the American National Standard. They do not have to be used if a note is placed on the drawing indicating that the welding is to be done to some specification or that instructions are given elsewhere as to the welding procedure to be used.

**Letter Designations:** American National Standard letter designations for welding and allied processes are shown in the table on page 1435.

**Further Information:** For complete information concerning welding specification by the use of standard symbols, reference should be made to American National Standard ANSI/AWS A2.4-79, which may be obtained from either the American National Standards Institute or the American Welding Society listed below.

**Welding Codes, Rules, Regulations, and Specifications.**—Codes recommending procedures for obtaining specified results in the welding of various structures have been established by societies, institutes, bureaus, and associations, as well as state and federal departments.

The latest codes, rules, etc., may be obtained from these agencies, whose names and addresses are listed as follows: PV = Pressure Vessels; P = Piping; T = Tanks; SB = Structural and Bridges; S = Ships; AC = Aircraft Construction; and EWM = Electrical Welding Machinery.

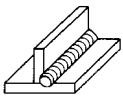
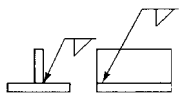
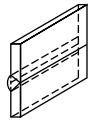
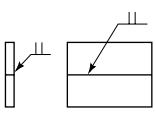
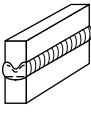
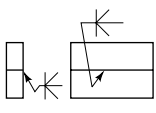
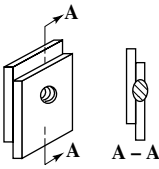
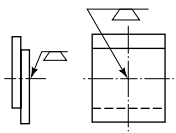
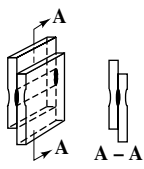
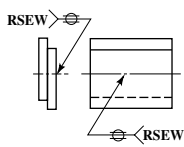
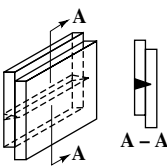
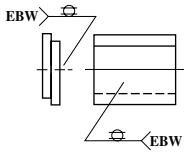
- Air Force/LGM, Department of the Air Force, Washington, DC 20330. (AC)
- American Bureau of Shipping, 45 Eisenhower Drive, Paramus, NJ 07652. (S)
- American Institute of Steel Construction., 1 E. Wacker Drive, Chicago, IL 60601. (SB)
- American National Standards Institute, 25 W. 43rd St. NY, NY 10036. (PV, P, EWM)
- American Petroleum Institute, 1220 L St., NW, Washington, DC 20005. (PV)
- American Society of Mechanical Engineers, 3 Park Avenue, NY, NY 10016. (PV)
- American Welding Society, 550 LeJeune Road, Miami, FL 33135. (T, S, SB, AC)
- Federal Aviation Administration, 800 Independence Avenue, S.W. Washington DC 20591. (AC)
- Insurance Services Office, 545 Washington Blvd., Jersey City, NJ 07310. (PV)
- Lloyd's Register of Shipping, 17 Battery Place, NY, NY 10004. (S)
- Mechanical Contractors Association., 1385 Piccard Drive, Rockville, MD 20850. (P)
- National Electrical Manufacturers. Association., 2100 North Street, Rosslyn, VA 22209. (EWM)
- Naval Facilities Engineering Command, 1322 Patterson Ave., Washington Navy Yard, DC 20374. (SB)
- Naval Ship Engineering Center, Dept. of the Navy, Hyattsville, MD 20782. (PV, S)
- U.S. Government Printing Office, Washington, 732 N. Capitol St, N.W. DC 20402. (PV)

**American National Standard Letter Designations for Welding and Allied Processes**  
ANSI/AWS A2.4-91

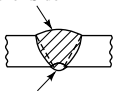
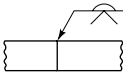
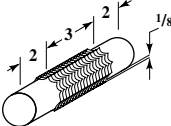
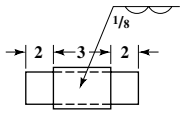

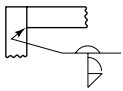
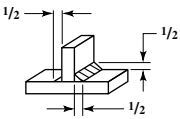
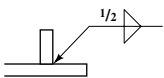
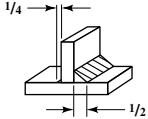
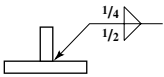
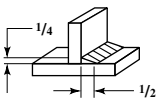
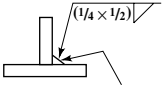
| Letter Designation | Welding and Allied Processes                   | Letter Designation | Welding and Allied Processes               |
|--------------------|--|--------------------|--|
| AAC                | air carbon arc cutting                         | HPW                | hot pressure welding                       |
| AAW                | air acetylene welding                          | IB                 | induction brazing                          |
| AB                 | arc brazing                                    | INS                | iron soldering                             |
| ABD                | adhesive bonding                               | IRB                | infrared brazing                           |
| AC                 | arc cutting                                    | IRS                | infrared soldering                         |
| AHW                | atomic hydrogen welding                        | IS                 | induction soldering                        |
| AOC                | oxygen arc cutting                             | IW                 | induction welding                          |
| ASP                | arc spraying                                   | LBC                | laser beam cutting                         |
| AW                 | carbon arc welding                             | LBC-A              | laser beam cutting—air                     |
| B                  | brazing  | LBC-EV             | laser beam cutting—<br>evaporative         |
| BB                 | block brazing                                  |                    |  |
| BMAW               | bare metal arc welding                         | LBC-IG             | laser beam cutting—<br>inert gas           |
| CAB                | carbon arc brazing                             |                    |  |
| CAC                | carbon arc cutting                             | LBC-O              | laser beam cutting—oxygen                  |
| CAW                | carbon arc welding                             | LBW                | laser beam welding                         |
| CAW-G              | gas carbon arc welding                         | LOC                | oxygen lance cutting                       |
| CAW-S              | shielded carbon arc welding                    | MAC                | metal arc cutting                          |
| CAW-T              | twin carbon arc welding                        | OAW                | oxyacetylene welding                       |
| CEW                | coextrusion welding                            | OC                 | oxygen cutting                             |
| CW                 | cold welding                                   | OFC                | oxyfuel gas cutting                        |
| DB                 | dip brazing                                    | OFC-A              | oxyacetylene cutting                       |
| DFB                | diffusion brazing                              | OFC-H              | oxyhydrogen cutting                        |
| DFW                | diffusion welding                              | OFC-N              | oxynatural gas cutting                     |
| DS                 | dip soldering                                  | OFC-P              | oxypropane cutting                         |
| EBC                | electron beam cutting                          | OFW                | oxyfuel gas cutting                        |
| EBW                | electron beam welding                          | OHW                | oxyhydrogen welding                        |
| EBW-HV             | electron beam welding—<br>high vacuum          | PAC                | plasma arc cutting                         |
|                    |  | PAW                | plasma arc welding                         |
| EBW-MV             | electron beam welding—<br>medium vacuum        | PEW                | percussion welding                         |
|                    |  | PGW                | pressure gas welding                       |
| EBW-NV             | electron beam welding—<br>nonvacuum            | POC                | metal powder cutting                       |
|                    |  | PSP                | plasma spraying                            |
| EGW                | electrogas welding                             | PW                 | projection welding                         |
| ESW                | electroslag welding                            | RB                 | resistance brazing                         |
| EXW                | explosion welding                              | RS                 | resistance soldering                       |
| FB                 | furnace brazing                                | RSEW               | resistance seam welding                    |
| FCAW               | flux-cored arc welding                         | RSEW-HF            | resistance seam welding—<br>high frequency |
| FLB                | flow brazing                                   |                    |  |
| FLOW               | flow welding                                   | RSEW-I             | resistance seam welding—<br>induction      |
| FLSP               | flame spraying                                 |                    |  |
| FOC                | chemical flux cutting                          | RSW                | resistance spot welding                    |
| FOW                | forge welding                                  | ROW                | roll welding                               |
| FRW                | friction welding                               | RW                 | resistance welding                         |
| FS                 | furnace soldering                              | S                  | soldering                                  |
| FW                 | flash welding                                  | SAW                | submerged arc welding                      |
| GMAC               | gas metal arc cutting                          | SAW-S              | series submerged arc<br>welding            |
| GMAW               | gas metal arc welding                          |                    |  |
| GMAW-P             | gas metal arc welding—pulsed arc               | SMAC               | shielded metal arc cutting                 |
| GMAW-S             | gas metal arc welding—<br>short-circuiting arc | SMAW               | shielded metal arc<br>welding              |
| GTAC               | gas tungsten arc cutting                       |                    |  |
| GTAW               | gas tungsten arc welding                       | SSW                | solid state welding                        |
| GTAW-P             | gas tungsten arc welding—<br>pulsed arc        | SW                 | stud arc welding                           |



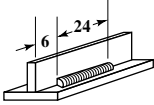
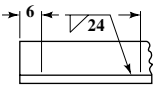
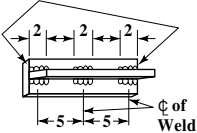
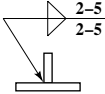
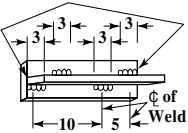
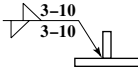
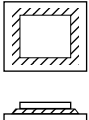
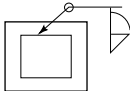
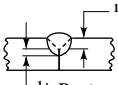
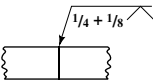
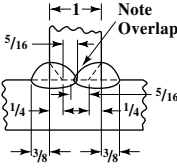
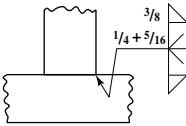
## Application of American National Standard Welding Symbols

| Desired Weld  | Symbol  | Symbol Meaning  |
|---|---|---|
|    |    | Symbol indicates fillet weld on <i>arrow side</i> of the joint.   |
|    |    | Symbol indicates square-groove weld on <i>other side</i> of the joint.  |
|    |    | Symbol indicates bevel-groove weld on both sides of joint. Breaks in arrow indicate bevels on upper member of joint. Breaks in arrows are used on symbols designating bevel and J-groove welds.   |
|   |   | Symbol indicates plug weld on <i>arrow side</i> of joint.   |
|  |  | Symbol indicates resistance-seam weld. Weld symbol appears on both sides of reference line pointing up the fact that <i>arrow</i> and <i>other side</i> of joint references have no significance. |
|   |  | Symbol indicates electron beam seam weld on <i>other side</i> of joint.   |

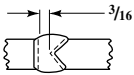
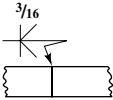
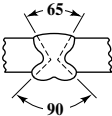
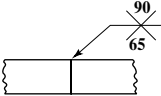

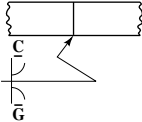
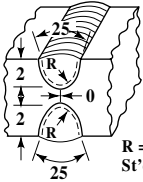
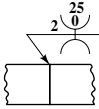
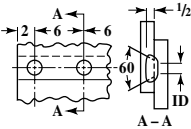
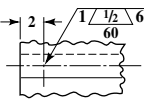
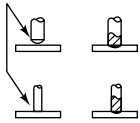
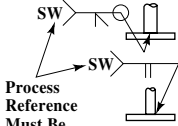
## Application of American National Standard Welding Symbols (Continued)

| Desired Weld   | Symbol  | Symbol Meaning   |
|--|---|--|
| <p>Groove Weld Made Before Welding Other Side</p>  <p>Back Weld</p> |                                        | <p>Symbol indicates single-pass back weld.</p>   |
|    |                                        | <p>Symbol indicates a built-up surface <math>\frac{1}{8}</math> inch thick.</p>  |
|   |                                        | <p>Symbol indicates a bead-type back weld on the <i>other side</i> of joint, and a J-groove grooved horizontal member (shown by break in arrow) and fillet weld on <i>arrow side</i> of the joint.</p> |
|   |                                       | <p>Symbol indicates two fillet welds, both with <math>\frac{1}{2}</math>-inch leg dimensions.</p>  |
|   |                                      | <p>Symbol indicates a <math>\frac{1}{2}</math>-inch fillet weld on <i>arrow side</i> of the joint and a <math>\frac{1}{4}</math>-inch fillet weld on <i>far side</i> of the joint.</p>                 |
|   |  <p>Orientation Shown on Drawing</p> | <p>Symbol indicates a fillet weld on <i>arrow side</i> of joint with <math>\frac{1}{4}</math>- and <math>\frac{1}{2}</math>-inch legs. Orientation of legs must be shown on drawing.</p>               |

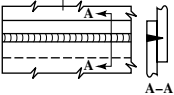
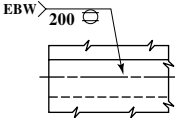
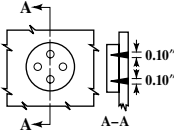
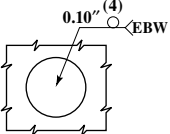
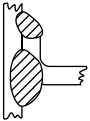
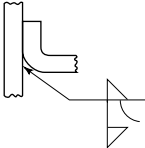
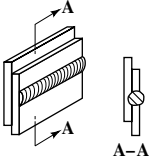
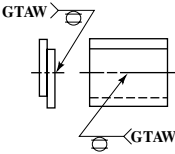
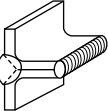
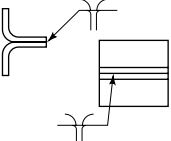

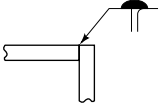
Application of American National Standard Welding Symbols (Continued)

| Desired Weld  | Symbol  | Symbol Meaning   |
|---|---|--|
|    |    | <p>Symbol indicates a 24-inch long fillet weld on the <i>arrow side</i> of the joint.</p>  |
| <p><b>Locate Welds at Ends of Joint</b></p>                   |    | <p>Symbol indicates a series of intermittent fillet welds each 2 inches long and spaced 5 inches apart on centers directly opposite each other on both sides of the joint.</p>                                   |
| <p><b>Locate Welds at Ends of Joint</b></p>                   |    | <p>Symbol indicates a series of intermittent fillet welds each 3 inches long and spaced 10 inches apart on centers. The centers of the welds on one side of the joint are displaced from those on the other.</p> |
|   |   | <p>Symbol indicates a fillet weld around the perimeter of the member.</p>  |
|  <p>1/4<br/>1/8 Root Penetration</p>                       |  | <p>Symbol indicates a 1/4-inch V-groove weld with a 1/8-inch root penetration.</p>   |
|  <p>Note Overlap<br/>5/16<br/>1<br/>1/4<br/>3/8<br/>3/8</p> |  | <p>Symbol indicates a 1/4-inch bevel weld with a 5/16-inch root penetration plus a subsequent 3/8-inch fillet weld.</p>  |

## Application of American National Standard Welding Symbols (Continued)

| Desired Weld  | Symbol  | Symbol Meaning  |
|---|---|---|
|                          |    | <p>Symbol indicates a bevel weld with a root opening of <math>\frac{3}{16}</math> inch.</p>   |
|                          |    | <p>Symbol indicates a V-groove weld with a groove angle of 65 degrees on the <i>arrow side</i> and 90 degrees on the <i>other side</i>.</p>   |
|                          |    | <p>Symbol indicates a flush surface with the reinforcement removed by chipping on the <i>other side</i> of the joint and a smooth grind on the <i>arrow side</i>. The symbols <i>C</i> and <i>G</i> should be the user's standard finish symbols.</p> |
|  <p>R = User's St'd.</p> |   | <p>Symbol indicates a 2-inch U-groove weld with a 25-degree groove angle and no root opening for both sides of the joint.</p>   |
|                         |    | <p>Symbol indicates plug welds of 1-inch diameter, a depth of filling of <math>\frac{1}{2}</math> inch and a 60-degree angle of countersink spaced 6 inches apart on centers.</p>   |
| <p>Preparation</p>     |  <p>Process Reference Must Be Placed on Symbol</p> | <p>Symbol indicates all-around bevel and square-groove weld of these studs.</p>   |

Application of American National Standard Welding Symbols (Continued)

| Desired Weld  | Symbol  | Symbol Meaning   |
|---|---|--|
| <p><b>Min. Acceptable Shear Strength 200 lb/lin. in.</b></p>  |    | <p>Symbol indicates an electron beam seam weld with a minimum acceptable joint strength of 200 pounds per lineal inch.</p>                                     |
|   |    | <p>Symbol indicates four 0.10-inch diameter electron beam spot welds located at random.</p>  |
|    |    | <p>Symbol indicates a fillet weld on the <i>other side</i> of joint and a flare-bevel-groove weld and a fillet weld on the <i>arrow side</i> of the joint.</p> |
|   |   | <p>Symbol indicates gas tungsten-arc seam weld on <i>arrow side</i> of joint.</p>  |
|    |  | <p>Symbol indicates edge-flange weld on <i>arrow side</i> of joint and flare-V-groove weld on <i>other side</i> of joint.</p>                                  |
|    |  | <p>Symbol indicates melt-thru weld. By convention, this symbol is placed on the opposite side of the reference line from the corner-flange symbol.</p>         |

### Nondestructive Testing

Nondestructive testing (NDT) is aimed at examination of a component or assembly, usually for surface or internal cracks or other nonhomogeneities, to determine the structure, or to measure thickness, by some means that will not impair its use for the intended purpose. Traditional methods include use of radiography, ultrasonic vibration, dye penetrants, magnetic particles, acoustic emission, leakage, and eddy currents. These methods are simple to use but some thought needs to be given to their application and to interpretation of the results. Space limitations preclude a full discussion of NDT here, but the nature of the welding process makes these methods particularly useful, so some information on use of NDT for testing welds is given below.

**Nondestructive Testing Symbol Application.**—The application of nondestructive testing symbols is also covered in American National Standard ANSI/AWS A2.4-79.

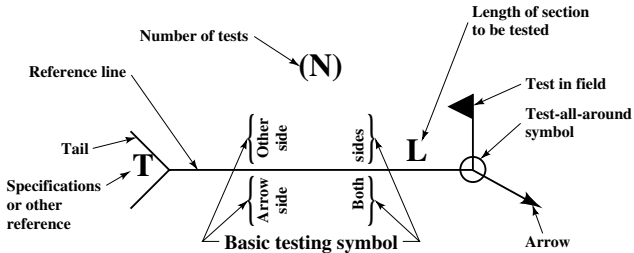
*Basic Testing Symbols:* These are shown in the following table.

**ANSI Basic Symbols for Nondestructive Testing ANSI/AWS A2.4-79**

| Symbol | Type of Test         | Symbol | Type of Test |
|--------|----------------------|--------|--------------|
| AET    | Acoustic Emission    | PT     | Penetrant    |
| ET     | Eddy Current         | PRT    | Proof        |
| LT     | Leak                 | RT     | Radiographic |
| MT     | Magnetic Particle    | UT     | Ultrasonic   |
| NRT    | Neutron Radiographic | VT     | Visual       |

*Testing Symbol Elements:* The testing symbol consists of the following elements: Reference Line, Arrow, Basic Testing Symbol, Test-all-around Symbol, (N) Number of Tests, Test in Field, Tail, and Specification or other reference.

The standard location of the testing symbol elements are shown in the following figure.



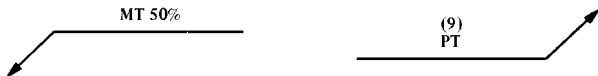
Locations of Testing Symbol Elements

The arrow connects the reference line to the part to be tested. The side of the part to which the arrow points is considered to be the *arrow side*. The side opposite the arrow side is considered to be the *other side*.

*Location of Testing Symbol:* Tests to be made on the arrow side of the part are indicated by the basic testing symbol on the side of the reference line toward the reader.



Tests to be made on the other side of the part are indicated by the basic testing symbol on the side of the reference line away from the reader.

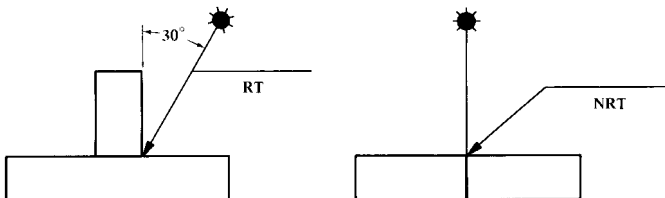


To specify where only a certain length of a section is to be considered, the actual length or percentage of length to be tested is shown to the right of the basic test symbol. To specify the number of tests to be taken on a joint or part, the number of tests is shown in parentheses.

Tests to be made on both sides of the part are indicated by test symbols on both sides of the reference line. Where nondestructive symbols have no arrow or other significance, the testing symbols are centered in the reference line.

*Combination of Symbols:* Nondestructive basic testing symbols may be combined and nondestructive and welding symbols may be combined.

*Direction of Radiation:* When specified, the direction of radiation may be shown in conjunction with the radiographic or neutron radiographic basic testing symbols by means of a radiation symbol located on the drawing at the desired angle.



*Tests Made All Around the Joint:* To specify tests to be made all around a joint a circular test-all-around symbol is used.



*Areas of Revolution:* For nondestructive testing of areas of revolution, the area is indicated by the test-all-around symbol and appropriate dimensions.

*Plane Areas:* The area to be examined is enclosed by straight broken lines having a small circle around the angle apex at each change in direction.

## LASERS

### Introduction

Lasers are used for cutting, welding, drilling, surface treatment, and marking. The word laser stands for Light Amplification by Stimulated Emission of Radiation, and a laser is a unit that produces optical-frequency radiation in intense, controllable quantities of energy. When directed against the surface of a material, this quantity of energy is high enough to cause a localized effect. Heating by a laser is controlled to produce only the desired result in a specific area, ensuring low part distortion.

The four basic components of a laser, shown in Fig. 1, are an amplifying medium, a means to excite this medium, mirrors arranged to form an optical resonator, and an output transmission device to cause beam energy to exit from the laser. The laser output wavelength is controlled by the type of amplifying medium used. The most efficient industrial lasers use optical excitation or electrical discharge to stimulate the medium and start the lasing action.

Solid-state lasers, in which the medium is a solid crystal of an optically pure material such as glass or yttrium aluminum garnet (YAG) doped with neodymium (Nd), are excited by a burst of light from a flashlamp(s) arranged in a reflective cavity that acts to concentrate the excitation energy into the crystal. Neodymium lasers emit radiation at  $1.06\ \mu\text{m}$  ( $1\ \mu\text{m} = 0.00004\ \text{in.}$ ), in the near infrared portion of the spectrum.

The carbon dioxide ( $\text{CO}_2$ ) laser uses a gaseous mixture of helium, nitrogen, and carbon dioxide. The gas molecules are energized by an electric discharge between strategically placed cathodes and anodes. The light produced by  $\text{CO}_2$  lasers has a wavelength of approximately  $10.6\ \mu\text{m}$ .

**Laser Light.**—The characteristics of light emitted from a laser are determined by the medium and the design of the optical resonator. Photons traveling parallel to the optical axis are amplified and the design provides for a certain portion of this light energy to be transmitted from the resonator. This amplifier/resonator action determines the wavelength and spatial distribution of the laser light.

The transmitted laser light beam is monochromatic (one color) and coherent (parallel rays), with low divergence and high brightness, characteristics that distinguish coherent laser light from ordinary incoherent light and set the laser apart as a beam source with high energy density. A typical industrial laser operating in a very narrow wavelength band determined by the laser medium is called monochromatic because it emits light in a specific segment of the optical spectrum. The wavelength is important for beam focusing and material absorption effects.

Coherent laser light can be 100,000 times higher in energy density than equivalent-power incoherent light. The most important aspect of coherent light for industrial laser applications is directionality, which reduces dispersion of energy as the beam is directed over comparatively long distances to the workpiece.

**Laser Beams.**—The slight tendency of a laser beam to expand in diameter as it moves away from its source is called beam divergence, and is important in determining the size of the spot where it is focused on the work surface. The beam-divergence angle for high-power lasers used in processing industrial materials is larger than the diffraction-limited value because the divergence angle tends to increase with increasing laser output power. The amount of divergence thus is a major factor in concentration of energy in the work.

The power emitted per unit area per unit solid angle is called brightness. Because the laser can produce very high levels of power in very narrowly collimated beams, it is a source of high brightness energy. This brightness factor is a major characteristic of solid-state lasers. Other important beam characteristics in industrial lasers include spatial mode and depth of focus. Ideally, the output beam of the laser selected should have a mode structure, divergence, and wavelength sufficient to process the application in optimum time and



with a minimum of heat input. A beam-quality factor,  $M^2$ , is commonly used to define the productive performance of a laser. This factor is a measure of the ratio between the spot diameter of a given laser to that of a theoretically perfect beam. Beam quality is expressed as “times diffraction” and is always greater than 1. For CO<sub>2</sub> lasers at the 1-kW level,  $M^2 = 1.5$ , and for YAG lasers at 500 W,  $M^2 = 12.0$  is typical.

The mode of a laser beam is described by the power distribution profile over its cross-section. Called transverse modes, these profiles are represented by the term TEM<sub>*m*,*n*</sub>, where TEM stands for transverse electromagnetic, and *m* and *n* are small integers indicating that power distribution is bell-shaped (Gaussian) TEM<sub>00</sub>, or donut-shaped TEM<sub>01</sub>\*.

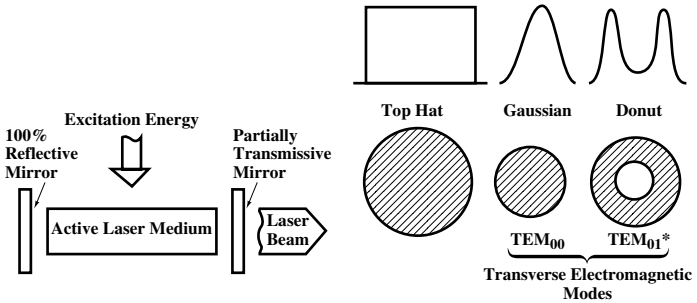


Fig. 1. Basic Components of a Laser

Fig. 2. Spatial Intensity Distribution in Laser Beams

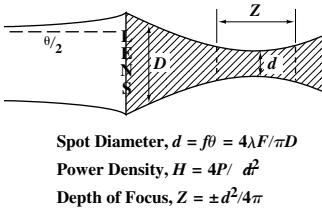
Fig. 2 shows various transverse electromagnetic modes commonly used in materials processing applications. For such applications, it is helpful to determine the peak and total power generated by the laser. Diffraction in Gaussian beams is inherently limited and other modes of operation may have larger beam-divergence angles, causing less power to be delivered to the workpiece. The selection process for industrial applications should consider only those lasers that produce the lowest-order mode beam, in a Gaussian-shaped energy profile (see Fig. 2), with a narrow beam divergence. Solid-state lasers do not meet all these criteria, and with high-power CO<sub>2</sub> lasers, it is sometimes necessary to compromise because of reduced output power, large physical size, and complexity of the laser design.

Although a laser with a TEM<sub>00</sub> output beam is preferred for optimum performance, the application may not always require such a beam. For example, many CO<sub>2</sub> laser cutting operations are performed with a TEM<sub>01</sub>\* beam and welding is often done with a mixture of each of these modes. Lasers can be operated in three temporal modes, continuous wave (CW), pulsed, and superpulsed (called Q-switched for YAG lasers), depending on the materials being processed.

The smallest focused spot diameter that will provide the highest energy intensity can be produced by a TEM<sub>00</sub> laser. The fundamental mode output of CO<sub>2</sub> lasers is limited to 2500 watts. Complex spatial patterns are often caused by inhomogeneities in solid-state laser crystals and are controlled by insertion of apertures that greatly reduce output power. However, standard lasers suit the needs of most industrial users as beam divergence is only one factor in laser design.

**Beam Focusing.**—The diameter of a focused laser beam spot can be estimated by multiplying the published beam divergence value by the focal length of the lensor by the relationship of the wavelength to the unfocused beam diameter. Thus, the beam from a CO<sub>2</sub>

laser operating at a 10.6- $\mu\text{m}$  wavelength, using the same focal length lens, will produce a focused spot ten times larger than the beam from a Nd:YAG laser operating at a 1.06- $\mu\text{m}$  wavelength.



$$\text{Spot Diameter, } d = f\theta = 4\lambda F/\pi D$$

$$\text{Power Density, } H = 4P/d^2$$

$$\text{Depth of Focus, } Z = \pm d^2/4\lambda$$

Fig. 3. Focus Characteristics of a Laser Beam.

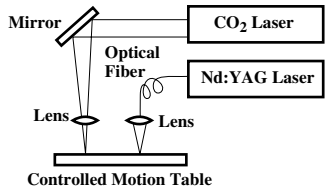


Fig. 4. Typical Laser Systems.

Effects of various beam spot sizes and depths of focus are shown in Fig. 3. High-power density is required for most focused beam applications such as cutting, welding, drilling, and scribing, so these applications generally require a tightly focused beam. The peak power density of a Gaussian beam is found by dividing the power at the workpiece by the area of the focused spot. Power density varies with the square of the area, so that a change in the focused spot size can influence power density by a factor of 4 and careful attention must be given to maintaining beam focus.

Another factor of concern in laser processing is depth of focus, defined as the range of depth over which the focused spot varies by  $\pm 5$  per cent. This relationship is extremely important in cutting sheet metal, where it is affected by variations in surface flatness. Cutting heads that adapt automatically to maintain constant surface-to-nozzle spacing are used to reduce this effect.

**Types of Industrial Lasers.**—Specific types of lasers are suited to specific applications, and Fig. 1 lists the most common lasers used in processing typical industrial materials. Solid-state lasers are typically used for drilling, cutting, spot and seam welding, and marking on thin sheet metal. CO<sub>2</sub> lasers are used to weld, cut, surface treat, and mark both metals and nonmetals. For example, CO<sub>2</sub> lasers are suited to ceramic scribing and Nd:YAG lasers for drilling turbine blades. Factors that affect suitability include wavelength, power density, and spot size. Some applications can use more than one laser type. Cutting sheet metal, an established kilowatt-level CO<sub>2</sub> laser application, can also be done with kilowatt-level Nd:YAG lasers. For some on-line applications that require multiaxis beam motion, the Nd:YAG laser may have advantages in close coupling the laser beam to the workpiece through fiber optics.

Table 1. Common Industrial Laser Applications

| Type            | Wavelength ( $\mu\text{m}$ ) | Operating Mode | Power Range (watts) | Applications  |
|-----------------|------------------------------|----------------|---------------------|---------------|
| Nd:YAG          | 1.06                         | Pulsed         | 10–2,000            | A, B, D, E, F |
| Nd: YAG         | 1.06                         | Continuous     | 500–3,000           | A, B, C       |
| Nd: YAG         | 1.06                         | Q-switched     | 5–150               | D, E, F       |
| CO <sub>2</sub> | 10.6                         | Pulsed         | 5–3,000             | A, B, D, E    |
| CO <sub>2</sub> | 10.6                         | Superpulsed    | 1,000–5,000         | A             |
| CO <sub>2</sub> | 10.6                         | Continuous     | 100–25,000          | A, B, C       |

Applications: A = cutting, B = welding, C = surface treatment, D = drilling, E = marking, F = micro-machining.

**Industrial Laser Systems.**—The laser should be located as close as possible to the workpiece to minimize beam-handling problems. Ability to locate the beam source away from

its power supply and ancillary equipment, and to arrange the beam source at an angle to the workpiece allows the laser to be used in many automatic and numerically controlled set ups. Fig. 4 shows typical laser system arrangements.

Lasers require power supplies and controllers for lasers are usually housed in industrial grade enclosures suited to factory floor conditions. Because the laser is a relatively inefficient converter of electrical energy to electromagnetic energy (light), the waste heat from the beam source must be removed by heat exchangers located away from the processing area. Flowing gas CO<sub>2</sub> lasers require a source of laser gas, used to make up any volume lost in the normal recycling process. Gas can be supplied from closely linked tanks or piped from remote bulk storage.

Delivery of a high-quality beam from the laser to the workpiece often requires sub-systems that change the beam path by optical means or cause the beam to be directed along two or more axes. Five-axis beam motion systems, for example, using multiple optical elements to move the beam in X, Y, Z, and rotation/tilt, are available.

Solid-state laser beams can be transmitted through flexible optical fibers. If there is no beam motion, the workpiece must be moved. The motion systems used can be as simple as an XY or rotary table, or as complex as a multistation, dual-feed table. Hybrid systems offer a combination of beam and workpiece motion and are frequently used in multi-axis cutting applications. All motions are controlled by an auxiliary unit such as a CNC, NC, paper tape, or programmable controller. Newer types of controllers interface with the beam source to control the entire process. Gas jet nozzles, wire feed, or seam tracking equipment are often used, and processing may be monitored and controlled by signals from height sensors, ionized by-product (plasma) detectors, and other systems.

**Safety.**—Safety for lasers is covered in ANSI Z136.1-2000: Safe Use Of Lasers. Most industrial lasers require substantial electrical input at high-voltage and -amperage conditions. Design of the beam source and the associated power supply should be to accepted industry electrical standards. Protective shielding is advised where an operator could interact, physically, with the laser beam, and would be similar to safety shields provided on other industrial equipment.

Radiation from a laser is intense light concentrated in tight bundles of energy. The high energy density and selective absorption characteristics of the laser beam have the potential to cause serious damage to the eye. For this reason, direct viewing of the beam from the laser should be restricted. Safety eyewear is commercially available to provide protection for each type of laser used. Certain lasers, such as the 1.06- $\mu\text{m}$  solid-state units, should be arranged in a system such that workers are shielded from direct and indirect radiation. Other types of lasers, such as the 10.6- $\mu\text{m}$  CO<sub>2</sub> laser, when operated without shielding, should meet industry standards for maximum permissible exposure levels. Much information is published on laser radiation safety, so that the subject is highly documented. Laser suppliers are very familiar with local regulations and are a good source for prepurchase information. Certain materials, notably many plastics compositions, when vaporized, will produce potentially harmful fumes. Precautionary measures such as workstation exhaust systems typically handle this problem.

**Laser Beam/Material Interaction.**—Industrial lasers fall into categories of effectiveness because the absorption of laser light by industrial materials depends on the specific wavelength. However, at room temperature, CO<sub>2</sub> laser light at 10.6  $\mu\text{m}$  wavelength is fully absorbed by most organic and inorganic nonmetals.

Both CO<sub>2</sub> and YAG can be used in metalworking applications, although YAG laser light at 1.06  $\mu\text{m}$  is absorbed to a higher degree in metals. Compensation for the lower absorption of CO<sub>2</sub> light by metals is afforded by high-energy-density beams, which create small amounts of surface temperature change that tend to increase the beam-coupling coefficient.

At  $\text{CO}_2$  power densities in excess of  $10^6 \text{ W/cm}^2$ , effective absorptivity in metals approaches that of nonmetals. Above certain temperatures, metals will absorb more infrared energy. In steel at  $400^\circ\text{C}$ , for instance, the absorption rate is increased by 50 per cent. In broad-area beam processing, where the energy density ( $10^4 \text{ W/cm}^2$ ) is low, some form of surface coating may be required to couple the beam energy into a metal surface.

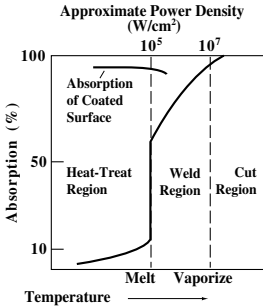


Fig. 5. Laser Energy Absorption Intensity vs. Temperature

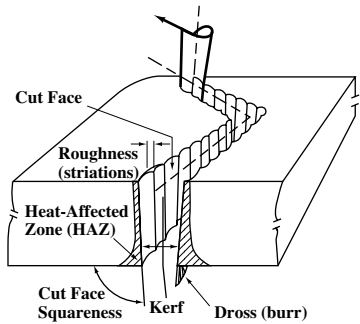


Fig. 6. Factors in Laser Cutting.

**Thermal Properties of Workpieces.**—When a laser beam is coupled to a workpiece, initial conversion of energy to work, in the form of heat, is confined to a very thin layer (100-200 Ångstroms) of surface material. The absorbed energy converted to heat will change the physical state of the workpiece, and depending on the energy intensity of the beam, a material will heat, melt, or vaporize. Fig. 5 shows percentage of energy absorption versus temperature for various phase changes in materials.

Heating, melting, and vaporization of a material by laser radiation depends on the thermal conductivity and specific heat of the material. The heating rate is inversely proportional to the specific heat per unit volume, so that the important factor for heat flow is the thermal diffusivity of the work material. This value determines how rapidly a material will accept and conduct thermal energy, and a high thermal diffusivity will allow a greater depth of fusion penetration with less risk of thermal cracking.

Heat produced by a laser in surface layers is rapidly quenched into the material and the complementary cooling rate is also rapid. In some metals, the rate is  $10^6 \text{ C}^\circ/\text{s}$ . This rapid cooling results in minimum residual heat effects, due to the slower thermal diffusivity of heat spreading from the processed area. However, rapid cooling may produce undesired effects in some metals. Cooling that is too rapid prevents chemical mixing and may result in brittle welds.

Thermosetting plastics are specifically sensitive to reheating, which may produce a gummy appearance or a charred, ashlike residue. Generally, the sensitivity of a material to heat from a laser is as apparent as with any other localized heating process. Any literature describing the behavior of materials when exposed to heat will apply to laser processing.

### Cutting Metal with Lasers

The energy in a laser beam is absorbed by the surface of the impinged material, and the energy is converted into work in the form of heat, which raises the temperature to the melting or vaporization point. A jet of gas is arranged to expel excess molten metal and vapor from the molten area. Moving the resulting molten-walled hole along a path with continuous or rapidly pulsed beam power produces a cut. The width of this cut (kerf), the quality of

the cut edges, and the appearance of the underside of the cut (where the dross collects) are determined by choice of laser, beam quality, delivered power, and type of motion employed (beam, workpiece, or combination). Fig. 6 identifies the factors involved in producing a high-quality cut.

Power versus penetration and cutting rate are essentially straight-line functions for most ferrous metals cut with lasers. A simple relationship states that process depth is proportional to power and inversely proportional to speed. Thus, for example, doubling power will double penetration depth. The maximum possible thickness that can be cut is, therefore, a function of power, cutting rate, and compromise on cut quality. Currently, 25 mm (1 in.) is considered the maximum thickness of steel alloys that can be cut. The most economically efficient range of thicknesses is up to 12.5 mm (0.49 in.).

Metals reflect laser light at increasing percentages with increasing wavelength. The high-energy densities generated by high-power CO<sub>2</sub> lasers overcome these reflectivity effects. Shorter-wavelength lasers such as Nd:YAG do not suffer these problems because more of their beam energy is absorbed.

**Beam Assistance Techniques.**—In cutting ferrous alloys, a jet of oxygen concentric with the laser beam is directed against the heated surface of the metal. The heat of the molten puddle of steel produced by the laser power causes the oxygen to combine with the metal, so that the jet burns through the entire thickness of the steel. This melt ablation process also uses the gas pressure to eject the molten metal from the cut kerf. Control of the gas pressure, shape of the gas stream, and positioning of the gas nozzle orifice above the metal surface are critical factors. A typical gas jet nozzle is shown in Fig. 7. Cutting highly alloyed steels, such as stainless steel, is done with pulsed CO<sub>2</sub> laser beams. High-pressure gas jets with the nozzle on the surface of the metal and nonoxidizing gas assistance can be used to minimize or eliminate clinging dross.

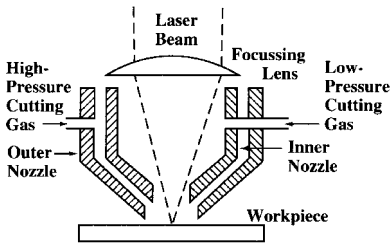


Fig. 7. Laser Gas Cutting Nozzle for Steel.

The narrow kerf produced by the laser allows cut patterns to be nested as close as one beam diameter apart, and sharply contoured and profiled cuts can be made, even in narrow angle locations. For this type of work and for other reasons, confining the kerf width to a dimension equal to, or slightly greater than, the diameter of the laser beam is important. Kerf width is a function of beam quality, focus, focus position, gas pressure, gas nozzle to surface spacing, and processing rate. Table 2 shows typical kerf widths.

**Cut Edge Roughness.**—Cutting with a continuous-wave (CW) output CO<sub>2</sub> laser can produce surface roughness values of 8–15 μm (315–590 μin) in 1.6-mm (0.063-in) cold-rolled steel and 30–35 μm (1180–1380 μin) in mild steel. Surface roughness of 30–50 μm (1180–1970 μin) in thin-gage stainless steel sheets is routine when using oxygen to assist cutting. Table 3 lists some surface roughness values.

**Table 2. Typical Kerf Widths in CO<sub>2</sub> Laser Cutting**

| Material     | Thickness |       | Kerf              |       |
|--------------|-----------|-------|-------------------|-------|
|              | mm        | in.   | mm                | in.   |
| Carbon Steel | 1.5       | 0.06  | 0.05              | 0.002 |
|              | 2.25      | 0.09  | 0.12              | 0.005 |
|              | 3.12      | 0.12  | 0.2               | 0.008 |
|              | 6.25      | 0.25  | 0.3               | 0.012 |
| Aluminum     | 2.25      | 0.09  | 0.25              | 0.01  |
| Plastics     | <4.0      | <0.16 | 2 × beam diameter |       |

**Table 3. Surface Roughness Values for Laser Cutting with Oxygen**

| Material          | Thickness |      | Surface Finish |      |
|-------------------|-----------|------|----------------|------|
|                   | mm        | in.  | μm             | μin  |
| Stainless Steel   | 1         | 0.04 | 30             | 1200 |
|                   | 2         | 0.08 | 35             | 1400 |
|                   | 3         | 0.12 | 50             | 2000 |
| Cold-Rolled Steel | 1         | 0.04 | 8              | 320  |
|                   | 2         | 0.08 | 10             | 400  |
|                   | 3         | 0.12 | 15             | 600  |
| Mild Steel        | 1         | 0.04 | 30             | 1200 |
|                   | 2         | 0.08 | 30             | 1200 |
|                   | 3         | 0.12 | 35             | 1400 |

**Heat-Affected Zones.**—Control of beam focus, focus position, assist gas conditions, and processing rates produces differences in hardness that are barely discernible in steels up to 2 mm (0.078 in.) thick. Small increases in hardness to a depth of 0.1–0.2 mm (0.004–0.008 in.) are common. Cutting with a pulsed CO<sub>2</sub> laser reduces these values to less than 0.1 mm (0.004 in.), making this mode of operation beneficial for some end-use applications. [Table 4](#) shows typical values for the heat-affected zone in mild steels.

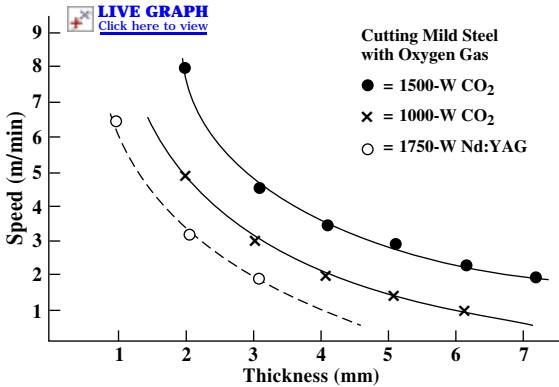
**Table 4. Heat-Affected Zone in Mild Steels**

| Material Thickness |       | CW HAZ |       | Pulsed HAZ |       |
|--------------------|-------|--------|-------|------------|-------|
| mm                 | in.   | mm     | in.   | mm         | in.   |
| 4                  | 0.157 | 0.50   | 0.020 | 0.15       | 0.006 |
| 3                  | 0.118 | 0.37   | 0.015 | 0.15       | 0.006 |
| 2                  | 0.078 | 0.10   | 0.004 | 0.12       | 0.005 |
| 1                  | 0.039 | 0.75   | 0.030 | 0.07       | 0.003 |

Rates for laser cutting of metals are typically reported as data developed under ideal conditions, that is, in a controlled development laboratory environment using technician-operated equipment. Rates achieved on the shop floor using semiskilled system operators to produce complicated shapes may vary dramatically from published data. Speed versus thickness for cutting steel is shown in [Fig. 8](#) for 1000- and 1500-W power levels, and cutting performance for several other metals of various thicknesses is shown in [Table 5](#). Cutting rate data for pulsed and CW Nd:YAG lasers for steel also are shown in [Fig. 8](#), and for Nd:YAG cutting of other metals in [Table 5](#).

**Table 5. CO<sub>2</sub> and Nd: YAG Cutting Speeds for Nonferrous Metals**

| Material    | CO <sub>2</sub> (1500 watts) |      |       |        | Nd: YAG   |       |       |        |                |
|-------------|------------------------------|------|-------|--------|-----------|-------|-------|--------|----------------|
|             | Thickness                    |      | Speed |        | Thickness |       | Speed |        | Power<br>watts |
|             | mm                           | in.  | m/min | ft/min | mm        | in.   | m/min | ft/min |                |
| Copper      | 1                            | 0.04 | 2.25  | 7.4    | ...       | ...   | ...   | ...    | ...            |
|             | 2                            | 0.08 | 0.75  | 2.5    | ...       | ...   | ...   | ...    | ...            |
|             | 3                            | 0.12 | 0.35  | 1.15   | ...       | ...   | ...   | ...    | ...            |
| Aluminum    | 1                            | 0.04 | 8     | 26.2   | 1.5       | 0.06  | 2.5   | 8.2    | 1000           |
|             | 2                            | 0.08 | 4     | 13.1   | 2.5       | 0.1   | 1.0   | 3.3    | 1000           |
|             | 3                            | 0.12 | 1.5   | 4.9    | 3.5       | 0.14  | 0.5   | 1.6    | 1000           |
| Titanium    | 1                            | 0.04 | 6     | 19.7   | 0.4       | 0.016 | 1.0   | 3.3    | 150            |
|             | 2                            | 0.08 | 3     | 9.8    | ...       | ...   | ...   | ...    | ...            |
| Tungsten    | ...                          | ...  | ...   | ...    | 0.08      | 0.003 | 0.03  | 0.1    | 250            |
| Brass       | 1                            | 0.04 | 3     | 9.8    | ...       | ...   | ...   | ...    | ...            |
|             | 2                            | 0.08 | 1.5   | 4.9    | ...       | ...   | ...   | ...    | ...            |
| Hastalloy   | 2.5                          | 0.1  | 2.8   | 9.2    | ...       | ...   | ...   | ...    | ...            |
| Hastalloy X | ...                          | ...  | ...   | ...    | 0.08      | 0.003 | 0.5   | 1.6    | 150            |
| Inconel 718 | 4                            | 0.16 | 1.1   | 3.6    | ...       | ...   | ...   | ...    | ...            |

Fig. 8. Typical Cutting Rates for CO<sub>2</sub> and YAG Lasers.

**Cutting of Nonmetals.**—Laser cutting of nonmetals has three requirements: a focused beam of energy at a wavelength that will be absorbed easily by the material so that melting or vaporization can occur; a concentric jet of gas, usually compressed air, to remove the by-products from the cut area; and a means to generate cuts in straight or curved outlines. Residual thermal effects resulting from the process present a greater problem than in cutting of metals and limit applications of lasers in nonmetal processing.

When subjected to a laser beam, paper, wood, and other cellular materials undergo vaporization caused by combustion. The cutting speed depends on laser power, material thickness, and water and air content of the material. Thermoplastic polymer materials are cut by melting and gas jet expulsion of the melted material from the cut area. The cutting speed is governed by laser power, material thickness, and pressure of gas used to eject the displaced material.

Polymers that may be cut by combustion or chemical degradation include the thermosetting plastics, for example, epoxies and phenolics. Cutting speed is determined by the laser

power and is higher for thermosets than for other polymers due to the phase change to vapor.

Composite materials are generally easy to cut, but the resulting cut may not be of the highest quality, depending on the heat sensitivity of the composite materials. High-pressure cutting processes such as fluid jets have proven to be more effective than lasers for cutting many composite materials.

Nonmetal cutting processes require moderate amounts of power, so the only limitation on cut thickness is the quality of the cut. In practice, the majority of cutting applications are to materials less than 12 mm thick. Cutting rates for some commonly used nonmetals are shown in Table 6. Nonmetal cutting applications require a gas jet to remove molten, vaporized, or chemically degraded matter from the cut area.

Compressed air is used for many plastics cutting applications because it is widely available and cheap to produce, so it is a small cost factor in nonmetal cutting. A narrow kerf is a feature of nonmetal cutting, and it is especially important in the cutting of compactly nested parts such as those produced in cutting of fabrics. Nonmetals react in a variety of ways to laser-generated heat, so that it is difficult to generalize on edge roughness, but thermally sensitive materials will usually show edge effects.

**Table 6. CO<sub>2</sub> Laser Cutting Rates for Nonmetals**

| Material      | Thickness |      | Speed |        | Power | Material   | Thickness |       | Speed |        | Power |
|---------------|-----------|------|-------|--------|-------|------------|-----------|-------|-------|--------|-------|
|               | mm        | in   | m/min | ft/min | watts |            | mm        | in    | m/min | ft/min | watts |
| Polythene     | 1         | 0.04 | 11    | 36     | 500   | Fiberglass | 1.6       | 0.063 | 5.2   | 17     | 450   |
| Polypropylene | 1         | 0.04 | 17    | 56     | 500   | Glass      | 1         | 0.04  | 1.5   | 4.9    | 500   |
| Polystyrene   | 1         | 0.04 | 19    | 62     | 500   | Alumina    | 1         | 0.04  | 1.4   | 4.6    | 500   |
| Nylon         | 1         | 0.04 | 20    | 66     | 500   | Hardwood   | 10        | 0.39  | 2.6   | 8.5    | 500   |
| ABS           | 1         | 0.04 | 21    | 69     | 500   | Plywood    | 12        | 0.47  | 4.8   | 15.7   | 1000  |
| Polycarbonate | 1         | 0.04 | 21    | 69     | 500   | Cardboard  | 4.6       | 0.18  | 9.0   | 29.5   | 350   |
| PVC           | 1         | 0.04 | 28    | 92     | 500   |            |           |       |       |        |       |

### Welding with Lasers

**Laser Welding Theory.**—Conversion of absorbed laser energy into heat causes metals to undergo a phase change from solid to liquid and, as energy is removed, back to solid. This fusion welding process is used to produce selective area spot welds or linear continuous seam welds. The two types of laser welding processes, conduction and deep penetration, or keyhole, are shown in Fig. 9.

*Conduction welding:* relies on the thermal diffusivity characteristics of the metal to conduct heat into the joint area. By concentrating heat into the focused beam diameter and programming this heat input for short time periods, more heat is conducted into the joint than is radiated outward from the joint. Conduction welds are generally used for spot welding and partial penetration seam welding.

*Deep penetration keyhole welding:* is produced by beam energy converted to heat that causes a hole to be produced through the thickness of the metal. Vapor pressure of evaporated metal holds a layer of molten metal in place against the hole wall.

Movement of the hole, by beam or workpiece motion, causes the molten metal to flow around the hole and solidify behind the beam interaction point. The resolidified metal has a different structure than the base metal. Maximum practical penetration limits are approximately 25 mm (2 in.) with today's available laser power technology.

If the physical change from solid to liquid to solid does not produce a ductile fusion zone, and if the brittleness of the resolidified metal cannot be reduced easily by postweld annealing, then the laser welding process, as with other fusion welding processes, may not be viable. If the metal-to-metal combination does not produce an effective weld, other



considerations such as filler metal additions to modify fusion zone chemistry should be considered.

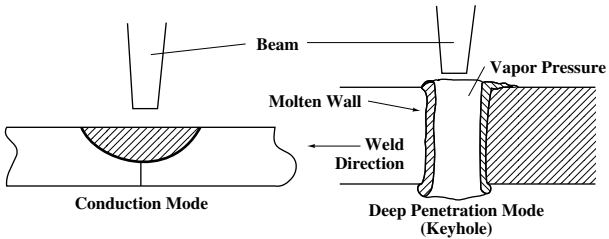


Fig. 9. Types of Laser Welds.

**Welded Joint Design.**—For optimum results, the edges of parts to be laser beam welded should be in close contact. When a part is being designed and there is a choice of welding process, designers should design joints and joint tolerances to the optimum for laser welding. Fig. 10 shows suitable joint designs for the laser fusion welding process. Joint tolerances are one of the more important parameters influencing part weldability, and for corner, tee, and lap joints, gaps should be not more than 25 per cent of the thickness of the thinnest section. For butt and edge joints, the percentage is reduced to 10. Addition of filler metal to compensate for large joint gaps is becoming popular.

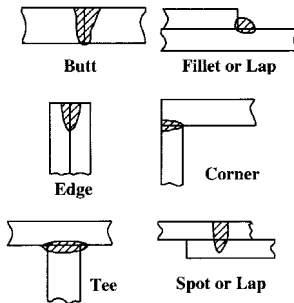


Fig. 10. Examples of Laser Weld Joint Designs.

**Welding Rates.**—The information presented in Fig. 11 for welding with  $\text{CO}_2$  and Nd:YAG lasers should be considered as typical for the specific lasers shown and is for use in optimum conditions. These data are provided only as guidelines.

**Processing Gas.**—The proper choice of processing gas is important for both conduction and keyhole welding. Gases that ionize easily should not be used to shield the beam/material interaction point. Energy intensities of  $10^6 \text{ W/cm}^2$  or higher can occur in the zone where incident and reflected laser light overlap and gases can vaporize, producing a plasma that attenuates further beam transmission.

One of the most important advantages of laser welding is the low total heat input characteristic of the focused high-energy density beam. Heat concentration resulting from the beam energy conversion at the workpiece surface causes most conduction to be perpendicular to the direction of motion. With the beam (or workpiece) moving faster than the speed of thermal conduction, there is significant heat flow only in the perpendicular direction. Thus, material solid to solid, or solid to liquid, changes tend to occur only in the narrow

path of heat conduction, and the amount of heat necessary to penetrate a given material thickness is reduced to only that needed to fuse the joint. With limited excess heat through the low total heat mechanism, parts can be produced by laser welding with minimum thermal distortion.

Helium is the ideal gas for laser welding, but other gases such as CO<sub>2</sub> and argon have been used. Neither CO<sub>2</sub> nor argon produces a clean, perfectly smooth weld, but weld integrity seems sufficient to suggest them as alternatives. The cost of welding assistance gas can be greater than for laser gases in CO<sub>2</sub> laser welding and may be a significant factor in manufacturing cost per welded part.

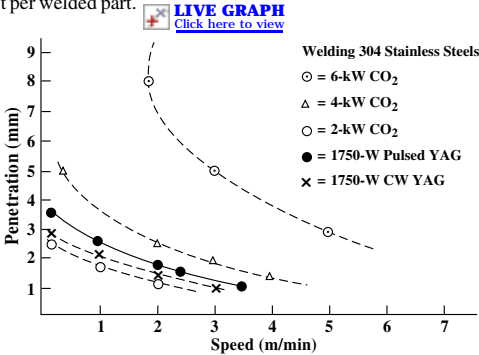


Fig. 11. Rates for CO<sub>2</sub> and Nd:YAG Laser Welding.

### Drilling with Lasers

**Laser Drilling Theory.**—Laser drilling is performed by direct, percussive, and trepanning methods that produce holes of increasing quality respectively, using increasingly more sophisticated equipment. The drilling process occurs when the localized heating of the material by a focused laser beam raises the surface temperature above the melting temperature for metal or, for nonmetals, above the vaporization temperature.

**Direct Drilling.**—The single-pulse, single-hole process is called direct drilling. The process hole size is determined by the thermal characteristics of the material, the beam spot size, the power density, the beam quality, and the focus location. Of these parameters, beam quality, in terms of beam divergence, is an important criterion because of its effect on the hole size. Single-pulse drilled holes are usually limited to a depth of 1.5 mm (0.06 in.) in metals and up to 8 mm (0.315 in.) in nonmetals. Maximum hole diameter for pulsed solid-state laser metal drilling is in the 0.5- to 0.75-mm (0.02- to 0.03-in.) range, and CO<sub>2</sub> direct drilling can produce holes up to 1.0 mm (0.04 in.) in diameter. The aspect ratio (depth to midhole diameter) is typically under 10:1 in metals and for many nonmetals it can be 15:1. Hole taper is usually present in direct drilling of metals. The amount of taper (entrance hole to exit hole diameter change) can be as much as 25 per cent in many metals. Direct drilling produces a recast layer with a depth of about 0.1 mm (0.004 in.). Diameter tolerances are  $\pm 10$  per cent for the entrance hole, depending on beam quality and assist gas pressure.

**Percussive Drilling.**—Firing a rapid sequence of pulses produces a hole of higher quality than direct drilling in metal thicknesses up to 25 mm (1 in.). This process is known as percussive drilling. Multiple pulses may be necessary, depending on the metal thickness. Typical results using percussion drilled holes are: maximum depth achievable, 25 mm (1 in.); maximum hole diameter, 1.5 mm (0.06 in.); aspect ratio, 50:1; recast layer, 0.5 mm (0.02 in.); taper under 10 per cent; and hole diameter tolerance  $\pm 5$  per cent.

**Trepanning.**—To improve hole quality, some companies use the trepanning method to cut a hole. In this process, a focused beam is moved around the circumference of the hole to be drilled by a rotating mirror assembly. The closeness of spacing of the beam pulses that need to be overlapped to produce the hole depends on the quality requirements. Typical results are: maximum hole depth, 10 mm (0.39 in.); maximum hole diameter, 2.5 mm (0.1 in.); and recast layer thickness, 25  $\mu\text{m}$  (985  $\mu\text{in}$ ).

**Drilling Rates.**—Laser drilling is a fast process but is very dependent on the above-mentioned process factors. It is difficult to generalize on laser drilling rates because of the large number of combinations of material, hole diameter, depth, number of holes per part, and part throughput. With Nd:YAG lasers, direct drilling rates of 1 ms are typical.

### Heat Treatment with Lasers

The defocused beam from a CO<sub>2</sub> laser impinging on a metal surface at room temperature will have 90 per cent or more of its power reflected. In steels, the value is about 93 per cent. Compared with focused beam processing, which uses power densities greater than 10<sup>5</sup> W/cm<sup>2</sup>, the power density of laser beams designed for heat treatment, at less than 10<sup>4</sup> W/cm<sup>2</sup>, is insufficient to overcome reflectivity effects. Therefore, the metal surface needs to be prepared by one of several processes that will enhance absorption characteristics. Surface roughening can be used to produce tiny craters that can trap portions of the beam long enough to raise the surface temperature to a point where more beam energy is absorbed. Coating the metal surface is a common expedient. Black enamel paint is easy to apply and the laser beam causes the enamel to vaporize, leaving a clean surface.

The absorbed laser beam energy, converted to heat, raises the temperature of the metal in the beam pattern for as long as the beam remains in one place. The length of the dwell time is used to control the depth of the heat treatment and is an extremely effective means for control of case depth in hardening.

**Materials Applicability.**—Hardenable ferrous metals, such as medium- and high-carbon steels, tool steels, low-alloy steels and cast irons, and steels with fine-carbide dispersion, are good candidates for laser heat treating. Marginally hardenable metals include annealed carbon steels, spheroidized carbon steels, mild-carbon steels (0.2 per cent C), and ferritic nodular cast irons. Low-carbon steels (<0.1 per cent C), austenitic stainless steels, and non-ferrous alloys and metals are not hardenable.

The effect of the metal microstructure on depth of hardening is an important factor. Cast iron, with a graphite and tempered martensite structure, presents a low carbon-diffusion distance that favors deep-hardened cases. The same is true for steel with a tempered martensite or bainite structure. On the other hand, cast iron with a graphite/ferrite structure and spheroidized iron (Fe<sub>3</sub>C plus ferrite) structures have large carbon-diffusion patterns and therefore produce very shallow or no case depths.

**Hardening Rates.**—Laser hardening is typically slower than conventional techniques such as induction heating. However, by limiting the area to be hardened, the laser can prove to be cost-effective through the elimination of residual heat effects that cause part distortion. A typical hardening rate is 130 cm<sup>2</sup>/min. (20 in<sup>2</sup>/min.) for a 1-mm (0.039-in) case depth in 4140 steel.

### Cladding with Lasers

In laser cladding, for applying a coating of a hard metal to a softer alloy, for instance, a shaped or defocused laser beam is used to heat either preplaced or gravity-fed powdered alloys. The cladding alloy melts and flows across the surface of the substrate, rapidly solidifying when laser power is removed. Control of laser power, beam or part travel speed, clad thickness, substrate thickness, powder feed rate, and shielding gas are process variables that are determined for each part.

Many of the alloys currently used in plasma arc or metal inert gas cladding techniques can be used with the laser cladding process. Among these materials, Stellites, Colmonoys, and other alloys containing carbides are included, plus Inconel, Triballoy, Fe-Cr-C-X alloys, and tungsten and titanium carbides.

Controlled minimal dilution may be the key technical advantage of the laser cladding process. Dilution is defined as the total volume of the surface layer contributed by melting of the substrate, and it increases with increasing power, but decreases with either increasing travel speed or increasing beam width transverse to the direction of travel. Tests comparing laser dilution to other cladding techniques show the laser at <2 per cent compared to 5–15 per cent for plasma arc and 20–25 per cent for stick electrode processes.

The laser cladding process results in a dense, homogenous, nonporous clad layer that is metallurgically bonded to the substrate. These qualities are in contrast to the mechanically bonded, more porous layer produced by other methods.

### Marking with Lasers

Laser marking technology can be divided into two groups; those that produce a repetitive mark are listed as mask marking, and those that involve rapid changes of mark characteristics are classified as scanned beam marking. The amount of data that can be marked in a unit of time (writing speed) depends on laser energy density, galvanometer speed, computer control, and the dimensions of the mark. Heat-type marks have been made at rates up to 2500 mm/s (100 in/s) and engraved marks at rates of 500–800 mm/s (20–30 in/s). Writing fields are of various sizes, but a typical field measures 100 × 100 mm (4 × 4 in.).

**Mask Marking.**—In mask marking, the beam from a CO<sub>2</sub> laser is projected through a reflective mask that passes beam energy only through uncoated areas. The beam energy is reimaged by a wide field lens onto the material's surface where the absorbed heat changes the molecular structure of the material to produce a visible mark. Examples are clouding PVC or acrylics, effecting a change in a colored surface (usually by adjusting proportions of pigment dyes), or by ablating a surface layer to expose a sublayer of a different color.

CO<sub>2</sub> lasers can be pulsed at high rates and have produced legible marks at line speeds of 20,000 marks/h. These lasers produce energy densities in the 1–20 J/cm<sup>2</sup> range, which corresponds to millions of watts/cm<sup>2</sup> of power density and allows marking to be performed in areas covering 0.06 to 6 cm<sup>2</sup>. The minimum width of an individual line is 0.1 mm (0.004 in.). Mask marking is done by allowing the beam from a laser to be projected through a mask containing the mark to be made. Reimaging the beam by optics onto the workpiece causes a visible change in the material, resulting in a permanent mark. Mask marking is used for materials that are compatible with the wavelength of the laser used.

**Scanned-Beam Marking.**—Focusing a pulsed laser beam to a small diameter concentrates the power and produces high-energy density that will cause a material to change its visual character. Identified by several names (spot, stroke, pattern generation, or engraving), this application is best known as scanned beam.

In the scanned-beam method, the beam from a pulsed YAG or CO<sub>2</sub> laser is directed onto the surface of a part by a controlled mirror oscillation that changes the beam path in a pre-programmed manner. The programming provides virtually unlimited choice of patterns to be traced on the part. The pulsed laser output can be sequenced with beam manipulation to produce a continuous line or a series of discrete spots that visually suggest a pattern (dot matrix).

The energy density in the focused beam is sufficient to produce a physical or chemical change in most materials. For certain highly reflective metals, such as aluminum, better results are obtained by pretreating the surface (anodizing). Not all scanned beam applications result in removal of base metal. Some remove only a coating or produce a discoloration, caused by heating, that serves as a mark.

## FINISHING OPERATIONS

## Power Brush Finishing

Power brush finishing is a production method of metal finishing that employs wire, elastomer bonded wire, or non-metallic (cord, natural fiber or synthetic) brushing wheels in automatic machines, semi-automatic machines and portable air tools to smooth or roughen surfaces, remove surface oxidation and weld scale or remove burrs.

**Description of Brushes.**—Brushes work in the following ways: the wire points of a brush can be considered to act as individual culling tools so that the brush, in effect, is a multiple-tipped cutting tool. The fill material, as it is rotated, contacts the surface of the work and imparts an impact action which produces a coldworking effect. The type of finish produced depends upon the wheel material, wheel speed, and how the wheel is applied.

Brushes differ in the following ways 1) fill material (wire—carbon steel, stainless steel; synthetic; Tampico; and cord); 2) length of fill material (or trim); and 3) the density of the fill material.

To aid in wheel selection and use, the accompanying table made up from information supplied by *The Osborn Manufacturing Company* lists the characteristics and mayor uses of brushing wheels.

**Use of Brushes.**—The brushes should be located so as to bring the full face of the brush in contact with the work. Full face contact is necessary to avoid grooving the brush. Operations that are set up with the brush face not in full contact with the work require some provision for dressing the brush face. When the tips of a brush, used with full face contact, become dull during use with subsequent loss of working clearance, reconditioning and resharping is necessary. This is accomplished simply and efficiently by alternately reversing the direction of rotation during use.

**Deburring and Producing a Radius on the Tooth Profile of Gears.**—The brush employed for deburring and producing a radius on the tooth profile of gears is a short trim, dense, wire-fill radial brush. The brush should be set up so as to brush across the edge as shown in Fig. 1A. Line contact brushing, as shown in Fig. 1B should be avoided because the Crisis face will wear non-uniformly; and the wire points, being flexible, tend to flare to the side, thus minimizing the effectiveness of the brushing operation. When brushing gears, the brushes are spaced and contact the tooth profile on the center line of the gear as shown in Fig. 2. This facilitates using brush reversal to maintain the wire brushing points at their maximum cutting efficiency.

The setup for brushing spline bores differs from brushing gears in that the brushes are located off-center, as illustrated in Fig. 3. When helical gears are brushed, it is sometimes necessary to favor the acute side of the gear tooth to develop a generous radius prior to shaving. This can be accomplished by locating the brushes as shown in Fig. 4. Elastomer bonded wire-filled brushes are used for deburring fine pitch gears. These brushes remove the burrs without leaving any secondary roll. The use of bonded brushes is necessary when the gears are not shaved after hobbing or gear shaping.

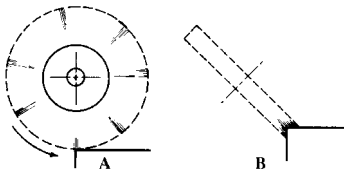


Fig. 1. Methods of Brushing an Edge; (A) Correct, (B) Incorrect

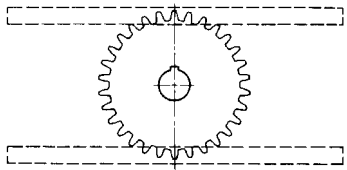


Fig. 2. Setup for Deburring Gears

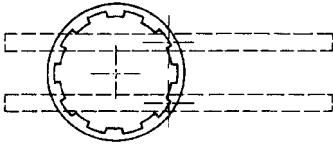


Fig. 3. Setup for Brushing Broached Splines

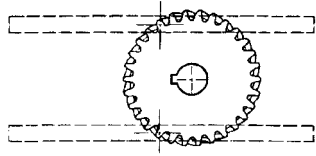


Fig. 4. Setup for Finishing Helical Gears

### Adjustments for Eliminating Undesirable Conditions in Power Brush Finishing

| Undesirable Condition                          | Possible Adjustments for Eliminating Condition  |
|--|---|
| Brush works too slowly                         | (1) Decrease trim length and increase fill density.<br>(2) Increase filament diameter.<br>(3) Increase surface speed by increasing R.P.M. or outside diameter.  |
| Brush works too fast                           | (1) Reduce filament diameter.<br>(2) Reduce surface speed by reducing R.P.M. or outside diameter.<br>(3) Reduce fill density.<br>(4) Increase trim length.  |
| Action of brush peens burr to adjacent surface | (1) Decrease trim length and increase fill density.<br>(2) If wire brush tests indicate metal too ductile (burr is peened rather than removed), change to nonmetallic brush such as a treated Tampico brush used with a burring compound. |
| Finer or smoother finish required              | (1) Decrease trim length and increase fill density.<br>(2) Decrease filament diameter.<br>(3) Try treated Tampico or cord brushes with suitable compounds at recommended speeds.<br>(4) Use auxiliary buffing compound with brush.        |
| Finish too smooth and lustrous                 | (1) Increase trim length.<br>(2) Reduce brush fill density.<br>(3) Reduce surface speed.<br>(4) Increase filament diameter.   |
| Brushing action not sufficiently uniform       | (1) Devise hand-held or mechanical fixture or machine which will avoid irregular off-hand manipulation.<br>(2) Increase trim length and decrease fill density.  |

### Polishing and Buffing

The terms "polishing" and "buffing" are sometimes applied to similar classes of work in different plants, but according to approved usage of the terms, there is the following distinction: Polishing is any operation performed with wheels having abrasive glued to the working surfaces, whereas buffing is done with wheels having the abrasive applied loosely instead of imbedding it into glue; moreover, buffing is not so harsh an operation as ordinary polishing, and it is commonly utilized to obtain very fine surfaces having a "grainless finish."

**Polishing Wheels.**—The principal materials from which polishing wheels are made are wood, leather, canvas, cotton cloth, plastics, felt, paper, sheepskin, impregnated rubber, canvas composition, and wool. Leather and canvas are the materials most commonly used in polishing wheel construction. Wooden wheels covered with material to which emery or some other abrasive is glued are employed extensively for polishing flat surfaces, espe-

**Characteristics and Applications of Brushes Used in Power Finishing**

| Brush Type   | Description  | Operating Speed Range, sfpm                              | Uses   | Remarks  |
|--|--|--|--|--|
| Radial, short trim dense wire fill   | Develops very little impact action but maximum cutting action.   | 6500   | Removal of burrs from gear teeth and sprockets. Produces blends and radii at juncture of intersecting surfaces.  | Brush should be set up so as to brush across any edge. Reversal of rotation needed to maintain maximum cutting efficiency of brush points.   |
| Radial, medium to long trim twisted knot wire fill                           | Normally used singly and on portable tools. Brush is versatile and provides high impact action.  | 7500–9500 for high speeds. 1200 for slow speeds.         | For cleaning welds in the automotive and pipeline industries. Also for cleaning surfaces prior to painting, stripping rubber flash from molded products and cleaning mesh-wire conveyor belts.                               | Surface speed plays an important role since at low speeds the brush is very flexible and at high speeds it is extremely hard and fast cutting.   |
| Radial, medium to long trim crimped wire fill                                | With the 4- to 8-inch diameter brush, part is hand held. With the 10- to 15-inch diameter brush, part is held by machine.                        | 4500–6000  | Serves as utility tool on bench grinder for removing feather grinding burrs, machining burrs, and for cleaning and producing a satin or matte finish.  | Good for hand held parts as brush is soft enough to conform to irregular surfaces and hard-to-reach areas. Smaller diameter brushes are not recommended for high-production operations.                      |
| Radial, sectional, non-metallic fill (treated and untreated Tampico or cord) | Provides means for improving finish or improving surface for plating. Works best with grease base deburring or buffing compound.                 | 5500–6500<br>7500 for polishing                          | For producing radii and improving surface finish. Removes the sharp peaks that fixed abrasives leave on a surface so that surface will accept a uniform plating. Polishing marks and draw marks can be successfully blended. | Brush is selective to an edge which means that it removes metal from an edge but not from adjoining surfaces. It will produce a very uniform radius without peening or rolling any secondary metal.          |
| Radial, wide-face, nonmetallic fill (natural fibers or synthetics)           | Can be used with flow-through mounting which facilitates feeding of cold water and hot alkaline solutions through brush face to prevent buildup. | 750–1200 for cleaning steel. 600 when used with slurries | For cleaning steel. Used in electrolytic tinplate lines, continuous galvanizing and annealing lines, and cold reduction lines. Used to produce dull or matte-type finishes on stainless steel and synthetics.                | Speeds above 3600 sfpm will not appreciably improve operation as brush wear will be excessive. Avoid excessive pressures. Ammeters should be installed in drive-motor circuit to indicate brushing pressure. |

### Characteristics and Applications of Brushes Used in Power Finishing (Continued)

| Brush Type  | Description  | Operating Speed Range, sfpm  | Uses  | Remarks   |
|---|--|--|---|---|
| Radial, wide face, metallic fill                                      | This brush is made to customer's specifications. It is dynamically balanced at the speed at which it will operate.                               | 2000–4000  | Removes buildup of aluminum oxide from work rolls in aluminum mill. Removes lime or magnesium coatings from certain types of steel. Burnishes hot-dipped galvanized steel to produce a minimum spangled surface.  | Each brush should have its own drive. An ammeter should be present in drive-motor circuit to measure brushing pressure. If strip is being brushed, a steel backup roll should be opposite the brush roll. |
| Radial, wide face, strip (interrupted brush face)                     | Performs cleaning operations that would cause a solid face brush to become loaded and unusable.  | When cleaning conveyor belts, brush speed is 2 to 3 times that of conveyor belt.         | Need for cleaning rubber and fabric conveyor belts of carry-back material which would normally foul snubber pulley and return idlers.   | Designed for medium- to light-duty work. Brush face does not load.  |
| Radial, Cup, Flared End, and Straight End, wire fill elastomer bonded | Extremely fast cutting with maximum operator safety. No loss of wire through fatigue. Always has uniform face.                                   | 3600–9000  | For removing oxide weld scale, burrs, and insulation from wire.   | Periodic reversing of brush direction will result in a brush life ten times greater than non-bonded wheels. Fast cutting action necessitates precise holding of part with respect to brush.               |
| Cup, twisted knot wire fill   | Fast cutting wheel used on portable tools to clean welds, scale, rust, and other oxides.   | 8000–10,000<br>4500–6500 for deburring and producing a radius around periphery of holes. | Used in shipyards and in structural steel industry. For cleaning outside diameter of pipe and removing burrs and producing radii on heat exchanger tube sheets and laminations for stator cores.                  | Fast acting brush cleans large areas economically. Setup time is short.   |
| Radial, wire or treated Tampico or cord                               | For use with standard centerless grinders. Brush will not remove metal from a cylindrical surface. Parts must be ground to size before brushing. | ...  | For removing feather grinding burrs and improving surface finish. Parts of 24 microinches can be finished down to 15 to 10 microinches. Parts of 10 to 12 microinches can be finished down to 7 to 4 microinches. | Follows centerless grinding principles, except that accuracy in pressure and adjustment is not critical. A machine no longer acceptable for grinding can be used for brushing.                            |



cially when good edges must be maintained. Cloth wheels are made in various ways; wheels having disks that are cemented together are very hard and used for rough, coarse work, whereas those having sewn disks are made of varying densities by sewing together a larger or smaller number of disks into sections and gluing them.

Wheels in which the disks are held together by thread or metal stitches and which are not stiffened by the use of glue usually require metal side plates to support the canvas disks. Muslin wheels are made from sewed or stapled buffs glued together, but the outer edges of a wheel frequently are left open or free from glue to provide an open face of any desired depth. Wool felt wheels are flexible and resilient, and the density may be varied by sewing two or more disks together and then cementing to form a wheel. Solid felt wheels are quite popular for fine finishing but have little value as general utility wheels. Paper wheels are made from strawboard paper disks and are cemented together under pressure to form a very hard wheel for rough work. Softer wheels are similarly made from felt paper. The "compress" canvas wheel has a cushion of polishing material formed by pieces of leather, canvas, or felt, that are held in a crosswise radial position by two side plates attached to the wheel hub. This cushion of polishing material may be varied in density to suit the requirements; it may be readily shaped to conform to the curvature of the work and this shape can be maintained. Sheepskin polishing wheels and paper wheels are little used.

**Polishing Operations and Abrasives.**—Polishing operations on such parts as chisels, hammers, screwdrivers, wrenches, and similar parts that are given a fine finish but are not plated, usually require four operations, which are "roughing," "dry fining," "greasing," and "coloring." The roughing is frequently regarded as a solid grinding wheel job. Sometimes there are two steps to the greasing operation—rough and fine greasing. For some hardware, such as the cheaper screwdrivers, wrenches, etc., the operations of roughing and dry fining are considered sufficient. For knife blades and cutlery, the roughing operation is performed with solid grinding wheels and the polishing is known as fine or blue glazing, but these terms are never used when referring to the polishing of hardware parts, plumbers' supplies, etc. A term used in finishing German silver, white metal, and similar materials is "sand-buffing," which, in distinction from the ordinary buffing operation that is used only to produce a very high finish, actually removes considerable metal, as in rough polishing or flexible grinding. For sand-buffing, pumice and other abrasive powders are loosely applied.

Aluminum oxide abrasives are widely used for polishing high-tensile-strength metals such as carbon and alloy steels, tough iron, and nonferrous alloys. Silicon carbide abrasives are recommended for hard, brittle substances such as grey iron, cemented carbide tools, and materials of low tensile strength such as brass, aluminum, and copper.

**Buffing Wheels.**—Buffing wheels are manufactured from disks (either whole or pieced) of bleached or unbleached cotton or woolen cloth, and they are used as the agent for carrying abrasive powders, such as tripoli, crocus, rouge, lime, etc., which are mixed with waxes or greases as a bond. There are two main classes of buffs, one of which is known as the "pieced-sewed" buffs, and is made from various weaves and weights of cloth. The other is the "full-disk" buffs, which are made from specially woven material. Bleached cloth is harder and stiffer than unbleached cloth, and is used for the faster cutting buffs. Coarsely woven unbleached cloth is recommended for highly colored work on soft metals, and the finer woven unbleached cloths are better adapted for harder metals. When working at the usual speed, a stiff buff is not suitable for "cutting down" soft metal or for light plated ware, but is used on harder metals and for heavy nickel-plated articles.

**Speed of Polishing Wheels.**—The proper speed for polishing is governed to some extent by the nature of the work, but for ordinary operations, the polishing wheel should have a peripheral speed of about 7500 ft/min. If run at a lower speed, the work tends to tear the polishing material from the wheel too readily, and the work is not as good in quality. Muslin, felt, or leather polishing wheels having wood or iron centers should be run at peripheral speeds varying from 300 to 7000 ft/min. It is rarely necessary to exceed 6000 ft/min, and

for most purposes, 4000 ft/min is sufficient. If the wheels are kept in good condition, in perfect balance, and are suitably mounted on substantial buffing lathes, they can be used safely at speeds within the limits given. However, manufacturers' recommendations concerning wheel speeds should be followed, where they apply.

**Grain Numbers of Emery.**—The numbers commonly used in designating the different grains of emery, corundum, and other abrasives are 10, 12, 14, 16, 18, 20, 24, 30, 36, 40, 46, 54, 60, 70, 80, 90, 100, 120, 150, 180, and 200, ranging from coarse to fine, respectively. These numbers represent the number of meshes per linear inch in the grading sieve. An abrasive finer than No. 200 is known as "flour" and the degree of fineness is designated by the letters CF, F, FF, FFF, FFFF, and PCF or SF, ranging from coarse to fine. The methods of grading flour-emery adopted by different manufacturers do not exactly agree, the letters differing somewhat for the finer grades. Again, manufacturers' recommendations should be followed.

**Grades of Emery Cloth.**—The coarseness of emery cloth is indicated by letters and numbers corresponding to the grain number of the loose emery used in the manufacture of the cloth. The letters and numbers for grits ranging from fine to coarse are as follows: FF, F, 120, 100, 90, 80, 70, 60, 54, 46, and 40. For large work roughly filed, use coarse cloth such as numbers 46 or 54, and then finer grades to obtain the required polish. If the work has been carefully filed, a good polish can be obtained with numbers 60 and 90 cloth, and a brilliant polish can be achieved by finishing with number 120 and flour-emery.

**Mixture for Cementing Emery Cloth to a Lapping Wheel.**—Many proprietary adhesives are available for application of emery cloth to the periphery of a buffing or lapping wheel, and generally are supplied with application instructions. In the absence of such instructions, clean the wheel thoroughly before applying the adhesive, and then rub the emery cloth down so as to exclude all air from between the surface of the wheel and the cloth.

### Etching and Etching Fluids

**Etching Fluids for Different Metals.**—A common method of etching names or simple designs upon steel is to apply a thin, even coating of beeswax or some similar substance which will resist acid; then mark the required lines or letters in the wax with a sharp-pointed scriber, thus exposing the steel (where the wax has been removed by the scriber point) to the action of an acid, which is finally applied. To apply a very thin coating of beeswax, place the latter in a silk cloth, warm the piece to be etched, and tub the pad over it. Regular coach varnish is also used instead of wax, as a "resist."

An etching fluid ordinarily used for carbon steel consists of nitric acid, 1 part; water, 4 parts. It may be necessary to vary the amount of water, as the exact proportion depends upon the carbon content and whether the steel is hard or soft. For hard steel, use nitric acid, 2 parts; acetic acid, 1 part. For high-speed steel, nickel or brass, use nitro-hydrochloric acid (nitric, 1 part; hydrochloric, 4 parts). For high-speed steel it is sometimes better to add a little more nitric acid. For etching bronze, use nitric acid, 100 parts; muriatic acid, 5 parts. For brass, nitric acid, 16 parts; water, 160 parts, dissolve 6 parts potassium chlorate in 100 parts of water; then mix the two solutions and apply.

A fluid which may be used either for producing a frosted effect or for deep etching (depending upon the time it is allowed to act) is composed of 1 ounce sulphate of copper (blue vitriol);  $\frac{1}{4}$  ounce alum;  $\frac{1}{2}$  teaspoonful of salt; 1 gill of vinegar, and 20 drops of nitric acid. For aluminum, use a solution composed of alcohol, 4 ounces; acetic acid, 6 ounces; antimony chloride, 4 ounces; water, 40 ounces.

Various acid-resisting materials are used for covering the surfaces of steel rules etc., prior to marking off the lines on a graduating machine. When the graduation lines are fine and very closely spaced, as on machinists' scales which are divided into hundredths or sixty-fourths, it is very important to use a thin resist that will cling to the metal and prevent

any under-cutting of the acid: the resist should also enable fine lines to be drawn without tearing or crumbling as the tool passes through it. One resist that has been extensively used is composed of about 50 per cent of asphaltum, 25 per cent of beeswax, and, in addition, a small percentage of Burgundy pitch, black pitch, and turpentine. A thin covering of this resisting material is applied to the clean polished surface to be graduated and, after it is dry, the work is ready for the graduating machine. For some classes of work, paraffin is used for protecting the surface surrounding the graduation lines which are to be etched. The method of application consists in melting the paraffin and raising its temperature high enough so that it will flow freely; then the work is held at a slight angle and the paraffin is poured on its upper surface. The melted paraffin forms a thin protective coating.

### **Conversion Coatings and the Coloring of Metals**

**Conversion Coatings.**—Conversion coatings are thin, adherent chemical compounds that are produced on metallic surfaces by chemical or electrochemical treatment. These coatings are insoluble, passive, and protective, and are divided into two basic systems: oxides or mixtures of oxides with other compounds, usually chromates or phosphates. Conversion coatings are used for corrosion protection, as an adherent paint base; and for decorative purposes because of their inherent color and because they can absorb dyes and colored sealants.

Conversion coatings are produced in three or four steps. First there is a pretreatment, which often involves mechanical surface preparation followed by decreasing and/or chemical or electrochemical cleaning or etching. Then thermal, chemical, or electrochemical surface conversion processes take place in acid or alkaline solutions applied by immersion spraying, or brushing. A post treatment follows, which includes rinsing and drying, and may also include sealing or dyeing. If coloring is the main purpose of the coating, then oiling, waxing, or lacquering may be required.

**Passivation of Copper.**—The blue-green patina that forms on copper alloys during atmospheric exposure is a passivated film; i.e., it prevents corrosion. This patina may be produced artificially or its growth may be accelerated by a solution of ammonium sulfate, 6 pounds; copper sulfate, 3 ounces; ammonia (technical grade, 0.90 specific gravity), 1.34 fluid ounces; and water, 6.5 gallons. This solution is applied as a fine spray to a chemically cleaned surface and is allowed to dry between each of five or six applications. In about 6 hours a patina somewhat bluer than natural begins to develop and continues after exposure to weathering.

Small copper parts can be coated with a passivated film by immersion in or brushing with a solution consisting of the following weight proportions: copper, 30; nitric acid, concentrated, 60; acetic acid (6%), 600; ammonium chloride, 11; and ammonium hydroxide (technical grade, 0.90 specific gravity), 20. To prepare the solution, the copper is dissolved in the nitric acid before the remaining chemicals are added, and the solution is allowed to stand for several days before use. A coating of linseed oil is applied to the treated parts.

**Coloring of Copper Alloys.**—Metals are colored to enhance their appearance, to produce an undercoat for an organic finish, or to reduce light reflection. Copper alloys can be treated to produce a variety of colors, with the final color depending on the base metal composition, the coloring solution's composition, the immersion time, and the operator's skill. Cleaning is an important part of the pretreatment; nitric and sulfuric acid solutions are used to remove oxides and to activate the surface.

The following solutions are used to color alloys that contain 85 per cent or more of copper. A dark red color is produced by immersing the parts in molten potassium nitrate, at 1200–1300°F, for up to 20 seconds, followed by a hot water quench. The parts must then be lacquered. A steel black color can be obtained by immersing the parts in a 180°F solution of arsenious oxide (white arsenic), 4 ounces; hydrochloric acid (1.16 specific gravity), 8 fluid ounces; and water, 1 gallon. The parts are immersed until a uniform color is

obtained; they are scratch brushed while wet, and then dried and lacquered. A light brown color is obtained using a room-temperature solution of barium sulfate, 0.5 ounce; ammonium carbonate, 0.25 ounce; and water, 1 gallon.

The following solutions are used to color alloys that contain less than 85 per cent copper. To color brass black, parts are placed in an oblique tumbling barrel made of stainless steel and covered with 3 to 5 gallons of water. Three ounces of copper sulfate and 6 ounces of sodium thiosulfate are dissolved in warm water and added to the barrel's contents. After tumbling for 15 to 30 minutes to obtain the finish, the solution is drained from the barrel, and the parts are washed thoroughly in clean water, dried in sawdust or air-blasted and, if necessary, lacquered. To produce a blue-black color, the parts are immersed in a 130–175°F solution of copper carbonate 1 pound; ammonium hydroxide (0.89 specific gravity), 1 quart; and water, 3 quarts. Excess copper carbonate should be present. The proper color is obtained in 1 minute. To color brass a hardware green, immerse the parts in a 160°F solution of ferric nitrate, 1 ounce; sodium thiosulfate, 6 ounces; and water, 1 gallon. To color brass a light brown, immerse the parts in a 195–212°F solution of potassium chlorate, 5.5 ounces; nickel sulfate, 2.75 ounces; copper sulfate, 24 ounces; and water, 1 gallon.

*Post treatment:* The treated parts should be scratch brushed to remove any excess or loose deposits. A contrast of colors may be obtained by brushing with a slurry of fine pumice, hand nabbing with an abrasive paste, mass finishing, or buffing to remove the color from the highlights. In order to prolong the life of parts used for outdoor decorative purposes, a clear lacquer should be applied. Parts intended for indoor purposes are often used without additional protection.

**Coloring of Iron and Steel.**—Thin black oxide coatings are applied to steel by immersing the parts to be coated in a boiling solution of sodium hydroxide and mixtures of nitrates nitrites. These coatings serve as paint bases and, in some cases, as final finishes. When the coatings are impregnated with oil or wax, they furnish fairly good corrosion resistance. These finishes are relatively inexpensive compared to other coatings.

*Phosphate Coatings:* Phosphate coatings are applied to iron and steel parts by reacting them with a dilute solution of phosphoric acid and other chemicals. The surface of the metal is converted into an integral, mildly protective layer of insoluble crystalline phosphate. Small items are coated in tumbling barrels; large items are spray coated on conveyors.

The three types of phosphate coatings in general use are zinc, iron, and manganese. Zinc phosphate coatings vary from light to dark gray. The color depends on the carbon content and pretreatment of the steel's surface, as well as the composition of the solution. Zinc phosphate coatings are generally used as a base for paint or oil, as an aid in cold working, for increased wear resistance, or for rustproofing. Iron phosphate coatings were the first type to be used; they produce dark gray coatings and their chief application is as a paint base. Manganese phosphate coatings are usually dark gray; however, since they are used almost exclusively as an oil base, for break in and to prevent galling, they become black in appearance.

In general, stainless steels and certain alloy steels cannot be phosphated. Most cast irons and alloy steels accept coating with various degrees of difficulty depending on alloy content.

**Anodizing Aluminum Alloys.**—In the anodizing process, the aluminum object to be treated is immersed as the anode in an acid electrolyte, and a direct current is applied. Oxidation of the surface occurs, producing a greatly thickened, hard, porous film of aluminum oxide. The object is then immersed in boiling water to seal the porosity and render the film impermeable. Before sealing, the film can be colored by impregnation with dyes or pigments. Special electrolytes may also be used to produce colored anodic films directly in the anodizing bath. The anodic coatings are used primarily for corrosion protection and abrasion resistance, and as a paint base.

The three principal types of anodizing processes are: chromic, in which the active agent is chromic acid; sulfuric, in which the active agent is sulfuric acid, and hard anodizing, in which sulfuric acid is used by itself or with additives in a low-temperature electrolyte bath. Most of the anodic coatings range in thickness from 0.2 to 0.7 mil. The hard anodizing process can produce coatings up to 2 mils. The chromic acid coating is less brittle than the sulfuric, and, since the chromic electrolyte does not attack aluminum, it does not present a corrosion problem when it is trapped in crevices. The chromic coating is less resistant to abrasion than the sulfuric, but it cannot be used with alloys containing more than 5 per cent copper due to corrosion of the base metal.

*Chemical Conversion Coatings for Aluminum:* Chemical conversion coatings for aluminum alloys are adherent surface layers of low volatility oxide, phosphate, or chromate compounds produced by the reaction of the metal surface with suitable reagents. The conversion coatings are much thinner and softer than anodic coatings but they are less expensive and serve as an excellent paint base.

**Magnesium Alloys.**—Chemical treatment of magnesium alloys is used to provide a paint base and to improve corrosion resistance. The popular conversion “dip” coatings are chrome pickle and dichromate treatments, and they are very thin. Anodic coatings are thicker and harder, and, after sealing, give the same protection against corrosion, although painting is still desirable.

**Titanium Alloys.**—Chemical conversion coatings are used on titanium alloys to improve lubricity by acting as a base for the retention of lubricants. The coatings are applied by immersion, spraying, or brushing. A popular coating bath is an aqueous solution of phosphates, fluorides, and hydrofluoric acid. The coating is composed primarily of titanium and potassium fluorides and phosphates.

### Plating

**Surface Coatings.**—The following is a list of military plating and coating specifications.

*Anodize (Chromic and Sulfuric), MIL-A-8625F:* Conventional Types I, IB, and II anodic coatings are intended to improve surface corrosion protection under severe conditions or as a base for paint systems. Coatings can be colored with a large variety of dyes and pigments. Class 1 is non-dyed; Class 2 dyed. Color is to be specified on the contract. Prior to dyeing or sealing, coatings shall meet the weight requirements.

Type I and IB coatings should be used on fatigue critical components (due to thinness of coating). Type I unless otherwise specified shall not be applied to aluminum alloys with over 5% copper or 7% silicon or total alloying constituents over 7.5%. Type IC is a mineral or mixed mineral/organic acid that anodizes. It provides a non-chromate alternative for Type I and IB coatings where corrosion resistance, paint adhesion, and fatigue resistance are required. Type IIB is a thin sulfuric anodizing coating for use as non-chromate alternatives for Type I and IB coatings where corrosion resistance, paint adhesion, and fatigue resistance are required. Be sure to specify the class of anodic coating and any special sealing requirements.

Types I, IB, IC, and IIB shall have a thickness between 0.00002 and 0.0007 in. Type II shall have a thickness between 0.0007 and 0.0010 in.

*Black Chrome, MIL-C-14538C:* A hard, non-reflective, abrasion, heat and corrosion resistant coating approximately 0.0002 in. thick. Provides limited corrosion protection, but added protection can be obtained by specifying underplate such as nickel. Color is a dull dark gray, approaching black and may be waxed or oiled to darken.

Black chromium has poor throwing power, and conforming anodes are necessary for intricate shapes. Apply coating after heat treating and all mechanical operations are performed. Steel parts with hardness in excess of 40 Rc shall be stress relieved prior to plating by baking one hour or more (300 to 500°F) and baked after plating (375°F ± 25°F) for 3 hours.

*Black Oxide Coating, MIL-C-13924C:* A uniform, mostly decorative black coating for ferrous metals used to decrease light reflection. Only very limited corrosion protection under mild corrosion conditions. Black oxide coatings should normally be given a supplementary treatment.

Used for moving parts that cannot tolerate the dimensional change of a more corrosion resistant finish. Use alkaline oxidizing for wrought iron, cast and malleable irons, plain carbon, low alloy steel and corrosion resistant steel alloys. Alkaline-chromite oxidizing may be used on certain corrosion resistant steel alloys tempered at less than 900°F Salt oxidizing is suitable for corrosion resistant steel alloys that are tempered at 900°F or higher.

*Cadmium, QQ-P-416F:* Cadmium plating is required to be smooth, adherent, uniform in appearance, free from blisters, pits, nodules, burning, and other defects when examined visually without magnification. Unless otherwise specified in the engineering drawing or procurement documentation, the use of brightening agents in the plating solution to modify luster is prohibited on components with a specified heat treatment of 180 ksi minimum tensile strength (or 40 Rc) and higher. Either a bright (not caused by brightening agents) or dull luster shall be acceptable. Baking on Types II and III shall be done prior to application of supplementary coatings. For Classes 1, 2, and 3 the minimum thicknesses shall be 0.0005, 0.0003, and 0.0002 in. respectively.

Type I is to be used as plated. Types II and III require supplementary chromate and phosphate treatment respectively. Chromate treatment required for type II may be colored iridescent bronze to brown including olive drab, yellow and forest green. Type II is recommended for corrosion resistance. Type III is used as a paint base and is excellent for plating stainless steels that are to be used in conjunction with aluminum to prevent galvanic corrosion. For Types II and III the minimum cadmium thickness requirement shall be met after the supplementary treatment.

*Chemical Films, MIL-C-5541E:* The materials that qualify produce coatings that range in color from clear to iridescent yellow or brown. Inspection difficulties may arise with clear coatings because of their invisibility.

Class 1A chemical conversion coatings are intended to provide corrosion prevention when left unpainted as well as to improve adhesion of paint finish systems on aluminum and aluminum alloys. May be used on tanks, tubings, and component structures where paint finishes are not required for the exterior surfaces but are required for the interior surfaces.

Class 3 chemical conversion coatings are intended for use as a corrosive film for electrical and electronic applications where lower resistant contacts are required. The primary difference between Class 1A and Class 3 coating is thickness.

*Chemical Finish: Black, MIL-F-495E:* A uniform black corrosion retardant for copper. Coating has no abrasion resistance. Used to blacken color and reduce gloss on copper-alloy surfaces other than food service and water supply items. Also used as a base for subsequent coatings such as lacquer, varnish, oil, and wax.

*Chrome, QQ-C-320B:* Has excellent hardness, wear resistance, and erosion resistance. In addition chrome has a low coefficient of friction, is resistant to heat, and can be rendered porous for lubrication purposes.

Types I and II have bright and satin appearances respectively.

Class 1 is used as plating for corrosion protection and Class 2, for engineering plating. Class 1 and 2 both shall have a minimum thickness of 0.00001 in. on all visible surfaces. If thickness is not specified use 0.002 in.

Class 2a will be plated to specified dimensions or processed to specified dimensions after plating. Class 2b will be used on parts below 40 Rc and subject to static loads or designed for limited life under dynamic loads. Class 2c will be used on parts below 40 Rc and designed for unlimited life under dynamic loads. Class 2d parts have hardness of 40 Rc or above, which are subject to static loads or designed for unlimited life under dynamic loads.

Class 2e parts have hardness of 40 Rc or above, which are designed for unlimited life under dynamic loads.

All coated steel parts having a hardness of Rc 36 and higher shall be baked at a minimum of 375°F ± 25°F per the following conditions. With a tensile strength of 160-180 (ksi), the time at temperature will be 3 hr.; at 181-220 ksi, the time will be 8 hr.; and at 221 ksi and above, the time will be 12 hr.

*Copper, MIL-C-14550B:* Has good corrosion resistance when used as an undercoat. A number of copper processes are available, each designed for a specific purpose such as, to improve brightness (to eliminate the need for buffing), high speed (for electro-forming), and fine grain (to prevent case-hardening).

All steel parts having a hardness of Rc 35 and higher shall be baked at 375°F ± 25°F for 24 hours, within four hours after plating to provide hydrogen embrittlement relief. Plated springs and other parts subject to flexure shall not be flexed prior to baking operations.

Class 0 will have a thickness 0.001 - 0.005 in. and is used for heat treatment stop-off; Class 1 is 0.001 in. and is used to provide carburizing shield, also for plated through printed circuit boards. Class 2 is 0.0005 in. thick and is used as an undercoat for nickel and other platings. Class 3 is 0.0002 in. thick and is used to prevent basis metal migration into tin (prevents poisoning solderability). Class 4 is 0.0001 in. thick.

*Tin Lead, MIL-P-81728A:* It has excellent solderability. Either a matte or bright luster is acceptable. For electronics components, use only parts with a matte or flow brightened finish.

For brightened electronic components, the maximum thickness will be 0.0003 in. Tin 50 to 70% by weight and with a lead remainder, 0.0003-0.0005 in.

*Magnesium Process, MIL-M-3171C:* Process #1-A chrome pickle treatment for magnesium. Color varies from matte gray to yellow-red. Has only fair corrosion resistance (< 24 hours, 20% salt spray resistance).

#7-A dichromate treatment for magnesium. Color varies from light brown to gray depending on alloy. Only fair corrosion resistance (< 24 hours, 20% salt spray resistance).

#9-A galvanic anodize treatment for magnesium. Produces a dark brown to black coating. Designed to give a protective film on alloys which do not react to Dow No. 7 treatment. Only fair corrosion resistance (< 24 hours, 20% salt spray resistance).

| Type/Class | Thickness (in.)   | Comments   |
|------------|---|--|
| Type I     | Removes metal. (approx. 0.0006 for wrought, less for die castings.) No dimensional change | Used for protecting magnesium during shipment, storage and machining. Can be used as a paint base. NOTE: Must remove Type I coating before applying Type III and Type IV treatments.   |
| Type III   | ...   | Note: precleaning and pickling may result in dimensional changes due to metal loss.  |
| Type IV    | No dimensional change   | Can be used as a paint base, and is applicable to all magnesium alloys. Used where optical properties (black) are required on close tolerance parts. NOTE: Precleaning and pickling may result in dimensional changes due to metal loss. |

*Magnesium Anodic Treatment, MIL-M-45202C:* The HAE anodic finish is probably the hardest coating currently available for magnesium. It exhibits stability at high temperatures and has good dielectric strength. It serves as an excellent paint base. It requires resin seal or paint for maximum corrosion protection.

| Type/Class             | Typical Thickness | Comments  |
|------------------------|-------------------|---|
| Type I, Light coating. |                   |   |
| Class A                | 0.2 mil           | Tan coating (HAE)   |
| Grade 1                | ...               | Without post treatment (dyed)   |
| Grade 2                | ...               | With bifluoride-dichromate post treatment   |
| Class C                | 0.3 mil           | Light green coating (Dow #17)   |
| Type II, Heavy coating |                   |   |
| Class A                | 1.5 mil           | Hard brown coating (HAE)  |
| Grade 1                | ...               | Without post treatment  |
| Grade 3                | ...               | With bifluoride-dichromate post treatment   |
| Grade 4                | ...               | With bifluoride-dichromate post treatment including moist heat aging                        |
| Grade 5                | ...               | With double application of bifluoride-dichromate post treatment including moist heat aging. |
| Class D                | 1.2 mil           | Dark green coating (Dow #17)  |

Coatings range from thin clear to light gray-green, to thick dark-green coatings. The clear coatings are used as a base for subsequent clear lacquers or paints to produce a final appearance similar to clear anodizing on aluminum. The light gray-green coatings are used in most applications which are to be painted. The thick, dark-green coating offers the best combination of abrasion resistance, protective value and paint base characteristics.

*Electroless Nickel, AMS 2404C, AMS 2405B, AMS 2433B:* Is typically used as a coating to provide a hard-ductile, wear-resistant, and corrosion-resistant surface for operation in service up to 1000°F, to provide uniform build-up on complex shapes.

AMS 2404C, is deposited directly on the basis metal without a flash coating of other metal, unless otherwise specified. AMS 2405B, is deposited directly on the basis metal except where parts fabricated from corrosion resistant steels or alloys where a "strike" coating of nickel or other suitable metal is required, unless otherwise specified. AMS 2433B, is a type of electroless nickel typically used to enhance the solderability of surfaces, but usage is not limited to such applications. Generally, the plate shall be placed directly on the basis metal. However, aluminum alloys shall be zinc immersion coated per ASTM B253 followed by copper flash; corrosion resistant steels and nickel and cobalt alloys or other basis metals may use a nickel or copper flash undercoat when the purchaser permits.

**Electroless Nickel Preparation:** Parts having a hardness higher than Rc 40 and have been machined or ground after heat treatment shall be suitably stress-relieved before cleaning and plating.

After treatment, parts having a hardness of Rc 33 and over shall be heated to 375°F ± 15°F for three hours. If such treatment is injurious to the parts, bake at 275°F ± 15°F for four hours.

Electroless Nickel, Low-Phosphorous

*Note:* If permitted by drawing, the maximum hardness and wear resistance are obtained by heating parts for 30-60 minutes, preferably in an inert atmosphere, at 750°F ± 15°F except aluminum parts shall be baked at 450°F ± 15°F for four hours. If such heating is not specified, bake at 375°F ± 15°F for three hours. If this treatment is injurious to parts or assemblies, bake at 275°F for five hours.

**Plating:** nickel-thallium-boron (Electroless Deposition) and nickel-boron (Electroless Deposition)

**Preparation:** All fabrication-type operations shall be completed.



Post-treatment: Cold worked or heat treated parts and aluminum alloys and other parts requiring special thermal treatment shall be post treated as agreed upon by purchaser and vendor. Other plated parts within four hours after plating shall be heat treated for  $90 \pm 10$  minutes at  $675^\circ\text{F} \pm 15^\circ\text{F}$ .

*Electropolishing, (No MIL-SPEC No.):* This process electrolytically removes or diminishes scratches, burrs, and unwanted sharp edges from most metals. Finishes from satin to mirror-bright are produced by controlling time, temperature, or both.

Typically the thickness loss is 0.0002 in. This process is not recommended for close tolerance surfaces.

*Gold, MIL-G-45204C:* Has a yellow to orange color depending on the proprietary process used. Will range from matte to bright finish depending on basis metal. It has good corrosive resistance and a high tarnish resistance. It provides a low contact resistance, is a good conductor of electricity, and has excellent solderability. If the hardness grade for the gold coating is not specified, Type I shall be furnished at a hardness of Grade A, and Type II furnished at a hardness of Grade C.

For soldering, a thin pure soft gold coating is preferred. A minimum and maximum thickness 0.00005 and 0.00010 in., respectively, shall be plated.

Unless otherwise specified, gold over silver underplate combinations shall be excluded from electronics hardware. Silver or copper plus silver may not be used as an underplate unless required by the item specification. When gold is applied to brass bronze or beryllium copper, or a copper plate or strike, an antidiffusion underplate such as nickel shall be applied.

Type I is 99.7% gold minimum (Grades A, B, or C); Type II is 99.0% (Grades B, C, or D); and Type III is 99.9% (Grade A only).

Grade A is 90 Knoop maximum; Grade B is 91-129 Knoop; Grade C is 130-200 Knoop; and Grade D is 201 Knoop and over.

Class 00 has a thickness of 0.00002 in. minimum; Class 0, 0.00003 in.; Class 1, 0.00005 in.; Class 2, 0.0001 in.; Class 3, 0.0002 in.; Class 4, 0.0003 in.; Class 5, 0.0005 in.; and Class 6, 0.0015 in.

*Hard Anodize, MIL-A-8625F:* The color will vary from light tan to black depending on alloy and thickness. Can be dyed in darker colors depending on the thickness. Coating penetrates base metal as much as builds up on the surface. The term thickness includes both the buildup and penetration. It provides a very hard ceramic type coating. Abrasion resistance will vary with alloy and thickness of coating. Has good dielectric properties.

Do not seal coatings where the main function is to obtain maximum abrasion or wear resistance. When used for exterior applications requiring corrosion resistance but permitting reduced abrasion, the coating shall be sealed (boiling deionized water or hot 5% sodium dichromate solution, or other suitable chemical solutions).

Type III will have a thickness specified on the contract or applicable drawing. If not specified use a nominal thickness of 0.002 in. Hard coatings may vary in thickness from 0.0005 - 0.0045 in.

Class 1 shall be not dyed or pigmented. Class 2 shall be dyed and the color specified on the contract. The process can be controlled to very close thickness tolerances. Where maximum serviceability or special properties are required, consult metal finisher for best alloy choice. Thick coatings (those over 0.004 in.) will tend to break down sharp edges. Can be used as an electrical insulation coating. "Flash" hard anodize may be used instead of conventional anodize for corrosion resistance and may be more economical in conjunction with other hard anodized areas.

*Lubrication, Solid Film MIL-L-46010D:* The Military Plating Specification establishes the requirements for three types of heat cured solid film lubricants that are intended to

reduce wear and prevent galling, corrosion, and seizure of metals. For use on aluminum, copper, steel, stainless steel, titanium, and chromium, and nickel bearing surfaces.

Types I, II, and III have a thicknesses of 0.008 - 0.013 mm. No single reading less than 0.005 mm or greater than 0.018 mm.

Type I has a curing temperature of  $150 \pm 15^\circ\text{C}$  and an endurance life of 250 minutes; Type II,  $204 \pm 15^\circ\text{C}$  and 450 minutes; and Type III is a low volatile organic compound (VOC) content lubricant with cure cycles of  $150 \pm 15^\circ\text{C}$  for two hours, or  $204 \pm 15^\circ\text{C}$  for one hour with an endurance life of 450 minutes. Color 1 has a natural product color and Color 2 has a black color.

*Nickel, QQ-N-290A:* There is a nickel finish for almost any need. Nickel can be deposited soft, hard-dull, or bright, depending on process used and conditions employed in plating. Thus, hardness can range from 150-500 Vickers. Nickel can be similar to stainless steel in color, or can be a dull gray (almost white) color. Corrosion resistance is a function of thickness. Nickel has a low coefficient of thermal expansion.

All steel parts having a tensile strength of 220,000 or greater shall not be a nickel plate without specific approval of procuring agency.

Class 1 is used for corrosion protection. Plating shall be applied over an underplating of copper or yellow brass on zinc and zinc based alloys. In no case, shall the copper underplate be substituted for any part of the specified nickel thickness. Class 2 is used in engineering applications.

Grade A has a thickness of 0.0016 in.; Grade B, 0.0012 in.; Grade C, 0.001 in.; Grade D, 0.0008 in.; Grade E, 0.0006 in.; Grade F, 0.0004 in.; and Grade G, 0.002 in.

*Palladium, MIL-P-45209B:* A gray, dense deposit good for undercoats. Has good wear characteristics, corrosion resistance, catalytic properties, and good conductivity.

The thickness shall be 0.00005 in. unless otherwise specified.

Steel springs and other steel parts subject to flexure or repeated impact and of hardness greater than Rc 40 shall be heated to  $375^\circ\text{F} \pm 25^\circ\text{F}$  for three hours after plating.

*Passivate, QQ-P-35C:* Intended to improve the corrosion resistance of parts made from austenitic, ferritic, and martensitic corrosion-resistant steels of the 200, 300, and 400 series and precipitation hardened corrosion resistant steels. 440C grades may be exempt from passivation treatments of the procuring activity.

Type II is a medium temperature nitric acid solution with sodium dichromate additive. Type VI, a low temperature nitric acid solution; Type VII, a medium temperature nitric acid solution; and Type VIII, a medium temperature high concentration nitric acid solution.

*Phosphate Coating: Light, TT-C-490D:* This specification covers cleaning methods and pretreatment processes.

| Methods /Types   | Typical Thickness (in.) | Comments   |
|------------------|-------------------------|--|
| Cleaning Methods |                         |  |
|                  | –                       | Light coating for use as a paint base.                       |
| Method I         | ...                     | Mechanical or abrasive cleaning (for ferrous surfaces only). |
| Method II        | ...                     | Used for solvent cleaning.                                   |
| Method III       | ...                     | Used for hot alkalines (for ferrous surfaces only).          |
| Method IV        | ...                     | Emulsion.  |
| Method V         | ...                     | Used for alkaline derusting (for ferrous surfaces only).     |
| Method VI        | ...                     | Phosphoric acid.   |

| Pretreatment Coatings |                 |   |
|-----------------------|-----------------|---|
| Type I                | ...             | Zinc phosphate. Class 1-spray application: Class 2A and 2B-Immersion or Dip application |
| Type II               | ...             | Aqueous Iron Phosphate  |
| Type III              | 0.0003 – 0.0005 | Is an organic pretreatment coating  |
| Type IV               | ...             | Non-aqueous iron phosphate  |
| Type V                | ...             | Zinc phosphate  |

Type I is intended as a general all-purpose pretreatment prior to painting. Type II and IV are intended primarily for use where metal parts are to be formed after painting. Type III is intended for use where size and shape preclude using Type I, II, or IV and where items containing mixed metal components are assembled prior to treatment.

*Phosphate Coating: Heavy, DOD-P-16232-F:* The primary differences are that Type M is used as a heavy manganese phosphate coating for corrosion and wear resistance and Type Z is used as a Zinc phosphate coating.

Type M has a thickness from 0.0002-0.0004 in. and Type Z, 0.0002-0.0006 in. Class 1, for both types has a supplementary preservative treatment or coating as specified; Class 2, has a supplementary treatment with lubricating oil; and Class 3, no supplementary treatment is required. For Type M, Class 4 is chemically converted (may be dyed to color as specified) with no supplementary coating or supplementary coating as specified. For Type Z, Class 4 is the same as Class 3.

This coating is for medium and low alloy steels. The coatings range from gray to black in color. The "heavy" phosphate coatings covered by this specification are intended as a base for holding/retaining supplemental coatings which provide the major portion of the corrosion resistance. "Light" phosphate coatings used for a paint base are covered by other specifications. Heavy zinc phosphate coatings may be used when paint and supplemental oil coatings are required on various parts or assemblies.

*Rhodium, MIL-R-46085B:* Rhodium is metallic and similar to stainless steel in color, has excellent corrosion and abrasion resistance, is almost as hard as chromium, and has a high reflectivity. Thicker coatings of Rhodium are very brittle.

| Class/Types | Thickness (in.) | Comments  |
|-------------|-----------------|---|
| Type I      | –               | Over nickel, silver, gold, or platinum.   |
| Type II     | –               | Over other metals, requires nickel undercoat.   |
| Class 1     | 0.000002        | Used on silver for tarnish resistance.  |
| Class 2     | 0.00001         |   |
| Class 3     | 0.00002         | Applications range from electronic to nose cones -wherever wear, corrosion resist solderability and reflectivity are important. |
| Class 4     | 0.00010         |   |
| Class 5     | 0.00025         |   |

Parts having a hardness of Rc 33 or above shall be baked at 375°F for three hours prior to cleaning. Parts having hardness of 40 Rc and above shall be baked within four hours after plating at 375°F for three hours.

*Silver, QQ-S-365D:* Silver has an increasing use in both decorative and engineering fields, including electrical and electronic fields.

Silver is white matte to very bright in appearance. Has good corrosion resistance, depending on base metal and will tarnish easily. Its hardness varies from about 90-135 Brinell depending on process and plating conditions. Solderability is excellent, but decreases with age. Silver is the best conductor of electricity. Has excellent lubricity and

smear characteristics for antigalling uses on static seals, bushing, etc. Stress relief steel parts at a minimum  $375^{\circ}\text{F} \pm 25^{\circ}\text{F}$  or more prior to cleaning and plating if they contain or are suspected of having damaging residual tensile stresses.

All types and grades will have a minimum thickness of 0.0005 in. unless otherwise specified. Type I is matte, Type II is semi-bright, and Type III is bright. Grade A has a chromate post-treatment to improve tarnish resistance. In contrast Grade B has no supplementary treatment.

*Tin, MIL-T-10727C:* There are two different types of coating methods used, electrodeposited (based on Use ASTM B545 standard specification for electrodeposited coatings of tin) and hot dipped.

Thickness as specified on drawing (thickness is not part of the specification) is 0.0001-0.0025 in., flash for soldering; 0.0002-0.0004 in., to prevent galling and seizing; 0.0003 in. minimum, where corrosion resistance is important; and 0.0002-0.0006 to prevent formation of case during nitriding.

Color is a gray-white color in plated condition. Tin is soft, but very ductile. It has good corrosion resistance, and has excellent solderability. Tin is not good for low temperature applications.

If a bright finish is desired to be used in lieu of fused tin, specify Bright Tin plate. Thickness can exceed that of fused tin and deposit shows excellent corrosion resistance and solderability.

*Vacuum Cadmium, MIL-C-8837B:* Is used primarily to provide corrosion resistance to ferrous parts free from hydrogen contamination and possible embrittlement. Recommended on steels with a strength of  $2.2 \times 10^5$  psi or above.

Coating is applied after all machining, brazing, welding, and forming has been completed. Prior to coating, all steel parts shall be stress relieved by baking at  $375^{\circ}\text{F} \pm 25$  for three hours if suspected of having residual tensile stresses. Immediately prior to coating, lightly dry abrasive blast areas are to be coated.

Type I shall be as plated; and Types II and III require supplementary chromate and phosphate treatments respectively.

Classes 1, 2, and 3 have thicknesses of 0.0005, 0.0003, and 0.0002 in. respectively.

Cadmium coating shall not be used, if in service, temperature reaches  $450^{\circ}\text{F}$ .

A salt spray test is required for type II and is 96 hours.

*Zinc, ASTM-B633:* This specification covers requirements for electrodeposited zinc coatings applied to iron or steel articles to protect them from corrosion. It does not cover zinc-coated wire or sheets.

Type I will be as plated; Type II will have colored chromate conversion coatings; Type III will have colorless chromate conversion coatings; and Type IV will have phosphate conversion coatings.

High strength steels (tensile strength over 1700 MPa) shall not be electroplated.

Stress relief: All parts with ultimate tensile strength 1000 MPa and above at minimum  $190^{\circ}\text{C}$  for three hours or more before cleaning and plating.

Hydrogen embrittlement relief: All electroplated parts 1200 MPa or higher shall be baked at  $190^{\circ}\text{C}$  for three hours or more within four hours after electroplating.

| Corrosion Resistance Requirements |                 |
|-----------------------------------|-----------------|
| Types                             | Test Period Hr. |
| II                                | 96              |
| III                               | 12              |

**Flame Spraying Process**

In this process, the forerunner of which was called the metal spraying process, metals, alloys, ceramics, and cermets are deposited on metallic or other surfaces. The object may be to build up worn or undersize parts, provide wear-resisting or corrosion-resisting surfaces, correct defective castings, etc.

Different types of equipment are available that provide the means of depositing the coatings on the surfaces. In one, wire is fed automatically through the nozzle of the spray gun; then a combustible gas, oxygen and compressed air serve to melt and blow the atomized metal against the surface to be coated. The gas usually used is acetylene but other gases may be used. Any desired thickness of metal may be deposited and the metals include steels, ranging from low to high carbon content, various brass and bronze compositions, babbitt metal, tin, zinc, lead, nickel, copper, and aluminum. The movement of the spray gun, in covering a given surface, is controlled either mechanically or by hand. In enlarging worn or undersize shafts, spindles, etc., it is common practice to clamp the gun in a lathe toolholder and use the feed mechanism to traverse the gun at a uniform rate while the metal is being deposited upon the rotating workpiece. The spraying operation may be followed by machining or grinding to obtain a more precise dimension.

Some typical production applications using the wire process are the coating of automotive exhaust valves, refinishing of transfer ink rollers for the printing industry and the rebuilding of worn truck clutch plates. Other production applications include the metallizing of glass meter box windows, the spraying of aluminum onto cloth gauze to produce electrolytic condenser plates, and the spraying of zinc or copper for coating ceramic insulators.

With another type of equipment, metal, refractory, and ceramic powder are used instead of wire. Ordinarily this equipment employs the use of two gases, oxygen and a fuel gas. The fuel gas is usually acetylene but in some instances hydrogen may be used. When hand-held, a small reservoir supplies the powder to the equipment but a larger reservoir is used for lathe-mounted equipment or for large-scale production work. The four basic types of coating powders used with this equipment are ceramics, oxidation-resistant metals and alloys, self-bonding alloys, and alloys for fused coatings. These powders are used to produce wear-resistant, corrosion-resistant, heat-resistant, and electrically conductive coatings.

Still other equipment employs the use of plasma flame with which vapors of materials are raised to a higher energy level than the ordinary gaseous state. Its use raises the temperature ceiling and provides a controlled atmosphere by permitting employment of an inert or chemically inactive gas so that chemical action, such as oxidation, during the heating and application of the spray material can be controlled. The temperatures that can be obtained with commercially available plasma equipment often exceed 30,000 degrees F but for most plasma flame spray processes the temperature range of from 12,000 to 20,000 degrees F is optimum. Plasma flame spray materials include alumina, zirconia, tungsten, molybdenum, tantalum, copper, aluminum, carbides, and nickel-base alloys.

Regardless of the equipment used, what is important is the proper preparation of the surface that will receive the sprayed coating. Preparation activities include the degreasing or solvent cleaning of the surface, undercutting of the surface to provide room for the proper coating thickness, abrasive or grit blasting the substrate to provide a roughened surface, grooving (in the case of flat surfaces) or rough threading (in the case of cylindrical work) the surface to be coated, preheating the base metal. Methods of obtaining a bond between the sprayed material and the substrate are: heating the base, roughening the base, or spraying a "self-bonding" material onto a smooth surface; however, heating alone is seldom used in machine element work as the elevated temperatures required to obtain the proper bond causes problems of warpage and surface corrosion.

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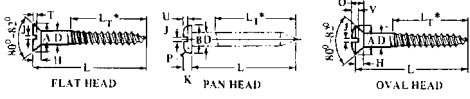


## NAILS, SPIKES, AND WOOD SCREWS

Standard Wire Nails and Spikes  
(Size, Length and Approximate Number to Pound)

| Size of Nail    | Length, Inches | Gage                        | Num/lb | Gage               | Num/lb | Gage           | Num/lb | Gage                          | Num/lb | Gage                    | Num/lb    |
|-----------------|----------------|-----------------------------|--------|--------------------|--------|----------------|--------|-------------------------------|--------|-------------------------|-----------|
|                 |                | Common Wire Nails and Brads |        | Flooring Brads     |        | Fence Nails    |        | Casing, Smooth and Barbed Box |        | Finishing Nails         |           |
| 2 d             | 1              | 15                          | 876    | ...                | ...    | ...            | ...    | 15 1/2                        | 1010   | 16 1/2                  | 1351      |
| 3 d             | 1 1/4          | 14                          | 568    | ...                | ...    | ...            | ...    | 14 1/2                        | 635    | 15 1/2                  | 807       |
| 4 d             | 1 1/2          | 12 1/2                      | 316    | ...                | ...    | ...            | ...    | 14                            | 473    | 15                      | 584       |
| 5 d             | 1 3/4          | 12 1/2                      | 271    | ...                | ...    | 10             | 142    | 14                            | 406    | 15                      | 500       |
| 6 d             | 2              | 11 1/2                      | 181    | 11                 | 157    | 10             | 124    | 12 1/2                        | 236    | 13 1/2                  | 309       |
| 7 d             | 2 1/4          | 11 1/2                      | 161    | 11                 | 139    | 9              | 92     | 12 1/2                        | 210    | 13                      | 238       |
| 8 d             | 2 1/2          | 10 1/4                      | 106    | 10                 | 99     | 9              | 82     | 11 1/2                        | 145    | 12 1/2                  | 189       |
| 9 d             | 2 3/4          | 10 1/4                      | 96     | 10                 | 90     | 8              | 62     | 11 1/2                        | 132    | 12 1/2                  | 172       |
| 10 d            | 3              | 9                           | 69     | 9                  | 69     | 7              | 50     | 10 1/2                        | 94     | 11 1/2                  | 121       |
| 12 d            | 3 1/4          | 9                           | 64     | 8                  | 54     | 6              | 40     | 10 1/2                        | 87     | 11 1/2                  | 113       |
| 16 d            | 3 1/2          | 8                           | 49     | 7                  | 43     | 5              | 30     | 10                            | 71     | 11                      | 90        |
| 20 d            | 4              | 6                           | 31     | 6                  | 31     | 4              | 23     | 9                             | 52     | 10                      | 62        |
| 30 d            | 4 1/2          | 5                           | 24     | ...                | ...    | ...            | ...    | 9                             | 46     | ...                     | ...       |
| 40 d            | 5              | 4                           | 18     | ...                | ...    | ...            | ...    | 8                             | 35     | ...                     | ...       |
| 50 d            | 5 1/2          | 3                           | 16     | ...                | ...    | ...            | ...    | ...                           | ...    | ...                     | ...       |
| 60 d            | 6              | 2                           | 11     | ...                | ...    | ...            | ...    | ...                           | ...    | ...                     | ...       |
| Size and Length |                | Hinge Nails, Heavy          |        | Hinge Nails, Light |        | Clinch Nails   |        | Barbed Car Nails, Heavy       |        | Barbed Car Nails, Light |           |
| 2 d             | 1              | ...                         | ...    | ...                | ...    | 14             | 710    | ...                           | ...    | ...                     | ...       |
| 3 d             | 1 1/4          | ...                         | ...    | ...                | ...    | 13             | 429    | ...                           | ...    | ...                     | ...       |
| 4 d             | 1 1/2          | 3                           | 50     | 6                  | 82     | 12             | 274    | 10                            | 165    | 12                      | 274       |
| 5 d             | 1 3/4          | 3                           | 38     | 6                  | 62     | 12             | 235    | 9                             | 118    | 10                      | 142       |
| 6 d             | 2              | 3                           | 30     | 6                  | 50     | 11             | 157    | 9                             | 103    | 10                      | 124       |
| 7 d             | 2 1/4          | 00                          | 12     | 3                  | 25     | 11             | 139    | 8                             | 76     | 9                       | 92        |
| 8 d             | 2 1/2          | 00                          | 11     | 3                  | 23     | 10             | 99     | 8                             | 69     | 9                       | 82        |
| 9 d             | 2 3/4          | 00                          | 10     | 3                  | 22     | 10             | 90     | 7                             | 54     | 8                       | 62        |
| 10 d            | 3              | 00                          | 9      | 3                  | 19     | 9              | 69     | 7                             | 50     | 8                       | 57        |
| 12 d            | 3 1/4          | ...                         | ...    | ...                | ...    | 9              | 62     | 6                             | 42     | 7                       | 50        |
| 16 d            | 3 1/2          | ...                         | ...    | ...                | ...    | 8              | 49     | 6                             | 35     | 7                       | 43        |
| 20 d            | 4              | ...                         | ...    | ...                | ...    | 7              | 37     | 5                             | 26     | 6                       | 31        |
| 30 d            | 4 1/2          | ...                         | ...    | ...                | ...    | ...            | ...    | 5                             | 24     | 6                       | 28        |
| 40 d            | 5              | ...                         | ...    | ...                | ...    | ...            | ...    | 4                             | 18     | 5                       | 21        |
| 50 d            | 5 1/2          | ...                         | ...    | ...                | ...    | ...            | ...    | 3                             | 15     | 4                       | 17        |
| 60 d            | 6              | ...                         | ...    | ...                | ...    | ...            | ...    | 3                             | 13     | 4                       | 15        |
| Size and Length |                | Boat Nails, Heavy           |        | Boat Nails, Light  |        | Slatting Nails |        | Spikes                        |        |                         |           |
| 2 d             | 1              | ...                         | ...    | ...                | ...    | 12             | 411    | Size and Length               |        | Gage                    | No. to Lb |
| 3 d             | 1 1/4          | ...                         | ...    | ...                | ...    | 10 1/2         | 225    |                               |        |                         |           |
| 4 d             | 1 1/2          | 1/4                         | 44     | 3/16               | 82     | 10 1/2         | 187    | 10 d                          | 3      | 6                       | 41        |
| 5 d             | 1 3/4          | ...                         | ...    | ...                | ...    | 10             | 142    | 12 d                          | 3 1/4  | 6                       | 38        |
| 6 d             | 2              | 1/4                         | 32     | 3/16               | 62     | 9              | 103    | 16 d                          | 3 1/2  | 5                       | 30        |
| 7 d             | 2 1/4          | ...                         | ...    | ...                | ...    | ...            | ...    | 20 d                          | 4      | 4                       | 23        |
| 8 d             | 2 1/2          | 1/4                         | 26     | 3/16               | 50     | ...            | ...    | 30 d                          | 4 1/2  | 3                       | 17        |
| 9 d             | 2 3/4          | ...                         | ...    | ...                | ...    | ...            | ...    | 40 d                          | 5      | 2                       | 13        |
| 10 d            | 3              | 3/8                         | 14     | 1/4                | 22     | ...            | ...    | 50 d                          | 5 1/2  | 1                       | 10        |
| 12 d            | 3 1/4          | 3/8                         | 13     | 1/4                | 20     | ...            | ...    | 60 d                          | 6      | 1                       | 8         |
| 16 d            | 3 1/2          | 3/8                         | 12     | 1/4                | 18     | ...            | ...    | ...                           | 7      | 0                       | 7         |
| 20 d            | 4              | 3/8                         | 10     | 1/4                | 16     | ...            | ...    | ...                           | 8      | 00                      | 6         |
| 30 d            | 4 1/2          | ...                         | ...    | ...                | ...    | ...            | ...    | ...                           | 9      | 00                      | 5         |
| 40 d            | 5              | ...                         | ...    | ...                | ...    | ...            | ...    | ...                           | 10     | 3/8                     | 4         |
| 50 d            | 5 1/2          | ...                         | ...    | ...                | ...    | ...            | ...    | ...                           | 12     | 3/8                     | 3         |
| 60 d            | 6              | ...                         | ...    | ...                | ...    | ...            | ...    | ...                           | ...    | ...                     | ...       |

ANSI Flat, Pan, and Oval Head Wood Screws ANSI B18.6.1-1981 (R1997)



| Nominal Size | Threads per inch | D <sup>a</sup>      |      | J             |      | A                |                            | B             |      | P           | H              |
|--------------|------------------|---------------------|------|---------------|------|------------------|----------------------------|---------------|------|-------------|----------------|
|              |                  | Basic Dia. of Screw |      | Width of Slot |      | Head Diameter    |                            | Head Diameter |      | Head Radius | Height of Head |
|              |                  | Max.                | Min. | Max.          | Min. | Max., Sharp Edge | Min., Edge Rounded or Flat | Max.          | Min. | Max.        | Ref.           |
| 0            | 32               | .060                | .023 | .016          | .119 | .099             | .116                       | .104          | .020 | .035        |                |
| 1            | 28               | .073                | .026 | .019          | .146 | .123             | .142                       | .130          | .025 | .043        |                |
| 2            | 26               | .086                | .031 | .023          | .172 | .147             | .167                       | .155          | .035 | .051        |                |
| 3            | 24               | .099                | .035 | .027          | .199 | .171             | .193                       | .180          | .037 | .059        |                |
| 4            | 22               | .112                | .039 | .031          | .225 | .195             | .219                       | .205          | .042 | .067        |                |
| 5            | 20               | .125                | .043 | .035          | .252 | .220             | .245                       | .231          | .044 | .075        |                |
| 6            | 18               | .138                | .048 | .039          | .279 | .244             | .270                       | .256          | .046 | .083        |                |
| 7            | 16               | .151                | .048 | .039          | .305 | .268             | .296                       | .281          | .049 | .091        |                |
| 8            | 15               | .164                | .054 | .045          | .332 | .292             | .322                       | .306          | .052 | .100        |                |
| 9            | 14               | .177                | .054 | .045          | .358 | .316             | .348                       | .331          | .056 | .108        |                |
| 10           | 13               | .190                | .060 | .050          | .385 | .340             | .373                       | .357          | .061 | .116        |                |
| 12           | 11               | .216                | .067 | .056          | .438 | .389             | .425                       | .407          | .078 | .132        |                |
| 14           | 10               | .242                | .075 | .064          | .507 | .452             | .492                       | .473          | .087 | .153        |                |
| 16           | 9                | .268                | .075 | .064          | .544 | .485             | .528                       | .508          | .094 | .164        |                |
| 18           | 8                | .294                | .084 | .072          | .635 | .568             | .615                       | .594          | .099 | .191        |                |
| 20           | 8                | .320                | .084 | .072          | .650 | .582             | .631                       | .608          | .121 | .196        |                |
| 24           | 7                | .372                | .094 | .081          | .762 | .685             | .740                       | .716          | .143 | .230        |                |

<sup>a</sup> Diameter Tolerance: Equals + 0.004 in. and - 0.007 in. for cut threads. For rolled thread body diameter tolerances, see ANSI 18.6.1-1981 (R1991).

| Nominal Size | Threads per inch | O                 |      | K              |      | T             |      | U             |      | V             |      |
|--------------|------------------|-------------------|------|----------------|------|---------------|------|---------------|------|---------------|------|
|              |                  | Tot. Hgt. of Head |      | Height of Head |      | Depth of Slot |      | Depth of Slot |      | Depth of Slot |      |
|              |                  | Max.              | Min. | Max.           | Min. | Max.          | Min. | Max.          | Min. | Max.          | Min. |
| 0            | 32               | .056              | .041 | .039           | .031 | .015          | .010 | .022          | .014 | .030          | .025 |
| 1            | 28               | .068              | .052 | .046           | .038 | .019          | .012 | .027          | .018 | .038          | .031 |
| 2            | 26               | .080              | .063 | .053           | .045 | .023          | .015 | .031          | .022 | .045          | .037 |
| 3            | 24               | .092              | .073 | .060           | .051 | .027          | .017 | .035          | .027 | .052          | .043 |
| 4            | 22               | .104              | .084 | .068           | .058 | .030          | .020 | .040          | .030 | .059          | .049 |
| 5            | 20               | .116              | .095 | .075           | .065 | .034          | .022 | .045          | .034 | .067          | .055 |
| 6            | 18               | .128              | .105 | .082           | .072 | .038          | .024 | .050          | .037 | .074          | .060 |
| 7            | 16               | .140              | .116 | .089           | .079 | .041          | .027 | .054          | .041 | .081          | .066 |
| 8            | 15               | .152              | .126 | .096           | .085 | .045          | .029 | .058          | .045 | .088          | .072 |
| 9            | 14               | .164              | .137 | .103           | .092 | .049          | .032 | .063          | .049 | .095          | .078 |
| 10           | 13               | .176              | .148 | .110           | .099 | .053          | .034 | .068          | .053 | .103          | .084 |
| 12           | 11               | .200              | .169 | .125           | .112 | .060          | .039 | .077          | .061 | .117          | .096 |
| 14           | 10               | .232              | .197 | .144           | .130 | .070          | .046 | .087          | .070 | .136          | .112 |
| 16           | 9                | .248              | .212 | .153           | .139 | .075          | .049 | .093          | .074 | .146          | .120 |
| 18           | 8                | .290              | .249 | .178           | .162 | .083          | .054 | .106          | .085 | .171          | .141 |
| 20           | 8                | .296              | .254 | .182           | .166 | .090          | .059 | .108          | .087 | .175          | .144 |
| 24           | 7                | .347              | .300 | .212           | .195 | .106          | .070 | .124          | .100 | .204          | .168 |

All dimensions in inches. The edge of flat and oval head screws may be flat or rounded. Wood screws are also available with Types I, IA, and II recessed heads. Consult the standard for recessed head dimensions. \*The length of the thread,  $L_T$ , on wood screws having cut threads shall be equivalent to approximately two-thirds of the nominal length of the screw. For rolled threads,  $L_T$  shall be at least four times the basic screw diameter or two-thirds of the nominal screw length, whichever is greater. Screws of nominal lengths that are too short to accommodate the minimum thread length shall have threads extending as close to the underside of the head as practicable.

Pilot Hole Drill Sizes for Wood Screws

| Work Material | Wood Screw Size |                |                |                |                |                |                |
|---------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|
|               | 2               | 4              | 6              | 8              | 10             | 12             | 14             |
| Hardwood      | $\frac{3}{64}$  | $\frac{1}{16}$ | $\frac{3}{64}$ | $\frac{3}{32}$ | $\frac{7}{64}$ | $\frac{1}{8}$  | $\frac{9}{64}$ |
| Softwood      | $\frac{1}{32}$  | $\frac{3}{64}$ | $\frac{1}{16}$ | $\frac{3}{64}$ | $\frac{3}{32}$ | $\frac{3}{64}$ | $\frac{1}{8}$  |

## RIVETS AND RIVETED JOINTS

### Riveted Joint Design

**Classes and Types of Riveted Joints.**—Riveted joints may be classified by application as: 1) pressure vessel; 2) structural; and 3) machine member.

For information and data concerning joints for pressure vessels such as boilers, reference should be made to standard sources such as the ASME Boiler Code. The following sections will cover only structural and machine-member riveted joints.

Basically there are two kinds of riveted joints, the *lap-joint* and the *butt-joint*. In the ordinary *lap-joint*, the plates overlap each other and are held together by one or more rows of rivets. In the *butt-joint*, the plates being joined are in the same plane and are joined by means of a cover plate or butt strap, which is riveted to both plates by one or more rows of rivets. The term *single riveting* means one row of rivets in a lap-joint or one row on each side of a butt-joint; *double riveting* means two rows of rivets in a lap-joint or two rows on each side of the joint in butt riveting. Joints are also triple and quadruple riveted. Lap-joints may also be made with inside or outside cover plates. Types of lap and butt joints are illustrated in the tables on starting at page 1482.

**General Design Considerations for Riveted Joints.**—Factors to be considered in the design or specification of a riveted joint are: type of joint; spacing of rivets; type and size of rivet; type and size of hole; and rivet material.

*Spacing of Rivets:* The spacing between rivet centers is called *pitch* and between row center lines, *back pitch* or *transverse pitch*. The distance between centers of rivets nearest each other in adjacent rows is called *diagonal pitch*. The distance from the edge of the plate to the center line of the nearest row of rivets is called *margin*.

Examination of a riveted joint made up of several rows of rivets will reveal that after progressing along the joint a given distance, the rivet pattern or arrangement is repeated. (For a butt joint, the length of a *repeating section* is usually equal to the *long pitch* or pitch of the rivets in the outer row, that is the row farthest from the edge of the joint.) For structural and machine-member joints, the proper pitch may be determined by making the tensile strength of the plate over the length of the repeating section, that is the distance between rivets in the outer row, equal to the total shear strength of the rivets in the repeating section. Minimum pitch and diagonal pitch are also governed by the clearance required for the hold-on (Dolly bar) and rivet set. Dimensions for different sizes of hold-ons and rivet sets are given in the table on page 1487.

When fastening thin plate, it is particularly important to maintain accurate spacing to avoid buckling.

*Size and Type of Rivets:* The rivet diameter  $d$  commonly falls between  $d = 1.2\sqrt{t}$  and  $d = 1.4\sqrt{t}$ , where  $t$  is the thickness of the plate. Dimensions for various types of American Standard large ( $\frac{1}{2}$ -inch diameter and up) rivets and small solid rivets are shown in tables that follow. It may be noted that countersunk heads are not as strong as other types.

*Size and Type of Hole:* Rivet holes may be punched, punched and reamed, or drilled. Rivet holes are usually made  $\frac{1}{16}$  inch larger in diameter than the nominal diameter of the rivet although in some classes of work in which the rivet is driven cold, as in automatic machine riveting, the holes are reamed to provide minimum clearance so that the rivet fills the hole completely.

When holes are punched in heavy steel plate, there may be considerable loss of strength unless the holes are reamed to remove the inferior metal immediately surrounding them. This results in the diameter of the punched hole being increased by from  $\frac{1}{16}$  to  $\frac{1}{8}$  inch. Annealing after punching tends to restore the strength of the plate in the vicinity of the holes.

**Rivet Material:** Rivets for structural and machine-member purposes are usually made of wrought iron or soft steel, but for aircraft and other applications where light weight or resistance to corrosion is important, copper, aluminum alloy, Monel, Inconel, etc., may be used as rivet material.

**Simplified Design Assumptions:** In the design of riveted joints, a simplified treatment is frequently used in which the following assumptions are made:

- 1) The load is carried equally by the rivets.
- 2) No combined stresses act on a rivet to cause failure.
- 3) The shearing stress in a rivet is uniform across the cross-section under question.
- 4) The load that would cause failure in single shear would have to be doubled to cause failure in double shear.
- 5) The bearing stress of rivet and plate is distributed equally over the projected area of the rivet.
- 6) The tensile stress is uniform in the section of metal between the rivets.

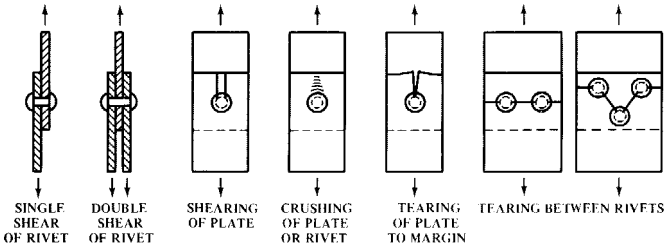
**Failure of Riveted Joints.**—Rivets may fail by:

- 1) Shearing through one cross-section (single shear)
- 2) Shearing through two cross-sections (double shear)
- 3) Crushing

Plates may fail by:

- 4) Shearing along two parallel lines extending from opposite sides of the rivet hole to the edge of the plate
- 5) Tearing along a single line from middle of rivet hole to edge of plate
- 6) Crushing
- 7) Tearing between adjacent rivets (tensile failure) in the same row or in adjacent rows

Types 4 and 5 failures are caused by rivets being placed too close to the edge of the plate. These types of failure are avoided by placing the center of the rivet at a minimum of one and one-half times the rivet diameter away from the edge.



Types of Rivet and Plate Failure

Failure due to tearing on a diagonal between rivets in adjacent rows when the pitch is four times the rivet diameter or less is avoided by making the transverse pitch one and three-quarters times the rivet diameter.

**Theoretical versus Actual Riveted Joint Failure:** If it is assumed that the rivets are placed the suggested distance from the edge of the plate and each row the suggested distance from another row, then the failure of a joint is most likely to occur as a result of shear failure of the rivets, bearing failure (crushing) of the plate or rivets, or tensile failure of the plate, alone or in combination depending on the makeup of the joints.

Joint failure in actuality is more complex than this. Rivets do not undergo pure shear especially in lap-joints where rivets are subjected to single shear. The rivet, in this instance, would be subject to a combination of tensile and shearing stresses and it would fail because

of combined stresses, not a single stress. Furthermore, the shearing stress is usually considered to be distributed evenly over the cross-section, which is also not the case.

Rivets that are usually driven hot contract on cooling. This contraction in the length of the rivet draws the plates together and sets up a stress in the rivet estimated to be equal in magnitude to the yield point of the rivet steel. The contraction in the diameter of the rivet results in a little clearance between the rivet and the hole in the plate. The tightness in the plates caused by the contraction in length of the rivet gives rise to a condition in which quite a sizeable frictional force would have to be overcome before the plates would slip over one another and subject the rivets to a shearing force. It is European practice to design joints for resistance to this slipping. It has been found, however, that the strength-basis designs obtained in American and English practice are not very different from European designs.

**Allowable Stresses.**—The design stresses for riveted joints are usually set by codes, practices, or specifications. The American Institute of Steel Construction issues specifications for the design, fabrication, and erection of structural steel for buildings in which the allowable stress permitted in tension for structural steel and rivets is specified at 20,000 pounds per square inch, the allowable bearing stress for rivets is 40,000 psi in double shear and 32,000 psi in single shear, and the allowable shearing stress for rivets is 15,000 psi. The American Society of Mechanical Engineers in its Boiler Code lists the following ultimate stresses: tensile, 55,000 psi; shearing, 44,000 psi; compressive or bearing, 95,000 psi. The design stresses usually are one-fifth of these, that is tensile, 11,000 psi; shearing, 8800 psi; compressive or bearing, 19,000 psi. In machine design work, values close to these or somewhat lower are commonly used.

**Analysis of Joint Strength.**—The following examples and strength analyses of riveted joints are based on the six previously outlined *Simplified Design Assumptions*.

*Example 1:* Consider a 12-inch section of single-riveted lap-joint made up with plates of  $\frac{1}{4}$ -inch thickness and six rivets,  $\frac{5}{8}$  inch in diameter. Assume that rivet holes are  $\frac{1}{16}$  inch larger in diameter than the rivets. In this joint, the entire load is transmitted from one plate to the other by means of the rivets. Each plate and the six rivets carry the entire load. The safe tensile load  $L$  and the efficiency  $\eta$  may be determined in the following way: Design stresses of 8500 psi for shear, 20,000 psi for bearing, and 10,000 psi for tension are arbitrarily assigned and it is assumed that the rivets will not tear or shear through the plate to the edge of the joint.

a) The safe tensile load  $L$  based on single shear of the rivets is equal to the number of rivets  $n$  times the cross-sectional area of one rivet  $A_r$  times the allowable shearing stress  $S_s$  or

$$L = n \times A_r \times S_s = 6 \times \frac{\pi}{4} (0.625)^2 \times 8500 = 15,647 \text{ pounds}$$

b) The safe tensile load  $L$  based on bearing stress is equal to the number of rivets  $n$  times the projected bearing area of the rivet  $A_b$  (diameter times thickness of plate) times the allowable bearing stress  $S_c$  or  $L = n \times A_b \times S_c = 6 \times (0.625 \times 0.25) \times 20,000 = 18,750$  pounds.

c) The safe load  $L$  based on the tensile stress is equal to the net cross-sectional area of the plate between rivet holes  $A_p$  times the allowable tensile stress  $S_t$  or

$$L = A_p \times S_t = 0.25[12 - 6(0.625 + 0.0625)] \times 10,000 = 19,688 \text{ pounds.}$$

The safe tensile load for the joint would be the least of the three loads just computed or 15,647 pounds and the efficiency  $\eta$  would be equal to this load divided by the tensile strength of the section of plate under consideration, if it were unperforated or

$$\eta = \frac{15,647}{12 \times 0.25 \times 10,000} \times 100 = 52.2 \text{ per cent}$$

*Example 2:* Under consideration is a 12-inch section of double-riveted butt-joint with main plates  $\frac{1}{2}$  inch thick and two cover plates each  $\frac{5}{16}$  inch thick. There are 3 rivets in the inner row and 2 on the outer and their diameters are  $\frac{7}{8}$  inch. Assume that the diameter of the

rivet holes is  $\frac{1}{16}$  inch larger than that of the rivets. The rivets are so placed that the main plates will not tear diagonally from one rivet row to the others nor will they tear or fail in shear out to their edges. The safe tensile load  $L$  and the efficiency  $\eta$  may be determined in the following way: Design stresses for 8500 psi for shear, 20,000 psi for bearing, and 10,000 psi for tension are arbitrarily assigned.

a) The safe tensile load  $L$  based on double shearing of the rivets is equal to the number of rivets  $n$  times the number of shearing planes per rivet times the cross-sectional area of one rivet  $A_r$  times the allowable shearing stress  $S_s$  or

$$L = n \times 2 \times A_r \times S_s = 5 \times 2 \times \frac{\pi}{4}(0.875)^2 \times 8500 = 51,112 \text{ pounds}$$

b) The safe tensile load  $L$  based on bearing stress is equal to the number of rivets  $n$  times the projected bearing area of the rivet  $A_b$  (diameter times thickness of plate) times the allowable bearing stress  $S_c$  or  $L = n \times A_b \times S_c = 5 \times (0.875 \times 0.5) \times 20,000 = 43,750$  pounds.

(Cover plates are not considered since their combined thickness is  $\frac{1}{4}$  inch greater than the main plate thickness.)

c) The safe tensile load  $L$  based on the tensile stress is equal to the net cross-sectional area of the plate between the two rivets in the outer row  $A_p$  times the allowable tensile stress  $S_t$  or  $L = A_p \times S_t = 0.5[12 - 2(0.875 + 0.0625)] \times 10,000 = 50,625$  pounds.

In completing the analysis, the sum of the load that would cause tearing between rivets in the three-hole section plus the load carried by the two rivets in the two-hole section is also investigated. The sum is necessary because if the joint is to fail, it must fail at both sections simultaneously. The least safe load that can be carried by the two rivets of the two-hole section is based on the bearing stress (see the foregoing calculations).

1) The safe tensile load  $L$  based on the bearing strength of two rivets of the two-hole section is  $L = n \times A_b \times S_c = 2 \times (0.875 \times 0.5) \times 20,000 = 17,500$  pounds.

2) The safe tensile load  $L$  based on the tensile strength of the main plate between holes in the three-hole section is  $L \times A_p \times S_t = 0.5[12 - 3(0.875 + 0.0625)] \times 10,000 = 45,938$  pounds.

The total safe tensile load based on this combination is  $17,500 + 45,938 = 63,438$  pounds, which is greater than any of the other results obtained.

The safe tensile load for the joint would be the least of the loads just computed or 43,750 pounds and the efficiency  $\eta$  would be equal to this load divided by the tensile strength of the section of plate under consideration, if it were unperforated or

$$\eta = \frac{43,750}{0.5 \times 12 \times 10,000} \times 100 = 72.9 \text{ per cent}$$

**Formulas for Riveted Joint Design.**—A riveted joint may fail by shearing through the rivets (single or double shear), crushing the rivets, tearing the plate between the rivets, crushing the plate or by a combination of two or more of the foregoing causes. Rivets placed too close to the edge of the plate may tear or shear the plate out to the edge but this type of failure is avoided by placing the center of the rivet 1.5 times the rivet diameter away from the edge.

The efficiency of a riveted joint is equal to the strength of the joint divided by the strength of the unriveted plate, expressed as a percentage.

In the following formulas, let

$d$  = diameter of holes     $t$  = thickness of plate     $t_c$  = thickness of cover plates

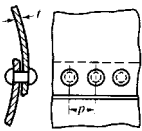
$p$  = pitch of inner row of rivets     $P$  = pitch of outer row of rivets

$S_s$  = shear stress for rivets     $S_t$  = tensile stress for plates

$S_c$  = compressive or bearing stress for rivets or plates

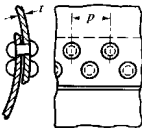
In the joint examples that follow, dimensions are usually specified in inches and stresses in pounds per square inch. See page 1480 for a discussion of allowable stresses that may be used in calculating the strengths given by the formulas. The design stresses are usually set by codes, practices, or specifications.

*Single-Riveted Lap-Joint*



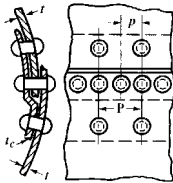
- (1) Resistance to shearing one rivet =  $\frac{\pi d^2}{4} S_s$
- (2) Resistance to tearing plate between rivets =  $(p - D)tS_t$
- (3) Resistance to crushing rivet or plate =  $dtS_c$

*Double-Riveted Lap-Joint*



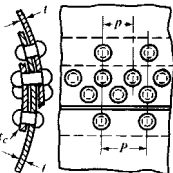
- (1) Resistance to shearing two rivets =  $\frac{2\pi d^2}{4} S_s$
- (2) Resistance to tearing between two rivets =  $(p - D)tS_t$
- (3) Resistance to crushing in front of two rivets =  $2dtS_c$

*Single-Riveted Lap-Joint with Inside Cover Plate*

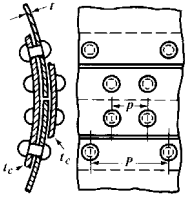


- (1) Resistance to tearing between outer row of rivets =  $(P - D)tS_t$
- (2) Resistance to tearing between inner row of rivets, and shearing outer row of rivets =  $(P - 2D)tS_t + \frac{\pi d^2}{4} S_s$
- (3) Resistance to shearing three rivets =  $\frac{3\pi d^2}{4} S_s$
- (4) Resistance to crushing in front of three rivets =  $3tS_c$
- (5) Resistance to tearing at inner row of rivets, and crushing in front of one rivet in outer row =  $(P - 2D)tS_t + tS_c$

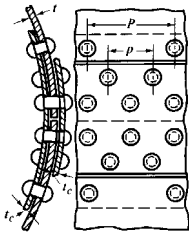
*Double-Riveted Lap-Joint with Inside Cover Plate*



- (1) Resistance to tearing at outer row of rivets =  $(P - D)tS_t$
- (2) Resistance to shearing four rivets =  $\frac{4\pi d^2}{4} S_s$
- (3) Resistance to tearing at inner row and shearing outer row of rivets =  $(P - 1\frac{1}{2}D)tS_t + \frac{\pi d^2}{4} S_s$
- (4) Resistance to crushing in front of four rivets =  $4tS_c$
- (5) Resistance to tearing at inner row of rivets, and crushing in front of one rivet =  $(P - 1\frac{1}{2}D)tS_t + tS_c$

*Double-Riveted Butt-Joint*

- (1) Resistance to tearing at outer row of rivets =  $(P - D)tS_t$
- (2) Resistance to shearing two rivets in double shear and one in single shear =  $\frac{5\pi d^2}{4} S_s$
- (3) Resistance to tearing at inner row of rivets and shearing one rivet of the outer row =  $(P - 2D)tS_t + \frac{\pi d^2}{4} S_s$
- (4) Resistance to crushing in front of three rivets =  $3tdS_c$
- (5) Resistance to tearing at inner row of rivets, and crushing in front of one rivet in outer row =  $(P - 2D)tS_t + tdS_c$

*Triple-Riveted Butt-Joint*

- (1) Resistance to tearing at outer row of rivets =  $(P - D)tS_t$
- (2) Resistance to shearing four rivets in double shear and one in single shear =  $\frac{9\pi d^2}{4} S_s$
- (3) Resistance to tearing at middle row of rivets and shearing one rivet =  $(P - 2D)tS_t + \frac{\pi d^2}{4} S_s$
- (4) Resistance to crushing in front of four rivets and shearing one rivet =  $4dtS_c + \frac{\pi d^2}{4} S_s$
- (5) Resistance to crushing in front of five rivets =  $4dtS_c + dt_c S_c$

**American National Standard Rivets**

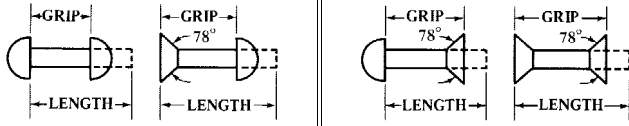
Standards for rivets published by the American National Standards Institute and the British Standards Institution are as follows:

**American National Standard Large Rivets.**—The types of rivets covered by this standard (ANSI B18.1.2-1972 (R1995)) are shown on pages 1485, 1486, and 1487. It may be noted, however, that when specified, the swell neck included in this standard is applicable to all standard large rivets except the flat countersunk head and oval countersunk head types. Also shown are the hold-on (dolly bar) and rivet set impression dimensions (see page 1487). All standard large rivets have fillets under the head not exceeding an 0.062-inch radius. The length tolerances for these rivets are given as follows: through 6 inches in length,  $\frac{1}{2}$ - and  $\frac{5}{8}$ -inch diameters,  $\pm 0.03$  inch;  $\frac{3}{4}$ - and  $\frac{7}{8}$ -inch diameters,  $\pm 0.06$ -inch; and 1-through  $1\frac{3}{4}$ -inch diameters,  $\pm 0.09$  inch. For rivets over 6 inches in length,  $\frac{1}{2}$ - and  $\frac{5}{8}$ -inch diameters,  $\pm 0.06$  inch;  $\frac{3}{4}$ - and  $\frac{7}{8}$ -inch diameters,  $\pm 0.12$  inch; and 1- through  $1\frac{3}{4}$ -inch diameters,  $\pm 0.19$  inch. Steel and wrought iron rivet materials appear in ASTM Specifications A31, A131, A152, and A502.

**American National Standard Small Solid Rivets.**—The types of rivets covered by this standard (ANSI/ASME B18.1.1-1972 (R1995)) are shown on pages 1488 through 1490. In addition, the standard gives the dimensions of 60-degree flat countersunk head rivets used to assemble ledger plates and guards for mower cutter bars, but these are not shown. As the heads of standard rivets are not machined or trimmed, the circumference may be somewhat irregular and edges may be rounded or flat. Rivets other than countersunk types are furnished with a definite fillet under the head, whose radius should not exceed 10 per cent of the maximum shank diameter or 0.03 inch, whichever is the smaller. With regard to head dimensions, tolerances shown in the dimensional tables are applicable to rivets pro-



**Rivet Lengths for Forming Round and Countersunk Heads<sup>a</sup>**

|  |                             |       |       |       |       |       |       |       |                           |                             |       |       |       |       |       |       |  |
|---|-----------------------------|-------|-------|-------|-------|-------|-------|-------|---------------------------|-----------------------------|-------|-------|-------|-------|-------|-------|--|
| Grip in Inches  | To Form Round Head          |       |       |       |       |       |       |       | Grip in Inches            | To Form Countersunk Head    |       |       |       |       |       |       |  |
|   | Diameter of Rivet in Inches |       |       |       |       |       |       |       |                           | Diameter of Rivet in Inches |       |       |       |       |       |       |  |
|   | 1/2                         | 5/8   | 3/4   | 7/8   | 1     | 1 1/8 | 1 1/4 | 1 1/2 |                           | 1/2                         | 5/8   | 3/4   | 7/8   | 1     | 1 1/8 | 1 1/4 |  |
| Length of Rivet in Inches   |                             |       |       |       |       |       |       |       | Length of Rivet in Inches |                             |       |       |       |       |       |       |  |
| 1/2   | 1 1/8                       | 1 7/8 | 1 7/8 | 2     | 2 1/8 | ...   | ...   | ...   | 1/2                       | 1                           | 1     | 1 1/8 | 1 1/4 | 1 1/4 | ...   | ...   |  |
| 5/8   | 1 3/4                       | 2     | 2     | 2 1/8 | 2 1/4 | ...   | ...   | ...   | 5/8                       | 1 1/8                       | 1 1/4 | 1 1/4 | 1 3/8 | 1 3/8 | ...   | ...   |  |
| 3/4   | 1 7/8                       | 2 1/8 | 2 1/8 | 2 1/4 | 2 3/8 | ...   | ...   | ...   | 3/4                       | 1 3/8                       | 1 3/8 | 1 3/8 | 1 1/2 | 1 1/2 | ...   | ...   |  |
| 7/8   | 2                           | 2 1/4 | 2 1/4 | 2 1/2 | 2 1/2 | ...   | ...   | ...   | 7/8                       | 1 1/2                       | 1 1/2 | 1 1/2 | 1 5/8 | 1 5/8 | ...   | ...   |  |
| 1   | 2 1/4                       | 2 3/8 | 2 3/8 | 2 1/2 | 2 5/8 | 2 1/2 | 2 1/2 | 2 1/2 | 1                         | 1 1/8                       | 1 1/8 | 1 1/8 | 1 3/4 | 1 3/4 | 1 7/8 | 1 7/8 |  |
| 1 1/8   | 2 3/8                       | 2 1/2 | 2 1/2 | 2 5/8 | 2 3/4 | 2 7/8 | 3     | 3     | 1 1/8                     | 1 3/4                       | 1 3/4 | 1 7/8 | 1 7/8 | 1 7/8 | 2     | 2     |  |
| 1 1/4   | 2 1/2                       | 2 5/8 | 2 5/8 | 2 3/4 | 2 7/8 | 3     | 3 1/2 | 3 1/2 | 1 1/4                     | 2                           | 2     | 2     | 2     | 2     | 2 1/8 | 2 1/8 |  |
| 1 3/8   | 2 5/8                       | 2 3/4 | 2 3/4 | 2 7/8 | 3     | 3 1/8 | 3 1/2 | 3 1/2 | 1 3/8                     | 2 1/8                       | 2 1/8 | 2 1/8 | 2 1/4 | 2 1/4 | 2 3/8 | 2 3/8 |  |
| 1 1/2   | 2 7/8                       | 3     | 3     | 3 1/8 | 3 1/4 | 3 3/8 | 3 1/2 | 3 1/2 | 1 1/2                     | 2 1/4                       | 2 1/4 | 2 1/4 | 2 5/8 | 2 5/8 | 2 1/2 | 2 1/2 |  |
| 1 5/8   | 3                           | 3 1/8 | 3 1/8 | 3 1/4 | 3 3/8 | 3 1/2 | 3 1/2 | 3 1/2 | 1 5/8                     | 2 3/8                       | 2 3/8 | 2 3/8 | 2 1/2 | 2 1/2 | 2 5/8 | 2 5/8 |  |
| 1 3/4   | 3 1/8                       | 3 1/4 | 3 1/4 | 3 1/2 | 3 3/8 | 3 3/4 | 3 3/4 | 3 3/4 | 1 3/4                     | 2 5/8                       | 2 5/8 | 2 5/8 | 2 5/8 | 2 5/8 | 2 3/4 | 2 3/4 |  |
| 1 7/8   | 3 1/4                       | 3 3/8 | 3 3/8 | 3 3/8 | 3 3/4 | 3 7/8 | 3 7/8 | 3 7/8 | 1 7/8                     | 2 3/4                       | 2 3/4 | 2 3/4 | 2 3/4 | 2 3/4 | 2 7/8 | 2 7/8 |  |
| 2   | 3 1/2                       | 3 1/2 | 3 3/8 | 3 3/4 | 3 7/8 | 4     | 4     | 4     | 2                         | 2 7/8                       | 2 7/8 | 2 7/8 | 2 7/8 | 2 7/8 | 3     | 3     |  |
| 2 1/8   | 3 3/8                       | 3 3/8 | 3 3/4 | 3 7/8 | 4     | 4 1/8 | 4 1/8 | 4 1/8 | 2 1/8                     | 3 3/8                       | 3     | 3     | 3     | 3     | 3 3/8 | 3 3/8 |  |
| 2 1/4   | 3 3/4                       | 3 3/8 | 3 3/8 | 4     | 4 1/8 | 4 1/4 | 4 1/4 | 4 1/4 | 2 1/4                     | 3 1/4                       | 3 3/8 | 3 3/8 | 3 3/8 | 3 3/4 | 3 3/4 | 3 3/4 |  |
| 2 3/8   | 4                           | 4     | 4     | 4 1/8 | 4 1/4 | 4 3/8 | 4 3/8 | 4 3/8 | 2 3/8                     | 3 3/8                       | 3 3/8 | 3 3/8 | 3 3/8 | 3 3/8 | 3 3/8 | 3 3/8 |  |
| 2 1/2   | 4 1/8                       | 4 1/8 | 4 1/4 | 4 1/4 | 4 3/8 | 4 1/2 | 4 1/2 | 4 1/2 | 2 1/2                     | 3 1/2                       | 3 1/2 | 3 1/2 | 3 1/2 | 3 1/2 | 3 3/8 | 3 3/8 |  |
| 2 5/8   | 4 1/4                       | 4 1/4 | 4 1/4 | 4 3/8 | 4 1/2 | 4 5/8 | 4 5/8 | 4 5/8 | 2 5/8                     | 3 3/4                       | 3 3/8 | 3 3/8 | 3 3/8 | 3 3/8 | 3 3/4 | 3 3/4 |  |
| 2 3/4   | 4 3/8                       | 4 3/8 | 4 3/8 | 4 1/2 | 4 3/4 | 4 3/4 | 4 3/4 | 4 3/4 | 2 3/4                     | 3 3/4                       | 3 3/4 | 3 3/4 | 3 3/4 | 3 3/4 | 3 3/4 | 3 3/4 |  |
| 2 7/8   | 4 3/8                       | 4 3/8 | 4 3/8 | 4 3/4 | 4 3/4 | 4 7/8 | 5     | 5     | 2 7/8                     | 4                           | 3 7/8 | 3 7/8 | 3 7/8 | 3 7/8 | 4     | 4     |  |
| 3   | ...                         | 4 3/4 | 4 3/4 | 4 7/8 | 5     | 5     | 5     | 5     | 3                         | ...                         | 4 1/4 | 4 1/4 | 4 1/4 | 4 1/4 | 4 1/4 | 4 1/4 |  |
| 3 1/8   | ...                         | 4 7/8 | 4 7/8 | 5     | 5 1/8 | 5 1/4 | 5 1/4 | 5 1/4 | 3 1/8                     | ...                         | 4 1/4 | 4 1/4 | 4 1/4 | 4 1/4 | 4 1/4 | 4 1/4 |  |
| 3 1/4   | ...                         | 5     | 5     | 5 1/8 | 5 1/4 | 5 3/8 | 5 3/8 | 5 3/8 | 3 1/4                     | ...                         | 4 3/8 | 4 3/8 | 4 3/8 | 4 3/8 | 4 3/8 | 4 3/8 |  |
| 3 3/8   | ...                         | 5 1/8 | 5 1/8 | 5 1/4 | 5 3/8 | 5 1/2 | 5 1/2 | 5 1/2 | 3 3/8                     | ...                         | 4 1/2 | 4 1/2 | 4 1/2 | 4 1/2 | 4 1/2 | 4 1/2 |  |
| 3 1/2   | ...                         | 5 3/8 | 5 3/8 | 5 3/8 | 5 1/2 | 5 5/8 | 5 5/8 | 5 5/8 | 3 1/2                     | ...                         | 4 3/4 | 4 3/4 | 4 3/4 | 4 3/4 | 4 3/4 | 4 3/4 |  |
| 3 5/8   | ...                         | 5 1/2 | 5 1/2 | 5 1/2 | 5 5/8 | 5 3/4 | 5 3/4 | 5 3/4 | 3 5/8                     | ...                         | 4 3/4 | 4 3/4 | 4 3/4 | 4 3/4 | 4 3/8 | 4 3/8 |  |
| 3 3/4   | ...                         | 5 5/8 | 5 5/8 | 5 5/8 | 5 3/4 | 5 5/8 | 5 5/8 | 5 5/8 | 3 3/4                     | ...                         | 5     | 5     | 5     | 5     | 5     | 5     |  |
| 3 7/8   | ...                         | 5 3/4 | 5 3/4 | 5 3/4 | 5 5/8 | 5 7/8 | 6     | 6     | 3 7/8                     | ...                         | 5 1/8 | 5 1/8 | 5 1/8 | 5 1/8 | 5 1/8 | 5 1/8 |  |
| 4   | ...                         | ...   | 5 7/8 | 6     | 6     | 6 1/8 | 6 1/4 | 6 1/4 | 4                         | ...                         | ...   | 5 1/4 | 5 1/4 | 5 1/4 | 5 1/4 | 5 1/4 |  |
| 4 1/8   | ...                         | ...   | 6     | 6 1/8 | 6 1/4 | 6 3/8 | 6 3/8 | 6 3/8 | 4 1/8                     | ...                         | ...   | 5 3/8 | 5 3/8 | 5 3/8 | 5 3/8 | 5 3/8 |  |
| 4 1/4   | ...                         | ...   | 6 1/8 | 6 1/4 | 6 1/2 | 6 1/2 | 6 1/2 | 6 1/2 | 4 1/4                     | ...                         | ...   | 5 1/2 | 5 1/2 | 5 1/2 | 5 1/2 | 5 1/2 |  |
| 4 3/8   | ...                         | ...   | 6 3/8 | 6 1/2 | 6 1/2 | 6 3/8 | 6 3/8 | 6 3/8 | 4 3/8                     | ...                         | ...   | 5 5/8 | 5 5/8 | 5 5/8 | 5 5/8 | 5 5/8 |  |
| 4 1/2   | ...                         | ...   | 6 1/2 | 6 3/8 | 6 3/8 | 6 3/4 | 6 3/4 | 6 3/4 | 4 1/2                     | ...                         | ...   | 5 3/4 | 5 3/4 | 5 3/4 | 5 3/4 | 5 3/4 |  |
| 4 5/8   | ...                         | ...   | 6 5/8 | 6 3/4 | 6 3/4 | 6 3/4 | 6 7/8 | 6 7/8 | 4 5/8                     | ...                         | ...   | 6     | 6     | 6     | 6     | 6     |  |
| 4 3/4   | ...                         | ...   | 6 3/4 | 6 7/8 | 6 7/8 | 7     | 7     | 7     | 4 3/4                     | ...                         | ...   | 6 1/8 | 6 1/8 | 6 1/8 | 6 1/8 | 6 1/8 |  |
| 4 7/8   | ...                         | ...   | 6 7/8 | 7     | 7     | 7 1/8 | 7 1/8 | 7 1/8 | 4 7/8                     | ...                         | ...   | 6 1/4 | 6 1/4 | 6 1/4 | 6 1/4 | 6 1/4 |  |
| 5   | ...                         | ...   | ...   | 7 1/8 | 7 1/8 | 7 1/4 | 7 1/4 | 7 1/4 | 5                         | ...                         | ...   | ...   | 6 3/8 | 6 3/8 | 6 3/8 | 6 3/8 |  |
| 5 1/8   | ...                         | ...   | ...   | 7 1/4 | 7 1/4 | 7 3/8 | 7 3/8 | 7 3/8 | 5 1/8                     | ...                         | ...   | ...   | 6 1/2 | 6 1/2 | 6 1/2 | 6 1/2 |  |
| 5 1/4   | ...                         | ...   | ...   | 7 3/8 | 7 3/8 | 7 1/2 | 7 1/2 | 7 1/2 | 5 1/4                     | ...                         | ...   | ...   | 6 5/8 | 6 5/8 | 6 5/8 | 6 5/8 |  |
| 5 3/8   | ...                         | ...   | ...   | 7 5/8 | 7 5/8 | 7 3/4 | 7 3/4 | 7 3/4 | 5 3/8                     | ...                         | ...   | ...   | 6 3/4 | 6 3/4 | 6 3/4 | 6 3/4 |  |
| 5 1/2   | ...                         | ...   | ...   | 7 3/4 | 7 3/4 | 7 7/8 | 7 7/8 | 7 7/8 | 5 1/2                     | ...                         | ...   | ...   | 6 7/8 | 6 7/8 | 6 7/8 | 6 7/8 |  |
| 5 5/8   | ...                         | ...   | ...   | 7 7/8 | 7 7/8 | 8     | 8     | 8     | 5 5/8                     | ...                         | ...   | ...   | 7     | 7     | 7     | 7     |  |
| 5 3/4   | ...                         | ...   | ...   | 8     | 8     | 8 1/8 | 8 1/8 | 8 1/8 | 5 3/4                     | ...                         | ...   | ...   | 7 1/4 | 7 1/4 | 7 1/4 | 7 1/4 |  |
| 5 7/8   | ...                         | ...   | ...   | 8 1/8 | 8 1/8 | 8 1/4 | 8 1/4 | 8 1/4 | 5 7/8                     | ...                         | ...   | ...   | 7 3/8 | 7 3/8 | 7 3/8 | 7 3/8 |  |

<sup>a</sup> As given by the American Institute of Steel Construction. Values may vary from standard practice of individual fabricators and should be checked against the fabricator's standard.

**Table 1a. American National Standard Large Rivets ANSI B18.1.2-1972 (R1995)**

| Flat Countersunk Head                  |       | Oval Countersunk Head |                       |                   |                           |  |  |
|--|-------|-----------------------|-----------------------|-------------------|---------------------------|--|--|
| Flat and Oval Countersunk Head         |       |                       |                       |                   |                           |  |  |
| Body Diameter <sup>a</sup><br><i>D</i> |       |                       | Head Dia.<br><i>A</i> |                   | Head<br>Depth<br><i>H</i> | Oval<br>Crown<br>Height <sup>a</sup><br><i>C</i> | Oval<br>Crown<br>Radius <sup>a</sup><br><i>G</i> |
| Nominal <sup>a</sup>                   | Max.  | Min.                  | Max. <sup>b</sup>     | Min. <sup>c</sup> | Ref.                      |  |  |
| 1/2                                    | 0.500 | 0.520                 | 0.478                 | 0.936             | 0.872                     | 0.260  | 1.125  |
| 3/8                                    | 0.625 | 0.655                 | 0.600                 | 1.194             | 1.112                     | 0.339  | 1.406  |
| 3/4                                    | 0.750 | 0.780                 | 0.725                 | 1.421             | 1.322                     | 0.400  | 1.688  |
| 7/8                                    | 0.875 | 0.905                 | 0.850                 | 1.647             | 1.532                     | 0.460  | 1.969  |
| 1                                      | 1.000 | 1.030                 | 0.975                 | 1.873             | 1.745                     | 0.520  | 2.250  |
| 1 1/8                                  | 1.125 | 1.160                 | 1.098                 | 2.114             | 1.973                     | 0.589  | 2.531  |
| 1 1/4                                  | 1.250 | 1.285                 | 1.223                 | 2.340             | 2.199                     | 0.650  | 2.812  |
| 1 3/8                                  | 1.375 | 1.415                 | 1.345                 | 2.567             | 2.426                     | 0.710  | 3.094  |
| 1 1/2                                  | 1.500 | 1.540                 | 1.470                 | 2.793             | 2.652                     | 0.771  | 3.375  |
| 1 5/8                                  | 1.625 | 1.665                 | 1.588                 | 3.019             | 2.878                     | 0.831  | 3.656  |
| 1 3/4                                  | 1.750 | 1.790                 | 1.713                 | 3.262             | 3.121                     | 0.901  | 3.938  |

<sup>a</sup> All dimensions are given in inches. Basic dimension as manufactured. For tolerances see table footnote on page 1483. The following formulas give basic dimensions for manufactured shapes: *Flat Countersunk Head*,  $A = 1.810D$ ;  $H = 1.192(\text{Max } A - D)/2$ ; included angle  $Q$  of head = 78 degrees. *Oval Countersunk Head*,  $A = 1.810D$ ;  $H = 1.192(\text{Max } A - D)/2$ ; included angle of head = 78 degrees. Length  $L$  is measured parallel to the rivet axis, from the extreme end to the intersection of the head top surface with the head diameter for countersunk head-type rivets.

<sup>b</sup> Sharp edged head.

<sup>c</sup> Rounded or flat edged irregularly shaped head (heads are not machined or trimmed).

duced by the normal cold heading process. Unless otherwise specified, rivets should have plain sheared ends that should be at right angles within 2 degrees to the axis of the rivet and be reasonably flat. When so specified by the user, rivets may have the standard header points shown on page 1485. Rivets may be made of ASTM Specification A31, Grade A steel; or may adhere to SAE Recommended Practice, Mechanical and Chemical Requirements for Nonthreaded Fasteners—SAE J430, Grade 0. When specified, rivets may be made of other materials.

ANSI/ASME B18.1.3M-1983 (R1995), Metric Small Solid Rivets, provides data for small, solid rivets with flat, round, and flat countersunk heads in metric dimensions. The main series of rivets has body diameters, in millimeters, of 1.6, 2, 2.5, 3, 4, 5, 6, 8, 10, and 12. A secondary series (nonpreferred) consists of sizes, 1, 1.2, 1.4, 3.5, 7, 9, and 11 millimeters.

### British Standard Rivets

**British Standard Rivets for General Engineering.**—Dimensions in metric units of rivets for general engineering purposes are given in this British Standard, BS 4620:1970, which is based on ISO Recommendation ISO/R 1051. The snap head rivet dimensions of 14 millimeters and above are taken from the German Standard DIN 124, Round Head Rivets for Steel Structures. The shapes of heads have been restricted to those in common use in

**Table 1b. American National Standard Large Rivets—ANSI B18.1.2-1972 (R1995)**

| Nom. Body Dia. $D^a$ | Head Dia. $A$     |                     | Height $H$        |                     | Head Dia. $A$                   |                     | Height $H$          |                       |  |
|----------------------|-------------------|---------------------|-------------------|---------------------|---------------------------------|---------------------|---------------------|-----------------------|--|
|                      | Mfd. <sup>b</sup> | Driven <sup>c</sup> | Mfd. <sup>b</sup> | Driven <sup>c</sup> | Mfd. <sup>b</sup>               | Driven <sup>c</sup> | Mfd. <sup>b,d</sup> | Driven <sup>c,d</sup> |  |
| <b>Button Head</b>   |                   |                     |                   |                     | <b>High Button Head (Acorn)</b> |                     |                     |                       |  |
| $\frac{1}{2}$        | 0.875             | 0.922               | 0.375             | 0.344               | 0.781                           | 0.875               | 0.500               | 0.375                 |  |
| $\frac{5}{8}$        | 1.094             | 1.141               | 0.469             | 0.438               | 0.969                           | 1.062               | 0.594               | 0.453                 |  |
| $\frac{3}{4}$        | 1.312             | 1.375               | 0.562             | 0.516               | 1.156                           | 1.250               | 0.688               | 0.531                 |  |
| $\frac{7}{8}$        | 1.531             | 1.594               | 0.656             | 0.609               | 1.344                           | 1.438               | 0.781               | 0.609                 |  |
| 1                    | 1.750             | 1.828               | 0.750             | 0.688               | 1.531                           | 1.625               | 0.875               | 0.688                 |  |
| $1\frac{1}{8}$       | 1.969             | 2.062               | 0.844             | 0.781               | 1.719                           | 1.812               | 0.969               | 0.766                 |  |
| $1\frac{1}{4}$       | 2.188             | 2.281               | 0.938             | 0.859               | 1.906                           | 2.000               | 1.062               | 0.844                 |  |
| $1\frac{3}{8}$       | 2.406             | 2.516               | 1.031             | 0.953               | 2.094                           | 2.188               | 1.156               | 0.938                 |  |
| $1\frac{1}{2}$       | 2.625             | 2.734               | 1.125             | 1.031               | 2.281                           | 2.375               | 1.250               | 1.000                 |  |
| $1\frac{5}{8}$       | 2.844             | 2.969               | 1.219             | 1.125               | 2.469                           | 2.562               | 1.344               | 1.094                 |  |
| $1\frac{3}{4}$       | 3.062             | 3.203               | 1.312             | 1.203               | 2.656                           | 2.750               | 1.438               | 1.172                 |  |
| <b>Cone Head</b>     |                   |                     |                   |                     | <b>Pan Head</b>                 |                     |                     |                       |  |
| $\frac{1}{2}$        | 0.875             | 0.922               | 0.438             | 0.406               | 0.800                           | 0.844               | 0.350               | 0.328                 |  |
| $\frac{5}{8}$        | 1.094             | 1.141               | 0.547             | 0.516               | 1.000                           | 1.047               | 0.438               | 0.406                 |  |
| $\frac{3}{4}$        | 1.312             | 1.375               | 0.656             | 0.625               | 1.200                           | 1.266               | 0.525               | 0.484                 |  |
| $\frac{7}{8}$        | 1.531             | 1.594               | 0.766             | 0.719               | 1.400                           | 1.469               | 0.612               | 0.578                 |  |
| 1                    | 1.750             | 1.828               | 0.875             | 0.828               | 1.600                           | 1.687               | 0.700               | 0.656                 |  |
| $1\frac{1}{8}$       | 1.969             | 2.063               | 0.984             | 0.938               | 1.800                           | 1.891               | 0.788               | 0.734                 |  |
| $1\frac{1}{4}$       | 2.188             | 2.281               | 1.094             | 1.031               | 2.000                           | 2.094               | 0.875               | 0.812                 |  |
| $1\frac{3}{8}$       | 2.406             | 2.516               | 1.203             | 1.141               | 2.200                           | 2.312               | 0.962               | 0.906                 |  |
| $1\frac{1}{2}$       | 2.625             | 2.734               | 1.312             | 1.250               | 2.400                           | 2.516               | 1.050               | 0.984                 |  |
| $1\frac{5}{8}$       | 2.844             | 2.969               | 1.422             | 1.344               | 2.600                           | 2.734               | 1.138               | 1.062                 |  |
| $1\frac{3}{4}$       | 3.062             | 3.203               | 1.531             | 1.453               | 2.800                           | 2.938               | 1.225               | 1.141                 |  |

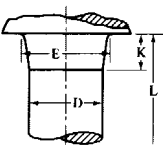
<sup>a</sup>Tolerance for diameter of body is plus and minus from nominal and for  $\frac{1}{2}$ -in. size equals  $+0.020, -0.022$ ; for sizes  $\frac{5}{8}$  to 1-in., incl., equals  $+0.030, -0.025$ ; for sizes  $1\frac{1}{8}$  and  $1\frac{1}{4}$ -in. equals  $+0.035, -0.027$ ; for sizes  $1\frac{3}{8}$  and  $1\frac{1}{2}$ -in. equals  $+0.040, -0.030$ ; for sizes  $1\frac{5}{8}$  and  $1\frac{3}{4}$ -in. equals  $+0.040, -0.037$ .

<sup>b</sup>Note 1. Basic dimensions of head as manufactured. All dimensions are given in inches. The following formulas give the basic dimensions for manufactured shapes: *Button Head*,  $A = 1.750D$ ;  $H = 0.750D$ ;  $G = 0.885D$ . *High Button Head*,  $A = 1.500D + 0.031$ ;  $H = 0.750D + 0.125$ ;  $F = 0.750D + 0.281$ ;  $G = 0.750D - 0.281$ . *Cone Head*,  $A = 1.750D$ ;  $B = 0.938D$ ;  $H = 0.875D$ . *Pan Head*,  $A = 1.600D$ ;  $B = 1.000D$ ;  $H = 0.700D$ . Length  $L$  is measured parallel to the rivet axis, from the extreme end to the bearing surface plane for flat bearing surface head type rivets, or to the intersection of the head top surface with the head diameter for countersunk head-type rivets.

<sup>c</sup>Note 2. Dimensions of manufactured head after driving and also of driven head.

<sup>d</sup>Note 3. Slight flat permissible within the specified head-height tolerance.

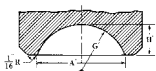
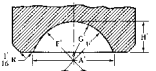
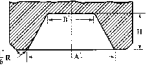
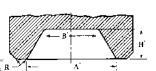
**Table 1c. American National Standard Large Rivets ANSI B18.1.2-1972 (R1995)**

| <br>Swell Neck | Swell Neck <sup>a</sup> |       |       |                              |       |                                   |
|---|-------------------------|-------|-------|------------------------------|-------|-----------------------------------|
|   | Body Diameter <i>D</i>  |       |       | Diameter Under Head <i>E</i> |       | Neck Length <i>K</i> <sup>b</sup> |
|   | Nominal <sup>b</sup>    | Max.  | Min.  | Max. (Basic)                 | Min.  |                                   |
| 1/2   | 0.500                   | 0.520 | 0.478 | 0.563                        | 0.543 | 0.250                             |
| 5/8   | 0.625                   | 0.655 | 0.600 | 0.688                        | 0.658 | 0.312                             |
| 3/4   | 0.750                   | 0.780 | 0.725 | 0.813                        | 0.783 | 0.375                             |
| 7/8   | 0.875                   | 0.905 | 0.850 | 0.938                        | 0.908 | 0.438                             |
| 1   | 1.000                   | 1.030 | 0.975 | 1.063                        | 1.033 | 0.500                             |
| 1 1/8   | 1.125                   | 1.160 | 1.098 | 1.188                        | 1.153 | 0.562                             |
| 1 1/4   | 1.250                   | 1.285 | 1.223 | 1.313                        | 1.278 | 0.625                             |
| 1 3/8   | 1.375                   | 1.415 | 1.345 | 1.438                        | 1.398 | 0.688                             |
| 1 1/2   | 1.500                   | 1.540 | 1.470 | 1.563                        | 1.523 | 0.750                             |
| 1 5/8   | 1.625                   | 1.665 | 1.588 | 1.688                        | 1.648 | 0.812                             |
| 1 3/4   | 1.750                   | 1.790 | 1.713 | 1.813                        | 1.773 | 0.875                             |

<sup>a</sup> The swell neck is applicable to all standard forms of large rivets except the flat countersunk and oval countersunk head types.

<sup>b</sup> All dimensions are given in inches. The following formulas give basic dimensions for manufactured shapes: *Swell Neck*,  $E = D + 0.063$ ;  $K = 0.500D$ . Length *L* is measured parallel to the rivet axis, from the extreme end to the bearing surface plane for flat bearing surface head-type rivets. Basic dimension as manufactured. For tolerances see table footnote on page 1483.

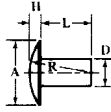
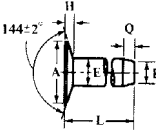
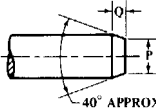
**American National Standard Dimensions for Hold-On (Dolly Bar) and Rivet Set Impression ANSI B18.1.2-1972 (R1995)**

|                              | <br>Button Head |       |       | <br>High Button Head |       |       |       | <br>Cone Head |       |       | <br>Pan Head |       |       |
|------------------------------|---|-------|-------|---|-------|-------|-------|--|-------|-------|---|-------|-------|
| Rivet Body Dia. <sup>a</sup> | A'  | H'    | G'    | A'  | H'    | F'    | G'    | A'   | B'    | H'    | A'  | B'    | H'    |
| 1/2                          | 0.906   | 0.312 | 0.484 | 0.859   | 0.344 | 0.562 | 0.375 | 0.891  | 0.469 | 0.391 | 0.812   | 0.500 | 0.297 |
| 5/8                          | 1.125   | 0.406 | 0.594 | 1.047   | 0.422 | 0.672 | 0.453 | 1.109  | 0.594 | 0.484 | 1.031   | 0.625 | 0.375 |
| 3/4                          | 1.344   | 0.484 | 0.719 | 1.234   | 0.500 | 0.797 | 0.531 | 1.328  | 0.703 | 0.578 | 1.234   | 0.750 | 0.453 |
| 7/8                          | 1.578   | 0.562 | 0.844 | 1.422   | 0.578 | 0.922 | 0.609 | 1.562  | 0.828 | 0.688 | 1.438   | 0.875 | 0.531 |
| 1                            | 1.812   | 0.641 | 0.953 | 1.609   | 0.656 | 1.031 | 0.688 | 1.781  | 0.938 | 0.781 | 1.641   | 1.000 | 0.609 |
| 1 1/8                        | 2.031   | 0.719 | 1.078 | 1.797   | 0.719 | 1.156 | 0.766 | 2.000  | 1.063 | 0.875 | 1.844   | 1.125 | 0.688 |
| 1 1/4                        | 2.250   | 0.797 | 1.188 | 1.984   | 0.797 | 1.266 | 0.844 | 2.219  | 1.172 | 0.969 | 2.047   | 1.250 | 0.766 |
| 1 3/8                        | 2.469   | 0.875 | 1.312 | 2.172   | 0.875 | 1.406 | 0.938 | 2.453  | 1.297 | 1.078 | 2.250   | 1.375 | 0.844 |
| 1 1/2                        | 2.703   | 0.953 | 1.438 | 2.344   | 0.953 | 1.500 | 1.000 | 2.672  | 1.406 | 1.172 | 2.453   | 1.500 | 0.906 |
| 1 5/8                        | 2.922   | 1.047 | 1.547 | 2.531   | 1.031 | 1.641 | 1.094 | 2.891  | 1.531 | 1.266 | 2.656   | 1.625 | 0.984 |
| 1 3/4                        | 3.156   | 1.125 | 1.672 | 2.719   | 1.109 | 1.750 | 1.172 | 3.109  | 1.641 | 1.375 | 2.875   | 1.750 | 1.063 |

<sup>a</sup> All dimensions are given in inches.

the United Kingdom. Table 3b shows the rivet dimensions. Table 3a shows a tentative range of preferred nominal lengths as given in an appendix to the Standard. It is stated that these lengths will be reviewed in the light of usage. The rivets are made by cold or hot forging methods from mild steel, copper, brass, pure aluminum, aluminum alloys, or other suitable metal. It is stated that the radius under the head of a rivet shall run smoothly into the face of the head and shank without step or discontinuity.

**Table 2a. American National Standard Small Solid Rivets**  
ANSI/ASME B18.1.1-1972 (R1995) and Appendix

|  |  |  | $P = D \times 0.818$<br>$Q = D \times 0.25$ |       |         |         |                            |                 |       |        |         |       |       |
|---|---|---|---|-------|---------|---------|----------------------------|-----------------|-------|--------|---------|-------|-------|
| Truss Head Rivets   | Coopers Rivets  | Point Dimensions  |   |       |         |         |                            |                 |       |        |         |       |       |
| Truss Head Rivets <sup>a</sup>  |   |   |   |       |         |         |                            |                 |       |        |         |       |       |
| Shank Dia., <sup>b</sup> D  | Head Dimensions   |   |   |       |         |         | Shank Dia., <sup>b</sup> D | Head Dimensions |       |        |         |       |       |
|   | Dia., A   |   | Height, H                                   |       | Rad. R  | Dia., A |                            | Height, H       |       | Rad. R |         |       |       |
|   | Max.  | Min.  | Max.  | Min.  | Approx. | Max.    |                            | Min.            | Max.  | Min.   | Approx. |       |       |
| Nominal   |   |   |   |       |         | Nominal |                            |                 |       |        |         |       |       |
| $\frac{3}{32}$  | 0.094   | 0.226   | 0.206                                       | 0.038 | 0.026   | 0.239   | $\frac{3}{32}$             | 0.281           | 0.661 | 0.631  | 0.103   | 0.085 | 0.706 |
| $\frac{1}{8}$   | 0.125   | 0.297   | 0.277                                       | 0.048 | 0.036   | 0.314   | $\frac{5}{16}$             | 0.312           | 0.732 | 0.702  | 0.113   | 0.095 | 0.784 |
| $\frac{5}{32}$  | 0.156   | 0.368   | 0.348                                       | 0.059 | 0.045   | 0.392   | $\frac{11}{32}$            | 0.344           | 0.806 | 0.776  | 0.124   | 0.104 | 0.862 |
| $\frac{3}{16}$  | 0.188   | 0.442   | 0.422                                       | 0.069 | 0.055   | 0.470   | $\frac{3}{8}$              | 0.375           | 0.878 | 0.848  | 0.135   | 0.115 | 0.942 |
| $\frac{7}{32}$  | 0.219   | 0.515   | 0.495                                       | 0.080 | 0.066   | 0.555   | $\frac{13}{32}$            | 0.406           | 0.949 | 0.919  | 0.145   | 0.123 | 1.028 |
| $\frac{1}{4}$   | 0.250   | 0.590   | 0.560                                       | 0.091 | 0.075   | 0.628   | $\frac{7}{16}$             | 0.438           | 1.020 | 0.990  | 0.157   | 0.135 | 1.098 |

<sup>a</sup> All dimensions in inches except where otherwise noted. Length tolerance of rivets is + or - .016 inch. Approximate proportions of rivets:  $A = 2.300 \times D$ ,  $H = 0.330 \times D$ ,  $R = 2.512 \times D$ .

<sup>b</sup> Tolerances on the nominal shank diameter in inches are given for the following body diameter ranges:  $\frac{3}{32}$  to  $\frac{5}{32}$ , plus 0.002, minus 0.004;  $\frac{3}{16}$  to  $\frac{1}{4}$ , plus 0.003, minus 0.006;  $\frac{5}{32}$  to  $\frac{11}{32}$ , plus 0.004, minus 0.008; and  $\frac{3}{8}$  to  $\frac{7}{16}$ , plus 0.005, minus 0.010.

| Coopers Rivets        |                   |       |                  |       |                |       |                               |           |           |       |
|-----------------------|-------------------|-------|------------------|-------|----------------|-------|-------------------------------|-----------|-----------|-------|
| Size No. <sup>a</sup> | Shank Diameter, D |       | Head Diameter, A |       | Head Height, H |       | Point Dimensions <sup>b</sup> |           | Length, L |       |
|                       | Max.              | Min.  | Max.             | Min.  | Max.           | Min.  | Dia., P                       | Length, Q | Max.      | Min.  |
|                       |                   |       |                  |       |                |       | Nom.                          | Nom.      |           |       |
| 1 lb                  | 0.111             | 0.105 | 0.291            | 0.271 | 0.045          | 0.031 | Not Pointed                   |           | 0.249     | 0.219 |
| $1\frac{1}{4}$ lb     | 0.122             | 0.116 | 0.324            | 0.302 | 0.050          | 0.036 | Not Pointed                   |           | 0.285     | 0.255 |
| $1\frac{1}{2}$ lb     | 0.132             | 0.126 | 0.324            | 0.302 | 0.050          | 0.036 | Not Pointed                   |           | 0.285     | 0.255 |
| $1\frac{3}{4}$ lb     | 0.136             | 0.130 | 0.324            | 0.302 | 0.052          | 0.034 | Not Pointed                   |           | 0.318     | 0.284 |
| 2 lb                  | 0.142             | 0.136 | 0.355            | 0.333 | 0.056          | 0.038 | Not Pointed                   |           | 0.322     | 0.288 |
| 3 lb                  | 0.158             | 0.152 | 0.386            | 0.364 | 0.058          | 0.040 | 0.123                         | 0.062     | 0.387     | 0.353 |
| 4 lb                  | 0.168             | 0.159 | 0.388            | 0.362 | 0.058          | 0.040 | 0.130                         | 0.062     | 0.418     | 0.388 |
| 5 lb                  | 0.183             | 0.174 | 0.419            | 0.393 | 0.063          | 0.045 | 0.144                         | 0.062     | 0.454     | 0.420 |
| 6 lb                  | 0.206             | 0.197 | 0.482            | 0.456 | 0.073          | 0.051 | 0.160                         | 0.094     | 0.498     | 0.457 |
| 7 lb                  | 0.223             | 0.214 | 0.513            | 0.487 | 0.076          | 0.054 | 0.175                         | 0.094     | 0.561     | 0.523 |
| 8 lb                  | 0.241             | 0.232 | 0.546            | 0.516 | 0.081          | 0.059 | 0.182                         | 0.094     | 0.597     | 0.559 |
| 9 lb                  | 0.248             | 0.239 | 0.578            | 0.548 | 0.085          | 0.063 | 0.197                         | 0.094     | 0.601     | 0.563 |
| 10 lb                 | 0.253             | 0.244 | 0.578            | 0.548 | 0.085          | 0.063 | 0.197                         | 0.094     | 0.632     | 0.594 |
| 12 lb                 | 0.263             | 0.251 | 0.580            | 0.546 | 0.086          | 0.060 | 0.214                         | 0.094     | 0.633     | 0.575 |
| 14 lb                 | 0.275             | 0.263 | 0.611            | 0.577 | 0.091          | 0.065 | 0.223                         | 0.094     | 0.670     | 0.612 |
| 16 lb                 | 0.285             | 0.273 | 0.611            | 0.577 | 0.089          | 0.063 | 0.223                         | 0.094     | 0.699     | 0.641 |
| 18 lb                 | 0.285             | 0.273 | 0.642            | 0.608 | 0.108          | 0.082 | 0.230                         | 0.125     | 0.749     | 0.691 |
| 20 lb                 | 0.316             | 0.304 | 0.705            | 0.671 | 0.128          | 0.102 | 0.250                         | 0.125     | 0.769     | 0.711 |
| $\frac{3}{8}$ in.     | 0.380             | 0.365 | 0.800            | 0.762 | 0.136          | 0.106 | 0.312                         | 0.125     | 0.840     | 0.778 |

<sup>a</sup> All dimensions in inches except where otherwise noted. Size numbers in pounds refer to the approximate weight of 1000 rivets.

<sup>b</sup> When specified American National Standard Small Solid Rivets may be obtained with points. Point dimensions for belt and coopers rivets are given in the accompanying tables. Formulas for calculating point dimensions of other rivets are given alongside the right diagram in Table 2a.

**Table 2b. American National Standard Small Solid Rivets**  
ANSI/ASME B18.1.1-1972 (R1995)

| Size No. <sup>a</sup> | Shank Diameter, <i>E</i> |       | Head Dia., <i>A</i> |       | Head Height, <i>H</i> |       | Length, <i>L</i> |       |       |
|-----------------------|--------------------------|-------|---------------------|-------|-----------------------|-------|------------------|-------|-------|
|                       | Max.                     | Min.  | Max.                | Min.  | Max.                  | Min.  | Nom.             | Max.  | Min.  |
| 6 oz.                 | 0.081                    | 0.075 | 0.213               | 0.193 | 0.028                 | 0.016 | 1/8              | 0.135 | 0.115 |
| 8 oz.                 | 0.091                    | 0.085 | 0.225               | 0.205 | 0.036                 | 0.024 | 5/32             | 0.166 | 0.146 |
| 10 oz.                | 0.097                    | 0.091 | 0.250               | 0.230 | 0.037                 | 0.025 | 11/64            | 0.182 | 0.162 |
| 12 oz.                | 0.107                    | 0.101 | 0.265               | 0.245 | 0.037                 | 0.025 | 3/16             | 0.198 | 0.178 |
| 14 oz.                | 0.111                    | 0.105 | 0.275               | 0.255 | 0.038                 | 0.026 | 3/16             | 0.198 | 0.178 |
| 1 lb                  | 0.113                    | 0.107 | 0.285               | 0.265 | 0.040                 | 0.028 | 13/64            | 0.213 | 0.193 |
| 1 1/4 lb              | 0.122                    | 0.116 | 0.295               | 0.275 | 0.045                 | 0.033 | 7/32             | 0.229 | 0.209 |
| 1 1/2 lb              | 0.132                    | 0.126 | 0.316               | 0.294 | 0.046                 | 0.034 | 15/64            | 0.244 | 0.224 |
| 1 3/4 lb              | 0.136                    | 0.130 | 0.331               | 0.309 | 0.049                 | 0.035 | 1/4              | 0.260 | 0.240 |
| 2 lb                  | 0.146                    | 0.140 | 0.341               | 0.319 | 0.050                 | 0.036 | 17/64            | 0.276 | 0.256 |
| 2 1/2 lb              | 0.150                    | 0.144 | 0.311               | 0.289 | 0.069                 | 0.055 | 9/32             | 0.291 | 0.271 |
| 3 lb                  | 0.163                    | 0.154 | 0.329               | 0.303 | 0.073                 | 0.059 | 5/16             | 0.323 | 0.303 |
| 3 1/2 lb              | 0.168                    | 0.159 | 0.348               | 0.322 | 0.074                 | 0.060 | 21/64            | 0.338 | 0.318 |
| 4 lb                  | 0.179                    | 0.170 | 0.368               | 0.342 | 0.076                 | 0.062 | 17/32            | 0.354 | 0.334 |
| 5 lb                  | 0.190                    | 0.181 | 0.388               | 0.362 | 0.084                 | 0.070 | 3/8              | 0.385 | 0.365 |
| 6 lb                  | 0.206                    | 0.197 | 0.419               | 0.393 | 0.090                 | 0.076 | 25/64            | 0.401 | 0.381 |
| 7 lb                  | 0.223                    | 0.214 | 0.431               | 0.405 | 0.094                 | 0.080 | 13/32            | 0.416 | 0.396 |
| 8 lb                  | 0.227                    | 0.218 | 0.475               | 0.445 | 0.101                 | 0.085 | 7/16             | 0.448 | 0.428 |
| 9 lb                  | 0.241                    | 0.232 | 0.490               | 0.460 | 0.103                 | 0.087 | 29/64            | 0.463 | 0.443 |
| 10 lb                 | 0.241                    | 0.232 | 0.505               | 0.475 | 0.104                 | 0.088 | 15/32            | 0.479 | 0.459 |
| 12 lb                 | 0.263                    | 0.251 | 0.532               | 0.498 | 0.108                 | 0.090 | 1/2              | 0.510 | 0.490 |
| 14 lb                 | 0.288                    | 0.276 | 0.577               | 0.543 | 0.113                 | 0.095 | 33/64            | 0.525 | 0.505 |
| 16 lb                 | 0.304                    | 0.292 | 0.597               | 0.563 | 0.128                 | 0.110 | 17/32            | 0.541 | 0.521 |
| 18 lb                 | 0.347                    | 0.335 | 0.706               | 0.668 | 0.156                 | 0.136 | 19/32            | 0.603 | 0.583 |

<sup>a</sup> All dimensions in inches. Size numbers refer to the approximate weight of 1000 rivets.

| Size No. <sup>b</sup> | Shank Diameter, <i>E</i> |       | Head Dia., <i>A</i> |       | Head Height, <i>H</i> |       | Point Dimensions <sup>c</sup> |                  |
|-----------------------|--------------------------|-------|---------------------|-------|-----------------------|-------|-------------------------------|------------------|
|                       | Max.                     | Min.  | Max.                | Min.  | Max.                  | Min.  | Dia., <i>P</i>                | Length, <i>Q</i> |
|                       |                          |       |                     |       |                       |       | Nominal                       | Nominal          |
| 14                    | 0.085                    | 0.079 | 0.260               | 0.240 | 0.042                 | 0.030 | 0.065                         | 0.078            |
| 13                    | 0.097                    | 0.091 | 0.322               | 0.302 | 0.051                 | 0.039 | 0.073                         | 0.078            |
| 12                    | 0.111                    | 0.105 | 0.353               | 0.333 | 0.054                 | 0.040 | 0.083                         | 0.078            |
| 11                    | 0.122                    | 0.116 | 0.383               | 0.363 | 0.059                 | 0.045 | 0.097                         | 0.078            |
| 10                    | 0.136                    | 0.130 | 0.417               | 0.395 | 0.065                 | 0.047 | 0.109                         | 0.094            |
| 9                     | 0.150                    | 0.144 | 0.448               | 0.426 | 0.069                 | 0.051 | 0.122                         | 0.094            |
| 8                     | 0.167                    | 0.161 | 0.481               | 0.455 | 0.072                 | 0.054 | 0.135                         | 0.094            |
| 7                     | 0.183                    | 0.174 | 0.513               | 0.487 | 0.075                 | 0.056 | 0.151                         | 0.125            |
| 6                     | 0.206                    | 0.197 | 0.606               | 0.580 | 0.090                 | 0.068 | 0.165                         | 0.125            |
| 5                     | 0.223                    | 0.214 | 0.700               | 0.674 | 0.105                 | 0.083 | 0.185                         | 0.125            |
| 4                     | 0.241                    | 0.232 | 0.921               | 0.893 | 0.138                 | 0.116 | 0.204                         | 0.141            |

<sup>a</sup> All dimensions in inches. Length tolerance on belt rivets is plus 0.031 inch, minus 0 inch.

<sup>b</sup> Size number refers to the Stub's iron wire gage number of the stock used in the shank of the rivet.

<sup>c</sup> Note: American National Standard Small Solid Rivets may be obtained with or without points. Point proportions are given in the diagram in Table 2a.

Table 2c. American National Standard Small Solid Rivets ANSI/ASME B18.1.1-1972 (R1995) and Appendix

| Shank Diameter |       | Flat Head <sup>a</sup> |       |         |       | Flat Countersunk Head <sup>a</sup> |       |                   |                   | Button Head <sup>a</sup> |                   |                   |           | Pan Head <sup>a</sup> |           |         |         |           |       |             |       |       |
|----------------|-------|------------------------|-------|---------|-------|------------------------------------|-------|-------------------|-------------------|--------------------------|-------------------|-------------------|-----------|-----------------------|-----------|---------|---------|-----------|-------|-------------|-------|-------|
|                |       | Head Dimensions        |       |         |       |                                    |       |                   |                   |                          |                   |                   |           |                       |           |         |         |           |       |             |       |       |
| D              |       | E                      |       | Dia., A |       | Height, H                          |       | Dia., A Sharp     |                   | Height <sup>b</sup> Ref. | Dia., A           |                   | Height, H |                       | Radius, R | Dia., A |         | Height, H |       | Radii       |       |       |
|                |       |                        |       | Max.    | Min.  | Max.                               | Min.  | Max.              | Min.              |                          | Max. <sup>c</sup> | Min. <sup>d</sup> | Max.      | Min.                  | Max.      | Min.    | Approx. | Max.      | Min.  | Max.        | Min.  | R1    |
| Nominal        |       | Max.                   | Min.  | Max.    | Min.  | Max.                               | Min.  | Max. <sup>c</sup> | Min. <sup>d</sup> | Ref.                     | Max.              | Min.              | Max.      | Min.                  | Approx.   | Max.    | Min.    | Max.      | Min.  | Approximate |       |       |
| 1/16           | 0.062 | 0.064                  | 0.059 | 0.140   | 0.120 | 0.027                              | 0.017 | 0.118             | 0.110             | 0.027                    | 0.122             | 0.102             | 0.052     | 0.042                 | 0.055     | 0.118   | 0.098   | 0.040     | 0.030 | 0.019       | 0.052 | 0.217 |
| 3/32           | 0.094 | 0.096                  | 0.090 | 0.200   | 0.180 | 0.038                              | 0.026 | 0.176             | 0.163             | 0.040                    | 0.182             | 0.162             | 0.077     | 0.065                 | 0.084     | 0.173   | 0.153   | 0.060     | 0.048 | 0.030       | 0.080 | 0.326 |
| 1/8            | 0.125 | 0.127                  | 0.121 | 0.260   | 0.240 | 0.048                              | 0.036 | 0.235             | 0.217             | 0.053                    | 0.235             | 0.215             | 0.100     | 0.088                 | 0.111     | 0.225   | 0.205   | 0.078     | 0.066 | 0.039       | 0.106 | 0.429 |
| 5/32           | 0.156 | 0.158                  | 0.152 | 0.323   | 0.301 | 0.059                              | 0.045 | 0.293             | 0.272             | 0.066                    | 0.290             | 0.268             | 0.124     | 0.110                 | 0.138     | 0.279   | 0.257   | 0.096     | 0.082 | 0.049       | 0.133 | 0.535 |
| 3/16           | 0.188 | 0.191                  | 0.182 | 0.387   | 0.361 | 0.069                              | 0.055 | 0.351             | 0.326             | 0.079                    | 0.348             | 0.322             | 0.147     | 0.133                 | 0.166     | 0.334   | 0.308   | 0.114     | 0.100 | 0.059       | 0.159 | 0.641 |
| 7/32           | 0.219 | 0.222                  | 0.213 | 0.453   | 0.427 | 0.080                              | 0.065 | 0.413             | 0.384             | 0.094                    | 0.405             | 0.379             | 0.172     | 0.158                 | 0.195     | 0.391   | 0.365   | 0.133     | 0.119 | 0.069       | 0.186 | 0.754 |
| 1/4            | 0.250 | 0.253                  | 0.244 | 0.515   | 0.485 | 0.091                              | 0.075 | 0.469             | 0.437             | 0.106                    | 0.460             | 0.430             | 0.196     | 0.180                 | 0.221     | 0.444   | 0.414   | 0.151     | 0.135 | 0.079       | 0.213 | 0.858 |
| 9/32           | 0.281 | 0.285                  | 0.273 | 0.579   | 0.545 | 0.103                              | 0.085 | 0.528             | 0.491             | 0.119                    | 0.518             | 0.484             | 0.220     | 0.202                 | 0.249     | 0.499   | 0.465   | 0.170     | 0.152 | 0.088       | 0.239 | 0.963 |
| 5/16           | 0.312 | 0.316                  | 0.304 | 0.641   | 0.607 | 0.113                              | 0.095 | 0.588             | 0.547             | 0.133                    | 0.572             | 0.538             | 0.243     | 0.225                 | 0.276     | 0.552   | 0.518   | 0.187     | 0.169 | 0.098       | 0.266 | 1.070 |
| 3/8            | 0.344 | 0.348                  | 0.336 | 0.705   | 0.667 | 0.124                              | 0.104 | 0.646             | 0.602             | 0.146                    | 0.630             | 0.592             | 0.267     | 0.247                 | 0.304     | 0.608   | 0.570   | 0.206     | 0.186 | 0.108       | 0.292 | 1.176 |
| 7/16           | 0.375 | 0.380                  | 0.365 | 0.769   | 0.731 | 0.135                              | 0.115 | 0.704             | 0.656             | 0.159                    | 0.684             | 0.646             | 0.291     | 0.271                 | 0.332     | 0.663   | 0.625   | 0.225     | 0.205 | 0.118       | 0.319 | 1.286 |
| 1/2            | 0.406 | 0.411                  | 0.396 | 0.834   | 0.790 | 0.146                              | 0.124 | 0.763             | 0.710             | 0.172                    | 0.743             | 0.699             | 0.316     | 0.294                 | 0.358     | 0.719   | 0.675   | 0.243     | 0.221 | 0.127       | 0.345 | 1.392 |
| 9/16           | 0.438 | 0.443                  | 0.428 | 0.896   | 0.852 | 0.157                              | 0.135 | 0.823             | 0.765             | 0.186                    | 0.798             | 0.754             | 0.339     | 0.317                 | 0.387     | 0.772   | 0.728   | 0.261     | 0.239 | 0.137       | 0.372 | 1.500 |

<sup>a</sup> All dimensions in inches. Length tolerance of all rivets is plus or minus 0.016 inch. Approximate proportions of rivets: flat head,  $A = 2.00 \times D$ ,  $H = 0.33 D$ ; flat countersunk head,  $A = 1.850 \times D$ ,  $H = 0.425 \times D$ ; button head,  $A = 1.750 \times D$ ,  $H = 0.750 \times D$ ,  $R = 0.885 \times D$ ; pan head,  $A = 1.720 \times D$ ,  $H = 0.570 \times D$ ,  $R_1 = 0.314 \times D$ ,  $R_2 = 0.850 \times D$ ,  $R_3 = 3.430 \times D$ . Note: ANSI Small Solid Rivets may be obtained with or without points. Point proportions are given in the diagram in Table 2a.

<sup>b</sup> Given for reference purposes only. Variations in this dimension are controlled by the head and shank diameters and the included angle of the head.

<sup>c</sup> Tabulated maximum values calculated on basic diameter of rivet and  $92^\circ$  included angle extended to a sharp edge.

<sup>d</sup> Minimum of rounded or flat-edged irregular-shaped head. Rivet heads are not machined or trimmed and the circumference may be irregular and edges rounded or flat.

In this Standard, **Tables 3a** and **3b**, the following definitions apply: 1) *Nominal diameter*: The diameter of the shank; 2) *Nominal length of rivets other than countersunk or raised countersunk rivets*: The length from the underside of the head to the end of the shank; 3) *Nominal length of countersunk and raised countersunk rivets*: The distance from the periphery of the head to the end of the rivet measured parallel to the axis of the rivet; and 4) *Manufactured head*: The head on the rivet as received from the manufacturer.

**Table 3a. Tentative Range of Lengths for Rivets** Appendix to BS 4620:1970 (1998)

| Nom. Shank Dia. | Nominal Length |     |     |     |     |     |     |     |     |      |     |      |     |      |     |      |     |      |     |     |     |
|-----------------|----------------|-----|-----|-----|-----|-----|-----|-----|-----|------|-----|------|-----|------|-----|------|-----|------|-----|-----|-----|
|                 | 3              | 4   | 5   | 6   | 8   | 10  | 12  | 14  | 16  | (18) | 20  | (22) | 25  | (28) | 30  | (32) | 35  | (38) | 40  | 45  | ... |
| 1               | d              | d   | d   | d   | d   | d   | d   | d   | d   | ...  | d   | ...  | ... | ...  | ... | ...  | ... | ...  | ... | ... | ... |
| 1.2             | d              | d   | d   | d   | d   | d   | d   | d   | d   | ...  | d   | ...  | ... | ...  | ... | ...  | ... | ...  | ... | ... | ... |
| 1.6             | d              | d   | d   | d   | d   | d   | d   | d   | d   | ...  | d   | ...  | ... | ...  | ... | ...  | ... | ...  | ... | ... | ... |
| 2               | d              | d   | d   | d   | d   | d   | d   | d   | d   | ...  | d   | d    | d   | ...  | ... | ...  | ... | ...  | ... | ... | ... |
| 2.5             | d              | d   | d   | d   | d   | d   | d   | d   | d   | d    | ... | d    | d   | ...  | ... | ...  | ... | ...  | ... | ... | ... |
| 3               | ...            | d   | d   | d   | d   | d   | d   | d   | d   | d    | d   | d    | d   | ...  | ... | ...  | ... | ...  | ... | ... | ... |
| (3.5)           | ...            | ... | ... | ... | ... | ... | ... | ... | ... | ...  | ... | ...  | ... | ...  | ... | ...  | ... | ...  | ... | ... | ... |
| 4               | ...            | ... | ... | d   | d   | d   | d   | d   | d   | d    | ... | d    | d   | ...  | ... | ...  | ... | ...  | ... | ... | ... |
| 5               | ...            | ... | ... | d   | d   | d   | d   | d   | d   | d    | d   | d    | d   | d    | d   | ...  | d   | d    | ... | ... | ... |
| 6               | ...            | ... | ... | d   | d   | d   | d   | d   | d   | d    | d   | d    | d   | d    | d   | ...  | d   | d    | ... | d   | ... |

| Nom. Shank Dia. | Nominal Length |     |     |     |      |     |      |     |      |     |      |     |      |     |     |     |     |     |     |     |     |
|-----------------|----------------|-----|-----|-----|------|-----|------|-----|------|-----|------|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|
|                 | 10             | 12  | 14  | 16  | (18) | 20  | (22) | 25  | (28) | 30  | (32) | 35  | (38) | 40  | 45  | 50  | 55  | 60  | 65  | 70  | 75  |
| (7)             | ...            | ... | ... | ... | ...  | ... | ...  | ... | ...  | ... | ...  | ... | ...  | ... | ... | ... | ... | ... | ... | ... | ... |
| 8               | d              | d   | d   | d   | d    | d   | d    | d   | d    | d   | ...  | d   | ...  | d   | d   | d   | ... | ... | ... | ... | ... |
| 10              | ...            | ... | d   | d   | d    | d   | d    | d   | d    | d   | ...  | d   | d    | d   | d   | d   | ... | ... | ... | ... | ... |
| 12              | ...            | ... | ... | ... | ...  | ... | ...  | d   | ...  | d   | ...  | d   | ...  | d   | ... | d   | ... | ... | ... | ... | d   |
| (14)            | ...            | ... | ... | ... | ...  | ... | ...  | ... | ...  | ... | ...  | ... | ...  | ... | ... | ... | ... | ... | ... | ... | ... |
| 16              | ...            | ... | ... | ... | ...  | ... | ...  | ... | ...  | ... | ...  | ... | ...  | d   | d   | d   | d   | d   | d   | d   | ... |

| Nom. Shank Dia. | Nominal Length |     |     |     |     |     |     |     |     |     |      |     |       |     |       |     |       |     |     |     |     |
|-----------------|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|-----|-------|-----|-------|-----|-------|-----|-----|-----|-----|
|                 | 45             | 50  | 55  | 60  | 65  | 70  | 75  | 80  | 85  | 90  | (95) | 100 | (105) | 110 | (115) | 120 | (125) | 130 | 140 | 150 | 160 |
| (18)            | ...            | ... | ... | ... | ... | ... | ... | ... | ... | ... | ...  | ... | ...   | ... | ...   | ... | ...   | ... | ... | ... | ... |
| 20              | d              | ... | ... | d   | ... | d   | ... | d   | ... | ... | ...  | ... | ...   | ... | ...   | ... | ...   | ... | ... | ... | ... |
| (22)            | ...            | ... | ... | ... | ... | ... | ... | ... | ... | ... | ...  | ... | ...   | ... | ...   | ... | ...   | ... | ... | ... | ... |
| 24              | ...            | ... | ... | ... | d   | ... | d   | ... | d   | d   | ...  | d   | ...   | ... | ...   | ... | ...   | ... | ... | ... | ... |
| (27)            | ...            | ... | ... | ... | ... | ... | ... | ... | ... | ... | ...  | ... | ...   | ... | ...   | ... | ...   | ... | ... | ... | ... |
| 30              | ...            | ... | ... | ... | ... | ... | ... | ... | d   | d   | ...  | d   | ...   | d   | ...   | d   | ...   | ... | ... | ... | ... |
| (33)            | ...            | ... | ... | ... | ... | ... | ... | ... | ... | ... | ...  | ... | ...   | ... | ...   | ... | ...   | ... | ... | ... | ... |
| 36              | ...            | ... | ... | ... | ... | ... | ... | ... | ... | ... | ...  | d   | ...   | d   | ...   | d   | ...   | d   | ... | ... | ... |
| (39)            | ...            | ... | ... | ... | ... | ... | ... | ... | ... | ... | ...  | ... | ...   | ... | d     | ... | d     | d   | d   | d   | ... |

All dimensions are in millimeters.

Note: Sizes and lengths shown in parenthesis are nonpreferred and should be avoided if possible.

**British Standard Small Rivets for General Purposes.**—Dimensions of small rivets for general purposes are given in British Standard 641:1951 and are shown in **Table 4** on page 1493. In addition, the standard lists the standard lengths of these rivets, gives the dimensions of washers to be used with countersunk head rivets (140°), indicates that the rivets may be made from mild steel, copper, brass, and a range of aluminum alloys and pure aluminum specified in B.S. 1473, and gives the dimensions of Coopers' flat head rivets ½ inch in diameter and below, in an appendix. In all types of rivets, except those with countersunk heads, there is a small radius or chamfer at the junction of the head and the shank.

**British Standard Dimensions of Rivets (½ to 1¾ inch diameter).**—The dimensions of rivets covered in BS 275:1927 (obsolescent) are given on page 1494 and do not apply to boiler rivets. With regard to this standard the terms "nominal diameter" and "standard diameter" are synonymous. The term "tolerance" refers to the variation from the nominal diameter of the rivet and not to the difference between the diameter under the head and the diameter near the point.



**Table 3b. British Standard Rivets for General Engineering Purposes**  
BS 4620:1970 (1998)

| 60° Csk. and Raised Csk. Head     |                   | 60° Csk. Head                 |                   | Snap Head   | Universal Head | Flat Head      |              |        |             |              |
|-----------------------------------|-------------------|-------------------------------|-------------------|-------------|----------------|----------------|--------------|--------|-------------|--------------|
|                                   |                   |                               |                   |             |                |                |              |        |             |              |
| *K = 0.43 d<br>(for ref. only)    |                   | †K = 0.5 d<br>(for ref. only) |                   |             |                |                |              |        |             |              |
| Hot Forged Rivets                 |                   |                               |                   |             |                |                |              |        |             |              |
| Nom. Shank Dia. <sup>a</sup><br>d | Tol. on Dia.<br>d | 60° Csk. and Raised Csk. Head |                   | Snap Head   |                | Universal Head |              |        |             |              |
|                                   |                   | Head Dimensions               |                   |             |                |                |              |        |             |              |
|                                   |                   | Nom. Dia. D                   | Height of Raise W | Nom. Dia. D | Nom. Depth K   | Nom. Dia. D    | Nom. Depth K | Rad. R | Rad. r      |              |
| (14)<br>16<br>(18)                | ±0.43             | 21                            | 2.8               | 22          | 9              | 28             | 5.6          | 42     | 8.4         |              |
| 20                                |                   | 24                            | 3.2               | 25          | 10             | 32             | 6.4          | 48     | 9.6         |              |
| (22)<br>24                        |                   | 27                            | 3.6               | 28          | 11.5           | 36             | 7.2          | 54     | 11          |              |
| 30                                | ±0.52             | 30                            | 4.0               | 32          | 13             | 40             | 8.0          | 60     | 12          |              |
| (33)<br>36                        |                   | 33                            | 4.4               | 36          | 14             | 44             | 8.8          | 66     | 13          |              |
| (39)                              |                   | 36                            | 4.8               | 40          | 16             | 48             | 9.6          | 72     | 14          |              |
| 40                                | ±0.62             | 40                            | 5.4               | 43          | 17             | 54             | 10.8         | 81     | 16          |              |
| 30                                |                   | 45                            | 6.0               | 48          | 19             | 60             | 12.0         | 90     | 18          |              |
| (33)                              |                   | 50                            | 6.6               | 53          | 21             | 66             | 13.2         | 99     | 20          |              |
| 36                                |                   | 55                            | 7.2               | 58          | 23             | 72             | 14.4         | 108    | 22          |              |
| (39)                              |                   | 59                            | 7.8               | 62          | 25             | 78             | 15.6         | 117    | 23          |              |
| Cold Forged Rivets                |                   |                               |                   |             |                |                |              |        |             |              |
| Nom. Shank Dia. <sup>a</sup><br>d | Tol. on Dia.<br>d | 90° Csk. Head                 | Snap Head         |             | Universal Head |                |              |        | Flat Head   |              |
|                                   |                   | Head Dimensions               |                   |             |                |                |              |        |             |              |
|                                   |                   | Nom. Dia. D                   | Nom. Dia. D       | Nom. Dia. K | Nom. Dia. D    | Nom. Depth K   | Rad. R       | Rad. r | Nom. Dia. D | Nom. Depth K |
| 1                                 | ±0.07             | 2                             | 1.8               | 0.6         | 2              | 0.4            | 3.0          | 0.6    | 2           | 0.25         |
| 1.2                               |                   | 2.4                           | 2.1               | 0.7         | 2.4            | 0.5            | 3.6          | 0.7    | 2.4         | 0.3          |
| 1.6                               |                   | 3.2                           | 2.8               | 1.0         | 3.2            | 0.6            | 4.8          | 1.0    | 3.2         | 0.4          |
| 2                                 |                   | 4                             | 3.5               | 1.2         | 4              | 0.8            | 6.0          | 1.2    | 4           | 0.5          |
| 2.5                               |                   | 5                             | 4.4               | 1.5         | 5              | 1.0            | 7.5          | 1.5    | 5           | 0.6          |
| 3                                 |                   | 6                             | 5.3               | 1.8         | 6              | 1.2            | 9.0          | 1.8    | 6           | 0.8          |
| (3.5)                             | ±0.09             | 7                             | 6.1               | 2.1         | 7              | 1.4            | 10.5         | 2.1    | 7           | 0.9          |
| 4                                 |                   | 8                             | 7                 | 2.4         | 8              | 1.6            | 12           | 2.4    | 8           | 1.0          |
| 5                                 |                   | 10                            | 8.8               | 3.0         | 10             | 2.0            | 15           | 3.0    | 10          | 1.3          |
| 6                                 |                   | 12                            | 10.5              | 3.6         | 12             | 2.4            | 18           | 3.6    | 12          | 1.5          |
| (7)                               | ±0.11             | 14                            | 12.3              | 4.2         | 14             | 2.8            | 21           | 4.2    | 14          | 1.8          |
| 8                                 |                   | 16                            | 14                | 4.8         | 16             | 3.2            | 24           | 4.8    | 16          | 2            |
| 10                                |                   | 20                            | 18                | 6.0         | 20             | 4.0            | 30           | 6      | 20          | 2.5          |
| 12                                | ±0.14             | 24                            | 21                | 7.2         | 24             | 4.8            | 36           | 7.2    | ...         | ...          |
| (14)                              |                   | ...                           | 25                | 8.4         | 28             | 5.6            | 42           | 8.4    | ...         | ...          |
| 16                                |                   | ...                           | 28                | 9.6         | 32             | 6.4            | 48           | 9.6    | ...         | ...          |

<sup>a</sup> All dimensions are in millimeters. Sizes shown in parentheses are nonpreferred.

**Table 4. British Standard Small Rivets for General Purposes**  
*BS 641:1951 (obsolescent)*

| Nom. Dia. <sup>a</sup><br><i>D</i> | Snap (or Round Head) |              |               | Mushroom Head |              |              | Flat Head     |              | Countersunk Head (90°) |              | Countersunk Head (120°) |              |
|------------------------------------|----------------------|--------------|---------------|---------------|--------------|--------------|---------------|--------------|------------------------|--------------|-------------------------|--------------|
|                                    | Head Dimensions      |              |               |               |              |              |               |              |                        |              |                         |              |
|                                    | Dia. <i>A</i>        | Ht. <i>H</i> | Rad. <i>R</i> | Dia. <i>A</i> | Ht. <i>H</i> | Rad <i>R</i> | Dia. <i>A</i> | Ht. <i>H</i> | Dia. <i>A</i>          | Ht. <i>H</i> | Dia. <i>A</i>           | Ht. <i>H</i> |
| 1/16                               | 0.109                | 0.047        | 0.055         | 0.141         | 0.031        | 0.095        | 0.125         | 0.016        | 0.125                  | 0.031        | ...                     | ...          |
| 3/32                               | 0.164                | 0.070        | 0.083         | 0.211         | 0.047        | 0.142        | 0.188         | 0.023        | 0.188                  | 0.047        | ...                     | ...          |
| 1/8                                | 0.219                | 0.094        | 0.111         | 0.281         | 0.063        | 0.189        | 0.250         | 0.031        | 0.250                  | 0.063        | 0.250                   | 0.036        |
| 5/32                               | 0.273                | 0.117        | 0.138         | 0.352         | 0.078        | 0.237        | 0.313         | 0.039        | 0.313                  | 0.078        | ...                     | ...          |
| 3/16                               | 0.328                | 0.141        | 0.166         | 0.422         | 0.094        | 0.284        | 0.375         | 0.047        | 0.375                  | 0.094        | 0.375                   | 0.054        |
| 1/4                                | 0.438                | 0.188        | 0.221         | 0.563         | 0.125        | 0.379        | 0.500         | 0.063        | 0.500                  | 0.125        | 0.500                   | 0.073        |
| 5/16                               | 0.547                | 0.234        | 0.277         | 0.703         | 0.156        | 0.474        | 0.625         | 0.078        | 0.625                  | 0.156        | 0.625                   | 0.091        |
| 3/8                                | 0.656                | 0.281        | 0.332         | 0.844         | 0.188        | 0.568        | 0.750         | 0.094        | 0.750                  | 0.188        | 0.750                   | 0.109        |
| 7/16                               | 0.766                | 0.328        | 0.387         | 0.984         | 0.219        | 0.663        | 0.875         | 0.109        | 0.875                  | 0.219        | ...                     | ...          |

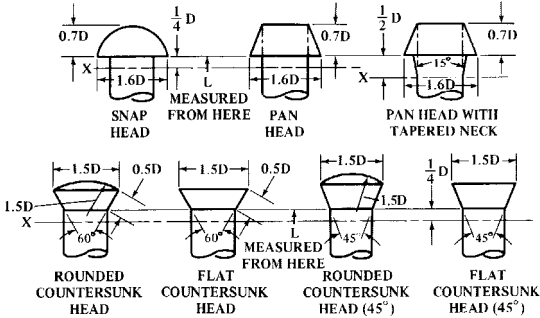
  

| Nominal Diameter <i>D</i> | Pan Head        |                       | Countersunk Head (60°) |              | Countersunk Head (140°) |              |               | Countersunk Head Reaper |               | Snap (or Round) Head Reaper |              |               |
|---------------------------|-----------------|-----------------------|------------------------|--------------|-------------------------|--------------|---------------|-------------------------|---------------|-----------------------------|--------------|---------------|
|                           | Head Dimensions |                       |                        |              |                         |              |               |                         |               |                             |              |               |
|                           | Inch            | Gage No. <sup>b</sup> | Dia. <i>A</i>          | Ht. <i>H</i> | Dia. <i>A</i>           | Ht. <i>H</i> | Dia. <i>A</i> | Ht. <i>C</i>            | Dia. <i>E</i> | Dia. <i>A</i>               | Ht. <i>H</i> | Dia. <i>A</i> |
| 0.104                     | 12              | ...                   | ...                    | ...          | ...                     | 0.286        | 0.042         | 0.082                   | ...           | ...                         | ...          | ...           |
| 0.116                     | 11              | ...                   | ...                    | ...          | ...                     | 0.319        | 0.046         | 0.092                   | ...           | ...                         | ...          | ...           |
| 0.128                     | 10              | ...                   | ...                    | ...          | ...                     | 0.352        | 0.051         | 0.101                   | ...           | ...                         | ...          | ...           |
| 0.144                     | 9               | ...                   | ...                    | ...          | ...                     | 0.396        | 0.058         | 0.114                   | ...           | ...                         | ...          | ...           |
| 0.160                     | 8               | ...                   | ...                    | ...          | ...                     | 0.440        | 0.064         | 0.126                   | ...           | ...                         | ...          | ...           |
| 0.176                     | 7               | ...                   | ...                    | ...          | ...                     | 0.484        | 0.070         | 0.139                   | ...           | ...                         | ...          | ...           |
| 3/16                      | ...             | 0.300                 | 0.131                  | 0.328        | 0.122                   | ...          | ...           | ...                     | ...           | ...                         | ...          | ...           |
| 0.192                     | 6               | ...                   | ...                    | ...          | ...                     | 0.528        | 0.077         | 0.152                   | 0.317         | 0.062                       | 0.307        | 0.115         |
| 0.202                     | ...             | ...                   | ...                    | ...          | ...                     | ...          | ...           | ...                     | 0.333         | 0.066                       | 0.323        | 0.121         |
| 0.212                     | 5               | ...                   | ...                    | ...          | ...                     | 0.583        | 0.085         | 0.167                   | 0.350         | 0.069                       | 0.339        | 0.127         |
| 0.232                     | 4               | ...                   | ...                    | ...          | ...                     | 0.638        | 0.093         | 0.183                   | 0.383         | 0.075                       | 0.371        | 0.139         |
| 1/4                       | ...             | 0.400                 | 0.175                  | 0.438        | 0.162                   | 0.688        | 0.100         | 0.198                   | ...           | ...                         | ...          | ...           |
| 0.252                     | 3               | ...                   | ...                    | ...          | ...                     | ...          | ...           | ...                     | 0.416         | 0.082                       | 0.403        | 0.151         |
| 5/16                      | ...             | 0.500                 | 0.219                  | 0.547        | 0.203                   | 0.859        | 0.125         | 0.247                   | ...           | ...                         | ...          | ...           |
| 3/8                       | ...             | 0.600                 | 0.263                  | 0.656        | 0.244                   | 10.031       | 0.150         | 0.296                   | ...           | ...                         | ...          | ...           |
| 7/16                      | ...             | 0.700                 | 0.306                  | 0.766        | 0.284                   | ...          | ...           | ...                     | ...           | ...                         | ...          | ...           |

<sup>a</sup> All dimensions in inches unless specified otherwise.

<sup>b</sup> Gage numbers are British Standard Wire Gage (S.W.G.) numbers.

**Head Dimensions and Diameters of British Standard Rivets**  
*BS 275:1927 (obsolescent)*



| Nominal Rivet Diameter, <sup>a</sup><br><i>D</i> | Shank Diameter <sup>b</sup> |                  |                            |                  |                            |
|--|-----------------------------|------------------|----------------------------|------------------|----------------------------|
|  | At Position X <sup>c</sup>  |                  | At Position Y <sup>c</sup> |                  | At Position Z <sup>c</sup> |
|  | Minimum                     | Maximum          | Minimum                    | Maximum          | Minimum                    |
| $\frac{1}{2}$                                    | $\frac{1}{2}$               | $\frac{17}{32}$  | $\frac{31}{64}$            | $\frac{1}{2}$    | $\frac{31}{64}$            |
| $\frac{9}{16}^d$                                 | $\frac{9}{16}$              | $\frac{19}{32}$  | $\frac{35}{64}$            | $\frac{9}{16}$   | $\frac{35}{64}$            |
| $\frac{5}{8}$                                    | $\frac{5}{8}$               | $\frac{21}{32}$  | $\frac{39}{64}$            | $\frac{5}{8}$    | $\frac{39}{64}$            |
| $\frac{11}{16}^d$                                | $\frac{11}{16}$             | $\frac{23}{32}$  | $\frac{43}{64}$            | $\frac{11}{16}$  | $\frac{43}{64}$            |
| $\frac{3}{4}$                                    | $\frac{3}{4}$               | $\frac{25}{32}$  | $\frac{47}{64}$            | $\frac{3}{4}$    | $\frac{47}{64}$            |
| $\frac{13}{16}^d$                                | $\frac{13}{16}$             | $\frac{27}{32}$  | $\frac{51}{64}$            | $\frac{13}{16}$  | $\frac{51}{64}$            |
| $\frac{7}{8}$                                    | $\frac{7}{8}$               | $\frac{29}{32}$  | $\frac{55}{64}$            | $\frac{7}{8}$    | $\frac{55}{64}$            |
| $\frac{15}{16}^d$                                | $\frac{15}{16}$             | $\frac{31}{32}$  | $\frac{59}{64}$            | $\frac{15}{16}$  | $\frac{59}{64}$            |
| 1  | 1                           | $\frac{1}{2}$    | $\frac{63}{64}$            | 1                | $\frac{63}{64}$            |
| $\frac{1}{16}^d$                                 | $\frac{1}{16}$              | $\frac{1}{8}$    | $\frac{1}{8}$              | $\frac{1}{16}$   | $\frac{1}{8}$              |
| $\frac{1}{8}$                                    | $\frac{1}{8}$               | $\frac{15}{32}$  | $\frac{1}{4}$              | $\frac{1}{8}$    | $\frac{1}{4}$              |
| $\frac{13}{16}^d$                                | $\frac{13}{16}$             | $\frac{1}{2}$    | $\frac{11}{64}$            | $\frac{13}{16}$  | $\frac{11}{64}$            |
| $\frac{1}{4}$                                    | $\frac{1}{4}$               | $\frac{19}{32}$  | $\frac{15}{64}$            | $\frac{1}{4}$    | $\frac{15}{64}$            |
| $\frac{15}{16}^d$                                | $\frac{15}{16}$             | $\frac{11}{8}$   | $\frac{19}{64}$            | $\frac{15}{16}$  | $\frac{19}{64}$            |
| $\frac{3}{8}$                                    | $\frac{3}{8}$               | $\frac{13}{32}$  | $\frac{13}{64}$            | $\frac{3}{8}$    | $\frac{13}{64}$            |
| $\frac{17}{16}^d$                                | $\frac{17}{16}$             | $\frac{15}{8}$   | $\frac{17}{64}$            | $\frac{17}{16}$  | $\frac{17}{64}$            |
| $\frac{1}{2}$                                    | $\frac{1}{2}$               | $\frac{17}{32}$  | $\frac{131}{64}$           | $\frac{1}{2}$    | $\frac{131}{64}$           |
| $\frac{19}{16}^d$                                | $\frac{19}{16}$             | $\frac{19}{8}$   | $\frac{135}{64}$           | $\frac{19}{16}$  | $\frac{135}{64}$           |
| $\frac{15}{8}$                                   | $\frac{15}{8}$              | $\frac{21}{32}$  | $\frac{139}{64}$           | $\frac{15}{8}$   | $\frac{139}{64}$           |
| $\frac{111}{16}^d$                               | $\frac{111}{16}$            | $\frac{123}{32}$ | $\frac{143}{64}$           | $\frac{111}{16}$ | $\frac{143}{64}$           |
| $\frac{13}{4}$                                   | $\frac{13}{4}$              | $\frac{125}{32}$ | $\frac{147}{64}$           | $\frac{13}{4}$   | $\frac{147}{64}$           |

<sup>a</sup> All dimensions that are tabulated are given in inches. This standard does not apply to Boiler Rivets

<sup>b</sup> Tolerances of the rivet diameter are as follows: at position X, plus  $\frac{1}{32}$  inch, minus zero; at position Y, plus zero, minus  $\frac{1}{64}$  inch; at position Z, minus  $\frac{1}{64}$  inch but in no case shall the difference between the diameters at positions X and Y exceed  $\frac{1}{32}$  inch, nor shall the diameter of the shank between positions X and Y be less than the minimum diameter specified at position Y.

<sup>c</sup> The location of positions Y and Z are as follows: Position Y is located  $\frac{1}{2}D$  from the end of the rivet for rivet lengths 5 diameters long and under. For longer rivets, position Y is located  $4\frac{1}{2}D$  from the head of the rivet. Position Z (found only on rivets longer than  $5D$ ) is located  $\frac{1}{2}D$  from the end of the rivet.

<sup>d</sup> At the recommendation of the British Standards Institution, these sizes are to be dispensed with wherever possible.

## TORQUE AND TENSION IN FASTENERS

**Tightening Bolts:** Bolts are often tightened by applying torque to the head or nut, which causes the bolt to stretch. The stretching results in bolt tension or preload, which is the force that holds a joint together. Torque is relatively easy to measure with a torque wrench, so it is the most frequently used indicator of bolt tension. Unfortunately, a torque wrench does not measure bolt tension accurately, mainly because it does not take friction into account. The friction depends on bolt, nut, and washer material, surface smoothness, machining accuracy, degree of lubrication, and the number of times a bolt has been installed. Fastener manufacturers often provide information for determining torque requirements for tightening various bolts, accounting for friction and other effects. If this information is not available, the methods described in what follows give general guidelines for determining how much tension should be present in a bolt, and how much torque may need to be applied to arrive at that tension.

High preload tension helps keep bolts tight, increases joint strength, creates friction between parts to resist shear, and improves the fatigue resistance of bolted connections. The recommended preload  $F_i$ , which can be used for either static (stationary) or fatigue (alternating) applications, can be determined from:  $F_i = 0.75 \times A_t \times S_p$  for reusable connections, and  $F_i = 0.9 \times A_t \times S_p$  for permanent connections. In these formulas,  $F_i$  is the bolt preload,  $A_t$  is the tensile stress area of the bolt, and  $S_p$  is the proof strength of the bolt. Determine  $A_t$  from screw-thread tables or by means of formulas in this section. Proof strength  $S_p$  of commonly used ASTM and SAE steel fasteners is given in this section and in the section on metric screws and bolts for those fasteners. For other materials, an approximate value of proof strength can be obtained from:  $S_p = 0.85 \times S_y$ , where  $S_y$  is the yield strength of the material. Soft materials should not be used for threaded fasteners.

Once the required preload has been determined, one of the best ways to be sure that a bolt is properly tensioned is to measure its tension directly with a strain gage. Next best is to measure the change in length (elongation) of the bolt during tightening, using a micrometer or dial indicator. Each of the following two formulas calculates the required change in length of a bolt needed to make the bolt tension equal to the recommended preload. The change in length  $\delta$  of the bolt is given by:

$$\delta = F_i \times \frac{A_d \times l_t + A_t \times l_d}{A_d \times A_t \times E} \quad (1) \quad \text{or} \quad \delta = \frac{F_i \times l}{A \times E} \quad (2)$$

In Equation (1),  $F_i$  is the bolt preload;  $A_d$  is the major-diameter area of the bolt;  $A_t$  is the tensile-stress area of the bolt;  $E$  is the bolt modulus of elasticity;  $l_t$  is the length of the threaded portion of the fastener within the grip; and  $l_d$  is the length of the unthreaded portion of the grip. Here, the grip is defined as the total thickness of the clamped material. Equation (2) is a simplified formula for use when the area of the fastener is constant, and gives approximately the same results as Equation (1). In Equation (2),  $l$  is the bolt length;  $A$  is the bolt area; and  $\delta$ ,  $F_i$ , and  $E$  are as described before.

If measuring bolt elongation is not possible, the torque necessary to tighten the bolt must be estimated. If the recommended preload is known, use the following general relation for the torque:  $T = K \times F_i \times d$ , where  $T$  is the wrench torque,  $K$  is a constant that depends on the bolt material and size,  $F_i$  is the preload, and  $d$  is the nominal bolt diameter. A value of  $K = 0.2$  may be used in this equation for mild-steel bolts in the size range of  $\frac{1}{4}$  to 1 inch. For other steel bolts, use the following values of  $K$ : nonplated black finish, 0.3; zinc-plated, 0.2; lubricated, 0.18; cadmium-plated, 0.16. Check with bolt manufacturers and suppliers for values of  $K$  to use with bolts of other sizes and materials.

The proper torque to use for tightening bolts in sizes up to about  $\frac{1}{2}$  inch may also be determined by trial. Test a bolt by measuring the amount of torque required to fracture it (use bolt, nut, and washers equivalent to those chosen for the real application). Then, use a tightening torque of about 50 to 60 per cent of the fracture torque determined by the test. The tension in a bolt tightened using this procedure will be about 60 to 70 per cent of the elastic limit (yield strength) of the bolt material.

The table that follows can be used to get a rough idea of the torque necessary to properly tension a bolt by using the bolt diameter  $d$  and the coefficients  $b$  and  $m$  from the table; the approximate tightening torque  $T$  in ft-lb for the listed fasteners is obtained by solving the equation  $T = 10^{b+m \log d}$ . This equation is approximate, for use with unlubricated fasteners as supplied by the mill. See the notes at the end of the table for more details on using the equation.

**Wrench Torque  $T = 10^{b+m \log d}$  for Steel Bolts, Studs, and Cap Screws (see notes)**

| Fastener Grade(s)                     | Bolt Diameter $d$ (in.)         | $m$   | $b$   |
|---------------------------------------|---------------------------------|-------|-------|
| SAE 2, ASTM A307                      | $\frac{1}{4}$ to 3              | 2.940 | 2.533 |
| SAE 3                                 | $\frac{1}{4}$ to 3              | 3.060 | 2.775 |
| ASTM A-449, A-354-BB, SAE 5           | $\frac{1}{4}$ to 3              | 2.965 | 2.759 |
| ASTM A-325 <sup>a</sup>               | $\frac{1}{2}$ to $1\frac{1}{2}$ | 2.922 | 2.893 |
| ASTM A-354-BC                         | $\frac{1}{4}$ to $\frac{5}{8}$  | 3.046 | 2.837 |
| SAE 6, SAE 7                          | $\frac{1}{4}$ to 3              | 3.095 | 2.948 |
| SAE 8                                 | $\frac{1}{4}$ to 3              | 3.095 | 2.983 |
| ASTM A-354-BD, ASTM A490 <sup>a</sup> | $\frac{3}{8}$ to $1\frac{3}{4}$ | 3.092 | 3.057 |
| Socket Head Cap Screws                | $\frac{1}{4}$ to 3              | 3.096 | 3.014 |

<sup>a</sup> Values for permanent fastenings on steel structures.

Usage: Values calculated using the preceding equation are for standard, unplated industrial fasteners as received from the manufacturer; for cadmium-plated cap screws, multiply the torque by 0.9; for cadmium-plated nuts and bolts, multiply the torque by 0.8; for fasteners used with special lubricants, multiply the torque by 0.9; for studs, use cap screw values for equivalent grade.

**Preload for Bolts in Loaded Joints.**—The following recommendations are based on MIL-HDBK-60, a subsection of FED-STD-H28, Screw Thread Standards for Federal Service. Generally, bolt preload in joints should be high enough to maintain joint members in contact and in compression. Loss of compression in a joint may result in leakage of pressurized fluids past compression gaskets, loosening of fasteners under conditions of cyclic loading, and reduction of fastener fatigue life.

The relationship between fastener fatigue life and fastener preload is illustrated by Fig. 1. An axially loaded bolted joint in which there is no bolt preload is represented by line OAB, that is, the bolt load is equal to the joint load. When joint load varies between  $P_a$  and  $P_b$ , the bolt load varies accordingly between  $P_{Ba}$  and  $P_{Bb}$ . However, if preload  $P_{B1}$  is applied to the bolt, the joint is compressed and bolt load changes more slowly than the joint load (indicated by line  $P_{B1}A$ , whose slope is less than line OAB) because some of the load is absorbed as a reduction of compression in the joint. Thus, the axial load applied to the joint varies between  $P_{Ba'}$  and  $P_{Bb'}$ , as joint load varies between  $P_a$  and  $P_b$ . This condition results in a considerable reduction in cyclic bolt-load variation and thereby increases the fatigue life of the fastener.

**Preload for Bolts In Shear.**—In shear-loaded joints, with members that slide, the joint members transmit shear loads to the fasteners in the joint and the preload must be sufficient to hold the joint members in contact. In joints that do not slide (i.e., there is no relative motion between joint members), shear loads are transmitted within the joint by frictional forces that mainly result from the preload. Therefore, preload must be great enough for the resulting friction forces to be greater than the applied shear force. With high applied shear loads, the shear stress induced in the fastener during application of the preload must also be

considered in the bolted-joint design. Joints with combined axial and shear loads must be analyzed to ensure that the bolts will not fail in either tension or shear.

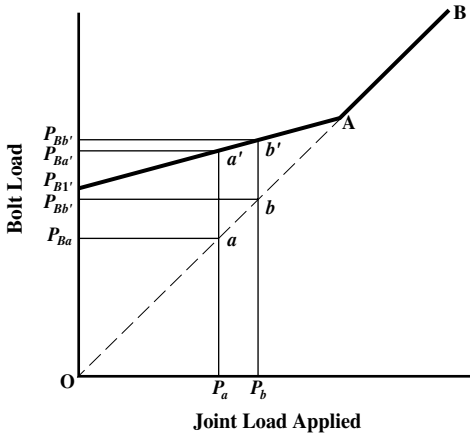


Fig. 1. Bolt Load in a Joint with Applied Axial Load

**General Application of Preload.**—Preload values should be based on joint requirements, as outlined before. Fastener applications are generally designed for maximum utilization of the fastener material; that is to say, the fastener size is the minimum required to perform its function and a maximum safe preload is generally applied to it. However, if a low-strength fastener is replaced by one of higher strength, for the sake of convenience or standardization, the preload in the replacement should not be increased beyond that required in the original fastener.

To utilize the maximum amount of bolt strength, bolts are sometimes tightened to or beyond the yield point of the material. This practice is generally limited to ductile materials, where there is considerable difference between the yield strength and the ultimate (breaking) strength, because low-ductility materials are more likely to fail due to unexpected overloads when preloaded to yield. Joints designed for primarily static load conditions that use ductile bolts, with a yield strain that is relatively far from the strain at fracture, are often preloaded above the yield point of the bolt material. Methods for tightening up to and beyond the yield point include tightening by feel without special tools, and the use of electronic equipment designed to compare the applied torque with the angular rotation of the fastener and detect changes that occur in the elastic properties of fasteners at yield.

Bolt loads are maintained below the yield point in joints subjected to cyclic loading and in joints using bolts of high-strength material where the yield strain is close to the strain at fracture. For these conditions, the maximum preloads generally fall within the following ranges: 50 to 80 per cent of the minimum tensile ultimate strength; 75 to 90 per cent of the minimum tensile yield strength or proof load; or 100 per cent of the observed proportional limit or onset of yield.

Bolt heads, driving recesses (in socket screws, for example), and the juncture of head and shank must be sufficiently strong to withstand the preload and any additional stress encountered during tightening. There must also be sufficient thread to prevent stripping (generally, at least three fully engaged threads). Materials susceptible to stress-corrosion cracking may require further preload limitations.

**Preload Adjustments.**—Preloads may be applied directly by axial loading or indirectly by turning of the nut or bolt. When preload is applied by turning of nuts or bolts, a torsion load component is added to the desired axial bolt load. This combined loading increases the tensile stress on the bolt. It is frequently assumed that the additional torsion load component dissipates quickly after the driving force is removed and, therefore, can be largely ignored. This assumption may be reasonable for fasteners loaded near to or beyond yield strength, but for critical applications where bolt tension must be maintained below yield, it is important to adjust the axial tension requirements to include the effects of the preload torsion. For this adjustment, the combined tensile stress (*von Mises* stress)  $F_{tc}$  in psi (MPa) can be calculated from the following:

$$F_{tc} = \sqrt{F_t^2 + 3F_s^2} \quad (3)$$

where  $F_t$  is the axial applied tensile stress in psi (MPa), and  $F_s$  is the shear stress in psi (MPa) caused by the torsion load application.

Some of the torsion load on a bolt, acquired when applying a preload, may be released by springback when the wrenching torque is removed. The amount of relaxation depends on the friction under the bolt head or nut. With controlled back turning of the nut, the torsional load may be reduced or eliminated without loss of axial load, reducing bolt stress and lowering creep and fatigue potential. However, calculation and control of the back-turn angle is difficult, so this method has limited application and cannot be used for short bolts because of the small angles involved.

For relatively soft work-hardenable materials, tightening bolts in a joint slightly beyond yield will work-harden the bolt to some degree. Back turning of the bolt to the desired tension will reduce embedment and metal flow and improve resistance to preload loss.

The following formula for use with single-start Unified inch screw threads calculates the combined tensile stress,  $F_{tc}$ :

$$F_{tc} = F_t \sqrt{1 + 3 \left( \frac{1.96 + 2.31\mu}{1 - 0.325P/d_2} - 1.96 \right)^2} \quad (4)$$

Single-start UNJ screw threads in accordance with MIL-S-8879 have a thread stress diameter equal to the bolt pitch diameter. For these threads,  $F_{tc}$  can be calculated from:

$$F_{tc} = F_t \sqrt{1 + 3 \left( \frac{0.637P}{d_2} + 2.31\mu \right)^2} \quad (5)$$

where  $\mu$  is the coefficient of friction between threads,  $P$  is the thread pitch ( $P = 1/n$ , and  $n$  is the number of threads per inch), and  $d_2$  is the bolt-thread pitch diameter in inches. Both Equations (2) and (3) are derived from Equation (1); thus, the quantity within the radical ( $\sqrt{\quad}$ ) represents the proportion of increase in axial bolt tension resulting from preload torsion. In these equations, tensile stress due to torsion load application becomes most significant when the thread friction,  $\mu$ , is high.

**Coefficients of Friction for Bolts and Nuts.**—Table 1 gives examples of coefficients of friction that are frequently used in determining torque requirements. Dry threads, indicated by the words "None added" in the Lubricant column, are assumed to have some residual machine oil lubrication. Table 1 values are not valid for threads that have been cleaned to remove all traces of lubrication because the coefficient of friction of these threads may be very much higher unless a plating or other film is acting as a lubricant.

**Table 1. Coefficients of Friction of Bolts and Nuts**

| Bolt/Nut Materials  | Lubricant                     | Coefficient of Friction, $\mu \pm 20\%$ |
|---|-------------------------------|---|
| Steel <sup>a</sup>  | Graphite in petrolatum or oil | 0.07                                    |
|   | Molybdenum disulfide grease   | 0.11                                    |
|   | Machine oil                   | 0.15                                    |
| Steel, <sup>a</sup> cadmium-plated                                      | None added                    | 0.12                                    |
| Steel, <sup>a</sup> zinc-plated   | None added                    | 0.17                                    |
| Steel <sup>a</sup> /bronze  | None added                    | 0.15                                    |
| Corrosion-resistant steel or nickel-base alloys/silver-plated materials | None added                    | 0.14                                    |
| Titanium/steel <sup>a</sup>   | Graphite in petrolatum        | 0.08                                    |
| Titanium  | Molybdenum disulfide grease   | 0.10                                    |

<sup>a</sup>"Steel" includes carbon and low-alloy steels but not corrosion-resistant steels.

Where two materials are separated by a slash (/), either may be the bolt material; the other is the nut material.

**Preload Relaxation.**—Local yielding, due to excess bearing stress under nuts and bolt heads (caused by high local spots, rough surface finish, and lack of perfect squareness of bolt and nut bearing surfaces), may result in preload relaxation after preloads are first applied to a bolt. Bolt tension also may be unevenly distributed over the threads in a joint, so thread deformation may occur, causing the load to be redistributed more evenly over the threaded length. Preload relaxation occurs over a period of minutes to hours after the application of the preload, so retightening after several minutes to several days may be required. As a general rule, an allowance for loss of preload of about 10 per cent may be made when designing a joint.

Increasing the resilience of a joint will make it more resistant to local yielding, that is, there will be less loss of preload due to yielding. When practical, a joint-length to bolt-diameter ratio of 4 or more is recommended (e.g., a ¼-inch bolt and a 1-inch or greater joint length). Through bolts, far-side tapped holes, spacers, and washers can be used in the joint design to improve the joint-length to bolt-diameter ratio.

Over an extended period of time, preload may be reduced or completely lost due to vibration; temperature cycling, including changes in ambient temperature; creep; joint load; and other factors. An increase in the initial bolt preload or the use of thread-locking methods that prevent relative motion of the joint may reduce the problem of preload relaxation due to vibration and temperature cycling. Creep is generally a high-temperature effect, although some loss of bolt tension can be expected even at normal temperatures. Harder materials and creep-resistant materials should be considered if creep is a problem or high-temperature service of the joint is expected.

The mechanical properties of fastener materials vary significantly with temperature, and allowance must be made for these changes when ambient temperatures range beyond 30 to 200°F. Mechanical properties that may change include tensile strength, yield strength, and modulus of elasticity. Where bolts and flange materials are generically dissimilar, such as carbon steel and corrosion-resistant steel or steel and brass, differences in thermal expansion that might cause preload to increase or decrease must be taken into consideration.

**Methods of Applying and Measuring Preload.**—Depending on the tightening method, the accuracy of preload application may vary up to 25 per cent or more. Care must be taken to maintain the calibration of torque and load indicators. Allowance should be made for uncertainties in bolt load to prevent overstressing the bolts or failing to obtain sufficient preload. The method of tensioning should be based on the required accuracy and relative costs.



The most common methods of bolt tension control are indirect because it is usually difficult or impractical to measure the tension produced in each fastener during assembly. Table 2 lists the most frequently used methods of applying bolt preload and the approximate accuracy of each method. For many applications, fastener tension can be satisfactorily controlled within certain limits by applying a known torque to the fastener. Laboratory tests have shown that whereas a satisfactory torque tension relationship can be established for a given set of conditions, a change of any of the variables, such as fastener material, surface finish, and the presence or absence of lubrication, may severely alter the relationship. Because most of the applied torque is absorbed in intermediate friction, a change in the surface roughness of the bearing surfaces or a change in the lubrication will drastically affect the friction and thus the torque tension relationship. Regardless of the method or accuracy of applying the preload, tension will decrease in time if the bolt, nut, or washer seating faces deform under load, if the bolt stretches or creeps under tensile load, or if cyclic loading causes relative motion between joint members.

**Table 2. Accuracy of Bolt Preload Application Methods**

| Method                    | Accuracy | Method                     | Accuracy |
|---------------------------|----------|----------------------------|----------|
| By feel                   | ±35%     | Computer-controlled wrench |          |
| Torque wrench             | ±25%     | below yield (turn-of-nut)  | ±15%     |
| Turn-of-nut               | ±15%     | yield-point sensing        | ±8%      |
| Preload indicating washer | ±10%     | Bolt elongation            | ±3–5%    |
| Strain gages              | ±1%      | Ultrasonic sensing         | ±1%      |

Tightening methods using power drivers are similar in accuracy to equivalent manual methods.

**Elongation Measurement.**— Bolt elongation is directly proportional to axial stress when the applied stress is within the elastic range of the material. If both ends of a bolt are accessible, a micrometer measurement of bolt length made before and after the application of tension will ensure the required axial stress is applied. The elongation  $\delta$  in inches (mm) can be determined from the formula  $\delta = F_t \times L_B \div E$ , given the required axial stress  $F_t$  in psi (MPa), the bolt modulus of elasticity  $E$  in psi (MPa), and the effective bolt length  $L_B$  in inches (mm).  $L_B$ , as indicated in Fig. 2, includes the contribution of bolt area and ends (head and nut) and is calculated from:

$$L_B = \left(\frac{d_{ts}}{d}\right)^2 \times \left(L_S + \frac{H_B}{2}\right) + L_J - L_S + \frac{H_N}{2} \quad (6)$$

where  $d_{ts}$  is the thread stress diameter,  $d$  is the bolt diameter,  $L_S$  is the unthreaded length of the bolt shank,  $L_J$  is the overall joint length,  $H_B$  is the height of the bolt head, and  $H_N$  is the height of the nut.

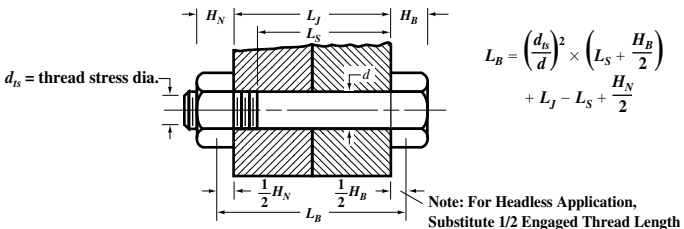


Fig. 2. Effective Length Applicable in Elongation Formulas

The micrometer method is most easily and accurately applied to bolts that are essentially uniform throughout the bolt length, that is, threaded along the entire length or that have only a few threads in the bolt grip area. If the bolt geometry is complex, such as tapered or stepped, the elongation is equal to the sum of the elongations of each section with allowances made for transitional stresses in bolt head height and nut engagement length.

The direct method of measuring elongation is practical only if both ends of a bolt are accessible. Otherwise, if the diameter of the bolt or stud is sufficiently large, an axial hole can be drilled, as shown in Fig. 3, and a micrometer depth gage or other means used to determine the change in length of the hole as the fastener is tightened. A similar method uses a special indicating bolt that has a blind axial hole containing a pin fixed at the bottom. The pin is usually made flush with the bolt head surface before load application. As the bolt is loaded, the elongation causes the end of the pin to move below the reference surface. The displacement of the pin can be converted directly into unit stress by means of a calibrated gage. In some bolts of this type, the pin is set a distance above the bolt so that the pin is flush with the bolt head when the required axial load is reached.

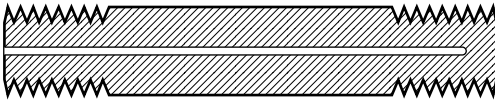


Fig. 3. Hole Drilled to Measure Elongation When One End of Stud or Bolt Is Not Accessible

The *ultrasonic method* of measuring elongation uses a sound pulse, generated at one end of a bolt, that travels the length of a bolt, bounces off the far end, and returns to the sound generator in a measured period of time. The time required for the sound pulse to return depends on the length of the bolt and the speed of sound in the bolt material. The speed of sound in the bolt depends on the material, the temperature, and the stress level. The ultrasonic measurement system can compute the stress, load, or elongation of the bolt at any time by comparing the pulse travel time in the loaded and unstressed conditions. In a similar method, measuring round-trip transit times of longitudinal and shear wave sonic pulses allows calculation of tensile stress in a bolt without consideration of bolt length. This method permits checking bolt tension at any time and does not require a record of the ultrasonic characteristics of each bolt at zero load.

To ensure consistent results, the ultrasonic method requires that both ends of the bolt be finished square to the bolt axis. The accuracy of ultrasonic measurement compares favorably with strain gage methods, but is limited by sonic velocity variations between bolts of the same material and by corrections that must be made for unstressed portions of the bolt heads and threads.

The *turn-of-nut method* applies preload by turning a nut through an angle that corresponds to a given elongation. The elongation of the bolt is related to the angle turned by the formula:  $\delta_B = \theta \times l \div 360$ , where  $\delta_B$  is the elongation in inches (mm),  $\theta$  is the turn angle of the nut in degrees, and  $l$  is the lead of the thread helix in inches (mm). Substituting  $F_t \times L_B \div E$  for elongation  $\delta_B$  in this equation gives the turn-of-nut angle required to attain preload  $F_t$ :

$$\theta = 360 \frac{F_t L_B}{E l} \quad (7)$$

where  $L_B$  is given by Equation (6), and  $E$  is the modulus of elasticity.

Accuracy of the turn-of-nut method is affected by elastic deformation of the threads, by roughness of the bearing surfaces, and by the difficulty of determining the starting point for measuring the angle. The starting point is usually found by tightening the nut enough to seat the contact surfaces firmly, and then loosening it just enough to release any tension and twisting in the bolt. The nut-turn angle will be different for each bolt size, length, mate-

rial, and thread lead. The preceding method of calculating the nut-turn angle also requires elongation of the bolt without a corresponding compression of the joint material. The turn-of-nut method, as just outlined, is not valid for joints with compressible gaskets or other soft material, or if there is a significant deformation of the nut and joint material relative to that of the bolt. The nut-turn angle would then have to be determined empirically using a simulated joint and a tension-measuring device.

The Japanese Industrial Standards (JIS) Handbook, *Fasteners and Screw Threads*, indicates that the turn-of-nut tightening method is applicable in both elastic and plastic region tightening. Refer to JIS B 1083 for more detail on this subject.

*Heating* causes a bolt to expand at a rate proportional to its coefficient of expansion. When a hot bolt and nut are fastened in a joint and cooled, the bolt shrinks and tension is developed. The temperature necessary to develop an axial stress,  $F_p$ , (when the stress is below the elastic limit) can be found as follows:

$$T = \frac{F_t}{Ee} + T_o \quad (8)$$

In this equation,  $T$  is the temperature in degrees Fahrenheit needed to develop the axial tensile stress  $F_t$  in psi,  $E$  is the bolt material modulus of elasticity in psi,  $e$  is the coefficient of linear expansion in in./in.-°F, and  $T_o$  is the temperature in degrees Fahrenheit to which the bolt will be cooled.  $T - T_o$  is, therefore, the temperature change of the bolt. In finite-element simulations, heating and cooling are frequently used to preload mesh elements in tension or compression. Equation (8) can be used to determine required temperature changes in such problems.

*Example:* A tensile stress of 40,000 psi is required for a steel bolt in a joint operating at 70°F. If  $E$  is  $30 \times 10^6$  psi and  $e$  is  $6.2 \times 10^{-6}$  in./in.-°F, determine the temperature of the bolt needed to develop the required stress on cooling.

$$T = \frac{40,000}{(30 \times 10^6)(6.2 \times 10^{-6})} + 70 = 285^\circ\text{F}$$

In practice, the bolt is heated slightly above the required temperature (to allow for some cooling while the nut is screwed down) and the nut is tightened snugly. Tension develops as the bolt cools. In another method, the nut is tightened snugly on the bolt, and the bolt is heated in place. When the bolt has elongated sufficiently, as indicated by inserting a thickness gage between the nut and the bearing surface of the joint, the nut is tightened. The bolt develops the required tension as it cools; however, preload may be lost if the joint temperature increases appreciably while the bolt is being heated.

**Calculating Thread Tensile-Stress Area.**—The tensile-stress area for Unified threads is based on a diameter equivalent to the mean of the pitch and minor diameters. The pitch and the minor diameters for Unified screw threads can be found from the major (nominal) diameter,  $d$ , and the screw pitch,  $P = 1/n$ , where  $n$  is the number of threads per inch, by use of the following formulas: the pitch diameter  $d_p = d - 0.649519 \times P$ ; the minor diameter  $d_m = d - 1.299038 \times P$ . The tensile stress area,  $A_s$ , for Unified threads can then be found as follows:

$$A_s = \frac{\pi}{4} \left( \frac{d_m + d_p}{2} \right)^2 \quad (9)$$

UNJ threads in accordance with MIL-S-8879 have a tensile thread area that is usually considered to be at the basic bolt pitch diameter, so for these threads,  $A_s = \pi d_p^2/4$ . The tensile stress area for Unified screw threads is smaller than this area, so the required tightening torque for UNJ threaded bolts is greater than for an equally stressed Unified threaded bolt

in an equivalent joint. To convert tightening torque for a Unified fastener to the equivalent torque required with a UNJ fastener, use the following relationship:

$$\text{UNJ}_{\text{torque}} = \left( \frac{d \times n - 0.6495}{d \times n - 0.9743} \right)^2 \times \text{Unified}_{\text{torque}} \quad (10)$$

where  $d$  is the basic thread major diameter, and  $n$  is the number of threads per inch.

The tensile stress area for metric threads is based on a diameter equivalent to the mean of the pitch diameter and a diameter obtained by subtracting  $\frac{1}{6}$  the height of the fundamental thread triangle from the external-thread minor diameter. The Japanese Industrial Standard JIS B 1082 (see also ISO 898/1) defines the stress area of metric screw threads as follows:

$$A_s = \frac{\pi}{4} \left( \frac{d_2 + d_3}{2} \right)^2 \quad (11)$$

In Equation (11),  $A_s$  is the stress area of the metric screw thread in  $\text{mm}^2$ ;  $d_2$  is the pitch diameter of the external thread in mm, given by  $d_2 = d - 0.649515 \times P$ ; and  $d_3$  is defined by  $d_3 = d_1 - H/6$ . Here,  $d$  is the nominal bolt diameter;  $P$  is the thread pitch;  $d_1 = d - 1.082532 \times P$  is the minor diameter of the external thread in mm; and  $H = 0.866025 \times P$  is the height of the fundamental thread triangle. Substituting the formulas for  $d_2$  and  $d_3$  into Equation (11) results in  $A_s = 0.7854(d - 0.9382P)^2$ .

The stress area,  $A_s$ , of Unified threads in  $\text{mm}^2$  is given in JIS B 1082 as:

$$A_s = 0.7854 \left( d - \frac{0.9743}{n} \times 25.4 \right)^2 \quad (12)$$

**Relation between Torque and Clamping Force.**—The Japanese Industrial Standard JIS B 1803 defines fastener tightening torque  $T_f$  as the sum of the bearing surface torque  $T_w$  and the shank (threaded) portion torque  $T_s$ . The relationship between the applied tightening torque and bolt preload  $F_{ft}$  is as follows:  $T_f = T_s + T_w = K \times F_f \times d$ . In the preceding,  $d$  is the nominal diameter of the screw thread, and  $K$  is the torque coefficient defined as follows:

$$K = \frac{1}{2d} \left( \frac{P}{\pi} + \mu_s d_2 \sec \alpha' + \mu_w D_w \right) \quad (13)$$

where  $P$  is the screw thread pitch;  $\mu_s$  is the coefficient of friction between threads;  $d_2$  is the pitch diameter of the thread;  $\mu_w$  is the coefficient of friction between bearing surfaces;  $D_w$  is the equivalent diameter of the friction torque bearing surfaces; and  $\alpha'$  is the flank angle at the ridge perpendicular section of the thread ridge, defined by  $\tan \alpha' = \tan \alpha \cos \beta$ , where  $\alpha$  is the thread half angle ( $30^\circ$ , for example), and  $\beta$  is the thread helix, or lead, angle.  $\beta$  can be found from  $\tan \beta = l \div 2\pi r$ , where  $l$  is the thread lead, and  $r$  is the thread radius (i.e., one-half the nominal diameter  $d$ ). When the bearing surface contact area is circular,  $D_w$  can be obtained as follows:

$$D_w = \frac{2}{3} \times \frac{D_o^3 - D_i^3}{D_o^2 - D_i^2} \quad (14)$$

where  $D_o$  and  $D_i$  are the outside and inside diameters, respectively, of the bearing surface contact area.

The torques attributable to the threaded portion of a fastener,  $T_s$ , and bearing surfaces of a joint,  $T_w$ , are as follows:

$$T_s = \frac{F_f}{2} \left( \frac{P}{\pi} + \mu_s d_2 \sec \alpha' \right) \quad (15)$$

$$T_w = \frac{F_f}{2} \mu_w D_w \quad (16)$$

where  $F_{fy}$ ,  $P$ ,  $\mu$ ,  $d_2$ ,  $\alpha'$ ,  $\mu_w$ , and  $D_w$  are as previously defined.

Tables 3 and 4 give values of torque coefficient  $K$  for coarse- and fine-pitch metric screw threads corresponding to various values of  $\mu_s$  and  $\mu_w$ . When a fastener material yields according to the shearing-strain energy theory, the torque corresponding to the yield clamping force (see Fig. 4) is  $T_{fy} = K \times F_{fy} \times d$ , where the yield clamping force  $F_{fy}$  is given by:

$$F_{fy} = \frac{\sigma_y A_s}{\sqrt{1 + 3 \left[ \frac{2}{d_A} \left( \frac{P}{\pi} + \mu_s d_2 \sec \alpha' \right) \right]^2}} \quad (17)$$

**Table 3. Torque Coefficients  $K$  for Metric Hexagon Head Bolt and Nut Coarse Screw Threads**

| Between Threads, $\mu_s$ | Coefficient of Friction<br>Between Bearing Surfaces, $\mu_w$ |       |       |       |       |       |       |       |       |       |
|--------------------------|--|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                          | 0.08   | 0.10  | 0.12  | 0.15  | 0.20  | 0.25  | 0.30  | 0.35  | 0.40  | 0.45  |
| 0.08                     | 0.117  | 0.130 | 0.143 | 0.163 | 0.195 | 0.228 | 0.261 | 0.293 | 0.326 | 0.359 |
| 0.10                     | 0.127  | 0.140 | 0.153 | 0.173 | 0.206 | 0.239 | 0.271 | 0.304 | 0.337 | 0.369 |
| 0.12                     | 0.138  | 0.151 | 0.164 | 0.184 | 0.216 | 0.249 | 0.282 | 0.314 | 0.347 | 0.380 |
| 0.15                     | 0.153  | 0.167 | 0.180 | 0.199 | 0.232 | 0.265 | 0.297 | 0.330 | 0.363 | 0.396 |
| 0.20                     | 0.180  | 0.193 | 0.206 | 0.226 | 0.258 | 0.291 | 0.324 | 0.356 | 0.389 | 0.422 |
| 0.25                     | 0.206  | 0.219 | 0.232 | 0.252 | 0.284 | 0.317 | 0.350 | 0.383 | 0.415 | 0.448 |
| 0.30                     | 0.232  | 0.245 | 0.258 | 0.278 | 0.311 | 0.343 | 0.376 | 0.409 | 0.442 | 0.474 |
| 0.35                     | 0.258  | 0.271 | 0.284 | 0.304 | 0.337 | 0.370 | 0.402 | 0.435 | 0.468 | 0.500 |
| 0.40                     | 0.285  | 0.298 | 0.311 | 0.330 | 0.363 | 0.396 | 0.428 | 0.461 | 0.494 | 0.527 |
| 0.45                     | 0.311  | 0.324 | 0.337 | 0.357 | 0.389 | 0.422 | 0.455 | 0.487 | 0.520 | 0.553 |

Values in the table are average values of torque coefficient calculated using: Equations (13) and (14) for  $K$  and  $D_w$ ; diameters  $d$  of 4, 5, 6, 8, 10, 12, 16, 20, 24, 30, and 36 mm; and selected corresponding pitches  $P$  and pitch diameters  $d_2$  according to JIS B 0205 (ISO 724) thread standard. Dimension  $D_i$  was obtained for a Class 2 fit without chamfer from JIS B 1001, Diameters of Clearance Holes and Counterbores for Bolts and Screws (equivalent to ISO 273-1979). The value of  $D_o$  was obtained by multiplying the reference dimension from JIS B 1002, width across the flats of the hexagon head, by 0.95.

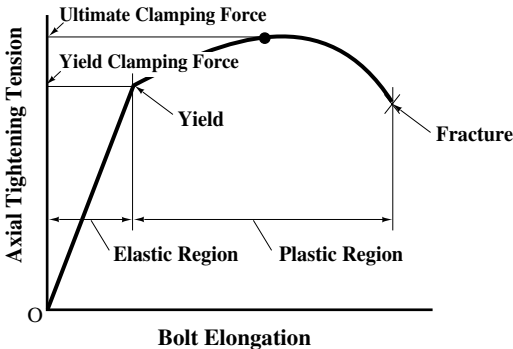


Fig. 4. The Relationship between Bolt Elongation and Axial Tightening Tension

**Table 4. Torque Coefficients  $K$  for Metric Hexagon Head Bolt and Nut Fine-Screw Threads**

|                             |                                   | Coefficient of Friction |       |       |       |       |       |       |       |       |
|-----------------------------|-----------------------------------|-------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Between Threads,<br>$\mu_s$ | Between Bearing Surfaces, $\mu_w$ |                         |       |       |       |       |       |       |       |       |
|                             | 0.08                              | 0.10                    | 0.12  | 0.15  | 0.20  | 0.25  | 0.30  | 0.35  | 0.40  | 0.45  |
| 0.08                        | 0.106                             | 0.118                   | 0.130 | 0.148 | 0.177 | 0.207 | 0.237 | 0.267 | 0.296 | 0.326 |
| 0.10                        | 0.117                             | 0.129                   | 0.141 | 0.158 | 0.188 | 0.218 | 0.248 | 0.278 | 0.307 | 0.337 |
| 0.12                        | 0.128                             | 0.140                   | 0.151 | 0.169 | 0.199 | 0.229 | 0.259 | 0.288 | 0.318 | 0.348 |
| 0.15                        | 0.144                             | 0.156                   | 0.168 | 0.186 | 0.215 | 0.245 | 0.275 | 0.305 | 0.334 | 0.364 |
| 0.20                        | 0.171                             | 0.183                   | 0.195 | 0.213 | 0.242 | 0.272 | 0.302 | 0.332 | 0.361 | 0.391 |
| 0.25                        | 0.198                             | 0.210                   | 0.222 | 0.240 | 0.270 | 0.299 | 0.329 | 0.359 | 0.389 | 0.418 |
| 0.30                        | 0.225                             | 0.237                   | 0.249 | 0.267 | 0.297 | 0.326 | 0.356 | 0.386 | 0.416 | 0.445 |
| 0.35                        | 0.252                             | 0.264                   | 0.276 | 0.294 | 0.324 | 0.353 | 0.383 | 0.413 | 0.443 | 0.472 |
| 0.40                        | 0.279                             | 0.291                   | 0.303 | 0.321 | 0.351 | 0.381 | 0.410 | 0.440 | 0.470 | 0.500 |
| 0.45                        | 0.306                             | 0.318                   | 0.330 | 0.348 | 0.378 | 0.408 | 0.437 | 0.467 | 0.497 | 0.527 |

Values in the table are average values of torque coefficient calculated using Equations (13) and (14) for  $K$  and  $D_w$ ; diameters  $d$  of 8, 10, 12, 16, 20, 24, 30, and 36 mm; and selected respective pitches  $P$  and pitch diameters  $d_2$  according to JIS B 0207 thread standard (ISO 724). Dimension  $D_i$  was obtained for a Class 1 fit without chamfer from JIS B 1001, Diameters of Clearance Holes and Counterbores for Bolts and Screws (equivalent to ISO 273-1979). The value of  $D_o$  was obtained by multiplying the reference dimension from JIS B 1002 (small type series), width across the flats of the hexagon head, by 0.95.

In Equation (17),  $\sigma_y$  is the yield point or proof stress of the bolt,  $A_s$  is the stress area of the thread, and  $d_A = (4A_s/\pi)^{1/2}$  is the diameter of a circle having an area equal to the stress area of the thread. The other variables have been identified previously.

*Example:* Find the torque required to tighten a 10-mm coarse-threaded ( $P = 1.5$ ) grade 8.8 bolt to yield assuming that both the thread- and bearing-friction coefficients are 0.12.

*Solution:* From Equation (17), calculate  $F_{fy}$  and then solve  $T_{fy} = KF_{fy}d$  to obtain the torque required to stress the bolt to the yield point.

$$\sigma_y = 800 \text{ N/mm}^2 \text{ (MPa) (minimum, based on 8.8 grade rating)}$$

$$A_s = 0.7854(10 - 0.9382 \times 1.5)^2 = 57.99 \text{ mm}^2$$

$$d_A = (4A_s/\pi)^{1/2} = 8.6 \text{ mm}$$

$$d_2 = 9.026 \text{ mm (see JIS B 0205 or ISO 724)}$$

Find  $\alpha'$  from  $\tan \alpha' = \tan \alpha \cos \beta$  using:

$$\alpha = 30^\circ; \tan \beta = l \div 2\pi r; l = P = 1.5; \text{ and } r = d \div 2 = 5 \text{ mm}$$

$$\tan \beta = 1.5 \div 10\pi = 0.048, \text{ therefore } \beta = 2.73^\circ$$

$$\tan \alpha' = \tan \alpha \cos \beta = \tan 30^\circ \times \cos 2.73^\circ = 0.577, \text{ and } \alpha' = 29.97^\circ$$

Solving Equation (17) gives the yield clamping force as follows:

$$F_{fy} = \frac{800 \times 58.0}{\sqrt{1 + 3 \left[ \frac{2}{8.6} \left( \frac{1.5}{\pi} + 0.12 \times 9.026 \times \sec 29.97^\circ \right) \right]^2}} = 38,075 \text{ N}$$

$K$  can be determined from Tables 3 (coarse thread) and Tables 4 (fine thread) or from Equations (13) and (14). From Table 3, for  $\mu_s$  and  $\mu_w$  equal to 0.12,  $K = 0.164$ . The yield-point tightening torque can then be found from  $T_{fy} = K \times F_{fy} \times d = 0.164 \times 38,075 \times 10 = 62.4 \times 10^3 \text{ N}\cdot\text{mm} = 62.4 \text{ N}\cdot\text{m}$ .

**Obtaining Torque and Friction Coefficients.**—Given suitable test equipment, the torque coefficient  $K$  and friction coefficients between threads  $\mu_s$  or between bearing surfaces  $\mu_w$  can be determined experimentally as follows: Measure the value of the axial tight-

ening tension and the corresponding tightening torque at an arbitrary point in the 50 to 80 per cent range of the bolt yield point or proof stress (for steel bolts, use the minimum value of the yield point or proof stress multiplied by the stress area of the bolt). Repeat this test several times and average the results. The tightening torque may be considered as the sum of the torque on the threads plus the torque on the bolt head- or nut-to-joint bearing surface. The torque coefficient can be found from  $K = T_f \div F_f \times d$ , where  $F_f$  is the measured axial tension, and  $T_f$  is the measured tightening torque.

To measure the coefficient of friction between threads or bearing surfaces, obtain the total tightening torque and that portion of the torque due to the thread or bearing surface friction. If only tightening torque and the torque on the bearing surfaces can be measured, then the difference between these two measurements can be taken as the thread-tightening torque. Likewise, if only the tightening torque and threaded-portion torque are known, the torque due to bearing can be taken as the difference between the known torques. The coefficients of friction between threads and bearing surfaces, respectively, can be obtained from the following:

$$\mu_s = \frac{2T_s \cos \alpha'}{d_2 F_f} - \cos \alpha' \tan \beta \quad (18) \quad \mu_w = \frac{2T_w}{D_w F_f} \quad (19)$$

As before,  $T_s$  is the torque attributable to the threaded portion of the screw,  $T_w$  is the torque due to bearing,  $D_w$  is the equivalent diameter of friction torque on bearing surfaces according to Equation (14), and  $F_f$  is the measured axial tension.

**Torque-Tension Relationships.**—Torque is usually applied to develop an axial load in a bolt. To achieve the desired axial load in a bolt, the torque must overcome friction in the threads and friction under the nut or bolt head. In Fig. 5, the axial load  $P_B$  is a component of the normal force developed between threads. The normal-force component perpendicular to the thread helix is  $P_{N\beta}$  and the other component of this force is the torque load  $P_B \tan \beta$  that is applied in tightening the fastener. Assuming the turning force is applied at the pitch diameter of the thread, the torque  $T_1$  needed to develop the axial load is  $T_1 = P_B \times \tan \beta \times d_2/2$ . Substituting  $\tan \beta = l \div \pi d_2$  into the previous expression gives  $T_1 = P_B \times l \div 2\pi$ .

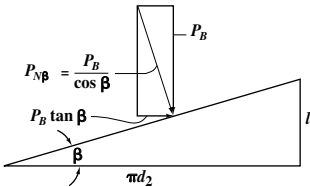


Fig. 5. Free Body Diagram of Thread Helix Forces

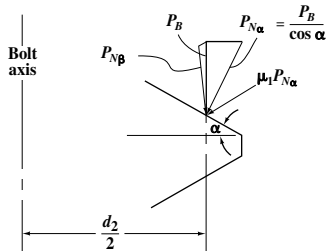


Fig. 6. Thread Friction Force

In Fig. 6, the normal-force component perpendicular to the thread flanks is  $P_{N\alpha}$ . With a coefficient of friction  $\mu_1$  between the threads, the friction load is equal to  $\mu_1 P_{N\alpha}$ , or  $\mu_1 P_B \div \cos \alpha$ . Assuming the force is applied at the pitch diameter of the thread, the torque  $T_2$  to overcome thread friction is given by:

$$T_2 = \frac{d_2 \mu_1 P_B}{2 \cos \alpha} \quad (20)$$

With the coefficient of friction  $\mu_2$  between a nut or bolt-head pressure face and a component face, as in Fig. 7, the friction load is equal to  $\mu_2 P_B$ . Assuming the force is applied midway between the nominal (bolt) diameter  $d$  and the pressure-face diameter  $b$ , the torque  $T_3$  to overcome the nut or bolt underhead friction is:

$$T_3 = \frac{d+b}{4} \mu_2 P_B \quad (21)$$

The total torque,  $T$ , required to develop axial bolt load,  $P_B$ , is equal to the sum of the torques  $T_1$ ,  $T_2$ , and  $T_3$  as follows:

$$T = P_B \left( \frac{l}{2\pi} + \frac{d_2 \mu_1}{2 \cos \alpha} + \frac{(d+b)\mu_2}{4} \right) \quad (22)$$

For a fastener system with  $60^\circ$  threads,  $\alpha = 30^\circ$  and  $d_2$  is approximately  $0.92d$ . If no loose washer is used under the rotated nut or bolt head,  $b$  is approximately  $1.5d$  and Equation (22) reduces to:

$$T = P_B [0.159 \times l + d(0.531 \mu_1 + 0.625 \mu_2)] \quad (23)$$

In addition to the conditions of Equation (23), if the thread and bearing friction coefficients,  $\mu_1$  and  $\mu_2$ , are equal (which is not necessarily so), then  $\mu_1 = \mu_2 = \mu$ , and the previous equation reduces to:

$$T = P_B (0.159l + 1.156\mu d) \quad (24)$$

*Example:* Estimate the torque required to tighten a UNC  $\frac{1}{2}$ -13 grade 8 steel bolt to a pre-load equivalent to 55 per cent of the minimum tensile bolt strength. Assume that the bolt is unplated and both the thread and bearing friction coefficients equal 0.15.

*Solution:* The minimum tensile strength for SAE grade 8 bolt material is 150,000 psi (from page 1508). To use Equation (24), find the stress area of the bolt using Equation (9) with  $P = 1/13$ ,  $d_m = d - 1.2990P$ , and  $d_p = d - 0.6495P$ , and then calculate the necessary preload,  $P_B$ , and the applied torque,  $T$ .

$$A_s = \frac{\pi}{4} \left( \frac{0.4500 + 0.4001}{2} \right)^2 = 0.1419 \text{ in.}^2$$

$$P_B = \sigma_{\text{allow}} \times A_s = 0.55 \times 150,000 \times 0.1419 = 11,707 \text{ lb}_f$$

$$T = 11,707 \left( \frac{0.159}{13} + 1.156 \times 0.15 \times 0.500 \right) = 1158 \text{ lb-in.} = 96.5 \text{ lb-ft}$$

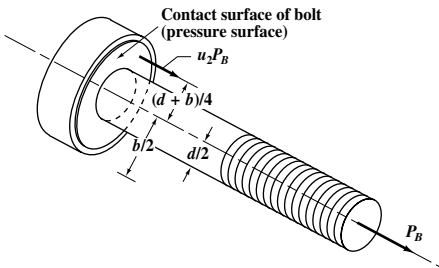
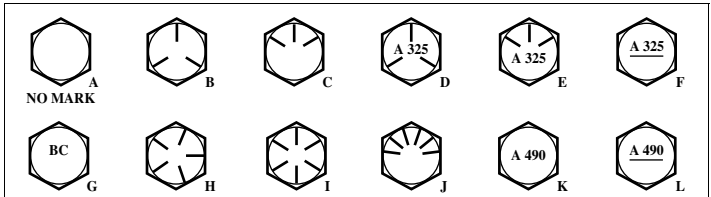


Fig. 7. Nut or Bolt Head Friction Force



**Grade Marks and Material Properties for Bolts and Screws.**—Bolts, screws, and other fasteners are marked on the head with a symbol that identifies the grade of the fastener. The grade specification establishes the minimum mechanical properties that the fastener must meet. Additionally, industrial fasteners must be stamped with a registered head mark that identifies the manufacturer. The grade identification table identifies the grade markings and gives mechanical properties for some commonly used ASTM and SAE steel fasteners. Metric fasteners are identified by property grade marks, which are specified in ISO and SAE standards. These marks are discussed with metric fasteners.

**Grade Identification Marks and Mechanical Properties of Bolts and Screws**



| Identifier | Grade               | Size (in.) | Min. Strength (10 <sup>3</sup> psi) |         |       | Material & Treatment |
|------------|---------------------|------------|-------------------------------------|---------|-------|----------------------|
|            |                     |            | Proof                               | Tensile | Yield |                      |
| A          | SAE Grade 1         | ¼ to 1½    | 33                                  | 60      | 36    | 1                    |
|            | ASTM A307           | ¼ to 1½    | 33                                  | 60      | 36    | 3                    |
|            | SAE Grade 2         | ¼ to ¾     | 55                                  | 74      | 57    | 1                    |
|            |                     | ¾ to 1½    | 33                                  | 60      | 36    |                      |
|            | SAE Grade 4         | ¼ to 1½    | 65                                  | 115     | 100   | 2, a                 |
| B          | SAE Grade 5         | ¼ to 1     | 85                                  | 120     | 92    | 2, b                 |
|            | ASTM A449           | 1⅛ to 1½   | 74                                  | 105     | 81    |                      |
|            | ASTM A449           | 1¾ to 3    | 55                                  | 90      | 58    |                      |
| C          | SAE Grade 5.2       | ¼ to 1     | 85                                  | 120     | 92    | 4, b                 |
| D          | ASTM A325, Type 1   | ½ to 1     | 85                                  | 120     | 92    | 2, b                 |
|            |                     | 1⅛ to 1½   | 74                                  | 105     | 81    |                      |
| E          | ASTM A325, Type 2   | ½ to 1     | 85                                  | 120     | 92    | 4, b                 |
|            |                     | 1⅛ to 1½   | 74                                  | 105     | 81    |                      |
| F          | ASTM A325, Type 3   | ½ to 1     | 85                                  | 120     | 92    | 5, b                 |
|            |                     | 1⅛ to 1½   | 74                                  | 105     | 81    |                      |
| G          | ASTM A354, Grade BC | ¼ to 2½    | 105                                 | 125     | 109   | 5, b                 |
|            |                     | 2¾ to 4    | 95                                  | 115     | 99    |                      |
| H          | SAE Grade 7         | ¼ to 1½    | 105                                 | 133     | 115   | 7, b                 |
| I          | SAE Grade 8         | ¼ to 1½    | 120                                 | 150     | 130   | 7, b                 |
|            | ASTM A354, Grade BD | ¼ to 1½    | 120                                 | 150     | 130   | 6, b                 |
| J          | SAE Grade 8.2       | ¼ to 1     | 120                                 | 150     | 130   | 4, b                 |
| K          | ASTM A490, Type 1   | ½ to 1½    | 120                                 | 150     | 130   | 6, b                 |
| L          | ASTM A490, Type 3   |            |                                     |         |       | 5, b                 |

Material Steel: 1—low or medium carbon; 2—medium carbon; 3—low carbon; 4—low-carbon martensite; 5—weathering steel; 6—alloy steel; 7— medium-carbon alloy. Treatment: a—cold drawn; b—quench and temper.

**Detecting Counterfeit Fasteners.**—Fasteners that have markings identifying them as belonging to a specific grade or property class are counterfeit if they do not meet the standards established for that class. Counterfeit fasteners may break unexpectedly at smaller loads than expected. Generally, these fasteners are made from the wrong material or they are not properly strengthened during manufacture. Either way, counterfeit fasteners can lead to dangerous failures in assemblies. The law now requires testing of fasteners used in some critical applications. Detection of counterfeit fasteners is difficult because the counterfeits look genuine. The only sure way to determine if a fastener meets its specification is to test it. However, reputable distributors will assist in verifying the authenticity of the fasteners they sell. For important applications, fasteners can be checked to determine whether they perform according to the standard. Typical laboratory checks used to detect fakes include testing hardness, elongation, and ultimate loading, and a variety of chemical tests.

**Mechanical Properties and Grade Markings of Nuts.**—Three grades of hex and square nuts designated Grades 2, 5, and 8 are specified by the SAE J995 standard covering nuts in the  $\frac{1}{4}$ - to  $1\frac{1}{2}$ -inch diameter range. Grades 2, 5, and 8 nuts roughly correspond to the SAE specified bolts of the same grade. Additional specifications are given for miscellaneous nuts such as hex jam nuts, hex slotted nuts, heavy hex nuts, etc. Generally speaking, use nuts of a grade equal to or greater than the grade of the bolt being used. Grade 2 nuts are not required to be marked, however, all Grades 5 and 8 nuts in the  $\frac{1}{4}$ - to  $1\frac{1}{2}$ -inch range must be marked in one of three ways: Grade 5 nuts may be marked with a dot on the face of the nut and a radial or circumferential mark at  $120^\circ$  counterclockwise from the dot; or a dot at one corner of the nut and a radial line at  $120^\circ$  clockwise from the nut, or one notch at each of the six corners of the nut. Grade 8 nuts may be identified by a dot on the face of the nut with a radial or circumferential mark at  $60^\circ$  counterclockwise from the dot; or a dot at one corner of the nut and a radial line at  $60^\circ$  clockwise from the nut, or two notches at each of the six corners of the nut.

**Working Strength of Bolts.**—When the nut on a bolt is tightened, an initial tensile load is placed on the bolt that must be taken into account in determining its safe working strength or external load-carrying capacity. The total load on the bolt theoretically varies from a maximum equal to the sum of the initial and external loads (when the bolt is absolutely rigid and the parts held together are elastic) to a minimum equal to either the initial or external loads, whichever is the greater (where the bolt is elastic and the parts held together are absolutely rigid). No material is absolutely rigid, so in practice the total load values fall somewhere between these maximum and minimum limits, depending upon the relative elasticity of the bolt and joint members.

Some experiments made at Cornell University to determine the initial stress due to tightening nuts on bolts sufficiently to make a packed joint steam-tight showed that experienced mechanics tighten nuts with a pull roughly proportional to the bolt diameter. It was also found that the stress due to nut tightening was often sufficient to break a  $\frac{1}{2}$ -inch (12.7-mm) bolt, but not larger sizes, assuming that the nut is tightened by an experienced mechanic. It may be concluded, therefore, that bolts smaller than  $\frac{5}{8}$  inch (15.9 mm) should not be used for holding cylinder heads or other parts requiring a tight joint. As a result of these tests, the following empirical formula was established for the working strength of bolts used for packed joints or joints where the elasticity of a gasket is greater than the elasticity of the studs or bolts.

$$W = S_t(0.55d^2 - 0.25d)$$

In this formula,  $W$  = working strength of bolt or permissible load, in pounds, after allowance is made for initial load due to tightening;  $S_t$  = allowable working stress in tension, pounds per square inch; and  $d$  = nominal outside diameter of stud or bolt, inches. A somewhat more convenient formula, and one that gives approximately the same results, is

$$W = S_t(A - 0.25d)$$

In this formula,  $W$ ,  $S_t$ , and  $d$  are as previously given, and  $A$  = area at the root of the thread, square inches.

*Example:* What is the working strength of a 1-inch bolt that is screwed tightly in a packed joint when the allowable working stress is 10,000 psi?

$$W = 10,000(0.55 \times 1 - 0.25 \times 1) = 3000 \text{ pounds approx.}$$

**Formulas for Stress Areas and Lengths of Engagement of Screw Threads.**—The critical areas of stress of mating screw threads are: 1) The effective cross-sectional area, or tensile-stress area, of the external thread; 2) the shear area of the external thread, which depends principally on the minor diameter of the tapped hole; and 3) the shear area of the internal thread, which depends principally on the major diameter of the external thread. The relation of these three stress areas to each other is an important factor in determining how a threaded connection will fail, whether by breakage in the threaded section of the screw (or bolt) or by stripping of either the external or internal thread.

If failure of a threaded assembly should occur, it is preferable for the screw to break rather than have either the external or internal thread strip. In other words, the length of engagement of mating threads should be sufficient to carry the full load necessary to break the screw without the threads stripping.

If mating internal and external threads are manufactured of materials having equal tensile strengths, then to prevent stripping of the external thread, the length of engagement should be not less than that given by [Formula \(1\)](#):

$$L_e = \frac{2 \times A_t}{3.1416 K_n \max[\frac{1}{2} + 0.57735n(E_s \min - K_n \max)]} \quad (1)$$

In this formula, the factor of 2 means that it is assumed that the area of the screw in shear must be twice the tensile-stress area to attain the full strength of the screw (this value is slightly larger than required and thus provides a small factor of safety against stripping);  $L_e$  = length of engagement, in inches;  $n$  = number of threads per inch;  $K_n \max$  = maximum minor diameter of internal thread;  $E_s \min$  = minimum pitch diameter of external thread for the class of thread specified; and  $A_t$  = tensile-stress area of screw thread given by [Formula \(2a\)](#) or [\(2b\)](#) or the thread tables for Unified threads, [Tables 4a](#) through [5h](#) starting on page [1763](#), which are based on [Formula \(2a\)](#).

For steels of up to 100,000 psi ultimate tensile strength,

$$A_t = 0.7854 \left( D - \frac{0.9743}{n} \right)^2 \quad (2a)$$

For steels of over 100,000 psi ultimate tensile strength,

$$A_t = 3.1416 \left( \frac{E_s \min}{2} - \frac{0.16238}{n} \right)^2 \quad (2b)$$

In these formulas,  $D$  = basic major diameter of the thread and the other symbols have the same meanings as before.

*Stripping of Internal Thread:* If the internal thread is made of material of lower strength than the external thread, stripping of the internal thread may take place before the screw breaks. To determine whether this condition exists, it is necessary to calculate the factor  $J$  for the relative strength of the external and internal threads given by [Formula \(3\)](#):

$$J = \frac{A_s \times \text{tensile strength of external thread material}}{A_n \times \text{tensile strength of internal thread material}} \quad (3)$$

If  $J$  is less than or equal to 1, the length of engagement determined by [Formula \(1\)](#) is adequate to prevent stripping of the internal thread; if  $J$  is greater than 1, the required length of engagement  $Q$  to prevent stripping of the internal thread is obtained by multiplying the length of engagement  $L_e$ , [Formula \(1\)](#), by  $J$ :

$$Q = JL_e \quad (4)$$

In [Formula \(3\)](#),  $A_s$  and  $A_n$  are the shear areas of the external and internal threads, respectively, given by [Formulas \(5\)](#) and [\(6\)](#):

$$A_s = 3.1416nL_eK_n \max \left[ \frac{1}{2n} + 0.57735(E_s \text{ min} - K_n \text{ max}) \right] \quad (5)$$

$$A_n = 3.1416nL_eD_s \text{ min} \left[ \frac{1}{2n} + 0.57735(D_s \text{ min} - E_n \text{ max}) \right] \quad (6)$$

In these formulas,  $n$  = threads per inch;  $L_e$  = length of engagement from [Formula \(1\)](#);  $K_n \text{ max}$  = maximum minor diameter of internal thread;  $E_s \text{ min}$  = minimum pitch diameter of the external thread for the class of thread specified;  $D_s \text{ min}$  = minimum major diameter of the external thread; and  $E_n \text{ max}$  = maximum pitch diameter of internal thread.

**Load to Break Threaded Portion of Screws and Bolts.**—The direct tensile load  $P$  to break the threaded portion of a screw or bolt (assuming that no shearing or torsional stresses are acting) can be determined from the following formula:

$$P = SA_t$$

where  $P$  = load in pounds to break screw;  $S$  = ultimate tensile strength of material of screw or bolt in pounds per square inch; and  $A_t$  = tensile-stress area in square inches from [Formula \(2a\)](#), [\(2b\)](#), or from the screw thread tables.

**Lock Wire Procedure Detail.**—Wire ties are frequently used as a locking device for bolted connections to prevent loosening due to vibration and loading conditions, or tampering. The use of safety wire ties is illustrated in [Figs. 1](#) and [2](#) below. The illustrations assume the use of right-hand threaded fasteners and the following additional rules apply:

1) No more than three (3) bolts may be tied together; 2) Bolt heads may be tied as shown only when the female thread receiver is captive; 3) Pre-drilled nuts may be tied in a fashion similar to that illustrated with the following conditions. a) Nuts must be heat-treated; and b) Nuts are factory drilled for use with lock wire.

4) Lock wire must fill a minimum of 75% of the drilled hole provided for the use of lock wire; and 5) Lock wire must be aircraft quality stainless steel of 0.508 mm (0.020 inch) diameter, 0.8128 mm (0.032 inch) diameter, or 1.067 mm (0.042 inch) diameter. Diameter of lock wire is determined by the thread size of the fastener to be safe-tied. a) Thread sizes of 6 mm (0.25 inch) and smaller use 0.508mm (0.020 inch) wire; b) Thread sizes of 6 mm (0.25 inch) to 12 mm (0.5 inch) use 0.8128 mm (0.032 inch) wire; c) Thread sizes > 12 mm (0.5 inch) use 1.067 mm (0.042 inch) wire; and d) The larger wire may be used in smaller bolts in cases of convenience, but smaller wire must not be used in larger fastener sizes.



Fig. 1. Three (3) Bolt Procedure



Fig. 2. Two (2) Bolt Procedure

## INCH THREADED FASTENERS

Dimensions of bolts, screws, nuts, and washers used in machine construction are given here. For data on thread forms, see the section *SCREW THREAD SYSTEMS* starting on page 1725.

**American Square and Hexagon Bolts, Screws, and Nuts.**—The 1941 American Standard ASA B18.2 covered head dimensions only. In 1952 and 1955 the Standard was revised to cover the entire product. Some bolt and nut classifications were simplified by elimination or consolidation in agreements reached with the British and Canadians. In 1965 ASA B18.2 was redesignated into two standards: B18.2.1 covering square and hexagon bolts and screws including hexagon cap screws and lag screws and B18.2.2 covering square and hexagon nuts. In B18.2.1-1965, hexagon head cap screws and finished hexagon bolts were consolidated into a single product heavy semifinished hexagon bolts and heavy finished hexagon bolts were consolidated into a single product; regular semifinished hexagon bolts were eliminated; a new tolerance pattern for all bolts and screws and a positive identification procedure for determining whether an externally threaded product should be designated as a bolt or screw were established. Also included in this standard are heavy hexagon bolts and heavy hexagon structural bolts. In B18.2.2-1965, regular semifinished nuts were discontinued; regular hexagon and heavy hexagon nuts in sizes  $\frac{1}{4}$  through 1 inch, finished hexagon nuts in sizes larger than  $1\frac{1}{2}$  inches, washer-faced semifinished style of finished nuts in sizes  $\frac{5}{8}$ -inch and smaller and heavy series nuts in sizes  $\frac{7}{16}$ -inch and smaller were eliminated.

Further revisions and refinements include the addition of askew head bolts and hex head lag screws and the specifying of countersunk diameters for the various hex nuts. Heavy hex structural bolts and heavy hex nuts were moved to a new structural applications standard. Additionally, B18.2.1 has been revised to allow easier conformance to Public Law 101-592. All these changes are reflected in ANSI/ASME B18.2.1-1996, and ANSI/ASME B18.2.2-1987 (R1999).

**Unified Square and Hexagon Bolts, Screws, and Nuts.**—Items that are recognized in the Standard as “unified” dimensionally with British and Canadian standards are shown in bold-face in certain tables.

The other items in the same tables are based on formulas accepted and published by the British for sizes outside the ranges listed in their standards which, as a matter of information, are BS 1768:1963 (obsolescent) for Precision (Normal Series) Unified Hexagon Bolts, Screws, Nuts (UNC and UNF Threads) and B.S. 1769 and amendments for Black (Heavy Series) Unified Hexagon Bolts, etc. Tolerances applied to comparable dimensions of American and British Unified bolts and nuts may differ because of rounding off practices and other factors.

**Differentiation between Bolt and Screw.**—A bolt is an externally threaded fastener designed for insertion through holes in assembled parts, and is normally intended to be tightened or released by torquing a nut.

A screw is an externally threaded fastener capable of being inserted into holes in assembled parts, of mating with a preformed internal thread or forming its own thread and of being tightened or released by torquing the head.

An externally threaded fastener which is prevented from being turned during assembly, and which can be tightened or released only by torquing a nut is a *bolt*. (Example: round head bolts, track bolts, plow bolts.)

An externally threaded fastener that has a thread form which prohibits assembly with a nut having a straight thread of multiple pitch length is a *screw*. (Example: wood screws, tapping screws.)

An externally threaded fastener that must be assembled with a nut to perform its intended service is a *bolt*. (Example: heavy hex structural bolt.)

An externally threaded fastener that must be torqued by its head into a tapped or other preformed hole to perform its intended service is a *screw*. (Example: square head set screw.)

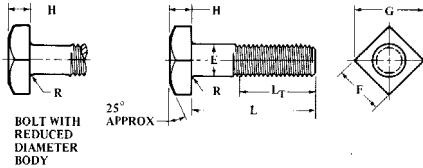


Fig. 1. Square Bolts (Table 1)

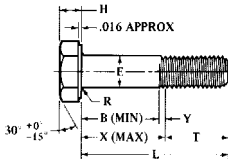


Fig. 2. Heavy Hex Structural Bolts (Table 2)

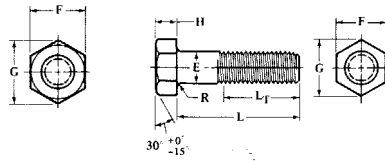


Fig. 3. Hex Bolts, Heavy Hex Bolts (Table 3)

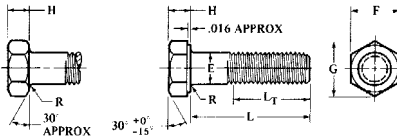


Fig. 4. Hex Cap Screws, Heavy Hex Screws (Table 4)

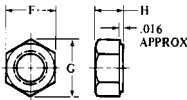


Fig. 5. Hex Nuts, Heavy Hex Nuts (Table 7)

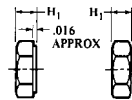


Fig. 6. Hex Jam Nuts, Heavy Hex Jam Nuts (Table 7)

**Square and Hex Bolts, Screws, and Nuts.**—The dimensions for square and hex bolts and screws given in the following tables have been taken from American National Standard ANSI/ASME B18.2.1-1996 and for nuts from American National Standard ANSI/ASME B18.2.2-1987 (R1999) Reference should be made to these Standards for information or data not found in the following text and tables:

*Designation:* Bolts and screws should be designated by the following data in the sequence shown: nominal size (fractional and decimal equivalent); threads per inch (omit for lag screws); product length for bolts and screws (fractional or two-place decimal equivalent); product name; material, including specification, where necessary; and protective finish, if required. Examples: (1)  $\frac{3}{8}$ -16  $\times$   $1\frac{1}{2}$  Square Bolt, Steel, Zinc Plated; (2)  $\frac{1}{2}$ -13  $\times$  3

Hex Cap Screw, SAE Grade 8 Steel; and (3) .75 × 5.00 Hex Lag Screw, Steel. (4) 1/2-13 Square Nut, Steel, Zinc Plated; (5) 3/4-16 Heavy Hex Nut, SAE J995 Grade 5 Steel; and (6) 1000-8 Hex Thick Slotted Nut, ASTM F594 (Alloy Group 1) Corrosion-Resistant Steel.

**Table 1. American National Standard and Unified Standard Square Bolts**  
ANSI/ASME B18.2.1-1996

| SQUARE BOLTS (Fig. 1)                           |               |                          |         |                      |              |                        |              |               |              |              |   |
|---|---------------|--------------------------|---------|----------------------|--------------|------------------------|--------------|---------------|--------------|--------------|---|
| Nominal Size <sup>a</sup> or Basic Product Dia. |               | Body Dia. <sup>b</sup> E |         | Width Across Flats F |              | Width Across Corners G |              | Head Height H |              |              | Thread Length <sup>c</sup> L <sub>T</sub> |
|   |               | Max.                     | Basic   | Max.                 | Min.         | Max.                   | Min.         | Basic         | Max.         | Min.         | Nom.                                      |
| 1/4   | <b>0.2500</b> | <b>0.260</b>             | 3/8     | <b>0.375</b>         | <b>0.362</b> | <b>0.530</b>           | <b>0.498</b> | 11/64         | <b>0.188</b> | <b>0.156</b> | 0.750                                     |
| 5/16  | <b>0.3125</b> | <b>0.324</b>             | 1/2     | <b>0.500</b>         | <b>0.484</b> | <b>0.707</b>           | <b>0.665</b> | 13/64         | <b>0.220</b> | <b>0.186</b> | 0.875                                     |
| 3/8   | <b>0.3750</b> | <b>0.388</b>             | 9/16    | <b>0.562</b>         | <b>0.544</b> | <b>0.795</b>           | <b>0.747</b> | 1/4           | <b>0.268</b> | <b>0.232</b> | 1.000                                     |
| 7/16  | <b>0.4375</b> | <b>0.452</b>             | 5/8     | <b>0.625</b>         | <b>0.603</b> | <b>0.884</b>           | <b>0.828</b> | 19/64         | <b>0.316</b> | <b>0.278</b> | 1.125                                     |
| 1/2   | <b>0.5000</b> | <b>0.515</b>             | 3/4     | <b>0.750</b>         | <b>0.725</b> | <b>1.061</b>           | <b>0.995</b> | 21/64         | <b>0.348</b> | <b>0.308</b> | 1.250                                     |
| 5/8   | <b>0.6250</b> | <b>0.642</b>             | 15/16   | <b>0.938</b>         | <b>0.906</b> | <b>1.326</b>           | <b>1.244</b> | 27/64         | <b>0.444</b> | <b>0.400</b> | 1.500                                     |
| 3/4   | <b>0.7500</b> | <b>0.768</b>             | 1 1/8   | <b>1.125</b>         | <b>1.088</b> | <b>1.591</b>           | <b>1.494</b> | 1/2           | <b>0.524</b> | <b>0.476</b> | 1.750                                     |
| 7/8   | <b>0.8750</b> | <b>0.895</b>             | 1 5/16  | <b>1.312</b>         | <b>1.269</b> | <b>1.856</b>           | <b>1.742</b> | 19/32         | <b>0.620</b> | <b>0.568</b> | 2.000                                     |
| <b>1</b>  | <b>1.0000</b> | <b>1.022</b>             | 1 1/2   | <b>1.500</b>         | <b>1.450</b> | <b>2.121</b>           | <b>1.991</b> | 21/32         | <b>0.684</b> | <b>0.628</b> | 2.250                                     |
| 1 1/8   | <b>1.1250</b> | <b>1.149</b>             | 1 11/16 | <b>1.688</b>         | <b>1.631</b> | <b>2.386</b>           | <b>2.239</b> | 3/4           | <b>0.780</b> | <b>0.720</b> | 2.500                                     |
| 1 1/4   | <b>1.2500</b> | <b>1.277</b>             | 1 7/8   | <b>1.875</b>         | <b>1.812</b> | <b>2.652</b>           | <b>2.489</b> | 27/32         | <b>0.876</b> | <b>0.812</b> | 2.750                                     |
| 1 3/8   | <b>1.3750</b> | <b>1.404</b>             | 2 1/16  | <b>2.602</b>         | <b>1.994</b> | <b>2.917</b>           | <b>2.738</b> | 29/32         | <b>0.940</b> | <b>0.872</b> | 3.000                                     |
| 1 1/2   | <b>1.5000</b> | <b>1.531</b>             | 2 1/4   | <b>2.250</b>         | <b>2.175</b> | <b>3.182</b>           | <b>2.986</b> | <b>1</b>      | <b>1.036</b> | <b>0.964</b> | 3.250                                     |

<sup>a</sup> Where specifying nominal size in decimals, zeros before the decimal point and in the fourth decimal place are omitted.

<sup>b</sup> See *Body Diameter* footnote in Table 3.

<sup>c</sup> Thread lengths, L<sub>T</sub>, shown are for bolt lengths 6 inches and shorter. For longer bolt lengths add 0.250 inch to thread lengths shown.

**Table 2. American National Standard Heavy Hex Structural Bolts**  
ANSI/ASME B18.2.1-1981 (R1992)<sup>a</sup>

| HEAVY HEX STRUCTURAL BOLTS (Fig. 2)             |        |                          |       |                      |       |                        |       |          |       |                    |       |                      |                    |
|---|--------|--------------------------|-------|----------------------|-------|------------------------|-------|----------|-------|--------------------|-------|----------------------|--------------------|
| Nominal Size <sup>a</sup> or Basic Product Dia. |        | Body Dia. <sup>b</sup> E |       | Width Across Flats F |       | Width Across Corners G |       | Height H |       | Radius of Fillet R |       | Thrd. L <sub>T</sub> | Transition Thrd. Y |
|   |        | Max.                     | Min.  | Max.                 | Min.  | Max.                   | Min.  | Max.     | Min.  | Max.               | Min.  | Basic                | Max.               |
| 1/2   | 0.5000 | 0.515                    | 0.482 | 0.875                | 0.850 | 1.010                  | 0.969 | 0.323    | 0.302 | 0.031              | 0.009 | 1.00                 | 0.19               |
| 5/8   | 0.6250 | 0.642                    | 0.605 | 1.062                | 1.031 | 1.227                  | 1.175 | 0.403    | 0.378 | 0.062              | 0.021 | 1.25                 | 0.22               |
| 3/4   | 0.7500 | 0.768                    | 0.729 | 1.250                | 1.212 | 1.443                  | 1.383 | 0.483    | 0.455 | 0.062              | 0.021 | 1.38                 | 0.25               |
| 7/8   | 0.8750 | 0.895                    | 0.852 | 1.438                | 1.394 | 1.660                  | 1.589 | 0.563    | 0.531 | 0.062              | 0.031 | 1.50                 | 0.28               |
| 1   | 1.0000 | 1.022                    | 0.976 | 1.625                | 1.575 | 1.876                  | 1.796 | 0.627    | 0.591 | 0.093              | 0.062 | 1.75                 | 0.31               |
| 1 1/8   | 1.1250 | 1.149                    | 1.098 | 1.812                | 1.756 | 2.093                  | 2.002 | 0.718    | 0.658 | 0.093              | 0.062 | 2.00                 | 0.34               |
| 1 1/4   | 1.2500 | 1.277                    | 1.223 | 2.000                | 1.938 | 2.309                  | 2.209 | 0.813    | 0.749 | 0.093              | 0.062 | 2.00                 | 0.38               |
| 1 3/8   | 1.3750 | 1.404                    | 1.345 | 2.188                | 2.119 | 2.526                  | 2.416 | 0.878    | 0.810 | 0.093              | 0.062 | 2.25                 | 0.44               |
| 1 1/2   | 1.5000 | 1.531                    | 1.470 | 2.375                | 2.300 | 2.742                  | 2.622 | 0.974    | 0.902 | 0.093              | 0.062 | 2.25                 | 0.44               |

<sup>a</sup> Heavy hex structural bolts have been removed from the latest version, ANSI/ASME B18.2.1-1996. The table has been included for reference.

All dimensions are in inches. **Bold type shows bolts unified dimensionally with British and Canadian Standards.** Threads, when rolled, shall be Unified Coarse, Fine, or 8-thread series (UNRC, UNRF, or 8 UNR Series), Class 2A. Threads produced by other methods may be Unified Coarse, Fine, or 8-thread series (UNC, UNF, or 8 UN Series), Class 2A.

**Table 3. American National Standard and Unified Standard Hex and Heavy Hex Bolts ANSI/ASME B18.2.1-1996**

| Nominal Size <sup>a</sup> or Basic Dia. | Full Size Body Dia. <i>E</i> | Width Across Flats <i>F</i> |                  |              | Width Across Corners <i>G</i> |              | Head Height <i>H</i> |                  |              | Thread Length <sup>b</sup> <i>L<sub>T</sub></i><br>Nom. |       |
|---|------------------------------|-----------------------------|------------------|--------------|-------------------------------|--------------|----------------------|------------------|--------------|---|-------|
|   |                              | Basic                       | Max.             | Min.         | Max.                          | Min.         | Basic                | Max.             | Min.         |   |       |
| <b>HEX BOLTS (Fig. 3)</b>               |                              |                             |                  |              |                               |              |                      |                  |              |   |       |
| $\frac{1}{4}$                           | <b>0.2500</b>                | <b>0.260</b>                | $\frac{7}{16}$   | <b>0.438</b> | <b>0.425</b>                  | <b>0.505</b> | <b>0.484</b>         | $\frac{11}{64}$  | <b>0.188</b> | <b>0.150</b>  | 0.750 |
| $\frac{5}{16}$                          | <b>0.3125</b>                | <b>0.324</b>                | $\frac{9}{16}$   | <b>0.500</b> | <b>0.484</b>                  | <b>0.577</b> | <b>0.552</b>         | $\frac{7}{32}$   | <b>0.235</b> | <b>0.195</b>  | 0.875 |
| $\frac{3}{8}$                           | <b>0.3750</b>                | <b>0.388</b>                | $\frac{5}{16}$   | <b>0.562</b> | <b>0.544</b>                  | <b>0.650</b> | <b>0.620</b>         | $\frac{1}{4}$    | <b>0.268</b> | <b>0.226</b>  | 1.000 |
| $\frac{7}{16}$                          | <b>0.4375</b>                | <b>0.452</b>                | $\frac{5}{8}$    | <b>0.625</b> | <b>0.603</b>                  | <b>0.722</b> | <b>0.687</b>         | $\frac{9}{64}$   | <b>0.316</b> | <b>0.272</b>  | 1.125 |
| $\frac{1}{2}$                           | <b>0.5000</b>                | <b>0.515</b>                | $\frac{3}{4}$    | <b>0.750</b> | <b>0.725</b>                  | <b>0.866</b> | <b>0.826</b>         | $\frac{11}{32}$  | <b>0.364</b> | <b>0.302</b>  | 1.250 |
| $\frac{5}{8}$                           | <b>0.6250</b>                | <b>0.642</b>                | $\frac{15}{16}$  | <b>0.938</b> | <b>0.906</b>                  | <b>1.083</b> | <b>1.033</b>         | $\frac{7}{64}$   | <b>0.444</b> | <b>0.378</b>  | 1.500 |
| $\frac{3}{4}$                           | <b>0.7500</b>                | <b>0.768</b>                | $1\frac{1}{8}$   | <b>1.125</b> | <b>1.088</b>                  | <b>1.299</b> | <b>1.240</b>         | $\frac{1}{2}$    | <b>0.524</b> | <b>0.455</b>  | 1.750 |
| $\frac{7}{8}$                           | <b>0.8750</b>                | <b>0.895</b>                | $1\frac{1}{16}$  | <b>1.312</b> | <b>1.269</b>                  | <b>1.516</b> | <b>1.447</b>         | $\frac{37}{64}$  | <b>0.604</b> | <b>0.531</b>  | 2.000 |
| 1                                       | <b>1.0000</b>                | <b>1.022</b>                | $1\frac{1}{2}$   | <b>1.500</b> | <b>1.450</b>                  | <b>1.732</b> | <b>1.653</b>         | $\frac{43}{64}$  | <b>0.700</b> | <b>0.591</b>  | 2.250 |
| $1\frac{1}{8}$                          | <b>1.1250</b>                | <b>1.149</b>                | $1\frac{13}{16}$ | <b>1.688</b> | <b>1.631</b>                  | <b>1.949</b> | <b>1.859</b>         | $\frac{3}{4}$    | <b>0.780</b> | <b>0.658</b>  | 2.500 |
| $1\frac{1}{4}$                          | <b>1.2500</b>                | <b>1.277</b>                | $1\frac{7}{8}$   | <b>1.875</b> | <b>1.812</b>                  | <b>2.165</b> | <b>2.066</b>         | $\frac{27}{32}$  | <b>0.876</b> | <b>0.749</b>  | 2.750 |
| $1\frac{3}{8}$                          | <b>1.3750</b>                | <b>1.404</b>                | $2\frac{1}{16}$  | <b>2.062</b> | <b>1.994</b>                  | <b>2.382</b> | <b>2.273</b>         | $\frac{29}{32}$  | <b>0.940</b> | <b>0.810</b>  | 3.000 |
| $1\frac{1}{2}$                          | <b>1.5000</b>                | <b>1.531</b>                | $2\frac{1}{4}$   | <b>2.250</b> | <b>2.175</b>                  | <b>2.598</b> | <b>2.480</b>         | 1                | <b>1.036</b> | <b>0.902</b>  | 3.250 |
| $1\frac{3}{4}$                          | <b>1.7500</b>                | <b>1.785</b>                | $2\frac{5}{8}$   | <b>2.625</b> | <b>2.538</b>                  | <b>3.031</b> | <b>2.893</b>         | $1\frac{5}{32}$  | <b>1.196</b> | <b>1.054</b>  | 3.750 |
| 2                                       | <b>2.0000</b>                | <b>2.039</b>                | 3                | <b>3.000</b> | <b>2.900</b>                  | <b>3.464</b> | <b>3.306</b>         | $1\frac{13}{32}$ | <b>1.388</b> | <b>1.175</b>  | 4.250 |
| $2\frac{1}{4}$                          | <b>2.2500</b>                | <b>2.305</b>                | $3\frac{3}{8}$   | <b>3.375</b> | <b>3.262</b>                  | <b>3.897</b> | <b>3.719</b>         | $1\frac{1}{2}$   | <b>1.548</b> | <b>1.327</b>  | 4.750 |
| $2\frac{1}{2}$                          | <b>2.5000</b>                | <b>2.559</b>                | $3\frac{3}{4}$   | <b>3.750</b> | <b>3.625</b>                  | <b>4.330</b> | <b>4.133</b>         | $1\frac{17}{32}$ | <b>1.708</b> | <b>1.479</b>  | 5.250 |
| $2\frac{3}{4}$                          | <b>2.7500</b>                | <b>2.827</b>                | $4\frac{1}{8}$   | <b>4.125</b> | <b>3.988</b>                  | <b>4.763</b> | <b>4.546</b>         | $1\frac{13}{16}$ | <b>1.869</b> | <b>1.632</b>  | 5.750 |
| 3                                       | <b>3.0000</b>                | <b>3.081</b>                | $4\frac{1}{2}$   | <b>4.500</b> | <b>4.350</b>                  | <b>5.196</b> | <b>4.959</b>         | 2                | <b>2.060</b> | <b>1.815</b>  | 6.250 |
| $3\frac{1}{2}$                          | <b>3.2500</b>                | <b>3.335</b>                | $4\frac{7}{8}$   | <b>4.875</b> | <b>4.712</b>                  | <b>5.629</b> | <b>5.372</b>         | $2\frac{3}{16}$  | <b>2.251</b> | <b>1.936</b>  | 6.750 |
| $3\frac{1}{2}$                          | <b>3.5000</b>                | <b>3.589</b>                | $5\frac{1}{4}$   | <b>5.250</b> | <b>5.075</b>                  | <b>6.062</b> | <b>5.786</b>         | $2\frac{1}{16}$  | <b>2.380</b> | <b>2.057</b>  | 7.250 |
| $3\frac{3}{4}$                          | <b>3.7500</b>                | <b>3.858</b>                | $5\frac{3}{8}$   | <b>5.625</b> | <b>5.437</b>                  | <b>6.495</b> | <b>6.198</b>         | $2\frac{1}{2}$   | <b>2.572</b> | <b>2.241</b>  | 7.750 |
| 4                                       | <b>4.0000</b>                | <b>4.111</b>                | 6                | <b>6.000</b> | <b>5.800</b>                  | <b>6.928</b> | <b>6.612</b>         | $2\frac{1}{16}$  | <b>2.764</b> | <b>2.424</b>  | 8.250 |
| <b>HEAVY HEX BOLTS (Fig. 3)</b>         |                              |                             |                  |              |                               |              |                      |                  |              |   |       |
| $\frac{1}{2}$                           | <b>0.5000</b>                | <b>0.515</b>                | $\frac{7}{8}$    | <b>0.875</b> | <b>0.850</b>                  | <b>1.010</b> | <b>0.969</b>         | $\frac{11}{32}$  | 0.364        | 0.302   | 1.250 |
| $\frac{5}{8}$                           | <b>0.6250</b>                | <b>0.642</b>                | $1\frac{1}{16}$  | <b>1.062</b> | <b>1.031</b>                  | <b>1.227</b> | <b>1.175</b>         | $\frac{7}{64}$   | 0.444        | 0.378   | 1.500 |
| $\frac{3}{4}$                           | <b>0.7500</b>                | <b>0.768</b>                | $1\frac{1}{4}$   | <b>1.250</b> | <b>1.212</b>                  | <b>1.443</b> | <b>1.383</b>         | $\frac{1}{2}$    | 0.524        | 0.455   | 1.750 |
| $\frac{7}{8}$                           | <b>0.8750</b>                | <b>0.895</b>                | $1\frac{7}{16}$  | <b>1.438</b> | <b>1.394</b>                  | <b>1.660</b> | <b>1.589</b>         | $\frac{37}{64}$  | 0.604        | 0.531   | 2.000 |
| 1                                       | <b>1.0000</b>                | <b>1.022</b>                | $1\frac{5}{8}$   | <b>1.625</b> | <b>1.575</b>                  | <b>1.876</b> | <b>1.796</b>         | $\frac{43}{64}$  | 0.700        | 0.591   | 2.250 |
| $1\frac{1}{8}$                          | <b>1.1250</b>                | <b>1.149</b>                | $1\frac{13}{16}$ | <b>1.812</b> | <b>1.756</b>                  | <b>2.093</b> | <b>2.002</b>         | $\frac{3}{4}$    | 0.780        | 0.658   | 2.500 |
| $1\frac{1}{4}$                          | <b>1.2500</b>                | <b>1.277</b>                | 2                | <b>2.000</b> | <b>1.938</b>                  | <b>2.309</b> | <b>2.209</b>         | $\frac{27}{32}$  | 0.876        | 0.749   | 2.750 |
| $1\frac{3}{8}$                          | <b>1.3750</b>                | <b>1.404</b>                | $2\frac{1}{16}$  | <b>2.188</b> | <b>2.119</b>                  | <b>2.526</b> | <b>2.416</b>         | $\frac{29}{32}$  | 0.940        | 0.810   | 3.000 |
| $1\frac{1}{2}$                          | <b>1.5000</b>                | <b>1.531</b>                | $2\frac{3}{8}$   | <b>2.375</b> | <b>2.300</b>                  | <b>2.742</b> | <b>2.622</b>         | 1                | 1.036        | 0.902   | 3.250 |
| $1\frac{3}{4}$                          | <b>1.7500</b>                | <b>1.785</b>                | $2\frac{5}{4}$   | <b>2.750</b> | <b>2.662</b>                  | <b>3.175</b> | <b>3.035</b>         | $1\frac{5}{32}$  | 1.196        | 1.054   | 3.750 |
| 2                                       | <b>2.0000</b>                | <b>2.039</b>                | $3\frac{1}{8}$   | <b>3.125</b> | <b>3.025</b>                  | <b>3.608</b> | <b>3.449</b>         | $1\frac{13}{32}$ | 1.388        | 1.175   | 4.250 |
| $2\frac{1}{4}$                          | <b>2.2500</b>                | <b>2.305</b>                | $3\frac{1}{2}$   | <b>3.500</b> | <b>3.388</b>                  | <b>4.041</b> | <b>3.862</b>         | $\frac{1}{2}$    | 1.548        | 1.327   | 4.750 |
| $2\frac{1}{2}$                          | <b>2.5000</b>                | <b>2.559</b>                | $3\frac{3}{8}$   | <b>3.875</b> | <b>3.750</b>                  | <b>4.474</b> | <b>4.275</b>         | $1\frac{17}{32}$ | 1.708        | 1.479   | 5.250 |
| $2\frac{3}{4}$                          | <b>2.7500</b>                | <b>2.827</b>                | $4\frac{1}{4}$   | <b>4.250</b> | <b>4.112</b>                  | <b>4.907</b> | <b>4.688</b>         | $1\frac{13}{16}$ | 1.869        | 1.632   | 5.750 |
| 3                                       | <b>3.0000</b>                | <b>3.081</b>                | $4\frac{3}{8}$   | <b>4.625</b> | <b>4.475</b>                  | <b>5.340</b> | <b>5.102</b>         | 2                | 2.060        | 1.815   | 6.250 |

<sup>a</sup> *Nominal Size*: Where specifying nominal size in decimals, zeros preceding the decimal point and in the fourth decimal place are omitted.

<sup>b</sup> Thread lengths, *L<sub>T</sub>*, shown are for bolt lengths 6 inches and shorter. For longer bolt lengths add 0.250 inch to thread lengths shown.

All dimensions are in inches.

**Bold type shows bolts unified dimensionally with British and Canadian Standards.**

*Threads*: Threads, when rolled, are Unified Coarse, Fine, or 8-thread series (UNRC, UNRF, or 8 UNR Series), Class 2A. Threads produced by other methods may be Unified Coarse, Fine or 8-thread series (UNC, UNF, or 8 UN Series), Class 2A.

*Body Diameter*: Bolts may be obtained in "reduced diameter body." Where "reduced diameter body" is specified, the body diameter may be reduced to approximately the pitch diameter of the thread. A shoulder of full body diameter under the head may be supplied at the option of the manufacturer.

*Material*: Unless otherwise specified, chemical and mechanical properties of steel bolts conform to ASTM A307, Grade A. Other materials are as agreed upon by manufacturer and purchaser.



**Table 4. American National Standard and Unified Standard Heavy Hex Screws and Hex Cap Screws ANSI/ASME B18.2.1-1996**

| Nominal Size <sup>a</sup><br>or Basic<br>Product Dia. | Body Dia.<br><i>E</i> |               | Width Across<br>Flats <i>F</i> |        |              | Width Across<br>Corners <i>G</i> |              | Height<br><i>H</i> |         |              | Thread<br>Length <sup>b</sup> <i>L<sub>T</sub></i> |                    |
|---|-----------------------|---------------|--------------------------------|--------|--------------|----------------------------------|--------------|--------------------|---------|--------------|--|--------------------|
|   | Max.                  | Min.          | Basic                          | Max.   | Min.         | Max.                             | Min.         | Basic              | Max.    | Min.         | Basic  |                    |
| <b>HEAVY HEX SCREWS (Fig. 4)</b>                      |                       |               |                                |        |              |                                  |              |                    |         |              |  |                    |
| 1/2   | <b>0.5000</b>         | <b>0.5000</b> | 0.482                          | 7/8    | <b>0.875</b> | <b>0.850</b>                     | <b>1.010</b> | <b>0.969</b>       | 5/16    | 0.323        | 0.302  | 1.250              |
|   | <b>0.6250</b>         | <b>0.6250</b> | 0.605                          | 1 1/16 | <b>1.062</b> | <b>1.031</b>                     | <b>1.227</b> | <b>1.175</b>       | 25/64   | 0.403        | 0.378  | 1.500              |
|   | <b>0.7500</b>         | <b>0.7500</b> | 0.729                          | 1 1/4  | <b>1.250</b> | <b>1.212</b>                     | <b>1.443</b> | <b>1.383</b>       | 15/32   | 0.483        | 0.455  | 1.750              |
|   | <b>0.8750</b>         | <b>0.8750</b> | 0.852                          | 1 1/2  | <b>1.438</b> | <b>1.394</b>                     | <b>1.660</b> | <b>1.589</b>       | 35/64   | 0.563        | 0.531  | 2.000              |
| <b>1</b>  | <b>1.0000</b>         | <b>1.0000</b> | 0.976                          | 1 5/8  | <b>1.625</b> | <b>1.575</b>                     | <b>1.876</b> | <b>1.796</b>       | 39/64   | 0.627        | 0.591  | 2.250              |
| <b>1 1/8</b>  | <b>1.1250</b>         | <b>1.1250</b> | 1.098                          | 1 3/4  | <b>1.812</b> | <b>1.756</b>                     | <b>2.093</b> | <b>2.002</b>       | 11/16   | 0.718        | 0.658  | 2.500              |
| <b>1 1/4</b>  | <b>1.2500</b>         | <b>1.2500</b> | 1.223                          | 2      | <b>2.000</b> | <b>1.938</b>                     | <b>2.309</b> | <b>2.209</b>       | 25/32   | 0.813        | 0.749  | 2.750              |
| <b>1 3/8</b>  | <b>1.3750</b>         | <b>1.3750</b> | 1.345                          | 2 3/16 | <b>2.188</b> | <b>2.119</b>                     | <b>2.526</b> | <b>2.416</b>       | 27/32   | 0.878        | 0.810  | 3.000              |
| <b>1 1/2</b>  | <b>1.5000</b>         | <b>1.5000</b> | 1.470                          | 2 1/4  | <b>2.375</b> | <b>2.300</b>                     | <b>2.742</b> | <b>2.622</b>       | 15/16   | 0.974        | 0.902  | 3.250              |
| <b>1 3/4</b>  | <b>1.7500</b>         | <b>1.7500</b> | 1.716                          | 2 3/4  | <b>2.750</b> | <b>2.662</b>                     | <b>3.175</b> | <b>3.035</b>       | 1 1/32  | 1.134        | 1.054  | 3.750              |
| <b>2</b>  | <b>2.0000</b>         | <b>2.0000</b> | 1.964                          | 3 1/8  | <b>3.125</b> | <b>3.025</b>                     | <b>3.608</b> | <b>3.449</b>       | 1 1/16  | 1.263        | 1.175  | 4.250              |
| 2 1/4   | 2.2500                | 2.2500        | 2.214                          | 3 1/2  | 3.500        | 3.388                            | 4.041        | 3.862              | 1 3/8   | 1.423        | 1.327  | 5.000 <sup>c</sup> |
| 2 1/2   | 2.5000                | 2.5000        | 2.461                          | 3 3/4  | 3.875        | 3.750                            | 4.474        | 4.275              | 1 7/32  | 1.583        | 1.479  | 5.500 <sup>c</sup> |
| 2 3/4   | 2.7500                | 2.7500        | 2.711                          | 4 1/4  | 4.250        | 4.112                            | 4.907        | 4.688              | 1 11/16 | 1.744        | 1.632  | 6.000 <sup>c</sup> |
| 3   | 3.0000                | 3.0000        | 2.961                          | 4 3/4  | 4.625        | 4.475                            | 5.340        | 5.102              | 1 7/8   | 1.935        | 1.815  | 6.500 <sup>c</sup> |
| <b>HEX CAP SCREWS (Finished Hex Bolts) (Fig. 4)</b>   |                       |               |                                |        |              |                                  |              |                    |         |              |  |                    |
| 1/4   | <b>0.2500</b>         | <b>0.2500</b> | <b>0.2450</b>                  | 7/16   | <b>0.438</b> | <b>0.428</b>                     | <b>0.505</b> | <b>0.488</b>       | 5/32    | <b>0.163</b> | <b>0.150</b>                                       | 0.750              |
| 5/16  | <b>0.3125</b>         | <b>0.3125</b> | <b>0.3065</b>                  | 1/2    | <b>0.500</b> | <b>0.489</b>                     | <b>0.577</b> | <b>0.557</b>       | 13/64   | <b>0.211</b> | <b>0.195</b>                                       | 0.875              |
| 3/8   | <b>0.3750</b>         | <b>0.3750</b> | <b>0.3690</b>                  | 9/16   | <b>0.562</b> | <b>0.551</b>                     | <b>0.650</b> | <b>0.628</b>       | 15/64   | <b>0.243</b> | <b>0.226</b>                                       | 1.000              |
| 7/16  | <b>0.4375</b>         | <b>0.4375</b> | <b>0.4305</b>                  | 5/8    | <b>0.625</b> | <b>0.612</b>                     | <b>0.722</b> | <b>0.698</b>       | 9/32    | <b>0.291</b> | <b>0.272</b>                                       | 1.125              |
| 1/2   | <b>0.5000</b>         | <b>0.5000</b> | <b>0.4930</b>                  | 3/4    | <b>0.750</b> | <b>0.736</b>                     | <b>0.866</b> | <b>0.840</b>       | 5/16    | <b>0.323</b> | <b>0.302</b>                                       | 1.250              |
| 9/16  | <b>0.5625</b>         | <b>0.5625</b> | <b>0.5545</b>                  | 13/16  | <b>0.812</b> | <b>0.798</b>                     | <b>0.938</b> | <b>0.910</b>       | 23/64   | <b>0.371</b> | <b>0.348</b>                                       | 1.375              |
| 5/8   | <b>0.6250</b>         | <b>0.6250</b> | <b>0.6170</b>                  | 15/16  | <b>0.938</b> | <b>0.922</b>                     | <b>1.083</b> | <b>1.051</b>       | 25/64   | <b>0.403</b> | <b>0.378</b>                                       | 1.500              |
| 3/4   | <b>0.7500</b>         | <b>0.7500</b> | <b>0.7410</b>                  | 1 1/8  | <b>1.125</b> | <b>1.100</b>                     | <b>1.299</b> | <b>1.254</b>       | 15/32   | <b>0.483</b> | <b>0.455</b>                                       | 1.750              |
| 7/8   | <b>0.8750</b>         | <b>0.8750</b> | <b>0.8660</b>                  | 1 1/4  | <b>1.312</b> | <b>1.285</b>                     | <b>1.516</b> | <b>1.465</b>       | 35/64   | <b>0.563</b> | <b>0.531</b>                                       | 2.000              |
| <b>1</b>  | <b>1.0000</b>         | <b>1.0000</b> | <b>0.9900</b>                  | 1 1/2  | <b>1.500</b> | <b>1.469</b>                     | <b>1.732</b> | <b>1.675</b>       | 39/64   | <b>0.627</b> | <b>0.591</b>                                       | 2.250              |
| <b>1 1/8</b>  | <b>1.1250</b>         | <b>1.1250</b> | <b>1.1140</b>                  | 1 3/4  | <b>1.688</b> | <b>1.631</b>                     | <b>1.949</b> | <b>1.859</b>       | 11/16   | <b>0.718</b> | <b>0.658</b>                                       | 2.500              |
| <b>1 1/4</b>  | <b>1.2500</b>         | <b>1.2500</b> | <b>1.2390</b>                  | 1 7/8  | <b>1.875</b> | <b>1.812</b>                     | <b>2.165</b> | <b>2.066</b>       | 25/32   | <b>0.813</b> | <b>0.749</b>                                       | 2.750              |
| <b>1 3/8</b>  | <b>1.3750</b>         | <b>1.3750</b> | <b>1.3630</b>                  | 2 1/16 | <b>2.062</b> | <b>1.994</b>                     | <b>2.382</b> | <b>2.273</b>       | 27/32   | <b>0.878</b> | <b>0.810</b>                                       | 3.000              |
| <b>1 1/2</b>  | <b>1.5000</b>         | <b>1.5000</b> | <b>1.4880</b>                  | 2 1/4  | <b>2.250</b> | <b>2.175</b>                     | <b>2.598</b> | <b>2.480</b>       | 15/16   | <b>0.974</b> | <b>0.902</b>                                       | 3.250              |
| <b>1 3/4</b>  | <b>1.7500</b>         | <b>1.7500</b> | <b>1.7380</b>                  | 2 3/8  | <b>2.625</b> | <b>2.538</b>                     | <b>3.031</b> | <b>2.893</b>       | 1 1/32  | <b>1.134</b> | <b>1.054</b>                                       | 3.750              |
| <b>2</b>  | <b>2.0000</b>         | <b>2.0000</b> | <b>1.9880</b>                  | 3      | <b>3.000</b> | <b>2.900</b>                     | <b>3.464</b> | <b>3.306</b>       | 1 7/32  | <b>1.263</b> | <b>1.175</b>                                       | 4.250              |
| 2 1/4   | 2.2500                | 2.2500        | 2.2380                         | 3 3/8  | 3.375        | 3.262                            | 3.897        | 3.719              | 1 3/8   | 1.423        | 1.327  | 5.000 <sup>c</sup> |
| 2 1/2   | 2.5000                | 2.5000        | 2.4880                         | 3 1/2  | 3.750        | 3.625                            | 4.330        | 4.133              | 1 7/16  | 1.583        | 1.479  | 5.500 <sup>c</sup> |
| 2 3/4   | 2.7500                | 2.7500        | 2.7380                         | 4 1/8  | 4.125        | 3.988                            | 4.763        | 4.546              | 1 11/16 | 1.744        | 1.632  | 6.000 <sup>c</sup> |
| 3   | 3.0000                | 3.0000        | 2.9880                         | 4 1/2  | 4.500        | 4.350                            | 5.196        | 4.959              | 1 7/8   | 1.935        | 1.815  | 6.500 <sup>c</sup> |

<sup>a</sup> *Nominal Size*: Where specifying nominal size in decimals, zeros preceding the decimal and in the fourth decimal place are omitted.

<sup>b</sup> Thread lengths, *L<sub>T</sub>*, shown are for bolt lengths 6 inches and shorter. For longer bolt lengths add 0.250 inch to thread lengths shown.

<sup>c</sup> Thread lengths, *L<sub>T</sub>*, shown are for bolt lengths over 6 inches.

All dimensions are in inches.

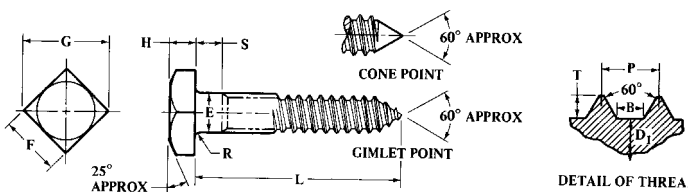
**Unification: Bold type indicates product features unified dimensionally with British and Canadian Standards.** Unification of fine thread products is limited to sizes 1 inch and smaller.

**Bearing Surface:** Bearing surface is flat and washer faced. Diameter of bearing surface is equal to the maximum width across flats within a tolerance of minus 10 per cent.

**Threads Series:** Threads, when rolled, are Unified Coarse, Fine, or 8-thread series (UNRC, UNRF, or 8 UNR Series), Class 2A. Threads produced by other methods shall preferably be UNRC, UNRF or 8 UNR but, at manufacturer's option, may be Unified Coarse, Fine or 8-thread series (UNC, UNF, or 8 UN Series), Class 2A.

**Material:** Chemical and mechanical properties of steel screws normally conform to Grades 2, 5, or 8 of SAE J429, ASTM A449 or ASTM A354 Grade BD. Where specified, screws may also be made from brass, bronze, corrosion-resisting steel, aluminum alloy or other materials.

Table 5. American National Standard Square Lag Screws ANSI/ASME B18.2.1-1996



| Nominal Size <sup>a</sup><br>or Basic<br>Product<br>Dia. | Body or<br>Shoulder<br>Dia. <i>E</i> |       | Width Across<br>Flats<br><i>F</i> |                 | Width Across<br>Corners<br><i>G</i> |       | Height<br><i>H</i> |       | Shoulder<br>Length<br><i>S</i> | Radius<br>of Fillet<br><i>R</i> | Thds.<br>per<br>Inch | Thread Dimensions |      |                   |                          |                           |                                    |       |
|--|--------------------------------------|-------|-----------------------------------|-----------------|-------------------------------------|-------|--------------------|-------|--------------------------------|---------------------------------|----------------------|-------------------|------|-------------------|--------------------------|---------------------------|------------------------------------|-------|
|  | Max.                                 | Min.  | Basic                             | Max.            | Min.                                | Max.  | Min.               | Basic |                                |                                 |                      | Max.              | Min. | Pitch<br><i>P</i> | Flat at<br>Root <i>B</i> | Depth of<br>Thd. <i>T</i> | Root<br>Dia. <i>D</i> <sub>1</sub> |       |
| No. 10   | 0.1900                               | 0.199 | 0.178                             | $\frac{5}{32}$  | 0.281                               | 0.271 | 0.398              | 0.372 | $\frac{1}{8}$                  | 0.140                           | 0.110                | 0.094             | 0.03 | 11                | 0.091                    | 0.039                     | 0.035                              | 0.120 |
| $\frac{1}{4}$  | 0.2500                               | 0.260 | 0.237                             | $\frac{3}{8}$   | 0.375                               | 0.362 | 0.530              | 0.498 | $\frac{11}{64}$                | 0.188                           | 0.156                | 0.094             | 0.03 | 10                | 0.100                    | 0.043                     | 0.039                              | 0.173 |
| $\frac{3}{16}$   | 0.3125                               | 0.324 | 0.298                             | $\frac{1}{2}$   | 0.500                               | 0.484 | 0.707              | 0.665 | $\frac{13}{64}$                | 0.220                           | 0.186                | 0.125             | 0.03 | 9                 | 0.111                    | 0.048                     | 0.043                              | 0.227 |
| $\frac{3}{8}$  | 0.3750                               | 0.388 | 0.360                             | $\frac{9}{16}$  | 0.562                               | 0.544 | 0.795              | 0.747 | $\frac{1}{4}$                  | 0.268                           | 0.232                | 0.125             | 0.03 | 7                 | 0.143                    | 0.062                     | 0.055                              | 0.265 |
| $\frac{7}{16}$   | 0.4375                               | 0.452 | 0.421                             | $\frac{5}{8}$   | 0.625                               | 0.603 | 0.884              | 0.828 | $\frac{9}{64}$                 | 0.316                           | 0.278                | 0.156             | 0.03 | 7                 | 0.143                    | 0.062                     | 0.055                              | 0.328 |
| $\frac{1}{2}$  | 0.5000                               | 0.515 | 0.482                             | $\frac{3}{4}$   | 0.750                               | 0.725 | 1.061              | 0.995 | $\frac{21}{64}$                | 0.348                           | 0.308                | 0.156             | 0.03 | 6                 | 0.167                    | 0.072                     | 0.064                              | 0.371 |
| $\frac{5}{8}$  | 0.6250                               | 0.642 | 0.605                             | $\frac{15}{16}$ | 0.938                               | 0.906 | 1.326              | 1.244 | $\frac{27}{64}$                | 0.444                           | 0.400                | 0.312             | 0.06 | 5                 | 0.200                    | 0.086                     | 0.077                              | 0.471 |
| $\frac{3}{4}$  | 0.7500                               | 0.768 | 0.729                             | $1\frac{1}{8}$  | 1.125                               | 1.088 | 1.591              | 1.494 | $\frac{1}{2}$                  | 0.524                           | 0.476                | 0.375             | 0.06 | 4 $\frac{1}{2}$   | 0.222                    | 0.096                     | 0.085                              | 0.579 |
| $\frac{7}{8}$  | 0.8750                               | 0.895 | 0.852                             | $1\frac{1}{16}$ | 1.312                               | 1.269 | 1.856              | 1.742 | $\frac{9}{32}$                 | 0.620                           | 0.568                | 0.375             | 0.06 | 4                 | 0.250                    | 0.108                     | 0.096                              | 0.683 |
| 1  | 1.0000                               | 1.022 | 0.976                             | $1\frac{1}{2}$  | 1.500                               | 1.450 | 2.121              | 1.991 | $\frac{21}{32}$                | 0.684                           | 0.628                | 0.625             | 0.09 | 3 $\frac{1}{2}$   | 0.286                    | 0.123                     | 0.110                              | 0.780 |
| $1\frac{1}{8}$   | 1.1250                               | 1.149 | 1.098                             | $1\frac{1}{16}$ | 1.688                               | 1.631 | 2.386              | 2.239 | $\frac{3}{4}$                  | 0.780                           | 0.720                | 0.625             | 0.09 | 3 $\frac{1}{4}$   | 0.308                    | 0.133                     | 0.119                              | 0.887 |
| $1\frac{1}{4}$   | 1.2500                               | 1.277 | 1.223                             | $1\frac{3}{8}$  | 1.875                               | 1.812 | 2.652              | 2.489 | $\frac{27}{32}$                | 0.876                           | 0.812                | 0.625             | 0.09 | 3 $\frac{1}{4}$   | 0.308                    | 0.133                     | 0.119                              | 1.012 |

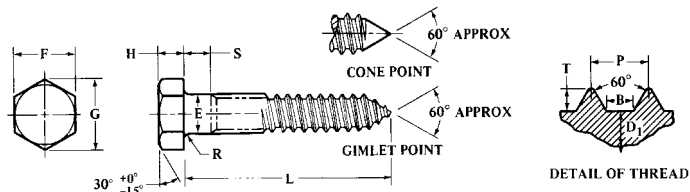
<sup>a</sup> When specifying decimal nominal size, zeros before decimal point and in fourth decimal place are omitted.

All dimensions in inches.

Minimum thread length is  $\frac{1}{2}$  length of screw plus 0.50 inch, or 6.00 inches, whichever is shorter. Screws too short for the formula thread length shall be threaded as close to the head as practicable.

Thread formulas: Pitch = 1 ÷ thds. per inch. Flat at root = 0.4305 × pitch. Depth of single thread = 0.385 × pitch.

Table 6. American National Standard Hex Lag Screws ANSI/ASME B18.2.1-1996



| Nominal Size <sup>a</sup><br>or Basic<br>Product Dia. | Body or<br>Shoulder Dia.<br>E |       | Width Across Flats<br>F |                  |       | Width Across Corners<br>G |       | Height<br>H |                 |       | Shoulder<br>Length<br>S | Radius<br>of Fillet<br>R | Thds.<br>per<br>Inch | Thread Dimensions |                   |                    |                             |       |
|---|-------------------------------|-------|-------------------------|------------------|-------|---------------------------|-------|-------------|-----------------|-------|-------------------------|--------------------------|----------------------|-------------------|-------------------|--------------------|-----------------------------|-------|
|   | Max.                          | Min.  | Basic                   | Max.             | Min.  | Max.                      | Min.  | Basic       | Max.            | Min.  | Min.                    | Max.                     |                      | Pitch<br>P        | Flat at Root<br>B | Depth of Thd.<br>T | Root Dia.<br>D <sub>1</sub> |       |
| No. 10  | 0.1900                        | 0.199 | 0.178                   | $\frac{5}{32}$   | 0.281 | 0.271                     | 0.323 | 0.309       | $\frac{1}{8}$   | 0.140 | 0.110                   | 0.094                    | 0.03                 | 11                | 0.091             | 0.039              | 0.035                       | 0.120 |
| $\frac{1}{4}$   | 0.2500                        | 0.260 | 0.237                   | $\frac{3}{8}$    | 0.438 | 0.425                     | 0.505 | 0.484       | $\frac{11}{64}$ | 0.188 | 0.150                   | 0.094                    | 0.03                 | 10                | 0.100             | 0.043              | 0.039                       | 0.173 |
| $\frac{5}{16}$  | 0.3125                        | 0.324 | 0.298                   | $\frac{1}{2}$    | 0.500 | 0.484                     | 0.577 | 0.552       | $\frac{7}{32}$  | 0.235 | 0.195                   | 0.125                    | 0.03                 | 9                 | 0.111             | 0.048              | 0.043                       | 0.227 |
| $\frac{3}{8}$   | 0.3750                        | 0.388 | 0.360                   | $\frac{9}{16}$   | 0.562 | 0.544                     | 0.650 | 0.620       | $\frac{1}{4}$   | 0.268 | 0.226                   | 0.125                    | 0.03                 | 7                 | 0.143             | 0.062              | 0.055                       | 0.265 |
| $\frac{7}{16}$  | 0.4375                        | 0.452 | 0.421                   | $\frac{5}{8}$    | 0.625 | 0.603                     | 0.722 | 0.687       | $\frac{9}{64}$  | 0.316 | 0.272                   | 0.156                    | 0.03                 | 7                 | 0.143             | 0.062              | 0.055                       | 0.328 |
| $\frac{1}{2}$   | 0.5000                        | 0.515 | 0.482                   | $\frac{3}{4}$    | 0.750 | 0.725                     | 0.866 | 0.826       | $\frac{11}{32}$ | 0.364 | 0.302                   | 0.156                    | 0.03                 | 6                 | 0.167             | 0.072              | 0.064                       | 0.371 |
| $\frac{5}{8}$   | 0.6250                        | 0.642 | 0.605                   | $\frac{15}{16}$  | 0.938 | 0.906                     | 1.083 | 1.033       | $\frac{7}{64}$  | 0.444 | 0.378                   | 0.132                    | 0.06                 | 5                 | 0.200             | 0.086              | 0.077                       | 0.471 |
| $\frac{3}{4}$   | 0.7500                        | 0.768 | 0.729                   | $1\frac{1}{8}$   | 1.125 | 1.088                     | 1.299 | 1.240       | $\frac{1}{2}$   | 0.524 | 0.455                   | 0.375                    | 0.06                 | 4 $\frac{1}{2}$   | 0.222             | 0.096              | 0.085                       | 0.579 |
| $\frac{7}{8}$   | 0.8750                        | 0.895 | 0.852                   | $1\frac{1}{4}$   | 1.312 | 1.269                     | 1.516 | 1.447       | $\frac{3}{64}$  | 0.604 | 0.531                   | 0.375                    | 0.06                 | 4                 | 0.250             | 0.108              | 0.096                       | 0.683 |
| 1   | 1.0000                        | 1.022 | 0.976                   | $1\frac{1}{2}$   | 1.500 | 1.450                     | 1.732 | 1.653       | $\frac{43}{64}$ | 0.700 | 0.591                   | 0.625                    | 0.09                 | 3 $\frac{1}{2}$   | 0.286             | 0.123              | 0.110                       | 0.780 |
| 1 $\frac{1}{8}$                                       | 1.1250                        | 1.149 | 1.098                   | $1\frac{13}{16}$ | 1.688 | 1.631                     | 1.949 | 1.859       | $\frac{3}{4}$   | 0.780 | 0.658                   | 0.625                    | 0.09                 | 3 $\frac{1}{4}$   | 0.308             | 0.133              | 0.119                       | 0.887 |
| 1 $\frac{1}{4}$                                       | 1.2500                        | 1.277 | 1.223                   | $1\frac{7}{8}$   | 1.875 | 1.812                     | 2.165 | 2.066       | $\frac{27}{32}$ | 0.876 | 0.749                   | 0.625                    | 0.09                 | 3 $\frac{1}{4}$   | 0.308             | 0.133              | 0.119                       | 1.012 |

<sup>a</sup>When specifying decimal nominal size, zeros before decimal point and in fourth decimal place are omitted.

All dimensions in inches.

Minimum thread length is  $\frac{1}{2}$  length of screw plus 0.50 inch, or 6.00 inches, whichever is shorter. Screws too short for the formula thread length shall be threaded as close to the head as practicable.

Thread formulas: Pitch = 1 ÷ thds. per inch. Flat at root = 0.4305 × pitch. Depth of single thread = 0.385 × pitch.

**Table 7. American National Standard and Unified Standard Hex Nuts and Jam Nuts and Heavy Hex Nuts and Jam Nuts ANSI/ASME B18.2.2-1987 (R1999)**

| Nominal Size<br>or Basic<br>Major Dia. of Thread        |               | Width Across<br>Flats <i>F</i> |              |              | Width Across<br>Corners <i>G</i> |               | Thickness, Nuts<br><i>H</i> |              |              | Thickness, Jam Nuts<br><i>H</i> <sub>1</sub> |              |              |
|---|---------------|--------------------------------|--------------|--------------|----------------------------------|---------------|-----------------------------|--------------|--------------|--|--------------|--------------|
|   |               | Basic                          | Max.         | Min.         | Max.                             | Min.          | Basic                       | Max.         | Min.         | Basic  | Max.         | Min.         |
| Hex Nuts (Fig. 5) and Hex Jam Nuts (Fig. 6)             |               |                                |              |              |                                  |               |                             |              |              |  |              |              |
| 1/4   | <b>0.2500</b> | 7/16                           | <b>0.438</b> | <b>0.428</b> | <b>0.505</b>                     | <b>0.488</b>  | 7/32                        | <b>0.226</b> | <b>0.212</b> | 5/32   | <b>0.163</b> | <b>0.150</b> |
| 5/16  | <b>0.3125</b> | 1/2                            | <b>0.500</b> | <b>0.489</b> | <b>0.577</b>                     | <b>0.557</b>  | 17/64                       | <b>0.273</b> | <b>0.258</b> | 3/16   | <b>0.195</b> | <b>0.180</b> |
| 3/8   | <b>0.3750</b> | 9/16                           | <b>0.562</b> | <b>0.551</b> | <b>0.650</b>                     | <b>0.628</b>  | 21/64                       | <b>0.337</b> | <b>0.320</b> | 7/32   | <b>0.227</b> | <b>0.210</b> |
| 7/16  | <b>0.4375</b> | 11/16                          | <b>0.688</b> | <b>0.675</b> | <b>0.794</b>                     | <b>0.768</b>  | 3/8                         | <b>0.385</b> | <b>0.365</b> | 1/4  | <b>0.260</b> | <b>0.240</b> |
| 1/2   | <b>0.5000</b> | 3/4                            | <b>0.750</b> | <b>0.736</b> | <b>0.866</b>                     | <b>0.840</b>  | 7/16                        | <b>0.448</b> | <b>0.427</b> | 5/16   | <b>0.323</b> | <b>0.302</b> |
| 9/16  | <b>0.5625</b> | 7/8                            | <b>0.875</b> | <b>0.861</b> | <b>1.010</b>                     | <b>0.982</b>  | 31/64                       | <b>0.496</b> | <b>0.473</b> | 5/16   | <b>0.324</b> | <b>0.301</b> |
| 5/8   | <b>0.6250</b> | 15/16                          | <b>0.938</b> | <b>0.922</b> | <b>1.083</b>                     | <b>1.051</b>  | 35/64                       | <b>0.559</b> | <b>0.535</b> | 3/8  | <b>0.387</b> | <b>0.363</b> |
| 3/4   | <b>0.7500</b> | 1 1/8                          | <b>1.125</b> | <b>1.088</b> | <b>1.299</b>                     | <b>1.240</b>  | 41/64                       | <b>0.665</b> | <b>0.617</b> | 27/64  | <b>0.446</b> | <b>0.398</b> |
| 7/8   | <b>0.8750</b> | 1 1/4                          | <b>1.312</b> | <b>1.269</b> | <b>1.516</b>                     | <b>1.447</b>  | 3/4                         | <b>0.776</b> | <b>0.724</b> | 31/64  | <b>0.510</b> | <b>0.458</b> |
| 1   | <b>1.0000</b> | 1 1/2                          | <b>1.500</b> | <b>1.450</b> | <b>1.732</b>                     | <b>1.653</b>  | 35/32                       | <b>0.887</b> | <b>0.831</b> | 35/64  | <b>0.575</b> | <b>0.519</b> |
| 1 1/8   | <b>1.1250</b> | 1 11/16                        | <b>1.688</b> | <b>1.631</b> | <b>1.949</b>                     | <b>1.859</b>  | 31/32                       | <b>0.999</b> | <b>0.939</b> | 39/64  | <b>0.639</b> | <b>0.579</b> |
| 1 1/4   | <b>1.2500</b> | 1 7/8                          | <b>1.875</b> | <b>1.812</b> | <b>2.165</b>                     | <b>2.066</b>  | 1 1/16                      | <b>1.094</b> | <b>1.030</b> | 23/32  | <b>0.751</b> | <b>0.687</b> |
| 1 3/8   | <b>1.3750</b> | 2 1/16                         | <b>2.062</b> | <b>1.994</b> | <b>2.382</b>                     | <b>2.273</b>  | 1 1/8                       | <b>1.206</b> | <b>1.138</b> | 25/32  | <b>0.815</b> | <b>0.747</b> |
| 1 1/2   | <b>1.5000</b> | 2 1/4                          | <b>2.250</b> | <b>2.175</b> | <b>2.598</b>                     | <b>2.480</b>  | 1 1/2                       | <b>1.317</b> | <b>1.245</b> | 27/32  | <b>0.880</b> | <b>0.808</b> |
| Heavy Hex Nuts (Fig. 5) and Heavy Hex Jam Nuts (Fig. 6) |               |                                |              |              |                                  |               |                             |              |              |  |              |              |
| 1/4   | 0.2500        | 1/2                            | 0.500        | 0.488        | 0.577                            | 0.556         | 15/64                       | 0.250        | 0.218        | 11/64  | 0.188        | 0.156        |
| 5/16  | 0.3125        | 9/16                           | 0.562        | 0.546        | 0.650                            | 0.622         | 19/64                       | 0.314        | 0.280        | 13/64  | 0.220        | 0.186        |
| 3/8   | 0.3750        | 1 1/16                         | 0.688        | 0.669        | 0.794                            | 0.763         | 23/64                       | 0.377        | 0.341        | 15/64  | 0.252        | 0.216        |
| 7/16  | 0.4375        | 3/4                            | 0.750        | 0.728        | 0.866                            | 0.830         | 27/64                       | 0.441        | 0.403        | 17/64  | 0.285        | 0.247        |
| 1/2   | <b>0.5000</b> | 7/8                            | <b>0.875</b> | <b>0.850</b> | <b>1.010</b>                     | <b>0.969</b>  | 31/64                       | <b>0.504</b> | <b>0.464</b> | 19/64  | <b>0.317</b> | <b>0.277</b> |
| 9/16  | 0.5625        | 15/16                          | 0.938        | 0.909        | 1.083                            | 1.037         | 35/64                       | 0.568        | 0.526        | 21/64  | 0.349        | 0.307        |
| 5/8   | <b>0.6250</b> | 1 1/16                         | <b>1.062</b> | <b>1.031</b> | <b>1.227</b>                     | <b>1.1175</b> | 39/64                       | <b>0.631</b> | <b>0.587</b> | 23/64  | <b>0.381</b> | <b>0.337</b> |
| 3/4   | <b>0.7500</b> | 1 1/4                          | <b>1.250</b> | <b>1.212</b> | <b>1.443</b>                     | <b>1.382</b>  | 47/64                       | <b>0.758</b> | <b>0.710</b> | 27/64  | <b>0.446</b> | <b>0.398</b> |
| 7/8   | <b>0.8750</b> | 1 7/16                         | <b>1.438</b> | <b>1.394</b> | <b>1.660</b>                     | <b>1.589</b>  | 55/64                       | <b>0.885</b> | <b>0.833</b> | 31/64  | <b>0.510</b> | <b>0.458</b> |
| 1   | <b>1.0000</b> | 1 5/8                          | <b>1.625</b> | <b>1.575</b> | <b>1.876</b>                     | <b>1.796</b>  | 63/64                       | <b>1.012</b> | <b>0.956</b> | 35/64  | <b>0.575</b> | <b>0.519</b> |
| 1 1/8   | <b>1.1250</b> | 1 13/16                        | <b>1.812</b> | <b>1.756</b> | <b>2.093</b>                     | <b>2.002</b>  | 1 1/64                      | <b>1.139</b> | <b>1.079</b> | 39/64  | <b>0.639</b> | <b>0.579</b> |
| 1 1/4   | <b>1.2500</b> | 2                              | <b>2.000</b> | <b>1.938</b> | <b>2.309</b>                     | <b>2.209</b>  | 1 1/32                      | <b>1.251</b> | <b>1.187</b> | 23/32  | <b>0.751</b> | <b>0.687</b> |
| 1 3/8   | <b>1.3750</b> | 2 3/16                         | <b>2.188</b> | <b>2.119</b> | <b>2.526</b>                     | <b>2.416</b>  | 1 11/32                     | <b>1.378</b> | <b>1.310</b> | 25/32  | <b>0.815</b> | <b>0.747</b> |
| 1 1/2   | <b>1.5000</b> | 2 3/8                          | <b>2.375</b> | <b>2.300</b> | <b>2.742</b>                     | <b>2.622</b>  | 1 15/32                     | <b>1.505</b> | <b>1.433</b> | 27/32  | <b>0.880</b> | <b>0.808</b> |
| 1 3/4   | 1.6250        | 2 9/16                         | 2.562        | 2.481        | 2.959                            | 2.828         | 1 19/32                     | 1.632        | 1.556        | 29/32  | 0.944        | 0.868        |
| 1 3/4   | <b>1.7500</b> | 2 5/8                          | <b>2.750</b> | <b>2.662</b> | <b>3.175</b>                     | <b>3.035</b>  | 1 23/32                     | <b>1.759</b> | <b>1.679</b> | 31/32  | <b>1.009</b> | <b>0.929</b> |
| 1 7/8   | 1.8750        | 2 15/16                        | 2.938        | 2.844        | 3.392                            | 3.242         | 1 27/32                     | 1.886        | 1.802        | 1 1/32                                       | 1.073        | 0.989        |
| 2   | <b>2.0000</b> | 3 1/8                          | <b>3.125</b> | <b>3.025</b> | <b>3.608</b>                     | <b>3.449</b>  | 1 31/32                     | <b>2.013</b> | <b>1.925</b> | 1 3/32                                       | <b>1.138</b> | <b>1.050</b> |
| 2 1/4   | 2.2500        | 3 1/2                          | 3.500        | 3.388        | 4.041                            | 3.862         | 2 13/64                     | 2.251        | 2.155        | 1 13/64                                      | 1.251        | 1.155        |
| 2 1/2   | 2.5000        | 3 7/8                          | 3.875        | 3.750        | 4.474                            | 4.275         | 2 29/64                     | 2.505        | 2.401        | 1 29/64                                      | 1.505        | 1.401        |
| 2 3/4   | 2.7500        | 4 1/4                          | 4.250        | 4.112        | 4.907                            | 4.688         | 2 45/64                     | 2.759        | 2.647        | 1 37/64                                      | 1.634        | 1.522        |
| 3   | 3.0000        | 4 3/8                          | 4.625        | 4.475        | 5.340                            | 5.102         | 2 61/64                     | 3.013        | 2.893        | 1 45/64                                      | 1.763        | 1.643        |
| 3 1/4   | 3.2500        | 5                              | 5.000        | 4.838        | 5.774                            | 5.515         | 3 3/16                      | 3.252        | 3.124        | 1 13/16                                      | 1.876        | 1.748        |
| 3 1/2   | 3.5000        | 5 3/8                          | 5.375        | 5.200        | 6.207                            | 5.928         | 3 7/16                      | 3.506        | 3.370        | 1 15/16                                      | 2.006        | 1.870        |
| 3 3/4   | 3.7500        | 5 3/4                          | 5.750        | 5.562        | 6.640                            | 6.341         | 3 11/16                     | 3.760        | 3.616        | 2 1/16                                       | 2.134        | 1.990        |
| 4   | 4.0000        | 6 1/8                          | 6.125        | 5.925        | 7.073                            | 6.755         | 3 15/16                     | 4.014        | 3.862        | 2 3/16                                       | 2.264        | 2.112        |

All dimensions are in inches.

**Bold type shows nuts unified dimensionally with British and Canadian Standards.**

Threads are Unified Coarse-, Fine-, or 8-thread series (UNC, UNF or 8UN), Class 2B. Unification of fine-thread nuts is limited to sizes 1 inch and under.

**Table 8. American National Standard and Unified Standard Hex Flat Nuts and Flat Jam Nuts and Heavy Hex Flat Nuts and Flat Jam Nuts**  
ANSI/ASME B18.2.2-1987 (R1999)

| Nominal Size or Basic Major Dia. of Thread               | Width Across Flats $F$ |                  |       | Width Across Corners $G$ |       | Thickness, Flat Nuts $H$ |                  |       | Thickness, Flat Jam Nuts $H_1$ |                 |       |       |
|--|------------------------|------------------|-------|--------------------------|-------|--------------------------|------------------|-------|--------------------------------|-----------------|-------|-------|
|  | Basic                  | Max.             | Min.  | Max.                     | Min.  | Basic                    | Max.             | Min.  | Basic                          | Max.            | Min.  |       |
| Hex Flat Nuts and Hex Flat Jam Nuts (Fig. 7)             |                        |                  |       |                          |       |                          |                  |       |                                |                 |       |       |
| $1\frac{1}{8}$   | 1.1250                 | $1\frac{11}{16}$ | 1.688 | 1.631                    | 1.949 | 1.859                    | 1                | 1.030 | 0.970                          | $\frac{5}{8}$   | 0.655 | 0.595 |
| $1\frac{1}{4}$   | 1.2500                 | $1\frac{7}{8}$   | 1.875 | 1.812                    | 2.165 | 2.066                    | $1\frac{1}{32}$  | 1.126 | 1.062                          | $\frac{3}{4}$   | 0.782 | 0.718 |
| $1\frac{3}{8}$   | 1.3750                 | $2\frac{1}{16}$  | 2.062 | 1.994                    | 2.382 | 2.273                    | $1\frac{13}{64}$ | 1.237 | 1.169                          | $\frac{13}{16}$ | 0.846 | 0.778 |
| $1\frac{1}{2}$   | 1.5000                 | $2\frac{1}{4}$   | 2.250 | 2.175                    | 2.598 | 2.480                    | $1\frac{5}{16}$  | 1.348 | 1.276                          | $\frac{7}{8}$   | 0.911 | 0.839 |
| Heavy Hex Flat Nuts and Heavy Hex Flat Jam Nuts (Fig. 7) |                        |                  |       |                          |       |                          |                  |       |                                |                 |       |       |
| $1\frac{1}{8}$   | 1.1250                 | $1\frac{13}{16}$ | 1.812 | 1.756                    | 2.093 | 2.002                    | $1\frac{1}{8}$   | 1.155 | 1.079                          | $\frac{5}{8}$   | 0.655 | 0.579 |
| $1\frac{1}{4}$   | 1.2500                 | 2                | 2.000 | 1.938                    | 2.309 | 2.209                    | $1\frac{1}{4}$   | 1.282 | 1.187                          | $\frac{3}{4}$   | 0.782 | 0.687 |
| $1\frac{3}{8}$   | 1.3750                 | $2\frac{3}{16}$  | 2.188 | 2.119                    | 2.526 | 2.416                    | $1\frac{3}{8}$   | 1.409 | 1.310                          | $\frac{13}{16}$ | 0.846 | 0.747 |
| $1\frac{1}{2}$   | 1.5000                 | $2\frac{3}{8}$   | 2.375 | 2.300                    | 2.742 | 2.622                    | $1\frac{1}{2}$   | 1.536 | 1.433                          | $\frac{7}{8}$   | 0.911 | 0.808 |
| $1\frac{3}{4}$   | 1.7500                 | $2\frac{3}{4}$   | 2.750 | 2.662                    | 3.175 | 3.035                    | $1\frac{3}{4}$   | 1.790 | 1.679                          | 1               | 1.040 | 0.929 |
| 2  | 2.0000                 | $3\frac{1}{8}$   | 3.125 | 3.025                    | 3.608 | 3.449                    | 2                | 2.044 | 1.925                          | $1\frac{1}{8}$  | 1.169 | 1.050 |
| $2\frac{1}{4}$   | 2.2500                 | $3\frac{1}{2}$   | 3.500 | 3.388                    | 4.041 | 3.862                    | $2\frac{1}{4}$   | 2.298 | 2.155                          | $1\frac{1}{4}$  | 1.298 | 1.155 |
| $2\frac{1}{2}$   | 2.5000                 | $3\frac{7}{8}$   | 3.875 | 3.750                    | 4.474 | 4.275                    | $2\frac{1}{2}$   | 2.552 | 2.401                          | $1\frac{1}{2}$  | 1.552 | 1.401 |
| $2\frac{3}{4}$   | 2.7500                 | 4 $\frac{1}{4}$  | 4.250 | 4.112                    | 4.907 | 4.688                    | $2\frac{3}{4}$   | 2.806 | 2.647                          | $1\frac{5}{8}$  | 1.681 | 1.522 |
| 3  | 3.0000                 | 4 $\frac{5}{8}$  | 4.625 | 4.475                    | 5.340 | 5.102                    | 3                | 3.060 | 2.893                          | $1\frac{3}{4}$  | 1.810 | 1.643 |
| $3\frac{1}{4}$   | 3.2500                 | 5                | 5.000 | 4.838                    | 5.774 | 5.515                    | $3\frac{1}{4}$   | 3.314 | 3.124                          | $1\frac{7}{8}$  | 1.939 | 1.748 |
| $3\frac{1}{2}$   | 3.5000                 | $5\frac{3}{8}$   | 5.375 | 5.200                    | 6.207 | 5.928                    | $3\frac{1}{2}$   | 3.568 | 3.370                          | 2               | 2.068 | 1.870 |
| $3\frac{3}{4}$   | 3.7500                 | $5\frac{3}{4}$   | 5.750 | 5.562                    | 6.640 | 6.341                    | $3\frac{3}{4}$   | 3.822 | 3.616                          | $2\frac{1}{8}$  | 2.197 | 1.990 |
| 4  | 4.0000                 | $6\frac{1}{8}$   | 6.125 | 5.925                    | 7.073 | 6.755                    | 4                | 4.076 | 3.862                          | $2\frac{1}{4}$  | 2.326 | 2.112 |

All dimensions are in inches.

**Bold type indicates nuts unified dimensionally with British and Canadian Standards.**

Threads are Unified Coarse-thread series (UNC), Class 2B.

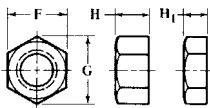


Fig. 7. Hex Flat Nuts, Heavy Hex Flat Nuts, Hex Flat Jam Nuts, and Heavy Hex Flat Jam Nuts (Table 8)

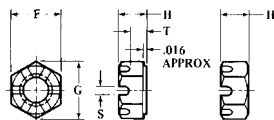


Fig. 8. Hex Slotted Nuts, Heavy Hex Slotted Nuts, and Hex Thick Slotted Nuts (Table 9)

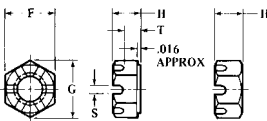


Fig. 9. Hex Thick Nuts (Table 10)

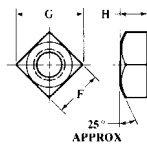


Fig. 10. Square Nuts, Heavy Square Nuts (Table 10)



**Table 10. American National and Unified Standard Square Nuts and Heavy Square Nuts and American National Standard Hex Thick Nuts**  
ANSI/ASME B18.2.2-1987 (R1999)

| Nominal Size or Basic Major Dia. of Thread |               | Width Across Flats <i>F</i> |              |              | Width Across Corners <i>G</i> |               | Thickness <i>H</i> |              |              |
|--|---------------|-----------------------------|--------------|--------------|-------------------------------|---------------|--------------------|--------------|--------------|
|  |               | Basic                       | Max.         | Min.         | Max.                          | Min.          | Basic              | Max.         | Min.         |
| Square Nuts <sup>a</sup> (Fig. 10)         |               |                             |              |              |                               |               |                    |              |              |
| $\frac{1}{4}$                              | <b>0.2500</b> | $\frac{7}{16}$              | <b>0.438</b> | <b>0.425</b> | <b>0.619</b>                  | <b>0.554</b>  | $\frac{7}{32}$     | <b>0.235</b> | <b>0.203</b> |
| $\frac{5}{16}$                             | <b>0.3125</b> | $\frac{9}{16}$              | <b>0.562</b> | <b>0.547</b> | <b>0.795</b>                  | <b>0.721</b>  | $\frac{17}{64}$    | <b>0.283</b> | <b>0.249</b> |
| $\frac{3}{8}$                              | <b>0.3750</b> | $\frac{5}{8}$               | <b>0.625</b> | <b>0.606</b> | <b>0.884</b>                  | <b>0.802</b>  | $\frac{21}{64}$    | <b>0.346</b> | <b>0.310</b> |
| $\frac{7}{16}$                             | <b>0.4375</b> | $\frac{3}{4}$               | <b>0.750</b> | <b>0.728</b> | <b>1.061</b>                  | <b>0.970</b>  | $\frac{3}{8}$      | <b>0.394</b> | <b>0.356</b> |
| $\frac{1}{2}$                              | <b>0.5000</b> | $\frac{13}{16}$             | <b>0.812</b> | <b>0.788</b> | <b>1.149</b>                  | <b>1.052</b>  | $\frac{7}{16}$     | <b>0.458</b> | <b>0.418</b> |
| $\frac{5}{8}$                              | <b>0.6250</b> | <b>1</b>                    | <b>1.000</b> | <b>0.969</b> | <b>1.414</b>                  | $\frac{3}{8}$ | <b>0.569</b>       | <b>0.525</b> |              |
| $\frac{3}{4}$                              | <b>0.7500</b> | $1\frac{1}{8}$              | <b>1.125</b> | <b>1.088</b> | <b>1.591</b>                  | <b>1.464</b>  | $\frac{21}{32}$    | <b>0.680</b> | <b>0.632</b> |
| $\frac{7}{8}$                              | <b>0.8750</b> | $1\frac{5}{16}$             | <b>1.312</b> | <b>1.269</b> | <b>1.856</b>                  | <b>1.712</b>  | $\frac{9}{16}$     | <b>0.792</b> | <b>0.740</b> |
| <b>1</b>                                   | <b>1.0000</b> | $1\frac{1}{2}$              | <b>1.500</b> | <b>1.450</b> | <b>2.121</b>                  | <b>1.961</b>  | $\frac{7}{8}$      | <b>0.903</b> | <b>0.847</b> |
| $1\frac{1}{8}$                             | <b>1.1250</b> | $1\frac{11}{16}$            | <b>1.688</b> | <b>1.631</b> | <b>2.386</b>                  | <b>2.209</b>  | <b>1</b>           | <b>1.030</b> | <b>0.970</b> |
| $1\frac{1}{4}$                             | <b>1.2500</b> | $1\frac{7}{8}$              | <b>1.875</b> | <b>1.812</b> | <b>2.652</b>                  | <b>2.458</b>  | $1\frac{13}{32}$   | <b>1.126</b> | <b>1.062</b> |
| $1\frac{3}{8}$                             | <b>1.3750</b> | $2\frac{1}{16}$             | <b>2.062</b> | <b>1.994</b> | <b>2.917</b>                  | <b>2.708</b>  | $1\frac{13}{64}$   | <b>1.237</b> | <b>1.169</b> |
| $1\frac{1}{2}$                             | <b>1.5000</b> | $2\frac{1}{4}$              | <b>2.250</b> | <b>2.175</b> | <b>3.182</b>                  | <b>2.956</b>  | $1\frac{5}{16}$    | <b>1.348</b> | <b>1.276</b> |
| Heavy Square Nuts <sup>a</sup> (Fig. 10)   |               |                             |              |              |                               |               |                    |              |              |
| $\frac{1}{4}$                              | 0.2500        | $\frac{1}{2}$               | 0.500        | 0.488        | 0.707                         | 0.640         | $\frac{1}{4}$      | 0.266        | 0.218        |
| $\frac{5}{16}$                             | 0.3125        | $\frac{9}{16}$              | 0.562        | 0.546        | 0.795                         | 0.720         | $\frac{5}{16}$     | 0.330        | 0.280        |
| $\frac{3}{8}$                              | 0.3750        | $1\frac{1}{16}$             | 0.688        | 0.669        | 0.973                         | 0.889         | $\frac{3}{8}$      | 0.393        | 0.341        |
| $\frac{7}{16}$                             | 0.4375        | $\frac{3}{4}$               | 0.750        | 0.728        | 1.060                         | 0.970         | $\frac{7}{16}$     | 0.456        | 0.403        |
| $\frac{1}{2}$                              | 0.5000        | $\frac{7}{8}$               | 0.875        | 0.850        | 1.237                         | 1.137         | $\frac{1}{2}$      | 0.520        | 0.464        |
| $\frac{5}{8}$                              | 0.6250        | $1\frac{1}{16}$             | 1.062        | 1.031        | 1.503                         | 1.386         | $\frac{5}{8}$      | 0.647        | 0.587        |
| $\frac{3}{4}$                              | 0.7500        | $1\frac{1}{4}$              | 1.250        | 1.212        | 1.768                         | 1.635         | $\frac{3}{4}$      | 0.774        | 0.710        |
| $\frac{7}{8}$                              | 0.8750        | $1\frac{7}{16}$             | 1.438        | 1.394        | 2.033                         | 1.884         | $\frac{7}{8}$      | 0.901        | 0.833        |
| <b>1</b>                                   | <b>1.0000</b> | $1\frac{5}{8}$              | <b>1.625</b> | <b>1.575</b> | <b>2.298</b>                  | <b>2.132</b>  | <b>1</b>           | <b>1.028</b> | <b>0.956</b> |
| $1\frac{1}{8}$                             | 1.1250        | $1\frac{13}{16}$            | 1.812        | 1.756        | 2.563                         | 2.381         | $1\frac{1}{8}$     | 1.155        | 1.079        |
| $1\frac{1}{4}$                             | 1.2500        | <b>2</b>                    | <b>2.000</b> | <b>1.938</b> | <b>2.828</b>                  | <b>2.631</b>  | $1\frac{1}{4}$     | 1.282        | 1.187        |
| $1\frac{3}{8}$                             | 1.3750        | $2\frac{3}{16}$             | 2.188        | 2.119        | 3.094                         | 2.879         | $1\frac{3}{8}$     | 1.409        | 1.310        |
| $1\frac{1}{2}$                             | 1.5000        | $2\frac{3}{8}$              | 2.375        | 2.300        | 3.359                         | 3.128         | $1\frac{1}{2}$     | 1.536        | 1.433        |
| Hex Thick Nuts <sup>b</sup> (Fig. 10)      |               |                             |              |              |                               |               |                    |              |              |
| $\frac{1}{4}$                              | 0.2500        | $\frac{7}{16}$              | 0.438        | 0.428        | 0.505                         | 0.488         | $\frac{9}{32}$     | 0.288        | 0.274        |
| $\frac{5}{16}$                             | 0.3125        | $\frac{1}{2}$               | 0.500        | 0.489        | 0.577                         | 0.557         | $\frac{21}{64}$    | 0.336        | 0.320        |
| $\frac{3}{8}$                              | 0.3750        | $\frac{9}{16}$              | 0.562        | 0.551        | 0.650                         | 0.628         | $\frac{13}{32}$    | 0.415        | 0.398        |
| $\frac{7}{16}$                             | 0.4375        | $1\frac{1}{16}$             | 0.688        | 0.675        | 0.794                         | 0.768         | $\frac{29}{64}$    | 0.463        | 0.444        |
| $\frac{1}{2}$                              | 0.5000        | $\frac{3}{4}$               | 0.750        | 0.736        | 0.866                         | 0.840         | $\frac{9}{16}$     | 0.573        | 0.552        |
| $\frac{5}{16}$                             | 0.5625        | $\frac{7}{8}$               | 0.875        | 0.861        | 1.010                         | 0.982         | $\frac{39}{64}$    | 0.621        | 0.598        |
| $\frac{3}{8}$                              | 0.6250        | $1\frac{1}{16}$             | 0.938        | 0.922        | 1.083                         | 1.051         | $\frac{25}{32}$    | 0.731        | 0.706        |
| $\frac{3}{4}$                              | 0.7500        | $1\frac{1}{8}$              | 1.125        | 1.088        | 1.299                         | 1.240         | $\frac{13}{16}$    | 0.827        | 0.798        |
| $\frac{7}{8}$                              | 0.8750        | $1\frac{5}{16}$             | 1.312        | 1.269        | 1.516                         | 1.447         | $\frac{29}{32}$    | 0.922        | 0.890        |
| <b>1</b>                                   | <b>1.0000</b> | $1\frac{1}{2}$              | <b>1.500</b> | <b>1.450</b> | <b>1.732</b>                  | <b>1.653</b>  | <b>1</b>           | <b>1.018</b> | <b>0.982</b> |
| $1\frac{1}{8}$                             | 1.1250        | $1\frac{11}{16}$            | 1.688        | 1.631        | 1.949                         | 1.859         | $1\frac{5}{32}$    | 1.176        | 1.136        |
| $1\frac{1}{4}$                             | 1.2500        | $1\frac{7}{8}$              | 1.875        | 1.812        | 2.165                         | 2.066         | $1\frac{1}{4}$     | 1.272        | 1.228        |
| $1\frac{3}{8}$                             | 1.3750        | $2\frac{1}{16}$             | 2.062        | 1.994        | 2.382                         | 2.273         | $1\frac{3}{8}$     | 1.399        | 1.351        |
| $1\frac{1}{2}$                             | 1.5000        | $2\frac{1}{4}$              | 2.250        | 2.175        | 2.598                         | 2.480         | $1\frac{1}{2}$     | 1.526        | 1.474        |

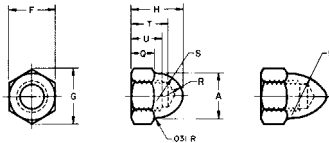
<sup>a</sup> Coarse-thread series, Class 2B.

<sup>b</sup> Unified Coarse-, Fine-, or 8-thread series (8 UN), Class 2B.

All dimensions are in inches.

**Bold type indicates nuts unified dimensionally with British and Canadian Standards.**

## Low and High Crown (Blind, Acorn) Nuts SAE Recommended Practice J483a



Low Crown

| Nom. Size <sup>a</sup><br>or Basic Major<br>Dia. of Thread | Width Across<br>Flats, <i>F</i> |                  |        | Width Across<br>Corners, <i>G</i> |       | Body<br>Dia.,<br><i>A</i> | Over-<br>all<br>Hgt., <i>H</i> | Hexa-<br>gon<br>Hgt., <i>Q</i> | Nose<br>Rad.,<br><i>R</i> | Body<br>Rad.,<br><i>S</i> | Drill<br>Dep., <i>T</i> |      | Full<br>Thd., <i>U</i> |  |
|--|---------------------------------|------------------|--------|-----------------------------------|-------|---------------------------|--------------------------------|--------------------------------|---------------------------|---------------------------|-------------------------|------|------------------------|--|
|  | Max.                            | (Basic)          | Min.   | Max.                              | Min.  |                           |                                |                                |                           |                           | Max.                    | Min. |                        |  |
| 6  | 0.1380                          | $\frac{5}{16}$   | 0.3125 | 0.302                             | 0.361 | 0.344                     | 0.30                           | 0.34                           | 0.16                      | 0.08                      | 0.17                    | 0.25 | 0.16                   |  |
| 8  | 0.1640                          | $\frac{5}{16}$   | 0.3125 | 0.302                             | 0.361 | 0.344                     | 0.30                           | 0.34                           | 0.16                      | 0.08                      | 0.17                    | 0.25 | 0.16                   |  |
| 10   | 0.1900                          | $\frac{3}{8}$    | 0.3750 | 0.362                             | 0.433 | 0.413                     | 0.36                           | 0.41                           | 0.19                      | 0.09                      | 0.22                    | 0.28 | 0.19                   |  |
| 12   | 0.2160                          | $\frac{3}{8}$    | 0.3750 | 0.362                             | 0.433 | 0.413                     | 0.36                           | 0.41                           | 0.19                      | 0.09                      | 0.22                    | 0.31 | 0.22                   |  |
| $\frac{1}{4}$  | 0.2500                          | $\frac{7}{16}$   | 0.4375 | 0.428                             | 0.505 | 0.488                     | 0.41                           | 0.47                           | 0.22                      | 0.11                      | 0.25                    | 0.34 | 0.25                   |  |
| $\frac{5}{16}$   | 0.3125                          | $\frac{1}{2}$    | 0.5000 | 0.489                             | 0.577 | 0.557                     | 0.47                           | 0.53                           | 0.25                      | 0.12                      | 0.28                    | 0.41 | 0.31                   |  |
| $\frac{3}{8}$  | 0.3750                          | $\frac{9}{16}$   | 0.5625 | 0.551                             | 0.650 | 0.628                     | 0.53                           | 0.62                           | 0.28                      | 0.14                      | 0.33                    | 0.45 | 0.38                   |  |
| $\frac{7}{16}$   | 0.4375                          | $\frac{5}{8}$    | 0.6250 | 0.612                             | 0.722 | 0.698                     | 0.59                           | 0.69                           | 0.31                      | 0.16                      | 0.36                    | 0.52 | 0.44                   |  |
| $\frac{1}{2}$  | 0.5000                          | $\frac{3}{4}$    | 0.7500 | 0.736                             | 0.866 | 0.840                     | 0.72                           | 0.81                           | 0.38                      | 0.19                      | 0.42                    | 0.59 | 0.50                   |  |
| $\frac{9}{16}$   | 0.5625                          | $\frac{7}{8}$    | 0.8750 | 0.861                             | 1.010 | 0.982                     | 0.84                           | 0.94                           | 0.44                      | 0.22                      | 0.50                    | 0.69 | 0.56                   |  |
| $\frac{5}{8}$  | 0.6250                          | $1\frac{1}{16}$  | 0.9375 | 0.922                             | 1.083 | 1.051                     | 0.91                           | 1.00                           | 0.47                      | 0.23                      | 0.53                    | 0.75 | 0.62                   |  |
| $\frac{3}{4}$  | 0.7500                          | $1\frac{1}{16}$  | 1.0625 | 1.045                             | 1.227 | 1.191                     | 1.03                           | 1.16                           | 0.53                      | 0.27                      | 0.59                    | 0.88 | 0.75                   |  |
| $\frac{7}{8}$  | 0.8750                          | $1\frac{1}{4}$   | 1.2500 | 1.231                             | 1.443 | 1.403                     | 1.22                           | 1.36                           | 0.62                      | 0.31                      | 0.70                    | 1.00 | 0.88                   |  |
| 1  | 1.0000                          | $1\frac{7}{16}$  | 1.4375 | 1.417                             | 1.660 | 1.615                     | 1.41                           | 1.55                           | 0.72                      | 0.36                      | 0.81                    | 1.12 | 1.00                   |  |
| $1\frac{1}{8}$   | 1.1250                          | $1\frac{5}{8}$   | 1.6250 | 1.602                             | 1.876 | 1.826                     | 1.59                           | 1.75                           | 0.81                      | 0.41                      | 0.92                    | 1.31 | 1.12                   |  |
| $1\frac{1}{4}$   | 1.2500                          | $1\frac{13}{16}$ | 1.8125 | 1.788                             | 2.093 | 2.038                     | 1.78                           | 1.95                           | 0.91                      | 0.45                      | 1.03                    | 1.44 | 1.25                   |  |

High Crown

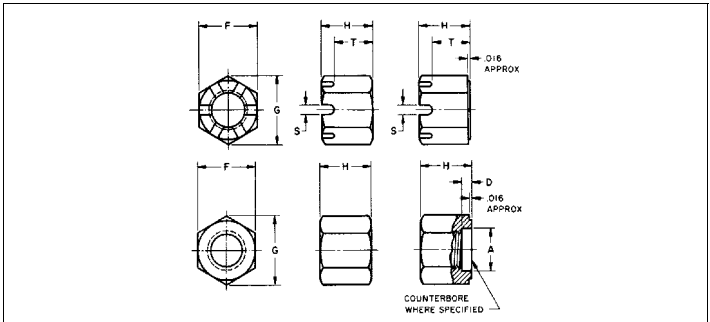
| Nom. Size <sup>a</sup><br>or Basic Major Dia.<br>of Thread | Width Across<br>Flats, <i>F</i> |                  |        | Width Across<br>Corners, <i>G</i> |       | Body<br>Dia.,<br><i>A</i> | Over-<br>all<br>Hgt., <i>H</i> | Hexa-<br>gon<br>Hgt., <i>Q</i> | Nose<br>Rad.,<br><i>R</i> | Body<br>Rad.,<br><i>S</i> | Drill<br>Dep., <i>T</i> |      | Full<br>Thd., <i>U</i> |  |
|--|---------------------------------|------------------|--------|-----------------------------------|-------|---------------------------|--------------------------------|--------------------------------|---------------------------|---------------------------|-------------------------|------|------------------------|--|
|  | Max.                            | (Basic)          | Min.   | Max.                              | Min.  |                           |                                |                                |                           |                           | Max.                    | Min. |                        |  |
| 6  | 0.1380                          | $\frac{5}{16}$   | 0.3125 | 0.302                             | 0.361 | 0.344                     | 0.30                           | 0.42                           | 0.17                      | 0.05                      | 0.25                    | 0.28 | 0.19                   |  |
| 8  | 0.1640                          | $\frac{5}{16}$   | 0.3125 | 0.302                             | 0.361 | 0.344                     | 0.30                           | 0.42                           | 0.17                      | 0.05                      | 0.25                    | 0.28 | 0.19                   |  |
| 10   | 0.1900                          | $\frac{3}{8}$    | 0.3750 | 0.362                             | 0.433 | 0.413                     | 0.36                           | 0.52                           | 0.20                      | 0.06                      | 0.30                    | 0.34 | 0.25                   |  |
| 12   | 0.2160                          | $\frac{3}{8}$    | 0.3750 | 0.362                             | 0.433 | 0.413                     | 0.36                           | 0.52                           | 0.20                      | 0.06                      | 0.30                    | 0.38 | 0.28                   |  |
| $\frac{1}{4}$  | 0.2500                          | $\frac{7}{16}$   | 0.4375 | 0.428                             | 0.505 | 0.488                     | 0.41                           | 0.59                           | 0.23                      | 0.06                      | 0.34                    | 0.41 | 0.31                   |  |
| $\frac{5}{16}$   | 0.3125                          | $\frac{1}{2}$    | 0.5000 | 0.489                             | 0.577 | 0.557                     | 0.47                           | 0.69                           | 0.28                      | 0.08                      | 0.41                    | 0.47 | 0.38                   |  |
| $\frac{3}{8}$  | 0.3750                          | $\frac{9}{16}$   | 0.5625 | 0.551                             | 0.650 | 0.628                     | 0.53                           | 0.78                           | 0.31                      | 0.09                      | 0.44                    | 0.56 | 0.47                   |  |
| $\frac{7}{16}$   | 0.4375                          | $\frac{5}{8}$    | 0.6250 | 0.612                             | 0.722 | 0.698                     | 0.59                           | 0.88                           | 0.34                      | 0.09                      | 0.50                    | 0.62 | 0.53                   |  |
| $\frac{1}{2}$  | 0.5000                          | $\frac{3}{4}$    | 0.7500 | 0.736                             | 0.866 | 0.840                     | 0.72                           | 1.03                           | 0.42                      | 0.12                      | 0.59                    | 0.75 | 0.62                   |  |
| $\frac{9}{16}$   | 0.5625                          | $\frac{7}{8}$    | 0.8750 | 0.861                             | 1.010 | 0.982                     | 0.84                           | 1.19                           | 0.48                      | 0.16                      | 0.69                    | 0.81 | 0.69                   |  |
| $\frac{5}{8}$  | 0.6250                          | $1\frac{1}{16}$  | 0.9375 | 0.922                             | 1.083 | 1.051                     | 0.91                           | 1.28                           | 0.53                      | 0.16                      | 0.75                    | 0.91 | 0.78                   |  |
| $\frac{3}{4}$  | 0.7500                          | $1\frac{1}{16}$  | 1.0625 | 1.045                             | 1.227 | 1.191                     | 1.03                           | 1.45                           | 0.59                      | 0.17                      | 0.84                    | 1.06 | 0.94                   |  |
| $\frac{7}{8}$  | 0.8750                          | $1\frac{1}{4}$   | 1.2500 | 1.231                             | 1.443 | 1.403                     | 1.22                           | 1.72                           | 0.70                      | 0.20                      | 0.98                    | 1.22 | 1.09                   |  |
| 1  | 1.0000                          | $1\frac{7}{16}$  | 1.4375 | 1.417                             | 1.660 | 1.615                     | 1.41                           | 1.97                           | 0.81                      | 0.23                      | 1.14                    | 1.38 | 1.25                   |  |
| $1\frac{1}{8}$   | 1.1250                          | $1\frac{5}{8}$   | 1.6250 | 1.602                             | 1.876 | 1.826                     | 1.59                           | 2.22                           | 0.92                      | 0.27                      | 1.28                    | 1.59 | 1.41                   |  |
| $1\frac{1}{4}$   | 1.2500                          | $1\frac{13}{16}$ | 1.8125 | 1.788                             | 2.093 | 2.038                     | 1.78                           | 2.47                           | 1.03                      | 0.28                      | 1.44                    | 1.75 | 1.56                   |  |

<sup>a</sup> When specifying a nominal size in decimals, any zero in the fourth decimal place is omitted. Reprinted with permission. Copyright © 1990, Society of Automotive Engineers, Inc. All rights reserved.

All dimensions are in inches. Threads are Unified Standard Class 2B, UNC or UNF Series.



Hex High and Hex Slotted High Nuts SAE Standard J482a

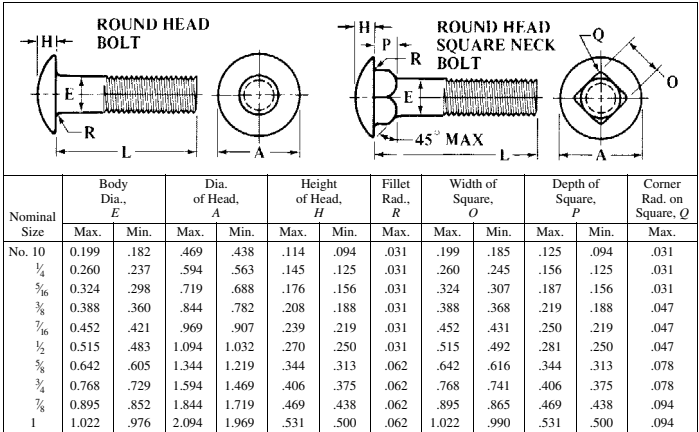


| Nominal Size <sup>a</sup><br>or Basic Major<br>Diameter of Thread |        | Width Across Flats, <i>F</i> |        |       | Width Across Corners, <i>G</i>   |       | Slot Width, <i>S</i>      |                 |
|---|--------|------------------------------|--------|-------|----------------------------------|-------|---------------------------|-----------------|
|   |        | Basic                        | Max.   | Min.  | Max.                             | Min.  | Min.                      | Max.            |
| 1/4   | 0.2500 | 3/16                         | 0.4375 | 0.428 | 0.505                            | 0.488 | 0.07                      | 0.10            |
| 5/16  | 0.3125 | 1/2                          | 0.5000 | 0.489 | 0.577                            | 0.557 | 0.09                      | 0.12            |
| 3/8   | 0.3750 | 9/16                         | 0.5625 | 0.551 | 0.650                            | 0.628 | 0.12                      | 0.15            |
| 7/16  | 0.4375 | 11/16                        | 0.6875 | 0.675 | 0.794                            | 0.768 | 0.12                      | 0.15            |
| 1/2   | 0.5000 | 3/4                          | 0.7500 | 0.736 | 0.866                            | 0.840 | 0.15                      | 0.18            |
| 9/16  | 0.5625 | 7/8                          | 0.8750 | 0.861 | 1.010                            | 0.982 | 0.15                      | 0.18            |
| 5/8   | 0.6250 | 15/16                        | 0.9375 | 0.922 | 1.083                            | 1.051 | 0.18                      | 0.24            |
| 3/4   | 0.7500 | 1 1/8                        | 1.1250 | 1.088 | 1.299                            | 1.240 | 0.18                      | 0.24            |
| 7/8   | 0.8750 | 1 5/16                       | 1.3125 | 1.269 | 1.516                            | 1.447 | 0.18                      | 0.24            |
| 1   | 1.0000 | 1 1/2                        | 1.5000 | 1.450 | 1.732                            | 1.653 | 0.24                      | 0.30            |
| 1 1/8   | 1.1250 | 1 11/16                      | 1.6875 | 1.631 | 1.949                            | 1.859 | 0.24                      | 0.33            |
| 1 1/4   | 1.2500 | 1 7/8                        | 1.8750 | 1.812 | 2.165                            | 2.066 | 0.31                      | 0.40            |
| Nominal Size <sup>a</sup><br>or Basic Major<br>Diameter of Thread |        | Thickness, <i>H</i>          |        |       | Unslotted<br>Thickness, <i>T</i> |       | Counterbore<br>(Optional) |                 |
|   |        | Basic                        | Max.   | Min.  | Max.                             | Min.  | Dia., <i>A</i>            | Depth, <i>D</i> |
| 1/4   | 0.2500 | 3/8                          | 0.382  | 0.368 | 0.29                             | 0.27  | 0.266                     | 0.062           |
| 5/16  | 0.3125 | 29/64                        | 0.461  | 0.445 | 0.37                             | 0.35  | 0.328                     | 0.078           |
| 3/8   | 0.3750 | 1/2                          | 0.509  | 0.491 | 0.38                             | 0.36  | 0.391                     | 0.094           |
| 7/16  | 0.4375 | 39/64                        | 0.619  | 0.599 | 0.46                             | 0.44  | 0.453                     | 0.109           |
| 1/2   | 0.5000 | 23/32                        | 0.667  | 0.645 | 0.51                             | 0.49  | 0.516                     | 0.125           |
| 9/16  | 0.5625 | 49/64                        | 0.778  | 0.754 | 0.59                             | 0.57  | 0.594                     | 0.141           |
| 5/8   | 0.6250 | 27/32                        | 0.857  | 0.831 | 0.63                             | 0.61  | 0.656                     | 0.156           |
| 3/4   | 0.7500 | 1                            | 1.015  | 0.985 | 0.76                             | 0.73  | 0.781                     | 0.188           |
| 7/8   | 0.8750 | 1 5/32                       | 1.172  | 1.140 | 0.92                             | 0.89  | 0.906                     | 0.219           |
| 1   | 1.0000 | 1 5/16                       | 1.330  | 1.292 | 1.05                             | 1.01  | 1.031                     | 0.250           |
| 1 1/8   | 1.1250 | 1 1/2                        | 1.520  | 1.480 | 1.18                             | 1.14  | 1.156                     | 0.281           |
| 1 1/4   | 1.2500 | 1 11/16                      | 1.710  | 1.666 | 1.34                             | 1.29  | 1.281                     | 0.312           |

<sup>a</sup> When specifying a nominal size in decimals, any zero in the fourth decimal place is omitted. Reprinted with permission. Copyright © 1990, Society of Automotive Engineers, Inc. All rights reserved.

All dimensions are in inches. Threads are Unified Standard Class 2B, UNC or UNF Series.

**American National Standard Round Head and Round Head Square Neck Bolts**  
ANSI/ASME B18.5-1990



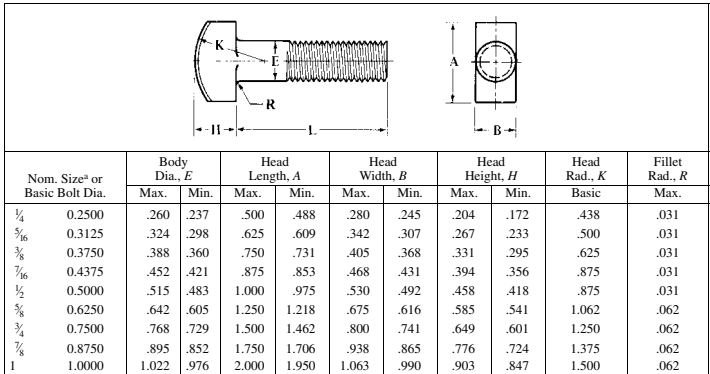
All dimensions are in inches unless otherwise specified.

Threads are Unified Standard, Class 2A, UNC Series, in accordance with ANSI B1.1. For threads with additive finish, the maximum diameters of Class 2A shall apply before plating or coating, whereas the basic diameters (Class 2A maximum diameters plus the allowance) shall apply to a bolt after plating or coating.

Bolts are designated in the sequence shown: nominal size (number, fraction or decimal equivalent); threads per inch; nominal length (fraction or decimal equivalent); product name; material; and protective finish, if required.

i.e.: ½-13 × 3 Round Head Square Neck Bolt, Steel .375-16 × 2.50 Step Bolt, Steel, Zinc Plated

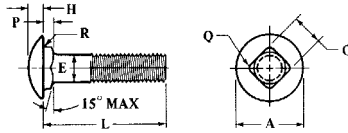
**American National Standard T-Head Bolts ANSI/ASME B18.5-1990**



<sup>a</sup> Where specifying nominal size in decimals, zeros preceding the decimal point and in the fourth decimal place are omitted. For information as to threads and method of bolt designation, see footnotes to preceding table.

All dimensions are given in inches.

**American National Standard Round Head Short Square Neck Bolts**  
ANSI/ASME B18.5-1990



| Nominal Size | Body Dia., E |       | Head Dia., A |       | Head Height, H |       | Square Width, O |       | Square Depth, P |       | Cor. Rad. on Sq., Q | Fillet Rad., R |
|--------------|--------------|-------|--------------|-------|----------------|-------|-----------------|-------|-----------------|-------|---------------------|----------------|
|              | Max          | Min   | Max          | Min   | Max            | Min   | Max             | Min   | Max             | Min   | Max                 | Max            |
| 1/4          | 0.260        | 0.213 | 0.594        | 0.563 | 0.145          | 0.125 | 0.260           | 0.245 | 0.124           | 0.093 | 0.031               | 0.031          |
| 5/16         | 0.324        | 0.272 | 0.719        | 0.688 | 0.176          | 0.156 | 0.324           | 0.307 | 0.124           | 0.093 | 0.031               | 0.031          |
| 3/8          | 0.388        | 0.329 | 0.844        | 0.782 | 0.208          | 0.188 | 0.388           | 0.368 | 0.156           | 0.125 | 0.047               | 0.031          |
| 7/16         | 0.452        | 0.385 | 0.969        | 0.907 | 0.239          | 0.219 | 0.452           | 0.431 | 0.156           | 0.125 | 0.047               | 0.031          |
| 1/2          | 0.515        | 0.444 | 1.094        | 1.032 | 0.270          | 0.250 | 0.515           | 0.492 | 0.156           | 0.125 | 0.047               | 0.031          |
| 5/8          | 0.642        | 0.559 | 1.344        | 1.219 | 0.344          | 0.313 | 0.642           | 0.616 | 0.218           | 0.187 | 0.078               | 0.062          |
| 3/4          | 0.768        | 0.678 | 1.594        | 1.469 | 0.406          | 0.375 | 0.768           | 0.741 | 0.218           | 0.187 | 0.078               | 0.062          |

All dimensions are given in inches.

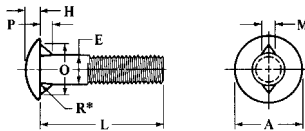
Threads are Unified Standard, Class 2A, UNC Series, in accordance with ANSI B1.1. For threads with additive finish, the maximum diameters of Class 2A apply before plating or coating, whereas the basic diameters (Class 2A maximum diameters plus the allowance) apply to a bolt after plating or coating.

Bolts are designated in the sequence shown: nominal size (number, fraction or decimal equivalent); threads per inch; nominal length (fraction or decimal equivalent); product name; material; and protective finish, if required. For example,

1/2-13 x 3 Round Head Short Square Neck Bolt, Steel

.375-16 x 2.50 Round Head Short Square Neck Bolt, Steel, Zinc Plated

**American National Standard Round Head Fin Neck Bolts ANSI/ASME B18.5-1990**



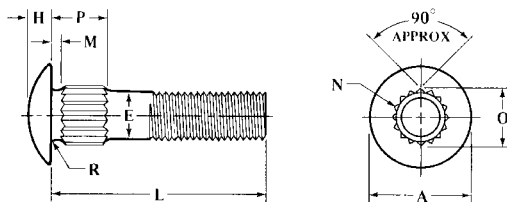
| Nominal Size | Body Dia., E |       | Head Dia., A |       | Head Height, H |       | Fin Thick., M |       | Dist. Across Fins, O |       | Fin Depth, P |       |
|--------------|--------------|-------|--------------|-------|----------------|-------|---------------|-------|----------------------|-------|--------------|-------|
|              | Max          | Min   | Max          | Min   | Max            | Min   | Max           | Min   | Max                  | Min   | Max          | Min   |
| No. 10       | 0.199        | 0.182 | 0.469        | 0.438 | 0.114          | 0.094 | 0.098         | 0.078 | 0.395                | 0.375 | 0.088        | 0.078 |
| 1/4          | 0.260        | 0.237 | 0.594        | 0.563 | 0.145          | 0.125 | 0.114         | 0.094 | 0.458                | 0.438 | 0.104        | 0.094 |
| 5/16         | 0.324        | 0.298 | 0.719        | 0.688 | 0.176          | 0.156 | 0.145         | 0.125 | 0.551                | 0.531 | 0.135        | 0.125 |
| 3/8          | 0.388        | 0.360 | 0.844        | 0.782 | 0.208          | 0.188 | 0.161         | 0.141 | 0.645                | 0.625 | 0.151        | 0.141 |
| 7/16         | 0.452        | 0.421 | 0.969        | 0.907 | 0.239          | 0.219 | 0.192         | 0.172 | 0.739                | 0.719 | 0.182        | 0.172 |
| 1/2          | 0.515        | 0.483 | 1.094        | 1.032 | 0.270          | 0.250 | 0.208         | 0.188 | 0.833                | 0.813 | 0.198        | 0.188 |

All dimensions are given in inches unless otherwise specified.

\*Maximum fillet radius R is 0.031 inch for all sizes.

For information as to threads and method of bolt designation, see footnotes to the preceding table.

American National Standard Round Head Ribbed Neck Bolts ANSI/ASME B18.5-1990



| Nominal Size <sup>a</sup> or Basic Bolt Diameter | Body Diameter, <i>E</i> |       | Head Diameter, <i>A</i> |       | Head Height, <i>H</i> |       | Head to Ribs, <i>M</i>        |                  | Number of Ribs, <i>N</i>      | Dia. Over Ribs, <i>O</i>      | Depth Over Ribs, <i>P</i>    |                  |       | Fillet Radius, <i>R</i> |
|--|-------------------------|-------|-------------------------|-------|-----------------------|-------|-------------------------------|------------------|-------------------------------|-------------------------------|------------------------------|------------------|-------|-------------------------|
|  |                         |       |                         |       |                       |       | For Lengths of                |                  |                               |                               | For Lengths of               |                  |       |                         |
|  | Max                     | Min   | Max                     | Min   | Max                   | Min   | $\frac{3}{8}$ in. and Shorter | 1 in. and Longer | $\frac{3}{8}$ in. and Shorter | 1 in. and 1 $\frac{1}{2}$ in. | $\frac{1}{2}$ in. and Longer | Max <sup>c</sup> |       |                         |
| No. 10 0.1900                                    | 0.199                   | 0.182 | 0.469                   | 0.438 | 0.114                 | 0.094 | 0.031 <sup>†</sup>            | 0.063            | 9                             | 0.210                         | 0.250                        | 0.407            | 0.594 | 0.031                   |
| $\frac{1}{4}$ 0.2500                             | 0.260                   | 0.237 | 0.594                   | 0.563 | 0.145                 | 0.125 | 0.031 <sup>†</sup>            | 0.063            | 10                            | 0.274                         | 0.250                        | 0.407            | 0.594 | 0.031                   |
| $\frac{5}{16}$ 0.3125                            | 0.324                   | 0.298 | 0.719                   | 0.688 | 0.176                 | 0.156 | 0.031 <sup>†</sup>            | 0.063            | 12                            | 0.340                         | 0.250                        | 0.407            | 0.594 | 0.031                   |
| $\frac{3}{8}$ 0.3750                             | 0.388                   | 0.360 | 0.844                   | 0.782 | 0.208                 | 0.188 | 0.031 <sup>†</sup>            | 0.063            | 12                            | 0.405                         | 0.250                        | 0.407            | 0.594 | 0.031                   |
| $\frac{7}{16}$ 0.4375                            | 0.452                   | 0.421 | 0.969                   | 0.907 | 0.239                 | 0.219 | 0.031 <sup>†</sup>            | 0.063            | 14                            | 0.470                         | 0.250                        | 0.407            | 0.594 | 0.031                   |
| $\frac{1}{2}$ 0.5000                             | 0.515                   | 0.483 | 1.094                   | 1.032 | 0.270                 | 0.250 | 0.031 <sup>†</sup>            | 0.063            | 16                            | 0.534                         | 0.250                        | 0.407            | 0.594 | 0.031                   |
| $\frac{5}{8}$ 0.6250                             | 0.642                   | 0.605 | 1.344                   | 1.219 | 0.344                 | 0.313 | 0.094                         | 0.094            | 19                            | 0.660                         | 0.313                        | 0.438            | 0.625 | 0.062                   |
| $\frac{3}{4}$ 0.7500                             | 0.768                   | 0.729 | 1.594                   | 1.469 | 0.406                 | 0.375 | 0.094                         | 0.094            | 22                            | 0.785                         | 0.313                        | 0.438            | 0.625 | 0.062                   |

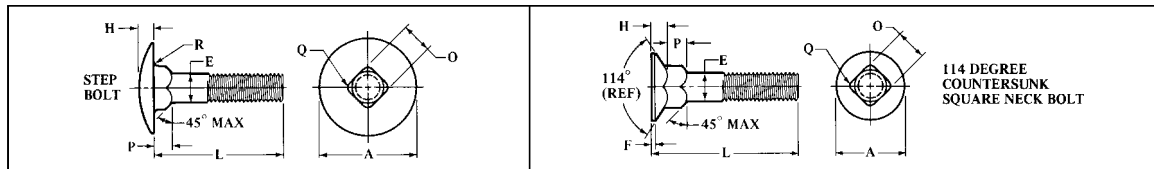
<sup>a</sup> Where specifying nominal size in decimals, zeros preceding decimal and in the fourth decimal place shall be omitted.

<sup>b</sup> Tolerance on the No. 10 through  $\frac{1}{2}$  in. sizes for nominal lengths  $\frac{3}{8}$  in. and shorter shall be +0.031 and -0.000.

<sup>c</sup> The minimum radius is one half of the value shown.

All dimensions are given in inches unless otherwise specified.  
For information as to threads and method of designating bolts, see following table.

**American National Standard Step and 114 Degree Countersunk Square Neck Bolts**  
ANSI/ASME B18.5-1990



| Nominal Size | Step & 114° Countersunk Bolts |       |                          |                    |       |                    | Step Bolts |                 |       |                   |       |                  | 114° Countersunk Square Neck Bolts |       |                 |       |                 |                   |       |
|--------------|-------------------------------|-------|--------------------------|--------------------|-------|--------------------|------------|-----------------|-------|-------------------|-------|------------------|------------------------------------|-------|-----------------|-------|-----------------|-------------------|-------|
|              | Body Dia., E                  |       | Corner Rad. on Square, Q | Width of Square, O |       | Depth of Square, P |            | Dia. of Head, A |       | Height of Head, H |       | Fillet Radius, R | Depth of Square, P                 |       | Dia. of Head, A |       | Flat on Head, F | Height of Head, H |       |
|              | Max.                          | Min.  | Max.                     | Min.               | Min.  | Max.               | Min.       | Max.            | Min.  | Max.              | Min.  | Max.             | Max.                               | Min.  | Max.            | Min.  | Min.            | Max.              | Min.  |
| No. 10       | 0.199                         | 0.182 | 0.031                    | 0.199              | 0.185 | 0.125              | 0.094      | 0.656           | 0.625 | 0.114             | 0.094 | 0.031            | 0.125                              | 0.094 | 0.548           | 0.500 | 0.015           | 0.131             | 0.112 |
| 1/4          | 0.260                         | 0.237 | 0.031                    | 0.260              | 0.245 | 0.156              | 0.125      | 0.844           | 0.813 | 0.145             | 0.125 | 0.031            | 0.156                              | 0.125 | 0.682           | 0.625 | 0.018           | 0.154             | 0.135 |
| 5/16         | 0.324                         | 0.298 | 0.031                    | 0.324              | 0.307 | 0.187              | 0.156      | 1.031           | 1.000 | 0.176             | 0.156 | 0.031            | 0.219                              | 0.188 | 0.821           | 0.750 | 0.023           | 0.184             | 0.159 |
| 3/8          | 0.388                         | 0.360 | 0.047                    | 0.388              | 0.368 | 0.219              | 0.188      | 1.219           | 1.188 | 0.208             | 0.188 | 0.031            | 0.250                              | 0.219 | 0.960           | 0.875 | 0.027           | 0.212             | 0.183 |
| 7/16         | 0.452                         | 0.421 | 0.047                    | 0.452              | 0.431 | 0.250              | 0.219      | 1.406           | 1.375 | 0.239             | 0.219 | 0.031            | 0.281                              | 0.250 | 1.093           | 1.000 | 0.030           | 0.235             | 0.205 |
| 1/2          | 0.515                         | 0.483 | 0.047                    | 0.515              | 0.492 | 0.281              | 0.250      | 1.594           | 1.563 | 0.270             | 0.250 | 0.031            | 0.312                              | 0.281 | 1.233           | 1.125 | 0.035           | 0.265             | 0.229 |
| 5/8          | .642                          | 0.605 | 0.078                    | 0.642              | 0.616 | ...                | ...        | ...             | ...   | ...               | ...   | ...              | 0.406                              | 0.375 | 1.495           | 1.375 | 0.038           | 0.316             | 0.272 |
| 3/4          | 0.768                         | 0.729 | 0.078                    | 0.768              | 0.741 | ...                | ...        | ...             | ...   | ...               | ...   | ...              | 0.500                              | 0.469 | 10.754          | 1.625 | 0.041           | 0.368             | 0.314 |

\*These sizes pertain to 114 degree countersunk square neck bolts only. Dimensions given in last seven columns to the right are for these bolts only.

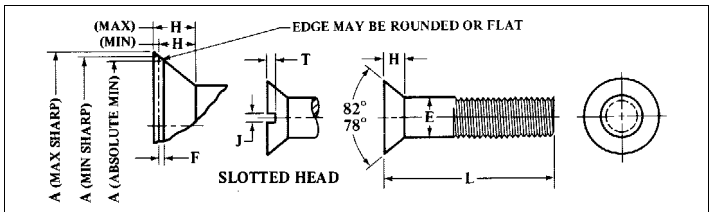
All dimensions are in inches unless otherwise specified.

Threads are Unified Standard, Class 2A, UNC Series, in accordance with ANSI B1.1. For threads with additive finish, the maximum diameters of Class 2A shall apply before plating or coating, whereas the basic diameters (Class 2A maximum diameters plus the allowance) shall apply to a bolt after plating or coating.

Bolts are designated in the sequence shown: nominal size (number, fraction or decimal equivalent); threads per inch; nominal length (fraction or decimal equivalent); product name; material; and protective finish, if required. For example

1/2-13 x 3 Round Head Square Neck Bolt, Steel .375-16 x 2.50 Step Bolt, Steel, Zinc Plated

**American National Standard Countersunk Bolts and Slotted Countersunk Bolts**  
ANSI/ASME B18.5-1990



| Nominal Size <sup>a</sup> or Basic Bolt Diameter | Body Diameter, E |                  | Head Diameter, A |                |                                   | Flat on Min Dia., Head, F <sup>b</sup><br>Max |       |
|--|------------------|------------------|------------------|----------------|-----------------------------------|---|-------|
|  | Max              | Min              | Max Edge Sharp   | Min Edge Sharp | Absolute Min Edge Rounded or Flat |   |       |
| 1/4  | 0.2500           | 0.260            | 0.237            | 0.493          | 0.477                             | 0.445   | 0.018 |
| 5/16   | 0.3125           | 0.324            | 0.298            | 0.618          | 0.598                             | 0.558   | 0.023 |
| 3/8  | 0.3750           | 0.388            | 0.360            | 0.740          | 0.715                             | 0.668   | 0.027 |
| 7/16   | 0.4375           | 0.452            | 0.421            | 0.803          | 0.778                             | 0.726   | 0.030 |
| 1/2  | 0.5000           | 0.515            | 0.483            | 0.935          | 0.905                             | 0.845   | 0.035 |
| 5/8  | 0.6250           | 0.642            | 0.605            | 1.169          | 1.132                             | 1.066   | 0.038 |
| 3/4  | 0.7500           | 0.768            | 0.729            | 1.402          | 1.357                             | 1.285   | 0.041 |
| 7/8  | 0.8750           | 0.895            | 0.852            | 1.637          | 1.584                             | 1.511   | 0.042 |
| 1  | 1.0000           | 1.022            | 0.976            | 1.869          | 1.810                             | 1.735   | 0.043 |
| 1 1/8  | 1.1250           | 1.149            | 1.098            | 2.104          | 2.037                             | 1.962   | 0.043 |
| 1 1/4  | 1.2500           | 1.277            | 1.223            | 2.337          | 2.262                             | 2.187   | 0.043 |
| 1 3/8  | 1.3750           | 1.404            | 1.345            | 2.571          | 2.489                             | 2.414   | 0.043 |
| 1 1/2  | 1.5000           | 1.531            | 1.470            | 2.804          | 2.715                             | 2.640   | 0.043 |
| Nom. Size or Basic Bolt Dia.                     | Head Height, H   |                  | Slot Width, J    |                | Slot Depth, T                     |   |       |
|  | Max <sup>c</sup> | Min <sup>d</sup> | Max              | Min            | Max                               | Min   |       |
| 1/4  | 0.2500           | 0.150            | 0.131            | 0.075          | 0.064                             | 0.068   | 0.045 |
| 5/16   | 0.3125           | 0.189            | 0.164            | 0.084          | 0.072                             | 0.086   | 0.057 |
| 3/8  | 0.3750           | 0.225            | 0.196            | 0.094          | 0.081                             | 0.103   | 0.068 |
| 7/16   | 0.4375           | 0.226            | 0.196            | 0.094          | 0.081                             | 0.103   | 0.068 |
| 1/2  | 0.5000           | 0.269            | 0.233            | 0.106          | 0.091                             | 0.103   | 0.068 |
| 5/8  | 0.6250           | 0.336            | 0.292            | 0.133          | 0.116                             | 0.137   | 0.091 |
| 3/4  | 0.7500           | 0.403            | 0.349            | 0.149          | 0.131                             | 0.171   | 0.115 |
| 7/8  | 0.8750           | 0.470            | 0.408            | 0.167          | 0.147                             | 0.206   | 0.138 |
| 1  | 1.0000           | 0.537            | 0.466            | 0.188          | 0.166                             | 0.240   | 0.162 |
| 1 1/8  | 1.1250           | 0.604            | 0.525            | 0.196          | 0.178                             | 0.257   | 0.173 |
| 1 1/4  | 1.2500           | 0.671            | 0.582            | 0.211          | 0.193                             | 0.291   | 0.197 |
| 1 3/8  | 1.3750           | 0.738            | 0.641            | 0.226          | 0.208                             | 0.326   | 0.220 |
| 1 1/2  | 1.5000           | 0.805            | 0.698            | 0.258          | 0.240                             | 0.360   | 0.244 |

<sup>a</sup> Where specifying size in decimals, zeros preceding decimal and in fourth decimal place are omitted.

<sup>b</sup> Flat on minimum diameter head calculated on minimum sharp and absolute minimum head diameters and 82° head angle.

<sup>c</sup> Maximum head height calculated on maximum sharp head diameter, basic bolt diameter, and 78° head angle.

<sup>d</sup> Minimum head height calculated on minimum sharp head diameter, basic bolt diameter, and 82° head angle.

All dimensions are given in inches.

For thread information and method of bolt designation see footnotes to previous table.

Heads are unslotted unless otherwise specified. For slot dimensions see Table 1 in Slotted Head Cap Screw section.

**Wrench Openings for Nuts ANSI/ASME B18.2.2-1987 (R1999), Appendix**

| Max. <sup>a</sup> Width Across Flats of Nut | Wrench Opening <sup>b</sup> |       | Max. <sup>a</sup> Width Across Flats of Nut | Wrench Opening <sup>b</sup> |       | Max. <sup>a</sup> Width Across Flats of Nut | Wrench Opening <sup>b</sup> |       |
|---|-----------------------------|-------|---|-----------------------------|-------|---|-----------------------------|-------|
|   | Min.                        | Max.  |   | Min.                        | Max.  |   | Min.                        | Max.  |
| 5/32  | 0.158                       | 0.163 | 1 1/4                                       | 1.257                       | 1.267 | 2 5/16                                      | 2.954                       | 2.973 |
| 3/16  | 0.190                       | 0.195 | 1 1/16                                      | 1.320                       | 1.331 | 3   | 3.016                       | 3.035 |
| 7/32  | 0.220                       | 0.225 | 1 3/8                                       | 1.383                       | 1.394 | 3 3/8                                       | 3.142                       | 3.162 |
| 1/4   | 0.252                       | 0.257 | 1 1/2                                       | 1.446                       | 1.457 | 3 3/4                                       | 3.293                       | 3.314 |
| 5/32  | 0.283                       | 0.288 | 1 7/8                                       | 1.508                       | 1.520 | 3 7/8                                       | 3.518                       | 3.540 |
| 3/16  | 0.316                       | 0.322 | 1 5/8                                       | 1.634                       | 1.646 | 3 1/2                                       | 3.770                       | 3.793 |
| 11/32                                       | 0.347                       | 0.353 | 1 11/16                                     | 1.696                       | 1.708 | 3 7/8                                       | 3.895                       | 3.918 |
| 3/8   | 0.378                       | 0.384 | 1 13/16                                     | 1.822                       | 1.835 | 4 1/8                                       | 4.147                       | 4.172 |
| 7/16  | 0.440                       | 0.446 | 1 7/8                                       | 1.885                       | 1.898 | 4 1/4                                       | 4.272                       | 4.297 |
| 1/2   | 0.504                       | 0.510 | 2   | 2.011                       | 2.025 | 4 1/2                                       | 4.524                       | 4.550 |
| 5/16  | 0.556                       | 0.573 | 2 1/16                                      | 2.074                       | 2.088 | 4 5/8                                       | 4.649                       | 4.676 |
| 3/8   | 0.629                       | 0.636 | 2 3/16                                      | 2.200                       | 2.215 | 4 7/8                                       | 4.900                       | 4.928 |
| 11/16                                       | 0.692                       | 0.699 | 2 1/4                                       | 2.262                       | 2.277 | 5   | 5.026                       | 5.055 |
| 3/4   | 0.755                       | 0.763 | 2 3/8                                       | 2.388                       | 2.404 | 5 1/4                                       | 5.277                       | 5.307 |
| 13/16                                       | 0.818                       | 0.826 | 2 7/16                                      | 2.450                       | 2.466 | 5 3/8                                       | 5.403                       | 5.434 |
| 7/8   | 0.880                       | 0.888 | 2 9/16                                      | 2.576                       | 2.593 | 5 5/8                                       | 5.654                       | 5.686 |
| 15/16                                       | 0.944                       | 0.953 | 2 5/8                                       | 2.639                       | 2.656 | 5 3/4                                       | 5.780                       | 5.813 |
| 1   | 1.006                       | 1.015 | 2 3/4                                       | 2.766                       | 2.783 | 6   | 6.031                       | 6.157 |
| 7/16  | 1.068                       | 1.077 | 2 11/16                                     | 2.827                       | 2.845 | 6 1/8                                       | 6.065                       | 6.192 |
| 1 1/8                                       | 1.132                       | 1.142 |   |                             |       |   |                             |       |

<sup>a</sup> Wrenches are marked with the "Nominal Size of Wrench," which is equal to the basic or maximum width across flats of the corresponding nut. Minimum wrench opening is (1.005W + 0.001). Tolerance on wrench opening is (0.005W + 0.004) from minimum, where W equals nominal size of wrench.

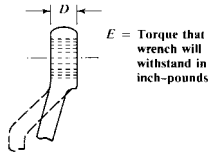
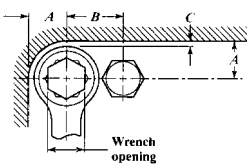
<sup>b</sup> Openings for 5/32 to 3/8 widths from old ASA B18.2-1960 and italic values are from former ANSI B18.2.2-1972.

All dimensions given in inches.

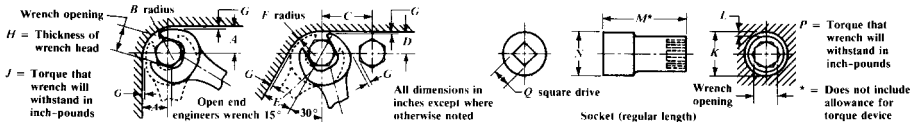
**Wrench Clearance Dimensions.**—Wrench clearances are given in Tables 1 and 2. They are based on a wrench opening corresponding to the dimensions across the flats of the fastener. The listed values were obtained from a composite study of the alloy steel wrenches that are commercially available and military specifications. They are suitable for general use as minimum requirements.

**Table 1. Wrench Clearances for Box Wrench—12 Point**  
From SAE Aeronautical Drafting Manual

| Wrench Opening | A     |       |       | D     |      | E              |       |       |       |       |       |
|----------------|-------|-------|-------|-------|------|----------------|-------|-------|-------|-------|-------|
|                | Min.  | Min.  | Ref.  | Max.  | Min. | Wrench Opening | Min.  | Min.  | Ref.  | Max.  | Min.  |
| 0.156          | 0.190 | 0.280 | 0.030 | 0.156 | 100  | 0.781          | 0.690 | 1.140 | 0.030 | 0.594 | 2600  |
| 0.188          | 0.200 | 0.309 | 0.030 | 0.172 | 150  | 0.812          | 0.720 | 1.190 | 0.030 | 0.594 | 3000  |
| 0.250          | 0.270 | 0.410 | 0.030 | 0.250 | 150  | 0.875          | 0.750 | 1.260 | 0.030 | 0.594 | 3300  |
| 0.312          | 0.300 | 0.480 | 0.030 | 0.281 | 210  | 0.938          | 0.780 | 1.320 | 0.030 | 0.656 | 4100  |
| 0.344          | 0.300 | 0.500 | 0.030 | 0.281 | 250  | 1.000          | 0.810 | 1.390 | 0.030 | 0.718 | 4900  |
| 0.375          | 0.340 | 0.560 | 0.030 | 0.344 | 370  | 1.062          | 0.840 | 1.450 | 0.030 | 0.781 | 5400  |
| 0.438          | 0.400 | 0.650 | 0.030 | 0.359 | 650  | 1.125          | 0.950 | 1.600 | 0.030 | 0.844 | 5900  |
| 0.500          | 0.450 | 0.740 | 0.030 | 0.375 | 1020 | 1.250          | 0.980 | 1.700 | 0.030 | 0.875 | 7200  |
| 0.562          | 0.500 | 0.830 | 0.030 | 0.406 | 1200 | 1.312          | 1.090 | 1.850 | 0.030 | 0.906 | 8000  |
| 0.594          | 0.530 | 0.870 | 0.030 | 0.469 | 1200 | 1.438          | 1.220 | 2.050 | 0.030 | 1.000 | 8400  |
| 0.625          | 0.560 | 0.920 | 0.030 | 0.469 | 2000 | 1.500          | 1.270 | 2.140 | 0.030 | 1.062 | 10450 |
| 0.688          | 0.590 | 0.990 | 0.030 | 0.531 | 2300 | 1.625          | 1.340 | 2.280 | 0.030 | 1.156 | 11750 |
| 0.750          | 0.660 | 1.090 | 0.030 | 0.594 | 2600 | ...            | ...   | ...   | ...   | ...   | ...   |



**Table 2. Wrench Clearances for Open End Engineers Wrench 15° and Socket Wrench (Regular Length)**  
 From SAE Aeronautical Drafting Manual; © Society of Automotive Engineers, Inc.



| Wrench Opening | Open End Engineers Wrench 15° |        |        |        |        |        |        |        |        |        |        | Socket (Regular Length) |        |        |          |        |        |          |        |        |          |        | Wrench Opening |        |     |     |       |
|----------------|-------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------------------------|--------|--------|----------|--------|--------|----------|--------|--------|----------|--------|----------------|--------|-----|-----|-------|
|                | A Min.                        | B Max. | C Min. | D Min. | E Min. | F Max. | G Ref. | H Max. | J Min. | K Min. | L Ref. | Q = .250                |        |        | Q = .375 |        |        | Q = .500 |        |        | Q = .750 |        |                |        |     |     |       |
|                |                               |        |        |        |        |        |        |        |        |        |        | M Max.                  | N Max. | P Min. | M Max.   | N Max. | P Min. | M Max.   | N Max. | P Min. | M Max.   | N Max. |                | P Min. |     |     |       |
| .156           | .220                          | .250   | .390   | .160   | .250   | .200   | .030   | .094   | 25     | ...    | ...    | ...                     | 1.000  | .510   | 125      | ...    | ...    | ...      | ...    | ...    | ...      | ...    | ...            | ...    | ... | ... | ...   |
| .188           | .250                          | .280   | .430   | .190   | .270   | .230   | .030   | .172   | 40     | .370   | .030   | ...                     | 1.000  | .510   | 200      | 1.250  | .690   | 250      | ...    | ...    | ...      | ...    | ...            | ...    | ... | ... | .188  |
| .250           | .280                          | .340   | .530   | .270   | .310   | .310   | .030   | .172   | 60     | .470   | .030   | 1.000                   | .510   | 300    | 1.250    | .690   | 400    | ...      | ...    | ...    | ...      | ...    | ...            | ...    | ... | ... | .250  |
| .312           | .380                          | .470   | .660   | .280   | .390   | .390   | .050   | .203   | 125    | .550   | .030   | 1.000                   | .510   | 300    | 1.250    | .690   | 400    | ...      | ...    | ...    | ...      | ...    | ...            | ...    | ... | ... | .312  |
| .344           | .420                          | .500   | .750   | .340   | .450   | .450   | .050   | .203   | 175    | .580   | .030   | 1.000                   | .519   | 450    | 1.250    | .690   | 675    | ...      | ...    | ...    | ...      | ...    | ...            | ...    | ... | ... | .344  |
| .375           | .420                          | .500   | .780   | .360   | .450   | .520   | .050   | .219   | 250    | .620   | .030   | 1.000                   | .580   | 550    | 1.250    | .690   | 900    | 1.500    | .880   | 1600   | ...      | ...    | ...            | ...    | ... | ... | .375  |
| .438           | .470                          | .590   | .890   | .420   | .520   | .640   | .050   | .250   | 375    | .750   | .030   | 1.000                   | .683   | 550    | 1.250    | .880   | 1250   | 1.500    | .940   | 1700   | ...      | ...    | ...            | ...    | ... | ... | .438  |
| .500           | .520                          | .640   | 1.000  | .470   | .580   | .660   | .050   | .266   | 490    | .810   | .030   | 1.000                   | .692   | 600    | 1.250    | .880   | 1450   | 1.500    | .940   | 2000   | ...      | ...    | ...            | ...    | ... | ... | .500  |
| .562           | .590                          | .770   | 1.110  | .520   | .660   | .700   | .050   | .297   | 700    | .870   | .030   | ...                     | ...    | ...    | 1.250    | .932   | 1600   | 1.500    | .940   | 2700   | ...      | ...    | ...            | ...    | ... | ... | .562  |
| .594           | .640                          | .830   | 1.210  | .530   | .700   | .700   | .050   | .344   | 800    | .920   | .030   | ...                     | ...    | ...    | 1.250    | .963   | 1750   | 1.562    | .970   | 3000   | ...      | ...    | ...            | ...    | ... | ... | .594  |
| .625           | .640                          | .830   | 1.230  | .550   | .700   | .700   | .050   | .344   | 935    | .950   | .030   | ...                     | ...    | ...    | 1.250    | .995   | 2000   | 1.562    | 1.000  | 3600   | ...      | ...    | ...            | ...    | ... | ... | .625  |
| .688           | .770                          | .920   | 1.470  | .660   | .880   | .800   | .060   | .375   | 1250   | 1.030  | .030   | ...                     | ...    | ...    | 1.250    | 1.058  | 2000   | 1.562    | 1.065  | 4300   | ...      | ...    | ...            | ...    | ... | ... | .688  |
| .750           | .770                          | .920   | 1.510  | .670   | .880   | .800   | .060   | .375   | 1500   | 1.120  | .030   | ...                     | ...    | ...    | 1.250    | 1.120  | 2000   | 1.562    | 1.130  | 5000   | ...      | ...    | ...            | ...    | ... | ... | .750  |
| .781           | .830                          | .950   | 1.550  | .690   | .890   | .840   | .060   | .375   | 1615   | 1.150  | .030   | ...                     | ...    | ...    | 1.250    | 1.126  | 2000   | 1.625    | 1.130  | 5000   | ...      | ...    | ...            | ...    | ... | ... | .781  |
| .812           | .910                          | 1.120  | 1.660  | .720   | .970   | .860   | .060   | .406   | 1710   | 1.200  | .030   | ...                     | ...    | ...    | 1.250    | 1.213  | 2000   | 1.625    | 1.222  | 5000   | ...      | ...    | ...            | ...    | ... | ... | .812  |
| .875           | .970                          | 1.150  | 1.810  | .800   | 1.060  | 910    | .060   | .438   | 2250   | 1.280  | .030   | ...                     | ...    | ...    | ...      | ...    | ...    | 1.750    | 1.285  | 5000   | ...      | ...    | ...            | ...    | ... | ... | .875  |
| .938           | .970                          | 1.150  | 1.850  | .810   | 1.060  | 950    | .060   | .438   | 2750   | 1.370  | .030   | ...                     | ...    | ...    | ...      | ...    | ...    | 1.750    | 1.410  | 5000   | ...      | ...    | ...            | ...    | ... | ... | .938  |
| 1.000          | 1.050                         | 1.230  | 2.000  | .880   | 1.160  | 1.060  | .060   | .500   | 3250   | 1.470  | .030   | ...                     | ...    | ...    | ...      | ...    | ...    | 1.750    | 1.410  | 5000   | ...      | ...    | ...            | ...    | ... | ... | 1.000 |
| 1.062          | 1.090                         | 1.250  | 2.100  | .970   | 1.200  | 1.200  | .080   | .500   | 3500   | 1.550  | .030   | ...                     | ...    | ...    | ...      | ...    | ...    | 1.844    | 1.505  | 5000   | ...      | ...    | ...            | ...    | ... | ... | 1.062 |
| 1.125          | 1.140                         | 1.370  | 2.210  | 1.000  | 1.270  | 1.230  | .080   | .500   | 4000   | 1.610  | .030   | ...                     | ...    | ...    | ...      | ...    | ...    | 1.938    | 1.567  | 5000   | ...      | ...    | ...            | ...    | ... | ... | 1.125 |
| 1.250          | 1.270                         | 1.420  | 2.440  | 1.080  | 1.390  | 1.310  | .080   | .562   | 5250   | 1.890  | .030   | ...                     | ...    | ...    | ...      | ...    | ...    | 2.000    | 1.723  | 5000   | 2.375    | 1.855  | 7250           | ...    | ... | ... | 1.250 |
| 1.312          | 1.390                         | 1.690  | 2.630  | 1.170  | 1.520  | 1.340  | .080   | .562   | 6000   | 1.980  | .030   | ...                     | ...    | ...    | ...      | ...    | ...    | ...      | ...    | ...    | 2.500    | 1.920  | 8000           | ...    | ... | ... | 1.312 |
| 1.438          | 1.470                         | 1.720  | 2.800  | 1.250  | 1.590  | 1.340  | .090   | .641   | 7500   | 2.140  | .030   | ...                     | ...    | ...    | ...      | ...    | ...    | ...      | ...    | ...    | 2.625    | 2.075  | 9550           | ...    | ... | ... | 1.438 |
| 1.500          | 1.470                         | 1.720  | 2.840  | 1.270  | 1.590  | 1.450  | .090   | .641   | 8250   | 2.200  | .030   | ...                     | ...    | ...    | ...      | ...    | ...    | ...      | ...    | ...    | 2.625    | 2.170  | 10450          | ...    | ... | ... | 1.500 |
| 1.625          | 1.560                         | 1.880  | 3.100  | 1.380  | 1.750  | 1.560  | .090   | .641   | 9000   | 2.390  | .030   | ...                     | ...    | ...    | ...      | ...    | ...    | ...      | ...    | ...    | 2.750    | 2.325  | 11750          | ...    | ... | ... | 1.625 |

WRENCH CLEARANCES



**Table 1a. American National Standard Type A Plain Washers—  
Preferred Sizes ANSI/ASME B18.22.1-1965 (R1998)**

| Nominal Washer Size <sup>a</sup> | Series | Inside Diameter |           |       | Outside Diameter |                    |       | Thickness |       |       |       |
|----------------------------------|--------|-----------------|-----------|-------|------------------|--------------------|-------|-----------|-------|-------|-------|
|                                  |        | Basic           | Tolerance |       | Basic            | Tolerance          |       | Basic     | Max.  | Min.  |       |
|                                  |        |                 | Plus      | Minus |                  | Plus               | Minus |           |       |       |       |
| —                                | —      | 0.078           | 0.000     | 0.005 | 0.188            | 0.000              | 0.005 | 0.020     | 0.025 | 0.016 |       |
| —                                | —      | 0.094           | 0.000     | 0.005 | 0.250            | 0.000              | 0.005 | 0.020     | 0.025 | 0.016 |       |
| —                                | —      | 0.125           | 0.008     | 0.005 | 0.312            | 0.008              | 0.005 | 0.032     | 0.040 | 0.025 |       |
| No. 6                            | 0.138  | 0.156           | 0.008     | 0.005 | 0.375            | 0.015              | 0.005 | 0.049     | 0.065 | 0.036 |       |
| No. 8                            | 0.164  | 0.188           | 0.008     | 0.005 | 0.438            | 0.015              | 0.005 | 0.049     | 0.065 | 0.036 |       |
| No. 10                           | 0.190  | 0.219           | 0.008     | 0.005 | 0.500            | 0.015              | 0.005 | 0.049     | 0.065 | 0.036 |       |
| $\frac{3}{16}$                   | 0.188  | 0.250           | 0.015     | 0.005 | 0.562            | 0.015              | 0.005 | 0.049     | 0.065 | 0.036 |       |
| No. 12                           | 0.216  | 0.250           | 0.015     | 0.005 | 0.562            | 0.015              | 0.005 | 0.065     | 0.080 | 0.051 |       |
| $\frac{1}{4}$                    | 0.250  | N               | 0.281     | 0.015 | 0.005            | 0.625              | 0.015 | 0.005     | 0.065 | 0.080 | 0.051 |
| $\frac{1}{4}$                    | 0.250  | W               | 0.312     | 0.015 | 0.005            | 0.734 <sup>b</sup> | 0.015 | 0.007     | 0.065 | 0.080 | 0.051 |
| $\frac{5}{16}$                   | 0.312  | N               | 0.344     | 0.015 | 0.005            | 0.688              | 0.015 | 0.007     | 0.065 | 0.080 | 0.051 |
| $\frac{5}{16}$                   | 0.312  | W               | 0.375     | 0.015 | 0.005            | 0.875              | 0.030 | 0.007     | 0.083 | 0.104 | 0.064 |
| $\frac{3}{8}$                    | 0.375  | N               | 0.406     | 0.015 | 0.005            | 0.812              | 0.015 | 0.007     | 0.065 | 0.080 | 0.051 |
| $\frac{3}{8}$                    | 0.375  | W               | 0.438     | 0.015 | 0.005            | 1.000              | 0.030 | 0.007     | 0.083 | 0.104 | 0.064 |
| $\frac{7}{16}$                   | 0.438  | N               | 0.469     | 0.015 | 0.005            | 0.922              | 0.015 | 0.007     | 0.065 | 0.080 | 0.051 |
| $\frac{7}{16}$                   | 0.438  | W               | 0.500     | 0.015 | 0.005            | 1.250              | 0.030 | 0.007     | 0.083 | 0.104 | 0.064 |
| $\frac{1}{2}$                    | 0.500  | N               | 0.531     | 0.015 | 0.005            | 1.062              | 0.030 | 0.007     | 0.095 | 0.121 | 0.074 |
| $\frac{1}{2}$                    | 0.500  | W               | 0.562     | 0.015 | 0.005            | 1.375              | 0.030 | 0.007     | 0.109 | 0.132 | 0.086 |
| $\frac{9}{16}$                   | 0.562  | N               | 0.594     | 0.015 | 0.005            | 1.156 <sup>b</sup> | 0.030 | 0.007     | 0.095 | 0.121 | 0.074 |
| $\frac{9}{16}$                   | 0.562  | W               | 0.625     | 0.015 | 0.005            | 1.469 <sup>b</sup> | 0.030 | 0.007     | 0.109 | 0.132 | 0.086 |
| $\frac{5}{8}$                    | 0.625  | N               | 0.656     | 0.030 | 0.007            | 1.312              | 0.030 | 0.007     | 0.095 | 0.121 | 0.074 |
| $\frac{5}{8}$                    | 0.625  | W               | 0.688     | 0.030 | 0.007            | 1.750              | 0.030 | 0.007     | 0.134 | 0.160 | 0.108 |
| $\frac{3}{4}$                    | 0.750  | N               | 0.812     | 0.030 | 0.007            | 1.469              | 0.030 | 0.007     | 0.134 | 0.160 | 0.108 |
| $\frac{3}{4}$                    | 0.750  | W               | 0.812     | 0.030 | 0.007            | 2.000              | 0.030 | 0.007     | 0.148 | 0.177 | 0.122 |
| $\frac{7}{8}$                    | 0.875  | N               | 0.938     | 0.030 | 0.007            | 1.750              | 0.030 | 0.007     | 0.134 | 0.160 | 0.108 |
| $\frac{7}{8}$                    | 0.875  | W               | 0.938     | 0.030 | 0.007            | 2.250              | 0.030 | 0.007     | 0.165 | 0.192 | 0.136 |
| 1                                | 1.000  | N               | 1.062     | 0.030 | 0.007            | 2.000              | 0.030 | 0.007     | 0.134 | 0.160 | 0.108 |
| 1                                | 1.000  | W               | 1.062     | 0.030 | 0.007            | 2.500              | 0.030 | 0.007     | 0.165 | 0.192 | 0.136 |
| $1\frac{1}{8}$                   | 1.125  | N               | 1.250     | 0.030 | 0.007            | 2.250              | 0.030 | 0.007     | 0.134 | 0.160 | 0.108 |
| $1\frac{1}{8}$                   | 1.125  | W               | 1.250     | 0.030 | 0.007            | 2.750              | 0.030 | 0.007     | 0.165 | 0.192 | 0.136 |
| $1\frac{1}{4}$                   | 1.250  | N               | 1.375     | 0.030 | 0.007            | 2.500              | 0.030 | 0.007     | 0.165 | 0.192 | 0.136 |
| $1\frac{1}{4}$                   | 1.250  | W               | 1.375     | 0.030 | 0.007            | 3.000              | 0.030 | 0.007     | 0.165 | 0.192 | 0.136 |
| $1\frac{3}{8}$                   | 1.375  | N               | 1.500     | 0.030 | 0.007            | 2.750              | 0.030 | 0.007     | 0.165 | 0.192 | 0.136 |
| $1\frac{3}{8}$                   | 1.375  | W               | 1.500     | 0.045 | 0.010            | 3.250              | 0.045 | 0.010     | 0.180 | 0.213 | 0.153 |
| $1\frac{1}{2}$                   | 1.500  | N               | 1.625     | 0.030 | 0.007            | 3.000              | 0.030 | 0.007     | 0.165 | 0.192 | 0.136 |
| $1\frac{1}{2}$                   | 1.500  | W               | 1.625     | 0.045 | 0.010            | 3.500              | 0.045 | 0.010     | 0.180 | 0.213 | 0.153 |
| $1\frac{5}{8}$                   | 1.625  | N               | 1.750     | 0.045 | 0.010            | 3.750              | 0.045 | 0.010     | 0.180 | 0.213 | 0.153 |
| $1\frac{5}{8}$                   | 1.625  | W               | 1.750     | 0.045 | 0.010            | 4.250              | 0.045 | 0.010     | 0.180 | 0.213 | 0.153 |
| $1\frac{3}{4}$                   | 1.750  | N               | 1.875     | 0.045 | 0.010            | 4.000              | 0.045 | 0.010     | 0.180 | 0.213 | 0.153 |
| $1\frac{3}{4}$                   | 1.750  | W               | 2.000     | 0.045 | 0.010            | 4.250              | 0.045 | 0.010     | 0.180 | 0.213 | 0.153 |
| 2                                | 2.000  | N               | 2.125     | 0.045 | 0.010            | 4.500              | 0.045 | 0.010     | 0.180 | 0.213 | 0.153 |
| $2\frac{1}{4}$                   | 2.250  | N               | 2.375     | 0.045 | 0.010            | 4.750              | 0.045 | 0.010     | 0.220 | 0.248 | 0.193 |
| $2\frac{1}{2}$                   | 2.500  | N               | 2.625     | 0.045 | 0.010            | 5.000              | 0.045 | 0.010     | 0.238 | 0.280 | 0.210 |
| $2\frac{3}{4}$                   | 2.750  | N               | 2.875     | 0.065 | 0.010            | 5.250              | 0.065 | 0.010     | 0.259 | 0.310 | 0.228 |
| 3                                | 3.000  | N               | 3.125     | 0.065 | 0.010            | 5.500              | 0.065 | 0.010     | 0.284 | 0.327 | 0.249 |

<sup>a</sup> Nominal washer sizes are intended for use with comparable nominal screw or bolt sizes.

<sup>b</sup> The 0.734-inch, 1.156-inch, and 1.469-inch outside diameters avoid washers which could be used in coin operated devices.

All dimensions are in inches.

Preferred sizes are for the most part from series previously designated "Standard Plate" and "SAE." Where common sizes existed in the two series, the SAE size is designated "N" (narrow) and the Standard Plate "W" (wide). These sizes as well as all other sizes of Type A Plain Washers are to be ordered by ID, OD, and thickness dimensions.

Additional selected sizes of Type A Plain Washers are shown in [Table 1b](#).

**Table 1b. American National Standard Type A Plain Washers — Additional Selected Sizes ANSI/ASME B18.22.1-1965 (R1998)**

| Inside Diameter |           |       | Outside Diameter   |           |       | Thickness |       |       |
|-----------------|-----------|-------|--------------------|-----------|-------|-----------|-------|-------|
| Basic           | Tolerance |       | Basic              | Tolerance |       | Basic     | Max.  | Min.  |
|                 | Plus      | Minus |                    | Plus      | Minus |           |       |       |
| 0.094           | 0.000     | 0.005 | 0.219              | 0.000     | 0.005 | 0.020     | 0.025 | 0.016 |
| 0.125           | 0.000     | 0.005 | 0.250              | 0.000     | 0.005 | 0.022     | 0.028 | 0.017 |
| 0.156           | 0.008     | 0.005 | 0.312              | 0.008     | 0.005 | 0.035     | 0.048 | 0.027 |
| 0.172           | 0.008     | 0.005 | 0.406              | 0.015     | 0.005 | 0.049     | 0.065 | 0.036 |
| 0.188           | 0.008     | 0.005 | 0.375              | 0.015     | 0.005 | 0.049     | 0.065 | 0.036 |
| 0.203           | 0.008     | 0.005 | 0.469              | 0.015     | 0.005 | 0.049     | 0.065 | 0.036 |
| 0.219           | 0.008     | 0.005 | 0.438              | 0.015     | 0.005 | 0.049     | 0.065 | 0.036 |
| 0.234           | 0.008     | 0.005 | 0.531              | 0.015     | 0.005 | 0.049     | 0.065 | 0.036 |
| 0.250           | 0.015     | 0.005 | 0.500              | 0.015     | 0.005 | 0.049     | 0.065 | 0.036 |
| 0.266           | 0.015     | 0.005 | 0.625              | 0.015     | 0.005 | 0.049     | 0.065 | 0.036 |
| 0.312           | 0.015     | 0.005 | 0.875              | 0.015     | 0.007 | 0.065     | 0.080 | 0.051 |
| 0.375           | 0.015     | 0.005 | 0.734 <sup>a</sup> | 0.015     | 0.007 | 0.065     | 0.080 | 0.051 |
| 0.375           | 0.015     | 0.005 | 1.125              | 0.015     | 0.007 | 0.065     | 0.080 | 0.051 |
| 0.438           | 0.015     | 0.005 | 0.875              | 0.030     | 0.007 | 0.083     | 0.104 | 0.064 |
| 0.438           | 0.015     | 0.005 | 1.375              | 0.030     | 0.007 | 0.083     | 0.104 | 0.064 |
| 0.500           | 0.015     | 0.005 | 1.125              | 0.030     | 0.007 | 0.083     | 0.104 | 0.064 |
| 0.500           | 0.015     | 0.005 | 1.625              | 0.030     | 0.007 | 0.083     | 0.104 | 0.064 |
| 0.562           | 0.015     | 0.005 | 1.250              | 0.030     | 0.007 | 0.109     | 0.132 | 0.086 |
| 0.562           | 0.015     | 0.005 | 1.875              | 0.030     | 0.007 | 0.109     | 0.132 | 0.086 |
| 0.625           | 0.015     | 0.005 | 1.375              | 0.030     | 0.007 | 0.109     | 0.132 | 0.086 |
| 0.625           | 0.015     | 0.005 | 2.125              | 0.030     | 0.007 | 0.134     | 0.160 | 0.108 |
| 0.688           | 0.030     | 0.007 | 1.469 <sup>a</sup> | 0.030     | 0.007 | 0.134     | 0.160 | 0.108 |
| 0.688           | 0.030     | 0.007 | 2.375              | 0.030     | 0.007 | 0.165     | 0.192 | 0.136 |
| 0.812           | 0.030     | 0.007 | 1.750              | 0.030     | 0.007 | 0.148     | 0.177 | 0.122 |
| 0.812           | 0.030     | 0.007 | 2.875              | 0.030     | 0.007 | 0.165     | 0.192 | 0.136 |
| 0.938           | 0.030     | 0.007 | 2.000              | 0.030     | 0.007 | 0.165     | 0.192 | 0.136 |
| 0.938           | 0.030     | 0.007 | 3.375              | 0.045     | 0.010 | 0.180     | 0.213 | 0.153 |
| 1.062           | 0.030     | 0.007 | 2.250              | 0.030     | 0.007 | 0.165     | 0.192 | 0.136 |
| 1.062           | 0.045     | 0.010 | 3.875              | 0.045     | 0.010 | 0.238     | 0.280 | 0.210 |
| 1.250           | 0.030     | 0.007 | 2.500              | 0.030     | 0.007 | 0.165     | 0.192 | 0.136 |
| 1.375           | 0.030     | 0.007 | 2.750              | 0.030     | 0.007 | 0.165     | 0.192 | 0.136 |
| 1.500           | 0.045     | 0.010 | 3.000              | 0.045     | 0.010 | 0.180     | 0.213 | 0.153 |
| 1.625           | 0.045     | 0.010 | 3.250              | 0.045     | 0.010 | 0.180     | 0.213 | 0.153 |
| 1.688           | 0.045     | 0.010 | 3.500              | 0.045     | 0.010 | 0.180     | 0.213 | 0.153 |
| 1.812           | 0.045     | 0.010 | 3.750              | 0.045     | 0.010 | 0.180     | 0.213 | 0.153 |
| 1.938           | 0.045     | 0.010 | 4.000              | 0.045     | 0.010 | 0.180     | 0.213 | 0.153 |
| 2.062           | 0.045     | 0.010 | 4.250              | 0.045     | 0.010 | 0.180     | 0.213 | 0.153 |

<sup>a</sup> The 0.734-inch and 1.469-inch outside diameters avoid washers which could be used in coin operated devices.

All dimensions are in inches.

The above sizes are to be ordered by ID, OD, and thickness dimensions.

Preferred Sizes of Type A Plain Washers are shown in [Table 1a](#).

**ANSI Standard Plain Washers.**—The Type A plain washers were originally developed in a light, medium, heavy and extra heavy series. These series have been discontinued and the washers are now designated by their nominal dimensions.

The Type B plain washers are available in a narrow, regular and wide series with proportions designed to distribute the load over larger areas of lower strength materials.

Plain washers are made of ferrous or non-ferrous metal, plastic or other material as specified. The tolerances indicated in the tables are intended for metal washers only.

**Table 2. American National Standard Type B Plain Washers —**

| Nominal Washer Size <sup>a</sup> |       | Series <sup>b</sup> | Inside Diameter |           |       | Outside Diameter   |           |       | Thickness |       |       |
|----------------------------------|-------|---------------------|-----------------|-----------|-------|--------------------|-----------|-------|-----------|-------|-------|
|                                  |       |                     | Basic           | Tolerance |       | Basic              | Tolerance |       | Basic     | Max.  | Min.  |
|                                  |       |                     |                 | Plus      | Minus |                    | Plus      | Minus |           |       |       |
| No. 0                            | 0.060 | N                   | 0.068           | 0.000     | 0.005 | 0.125              | 0.000     | 0.005 | 0.025     | 0.028 | 0.022 |
|                                  |       | R                   | 0.068           | 0.000     | 0.005 | 0.188              | 0.000     | 0.005 | 0.025     | 0.028 | 0.022 |
|                                  |       | W                   | 0.068           | 0.000     | 0.005 | 0.250              | 0.000     | 0.005 | 0.025     | 0.028 | 0.022 |
| No. 1                            | 0.073 | N                   | 0.084           | 0.000     | 0.005 | 0.156              | 0.000     | 0.005 | 0.025     | 0.028 | 0.022 |
|                                  |       | R                   | 0.084           | 0.000     | 0.005 | 0.219              | 0.000     | 0.005 | 0.025     | 0.028 | 0.022 |
|                                  |       | W                   | 0.084           | 0.000     | 0.005 | 0.281              | 0.000     | 0.005 | 0.032     | 0.036 | 0.028 |
| No. 2                            | 0.086 | N                   | 0.094           | 0.000     | 0.005 | 0.188              | 0.000     | 0.005 | 0.025     | 0.028 | 0.022 |
|                                  |       | R                   | 0.094           | 0.000     | 0.005 | 0.250              | 0.000     | 0.005 | 0.032     | 0.036 | 0.028 |
|                                  |       | W                   | 0.094           | 0.000     | 0.005 | 0.344              | 0.000     | 0.005 | 0.032     | 0.036 | 0.028 |
| No. 3                            | 0.099 | N                   | 0.109           | 0.000     | 0.005 | 0.219              | 0.000     | 0.005 | 0.025     | 0.028 | 0.022 |
|                                  |       | R                   | 0.109           | 0.000     | 0.005 | 0.312              | 0.000     | 0.005 | 0.032     | 0.036 | 0.028 |
|                                  |       | W                   | 0.109           | 0.008     | 0.005 | 0.406              | 0.008     | 0.005 | 0.040     | 0.045 | 0.036 |
| No. 4                            | 0.112 | N                   | 0.125           | 0.000     | 0.005 | 0.250              | 0.000     | 0.005 | 0.032     | 0.036 | 0.028 |
|                                  |       | R                   | 0.125           | 0.008     | 0.005 | 0.375              | 0.008     | 0.005 | 0.040     | 0.045 | 0.036 |
|                                  |       | W                   | 0.125           | 0.008     | 0.005 | 0.438              | 0.008     | 0.005 | 0.040     | 0.045 | 0.036 |
| No. 5                            | 0.125 | N                   | 0.141           | 0.000     | 0.005 | 0.281              | 0.000     | 0.005 | 0.032     | 0.036 | 0.028 |
|                                  |       | R                   | 0.141           | 0.008     | 0.005 | 0.406              | 0.008     | 0.005 | 0.040     | 0.045 | 0.036 |
|                                  |       | W                   | 0.141           | 0.008     | 0.005 | 0.500              | 0.008     | 0.005 | 0.040     | 0.045 | 0.036 |
| No. 6                            | 0.138 | N                   | 0.156           | 0.000     | 0.005 | 0.312              | 0.000     | 0.005 | 0.032     | 0.036 | 0.028 |
|                                  |       | R                   | 0.156           | 0.008     | 0.005 | 0.438              | 0.008     | 0.005 | 0.040     | 0.045 | 0.036 |
|                                  |       | W                   | 0.156           | 0.008     | 0.005 | 0.562              | 0.008     | 0.005 | 0.040     | 0.045 | 0.036 |
| No. 8                            | 0.164 | N                   | 0.188           | 0.008     | 0.005 | 0.375              | 0.008     | 0.005 | 0.040     | 0.045 | 0.036 |
|                                  |       | R                   | 0.188           | 0.008     | 0.005 | 0.500              | 0.008     | 0.005 | 0.040     | 0.045 | 0.036 |
|                                  |       | W                   | 0.188           | 0.008     | 0.005 | 0.625              | 0.015     | 0.005 | 0.063     | 0.071 | 0.056 |
| No. 10                           | 0.190 | N                   | 0.203           | 0.008     | 0.005 | 0.406              | 0.008     | 0.005 | 0.040     | 0.045 | 0.036 |
|                                  |       | R                   | 0.203           | 0.008     | 0.005 | 0.562              | 0.008     | 0.005 | 0.040     | 0.045 | 0.036 |
|                                  |       | W                   | 0.203           | 0.008     | 0.005 | 0.734 <sup>c</sup> | 0.015     | 0.007 | 0.063     | 0.071 | 0.056 |
| No. 12                           | 0.216 | N                   | 0.234           | 0.008     | 0.005 | 0.438              | 0.008     | 0.005 | 0.040     | 0.045 | 0.036 |
|                                  |       | R                   | 0.234           | 0.008     | 0.005 | 0.625              | 0.015     | 0.005 | 0.063     | 0.071 | 0.056 |
|                                  |       | W                   | 0.234           | 0.008     | 0.005 | 0.875              | 0.015     | 0.007 | 0.063     | 0.071 | 0.056 |
| ¼                                | 0.250 | N                   | 0.281           | 0.015     | 0.005 | 0.500              | 0.015     | 0.005 | 0.063     | 0.071 | 0.056 |
|                                  |       | R                   | 0.281           | 0.015     | 0.005 | 0.734 <sup>c</sup> | 0.015     | 0.007 | 0.063     | 0.071 | 0.056 |
|                                  |       | W                   | 0.281           | 0.015     | 0.005 | 1.000              | 0.015     | 0.007 | 0.063     | 0.071 | 0.056 |
| ⅝ <sub>16</sub>                  | 0.312 | N                   | 0.344           | 0.015     | 0.005 | 0.625              | 0.015     | 0.005 | 0.063     | 0.071 | 0.056 |
|                                  |       | R                   | 0.344           | 0.015     | 0.005 | 0.875              | 0.015     | 0.007 | 0.063     | 0.071 | 0.056 |
|                                  |       | W                   | 0.344           | 0.015     | 0.005 | 1.125              | 0.015     | 0.007 | 0.063     | 0.071 | 0.056 |
| ¾ <sub>8</sub>                   | 0.375 | N                   | 0.406           | 0.015     | 0.005 | 0.734 <sup>c</sup> | 0.015     | 0.007 | 0.063     | 0.071 | 0.056 |
|                                  |       | R                   | 0.406           | 0.015     | 0.005 | 1.000              | 0.015     | 0.007 | 0.063     | 0.071 | 0.056 |
|                                  |       | W                   | 0.406           | 0.015     | 0.005 | 1.250              | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
| 7/16                             | 0.438 | N                   | 0.469           | 0.015     | 0.005 | 0.875              | 0.015     | 0.007 | 0.063     | 0.071 | 0.056 |
|                                  |       | R                   | 0.469           | 0.015     | 0.005 | 1.125              | 0.015     | 0.007 | 0.063     | 0.071 | 0.056 |
|                                  |       | W                   | 0.469           | 0.015     | 0.005 | 1.469 <sup>c</sup> | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
| ½                                | 0.500 | N                   | 0.531           | 0.015     | 0.005 | 1.000              | 0.015     | 0.007 | 0.063     | 0.071 | 0.056 |
|                                  |       | R                   | 0.531           | 0.015     | 0.005 | 1.250              | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
|                                  |       | W                   | 0.531           | 0.015     | 0.005 | 1.750              | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
| 9/16                             | 0.562 | N                   | 0.594           | 0.015     | 0.005 | 1.125              | 0.015     | 0.007 | 0.063     | 0.071 | 0.056 |
|                                  |       | R                   | 0.594           | 0.015     | 0.005 | 1.469 <sup>c</sup> | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
|                                  |       | W                   | 0.594           | 0.015     | 0.005 | 2.000              | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
| 5/8                              | 0.625 | N                   | 0.656           | 0.030     | 0.007 | 1.250              | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
|                                  |       | R                   | 0.656           | 0.030     | 0.007 | 1.750              | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
|                                  |       | W                   | 0.656           | 0.030     | 0.007 | 2.250              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |

**Table 2. (Continued) American National Standard Type B Plain Washers —**

| Nominal Washer Size <sup>a</sup> |       | Series <sup>b</sup> | Inside Diameter |           |       | Outside Diameter   |           |       | Thickness |       |       |
|----------------------------------|-------|---------------------|-----------------|-----------|-------|--------------------|-----------|-------|-----------|-------|-------|
|                                  |       |                     | Basic           | Tolerance |       | Basic              | Tolerance |       | Basic     | Max.  | Min.  |
|                                  |       |                     |                 | Plus      | Minus |                    | Plus      | Minus |           |       |       |
| 3/4                              | 0.750 | N                   | 0.812           | 0.030     | 0.007 | 1.375              | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
|                                  |       | R                   | 0.812           | 0.030     | 0.007 | 2.000              | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
|                                  |       | W                   | 0.812           | 0.030     | 0.007 | 2.500              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
| 7/8                              | 0.875 | N                   | 0.938           | 0.030     | 0.007 | 1.469 <sup>c</sup> | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
|                                  |       | R                   | 0.938           | 0.030     | 0.007 | 2.250              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
|                                  |       | W                   | 0.938           | 0.030     | 0.007 | 2.750              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
| 1                                | 1.000 | N                   | 1.062           | 0.030     | 0.007 | 1.750              | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
|                                  |       | R                   | 1.062           | 0.030     | 0.007 | 2.500              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
|                                  |       | W                   | 1.062           | 0.030     | 0.007 | 3.000              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
| 1 1/8                            | 1.125 | N                   | 1.188           | 0.030     | 0.007 | 2.000              | 0.030     | 0.007 | 0.100     | 0.112 | 0.090 |
|                                  |       | R                   | 1.188           | 0.030     | 0.007 | 2.750              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
|                                  |       | W                   | 1.188           | 0.030     | 0.007 | 3.250              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
| 1 1/4                            | 1.250 | N                   | 1.312           | 0.030     | 0.007 | 2.250              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
|                                  |       | R                   | 1.312           | 0.030     | 0.007 | 3.000              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
|                                  |       | W                   | 1.312           | 0.045     | 0.010 | 3.500              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
| 1 3/8                            | 1.375 | N                   | 1.438           | 0.030     | 0.007 | 2.500              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
|                                  |       | R                   | 1.438           | 0.030     | 0.007 | 3.250              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
|                                  |       | W                   | 1.438           | 0.045     | 0.010 | 3.750              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
| 1 1/2                            | 1.500 | N                   | 1.562           | 0.030     | 0.007 | 2.750              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
|                                  |       | R                   | 1.562           | 0.045     | 0.010 | 3.500              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
|                                  |       | W                   | 1.562           | 0.045     | 0.010 | 4.000              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
| 1 5/8                            | 1.625 | N                   | 1.750           | 0.030     | 0.007 | 3.000              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
|                                  |       | R                   | 1.750           | 0.045     | 0.010 | 3.750              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
|                                  |       | W                   | 1.750           | 0.045     | 0.010 | 4.250              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
| 1 3/4                            | 1.750 | N                   | 1.875           | 0.030     | 0.007 | 3.250              | 0.030     | 0.007 | 0.160     | 0.174 | 0.146 |
|                                  |       | R                   | 1.875           | 0.045     | 0.010 | 4.000              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
|                                  |       | W                   | 1.875           | 0.045     | 0.010 | 4.500              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
| 1 7/8                            | 1.875 | N                   | 2.000           | 0.045     | 0.010 | 3.500              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
|                                  |       | R                   | 2.000           | 0.045     | 0.010 | 4.250              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
|                                  |       | W                   | 2.000           | 0.045     | 0.010 | 4.750              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
| 2                                | 2.000 | N                   | 2.125           | 0.045     | 0.010 | 3.750              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
|                                  |       | R                   | 2.125           | 0.045     | 0.010 | 4.500              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |
|                                  |       | W                   | 2.125           | 0.045     | 0.010 | 5.000              | 0.045     | 0.010 | 0.250     | 0.266 | 0.234 |

<sup>a</sup> Nominal washer sizes are intended for use with comparable nominal screw or bolt sizes.

<sup>b</sup> N indicates Narrow; R, Regular; and W, Wide Series.

<sup>c</sup> The 0.734-inch and 1.469-inch outside diameter avoids washers which could be used in coin operated devices.

All dimensions are in inches.

Inside and outside diameters shall be concentric within at least the inside diameter tolerance.

Washers shall be flat within 0.005-inch for basic outside diameters up through 0.875-inch and within 0.010 inch for larger outside diameters.

For 2 1/4-, 2 1/2-, 2 3/4-, and 3-inch sizes see ANSI/ASME B18.22.1-1965 (R1998).

**American National Standard Helical Spring and Tooth Lock Washers ANSI/ASME B18.21.1-1994.**— This standard covers helical spring lock washers of carbon steel; boron steel; corrosion resistant steel, Types 302 and 305; aluminum-zinc alloy; phosphor-bronze; silicon-bronze; and K-Monel; in various series. Tooth lock washers of carbon steel having internal teeth, external teeth, and both internal and external teeth, of two constructions, designated as Type A and Type B. Washers intended for general industrial application are also covered. American National Standard Lock Washers (Metric Series) ANSI/ASME B18.21.2M-1994 covers metric sizes for helical spring and tooth lock washers.

*Helical spring lock washers:* These washers are used to provide: 1) good bolt tension per unit of applied torque for tight assemblies; 2) hardened bearing surfaces to create uniform torque control; 3) uniform load distribution through controlled radii—section—cut-off; and 4) protection against looseness resulting from vibration and corrosion.

Nominal washer sizes are intended for use with comparable nominal screw or bolt sizes. These washers are designated by the following data in the sequence shown: Product name; nominal size (number, fraction or decimal equivalent); series; material; and protective finish, if required. For example: Helical Spring Lock Washer, 0.375 Extra Duty, Steel, Phosphate Coated.

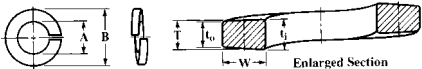
Helical spring lock washers are available in four series: Regular, heavy, extra duty and hi-collar as given in [Tables 2 and 1](#). Helical spring lock washers made of materials other than carbon steel are available in the regular series as given in [Table 2](#).

**Table 1. American National Standard Hi-Collar Helical Spring Lock Washers**  
ANSI/ASME B18.21.1-1994

| Nominal Washer Size |        | Inside Diameter |       | Outside Diameter | Washer Section |                        |
|---------------------|--------|-----------------|-------|------------------|----------------|------------------------|
|                     |        |                 |       |                  | Width          | Thickness <sup>a</sup> |
|                     |        | Min.            | Max.  | Max.             | Min.           | Min.                   |
| No. 4               | 0.112  | 0.114           | 0.120 | 0.173            | 0.022          | 0.022                  |
| No. 5               | 0.125  | 0.127           | 0.133 | 0.202            | 0.030          | 0.030                  |
| No. 6               | 0.138  | 0.141           | 0.148 | 0.216            | 0.030          | 0.030                  |
| No. 8               | 0.164  | 0.167           | 0.174 | 0.267            | 0.042          | 0.047                  |
| No. 10              | 0.190  | 0.193           | 0.200 | 0.294            | 0.042          | 0.047                  |
| ¼                   | 0.250  | 0.252           | 0.260 | 0.363            | 0.047          | 0.078                  |
| ⅝ <sub>16</sub>     | 0.3125 | 0.314           | 0.322 | 0.457            | 0.062          | 0.093                  |
| ⅜                   | 0.375  | 0.377           | 0.385 | 0.550            | 0.076          | 0.125                  |
| 7 <sub>16</sub>     | 0.4375 | 0.440           | 0.450 | 0.644            | 0.090          | 0.140                  |
| ½                   | 0.500  | 0.502           | 0.512 | 0.733            | 0.103          | 0.172                  |
| ⅝ <sub>8</sub>      | 0.625  | 0.628           | 0.640 | 0.917            | 0.125          | 0.203                  |
| ¾                   | 0.750  | 0.753           | 0.765 | 1.105            | 0.154          | 0.218                  |
| 7 <sub>8</sub>      | 0.875  | 0.878           | 0.890 | 1.291            | 0.182          | 0.234                  |
| 1                   | 1.000  | 1.003           | 1.015 | 1.478            | 0.208          | 0.250                  |
| 1 <sub>8</sub>      | 1.125  | 1.129           | 1.144 | 1.663            | 0.236          | 0.313                  |
| 1¼                  | 1.250  | 1.254           | 1.272 | 1.790            | 0.236          | 0.313                  |
| 1 <sub>8</sub>      | 1.375  | 1.379           | 1.399 | 2.031            | 0.292          | 0.375                  |
| 1½                  | 1.500  | 1.504           | 1.524 | 2.159            | 0.292          | 0.375                  |
| 1¾                  | 1.750  | 1.758           | 1.778 | 2.596            | 0.383          | 0.469                  |
| 2                   | 2.000  | 2.008           | 2.028 | 2.846            | 0.383          | 0.469                  |
| 2¼                  | 2.250  | 2.262           | 2.287 | 3.345            | 0.508          | 0.508                  |
| 2½                  | 2.500  | 2.512           | 2.537 | 3.559            | 0.508          | 0.508                  |
| 2¾                  | 2.750  | 2.762           | 2.787 | 4.095            | 0.633          | 0.633                  |
| 3                   | 3.000  | 3.012           | 3.037 | 4.345            | 0.633          | 0.633                  |

<sup>a</sup> Mean section thickness = (inside thickness + outside thickness) ÷ 2.

Table 2. American National Standard Helical Spring Lock Washers ANSI/ASME B18.21.1-1994



| Nominal Washer Size | Inside Diameter, A |       | Regular      |                  |                                   | Heavy        |                  |                                   | Extra Duty   |                  |                                   |       |
|---------------------|--------------------|-------|--------------|------------------|-----------------------------------|--------------|------------------|-----------------------------------|--------------|------------------|-----------------------------------|-------|
|                     | Max.               | Min.  | O.D., B Max. | Section Width, W | Section Thickness, T <sup>a</sup> | O.D., B Max. | Section Width, W | Section Thickness, T <sup>a</sup> | O.D., B Max. | Section Width, W | Section Thickness, T <sup>a</sup> |       |
| No. 2               | 0.086              | 0.094 | 0.088        | 0.172            | 0.035                             | 0.020        | 0.182            | 0.040                             | 0.025        | 0.208            | 0.053                             | 0.027 |
| No. 3               | 0.099              | 0.107 | 0.101        | 0.195            | 0.040                             | 0.025        | 0.209            | 0.047                             | 0.031        | 0.239            | 0.062                             | 0.034 |
| No. 4               | 0.112              | 0.120 | 0.114        | 0.209            | 0.040                             | 0.025        | 0.223            | 0.047                             | 0.031        | 0.253            | 0.062                             | 0.034 |
| No. 5               | 0.125              | 0.133 | 0.127        | 0.236            | 0.047                             | 0.031        | 0.252            | 0.055                             | 0.040        | 0.300            | 0.079                             | 0.045 |
| No. 6               | 0.138              | 0.148 | 0.141        | 0.250            | 0.047                             | 0.031        | 0.266            | 0.055                             | 0.040        | 0.314            | 0.079                             | 0.045 |
| No. 8               | 0.164              | 0.174 | 0.167        | 0.293            | 0.055                             | 0.040        | 0.307            | 0.062                             | 0.047        | 0.375            | 0.096                             | 0.057 |
| No. 10              | 0.190              | 0.200 | 0.193        | 0.334            | 0.062                             | 0.047        | 0.350            | 0.070                             | 0.056        | 0.434            | 0.112                             | 0.068 |
| No. 12              | 0.216              | 0.227 | 0.220        | 0.377            | 0.070                             | 0.056        | 0.391            | 0.077                             | 0.063        | 0.497            | 0.130                             | 0.080 |
| 1/4                 | 0.250              | 0.260 | 0.252        | 0.487            | 0.109                             | 0.062        | 0.489            | 0.110                             | 0.077        | 0.533            | 0.132                             | 0.084 |
| 5/16                | 0.3125             | 0.322 | 0.314        | 0.583            | 0.125                             | 0.078        | 0.293            | 0.130                             | 0.097        | 0.619            | 0.143                             | 0.108 |
| 3/8                 | 0.375              | 0.385 | 0.377        | 0.680            | 0.141                             | 0.094        | 0.688            | 0.145                             | 0.115        | 0.738            | 0.170                             | 0.123 |
| 7/16                | 0.4375             | 0.450 | 0.440        | 0.776            | 0.156                             | 0.109        | 0.784            | 0.160                             | 0.133        | 0.836            | 0.186                             | 0.143 |
| 1/2                 | 0.500              | 0.512 | 0.502        | 0.869            | 0.171                             | 0.125        | 0.879            | 0.176                             | 0.151        | 0.935            | 0.204                             | 0.162 |
| 9/16                | 0.5625             | 0.574 | 0.564        | 0.965            | 0.188                             | 0.141        | 0.975            | 0.193                             | 0.170        | 1.035            | 0.223                             | 0.182 |
| 5/8                 | 0.625              | 0.641 | 0.628        | 1.073            | 0.203                             | 0.156        | 1.087            | 0.210                             | 0.189        | 1.151            | 0.242                             | 0.202 |
| 11/16               | 0.6875             | 0.704 | 0.691        | 1.170            | 0.219                             | 0.172        | 1.186            | 0.227                             | 0.207        | 1.252            | 0.260                             | 0.221 |
| 3/4                 | 0.750              | 0.766 | 0.753        | 1.265            | 0.234                             | 0.188        | 1.285            | 0.244                             | 0.226        | 1.355            | 0.279                             | 0.241 |
| 13/16               | 0.8125             | 0.832 | 0.816        | 1.363            | 0.250                             | 0.203        | 1.387            | 0.262                             | 0.246        | 1.458            | 0.298                             | 0.261 |
| 7/8                 | 0.875              | 0.894 | 0.878        | 1.459            | 0.266                             | 0.219        | 1.489            | 0.281                             | 0.266        | 1.571            | 0.322                             | 0.285 |
| 15/16               | 0.9375             | 0.958 | 0.941        | 1.556            | 0.281                             | 0.234        | 1.590            | 0.298                             | 0.284        | 1.684            | 0.345                             | 0.308 |
| 1                   | 1.000              | 1.024 | 1.003        | 1.656            | 0.297                             | 0.250        | 1.700            | 0.319                             | 0.306        | 1.794            | 0.366                             | 0.330 |
| 1 1/16              | 1.0625             | 1.087 | 1.066        | 1.751            | 0.312                             | 0.266        | 1.803            | 0.338                             | 0.326        | 1.905            | 0.389                             | 0.352 |
| 1 1/8               | 1.125              | 1.153 | 1.129        | 1.847            | 0.328                             | 0.281        | 1.903            | 0.356                             | 0.345        | 2.013            | 0.411                             | 0.375 |
| 1 3/16              | 1.1875             | 1.217 | 1.192        | 1.943            | 0.344                             | 0.297        | 2.001            | 0.373                             | 0.364        | 2.107            | 0.431                             | 0.396 |
| 1 1/4               | 1.250              | 1.280 | 1.254        | 2.036            | 0.359                             | 0.312        | 2.104            | 0.393                             | 0.384        | 2.222            | 0.452                             | 0.417 |
| 1 5/16              | 1.3125             | 1.344 | 1.317        | 2.133            | 0.375                             | 0.328        | 2.203            | 0.410                             | 0.403        | 2.327            | 0.472                             | 0.438 |
| 1 3/8               | 1.375              | 1.408 | 1.379        | 2.219            | 0.391                             | 0.344        | 2.301            | 0.427                             | 0.422        | 2.429            | 0.491                             | 0.458 |
| 1 7/16              | 1.4375             | 1.472 | 1.442        | 2.324            | 0.406                             | 0.359        | 2.396            | 0.442                             | 0.440        | 2.530            | 0.509                             | 0.478 |
| 1 1/2               | 1.500              | 1.534 | 1.504        | 2.419            | 0.422                             | 0.375        | 2.491            | 0.458                             | 0.458        | 2.627            | 0.526                             | 0.496 |

<sup>a</sup>T = mean section thickness = (t<sub>1</sub> + t<sub>2</sub>) ÷ 2.

WASHERS

All dimensions are given in inches.\*See ANSI/ASME B18.21.1-1994 standard for sizes over 1½ to 3, inclusive, for regular and heavy helical spring lock washers and over 1½ to 2, inclusive, for extra-duty helical spring lock washers.

When carbon steel helical spring lock washers are to be hot-dipped galvanized for use with hot-dipped galvanized bolts or screws, they are to be coated to limits onto inch in excess of those specified in Tables 2 and 1 for minimum inside diameter and maximum outside diameter. Galvanizing washers under ¼ inch nominal size are not recommended.

*Tooth lock washers:* These washers serve to lock fasteners, such as bolts and nuts, to the component parts of an assembly, or increase the friction between the fasteners and the assembly. They are designated in a manner similar to helical spring lock washers, and are available in carbon steel. Dimensions are given in Tables 3 and 4.

**Table 3. American National Standard Internal-External Tooth Lock Washers**  
ANSI/ASME B18.21.1-1994

All dimensions are given in inches except whole numbers under "Size"

| Size   | A               |      | B                |       |           |      | Size | A               |       | B                |       |           |      |
|--------|-----------------|------|------------------|-------|-----------|------|------|-----------------|-------|------------------|-------|-----------|------|
|        | Inside Diameter |      | Outside Diameter |       | Thickness |      |      | Inside Diameter |       | Outside Diameter |       | Thickness |      |
|        | Max.            | Min. | Max.             | Min.  | Max.      | Min. |      | Max.            | Min.  | Max.             | Min.  | Max.      | Min. |
| No. 4  | .123            | .115 | .475             | .460  | .021      | .016 | 5/16 | .332            | .320  | .900             | .865  | .040      | .032 |
|        |                 |      | .510             | .495  | .021      | .017 |      |                 |       | .985             | .965  | .045      | .037 |
|        |                 |      | .610             | .580  | .021      | .017 |      |                 |       | 1.070            | 1.045 | .050      | .042 |
| No. 6  | .150            | .141 | .510             | .495  | .028      | .023 | 3/8  | .398            | .384  | .985             | .965  | .045      | .037 |
|        |                 |      | .610             | .580  | .028      | .023 |      |                 |       | 1.070            | 1.045 | .050      | .042 |
|        |                 |      | .690             | .670  | .028      | .023 |      |                 |       | 1.260            | 1.220 | .050      | .042 |
| No. 8  | .176            | .168 | .610             | .580  | .034      | .028 | 7/16 | .464            | .448  | 1.070            | 1.045 | .050      | .042 |
|        |                 |      | .690             | .670  | .034      | .028 |      |                 |       | 1.155            | 1.130 | .050      | .042 |
|        |                 |      | .760             | .740  | .034      | .028 |      |                 |       | 1.260            | 1.220 | .055      | .047 |
| No. 10 | .204            | .195 | .610             | .580  | .034      | .028 | 1/2  | .530            | .512  | 1.315            | 1.290 | .055      | .047 |
|        |                 |      | .690             | .670  | .040      | .032 |      |                 |       | 1.410            | 1.380 | .060      | .052 |
|        |                 |      | .760             | .740  | .040      | .032 |      |                 |       | 1.620            | 1.590 | .067      | .059 |
| No. 12 | .231            | .221 | .900             | .880  | .040      | .032 | 5/8  | .596            | .576  | 1.315            | 1.290 | .055      | .047 |
|        |                 |      | .985             | .965  | .045      | .037 |      |                 |       | 1.430            | 1.380 | .060      | .052 |
|        |                 |      | .760             | .725  | .040      | .032 |      |                 |       | 1.620            | 1.590 | .067      | .059 |
| 1/4    | .267            | .256 | .900             | .880  | .045      | .037 | 7/8  | .663            | .640  | 1.830            | 1.797 | .067      | .059 |
|        |                 |      | .985             | .965  | .045      | .037 |      |                 |       | 1.410            | 1.380 | .060      | .052 |
|        |                 |      | 1.070            | 1.045 | .045      | .037 |      |                 |       | 1.620            | 1.590 | .067      | .059 |
|        |                 |      |                  |       |           |      |      |                 | 1.830 | 1.797            | .067  | .059      |      |
|        |                 |      |                  |       |           |      |      |                 | 1.975 | 1.935            | .067  | .059      |      |

Table 4. American National Standard Internal and External Tooth Lock Washers ANSI/ASME B18.21.1-1994

|                                   |      | TYPE A         |                | TYPE B         |                | TYPE A         |                | TYPE B         |               | TYPE A 80°-82°                                       |                | TYPE B 80°-82°             |                |               |                |               |                 |               |                 |                |               |                 |                 |
|-----------------------------------|------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|---------------|--|----------------|----------------------------|----------------|---------------|----------------|---------------|-----------------|---------------|-----------------|----------------|---------------|-----------------|-----------------|
|                                   |      | Internal Tooth |                | Internal Tooth |                | External Tooth |                | External Tooth |               | Countersunk External Tooth                           |                | Countersunk External Tooth |                |               |                |               |                 |               |                 |                |               |                 |                 |
| Internal Tooth Lock Washers       |      |                |                |                |                |                |                |                |               |  |                |                            |                |               |                |               |                 |               |                 |                |               |                 |                 |
|                                   | Size | #2             | #3             | #4             | #5             | #6             | #8             | #10            | #12           | $\frac{1}{4}$  | $\frac{5}{16}$ | $\frac{3}{8}$              | $\frac{7}{16}$ | $\frac{1}{2}$ | $\frac{9}{16}$ | $\frac{5}{8}$ | $\frac{11}{16}$ | $\frac{3}{4}$ | $\frac{13}{16}$ | $\frac{7}{8}$  | 1             | 1 $\frac{1}{8}$ | 1 $\frac{1}{4}$ |
| A                                 | Max  | 0.095          | 0.109          | 0.123          | 0.136          | 0.150          | 0.176          | 0.204          | 0.231         | 0.267  | 0.332          | 0.398                      | 0.464          | 0.530         | 0.596          | 0.663         | 0.728           | 0.795         | 0.861           | 0.927          | 1.060         | 1.192           | 1.325           |
|                                   | Min  | 0.089          | 0.102          | 0.115          | 0.129          | 0.141          | 0.168          | 0.195          | 0.221         | 0.256  | 0.320          | 0.384                      | 0.448          | 0.512         | 0.576          | 0.640         | 0.704           | 0.769         | 0.832           | 0.894          | 1.019         | 1.144           | 1.275           |
| B                                 | Max  | 0.200          | 0.232          | 0.270          | 0.280          | 0.295          | 0.340          | 0.381          | 0.410         | 0.478  | 0.610          | 0.692                      | 0.789          | 0.900         | 0.985          | 1.071         | 1.166           | 1.245         | 1.315           | 1.410          | 1.637         | 1.830           | 1.975           |
|                                   | Min  | 0.175          | 0.215          | 0.245          | 0.255          | 0.275          | 0.325          | 0.365          | 0.394         | 0.460  | 0.594          | 0.670                      | 0.740          | 0.867         | 0.957          | 1.045         | 1.130           | 1.220         | 1.290           | 1.364          | 1.590         | 1.799           | 1.921           |
| C                                 | Max  | 0.015          | 0.019          | 0.019          | 0.021          | 0.021          | 0.023          | 0.025          | 0.025         | 0.028  | 0.034          | 0.040                      | 0.040          | 0.045         | 0.045          | 0.050         | 0.050           | 0.055         | 0.055           | 0.060          | 0.067         | 0.067           | 0.067           |
|                                   | Min  | 0.010          | 0.012          | 0.015          | 0.017          | 0.017          | 0.018          | 0.020          | 0.020         | 0.023  | 0.028          | 0.032                      | 0.032          | 0.037         | 0.037          | 0.042         | 0.042           | 0.047         | 0.047           | 0.052          | 0.059         | 0.059           | 0.059           |
| External Tooth Lock Washers       |      |                |                |                |                |                |                |                |               |  |                |                            |                |               |                |               |                 |               |                 |                |               |                 |                 |
| A                                 | Max  | ...            | 0.109          | 0.123          | 0.136          | 0.150          | 0.176          | 0.204          | 0.231         | 0.267  | 0.332          | 0.398                      | 0.464          | 0.530         | 0.596          | 0.663         | 0.728           | 0.795         | 0.861           | 0.927          | 1.060         | ...             | ...             |
|                                   | Min  | ...            | 0.102          | 0.115          | 0.129          | 0.141          | 0.168          | 0.195          | 0.221         | 0.256  | 0.320          | 0.384                      | 0.448          | 0.513         | 0.576          | 0.641         | 0.704           | 0.768         | 0.833           | 0.897          | 1.025         | ...             | ...             |
| B                                 | Max  | ...            | 0.235          | 0.260          | 0.285          | 0.320          | 0.381          | 0.410          | 0.475         | 0.510  | 0.610          | 0.694                      | 0.760          | 0.900         | 0.985          | 1.070         | 1.155           | 1.260         | 1.315           | 1.410          | 1.620         | ...             | ...             |
|                                   | Min  | ...            | 0.220          | 0.245          | 0.270          | 0.305          | 0.365          | 0.395          | 0.460         | 0.494  | 0.588          | 0.670                      | 0.740          | 0.880         | 0.960          | 1.045         | 1.130           | 1.220         | 1.290           | 1.380          | 1.590         | ...             | ...             |
| C                                 | Max  | ...            | 0.015          | 0.019          | 0.019          | 0.022          | 0.023          | 0.025          | 0.028         | 0.028  | 0.034          | 0.040                      | 0.040          | 0.045         | 0.045          | 0.050         | 0.050           | 0.055         | 0.055           | 0.060          | 0.067         | ...             | ...             |
|                                   | Min  | ...            | 0.012          | 0.014          | 0.015          | 0.016          | 0.018          | 0.020          | 0.023         | 0.023  | 0.028          | 0.032                      | 0.032          | 0.037         | 0.037          | 0.042         | 0.042           | 0.047         | 0.047           | 0.052          | 0.059         | ...             | ...             |
| Heavy Internal Tooth Lock Washers |      |                |                |                |                |                |                |                |               | Countersunk External Tooth Lock Washers <sup>a</sup> |                |                            |                |               |                |               |                 |               |                 |                |               |                 |                 |
|                                   | Size | $\frac{1}{4}$  | $\frac{5}{16}$ | $\frac{3}{8}$  | $\frac{7}{16}$ | $\frac{1}{2}$  | $\frac{9}{16}$ | $\frac{5}{8}$  | $\frac{3}{4}$ | $\frac{7}{8}$  |                | Size                       | #4             | #6            | #8             | #10           | #12             | $\frac{1}{4}$ | #16             | $\frac{5}{16}$ | $\frac{3}{8}$ | $\frac{7}{16}$  | $\frac{1}{2}$   |
| A                                 | Max  | 0.267          | 0.332          | 0.398          | 0.464          | 0.530          | 0.596          | 0.663          | 0.795         | 0.927  | A              | Max                        | 0.123          | 0.150         | 0.177          | 0.205         | 0.231           | 0.267         | 0.287           | 0.333          | 0.398         | 0.463           | 0.529           |
|                                   | Min  | 0.256          | 0.320          | 0.384          | 0.448          | 0.512          | 0.576          | 0.640          | 0.768         | 0.894  | Min            | 0.113                      | 0.140          | 0.167         | 0.195          | 0.220         | 0.255           | 0.273         | 0.318           | 0.383          | 0.448         | 0.512           |                 |
| B                                 | Max  | 0.536          | 0.607          | 0.748          | 0.858          | 0.924          | 1.034          | 1.135          | 1.265         | 1.447  | C              | Max                        | 0.019          | 0.021         | 0.021          | 0.025         | 0.025           | 0.025         | 0.028           | 0.028          | 0.034         | 0.045           | 0.045           |
|                                   | Min  | 0.500          | 0.590          | 0.700          | 0.800          | 0.880          | 0.990          | 1.100          | 1.240         | 1.400  | Min            | 0.015                      | 0.017          | 0.017         | 0.020          | 0.020         | 0.020           | 0.023         | 0.023           | 0.028          | 0.037         | 0.037           |                 |
| C                                 | Max  | 0.045          | 0.050          | 0.050          | 0.067          | 0.067          | 0.067          | 0.067          | 0.084         | 0.084  | D              | Max                        | 0.065          | 0.092         | 0.105          | 0.099         | 0.128           | 0.128         | 0.147           | 0.192          | 0.255         | 0.270           | 0.304           |
|                                   | Min  | 0.035          | 0.040          | 0.042          | 0.050          | 0.055          | 0.055          | 0.059          | 0.070         | 0.075  | Min            | 0.050                      | 0.082          | 0.088         | 0.083          | 0.118         | 0.113           | 0.137         | 0.165           | 0.242          | 0.260         | 0.294           |                 |

<sup>a</sup> Starting with #4, approx. O.D.'s are: 0.213, 0.289, 0.322, 0.354, 0.421, 0.454, 0.505, 0.599, 0.765, 0.867, and 0.976.

All dimensions are given in inches.



**METRIC THREADED FASTENERS**

A number of American National Standards covering metric bolts, screws, nuts, and washers have been established in cooperation with the Department of Defense in such a way that they could be used by the Government for procurement purposes. Extensive information concerning these metric fasteners is given in the following text and tables, but for additional manufacturing and acceptance specifications reference should be made to the respective Standards which may be obtained by nongovernmental agencies from the American National Standards Institute, 25 West 43rd Street, New York, N.Y. 10036. These Standards are:

|  |          |
|--|----------|
| ANSI B18.2.3.1M-1979 (R1989) Metric Hex Cap Screws             | Table 1  |
| ANSI B18.2.3.2M-1979 (R1989) Metric Formed Hex Screws          | Table 2  |
| ANSI B18.2.3.3M-1979 (R1989) Metric Heavy Hex Screws           | Table 3  |
| ANSI B18.2.3.8M-1981 (R1991) Metric Hex Lag Screws             | Table 5  |
| ANSI B18.2.3.9M-1984 Metric Heavy Hex Flange Screws            | Table 6  |
| ANSI B18.2.3.4M-1984 Metric Hex Flange Screws                  | Table 7  |
| ANSI B18.5.2.2M-1982 Metric Round Head Square Neck Bolts       | Table 9  |
| ANSI B18.2.3.6M-1979 (R1989) Metric Heavy Hex Bolts            | Table 10 |
| ANSI B18.2.3.7M-1979 (R1989) Metric Heavy Hex Structural Bolts | Table 11 |
| ANSI B18.2.3.5M-1979 (R1989) Metric Hex Bolts                  | Table 12 |
| ANSI B18.3.1M-1986 Socket Head Cap Screws (Metric Series)      | Table 24 |
| ANSI B18.2.4.1M-1979 (R1989) Metric Hex Nuts, Style 1          | Table 26 |
| ANSI B18.2.4.2M-1979 (R1989) Metric Hex Nuts, Style 2          | Table 26 |
| ANSI B18.2.4.3M-1979 (R1989) Metric Slotted Hex Nuts           | Table 27 |
| ANSI B18.2.4.4M-1982 Metric Hex Flange Nuts                    | Table 28 |
| ANSI B18.16.3M-1998 Prevailing-Torque Metric Hex Nuts          | Table 29 |
| ANSI B18.16.3M-1998 Prevailing-Torque Metric Hex Flange Nuts   | Table 30 |
| ANSI B18.2.4.5M-1979 Metric Hex Jam Nuts                       | Table 31 |
| ANSI B18.2.4.6M-1979 (R1990) Metric Heavy Hex Nuts             | Table 31 |
| ANSI B18.22M-1981 (R1990) Metric Plain Washers                 | Table 32 |

Manufacturers should be consulted concerning which items and sizes are in stock production.

**Comparison with ISO Standards.**—American National Standards for metric bolts, screws and nuts have been coordinated to the extent possible with the comparable ISO Standards or proposed Standards. The dimensional differences between the ANSI and the comparable ISO Standards or proposed Standards are few, relatively minor, and none will affect the functional interchangeability of bolts, screws, and nuts manufactured to the requirements of either.

Where no comparable ISO Standard had been developed, as was the case when the ANSI Standards for Metric Heavy Hex Screws, Metric Heavy Hex Bolts, and Metric Hex Lag Screws were adopted, nominal diameters, thread pitches, body diameters, widths across flats, head heights, thread lengths, thread dimensions, and nominal lengths are in accord with ISO Standards for related hex head screws and bolts. At the time of ANSI adoption (1982) there was no ISO Standard for round head square neck bolts.

The following functional characteristics of hex head screws and bolts are in agreement between the respective ANSI Standard and the comparable ISO Standard or proposed Standard: diameters and thread pitches, body diameters, widths across flats (see exception below), bearing surface diameters (except for metric hex bolts), flange diameters (for metric hex flange screws), head heights, thread lengths, thread dimensions, and nominal lengths.

**Table 1. American National Standard Metric Hex Cap Screws**  
ANSI/ASME B18.2.3.1M-1979 (R1995)

**PROPERTY CLASS AND MANUFACTURER'S IDENTIFICATION TO APPEAR ON TOP OF HEAD**

| Nominal Screw Dia., $D$ , and Thread Pitch | Body Dia., $D_s$ |       | Width Across Flats, $S$ |        | Width Across Corners, $E$ |        | Head Height, $K$ |       | Wrenching Height, $K_f$ | Washer Face Thick., $C$ |     | Washer Face Dia., $D_w$ |
|--|------------------|-------|-------------------------|--------|---------------------------|--------|------------------|-------|-------------------------|-------------------------|-----|-------------------------|
|  | Max              | Min   | Max                     | Min    | Max                       | Min    | Max              | Min   |                         | Min                     | Max |                         |
| M5 × 0.8                                   | 5.00             | 4.82  | 8.00                    | 7.78   | 9.24                      | 8.79   | 3.65             | 3.35  | 2.4                     | 0.5                     | 0.2 | 7.0                     |
| M6 × 1                                     | 6.00             | 5.82  | 10.00                   | 9.78   | 11.55                     | 11.05  | 4.15             | 3.85  | 2.8                     | 0.5                     | 0.2 | 8.9                     |
| M8 × 1.25                                  | 8.00             | 7.78  | 13.00                   | 12.73  | 15.01                     | 14.38  | 5.50             | 5.10  | 3.7                     | 0.6                     | 0.3 | 11.6                    |
| *M10 × 1.5                                 | 10.00            | 9.78  | 15.00                   | 14.73  | 17.32                     | 16.64  | 6.63             | 6.17  | 4.5                     | 0.6                     | 0.3 | 13.6                    |
| M10 × 1.5                                  | 10.00            | 9.78  | 16.00                   | 15.73  | 18.48                     | 17.77  | 6.63             | 6.17  | 4.5                     | 0.6                     | 0.3 | 14.6                    |
| M12 × 1.75                                 | 12.00            | 11.73 | 18.00                   | 17.73  | 20.78                     | 20.03  | 7.76             | 7.24  | 5.2                     | 0.6                     | 0.3 | 16.6                    |
| M14 × 2                                    | 14.00            | 13.73 | 21.00                   | 20.67  | 24.25                     | 23.35  | 9.09             | 8.51  | 6.2                     | 0.6                     | 0.3 | 19.6                    |
| M16 × 2                                    | 16.00            | 15.73 | 24.00                   | 23.67  | 27.71                     | 26.75  | 10.32            | 9.68  | 7.0                     | 0.8                     | 0.4 | 22.5                    |
| M20 × 2.5                                  | 20.00            | 19.67 | 30.00                   | 29.16  | 34.64                     | 32.95  | 12.88            | 12.12 | 8.8                     | 0.8                     | 0.4 | 27.7                    |
| M24 × 3                                    | 24.00            | 23.67 | 36.00                   | 35.00  | 41.57                     | 39.55  | 15.44            | 14.56 | 10.5                    | 0.8                     | 0.4 | 33.2                    |
| M30 × 3.5                                  | 30.00            | 29.67 | 46.00                   | 45.00  | 53.12                     | 50.85  | 19.48            | 17.92 | 13.1                    | 0.8                     | 0.4 | 42.7                    |
| M36 × 4                                    | 36.00            | 35.61 | 55.00                   | 53.80  | 63.51                     | 60.79  | 23.38            | 21.62 | 15.8                    | 0.8                     | 0.4 | 51.1                    |
| M42 × 4.5                                  | 42.00            | 41.38 | 65.00                   | 62.90  | 75.06                     | 71.71  | 26.97            | 25.03 | 18.2                    | 1.0                     | 0.5 | 59.8                    |
| M48 × 5                                    | 48.00            | 47.38 | 75.00                   | 72.60  | 86.60                     | 82.76  | 31.07            | 28.93 | 21.0                    | 1.0                     | 0.5 | 69.0                    |
| M56 × 5.5                                  | 56.00            | 55.26 | 85.00                   | 82.20  | 98.15                     | 93.71  | 36.20            | 33.80 | 24.5                    | 1.0                     | 0.5 | 78.1                    |
| M64 × 6                                    | 64.00            | 63.26 | 95.00                   | 91.80  | 109.70                    | 104.65 | 41.32            | 38.68 | 28.0                    | 1.0                     | 0.5 | 87.2                    |
| M72 × 6                                    | 72.00            | 71.26 | 105.00                  | 101.40 | 121.24                    | 115.60 | 46.45            | 43.55 | 31.5                    | 1.2                     | 0.6 | 96.3                    |
| M80 × 6                                    | 80.00            | 79.26 | 115.00                  | 111.00 | 132.72                    | 126.54 | 51.58            | 48.42 | 35.0                    | 1.2                     | 0.6 | 105.4                   |
| M90 × 6                                    | 90.00            | 89.13 | 130.00                  | 125.50 | 150.11                    | 143.07 | 57.74            | 54.26 | 39.2                    | 1.2                     | 0.6 | 119.2                   |
| M100 × 6                                   | 100.00           | 99.13 | 145.00                  | 140.00 | 167.43                    | 159.60 | 63.90            | 60.10 | 43.4                    | 1.2                     | 0.6 | 133.0                   |

\* This size with width across flats of 15 mm is not standard. Unless specifically ordered, M10 hex cap screws with 16 mm width across flats will be furnished.

All dimensions are in millimeters.

Basic thread lengths,  $B$ , are the same as given in Table 12.

Transition thread length,  $X$ , includes the length of incomplete threads and tolerances on grip gaging length and body length. It is intended for calculation purposes.

For additional manufacturing and acceptance specifications, reference should be made to the ANSI/ASME B18.2.3.1M-1979 (R1995).

**Table 2. American National Standard Metric Formed Hex Screws**  
ANSI/ASME B18.2.3.2M-1979 (R1995)

| Nominal Screw Dia., $D$ , and Thread Pitch | Body Dia., $D_s$ |       | Width Across Flats, $S$ |       | Width Across Corners, $E$ |       | Head Height, $K$ |       | Wrenching Height, $K_1$ | Washer Face Thick., $C$ |     | Washer Face Dia., $D_w$ |
|--|------------------|-------|-------------------------|-------|---------------------------|-------|------------------|-------|-------------------------|-------------------------|-----|-------------------------|
|  | Max              | Min   | Max                     | Min   | Max                       | Min   | Max              | Min   | Min                     | Max                     | Min | Max                     |
| M5 $\times$ 0.8                            | 5.00             | 4.82  | 8.00                    | 7.64  | 9.24                      | 8.56  | 3.65             | 3.35  | 2.4                     | 0.5                     | 0.2 | 6.9                     |
| M6 $\times$ 1                              | 6.00             | 5.82  | 10.00                   | 9.64  | 11.55                     | 10.80 | 4.15             | 3.85  | 2.0                     | 0.5                     | 0.2 | 8.9                     |
| M8 $\times$ 1.25                           | 8.00             | 7.78  | 13.00                   | 12.57 | 15.01                     | 14.08 | 5.50             | 5.10  | 3.7                     | 0.6                     | 0.3 | 11.6                    |
| *M10 $\times$ 1.5                          | 10.00            | 9.78  | 15.00                   | 14.57 | 17.32                     | 16.32 | 6.63             | 6.17  | 4.5                     | 0.6                     | 0.3 | 13.6                    |
| M10 $\times$ 1.5                           | 10.00            | 9.78  | 16.00                   | 15.57 | 18.48                     | 17.43 | 6.63             | 6.17  | 4.5                     | 0.6                     | 0.3 | 14.6                    |
| M12 $\times$ 1.75                          | 12.00            | 11.73 | 18.00                   | 17.57 | 20.78                     | 19.68 | 7.76             | 7.24  | 5.2                     | 0.6                     | 0.3 | 16.6                    |
| M14 $\times$ 2                             | 14.00            | 13.73 | 21.00                   | 20.16 | 24.25                     | 22.58 | 9.09             | 8.51  | 6.2                     | 0.6                     | 0.3 | 19.6                    |
| M16 $\times$ 2                             | 16.00            | 15.73 | 24.00                   | 23.16 | 27.71                     | 25.94 | 10.32            | 9.68  | 7.0                     | 0.8                     | 0.4 | 22.5                    |
| M20 $\times$ 2.5                           | 20.00            | 19.67 | 30.00                   | 29.16 | 34.64                     | 32.66 | 12.88            | 12.12 | 8.8                     | 0.8                     | 0.4 | 27.7                    |
| M24 $\times$ 3                             | 24.00            | 23.67 | 36.00                   | 35.00 | 41.57                     | 39.20 | 15.44            | 14.56 | 10.5                    | 0.8                     | 0.4 | 33.2                    |

<sup>a</sup>This size with width across flats of 15 mm is not standard. Unless specifically ordered, M10 formed hex screws with 16 mm width across flats will be furnished.

All dimensions are in millimeters.

†Basic thread lengths,  $B$ , are the same as given in Table 12.

‡Transition thread length,  $X$ , includes the length of incomplete threads and tolerances on the grip gaging length and body length. It is intended for calculation purposes.

For additional manufacturing and acceptance specifications, reference should be made to the Standard.

Socket head cap screws ANSI B18.3.1M-1986 are functionally interchangeable with screws which conform to ISO R861-1968 or ISO 4762-1977. However, the thread lengths specified in the ANSI Standard are equal to or longer than required by either ISO Standard. Consequently the grip lengths also vary on screws where the North American thread length practice differs. Minor variations in head diameter, head height, key engagement and wall thickness are due to diverse tolerancing practice and will be found documented in the ANSI Standard.

One exception with respect to width across flats for metric hex cap screws, formed hex screws, and hex bolts is the M10 size. These are currently being produced in the United States with a width across flats of 15 mm. This size, however, is not an ISO Standard. Unless these M10 screws and bolts with 15 mm width across flats are specifically ordered, the M10 size with 16 mm across flats will be furnished.

**Table 3. American National Standard Metric Heavy Hex Screws**  
ANSI B18.2.3.3M-1979 (R1995)

**PROPERTY CLASS AND MANUFACTURER'S IDENTIFICATION TO APPEAR ON TOP OF HEAD**

| Nominal Screw Dia., $D$ , and Thread Pitch | Body Diameter, $D_s$ |       | Width Across Flats, $S$ |       | Width Across Corners, $E$ |       | Head Height, $K$ |       | Wrenching Height, $K_1$ | Washer Face Thickness, $C$ |     | Washer Face Dia., $D_w$ |
|--|----------------------|-------|-------------------------|-------|---------------------------|-------|------------------|-------|-------------------------|----------------------------|-----|-------------------------|
|  | Max                  | Min   | Max                     | Min   | Max                       | Min   | Max              | Min   | Min                     | Max                        | Min | Min                     |
| M12 × 1.75                                 | 12.00                | 11.73 | 21.00                   | 20.67 | 24.25                     | 23.35 | 7.76             | 7.24  | 5.2                     | 0.6                        | 0.3 | 19.6                    |
| M14 × 2                                    | 14.00                | 13.73 | 24.00                   | 23.67 | 27.71                     | 26.75 | 9.09             | 8.51  | 6.2                     | 0.6                        | 0.3 | 22.5                    |
| M16 × 2                                    | 16.00                | 15.73 | 27.00                   | 26.67 | 31.18                     | 30.14 | 10.32            | 9.68  | 7.0                     | 0.8                        | 0.4 | 25.3                    |
| M20 × 2.5                                  | 20.00                | 19.67 | 34.00                   | 33.00 | 39.26                     | 37.29 | 12.88            | 12.12 | 8.8                     | 0.8                        | 0.4 | 31.4                    |
| M24 × 3                                    | 24.00                | 23.67 | 41.00                   | 40.00 | 47.34                     | 45.20 | 15.44            | 14.56 | 10.5                    | 0.8                        | 0.4 | 38.0                    |
| M30 × 3.5                                  | 30.00                | 29.67 | 50.00                   | 49.00 | 57.74                     | 55.37 | 19.48            | 17.92 | 13.1                    | 0.8                        | 0.4 | 46.6                    |
| M36 × 4                                    | 36.00                | 35.61 | 60.00                   | 58.80 | 69.28                     | 66.44 | 23.38            | 21.72 | 15.8                    | 0.8                        | 0.4 | 55.9                    |

All dimensions are in millimeters.

Basic thread lengths,  $B$ , are the same as given in Table 12.

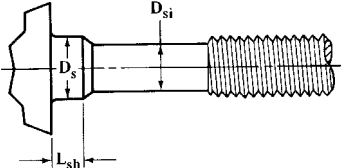
Transition thread length,  $X$ , includes the length of incomplete threads and tolerances on grip gaging length and body length. It is intended for calculation purposes.

For additional manufacturing and acceptance specifications, reference should be made to the Standard.

ANSI letter symbols designating dimensional characteristics are in accord with those used in ISO Standards except capitals have been used for data processing convenience instead of the lower case letters used in the ISO Standards.

**Metric Screw and Bolt Diameters.**—Metric screws and bolts are furnished with full diameter body within the limits shown in the respective dimensional tables, or are threaded to the head (see *Metric Screw and Bolt Thread Lengths* on page 1551) unless the purchaser specifies "reduced body diameter." Metric formed hex screws (Table 4), hex flange screws (Table 4), hex bolts (Table 4), heavy hex bolts (Table 4), hex lag screws (Table 5), heavy hex flange screws (Table 6), and round head square neck bolts (Table 8) may be obtained with reduced diameter body, if so specified; however, formed hex screws, hex flange screws, heavy hex flange screws, hex bolts, or heavy hex bolts with nominal lengths shorter than  $4D$ , where  $D$  is the nominal diameter, are not recommended. Metric formed hex screws, hex flange screws, heavy hex flange screws, and hex lag screws with reduced body diameter will be furnished with a shoulder under the head. For metric hex bolts and heavy hex bolts this is optional with the manufacturer.

For bolts and lag screws there may be a reasonable swell, fin, or die seam on the body adjacent to the head not exceeding the nominal bolt diameter by: 0.50 mm for M5, 0.65 mm for M6, 0.75 mm for M8 through M14, 1.25 mm for M16, 1.50 mm for M20 through M30, 2.30 mm for M36 through M48, 3.00 mm for M56 through M72, and 4.80 mm for M80 through M100.

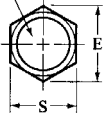
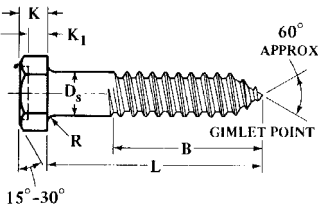
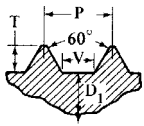
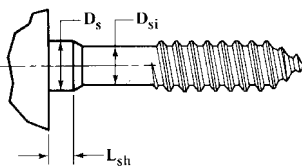
**Table 4. American National Standard Metric Hex Screws and Bolts — Reduced Body Diameters**


| Nominal Dia., $D$ , and Thread Pitch                   | Shoulder Diameter, <sup>a</sup> $D_s$ |       | Body Diameter, $D_{si}$ |       | Shoulder Length, <sup>a</sup> $L_{sh}$ |     | Nominal Dia., $D$ , and Thread Pitch | Shoulder Diameter, <sup>a</sup> $D_s$ |       | Body Diameter, $D_{si}$ |       | Shoulder Length, <sup>a</sup> $L_{sh}$ |      |
|--|---------------------------------------|-------|-------------------------|-------|--|-----|--------------------------------------|---------------------------------------|-------|-------------------------|-------|--|------|
|  | Max                                   | Min   | Max                     | Min   | Max                                    | Min |                                      | Max                                   | Min   | Max                     | Min   | Max                                    | Min  |
| Metric Formed Hex Screws (ANSI B18.2.3.2M-1979, R1989) |                                       |       |                         |       |  |     |                                      |                                       |       |                         |       |  |      |
| M5 × 0.8   | 5.00                                  | 4.82  | 4.46                    | 4.36  | 3.5                                    | 2.5 | M14 × 2                              | 14.00                                 | 13.73 | 12.77                   | 12.50 | 8.0                                    | 7.0  |
| M6 × 1   | 6.00                                  | 5.82  | 5.39                    | 5.21  | 4.0                                    | 3.0 | M16 × 2                              | 16.00                                 | 15.73 | 14.77                   | 14.50 | 9.0                                    | 8.0  |
| M8 × 1.25  | 8.00                                  | 7.78  | 7.26                    | 7.04  | 5.0                                    | 4.0 | M20 × 2.5                            | 20.00                                 | 19.67 | 18.49                   | 18.16 | 11.0                                   | 10.0 |
| M10 × 1.5  | 10.00                                 | 9.78  | 9.08                    | 8.86  | 6.0                                    | 5.0 | M24 × 3                              | 24.00                                 | 23.67 | 22.13                   | 21.80 | 13.0                                   | 12.0 |
| M12 × 1.75   | 12.00                                 | 11.73 | 10.95                   | 10.68 | 7.0                                    | 6.0 | ...                                  | ...                                   | ...   | ...                     | ...   | ...                                    | ...  |
| Metric Hex Flange Screws (ANSI B18.2.3.4M-1984)        |                                       |       |                         |       |  |     |                                      |                                       |       |                         |       |  |      |
| M5 × 0.8   | 5.00                                  | 4.82  | 4.46                    | 4.36  | 3.5                                    | 2.5 | M12 × 1.75                           | 12.00                                 | 11.73 | 10.95                   | 10.68 | 7.0                                    | 6.0  |
| M6 × 1   | 6.00                                  | 5.82  | 5.39                    | 5.21  | 4.0                                    | 3.0 | M14 × 2                              | 14.00                                 | 13.73 | 12.77                   | 12.50 | 8.0                                    | 7.0  |
| M8 × 1.25  | 8.00                                  | 7.78  | 7.26                    | 7.04  | 5.0                                    | 4.0 | M16 × 2                              | 16.00                                 | 15.73 | 14.77                   | 14.50 | 9.0                                    | 8.0  |
| M10 × 1.5  | 10.00                                 | 9.78  | 9.08                    | 8.86  | 6.0                                    | 5.0 | ...                                  | ...                                   | ...   | ...                     | ...   | ...                                    | ...  |
| Metric Hex Bolts (ANSI B18.2.3.5M-1979, R1989)         |                                       |       |                         |       |  |     |                                      |                                       |       |                         |       |  |      |
| M5 × 0.8   | 5.48                                  | 4.52  | 4.46                    | 4.36  | 3.5                                    | 2.5 | M14 × 2                              | 14.70                                 | 13.30 | 12.77                   | 12.50 | 8.0                                    | 7.0  |
| M6 × 1   | 6.48                                  | 5.52  | 5.39                    | 5.21  | 4.0                                    | 3.0 | M16 × 2                              | 16.70                                 | 15.30 | 14.77                   | 14.50 | 9.0                                    | 8.0  |
| M8 × 1.25  | 8.58                                  | 7.42  | 7.26                    | 7.04  | 5.0                                    | 4.0 | M20 × 2.5                            | 20.84                                 | 19.16 | 18.49                   | 18.16 | 11.0                                   | 10.0 |
| M10 × 1.5  | 10.58                                 | 9.42  | 9.08                    | 8.86  | 6.0                                    | 5.0 | M24 × 3                              | 24.84                                 | 23.16 | 22.13                   | 21.80 | 13.0                                   | 12.0 |
| M12 × 1.75   | 12.70                                 | 11.30 | 10.95                   | 10.68 | 7.0                                    | 6.0 | ...                                  | ...                                   | ...   | ...                     | ...   | ...                                    | ...  |
| Metric Heavy Hex Bolts (ANSI B18.2.3.6M-1979, R1989)   |                                       |       |                         |       |  |     |                                      |                                       |       |                         |       |  |      |
| M12 × 1.75   | 12.70                                 | 11.30 | 10.95                   | 10.68 | 7.0                                    | 6.0 | M20 × 2.5                            | 20.84                                 | 19.16 | 18.49                   | 18.16 | 11.0                                   | 10.0 |
| M14 × 2  | 14.70                                 | 13.30 | 12.77                   | 12.50 | 8.0                                    | 7.0 | M24 × 3                              | 24.84                                 | 23.16 | 22.13                   | 21.80 | 13.0                                   | 12.0 |
| M16 × 2  | 16.70                                 | 15.30 | 14.77                   | 14.50 | 9.0                                    | 8.0 | ...                                  | ...                                   | ...   | ...                     | ...   | ...                                    | ...  |
| Metric Heavy Hex Flange Screws (ANSI B18.2.3.9M-1984)  |                                       |       |                         |       |  |     |                                      |                                       |       |                         |       |  |      |
| M10 × 1.5  | 10.00                                 | 9.78  | 9.08                    | 8.86  | 6.0                                    | 5.0 | M16 × 2                              | 16.00                                 | 15.73 | 14.77                   | 14.50 | 9.0                                    | 8.0  |
| M12 × 1.75   | 12.00                                 | 11.73 | 10.95                   | 10.68 | 7.0                                    | 6.0 | M20 × 2.5                            | 20.00                                 | 19.67 | 18.49                   | 18.16 | 11.0                                   | 10.0 |
| M14 × 2  | 14.00                                 | 13.73 | 12.77                   | 12.50 | 8.0                                    | 7.0 | ...                                  | ...                                   | ...   | ...                     | ...   | ...                                    | ...  |

<sup>a</sup> Shoulder is mandatory for formed hex screws, hex flange screws, and heavy hex flange screws. Shoulder is optional for hex bolts and heavy hex bolts.

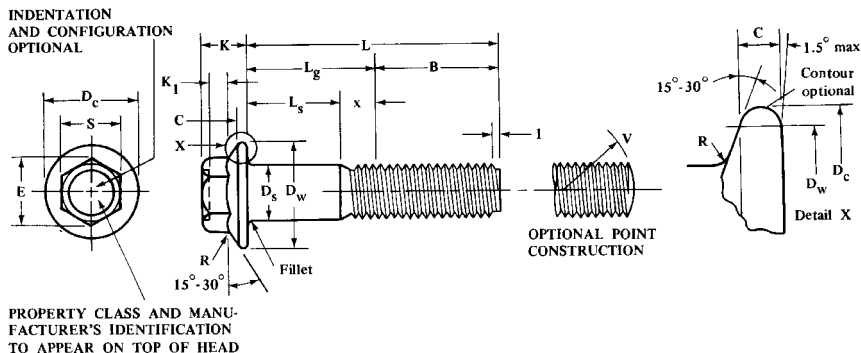
All dimensions are in millimeters.

**Table 5. American National Standard Metric Hex Lag Screws**  
ANSI B18.2.3.8M-1981, R1991

| INDENTATION AND CONFIGURATION OPTIONAL.   |                          |   |                           |                  |                           |                          |   |                           |                         |
|---|--------------------------|---|---------------------------|------------------|---------------------------|--------------------------|---|---------------------------|-------------------------|
|    |                          |  |                           |                  |                           |                          |  |                           |                         |
|   |                          |   |                           |                  |                           |                          |   |                           | DETAIL OF THREAD        |
| Nominal Screw Dia., $D$   | Body Diameter, $D_s$     |   | Width Across Flats, $S$   |                  | Width Across Corners, $E$ |                          | Head Height, $K$  |                           | Wrenching Height, $K_1$ |
|   | Max                      | Min   | Max                       | Min              | Max                       | Min                      | Max   | Min                       | Min                     |
| 5   | 5.48                     | 4.52  | 8.00                      | 7.64             | 9.24                      | 8.63                     | 3.9   | 3.1                       | 2.4                     |
| 6   | 6.48                     | 5.52  | 10.00                     | 9.64             | 11.55                     | 10.89                    | 4.4   | 3.6                       | 2.8                     |
| 8   | 8.58                     | 7.42  | 13.00                     | 12.57            | 15.01                     | 14.20                    | 5.7   | 4.9                       | 3.7                     |
| 10  | 10.58                    | 9.42  | 16.00                     | 15.57            | 18.48                     | 17.59                    | 6.9   | 5.9                       | 4.5                     |
| 12  | 12.70                    | 11.30   | 18.00                     | 17.57            | 20.78                     | 19.85                    | 8.0   | 7.0                       | 5.2                     |
| 16  | 16.70                    | 15.30   | 24.00                     | 23.16            | 27.71                     | 26.17                    | 10.8  | 9.3                       | 7.0                     |
| 20  | 20.84                    | 19.16   | 30.00                     | 29.16            | 34.64                     | 32.95                    | 13.4  | 11.6                      | 8.8                     |
| 24  | 24.84                    | 23.16   | 36.00                     | 35.00            | 41.57                     | 39.55                    | 15.9  | 14.1                      | 10.5                    |
| Nominal Screw Dia., $D$   | Thread Dimensions        |   |                           |                  | Nominal Screw Dia., $D$   | Thread Dimensions        |   |                           |                         |
|   | Thread Pitch, $P$        | Flat at Root, $V$   | Depth of Thread, $T$      | Root Dia., $D_1$ |                           | Thread Pitch, $P$        | Flat at Root, $V$   | Depth of Thread, $T$      | Root Dia., $D_1$        |
| 5   | 2.3                      | 1.0   | 0.9                       | 3.2              | 12                        | 4.2                      | 1.8   | 1.6                       | 8.7                     |
| 6   | 2.5                      | 1.1   | 1.0                       | 4.0              | 16                        | 5.1                      | 2.2   | 2.0                       | 12.0                    |
| 8   | 2.8                      | 1.2   | 1.1                       | 5.8              | 20                        | 5.6                      | 2.4   | 2.2                       | 15.6                    |
| 10  | 3.6                      | 1.6   | 1.4                       | 7.2              | 24                        | 7.3                      | 3.1   | 2.8                       | 18.1                    |
| REDUCED BODY DIAMETER   |                          |   |                           |                  |                           |                          |   |                           |                         |
|  |                          |   |                           |                  |                           |                          |   |                           |                         |
| Nominal Screw Dia., $D$   | Shoulder Diameter, $D_s$ |   | Shoulder Length, $L_{sh}$ |                  | Nominal Screw Dia., $D$   | Shoulder Diameter, $D_s$ |   | Shoulder Length, $L_{sh}$ |                         |
|   | Max                      | Min   | Max                       | Min              |                           | Max                      | Min   | Max                       | Min                     |
| 5   | 5.48                     | 4.52  | 3.5                       | 2.5              | 12                        | 12.70                    | 11.30   | 7.0                       | 6.0                     |
| 6   | 6.48                     | 5.52  | 4.0                       | 3.0              | 16                        | 16.70                    | 15.30   | 9.0                       | 8.0                     |
| 8   | 8.58                     | 7.42  | 5.0                       | 4.0              | 20                        | 20.84                    | 19.16   | 11.0                      | 10.0                    |
| 10  | 10.58                    | 9.42  | 6.0                       | 5.0              | 24                        | 24.84                    | 23.16   | 13.0                      | 12.0                    |

All dimensions are in millimeters. Reduced body diameter,  $D_{si}$ , is the blank diameter before rolling. Shoulder is mandatory when body diameter is reduced.

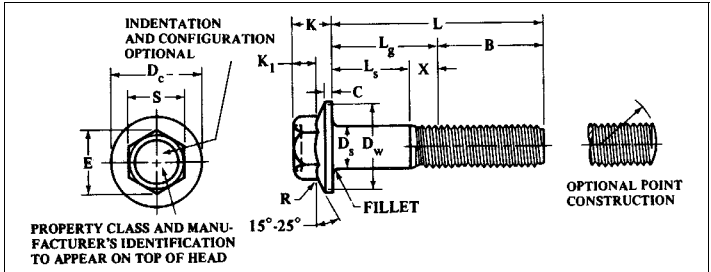
Table 6. American National Standard Metric Heavy Hex Flange Screws ANSI/ASME B18.2.3.9M-1984



| Nominal Screw Dia., $D$ , and Thread Pitch | Body Dia., $D_s$ |       | Width Across Flats, $S$ |       | Width Across Corners, $E$ |       | Flange Dia., $D_c$ | Bearing Circle Dia., $D_w$ | Flange Edge Thickness, $C$ | Head Height, $K$ | Wrenching Height $K_1$ | Fillet Radius, $R$ |
|--|------------------|-------|-------------------------|-------|---------------------------|-------|--------------------|----------------------------|----------------------------|------------------|------------------------|--------------------|
|  | Max              | Min   | Max                     | Min   | Max                       | Min   | Max                | Min                        | Min                        | Max              | Min                    | Max                |
| M10 $\times$ 1.5                           | 10.00            | 9.78  | 15.00                   | 14.57 | 17.32                     | 16.32 | 22.3               | 19.6                       | 1.5                        | 8.6              | 3.70                   | 0.6                |
| M12 $\times$ 1.75                          | 12.00            | 11.73 | 18.00                   | 17.57 | 20.78                     | 19.68 | 26.6               | 23.8                       | 1.8                        | 10.4             | 4.60                   | 0.7                |
| M14 $\times$ 2                             | 14.00            | 13.73 | 21.00                   | 20.48 | 24.25                     | 22.94 | 30.5               | 27.6                       | 2.1                        | 12.4             | 5.50                   | 0.9                |
| M16 $\times$ 2                             | 16.00            | 15.73 | 24.00                   | 23.16 | 27.71                     | 25.94 | 35.0               | 31.9                       | 2.4                        | 14.1             | 6.20                   | 1.0                |
| M20 $\times$ 2.5                           | 20.00            | 19.67 | 30.00                   | 29.16 | 34.64                     | 32.66 | 43.0               | 39.9                       | 3.0                        | 17.7             | 7.90                   | 1.2                |

All dimensions are in millimeters. Basic thread lengths,  $B$ , are as given in Table 12. Transition thread length,  $x$ , includes the length of incomplete threads and tolerances on grip gaging length and body length. It is intended for calculation purposes. For additional manufacturing and acceptance specifications, reference should be made to ANSI/ASME B18.2.3.9M-1984 standard.

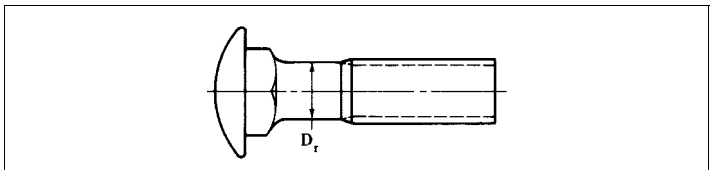
**Table 7. American National Standard Metric Hex Flange Screws**  
ANSI/ASME B18.2.3.4M-1984



| Nominal Screw Dia., $D$ , and Thread Pitch | Body Dia., $D_s$ |       | Width Across Flats, $S$ |       | Width Across Corners, $E$ |       | Flange Dia., $D_c$ | Bearing Circle Dia., $D_b$ | Flange Edge Thickness, $C$ | Head Height, $K$ | Wrenching Height, $K_1$ | Fillet Radius, $R$ |
|--|------------------|-------|-------------------------|-------|---------------------------|-------|--------------------|----------------------------|----------------------------|------------------|-------------------------|--------------------|
|  | Max              | Min   | Max                     | Min   | Max                       | Min   | Max                | Min                        | Min                        | Max              | Min                     | Max                |
| M5 × 0.8                                   | 5.00             | 4.82  | 7.00                    | 6.64  | 8.08                      | 7.44  | 11.4               | 9.4                        | 1.0                        | 5.6              | 2.30                    | 0.3                |
| M6 × 1                                     | 6.00             | 5.82  | 8.00                    | 7.64  | 9.24                      | 8.56  | 13.6               | 11.6                       | 1.1                        | 6.8              | 2.90                    | 0.4                |
| M8 × 1.25                                  | 8.00             | 7.78  | 10.00                   | 9.64  | 11.55                     | 10.80 | 17.0               | 14.9                       | 1.2                        | 8.5              | 3.80                    | 0.5                |
| M10 × 1.5                                  | 10.00            | 9.78  | 13.00                   | 12.57 | 15.01                     | 14.08 | 20.8               | 18.7                       | 1.5                        | 9.7              | 4.30                    | 0.6                |
| M12 × 1.75                                 | 12.00            | 11.73 | 15.00                   | 14.57 | 17.32                     | 16.32 | 24.7               | 22.0                       | 1.8                        | 11.9             | 5.40                    | 0.7                |
| M14 × 2                                    | 14.00            | 13.73 | 18.00                   | 17.57 | 20.78                     | 19.68 | 28.6               | 25.9                       | 2.1                        | 12.9             | 5.60                    | 0.8                |
| M16 × 2                                    | 16.00            | 15.73 | 21.00                   | 20.48 | 24.25                     | 22.94 | 32.8               | 30.1                       | 2.4                        | 15.1             | 6.70                    | 1.0                |

All dimensions are in millimeters. Basic thread lengths,  $B$ , are the same as given in Table 12. Transition thread length,  $x$ , includes the length of incomplete threads and tolerances on grip gaging length and body length. This dimension is intended for calculation purposes only. For additional manufacturing and acceptance specifications, reference should be made to ANSI/ASME B18.2.3.4M-1984 standard.

**Table 8. American National Standard Metric Round Head Square Neck Bolts**  
Reduced Body Diameters ANSI/ASME B18.5.2.2M-1982 (R1993)

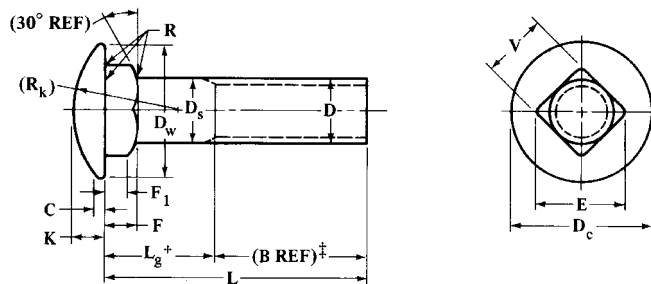


| Nominal Bolt Dia., $D$ and Thread Pitch | Diameter of Reduced Body $D_r$ |       | Nominal Bolt Dia., $D$ and Thread Pitch | Diameter of Reduced Body $D_r$ |       |
|---|--------------------------------|-------|---|--------------------------------|-------|
|   | Max                            | Min   |   | Max                            | Min   |
| M5 × 0.8                                | 5.00                           | 4.36  | M14 × 2                                 | 14.00                          | 12.50 |
| M6 × 1                                  | 6.00                           | 5.21  | M16 × 2                                 | 16.00                          | 14.50 |
| M8 × 1.25                               | 8.00                           | 7.04  | M20 × 2.5                               | 20.00                          | 18.16 |
| M10 × 1.5                               | 10.00                          | 8.86  | M24 × 3                                 | 24.00                          | 21.80 |
| M12 × 1.75                              | 12.00                          | 10.68 | ...                                     | ...                            | ...   |

All dimensions are in millimeters.



Table 9. American National Standard Metric Round Head Square Neck Bolts ANSI B18.2.3.7M-1979 (R1989)



| Nominal Bolt Dia.,<br><i>D</i> and Thread Pitch | Diameter of Full Body,<br><i>D<sub>s</sub></i> |       | Head Radius,<br>( <i>R<sub>k</sub></i> ) | Head height,<br><i>K</i> |      | Head Edge Thickness,<br><i>C</i> |     | Head Dia.,<br><i>D<sub>c</sub></i> | Bearing Surface Dia.,<br><i>D<sub>w</sub></i> | Square Depth,<br><i>F</i> |      | Square Corner Depth,<br><i>F<sub>1</sub></i> | Square Width Across Flats,<br><i>V</i> |       | Square Width Across Corners,<br><i>E</i> |       |
|---|--|-------|--|--------------------------|------|----------------------------------|-----|------------------------------------|---|---------------------------|------|--|--|-------|--|-------|
|   | Max  | Min   |  | Ref.                     | Max  | Min                              | Max |                                    |   | Min                       | Max  |  | Min                                    | Min   | Max                                      | Min   |
| M5 × 0.8  | 5.48   | 4.52  | 8.8                                      | 3.1                      | 2.5  | 1.8                              | 1.0 | 11.8                               | 9.8   | 3.1                       | 2.5  | 1.6  | 5.48                                   | 4.88  | 7.75                                     | 6.34  |
| M6 × 1  | 6.48   | 5.52  | 10.7                                     | 3.6                      | 3.0  | 1.9                              | 1.1 | 14.2                               | 12.2  | 3.6                       | 3.0  | 1.9  | 6.48                                   | 5.88  | 9.16                                     | 7.64  |
| M8 × 1.25                                       | 8.58   | 7.42  | 12.5                                     | 4.8                      | 4.0  | 2.2                              | 1.2 | 18.0                               | 15.8  | 4.8                       | 4.0  | 2.5  | 8.58                                   | 7.85  | 12.13                                    | 10.20 |
| M10 × 1.5                                       | 10.58  | 9.42  | 15.5                                     | 5.8                      | 5.0  | 2.5                              | 1.5 | 22.3                               | 19.6  | 5.8                       | 5.0  | 3.2  | 10.58                                  | 9.85  | 14.96                                    | 12.80 |
| M12 × 1.75                                      | 12.70  | 11.30 | 19.0                                     | 6.8                      | 6.0  | 2.8                              | 1.8 | 26.6                               | 23.8  | 6.8                       | 6.0  | 3.8  | 12.70                                  | 11.82 | 17.96                                    | 15.37 |
| M14 × 2   | 14.70  | 13.30 | 21.9                                     | 7.9                      | 7.0  | 3.3                              | 2.1 | 30.5                               | 27.6  | 7.9                       | 7.0  | 4.4  | 14.70                                  | 13.82 | 20.79                                    | 17.97 |
| M16 × 2   | 16.70  | 15.30 | 25.5                                     | 8.9                      | 8.0  | 3.6                              | 2.4 | 35.0                               | 31.9  | 8.9                       | 8.0  | 5.0  | 16.70                                  | 15.82 | 23.62                                    | 20.57 |
| M20 × 2.5                                       | 20.84  | 19.16 | 31.9                                     | 10.9                     | 10.0 | 4.2                              | 3.0 | 43.0                               | 39.9  | 10.9                      | 10.0 | 6.3  | 20.84                                  | 19.79 | 29.47                                    | 25.73 |
| M24 × 3   | 24.84  | 23.16 | 37.9                                     | 13.1                     | 12.0 | 5.1                              | 3.6 | 51.0                               | 47.6  | 13.1                      | 12.0 | 7.6  | 24.84                                  | 23.79 | 35.13                                    | 30.93 |

All dimensions are in millimeters.

† $L_g$  is the grip gaging length which controls the length of thread *B*.

‡ $B$  is the basic thread length and is a reference dimension (see Table 13).

For additional manufacturing and acceptance specifications, see ANSI/ASME B18.5.2.2M-1982, R1993.

**Table 10. ANSI Heavy Hex Bolts ANSI B18.2.3.6M-1979 (R1989)**

PROPERTY CLASS AND MANUFACTURER'S IDENTIFICATION TO APPEAR ON TOP OF HEAD

| Nominal Dia., <i>D</i> and Thread Pitch | Body Diameter, <i>D<sub>s</sub></i> |       | Width Across Flats, <i>S</i> |       | Width Across Corners, <i>E</i> |       | Head Height, <i>K</i> |       | Wrenching Height, <i>K<sub>1</sub></i> |
|---|-------------------------------------|-------|------------------------------|-------|--------------------------------|-------|-----------------------|-------|--|
|   | Max                                 | Min   | Max                          | Min   | Max                            | Min   | Max                   | Min   | Min                                    |
| M12 × 1.75                              | 12.70                               | 11.30 | 21.00                        | 20.16 | 24.25                          | 22.78 | 7.95                  | 7.24  | 5.2                                    |
| M14 × 2                                 | 14.70                               | 13.30 | 24.00                        | 23.16 | 27.71                          | 26.17 | 9.25                  | 8.51  | 6.2                                    |
| M16 × 2                                 | 16.70                               | 15.30 | 27.00                        | 26.16 | 31.18                          | 29.56 | 10.75                 | 9.68  | 7.0                                    |
| M20 × 2.5                               | 20.84                               | 19.16 | 34.00                        | 33.00 | 39.26                          | 37.29 | 13.40                 | 12.12 | 8.8                                    |
| M24 × 3                                 | 24.84                               | 23.16 | 41.00                        | 40.00 | 47.34                          | 45.20 | 15.90                 | 14.56 | 10.5                                   |
| M30 × 3.5                               | 30.84                               | 29.16 | 50.00                        | 49.00 | 57.74                          | 55.37 | 19.75                 | 17.92 | 13.1                                   |
| M36 × 4                                 | 37.00                               | 35.00 | 60.00                        | 58.80 | 69.28                          | 66.44 | 23.55                 | 21.72 | 15.8                                   |

All dimensions are in millimeters.\*Basic thread lengths, *B*, are the same as given in Table 12. For additional manufacturing and acceptance specifications, reference should be made to the ANSI B18.2.3.6M-1979, R1989 standard.

**Table 11. ANSI Metric Heavy Hex Structural Bolts ANSI B18.2.3.7M-1979 (R1989)**

PROPERTY CLASS AND MANUFACTURER'S IDENTIFICATION TO APPEAR ON TOP OF HEAD

| Dia. <i>D</i> , and Thread Pitch | Body Diameter, <i>D<sub>s</sub></i> |       | Width Across Flats, <i>S</i> |       | Width Across Corners, <i>E</i> |       | Head Height, <i>K</i> |       | Wrenching Height, <i>K<sub>1</sub></i> | Washer Face Dia., <i>D<sub>w</sub></i> | Washer Face Thickness, <i>C</i> |     | Thread Length, <i>B<sup>a</sup></i> |               | Transition Thread Length, <i>X<sup>b</sup></i> |
|----------------------------------|-------------------------------------|-------|------------------------------|-------|--------------------------------|-------|-----------------------|-------|--|--|---------------------------------|-----|-------------------------------------|---------------|--|
|                                  | Max                                 | Min   | Max                          | Min   | Max                            | Min   | Max                   | Min   |  |  | Max                             | Min | Lengths ≤ 100                       | Lengths > 100 |  |
|                                  | M16 × 2                             | 16.70 | 15.30                        | 27.00 | 26.16                          | 31.18 | 29.56                 | 10.75 | 9.25                                   | 6.5                                    | 24.9                            | 0.8 | 0.4                                 | 31            | 38   |
| M20 × 2.5                        | 20.84                               | 19.16 | 34.00                        | 33.00 | 39.26                          | 37.29 | 13.40                 | 11.60 | 8.1                                    | 31.4                                   | 0.8                             | 0.4 | 36                                  | 43            | 7.5  |
| M22 × 2.5                        | 22.84                               | 21.16 | 36.00                        | 35.00 | 41.57                          | 39.55 | 14.90                 | 13.10 | 9.2                                    | 33.3                                   | 0.8                             | 0.4 | 38                                  | 45            | 7.5  |
| M24 × 3                          | 24.84                               | 23.16 | 41.00                        | 40.00 | 47.34                          | 45.20 | 15.90                 | 14.10 | 9.9                                    | 38.0                                   | 0.8                             | 0.4 | 41                                  | 48            | 9.0  |
| M27 × 3                          | 27.84                               | 26.16 | 46.00                        | 45.00 | 53.12                          | 50.85 | 17.90                 | 16.10 | 11.3                                   | 42.8                                   | 0.8                             | 0.4 | 44                                  | 51            | 9.0  |
| M30 × 3.5                        | 30.84                               | 29.16 | 50.00                        | 49.00 | 57.74                          | 55.37 | 19.75                 | 17.65 | 12.4                                   | 46.5                                   | 0.8                             | 0.4 | 49                                  | 56            | 10.5   |
| M36 × 4                          | 37.00                               | 35.00 | 60.00                        | 58.80 | 69.28                          | 66.44 | 23.55                 | 21.45 | 15.0                                   | 55.9                                   | 0.8                             | 0.4 | 56                                  | 63            | 12.0   |

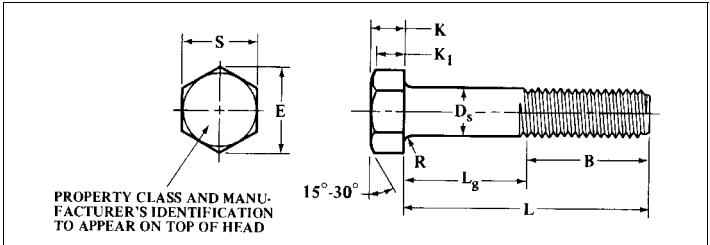
<sup>a</sup> Basic thread length, *B*, is a reference dimension.

<sup>b</sup> Transition thread length, *X*, includes the length of incomplete threads and tolerances on grip gaging length and body length. It is intended for calculation purposes.

All dimensions are in millimeters.

For additional manufacturing and acceptance specifications, reference should be made to the ANSI B18.2.3.7M-1979 (R1995) standard.

**Table 12. American National Standard Metric Hex Bolts**  
ANSI/ASME B18.2.3.5M-1989



| Nominal Bolt Dia., $D$ and Thread Pitch | Body Diameter, $D_s$ |       | Width Across Flats, $S$ |        | Width Across Corners, $E$ |        | Head Height, $K$ |       | Wrenching Height, $K_1$ | For Bolt Lengths                      |                |        |
|---|----------------------|-------|-------------------------|--------|---------------------------|--------|------------------|-------|-------------------------|---------------------------------------|----------------|--------|
|   |                      |       |                         |        |                           |        |                  |       |                         | 125 mm                                | 125 and 200 mm | 200 mm |
|   | Max                  | Min   | Max                     | Min    | Max                       | Min    | Max              | Min   | Min                     | Basic Thread Length, <sup>a</sup> $B$ |                |        |
| M5 × 0.8                                | 5.48                 | 4.52  | 8.00                    | 7.64   | 9.24                      | 8.63   | 3.58             | 3.35  | 2.4                     | 16                                    | 22             | 35     |
| M6 × 1                                  | 6.19                 | 5.52  | 10.00                   | 9.64   | 11.55                     | 10.89  | 4.38             | 3.55  | 2.8                     | 18                                    | 24             | 37     |
| M8 × 1.25                               | 8.58                 | 7.42  | 13.00                   | 12.57  | 15.01                     | 14.20  | 5.68             | 5.10  | 3.7                     | 22                                    | 28             | 41     |
| <sup>b</sup> M10 × 1.5                  | 10.58                | 9.42  | 15.00                   | 14.57  | 17.32                     | 16.46  | 6.85             | 6.17  | 4.5                     | 26                                    | 32             | 45     |
| M10 × 1.5                               | 10.58                | 9.42  | 16.00                   | 15.57  | 18.48                     | 17.59  | 6.85             | 6.17  | 4.5                     | 26                                    | 32             | 45     |
| M12 × 1.75                              | 12.70                | 11.30 | 18.00                   | 17.57  | 20.78                     | 19.85  | 7.95             | 7.24  | 5.2                     | 30                                    | 36             | 49     |
| M14 × 2                                 | 14.70                | 13.30 | 21.00                   | 20.16  | 24.25                     | 22.78  | 9.25             | 8.51  | 6.2                     | 34                                    | 40             | 53     |
| M16 × 2                                 | 16.70                | 15.30 | 24.00                   | 23.16  | 27.71                     | 26.17  | 10.75            | 9.68  | 7.0                     | 38                                    | 44             | 57     |
| M20 × 2.5                               | 20.84                | 19.16 | 30.00                   | 29.16  | 34.64                     | 32.95  | 13.40            | 12.12 | 8.8                     | 46                                    | 52             | 65     |
| M24 × 3                                 | 24.84                | 23.16 | 36.00                   | 35.00  | 41.57                     | 39.55  | 15.90            | 14.56 | 10.5                    | 54                                    | 60             | 73     |
| M30 × 3.5                               | 30.84                | 29.16 | 46.00                   | 45.00  | 53.12                     | 50.55  | 19.75            | 17.92 | 13.1                    | 66                                    | 72             | 85     |
| M36 × 4                                 | 37.00                | 35.00 | 55.00                   | 53.80  | 63.51                     | 60.79  | 23.55            | 21.72 | 15.8                    | 78                                    | 84             | 97     |
| M42 × 4.5                               | 43.00                | 41.00 | 65.00                   | 62.90  | 75.06                     | 71.71  | 27.05            | 25.03 | 18.2                    | 90                                    | 96             | 109    |
| M48 × 5                                 | 49.00                | 47.00 | 75.00                   | 72.60  | 86.60                     | 82.76  | 31.07            | 28.93 | 21.0                    | 102                                   | 108            | 121    |
| M56 × 5.5                               | 57.20                | 54.80 | 85.00                   | 82.20  | 98.15                     | 93.71  | 36.20            | 33.80 | 24.5                    | ...                                   | 124            | 137    |
| M64 × 6                                 | 65.52                | 62.80 | 95.00                   | 91.80  | 109.70                    | 104.65 | 41.32            | 38.68 | 28.0                    | ...                                   | 140            | 153    |
| M72 × 6                                 | 73.84                | 70.80 | 105.00                  | 101.40 | 121.24                    | 115.60 | 46.45            | 43.55 | 31.5                    | ...                                   | 156            | 169    |
| M80 × 6                                 | 82.16                | 78.80 | 115.00                  | 111.00 | 132.79                    | 126.54 | 51.58            | 48.42 | 35.0                    | ...                                   | 172            | 185    |
| M90 × 6                                 | 92.48                | 88.60 | 130.00                  | 125.50 | 150.11                    | 143.07 | 57.74            | 54.26 | 39.2                    | ...                                   | 192            | 205    |
| M100 × 6                                | 102.80               | 98.60 | 145.00                  | 140.00 | 167.43                    | 159.60 | 63.90            | 60.10 | 43.4                    | ...                                   | 212            | 225    |

<sup>a</sup> Basic thread length,  $B$ , is a reference dimension.

<sup>b</sup> This size with width across flats of 15 mm is not standard. Unless specifically ordered, M10 hex bolts with 16 mm width across flats will be furnished.

All dimensions are in millimeters.

For additional manufacturing and acceptance specifications, reference should be made to the ANSI B18.2.3.5M-1979 (R1995) standard.

**Materials and Mechanical Properties.**—Unless otherwise specified, steel metric screws and bolts, with the exception of heavy hex structural bolts, hex lag screws, and socket head cap screws, conform to the requirements specified in SAE J1199 or ASTM F568. Steel heavy hex structural bolts conform to ASTM A325M or ASTM A490M. Alloy steel socket head cap screws conform to ASTM A574M, property class 12.9, where the numeral 12 represents approximately one-hundredth of the minimum tensile strength in megapascals and the decimal .9 approximates the ratio of the minimum yield stress to the minimum tensile stress. This is in accord with ISO designation practice. Screws and bolts

of other materials, and all materials for hex lag bolts, have properties as agreed upon by the purchaser and the manufacturer.

Except for socket head cap screws, metric screws and bolts are furnished with a natural (as processed) finish, unplated or uncoated unless otherwise specified.

Alloy steel socket head cap screws are furnished with an oiled black oxide coating (thermal or chemical) unless a protective plating or coating is specified by the purchaser.

**Metric Screw and Bolt Identification Symbols.**—Screws and bolts are identified on the top of the head by property class symbols and manufacturer's identification symbol.

**Metric Screw and Bolt Designation.**—Metric screws and bolts with the exception of socket head cap screws are designated by the following data, preferably in the sequence shown: product name, nominal diameter and thread pitch (except for hex lag screws), nominal length, steel property class or material identification, and protective coating, if required.

*Example:* Hex cap screw, M10 × 1.5 × 50, class 9.8, zinc plated

Heavy hex structural bolt, M24 × 3 × 80, ASTM A490M

Hex lag screw, 6 × 35, silicon bronze.

Socket head cap screws (metric series) are designated by the following data in the order shown: ANSI Standard number, nominal size, thread pitch, nominal screw length, name of product (may be abbreviated SHCS), material and property class (alloy steel screws are supplied to property class 12.9 as specified in ASTM A574M: corrosion-resistant steel screws are specified to the property class and material requirements in ASTM F837M), and protective finish, if required.

*Example:* B18.3.1M—6 × 1 × 20 Hexagon Socket Head Cap Screw, Alloy Steel

B18.3.1M—10 × 1.5 × 40 SHCS, Alloy Steel Zinc Plated.

**Metric Screw and Bolt Thread Lengths.**—The length of thread on metric screws and bolts (except for metric lag screws) is controlled by the grip gaging length,  $L_g$  max. This is the distance measured parallel to the axis of the screw or bolt, from under the head bearing surface to the face of a noncounterbored or noncountersunk standard GO thread ring gage assembled by hand as far as the thread will permit. The maximum grip gaging length, as calculated and rounded to one decimal place, is equal to the nominal screw length,  $L$ , minus the basic thread length,  $B$ , or in the case of socket head cap screws, minus the minimum thread length  $L_T$ .  $B$  and  $L_T$  are reference dimensions intended for calculation purposes only and will be found in Tables 12 and 14, respectively.

**Table 13. Basic Thread Lengths for Metric Round Head Square Neck Bolts**  
ANSI/ASME B18.5.2.2M-1982, R1993

| Nom. Bolt Dia., $D$ and Thread Pitch | Bolt Length, $L$         |                 |       | Nom. Bolt Dia., $D$ and Thread Pitch | Bolt Length, $L$         |                 |       |
|--------------------------------------|--------------------------|-----------------|-------|--------------------------------------|--------------------------|-----------------|-------|
|                                      | ≤ 125                    | > 125 and ≤ 200 | > 200 |                                      | ≤ 125                    | > 125 and ≤ 200 | > 200 |
|                                      | Basic Thread Length, $B$ |                 |       |                                      | Basic Thread length, $B$ |                 |       |
| M5 × 0.8                             | 16                       | 22              | 35    | M14 × 2                              | 34                       | 40              | 53    |
| M6 × 1                               | 18                       | 24              | 37    | M16 × 2                              | 38                       | 44              | 57    |
| M8 × 1.25                            | 22                       | 28              | 41    | M20 × 2.5                            | 46                       | 52              | 65    |
| M10 × 1.5                            | 26                       | 32              | 45    | M24 × 3                              | 54                       | 60              | 73    |
| M12 × 1.75                           | 30                       | 36              | 49    | ...                                  | ...                      | ...             | ...   |

All dimensions are in millimeters

Basic thread length  $B$  is a reference dimension intended for calculation purposes only.

**Table 14. Socket Head Cap Screws (Metric Series)—Length of Complete Thread**  
*ANSI/ASME B18.3.1M-1986*

| Nominal Size | Length of Complete Thread, $L_T$ | Nominal Size | Length of Complete Thread, $L_T$ | Nominal Size | Length of Complete Thread, $L_T$ |
|--------------|----------------------------------|--------------|----------------------------------|--------------|----------------------------------|
| M1.6         | 15.2                             | M6           | 24.0                             | M20          | 52.0                             |
| M2           | 16.0                             | M8           | 28.0                             | M24          | 60.0                             |
| M2.5         | 17.0                             | M10          | 32.0                             | M30          | 72.0                             |
| M3           | 18.0                             | M12          | 36.0                             | M36          | 84.0                             |
| M4           | 20.0                             | M14          | 40.0                             | M42          | 96.0                             |
| M5           | 22.0                             | M16          | 44.0                             | M48          | 108.0                            |

Grip length,  $L_G$  equals screw length,  $L$ , minus  $L_T$ . Total length of thread  $L_{TT}$  equals  $L_T$  plus 5 times the pitch of the coarse thread for the respective screw size. Body length  $L_B$  equals  $L$  minus  $L_{TT}$ .

The minimum thread length for hex lag screws is equal to one-half the nominal screw length plus 12 mm, or 150 mm, whichever is shorter. Screws too short for this formula to apply are threaded as close to the head as practicable.

**Metric Screw and Bolt Diameter-Length Combinations.**—For a given diameter, the recommended range of lengths of metric cap screws, formed hex screws, heavy hex screws, hex flange screws, and heavy hex flange screws can be found in Table 16, for heavy hex structural bolts in Table 17, for hex lag screws in Table 15, for round head square neck bolts in Table 18, and for socket head cap screws in Table 19. No recommendations for diameter-length combinations are given in the Standards for hex bolts and heavy hex bolts.

Hex bolts in sizes M5 through M24 and heavy hex bolts in sizes M12 through M24 are standard only in lengths longer than 150 mm or  $10D$ , whichever is shorter. When shorter lengths of these sizes are ordered, hex cap screws are normally supplied in place of hex bolts and heavy hex screws in place of heavy hex bolts. Hex bolts in sizes M30 and larger and heavy hex bolts in sizes M30 and M36 are standard in all lengths; however, at manufacturer's option, hex cap screws may be substituted for hex bolts and heavy hex screws for heavy hex bolts for any diameter-length combination.

**Table 15. Recommended Diameter-Length Combinations for Metric Hex Lag Screws**  
*ANSI B18.2.3.8M-1981 (R1999)*

| Nominal Length, $L$ | Nominal Screw Diameter |     |     |     |     |     |     |     | Nominal Length, $L$ | Nominal Screw Diameter |     |     |     |    |
|---------------------|------------------------|-----|-----|-----|-----|-----|-----|-----|---------------------|------------------------|-----|-----|-----|----|
|                     | 5                      | 6   | 8   | 10  | 12  | 16  | 20  | 24  |                     | 10                     | 12  | 16  | 20  | 24 |
| 8                   | d                      | ... | ... | ... | ... | ... | ... | ... | 90                  | d                      | d   | d   | d   | d  |
| 10                  | d                      | d   | ... | ... | ... | ... | ... | ... | 100                 | d                      | d   | d   | d   | d  |
| 12                  | d                      | d   | d   | ... | ... | ... | ... | ... | 110                 | ...                    | d   | d   | d   | d  |
| 14                  | d                      | d   | d   | ... | ... | ... | ... | ... | 120                 | ...                    | d   | d   | d   | d  |
| 16                  | d                      | d   | d   | d   | ... | ... | ... | ... | 130                 | ...                    | ... | d   | d   | d  |
| 20                  | d                      | d   | d   | d   | d   | ... | ... | ... | 140                 | ...                    | ... | d   | d   | d  |
| 25                  | d                      | d   | d   | d   | d   | d   | ... | ... | 150                 | ...                    | ... | d   | d   | d  |
| 30                  | d                      | d   | d   | d   | d   | d   | d   | ... | 160                 | ...                    | ... | d   | d   | d  |
| 35                  | d                      | d   | d   | d   | d   | d   | d   | d   | 180                 | ...                    | ... | ... | d   | d  |
| 40                  | d                      | d   | d   | d   | d   | d   | d   | d   | 200                 | ...                    | ... | ... | d   | d  |
| 45                  | d                      | d   | d   | d   | d   | d   | d   | d   | 220                 | ...                    | ... | ... | ... | d  |
| 50                  | d                      | d   | d   | d   | d   | d   | d   | d   | 240                 | ...                    | ... | ... | ... | d  |
| 60                  | ...                    | d   | d   | d   | d   | d   | d   | d   | 260                 | ...                    | ... | ... | ... | d  |
| 70                  | ...                    | ... | d   | d   | d   | d   | d   | d   | 280                 | ...                    | ... | ... | ... | d  |
| 80                  | ...                    | ... | d   | d   | d   | d   | d   | d   | 300                 | ...                    | ... | ... | ... | d  |

All dimensions are in millimeters.

Recommended diameter-length combinations are indicated by the symbol  $d$ .

**Table 16. Rec'd Diameter-Length Combinations for Metric Hex Cap Screws, Formed Hex and Heavy Hex Screws, Hex Flange and Heavy Hex Flange Screws**

| Nominal Length <sup>a</sup> | Diameter—Pitch |          |             |                |                |                |           |             |           |             |           |
|-----------------------------|----------------|----------|-------------|----------------|----------------|----------------|-----------|-------------|-----------|-------------|-----------|
|                             | M5<br>×0.8     | M6<br>×1 | M8<br>×1.25 | M10<br>×1.5    | M12<br>×1.75   | M14<br>×2      | M16<br>×2 | M20<br>×2.5 | M24<br>×3 | M30<br>×3.5 | M36<br>×4 |
| 8                           | d              | ...      | ...         | ...            | ...            | ...            | ...       | ...         | ...       | ...         | ...       |
| 10                          | d              | d        | ...         | ...            | ...            | ...            | ...       | ...         | ...       | ...         | ...       |
| 12                          | d              | d        | d           | ...            | ...            | ...            | ...       | ...         | ...       | ...         | ...       |
| 14                          | d              | d        | d           | d <sup>b</sup> | ...            | ...            | ...       | ...         | ...       | ...         | ...       |
| 16                          | d              | d        | d           | d              | d <sup>b</sup> | d <sup>b</sup> | ...       | ...         | ...       | ...         | ...       |
| 20                          | d              | d        | d           | d              | d              | d              | ...       | ...         | ...       | ...         | ...       |
| 25                          | d              | d        | d           | d              | d              | d              | d         | ...         | ...       | ...         | ...       |
| 30                          | d              | d        | d           | d              | d              | d              | d         | d           | ...       | ...         | ...       |
| 35                          | d              | d        | d           | d              | d              | d              | d         | d           | d         | ...         | ...       |
| 40                          | d              | d        | d           | d              | d              | d              | d         | d           | d         | d           | ...       |
| 45                          | d              | d        | d           | d              | d              | d              | d         | d           | d         | d           | ...       |
| 50                          | d              | d        | d           | d              | d              | d              | d         | d           | d         | d           | d         |
| (55)                        | ...            | d        | d           | d              | d              | d              | d         | d           | d         | d           | d         |
| 60                          | ...            | d        | d           | d              | d              | d              | d         | d           | d         | d           | d         |
| (65)                        | ...            | ...      | d           | d              | d              | d              | d         | d           | d         | d           | d         |
| 70                          | ...            | ...      | d           | d              | d              | d              | d         | d           | d         | d           | d         |
| (75)                        | ...            | ...      | d           | d              | d              | d              | d         | d           | d         | d           | d         |
| 80                          | ...            | ...      | d           | d              | d              | d              | d         | d           | d         | d           | d         |
| (85)                        | ...            | ...      | ...         | d              | d              | d              | d         | d           | d         | d           | d         |
| 90                          | ...            | ...      | ...         | d              | d              | d              | d         | d           | d         | d           | d         |
| 100                         | ...            | ...      | ...         | d              | d              | d              | d         | d           | d         | d           | d         |
| 110                         | ...            | ...      | ...         | ...            | d              | d              | d         | d           | d         | d           | d         |
| 120                         | ...            | ...      | ...         | ...            | d              | d              | d         | d           | d         | d           | d         |
| 130                         | ...            | ...      | ...         | ...            | ...            | d              | d         | d           | d         | d           | d         |
| 140                         | ...            | ...      | ...         | ...            | ...            | d              | d         | d           | d         | d           | d         |
| 150                         | ...            | ...      | ...         | ...            | ...            | ...            | d         | d           | d         | d           | d         |
| 160                         | ...            | ...      | ...         | ...            | ...            | ...            | d         | d           | d         | d           | d         |
| (170)                       | ...            | ...      | ...         | ...            | ...            | ...            | ...       | d           | d         | d           | d         |
| 180                         | ...            | ...      | ...         | ...            | ...            | ...            | ...       | d           | d         | d           | d         |
| (190)                       | ...            | ...      | ...         | ...            | ...            | ...            | ...       | d           | d         | d           | d         |
| 200                         | ...            | ...      | ...         | ...            | ...            | ...            | ...       | d           | d         | d           | d         |
| 220                         | ...            | ...      | ...         | ...            | ...            | ...            | ...       | ...         | d         | d           | d         |
| 240                         | ...            | ...      | ...         | ...            | ...            | ...            | ...       | ...         | d         | d           | d         |
| 260                         | ...            | ...      | ...         | ...            | ...            | ...            | ...       | ...         | ...       | d           | d         |
| 280                         | ...            | ...      | ...         | ...            | ...            | ...            | ...       | ...         | ...       | d           | d         |
| 300                         | ...            | ...      | ...         | ...            | ...            | ...            | ...       | ...         | ...       | d           | d         |

<sup>a</sup> Lengths in parentheses are not recommended. Recommended lengths of formed hex screws, hex flange screws, and heavy hex flange screws do not extend above 150 mm. Recommended lengths of heavy hex screws do not extend below 20 mm. Standard sizes for government use. Recommended diameter-length combinations are indicated by the symbol *d*. Screws with lengths above heavy cross lines are threaded full length.

<sup>b</sup> Does not apply to hex flange screws and heavy hex flange screws.

All dimensions are in millimeters.

For available diameters of each type of screw, see respective dimensional table.

**Table 17. Recommended Diameter-Length Combinations for Metric Heavy Hex Structural Bolts**

| Nominal Length, <i>L</i> | Nominal Diameter and Thread Pitch |           |           |         |         |           |         |
|--------------------------|-----------------------------------|-----------|-----------|---------|---------|-----------|---------|
|                          | M16 × 2                           | M20 × 2.5 | M22 × 2.5 | M24 × 3 | M27 × 3 | M30 × 3.5 | M36 × 4 |
| 45                       | d                                 | ...       | ...       | ...     | ...     | ...       | ...     |
| 50                       | d                                 | d         | ...       | ...     | ...     | ...       | ...     |
| 55                       | d                                 | d         | ...       | ...     | ...     | ...       | ...     |
| 60                       | d                                 | d         | d         | d       | ...     | ...       | ...     |
| 65                       | d                                 | d         | d         | d       | d       | ...       | ...     |
| 70                       | d                                 | d         | d         | d       | d       | d         | ...     |
| 75                       | d                                 | d         | d         | d       | d       | d         | ...     |
| 80                       | d                                 | d         | d         | d       | d       | d         | d       |
| 85                       | d                                 | d         | d         | d       | d       | d         | d       |
| 90                       | d                                 | d         | d         | d       | d       | d         | d       |
| 95                       | d                                 | d         | d         | d       | d       | d         | d       |
| 100                      | d                                 | d         | d         | d       | d       | d         | d       |
| 110                      | d                                 | d         | d         | d       | d       | d         | d       |
| 120                      | d                                 | d         | d         | d       | d       | d         | d       |
| 130                      | d                                 | d         | d         | d       | d       | d         | d       |
| 140                      | d                                 | d         | d         | d       | d       | d         | d       |
| 150                      | d                                 | d         | d         | d       | d       | d         | d       |
| 160                      | d                                 | d         | d         | d       | d       | d         | d       |
| 170                      | d                                 | d         | d         | d       | d       | d         | d       |
| 180                      | d                                 | d         | d         | d       | d       | d         | d       |
| 190                      | d                                 | d         | d         | d       | d       | d         | d       |
| 200                      | d                                 | d         | d         | d       | d       | d         | d       |
| 210                      | d                                 | d         | d         | d       | d       | d         | d       |
| 220                      | d                                 | d         | d         | d       | d       | d         | d       |
| 230                      | d                                 | d         | d         | d       | d       | d         | d       |
| 240                      | d                                 | d         | d         | d       | d       | d         | d       |
| 250                      | d                                 | d         | d         | d       | d       | d         | d       |
| 260                      | d                                 | d         | d         | d       | d       | d         | d       |
| 270                      | d                                 | d         | d         | d       | d       | d         | d       |
| 280                      | d                                 | d         | d         | d       | d       | d         | d       |
| 290                      | d                                 | d         | d         | d       | d       | d         | d       |
| 300                      | d                                 | d         | d         | d       | d       | d         | d       |

All dimensions are in millimeters.

Recommended diameter-length combinations are indicated by the symbol *d*.

Bolts with lengths above the heavy cross lines are threaded full length.

**Table 18. Recommended Diameter-Length Combinations for Metric Round Head Square Neck Bolts**

| Nominal Length, <sup>a</sup> <i>L</i> | Nominal Diameter and Thread Pitch |        |           |           |            |         |         |           |         |
|---------------------------------------|-----------------------------------|--------|-----------|-----------|------------|---------|---------|-----------|---------|
|                                       | M5 × 0.8                          | M6 × 1 | M8 × 1.25 | M10 × 1.5 | M12 × 1.75 | M14 × 2 | M16 × 2 | M20 × 2.5 | M24 × 3 |
| 10                                    | d                                 | ...    | ...       | ...       | ...        | ...     | ...     | ...       | ...     |
| 12                                    | d                                 | d      | ...       | ...       | ...        | ...     | ...     | ...       | ...     |
| (14)                                  | d                                 | d      | ...       | ...       | ...        | ...     | ...     | ...       | ...     |
| 16                                    | d                                 | d      | d         | ...       | ...        | ...     | ...     | ...       | ...     |
| 20                                    | d                                 | d      | d         | d         | ...        | ...     | ...     | ...       | ...     |
| 25                                    | d                                 | d      | d         | d         | d          | ...     | ...     | ...       | ...     |
| 30                                    | d                                 | d      | d         | d         | d          | d       | d       | ...       | ...     |
| 35                                    | d                                 | d      | d         | d         | d          | d       | d       | ...       | ...     |
| 40                                    | d                                 | d      | d         | d         | d          | d       | d       | d         | ...     |
| 45                                    | d                                 | d      | d         | d         | d          | d       | d       | d         | d       |
| 50                                    | d                                 | d      | d         | d         | d          | d       | d       | d         | d       |
| (55)                                  | ...                               | d      | d         | d         | d          | d       | d       | d         | d       |
| 60                                    | ...                               | d      | d         | d         | d          | d       | d       | d         | d       |
| (65)                                  | ...                               | ...    | d         | d         | d          | d       | d       | d         | d       |
| 70                                    | ...                               | ...    | d         | d         | d          | d       | d       | d         | d       |
| (75)                                  | ...                               | ...    | d         | d         | d          | d       | d       | d         | d       |
| 80                                    | ...                               | ...    | d         | d         | d          | d       | d       | d         | d       |

**Table 18. (Continued) Recommended Diameter-Length Combinations for Metric Round Head Square Neck Bolts**

| Nominal Length, <sup>a</sup><br><i>L</i> | Nominal Diameter and Thread Pitch |           |              |              |               |            |            |              |            |
|--|-----------------------------------|-----------|--------------|--------------|---------------|------------|------------|--------------|------------|
|  | M5<br>× 0.8                       | M6<br>× 1 | M8<br>× 1.25 | M10<br>× 1.5 | M12<br>× 1.75 | M14<br>× 2 | M16<br>× 2 | M20<br>× 2.5 | M24<br>× 3 |
| (85)                                     | ...                               | ...       | ...          | d            | d             | d          | d          | d            | d          |
| 90                                       | ...                               | ...       | ...          | d            | d             | d          | d          | d            | d          |
| 100                                      | ...                               | ...       | ...          | d            | d             | d          | d          | d            | d          |
| 110                                      | ...                               | ...       | ...          | ...          | d             | d          | d          | d            | d          |
| 120                                      | ...                               | ...       | ...          | ...          | d             | d          | d          | d            | d          |
| 130                                      | ...                               | ...       | ...          | ...          | ...           | d          | d          | d            | d          |
| 140                                      | ...                               | ...       | ...          | ...          | ...           | d          | d          | d            | d          |
| 150                                      | ...                               | ...       | ...          | ...          | ...           | ...        | d          | d            | d          |
| 160                                      | ...                               | ...       | ...          | ...          | ...           | ...        | d          | d            | d          |
| (170)                                    | ...                               | ...       | ...          | ...          | ...           | ...        | ...        | d            | d          |
| 180                                      | ...                               | ...       | ...          | ...          | ...           | ...        | ...        | d            | d          |
| (190)                                    | ...                               | ...       | ...          | ...          | ...           | ...        | ...        | d            | d          |
| 200                                      | ...                               | ...       | ...          | ...          | ...           | ...        | ...        | d            | d          |
| 220                                      | ...                               | ...       | ...          | ...          | ...           | ...        | ...        | ...          | d          |
| 240                                      | ...                               | ...       | ...          | ...          | ...           | ...        | ...        | ...          | d          |

<sup>a</sup> Bolts with lengths above the heavy cross lines are threaded full length. Lengths in ( ) are not recommended.

All dimensions are in millimeters. Recommended diameter-length combinations are indicated by the symbol *a*. Standard sizes for government use.

**Table 19. Diameter-Length Combinations for Socket Head Cap Screws (Metric Series)**

| Nominal Length,<br><i>L</i> | Nominal Size |     |      |     |     |     |     |     |     |     |     |     |     |     |
|-----------------------------|--------------|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                             | M1.6         | M2  | M2.5 | M3  | M4  | M5  | M6  | M8  | M10 | M12 | M14 | M16 | M20 | M24 |
| 20                          | d            | d   |      |     |     |     |     |     |     |     |     |     |     |     |
| 25                          | d            | d   | d    | d   |     |     |     |     |     |     |     |     |     |     |
| 30                          | d            | d   | d    | d   | d   |     |     |     |     |     |     |     |     |     |
| 35                          | ...          | d   | d    | d   | d   | d   | d   |     |     |     |     |     |     |     |
| 40                          | ...          | d   | d    | d   | d   | d   | d   | d   |     |     |     |     |     |     |
| 45                          | ...          | ... | d    | d   | d   | d   | d   | d   | d   |     |     |     |     |     |
| 50                          | ...          | ... | d    | d   | d   | d   | d   | d   | d   | d   |     |     |     |     |
| 55                          | ...          | ... | ...  | d   | d   | d   | d   | d   | d   | d   | d   |     |     |     |
| 60                          | ...          | ... | ...  | d   | d   | d   | d   | d   | d   | d   | d   | d   |     |     |
| 65                          | ...          | ... | ...  | d   | d   | d   | d   | d   | d   | d   | d   | d   | d   |     |
| 70                          | ...          | ... | ...  | ... | d   | d   | d   | d   | d   | d   | d   | d   | d   | d   |
| 80                          | ...          | ... | ...  | ... | d   | d   | d   | d   | d   | d   | d   | d   | d   | d   |
| 90                          | ...          | ... | ...  | ... | ... | d   | d   | d   | d   | d   | d   | d   | d   | d   |
| 100                         | ...          | ... | ...  | ... | ... | d   | d   | d   | d   | d   | d   | d   | d   | d   |
| 110                         | ...          | ... | ...  | ... | ... | ... | d   | d   | d   | d   | d   | d   | d   | d   |
| 120                         | ...          | ... | ...  | ... | ... | ... | ... | d   | d   | d   | d   | d   | d   | d   |
| 130                         | ...          | ... | ...  | ... | ... | ... | ... | d   | d   | d   | d   | d   | d   | d   |
| 140                         | ...          | ... | ...  | ... | ... | ... | ... | d   | d   | d   | d   | d   | d   | d   |
| 150                         | ...          | ... | ...  | ... | ... | ... | ... | d   | d   | d   | d   | d   | d   | d   |
| 160                         | ...          | ... | ...  | ... | ... | ... | ... | d   | d   | d   | d   | d   | d   | d   |
| 180                         | ...          | ... | ...  | ... | ... | ... | ... | ... | d   | d   | d   | d   | d   | d   |
| 200                         | ...          | ... | ...  | ... | ... | ... | ... | ... | d   | d   | d   | d   | d   | d   |
| 220                         | ...          | ... | ...  | ... | ... | ... | ... | ... | ... | d   | d   | d   | d   | d   |
| 240                         | ...          | ... | ...  | ... | ... | ... | ... | ... | ... | d   | d   | d   | d   | d   |
| 260                         | ...          | ... | ...  | ... | ... | ... | ... | ... | ... | ... | d   | d   | d   | d   |
| 300                         | ...          | ... | ...  | ... | ... | ... | ... | ... | ... | ... | ... | d   | d   | d   |

All dimensions are in millimeters. Screws with lengths above heavy cross lines are threaded full length. Diameter-length combinations are indicated by the symbol *a*. Standard sizes for government use. In addition to the lengths shown, the following lengths are standard: 3, 4, 5, 6, 8, 10, 12, and 16 mm. No diameter-length combinations are given in the Standard for these lengths. Screws larger than M24 with lengths equal to or shorter than  $L_{TT}$  (see Table 14 footnote) are threaded full length.



**Metric Screw and Bolt Thread Series.**—Unless otherwise specified, metric screws and bolts, except for hex lag screws, are furnished with metric coarse threads conforming to the dimensions for general purpose threads given in ANSI B1.13M (see *American National Standard Metric Screw Threads M Profile* on page 1783). Except for socket head cap screws, the tolerance class is 6g, which applies to plain finish (unplated or uncoated) screws or bolts and to plated or coated screws or bolts before plating or coating. For screws with additive finish, the 6g diameters may be exceeded by the amount of the allowance, i.e. the basic diameters apply to the screws or bolts after plating or coating. For socket head cap screws, the tolerance class is 4g6g, but for plated screws, the allowance g may be consumed by the thickness of plating so that the maximum limit of size after plating is tolerance class 4h6h. Thread limits are in accordance with ANSI B1.13M. Metric hex lag screws have a special thread which is covered in Table 5.

**Metric Screw and Bolt Clearance Holes.**—Clearance holes for screws and bolts with the exception of hex lag screws, socket head cap screws, and round head square neck bolts are given in Table 20. Clearance holes for round head square neck bolts are given in Table 8 and drill and counterbore sizes for socket head cap screws are given in Table 21.

**Table 20. Recommended Clearance Holes for Metric Hex Screws and Bolts**

| Nominal Dia., $D$ and Thread Pitch | Clearance Hole Dia., Basic, $D_h$ |                   |       | Nominal Dia., $D$ and Thread Pitch | Clearance Hole Dia., Basic, $D_h$ |                   |       |
|------------------------------------|-----------------------------------|-------------------|-------|------------------------------------|-----------------------------------|-------------------|-------|
|                                    | Close                             | Normal, Preferred | Loose |                                    | Close                             | Normal, Preferred | Loose |
| M5 × 0.8                           | 5.3                               | 5.5               | 5.8   | M30 × 3.5                          | 31.0                              | 33.0              | 35.0  |
| M6 × 1                             | 6.4                               | 6.6               | 7.0   | M36 × 4                            | 37.0                              | 39.0              | 42.0  |
| M8 × 1.25                          | 8.4                               | 9.0               | 10.0  | M42 × 4.5                          | 43.0                              | 45.0              | 48.0  |
| M10 × 1.5                          | 10.5                              | 11.0              | 12.0  | M48 × 5                            | 50.0                              | 52.0              | 56.0  |
| M12 × 1.75                         | 13.0                              | 13.5              | 14.5  | M56 × 5.5                          | 58.0                              | 62.0              | 66.0  |
| M14 × 2                            | 15.0                              | 15.5              | 16.5  | M64 × 6                            | 66.0                              | 70.0              | 74.0  |
| M16 × 2                            | 17.0                              | 17.5              | 18.5  | M72 × 6                            | 74.0                              | 78.0              | 82.0  |
| M20 × 2.5                          | 21.0                              | 22.0              | 24.0  | M80 × 6                            | 82.0                              | 86.0              | 91.0  |
| M22 × 2.5 <sup>a</sup>             | 23.0                              | 24.0              | 26.0  | M90 × 6                            | 93.0                              | 96.0              | 101.0 |
| M24 × 3                            | 25.0                              | 26.0              | 28.0  | M100 × 6                           | 104.0                             | 107.0             | 112.0 |
| M27 × 3 <sup>a</sup>               | 28.0                              | 30.0              | 32.0  | ...                                | ...                               | ...               | ...   |

<sup>a</sup> Applies only to heavy hex structural bolts.

All dimensions are in millimeters.

Does not apply to hex lag screws, hex socket head cap screws, or round head square neck bolts.

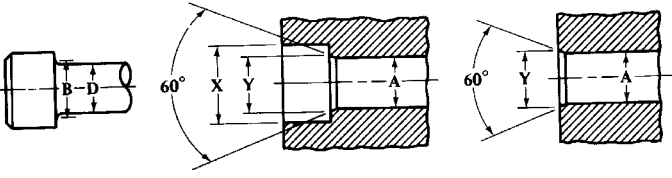
**Normal Clearance:** This is preferred for general purpose applications and should be specified unless special design considerations dictate the need for either a close or loose clearance hole.

**Close Clearance:** This should be specified only where conditions such as critical alignment of assembled parts, wall thickness or other limitations necessitate use of a minimum hole. When close clearance holes are specified, special provision (e.g. countersinking) must be made at the screw or bolt entry side to permit proper seating of the screw or bolt head.

**Loose Clearance:** This should be specified only for applications where maximum adjustment capability between components being assembled is necessary.

**Recommended Tolerances:** The clearance hole diameters given in this table are minimum size. Recommended tolerances are: for screw or bolt diameter M5, +0.2 mm; for M6 through M16, +0.3 mm; for M20 through M42, +0.4 mm; for M48 through M72, +0.5 mm; and for M80 through M100, +0.6 mm.

Table 21. Drill and Counterbore Sizes for Metric Socket Head Cap Screws



| Nominal Size or Basic Screw Diameter | Nominal Drill Size, A  |                         | Counterbore Diameter, X | Countersink Diameter, <sup>a</sup> Y |
|--------------------------------------|------------------------|-------------------------|-------------------------|--------------------------------------|
|                                      | Close Fit <sup>b</sup> | Normal Fit <sup>c</sup> |                         |                                      |
| M1.6                                 | 1.80                   | 1.95                    | 3.50                    | 2.0                                  |
| M2                                   | 2.20                   | 2.40                    | 4.40                    | 2.6                                  |
| M2.5                                 | 2.70                   | 3.00                    | 5.40                    | 3.1                                  |
| M3                                   | 3.40                   | 3.70                    | 6.50                    | 3.6                                  |
| M4                                   | 4.40                   | 4.80                    | 8.25                    | 4.7                                  |
| M5                                   | 5.40                   | 5.80                    | 9.75                    | 5.7                                  |
| M6                                   | 6.40                   | 6.80                    | 11.25                   | 6.8                                  |
| M8                                   | 8.40                   | 8.80                    | 14.25                   | 9.2                                  |
| M10                                  | 10.50                  | 10.80                   | 17.25                   | 11.2                                 |
| M12                                  | 12.50                  | 12.80                   | 19.25                   | 14.2                                 |
| M14                                  | 14.50                  | 14.75                   | 22.25                   | 16.2                                 |
| M16                                  | 16.50                  | 16.75                   | 25.50                   | 18.2                                 |
| M20                                  | 20.50                  | 20.75                   | 31.50                   | 22.4                                 |
| M24                                  | 24.50                  | 24.75                   | 37.50                   | 26.4                                 |
| M30                                  | 30.75                  | 31.75                   | 47.50                   | 33.4                                 |
| M36                                  | 37.00                  | 37.50                   | 56.50                   | 39.4                                 |
| M42                                  | 43.00                  | 44.00                   | 66.00                   | 45.6                                 |
| M48                                  | 49.00                  | 50.00                   | 75.00                   | 52.6                                 |

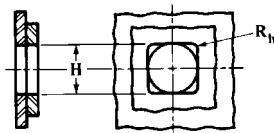
<sup>a</sup> *Countersink*: It is considered good practice to countersink or break the edges of holes which are smaller than  $B$  Max. (see Table 24) in parts having a hardness which approaches, equals, or exceeds the screw hardness. If such holes are not countersunk, the heads of screws may not seat properly or the sharp edges on holes may deform the fillets on screws, thereby making them susceptible to fatigue in applications involving dynamic loading. The countersink or corner relief, however, should not be larger than is necessary to ensure that the fillet on the screw is cleared. Normally, the diameter of countersink does not have to exceed  $B$  Max. Countersinks or corner reliefs in excess of this diameter reduce the effective bearing area and introduce the possibility of embedment where the parts to be fastened are softer than the screws or of brinelling or flaring the heads of the screws where the parts to be fastened are harder than the screws.

<sup>b</sup> *Close Fit*: The close fit is normally limited to holes for those lengths of screws which are threaded to the head in assemblies where only one screw is to be used or where two or more screws are to be used and the mating holes are to be produced either at assembly or by matched and coordinated tooling.

<sup>c</sup> *Normal Fit*: The normal fit is intended for screws of relatively long length or for assemblies involving two or more screws where the mating holes are to be produced by conventional tolerancing methods. It provides for the maximum allowable eccentricity of the longest standard screws and for certain variations in the parts to be fastened, such as: deviations in hole straightness, angularity between the axis of the tapped hole and that of the hole for shank, differences in center distances of the mating holes, etc.

All dimensions are in millimeters.

**Table 22. Recommended Clearance Holes for Metric Round Head Square Neck Bolts**



| Nom. Bolt Dia., $D$ and Thd. Pitch | Clearance                                  |                     |                    | Corner Radius $R_h$ | Nom. Bolt Dia., $D$ and Thd. Pitch | Clearance                                  |                     |                    | Corner Radius $R_h$ |
|------------------------------------|--|---------------------|--------------------|---------------------|------------------------------------|--|---------------------|--------------------|---------------------|
|                                    | Close <sup>a</sup>                         | Normal <sup>b</sup> | Loose <sup>c</sup> |                     |                                    | Close <sup>a</sup>                         | Normal <sup>b</sup> | Loose <sup>c</sup> |                     |
|                                    | Minimum Hole Diameter or Square Width, $H$ |                     |                    |                     |                                    | Minimum Hole Diameter or Square Width, $H$ |                     |                    |                     |
| M5 × 0.8                           | 5.5  | ...                 | 5.8                | 0.2                 | M14 × 2                            | 15.0                                       | 15.5                | 16.5               | 0.6                 |
| M6 × 1                             | 6.6  | ...                 | 7.0                | 0.3                 | M16 × 2                            | 17.0                                       | 17.5                | 18.5               | 0.6                 |
| M8 × 1.25                          | ...  | 9.0                 | 10.0               | 0.4                 | M20 × 2.5                          | 21.0                                       | 22.0                | 24.0               | 0.8                 |
| M10 × 1.5                          | ...  | 11.0                | 12.0               | 0.4                 | M24 × 3                            | 25.0                                       | 26.0                | 28.0               | 1.0                 |
| M12 × 1.75                         | 13.0                                       | 13.5                | 14.5               | 0.6                 | ...                                | ...  | ...                 | ...                | ...                 |

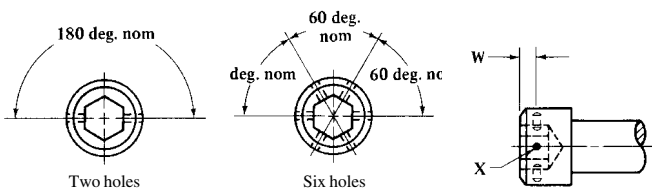
<sup>a</sup> *Close Clearance:* Close clearance should be specified only for square holes in very thin and/or soft material, or for slots, or where conditions such as critical alignment of assembled parts, wall thickness, or other limitations necessitate use of a minimal hole. Allowable swell or fins on the bolt body and/or fins on the corners of the square neck may interfere with close clearance round or square holes.

<sup>b</sup> *Normal Clearance:* Normal clearance hole sizes are preferred for general purpose applications and should be specified unless special design considerations dictate the need for either a close or loose clearance hole.

<sup>c</sup> *Loose Clearance:* Loose clearance hole sizes should be specified only for applications where maximum adjustment capability between components being assembled is necessary. Loose clearance square hole or slots may not prevent bolt turning during wrenching.

All dimensions are in millimeters.

**Table 23. Drilled Head Dimensions for Metric Hex Socket Head Cap Screws**



| Nominal Size or Basic Screw Diameter | Hole Center Location, $W$ |       | Drilled Hole Diameter, $X$ |      | Hole Alignment Check Plug Diameter |
|--------------------------------------|---------------------------|-------|----------------------------|------|------------------------------------|
|                                      | Max                       | Min   | Max                        | Min  | Basic                              |
| M3                                   | 1.20                      | 0.80  | 0.95                       | 0.80 | 0.75                               |
| M4                                   | 1.60                      | 1.20  | 1.35                       | 1.20 | 0.90                               |
| M5                                   | 2.00                      | 1.50  | 1.35                       | 1.20 | 0.90                               |
| M6                                   | 2.30                      | 1.80  | 1.35                       | 1.20 | 0.90                               |
| M8                                   | 2.70                      | 2.20  | 1.35                       | 1.20 | 0.90                               |
| M10                                  | 3.30                      | 2.80  | 1.65                       | 1.50 | 1.40                               |
| M12                                  | 4.00                      | 3.50  | 1.65                       | 1.50 | 1.40                               |
| M16                                  | 5.00                      | 4.50  | 1.65                       | 1.50 | 1.40                               |
| M20                                  | 6.30                      | 5.80  | 2.15                       | 2.00 | 1.80                               |
| M24                                  | 7.30                      | 6.80  | 2.15                       | 2.00 | 1.80                               |
| M30                                  | 9.00                      | 8.50  | 2.15                       | 2.00 | 1.80                               |
| M36                                  | 10.50                     | 10.00 | 2.15                       | 2.00 | 1.80                               |

All dimensions are in millimeters.

Drilled head metric hexagon socket head cap screws normally are not available in screw sizes smaller than M3 nor larger than M36. The M3 and M4 nominal screw sizes have two drilled holes spaced 180 degrees apart. Nominal screw sizes M5 and larger have six drilled holes spaced 60 degrees apart unless the purchaser specifies two drilled holes. The positioning of holes on opposite sides of the socket should be such that the hole alignment check plug will pass completely through the head without any deflection. When so specified by the purchaser, the edges of holes on the outside surface of the head will be chamfered 45 degrees to a depth of 0.30 to 0.50 mm.

**Table 24. American National Standard Socket Head Cap Screws—  
Metric Series ANSI/ASME B18.3.1M-1986**

| Nom. Size and Thread Pitch | Body Diameter, <i>D</i> |       | Head Diameter <i>A</i> |       | Head Height <i>H</i> |       | Chamfer or Radius <i>S</i> | Hexagon Socket Size <sup>a</sup> <i>J</i> | Spline Socket Size <sup>a</sup> <i>M</i> | Key Engagement <i>T</i> | Transition Dia. <i>B</i> <sup>b</sup> |
|----------------------------|-------------------------|-------|------------------------|-------|----------------------|-------|----------------------------|---|--|-------------------------|---------------------------------------|
|                            | Max                     | Min   | Max                    | Min   | Max                  | Min   | Max                        | Nom.                                      | Nom.                                     | Min                     | Max                                   |
| M1.6 × 0.35                | 1.60                    | 1.46  | 3.00                   | 2.87  | 1.60                 | 1.52  | 0.16                       | 1.5                                       | 1.829                                    | 0.80                    | 2.0                                   |
| M2 × 0.4                   | 2.00                    | 1.86  | 3.80                   | 3.65  | 2.00                 | 1.91  | 0.20                       | 1.5                                       | 1.829                                    | 1.00                    | 2.6                                   |
| M2.5 × 0.45                | 2.50                    | 2.36  | 4.50                   | 4.33  | 2.50                 | 2.40  | 0.25                       | 2.0                                       | 2.438                                    | 1.25                    | 3.1                                   |
| M3 × 0.5                   | 3.00                    | 2.86  | 5.50                   | 5.32  | 3.00                 | 2.89  | 0.30                       | 2.5                                       | 2.819                                    | 1.50                    | 3.6                                   |
| M4 × 0.7                   | 4.00                    | 3.82  | 7.00                   | 6.80  | 4.00                 | 3.88  | 0.40                       | 3.0                                       | 3.378                                    | 2.00                    | 4.7                                   |
| M5 × 0.8                   | 5.00                    | 4.82  | 8.50                   | 8.27  | 5.00                 | 4.86  | 0.50                       | 4.0                                       | 4.648                                    | 2.50                    | 5.7                                   |
| M6 × 1                     | 6.00                    | 5.82  | 10.00                  | 9.74  | 6.00                 | 5.85  | 0.60                       | 5.0                                       | 5.486                                    | 3.00                    | 6.8                                   |
| M8 × 1.25                  | 8.00                    | 7.78  | 13.00                  | 12.70 | 8.00                 | 7.83  | 0.80                       | 6.0                                       | 7.391                                    | 4.00                    | 9.2                                   |
| M10 × 1.5                  | 10.00                   | 9.78  | 16.00                  | 15.67 | 10.00                | 9.81  | 1.00                       | 8.0                                       | ...                                      | 5.00                    | 11.2                                  |
| M12 × 1.75                 | 12.00                   | 11.73 | 18.00                  | 17.63 | 12.00                | 11.79 | 1.20                       | 10.0                                      | ...                                      | 6.00                    | 14.2                                  |
| M14 × 2 <sup>b</sup>       | 14.00                   | 13.73 | 21.00                  | 20.60 | 14.00                | 13.77 | 1.40                       | 12.0                                      | ...                                      | 7.00                    | 16.2                                  |
| M16 × 2                    | 16.00                   | 15.73 | 24.00                  | 23.58 | 16.00                | 15.76 | 1.60                       | 14.0                                      | ...                                      | 8.00                    | 18.2                                  |
| M20 × 2.5                  | 20.00                   | 19.67 | 30.00                  | 29.53 | 20.00                | 19.73 | 2.00                       | 17.0                                      | ...                                      | 10.00                   | 22.4                                  |
| M24 × 3                    | 24.00                   | 23.67 | 36.00                  | 35.48 | 24.00                | 23.70 | 2.40                       | 19.0                                      | ...                                      | 12.00                   | 26.4                                  |
| M30 × 3.5                  | 30.00                   | 29.67 | 45.00                  | 44.42 | 30.00                | 29.67 | 3.00                       | 22.0                                      | ...                                      | 15.00                   | 33.4                                  |
| M36 × 4                    | 36.00                   | 35.61 | 54.00                  | 53.37 | 36.00                | 35.64 | 3.60                       | 27.0                                      | ...                                      | 18.00                   | 39.4                                  |
| M42 × 4.5                  | 42.00                   | 41.61 | 63.00                  | 62.31 | 42.00                | 41.61 | 4.20                       | 32.0                                      | ...                                      | 21.00                   | 45.6                                  |
| M48 × 5                    | 48.00                   | 47.61 | 72.00                  | 71.27 | 48.00                | 47.58 | 4.80                       | 36.0                                      | ...                                      | 24.00                   | 52.6                                  |

<sup>a</sup> See also Table 25.

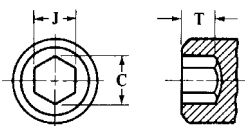
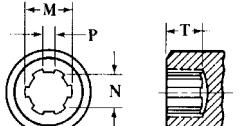
<sup>b</sup> The M14 × 2 size is not recommended for use in new designs.

All dimensions are in millimeters

$L_G$  is grip length and  $L_B$  is body length (see Table 14). For length of complete thread, see Table 14.

For additional manufacturing and acceptance specifications, see ANSI/ASME B18.3.1M-1986.

**Table 25. American National Standard Hexagon and Spline Sockets for Socket Head Cap Screws—Metric Series ANSI/ASME B18.3.1M-1986**

|  <p>METRIC HEXAGON SOCKETS</p> <p>See Table 24</p> |                                |                                  |  <p>METRIC SPLINE SOCKET</p> <p>See Table 24</p> |                                |                                  |        |
|--|--------------------------------|----------------------------------|---|--------------------------------|----------------------------------|--------|
| Nominal Hexagon Socket Size  | Socket Width Across Flats, $J$ | Socket Width Across Corners, $C$ | Nominal Hexagon Socket Size   | Socket Width Across Flats, $J$ | Socket Width Across Corners, $C$ |        |
| Metric Hexagon Sockets   |                                |                                  |   |                                |                                  |        |
|  | Max                            | Min                              |   | Max                            | Min                              |        |
| 1.5  | 1.545                          | 1.520                            | 12  | 12.146                         | 12.032                           |        |
| 2  | 2.045                          | 2.020                            | 14  | 14.159                         | 14.032                           |        |
| 2.5  | 2.560                          | 2.520                            | 17  | 17.216                         | 17.050                           |        |
| 3  | 3.071                          | 3.020                            | 19  | 19.243                         | 19.065                           |        |
| 4  | 4.084                          | 4.020                            | 22  | 22.319                         | 22.065                           |        |
| 5  | 5.084                          | 5.020                            | 24  | 24.319                         | 24.065                           |        |
| 6  | 6.095                          | 6.020                            | 27  | 27.319                         | 27.065                           |        |
| 8  | 8.115                          | 8.025                            | 32  | 32.461                         | 32.080                           |        |
| 10   | 10.127                         | 10.025                           | 36  | 36.461                         | 36.080                           |        |
| Metric Spline Sockets <sup>a</sup>   |                                |                                  |   |                                |                                  |        |
| Nominal Spline Socket Size   | Socket Major Diameter, $M$     |                                  | Socket Minor Diameter, $N$  |                                | Width of Tooth, $P$              |        |
|  | Max                            | Min                              | Max   | Min                            | Max                              | Min    |
| 1.829  | 1.8796                         | 1.8542                           | 1.6256  | 1.6002                         | 0.4064                           | 0.3810 |
| 2.438  | 2.4892                         | 2.4638                           | 2.0828  | 2.0320                         | 0.5588                           | 0.5334 |
| 2.819  | 2.9210                         | 2.8702                           | 2.4892  | 2.4384                         | 0.6350                           | 0.5842 |
| 3.378  | 3.4798                         | 3.4290                           | 2.9972  | 2.9464                         | 0.7620                           | 0.7112 |
| 4.648  | 4.7752                         | 4.7244                           | 4.1402  | 4.0894                         | 0.9906                           | 0.9398 |
| 5.486  | 5.6134                         | 5.5626                           | 4.8260  | 4.7752                         | 1.2700                           | 1.2192 |
| 7.391  | 7.5692                         | 7.5184                           | 6.4516  | 6.4008                         | 1.7272                           | 2.6764 |

<sup>a</sup> The tabulated dimensions represent direct metric conversions of the equivalent inch size spline sockets shown in American National Standard Socket Cap, Shoulder and Set Screws — Inch Series ANSI B18.3. Therefore, the spline keys and bits shown therein are applicable for wrenching the corresponding size metric spline sockets.

**Metric Nuts**

The American National Standards covering metric nuts have been established in cooperation with the Department of Defense in such a way that they could be used by the Government for procurement purposes. Extensive information concerning these nuts is given in the following text and tables, but for more complete manufacturing and acceptance specifications, reference should be made to the respective Standards, which may be obtained by

non-governmental agencies from the American National Standards Institute, 25 West 43rd Street, New York, N. Y. 10036. Manufacturers should be consulted concerning items and sizes which are in stock production.

**Comparison with ISO Standards.**—American National Standards for metric nuts have been coordinated to the extent possible with comparable ISO Standards or proposed Standards, thus: ANSI B18.2.4.1M Metric Hex Nuts, Style 1 with ISO 4032; B18.2.4.2M Metric Hex Nuts, Style 2 with ISO 4033; B18.2.4.4M Metric Hex Flange Nuts with ISO 4161; B18.2.4.5M Metric Hex Jam Nuts with ISO 4035; and B18.2.4.3M Metric Slotted Hex Nuts, B18.2.4.6M Metric Heavy Hex Nuts in sizes M12 through M36, and B18.16.3M Prevailing-Torque Type Steel Metric Hex Nuts and Hex Flange Nuts with comparable draft ISO Standards. The dimensional differences between each ANSI Standard and the comparable ISO Standard or draft Standard are very few, relatively minor, and none will affect the interchangeability of nuts manufactured to the requirements of either.

At its meeting in Varna, May 1977, ISO/TC2 studied several technical reports analyzing design considerations influencing determination of the best series of widths across flats for hex bolts, screws, and nuts. A primary technical objective was to achieve a logical ratio between under head (nut) bearing surface area (which determines the magnitude of compressive stress on the bolted members) and the tensile stress area of the screw thread (which governs the clamping force that can be developed by tightening the fastener). The series of widths across flats in the ANSI Standards agree with those which were selected by ISO/TC2 to be ISO Standards.

One exception for width across flats of metric hex nuts, styles 1 and 2, metric slotted hex nuts, metric hex jam nuts, and prevailing-torque metric hex nuts is the M10 size. These nuts in M10 size are currently being produced in the United States with a width across flats of 15 mm. This width, however, is not an ISO Standard. Unless these M10 nuts with width across flats of 15 mm are specifically ordered, the M10 size with 16 mm width across flats will be furnished.

In ANSI Standards for metric nuts, letter symbols designating dimensional characteristics are in accord with those used in ISO Standards, except capitals have been used for data processing convenience instead of lower case letters used in ISO Standards.

**Metric Nut Tops and Bearing Surfaces.**—Metric hex nuts, styles 1 and 2, slotted hex nuts, and hex jam nuts are double chamfered in sizes M16 and smaller and in sizes M20 and larger may either be double chamfered or have a washer-faced bearing surface and a chamfered top at the option of the manufacturer. Metric heavy hex nuts are optional either way in all sizes. Metric hex flange nuts have a flange bearing surface and a chamfered top and prevailing-torque type metric hex nuts have a chamfered bearing surface. Prevailing-torque type metric hex flange nuts have a flange bearing surface. All types of metric nuts have the tapped hole countersunk on the bearing face and metric slotted hex nuts, hex flange nuts, and prevailing-torque type hex nuts and hex flange nuts may be countersunk on the top face.

**Materials and Mechanical Properties.**—Nonheat-treated carbon steel metric hex nuts, style 1 and slotted hex nuts conform to material and property class requirements specified for property class 5 nuts; hex nuts, style 2 and hex flange nuts to property class 9 nuts; hex jam nuts to property class 04 nuts, and nonheat-treated carbon and alloy steel heavy hex nuts to property classes 5, 9, 8S, or 8S3 nuts; all as covered in ASTM A563M. Carbon steel metric hex nuts, style 1 and slotted hex nuts that have specified heat treatment conform to material and property class requirements specified for property class 10 nuts; hex nuts, style 2 to property class 12 nuts; hex jam nuts to property class 05 nuts; hex flange nuts to property classes 10 and 12 nuts; and carbon or alloy steel heavy hex nuts to property classes 10S, 10S3, or 12 nuts, all as covered in ASTM A563M. Carbon steel prevailing-torque type hex nuts and hex flange nuts conform to mechanical and property class requirements as given in ANSI B18.16.1M.

**Table 26. American National Standard Metric Hex Nuts, Styles 1 and 2**  
*ANSI/ASME B18.2.4.1M and B18.2.4.2M-1979 (R1995)*

| Nominal Nut Dia. and Thread Pitch | Width Across Flats, <i>S</i> |       | Width Across Corners, <i>E</i> |       | Thickness, <i>M</i> |       | Bearing Face Dia., <i>D<sub>w</sub></i> | Washer Face Thickness, <i>C</i> |     |
|-----------------------------------|------------------------------|-------|--------------------------------|-------|---------------------|-------|---|---------------------------------|-----|
|                                   | Max                          | Min   | Max                            | Min   | Max                 | Min   | Min                                     | Max                             | Min |
| Metric Hex Nuts — Style 1         |                              |       |                                |       |                     |       |   |                                 |     |
| M1.6 × 0.35                       | 3.20                         | 3.02  | 3.70                           | 3.41  | 1.30                | 1.05  | 2.3                                     | ...                             | ... |
| M2 × 0.4                          | 4.00                         | 3.82  | 4.62                           | 4.32  | 1.60                | 1.35  | 3.1                                     | ...                             | ... |
| M2.5 × 0.45                       | 5.00                         | 4.82  | 5.77                           | 5.45  | 2.00                | 1.75  | 4.1                                     | ...                             | ... |
| M3 × 0.5                          | 5.50                         | 5.32  | 6.35                           | 6.01  | 2.40                | 2.15  | 4.6                                     | ...                             | ... |
| M3.5 × 0.6                        | 6.00                         | 5.82  | 6.93                           | 6.58  | 2.80                | 2.55  | 5.1                                     | ...                             | ... |
| M4 × 0.7                          | 7.00                         | 6.78  | 8.08                           | 7.66  | 3.20                | 2.90  | 6.0                                     | ...                             | ... |
| M5 × 0.8                          | 8.00                         | 7.78  | 9.24                           | 8.79  | 4.70                | 4.40  | 7.0                                     | ...                             | ... |
| M6 × 1                            | 10.00                        | 9.78  | 11.55                          | 11.05 | 5.20                | 4.90  | 8.9                                     | ...                             | ... |
| M8 × 1.25                         | 13.00                        | 12.73 | 15.01                          | 14.38 | 6.80                | 6.44  | 11.6                                    | ...                             | ... |
| <sup>a</sup> M10 × 1.5            | 15.00                        | 14.73 | 17.32                          | 16.64 | 9.1                 | 8.7   | 13.6                                    | 0.6                             | 0.3 |
| M10 × 1.5                         | 16.00                        | 15.73 | 18.48                          | 17.77 | 8.40                | 8.04  | 14.6                                    | ...                             | ... |
| M12 × 1.75                        | 18.00                        | 17.73 | 20.78                          | 20.03 | 10.80               | 10.37 | 16.6                                    | ...                             | ... |
| M14 × 2                           | 21.00                        | 20.67 | 24.25                          | 23.36 | 12.80               | 12.10 | 19.4                                    | ...                             | ... |
| M16 × 2                           | 24.00                        | 23.67 | 27.71                          | 26.75 | 14.80               | 14.10 | 22.4                                    | ...                             | ... |
| M20 × 2.5                         | 30.00                        | 29.16 | 34.64                          | 32.95 | 18.00               | 16.90 | 27.9                                    | 0.8                             | 0.4 |
| M24 × 3                           | 36.00                        | 35.00 | 41.57                          | 39.55 | 21.50               | 20.20 | 32.5                                    | 0.8                             | 0.4 |
| M30 × 3.5                         | 46.00                        | 45.00 | 53.12                          | 50.85 | 25.60               | 24.30 | 42.5                                    | 0.8                             | 0.4 |
| M36 × 4                           | 55.00                        | 53.80 | 63.51                          | 60.79 | 31.00               | 29.40 | 50.8                                    | 0.8                             | 0.4 |
| Metric Hex Nuts — Style 2         |                              |       |                                |       |                     |       |   |                                 |     |
| M3 × 0.5                          | 5.50                         | 5.32  | 6.35                           | 6.01  | 2.90                | 2.65  | 4.6                                     | ...                             | ... |
| M3.5 × 0.6                        | 6.00                         | 5.82  | 6.93                           | 6.58  | 3.30                | 3.00  | 5.1                                     | ...                             | ... |
| M4 × 0.7                          | 7.00                         | 6.78  | 8.08                           | 7.66  | 3.80                | 3.50  | 5.9                                     | ...                             | ... |
| M5 × 0.8                          | 8.00                         | 7.78  | 9.24                           | 8.79  | 5.10                | 4.80  | 6.9                                     | ...                             | ... |
| M6 × 1                            | 10.00                        | 9.78  | 11.55                          | 11.05 | 5.70                | 5.40  | 8.9                                     | ...                             | ... |
| M8 × 1.25                         | 13.00                        | 12.73 | 15.01                          | 14.38 | 7.50                | 7.14  | 11.6                                    | ...                             | ... |
| <sup>a</sup> M10 × 1.5            | 15.00                        | 14.73 | 17.32                          | 16.64 | 10.0                | 9.6   | 13.6                                    | 0.6                             | 0.3 |
| M10 × 1.5                         | 16.00                        | 15.73 | 18.48                          | 17.77 | 9.30                | 8.94  | 14.6                                    | ...                             | ... |
| M12 × 1.75                        | 18.00                        | 17.73 | 20.78                          | 20.03 | 12.00               | 11.57 | 16.6                                    | ...                             | ... |
| M14 × 2                           | 21.00                        | 20.67 | 24.25                          | 23.35 | 14.10               | 13.40 | 19.6                                    | ...                             | ... |
| M16 × 2                           | 24.00                        | 23.67 | 27.71                          | 26.75 | 16.40               | 15.70 | 22.5                                    | ...                             | ... |
| M20 × 2.5                         | 30.00                        | 29.16 | 34.64                          | 32.95 | 20.30               | 19.00 | 27.7                                    | 0.8                             | 0.4 |
| M24 × 3                           | 36.00                        | 35.00 | 41.57                          | 39.55 | 23.90               | 22.60 | 33.2                                    | 0.8                             | 0.4 |
| M30 × 3.5                         | 46.00                        | 45.00 | 53.12                          | 50.85 | 28.60               | 27.30 | 42.7                                    | 0.8                             | 0.4 |
| M36 × 4                           | 55.00                        | 53.80 | 63.51                          | 60.79 | 34.70               | 33.10 | 51.1                                    | 0.8                             | 0.4 |

<sup>a</sup>This size with width across flats of 15 mm is not standard. Unless specifically ordered, M10 hex nuts with 16 mm width across flats will be furnished.

All dimensions are in millimeters.

**Table 27. American National Standard Metric Slotted Hex Nuts**  
ANSI B18.2.4M-1982 (R1999)

| Nominal Nut Dia. and Thread Pitch | Width Across Flats, S |       | Width Across Corners, E |       | Thickness, M |       | Bearing Face Dia., Dw | Unslotted Thickness, F |      | Width of Slot, N |     | Washer Face Thickness C |     |
|-----------------------------------|-----------------------|-------|-------------------------|-------|--------------|-------|-----------------------|------------------------|------|------------------|-----|-------------------------|-----|
|                                   | Max                   | Min   | Max                     | Min   | Max          | Min   | Min                   | Max                    | Min  | Max              | Min | Max                     | Min |
| M5 × 0.8                          | 8.00                  | 7.78  | 9.24                    | 8.79  | 5.10         | 4.80  | 6.9                   | 3.2                    | 2.9  | 2.0              | 1.4 | ...                     | ... |
| M6 × 1                            | 10.00                 | 9.78  | 11.55                   | 11.05 | 5.70         | 5.40  | 8.9                   | 3.5                    | 3.2  | 2.4              | 1.8 | ...                     | ... |
| M8 × 1.25                         | 13.00                 | 12.73 | 15.01                   | 14.38 | 7.50         | 7.14  | 11.6                  | 4.4                    | 4.1  | 2.9              | 2.3 | ...                     | ... |
| *M10 × 1.5                        | 15.00                 | 14.73 | 17.32                   | 16.64 | 10.0         | 9.6   | 13.6                  | 5.7                    | 5.4  | 3.4              | 2.8 | 0.6                     | 0.3 |
| M10 × 1.5                         | 16.00                 | 15.73 | 18.48                   | 17.77 | 9.30         | 8.94  | 14.6                  | 5.2                    | 4.9  | 3.4              | 2.8 | ...                     | ... |
| M12 × 1.75                        | 18.00                 | 17.73 | 20.78                   | 20.03 | 12.00        | 11.57 | 16.6                  | 7.3                    | 6.9  | 4.0              | 3.2 | ...                     | ... |
| M14 × 2                           | 21.00                 | 20.67 | 24.25                   | 23.35 | 14.10        | 13.40 | 19.6                  | 8.6                    | 8.0  | 4.3              | 3.5 | ...                     | ... |
| M16 × 2                           | 24.00                 | 23.67 | 27.71                   | 26.75 | 16.40        | 15.70 | 22.5                  | 9.9                    | 9.3  | 5.3              | 4.5 | ...                     | ... |
| M20 × 2.5                         | 30.00                 | 29.16 | 34.64                   | 32.95 | 20.30        | 19.00 | 27.7                  | 13.3                   | 12.2 | 5.7              | 4.5 | 0.8                     | 0.4 |
| M24 × 3                           | 36.00                 | 35.00 | 41.57                   | 39.55 | 23.90        | 22.60 | 33.2                  | 15.4                   | 14.3 | 6.7              | 5.5 | 0.8                     | 0.4 |
| M30 × 3.5                         | 46.00                 | 45.00 | 53.12                   | 50.85 | 28.60        | 27.30 | 42.7                  | 18.1                   | 16.8 | 8.5              | 7.0 | 0.8                     | 0.4 |
| M36 × 4                           | 55.00                 | 53.80 | 63.51                   | 60.79 | 34.70        | 33.10 | 51.1                  | 23.7                   | 22.4 | 8.5              | 7.0 | 0.8                     | 0.4 |

\*This size with width across flats of 15 mm is not standard. Unless specifically ordered, M10 slotted hex nuts with 16 mm width across flats will be furnished.

All dimensions are in millimeters.

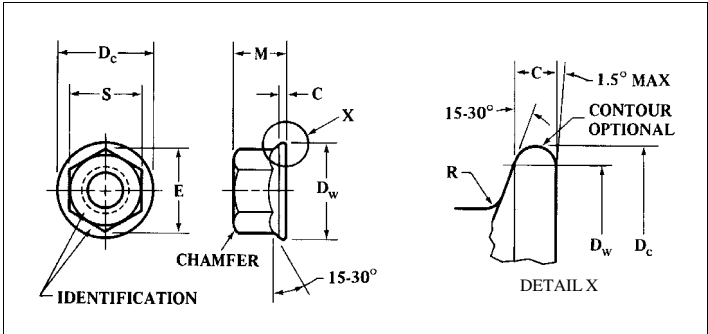
Metric nuts of other materials, such as stainless steel, brass, bronze, and aluminum alloys, have properties as agreed upon by the manufacturer and purchaser. Properties of nuts of several grades of non-ferrous materials are covered in ASTM F467M.

Unless otherwise specified, metric nuts are furnished with a natural (unprocessed) finish, unplated or uncoated.

**Metric Nut Thread Series.**—Metric nuts have metric coarse threads with class 6H tolerances in accordance with ANSI B1.13M (see *Metric Screw and Bolt Diameter-Length Combinations* Metric Screw Threads in index). For prevailing-torque type metric nuts this condition applies before introduction of the prevailing torque feature. Nuts intended for use with externally threaded fasteners which are plated or coated with a plating or coating thickness (e.g., hot dip galvanized) requiring overtapping of the nut thread to permit assembly, have over-tapped threads in conformance with requirements specified in ASTM A563M.



**Table 28. American National Standard Metric Hex Flange Nuts**  
ANSI B18.2.4.4M-1982 (R1999)



| Nominal Nut Dia. and Thread Pitch | Width Across Flats, $S$ |       | Width Across Corners, $E$ |       | Flange Dia., $D_c$ | Bearing Circle Dia., $D_w$ | Flange Edge Thickness, $C$ | Thickness, $M$ |       | Flange Top Fillet Radius, $R$ |
|-----------------------------------|-------------------------|-------|---------------------------|-------|--------------------|----------------------------|----------------------------|----------------|-------|-------------------------------|
|                                   | Max                     | Min   | Max                       | Min   |                    |                            |                            | Max            | Min   |                               |
| M5 × 0.8                          | 8.00                    | 7.78  | 9.24                      | 8.79  | 11.8               | 9.8                        | 1.0                        | 5.00           | 4.70  | 0.3                           |
| M6 × 1                            | 10.00                   | 9.78  | 11.55                     | 11.05 | 14.2               | 12.2                       | 1.1                        | 6.00           | 5.70  | 0.4                           |
| M8 × 1.25                         | 13.00                   | 12.73 | 15.01                     | 14.38 | 17.9               | 15.8                       | 1.2                        | 8.00           | 7.60  | 0.5                           |
| M10 × 1.5                         | 15.00                   | 14.73 | 17.32                     | 16.64 | 21.8               | 19.6                       | 1.5                        | 10.00          | 9.60  | 0.6                           |
| M12 × 1.75                        | 18.00                   | 17.73 | 20.78                     | 20.03 | 26.0               | 23.8                       | 1.8                        | 12.00          | 11.60 | 0.7                           |
| M14 × 2                           | 21.00                   | 20.67 | 24.25                     | 23.35 | 29.9               | 27.6                       | 2.1                        | 14.00          | 13.30 | 0.9                           |
| M16 × 2                           | 24.00                   | 23.67 | 27.71                     | 26.75 | 34.5               | 31.9                       | 2.4                        | 16.00          | 15.30 | 1.0                           |
| M20 × 2.5                         | 30.00                   | 29.16 | 34.64                     | 32.95 | 42.8               | 39.9                       | 3.0                        | 20.00          | 18.90 | 1.2                           |

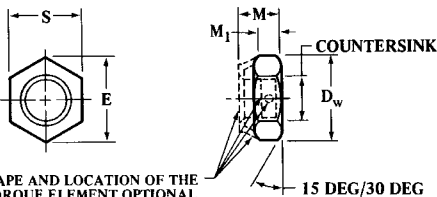
All dimensions are in millimeters.

**Types of Metric Prevailing-Torque Type Nuts.**—There are three basic designs for prevailing-torque type nuts:

- 1) All-metal, one-piece construction nuts which derive their prevailing-torque characteristics from controlled distortion of the nut thread and/or body.
- 2) Metal nuts which derive their prevailing-torque characteristics from addition or fusion of a nonmetallic insert, plug, or patch in their threads.
- 3) Top insert, two-piece construction nuts which derive their prevailing-torque characteristics from an insert, usually a full ring of non-metallic material, located and retained in the nut at its top surface.

The first two designs are designated in [Tables 29](#) and [30](#) as “all-metal” type and the third design as “top-insert” type.

**Table 29. American National Standard Prevailing-Torque Metric Hex Nuts —  
Property Classes 5, 9, and 10 ANS/ASME B18.16.3M-1998**



NOTE: SIZE, SHAPE AND LOCATION OF THE PREVAILING-TORQUE ELEMENT OPTIONAL

15 DEG/30 DEG

| Nominal<br>Nut Dia. and<br>Thread Pitch | Width<br>Across<br>Flats,<br>S |       | Width<br>Across<br>Corners,<br>E |       | Property Classes 5 and 10 Nuts |       |                 |       | Property Class 9 Nuts |       |                 |       | Property Class   |           | Bearing<br>Face<br>Dia.,<br>D <sub>w</sub> |                                     |     |
|---|--------------------------------|-------|----------------------------------|-------|--------------------------------|-------|-----------------|-------|-----------------------|-------|-----------------|-------|------------------|-----------|--|-------------------------------------|-----|
|   |                                |       |                                  |       | All Metal <sup>a</sup> Type    |       | Top Insert Type |       | All Metal Type        |       | Top Insert Type |       | 5 and 10<br>Nuts | 9<br>Nuts |  |                                     |     |
|   | Thickness, M                   |       |                                  |       |                                |       |                 |       |                       |       |                 |       |                  |           |  | Wrenching Height,<br>M <sub>1</sub> |     |
|   | Max                            | Min   | Max                              | Min   | Max                            | Min   | Max             | Min   | Max                   | Min   | Max             | Min   | Max              | Min       |  | Min                                 | Min |
| M3 × 0.5                                | 5.50                           | 5.32  | 6.35                             | 6.01  | 3.10                           | 2.65  | 4.50            | 3.90  | 3.10                  | 2.65  | 4.50            | 3.90  | 1.4              | 1.4       | 4.6  |                                     |     |
| M3.5 × 0.6                              | 6.00                           | 5.82  | 6.93                             | 6.58  | 3.50                           | 3.00  | 5.00            | 4.30  | 3.50                  | 3.00  | 5.00            | 4.30  | 1.7              | 1.7       | 5.1  |                                     |     |
| M4 × 0.7                                | 7.00                           | 6.78  | 8.08                             | 7.66  | 4.00                           | 3.50  | 6.00            | 5.30  | 4.00                  | 3.50  | 6.00            | 5.30  | 1.9              | 1.9       | 5.9  |                                     |     |
| M5 × 0.8                                | 8.00                           | 7.78  | 9.24                             | 8.79  | 5.30                           | 4.80  | 6.80            | 6.00  | 5.30                  | 4.80  | 7.20            | 6.40  | 2.7              | 2.7       | 6.9  |                                     |     |
| M6 × 1                                  | 10.00                          | 9.78  | 11.55                            | 11.05 | 5.90                           | 5.40  | 8.00            | 7.20  | 6.70                  | 5.40  | 8.50            | 7.70  | 3.0              | 3.0       | 8.9  |                                     |     |
| M8 × 1.25                               | 13.00                          | 12.73 | 15.01                            | 14.38 | 7.10                           | 6.44  | 9.50            | 8.50  | 8.00                  | 7.14  | 10.20           | 9.20  | 3.7              | 4.3       | 11.6                                       |                                     |     |
| <sup>b</sup> M10 × 1.5                  | 15.00                          | 14.73 | 17.32                            | 16.64 | 9.70                           | 8.70  | 12.50           | 11.50 | 11.20                 | 9.60  | 13.50           | 12.50 | 5.6              | 6.2       | 13.6                                       |                                     |     |
| M10 × 1.5                               | 16.00                          | 15.73 | 18.48                            | 17.77 | 9.00                           | 8.04  | 11.90           | 10.90 | 10.50                 | 8.94  | 12.80           | 11.80 | 4.8              | 5.6       | 14.6                                       |                                     |     |
| M12 × 1.75                              | 18.00                          | 17.73 | 20.78                            | 20.03 | 11.60                          | 10.37 | 14.90           | 13.90 | 13.30                 | 11.57 | 16.10           | 15.10 | 6.7              | 7.7       | 16.6                                       |                                     |     |
| M14 × 2                                 | 21.00                          | 20.67 | 24.25                            | 23.35 | 13.20                          | 12.10 | 17.00           | 15.80 | 15.40                 | 13.40 | 18.30           | 17.10 | 7.8              | 8.9       | 19.6                                       |                                     |     |
| M16 × 2                                 | 24.00                          | 23.67 | 27.71                            | 26.75 | 15.20                          | 14.10 | 19.10           | 17.90 | 17.90                 | 15.70 | 20.70           | 19.50 | 9.1              | 10.5      | 22.5                                       |                                     |     |
| M20 × 2.5                               | 30.00                          | 29.16 | 34.64                            | 32.95 | 19.00                          | 16.90 | 22.80           | 21.50 | 21.80                 | 19.00 | 25.10           | 23.80 | 10.9             | 12.7      | 27.7                                       |                                     |     |
| M24 × 3                                 | 36.00                          | 35.00 | 41.57                            | 39.55 | 23.00                          | 20.20 | 27.10           | 25.60 | 26.40                 | 22.60 | 29.50           | 28.00 | 13.0             | 15.1      | 33.2                                       |                                     |     |
| M30 × 3.5                               | 46.00                          | 45.00 | 53.12                            | 50.85 | 26.90                          | 24.30 | 32.60           | 30.60 | 31.80                 | 27.30 | 35.60           | 33.60 | 15.7             | 18.2      | 42.7                                       |                                     |     |
| M36 × 4                                 | 55.00                          | 53.80 | 63.51                            | 60.79 | 32.50                          | 29.40 | 38.90           | 36.90 | 38.50                 | 33.10 | 42.60           | 40.60 | 19.0             | 22.1      | 51.1                                       |                                     |     |

<sup>a</sup> Also includes metal nuts with non-metallic inserts, plugs, or patches in their threads.

<sup>b</sup> This size with width across flats of 15 mm is not standard. Unless specifically ordered, M10 slotted hex nuts with 16 mm width across flats will be furnished.

All dimensions are in millimeters.

**Table 30. American National Standard Prevailing-Torque Metric Hex Flange Nuts ANSI B18.16.3M-1998**

**NOTE: SIZE, SHAPE AND LOCATION OF THE PREVAILING-TORQUE ELEMENT OPTIONAL**

| Nominal Dia. and Thread Pitch | Width Across Flats, <i>S</i> |       | Width Across Corners, <i>E</i> |       | All Metal Type <sup>a</sup>                    |       |       |       | Top Insert Type |      | Flange Dia., <i>D<sub>c</sub></i> | Bearing Circle Dia., <i>D<sub>w</sub></i> | Flange Edge Thickness, <i>C</i> | Flange Top Fillet Radius, <i>R</i> |
|-------------------------------|------------------------------|-------|--------------------------------|-------|--|-------|-------|-------|-----------------|------|-----------------------------------|---|---------------------------------|------------------------------------|
|                               |                              |       |                                |       | Thickness, <i>M</i> (All Nut Property Classes) |       |       |       | Max             | Min  |                                   |   |                                 |                                    |
|                               | Max                          | Min   | Max                            | Min   | Max  | Min   | Max   | Min   |                 |      |                                   |   |                                 |                                    |
| M6 × 1                        | 10.00                        | 9.78  | 11.55                          | 11.05 | 7.30   | 5.70  | 8.80  | 8.00  | 14.2            | 12.2 | 1.1                               | 0.4                                       |                                 |                                    |
| M8 × 1.25                     | 13.00                        | 12.73 | 15.01                          | 14.38 | 9.40   | 7.60  | 10.70 | 9.70  | 17.9            | 15.8 | 1.2                               | 0.5                                       |                                 |                                    |
| M10 × 1.5                     | 15.00                        | 14.73 | 17.32                          | 16.64 | 11.40  | 9.60  | 13.50 | 12.50 | 21.8            | 19.6 | 1.5                               | 0.6                                       |                                 |                                    |
| M12 × 1.75                    | 18.00                        | 17.73 | 20.78                          | 20.03 | 13.80  | 11.60 | 16.10 | 15.10 | 26.0            | 23.8 | 1.8                               | 0.7                                       |                                 |                                    |
| M14 × 2                       | 21.00                        | 20.67 | 24.25                          | 23.35 | 15.90  | 13.30 | 18.20 | 17.00 | 29.9            | 27.6 | 2.1                               | 0.9                                       |                                 |                                    |
| M16 × 2                       | 24.00                        | 23.67 | 27.71                          | 26.75 | 18.30  | 15.30 | 20.30 | 19.10 | 34.5            | 31.9 | 2.4                               | 1.0                                       |                                 |                                    |
| M20 × 2.5                     | 30.00                        | 29.16 | 34.64                          | 32.95 | 22.40  | 18.90 | 24.80 | 23.50 | 42.8            | 39.9 | 3.0                               | 1.2                                       |                                 |                                    |

<sup>a</sup> Also includes metal nuts with nonmetallic inserts, plugs, or patches in their threads.

All dimensions are in millimeters.

**Metric Nut Identification Symbols.**—Carbon steel hex nuts, styles 1 and 2, hex flange nuts, and carbon and alloy steel heavy hex nuts are marked to identify the property class and manufacturer in accordance with requirements specified in ASTM A563M. The aforementioned nuts when made of other materials, as well as slotted hex nuts and hex jam nuts, are marked to identify the property class and manufacturer as agreed upon by manufacturer and purchaser. Carbon steel prevailing-torque type hex nuts and hex flange nuts are marked to identify property class and manufacturer as specified in ANSI B18.16.1M. Prevailing-torque type nuts of other materials are identified as agreed upon by the manufacturer and purchaser.

**Metric Nut Designation.**—Metric nuts are designated by the following data, preferably in the sequence shown: product name, nominal diameter and thread pitch, steel property class or material identification, and protective coating, if required. (Note: It is common practice in ISO Standards to omit thread pitch from the product designation when the nut threads are the metric coarse thread series, e.g., M10 stands for M10 × 1.5).

*Example:* Hex nut, style 1, M10 × 1.5, ASTM A563M class 10, zinc plated  
 Heavy hex nut, M20 × 2.5, silicon bronze, ASTM F467, grade 651  
 Slotted hex nut, M20, ASTM A563M class 10.

**Table 31. American National Standard Metric Hex Jam Nuts and Heavy Hex Nuts**  
*ANSI B18.2.4.5M and B18.2.4.6M-1979 (R1998)*

| Nominal Nut Dia. and Thread Pitch | Width Across Flats, $S$ |        | Width Across Corners, $E$ |        | Thickness, $M$ |       | Bearing Face Dia., $D_w$ | Washer Face Thickness, $C$ |     |
|-----------------------------------|-------------------------|--------|---------------------------|--------|----------------|-------|--------------------------|----------------------------|-----|
|                                   | Max                     | Min    | Max                       | Min    | Max            | Min   | Min                      | Max                        | Min |
| Metric Hex Jam Nuts               |                         |        |                           |        |                |       |                          |                            |     |
| M5 × 0.8                          | 8.00                    | 7.78   | 9.24                      | 8.79   | 2.70           | 2.45  | 6.9                      | ...                        | ... |
| M6 × 1                            | 10.00                   | 9.78   | 11.55                     | 11.05  | 3.20           | 2.90  | 8.9                      | ...                        | ... |
| M8 × 1.25                         | 13.00                   | 12.73  | 15.01                     | 14.38  | 4.00           | 3.70  | 11.6                     | ...                        | ... |
| <sup>a</sup> M10 × 1.5            | 15.00                   | 14.73  | 17.32                     | 16.64  | 5.00           | 4.70  | 13.6                     | ...                        | ... |
| M10 × 1.5                         | 16.00                   | 15.73  | 18.48                     | 17.77  | 5.00           | 4.70  | 14.6                     | ...                        | ... |
| M12 × 1.75                        | 18.00                   | 17.73  | 20.78                     | 20.03  | 6.00           | 5.70  | 16.6                     | ...                        | ... |
| M14 × 2                           | 21.00                   | 20.67  | 24.25                     | 23.35  | 7.00           | 6.42  | 19.6                     | ...                        | ... |
| M16 × 2                           | 24.00                   | 23.67  | 27.71                     | 26.75  | 8.00           | 7.42  | 22.5                     | ...                        | ... |
| M20 × 2.5                         | 30.00                   | 29.16  | 34.64                     | 32.95  | 10.00          | 9.10  | 27.7                     | 0.8                        | 0.4 |
| M24 × 3                           | 36.00                   | 35.00  | 41.57                     | 39.55  | 12.00          | 10.90 | 33.2                     | 0.8                        | 0.4 |
| M30 × 3.5                         | 46.00                   | 45.00  | 53.12                     | 50.85  | 15.00          | 13.90 | 42.7                     | 0.8                        | 0.4 |
| M36 × 4                           | 55.00                   | 53.80  | 63.51                     | 60.79  | 18.00          | 16.90 | 51.1                     | 0.8                        | 0.4 |
| Metric Heavy Hex Nuts             |                         |        |                           |        |                |       |                          |                            |     |
| M12 × 1.75                        | 21.00                   | 20.16  | 24.25                     | 22.78  | 12.3           | 11.9  | 19.2                     | 0.8                        | 0.4 |
| M14 × 2                           | 24.00                   | 23.16  | 27.71                     | 26.17  | 14.3           | 13.6  | 22.0                     | 0.8                        | 0.4 |
| M16 × 2                           | 27.00                   | 26.16  | 31.18                     | 29.56  | 17.1           | 16.4  | 24.9                     | 0.8                        | 0.4 |
| M20 × 2.5                         | 34.00                   | 33.00  | 39.26                     | 37.29  | 20.7           | 19.4  | 31.4                     | 0.8                        | 0.4 |
| M22 × 2.5                         | 36.00                   | 35.00  | 41.57                     | 39.55  | 23.6           | 22.3  | 33.3                     | 0.8                        | 0.4 |
| M24 × 3                           | 41.00                   | 40.00  | 47.34                     | 45.20  | 24.2           | 22.9  | 38.0                     | 0.8                        | 0.4 |
| M27 × 3                           | 46.00                   | 45.00  | 53.12                     | 50.85  | 27.6           | 26.3  | 42.8                     | 0.8                        | 0.4 |
| M30 × 3.5                         | 50.00                   | 49.00  | 57.74                     | 55.37  | 30.7           | 29.1  | 46.6                     | 0.8                        | 0.4 |
| M36 × 4                           | 60.00                   | 58.80  | 69.28                     | 66.44  | 36.6           | 35.0  | 55.9                     | 0.8                        | 0.4 |
| M42 × 4.5                         | 70.00                   | 67.90  | 80.83                     | 77.41  | 42.0           | 40.4  | 64.5                     | 1.0                        | 0.5 |
| M48 × 5                           | 80.00                   | 77.60  | 92.38                     | 88.46  | 48.0           | 46.4  | 73.7                     | 1.0                        | 0.5 |
| M56 × 5.5                         | 90.00                   | 87.20  | 103.92                    | 99.41  | 56.0           | 54.1  | 82.8                     | 1.0                        | 0.5 |
| M64 × 6                           | 100.00                  | 96.80  | 115.47                    | 110.35 | 64.0           | 62.1  | 92.0                     | 1.0                        | 0.5 |
| M72 × 6                           | 110.00                  | 106.40 | 127.02                    | 121.30 | 72.0           | 70.1  | 101.1                    | 1.2                        | 0.6 |
| M80 × 6                           | 120.00                  | 116.00 | 138.56                    | 132.24 | 80.0           | 78.1  | 110.2                    | 1.2                        | 0.6 |
| M90 × 6                           | 135.00                  | 130.50 | 155.88                    | 148.77 | 90.0           | 87.8  | 124.0                    | 1.2                        | 0.6 |
| M100 × 6                          | 150.00                  | 145.00 | 173.21                    | 165.30 | 100.0          | 97.8  | 137.8                    | 1.2                        | 0.6 |

<sup>a</sup> This size with width across flats of 15 mm is not standard. Unless specifically ordered, M10 hex jam nuts with 16 mm width across flats will be furnished.

All dimensions are in millimeters.

**Metric Washers**

**Metric Plain Washers.**—American National Standard ANSI B18.22M-1981 (R1990) covers general specifications and dimensions for flat, round-hole washers, both soft (as fabricated) and hardened, intended for use in general-purpose applications. Dimensions are given in the following table. Manufacturers should be consulted for current information on stock sizes.

**Comparison with ISO Standards.**—The washers covered by this ANSI Standard are nominally similar to those covered in various ISO documents. Outside diameters were selected, where possible, from ISO/TC2/WG6/N47 “General Plan for Plain Washers for Metric Bolts, Screws, and Nuts.” The thicknesses given in the ANSI Standard are similar to the nominal ISO thicknesses, however the tolerances differ. Inside diameters also differ.

ISO metric washers are currently covered in ISO 887, “Plain Washers for Metric Bolts, Screws, and Nuts – General Plan.”

**Types of Metric Plain Washers.**—Soft (as fabricated) washers are generally available in nominal sizes 1.6 mm through 36 mm in a variety of materials. They are normally used in low-strength applications to distribute bearing load, to provide a uniform bearing surface, and to prevent marring of the work surface.

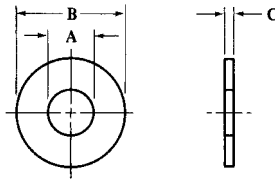
Hardened steel washers are normally available in sizes 6 mm through 36 mm in the narrow and regular series. They are intended primarily for use in high-strength joints to minimize embedment, to provide a uniform bearing surface, and to bridge large clearance holes and slots.

**Metric Plain Washer Materials and Finish.**—Soft (as fabricated) washers are made of nonhardened steel unless otherwise specified by the purchaser. Hardened washers are made of through-hardened steel tempered to a hardness of 38 to 45 Rockwell C.

Unless otherwise specified, washers are furnished with a natural (as fabricated) finish, unplated or uncoated with a light film of oil or rust inhibitor.

**Metric Plain Washer Designation.**—When specifying metric plain washers, the designation should include the following data in the sequence shown: description, nominal size, series, material type, and finish, if required.

*Example:* Plain washer, 6 mm, narrow, soft, steel, zinc plated  
Plain washer, 10 mm, regular, hardened steel.



**Table 32. American National Standard Metric Plain Washers**  
ANSI B18.22M-1981, R1990

| Nominal Washer Size <sup>a</sup> | Washer Series | Inside Diameter, A |       | Outside Diameter, B |                    | Thickness, C |      |
|----------------------------------|---------------|--------------------|-------|---------------------|--------------------|--------------|------|
|                                  |               | Max                | Min   | Max                 | Min                | Max          | Min  |
| 1.6                              | Narrow        | 2.09               | 1.95  | 4.00                | 3.70               | 0.70         | 0.50 |
|                                  | Regular       | 2.09               | 1.95  | 5.00                | 4.70               | 0.70         | 0.50 |
|                                  | Wide          | 2.09               | 1.95  | 6.00                | 5.70               | 0.90         | 0.60 |
| 2                                | Narrow        | 2.64               | 2.50  | 5.00                | 4.70               | 0.90         | 0.60 |
|                                  | Regular       | 2.64               | 2.50  | 6.00                | 5.70               | 0.90         | 0.60 |
|                                  | Wide          | 2.64               | 2.50  | 8.00                | 7.64               | 0.90         | 0.60 |
| 2.5                              | Narrow        | 3.14               | 3.00  | 6.00                | 5.70               | 0.90         | 0.60 |
|                                  | Regular       | 3.14               | 3.00  | 8.00                | 7.64               | 0.90         | 0.60 |
|                                  | Wide          | 3.14               | 3.00  | 10.00               | 9.64               | 1.20         | 0.80 |
| 3                                | Narrow        | 3.68               | 3.50  | 7.00                | 6.64               | 0.90         | 0.60 |
|                                  | Regular       | 3.68               | 3.50  | 10.00               | 9.64               | 1.20         | 0.80 |
|                                  | Wide          | 3.68               | 3.50  | 12.00               | 11.57              | 1.40         | 1.00 |
| 3.5                              | Narrow        | 4.18               | 4.00  | 9.00                | 8.64               | 1.20         | 0.80 |
|                                  | Regular       | 4.18               | 4.00  | 10.00               | 9.64               | 1.40         | 1.00 |
|                                  | Wide          | 4.18               | 4.00  | 15.00               | 14.57              | 1.75         | 1.20 |
| 4                                | Narrow        | 4.88               | 4.70  | 10.00               | 9.64               | 1.20         | 0.80 |
|                                  | Regular       | 4.88               | 4.70  | 12.00               | 11.57              | 1.40         | 1.00 |
|                                  | Wide          | 4.88               | 4.70  | 16.00               | 15.57              | 2.30         | 1.60 |
| 5                                | Narrow        | 5.78               | 5.50  | 11.00               | 10.57              | 1.40         | 1.00 |
|                                  | Regular       | 5.78               | 5.50  | 15.00               | 14.57              | 1.75         | 1.20 |
|                                  | Wide          | 5.78               | 5.50  | 20.00               | 19.48              | 2.30         | 1.60 |
| 6                                | Narrow        | 6.87               | 6.65  | 13.00               | 12.57              | 1.75         | 1.20 |
|                                  | Regular       | 6.87               | 6.65  | 18.80               | 18.37              | 1.75         | 1.20 |
|                                  | Wide          | 6.87               | 6.65  | 25.40               | 24.88              | 2.30         | 1.60 |
| 8                                | Narrow        | 9.12               | 8.90  | 18.80 <sup>b</sup>  | 18.37 <sup>b</sup> | 2.30         | 1.60 |
|                                  | Regular       | 9.12               | 8.90  | 25.40 <sup>b</sup>  | 24.48 <sup>b</sup> | 2.30         | 1.60 |
|                                  | Wide          | 9.12               | 8.90  | 32.00               | 31.38              | 2.80         | 2.00 |
| 10                               | Narrow        | 11.12              | 10.85 | 20.00               | 19.48              | 2.30         | 1.60 |
|                                  | Regular       | 11.12              | 10.85 | 28.00               | 27.48              | 2.80         | 2.00 |
|                                  | Wide          | 11.12              | 10.85 | 39.00               | 38.38              | 3.50         | 2.50 |
| 12                               | Narrow        | 13.57              | 13.30 | 25.40               | 24.88              | 2.80         | 2.00 |
|                                  | Regular       | 13.57              | 13.30 | 34.00               | 33.38              | 3.50         | 2.50 |
|                                  | Wide          | 13.57              | 13.30 | 44.00               | 43.38              | 3.50         | 2.50 |
| 14                               | Narrow        | 15.52              | 15.25 | 28.00               | 27.48              | 2.80         | 2.00 |
|                                  | Regular       | 15.52              | 15.25 | 39.00               | 38.38              | 3.50         | 2.50 |
|                                  | Wide          | 15.52              | 15.25 | 50.00               | 49.38              | 4.00         | 3.00 |
| 16                               | Narrow        | 17.52              | 17.25 | 32.00               | 31.38              | 3.50         | 2.50 |
|                                  | Regular       | 17.52              | 17.25 | 44.00               | 43.38              | 4.00         | 3.00 |
|                                  | Wide          | 17.52              | 17.25 | 56.00               | 54.80              | 4.60         | 3.50 |
| 20                               | Narrow        | 22.32              | 21.80 | 39.00               | 38.38              | 4.00         | 3.00 |
|                                  | Regular       | 22.32              | 21.80 | 50.00               | 49.38              | 4.60         | 3.50 |
|                                  | Wide          | 22.32              | 21.80 | 66.00               | 64.80              | 5.10         | 4.00 |
| 24                               | Narrow        | 26.12              | 25.60 | 44.00               | 43.38              | 4.60         | 3.50 |
|                                  | Regular       | 26.12              | 25.60 | 56.00               | 54.80              | 5.10         | 4.00 |
|                                  | Wide          | 26.12              | 25.60 | 72.00               | 70.80              | 5.60         | 4.50 |
| 30                               | Narrow        | 33.02              | 32.40 | 56.00               | 54.80              | 5.10         | 4.00 |
|                                  | Regular       | 33.02              | 32.40 | 72.00               | 70.80              | 5.60         | 4.50 |
|                                  | Wide          | 33.02              | 32.40 | 90.00               | 88.60              | 6.40         | 5.00 |
| 36                               | Narrow        | 38.92              | 38.30 | 66.00               | 64.80              | 5.60         | 4.50 |
|                                  | Regular       | 38.92              | 38.30 | 90.00               | 88.60              | 6.40         | 5.00 |
|                                  | Wide          | 38.92              | 38.30 | 110.00              | 108.60             | 8.50         | 7.00 |

<sup>a</sup> Nominal washer sizes are intended for use with comparable screw and bolt sizes.

<sup>b</sup> The 18.80/18.37 and 25.40/24.48 mm outside diameters avoid washers which could be used in coin-operated devices.

All dimensions are in millimeters.

## BRITISH FASTENERS

**British Standard Square and Hexagon Bolts, Screws and Nuts.**—Important dimensions of precision hexagon bolts, screws and nuts (BSW and BSF threads) as covered by British Standard 1083:1965 are given in [Tables 1](#) and [2](#). The use of fasteners in this standard will decrease as fasteners having Unified inch and ISO metric threads come into increasing use.

Dimensions of Unified precision hexagon bolts, screws and nuts (UNC and UNF threads) are given in BS 1768:1963 (obsolescent); of Unified black hexagon bolts, screws and nuts (UNC and UNF threads) in BS 1769:1951 (obsolescent); and of Unified black square and hexagon bolts, screws and nuts (UNC and UNF threads) in BS 2708:1956 (withdrawn). Unified nominal and basic dimensions in these British Standards are the same as the comparable dimensions in the American Standards, but the tolerances applied to these basic dimensions may differ because of rounding-off practices and other factors. For Unified dimensions of square and hexagon bolts and nuts as given in ANSI/ASME B18.2.1-1996 and ANSI/ASME B18.2.2-1987 (R1999) see [Tables 1](#) through [4](#) starting on page [1514](#), and [7](#) to [10](#) starting on page [1519](#).

ISO metric precision hexagon bolts, screws and nuts are specified in the British Standard BS 3692:1967 (obsolescent) (see *British Standard ISO Metric Precision Hexagon Bolts, Screws and Nuts* starting on page [1578](#)), and ISO metric black hexagon bolts, screws and nuts are covered by British Standard BS 4190:1967 (obsolescent).

See the section *MACHINE SCREWS AND NUTS* starting on page [1587](#) for information on British Standard metric, Unified, Whitworth, and BSF machine screws and nuts.

**British Standard Screwed Studs.**—General purpose screwed studs are covered in British Standard 2693: Part 1:1956. The aim in this standard is to provide for a stud having tolerances which would not render it expensive to manufacture and which could be used in association with standard tapped holes for most purposes. Provision has been made for the use of both Unified Fine threads, Unified Coarse threads, British Standard Fine threads, and British Standard Whitworth threads as shown in the table on page [1573](#).

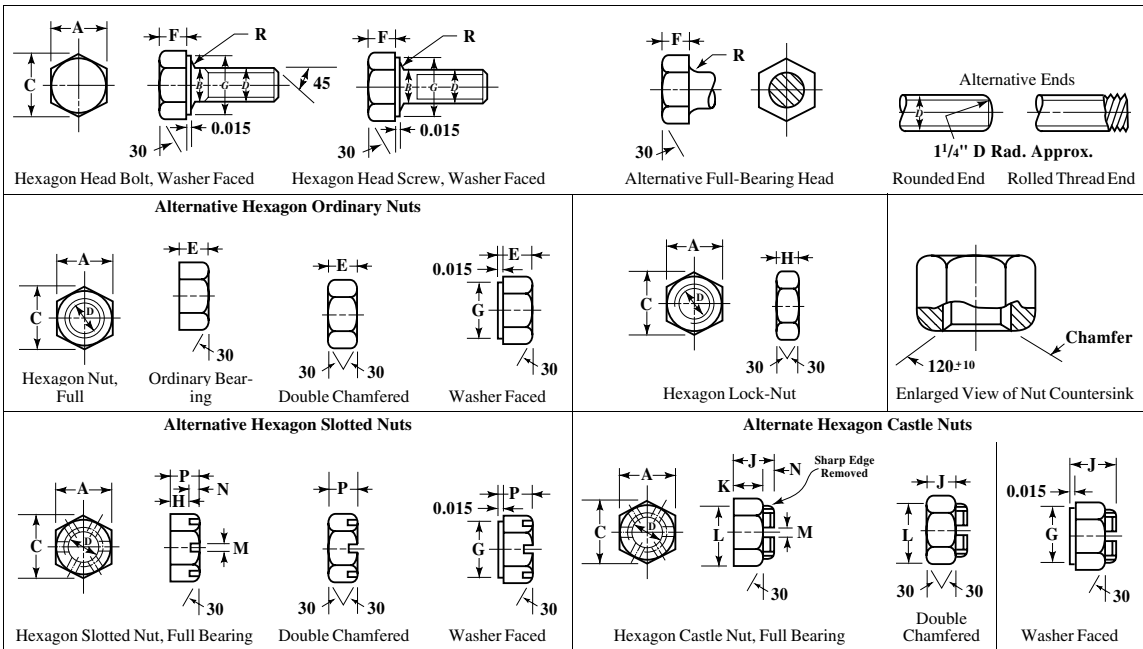
*Designations:* The *metal end* of the stud is the end which is screwed into the component. The *nut end* is the end of the screw of the stud which is not screwed into the component. The *plain portion* of the stud is the unthreaded length.

*Recommended Fitting Practices for Metal End of Stud:* It is recommended that holes tapped to Class 3B limits (see [Table 3](#) starting on page [1736](#)) in accordance with B.S. 1580 “Unified Screw Threads” or to Close Class limits in accordance with B.S. 84 “Screw Threads of Whitworth Form” as appropriate, be used in association with the metal end of the stud specified in this standard. Where fits are not critical, however, holes may be tapped to Class 2B limits (see table on page [1736](#)) in accordance with B.S. 1580 or Normal Class limits in accordance with B.S. 84.

It is recommended that the B.A. stud specified in this standard be associated with holes tapped to the limits specified for nuts in B.S. 93, 1919 edition. Where fits for these studs are not critical, holes may be tapped to limits specified for nuts in the current edition of B.S. 93.

In general, it will be found that the amount of oversize specified for the studs will produce a satisfactory fit in conjunction with the standard tapping as above. Even when interference is not present, locking will take place on the thread runout which has been carefully controlled for this purpose. Where it is considered essential to assure a true interference fit, higher grade studs should be used. It is recommended that standard studs be used even under special conditions where selective assembly may be necessary.

British Standard Whitworth (BSW) and Fine (BSF) Precision Hexagon Bolts, Screws, and Nuts



For dimensions, see [Tables 1 and 2](#).



**Table 1. British Standard Whitworth (BSW) and Fine (BSF) Precision Hexagon Slotted and Castle Nuts BS 1083:1965 (obsolescent)**

| Nominal Size<br><i>D</i>    | Number of Threads per Inch |      | Bolts, Screws, and Nuts  |                            |      |                                     |                               | Bolts and Screws |   |        |           |       | Nuts      |       |       |       |       |
|-----------------------------|----------------------------|------|--------------------------|----------------------------|------|-------------------------------------|-------------------------------|------------------|---|--------|-----------|-------|-----------|-------|-------|-------|-------|
|                             |                            |      | Width                    |                            |      | Diameter of Washer Face<br><i>G</i> | Radius Under Head<br><i>R</i> |                  | Diameter of Unthreaded Portion of Shank<br><i>B</i> |        | Thickness |       | Thickness |       |       |       |       |
|                             |                            |      | Across Flats<br><i>A</i> | Across Corners<br><i>C</i> | Max. |                                     |                               |                  |   |        | Max.      | Max.  | Min.      | Max.  | Min.  | Max.  | Min.  |
|                             | Max.                       | Min. |                          |                            |      | Max.                                | Min.                          | Max.             | Min.  | Max.   |           |       |           |       |       |       |       |
| $\frac{1}{4}$               | 20                         | 26   | 0.445                    | 0.438                      | 0.51 | 0.428                               | 0.418                         | 0.025            | 0.015   | 0.2500 | 0.2465    | 0.176 | 0.166     | 0.200 | 0.190 | 0.185 | 0.180 |
| $\frac{3}{16}$              | 18                         | 22   | 0.525                    | 0.518                      | 0.61 | 0.508                               | 0.498                         | 0.025            | 0.015   | 0.3125 | 0.3090    | 0.218 | 0.208     | 0.250 | 0.240 | 0.210 | 0.200 |
| $\frac{3}{8}$               | 16                         | 20   | 0.600                    | 0.592                      | 0.69 | 0.582                               | 0.572                         | 0.025            | 0.015   | 0.3750 | 0.3715    | 0.260 | 0.250     | 0.312 | 0.302 | 0.260 | 0.250 |
| $\frac{7}{16}$              | 14                         | 18   | 0.710                    | 0.702                      | 0.82 | 0.690                               | 0.680                         | 0.025            | 0.015   | 0.4375 | 0.4335    | 0.302 | 0.292     | 0.375 | 0.365 | 0.275 | 0.265 |
| $\frac{1}{2}$               | 12                         | 16   | 0.820                    | 0.812                      | 0.95 | 0.800                               | 0.790                         | 0.025            | 0.015   | 0.5000 | 0.4960    | 0.343 | 0.333     | 0.437 | 0.427 | 0.300 | 0.290 |
| $\frac{9}{16}$              | 12                         | 16   | 0.920                    | 0.912                      | 1.06 | 0.900                               | 0.890                         | 0.045            | 0.020   | 0.5625 | 0.5585    | 0.375 | 0.365     | 0.500 | 0.490 | 0.333 | 0.323 |
| $\frac{5}{8}$               | 11                         | 14   | 1.010                    | 1.000                      | 1.17 | 0.985                               | 0.975                         | 0.045            | 0.020   | 0.6250 | 0.6190    | 0.417 | 0.407     | 0.562 | 0.552 | 0.375 | 0.365 |
| $\frac{3}{4}$               | 10                         | 12   | 1.200                    | 1.190                      | 1.39 | 1.175                               | 1.165                         | 0.045            | 0.020   | 0.7500 | 0.7440    | 0.500 | 0.480     | 0.687 | 0.677 | 0.458 | 0.448 |
| $\frac{7}{8}$               | 9                          | 11   | 1.300                    | 1.288                      | 1.50 | 1.273                               | 1.263                         | 0.065            | 0.040   | 0.8750 | 0.8670    | 0.583 | 0.563     | 0.750 | 0.740 | 0.500 | 0.490 |
| 1                           | 8                          | 10   | 1.480                    | 1.468                      | 1.71 | 1.453                               | 1.443                         | 0.095            | 0.060   | 1.0000 | 0.9920    | 0.666 | 0.636     | 0.875 | 0.865 | 0.583 | 0.573 |
| $1\frac{1}{8}$              | 7                          | 9    | 1.670                    | 1.640                      | 1.93 | 1.620                               | 1.610                         | 0.095            | 0.060   | 1.1250 | 1.1170    | 0.750 | 0.710     | 1.000 | 0.990 | 0.666 | 0.656 |
| $1\frac{1}{4}$              | 7                          | 9    | 1.860                    | 1.815                      | 2.15 | 1.795                               | 1.785                         | 0.095            | 0.060   | 1.2500 | 1.2420    | 0.830 | 0.790     | 1.125 | 1.105 | 0.750 | 0.730 |
| $1\frac{3}{8}$ <sup>b</sup> | ...                        | 8    | 2.050                    | 2.005                      | 2.37 | 1.985                               | 1.975                         | 0.095            | 0.060   | 1.3750 | 1.3650    | 0.920 | 0.880     | 1.250 | 1.230 | 0.833 | 0.813 |
| $1\frac{1}{2}$              | 6                          | 8    | 2.220                    | 2.175                      | 2.56 | 2.155                               | 2.145                         | 0.095            | 0.060   | 1.5000 | 1.4900    | 1.000 | 0.960     | 1.375 | 1.355 | 0.916 | 0.896 |
| $1\frac{3}{4}$              | 5                          | 7    | 2.580                    | 2.520                      | 2.98 | 2.495                               | 2.485                         | 0.095            | 0.060   | 1.7500 | 1.7400    | 1.170 | 1.110     | 1.625 | 1.605 | 1.083 | 1.063 |
| 2                           | 4.5                        | 7    | 2.760                    | 2.700                      | 3.19 | 2.675                               | 2.665                         | 0.095            | 0.060   | 2.0000 | 1.9900    | 1.330 | 1.270     | 1.750 | 1.730 | 1.166 | 1.146 |

<sup>a</sup>When bolts from  $\frac{1}{4}$  to 1 inch are hot forged, the tolerance on the width across flats shall be two and a half times the tolerance shown in the table and shall be unilaterally minus from maximum size. For dimensional notation, see diagram on page 1571.

<sup>b</sup>Noted standard with BSW thread.

All dimensions in inches except where otherwise noted.

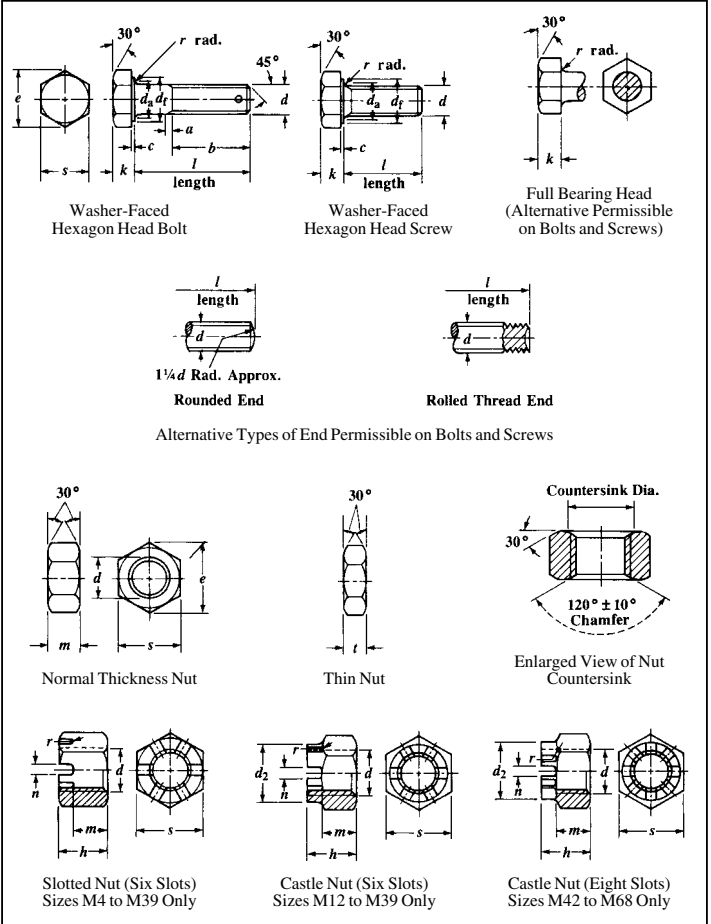
**Table 2. British Standard Whitworth (BSW) and Fine (BSF) Precision Hexagon Slotted and Castle Nuts BS 1083:1965 (obsolescent)**

| Nominal Size<br><i>D</i> | Number of Threads per Inch |     | Slotted Nuts          |       |  |       | Castle Nuts                 |       |  |       |                      |       | Slotted and Castle Nuts |       |                   |
|--------------------------|----------------------------|-----|-----------------------|-------|--|-------|-----------------------------|-------|--|-------|----------------------|-------|-------------------------|-------|-------------------|
|                          |                            |     | Thickness<br><i>P</i> |       | Lower Face to Bottom of Slot<br><i>H</i> |       | Total Thickness<br><i>J</i> |       | Lower Face to Bottom of Slot<br><i>K</i> |       | Castellated Portion  |       | Slots                   |       |                   |
|                          |                            |     |                       |       |  |       |                             |       |  |       | Diameter<br><i>L</i> |       | Width<br><i>M</i>       |       | Depth<br><i>N</i> |
|                          | BSW                        | BSF | Max.                  | Min.  | Max.                                     | Min.  | Max.                        | Min.  | Max.                                     | Min.  | Max.                 | Min.  | Max.                    | Min.  | Approx.           |
| 1/4                      | 20                         | 26  | 0.200                 | 0.190 | 0.170                                    | 0.160 | 0.290                       | 0.280 | 0.200                                    | 0.190 | 0.430                | 0.425 | 0.100                   | 0.090 | 0.090             |
| 5/16                     | 18                         | 22  | 0.250                 | 0.240 | 0.190                                    | 0.180 | 0.340                       | 0.330 | 0.250                                    | 0.240 | 0.510                | 0.500 | 0.100                   | 0.090 | 0.090             |
| 3/8                      | 16                         | 20  | 0.312                 | 0.302 | 0.222                                    | 0.212 | 0.402                       | 0.392 | 0.312                                    | 0.302 | 0.585                | 0.575 | 0.100                   | 0.090 | 0.090             |
| 7/16                     | 14                         | 18  | 0.375                 | 0.365 | 0.235                                    | 0.225 | 0.515                       | 0.505 | 0.375                                    | 0.365 | 0.695                | 0.685 | 0.135                   | 0.125 | 0.140             |
| 1/2                      | 12                         | 16  | 0.437                 | 0.427 | 0.297                                    | 0.287 | 0.577                       | 0.567 | 0.437                                    | 0.427 | 0.805                | 0.795 | 0.135                   | 0.125 | 0.140             |
| 9/16                     | 12                         | 16  | 0.500                 | 0.490 | 0.313                                    | 0.303 | 0.687                       | 0.677 | 0.500                                    | 0.490 | 0.905                | 0.895 | 0.175                   | 0.165 | 0.187             |
| 5/8                      | 11                         | 14  | 0.562                 | 0.552 | 0.375                                    | 0.365 | 0.749                       | 0.739 | 0.562                                    | 0.552 | 0.995                | 0.985 | 0.175                   | 0.165 | 0.187             |
| 3/4                      | 10                         | 12  | 0.687                 | 0.677 | 0.453                                    | 0.443 | 0.921                       | 0.911 | 0.687                                    | 0.677 | 1.185                | 1.165 | 0.218                   | 0.208 | 0.234             |
| 7/8                      | 9                          | 11  | 0.750                 | 0.740 | 0.516                                    | 0.506 | 0.984                       | 0.974 | 0.750                                    | 0.740 | 1.285                | 1.265 | 0.218                   | 0.208 | 0.234             |
| 1                        | 8                          | 10  | 0.875                 | 0.865 | 0.595                                    | 0.585 | 1.155                       | 1.145 | 0.875                                    | 0.865 | 1.465                | 1.445 | 0.260                   | 0.250 | 0.280             |
| 1 1/8                    | 7                          | 9   | 1.000                 | 0.990 | 0.720                                    | 0.710 | 1.280                       | 1.270 | 1.000                                    | 0.990 | 1.655                | 1.635 | 0.260                   | 0.250 | 0.280             |
| 1 1/4                    | 7                          | 9   | 1.125                 | 1.105 | 0.797                                    | 0.777 | 1.453                       | 1.433 | 1.125                                    | 1.105 | 1.845                | 1.825 | 0.300                   | 0.290 | 0.328             |
| 1 3/8 <sup>a</sup>       | ...                        | 8   | 1.250                 | 1.230 | 0.922                                    | 0.902 | 1.578                       | 1.558 | 1.250                                    | 1.230 | 2.035                | 2.015 | 0.300                   | 0.290 | 0.328             |
| 1 1/2                    | 6                          | 8   | 1.375                 | 1.355 | 1.047                                    | 1.027 | 1.703                       | 1.683 | 1.375                                    | 1.355 | 2.200                | 2.180 | 0.300                   | 0.290 | 0.328             |
| 1 3/4                    | 5                          | 7   | 1.625                 | 1.605 | 1.250                                    | 1.230 | 2.000                       | 1.980 | 1.625                                    | 1.605 | 2.555                | 2.535 | 0.343                   | 0.333 | 0.375             |
| 2                        | 4.5                        | 7   | 1.750                 | 1.730 | 1.282                                    | 1.262 | 2.218                       | 2.198 | 1.750                                    | 1.730 | 2.735                | 2.715 | 0.426                   | 0.416 | 0.468             |

<sup>a</sup> Not standard with BSW thread. For widths across flats, widths across corners, and diameter of washer face see [Table 1](#). For dimensional notation, see diagram on page [1571](#).

All dimensions in inches except where otherwise noted.

**Table 3. British Standard ISO Metric Precision Hexagon Bolts, Screws and Nuts**  
*BS 3692:1967 (obsolescent)*



**Table 4. British Standard ISO Metric Precision Hexagon Bolts and Screws BS 3692:1967 (obsolescent)**

| Nom.Size and Thread Dia. <sup>a</sup> <i>d</i> | Pitch of Thread (Coarse Pitch-Series) | Thread Runout <i>a</i> |      | Dia. of Unthreaded Shank <i>d</i> |       | Width Across Flats <i>s</i> |       | Width Across Corners <i>e</i> |       | Dia. of Washer Face <i>d<sub>f</sub></i> |      | Depth of Washer Face <i>c</i> | Transition Dia. <sup>b</sup> <i>d<sub>a</sub></i> |      | Radius Under Head <sup>b</sup> <i>r</i> |        | Height of Head <i>k</i> |      | Eccentricity of Head | Eccentricity of Shank and Split Pin Hole to the Thread |
|--|---------------------------------------|------------------------|------|-----------------------------------|-------|-----------------------------|-------|-------------------------------|-------|--|------|-------------------------------|---|------|---|--------|-------------------------|------|----------------------|--|
|  |                                       | Max.                   | Min. | Max.                              | Min.  | Max.                        | Min.  | Max.                          | Min.  | Max.                                     | Min. |                               | Max.  | Min. | Max.                                    | Min.   | Max.                    | Min. |                      |  |
| M1.6   | 0.35                                  | 0.8                    | 1.6  | 1.46                              | 3.2   | 3.08                        | 3.7   | 3.48                          | ...   | ...                                      | ...  | 2.0                           | 0.2   | 0.1  | 1.225                                   | 0.975  | 0.18                    | 0.14 |                      |  |
| M2   | 0.4                                   | 1.0                    | 2.0  | 1.86                              | 4.0   | 3.88                        | 4.6   | 4.38                          | ...   | ...                                      | ...  | 2.6                           | 0.3   | 0.1  | 1.525                                   | 1.275  | 0.18                    | 0.14 |                      |  |
| M2.5   | 0.45                                  | 1.0                    | 2.5  | 2.36                              | 5.0   | 4.88                        | 5.8   | 5.51                          | ...   | ...                                      | ...  | 3.1                           | 0.3   | 0.1  | 2.125                                   | 1.875  | 0.18                    | 0.14 |                      |  |
| M3   | 0.5                                   | 1.2                    | 3.0  | 2.86                              | 5.5   | 5.38                        | 6.4   | 6.08                          | 5.08  | 4.83                                     | 0.1  | 3.6                           | 0.3   | 0.1  | 2.125                                   | 1.875  | 0.18                    | 0.14 |                      |  |
| M4   | 0.7                                   | 1.6                    | 4.0  | 3.82                              | 7.0   | 6.85                        | 8.1   | 7.74                          | 6.55  | 6.30                                     | 0.1  | 4.7                           | 0.35  | 0.2  | 2.925                                   | 2.675  | 0.22                    | 0.18 |                      |  |
| M5   | 0.8                                   | 2.0                    | 5.0  | 4.82                              | 8.0   | 7.85                        | 9.2   | 8.87                          | 7.55  | 7.30                                     | 0.2  | 5.7                           | 0.35  | 0.2  | 3.650                                   | 3.35   | 0.22                    | 0.18 |                      |  |
| M6   | 1                                     | 2.5                    | 6.0  | 5.82                              | 10.0  | 9.78                        | 11.5  | 11.05                         | 9.48  | 9.23                                     | 0.3  | 6.8                           | 0.4   | 0.25 | 4.15                                    | 3.85   | 0.22                    | 0.18 |                      |  |
| M8   | 1.25                                  | 3.0                    | 8.0  | 7.78                              | 13.0  | 12.73                       | 15.0  | 14.38                         | 12.43 | 12.18                                    | 0.4  | 9.2                           | 0.6   | 0.4  | 5.65                                    | 5.35   | 0.27                    | 0.22 |                      |  |
| M10  | 1.5                                   | 3.5                    | 10.0 | 9.78                              | 17.0  | 16.73                       | 19.6  | 18.90                         | 16.43 | 16.18                                    | 0.4  | 11.2                          | 0.6   | 0.4  | 7.18                                    | 6.82   | 0.27                    | 0.22 |                      |  |
| M12  | 1.75                                  | 4.0                    | 12.0 | 11.73                             | 19.0  | 18.67                       | 21.9  | 21.10                         | 18.37 | 18.12                                    | 0.4  | 14.2                          | 1.1   | 0.6  | 8.18                                    | 7.82   | 0.33                    | 0.27 |                      |  |
| (M14)  | 2                                     | 5.0                    | 14.0 | 13.73                             | 22.0  | 21.67                       | 25.4  | 24.49                         | 21.37 | 21.12                                    | 0.4  | 16.2                          | 1.1   | 0.6  | 9.18                                    | 8.82   | 0.33                    | 0.27 |                      |  |
| M16  | 2                                     | 5.0                    | 16.0 | 15.73                             | 24.0  | 23.67                       | 27.7  | 26.75                         | 23.27 | 23.02                                    | 0.4  | 18.2                          | 1.1   | 0.6  | 10.18                                   | 9.82   | 0.33                    | 0.27 |                      |  |
| (M18)  | 2.5                                   | 6.0                    | 18.0 | 17.73                             | 27.0  | 26.67                       | 31.2  | 30.14                         | 26.27 | 26.02                                    | 0.4  | 20.2                          | 1.1   | 0.6  | 12.215                                  | 11.785 | 0.33                    | 0.27 |                      |  |
| M20  | 2.5                                   | 6.0                    | 20.0 | 19.67                             | 30.0  | 29.67                       | 34.6  | 33.53                         | 29.27 | 28.80                                    | 0.4  | 22.4                          | 1.2   | 0.8  | 13.215                                  | 12.785 | 0.33                    | 0.33 |                      |  |
| (M22)  | 2.5                                   | 6.0                    | 22.0 | 21.67                             | 32.0  | 31.61                       | 36.9  | 35.72                         | 31.21 | 30.74                                    | 0.4  | 24.4                          | 1.2   | 0.8  | 14.215                                  | 13.785 | 0.39                    | 0.33 |                      |  |
| M24  | 3                                     | 7.0                    | 24.0 | 23.67                             | 36.0  | 35.38                       | 41.6  | 39.98                         | 34.98 | 34.51                                    | 0.5  | 26.4                          | 1.2   | 0.8  | 15.215                                  | 14.785 | 0.39                    | 0.33 |                      |  |
| (M27)  | 3                                     | 7.0                    | 27.0 | 26.67                             | 41.0  | 40.38                       | 47.3  | 45.63                         | 39.98 | 39.36                                    | 0.5  | 30.4                          | 1.7   | 1.0  | 17.215                                  | 16.785 | 0.39                    | 0.33 |                      |  |
| M30  | 3.5                                   | 8.0                    | 30.0 | 29.67                             | 46.0  | 45.38                       | 53.1  | 51.28                         | 44.98 | 44.36                                    | 0.5  | 33.4                          | 1.7   | 1.0  | 19.26                                   | 18.74  | 0.39                    | 0.33 |                      |  |
| (M33)  | 3.5                                   | 8.0                    | 33.0 | 32.61                             | 50.0  | 49.38                       | 57.7  | 55.80                         | 48.98 | 48.36                                    | 0.5  | 36.4                          | 1.7   | 1.0  | 21.26                                   | 20.74  | 0.39                    | 0.39 |                      |  |
| M36  | 4                                     | 10.0                   | 36.0 | 35.61                             | 55.0  | 54.26                       | 63.5  | 61.31                         | 53.86 | 53.24                                    | 0.5  | 39.4                          | 1.7   | 1.0  | 23.26                                   | 22.74  | 0.46                    | 0.39 |                      |  |
| (M39)  | 4                                     | 10.0                   | 39.0 | 38.61                             | 60.0  | 59.26                       | 69.3  | 66.96                         | 58.86 | 58.24                                    | 0.6  | 42.4                          | 1.7   | 1.0  | 25.26                                   | 24.74  | 0.46                    | 0.39 |                      |  |
| M42  | 4.5                                   | 11.0                   | 42.0 | 41.61                             | 65.0  | 64.26                       | 75.1  | 72.61                         | 63.76 | 63.04                                    | 0.6  | 45.6                          | 1.8   | 1.2  | 26.26                                   | 25.74  | 0.46                    | 0.39 |                      |  |
| (M45)  | 4.5                                   | 11.0                   | 45.0 | 44.61                             | 70.0  | 69.26                       | 80.8  | 78.26                         | 68.76 | 68.04                                    | 0.6  | 48.6                          | 1.8   | 1.2  | 28.26                                   | 27.74  | 0.46                    | 0.39 |                      |  |
| M48  | 5                                     | 12.0                   | 48.0 | 47.61                             | 75.0  | 74.26                       | 86.6  | 83.91                         | 73.76 | 73.04                                    | 0.6  | 52.6                          | 2.3   | 1.6  | 30.26                                   | 29.74  | 0.46                    | 0.39 |                      |  |
| (M52)  | 5                                     | 12.0                   | 52.0 | 51.54                             | 80.0  | 79.26                       | 92.4  | 89.56                         | ...   | ...                                      | ...  | 56.6                          | 2.3   | 1.6  | 33.31                                   | 32.69  | 0.46                    | 0.46 |                      |  |
| M56  | 5.5                                   | 19.0                   | 56.0 | 55.54                             | 85.0  | 84.13                       | 98.1  | 95.07                         | ...   | ...                                      | ...  | 63.0                          | 3.5   | 2.0  | 35.31                                   | 34.69  | 0.54                    | 0.46 |                      |  |
| (M60)  | 5.5                                   | 19.0                   | 60.0 | 59.54                             | 90.0  | 89.13                       | 103.9 | 100.72                        | ...   | ...                                      | ...  | 67.0                          | 3.5   | 2.0  | 38.31                                   | 37.69  | 0.54                    | 0.46 |                      |  |
| M64  | 6                                     | 21.0                   | 64.0 | 63.54                             | 95.0  | 94.13                       | 109.7 | 106.37                        | ...   | ...                                      | ...  | 71.0                          | 3.5   | 2.0  | 40.31                                   | 39.69  | 0.54                    | 0.46 |                      |  |
| (M68)  | 6                                     | 21.0                   | 68.0 | 67.54                             | 100.0 | 99.13                       | 115.5 | 112.02                        | ...   | ...                                      | ...  | 75.0                          | 3.5   | 2.0  | 43.31                                   | 42.69  | 0.54                    | 0.46 |                      |  |

<sup>a</sup> Sizes shown in parentheses are non-preferred.<sup>b</sup> A true radius is not essential provided that the curve is smooth and lies wholly within the maximum radius, determined from the maximum transitional diameter, and the minimum radius specified.All dimensions are in millimeters. For illustration of bolts and screws see [Table 3](#).

**Table 5. British Standard ISO Metric Precision Hexagon Nuts and Thin Nuts BS 3692:1967 (obsolescent)**

| Nominal Size and Thread Diameter <sup>a</sup><br><i>d</i> | Pitch of Thread (Coarse Pitch Series) | Width Across Flats<br><i>s</i> |       | Width Across Corners<br><i>e</i> |        | Thickness of Normal Nut<br><i>m</i> |       | Tolerance on Squareness of Thread to Face of Nut <sup>b</sup> | Eccentricity of Hexagon | Thickness of Thin Nut<br><i>t</i> |       |
|---|---------------------------------------|--------------------------------|-------|----------------------------------|--------|-------------------------------------|-------|---|-------------------------|-----------------------------------|-------|
|   |                                       | Max.                           | Min.  | Max.                             | Min.   | Max.                                | Min.  | Max.  |                         | Max.                              | Min.  |
| M1.6  | 0.35                                  | 3.20                           | 3.08  | 3.70                             | 3.48   | 1.30                                | 1.05  | 0.05  | 0.14                    | ...                               | ...   |
| M2  | 0.4                                   | 4.00                           | 3.88  | 4.60                             | 4.38   | 1.60                                | 1.35  | 0.06  | 0.14                    | ...                               | ...   |
| M2.5  | 0.45                                  | 5.00                           | 4.88  | 5.80                             | 5.51   | 2.00                                | 1.75  | 0.08  | 0.14                    | ...                               | ...   |
| M3  | 0.5                                   | 5.50                           | 5.38  | 6.40                             | 6.08   | 2.40                                | 2.15  | 0.09  | 0.14                    | ...                               | ...   |
| M4  | 0.7                                   | 7.00                           | 6.85  | 8.10                             | 7.74   | 3.20                                | 2.90  | 0.11  | 0.18                    | ...                               | ...   |
| M5  | 0.8                                   | 8.00                           | 7.85  | 9.20                             | 8.87   | 4.00                                | 3.70  | 0.13  | 0.18                    | ...                               | ...   |
| M6  | 1                                     | 10.00                          | 9.78  | 11.50                            | 11.05  | 5.00                                | 4.70  | 0.17  | 0.18                    | ...                               | ...   |
| M8  | 1.25                                  | 13.00                          | 12.73 | 15.00                            | 14.38  | 6.50                                | 6.14  | 0.22  | 0.22                    | 5.0                               | 4.70  |
| M10   | 1.5                                   | 17.00                          | 16.73 | 19.60                            | 18.90  | 8.00                                | 7.64  | 0.29  | 0.22                    | 6.0                               | 5.70  |
| M12   | 1.75                                  | 19.00                          | 18.67 | 21.90                            | 21.10  | 10.00                               | 9.64  | 0.32  | 0.27                    | 7.0                               | 6.64  |
| (M14)   | 2                                     | 22.00                          | 21.67 | 25.4                             | 24.49  | 11.00                               | 10.57 | 0.37  | 0.27                    | 8.0                               | 7.64  |
| M16   | 2                                     | 24.00                          | 23.67 | 27.7                             | 6.75   | 13.00                               | 12.57 | 0.41  | 0.27                    | 8.0                               | 7.64  |
| (M18)   | 2.5                                   | 27.00                          | 26.67 | 31.20                            | 30.14  | 15.00                               | 14.57 | 0.46  | 0.27                    | 9.0                               | 8.64  |
| M20   | 2.5                                   | 30.00                          | 29.67 | 34.60                            | 33.53  | 16.00                               | 15.57 | 0.51  | 0.33                    | 9.0                               | 8.64  |
| (M22)   | 2.5                                   | 32.00                          | 31.61 | 36.90                            | 35.72  | 18.00                               | 17.57 | 0.54  | 0.33                    | 10.0                              | 9.64  |
| M24   | 3                                     | 36.00                          | 35.38 | 41.60                            | 39.98  | 19.00                               | 18.48 | 0.61  | 0.33                    | 10.0                              | 9.64  |
| (M27)   | 3                                     | 41.00                          | 40.38 | 47.3                             | 45.63  | 22.00                               | 21.48 | 0.70  | 0.33                    | 12.0                              | 11.57 |
| M30   | 3.5                                   | 46.00                          | 45.38 | 53.1                             | 51.28  | 24.00                               | 23.48 | 0.78  | 0.33                    | 12.0                              | 11.57 |
| (M33)   | 3.5                                   | 50.00                          | 49.38 | 57.0                             | 55.80  | 26.00                               | 25.48 | 0.85  | 0.39                    | 14.0                              | 13.57 |
| M36   | 4                                     | 55.00                          | 54.26 | 63.50                            | 61.31  | 29.00                               | 28.48 | 0.94  | 0.39                    | 14.0                              | 13.57 |
| (M39)   | 4                                     | 60.00                          | 59.26 | 69.30                            | 66.96  | 31.00                               | 30.38 | 1.03  | 0.39                    | 16.0                              | 15.57 |
| M42   | 4.5                                   | 65.00                          | 64.26 | 75.10                            | 72.61  | 34.00                               | 33.38 | 1.11  | 0.39                    | 16.0                              | 15.57 |
| (M45)   | 4.5                                   | 70.00                          | 69.26 | 80.80                            | 78.26  | 36.00                               | 35.38 | 1.20  | 0.39                    | 18.0                              | 17.57 |
| M48   | 5                                     | 75.00                          | 74.26 | 86.60                            | 83.91  | 38.00                               | 37.38 | 1.29  | 0.39                    | 18.0                              | 17.57 |
| (M52)   | 5                                     | 80.00                          | 79.26 | 92.40                            | 89.56  | 42.00                               | 41.38 | 1.37  | 0.46                    | 20.0                              | 19.48 |
| M56   | 5.5                                   | 85.00                          | 84.13 | 98.10                            | 95.07  | 45.00                               | 44.38 | 1.46  | 0.46                    | ...                               | ...   |
| (M60)   | 5.5                                   | 90.00                          | 89.13 | 103.90                           | 100.72 | 48.00                               | 47.38 | 1.55  | 0.46                    | ...                               | ...   |
| M64   | 6                                     | 95.00                          | 94.13 | 109.70                           | 106.37 | 51.00                               | 50.26 | 1.63  | 0.46                    | ...                               | ...   |
| (M68)   | 6                                     | 100.00                         | 99.13 | 115.50                           | 112.02 | 54.00                               | 53.26 | 1.72  | 0.46                    | ...                               | ...   |

<sup>a</sup> Sizes shown in parentheses are non-preferred.<sup>b</sup> As measured with the nut squareness gage described in the text and illustrated in Appendix A of the Standard and a feeler gage.All dimensions are in millimeters. For illustration of hexagon nuts and thin nuts see [Table 3](#).

**Table 6. British Standard ISO Metric Precision Hexagon Slotted Nuts and Castle Nuts BS 3692:1967 (obsolescent)**

| Nominal Size and Thread Diameter <sup>a</sup><br><i>d</i> | Width Across Flats<br><i>s</i> |       | Width Across Corners<br><i>e</i> |        | Diameter<br><i>d<sub>2</sub></i> |       | Thickness<br><i>h</i> |       | Lower Face of Nut to Bottom of Slot<br><i>m</i> |       | Width of Slot<br><i>n</i> |      | Radius (0.25 <i>n</i> )<br><i>r</i> | Eccentricity of the Slots |
|---|--------------------------------|-------|----------------------------------|--------|----------------------------------|-------|-----------------------|-------|---|-------|---------------------------|------|-------------------------------------|---------------------------|
|   | Max.                           | Min.  | Max.                             | Min.   | Max.                             | Min.  | Max.                  | Min.  | Max.  | Min.  | Max.                      | Min. | Min.                                | Max.                      |
| M4  | 7.00                           | 6.85  | 8.10                             | 7.74   | ...                              | ...   | 5                     | 4.70  | 3.2   | 2.90  | 1.45                      | 1.2  | 0.3                                 | 0.18                      |
| M5  | 8.00                           | 7.85  | 9.20                             | 8.87   | ...                              | ...   | 6                     | 5.70  | 4.0   | 3.70  | 1.65                      | 1.4  | 0.35                                | 0.18                      |
| M6  | 10.00                          | 9.78  | 11.50                            | 11.05  | ...                              | ...   | 7.5                   | 7.14  | 5   | 4.70  | 2.25                      | 2    | 0.5                                 | 0.18                      |
| M8  | 13.00                          | 12.73 | 15.00                            | 14.38  | ...                              | ...   | 9.5                   | 9.14  | 6.5   | 6.14  | 2.75                      | 2.5  | 0.625                               | 0.22                      |
| M10   | 17.00                          | 16.73 | 19.60                            | 18.90  | ...                              | ...   | 12                    | 11.57 | 8   | 7.64  | 3.05                      | 2.8  | 0.70                                | 0.22                      |
| M12   | 19.00                          | 18.67 | 21.90                            | 21.10  | 17                               | 16.57 | 15                    | 14.57 | 10  | 9.64  | 3.80                      | 3.5  | 0.875                               | 0.27                      |
| (M14)   | 22.00                          | 21.67 | 25.4                             | 24.49  | 19                               | 18.48 | 16                    | 15.57 | 11  | 10.57 | 3.80                      | 3.5  | 0.875                               | 0.27                      |
| M16   | 24.00                          | 23.67 | 27.7                             | 26.75  | 22                               | 21.48 | 19                    | 18.48 | 13  | 12.57 | 4.80                      | 4.5  | 1.125                               | 0.27                      |
| (M18)   | 27.00                          | 26.67 | 31.20                            | 30.14  | 25                               | 24.48 | 21                    | 20.48 | 15  | 14.57 | 4.80                      | 4.5  | 1.125                               | 0.27                      |
| M20   | 30.00                          | 29.67 | 34.60                            | 33.53  | 28                               | 27.48 | 22                    | 21.48 | 16  | 15.57 | 4.80                      | 4.5  | 1.125                               | 0.33                      |
| (M22)   | 32.00                          | 31.61 | 36.90                            | 35.72  | 30                               | 29.48 | 26                    | 25.48 | 18  | 17.57 | 5.80                      | 5.5  | 1.375                               | 0.33                      |
| M24   | 36.00                          | 35.38 | 41.60                            | 39.98  | 34                               | 33.38 | 27                    | 26.48 | 19  | 18.48 | 5.80                      | 5.5  | 1.375                               | 0.33                      |
| (M27)   | 41.00                          | 40.38 | 47.3                             | 45.63  | 38                               | 37.38 | 30                    | 29.48 | 22  | 21.48 | 5.80                      | 5.5  | 1.375                               | 0.33                      |
| M30   | 46.00                          | 45.38 | 53.1                             | 51.28  | 42                               | 41.38 | 33                    | 32.38 | 24  | 23.48 | 7.36                      | 7    | 1.75                                | 0.33                      |
| (M33)   | 50.00                          | 49.38 | 57.70                            | 55.80  | 46                               | 45.38 | 35                    | 34.38 | 26  | 25.48 | 7.36                      | 7    | 1.75                                | 0.39                      |
| M36   | 55.00                          | 54.26 | 63.50                            | 61.31  | 50                               | 49.38 | 38                    | 37.38 | 29  | 28.48 | 7.36                      | 7    | 1.75                                | 0.39                      |
| (M39)   | 60.00                          | 59.26 | 69.30                            | 66.96  | 55                               | 54.26 | 40                    | 39.38 | 31  | 30.38 | 7.36                      | 7    | 1.75                                | 0.39                      |
| M42   | 65.00                          | 64.26 | 75.10                            | 72.61  | 58                               | 57.26 | 46                    | 45.38 | 34  | 33.38 | 9.36                      | 9    | 2.25                                | 0.39                      |
| (M45)   | 70.00                          | 69.26 | 80.80                            | 78.26  | 62                               | 61.26 | 48                    | 47.38 | 36  | 35.38 | 9.36                      | 9    | 2.25                                | 0.39                      |
| M48   | 75.00                          | 74.26 | 86.60                            | 83.91  | 65                               | 64.26 | 50                    | 49.38 | 38  | 37.38 | 9.36                      | 9    | 2.25                                | 0.39                      |
| (M52)   | 80.00                          | 79.26 | 92.40                            | 89.56  | 70                               | 69.26 | 54                    | 53.26 | 42  | 41.38 | 9.36                      | 9    | 2.25                                | 0.46                      |
| M56   | 85.00                          | 84.13 | 98.10                            | 95.07  | 75                               | 74.26 | 57                    | 56.26 | 45  | 44.38 | 9.36                      | 9    | 2.25                                | 0.46                      |
| (M60)   | 90.00                          | 89.13 | 103.90                           | 100.72 | 80                               | 79.26 | 63                    | 62.26 | 48  | 47.38 | 11.43                     | 11   | 2.75                                | 0.46                      |
| M64   | 95.00                          | 94.13 | 109.70                           | 106.37 | 85                               | 84.13 | 66                    | 65.26 | 51  | 50.26 | 11.43                     | 11   | 2.75                                | 0.46                      |
| (M68)   | 100.00                         | 99.13 | 115.50                           | 112.02 | 90                               | 89.13 | 69                    | 68.26 | 54  | 53.26 | 11.43                     | 11   | 2.75                                | 0.46                      |

<sup>a</sup> Sizes shown in parentheses are non-preferred.

All dimensions are in millimeters. For illustration of hexagon slotted nuts and castle nuts see [Table 3](#).

After several years of use of BS 2693:Part 1:1956 (obsolescent), it was recognized that it would not meet the requirements of all stud users. The thread tolerances specified could result in clearance of interference fits because locking depended on the run-out threads. Thus, some users felt that true interference fits were essential for their needs. As a result, the British Standards Committee has incorporated the Class 5 interference fit threads specified in American Standard ASA B1.12 into the BS 2693:Part 2:1964, "Recommendations for High Grade Studs."

**British Standard ISO Metric Precision Hexagon Bolts, Screws and Nuts.**—This British Standard BS 3692:1967 (obsolescent) gives the general dimensions and tolerances of precision hexagon bolts, screws and nuts with ISO metric threads in diameters from 1.6 to 68 mm. It is based on the following ISO recommendations and draft recommendations: R 272, R 288, DR 911, DR 947, DR 950, DR 952 and DR 987. Mechanical properties are given only with respect to carbon or alloy steel bolts, screws and nuts, which are not to be used for special applications such as those requiring weldability, corrosion resistance or ability to withstand temperatures above 300°C or below -50°C. The dimensional requirements of this standard also apply to non-ferrous and stainless steel bolts, screws and nuts.

*Finish:* Finishes may be dull black which results from the heat-treating operation or may be bright finish, the result of bright drawing. Other finishes are possible by mutual agreement between purchaser and producer. It is recommended that reference be made to BS 3382 "Electroplated Coatings on Threaded Components" in this respect.

*General Dimensions:* The bolts, screws and nuts conform to the general dimensions given in Tables 3, 4, 5 and 6.

*Nominal Lengths of Bolts and Screws:* The nominal length of a bolt or screw is the distance from the underside of the head to the extreme end of the shank including any chamfer or radius. Standard nominal lengths and tolerances thereon are given in Table 7.

**Table 7. British Standard ISO Metric Bolt and Screw Nominal Lengths**  
*BS 3692:1967 (obsolescent)*

| Nominal Length <sup>a</sup><br><i>l</i> | Tolerance | Nominal Length <sup>a</sup><br><i>l</i> | Tolerance | Nominal Length <sup>a</sup><br><i>l</i> | Tolerance | Nominal Length <sup>a</sup><br><i>l</i> | Tolerance |
|---|-----------|---|-----------|---|-----------|---|-----------|
| 5                                       | ± 0.24    | 30                                      | ± 0.42    | 90                                      | ± 0.70    | 200                                     | ± 0.925   |
| 6                                       | ± 0.24    | (32)                                    | ± 0.50    | (95)                                    | ± 0.70    | 220                                     | ± 0.925   |
| (7)                                     | ± 0.29    | 35                                      | ± 0.50    | 100                                     | ± 0.70    | 240                                     | ± 0.925   |
| 8                                       | ± 0.29    | (38)                                    | ± 0.50    | (105)                                   | ± 0.70    | 260                                     | ± 1.05    |
| (9)                                     | ± 0.29    | 40                                      | ± 0.50    | 110                                     | ± 0.70    | 280                                     | ± 1.05    |
| 10                                      | ± 0.29    | 45                                      | ± 0.50    | (115)                                   | ± 0.70    | 300                                     | ± 1.05    |
| (11)                                    | ± 0.35    | 50                                      | ± 0.50    | 120                                     | ± 0.70    | 325                                     | ± 1.15    |
| 12                                      | ± 0.35    | 55                                      | ± 0.60    | (125)                                   | ± 0.80    | 350                                     | ± 1.15    |
| 14                                      | ± 0.35    | 60                                      | ± 0.60    | 130                                     | ± 0.80    | 375                                     | ± 1.15    |
| 16                                      | ± 0.35    | 65                                      | ± 0.60    | 140                                     | ± 0.80    | 400                                     | ± 1.15    |
| (18)                                    | ± 0.35    | 70                                      | ± 0.60    | 150                                     | ± 0.80    | 425                                     | ± 1.25    |
| 20                                      | ± 0.42    | 75                                      | ± 0.60    | 160                                     | ± 0.80    | 450                                     | ± 1.25    |
| (22)                                    | ± 0.42    | 80                                      | ± 0.60    | 170                                     | ± 0.80    | 475                                     | ± 1.25    |
| 25                                      | ± 0.42    | 85                                      | ± 0.70    | 180                                     | ± 0.80    | 500                                     | ± 1.25    |
| (28)                                    | ± 0.42    | ...                                     | ...       | 190                                     | ± 0.925   | ...                                     | ...       |

<sup>a</sup> Nominal lengths shown in parentheses are non-preferred.

All dimensions are in millimeters.

*Bolt and Screw Ends:* The ends of bolts and screws may be finished with either a 45-degree chamfer to a depth slightly exceeding the depth of thread or a radius approximately

equal to  $1\frac{1}{4}$  times the nominal diameter of the shank. With rolled threads, the lead formed at the end of the bolt by the thread rolling operation may be regarded as providing the necessary chamfer to the end; the end being reasonably square with the center line of the shank.

*Screw Thread Form:* The form of thread and diameters and associated pitches of standard ISO metric bolts, screws, and nuts are in accordance with BS 3643:Part 1:1981 (1998), "Principles and Basic Data" The screw threads are made to the tolerances for the medium class of fit (6H/6g) as specified in BS 3643:Part 2:1981 (1998), "Specification for Selected Limits of Size."

*Length of Thread on Bolts:* The length of thread on bolts is the distance from the end of the bolt (including any chamfer or radius) to the leading face of a screw ring gage which has been screwed as far as possible onto the bolt by hand. Standard thread lengths of bolts are  $2d + 6$  mm for a nominal length of bolt up to and including 125 mm,  $2d + 12$  mm for a nominal bolt length over 125 mm up to and including 200 mm, and  $2d + 25$  mm for a nominal bolt length over 200 mm. Bolts that are too short for minimum thread lengths are threaded as screws and designated as screws. The tolerance on bolt thread lengths are plus two pitches for all diameters.

*Length of Thread on Screws:* Screws are threaded to permit a screw ring gage being screwed by hand to within a distance from the underside of the head not exceeding two and a half times the pitch for diameters up to and including 52 mm and three and a half times the pitch for diameters over 52 mm.

*Angularity and Eccentricity of Bolts, Screws and Nuts:* The axis of the thread of the nut is square to the face of the nut subject to the "squareness tolerance" given in Table 5.

In gaging, the nut is screwed by hand onto a gage, having a truncated taper thread, until the thread of the nut is tight on the thread of the gage. A sleeve sliding on a parallel extension of the gage, which has a face of diameter equal to the minimum distance across the flats of the nut and exactly at 90 degrees to the axis of the gage, is brought into contact with the leading face of the nut. With the sleeve in this position, it should not be possible for a feeler gage of thickness equal to the "squareness tolerance" to enter anywhere between the leading nut face and sleeve face.

The hexagon flats of bolts, screws and nuts are square to the bearing face, and the angularity of the head is within the limits of 90 degrees, plus or minus 1 degree. The eccentricity of the hexagon flats of nuts relative to the thread diameter should not exceed the values given in Table 5 and the eccentricity of the head relative to the width across flats and eccentricity between the shank and thread of bolts and screws should not exceed the values given in Table 4.

*Chamfering, Washer Facing and Countersinking:* Bolt and screw heads have a chamfer of approximately 30 degrees on their upper faces and, at the option of the manufacturer, a washer face or full bearing face on the underside. Nuts are countersunk at an included angle of 120 degrees plus or minus 10 degrees at both ends of the thread. The diameter of the countersink should not exceed the nominal major diameter of the thread plus 0.13 mm up to and including 12 mm diameter, and plus 0.25 mm above 12 mm diameter. This stipulation does not apply to slotted, castle or thin nuts.

*Strength Grade Designation System for Steel Bolts and Screws:* This Standard includes a strength grade designation system consisting of two figures. The first figure is one tenth of the minimum tensile strength in  $\text{kgf/mm}^2$ , and the second figure is one tenth of the ratio between the minimum yield stress (or stress at permanent set limit,  $R_{0.2}$ ) and the minimum tensile strength, expressed as a percentage. For example with the strength designation grade 8.8, the first figure 8 represents  $\frac{1}{10}$  the minimum tensile strength of 80  $\text{kgf/mm}^2$  and the second figure 8 represents  $\frac{1}{10}$  the ratio



$$\frac{\text{stress at permanent set limit } R_{0.2}\%}{\text{minimum tensile strength}} = \frac{1}{10} \times \frac{64}{80} \times \frac{100}{1}$$

the numerical values of stress and strength being obtained from the accompanying table.

### Strength Grade Designations of Steel Bolts and Screws

| Strength Grade Designation                        | 4.6 | 4.8 | 5.6 | 5.8 | 6.6 | 6.8 | 8.8 | 10.9 | 12.9 | 14.9 |
|---|-----|-----|-----|-----|-----|-----|-----|------|------|------|
| Tensile Strength ( $R_m$ ), Min.                  | 40  | 40  | 50  | 50  | 60  | 60  | 80  | 100  | 120  | 140  |
| Yield Stress ( $R_e$ ), Min.                      | 24  | 32  | 30  | 40  | 36  | 48  | ... | ...  | ...  | ...  |
| Stress at Permanent Set Limit ( $R_{0.2}$ ), Min. | ... | ... | ... | ... | ... | ... | 64  | 90   | 108  | 126  |

All stress and strength values are in kgf/mm<sup>2</sup> units.

**Strength Grade Designation System for Steel Nuts:** The strength grade designation system for steel nuts is a number which is one-tenth of the specified proof load stress in kgf/mm<sup>2</sup>. The proof load stress corresponds to the minimum tensile strength of the highest grade of bolt or screw with which the nut can be used.

### Strength Grade Designations of Steel Nuts

| Strength Grade Designation               | 4  | 5  | 6  | 8  | 12  | 14  |
|--|----|----|----|----|-----|-----|
| Proof Load Stress (kgf/mm <sup>2</sup> ) | 40 | 50 | 60 | 80 | 120 | 140 |

### Recommended Bolt and Nut Combinations

| Grade of Bolt            | 4.6 | 4.8 | 5.6 | 5.8 | 6.6 | 6.8 | 8.8 | 10.9 | 12.9 | 14.9 |
|--------------------------|-----|-----|-----|-----|-----|-----|-----|------|------|------|
| Recommended Grade of Nut | 4   | 4   | 5   | 5   | 6   | 6   | 8   | 12   | 12   | 14   |

*Note:* Nuts of a higher strength grade may be substituted for nuts of a lower strength grade.

**Marking:** The marking and identification requirements of this Standard are only mandatory for steel bolts, screws and nuts of 6 mm diameter and larger; manufactured to strength grade designations 8.8 (for bolts or screws) and 8 (for nuts) or higher. Bolts and screws are identified as ISO metric by either of the symbols "ISO M" or "M", embossed or indented on top of the head. Nuts may be indented or embossed by alternative methods depending on their method of manufacture.

**Designation:** Bolts 10 mm diameter, 50 mm long manufactured from steel of strength grade 8.8, would be designated:

"Bolts M10 × 50 to BS 3692 — 8.8."

Brass screws 8 mm diameter, 20 mm long would be designated:

"Brass screws M8 × 20 to BS 3692."

Nuts 12 mm diameter, manufactured from steel of strength grade 6, cadmium plated could be designated:

"Nuts M12 to BS 3692 — 6, plated to BS 3382: Part 1."

**Miscellaneous Information:** The Standard also gives mechanical properties of steel bolts, screws and nuts [i.e., tensile strengths; hardnesses (Brinell, Rockwell, Vickers); stresses (yield, proof load); etc.], material and manufacture of steel bolts, screws and nuts; and information on inspection and testing. Appendices to the Standard give information on gaging; chemical composition; testing of mechanical properties; examples of marking of bolts, screws and nuts; and a table of preferred standard sizes of bolts and screws, to name some.

**British Standard General Purpose Studs BS 2693:Part 1:1956 (obsolescent)**

| Limits for End Screwed into Component (All threads except BA) |            |               |             |                    |        |                |        |               |             |                    |        |            |        |  |
|---|------------|---------------|-------------|--------------------|--------|----------------|--------|---------------|-------------|--------------------|--------|------------|--------|--|
| Nom. Stud Dia. D  | Major Dia. | Thds. per In. |             | Effective Diameter |        | Minor Diameter |        | Thds. per In. | Major Dia.  | Effective Diameter |        | Minor Dia. |        |  |
|   |            | Max.          | Min.        | Max.               | Min.   | Max.           | Min.   |               |             | Max.               | Min.   |            |        |  |
| UN THREADS  |            |               | UNF THREADS |                    |        |                |        |               | UNC THREADS |                    |        |            |        |  |
| 1/4   | 0.2500     | 28            | 0.2435      | 0.2294             | 0.2265 | 0.2088         | 0.2037 | 20            | 0.2419      | 0.2201             | 0.2172 | 0.1913     | 0.1849 |  |
| 5/16  | 0.3125     | 24            | 0.3053      | 0.2883             | 0.2852 | 0.2643         | 0.2586 | 18            | 0.3038      | 0.2793             | 0.2762 | 0.2472     | 0.2402 |  |
| 3/8   | 0.3750     | 24            | 0.3678      | 0.3510             | 0.3478 | 0.3270         | 0.3211 | 16            | 0.3656      | 0.3375             | 0.3343 | 0.3014     | 0.2936 |  |
| 7/16  | 0.4375     | 20            | 0.4294      | 0.4084             | 0.4050 | 0.3796         | 0.3729 | 14            | 0.4272      | 0.3945             | 0.3911 | 0.3533     | 0.3447 |  |
| 1/2   | 0.5000     | 20            | 0.4919      | 0.4712             | 0.4675 | 0.4424         | 0.4356 | 13            | 0.4891      | 0.4537             | 0.4500 | 0.4093     | 0.4000 |  |
| 9/16  | 0.5625     | 18            | 0.5538      | 0.5302             | 0.5264 | 0.4981         | 0.4907 | 12            | 0.5511      | 0.5122             | 0.5084 | 0.4641     | 0.4542 |  |
| 5/8   | 0.6250     | 18            | 0.6163      | 0.5929             | 0.5889 | 0.5608         | 0.5533 | 11            | 0.6129      | 0.5700             | 0.5660 | 0.5175     | 0.5069 |  |
| 3/4   | 0.7500     | 16            | 0.7406      | 0.7137             | 0.7094 | 0.6776         | 0.6693 | 10            | 0.7371      | 0.6893             | 0.6850 | 0.6316     | 0.6200 |  |
| 7/8   | 0.8750     | 14            | 0.8647      | 0.8332             | 0.8286 | 0.7920         | 0.7828 | 9             | 0.8611      | 0.8074             | 0.8028 | 0.7433     | 0.7306 |  |
| 1   | 1.0000     | 12            | 0.9886      | 0.9510             | 0.9459 | 0.9029         | 0.8925 | 8             | 0.9850      | 0.9239             | 0.9188 | 0.8517     | 0.8376 |  |
| 1 1/8   | 1.1250     | 12            | 1.1136      | 1.0762             | 1.0709 | 1.0281         | 1.0176 | 7             | 1.1086      | 1.0375             | 1.0322 | 0.9550     | 0.9393 |  |
| 1 1/4   | 1.2500     | 12            | 1.2386      | 1.2014             | 1.1959 | 1.1533         | 1.1427 | 7             | 1.2336      | 1.1627             | 1.1572 | 1.0802     | 1.0644 |  |
| 1 3/8   | 1.3750     | 12            | 1.3636      | 1.3265             | 1.3209 | 1.2784         | 1.2677 | 6             | 1.3568      | 1.2723             | 1.2667 | 1.1761     | 1.1581 |  |
| 1 1/2   | 1.5000     | 12            | 1.4886      | 1.4517             | 1.4459 | 1.4036         | 1.3928 | 6             | 1.4818      | 1.3975             | 1.3917 | 1.3013     | 1.2832 |  |
| BS THREADS  |            |               | BSF THREADS |                    |        |                |        |               | BSW THREADS |                    |        |            |        |  |
| 1/4   | 0.2500     | 26            | 0.2455      | 0.2280             | 0.2251 | 0.2034         | 0.1984 | 20            | 0.2452      | 0.2206             | 0.2177 | 0.1886     | 0.1831 |  |
| 5/16  | 0.3125     | 22            | 0.3077      | 0.2863             | 0.2832 | 0.2572         | 0.2517 | 18            | 0.3073      | 0.2798             | 0.2767 | 0.2442     | 0.2383 |  |
| 3/8   | 0.3750     | 20            | 0.3699      | 0.3461             | 0.3429 | 0.3141         | 0.3083 | 16            | 0.3695      | 0.3381             | 0.3349 | 0.0981     | 0.2919 |  |
| 7/16  | 0.4375     | 18            | 0.4320      | 0.4053             | 0.4019 | 0.3697         | 0.3635 | 14            | 0.4316      | 0.3952             | 0.3918 | 0.3495     | 0.3428 |  |
| 1/2   | 0.5000     | 16            | 0.4942      | 0.4637             | 0.4600 | 0.4237         | 0.4172 | 12            | 0.4937      | 0.4503             | 0.4466 | 0.3969     | 0.3897 |  |
| 9/16  | 0.5625     | 16            | 0.5566      | 0.5263             | 0.5225 | 0.4863         | 0.4797 | 12            | 0.5560      | 0.5129             | 0.5091 | 0.4595     | 0.4521 |  |
| 5/8   | 0.6250     | 14            | 0.6187      | 0.5833             | 0.5793 | 0.5376         | 0.5305 | 11            | 0.6183      | 0.5708             | 0.5668 | 0.5126     | 0.5050 |  |
| 3/4   | 0.7500     | 12            | 0.7432      | 0.7009             | 0.6966 | 0.6475         | 0.6398 | 10            | 0.7428      | 0.6903             | 0.6860 | 0.6263     | 0.6182 |  |
| 7/8   | 0.8750     | 11            | 0.8678      | 0.8214             | 0.8168 | 0.7632         | 0.7551 | 9             | 0.8674      | 0.8085             | 0.8039 | 0.7374     | 0.7288 |  |
| 1   | 1.0000     | 10            | 0.9924      | 0.9411             | 0.9360 | 0.8771         | 0.8686 | 8             | 0.9920      | 0.9251             | 0.9200 | 0.8451     | 0.8360 |  |
| 1 1/8   | 1.1250     | 9             | 1.1171      | 1.0592             | 1.0539 | 0.9881         | 0.9792 | 7             | 1.1164      | 1.0388             | 1.0335 | 0.9473     | 0.9376 |  |
| 1 1/4   | 1.2500     | 9             | 1.2419      | 1.1844             | 1.1789 | 1.1133         | 1.1042 | 7             | 1.2413      | 1.1640             | 1.1585 | 1.0725     | 1.0627 |  |
| 1 3/8   | 1.3750     | 8             | 1.3665      | 1.3006             | 1.2950 | 1.2206         | 1.2110 | 6             | 1.4906      | 1.3991             | 1.3933 | 1.2924     | 1.2818 |  |
| 1 1/2   | 1.5000     | 8             | 1.4913      | 1.4258             | 1.4200 | 1.3458         | 1.3360 | ...           | ...         | ...                | ...    | ...        | ...    |  |

Limits for End Screwed into Component (BA Threads)<sup>a</sup>

| Designation No. | Pitch       | Major Diameter |            | Effective Diameter |            | Minor Diameter |            |
|-----------------|-------------|----------------|------------|--------------------|------------|----------------|------------|
|                 |             | Max.           | Min.       | Max.               | Min.       | Max.           | Min.       |
| 2               | 0.8100 mm   | 4.700 mm       | 4.580 mm   | 4.275 mm           | 4.200 mm   | 3.790 mm       | 3.620 mm   |
|                 | 0.03189 in. | 0.1850 in.     | 0.1803 in. | 0.1683 in.         | 0.1654 in. | 0.1492 in.     | 0.1425 in. |
| 4               | 0.6600 mm   | 3.600 mm       | 3.500 mm   | 3.260 mm           | 3.190 mm   | 2.865 mm       | 2.720 mm   |
|                 | 0.2598 in.  | 0.1417 in.     | 0.1378 in. | 0.1283 in.         | 0.1256 in. | 0.1128 in.     | 0.1071 in. |

<sup>a</sup> Approximate inch equivalents are shown below the dimensions given in mm.

Minimum Nominal Lengths of Studs<sup>a</sup>

| Nom. Stud Dia. | For Thread Length (Component End) of |       | Nom. Stud Dia. | For Thread Length (Component End) of |       | Nom. Stud Dia. | For Thread Length (Component End) of |       |
|----------------|--------------------------------------|-------|----------------|--------------------------------------|-------|----------------|--------------------------------------|-------|
|                | 1D                                   | 1.5D  |                | 1D                                   | 1.5D  |                | 1D                                   | 1.5D  |
| 1/4            | 7/8                                  | 1     | 9/16           | 2                                    | 2 3/8 | 1 1/8          | 4                                    | 4 3/8 |
| 5/16           | 1 1/8                                | 1 3/8 | 5/8            | 2 1/4                                | 2 5/8 | 1 1/4          | 4 3/4                                | 5 1/2 |
| 3/8            | 1 3/8                                | 1 5/8 | 3/4            | 2 5/8                                | 3     | 1 3/8          | 5                                    | 5 3/4 |
| 7/16           | 1 5/8                                | 1 7/8 | 7/8            | 3 1/8                                | 3 5/8 | 1 1/2          | 5 1/4                                | 6     |
| 1/2            | 1 3/4                                | 2     | 1              | 3 1/2                                | 4     | ...            | ...                                  | ...   |

<sup>a</sup> The standard also gives preferred and standard lengths of studs: Preferred lengths of studs: 7/8, 1, 1 1/8, 1 1/4, 1 3/8, 1 1/2, 1 3/4, 2, 2 1/4, 2 1/2, 2 3/4, 3, 3 1/4, 3 1/2 and for lengths above 3 1/2 the preferred increment is 1/2. Standard lengths of studs: 7/8, 1, 1 1/8, 1 1/4, 1 3/8, 1 1/2, 1 5/8, 1 3/4, 1 7/8, 2, 2 1/8, 2 1/4, 2 3/8, 2 1/2, 2 5/8, 2 3/4, 2 7/8, 3, 3 1/8, 3 1/4, 3 3/8, 3 1/2 and for lengths above 3 1/2 the standard increment is 1/4.

All dimensions are in inches except where otherwise noted.  
See page 1877 for interference-fit threads.

**British Standard Single Coil Rectangular Section Spring Washers  
Metric Series — Types B and BP BS 4464:1969 (1998)**

$h_1 = (2s + 2k) \pm 15\%$      $h_2 = 2s \pm 15\%$

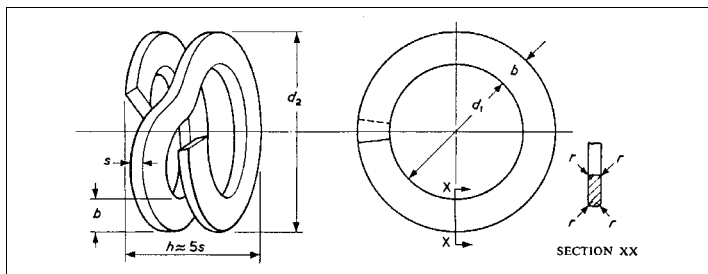
**Type BP                      Type B**

**Section X X**

| Nom. Size & Thread Dia., $d$ | Inside Dia., $d_1$ |      | Width, $b$     | Thickness, $s$ | Outside Dia., $d_2$ Max | Radius, $r$ Max | $k$ (Type BP Only) |
|------------------------------|--------------------|------|----------------|----------------|-------------------------|-----------------|--------------------|
|                              | Max                | Min  |                |                |                         |                 |                    |
| M1.6                         | 1.9                | 1.7  | $0.7 \pm 0.1$  | $0.4 \pm 0.1$  | 3.5                     | 0.15            | ...                |
| M2                           | 2.3                | 2.1  | $0.9 \pm 0.1$  | $0.5 \pm 0.1$  | 4.3                     | 0.15            | ...                |
| (M2.2)                       | 2.5                | 2.3  | $1.0 \pm 0.1$  | $0.6 \pm 0.1$  | 4.7                     | 0.2             | ...                |
| M2.5                         | 2.8                | 2.6  | $1.0 \pm 0.1$  | $0.6 \pm 0.1$  | 5.0                     | 0.2             | ...                |
| M3                           | 3.3                | 3.1  | $1.3 \pm 0.1$  | $0.8 \pm 0.1$  | 6.1                     | 0.25            | ...                |
| (M3.5)                       | 3.8                | 3.6  | $1.3 \pm 0.1$  | $0.8 \pm 0.1$  | 6.6                     | 0.25            | 0.15               |
| M4                           | 4.35               | 4.1  | $1.5 \pm 0.1$  | $0.9 \pm 0.1$  | 7.55                    | 0.3             | 0.15               |
| M5                           | 5.35               | 5.1  | $1.8 \pm 0.1$  | $1.2 \pm 0.1$  | 9.15                    | 0.4             | 0.15               |
| M6                           | 6.4                | 6.1  | $2.5 \pm 0.15$ | $1.6 \pm 0.1$  | 11.7                    | 0.5             | 0.2                |
| M8                           | 8.55               | 8.2  | $3 \pm 0.15$   | $2 \pm 0.1$    | 14.85                   | 0.65            | 0.3                |
| M10                          | 10.6               | 10.2 | $3.5 \pm 0.2$  | $2.2 \pm 0.15$ | 18.0                    | 0.7             | 0.3                |
| M12                          | 12.6               | 12.2 | $4 \pm 0.2$    | $2.5 \pm 0.15$ | 21.0                    | 0.8             | 0.4                |
| (M14)                        | 14.7               | 14.2 | $4.5 \pm 0.2$  | $3 \pm 0.15$   | 24.1                    | 1.0             | 0.4                |
| M16                          | 16.9               | 16.3 | $5 \pm 0.2$    | $3.5 \pm 0.2$  | 27.3                    | 1.15            | 0.4                |
| (M18)                        | 19.0               | 18.3 | $5 \pm 0.2$    | $3.5 \pm 0.2$  | 29.4                    | 1.15            | 0.4                |
| M20                          | 21.1               | 20.3 | $6 \pm 0.2$    | $4 \pm 0.2$    | 33.5                    | 1.3             | 0.4                |
| (M22)                        | 23.3               | 22.4 | $6 \pm 0.2$    | $4 \pm 0.2$    | 35.7                    | 1.3             | 0.4                |
| M24                          | 25.3               | 24.4 | $7 \pm 0.25$   | $5 \pm 0.2$    | 39.8                    | 1.65            | 0.5                |
| (M27)                        | 28.5               | 27.5 | $7 \pm 0.25$   | $5 \pm 0.2$    | 43.0                    | 1.65            | 0.5                |
| M30                          | 31.5               | 30.5 | $8 \pm 0.25$   | $6 \pm 0.25$   | 48.0                    | 2.0             | 0.8                |
| (M33)                        | 34.6               | 33.5 | $10 \pm 0.25$  | $6 \pm 0.25$   | 55.1                    | 2.0             | 0.8                |
| M36                          | 37.6               | 36.5 | $10 \pm 0.25$  | $6 \pm 0.25$   | 58.1                    | 2.0             | 0.8                |
| (M39)                        | 40.8               | 39.6 | $10 \pm 0.25$  | $6 \pm 0.25$   | 61.3                    | 2.0             | 0.8                |
| M42                          | 43.8               | 42.6 | $12 \pm 0.25$  | $7 \pm 0.25$   | 68.3                    | 2.3             | 0.8                |
| (M45)                        | 46.8               | 45.6 | $12 \pm 0.25$  | $7 \pm 0.25$   | 71.3                    | 2.3             | 0.8                |
| M48                          | 50.0               | 48.8 | $12 \pm 0.25$  | $7 \pm 0.25$   | 74.5                    | 2.3             | 0.8                |
| (M52)                        | 54.1               | 52.8 | $14 \pm 0.25$  | $8 \pm 0.25$   | 82.6                    | 2.65            | 1.0                |
| M56                          | 58.1               | 56.8 | $14 \pm 0.25$  | $8 \pm 0.25$   | 86.6                    | 2.65            | 1.0                |
| (M60)                        | 62.3               | 60.9 | $14 \pm 0.25$  | $8 \pm 0.25$   | 90.8                    | 2.65            | 1.0                |
| M64                          | 66.3               | 64.9 | $14 \pm 0.25$  | $8 \pm 0.25$   | 93.8                    | 2.65            | 1.0                |
| (M68)                        | 70.5               | 69.0 | $14 \pm 0.25$  | $8 \pm 0.25$   | 99.0                    | 2.65            | 1.0                |

All dimensions are given in millimeters. Sizes shown in parentheses are non-preferred, and are not usually stock sizes.

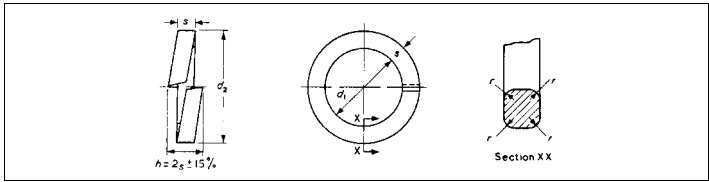
**British Standard Double Coil Rectangular Section Spring Washers; Metric Series —  
Type D BS 4464:1969 (1998)**



| Nom. Size, $d$ | Inside Dia., $d_1$ |      | Width, $b$     | Thickness, $s$  | O.D., $d_2$<br>Max | Radius, $r$<br>Max |
|----------------|--------------------|------|----------------|-----------------|--------------------|--------------------|
|                | Max                | Min  |                |                 |                    |                    |
| M2             | 2.4                | 2.1  | $0.9 \pm 0.1$  | $0.5 \pm 0.05$  | 4.4                | 0.15               |
| (M2.2)         | 2.6                | 2.3  | $1.0 \pm 0.1$  | $0.6 \pm 0.05$  | 4.8                | 0.2                |
| M2.5           | 2.9                | 2.6  | $1.2 \pm 0.1$  | $0.7 \pm 0.1$   | 5.5                | 0.23               |
| M3.0           | 3.6                | 3.3  | $1.2 \pm 0.1$  | $0.8 \pm 0.1$   | 6.2                | 0.25               |
| (M3.5)         | 4.1                | 3.8  | $1.6 \pm 0.1$  | $0.8 \pm 0.1$   | 7.5                | 0.25               |
| M4             | 4.6                | 4.3  | $1.6 \pm 0.1$  | $0.8 \pm 0.1$   | 8.0                | 0.25               |
| M5             | 5.6                | 5.3  | $2 \pm 0.1$    | $0.9 \pm 0.1$   | 9.8                | 0.3                |
| M6             | 6.6                | 6.3  | $3 \pm 0.15$   | $1 \pm 0.1$     | 12.9               | 0.33               |
| M8             | 8.8                | 8.4  | $3 \pm 0.15$   | $1.2 \pm 0.1$   | 15.1               | 0.4                |
| M10            | 10.8               | 10.4 | $3.5 \pm 0.20$ | $1.2 \pm 0.1$   | 18.2               | 0.4                |
| M12            | 12.8               | 12.4 | $3.5 \pm 0.2$  | $1.6 \pm 0.1$   | 20.2               | 0.5                |
| (M14)          | 15.0               | 14.5 | $5 \pm 0.2$    | $1.6 \pm 0.1$   | 25.4               | 0.5                |
| M16            | 17.0               | 16.5 | $5 \pm 0.2$    | $2 \pm 0.1$     | 27.4               | 0.65               |
| (M18)          | 19.0               | 18.5 | $5 \pm 0.2$    | $2 \pm 0.1$     | 29.4               | 0.65               |
| M20            | 21.5               | 20.8 | $5 \pm 0.2$    | $2 \pm 0.1$     | 31.9               | 0.65               |
| (M22)          | 23.5               | 22.8 | $6 \pm 0.2$    | $2.5 \pm 0.15$  | 35.9               | 0.8                |
| M24            | 26.0               | 25.0 | $6.5 \pm 0.2$  | $3.25 \pm 0.15$ | 39.4               | 1.1                |
| (M27)          | 29.5               | 28.0 | $7 \pm 0.25$   | $3.25 \pm 0.15$ | 44.0               | 1.1                |
| M30            | 33.0               | 31.5 | $8 \pm 0.25$   | $3.25 \pm 0.15$ | 49.5               | 1.1                |
| (M33)          | 36.0               | 34.5 | $8 \pm 0.25$   | $3.25 \pm 0.15$ | 52.5               | 1.1                |
| M36            | 40.0               | 38.0 | $10 \pm 0.25$  | $3.25 \pm 0.15$ | 60.5               | 1.1                |
| (M39)          | 43.0               | 41.0 | $10 \pm 0.25$  | $3.25 \pm 0.15$ | 63.5               | 1.1                |
| M42            | 46.0               | 44.0 | $10 \pm 0.25$  | $4.5 \pm 0.2$   | 66.5               | 1.5                |
| M48            | 52.0               | 50.0 | $10 \pm 0.25$  | $4.5 \pm 0.2$   | 72.5               | 1.5                |
| M56            | 60.0               | 58.0 | $12 \pm 0.25$  | $4.5 \pm 0.2$   | 84.5               | 1.5                |
| M64            | 70.0               | 67.0 | $12 \pm 0.25$  | $4.5 \pm 0.2$   | 94.5               | 1.5                |

All dimensions are given in millimeters. Sizes shown in parentheses are non-preferred, and are not usually stock sizes. The free height of double coil washers before compression is normally approximately five times the thickness but, if required, washers with other free heights may be obtained by arrangement with manufacturer.

**British Standard Single Coil Square Section Spring Washers; Metric Series —  
Type A-1 BS 4464:1969 (1998)**



**British Standard Single Coil Square Section Spring Washers; Metric Series —  
Type A-2 BS 4464:1969 (1998)**

| Nom. Size, $d$ | Inside Dia., $d_1$ |      | Thickness & Width, $s$ | O.D., $d_2$<br>Max | Radius, $r$<br>Max |
|----------------|--------------------|------|------------------------|--------------------|--------------------|
|                | Max                | Min  |                        |                    |                    |
| M3             | 3.3                | 3.1  | 1 ± 0.1                | 5.5                | 0.3                |
| (M3.5)         | 3.8                | 3.6  | 1 ± 0.1                | 6.0                | 0.3                |
| M4             | 4.35               | 4.1  | 1.2 ± 0.1              | 6.95               | 0.4                |
| M5             | 5.35               | 5.1  | 1.5 ± 0.1              | 8.55               | 0.5                |
| M6             | 6.4                | 6.1  | 1.5 ± 0.1              | 9.6                | 0.5                |
| M8             | 8.55               | 8.2  | 2 ± 0.1                | 12.75              | 0.65               |
| M10            | 10.6               | 10.2 | 2.5 ± 0.15             | 15.9               | 0.8                |
| M12            | 12.6               | 12.2 | 2.5 ± 0.15             | 17.9               | 0.8                |
| (M14)          | 14.7               | 14.2 | 3 ± 0.2                | 21.1               | 1.0                |
| M16            | 16.9               | 16.3 | 3.5 ± 0.2              | 24.3               | 1.15               |
| (M18)          | 19.0               | 18.3 | 3.5 ± 0.2              | 26.4               | 1.15               |
| M20            | 21.1               | 20.3 | 4.5 ± 0.2              | 30.5               | 1.5                |
| (M22)          | 23.3               | 22.4 | 4.5 ± 0.2              | 32.7               | 1.5                |
| M24            | 25.3               | 24.4 | 5 ± 0.2                | 35.7               | 1.65               |
| (M27)          | 28.5               | 27.5 | 5 ± 0.2                | 38.9               | 1.65               |
| M30            | 31.5               | 30.5 | 6 ± 0.2                | 43.9               | 2.0                |
| (M33)          | 34.6               | 33.5 | 6 ± 0.2                | 47.0               | 2.0                |
| M36            | 37.6               | 36.5 | 7 ± 0.25               | 52.1               | 2.3                |
| (M39)          | 40.8               | 39.6 | 7 ± 0.25               | 55.3               | 2.3                |
| M42            | 43.8               | 42.6 | 8 ± 0.25               | 60.3               | 2.65               |
| (M45)          | 46.8               | 45.6 | 8 ± 0.25               | 63.3               | 2.65               |
| M48            | 50.0               | 48.8 | 8 ± 0.25               | 66.5               | 2.65               |

All dimensions are in millimeters. Sizes shown in parentheses are nonpreferred and are not usually stock sizes.

**British Standard for Metric Series Metal Washers.**—BS 4320:1968 (1998) specifies bright and black metal washers for general engineering purposes.

**Bright Metal Washers:** These washers are made from either CS4 cold-rolled strip steel BS 1449:Part 3B or from CZ 108 brass strip B.S. 2870: 1980, both in the hard condition. However, by mutual agreement between purchaser and supplier, washers may be made available with the material in any other condition, or they may be made from another material, or may be coated with a protective or decorative finish to some appropriate British Standard. Washers are reasonably flat and free from burrs and are normally supplied unchamfered. They may, however, have a 30-degree chamfer on one edge of the external diameter. These washers are made available in two size categories, normal and large diameter, and in two thicknesses, normal (Form A or C) and light (Form B or D). The thickness of a light-range washer is from  $\frac{1}{2}$  to  $\frac{2}{3}$  the thickness of a normal range washer.

**Black Metal Washers:** These washers are made from mild steel, and can be supplied in three size categories designated normal, large, and extra large diameters. The normal-diameter series is intended for bolts ranging from M5 to M68 (Form E washers), the large-diameter series for bolts ranging from M8 to M39 (Form F washers), and the extra large series for bolts from M5 to M39 (Form G washers). A protective finish can be specified by the purchaser in accordance with any appropriate British Standard.

*Washer Designations:* The Standard specifies the details that should be given when ordering or placing an inquiry for washers. These details are the general description, namely, bright or black washers; the nominal size of the bolt or screw involved, for example, M5; the designated form, for example, Form A or Form E; the dimensions of any chamfer required on bright washers; the number of the Standard BS 4320:1968 (1998), and coating information if required, with the number of the appropriate British Standard and the coating thickness needed. As an example, in the use of this information, the designation for a chamfered, normal-diameter series washer of normal-range thickness to suit a 12-mm diameter bolt would be: Bright washers M12 (Form A) chamfered to B.S. 4320.

### British Standard Bright Metal Washers — Metric Series BS 4320:1968 (1998)

| NORMAL DIAMETER SIZES         |                 |      |      |                  |      |      |                       |     |     |                      |      |      |
|-------------------------------|-----------------|------|------|------------------|------|------|-----------------------|-----|-----|----------------------|------|------|
| Nominal Size of Bolt or Screw | Inside Diameter |      |      | Outside Diameter |      |      | Thickness             |     |     |                      |      |      |
|                               |                 |      |      |                  |      |      | Form A (Normal Range) |     |     | Form B (Light Range) |      |      |
|                               | Nom             | Max  | Min  | Nom              | Max  | Min  | Nom                   | Max | Min | Nom                  | Max  | Min  |
| M 1.0                         | 1.1             | 1.25 | 1.1  | 2.5              | 2.5  | 2.3  | 0.3                   | 0.4 | 0.2 | ...                  | ...  | ...  |
| M 1.2                         | 1.3             | 1.45 | 1.3  | 3.0              | 3.0  | 2.8  | 0.3                   | 0.4 | 0.2 | ...                  | ...  | ...  |
| (M 1.4)                       | 1.5             | 1.65 | 1.5  | 3.0              | 3.0  | 2.8  | 0.3                   | 0.4 | 0.2 | ...                  | ...  | ...  |
| M 1.6                         | 1.7             | 1.85 | 1.7  | 4.0              | 4.0  | 3.7  | 0.3                   | 0.4 | 0.2 | ...                  | ...  | ...  |
| M 2.0                         | 2.2             | 2.35 | 2.2  | 5.0              | 5.0  | 4.7  | 0.3                   | 0.4 | 0.2 | ...                  | ...  | ...  |
| (M 2.2)                       | 2.4             | 2.55 | 2.4  | 5.0              | 5.0  | 4.7  | 0.5                   | 0.6 | 0.4 | ...                  | ...  | ...  |
| M 2.5                         | 2.7             | 2.85 | 2.7  | 6.5              | 6.5  | 6.2  | 0.5                   | 0.6 | 0.4 | ...                  | ...  | ...  |
| M3                            | 3.2             | 3.4  | 3.2  | 7                | 7    | 6.7  | 0.5                   | 0.6 | 0.4 | ...                  | ...  | ...  |
| (M 3.5)                       | 3.7             | 3.9  | 3.7  | 7                | 7    | 6.7  | 0.5                   | 0.6 | 0.4 | ...                  | ...  | ...  |
| M4                            | 4.3             | 4.5  | 4.3  | 9                | 9    | 8.7  | 0.8                   | 0.9 | 0.7 | ...                  | ...  | ...  |
| (M 4.5)                       | 4.8             | 5.0  | 4.8  | 9                | 9    | 8.7  | 0.8                   | 0.9 | 0.7 | ...                  | ...  | ...  |
| M 5                           | 5.3             | 5.5  | 5.3  | 10               | 10   | 9.7  | 1.0                   | 1.1 | 0.9 | ...                  | ...  | ...  |
| M 6                           | 6.4             | 6.7  | 6.4  | 12.5             | 12.5 | 12.1 | 1.6                   | 1.8 | 1.4 | 0.8                  | 0.9  | 0.7  |
| (M 7)                         | 7.4             | 7.7  | 7.4  | 14               | 14   | 13.6 | 1.6                   | 1.8 | 1.4 | 0.8                  | 0.9  | 0.7  |
| M 8                           | 8.4             | 8.7  | 8.4  | 17               | 17   | 16.6 | 1.6                   | 1.8 | 1.4 | 1.0                  | 1.1  | 0.9  |
| M 10                          | 10.5            | 10.9 | 10.5 | 21               | 21   | 20.5 | 2.0                   | 2.2 | 1.8 | 1.25                 | 1.45 | 1.05 |
| M 12                          | 13.0            | 13.4 | 13.0 | 24               | 24   | 23.5 | 2.5                   | 2.7 | 2.3 | 1.6                  | 1.80 | 1.40 |
| (M 14)                        | 15.0            | 15.4 | 15.0 | 28               | 28   | 27.5 | 2.5                   | 2.7 | 2.3 | 1.6                  | 1.8  | 1.4  |
| M 16                          | 17.0            | 17.4 | 17.0 | 30               | 30   | 29.5 | 3.0                   | 3.3 | 2.7 | 2.0                  | 2.2  | 1.8  |
| (M 18)                        | 19.0            | 19.5 | 19.0 | 34               | 34   | 33.2 | 3.0                   | 3.3 | 2.7 | 2.0                  | 2.2  | 1.8  |
| M 20                          | 21              | 21.5 | 21   | 37               | 37   | 36.2 | 3.0                   | 3.3 | 2.7 | 2.0                  | 2.2  | 1.8  |
| (M 22)                        | 23              | 23.5 | 23   | 39               | 39   | 38.2 | 3.0                   | 3.3 | 2.7 | 2.0                  | 2.2  | 1.8  |
| M24                           | 25              | 25.5 | 25   | 44               | 44   | 43.2 | 4.0                   | 4.3 | 3.7 | 2.5                  | 2.7  | 2.3  |
| (M 27)                        | 28              | 28.5 | 28   | 50               | 50   | 49.2 | 4.0                   | 4.3 | 3.7 | 2.5                  | 2.7  | 2.3  |
| M30                           | 31              | 31.6 | 31   | 56               | 56   | 55.0 | 4.0                   | 4.3 | 3.7 | 2.5                  | 2.7  | 2.3  |
| (M 33)                        | 34              | 34.6 | 34   | 60               | 60   | 59.0 | 5.0                   | 5.6 | 4.4 | 3.0                  | 3.3  | 2.7  |
| M 36                          | 37              | 37.6 | 37   | 66               | 66   | 65.0 | 5.0                   | 5.6 | 4.4 | 3.0                  | 3.3  | 2.7  |
| (M 39)                        | 40              | 40.6 | 40   | 72               | 72   | 71.0 | 6.0                   | 6.6 | 5.4 | 3.0                  | 3.3  | 2.7  |
| LARGE DIAMETER SIZES          |                 |      |      |                  |      |      |                       |     |     |                      |      |      |
| Nominal Size of Bolt or Screw | Inside Diameter |      |      | Outside Diameter |      |      | Thickness             |     |     |                      |      |      |
|                               |                 |      |      |                  |      |      | Form C (Normal Range) |     |     | Form D (Light Range) |      |      |
|                               | Nom             | Max  | Min  | Nom              | Max  | Min  | Nom                   | Max | Min | Nom                  | Max  | Min  |
| M 4                           | 4.3             | 4.5  | 4.3  | 10.0             | 10.0 | 9.7  | 0.8                   | 0.9 | 0.7 | ...                  | ...  | ...  |
| M 5                           | 5.3             | 5.5  | 5.3  | 12.5             | 12.5 | 12.1 | 1.0                   | 1.1 | 0.9 | ...                  | ...  | ...  |
| M 6                           | 6.4             | 6.7  | 6.4  | 14               | 14   | 13.6 | 1.6                   | 1.8 | 1.4 | 0.8                  | 0.9  | 0.7  |
| M 8                           | 8.4             | 8.7  | 8.4  | 21               | 21   | 20.5 | 1.6                   | 1.8 | 1.4 | 1.0                  | 1.1  | 0.9  |
| M 10                          | 10.5            | 10.9 | 10.5 | 24               | 24   | 23.5 | 2.0                   | 2.2 | 1.8 | 1.25                 | 1.45 | 1.05 |
| M 12                          | 13.0            | 13.4 | 13.0 | 28               | 28   | 27.5 | 2.5                   | 2.7 | 2.3 | 1.6                  | 1.8  | 1.4  |
| (M 14)                        | 15.0            | 15.4 | 15   | 30               | 30   | 29.5 | 2.5                   | 2.7 | 2.3 | 1.6                  | 1.8  | 1.4  |
| M 16                          | 17.0            | 17.4 | 17   | 34               | 34   | 33.2 | 3.0                   | 3.3 | 2.7 | 2.0                  | 2.2  | 1.8  |
| (M 18)                        | 19.0            | 19.5 | 19   | 37               | 37   | 36.2 | 3.0                   | 3.3 | 2.7 | 2.0                  | 2.2  | 1.8  |
| M 20                          | 21              | 21.5 | 21   | 39               | 39   | 38.2 | 3.0                   | 3.3 | 2.7 | 2.0                  | 2.2  | 1.8  |
| (M 22)                        | 23              | 23.5 | 23   | 44               | 44   | 43.2 | 3.0                   | 3.3 | 2.7 | 2.0                  | 2.2  | 1.8  |
| M 24                          | 25              | 25.5 | 25   | 50               | 50   | 49.2 | 4.0                   | 4.3 | 3.7 | 2.5                  | 2.7  | 2.3  |
| (M 27)                        | 28              | 28.5 | 28   | 56               | 56   | 55   | 4.0                   | 4.3 | 3.7 | 2.5                  | 2.7  | 2.3  |
| M 30                          | 31              | 31.6 | 31   | 60               | 60   | 59   | 4.0                   | 4.3 | 3.7 | 2.5                  | 2.7  | 2.3  |
| (M 33)                        | 34              | 34.6 | 34   | 66               | 66   | 65   | 5.0                   | 5.6 | 4.4 | 3.0                  | 3.3  | 2.7  |
| M 36                          | 37              | 37.6 | 37   | 72               | 72   | 71   | 5.0                   | 5.6 | 4.4 | 3.0                  | 3.3  | 2.7  |
| (M 39)                        | 40              | 40.6 | 40   | 77               | 77   | 76   | 6.0                   | 6.6 | 5.4 | 3.0                  | 3.3  | 2.7  |

All dimensions are in millimeters.

Nominal bolt or screw sizes shown in parentheses are nonpreferred.

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## WASHERS

## British Standard Black Metal Washers — Metric Series BS 4320:1968 (1998)

| NORMAL DIAMETER SIZES (Form E)      |                 |      |      |                  |      |      |           |      |     |
|-------------------------------------|-----------------|------|------|------------------|------|------|-----------|------|-----|
| Nom Bolt or<br>Screw<br>Size        | Inside Diameter |      |      | Outside Diameter |      |      | Thickness |      |     |
|                                     | Nom             | Max  | Min  | Nom              | Max  | Min  | Nom       | Max  | Min |
| M 5                                 | 5.5             | 5.8  | 5.5  | 10.0             | 10.0 | 9.2  | 1.0       | 1.2  | 0.8 |
| M 6                                 | 6.6             | 7.0  | 6.6  | 12.5             | 12.5 | 11.7 | 1.6       | 1.9  | 1.3 |
| (M 7)                               | 7.6             | 8.0  | 7.6  | 14.0             | 14.0 | 13.2 | 1.6       | 1.9  | 1.3 |
| M 8                                 | 9.0             | 9.4  | 9.0  | 17               | 17   | 16.2 | 1.6       | 1.9  | 1.3 |
| M 10                                | 11.0            | 11.5 | 11.0 | 21               | 21   | 20.2 | 2.0       | 2.3  | 1.7 |
| M 12                                | 14              | 14.5 | 14   | 24               | 24   | 23.2 | 2.5       | 2.8  | 2.2 |
| (M 14)                              | 16              | 16.5 | 16   | 28               | 28   | 27.2 | 2.5       | 2.8  | 2.2 |
| M 16                                | 18              | 18.5 | 18   | 30               | 30   | 29.2 | 3.0       | 3.6  | 2.4 |
| (M 18)                              | 20              | 20.6 | 20   | 34               | 34   | 32.8 | 3.0       | 3.6  | 2.4 |
| M 20                                | 22              | 22.6 | 22   | 37               | 37   | 35.8 | 3.0       | 3.6  | 2.4 |
| (M 22)                              | 24              | 24.6 | 24   | 39               | 39   | 37.8 | 3.0       | 3.6  | 2.4 |
| M 24                                | 26              | 26.6 | 26   | 44               | 44   | 42.8 | 4         | 4.6  | 3.4 |
| (M 27)                              | 30              | 30.6 | 30   | 50               | 50   | 48.8 | 4         | 4.6  | 3.4 |
| M 30                                | 33              | 33.8 | 33   | 56               | 56   | 54.5 | 4         | 4.6  | 3.4 |
| (M 33)                              | 36              | 36.8 | 36   | 60               | 60   | 58.5 | 5         | 6.0  | 4.0 |
| M 36                                | 39              | 39.8 | 39   | 66               | 66   | 64.5 | 5         | 6.0  | 4.0 |
| (M 39)                              | 42              | 42.8 | 42   | 72               | 72   | 70.5 | 6         | 7.0  | 5.0 |
| M 42                                | 45              | 45.8 | 45   | 78               | 78   | 76.5 | 7         | 8.2  | 5.8 |
| (M 45)                              | 48              | 48.8 | 48   | 85               | 85   | 83   | 7         | 8.2  | 5.8 |
| M 48                                | 52              | 53   | 52   | 92               | 92   | 90   | 8         | 9.2  | 6.8 |
| (M 52)                              | 56              | 57   | 56   | 98               | 98   | 96   | 8         | 9.2  | 6.8 |
| M 56                                | 62              | 63   | 62   | 105              | 105  | 103  | 9         | 10.2 | 7.8 |
| (M 60)                              | 66              | 67   | 66   | 110              | 110  | 108  | 9         | 10.2 | 7.8 |
| M 64                                | 70              | 71   | 70   | 115              | 115  | 113  | 9         | 10.2 | 7.8 |
| (M 68)                              | 74              | 75   | 74   | 120              | 120  | 118  | 10        | 11.2 | 8.8 |
| LARGE DIAMETER SIZES (Form F)       |                 |      |      |                  |      |      |           |      |     |
| M 8                                 | 9               | 9.4  | 9.0  | 21               | 21   | 20.2 | 1.6       | 1.9  | 1.3 |
| M 10                                | 11              | 11.5 | 11   | 24               | 24   | 23.2 | 2         | 2.3  | 1.7 |
| M 12                                | 14              | 14.5 | 14   | 28               | 28   | 27.2 | 2.5       | 2.8  | 2.2 |
| (M 14)                              | 16              | 16.5 | 16   | 30               | 30   | 29.2 | 2.5       | 2.8  | 2.2 |
| M 16                                | 18              | 18.5 | 18   | 34               | 34   | 32.8 | 3         | 3.6  | 2.4 |
| (M 18)                              | 20              | 20.6 | 20   | 37               | 37   | 35.8 | 3         | 3.6  | 2.4 |
| M 20                                | 22              | 22.6 | 22   | 39               | 39   | 37.8 | 3         | 3.6  | 2.4 |
| (M 22)                              | 24              | 24.6 | 24   | 44               | 44   | 42.8 | 3         | 3.6  | 2.4 |
| M 24                                | 26              | 26.6 | 26   | 50               | 50   | 48.8 | 4         | 4.6  | 3.4 |
| (M 27)                              | 30              | 30.6 | 30   | 56               | 56   | 54.5 | 4         | 4.6  | 3.4 |
| M 30                                | 33              | 33.8 | 33   | 60               | 60   | 58.5 | 4         | 4.6  | 3.4 |
| (M 33)                              | 36              | 36.8 | 36   | 66               | 66   | 64.5 | 5         | 6.0  | 4   |
| M 36                                | 39              | 39.8 | 39   | 72               | 72   | 70.5 | 5         | 6.0  | 4   |
| (M 39)                              | 42              | 42.8 | 42   | 77               | 77   | 75.5 | 6         | 7    | 5   |
| EXTRA LARGE DIAMETER SIZES (Form G) |                 |      |      |                  |      |      |           |      |     |
| M 5                                 | 5.5             | 5.8  | 5.5  | 15               | 15   | 14.2 | 1.6       | 1.9  | 1.3 |
| M 6                                 | 6.6             | 7.0  | 6.6  | 18               | 18   | 17.2 | 2         | 2.3  | 1.7 |
| (M 7)                               | 7.6             | 8.0  | 7.6  | 21               | 21   | 20.2 | 2         | 2.3  | 1.7 |
| M 8                                 | 9               | 9.4  | 9.0  | 24               | 24   | 23.2 | 2         | 2.3  | 1.7 |
| M 10                                | 11              | 11.5 | 11.0 | 30               | 30   | 29.2 | 2.5       | 2.8  | 2.2 |
| M 12                                | 14              | 14.5 | 14.0 | 36               | 36   | 34.8 | 3         | 3.6  | 2.4 |
| (M 14)                              | 16              | 16.5 | 16.0 | 42               | 42   | 40.8 | 3         | 3.6  | 2.4 |
| M 16                                | 18              | 18.5 | 18   | 48               | 48   | 46.8 | 4         | 4.6  | 3.4 |
| (M 18)                              | 20              | 20.6 | 20   | 54               | 54   | 52.5 | 4         | 4.6  | 3.4 |
| M 20                                | 22              | 22.6 | 22   | 60               | 60   | 58.5 | 5         | 6.0  | 4   |
| (M 22)                              | 24              | 24.6 | 24   | 66               | 66   | 64.5 | 5         | 6.0  | 4   |
| M 24                                | 26              | 26.6 | 26   | 72               | 72   | 70.5 | 6         | 7    | 5   |
| (M 27)                              | 30              | 30.6 | 30   | 81               | 81   | 79   | 6         | 7    | 5   |
| M 30                                | 33              | 33.8 | 33   | 90               | 90   | 88   | 8         | 9.2  | 6.8 |
| (M 33)                              | 36              | 36.8 | 36   | 99               | 99   | 97   | 8         | 9.2  | 6.8 |
| M 36                                | 39              | 39.8 | 39   | 108              | 108  | 106  | 10        | 11.2 | 8.8 |
| (M39)                               | 42              | 42.8 | 42   | 117              | 117  | 115  | 10        | 11.2 | 8.8 |

All dimensions are in millimeters.

Nominal bolt or screw sizes shown in parentheses are nonpreferred.

MACHINE SCREWS AND NUTS

**American National Standard Machine Screws and Machine Screw Nuts.**—This Standard ANSI B18.6.3 covers both slotted and recessed head machine screws. Dimensions of various types of slotted machine screws, machine screw nuts, and header points are given in Tables 1 through 12. The Standard also covers flat trim head, oval trim head and drilled fillister head machine screws and gives cross recess dimensions and gaging dimensions for all types of machine screw heads. Information on metric machine screws B18.6.7M is given beginning on page 1596.

**Threads:** Except for sizes 0000, 000, and 00, machine screw threads may be either Unified Coarse (UNC) and Fine thread (UNF) Class 2A (see *American Standard for Unified Screw Threads* starting on page 1732) or UNRC and UNRF Series, at option of manufacturer. Thread dimensions for sizes 0000, 000, and 00 are given in Table 7 on page 1592.

Threads for hexagon machine screw nuts may be either UNC or UNF, Class 2B, and for square machine screw nuts are UNC Class 2B.

**Length of thread:** Machine screws of sizes No. 5 and smaller with nominal lengths equal to 3 diameters and shorter have full form threads extending to within 1 pitch (thread) of the bearing surface of the head, or closer, if practicable. Nominal lengths greater than 3 diameters, up to and including 1 1/8 inch, have full form threads extending to within two pitches (threads) of the bearing surface of the head, or closer, if practicable. Unless otherwise specified, screws of longer nominal length have a minimum length of full form thread of 1.00 inch. Machine screws of sizes No. 6 and larger with nominal length equal to 3 diameters and shorter have full form threads extending to within 1 pitch (thread) of the bearing surface of the head, or closer, if practicable. Nominal lengths greater than 3 diameters, up to and including 2 inches, have full form threads extending to within 2 pitches (threads) of the bearing surface of the head, or closer, if practicable. Screws of longer nominal length, unless otherwise specified, have a minimum length of full form thread of 1.50 inches.

**Table 1. Square and Hexagon Machine Screw Nuts ANSI B18.6.3-1972 (R1991)**

| Nom. Size | Basic Dia. | Basic F | Max. F | Min. F | Max. G | Min. G | Max. G <sub>1</sub> | Min. G <sub>1</sub> | Max. H | Min. H |
|-----------|------------|---------|--------|--------|--------|--------|---------------------|---------------------|--------|--------|
| 0         | 0.0600     | 5/32    | 0.156  | 0.150  | 0.221  | 0.206  | 0.180               | 0.171               | 0.050  | 0.043  |
| 1         | 0.0730     | 5/32    | 0.156  | 0.150  | 0.221  | 0.206  | 0.180               | 0.171               | 0.050  | 0.043  |
| 2         | 0.0860     | 3/16    | 0.188  | 0.180  | 0.265  | 0.247  | 0.217               | 0.205               | 0.066  | 0.057  |
| 3         | 0.0990     | 3/16    | 0.188  | 0.180  | 0.265  | 0.247  | 0.217               | 0.205               | 0.066  | 0.057  |
| 4         | 0.1120     | 1/4     | 0.250  | 0.241  | 0.354  | 0.331  | 0.289               | 0.275               | 0.098  | 0.087  |
| 5         | 0.1250     | 5/16    | 0.312  | 0.302  | 0.442  | 0.415  | 0.361               | 0.344               | 0.114  | 0.102  |
| 6         | 0.1380     | 5/16    | 0.312  | 0.302  | 0.442  | 0.415  | 0.361               | 0.344               | 0.114  | 0.102  |
| 8         | 0.1640     | 11/32   | 0.344  | 0.332  | 0.486  | 0.456  | 0.397               | 0.378               | 0.130  | 0.117  |
| 10        | 0.1900     | 3/8     | 0.375  | 0.362  | 0.530  | 0.497  | 0.433               | 0.413               | 0.130  | 0.117  |
| 12        | 0.2160     | 7/16    | 0.438  | 0.423  | 0.619  | 0.581  | 0.505               | 0.482               | 0.161  | 0.148  |
| 1/4       | 0.2500     | 7/16    | 0.438  | 0.423  | 0.619  | 0.581  | 0.505               | 0.482               | 0.193  | 0.178  |
| 3/16      | 0.3125     | 9/16    | 0.562  | 0.545  | 0.795  | 0.748  | 0.650               | 0.621               | 0.225  | 0.208  |
| 3/8       | 0.3750     | 5/8     | 0.625  | 0.607  | 0.884  | 0.833  | 0.722               | 0.692               | 0.257  | 0.239  |

All dimensions in inches. Hexagon machine screw nuts have tops flat and chamfered. Diameter of top circle should be the maximum width across flats within a tolerance of minus 15 per cent. Bottoms are flat but may be chamfered if so specified. Square machine screw nuts have tops and bottoms flat without chamfer.



*Diameter of body:* The diameter of machine screw bodies is not less than Class 2A thread minimum pitch diameter nor greater than the basic major diameter of the thread. Cross-recessed trim head machine screws not threaded to the head have an 0.062 in. minimum length shoulder under the head with diameter limits as specified in the dimensional tables in the standard.

*Designation:* Machine screws are designated by the following data in the sequence shown: Nominal size (number, fraction, or decimal equivalent); threads per inch; nominal length (fraction or decimal equivalent); product name, including head type and driving provision; header point, if desired; material; and protective finish, if required. For example:

$\frac{1}{4}$  - 20 x  $1\frac{1}{4}$  Slotted Pan Head Machine Screw, Steel, Zinc Plated

6 - 32 x  $\frac{3}{4}$  Type IA Cross Recessed Fillister Head Machine Screw, Brass

Machine screw nuts are designated by the following data in the sequence shown: Nominal size (number, fraction, or decimal equivalent); threads per inch; product name; material; and protective finish, if required. For example:

10 - 24 Hexagon Machine Screw Nut, Steel, Zinc Plated

0.138 - 32 Square Machine Screw Nut, Brass

**Table 2. American National Standard Slotted 100-Degree Flat Countersunk Head Machine Screws ANSI B18.6.3-1972 (R1977)**

| Nominal Size <sup>a</sup> or Basic Screw Dia. | Head Dia., A     |                            | Head Height, H | Slot Width, J |       | Slot Depth, T |       |       |
|---|------------------|----------------------------|----------------|---------------|-------|---------------|-------|-------|
|   | Max., Edge Sharp | Min., Edge Rounded or Flat |                | Ref.          | Max.  | Min.          | Max.  | Min.  |
|   |                  |                            | 0000           |               |       |               |       |       |
| 000   | 0.0340           | 0.064                      | 0.058          | 0.014         | 0.012 | 0.008         | 0.011 | 0.007 |
| 00  | 0.0470           | 0.093                      | 0.085          | 0.020         | 0.017 | 0.010         | 0.013 | 0.008 |
| 0   | 0.0600           | 0.119                      | 0.096          | 0.026         | 0.023 | 0.016         | 0.013 | 0.008 |
| 1   | 0.0730           | 0.146                      | 0.120          | 0.031         | 0.026 | 0.019         | 0.016 | 0.010 |
| 2   | 0.0860           | 0.172                      | 0.143          | 0.037         | 0.031 | 0.023         | 0.019 | 0.012 |
| 3   | 0.0990           | 0.199                      | 0.167          | 0.043         | 0.035 | 0.027         | 0.022 | 0.014 |
| 4   | 0.1120           | 0.225                      | 0.191          | 0.049         | 0.039 | 0.031         | 0.024 | 0.017 |
| 6   | 0.1380           | 0.279                      | 0.238          | 0.060         | 0.048 | 0.039         | 0.030 | 0.022 |
| 8   | 0.1640           | 0.332                      | 0.285          | 0.072         | 0.054 | 0.045         | 0.036 | 0.027 |
| 10  | 0.1900           | 0.385                      | 0.333          | 0.083         | 0.060 | 0.050         | 0.042 | 0.031 |
| $\frac{1}{4}$                                 | 0.2500           | 0.507                      | 0.442          | 0.110         | 0.075 | 0.064         | 0.055 | 0.042 |
| $\frac{5}{16}$                                | 0.3125           | 0.635                      | 0.556          | 0.138         | 0.084 | 0.072         | 0.069 | 0.053 |
| $\frac{3}{8}$                                 | 0.3750           | 0.762                      | 0.670          | 0.165         | 0.094 | 0.081         | 0.083 | 0.065 |

<sup>a</sup> When specifying nominal size in decimals, zeros preceding the decimal point and in the fourth decimal place are omitted.

All dimensions are in inches.

**Table 3. American National Standard Slotted Flat Countersunk Head and Close Tolerance 100-Degree Flat Countersunk Head Machine Screws**  
ANSI B18.6.3-1972 (R1991)

| SLOTTED FLAT COUNTERSUNK HEAD TYPE            |        |                      |                  |                         |                        |               |       |               |       |
|---|--------|----------------------|------------------|-------------------------|------------------------|---------------|-------|---------------|-------|
| Nominal Size <sup>a</sup> or Basic Screw Dia. |        | Max., L <sup>b</sup> | Head Dia., A     |                         | Head Height, H<br>Ref. | Slot Width, J |       | Slot Depth, T |       |
|   |        |                      | Max., Edge Sharp | Min., Edge <sup>c</sup> |                        | Max.          | Min.  | Max.          | Min.  |
| 0000  | 0.0210 | ....                 | 0.043            | 0.037                   | 0.011                  | 0.008         | 0.004 | 0.007         | 0.003 |
| 000   | 0.0340 | ....                 | 0.064            | 0.058                   | 0.016                  | 0.011         | 0.007 | 0.009         | 0.005 |
| 00  | 0.0470 | ....                 | 0.093            | 0.085                   | 0.028                  | 0.017         | 0.010 | 0.014         | 0.009 |
| 0   | 0.0600 | 1/16                 | 0.119            | 0.099                   | 0.035                  | 0.023         | 0.016 | 0.015         | 0.010 |
| 1   | 0.0730 | 1/8                  | 0.146            | 0.123                   | 0.043                  | 0.026         | 0.019 | 0.019         | 0.012 |
| 2   | 0.0860 | 1/8                  | 0.172            | 0.147                   | 0.051                  | 0.031         | 0.023 | 0.023         | 0.015 |
| 3   | 0.0990 | 1/8                  | 0.199            | 0.171                   | 0.059                  | 0.035         | 0.027 | 0.027         | 0.017 |
| 4   | 0.1120 | 3/16                 | 0.225            | 0.195                   | 0.067                  | 0.039         | 0.031 | 0.030         | 0.020 |
| 5   | 0.1250 | 3/16                 | 0.252            | 0.220                   | 0.075                  | 0.043         | 0.035 | 0.034         | 0.022 |
| 6   | 0.1380 | 3/16                 | 0.279            | 0.244                   | 0.083                  | 0.048         | 0.039 | 0.038         | 0.024 |
| 8   | 0.1640 | 1/4                  | 0.332            | 0.292                   | 0.100                  | 0.054         | 0.045 | 0.045         | 0.029 |
| 10  | 0.1900 | 5/16                 | 0.385            | 0.340                   | 0.116                  | 0.060         | 0.050 | 0.053         | 0.034 |
| 12  | 0.2160 | 3/8                  | 0.438            | 0.389                   | 0.132                  | 0.067         | 0.056 | 0.060         | 0.039 |
| 1/4   | 0.2500 | 7/16                 | 0.507            | 0.452                   | 0.153                  | 0.075         | 0.064 | 0.070         | 0.046 |
| 5/16  | 0.3125 | 1/2                  | 0.635            | 0.568                   | 0.191                  | 0.084         | 0.072 | 0.088         | 0.058 |
| 3/8   | 0.3750 | 9/16                 | 0.762            | 0.685                   | 0.230                  | 0.094         | 0.081 | 0.106         | 0.070 |
| 7/16  | 0.4375 | 5/8                  | 0.812            | 0.723                   | 0.223                  | 0.094         | 0.081 | 0.103         | 0.066 |
| 1/2   | 0.5000 | 3/4                  | 0.875            | 0.775                   | 0.223                  | 0.106         | 0.091 | 0.103         | 0.065 |
| 9/16  | 0.5625 | ...                  | 1.000            | 0.889                   | 0.260                  | 0.118         | 0.102 | 0.120         | 0.077 |
| 5/8   | 0.6250 | ...                  | 1.125            | 1.002                   | 0.298                  | 0.133         | 0.116 | 0.137         | 0.088 |
| 3/4   | 0.7500 | ...                  | 1.375            | 1.230                   | 0.372                  | 0.149         | 0.131 | 0.171         | 0.111 |

<sup>a</sup> When specifying nominal size in decimals, zeros preceding the decimal point and in the fourth decimal place are omitted.

<sup>b</sup> These lengths or shorter are undercut.

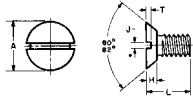
<sup>c</sup> May be rounded or flat.

| CLOSE TOLERANCE 100-DEGREE FLAT COUNTERSUNK HEAD TYPE |        |                  |                         |                        |               |       |               |       |  |
|---|--------|------------------|-------------------------|------------------------|---------------|-------|---------------|-------|--|
| Nominal Size <sup>a</sup> or Basic Screw Dia.         |        | Head Diameter, A |                         | Head Height, H<br>Ref. | Slot Width, J |       | Slot Depth, T |       |  |
|   |        | Max., Edge Sharp | Min., Edge <sup>c</sup> |                        | Max.          | Min.  | Max.          | Min.  |  |
| 4   | 0.1120 | 0.225            | 0.191                   | 0.049                  | 0.039         | 0.031 | 0.024         | 0.017 |  |
| 6   | 0.1380 | 0.279            | 0.238                   | 0.060                  | 0.048         | 0.039 | 0.030         | 0.022 |  |
| 8   | 0.1640 | 0.332            | 0.285                   | 0.072                  | 0.054         | 0.045 | 0.036         | 0.027 |  |
| 10  | 0.1900 | 0.385            | 0.333                   | 0.083                  | 0.060         | 0.050 | 0.042         | 0.031 |  |
| 1/4   | 0.2500 | 0.507            | 0.442                   | 0.110                  | 0.075         | 0.064 | 0.055         | 0.042 |  |
| 5/16  | 0.3125 | 0.635            | 0.556                   | 0.138                  | 0.084         | 0.072 | 0.069         | 0.053 |  |
| 3/8   | 0.3750 | 0.762            | 0.670                   | 0.165                  | 0.094         | 0.081 | 0.083         | 0.065 |  |
| 7/16  | 0.4375 | 0.890            | 0.783                   | 0.193                  | 0.094         | 0.081 | 0.097         | 0.076 |  |
| 1/2   | 0.5000 | 1.017            | 0.897                   | 0.221                  | 0.106         | 0.091 | 0.111         | 0.088 |  |
| 9/16  | 0.5625 | 1.145            | 1.011                   | 0.249                  | 0.118         | 0.102 | 0.125         | 0.099 |  |
| 5/8   | 0.6250 | 1.272            | 1.124                   | 0.276                  | 0.133         | 0.116 | 0.139         | 0.111 |  |

All dimensions are in inches.

**Table 4. American National Standard Slotted Undercut Flat Countersunk Head and Plain and Slotted Hex Washer Head Machine Screws ANSI B18.6.3-1972 (R1991)**

| SLOTTED UNDERCUT FLAT COUNTERSUNK HEAD TYPE   |                      |                  |                           |                |       |               |       |               |       |       |
|---|----------------------|------------------|---------------------------|----------------|-------|---------------|-------|---------------|-------|-------|
| Nominal Size <sup>a</sup> or Basic Screw Dia. | Max., L <sup>b</sup> | Head Dia., A     |                           | Head Height, H |       | Slot Width, J |       | Slot Depth, T |       |       |
|   |                      | Max., Edge Sharp | Min., Edge Rnded. or Flat | Max.           | Min.  | Max.          | Min.  | Max.          | Min.  |       |
|   |                      |                  |                           |                |       |               |       |               |       |       |
| 0   | 0.0600               | 1/8              | 0.119                     | 0.099          | 0.025 | 0.018         | 0.023 | 0.016         | 0.011 | 0.007 |
| 1   | 0.0730               | 1/8              | 0.146                     | 0.123          | 0.031 | 0.023         | 0.026 | 0.019         | 0.014 | 0.009 |
| 2   | 0.0860               | 1/8              | 0.172                     | 0.147          | 0.036 | 0.028         | 0.031 | 0.023         | 0.016 | 0.011 |
| 3   | 0.0990               | 1/8              | 0.199                     | 0.171          | 0.042 | 0.033         | 0.035 | 0.027         | 0.019 | 0.012 |
| 4   | 0.1120               | 3/16             | 0.225                     | 0.195          | 0.047 | 0.038         | 0.039 | 0.031         | 0.022 | 0.014 |
| 5   | 0.1250               | 3/16             | 0.252                     | 0.220          | 0.053 | 0.043         | 0.043 | 0.035         | 0.024 | 0.016 |
| 6   | 0.1380               | 3/16             | 0.279                     | 0.244          | 0.059 | 0.048         | 0.048 | 0.039         | 0.027 | 0.017 |
| 8   | 0.1640               | 1/4              | 0.332                     | 0.292          | 0.070 | 0.058         | 0.054 | 0.045         | 0.032 | 0.021 |
| 10  | 0.1900               | 3/16             | 0.385                     | 0.340          | 0.081 | 0.068         | 0.060 | 0.050         | 0.037 | 0.024 |
| 12  | 0.2160               | 3/8              | 0.438                     | 0.389          | 0.092 | 0.078         | 0.067 | 0.056         | 0.043 | 0.028 |
| 1/4   | 0.2500               | 3/16             | 0.507                     | 0.452          | 0.107 | 0.092         | 0.075 | 0.064         | 0.050 | 0.032 |
| 5/16  | 0.3125               | 1/2              | 0.635                     | 0.568          | 0.134 | 0.116         | 0.084 | 0.072         | 0.062 | 0.041 |
| 3/8   | 0.3750               | 5/16             | 0.762                     | 0.685          | 0.161 | 0.140         | 0.094 | 0.081         | 0.075 | 0.049 |
| 7/16  | 0.4375               | 3/8              | 0.812                     | 0.723          | 0.156 | 0.133         | 0.094 | 0.081         | 0.072 | 0.045 |
| 1/2   | 0.5000               | 3/4              | 0.875                     | 0.775          | 0.156 | 0.130         | 0.106 | 0.091         | 0.072 | 0.046 |



<sup>a</sup> When specifying nominal size in decimals, zeros preceding the decimal point and in the fourth decimal place are omitted.

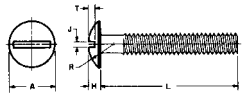
<sup>b</sup> These lengths or shorter are undercut.

| PLAIN AND SLOTTED HEX WASHER HEAD TYPES       |                       |       |                       |                |       |                |       |                  |       |                            |       |                            |       |       |
|---|-----------------------|-------|-----------------------|----------------|-------|----------------|-------|------------------|-------|----------------------------|-------|----------------------------|-------|-------|
| Nominal Size <sup>a</sup> or Basic Screw Dia. | Width Across Flats, A |       | Width Across Corn., W | Head Height, H |       | Washer Dia., B |       | Washer Thick., U |       | Slot <sup>a</sup> Width, J |       | Slot <sup>a</sup> Depth, T |       |       |
|   | Max.                  | Min.  | Min.                  | Max.           | Min.  | Max.           | Min.  | Max.             | Min.  | Max.                       | Min.  | Max.                       | Min.  |       |
|   |                       |       |                       |                |       |                |       |                  |       |                            |       |                            |       |       |
| 2   | 0.0860                | 0.125 | 0.120                 | 0.134          | 0.050 | 0.040          | 0.166 | 0.154            | 0.016 | 0.010                      | ....  | ....                       | ....  | ....  |
| 3   | 0.0990                | 0.125 | 0.120                 | 0.134          | 0.055 | 0.044          | 0.177 | 0.163            | 0.016 | 0.010                      | ....  | ....                       | ....  | ....  |
| 4   | 0.1120                | 0.188 | 0.181                 | 0.202          | 0.060 | 0.049          | 0.243 | 0.225            | 0.019 | 0.011                      | 0.039 | 0.031                      | 0.042 | 0.025 |
| 5   | 0.1250                | 0.188 | 0.181                 | 0.202          | 0.070 | 0.058          | 0.260 | 0.240            | 0.025 | 0.015                      | 0.043 | 0.035                      | 0.049 | 0.030 |
| 6   | 0.1380                | 0.250 | 0.244                 | 0.272          | 0.093 | 0.080          | 0.328 | 0.302            | 0.025 | 0.015                      | 0.048 | 0.039                      | 0.053 | 0.033 |
| 8   | 0.1640                | 0.250 | 0.244                 | 0.272          | 0.110 | 0.096          | 0.348 | 0.322            | 0.031 | 0.019                      | 0.054 | 0.045                      | 0.074 | 0.052 |
| 10  | 0.1900                | 0.312 | 0.305                 | 0.340          | 0.120 | 0.105          | 0.414 | 0.384            | 0.031 | 0.019                      | 0.060 | 0.050                      | 0.080 | 0.057 |
| 12  | 0.2160                | 0.312 | 0.305                 | 0.340          | 0.155 | 0.139          | 0.432 | 0.398            | 0.039 | 0.022                      | 0.067 | 0.056                      | 0.103 | 0.077 |
| 1/4   | 0.2500                | 0.375 | 0.367                 | 0.409          | 0.190 | 0.172          | 0.520 | 0.480            | 0.050 | 0.030                      | 0.075 | 0.064                      | 0.111 | 0.083 |
| 5/16  | 0.3125                | 0.500 | 0.489                 | 0.545          | 0.230 | 0.208          | 0.676 | 0.624            | 0.055 | 0.035                      | 0.084 | 0.072                      | 0.134 | 0.100 |
| 3/8   | 0.3750                | 0.562 | 0.551                 | 0.614          | 0.295 | 0.270          | 0.780 | 0.720            | 0.063 | 0.037                      | 0.094 | 0.081                      | 0.168 | 0.131 |

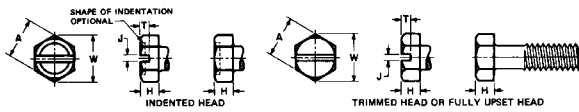
<sup>a</sup> Unless otherwise specified, hexagon washer head machine screws are not slotted.

All dimensions are in inches.

**Table 5. American National Standard Slotted Truss Head and Plain and Slotted Hexagon Head Machine Screws ANSI B18.6.3-1972 (R1991)**

| SLOTTED TRUSS HEAD TYPE   |              |       |                |       |                |               |       |               |       |       |
|---|--------------|-------|----------------|-------|----------------|---------------|-------|---------------|-------|-------|
|  |              |       |                |       |                |               |       |               |       |       |
| Nominal Size <sup>a</sup> or Basic Screw Dia.                                     | Head Dia., A |       | Head Height, H |       | Head Radius, R | Slot Width, J |       | Slot Depth, T |       |       |
|   | Max.         | Min.  | Max.           | Min.  | Max.           | Max.          | Min.  | Max.          | Min.  |       |
| 0000  | 0.0210       | 0.049 | 0.043          | 0.014 | 0.010          | 0.032         | 0.009 | 0.005         | 0.009 | 0.005 |
| 000   | 0.0340       | 0.077 | 0.071          | 0.022 | 0.018          | 0.051         | 0.013 | 0.009         | 0.013 | 0.009 |
| 00  | 0.0470       | 0.106 | 0.098          | 0.030 | 0.024          | 0.070         | 0.017 | 0.010         | 0.018 | 0.012 |
| 0   | 0.0600       | 0.131 | 0.119          | 0.037 | 0.029          | 0.087         | 0.023 | 0.016         | 0.022 | 0.014 |
| 1   | 0.0730       | 0.164 | 0.149          | 0.045 | 0.037          | 0.107         | 0.026 | 0.019         | 0.027 | 0.018 |
| 2   | 0.0860       | 0.194 | 0.180          | 0.053 | 0.044          | 0.129         | 0.031 | 0.023         | 0.031 | 0.022 |
| 3   | 0.0990       | 0.226 | 0.211          | 0.061 | 0.051          | 0.151         | 0.035 | 0.027         | 0.036 | 0.026 |
| 4   | 0.1120       | 0.257 | 0.241          | 0.069 | 0.059          | 0.169         | 0.039 | 0.031         | 0.040 | 0.030 |
| 5   | 0.1250       | 0.289 | 0.272          | 0.078 | 0.066          | 0.191         | 0.043 | 0.035         | 0.045 | 0.034 |
| 6   | 0.1380       | 0.321 | 0.303          | 0.086 | 0.074          | 0.211         | 0.048 | 0.039         | 0.050 | 0.037 |
| 8   | 0.1640       | 0.384 | 0.364          | 0.102 | 0.088          | 0.254         | 0.054 | 0.045         | 0.058 | 0.045 |
| 10  | 0.1900       | 0.448 | 0.425          | 0.118 | 0.103          | 0.283         | 0.060 | 0.050         | 0.068 | 0.053 |
| 12  | 0.2160       | 0.511 | 0.487          | 0.134 | 0.118          | 0.336         | 0.067 | 0.056         | 0.077 | 0.061 |
| 1/4   | 0.2500       | 0.573 | 0.546          | 0.150 | 0.133          | 0.375         | 0.075 | 0.064         | 0.087 | 0.070 |
| 3/16  | 0.3125       | 0.698 | 0.666          | 0.183 | 0.162          | 0.457         | 0.084 | 0.072         | 0.106 | 0.085 |
| 3/8   | 0.3750       | 0.823 | 0.787          | 0.215 | 0.191          | 0.538         | 0.094 | 0.081         | 0.124 | 0.100 |
| 7/16  | 0.4375       | 0.948 | 0.907          | 0.248 | 0.221          | 0.619         | 0.094 | 0.081         | 0.142 | 0.116 |
| 1/2   | 0.5000       | 1.073 | 1.028          | 0.280 | 0.250          | 0.701         | 0.106 | 0.091         | 0.161 | 0.131 |
| 9/16  | 0.5625       | 1.198 | 1.149          | 0.312 | 0.279          | 0.783         | 0.118 | 0.102         | 0.179 | 0.146 |
| 5/8   | 0.6250       | 1.323 | 1.269          | 0.345 | 0.309          | 0.863         | 0.133 | 0.116         | 0.196 | 0.162 |
| 3/4   | 0.7500       | 1.573 | 1.511          | 0.410 | 0.368          | 1.024         | 0.149 | 0.131         | 0.234 | 0.182 |

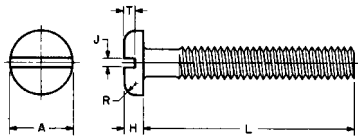
<sup>a</sup> Where specifying nominal size in decimals, zeros preceding decimal points and in the fourth decimal place are omitted.

| PLAIN AND SLOTTED HEXAGON HEAD TYPES   |                       |      |                 |                       |      |                 |                |      |                            |      |                            |      |      |
|--|-----------------------|------|-----------------|-----------------------|------|-----------------|----------------|------|----------------------------|------|----------------------------|------|------|
|  |                       |      |                 |                       |      |                 |                |      |                            |      |                            |      |      |
| Nominal Size <sup>a</sup> or Basic Screw Dia.                                      | Regular Head          |      |                 | Large Head            |      |                 | Head Height, H |      | Slot <sup>a</sup> Width, J |      | Slot <sup>a</sup> Depth, T |      |      |
|  | Width Across Flats, A |      | Across Corn., W | Width Across Flats, A |      | Across Corn., W | Max.           | Min. | Max.                       | Min. | Max.                       | Min. |      |
|  | Max.                  | Min. | Min.            | Max.                  | Min. | Min.            | Max.           | Min. | Max.                       | Min. | Max.                       | Min. |      |
| 1  | .0730                 | .125 | .120            | .134                  | .... | ....            | ....           | .044 | .036                       | .... | ....                       | .... | .... |
| 2  | 0.0860                | .125 | .120            | .134                  | .... | ....            | ....           | .050 | .040                       | .... | ....                       | .... | .... |
| 3  | 0.0990                | .188 | .181            | .202                  | .... | ....            | ....           | .055 | .044                       | .... | ....                       | .... | .... |
| 4  | 0.1120                | .188 | .181            | .202                  | .219 | .213            | .238           | .060 | .049                       | .039 | .031                       | .036 | .02  |
| 5  | 0.1250                | .188 | .181            | .202                  | .250 | .244            | .272           | .070 | .058                       | .043 | .035                       | .042 | .03  |
| 6  | 0.1380                | .250 | .244            | .272                  | .... | ....            | ....           | .093 | .080                       | .048 | .039                       | .046 | .03  |
| 8  | 0.1640                | .250 | .244            | .272                  | .312 | .305            | .340           | .110 | .096                       | .054 | .045                       | .066 | .05  |
| 10   | 0.1900                | .312 | .305            | .340                  | .... | ....            | ....           | .120 | .105                       | .060 | .050                       | .072 | .057 |
| 12   | 0.2160                | .312 | .305            | .340                  | .375 | .367            | .409           | .155 | .139                       | .067 | .056                       | .093 | .07  |
| 1/4  | 0.2500                | .375 | .367            | .409                  | .438 | .428            | .477           | .190 | .172                       | .075 | .064                       | .101 | .08  |
| 3/16   | 0.3125                | .500 | .489            | .545                  | .... | ....            | ....           | .230 | .208                       | .084 | .072                       | .122 | .10  |
| 3/8  | 0.3750                | .562 | .551            | .614                  | .... | ....            | ....           | .295 | .270                       | .094 | .081                       | .156 | .13  |

<sup>a</sup> Unless otherwise specified, hexagon head machine screws are not slotted.

All dimensions are in inches.

**Table 6. American National Standard Slotted Pan Head Machine Screws  
ANSI B18.6.3-1972 (R1991)**



| Nominal Size <sup>a</sup> or Basic Screw Dia. | Head Dia., A |       | Head Height, H |      | Head Radius, R | Slot Width, J |      | Slot Depth, T |      |      |
|---|--------------|-------|----------------|------|----------------|---------------|------|---------------|------|------|
|   | Max.         | Min.  | Max.           | Min. | Max.           | Max.          | Min. | Max.          | Min. |      |
| 0000  | 0.0210       | .042  | .036           | .016 | .010           | .007          | .008 | .004          | .008 | .004 |
| 000   | 0.0340       | .066  | .060           | .023 | .017           | .010          | .012 | .008          | .012 | .008 |
| 00  | 0.0470       | .090  | .082           | .032 | .025           | .015          | .017 | .010          | .016 | .010 |
| 0   | 0.0600       | .116  | .104           | .039 | .031           | .020          | .023 | .016          | .022 | .014 |
| 1   | 0.0730       | .142  | .130           | .046 | .038           | .025          | .026 | .019          | .027 | .018 |
| 2   | 0.0860       | .167  | .155           | .053 | .045           | .035          | .031 | .023          | .031 | .022 |
| 3   | 0.0990       | .193  | .180           | .060 | .051           | .037          | .035 | .027          | .036 | .026 |
| 4   | 0.1120       | .219  | .205           | .068 | .058           | .042          | .039 | .031          | .040 | .030 |
| 5   | 0.1250       | .245  | .231           | .075 | .065           | .044          | .043 | .035          | .045 | .034 |
| 6   | 0.1380       | .270  | .256           | .082 | .072           | .046          | .048 | .039          | .050 | .037 |
| 8   | 0.1640       | .322  | .306           | .096 | .085           | .052          | .054 | .045          | .058 | .045 |
| 10  | 0.1900       | .373  | .357           | .110 | .099           | .061          | .060 | .050          | .068 | .053 |
| 12  | 0.2160       | .425  | .407           | .125 | .112           | .078          | .067 | .056          | .077 | .061 |
| 1/4   | 0.2500       | .492  | .473           | .144 | .130           | .087          | .075 | .064          | .087 | .070 |
| 3/16  | 0.3125       | .615  | .594           | .178 | .162           | .099          | .084 | .072          | .106 | .085 |
| 5/16  | 0.3750       | .740  | .716           | .212 | .195           | .143          | .094 | .081          | .124 | .100 |
| 7/16  | 0.4375       | .863  | .837           | .247 | .228           | .153          | .094 | .081          | .142 | .116 |
| 1/2   | 0.5000       | .987  | .958           | .281 | .260           | .175          | .106 | .091          | .161 | .131 |
| 9/16  | 0.5625       | 1.041 | 1.000          | .315 | .293           | .197          | .118 | .102          | .179 | .146 |
| 5/8   | 0.6250       | 1.172 | 1.125          | .350 | .325           | .219          | .133 | .116          | .197 | .162 |
| 3/4   | 0.7500       | 1.435 | 1.375          | .419 | .390           | .263          | .149 | .131          | .234 | .192 |

<sup>a</sup> Where specifying nominal size in decimals, zeros preceding decimal and in the fourth decimal place are omitted.

All dimensions are in inches.

**Table 7. Nos. 0000, 000 and 00 Threads ANSI B18.6.3-1972 (R1991) Appendix**

| Nominal Size <sup>a</sup> and Threads Per Inch | Series Designat. | External <sup>b</sup> |                |       |                |       |       | Internal <sup>c</sup> |       |                |       |       |            |
|--|------------------|-----------------------|----------------|-------|----------------|-------|-------|-----------------------|-------|----------------|-------|-------|------------|
|  |                  | Class                 | Major Diameter |       | Pitch Diameter |       |       | Minor Dia.            | Class | Pitch Diameter |       |       | Major Dia. |
|  |                  |                       | Max.           | Min.  | Max.           | Min.  | Tol.  |                       |       | Min.           | Max.  | Tol.  |            |
| 0000-160 or 0.0210-160                         | NS               | 2                     | .0210          | .0195 | .0169          | .0158 | .0011 | .0128                 | 2     | .0169          | .0181 | .0012 | .0210      |
| 000-120 or 0.0340-120                          | NS               | 2                     | .0340          | .0325 | .0286          | 0.272 | .0014 | .0232                 | 2     | .0286          | .0300 | .0014 | .034       |
| 00-90 or 0.0470-90                             | NS               | 2                     | .0470          | .0450 | .0398          | .0382 | .0016 | .0326                 | 2     | .0398          | .0414 | .0016 | .047       |
| 00-96 or 0.0470-96                             | NS               | 2                     | .0470          | .0450 | .0402          | .0386 | .0016 | .0334                 | 2     | .0402          | .0418 | .0016 | .047       |

<sup>a</sup> Where specifying nominal size in decimals, zeros preceding decimal and in the fourth decimal place are omitted.

<sup>b</sup> There is no allowance provided on the external threads.

<sup>c</sup> The minor diameter limits for internal threads are not specified, they being determined by the amount of thread engagement necessary to satisfy the strength requirements and tapping performance in the intended application.

All dimensions are in inches.

**Table 8. American National Standard Slotted Fillister and Slotted Drilled Fillister Head Machine Screws ANSI B18.6.3-1972 (R1991)**

| SLOTTED FILLISTER HEAD TYPE                   |              |       |                     |      |                      |      |               |      |               |      |      |
|---|--------------|-------|---------------------|------|----------------------|------|---------------|------|---------------|------|------|
| Nominal Size <sup>1</sup> or Basic Screw Dia. | Head Dia., A |       | Head Side Height, H |      | Total Head Height, O |      | Slot Width, J |      | Slot Depth, T |      |      |
|   | Max.         | Min.  | Max.                | Min. | Max.                 | Min. | Max.          | Min. | Max.          | Min. |      |
| 0000  | 0.0210       | .038  | .032                | .019 | .011                 | .025 | .15           | .008 | .004          | .012 | .006 |
| 000   | 0.0340       | .059  | .053                | .029 | .021                 | .035 | .027          | .012 | .006          | .017 | .011 |
| 00  | 0.0470       | .082  | .072                | .037 | .028                 | .047 | .039          | .017 | .010          | .022 | .015 |
| 0   | 0.0600       | .096  | .083                | .043 | .038                 | .055 | .047          | .023 | .016          | .025 | .015 |
| 1   | 0.0730       | .118  | .104                | .053 | .045                 | .066 | .058          | .026 | .019          | .031 | .020 |
| 2   | 0.0860       | .140  | .124                | .062 | .053                 | .083 | .066          | .031 | .023          | .037 | .025 |
| 3   | 0.0990       | .161  | .145                | .070 | .061                 | .095 | .077          | .035 | .027          | .043 | .030 |
| 4   | 0.1120       | .183  | .166                | .079 | .069                 | .107 | .088          | .039 | .031          | .048 | .035 |
| 5   | 0.1250       | .205  | .187                | .088 | .078                 | .120 | .100          | .043 | .035          | .054 | .040 |
| 6   | 0.1380       | .226  | .208                | .096 | .086                 | .132 | .111          | .048 | .039          | .060 | .045 |
| 8   | 0.1640       | .270  | .250                | .113 | .102                 | .156 | .133          | .054 | .045          | .071 | .054 |
| 10  | 0.1900       | .313  | .292                | .130 | .118                 | .180 | .156          | .060 | .050          | .083 | .064 |
| 12  | 0.2160       | .357  | .334                | .148 | .134                 | .205 | .178          | .067 | .056          | .094 | .074 |
| 1/4   | 0.2500       | .414  | .389                | .170 | .155                 | .237 | .207          | .075 | .064          | .109 | .087 |
| 5/16  | 0.3125       | .518  | .490                | .211 | .194                 | .295 | .262          | .084 | .072          | .137 | .110 |
| 3/8   | 0.3750       | .622  | .590                | .253 | .233                 | .355 | .315          | .094 | .081          | .164 | .133 |
| 7/16  | 0.4375       | .625  | .589                | .265 | .242                 | .368 | .321          | .094 | .081          | .170 | .135 |
| 1/2   | 0.5000       | .750  | .710                | .297 | .273                 | .412 | .362          | .106 | .091          | .190 | .151 |
| 9/16  | 0.5625       | .812  | .768                | .336 | .308                 | .466 | .410          | .118 | .102          | .214 | .172 |
| 5/8   | 0.6250       | .875  | .827                | .375 | .345                 | .521 | .461          | .133 | .116          | .240 | .193 |
| 3/4   | 0.7500       | 1.000 | .945                | .441 | .406                 | .612 | .542          | .149 | .131          | .281 | .226 |

| SLOTTED DRILLED FILLISTER HEAD TYPE           |              |      |                     |      |                      |      |               |      |               |      |                        |                      |      |
|---|--------------|------|---------------------|------|----------------------|------|---------------|------|---------------|------|------------------------|----------------------|------|
| Nominal Size <sup>1</sup> or Basic Screw Dia. | Head Dia., A |      | Head Side Height, H |      | Total Head Height, O |      | Slot Width, J |      | Slot Depth, T |      | Drilled Hole Locat., E | Drilled Hole Dia., F |      |
|   | Max.         | Min. | Max.                | Min. | Max.                 | Min. | Max.          | Min. | Max.          | Min. | Basic                  | Basic                |      |
| 2   | 0.0860       | .140 | .124                | .062 | .055                 | .083 | .070          | .031 | .023          | .030 | .022                   | .026                 | .031 |
| 3   | 0.0990       | .161 | .145                | .070 | .064                 | .095 | .082          | .035 | .027          | .034 | .026                   | .030                 | .037 |
| 4   | 0.1120       | .183 | .166                | .079 | .072                 | .107 | .094          | .039 | .031          | .038 | .030                   | .035                 | .037 |
| 5   | 0.1250       | .205 | .187                | .088 | .081                 | .120 | .106          | .043 | .035          | .042 | .033                   | .038                 | .046 |
| 6   | 0.1380       | .226 | .208                | .096 | .089                 | .132 | .118          | .048 | .039          | .045 | .035                   | .043                 | .046 |
| 8   | 0.1640       | .270 | .250                | .113 | .106                 | .156 | .141          | .054 | .045          | .065 | .054                   | .043                 | .046 |
| 10  | 0.1900       | .313 | .292                | .130 | .123                 | .180 | .165          | .060 | .050          | .075 | .064                   | .043                 | .046 |
| 12  | 0.2160       | .357 | .334                | .148 | .139                 | .205 | .188          | .067 | .056          | .087 | .074                   | .053                 | .046 |
| 1/4   | 0.2500       | .414 | .389                | .170 | .161                 | .237 | .219          | .075 | .064          | .102 | .087                   | .062                 | .062 |
| 5/16  | 0.3125       | .518 | .490                | .211 | .201                 | .295 | .276          | .084 | .072          | .130 | .110                   | .078                 | .070 |
| 3/8   | 0.3750       | .622 | .590                | .253 | .242                 | .355 | .333          | .094 | .081          | .154 | .134                   | .094                 | .070 |

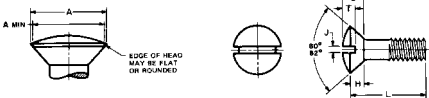
All dimensions are in inches.

<sup>1</sup>Where specifying nominal size in decimals, zeros preceding decimal points and in the fourth decimal place are omitted.

<sup>2</sup>Drilled hole shall be approximately perpendicular to the axis of slot and may be permitted to break through bottom of the slot. Edges of the hole shall be free from burrs.

<sup>3</sup>A slight rounding of the edges at periphery of head is permissible provided the diameter of the bearing circle is equal to no less than 90 per cent of the specified minimum head diameter.

**Table 9. American National Standard Slotted Oval Countersunk Head Machine Screws ANSI B18.6.3-1972 (R1991)**



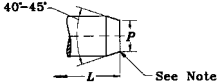
| Nominal Size <sup>a</sup> or Basic Screw Dia. | Max L <sup>b</sup> | Head Dia., A     |                          | Head Side Height, H, | Total Head Height, O |      | Slot Width, J |      | Slot Depth, T |      |      |
|---|--------------------|------------------|--------------------------|----------------------|----------------------|------|---------------|------|---------------|------|------|
|   |                    | Max., Edge Sharp | Min., Edge Rndd. or Flat |                      | Max.                 | Min. | Max.          | Min. | Max.          | Min. |      |
|   |                    | Ref.             | Max.                     | Min.                 | Max.                 | Min. | Max.          | Min. |               |      |      |
| 00  | 0.0470             | ...              | .093                     | .085                 | .028                 | .042 | .034          | .017 | .010          | .023 | .016 |
| 0   | 0.0600             | 1/8              | .119                     | .099                 | .035                 | .056 | .041          | .023 | .016          | .030 | .025 |
| 1   | 0.0730             | 3/8              | .146                     | .123                 | .043                 | .068 | .052          | .026 | .019          | .038 | .031 |
| 2   | 0.0860             | 1/8              | .172                     | .147                 | .051                 | .080 | .063          | .031 | .023          | .045 | .037 |
| 3   | 0.0990             | 3/8              | .199                     | .171                 | .059                 | .092 | .073          | .035 | .027          | .052 | .043 |
| 4   | 0.1120             | 3/16             | .225                     | .195                 | .067                 | .104 | .084          | .039 | .031          | .059 | .049 |
| 5   | 0.1250             | 3/16             | .252                     | .220                 | .075                 | .116 | .095          | .043 | .035          | .067 | .055 |
| 6   | 0.1380             | 3/16             | .279                     | .244                 | .083                 | .128 | .105          | .048 | .039          | .074 | .060 |
| 8   | 0.1640             | 1/4              | .332                     | .292                 | .100                 | .152 | .126          | .054 | .045          | .088 | .072 |
| 10  | 0.1900             | 3/16             | .385                     | .340                 | .116                 | .176 | .148          | .060 | .050          | .103 | .084 |
| 12  | 0.2160             | 3/8              | .438                     | .389                 | .132                 | .200 | .169          | .067 | .056          | .117 | .096 |
| 1/4   | 0.2500             | 3/16             | .507                     | .452                 | .153                 | .232 | .197          | .075 | .064          | .136 | .112 |
| 5/16  | 0.3125             | 1/2              | .635                     | .568                 | .191                 | .290 | .249          | .084 | .072          | .171 | .141 |
| 3/8   | 0.3750             | 9/16             | .762                     | .685                 | .230                 | .347 | .300          | .094 | .081          | .206 | .170 |
| 7/16  | 0.4375             | 3/8              | .812                     | .723                 | .223                 | .345 | .295          | .094 | .081          | .210 | .174 |
| 1/2   | 0.5000             | 3/4              | .875                     | .775                 | .223                 | .354 | .299          | .106 | .091          | .216 | .176 |
| 9/16  | 0.5625             | ...              | 1.000                    | .889                 | .260                 | .410 | .350          | .118 | .102          | .250 | .207 |
| 5/8   | 0.6250             | ...              | 1.125                    | 1.002                | .298                 | .467 | .399          | .133 | .116          | .285 | .235 |
| 3/4   | 0.7500             | ...              | 1.375                    | 1.230                | .372                 | .578 | .497          | .149 | .131          | .353 | .293 |

<sup>a</sup> When specifying nominal size in decimals, zeros preceding decimal points and in the fourth decimal place are omitted.

<sup>b</sup> These lengths or shorter are undercut.

All dimensions are in inches.

**Table 10. American National Standard Header Points for Machine Screws before Threading ANSI B18.6.3-1972 (R1991)**



| Nom. Size. | Threads per Inch | Max. P | Min. P | Max. L | Nom. Size | Threads per Inch | Max. P | Min. P | Max. L |
|------------|------------------|--------|--------|--------|-----------|------------------|--------|--------|--------|
|            |                  |        |        |        | 10        | 24               | 0.125  | 0.112  | 1/4    |
| 12         | 24               | 0.149  | 0.134  | 13/8   | 28        | 0.156            | 0.141  |        |        |
| 2          | 56               | 0.057  | 0.050  | 1/2    | 20        | 0.170            | 0.153  |        |        |
|            | 64               | 0.060  | 0.053  | 1/2    | 28        | 0.187            | 0.169  |        |        |
| 4          | 40               | 0.074  | 0.065  | 1/2    | 18        | 0.221            | 0.200  |        |        |
|            | 48               | 0.079  | 0.070  | 1/2    | 24        | 0.237            | 0.215  |        |        |
| 5          | 40               | 0.086  | 0.076  | 1/2    | 16        | 0.270            | 0.244  |        |        |
|            | 44               | 0.088  | 0.079  | 1/2    | 24        | 0.295            | 0.267  |        |        |
| 6          | 32               | 0.090  | 0.080  | 3/4    | 14        | 0.316            | 0.287  |        |        |
|            | 40               | 0.098  | 0.087  | 3/4    | 20        | 0.342            | 0.310  |        |        |
| 8          | 32               | 0.114  | 0.102  | 1      | 13        | 0.367            | 0.333  |        |        |
|            | 36               | 0.118  | 0.106  | 1      | 20        | 0.399            | 0.362  |        |        |

All dimensions in inches. Edges of point may be rounded and end of point need not be flat nor perpendicular to shank. Machine screws normally have plain sheared ends but when specified may have header points, as shown above.

**Table 11. American National Standard Slotted Binding Head and Slotted Undercut Oval Countersunk Head Machine Screws ANSI B18.6.3-1972 (R1991)**

| SLOTTED BINDING HEAD TYPE                     |              |      |                      |      |                     |      |               |      |               |      |                               |      |                                |      |      |
|---|--------------|------|----------------------|------|---------------------|------|---------------|------|---------------|------|-------------------------------|------|--------------------------------|------|------|
| Nominal Size <sup>a</sup> or Basic Screw Dia. | Head Dia., A |      | Total Head Height, O |      | Head Oval Height, F |      | Slot Width, J |      | Slot Depth, T |      | Undercut <sup>b</sup> Dia., U |      | Undercut <sup>b</sup> Depth, X |      |      |
|   | Max.         | Min. | Max.                 | Min. | Max.                | Min. | Max.          | Min. | Max.          | Min. | Max.                          | Min. | Max.                           | Min. |      |
| 0000  | 0.0210       | .046 | .040                 | .014 | .009                | .006 | .003          | .008 | .004          | .009 | .005                          | ...  | ...                            | ...  | ...  |
| 000   | 0.0340       | .073 | .067                 | .021 | .015                | .008 | .005          | .012 | .006          | .013 | .009                          | ...  | ...                            | ...  | ...  |
| 00  | 0.0470       | .098 | .090                 | .028 | .023                | .011 | .007          | .017 | .010          | .018 | .012                          | ...  | ...                            | ...  | ...  |
| 0   | 0.0600       | .126 | .119                 | .032 | .026                | .012 | .008          | .023 | .016          | .018 | .009                          | .098 | .086                           | .007 | .002 |
| 1   | 0.0730       | .153 | .145                 | .041 | .035                | .015 | .011          | .026 | .019          | .024 | .014                          | .120 | .105                           | .008 | .003 |
| 2   | 0.0860       | .181 | .171                 | .050 | .043                | .018 | .013          | .031 | .023          | .030 | .020                          | .141 | .124                           | .010 | .005 |
| 3   | 0.0990       | .208 | .197                 | .059 | .052                | .022 | .016          | .035 | .027          | .036 | .025                          | .162 | .143                           | .011 | .006 |
| 4   | 0.1120       | .235 | .223                 | .068 | .061                | .025 | .018          | .039 | .031          | .042 | .030                          | .184 | .161                           | .012 | .007 |
| 5   | 0.1250       | .263 | .249                 | .078 | .069                | .029 | .021          | .043 | .035          | .048 | .035                          | .205 | .180                           | .014 | .009 |
| 6   | 0.1380       | .290 | .275                 | .087 | .078                | .032 | .024          | .048 | .039          | .053 | .040                          | .226 | .199                           | .015 | .010 |
| 8   | 0.1640       | .344 | .326                 | .105 | .095                | .039 | .029          | .054 | .045          | .065 | .050                          | .269 | .236                           | .017 | .012 |
| 10  | 0.1900       | .399 | .378                 | .123 | .112                | .045 | .034          | .060 | .050          | .077 | .060                          | .312 | .274                           | .020 | .015 |
| 12  | 0.2160       | .454 | .430                 | .141 | .130                | .052 | .039          | .067 | .056          | .089 | .070                          | .354 | .311                           | .023 | .018 |
| ¼   | 0.2500       | .525 | .498                 | .165 | .152                | .061 | .046          | .075 | .064          | .105 | .084                          | .410 | .360                           | .026 | .021 |
| ⅜   | 0.3125       | .656 | .622                 | .209 | .194                | .077 | .059          | .084 | .072          | .134 | .108                          | .513 | .450                           | .032 | .027 |
| ½   | 0.3750       | .788 | .746                 | .253 | .235                | .094 | .071          | .094 | .081          | .163 | .132                          | .615 | .540                           | .039 | .034 |

<sup>a</sup> Where specifying nominal size in decimals, zeros preceding decimal points and in the fourth decimal place are omitted.

<sup>b</sup> Unless otherwise specified, slotted binding head machine screws are not undercut.

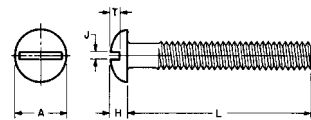
| SLOTTED UNDERCUT OVAL COUNTERSUNK HEAD TYPES  |                     |                  |                           |                     |                      |      |               |      |               |      |      |
|---|---------------------|------------------|---------------------------|---------------------|----------------------|------|---------------|------|---------------|------|------|
| Nominal Size <sup>a</sup> or Basic Screw Dia. | Max. L <sup>a</sup> | Head Dia., A     |                           | Head Side Height, H | Total Head Height, O |      | Slot Width, J |      | Slot Depth, T |      |      |
|   |                     | Max., Edge Sharp | Min., Edge Rnded. or Flat |                     | Max.                 | Min. | Max.          | Min. | Max.          | Min. |      |
|   |                     | Ref.             | Max.                      | Min.                | Max.                 | Min. | Max.          | Min. | Max.          | Min. |      |
| 0   | 0.0600              | ¼                | .119                      | .099                | .025                 | .046 | .033          | .023 | .016          | .028 | .022 |
| 1   | 0.0730              | ⅛                | .146                      | .123                | .031                 | .056 | .042          | .026 | .019          | .034 | .027 |
| 2   | 0.0860              | ⅛                | .172                      | .147                | .036                 | .065 | .050          | .031 | .023          | .040 | .033 |
| 3   | 0.0990              | ⅛                | .199                      | .171                | .042                 | .075 | .059          | .035 | .027          | .047 | .038 |
| 4   | 0.1120              | ⅜ <sub>16</sub>  | .225                      | .195                | .047                 | .084 | .067          | .039 | .031          | .053 | .043 |
| 5   | 0.1250              | ⅜ <sub>16</sub>  | .252                      | .220                | .053                 | .094 | .076          | .043 | .035          | .059 | .048 |
| 6   | 0.1380              | ⅜ <sub>16</sub>  | .279                      | .244                | .059                 | .104 | .084          | .048 | .039          | .065 | .053 |
| 8   | 0.1640              | ¼                | .332                      | .292                | .070                 | .123 | .101          | .054 | .045          | .078 | .064 |
| 10  | 0.1900              | ⅜ <sub>16</sub>  | .385                      | .340                | .081                 | .142 | .118          | .060 | .050          | .090 | .074 |
| 12  | 0.2160              | ⅜ <sub>16</sub>  | .438                      | .389                | .092                 | .161 | .135          | .067 | .056          | .103 | .085 |
| ¼   | 0.2500              | ⅜ <sub>16</sub>  | .507                      | .452                | .107                 | .186 | .158          | .075 | .064          | .119 | .098 |
| ⅜   | 0.3125              | ½                | .635                      | .568                | .134                 | .232 | .198          | .084 | .072          | .149 | .124 |
| ½   | 0.3750              | ⅝ <sub>16</sub>  | .762                      | .685                | .161                 | .278 | .239          | .094 | .081          | .179 | .149 |
| ⅝   | 0.4375              | ⅝ <sub>16</sub>  | .812                      | .723                | .156                 | .279 | .239          | .094 | .081          | .184 | .154 |
| ¾   | 0.5000              | ¾                | .875                      | .775                | .156                 | .288 | .244          | .106 | .091          | .204 | .169 |

<sup>a</sup> These lengths or shorter are undercut.

All dimensions are in inches.



**Table 12. Slotted Round Head Machine Screws**  
ANSI B18.6.3-1972 (R1991) Appendix



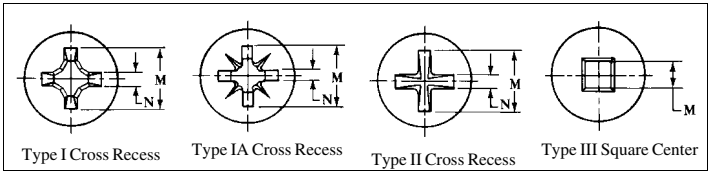
| Nominal Size <sup>a</sup> or Basic Screw Dia. |        | Head Diameter, A |       | Head Height, H |      | Slot Width, J |      | Slot Depth, T |      |
|---|--------|------------------|-------|----------------|------|---------------|------|---------------|------|
|   |        | Max.             | Min.  | Max.           | Min. | Max.          | Min. | Max.          | Min. |
| 0000  | 0.0210 | .041             | .035  | .022           | .016 | .008          | .004 | .017          | .013 |
| 000   | 0.0340 | .062             | .056  | .031           | .025 | .012          | .008 | .018          | .012 |
| 00  | 0.0470 | .089             | .080  | .045           | .036 | .017          | .010 | .026          | .018 |
| 0   | 0.0600 | .113             | .099  | .053           | .043 | .023          | .016 | .039          | .029 |
| 1   | 0.0730 | .138             | .122  | .061           | .051 | .026          | .019 | .044          | .033 |
| 2   | 0.0860 | .162             | .146  | .069           | .059 | .031          | .023 | .048          | .037 |
| 3   | 0.0990 | .187             | .169  | .078           | .067 | .035          | .027 | .053          | .040 |
| 4   | 0.1120 | .211             | .193  | .086           | .075 | .039          | .031 | .058          | .044 |
| 5   | 0.1250 | .236             | .217  | .095           | .083 | .043          | .035 | .063          | .047 |
| 6   | 0.1380 | .260             | .240  | .103           | .091 | .048          | .039 | .068          | .051 |
| 8   | 0.1640 | .309             | .287  | .120           | .107 | .054          | .045 | .077          | .058 |
| 10  | 0.1900 | .359             | .334  | .137           | .123 | .060          | .050 | .087          | .065 |
| 12  | 0.2160 | .408             | .382  | .153           | .139 | .067          | .056 | .096          | .073 |
| ¼   | 0.2500 | .472             | .443  | .175           | .160 | .075          | .064 | .109          | .082 |
| ⅜   | 0.3125 | .590             | .557  | .216           | .198 | .084          | .072 | .132          | .099 |
| ½   | 0.3750 | .708             | .670  | .256           | .237 | .094          | .081 | .155          | .117 |
| ⅝   | 0.4375 | .750             | .707  | .328           | .307 | .094          | .081 | .196          | .148 |
| ¾   | 0.5000 | .813             | .766  | .355           | .332 | .106          | .091 | .211          | .159 |
| ⅞   | 0.5625 | .938             | .887  | .410           | .385 | .118          | .102 | .242          | .183 |
| 1   | 0.6250 | 1.000            | .944  | .438           | .411 | .133          | .116 | .258          | .195 |
| 1¼  | 0.7500 | 1.250            | 1.185 | .547           | .516 | .149          | .131 | .320          | .242 |

<sup>a</sup> When specifying nominal size in decimals, zeros preceding decimal point and in the fourth decimal place are omitted.

All dimensions are in inches.

Not recommended, use Pan Head machine screws.

**ANSI Cross References for Machine Screws and Metric Machine Screw**



**Machine Screw Cross Recesses.**—Four cross recesses, Types I, IA, II, and III, may be used in lieu of slots in machine screw heads. Dimensions for recess diameter *M*, width *N*, and depth *T* (not shown above) together with recess penetration gaging depths are given in American National Standard ANSI B18.6.3-1972 (R1991) for machine screws, and in ANSI/ASME B18.6.7M-1985 for metric machine screws.

**American National Standard Metric Machine Screws.**—This Standard B18.6.7M covers metric flat and oval countersunk and slotted and recessed pan head machine screws and metric hex head and hex flange head machine screws. Dimensions are given in [Tables 1 through 4](#) and 6.

**Table 1. American National Standard Thread Lengths for Metric Machine Screws**  
*ANSI/ASME B18.6.7M-1985*

| Nominal<br>Screw<br>Size<br>and<br>Thread<br>Pitch | Pan, Hex, and Hex Flange Head<br>Screws                                      |                                   |                  | Flat and Oval Countersunk Head<br>Screws |                          |                                   | Heat-Treated Recessed Flat<br>Countersunk Head Screws |   |   |
|--|--|-----------------------------------|------------------|--|--------------------------|-----------------------------------|---|---|---|
|  | L  | $L_{US}$                          | $L_U$            | L  |                          | $L_{US}$                          | $L_U L$   | L   | B   |
|  | Nominal<br>Screw<br>Length<br>Equal<br>to or<br>Shorter<br>than <sup>a</sup> | Unthreaded<br>Length <sup>b</sup> |                  | Nominal<br>Screw<br>Length <sup>a</sup>  |                          | Unthreaded<br>Length <sup>b</sup> |   | Nominal<br>Screw<br>Length<br>Longer<br>than <sup>a</sup> | Full<br>Form<br>Thread<br>Length <sup>c</sup> |
|  |  | Max <sup>d</sup>                  | Max <sup>e</sup> | Over                                     | To and<br>Includ-<br>ing | Max <sup>d</sup>                  | Max <sup>e</sup>                                      |   |   |
| M2 × 0.4   | 6  | 1.0                               | 0.4              | 6  | 30                       | 1.0                               | 0.8   | 30  | 25.0  |
| M2.5 × 0.45  | 8  | 1.1                               | 0.5              | 8  | 30                       | 1.1                               | 0.9   | 30  | 25.0  |
| M3 × 0.5   | 9  | 1.2                               | 0.5              | 9  | 30                       | 1.2                               | 1.0   | 30  | 25.0  |
| M3.5 × 0.6   | 10   | 1.5                               | 0.6              | 10                                       | 50                       | 1.5                               | 1.2   | 50  | 38.0  |
| M4 × 0.7   | 12   | 1.8                               | 0.7              | 12                                       | 50                       | 1.8                               | 1.4   | 50  | 38.0  |
| M5 × 0.8   | 15   | 2.0                               | 0.8              | 15                                       | 50                       | 2.0                               | 1.6   | 50  | 38.0  |
| M6 × 1   | 18   | 2.5                               | 1.0              | 18                                       | 50                       | 2.5                               | 2.0   | 50  | 38.0  |
| M8 × 1.25  | 24   | 3.1                               | 1.2              | 24                                       | 50                       | 3.1                               | 2.5   | 50  | 38.0  |
| M10 × 1.5  | 30   | 3.8                               | 1.5              | 30                                       | 50                       | 3.8                               | 3.0   | 50  | 38.0  |
| M12 × 1.75   | 36   | 4.4                               | 1.8              | 36                                       | 50                       | 4.4                               | 3.5   | 50  | 38.0  |

<sup>a</sup>The length tolerances for metric machine screws are: up to 3 mm, incl., ± 0.2 mm; over 3 to 10 mm, incl., ± 0.3 mm; over 10 to 16 mm, incl., ± 0.4 mm; over 16 to 50 mm, incl., ± 0.5 mm; over 50 mm, ± 1.0 mm.

<sup>b</sup>Unthreaded lengths  $L_U$  and  $L_{US}$  represent the distance, measured parallel to the axis of screw, from the underside of the head to the face of a nonchamfered or noncounterbored standard GO thread ring gage assembled by hand as far as the thread will permit.

<sup>c</sup>Refer to the illustrations for respective screw head styles.

<sup>d</sup>The  $L_{US}$  values apply only to heat treated recessed flat countersunk head screws.

<sup>e</sup>The  $L_U$  values apply to all screws except heat treated recessed flat countersunk head screws.

All dimensions in millimeters.

**Table 2. American National Standard Slotted, Cross and Square Recessed Flat Countersunk Head Metric Machine Screws**  
ANSI/ASME B18.6.7M-1985

| Nominal Screw Size and Thread Pitch | Slotted and Style A |      | Style B                      |                   |                |                              |      | D <sub>K</sub>    |      |        | K       | R           |                         | N   |            | T   |            |
|-------------------------------------|---------------------|------|------------------------------|-------------------|----------------|------------------------------|------|-------------------|------|--------|---------|-------------|-------------------------|-----|------------|-----|------------|
|                                     | D <sub>S</sub>      |      | D <sub>SH</sub> <sup>a</sup> |                   | D <sub>S</sub> | L <sub>SH</sub> <sup>a</sup> |      | Head Diameter     |      |        |         | Head Height | Underhead Fillet Radius |     | Slot Width |     | Slot Depth |
|                                     | Body Diameter       |      | Body and Shoulder Diameter   | Shoulder Diameter | Body Diameter  | Shoulder Length              |      | Theoretical Sharp |      | Actual | Max Ref |             | Max                     | Min | Max        | Min | Max        |
|                                     | Max                 | Min  | Max                          | Min               | Min            | Max                          | Min  | Max               | Min  | Min    |         | Max         | Min                     | Max | Min        | Max | Min        |
| M2 × 0.4 <sup>b</sup>               | 2.00                | 1.65 | 2.00                         | 1.86              | 1.65           | 0.50                         | 0.30 | 4.4               | 4.1  | 3.5    | 1.2     | 0.8         | 0.4                     | 0.7 | 0.5        | 0.6 | 0.4        |
| M2.5 × 0.45                         | 2.50                | 2.12 | 2.50                         | 2.36              | 2.12           | 0.55                         | 0.35 | 5.5               | 5.1  | 4.4    | 1.5     | 1.0         | 0.5                     | 0.8 | 0.6        | 0.7 | 0.5        |
| M3 × 0.5                            | 3.00                | 2.58 | 3.00                         | 2.86              | 2.58           | 0.60                         | 0.40 | 6.3               | 5.9  | 5.2    | 1.7     | 1.2         | 0.6                     | 1.0 | 0.8        | 0.9 | 0.6        |
| M3.5 × 0.6                          | 3.50                | 3.00 | 3.50                         | 3.32              | 3.00           | 0.70                         | 0.50 | 8.2               | 7.7  | 6.9    | 2.3     | 1.4         | 0.7                     | 1.2 | 1.0        | 1.2 | 0.9        |
| M4 × 0.7                            | 4.00                | 3.43 | 4.00                         | 3.82              | 3.43           | 0.80                         | 0.60 | 9.4               | 8.9  | 8.0    | 2.7     | 1.6         | 0.8                     | 1.5 | 1.2        | 1.3 | 1.0        |
| M5 × 0.8                            | 5.00                | 4.36 | 5.00                         | 4.82              | 4.36           | 0.90                         | 0.70 | 10.4              | 9.8  | 8.9    | 2.7     | 2.0         | 1.0                     | 1.5 | 1.2        | 1.4 | 1.1        |
| M6 × 1                              | 6.00                | 5.21 | 6.00                         | 5.82              | 5.21           | 1.10                         | 0.90 | 12.6              | 11.9 | 10.9   | 3.3     | 2.4         | 1.2                     | 1.9 | 1.6        | 1.6 | 1.2        |
| M8 × 1.25                           | 8.00                | 7.04 | 8.00                         | 7.78              | 7.04           | 1.40                         | 1.10 | 17.3              | 16.5 | 15.4   | 4.6     | 3.2         | 1.6                     | 2.3 | 2.0        | 2.3 | 1.8        |
| M10 × 1.5                           | 10.00               | 8.86 | 10.00                        | 9.78              | 8.86           | 1.70                         | 1.30 | 20.0              | 19.2 | 17.8   | 5.0     | 4.0         | 2.0                     | 2.8 | 2.5        | 2.6 | 2.0        |

<sup>a</sup> All recessed head heat-treated steel screws of property class 9.8 or higher strength have the Style B head form. Recessed head screws other than those specifically designated to be Style B have the Style A head form. The underhead shoulder on the Style B head form is mandatory and all other head dimensions are common to both the Style A and Style B head forms.

<sup>b</sup> This size is not specified for Type III square recessed flat countersunk heads; Type II cross recess is not specified for any size.

All dimensions in millimeters.

For dimension *B*, see [Table 1](#).

For dimension *L*, see [Table 7](#).

**Table 3. American National Standard Slotted, Cross and Square Recessed Oval Countersunk Head Metric Machine Screws**  
ANSI/ASME B18.6.7M-1985

| Nominal<br>Screw<br>Size<br>and<br>Thread<br>Pitch | $D_S$            |      | $D_K$                |      |      | $K$                    | $F$                      | $R_F$                 | $R$                           |     | $N$           |     | $T$           |     |
|--|------------------|------|----------------------|------|------|------------------------|--------------------------|-----------------------|-------------------------------|-----|---------------|-----|---------------|-----|
|  | Body<br>Diameter |      | Head Diameter        |      |      | Head<br>Side<br>Height | Raised<br>Head<br>Height | Head<br>Top<br>Radius | Underhead<br>Fillet<br>Radius |     | Slot<br>Width |     | Slot<br>Depth |     |
|  |                  |      | Theoretical<br>Sharp |      |      |                        |                          |                       |                               |     |               |     |               |     |
|  | Max              | Min  | Max                  | Min  | Min  | Max<br>Ref             | Max                      | Approx                | Max                           | Min | Max           | Min | Max           | Min |
| M2 × 0.4 <sup>a</sup>                              | 2.00             | 1.65 | 4.4                  | 4.1  | 3.5  | 1.2                    | 0.5                      | 5.0                   | 0.8                           | 0.4 | 0.7           | 0.5 | 1.0           | 0.8 |
| M2.5 × 0.45  | 2.50             | 2.12 | 5.5                  | 5.1  | 4.4  | 1.5                    | 0.6                      | 6.6                   | 1.0                           | 0.5 | 0.8           | 0.6 | 1.2           | 1.0 |
| M3 × 0.5   | 3.00             | 2.58 | 6.3                  | 5.9  | 5.2  | 1.7                    | 0.7                      | 7.4                   | 1.2                           | 0.6 | 1.0           | 0.8 | 1.5           | 1.2 |
| M3.5 × 0.6   | 3.50             | 3.00 | 8.2                  | 7.7  | 6.9  | 2.3                    | 0.8                      | 10.9                  | 1.4                           | 0.7 | 1.2           | 1.0 | 1.7           | 1.4 |
| M4 × 0.7   | 4.00             | 3.43 | 9.4                  | 8.9  | 8.0  | 2.7                    | 1.0                      | 11.6                  | 1.6                           | 0.8 | 1.5           | 1.2 | 1.9           | 1.6 |
| M5 × 0.8   | 5.00             | 4.36 | 10.4                 | 9.8  | 8.9  | 2.7                    | 1.2                      | 11.9                  | 2.0                           | 1.0 | 1.5           | 1.2 | 2.4           | 2.0 |
| M6 × 1   | 6.00             | 5.21 | 12.6                 | 11.9 | 10.9 | 3.3                    | 1.4                      | 14.9                  | 2.4                           | 1.2 | 1.9           | 1.6 | 2.8           | 2.4 |
| M8 × 1.25  | 8.00             | 7.04 | 17.3                 | 16.5 | 15.4 | 4.6                    | 2.0                      | 19.7                  | 3.2                           | 1.6 | 2.3           | 2.0 | 3.7           | 3.2 |
| M10 × 1.5  | 10.00            | 8.86 | 20.0                 | 19.2 | 17.8 | 5.0                    | 2.3                      | 22.9                  | 4.0                           | 2.0 | 2.8           | 2.5 | 4.4           | 3.8 |

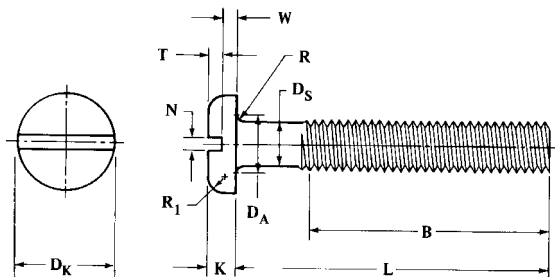
<sup>a</sup>This size is not specified for Type III square recessed oval countersunk heads; Type II cross recess is not specified for any size.

All dimensions in millimeters.

For dimension  $B$ , see [Table 1](#).

For dimension  $L$ , see [Table 7](#).

**Table 4. American National Standard Slotted and Cross and Square Recessed Pan Head Metric Machine Screws**  
ANSI/ASME B18.6.7M-1985



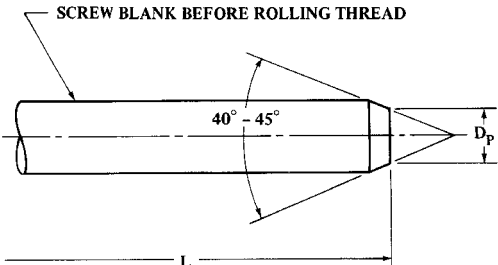
| Nominal<br>Screw<br>Size<br>and<br>Thread<br>Pitch | D <sub>s</sub>   |      | D <sub>k</sub>   |      | Slotted        |     |                |     | Cross and<br>Square Recess |      |                |     | D <sub>A</sub>   | R   | N             |     | T             | W   |                                |     |
|--|------------------|------|------------------|------|----------------|-----|----------------|-----|----------------------------|------|----------------|-----|------------------|-----|---------------|-----|---------------|-----|--------------------------------|-----|
|  |                  |      |                  |      | K              |     | R <sub>1</sub> |     | K                          |      | R <sub>1</sub> |     |                  |     |               |     |               |     |                                |     |
|  | Body<br>Diameter |      | Head<br>Diameter |      | Head<br>Height |     | Head<br>Radius |     | Head<br>Height             |      | Head<br>Radius |     | Underhead Fillet |     | Slot<br>Width |     | Slot<br>Depth |     | Unslotted<br>Head<br>Thickness |     |
|  | Max              | Min  | Max              | Min  | Max            | Min | Max            | Min | Max                        | Min  | Ref            | Max | Min              | Max | Min           | Max | Min           | Max | Min                            | Max |
| M2 × 0.4 <sup>a</sup>                              | 2.00             | 1.65 | 4.0              | 3.7  | 1.3            | 1.1 | 0.8            | 1.6 | 1.4                        | 3.2  | 2.6            | 0.1 | 0.7              | 0.5 | 0.5           | 0.4 | 0.5           | 0.4 | 0.5                            | 0.4 |
| M2.5 × 0.45  | 2.50             | 2.12 | 5.0              | 4.7  | 1.5            | 1.3 | 1.0            | 2.1 | 1.9                        | 4.0  | 3.1            | 0.1 | 0.8              | 0.6 | 0.6           | 0.5 | 0.6           | 0.5 | 0.6                            | 0.5 |
| M3 × 0.5   | 3.00             | 2.58 | 5.6              | 5.3  | 1.8            | 1.6 | 1.2            | 2.4 | 2.2                        | 5.0  | 3.6            | 0.1 | 1.0              | 0.8 | 0.7           | 0.7 | 0.8           | 0.7 | 0.8                            | 0.7 |
| M3.5 × 0.6   | 3.50             | 3.00 | 7.0              | 6.6  | 2.1            | 1.9 | 1.4            | 2.6 | 2.3                        | 6.0  | 4.1            | 0.1 | 1.2              | 1.0 | 0.8           | 0.8 | 1.0           | 0.8 | 0.8                            | 0.8 |
| M4 × 0.7   | 4.00             | 3.43 | 8.0              | 7.6  | 2.4            | 2.2 | 1.6            | 3.1 | 2.8                        | 6.5  | 4.7            | 0.2 | 1.5              | 1.2 | 1.0           | 0.9 | 1.2           | 1.0 | 1.0                            | 0.9 |
| M5 × 0.8   | 5.00             | 4.36 | 9.5              | 9.1  | 3.0            | 2.7 | 2.0            | 3.7 | 3.4                        | 8.0  | 5.7            | 0.2 | 1.5              | 1.2 | 1.2           | 1.2 | 1.2           | 1.2 | 1.2                            | 1.2 |
| M6 × 1   | 6.00             | 5.21 | 12.0             | 11.5 | 3.6            | 3.3 | 2.5            | 4.6 | 4.3                        | 10.0 | 6.8            | 0.3 | 1.9              | 1.6 | 1.4           | 1.4 | 1.6           | 1.4 | 1.4                            | 1.4 |
| M8 × 1.25  | 8.00             | 7.04 | 16.0             | 15.5 | 4.8            | 4.5 | 3.2            | 6.0 | 5.6                        | 13.0 | 9.2            | 0.4 | 2.3              | 2.0 | 1.9           | 1.9 | 2.0           | 1.9 | 1.9                            | 1.9 |
| M10 × 1.5  | 10.00            | 8.86 | 20.0             | 19.4 | 6.0            | 5.7 | 4.0            | 7.5 | 7.1                        | 16.0 | 11.2           | 0.4 | 2.8              | 2.5 | 2.4           | 2.4 | 2.8           | 2.5 | 2.4                            | 2.4 |

<sup>a</sup>This size not specified for Type III square recessed pan heads; Type II cross recess is not specified for any size.

All dimensions in millimeters.

For dimension *B*, see [Table 1](#).

For dimension *L*, see [Table 7](#).

**Table 5. American National Standard Header Points for Metric Machine Screws Before Threading** *ANSI/ASME B18.6.7M-1985*


| Nominal Screw Size and Thread Pitch | $D_p$          |      | $L^a$                |
|-------------------------------------|----------------|------|----------------------|
|                                     | Point Diameter |      | Nominal Screw Length |
|                                     | Max            | Min  | Max                  |
| M2 × 0.4                            | 1.33           | 1.21 | 13                   |
| M2.5 × 0.45                         | 1.73           | 1.57 | 13                   |
| M3 × 0.5                            | 2.12           | 1.93 | 16                   |
| M3.5 × 0.6                          | 2.46           | 2.24 | 20                   |
| M4 × 0.7                            | 2.80           | 2.55 | 25                   |
| M5 × 0.8                            | 3.60           | 3.28 | 30                   |
| M6 × 1                              | 4.25           | 3.85 | 40                   |
| M8 × 1.25                           | 5.82           | 5.30 | 40                   |
| M10 × 1.5                           | 7.36           | 6.71 | 40                   |
| M12 × 1.75                          | 8.90           | 8.11 | 45                   |

<sup>a</sup> Header points apply to these nominal lengths or shorter. The pointing of longer lengths may require machining to the dimensions specified.

All dimensions in millimeters.

The edge of the point may be rounded and the end of point need not be flat nor perpendicular to the axis of screw shank.

**Threads:** Threads for metric machine screws are coarse M profile threads, as given in ANSI B1.13M (see page 1783), unless otherwise specified.

**Length of Thread:** The lengths of threads on metric machine screws are given in Table 1 for the applicable screw type, size, and length.

**Diameter of Body:** The body diameters of metric machine screws are within the limits specified in the dimensional tables (Tables 3 through 4 and 6).

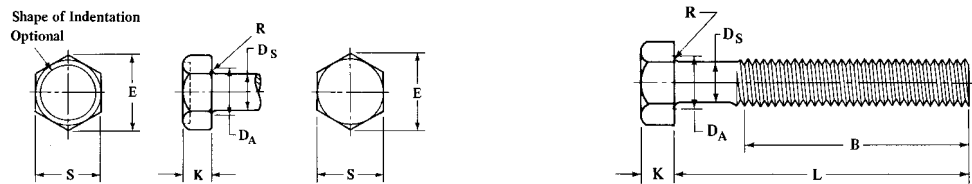
**Designation:** Metric machine screws are designated by the following data in the sequence shown: Nominal size and thread pitch; nominal length; product name, including head type and driving provision; header point if desired; material (including property class, if steel); and protective finish, if required. For example:

M8 × 1.25 × 30 Slotted Pan Head Machine Screw, Class 4.8 Steel, Zinc Plated

M3.5 × 0.6 × 20 Type IA Cross Recessed Oval Countersunk Head Machine Screw, Header Point, Brass

It is common ISO practice to omit the thread pitch from the product size designation when screw threads are the metric coarse thread series, e.g., M10 stands for M10 × 1.5.

Table 6. American National Standard Hex and Hex Flange Head Metric Machine Screws ANSI/ASME B18.6.7M-1985

| Hex Head   |                |       |                           |       |                                |                |     |                   |        |
|--|----------------|-------|---------------------------|-------|--------------------------------|----------------|-----|-------------------|--------|
|  |                |       |                           |       |                                |                |     |                   |        |
| Nominal<br>Screw<br>Size and<br>Thread<br>Pitch                                    | D <sub>S</sub> |       | S <sup>a</sup>            |       | E <sup>a</sup>                 | K              |     | D <sub>A</sub>    | R      |
|  | Body Diameter  |       | Hex Width<br>Across Flats |       | Hex Width<br>Across<br>Corners | Head<br>Height |     | Underhead Fillet  |        |
|  | Max            | Min   | Max                       | Min   | Min                            | Max            | Min | Transition<br>Dia | Radius |
| M2 × 0.4   | 2.00           | 1.65  | 3.20                      | 3.02  | 3.38                           | 1.6            | 1.3 | 2.6               | 0.1    |
| M2.5 × 0.45  | 2.50           | 2.12  | 4.00                      | 3.82  | 4.28                           | 2.1            | 1.8 | 3.1               | 0.1    |
| M3 × 0.5   | 3.00           | 2.58  | 5.00                      | 4.82  | 5.40                           | 2.3            | 2.0 | 3.6               | 0.1    |
| M3.5 × 0.6   | 3.50           | 3.00  | 5.50                      | 5.32  | 5.96                           | 2.6            | 2.3 | 4.1               | 0.1    |
| M4 × 0.7   | 4.00           | 3.43  | 7.00                      | 6.78  | 7.59                           | 3.0            | 2.6 | 4.7               | 0.2    |
| M5 × 0.8   | 5.00           | 4.36  | 8.00                      | 7.78  | 8.71                           | 3.8            | 3.3 | 5.7               | 0.2    |
| M6 × 1   | 6.00           | 5.21  | 10.00                     | 9.78  | 10.95                          | 4.7            | 4.1 | 6.8               | 0.3    |
| M8 × 1.25  | 8.00           | 7.04  | 13.00                     | 12.73 | 14.26                          | 6.0            | 5.2 | 9.2               | 0.4    |
| M10 × 1.5  | 10.00          | 8.86  | 16.00                     | 15.73 | 17.62                          | 7.5            | 6.5 | 11.2              | 0.4    |
| M12 × 1.75   | 12.00          | 10.68 | 18.00                     | 17.73 | 19.86                          | 9.0            | 7.8 | 13.2              | 0.4    |
| M10 × 1.5 <sup>b</sup>   | 10.00          | 8.86  | 15.00                     | 14.73 | 16.50                          | 7.5            | 6.5 | 11.2              | 0.4    |

<sup>a</sup> Dimensions across flats and across corners of the head are measured at the point of maximum metal. Taper of sides of head (angle between one side and the axis) shall not exceed 2° or 0.10 mm, whichever is greater, the specified width across flats being the large dimension.

<sup>b</sup> The M10 size screws having heads with 15 mm width across flats are not ISO Standard. Unless M10 size screws with 15 mm width across flats are specifically ordered, M10 size screws with 16 mm width across flats shall be furnished.

Table 6. (Continued) American National Standard Hex and Hex Flange Head Metric Machine Screws ANSI/ASME B18.6.7M-1985

| Hex Flange Head                     |                      |       |                               |       |                                 |                        |      |                          |                        |                                  |                                     |                           |                 |
|-------------------------------------|----------------------|-------|-------------------------------|-------|---------------------------------|------------------------|------|--------------------------|------------------------|----------------------------------|-------------------------------------|---------------------------|-----------------|
|                                     |                      |       |                               |       |                                 |                        |      |                          |                        |                                  |                                     |                           |                 |
| Nominal Screw Size and Thread Pitch | Body Diameter, $D_S$ |       | Hex Width Across Flats, $S^a$ |       | Hex Width Across Corners, $E^b$ | Flange Diameter, $D_C$ |      | Overall Head Height, $K$ | Hex Height, $K_1$ Min. | Flange Edge Thickness, $C^b$ Min | Flange Top Fillet Radius, $R_1$ Max | Underhead Fillet          |                 |
|                                     | Max                  | Min   | Max                           | Min   |                                 | Max                    | Min  |                          |                        |                                  |                                     | Max Transition Dia, $D_A$ | Min Radius, $R$ |
| M2 × 0.4                            | 2.00                 | 1.65  | 3.00                          | 2.84  | 3.16                            | 4.5                    | 4.1  | 2.2                      | 1.3                    | 0.3                              | 0.1                                 | 2.6                       | 0.1             |
| M2.5 × 0.45                         | 2.50                 | 2.12  | 3.20                          | 3.04  | 3.39                            | 5.4                    | 5.0  | 2.7                      | 1.6                    | 0.3                              | 0.2                                 | 3.1                       | 0.1             |
| M3 × 0.5                            | 3.00                 | 2.58  | 4.00                          | 3.84  | 4.27                            | 6.4                    | 5.9  | 3.2                      | 1.9                    | 0.4                              | 0.2                                 | 3.6                       | 0.1             |
| M3.5 × 0.6                          | 3.50                 | 3.00  | 5.00                          | 4.82  | 5.36                            | 7.5                    | 6.9  | 3.8                      | 2.4                    | 0.5                              | 0.2                                 | 4.1                       | 0.1             |
| M4 × 0.7                            | 4.00                 | 3.43  | 5.50                          | 5.32  | 5.92                            | 8.5                    | 7.8  | 4.3                      | 2.8                    | 0.6                              | 0.2                                 | 4.7                       | 0.2             |
| M5 × 0.8                            | 5.00                 | 4.36  | 7.00                          | 6.78  | 7.55                            | 10.6                   | 9.8  | 5.4                      | 3.5                    | 0.7                              | 0.3                                 | 5.7                       | 0.2             |
| M6 × 1                              | 6.00                 | 5.21  | 8.00                          | 7.78  | 8.66                            | 12.8                   | 11.8 | 6.7                      | 4.2                    | 1.0                              | 0.4                                 | 6.8                       | 0.3             |
| M8 × 1.25                           | 8.00                 | 7.04  | 10.00                         | 9.78  | 10.89                           | 16.8                   | 15.5 | 8.6                      | 5.6                    | 1.2                              | 0.5                                 | 9.2                       | 0.4             |
| M10 × 1.5                           | 10.00                | 8.86  | 13.00                         | 12.72 | 14.16                           | 21.0                   | 19.3 | 10.7                     | 7.0                    | 1.4                              | 0.6                                 | 11.2                      | 0.4             |
| M12 × 1.75                          | 12.00                | 10.68 | 15.00                         | 14.72 | 16.38                           | 24.8                   | 23.3 | 13.7                     | 8.4                    | 1.8                              | 0.7                                 | 13.2                      | 0.4             |

<sup>a</sup>Dimensions across flats and across corners of the head are measured at the point of maximum metal. Taper of sides of head (angle between one side and the axis) shall not exceed 2° or 0.10 mm, whichever is greater, the specified width across flats being the large dimension.

<sup>b</sup>The contour of the edge at periphery of flange is optional provided the minimum flange thickness is maintained at the minimum flange diameter. The top surface of flange may be straight or slightly rounded (convex) upward.

All dimensions in millimeters.

A slight rounding of all edges of the hexagon surfaces of indented hex heads is permissible provided the diameter of the bearing circle is not less than the equivalent of 90 per cent of the specified minimum width across flats dimension.

Heads may be indented, trimmed, or fully upset at the option of the manufacturer.

For dimension  $B$ , see Table 1.

For dimension  $L$ , see Table 7.



**Table 7. Recommended Nominal Screw Lengths for Metric Machine Screws**

| Nominal Screw Length | Nominal Screw Size |      |    |      |    |    |    |    |     |     |
|----------------------|--------------------|------|----|------|----|----|----|----|-----|-----|
|                      | M2                 | M2.5 | M3 | M3.5 | M4 | M5 | M6 | M8 | M10 | M12 |
| 2.5                  | PH                 |      |    |      |    |    |    |    |     |     |
| 3                    | A                  | PH   |    |      |    |    |    |    |     |     |
| 4                    | A                  | A    | PH |      |    |    |    |    |     |     |
| 5                    | A                  | A    | A  | PH   | PH |    |    |    |     |     |
| 6                    | A                  | A    | A  | A    | A  | PH |    |    |     |     |
| 8                    | A                  | A    | A  | A    | A  | A  | A  |    |     |     |
| 10                   | A                  | A    | A  | A    | A  | A  | A  | A  |     |     |
| 13                   | A                  | A    | A  | A    | A  | A  | A  | A  | A   |     |
| 16                   | A                  | A    | A  | A    | A  | A  | A  | A  | A   | H   |
| 20                   | A                  | A    | A  | A    | A  | A  | A  | A  | A   | H   |
| 25                   |                    | A    | A  | A    | A  | A  | A  | A  | A   | H   |
| 30                   |                    |      | A  | A    | A  | A  | A  | A  | A   | H   |
| 35                   |                    |      |    | A    | A  | A  | A  | A  | A   | H   |
| 40                   |                    |      |    |      | A  | A  | A  | A  | A   | H   |
| 45                   |                    |      |    |      |    | A  | A  | A  | A   | H   |
| 50                   |                    |      |    |      |    | A  | A  | A  | A   | H   |
| 55                   |                    |      |    |      |    |    | A  | A  | A   | H   |
| 60                   |                    |      |    |      |    |    | A  | A  | A   | H   |
| 65                   |                    |      |    |      |    |    |    | A  | A   | H   |
| 70                   |                    |      |    |      |    |    |    | A  | A   | H   |
| 80                   |                    |      |    |      |    |    |    | A  | A   | H   |
| 90                   |                    |      |    |      |    |    |    |    | A   | H   |

All dimensions in millimeters.

<sup>1</sup>The nominal screw lengths included between the heavy lines are recommended for the respective screw sizes and screw head styles as designated by the symbols.

A — Signifies screws of all head styles covered in this standard.

P — Signifies pan head screws.

H — Signifies hex and hex flange head screws.

**Table 8. Clearance Holes for Metric Machine Screws  
ANSI/ASME B18.6.7M-1985 Appendix**

| Nominal Screw Size | Basic Clearance Hole Diameter <sup>a</sup> |   |                              |
|--------------------|--|---|------------------------------|
|                    | Close Clearance <sup>b</sup>               | Normal Clearance (Preferred) <sup>b</sup> | Loose Clearance <sup>b</sup> |
| M2                 | 2.20                                       | 2.40                                      | 2.60                         |
| M2.5               | 2.70                                       | 2.90                                      | 3.10                         |
| M3                 | 3.20                                       | 3.40                                      | 3.60                         |
| M3.5               | 3.70                                       | 3.90                                      | 4.20                         |
| M4                 | 4.30                                       | 4.50                                      | 4.80                         |
| M5                 | 5.30                                       | 5.50                                      | 5.80                         |
| M6                 | 6.40                                       | 6.60                                      | 7.00                         |
| M8                 | 8.40                                       | 9.00                                      | 10.00                        |
| M10                | 10.50                                      | 11.00                                     | 12.00                        |
| M12                | 13.00                                      | 13.50                                     | 14.50                        |

<sup>a</sup>The values given in this table are minimum limits. The recommended plus tolerances are as follows: for clearance hole diameters over 1.70 to and including 5.80 mm, plus 0.12, 0.20, and 0.30 mm for close, normal, and loose clearances, respectively; for clearance hole diameters over 5.80 to 14.50 mm, plus 0.18, 0.30, and 0.45 mm for close, normal, and loose clearances, respectively.

<sup>b</sup>Normal clearance hole sizes are preferred. Close clearance hole sizes are for situations such as critical alignment of assembled components, wall thickness, or other limitations which necessitate the use of a minimal hole. Countersinking or counterboring at the fastener entry side may be necessary for the proper seating of the head. Loose clearance hole sizes are for applications where maximum adjustment capability between the components being assembled is necessary.

All dimensions in millimeters.

**British Machine Screws.**—Many of these classifications of fasteners are covered in British Standards B.S. 57:1951, “B.A. Screws, Bolts and Nuts”; BS 450:1958 (obsolescent), “Machine Screws and Machine Screw Nuts (BSW and BSF Threads)”; B.S. 1981:1953, “Unified Machine Screws and Machine Screw Nuts”; BS 2827:1957 (obsolescent):1957, “Machine Screw Nuts, Pressed Type (B.A. and Whitworth Form Threads)”; B.S. 3155:1960, “American Machine Screws and Nuts in Sizes Below  $\frac{1}{4}$  inch Diameter”; and BS 4183:1967 (obsolescent), “Machine Screws and Machine Screw Nuts, Metric Series.” At a conference organized by the British Standards Institution in 1965 at which the major sectors of British industry were represented, a policy statement was approved that urged British firms to regard the traditional screw thread systems—Whitworth, B.A. and BSF—as obsolescent, and to make the internationally-agreed ISO metric thread their first choice (with ISO Unified thread as second choice) for all future designs. It is recognized that some sections of British industry already using ISO inch (Unified) screw threads may find it necessary, for various reasons, to continue with their use for some time: Whitworth and B.A. threads should, however, be superseded by ISO metric threads in preference to an intermediate change to ISO inch threads. Fasteners covered by B.S. 57, B.S. 450 and BS 2827:1957 (obsolescent) eventually would be superseded and replaced by fasteners specified by B.S. 4183.

**British Standard Whitworth (BSW) and Fine (BSF) Machine Screws.**—British Standard BS 450:1958 (obsolescent) covers machine screws and nuts with British Standard Whitworth and British Standard Fine threads. All the various heads in common use in both slotted and recessed forms are covered. Head shapes are shown on page 1614 and dimensions on page 1617. It is intended that this standard will eventually be superseded by B.S. 4183, “Machine Screws and Machine Screw Nuts, Metric Series.”

**British Standard Machine Screws and Machine Screw Nuts, Metric Series.**—British Standard BS 4183:1967 (obsolescent) gives dimensions and tolerances for: countersunk head, raised countersunk head, and cheese head slotted head screws in a diameter range from M1 (1 mm) to M20 (20 mm); pan head slotted head screws in a diameter range from M2.5 (2.5 mm) to M10 (10 mm); countersunk head and raised countersunk head recessed head screws in a diameter range from M2.5 (2.5 mm) to M12 (12 mm); pan head recessed head screws in a diameter range from M2.5 (2.5 mm) to M10 (10 mm); and square and hexagon machine screw nuts in a diameter range from M1.6 (1.6 mm) to M10 (10 mm). Mechanical properties are also specified for steel, brass and aluminum alloy machine screws and machine screw nuts in this standard.

*Material:* The materials from which the screws and nuts are manufactured have a tensile strength not less than the following: steel, 40 kgf/mm<sup>2</sup> (392 N/mm<sup>2</sup>); brass, 32 kgf/mm<sup>2</sup> (314 N/mm<sup>2</sup>); and aluminum alloy, 32 kgf/mm<sup>2</sup> (314 N/mm<sup>2</sup>). The unit, kgf/mm<sup>2</sup> is in accordance with ISO DR 911 and the unit in parentheses has the relationship, 1 kgf = 9.80665 Newtons. These minimum strengths are applicable to the finished products. Steel machine screws conform to the requirements for strength grade designation 4.8. The strength grade designation system for machine screws consists of two figures, the first is  $\frac{1}{10}$  of the minimum tensile strength in kgf/mm<sup>2</sup>, the second is  $\frac{1}{10}$  of the ratio between the yield stress and the minimum tensile strength expressed as a percentage:  $\frac{1}{10}$  minimum tensile strength of 40 kgf/mm<sup>2</sup> gives the symbol “4”;  $\frac{1}{10}$  ratio  $\frac{\text{yield stress}}{\text{minimum tensile strength}} \% = \frac{1}{10} \times \frac{32}{40} \times 100/1 = “8”$ ; giving the strength grade designation “4.8.” Multiplication of these two figures gives the minimum yield stress in kgf/mm<sup>2</sup>.

*Coating of Screws and Nuts:* It is recommended that the coating comply with the appropriate part of BS 3382. “Electroplated Coatings on Threaded Components.”

**Screw Threads:** Screw threads are ISO metric coarse pitch series threads in accordance with B.S. 3643. "ISO Metric Screw Threads," Part 1, "Thread Data and Standard Thread Series." The external threads used for screws conform to tolerance Class 6g limits (medium fit) as given in B.S. 3643, "ISO Metric Screw Threads," Part 2, "Limits and Tolerances for Coarse Pitch Series Threads." The internal threads used for nuts conform to tolerance Class 6H limits (medium fit) as given in B.S. 3643: Part 2.

**Nominal Lengths of Screws:** For countersunk head screws the nominal length is the distance from the upper surface of the head to the extreme end of the shank, including any chamfer, radius, or cone point. For raised countersunk head screws the nominal length is the distance from the upper surface of the head (excluding the raised portion) to the extreme end of the shank, including any chamfer, radius, or cone point. For pan and cheese head screws the nominal length is the distance from the underside of the head to the extreme end of the shank, including any chamfer, radius, or cone point. Standard nominal lengths and tolerances are given in [Table 5](#).

**Lengths of Thread on Screws:** The length of thread is the distance from the end of the screw (including any chamfer, radius, or cone point) to the leading face of a nut without countersink which has been screwed as far as possible onto the screw by hand. The minimum thread length is shown in the following table:

|                            |        |      |        |      |     |        |       |     |        |     |
|----------------------------|--------|------|--------|------|-----|--------|-------|-----|--------|-----|
| Nominal Thread Dia., $d^a$ | M1     | M1.2 | (M1.4) | M1.6 | M2  | (M2.2) | M2.5  | M3  | (M3.5) | M4  |
| Thread Length $b$ (Min.)   | b      | b    | b      | 15   | 16  | 17     | 18    | 19  | 20     | 22  |
| Nominal Thread Dia., $d^a$ | (M4.5) | M5   | M6     | M8   | M10 | M12    | (M14) | M16 | (M18)  | M20 |
| Thread Length $b$ (Min.)   | 24     | 25   | 28     | 34   | 40  | 46     | 52    | 58  | 64     | 70  |

<sup>a</sup> Items shown in parentheses are non-preferred.

<sup>b</sup> Threaded up to the head.

All dimensions are in millimeters.

Screws of nominal thread diameter M1, M1.2 and M1.4 and screws of larger diameters that are too short for the above thread lengths are threaded as far as possible up to the head.

In these screws the length of unthreaded shank under the head does not exceed  $1\frac{1}{2}$  pitches for lengths up to twice the diameter and 2 pitches for longer lengths, and is defined as the distance from the leading face of a nut that has been screwed as far as possible onto the screw by hand to: 1) the junction of the basic major diameter and the countersunk portion of the head on countersunk and raised countersunk heads; and 2) the underside of the head on other types of heads.

**Diameter of Unthreaded Shank on Screws:** The diameter of the unthreaded portion of the shank on screws is not greater than the basic major diameter of the screw thread and not less than the minimum effective diameter of the screw thread. The diameter of the unthreaded portion of shank is closely associated with the method of manufacture; it will generally be nearer the major diameter of the thread for turned screws and nearer the effective diameter for those produced by cold heading.

**Radius Under the Head of Screws:** The radius under the head of pan and cheese head screws runs smoothly into the face of the head and shank without any step or discontinuity. A true radius is not essential providing that the curve is smooth and lies wholly within the maximum radius. Any radius under the head of countersunk head screws runs smoothly into the conical bearing surface of the head and the shank without any step or discontinuity. The radius values given in [Tables 1](#) and [2](#) are regarded as the maximum where the shank diameter is equal to the major diameter of the thread and minimum where the shank diameter is approximately equal to the effective diameter of the thread.

**Table 1. British Standard Slotted Countersunk Head Machine Screws—Metric Series BS 4183:1967 (obsolescent)**

| Nominal Size<br>$d^a$ | Head Diameter<br>$D$           |                 | Head Height<br>$k$ |                 | Radius<br>$r^b$ | Thread Length<br>$b$ | Thread Run-out<br>$a$ | Flushness Tolerance <sup>c</sup> | Slot Width<br>$n$ |      | Slot Depth<br>$t$ |                |
|-----------------------|--------------------------------|-----------------|--------------------|-----------------|-----------------|----------------------|-----------------------|----------------------------------|-------------------|------|-------------------|----------------|
|                       | Max.<br>(Theor. Sharp)<br>$2d$ | Min.<br>$1.75d$ | Max.<br>$0.5d$     | Min.<br>$0.45d$ |                 | Min.                 | Max.<br>$2p^d$        |                                  | Max.              | Max. | Min.              | Max.<br>$0.3d$ |
|                       |                                |                 |                    |                 |                 |                      |                       |                                  |                   |      |                   |                |
| M1                    | 2.00                           | 1.75            | 0.50               | 0.45            | 0.1             | e                    | 0.50                  | ....                             | 0.45              | 0.31 | 0.30              | 0.20           |
| M1.2                  | 2.40                           | 2.10            | 0.60               | 0.54            | 0.1             | e                    | 0.50                  | ....                             | 0.50              | 0.36 | 0.36              | 0.24           |
| (M1.4)                | 2.80                           | 2.45            | 0.70               | 0.63            | 0.1             | e                    | 0.60                  | ....                             | 0.50              | 0.36 | 0.42              | 0.28           |
| M1.6                  | 3.20                           | 2.80            | 0.80               | 0.72            | 0.1             | 15.0                 | 0.70                  | ....                             | 0.60              | 0.46 | 0.48              | 0.32           |
| M2.0                  | 4.00                           | 3.50            | 1.00               | 0.90            | 0.1             | 16.0                 | 0.80                  | ....                             | 0.70              | 0.56 | 0.60              | 0.40           |
| (M2.2)                | 4.40                           | 3.85            | 1.10               | 0.99            | 0.1             | 17.0                 | 0.90                  | ....                             | 0.80              | 0.66 | 0.66              | 0.44           |
| M2.5                  | 5.00                           | 4.38            | 1.25               | 1.12            | 0.1             | 18.0                 | 0.90                  | 0.10                             | 0.80              | 0.66 | 0.75              | 0.50           |
| M3                    | 6.00                           | 5.25            | 1.50               | 1.35            | 0.1             | 19.0                 | 1.00                  | 0.12                             | 1.00              | 0.86 | 0.90              | 0.60           |
| (M3.5)                | 7.00                           | 6.10            | 1.75               | 1.57            | 0.2             | 20.0                 | 1.20                  | 0.13                             | 1.00              | 0.86 | 1.05              | 0.70           |
| M4                    | 8.00                           | 7.00            | 2.00               | 1.80            | 0.2             | 22.0                 | 1.40                  | 0.15                             | 1.20              | 1.06 | 1.20              | 0.80           |
| (M4.5)                | 9.00                           | 7.85            | 2.25               | 2.03            | 0.2             | 24.0                 | 1.50                  | 0.17                             | 1.20              | 1.06 | 1.35              | 0.90           |
| M5                    | 10.00                          | 8.75            | 2.50               | 2.25            | 0.2             | 25.0                 | 1.60                  | 0.19                             | 1.51              | 1.26 | 1.50              | 1.00           |
| M6                    | 12.00                          | 10.50           | 3.00               | 2.70            | 0.25            | 28.0                 | 2.00                  | 0.23                             | 1.91              | 1.66 | 1.80              | 1.20           |
| M8                    | 16.00                          | 14.00           | 4.00               | 3.60            | 0.4             | 34.0                 | 2.50                  | 0.29                             | 2.31              | 2.06 | 2.40              | 1.60           |
| M10                   | 20.00                          | 17.50           | 5.00               | 4.50            | 0.4             | 40.0                 | 3.00                  | 0.37                             | 2.81              | 2.56 | 3.00              | 2.00           |
| M12                   | 24.00                          | 21.00           | 6.00               | 5.40            | 0.6             | 46.0                 | 3.50                  | 0.44                             | 3.31              | 3.06 | 3.60              | 2.40           |
| (M14)                 | 28.00                          | 24.50           | 7.00               | 6.30            | 0.6             | 52.0                 | 4.00                  | 0.52                             | 3.31              | 3.06 | 4.20              | 2.80           |
| M16                   | 32.00                          | 28.00           | 8.00               | 7.20            | 0.6             | 58.0                 | 4.00                  | 0.60                             | 4.37              | 4.07 | 4.80              | 3.20           |
| (M18)                 | 36.00                          | 31.50           | 9.00               | 8.10            | 0.6             | 64.0                 | 5.00                  | 0.67                             | 4.37              | 4.07 | 5.40              | 3.60           |
| M20                   | 40.00                          | 35.00           | 10.00              | 9.00            | 0.8             | 70.0                 | 5.00                  | 0.75                             | 5.37              | 5.07 | 6.00              | 4.00           |

<sup>a</sup>Nominal sizes shown in parentheses are non-preferred.<sup>b</sup>See *Radius Under the Head of Screws* description in text.<sup>c</sup>See *Dimensions of 90-Degree Countersunk Head Screws* description in text.<sup>d</sup>See text following table in *Lengths of Thread on Screws* description in text.<sup>e</sup>Threaded up to head.

All dimensions are given in millimeters. For dimensional notation, see diagram on page 1610. Recessed head screws are also standard and are available. For dimensions see British Standard.

**Table 2. British Standard Slotted Raised Countersunk Head Machine Screws—Metric Series BS 4183:1967 (obsolescent)**

| Nominal Size<br>$d^a$ | Head Diameter<br>$D$           |                 | Head Height<br>$k$ |                 | Radius Under Head<br>$r^b$ | Thread Length<br>$b$ | Thread Run-out<br>$a$ | Height of Raised Portion<br>$f$ | Head Radius<br>$R$ | Slot Width<br>$n$ |                | Slot Depth<br>$t$ |      |      |      |                |                |
|-----------------------|--------------------------------|-----------------|--------------------|-----------------|----------------------------|----------------------|-----------------------|---------------------------------|--------------------|-------------------|----------------|-------------------|------|------|------|----------------|----------------|
|                       | Max.<br>(Theor. Sharp)<br>$2d$ | Min.<br>$1.75d$ | Max.<br>$0.5d$     | Min.<br>$0.45d$ |                            |                      |                       |                                 |                    | Min.              | Max.<br>$2p^c$ | Nom.<br>$0.25d$   | Nom. | Max. | Min. | Max.<br>$0.5d$ | Min.<br>$0.4d$ |
|                       |                                |                 |                    |                 |                            |                      |                       |                                 |                    |                   |                |                   |      |      |      |                |                |
| M1                    | 2.00                           | 1.75            | 0.50               | 0.45            | 0.1                        | $d$                  | 0.50                  | 0.25                            | 2.0                | 0.45              | 0.31           | 0.50              | 0.40 |      |      |                |                |
| M1.2                  | 2.40                           | 2.10            | 0.60               | 0.54            | 0.1                        | $d$                  | 0.50                  | 0.30                            | 2.5                | 0.50              | 0.36           | 0.60              | 0.48 |      |      |                |                |
| (M1.4)                | 2.80                           | 2.45            | 0.70               | 0.63            | 0.1                        | $d$                  | 0.60                  | 0.35                            | 2.5                | 0.50              | 0.36           | 0.70              | 0.56 |      |      |                |                |
| M1.6                  | 3.20                           | 2.80            | 0.80               | 0.72            | 0.1                        | 15.0                 | 0.70                  | 0.40                            | 3.0                | 0.60              | 0.46           | 0.80              | 0.64 |      |      |                |                |
| M2.0                  | 4.00                           | 3.50            | 1.00               | 0.90            | 0.1                        | 16.0                 | 0.80                  | 0.50                            | 4.0                | 0.70              | 0.56           | 1.00              | 0.80 |      |      |                |                |
| (M2.2)                | 4.40                           | 3.85            | 1.10               | 0.99            | 0.1                        | 17.0                 | 0.90                  | 0.55                            | 4.0                | 0.80              | 0.66           | 1.10              | 0.88 |      |      |                |                |
| M2.5                  | 5.00                           | 4.38            | 1.25               | 1.12            | 0.1                        | 18.0                 | 0.90                  | 0.60                            | 5.0                | 0.80              | 0.66           | 1.25              | 1.00 |      |      |                |                |
| M3                    | 6.00                           | 5.25            | 1.50               | 1.35            | 0.1                        | 19.0                 | 1.00                  | 0.75                            | 6.0                | 1.00              | 0.86           | 1.50              | 1.20 |      |      |                |                |
| (M3.5)                | 7.00                           | 6.10            | 1.75               | 1.57            | 0.2                        | 20.0                 | 1.20                  | 0.90                            | 6.0                | 1.00              | 0.86           | 1.75              | 1.40 |      |      |                |                |
| M4                    | 8.00                           | 7.00            | 2.00               | 1.80            | 0.2                        | 22.0                 | 1.40                  | 1.00                            | 8.0                | 1.20              | 1.06           | 2.00              | 1.60 |      |      |                |                |
| (M4.5)                | 9.00                           | 7.85            | 2.25               | 2.03            | 0.2                        | 24.0                 | 1.50                  | 1.10                            | 8.0                | 1.20              | 1.06           | 2.25              | 1.80 |      |      |                |                |
| M5                    | 10.00                          | 8.75            | 2.50               | 2.25            | 0.2                        | 25.0                 | 1.60                  | 1.25                            | 10.0               | 1.51              | 1.26           | 2.50              | 2.00 |      |      |                |                |
| M6                    | 12.00                          | 10.50           | 3.00               | 2.70            | 0.25                       | 28.0                 | 2.00                  | 1.50                            | 12.0               | 1.91              | 1.66           | 3.00              | 2.40 |      |      |                |                |
| M8                    | 16.00                          | 14.00           | 4.00               | 3.60            | 0.4                        | 34.0                 | 2.50                  | 2.00                            | 16.0               | 2.31              | 2.06           | 4.00              | 3.20 |      |      |                |                |
| M10                   | 20.00                          | 17.50           | 5.00               | 4.50            | 0.4                        | 40.0                 | 3.00                  | 2.50                            | 20.0               | 2.81              | 2.56           | 5.00              | 4.00 |      |      |                |                |
| M12                   | 24.00                          | 21.00           | 6.00               | 5.40            | 0.6                        | 46.0                 | 3.50                  | 3.00                            | 25.0               | 3.31              | 3.06           | 6.00              | 4.80 |      |      |                |                |
| (M14)                 | 28.00                          | 24.50           | 7.00               | 6.30            | 0.6                        | 52.0                 | 4.00                  | 3.50                            | 25.0               | 3.31              | 3.06           | 7.00              | 5.60 |      |      |                |                |
| M16                   | 32.00                          | 28.00           | 8.00               | 7.20            | 0.6                        | 58.0                 | 4.00                  | 4.00                            | 32.0               | 4.37              | 4.07           | 8.00              | 6.40 |      |      |                |                |
| (M18)                 | 36.00                          | 31.50           | 9.00               | 8.10            | 0.6                        | 64.0                 | 5.00                  | 4.50                            | 32.0               | 4.37              | 4.07           | 9.00              | 7.20 |      |      |                |                |
| M20                   | 40.00                          | 35.00           | 10.00              | 9.00            | 0.8                        | 70.0                 | 5.00                  | 5.00                            | 40.0               | 5.37              | 5.07           | 10.00             | 8.00 |      |      |                |                |

<sup>a</sup>Nominal sizes shown in parentheses are non-preferred.<sup>b</sup>See *Radius Under the Head of Screws* description in text.<sup>c</sup>See text following table in *Lengths of Thread on Screws* description in text.<sup>d</sup>Threaded up to head.

All dimensions are given in millimeters. For dimensional notation see diagram on page 1610. Recessed head screws are also standard and available. For dimensions see British Standard.

*Ends of Screws:* When screws are made with rolled threads, the "lead" formed by the thread rolling operation is normally regarded as providing the necessary chamfer and no other machining is necessary. The ends of screws with cut threads are normally finished with a chamfer conforming to the dimension in Fig. 1a through Fig. 1d. At the option of the manufacturer, the ends of screws smaller than M6 (6-mm diameter) may be finished with a radius approximately equal to  $1\frac{1}{4}$  times the nominal diameter of the shank. When cone point ends are required, they should have the dimensions given in Fig. 1a through Fig. 1d.

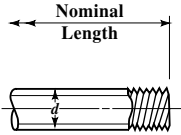
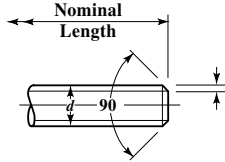


Fig. 1a. Rolled Thread End (Approximate Form as Rolled)



Cut Thread Chamfered End

Fig. 1b. Chamfer to Extend to Slightly Below the Minor Dia.

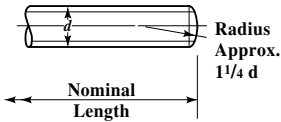


Fig. 1c. Cut Thread Radiused End (Permissible on Sizes Below M6 Dia.)

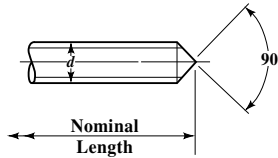


Fig. 1d. Cone Pointed End (Permissible on Cut or Rolled Thread Screws, but Regarded as "Special")

*Dimensions of 90-Degree Countersunk Head Screws:* One of the appendices to this British Standard states that countersunk head screws should fit into the countersunk hole with as great a degree of flushness as possible. To achieve this condition, it is necessary for the dimensions of both the head of the screw and the countersunk hole to be controlled within prescribed limits. The maximum or design size of the head is controlled by a theoretical diameter to a sharp corner and the minimum head angle of 90 degrees. The minimum head size is controlled by a minimum head diameter, the maximum head angle of 92 degrees and a flushness tolerance (see Fig. 2). The edge of the head may be flat or rounded, as shown in Fig. 3.

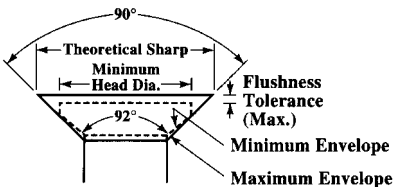


Fig. 2. Head Configuration

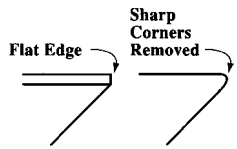
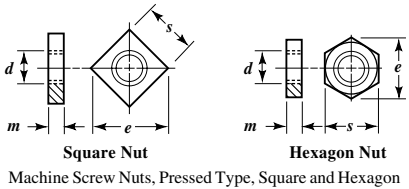
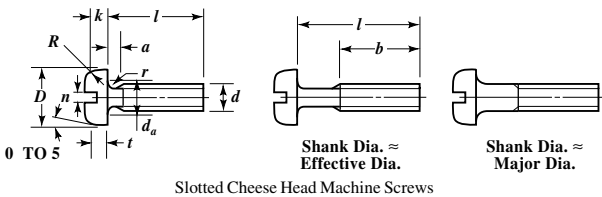
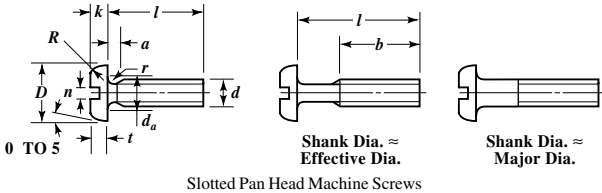
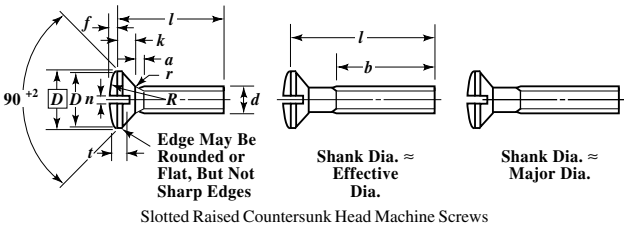
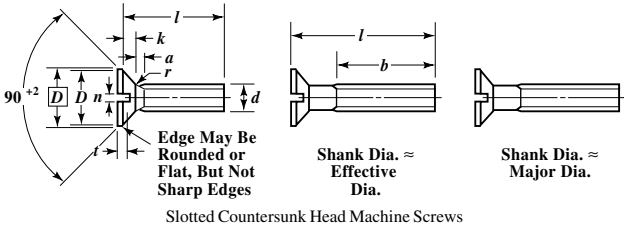


Fig. 3. Edge Configuration

British Standard Machine Screws and Machine Screw Nuts—Metric Series



For dimensions, see Tables 1 through 5.

**Table 3. British Standard Slotted Pan Head Machine Screws—  
Metric Series BS 4183:1967 (obsolescent)**

| Nominal<br>Size<br>$d^a$ | Head<br>Diameter<br>$D$ |       | Head<br>Height<br>$k$ |      | Head<br>Radius<br>$R$ | Radius<br>Under<br>Head<br>$r$ | Transition<br>Diameter<br>$d_a$ |
|--------------------------|-------------------------|-------|-----------------------|------|-----------------------|--------------------------------|---------------------------------|
|                          | Max.<br>$2d$            | Min.  | Max.<br>$0.6d$        | Min. | Max<br>$0.4d$         | Min.                           | Max.                            |
| M2.5                     | 5.00                    | 4.70  | 1.50                  | 1.36 | 1.00                  | 0.10                           | 3.10                            |
| M3                       | 6.00                    | 5.70  | 1.80                  | 1.66 | 1.20                  | 0.10                           | 3.60                            |
| (M3.5)                   | 7.00                    | 6.64  | 2.10                  | 1.96 | 1.40                  | 0.20                           | 4.30                            |
| M4                       | 8.00                    | 7.64  | 2.40                  | 2.26 | 1.60                  | 0.20                           | 4.70                            |
| (M4.5)                   | 9.00                    | 8.64  | 2.70                  | 2.56 | 1.80                  | 0.20                           | 5.20                            |
| M5                       | 10.00                   | 9.64  | 3.00                  | 2.86 | 2.00                  | 0.20                           | 5.70                            |
| M6                       | 12.00                   | 11.57 | 3.60                  | 3.42 | 2.50                  | 0.25                           | 6.80                            |
| M8                       | 16.00                   | 15.57 | 4.80                  | 4.62 | 3.20                  | 0.40                           | 9.20                            |
| M10                      | 20.00                   | 19.48 | 6.00                  | 5.82 | 4.00                  | 0.40                           | 11.20                           |

<sup>a</sup> Nominal sizes shown in parentheses are non-preferred.

| Nominal<br>Size<br>$d^a$ | Thread<br>Length<br>$b$ | Thread<br>Run-out<br>$a$ | Slot<br>Width<br>$n$ |      | Slot<br>Depth<br>$t$ |                |
|--------------------------|-------------------------|--------------------------|----------------------|------|----------------------|----------------|
|                          | Min.                    | Max.<br>$2p^b$           | Max.                 | Min. | Max.<br>$0.6k$       | Min.<br>$0.4k$ |
| M2.5                     | 18.00                   | 0.90                     | 0.80                 | 0.66 | 0.90                 | 0.60           |
| M3                       | 19.00                   | 1.00                     | 1.00                 | 0.86 | 1.08                 | 0.72           |
| (M3.5)                   | 20.00                   | 1.20                     | 1.00                 | 0.86 | 1.26                 | 0.84           |
| M4                       | 22.00                   | 1.40                     | 1.20                 | 1.06 | 1.44                 | 0.96           |
| (M4.5)                   | 24.00                   | 1.50                     | 1.20                 | 1.06 | 1.62                 | 1.08           |
| M5                       | 25.00                   | 1.60                     | 1.51                 | 1.26 | 1.80                 | 1.20           |
| M6                       | 28.00                   | 2.00                     | 1.91                 | 1.66 | 2.16                 | 1.44           |
| M8                       | 34.00                   | 2.50                     | 2.31                 | 2.06 | 2.88                 | 1.92           |
| M10                      | 40.00                   | 3.00                     | 2.81                 | 2.56 | 3.60                 | 2.40           |

<sup>a</sup> Nominal sizes shown in parentheses are non-preferred.

<sup>b</sup> See *Lengths of Thread on Screws* on page 1606.

All dimensions are in millimeters. For dimensional notation, see diagram on page 1610. Recessed head screws are also standard and available. For dimensions, see British Standard.



**Table 4. British Standard Slotted Cheese Head Machine Screws—Metric Series BS 4183:1967 (obsolescent)**

| Nominal Size<br>$d^a$ | Head Diameter<br>$D$ |       | Head Height<br>$k$ |       | Radius<br>$r^b$ | Transition Diameter<br>$d_a$ | Thread Length<br>$l^b$ | Thread Run-out<br>$a$ | Slot Width<br>$n$ |      | Slot Depth<br>$t$ |      |
|-----------------------|----------------------|-------|--------------------|-------|-----------------|------------------------------|------------------------|-----------------------|-------------------|------|-------------------|------|
|                       | Max.                 | Min.  | Max.               | Min.  | Min.            | Max.                         | Min.                   | Max. <sup>c</sup>     | Max.              | Min. | Max.              | Min. |
| M1                    | 2.00                 | 1.75  | 0.70               | 0.56  | 0.10            | 1.30                         | b                      | 0.50                  | 0.45              | 0.31 | 0.44              | 0.30 |
| M1.2                  | 2.30                 | 2.05  | 0.80               | 0.66  | 0.10            | 1.50                         | b                      | 0.50                  | 0.50              | 0.36 | 0.49              | 0.35 |
| (M1.4)                | 2.60                 | 2.35  | 0.90               | 0.76  | 0.10            | 1.70                         | b                      | 0.60                  | 0.50              | 0.36 | 0.60              | 0.40 |
| M1.6                  | 3.00                 | 2.75  | 1.00               | 0.86  | 0.10            | 2.00                         | 15.00                  | 0.70                  | 0.60              | 0.46 | 0.65              | 0.45 |
| M2                    | 3.80                 | 3.50  | 1.30               | 1.16  | 0.10            | 2.60                         | 16.00                  | 0.80                  | 0.70              | 0.56 | 0.85              | 0.60 |
| (M2.2)                | 4.00                 | 3.70  | 1.50               | 1.36  | 0.10            | 2.80                         | 17.00                  | 0.90                  | 0.80              | 0.66 | 1.00              | 0.70 |
| M2.5                  | 4.50                 | 4.20  | 1.60               | 1.46  | 0.10            | 3.10                         | 18.00                  | 0.90                  | 0.80              | 0.66 | 1.00              | 0.70 |
| M3                    | 5.50                 | 5.20  | 2.00               | 1.86  | 0.10            | 3.60                         | 19.00                  | 1.00                  | 1.00              | 0.86 | 1.30              | 0.90 |
| (M3.5)                | 6.00                 | 5.70  | 2.40               | 2.26  | 0.10            | 4.10                         | 20.00                  | 1.20                  | 1.00              | 0.86 | 1.40              | 1.00 |
| M4                    | 7.00                 | 6.64  | 2.60               | 2.46  | 0.20            | 4.70                         | 22.00                  | 1.40                  | 1.20              | 1.06 | 1.60              | 1.20 |
| (M4.5)                | 8.00                 | 7.64  | 3.10               | 2.92  | 0.20            | 5.20                         | 24.00                  | 1.50                  | 1.20              | 1.06 | 1.80              | 1.40 |
| M5                    | 8.50                 | 8.14  | 3.30               | 3.12  | 0.20            | 5.70                         | 25.00                  | 1.60                  | 1.51              | 1.26 | 2.00              | 1.50 |
| M6                    | 10.00                | 9.64  | 3.90               | 3.72  | 0.25            | 6.80                         | 28.00                  | 2.00                  | 1.91              | 1.66 | 2.30              | 1.80 |
| M8                    | 13.00                | 12.57 | 5.00               | 4.82  | 0.40            | 9.20                         | 34.00                  | 2.50                  | 2.31              | 2.06 | 2.80              | 2.30 |
| M10                   | 16.00                | 15.57 | 6.00               | 5.82  | 0.40            | 11.20                        | 40.00                  | 3.00                  | 2.81              | 2.56 | 3.20              | 2.70 |
| M12                   | 18.00                | 17.57 | 7.00               | 6.78  | 0.60            | 14.20                        | 46.00                  | 3.50                  | 3.31              | 3.06 | 3.80              | 3.20 |
| (M14)                 | 21.00                | 20.48 | 8.00               | 7.78  | 0.60            | 16.20                        | 52.00                  | 4.00                  | 3.31              | 3.06 | 4.20              | 3.60 |
| M16                   | 24.00                | 23.48 | 9.00               | 8.78  | 0.60            | 18.20                        | 58.00                  | 4.00                  | 4.37              | 4.07 | 4.60              | 4.00 |
| (M18)                 | 27.00                | 26.48 | 10.00              | 9.78  | 0.60            | 20.20                        | 64.00                  | 5.00                  | 4.37              | 4.07 | 5.10              | 4.50 |
| M20                   | 30.00                | 29.48 | 11.00              | 10.73 | 0.80            | 22.40                        | 70.00                  | 5.00                  | 5.27              | 5.07 | 5.60              | 5.00 |

<sup>a</sup>Nominal sizes shown in parentheses are non-preferred.<sup>b</sup>Threaded up to head.<sup>c</sup>See text following table in *Lengths of Thread on Screws* description in text.

All dimensions are given in millimeters. For dimensional notation, see diagram on page 1610.

**General Dimensions:** The general dimensions and tolerances for screws and nuts are given in the accompanying tables. Although slotted screw dimensions are given, recessed head screws are also standard and available. Dimensions of recessed head screws are given in BS 4183:1967 (obsolescent).

**Table 5. British Standard Machine Screws and Nuts — Metric Series BS 4183:1967 (obsolescent)**

| Concentricity Tolerances    |   | Nominal Lengths and Tolerances on Length for Machine Screws |                             |            |                             | Dimensions of Machine Screw Nuts, Pressed Type, Square and Hexagon |                    |              |        |             |
|-----------------------------|---|---|-----------------------------|------------|-----------------------------|--|--------------------|--------------|--------|-------------|
| Nominal Size $d^a$          | Head to Shank and Slot to Head (IT 13)  |   | Nominal Length <sup>a</sup> | Tolerance  | Nominal Length <sup>a</sup> | Tolerance  | Nominal Size $d^a$ | Width Across |        |             |
|                             | Countersunk, Raised Csk., and Pan Heads | Cheese Heads  |                             |            |                             |  |                    | Flats $s$    |        | Corners $e$ |
|                             |   |   |                             |            |                             |  | Max.               | Min.         | Square |             |
| M1, M1.2, (M1.4)            | 0.14                                    | 0.14  | 20                          | $\pm 0.42$ | (125)                       | $\pm 0.70$   | M1.6               | 3.7          | 1.0    | 0.75        |
| M1.6                        | 0.18                                    | 0.14  | (22)                        | $\pm 0.42$ | 130                         | $\pm 0.80$   | M2                 | 4.6          | 1.2    | 0.95        |
| M2, (M2.2), M2.5, M3 (M3.5) | 0.18                                    | 0.18  | 25                          | $\pm 0.42$ | 140                         | $\pm 0.80$   | (M2.2)             | 5.2          | 1.2    | 0.95        |
| M4, (M4.5), M5              | 0.22                                    | 0.18  | (28)                        | $\pm 0.42$ | 150                         | $\pm 0.80$   | M2.5               | 5.8          | 1.6    | 1.35        |
| M6                          | 0.27                                    | 0.22  | 30                          | $\pm 0.42$ | 160                         | $\pm 0.80$   | M3                 | 6.4          | 1.6    | 1.35        |
| M8                          | 0.27                                    | 0.27  | (38)                        | $\pm 0.50$ | 190                         | $\pm 0.925$  | (M3.5)             | 6.9          | 2.0    | 1.75        |
| M10, M12 (M14)              | 0.33                                    | 0.27  | 40                          | $\pm 0.50$ | 200                         | $\pm 0.925$  | M4                 | 8.1          | 2.0    | 1.75        |
| M16, (M18), M20             | 0.33                                    | 0.33  |                             |            |                             |  | M5                 | 9.2          | 2.5    | 2.25        |
|                             | 0.39                                    | 0.33  |                             |            |                             |  | M6                 | 11.5         | 3.0    | 2.75        |
|                             |   |   |                             |            |                             |  | M8                 | 15.0         | 4.0    | 3.70        |
|                             |   |   |                             |            |                             |  | M10                | 19.6         | 5.0    | 4.70        |
|                             |   |   |                             |            |                             |  | M8                 | 13.0         | 12.73  | 18.4        |
|                             |   |   |                             |            |                             |  | M10                | 17.0         | 16.73  | 24.0        |

<sup>a</sup>Nominal sizes and lengths shown in parentheses are non-preferred.

All dimensions are given in millimeters. For dimensional notation, see diagram on page 1610.

**British Unified Machine Screws and Nuts.**—British Standard B.S. 1981:1953 covers certain types of machine screws and machine screw nuts for which agreement has been reached with the United States and Canada as to general dimensions for interchangeability. These types are: countersunk, raised-countersunk, pan, and raised-cheese head screws with slotted or recessed heads; small hexagon head screws; and precision and pressed nuts. All have Unified threads. Head shapes are shown on page 1614 and dimensions are given on page 1616.

*Identification:* As revised by Amendment No. 1 in February 1955, this standard now requires that the above-mentioned screws and nuts that conform to this standard should have a distinguishing feature applied to identify them as Unified. All *recessed head screws* are to be identified as Unified by a groove in the form of four arcs of a circle in the upper surface of the head. All *hexagon head screws* are to be identified as Unified by: 1) a circular recess in the upper surface of the head; 2) a continuous line of circles indented on one or more of the flats of the hexagon and parallel to the screw axis; and 3) at least two contiguous circles indented on the upper surface of the head. All *machine screw nuts* of the pressed type shall be identified as Unified by means of the application of a groove indented in one face of the nut approximately midway between the major diameter of the thread and flats of the square or hexagon. *Slotted head screws* shall be identified as Unified either by a circular recess or by a circular platform or raised portion on the upper surface of the head. *Machine screw nuts* of the *precision type* shall be identified as Unified by either a groove indented on one face of the front approximately midway between the major diameter of the thread and the flats of the hexagon or a continuous line of circles indented on one or more of the flats of the hexagon and parallel to the nut axis.



Recessed and Hexagon Head Screws



Precision Type

Pressed Type

Hexagon Machine Screw Nuts

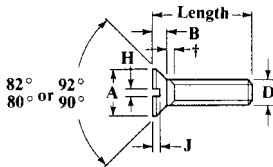


Slotted Head Screws

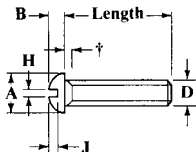
Identification Markings for British Standard Unified Machine Screws

**British Standard Machine Screws and Nuts**

*ricc:1958 (obsolescent) and B.S. 1981:1953*



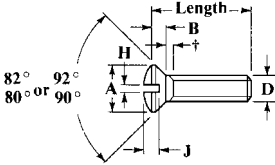
80° Countersunk head screw (Unified)  
90° Countersink head screw (BSW & BSF)



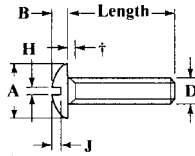
Round head screw (BSW & BSF)

**British Standard Machine Screws and Nuts (Continued)**

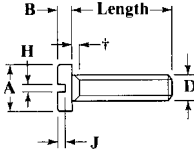
*rics:1958 (obsolescent) and B.S. 1981:1953*



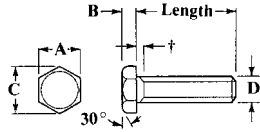
80° Raised countersunk head screw (Unified)  
90° Raised countersunk head screw (BSW & BSF)



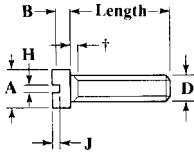
Mushroom head screw (BSW & BSF)



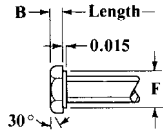
Pan head screw (Unified, BSW & BSF)



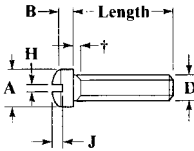
Hexagon head screw (Unified)



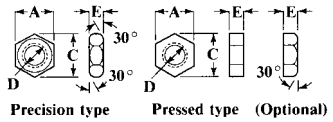
Cheese head screw (BSW & BSF)



Hexagon head screw (Unified) alternate design



Raised cheese head screw (Unified)



Hexagon machine screw nut (Unified)

\*Countersinks to suit the screws should have a maximum angle of 80° (Unified) or 90° (BSF and BSW) with a negative tolerance.

†Unified countersunk and raised countersunk head screws 2 inches long and under are threaded right up to the head. Other Unified, BSW and BSF machine screws 2 inches long and under have an unthread shank equal to twice the pitch. All Unified, BSW and BSF machine screws longer than 2 inches have a minimum thread length of 1¼ inches.

**British Standard Unified Machine Screws and Nuts B.S. 1981:1953**

| Nom. Size of Screw                         | Basic Dia. <i>D</i> | Threads per Inch |     | Dia. of Head <i>A</i> |                    | Depth of Head <i>B</i> |       | Width of Slot <i>H</i> |       | Depth of Slot <i>J</i> |
|--|---------------------|------------------|-----|-----------------------|--------------------|------------------------|-------|------------------------|-------|------------------------|
|  |                     | UNC              | UNF | Max.                  | Min.               | Max.                   | Min.  | Max.                   | Min.  |                        |
| 80° Countersunk Head Screws <sup>a,b</sup> |                     |                  |     |                       |                    |                        |       |                        |       |                        |
| 4  | 0.112               | 40               | ... | 0.211                 | 0.194              | 0.067                  | ...   | 0.039                  | 0.031 | 0.025                  |
| 6  | 0.138               | 32               | ... | 0.260                 | 0.242              | 0.083                  | ...   | 0.048                  | 0.039 | 0.031                  |
| 8  | 0.164               | 32               | ... | 0.310                 | 0.291              | 0.100                  | ...   | 0.054                  | 0.045 | 0.037                  |
| 10   | 0.190               | 24 <sup>c</sup>  | 32  | 0.359                 | 0.339              | 0.116                  | ...   | 0.060                  | 0.050 | 0.044                  |
| 1/4  | 0.250               | 20               | 28  | 0.473                 | 0.450              | 0.153                  | ...   | 0.075                  | 0.064 | 0.058                  |
| 5/16                                       | 0.3125              | 18               | 24  | 0.593                 | 0.565              | 0.191                  | ...   | 0.084                  | 0.072 | 0.073                  |
| 3/8  | 0.375               | 16               | 24  | 0.712                 | 0.681              | 0.230                  | ...   | 0.094                  | 0.081 | 0.086                  |
| 7/16                                       | 0.4375              | 14               | 20  | 0.753                 | 0.719              | 0.223                  | ...   | 0.094                  | 0.081 | 0.086                  |
| 1/2  | 0.500               | 13               | 20  | 0.808                 | 0.770              | 0.223                  | ...   | 0.106                  | 0.091 | 0.086                  |
| 5/8  | 0.625               | 11               | 18  | 1.041                 | 0.996              | 0.298                  | ...   | 0.133                  | 0.116 | 0.113                  |
| 3/4  | 0.750               | 10               | 16  | 1.275                 | 1.223              | 0.372                  | ...   | 0.149                  | 0.131 | 0.141                  |
| Pan Head Screws <sup>b</sup>               |                     |                  |     |                       |                    |                        |       |                        |       |                        |
| 4  | 0.112               | 40               | ... | 0.219                 | 0.205              | 0.068                  | 0.058 | 0.039                  | 0.031 | 0.036                  |
| 6  | 0.138               | 32               | ... | 0.270                 | 0.256              | 0.082                  | 0.072 | 0.048                  | 0.039 | 0.044                  |
| 8  | 0.164               | 32               | ... | 0.322                 | 0.306              | 0.096                  | 0.085 | 0.054                  | 0.045 | 0.051                  |
| 10   | 0.190               | 24 <sup>c</sup>  | 32  | 0.373                 | 0.357              | 0.110                  | 0.099 | 0.060                  | 0.050 | 0.059                  |
| 1/4  | 0.250               | 20               | 28  | 0.492                 | 0.473 <sup>d</sup> | 0.144                  | 0.130 | 0.075                  | 0.064 | 0.079                  |
| 5/16                                       | 0.3125              | 18               | 24  | 0.615                 | 0.594              | 0.178                  | 0.162 | 0.084                  | 0.072 | 0.101                  |
| 3/8  | 0.375               | 16               | 24  | 0.740                 | 0.716              | 0.212                  | 0.195 | 0.094                  | 0.081 | 0.122                  |
| 7/16                                       | 0.4375              | 14               | 20  | 0.863                 | 0.838              | 0.247                  | 0.227 | 0.094                  | 0.081 | 0.133                  |
| 1/2  | 0.500               | 13               | 20  | 0.987                 | 0.958              | 0.281                  | 0.260 | 0.106                  | 0.091 | 0.152                  |
| 5/8  | 0.625               | 11               | 18  | 1.125                 | 1.090              | 0.350                  | 0.325 | 0.133                  | 0.116 | 0.189                  |
| 3/4  | 0.750               | 10               | 16  | 1.250                 | 1.209              | 0.419                  | 0.390 | 0.149                  | 0.131 | 0.226                  |
| Raised Cheese-Head Screws <sup>b</sup>     |                     |                  |     |                       |                    |                        |       |                        |       |                        |
| 4  | 0.112               | 40               | ... | 0.183                 | 0.166              | 0.107                  | 0.088 | 0.039                  | 0.031 | 0.042                  |
| 6  | 0.138               | 32               | ... | 0.226                 | 0.208              | 0.132                  | 0.111 | 0.048                  | 0.039 | 0.053                  |
| 8  | 0.164               | 32               | ... | 0.270                 | 0.250              | 0.156                  | 0.133 | 0.054                  | 0.045 | 0.063                  |
| 10   | 0.190               | 24 <sup>c</sup>  | 32  | 0.313                 | 0.292              | 0.180                  | 0.156 | 0.060                  | 0.050 | 0.074                  |
| 1/4  | 0.250               | 20               | 28  | 0.414                 | 0.389              | 0.237                  | 0.207 | 0.075                  | 0.064 | 0.098                  |
| 5/16                                       | 0.3125              | 18               | 24  | 0.518                 | 0.490              | 0.295                  | 0.262 | 0.084                  | 0.072 | 0.124                  |
| 3/8  | 0.375               | 16               | 24  | 0.622                 | 0.590              | 0.355                  | 0.315 | 0.094                  | 0.081 | 0.149                  |
| 7/16                                       | 0.4375              | 14               | 20  | 0.625                 | 0.589              | 0.368                  | 0.321 | 0.094                  | 0.081 | 0.153                  |
| 1/2  | 0.500               | 13               | 20  | 0.750                 | 0.710              | 0.412                  | 0.362 | 0.106                  | 0.091 | 0.171                  |
| 5/8  | 0.625               | 11               | 18  | 0.875                 | 0.827              | 0.521                  | 0.461 | 0.133                  | 0.116 | 0.217                  |
| 3/4  | 0.750               | 10               | 16  | 1.000                 | 0.945              | 0.612                  | 0.542 | 0.149                  | 0.131 | 0.254                  |

<sup>a</sup> All dimensions, except *J*, given for the No. 4 to 3/8-inch sizes, incl., also apply to all the 80° Raised Countersunk Head Screws given in the Standard.

<sup>b</sup> Also available with recessed heads.

<sup>c</sup> Non-preferred.

<sup>d</sup> By arrangement may also be 0.468.

| Nom. Size                                 | Basic Dia. <i>D</i> | Threads per Inch |     | Width Across   |        |                  | H'd Depth <i>B</i>  |       | Wash. Face    |       |
|---|---------------------|------------------|-----|----------------|--------|------------------|---------------------|-------|---------------|-------|
|   |                     |                  |     | Flats <i>A</i> |        | Corners <i>C</i> | Nut Thick. <i>E</i> |       | Dia. <i>F</i> |       |
|   |                     | UNC              | UNF | Max.           | Min.   |                  | Max.                | Min.  | Max.          | Min.  |
| Hexagon Head Screws                       |                     |                  |     |                |        |                  |                     |       |               |       |
| 4   | 0.112               | 40               | ... | 0.1875         | 0.1835 | 0.216            | 0.060               | 0.055 | 0.183         | 0.173 |
| 6   | 0.138               | 32               | ... | 0.2500         | 0.2450 | 0.289            | 0.080               | 0.074 | 0.245         | 0.235 |
| 8   | 0.164               | 32               | ... | 0.2500         | 0.2450 | 0.289            | 0.110               | 0.104 | 0.245         | 0.235 |
| 10  | 0.190               | 24 <sup>c</sup>  | 32  | 0.3125         | 0.3075 | 0.361            | 0.120               | 0.113 | 0.307         | 0.297 |
| Hexagon Machine Screw Nuts—Precision Type |                     |                  |     |                |        |                  |                     |       |               |       |
| 4   | 0.112               | 40               | ... | 0.1875         | 0.1835 | 0.216            | 0.098               | 0.087 | ...           | ...   |
| 6   | 0.138               | 32               | ... | 0.2500         | 0.2450 | 0.269            | 0.114               | 0.102 | ...           | ...   |
| 8   | 0.164               | 32               | ... | 0.3125         | 0.3075 | 0.361            | 0.130               | 0.117 | ...           | ...   |
| 10  | 0.190               | 24 <sup>c</sup>  | ... | 0.3125         | 0.3075 | 0.361            | 0.130               | 0.117 | ...           | ...   |
| Hexagon Machine Screw Nuts—Pressed Type   |                     |                  |     |                |        |                  |                     |       |               |       |
| 4   | 0.112               | 40               | ... | 0.2500         | 0.2410 | 0.289            | 0.087               | 0.077 | ...           | ...   |
| 6   | 0.138               | 32               | ... | 0.3125         | 0.3020 | 0.361            | 0.114               | 0.102 | ...           | ...   |
| 8   | 0.164               | 32               | ... | 0.3438         | 0.3320 | 0.397            | 0.130               | 0.117 | ...           | ...   |
| 10  | 0.190               | 24 <sup>c</sup>  | 32  | 0.3750         | 0.3620 | 0.433            | 0.130               | 0.117 | ...           | ...   |
| 1/4                                       | 0.250               | 20               | 28  | 0.4375         | 0.4230 | 0.505            | 0.193               | 0.178 | ...           | ...   |
| 5/16                                      | 0.3125              | 18               | 24  | 0.5625         | 0.5450 | 0.649            | 0.225               | 0.208 | ...           | ...   |
| 3/8                                       | 0.375               | 16               | 24  | 0.6250         | 0.6070 | 0.722            | 0.257               | 0.239 | ...           | ...   |

All dimensions in inches. See page 1614 for a pictorial representation and letter dimensions.

**British Standard Whitworth (BSW) and Fine (BSF) Machine Screws**  
*BS 450:1958 (obsolescent)*

|  | Nom. Size of Screw | Basic Dia. <i>D</i> | Threads per Inch |                 | Dia. of Head <i>A</i> |                    | Depth of Head <i>B</i> |       | Width of Slot <i>H</i> |       | Depth of Slot <i>J</i> |
|--|--------------------|---------------------|------------------|-----------------|-----------------------|--------------------|------------------------|-------|------------------------|-------|------------------------|
|  |                    |                     | BSW              | BSF             | Max.                  | Min.               | Max.                   | Min.  | Max.                   | Min.  |                        |
| 90° Countersunk Head Screws <sup>a,b</sup> | 1/8                | 0.1250              | 40               | ...             | 0.219                 | 0.201              | 0.056                  | ...   | 0.039                  | 0.032 | 0.027                  |
|  | 3/16               | 0.1875              | 24               | 32 <sup>c</sup> | 0.328                 | 0.307              | 0.084                  | ...   | 0.050                  | 0.042 | 0.041                  |
|  | 7/32               | 0.2188              | ...              | 28 <sup>c</sup> | 0.383                 | 0.360              | 0.098                  | ...   | 0.055                  | 0.046 | 0.048                  |
|  | 1/4                | 0.2500              | 20               | 26              | 0.438                 | 0.412              | 0.113                  | ...   | 0.061                  | 0.051 | 0.055                  |
|  | 5/16               | 0.3125              | 18               | 22              | 0.547                 | 0.518              | 0.141                  | ...   | 0.071                  | 0.061 | 0.069                  |
|  | 3/8                | 0.3750              | 16               | 20              | 0.656                 | 0.624              | 0.169                  | ...   | 0.082                  | 0.072 | 0.083                  |
|  | 7/16               | 0.4375              | 14               | 18              | 0.766                 | 0.729              | 0.197                  | ...   | 0.093                  | 0.082 | 0.097                  |
|  | 1/2                | 0.5000              | 12               | 16              | 0.875                 | 0.835              | 0.225                  | ...   | 0.104                  | 0.092 | 0.111                  |
|  | 9/16               | 0.5625              | 12 <sup>c</sup>  | 16 <sup>c</sup> | 0.984                 | 0.941              | 0.253                  | ...   | 0.115                  | 0.103 | 0.125                  |
|  | 5/8                | 0.6250              | 11               | 14              | 1.094                 | 1.046              | 0.281                  | ...   | 0.126                  | 0.113 | 0.138                  |
| 3/4  | 0.7500             | 10                  | 12               | 1.312           | 1.257                 | 0.338              | ...                    | 0.148 | 0.134                  | 0.166 |                        |
| Round Head Screws <sup>b</sup>             | 1/8                | 0.1250              | 40               | ...             | 0.219                 | 0.206              | 0.087                  | 0.082 | 0.039                  | 0.032 | 0.048                  |
|  | 3/16               | 0.1875              | 24               | 32 <sup>c</sup> | 0.328                 | 0.312 <sup>d</sup> | 0.131                  | 0.124 | 0.050                  | 0.042 | 0.072                  |
|  | 7/32               | 0.2188              | ...              | 28 <sup>c</sup> | 0.383                 | 0.365              | 0.153                  | 0.145 | 0.055                  | 0.046 | 0.084                  |
|  | 1/4                | 0.2500              | 20               | 26              | 0.438                 | 0.417              | 0.175                  | 0.165 | 0.061                  | 0.051 | 0.096                  |
|  | 5/16               | 0.3125              | 18               | 22              | 0.547                 | 0.524              | 0.219                  | 0.207 | 0.071                  | 0.061 | 0.120                  |
|  | 3/8                | 0.3750              | 16               | 20              | 0.656                 | 0.629              | 0.262                  | 0.249 | 0.082                  | 0.072 | 0.144                  |
|  | 7/16               | 0.4375              | 14               | 18              | 0.766                 | 0.735              | 0.306                  | 0.291 | 0.093                  | 0.082 | 0.168                  |
|  | 1/2                | 0.5000              | 12               | 16              | 0.875                 | 0.840              | 0.350                  | 0.333 | 0.104                  | 0.092 | 0.192                  |
|  | 9/16               | 0.5625              | 12 <sup>c</sup>  | 16 <sup>c</sup> | 0.984                 | 0.946              | 0.394                  | 0.375 | 0.115                  | 0.103 | 0.217                  |
|  | 5/8                | 0.6250              | 11               | 14              | 1.094                 | 1.051              | 0.437                  | 0.417 | 0.126                  | 0.113 | 0.240                  |
| 3/4  | 0.7500             | 10                  | 12               | 1.312           | 1.262                 | 0.525              | 0.500                  | 0.148 | 0.134                  | 0.288 |                        |
| Pan Head Screws <sup>b</sup>               | 1/8                | 0.1250              | 40               | ...             | 0.245                 | 0.231              | 0.075                  | 0.065 | 0.039                  | 0.032 | 0.040                  |
|  | 3/16               | 0.1875              | 24               | 32 <sup>c</sup> | 0.373                 | 0.375              | 0.110                  | 0.099 | 0.050                  | 0.042 | 0.061                  |
|  | 7/32               | 0.2188              | ...              | 28 <sup>c</sup> | 0.425                 | 0.407              | 0.125                  | 0.112 | 0.055                  | 0.046 | 0.069                  |
|  | 1/4                | 0.2500              | 20               | 26              | 0.492                 | 0.473 <sup>e</sup> | 0.144                  | 0.130 | 0.061                  | 0.051 | 0.078                  |
|  | 5/16               | 0.3125              | 18               | 22              | 0.615                 | 0.594              | 0.178                  | 0.162 | 0.071                  | 0.061 | 0.095                  |
|  | 3/8                | 0.3750              | 16               | 20              | 0.740                 | 0.716              | 0.212                  | 0.195 | 0.082                  | 0.072 | 0.112                  |
|  | 7/16               | 0.4375              | 14               | 18              | 0.863                 | 0.838              | 0.247                  | 0.227 | 0.093                  | 0.082 | 0.129                  |
|  | 1/2                | 0.5000              | 12               | 16              | 0.987                 | 0.958              | 0.281                  | 0.260 | 0.104                  | 0.092 | 0.145                  |
|  | 9/16               | 0.5625              | 12 <sup>c</sup>  | 16 <sup>c</sup> | 1.031                 | 0.999              | 0.315                  | 0.293 | 0.115                  | 0.103 | 0.162                  |
|  | 5/8                | 0.6250              | 11               | 14              | 1.125                 | 1.090              | 0.350                  | 0.325 | 0.126                  | 0.113 | 0.179                  |
| 3/4  | 0.7500             | 10                  | 12               | 1.250           | 1.209                 | 0.419              | 0.390                  | 0.148 | 0.134                  | 0.213 |                        |
| Cheese Head Screws <sup>b</sup>            | 1/8                | 0.1250              | 40               | ...             | 0.188                 | 0.180              | 0.087                  | 0.082 | 0.039                  | 0.032 | 0.039                  |
|  | 3/16               | 0.1875              | 24               | 32 <sup>c</sup> | 0.281                 | 0.270              | 0.131                  | 0.124 | 0.050                  | 0.042 | 0.059                  |
|  | 7/32               | 0.2188              | ...              | 28 <sup>c</sup> | 0.328                 | 0.315              | 0.153                  | 0.145 | 0.055                  | 0.046 | 0.069                  |
|  | 1/4                | 0.2500              | 20               | 26              | 0.375                 | 0.360              | 0.175                  | 0.165 | 0.061                  | 0.051 | 0.079                  |
|  | 5/16               | 0.3125              | 18               | 22              | 0.469                 | 0.450              | 0.219                  | 0.207 | 0.071                  | 0.061 | 0.098                  |
|  | 3/8                | 0.3750              | 16               | 20              | 0.562                 | 0.540              | 0.262                  | 0.249 | 0.082                  | 0.072 | 0.118                  |
|  | 7/16               | 0.4375              | 14               | 18              | 0.656                 | 0.630              | 0.306                  | 0.291 | 0.093                  | 0.082 | 0.138                  |
|  | 1/2                | 0.5000              | 12               | 16              | 0.750                 | 0.720              | 0.350                  | 0.333 | 0.104                  | 0.092 | 0.157                  |
|  | 9/16               | 0.5625              | 12 <sup>c</sup>  | 16 <sup>c</sup> | 0.844                 | 0.810              | 0.394                  | 0.375 | 0.115                  | 0.103 | 0.177                  |
|  | 5/8                | 0.6250              | 11               | 14              | 0.938                 | 0.900              | 0.437                  | 0.417 | 0.126                  | 0.113 | 0.197                  |
| 3/4  | 0.7500             | 10                  | 12               | 1.125           | 1.080                 | 0.525              | 0.500                  | 0.148 | 0.134                  | 0.236 |                        |
| Mushroom Head Screw <sup>b</sup>           | 1/8                | 0.1250              | 40               | ...             | 0.289                 | 0.272              | 0.078                  | 0.066 | 0.043                  | 0.035 | 0.040                  |
|  | 3/16               | 0.1875              | 24               | 32 <sup>c</sup> | 0.448                 | 0.425              | 0.118                  | 0.103 | 0.060                  | 0.050 | 0.061                  |
|  | 1/4                | 0.2500              | 20               | 26              | 0.573                 | 0.546              | 0.150                  | 0.133 | 0.075                  | 0.064 | 0.079                  |
|  | 5/16               | 0.3125              | 18               | 22              | 0.698                 | 0.666              | 0.183                  | 0.162 | 0.084                  | 0.072 | 0.096                  |
|  | 3/8                | 0.3750              | 16               | 20              | 0.823                 | 0.787              | 0.215                  | 0.191 | 0.094                  | 0.081 | 0.112                  |

<sup>a</sup> All dimensions, except *J*, given for the 1/8-inch through 5/8-inch sizes also apply to all the 90° Raised Countersunk Head Screw dimensions given in the Standard.

<sup>b</sup> These screws are also available with recessed heads; dimensions of recess are not given here but may be found in the Standard.

<sup>c</sup> Non-preferred size; avoid use whenever possible.

<sup>d</sup> By arrangement may also be 0.309.

<sup>e</sup> By arrangement may also be 0.468.

All dimensions in inches.

See diagram on page 1614 for a pictorial representation of screws and letter dimensions.

CAP AND SET SCREWS

**Slotted Head Cap Screws.**— American National Standard ANSI/ASME B18.6.2-1998 is intended to cover the complete general and dimensional data for the various styles of slotted head cap screws as well as square head and slotted headless set screws (see page 1625). Reference should be made to this Standard for information or data not found in the following text or tables.

*Length of Thread:* The length of complete (full form) thread on cap screws is equal to twice the basic screw diameter plus 0.250 in. with a plus tolerance of 0.188 in. or an amount equal to 2½ times the pitch of the thread, whichever is greater. Cap screws of lengths too short to accommodate the minimum thread length have full form threads extending to within a distance equal to 2½ pitches (threads) of the head.

*Designation:* Slotted head cap screws are designated by the following data in the sequence shown: Nominal size (fraction or decimal equivalent); threads per inch; screw length (fraction or decimal equivalent); product name; material; and protective finish, if required. Examples: ½-13 × 3 Slotted Round Head Cap Screw, SAE Grade 2 Steel, Zinc Plated. .750-16 × 2.25 Slotted Flat Countersunk Head Cap Screw, Corrosion Resistant Steel.

**Table 1. American National Standard Slotted Flat Countersunk Head Cap Screws  
ANSI/ASME B18.6.2-1998**

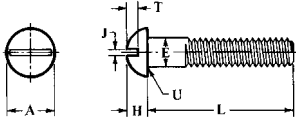
| Nominal Size <sup>a</sup> or Basic Screw Dia. | Body Dia., E |        | Head Dia., A |                     | Head Hgt., H | Slot Width, J |      | Slot Depth, T |      | Fillet Rad., U |      |
|---|--------------|--------|--------------|---------------------|--------------|---------------|------|---------------|------|----------------|------|
|   |              |        | Edge Sharp   | Edge Rnd'd. or Flat |              |               |      |               |      |                |      |
|   | Max.         | Min.   | Max.         | Min.                | Ref.         | Max.          | Min. | Max.          | Min. | Max.           |      |
| ¼   | 0.2500       | .2500  | .2450        | .500                | .452         | .140          | .075 | .064          | .068 | .045           | .100 |
| ⅜   | 0.3125       | .3125  | .3070        | .625                | .567         | .177          | .084 | .072          | .086 | .057           | .125 |
| ½   | 0.3750       | .3750  | .3690        | .750                | .682         | .210          | .094 | .081          | .103 | .068           | .150 |
| ⅝   | 0.4375       | .4375  | .4310        | .812                | .736         | .210          | .094 | .081          | .103 | .068           | .175 |
| ¾   | 0.5000       | .5000  | .4930        | .875                | .791         | .210          | .106 | .091          | .103 | .068           | .200 |
| ⅞   | 0.5625       | .5625  | .5550        | 1.000               | .906         | .244          | .118 | .102          | .120 | .080           | .225 |
| 1   | 0.6250       | .6250  | .6170        | 1.125               | 1.020        | .281          | .133 | .116          | .137 | .091           | .250 |
| 1¼  | 0.7500       | .7500  | .7420        | 1.375               | 1.251        | .352          | .149 | .131          | .171 | .115           | .300 |
| 1½  | 0.8750       | .8750  | .8660        | 1.625               | 1.480        | .423          | .167 | .147          | .206 | .138           | .350 |
| 1¾  | 1.0000       | 1.0000 | .9900        | 1.875               | 1.711        | .494          | .188 | .166          | .240 | .162           | .400 |
| 2   | 1.1250       | 1.1250 | 1.1140       | 2.062               | 1.880        | .529          | .196 | .178          | .257 | .173           | .450 |
| 2¼  | 1.2500       | 1.2500 | 1.2390       | 2.312               | 2.110        | .600          | .211 | .193          | .291 | .197           | .500 |
| 2½  | 1.3750       | 1.3750 | 1.3630       | 2.562               | 2.340        | .665          | .226 | .208          | .326 | .220           | .550 |
| 2¾  | 1.5000       | 1.5000 | 1.4880       | 2.812               | 2.570        | .742          | .258 | .240          | .360 | .244           | .600 |

<sup>a</sup> When specifying a nominal size in decimals, the zero preceding the decimal point is omitted as is any zero in the fourth decimal place.

All dimensions are in inches.

*Threads:* Threads are Unified Standard Class 2A; UNC, UNF and 8 UN Series or UNRC, UNRF, and 8 UNR Series.

**Table 2. American National Standard Slotted Round Head Cap Screws**  
ANSI/ASME B18.6.2-1998



| Nom. Size <sup>a</sup><br>or Basic<br>Screw Diameter | Body<br>Diameter, <i>E</i> |       | Head<br>Diameter, <i>A</i> |       | Head<br>Height, <i>H</i> |      | Slot<br>Width, <i>J</i> |      | Slot<br>Depth, <i>T</i> |      |      |
|--|----------------------------|-------|----------------------------|-------|--------------------------|------|-------------------------|------|-------------------------|------|------|
|  | Max.                       | Min.  | Max.                       | Min.  | Max.                     | Min. | Max.                    | Min. | Max.                    | Min. |      |
| ¼  | 0.2500                     | .2500 | .2450                      | .437  | .418                     | .191 | .175                    | .075 | .064                    | .117 | .097 |
| ⅜  | 0.3125                     | .3125 | .3070                      | .562  | .540                     | .245 | .226                    | .084 | .072                    | .151 | .126 |
| ½  | 0.3750                     | .3750 | .3690                      | .625  | .603                     | .273 | .252                    | .094 | .081                    | .168 | .138 |
| ⅝  | 0.4375                     | .4375 | .4310                      | .750  | .725                     | .328 | .302                    | .094 | .081                    | .202 | .167 |
| ¾  | 0.5000                     | .5000 | .4930                      | .812  | .786                     | .354 | .327                    | .106 | .091                    | .218 | .178 |
| 7/16   | 0.5625                     | .5625 | .5550                      | .937  | .909                     | .409 | .378                    | .118 | .102                    | .252 | .207 |
| 1  | 0.6250                     | .6250 | .6170                      | 1.000 | .970                     | .437 | .405                    | .133 | .116                    | .270 | .220 |
| 1 ¼  | 0.7500                     | .7500 | .7420                      | 1.250 | 1.215                    | .546 | .507                    | .149 | .131                    | .338 | .278 |

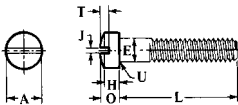
<sup>a</sup> When specifying a nominal size in decimals, the zero preceding the decimal point is omitted as is any zero in the fourth decimal place.

All dimensions are in inches.

*Fillet Radius, U:* For fillet radius see footnote to table below.

*Threads:* Threads are Unified Standard Class 2A; UNC, UNF and 8 UN Series or UNRC, UNRF and 8 UNR Series.

**Table 3. American National Standard Slotted Fillister Head Cap Screws**  
ANSI/ASME B18.6.2-1998



| Nom. Size <sup>a</sup><br>or Basic<br>Screw Dia. | Body<br>Dia., <i>E</i> |        | Head<br>Dia., <i>A</i> |       | Head<br>Side<br>Height, <i>H</i> |      | Total<br>Head<br>Height, <i>O</i> |      | Slot<br>Width, <i>J</i> |      | Slot<br>Depth, <i>T</i> |      |      |
|--|------------------------|--------|------------------------|-------|----------------------------------|------|-----------------------------------|------|-------------------------|------|-------------------------|------|------|
|  | Max.                   | Min.   | Max.                   | Min.  | Max.                             | Min. | Max.                              | Min. | Max.                    | Min. | Max.                    | Min. |      |
| ¼  | 0.2500                 | .2500  | .2450                  | .375  | .363                             | .172 | .157                              | .216 | .194                    | .075 | .064                    | .097 | .077 |
| ⅜  | 0.3125                 | .3125  | .3070                  | .437  | .424                             | .203 | .186                              | .253 | .230                    | .084 | .072                    | .115 | .090 |
| ½  | 0.3750                 | .3750  | .3690                  | .562  | .547                             | .250 | .229                              | .314 | .284                    | .094 | .081                    | .142 | .112 |
| ⅝  | 0.4375                 | .4375  | .4310                  | .625  | .608                             | .297 | .274                              | .368 | .336                    | .094 | .081                    | .168 | .133 |
| ¾  | 0.5000                 | .5000  | .4930                  | .750  | .731                             | .328 | .301                              | .413 | .376                    | .106 | .091                    | .193 | .153 |
| 7/16   | 0.5625                 | .5625  | .5550                  | .812  | .792                             | .375 | .346                              | .467 | .427                    | .118 | .102                    | .213 | .168 |
| 1  | 0.6250                 | .6250  | .6170                  | .875  | .853                             | .422 | .391                              | .521 | .478                    | .133 | .116                    | .239 | .189 |
| 1 ¼  | 0.7500                 | .7500  | .7420                  | 1.000 | .976                             | .500 | .466                              | .612 | .566                    | .149 | .131                    | .283 | .223 |
| 1 ½  | 0.8750                 | .8750  | .8660                  | 1.125 | 1.098                            | .594 | .556                              | .720 | .668                    | .167 | .147                    | .334 | .264 |
| 2  | 1.0000                 | 1.0000 | .9900                  | 1.312 | 1.282                            | .656 | .612                              | .803 | .743                    | .188 | .166                    | .371 | .291 |

<sup>a</sup> When specifying nominal size in decimals, the zero preceding the decimal point is omitted as is any zero in the fourth decimal place.

All dimensions are in inches.

*Fillet Radius, U:* The fillet radius is as follows: For screw sizes ¼ to ⅜ incl., .031 max. and .016 min.; ⅝ to 1, incl., .047 max., .016 min.; and for 1 ¼ to 2, incl., .062 max., .031 min.

*Threads:* Threads are Unified Standard Class 2A; UNC, UNF and 8 UN Series or UNRC, UNRF and 8 UNR Series.



**Table 4. American National Standard Hexagon and Spline Socket Head Cap Screws ANSI/ASME B18.3-1998**

| Nominal Size | Body Diameter, <i>D</i> |        | Head Diameter, <i>A</i> |       | Head Height, <i>H</i> |       | Spline Socket <sup>a</sup> Size, <i>M</i> | Nom. Hex. Socket Size, <i>J</i> |       | Fillet Ext., <i>F</i> Max | Key Engagement <sup>a</sup> , <i>T</i> |
|--------------|-------------------------|--------|-------------------------|-------|-----------------------|-------|---|---------------------------------|-------|---------------------------|--|
|              | Max                     | Min    | Max                     | Min   | Max                   | Min   |   | Max                             | Min   |                           |  |
| 0            | 0.0600                  | 0.0568 | 0.096                   | 0.091 | 0.060                 | 0.057 | 0.060                                     | 0.050                           |       | 0.007                     | 0.025                                  |
| 1            | 0.0730                  | 0.0695 | 0.118                   | 0.112 | 0.073                 | 0.070 | 0.072                                     | 1/16                            | 0.062 | 0.007                     | 0.031                                  |
| 2            | 0.0860                  | 0.0822 | 0.140                   | 0.134 | 0.086                 | 0.083 | 0.096                                     | 5/64                            | 0.078 | 0.008                     | 0.038                                  |
| 3            | 0.0990                  | 0.0949 | 0.161                   | 0.154 | 0.099                 | 0.095 | 0.096                                     | 5/64                            | 0.078 | 0.008                     | 0.044                                  |
| 4            | 0.1120                  | 0.1075 | 0.183                   | 0.176 | 0.112                 | 0.108 | 0.111                                     | 3/32                            | 0.094 | 0.009                     | 0.051                                  |
| 5            | 0.1250                  | 0.1202 | 0.205                   | 0.198 | 0.125                 | 0.121 | 0.111                                     | 3/32                            | 0.094 | 0.010                     | 0.057                                  |
| 6            | 0.1380                  | 0.1329 | 0.226                   | 0.218 | 0.138                 | 0.134 | 0.133                                     | 7/64                            | 0.109 | 0.010                     | 0.064                                  |
| 8            | 0.1640                  | 0.1585 | 0.270                   | 0.262 | 0.164                 | 0.159 | 0.168                                     | 5/64                            | 0.141 | 0.012                     | 0.077                                  |
| 10           | 0.1900                  | 0.1840 | 0.312                   | 0.303 | 0.190                 | 0.185 | 0.183                                     | 5/32                            | 0.156 | 0.014                     | 0.090                                  |
| 1/4          | 0.2500                  | 0.2435 | 0.375                   | 0.365 | 0.250                 | 0.244 | 0.216                                     | 3/16                            | 0.188 | 0.014                     | 0.120                                  |
| 5/16         | 0.3125                  | 0.3053 | 0.469                   | 0.457 | 0.312                 | 0.306 | 0.291                                     | 1/4                             | 0.250 | 0.017                     | 0.151                                  |
| 3/8          | 0.3750                  | 0.3678 | 0.562                   | 0.550 | 0.375                 | 0.368 | 0.372                                     | 5/16                            | 0.312 | 0.020                     | 0.182                                  |
| 7/16         | 0.4375                  | 0.4294 | 0.656                   | 0.642 | 0.438                 | 0.430 | 0.454                                     | 3/8                             | 0.375 | 0.023                     | 0.213                                  |
| 1/2          | 0.5000                  | 0.4919 | 0.750                   | 0.735 | 0.500                 | 0.492 | 0.454                                     | 3/8                             | 0.375 | 0.026                     | 0.245                                  |
| 5/8          | 0.6250                  | 0.6163 | 0.938                   | 0.921 | 0.625                 | 0.616 | 0.595                                     | 1/2                             | 0.500 | 0.032                     | 0.307                                  |
| 3/4          | 0.7500                  | 0.7406 | 1.125                   | 1.107 | 0.750                 | 0.740 | 0.620                                     | 5/8                             | 0.625 | 0.039                     | 0.370                                  |
| 7/8          | 0.8750                  | 0.8647 | 1.312                   | 1.293 | 0.875                 | 0.864 | 0.698                                     | 3/4                             | 0.750 | 0.044                     | 0.432                                  |
| 1            | 1.0000                  | 0.9886 | 1.500                   | 1.479 | 1.000                 | 0.988 | 0.790                                     | 3/4                             | 0.750 | 0.050                     | 0.495                                  |
| 1 1/8        | 1.1250                  | 1.1086 | 1.688                   | 1.665 | 1.125                 | 1.111 | ...                                       | 7/8                             | 0.875 | 0.055                     | 0.557                                  |
| 1 1/4        | 1.2500                  | 1.2336 | 1.875                   | 1.852 | 1.250                 | 1.236 | ...                                       | 7/8                             | 0.875 | 0.060                     | 0.620                                  |
| 1 3/8        | 1.3750                  | 1.3568 | 2.062                   | 2.038 | 1.375                 | 1.360 | ...                                       | 1                               | 1.000 | 0.065                     | 0.682                                  |
| 1 1/2        | 1.5000                  | 1.4818 | 2.250                   | 2.224 | 1.500                 | 1.485 | ...                                       | 1                               | 1.000 | 0.070                     | 0.745                                  |
| 1 3/4        | 1.7500                  | 1.7295 | 2.625                   | 2.597 | 1.750                 | 1.734 | ...                                       | 1 1/4                           | 1.250 | 0.080                     | 0.870                                  |
| 2            | 2.0000                  | 1.9780 | 3.000                   | 2.970 | 2.000                 | 1.983 | ...                                       | 1 1/2                           | 1.500 | 0.090                     | 0.995                                  |
| 2 1/4        | 2.2500                  | 2.2280 | 3.375                   | 3.344 | 2.250                 | 2.232 | ...                                       | 1 3/4                           | 1.750 | 0.100                     | 1.120                                  |
| 2 1/2        | 2.5000                  | 2.4762 | 3.750                   | 3.717 | 2.500                 | 2.481 | ...                                       | 1 3/4                           | 1.750 | 0.110                     | 1.245                                  |
| 2 3/4        | 2.7500                  | 2.7262 | 4.125                   | 4.090 | 2.750                 | 2.730 | ...                                       | 2                               | 2.000 | 0.120                     | 1.370                                  |
| 3            | 3.0000                  | 2.9762 | 4.500                   | 4.464 | 3.000                 | 2.979 | ...                                       | 2 1/4                           | 2.250 | 0.130                     | 1.495                                  |
| 3 1/4        | 3.2500                  | 3.2262 | 4.875                   | 4.837 | 3.250                 | 3.228 | ...                                       | 2 1/4                           | 2.250 | 0.140                     | 1.620                                  |
| 3 1/2        | 3.5000                  | 3.4762 | 5.250                   | 5.211 | 3.500                 | 3.478 | ...                                       | 2 3/4                           | 2.750 | 0.150                     | 1.745                                  |
| 3 3/4        | 3.7500                  | 3.7262 | 5.625                   | 5.584 | 3.750                 | 3.727 | ...                                       | 2 3/4                           | 2.750 | 0.160                     | 1.870                                  |
| 4            | 4.0000                  | 3.9762 | 6.000                   | 5.958 | 4.000                 | 3.976 | ...                                       | 3                               | 3.000 | 0.170                     | 1.995                                  |

<sup>a</sup> Key engagement depths are minimum. Spline socket sizes are nominal.

All dimensions in inches. The body length  $L_B$  of the screw is the length of the unthreaded cylindrical portion of the shank. The length of thread,  $L_T$ , is the distance from the extreme point to the last complete (full form) thread. Standard length increments for screw diameters up to 1 inch are 1/16 inch for lengths 1/8 through 1/4 inch, 1/8 inch for lengths 1/4 through 1 inch, 1/4 inch for lengths 1 through 3 1/2 inches, 1/2 inch for lengths 3 1/2 through 7 inches, 1 inch for lengths 7 through 10 inches and for diameters over 1 inch are 1/2 inch for lengths 1 through 7 inches, 1 inch for lengths 7 through 10 inches, and 2 inches for lengths over 10 inches.

Heads may be plain or knurled, and chamfered to an angle  $E$  of 30 to 45 degrees with the surface of the flat. The thread conforms to the Unified Standard with radius root, Class 3A UNRC and UNRF for screw sizes No. 0 through 1 inch inclusive, Class 2A UNRC and UNRF for over 1 inch through 1 1/2 inches inclusive, and Class 2A UNRC for larger sizes. Socket dimensions are given in Table 11. For details not shown, including materials, see ANSI/ASME B18.3-1998.

Table 5. Drill and Counterbore Sizes For Socket Head Cap Screws (1960 Series)

| Nominal Size or Basic Screw Diameter | Nominal Drill Size        |                  |                           |                  | Counterbore Diameter | Countersink Diameter <sup>a</sup> |       |
|--------------------------------------|---------------------------|------------------|---------------------------|------------------|----------------------|-----------------------------------|-------|
|                                      | Close Fit <sup>b</sup>    |                  | Normal Fit <sup>c</sup>   |                  |                      |                                   |       |
|                                      | Number or Fractional Size | Decimal Size     | Number or Fractional Size | Decimal Size     |                      |                                   |       |
| A                                    |                           |                  |                           |                  | B                    | C                                 |       |
| 0                                    | 0.0600                    | 51               | 0.067                     | 49               | 0.073                | $\frac{1}{8}$                     | 0.074 |
| 1                                    | 0.0730                    | 46               | 0.081                     | 43               | 0.089                | $\frac{5}{32}$                    | 0.087 |
| 2                                    | 0.0860                    | $\frac{3}{32}$   | 0.094                     | 36               | 0.106                | $\frac{3}{16}$                    | 0.102 |
| 3                                    | 0.0990                    | 36               | 0.106                     | 31               | 0.120                | $\frac{7}{32}$                    | 0.115 |
| 4                                    | 0.1120                    | $\frac{1}{8}$    | 0.125                     | 29               | 0.136                | $\frac{7}{32}$                    | 0.130 |
| 5                                    | 0.1250                    | $\frac{9}{64}$   | 0.141                     | 23               | 0.154                | $\frac{1}{4}$                     | 0.145 |
| 6                                    | 0.1380                    | 23               | 0.154                     | 18               | 0.170                | $\frac{9}{32}$                    | 0.158 |
| 8                                    | 0.1640                    | 15               | 0.180                     | 10               | 0.194                | $\frac{5}{16}$                    | 0.188 |
| 10                                   | 0.1900                    | 5                | 0.206                     | 2                | 0.221                | $\frac{3}{8}$                     | 0.218 |
| $\frac{1}{4}$                        | 0.2500                    | $\frac{17}{64}$  | 0.266                     | $\frac{9}{32}$   | 0.281                | $\frac{7}{16}$                    | 0.278 |
| $\frac{3}{16}$                       | 0.3125                    | $\frac{21}{64}$  | 0.328                     | $\frac{11}{32}$  | 0.344                | $\frac{17}{32}$                   | 0.346 |
| $\frac{3}{8}$                        | 0.3750                    | $\frac{25}{64}$  | 0.391                     | $\frac{13}{32}$  | 0.406                | $\frac{5}{8}$                     | 0.415 |
| $\frac{7}{16}$                       | 0.4375                    | $\frac{29}{64}$  | 0.453                     | $\frac{15}{32}$  | 0.469                | $\frac{23}{32}$                   | 0.483 |
| $\frac{1}{2}$                        | 0.5000                    | $\frac{33}{64}$  | 0.516                     | $\frac{17}{32}$  | 0.531                | $\frac{13}{16}$                   | 0.552 |
| $\frac{5}{8}$                        | 0.6250                    | $\frac{41}{64}$  | 0.641                     | $\frac{21}{32}$  | 0.656                | 1                                 | 0.689 |
| $\frac{3}{4}$                        | 0.7500                    | $\frac{49}{64}$  | 0.766                     | $\frac{25}{32}$  | 0.781                | $1\frac{3}{16}$                   | 0.828 |
| $\frac{7}{8}$                        | 0.8750                    | $\frac{57}{64}$  | 0.891                     | $\frac{29}{32}$  | 0.906                | $1\frac{3}{8}$                    | 0.963 |
| 1                                    | 1.0000                    | $1\frac{1}{64}$  | 1.016                     | $1\frac{1}{32}$  | 1.031                | $1\frac{5}{8}$                    | 1.100 |
| $1\frac{1}{4}$                       | 1.2500                    | $1\frac{9}{32}$  | 1.281                     | $1\frac{5}{16}$  | 1.312                | 2                                 | 1.370 |
| $1\frac{1}{2}$                       | 1.5000                    | $1\frac{17}{32}$ | 1.531                     | $1\frac{9}{16}$  | 1.562                | $2\frac{3}{8}$                    | 1.640 |
| $1\frac{3}{4}$                       | 1.7500                    | $1\frac{25}{32}$ | 1.781                     | $1\frac{13}{16}$ | 1.812                | $2\frac{3}{4}$                    | 1.910 |
| 2                                    | 2.0000                    | $2\frac{1}{32}$  | 2.031                     | $2\frac{1}{16}$  | 2.062                | $3\frac{1}{8}$                    | 2.180 |

<sup>a</sup> **Countersink:** It is considered good practice to countersink or break the edges of holes which are smaller than  $(D \text{ Max} + 2F \text{ Max})$  in parts having a hardness which approaches, equals or exceeds the screw hardness. If such holes are not countersunk, the heads of screws may not seat properly or the sharp edges on holes may deform the fillets on screws thereby making them susceptible to fatigue in applications involving dynamic loading. The countersink or corner relief, however, should not be larger than is necessary to insure that the fillet on the screw is cleared.

<sup>b</sup> **Close Fit:** The close fit is normally limited to holes for those lengths of screws which are threaded to the head in assemblies where only one screw is to be used or where two or more screws are to be used and the mating holes are to be produced either at assembly or by matched and coordinated tooling.

<sup>c</sup> **Normal Fit:** The normal fit is intended for screws of relatively long length or for assemblies involving two or more screws where the mating holes are to be produced by conventional tolerancing methods. It provides for the maximum allowable eccentricity of the longest standard screws and for certain variations in the parts to be fastened, such as: deviations in hole straightness, angularity between the axis of the tapped hole and that of the hole for the shank, differences in center distances of the mating holes, etc.

All dimensions in inches.

Source: Appendix to American National Standard ANSI/ASME B18.3-1998.

**Table 6. American National Standard Hexagon and Spline Socket Flat Countersunk Head Cap Screws ANSI/ASME B18.3-1998**

| Nominal Size | Body Diameter |        | Head Diameter     |           | Head-Height Reference | Spline Socket Size | Hexagon Socket Size | Key Engagement |
|--------------|---------------|--------|-------------------|-----------|-----------------------|--------------------|---------------------|----------------|
|              |               |        | Theoretical Sharp | Abs. Min. |                       |                    |                     |                |
|              | Max.          | Min.   | Max.              | Min.      | <i>M</i>              | Nom.               | Min.                |                |
|              | <i>D</i>      |        | <i>A</i>          | <i>H</i>  |                       | <i>J</i>           | <i>T</i>            |                |
| 0            | 0.0600        | 0.0568 | 0.138             | 0.117     | 0.044                 | 0.048              | 0.035               | 0.025          |
| 1            | 0.0730        | 0.0695 | 0.168             | 0.143     | 0.054                 | 0.060              | 0.050               | 0.031          |
| 2            | 0.0860        | 0.0822 | 0.197             | 0.168     | 0.064                 | 0.060              | 0.050               | 0.038          |
| 3            | 0.0990        | 0.0949 | 0.226             | 0.193     | 0.073                 | 0.072              | 1/16                | 0.044          |
| 4            | 0.1120        | 0.1075 | 0.255             | 0.218     | 0.083                 | 0.072              | 1/16                | 0.055          |
| 5            | 0.1250        | 0.1202 | 0.281             | 0.240     | 0.090                 | 0.096              | 5/64                | 0.061          |
| 6            | 0.1380        | 0.1329 | 0.307             | 0.263     | 0.097                 | 0.096              | 3/64                | 0.066          |
| 8            | 0.1640        | 0.1585 | 0.359             | 0.311     | 0.112                 | 0.111              | 3/32                | 0.076          |
| 10           | 0.1900        | 0.1840 | 0.411             | 0.359     | 0.127                 | 0.145              | 1/8                 | 0.087          |
| 1/4          | 0.2500        | 0.2435 | 0.531             | 0.480     | 0.161                 | 0.183              | 5/32                | 0.111          |
| 5/16         | 0.3125        | 0.3053 | 0.656             | 0.600     | 0.198                 | 0.216              | 3/16                | 0.135          |
| 3/8          | 0.3750        | 0.3678 | 0.781             | 0.720     | 0.234                 | 0.251              | 7/32                | 0.159          |
| 7/16         | 0.4375        | 0.4294 | 0.844             | 0.781     | 0.234                 | 0.291              | 1/4                 | 0.159          |
| 1/2          | 0.5000        | 0.4919 | 0.938             | 0.872     | 0.251                 | 0.372              | 5/16                | 0.172          |
| 5/8          | 0.6250        | 0.6163 | 1.188             | 1.112     | 0.324                 | 0.454              | 3/8                 | 0.220          |
| 3/4          | 0.7500        | 0.7406 | 1.438             | 1.355     | 0.396                 | 0.454              | 1/2                 | 0.220          |
| 7/8          | 0.8750        | 0.8647 | 1.688             | 1.604     | 0.468                 | ...                | 5/8                 | 0.248          |
| 1            | 1.0000        | 0.9886 | 1.938             | 1.841     | 0.540                 | ...                | 3/4                 | 0.297          |
| 1 1/8        | 1.1250        | 1.1086 | 2.188             | 2.079     | 0.611                 | ...                | 7/8                 | 0.325          |
| 1 1/4        | 1.2500        | 1.2336 | 2.438             | 2.316     | 0.683                 | ...                | 1                   | 0.358          |
| 1 3/8        | 1.3750        | 1.3568 | 2.688             | 2.553     | 0.755                 | ...                | 1                   | 0.402          |
| 1 1/2        | 1.5000        | 1.4818 | 2.938             | 2.791     | 0.827                 | ...                | 1                   | 0.435          |

All dimensions in inches.

The body of the screw is the unthreaded cylindrical portion of the shank where not threaded to the head; the shank being the portion of the screw from the point of juncture of the conical bearing surface and the body to the flat of the point. The length of thread  $L_T$  is the distance measured from the extreme point to the last complete (full form) thread.

Standard length increments of No. 0 through 1-inch sizes are as follows: 1/16 inch for nominal screw lengths of 1/8 through 1/4 inch; 1/8 inch for lengths of 1/4 through 1 inch; 1/4 inch for lengths of 1 inch through 3 1/2 inches; 1/2 inch for lengths of 3 1/2 through 7 inches; and 1 inch for lengths of 7 through 10 inches, incl. For screw sizes over 1 inch, length increments are: 1/2 inch for nominal screw lengths of 1 inch through 7 inches; 1 inch for lengths of 7 through 10 inches; and 2 inches for lengths over 10 inches.

Threads shall be Unified external threads with radius root; Class 3A UNRC and UNRF series for sizes No. 0 through 1 inch and Class 2A UNRC and UNRF series for sizes over 1 inch to 1 1/2 inches, incl.

For manufacturing details not shown, including materials, see American National Standard ANSI/ASME B18.3-1998 Socket dimensions are given in [Table 11](#).

**Table 7. American National Standard Hexagon Socket and Spline Socket Button Head Cap Screws ANSI/ASME B18.3-1998**

| Nominal Size | Screw Diameter | Head Diameter |       | Head Height |       | Head Side Height | Spline Socket Size <sup>a</sup> | Hexagon Socket Size <sup>a</sup> | Standard Length |
|--------------|----------------|---------------|-------|-------------|-------|------------------|---------------------------------|----------------------------------|-----------------|
|              | Basic          | Max.          | Min.  | Max.        | Min.  | Ref.             | Nom.                            | Nom.                             | Max.            |
|              | <i>D</i>       | <i>A</i>      |       | <i>H</i>    |       | <i>S</i>         | <i>M</i>                        | <i>J</i>                         | <i>L</i>        |
| 0            | 0.0600         | 0.114         | 0.104 | 0.032       | 0.026 | 0.010            | 0.048                           | 0.035                            | ½               |
| 1            | 0.0730         | 0.139         | 0.129 | 0.039       | 0.033 | 0.010            | 0.060                           | 0.050                            | ½               |
| 2            | 0.0860         | 0.164         | 0.154 | 0.046       | 0.038 | 0.010            | 0.060                           | 0.050                            | ½               |
| 3            | 0.0990         | 0.188         | 0.176 | 0.052       | 0.044 | 0.010            | 0.072                           | ⅛                                | ½               |
| 4            | 0.1120         | 0.213         | 0.201 | 0.059       | 0.051 | 0.015            | 0.072                           | ⅛                                | ½               |
| 5            | 0.1250         | 0.238         | 0.226 | 0.066       | 0.058 | 0.015            | 0.096                           | ⅜                                | ½               |
| 6            | 0.1380         | 0.262         | 0.250 | 0.073       | 0.063 | 0.015            | 0.096                           | ⅜                                | ⅝               |
| 8            | 0.1640         | 0.312         | 0.298 | 0.087       | 0.077 | 0.015            | 0.111                           | ⅜                                | ¾               |
| 10           | 0.1900         | 0.361         | 0.347 | 0.101       | 0.091 | 0.020            | 0.145                           | ⅜                                | 1               |
| ¼            | 0.2500         | 0.437         | 0.419 | 0.132       | 0.122 | 0.031            | 0.183                           | ⅜                                | 1               |
| ⅜            | 0.3125         | 0.547         | 0.527 | 0.166       | 0.152 | 0.031            | 0.216                           | ⅜                                | 1               |
| ½            | 0.3750         | 0.656         | 0.636 | 0.199       | 0.185 | 0.031            | 0.251                           | ⅜                                | 1¼              |
| ⅝            | 0.5000         | 0.875         | 0.851 | 0.265       | 0.245 | 0.046            | 0.372                           | ⅜                                | 2               |
| ¾            | 0.6250         | 1.000         | 0.970 | 0.331       | 0.311 | 0.062            | 0.454                           | ⅜                                | 2               |

<sup>a</sup> Socket dimensions are given in Table 11.

All dimensions in inches.

These cap screws have been designed and recommended for light fastening applications. They are not suggested for use in critical high-strength applications where socket head cap screws should normally be used.

Standard length increments for socket button head cap screws are as follows: ⅛ inch for nominal screw lengths of ⅛ through ¼ inch, ⅜ inch for nominal screw lengths of ¼ through 1 inch, and ¼ inch for nominal screw lengths of 1 inch through 2 inches. Tolerances on lengths are -0.03 inch for lengths up to 1 inch inclusive. For lengths from 1 through 2 inches, inclusive, length tolerances are -0.04 inch.

The thread conforms to the Unified standard, Class 3A, with radius root, UNRC and UNRF.

To prevent interference, American National Standard ANSI/ASME B18.3.4M-1986 gives metric dimensional and general requirements for a lower head profile hexagon socket button head cap screw. Because of its design, wrenchability and other design factors are reduced; therefore, B18.3.4M should be reviewed carefully. Available only in metric sizes and with metric threads.

For manufacturing details, including materials, not shown, see American National Standard ANSI/ASME B18.3-1998

**Table 8. American National Standard Hexagon Socket Head Shoulder Screws  
ANSI/ASME B18.3-1998**

| Nominal Size | Shoulder Diameter |        | Head Diameter |       | Head Height |       | Head Side Height | Nominal Thread Size | Thread Length |
|--------------|-------------------|--------|---------------|-------|-------------|-------|------------------|---------------------|---------------|
|              | Max.              | Min.   | Max.          | Min.  | Max.        | Min.  | Min.             |                     |               |
|              | D                 |        | A             |       | H           |       | S                | D <sub>1</sub>      | E             |
| 1/4          | 0.2480            | 0.2460 | 0.375         | 0.357 | 0.188       | 0.177 | 0.157            | 10-24               | 0.375         |
| 5/16         | 0.3105            | 0.3085 | 0.438         | 0.419 | 0.219       | 0.209 | 0.183            | 1/2-20              | 0.438         |
| 3/8          | 0.3730            | 0.3710 | 0.562         | 0.543 | 0.250       | 0.240 | 0.209            | 5/16-18             | 0.500         |
| 1/2          | 0.4980            | 0.4960 | 0.750         | 0.729 | 0.312       | 0.302 | 0.262            | 3/8-16              | 0.625         |
| 5/8          | 0.6230            | 0.6210 | 0.875         | 0.853 | 0.375       | 0.365 | 0.315            | 1/2-13              | 0.750         |
| 3/4          | 0.7480            | 0.7460 | 1.000         | 0.977 | 0.500       | 0.490 | 0.421            | 5/8-11              | 0.875         |
| 1            | 0.9980            | 0.9960 | 1.312         | 1.287 | 0.625       | 0.610 | 0.527            | 3/4-10              | 1.000         |
| 1 1/4        | 1.2480            | 1.2460 | 1.750         | 1.723 | 0.750       | 0.735 | 0.633            | 7/8-9               | 1.125         |
| 1 1/2        | 1.4980            | 1.4960 | 2.125         | 2.095 | 1.000       | 0.980 | 0.842            | 1 1/8-7             | 1.500         |
| 1 3/4        | 1.7480            | 1.7460 | 2.375         | 2.345 | 1.125       | 1.105 | 0.948            | 1 1/4-7             | 1.750         |
| 2            | 1.9980            | 1.9960 | 2.750         | 2.720 | 1.250       | 1.230 | 1.054            | 1 1/2-6             | 2.000         |

| Nominal Size | Thread Neck Diameter |       | Thread Neck Width | Shoulder Neck Dia. | Shoulder Neck Width | Thread Neck Fillet |       | Head Fillet Extension Above D | Hexagon Socket Size |
|--------------|----------------------|-------|-------------------|--------------------|---------------------|--------------------|-------|-------------------------------|---------------------|
|              | Max.                 | Min.  | Max.              | Min.               | Max.                | Max.               | Min.  | Max.                          | Nom.                |
|              | G                    |       | I                 | K                  | F                   | N                  |       | M                             | J                   |
| 1/4          | 0.142                | 0.133 | 0.083             | 0.227              | 0.093               | 0.023              | 0.017 | 0.014                         | 1/8                 |
| 5/16         | 0.193                | 0.182 | 0.100             | 0.289              | 0.093               | 0.028              | 0.022 | 0.017                         | 5/32                |
| 3/8          | 0.249                | 0.237 | 0.111             | 0.352              | 0.093               | 0.031              | 0.025 | 0.020                         | 3/16                |
| 1/2          | 0.304                | 0.291 | 0.125             | 0.477              | 0.093               | 0.035              | 0.029 | 0.026                         | 1/4                 |
| 5/8          | 0.414                | 0.397 | 0.154             | 0.602              | 0.093               | 0.042              | 0.036 | 0.032                         | 5/16                |
| 3/4          | 0.521                | 0.502 | 0.182             | 0.727              | 0.093               | 0.051              | 0.045 | 0.039                         | 3/8                 |
| 1            | 0.638                | 0.616 | 0.200             | 0.977              | 0.125               | 0.055              | 0.049 | 0.050                         | 1/2                 |
| 1 1/4        | 0.750                | 0.726 | 0.222             | 1.227              | 0.125               | 0.062              | 0.056 | 0.060                         | 5/8                 |
| 1 1/2        | 0.964                | 0.934 | 0.286             | 1.478              | 0.125               | 0.072              | 0.066 | 0.070                         | 7/8                 |
| 1 3/4        | 1.089                | 1.059 | 0.286             | 1.728              | 0.125               | 0.072              | 0.066 | 0.080                         | 1                   |
| 2            | 1.307                | 1.277 | 0.333             | 1.978              | 0.125               | 0.102              | 0.096 | 0.090                         | 1 1/4               |

All dimensions are in inches. The shoulder is the enlarged, unthreaded portion of the screw. Standard length increments for shoulder screws are: 1/8 inch for nominal screw lengths of 1/4 through 3/4 inch; 1/4 inch for lengths above 3/4 through 5 inches; and 1/2 inch for lengths over 5 inches. The thread conforms to the Unified Standard Class 3A, UNC. Hexagon socket sizes for the respective shoulder screw sizes are the same as for set screws of the same nominal size (see Table 7) except for shoulder screw size 1 inch, socket size is 1/2 inch, for screw size 1 1/2 inches, socket size is 7/8 inch, and for screw size 2 inches, socket size is 1 1/4 inches. For details not shown, including materials, see ANSI/ASME B18.3-1998.

**Table 9. American National Standard Slotted Headless Set Screws**  
ANSI/ASME B18.6.2-1998

| Nominal Size <sup>a</sup><br>or Basic<br>Screw<br>Diameter | Slot<br>Width, <i>J</i> |           | Slot<br>Depth, <i>T</i> |           | Cup and<br>Flat Point<br>Dia., <i>C</i> |           | Dog<br>Point<br>Dia., <i>P</i> |      | Point Length  |      |                        |      |
|--|-------------------------|-----------|-------------------------|-----------|---|-----------|--------------------------------|------|---------------|------|------------------------|------|
|  | Max.                    | Min.      | Max.                    | Min.      | Max.                                    | Min.      | Max.                           | Min. | Dog, <i>Q</i> |      | Half<br>Dog, <i>Q1</i> |      |
|  |                         |           |                         |           |   |           |                                |      | Max.          | Min. | Max.                   | Min. |
| 0  | 0.0600                  | .014 .010 | .020 .016               | .033 .027 | .040 .037                               | .032 .028 | .017 .013                      |      |               |      |                        |      |
| 1  | 0.0730                  | .016 .012 | .020 .016               | .040 .033 | .049 .045                               | .040 .036 | .021 .017                      |      |               |      |                        |      |
| 2  | 0.0860                  | .018 .014 | .025 .019               | .047 .039 | .057 .053                               | .046 .042 | .024 .020                      |      |               |      |                        |      |
| 3  | 0.0990                  | .020 .016 | .028 .022               | .054 .045 | .066 .062                               | .052 .048 | .027 .023                      |      |               |      |                        |      |
| 4  | 0.1120                  | .024 .018 | .031 .025               | .061 .051 | .075 .070                               | .058 .054 | .030 .026                      |      |               |      |                        |      |
| 5  | 0.1250                  | .026 .020 | .036 .026               | .067 .057 | .083 .078                               | .063 .057 | .033 .027                      |      |               |      |                        |      |
| 6  | 0.1380                  | .028 .022 | .040 .030               | .074 .064 | .092 .087                               | .073 .067 | .038 .032                      |      |               |      |                        |      |
| 8  | 0.1640                  | .032 .026 | .046 .036               | .087 .076 | .109 .103                               | .083 .077 | .043 .037                      |      |               |      |                        |      |
| 10   | 0.1900                  | .035 .029 | .053 .043               | .102 .088 | .127 .120                               | .095 .085 | .050 .040                      |      |               |      |                        |      |
| 12   | 0.2160                  | .042 .035 | .061 .051               | .115 .101 | .144 .137                               | .115 .105 | .060 .050                      |      |               |      |                        |      |
| ¼  | 0.2500                  | .049 .041 | .068 .058               | .132 .118 | .156 .149                               | .130 .120 | .068 .058                      |      |               |      |                        |      |
| ⅜  | 0.3125                  | .055 .047 | .083 .073               | .172 .156 | .203 .195                               | .161 .151 | .083 .073                      |      |               |      |                        |      |
| ½  | 0.3750                  | .068 .060 | .099 .089               | .212 .194 | .250 .241                               | .193 .183 | .099 .089                      |      |               |      |                        |      |
| ⅝  | 0.4375                  | .076 .068 | .114 .104               | .252 .232 | .297 .287                               | .224 .214 | .114 .104                      |      |               |      |                        |      |
| ¾  | 0.5000                  | .086 .076 | .130 .120               | .291 .270 | .344 .334                               | .255 .245 | .130 .120                      |      |               |      |                        |      |
| ⅞  | 0.5625                  | .096 .086 | .146 .136               | .332 .309 | .391 .379                               | .287 .275 | .146 .134                      |      |               |      |                        |      |
| 1  | 0.6250                  | .107 .097 | .161 .151               | .371 .347 | .469 .456                               | .321 .305 | .164 .148                      |      |               |      |                        |      |
| 1 ¼  | 0.7500                  | .134 .124 | .193 .183               | .450 .425 | .562 .549                               | .383 .367 | .196 .180                      |      |               |      |                        |      |

<sup>a</sup> When specifying a nominal size in decimals a zero preceding the decimal point or any zero in the fourth decimal place is omitted.

All dimensions are in inches.

**Crown Radius, *I*:** The crown radius has the same value as the basic screw diameter to three decimal places.

**Oval Point Radius, *R*:** Values of the oval point radius according to nominal screw size are: For a screw size of 0, a radius of .045; 1, .055; 2, .064; 3, .074; 4, .084; 5, .094; 6, .104; 8, .123; 10, .142; 12, .162; ¼, .188; ⅜, .234; ½, .281; ⅝, .328; ¾, .375; ⅞, .422; 1, .469; and for ¼, .562.

**Cone Point Angle, *Y*:** The cone point angle is 90° ± 2° for the following nominal lengths, or longer, shown according to screw size: For nominal size 0, a length of ⅜; 1, ⅜; 2, ⅞; 3, 1; 4, ⅝; 5, ⅝; 6, ⅝; 8, 1; 10, 1; 12, 1; ¼, 1; ⅜, 1; ½, 1; ⅝, 1; ¾, 1; 1, 1; 1 ¼, 1; 1 ½, 1; 1 ¾, 1; 2, 1; 2 ¼, 1; 2 ½, 1; 2 ¾, 1; 3, 1; 3 ¼, 1; and for ¼, ⅞. For shorter screws, the cone point angle is 118° ± 2°.

**Point Angle *X*:** The point angle is 45°, +5°, -0°, for screws of nominal lengths, or longer, as given just above for cone point angle, and 30°, min. for shorter screws.

**Threads:** are Unified Standard Class 2A; UNC and UNF Series or UNRC and UNRF Series.

**Table 10. American National Standard Hexagon and Spline Socket Set Screw  
Optional Cup Points ANSI/ASME B18.3-1998**

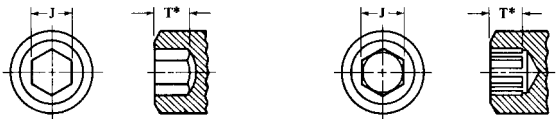
\* This diameter may be counterbored.

| Nom. Size | Point Dia. |       | Point Dia. |       | Point Dia. |       | Point Length |       |
|-----------|------------|-------|------------|-------|------------|-------|--------------|-------|
|           | Max.       | Min.  | Max.       | Min.  | Max.       | Min.  | Max.         | Min.  |
|           | C          |       | C1         |       | C2         |       | S            |       |
| 0         | 0.033      | 0.027 | 0.032      | 0.027 | 0.027      | 0.022 | 0.007        | 0.004 |
| 1         | 0.040      | 0.033 | 0.038      | 0.033 | 0.035      | 0.030 | 0.008        | 0.005 |
| 2         | 0.047      | 0.039 | 0.043      | 0.038 | 0.043      | 0.038 | 0.010        | 0.007 |
| 3         | 0.054      | 0.045 | 0.050      | 0.045 | 0.051      | 0.046 | 0.011        | 0.007 |
| 4         | 0.061      | 0.051 | 0.056      | 0.051 | 0.059      | 0.054 | 0.013        | 0.008 |
| 5         | 0.067      | 0.057 | 0.062      | 0.056 | 0.068      | 0.063 | 0.014        | 0.009 |
| 6         | 0.074      | 0.064 | 0.069      | 0.062 | 0.074      | 0.068 | 0.017        | 0.012 |
| 8         | 0.087      | 0.076 | 0.082      | 0.074 | 0.090      | 0.084 | 0.021        | 0.016 |
| 10        | 0.102      | 0.088 | 0.095      | 0.086 | 0.101      | 0.095 | 0.024        | 0.019 |
| ¼         | 0.132      | 0.118 | 0.125      | 0.114 | 0.156      | 0.150 | 0.027        | 0.022 |
| ⅜         | 0.172      | 0.156 | 0.156      | 0.144 | 0.190      | 0.185 | 0.038        | 0.033 |
| ½         | 0.212      | 0.194 | 0.187      | 0.174 | 0.241      | 0.236 | 0.041        | 0.036 |
| ⅝         | 0.252      | 0.232 | 0.218      | 0.204 | 0.286      | 0.281 | 0.047        | 0.042 |
| ¾         | 0.291      | 0.270 | 0.250      | 0.235 | 0.333      | 0.328 | 0.054        | 0.049 |
| ⅞         | 0.371      | 0.347 | 0.312      | 0.295 | 0.425      | 0.420 | 0.067        | 0.062 |
| 1         | 0.450      | 0.425 | 0.375      | 0.357 | 0.523      | 0.518 | 0.081        | 0.076 |
| 1 ⅛       | 0.530      | 0.502 | 0.437      | 0.418 | ...        | ...   | ...          | ...   |
| 1 ¼       | 0.609      | 0.579 | 0.500      | 0.480 | ...        | ...   | ...          | ...   |
| 1 ⅝       | 0.689      | 0.655 | 0.562      | 0.542 | ...        | ...   | ...          | ...   |
| 1 ¾       | 0.767      | 0.733 | 0.625      | 0.605 | ...        | ...   | ...          | ...   |
| 1 ⅞       | 0.848      | 0.808 | 0.687      | 0.667 | ...        | ...   | ...          | ...   |
| 1 ½       | 0.926      | 0.886 | 0.750      | 0.730 | ...        | ...   | ...          | ...   |
| 1 ¾       | 1.086      | 1.039 | 0.875      | 0.855 | ...        | ...   | ...          | ...   |
| 2         | 1.244      | 1.193 | 1.000      | 0.980 | ...        | ...   | ...          | ...   |

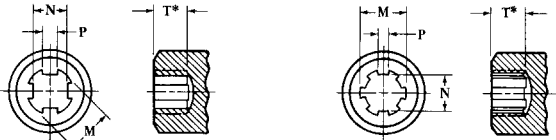
All dimensions are in inches.

The cup point types shown are those available from various manufacturers.

**Table 11. American National Standard Hexagon and Spline Sockets**  
ANSI/ASME B18.3-1998

|  |                           |        |                     |                           |        |                     |                           |        |                     |                           |        |
|---|---------------------------|--------|---------------------|---------------------------|--------|---------------------|---------------------------|--------|---------------------|---------------------------|--------|
| BROACHED SOCKET<br>HEXAGON SOCKETS  |                           |        |                     |                           |        |                     |                           |        |                     |                           |        |
| Nominal Socket Size   | Socket Width Across Flats |        | Nominal Socket Size | Socket Width Across Flats |        | Nominal Socket Size | Socket Width Across Flats |        | Nominal Socket Size | Socket Width Across Flats |        |
|   | Max.                      | Min.   |                     | Max.                      | Min.   |                     | Max.                      | Min.   |                     | Max.                      | Min.   |
|   | J                         |        |                     | J                         |        |                     | J                         |        |                     | J                         |        |
| 0.028   | 0.0285                    | 0.0280 | $\frac{3}{64}$      | 0.1426                    | 0.1406 | $\frac{7}{16}$      | 0.4420                    | 0.4375 | $1\frac{1}{4}$      | 1.2750                    | 1.2500 |
| 0.035   | 0.0355                    | 0.0350 | $\frac{3}{32}$      | 0.1587                    | 0.1562 | $\frac{1}{2}$       | 0.5050                    | 0.5000 | $1\frac{1}{2}$      | 1.5300                    | 1.5000 |
| 0.050   | 0.0510                    | 0.0500 | $\frac{3}{16}$      | 0.1900                    | 0.1875 | $\frac{9}{16}$      | 0.5680                    | 0.5625 | $1\frac{3}{4}$      | 1.7850                    | 1.7500 |
| $\frac{1}{16}$  | 0.0635                    | 0.0625 | $\frac{7}{32}$      | 0.2217                    | 0.2187 | $\frac{5}{8}$       | 0.6310                    | 0.6250 | 2                   | 2.0400                    | 2.0000 |
| $\frac{5}{64}$  | 0.0791                    | 0.0781 | $\frac{1}{4}$       | 0.2530                    | 0.2500 | $\frac{3}{4}$       | 0.7570                    | 0.7500 | $2\frac{1}{4}$      | 2.2950                    | 2.2500 |
| $\frac{3}{32}$  | 0.0952                    | 0.0937 | $\frac{5}{16}$      | 0.3160                    | 0.3125 | $\frac{7}{8}$       | 0.8850                    | 0.8750 | $2\frac{3}{4}$      | 2.8050                    | 2.7500 |
| $\frac{7}{64}$  | 0.1111                    | 0.1094 | $\frac{3}{8}$       | 0.3790                    | 0.3750 | 1                   | 1.0200                    | 1.0000 | 3                   | 3.0600                    | 3.0000 |
| $\frac{1}{8}$   | 0.1270                    | 0.1250 | ...                 | ...                       | ...    | ...                 | ...                       | ...    | ...                 | ...                       | ...    |

|  |                 |                       |        |                       |        |                |        |
|---|-----------------|-----------------------|--------|-----------------------|--------|----------------|--------|
| SPLINE SOCKETS  |                 |                       |        |                       |        |                |        |
| Nominal Socket Size   | Number of Teeth | Socket Major Diameter |        | Socket Minor Diameter |        | Width of Tooth |        |
|   |                 | Max.                  | Min.   | Max.                  | Min.   | Max.           | Min.   |
|   |                 | M                     |        | N                     |        | P              |        |
| 0.033   | 4               | 0.0350                | 0.0340 | 0.0260                | 0.0255 | 0.0120         | 0.0115 |
| 0.048   | 6               | 0.050                 | 0.049  | 0.041                 | 0.040  | 0.011          | 0.010  |
| 0.060   | 6               | 0.062                 | 0.061  | 0.051                 | 0.050  | 0.014          | 0.013  |
| 0.072   | 6               | 0.074                 | 0.073  | 0.064                 | 0.063  | 0.016          | 0.015  |
| 0.096   | 6               | 0.098                 | 0.097  | 0.082                 | 0.080  | 0.022          | 0.021  |
| 0.111   | 6               | 0.115                 | 0.113  | 0.098                 | 0.096  | 0.025          | 0.023  |
| 0.133   | 6               | 0.137                 | 0.135  | 0.118                 | 0.116  | 0.030          | 0.028  |
| 0.145   | 6               | 0.149                 | 0.147  | 0.128                 | 0.126  | 0.032          | 0.030  |
| 0.168   | 6               | 0.173                 | 0.171  | 0.150                 | 0.147  | 0.036          | 0.033  |
| 0.183   | 6               | 0.188                 | 0.186  | 0.163                 | 0.161  | 0.039          | 0.037  |
| 0.216   | 6               | 0.221                 | 0.219  | 0.190                 | 0.188  | 0.050          | 0.048  |
| 0.251   | 6               | 0.256                 | 0.254  | 0.221                 | 0.219  | 0.060          | 0.058  |
| 0.291   | 6               | 0.298                 | 0.296  | 0.254                 | 0.252  | 0.068          | 0.066  |
| 0.372   | 6               | 0.380                 | 0.377  | 0.319                 | 0.316  | 0.092          | 0.089  |
| 0.454   | 6               | 0.463                 | 0.460  | 0.386                 | 0.383  | 0.112          | 0.109  |
| 0.595   | 6               | 0.604                 | 0.601  | 0.509                 | 0.506  | 0.138          | 0.134  |
| 0.620   | 6               | 0.631                 | 0.627  | 0.535                 | 0.531  | 0.149          | 0.145  |
| 0.698   | 6               | 0.709                 | 0.705  | 0.604                 | 0.600  | 0.168          | 0.164  |
| 0.790   | 6               | 0.801                 | 0.797  | 0.685                 | 0.681  | 0.189          | 0.185  |

All dimensions are in inches.

\* Socket depths, T, for various screw types are given in the standard but are not shown here.

Where sockets are chamfered, the depth of chamfer shall not exceed 10 per cent of the nominal socket size for sizes up to and including  $\frac{1}{16}$  inch for hexagon sockets and 0.060 for spline sockets, and 7.5 per cent for larger sizes.



**Table 12. American National Standard Square Head Set Screws**  
ANSI/ASME B18.6.2-1998

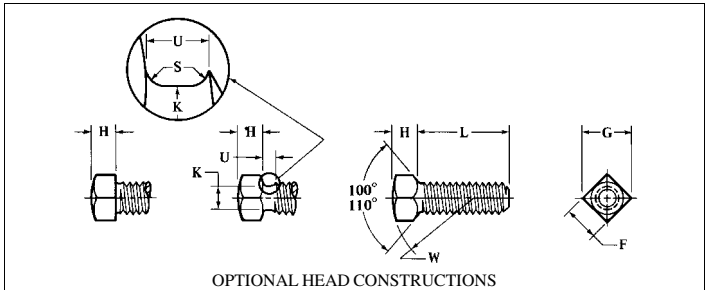
| Nominal Size* or Basic Screw Diameter | Cup and Flat Point Diams., C | Dog and Half Dog Point Diams., P | Point Length |           |              |       | Oval Point Rad., R |
|---------------------------------------|------------------------------|----------------------------------|--------------|-----------|--------------|-------|--------------------|
|                                       |                              |                                  | Dog, Q       |           | Half Dog, Q1 |       |                    |
|                                       |                              |                                  | Max.         | Min.      | Max.         | Min.  |                    |
| 10                                    | 0.1900                       | .102 .088                        | .127 .120    | .095 .085 | .050 .040    | .142  |                    |
| 1/4                                   | 0.2500                       | .132 .118                        | .156 .149    | .130 .120 | .068 .058    | .188  |                    |
| 5/16                                  | 0.3125                       | .172 .156                        | .203 .195    | .161 .151 | .083 .073    | .234  |                    |
| 3/8                                   | 0.3750                       | .212 .194                        | .250 .241    | .193 .183 | .099 .089    | .281  |                    |
| 7/16                                  | 0.4375                       | .252 .232                        | .297 .287    | .224 .214 | .114 .104    | .328  |                    |
| 1/2                                   | 0.500                        | .291 .270                        | .344 .334    | .255 .245 | .130 .120    | .375  |                    |
| 9/16                                  | 0.5625                       | .332 .309                        | .391 .379    | .287 .275 | .146 .134    | .422  |                    |
| 5/8                                   | 0.6250                       | .371 .347                        | .469 .456    | .321 .305 | .164 .148    | .469  |                    |
| 3/4                                   | 0.7500                       | .450 .425                        | .562 .549    | .383 .367 | .196 .180    | .562  |                    |
| 7/8                                   | 0.8750                       | .530 .502                        | .656 .642    | .446 .430 | .227 .211    | .656  |                    |
| 1                                     | 1.0000                       | .609 .579                        | .750 .734    | .510 .490 | .260 .240    | .750  |                    |
| 1 1/8                                 | 1.1250                       | .689 .655                        | .844 .826    | .572 .552 | .291 .271    | .844  |                    |
| 1 1/4                                 | 1.2500                       | .767 .733                        | .938 .920    | .635 .615 | .323 .303    | .938  |                    |
| 1 3/8                                 | 1.3750                       | .848 .808                        | 1.031 1.011  | .698 .678 | .354 .334    | 1.031 |                    |
| 1 1/2                                 | 1.5000                       | .926 .886                        | 1.125 1.105  | .760 .740 | .385 .365    | 1.125 |                    |

All dimensions are in inches.

\*Threads: Threads are Unified Standard Class 2A; UNC, UNF and 8 UN Series or UNRC, UNRF and 8 UNR Series.

**Length of Thread:** Square head set screws have complete (full form) threads extending over that portion of the screw length which is not affected by the point. For the respective constructions, threads extend into the neck relief, to the conical underside of head, or to within one thread (as measured with a thread ring gage) from the flat underside of the head. Threads through angular or crowned portions of points have fully formed roots with partial crests.

\*When specifying a nominal size in decimals, the zero preceding the decimal point is omitted as is any zero in the fourth decimal place.

**Table 13. American National Standard Square Head Set Screws**  
ANSI/ASME B18.6.2-1998

OPTIONAL HEAD CONSTRUCTIONS

| Nominal<br>Size or Basic<br>Screw Diameter | Width Across<br>Flats, <i>F</i> |       | Width Across<br>Corners, <i>G</i> |       | Head Height,<br><i>H</i> |       | Neck Relief<br>Diameter, <i>K</i> |       | Neck<br>Relief<br>Fillet<br>Rad., <i>S</i> |      | Neck<br>Relief<br>Width, <i>U</i> |      | Head<br>Rad., <i>W</i> |
|--|---------------------------------|-------|-----------------------------------|-------|--------------------------|-------|-----------------------------------|-------|--|------|-----------------------------------|------|------------------------|
|  | Max.                            | Min.  | Max.                              | Min.  | Max.                     | Min.  | Max.                              | Min.  | Max.                                       | Min. | Min.                              |      |                        |
| 10   | 0.1900                          | .188  | .180                              | .265  | .247                     | .148  | .134                              | .145  | .140                                       | .027 | .083                              | 0.48 |                        |
| $\frac{1}{4}$                              | 0.2500                          | .250  | .241                              | .354  | .331                     | .196  | .178                              | .185  | .170                                       | .032 | .100                              | 0.62 |                        |
| $\frac{5}{16}$                             | 0.3125                          | .312  | .302                              | .442  | .415                     | .245  | .224                              | .240  | .225                                       | .036 | .111                              | 0.78 |                        |
| $\frac{3}{8}$                              | 0.3750                          | .375  | .362                              | .530  | .497                     | .293  | .270                              | .294  | .279                                       | .041 | .125                              | 0.94 |                        |
| $\frac{7}{16}$                             | 0.4375                          | .438  | .423                              | .619  | .581                     | .341  | .315                              | .345  | .330                                       | .046 | .143                              | 1.09 |                        |
| $\frac{1}{2}$                              | 0.5000                          | .500  | .484                              | .707  | .665                     | .389  | .361                              | .400  | .385                                       | .050 | .154                              | 1.25 |                        |
| $\frac{9}{16}$                             | 0.5625                          | .562  | .545                              | .795  | .748                     | .437  | .407                              | .454  | .439                                       | .054 | .167                              | 1.41 |                        |
| $\frac{5}{8}$                              | 0.6250                          | .625  | .606                              | .884  | .833                     | .485  | .452                              | .507  | .492                                       | .059 | .182                              | 1.56 |                        |
| $\frac{3}{4}$                              | 0.7500                          | .750  | .729                              | 1.060 | 1.001                    | .582  | .544                              | .620  | .605                                       | .065 | .200                              | 1.88 |                        |
| $\frac{7}{8}$                              | 0.8750                          | .875  | .852                              | 1.237 | 1.170                    | .678  | .635                              | .731  | .716                                       | .072 | .222                              | 2.19 |                        |
| 1  | 1.0000                          | 1.000 | .974                              | 1.414 | 1.337                    | .774  | .726                              | .838  | .823                                       | .081 | .250                              | 2.50 |                        |
| $1\frac{1}{8}$                             | 1.1250                          | 1.125 | 1.096                             | 1.591 | 1.505                    | .870  | .817                              | .939  | .914                                       | .092 | .283                              | 2.81 |                        |
| $1\frac{1}{4}$                             | 1.2500                          | 1.250 | 1.219                             | 1.768 | 1.674                    | .966  | .908                              | 1.064 | 1.039                                      | .092 | .283                              | 3.12 |                        |
| $1\frac{3}{8}$                             | 1.3750                          | 1.375 | 1.342                             | 1.945 | 1.843                    | 1.063 | 1.000                             | 1.159 | 1.134                                      | .109 | .333                              | 3.44 |                        |
| $1\frac{1}{2}$                             | 1.5000                          | 1.500 | 1.464                             | 2.121 | 2.010                    | 1.159 | 1.091                             | 1.284 | 1.259                                      | .109 | .333                              | 3.75 |                        |

**Designation:** Square head set screws are designated by the following data in the sequence shown: Nominal size (number, fraction or decimal equivalent); threads per inch; screw length (fraction or decimal equivalent); product name; point style; material; and protective finish, if required. Examples:  $\frac{1}{4}$  - 20  $\times$   $\frac{3}{4}$  Square Head Set Screw, Flat Point, Steel, Cadmium Plated. .500 - 13  $\times$  1.25 Square Head Set Screw, Cone Point, Corrosion Resistant Steel.

**Cone Point Angle, *Y*:** For the following nominal lengths, or longer, shown according to nominal size, the cone point angle is  $90^\circ \pm 2^\circ$ : For size No. 10,  $\frac{1}{4}$ ,  $\frac{1}{4}$ ,  $\frac{5}{16}$ ,  $\frac{5}{16}$ ,  $\frac{3}{8}$ ,  $\frac{3}{8}$ ,  $\frac{7}{16}$ ,  $\frac{7}{16}$ ,  $\frac{1}{2}$ ,  $\frac{1}{2}$ ,  $\frac{9}{16}$ ,  $\frac{9}{16}$ ,  $\frac{5}{8}$ ,  $\frac{5}{8}$ ,  $\frac{3}{4}$ ,  $\frac{3}{4}$ ,  $\frac{7}{8}$ ,  $\frac{7}{8}$ ; 1; 1,  $1\frac{1}{8}$ ,  $1\frac{1}{8}$ ,  $1\frac{1}{4}$ ,  $1\frac{1}{4}$ ,  $1\frac{1}{2}$ ,  $1\frac{3}{8}$ ,  $1\frac{5}{8}$ ; and for  $1\frac{1}{2}$ ,  $1\frac{3}{4}$ . For shorter screws the cone point angle is  $118^\circ \pm 2^\circ$ .

**Point Types:** Unless otherwise specified, square head set screws are supplied with cup points. Cup points as furnished by some manufacturers may be externally or internally knurled. Where so specified by the purchaser, screws have cone, dog, half-dog, flat or oval points as given on the following page.

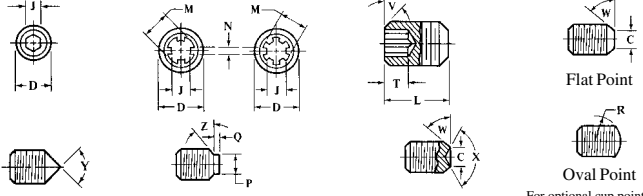
**Point Angle, *X*:** The point angle is  $45^\circ$ ,  $+5^\circ$ ,  $-0^\circ$  for screws of the nominal lengths, or longer, given just above for cone point angle, and  $30^\circ$  min. for shorter lengths.

**Table 14. Applicability of Hexagon and Spline Keys and Bits**

| Nominal Key or Bit Size      | Cap Screws 1960 Series          | Flat Countersunk Head Cap Screws | Button Head Cap Screws | Shoulder Screws | Set Screws                      |
|------------------------------|---------------------------------|----------------------------------|------------------------|-----------------|---------------------------------|
|                              | Nominal Screw Sizes             |                                  |                        |                 |                                 |
| <b>HEXAGON KEYS AND BITS</b> |                                 |                                  |                        |                 |                                 |
| 0.028                        | ...                             | ...                              | ...                    | ...             | 0                               |
| 0.035                        | ...                             | 0                                | 0                      | ...             | 1 & 2                           |
| 0.050                        | 0                               | 1 & 2                            | 1 & 2                  | ...             | 3 & 4                           |
| $\frac{1}{16}$ 0.062         | 1                               | 3 & 4                            | 3 & 4                  | ...             | 5 & 6                           |
| $\frac{3}{64}$ 0.078         | 2 & 3                           | 5 & 6                            | 5 & 6                  | ...             | 8                               |
| $\frac{3}{32}$ 0.094         | 4 & 5                           | 8                                | 8                      | ...             | 10                              |
| $\frac{7}{64}$ 0.109         | 6                               | ...                              | ...                    | ...             | ...                             |
| $\frac{1}{8}$ 0.125          | ...                             | 10                               | 10                     | $\frac{1}{4}$   | $\frac{1}{4}$                   |
| $\frac{9}{64}$ 0.141         | 8                               | ...                              | ...                    | ...             | ...                             |
| $\frac{5}{32}$ 0.156         | 10                              | $\frac{1}{4}$                    | $\frac{1}{4}$          | $\frac{3}{16}$  | $\frac{3}{16}$                  |
| $\frac{7}{16}$ 0.188         | $\frac{1}{4}$                   | $\frac{3}{8}$                    | $\frac{3}{8}$          | $\frac{3}{8}$   | $\frac{3}{8}$                   |
| $\frac{7}{32}$ 0.219         | ...                             | $\frac{3}{8}$                    | $\frac{3}{8}$          | ...             | $\frac{7}{16}$                  |
| $\frac{1}{4}$ 0.250          | $\frac{3}{16}$                  | $\frac{7}{16}$                   | ...                    | $\frac{1}{2}$   | $\frac{1}{2}$                   |
| $\frac{5}{16}$ 0.312         | $\frac{3}{8}$                   | $\frac{1}{2}$                    | $\frac{1}{2}$          | $\frac{5}{8}$   | $\frac{5}{8}$                   |
| $\frac{3}{8}$ 0.375          | $\frac{7}{16}$ & $\frac{1}{2}$  | $\frac{5}{8}$                    | $\frac{5}{8}$          | $\frac{3}{4}$   | $\frac{3}{4}$                   |
| $\frac{7}{16}$ 0.438         | ...                             | ...                              | ...                    | ...             | ...                             |
| $\frac{1}{2}$ 0.500          | $\frac{5}{8}$                   | $\frac{3}{4}$                    | ...                    | 1               | $\frac{7}{8}$                   |
| $\frac{9}{16}$ 0.562         | ...                             | $\frac{7}{8}$                    | ...                    | ...             | 1 & $1\frac{1}{8}$              |
| $\frac{5}{8}$ 0.625          | $\frac{3}{4}$                   | 1                                | ...                    | $1\frac{1}{4}$  | $1\frac{1}{4}$ & $1\frac{3}{8}$ |
| $\frac{3}{4}$ 0.750          | $\frac{7}{8}$ & 1               | $1\frac{1}{8}$                   | ...                    | ...             | $1\frac{1}{2}$                  |
| $\frac{7}{8}$ 0.875          | $1\frac{1}{8}$ & $1\frac{1}{4}$ | $1\frac{1}{4}$ & $1\frac{3}{8}$  | ...                    | $1\frac{1}{2}$  | ...                             |
| 1 1.000                      | $1\frac{3}{8}$ & $1\frac{1}{2}$ | $1\frac{1}{2}$                   | ...                    | $1\frac{3}{4}$  | $1\frac{3}{4}$ & 2              |
| $1\frac{1}{4}$ 1.250         | $1\frac{3}{4}$                  | ...                              | ...                    | 2               | ...                             |
| $1\frac{1}{2}$ 1.500         | 2                               | ...                              | ...                    | ...             | ...                             |
| $1\frac{3}{4}$ 1.750         | $2\frac{1}{4}$ & $2\frac{1}{2}$ | ...                              | ...                    | ...             | ...                             |
| 2 2.000                      | $2\frac{3}{4}$                  | ...                              | ...                    | ...             | ...                             |
| $2\frac{1}{4}$ 2.250         | 3 & $3\frac{1}{4}$              | ...                              | ...                    | ...             | ...                             |
| $2\frac{3}{4}$ 2.750         | $3\frac{1}{2}$ & $3\frac{3}{4}$ | ...                              | ...                    | ...             | ...                             |
| 3 3.000                      | 4                               | ...                              | ...                    | ...             | ...                             |
| <b>SPLINE KEYS AND BITS</b>  |                                 |                                  |                        |                 |                                 |
| 0.033                        | ...                             | ...                              | ...                    | ...             | 0 & 1                           |
| 0.048                        | ...                             | 0                                | 0                      | ...             | 2 & 3                           |
| 0.060                        | 0                               | 1 & 2                            | 1 & 2                  | ...             | 4                               |
| 0.072                        | 1                               | 3 & 4                            | 3 & 4                  | ...             | 5 & 6                           |
| 0.096                        | 2 & 3                           | 5 & 6                            | 5 & 6                  | ...             | 8                               |
| 0.111                        | 4 & 5                           | 8                                | 8                      | ...             | 10                              |
| 0.133                        | 6                               | ...                              | ...                    | ...             | ...                             |
| 0.145                        | ...                             | 10                               | 10                     | ...             | $\frac{1}{4}$                   |
| 0.168                        | 8                               | ...                              | ...                    | ...             | ...                             |
| 0.183                        | 10                              | $\frac{1}{4}$                    | $\frac{1}{4}$          | ...             | $\frac{3}{16}$                  |
| 0.216                        | $\frac{1}{4}$                   | $\frac{3}{8}$                    | $\frac{3}{8}$          | ...             | $\frac{3}{8}$                   |
| 0.251                        | ...                             | $\frac{3}{8}$                    | $\frac{3}{8}$          | ...             | $\frac{7}{16}$                  |
| 0.291                        | $\frac{3}{16}$                  | $\frac{7}{16}$                   | ...                    | ...             | $\frac{1}{2}$                   |
| 0.372                        | $\frac{3}{8}$                   | $\frac{1}{2}$                    | $\frac{1}{2}$          | ...             | $\frac{5}{8}$                   |
| 0.454                        | $\frac{7}{16}$ & $\frac{1}{2}$  | $\frac{5}{8}$ & $\frac{3}{4}$    | $\frac{5}{8}$          | ...             | $\frac{3}{4}$                   |
| 0.595                        | $\frac{5}{8}$                   | ...                              | ...                    | ...             | $\frac{7}{8}$                   |
| 0.620                        | $\frac{3}{4}$                   | ...                              | ...                    | ...             | ...                             |
| 0.698                        | $\frac{7}{8}$                   | ...                              | ...                    | ...             | ...                             |
| 0.790                        | 1                               | ...                              | ...                    | ...             | ...                             |

Source: Appendix to American National Standard ANSI/ASME B18.3-1998.

**Table 15. ANSI Hexagon and Spline Socket Set Screws ANSI/ASME B18.3-1998**



| Nominal Size or Basic Screw Diameter | Socket Size |           | Cup and Flat Point Diameters |       | Half Dog Point |            | Oval Point Radius | Min. Key Engagement Depth |              | Lgth. Limit for Angle |
|--------------------------------------|-------------|-----------|------------------------------|-------|----------------|------------|-------------------|---------------------------|--------------|-----------------------|
|                                      | Hex. Nom.   | Spl. Nom. | Max.                         | Min.  | Dia. Max.      | Lgth. Max. | Basic             | Hex. $T_H^a$              | Spl. $T_S^a$ |                       |
|                                      | <i>J</i>    | <i>M</i>  | <i>C</i>                     |       | <i>P</i>       | <i>Q</i>   | <i>R</i>          |                           |              |                       |
|                                      |             |           |                              |       |                |            |                   |                           |              |                       |
| 0                                    | 0.0600      | 0.028     | 0.033                        | 0.027 | 0.040          | 0.017      | 0.045             | 0.050                     | 0.026        | 0.09                  |
| 1                                    | 0.0730      | 0.035     | 0.033                        | 0.040 | 0.049          | 0.021      | 0.055             | 0.060                     | 0.035        | 0.09                  |
| 2                                    | 0.0860      | 0.035     | 0.048                        | 0.047 | 0.057          | 0.024      | 0.064             | 0.060                     | 0.040        | 0.13                  |
| 3                                    | 0.0990      | 0.050     | 0.048                        | 0.054 | 0.066          | 0.027      | 0.074             | 0.070                     | 0.040        | 0.13                  |
| 4                                    | 0.1120      | 0.050     | 0.060                        | 0.061 | 0.075          | 0.030      | 0.084             | 0.070                     | 0.045        | 0.19                  |
| 5                                    | 0.1250      | 1/16      | 0.072                        | 0.067 | 0.083          | 0.033      | 0.094             | 0.080                     | 0.055        | 0.19                  |
| 6                                    | 0.1380      | 1/16      | 0.072                        | 0.074 | 0.092          | 0.038      | 0.104             | 0.080                     | 0.055        | 0.19                  |
| 8                                    | 0.1640      | 5/64      | 0.096                        | 0.087 | 0.109          | 0.043      | 0.123             | 0.090                     | 0.080        | 0.25                  |
| 10                                   | 0.1900      | 3/32      | 0.111                        | 0.102 | 0.127          | 0.049      | 0.142             | 0.100                     | 0.080        | 0.25                  |
| 1/4                                  | 0.2500      | 1/8       | 0.145                        | 0.132 | 0.118          | 0.156      | 0.188             | 0.125                     | 0.125        | 0.31                  |
| 3/16                                 | 0.3125      | 3/32      | 0.183                        | 0.172 | 0.156          | 0.203      | 0.234             | 0.156                     | 0.156        | 0.38                  |
| 3/8                                  | 0.3750      | 3/16      | 0.216                        | 0.212 | 0.194          | 0.250      | 0.281             | 0.188                     | 0.188        | 0.44                  |
| 7/16                                 | 0.4375      | 7/32      | 0.251                        | 0.252 | 0.232          | 0.297      | 0.328             | 0.219                     | 0.219        | 0.50                  |
| 1/2                                  | 0.5000      | 1/4       | 0.291                        | 0.291 | 0.270          | 0.344      | 0.375             | 0.250                     | 0.250        | 0.57                  |
| 5/8                                  | 0.6250      | 5/16      | 0.372                        | 0.371 | 0.347          | 0.469      | 0.469             | 0.312                     | 0.312        | 0.75                  |
| 3/4                                  | 0.7500      | 3/8       | 0.454                        | 0.450 | 0.425          | 0.562      | 0.562             | 0.375                     | 0.375        | 0.88                  |
| 7/8                                  | 0.8750      | 1/2       | 0.595                        | 0.530 | 0.502          | 0.656      | 0.656             | 0.500                     | 0.500        | 1.00                  |
| 1                                    | 1.0000      | 9/16      | ...                          | 0.609 | 0.579          | 0.750      | 0.750             | 0.562                     | ...          | 1.13                  |
| 1 1/8                                | 1.1250      | 11/16     | ...                          | 0.689 | 0.655          | 0.844      | 0.844             | 0.562                     | ...          | 1.25                  |
| 1 1/4                                | 1.2500      | 5/8       | ...                          | 0.767 | 0.733          | 0.938      | 0.938             | 0.625                     | ...          | 1.50                  |
| 1 3/8                                | 1.3750      | 3/4       | ...                          | 0.848 | 0.808          | 1.031      | 1.031             | 0.625                     | ...          | 1.63                  |
| 1 1/2                                | 1.5000      | 3/4       | ...                          | 0.926 | 0.886          | 1.125      | 1.125             | 0.750                     | ...          | 1.75                  |
| 1 3/4                                | 1.7500      | 1         | ...                          | 1.086 | 1.039          | 1.312      | 1.321             | 1.000                     | ...          | 2.00                  |
| 2                                    | 2.0000      | 1         | ...                          | 1.244 | 1.193          | 1.500      | 1.510             | 1.500                     | ...          | 2.25                  |

For optional cup points and their dimensions see Table 10.

<sup>a</sup> Reference should be made to the Standard for shortest optimum nominal lengths to which the minimum key engagement depths  $T_H$  and  $T_S$  apply.

<sup>b</sup> Cone point angle  $Y$  is 90 degrees plus or minus 2 degrees for these nominal lengths or longer and 118 degrees plus or minus 2 degrees for shorter nominal lengths.

All dimensions are in inches. The thread conforms to the Unified Standard, Class 3A, UNC and UNF series. The socket depth  $T$  is included in the Standard and some are shown here. The nominal length  $L$  of all socket type set screws is the total or overall length. For nominal screw lengths of 1/16 through 3/16 inch (0 through 3 sizes incl.) the standard length increment is 0.06 inch; for lengths 1/8 through 1 inch the increment is 1/8 inch; for lengths 1 through 2 inches the increment is 1/4 inch; for lengths 2 through 6 inches the increment is 1/2 inch; for lengths 6 inches and longer the increment is 1 inch. Socket dimensions are given in Table 11.

Length Tolerance: The allowable tolerance on length  $L$  for all set screws of the socket type is  $\pm 0.01$  inch for set screws up to 5/8 inch long;  $\pm 0.02$  inch for screws over 5/8 to 2 inches long;  $\pm 0.03$  inch for screws over 2 to 6 inches long and  $\pm 0.06$  inch for screws over 6 inches long. Socket dimensions are given in Table 11.

For manufacturing details, including materials, not shown, see American National Standard ANSI/ASME B18.3-1998.

**British Standard Hexagon Socket Screws — Metric Series.**—The first five parts of British Standard BS 4168: 1981 provide specifications for hexagon socket head cap screws and hexagon socket set screws.

*Hexagon Socket Head Cap Screws:* The dimensional data in [Table 1](#) are based upon BS 4168: Part 1: 1981. These screws are available in stainless steel and alloy steel, the latter having class 12.9 properties as specified in BS 6104:Part 1. When ordering these screws, the designation “Hexagon socket head cap screw BS 4168 M5 × 20-12.9” would mean, as an example, a cap screw having a thread size of  $d = M5$ , nominal length  $l = 20$  mm, and property class 12.9. Alloy steel cap screws are furnished with a black oxide finish (thermal or chemical); stainless steel cap screws with a plain finish. Combinations of thread size, nominal length, and length of thread are shown in [Table 2](#); the screw threads in these combinations are in the ISO metric coarse pitch series specified in BS 3643 with tolerances in the 5g6g class. (See Metric Screw Threads in Index.)

*Hexagon Socket Set Screws:* Part 2 of B.S. 4168:1981 specifies requirements for hexagon socket set screws with flat point having ISO metric threads, and diameters from 1.6 mm up to and including 24 mm. The dimensions of these set screws along with those of cone-point, dog-point, and cup-point set screws in accord, respectively, with Parts 3, 4, and 5 of the Standard are given in [Table 3](#) and the accompanying illustration. All of these set screws are available in either steel processed to mechanical properties class 45H B.S. 6104:Part 3; or stainless steel processed to mechanical properties described in B.S. 6105. Steel set screws are furnished with black oxide (thermal or chemical) finish; stainless steel set screws are furnished plain. The tolerances applied to the threads of these set screws are for ISO product grade A, based on ISO 4759/1-1978 “Tolerances for fasteners — Part 1: Bolts, screws, and nuts with thread diameters greater than or equal to 1.6 mm and less than or equal to 150 mm and product grades A, B, and C.”

Hexagon socket set screws are designated by the type, the thread size, nominal length, and property class. As an example, for a flat-point set screw of thread size  $d = M6$ , nominal length  $l = 12$  mm, and property class 45H:

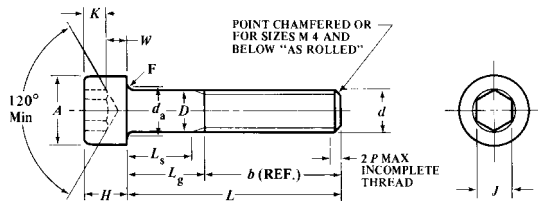
Hexagon socket set screw flat point BS 4168 M6 × 12-45H

*British Standard Hexagon Socket Countersunk and Button Head Screws — Metric Series:* British Standard BS 4168:1967 provides a metric series of hexagon socket countersunk and button head screws. The dimensions of these screws are given in [Table 4](#). The revision of this Standard will constitute Parts 6 and 8 of BS 4168.

*British Standards for Mechanical Properties of Fasteners:* B.S. 6104: Part 1:1981 specifies mechanical properties for bolts, screws, and studs with nominal diameters up to and including 39 mm of any triangular ISO thread and made of carbon or alloy steel. It does not apply to set screws and similar threaded fasteners. Part 2 of this Standard specifies the mechanical properties of set screws and similar fasteners, not under tensile stress, in the range from M1.6 up to and including M39 and made of carbon or alloy steel.

B.S. 6105:1981 provides specifications for bolts, screws, studs, and nuts made from austenitic, ferritic, and martensitic grades of corrosion-resistant steels. This Standard applies only to fastener components after completion of manufacture with nominal diameters from M1.6 up to and including M39. These Standards are not described further here. Copies may be obtained from the British Standards Institution, 2 Park Street, London W1A 2BS and also from the American National Standards Institute, 25 West 43rd Street, New York, N.Y. 10036.

**Table 1. British Standard Hexagon Socket Head Cap Screws—Metric Series**  
*BS 4168:Part 1:1981 (obsolescent)*



| Nominal Size, <sup>a</sup><br><i>d</i> | Body Diameter,<br><i>D</i> |       | Head Diameter,<br><i>A</i> |                  |       | Head Height,<br><i>H</i> |       | Hexagon Socket Size,<br><i>J</i> <sup>b</sup> | Key Engagement,<br><i>K</i> | Wall Thickness,<br><i>W</i> | Fillet            |                               |
|--|----------------------------|-------|----------------------------|------------------|-------|--------------------------|-------|---|-----------------------------|-----------------------------|-------------------|-------------------------------|
|  | Max                        | Min   | Max <sup>c</sup>           | Max <sup>d</sup> | Min   | Max                      | Min   | Nom   | Min                         | Min                         | Rad.,<br><i>F</i> | Dia.,<br><i>d<sub>a</sub></i> |
|  |                            |       |                            |                  |       |                          |       |   |                             |                             | Min               | Max                           |
| M1.6                                   | 1.6                        | 1.46  | 3                          | 3.14             | 2.86  | 1.6                      | 1.46  | 1.5   | 0.7                         | 0.55                        | 0.1               | 2                             |
| M2                                     | 2                          | 1.86  | 3.8                        | 3.98             | 3.62  | 2                        | 1.86  | 1.5   | 1                           | 0.55                        | 0.1               | 2.6                           |
| M2.5                                   | 2.5                        | 2.36  | 4.5                        | 4.68             | 4.32  | 2.5                      | 2.36  | 2   | 1.1                         | 0.85                        | 0.1               | 3.1                           |
| M3                                     | 3                          | 2.86  | 5.5                        | 5.68             | 5.32  | 3                        | 2.86  | 2.5   | 1.3                         | 1.15                        | 0.1               | 3.6                           |
| M4                                     | 4                          | 3.82  | 7                          | 7.22             | 6.78  | 4                        | 3.82  | 3   | 2                           | 1.4                         | 0.2               | 4.7                           |
| M5                                     | 5                          | 4.82  | 8.5                        | 8.72             | 8.28  | 5                        | 4.82  | 4   | 2.5                         | 1.9                         | 0.2               | 5.7                           |
| M6                                     | 6                          | 5.82  | 10                         | 10.22            | 9.78  | 6                        | 5.70  | 5   | 3                           | 2.3                         | 0.25              | 6.8                           |
| M8                                     | 8                          | 7.78  | 13                         | 13.27            | 12.73 | 8                        | 7.64  | 6   | 4                           | 3.3                         | 0.4               | 9.2                           |
| M10                                    | 10                         | 9.78  | 16                         | 16.27            | 15.73 | 10                       | 9.64  | 8   | 5                           | 4                           | 0.4               | 11.2                          |
| M12                                    | 12                         | 11.73 | 18                         | 18.27            | 17.73 | 12                       | 11.57 | 10  | 6                           | 4.8                         | 0.6               | 14.2                          |
| (M14)                                  | 14                         | 13.73 | 21                         | 21.33            | 20.67 | 14                       | 13.57 | 12  | 7                           | 5.8                         | 0.6               | 16.2                          |
| M16                                    | 16                         | 15.73 | 24                         | 24.33            | 23.67 | 16                       | 15.57 | 14  | 8                           | 6.8                         | 0.6               | 18.2                          |
| M20                                    | 20                         | 19.67 | 30                         | 30.33            | 29.67 | 20                       | 19.48 | 17  | 10                          | 8.6                         | 0.8               | 22.4                          |
| M24                                    | 24                         | 23.67 | 36                         | 36.39            | 35.61 | 24                       | 23.48 | 19  | 12                          | 10.4                        | 0.8               | 26.4                          |
| M30                                    | 30                         | 29.67 | 45                         | 45.39            | 44.61 | 30                       | 29.48 | 22  | 15.5                        | 13.1                        | 1                 | 33.4                          |
| M36                                    | 36                         | 35.61 | 54                         | 54.46            | 53.54 | 36                       | 35.38 | 27  | 19                          | 15.3                        | 1                 | 39.4                          |

<sup>a</sup>The size shown in ( ) is non-preferred.

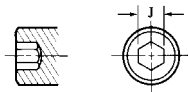
<sup>b</sup>See Table 2 for min/max.

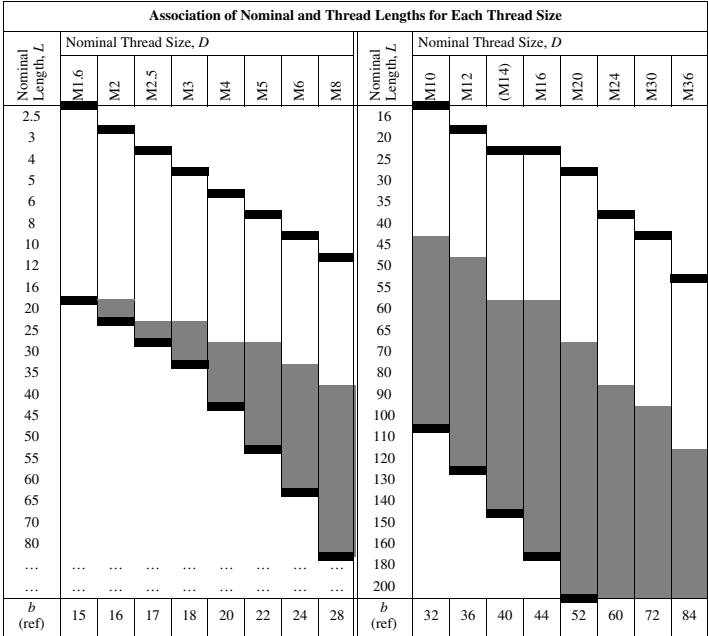
<sup>c</sup>For plain heads.

<sup>d</sup>For knurled heads.

All dimensions are given in millimeters.

**Table 2. British Standard Hexagon Socket Screws — Metric Series**  
*BS 4168:Part 1:1981 (obsolescent)*

| Dimensions of Hexagon Sockets   |                                     |      |                     |                                     |        |
|---|-------------------------------------|------|---------------------|-------------------------------------|--------|
|  |                                     |      |                     |                                     |        |
| Nominal Socket Size   | Socket Width Across Flats, <i>J</i> |      | Nominal Socket Size | Socket Width Across Flats, <i>J</i> |        |
|   | Max.                                | Min. |                     | Max.                                | Min.   |
| 1.5   | 1.545                               | 1.52 | 6                   | 6.095                               | 6.02   |
| 2.0   | 2.045                               | 2.02 | 8                   | 8.115                               | 8.025  |
| 2.5   | 2.56                                | 2.52 | 10                  | 10.115                              | 10.025 |
| 3   | 3.08                                | 3.02 | 12                  | 12.142                              | 12.032 |
| 4   | 4.095                               | 4.02 | 14                  | 14.142                              | 14.032 |
| 5   | 5.095                               | 5.02 | 17                  | 17.23                               | 17.05  |
| ...   | ...                                 | ...  | 19                  | 19.275                              | 19.065 |



All dimensions are in millimeters.

The popular lengths are those between the stepped solid lines. Lengths above the shaded areas are threaded to the head within 3 pitch lengths ( $3P$ ). Lengths within and below the shaded areas have values of  $L_g$  and  $L_s$  (see Table 1) given by the formulas:  $L_g \text{ max} = L \text{ nom} - b \text{ ref}$ , and  $L_s \text{ min} = L_g \text{ max} - 5P$ .

**Table 3. British Standard Hexagon Socket Set Screws — Metric Series**  
*BS 4168:Parts 2, 3, 4, and 5:1994*

| Nom. Size, <i>d</i> | Pitch, <i>P</i> | Socket Size, <i>s</i> | Depth of Key Engagement, <i>r</i> <sup>a</sup> |      | Range of Popular Lengths |            |           |           | Length of Dog on Dog Point Screws <sup>b</sup> |      |                    |       | End Diameters                    |                                 |                                 |                                 |          |
|---------------------|-----------------|-----------------------|--|------|--------------------------|------------|-----------|-----------|--|------|--------------------|-------|----------------------------------|---------------------------------|---------------------------------|---------------------------------|----------|
|                     |                 |                       |  |      | Flat Point               | Cone Point | Dog Point | Cup Point | Short Dog, <i>z</i>                            |      | Long Dog, <i>z</i> |       | Flat Point, <i>d<sub>z</sub></i> | Cone Point <i>d<sub>t</sub></i> | Dog Point, <i>d<sub>p</sub></i> | Cup Point, <i>d<sub>c</sub></i> |          |
|                     |                 |                       |  |      |                          |            |           |           | min  | max  | min                | max   |                                  |                                 |                                 |                                 | <i>b</i> |
| M1.6                | 0.35            | 0.7                   | 0.7  | 1.5  | 2–8                      | 2–8        | 2–8       | 2–8       | 0.4  | 0.65 | 0.8                | 1.05  | 2.5                              | 0.8                             | 0                               | 0.8                             | 0.8      |
| M2                  | 0.4             | 0.9                   | 0.8  | 1.7  | 2–10                     | 2–10       | 2.5–10    | 2–10      | 0.5  | 0.75 | 1.0                | 1.25  | 3.0                              | 1.0                             | 0                               | 1.0                             | 1.0      |
| M2.5                | 0.45            | 1.3                   | 1.2  | 2.0  | 2–12                     | 2.5–12     | 3–12      | 2–12      | 0.63   | 0.88 | 1.25               | 1.5   | 4                                | 1.5                             | 0                               | 1.5                             | 1.2      |
| M3                  | 0.5             | 1.5                   | 1.2  | 2.0  | 2–16                     | 2.5–16     | 4–16      | 2.5–16    | 0.75   | 1.0  | 1.5                | 1.75  | 5                                | 2.0                             | 0                               | 2.0                             | 1.4      |
| M4                  | 0.7             | 2.0                   | 1.5  | 2.5  | 2.5–20                   | 3–20       | 5–20      | 3–20      | 1.0  | 1.25 | 2.0                | 2.25  | 6                                | 2.5                             | 0                               | 2.5                             | 2.0      |
| M5                  | 0.8             | 2.5                   | 2.0  | 3.0  | 3–25                     | 4–25       | 6–25      | 4–25      | 1.25   | 1.5  | 2.5                | 2.75  | 6                                | 3.5                             | 0                               | 3.5                             | 2.5      |
| M6                  | 1.0             | 3.0                   | 2.0  | 3.5  | 4–30                     | 5–30       | 8–30      | 5–30      | 1.5  | 1.75 | 3.0                | 3.25  | 8                                | 4.0                             | 1.5                             | 4.0                             | 3.0      |
| M8                  | 1.25            | 4.0                   | 3.0  | 5.0  | 5–40                     | 6–40       | 8–40      | 6–40      | 2.0  | 2.25 | 4.0                | 4.3   | 10                               | 5.5                             | 2.0                             | 5.5                             | 5.0      |
| M10                 | 1.5             | 5.0                   | 4.0  | 6.0  | 6–50                     | 8–50       | 10–50     | 8–50      | 2.5  | 2.75 | 5.0                | 5.3   | 12                               | 7.0                             | 2.5                             | 7.0                             | 6.0      |
| M12                 | 1.75            | 6.0                   | 4.8  | 8.0  | 8–60                     | 10–60      | 12–60     | 10–60     | 3.0  | 3.25 | 6.0                | 6.3   | 16                               | 8.5                             | 3.0                             | 8.5                             | 8.0      |
| M16                 | 2.0             | 8.0                   | 6.4  | 10.0 | 10–60                    | 12–60      | 16–60     | 12–60     | 4.0  | 4.3  | 8.0                | 8.36  | 20                               | 12.0                            | 4.0                             | 12.0                            | 10.0     |
| M20                 | 2.5             | 10.0                  | 8.0  | 12.0 | 12–60                    | 16–60      | 20–60     | 16–60     | 5.0  | 5.3  | 10.0               | 10.36 | 25                               | 15.0                            | 5.0                             | 15.0                            | 14.0     |
| M24                 | 3.0             | 12.0                  | 10.0   | 15.0 | 16–60                    | 20–60      | 25–60     | 20–60     | 6.0  | 6.3  | 12.0               | 12.43 | 30                               | 18.0                            | 6.0                             | 18.0                            | 16.0     |

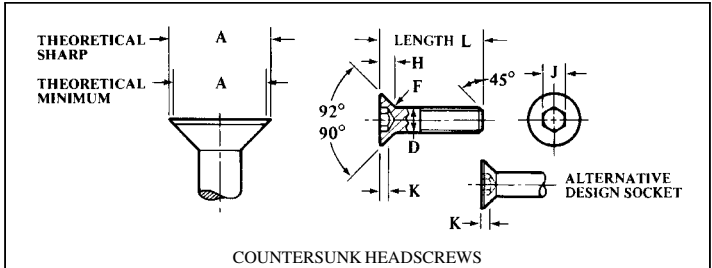
<sup>a</sup>The smaller of the two *t* min. values applies to certain short-length set screws. These short-length screws are those whose length is approximately equal to the diameter of the screw. The larger *t* min. values apply to longer-length screws.

<sup>b</sup>A dog point set screw having a nominal length equal to or less than the length shown in the (\*) column of the table is supplied with length *z* shown in the short dog column. For set screws of lengths greater than shown in the (\*) column, *z* for long dogs applies.

All dimensions are in millimeters. For dimensional notation, see diagram, page 1637.



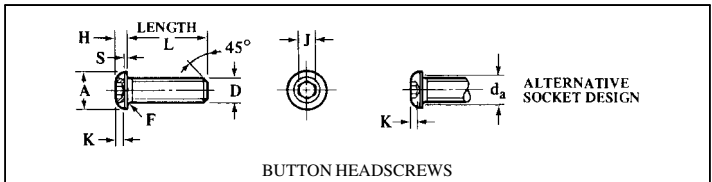
**Table 4. British Standard Hexagon Socket Countersunk and Button Head Screws — Metric Series BS 4168:1967**



COUNTERSUNK HEADSCREWS

| Nom. Size <sup>a</sup> | Body Diameter, D |       | Head Diameter, A  |               | Head Height, H |                     | Hexagon Socket Size, J | Key Engagement, K | Fillet Radius, F |
|------------------------|------------------|-------|-------------------|---------------|----------------|---------------------|------------------------|-------------------|------------------|
|                        | Max.             | Min.  | Theor. Sharp Max. | Absolute Min. | Ref.           | Flushness Tolerance |                        |                   |                  |
| M3                     | 3.00             | 2.86  | 6.72              | 5.82          | 1.86           | 0.20                | 2.00                   | 1.05              | 0.40             |
| M4                     | 4.00             | 3.82  | 8.96              | 7.78          | 2.48           | 0.20                | 2.50                   | 1.49              | 0.40             |
| M5                     | 5.00             | 4.82  | 11.20             | 9.78          | 3.10           | 0.20                | 3.00                   | 1.86              | 0.40             |
| M6                     | 6.00             | 5.82  | 13.44             | 11.73         | 3.72           | 0.20                | 4.00                   | 2.16              | 0.60             |
| M8                     | 8.00             | 7.78  | 17.92             | 15.73         | 4.96           | 0.24                | 5.00                   | 2.85              | 0.70             |
| M10                    | 10.00            | 9.78  | 22.40             | 19.67         | 6.20           | 0.30                | 6.00                   | 3.60              | 0.80             |
| M12                    | 12.00            | 11.73 | 26.88             | 23.67         | 7.44           | 0.36                | 8.00                   | 4.35              | 1.10             |
| (M14)                  | 14.00            | 13.73 | 30.24             | 26.67         | 8.12           | 0.40                | 10.00                  | 4.65              | 1.10             |
| M16                    | 16.00            | 15.73 | 33.60             | 29.67         | 8.80           | 0.45                | 10.00                  | 4.89              | 1.10             |
| (M18)                  | 18.00            | 17.73 | 36.96             | 32.61         | 9.48           | 0.50                | 12.00                  | 5.25              | 1.10             |
| M20                    | 20.00            | 19.67 | 40.32             | 35.61         | 10.16          | 0.54                | 12.00                  | 5.45              | 1.10             |

<sup>a</sup> Sizes shown in parentheses are non-preferred.



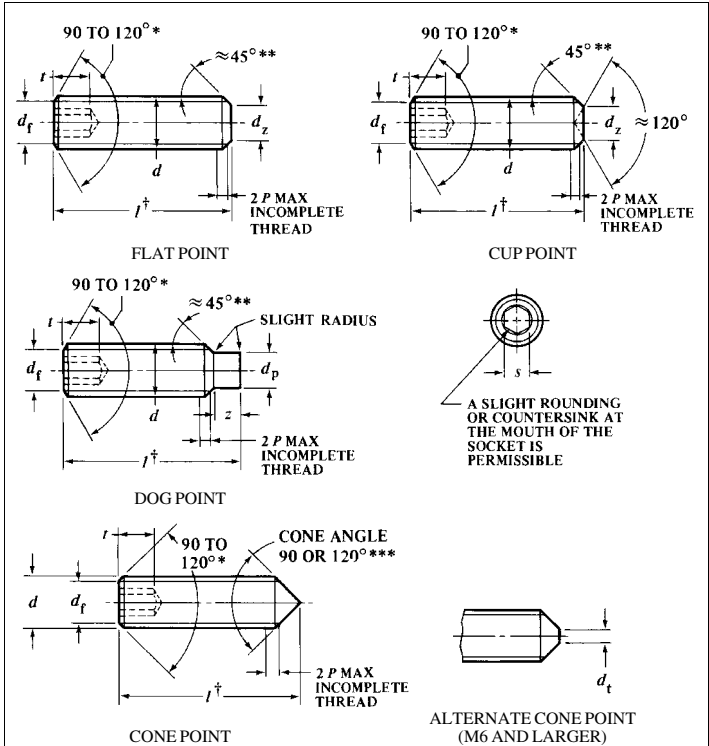
BUTTON HEADSCREWS

| Nom. Size, D | Head Diameter, A |       | Head Height, H |      | Head Side Height, S | Hexagon Socket Size, J | Key Engagement, K | Fillet Radius |                |
|--------------|------------------|-------|----------------|------|---------------------|------------------------|-------------------|---------------|----------------|
|              | Max.             | Min.  | Max.           | Min. |                     |                        |                   | F             | d <sub>a</sub> |
| M3           | 5.50             | 5.32  | 1.60           | 1.40 | 0.38                | 2.00                   | 1.04              | 0.10          | 3.60           |
| M4           | 7.50             | 7.28  | 2.10           | 1.85 | 0.38                | 2.50                   | 1.30              | 0.20          | 4.70           |
| M5           | 9.50             | 9.28  | 2.70           | 2.45 | 0.50                | 3.00                   | 1.56              | 0.20          | 5.70           |
| M6           | 10.50            | 10.23 | 3.20           | 2.95 | 0.80                | 4.00                   | 2.08              | 0.25          | 6.80           |
| M8           | 14.00            | 13.73 | 4.30           | 3.95 | 0.80                | 5.00                   | 2.60              | 0.40          | 9.20           |
| M10          | 18.00            | 17.73 | 5.30           | 4.95 | 0.80                | 6.00                   | 3.12              | 0.40          | 11.20          |
| M12          | 21.00            | 20.67 | 6.40           | 5.90 | 0.80                | 8.00                   | 4.16              | 0.60          | 14.20          |

All dimensions are given in millimeters.

## British Standard Hexagon Socket Set Screws — Metric Series

BS 4168: Parts 2, 3, 4, and 5: 1994



\*The 120° angle is mandatory for short-length screws shown in the Standard. Short-length screws are those whose length is, approximately, equal to the diameter of the screw.

\*\*The 45° angle applies only to that portion of the point below the root diameter,  $d_f$ , of the thread.

\*\*\*The cone angle applies only to the portion of the point below the root diameter,  $d_f$ , of the thread and shall be 120° for certain short lengths listed in the Standard. All other lengths have a 90° cone angle.

†The popular length ranges of these set screws are listed in Table 3. These lengths have been selected from the following nominal lengths: 2, 2.5, 3, 4, 6, 8, 10, 12, 16, 20, 25, 30, 35, 40, 45, 50, 55, and 60 millimeters.

**Holding Power of Set-screws.**— While the amount of power a set-screw of given size will transmit without slipping (when used for holding a pulley, gear, or other part from turning relative to a shaft) varies somewhat according to the physical properties of both set-screw and shaft and other variable factors, experiments have shown that the safe holding force in pounds for different diameters of set-screws should be approximately as follows: For  $\frac{1}{4}$ -inch diameter set-screws the safe holding force is 100 pounds, for  $\frac{3}{8}$ -inch

diameter set-screws the safe holding force is 250 pounds, for 1/2-inch diameter set-screws the safe holding force is 500 pounds, for 3/4-inch diameter set-screws the safe holding force is 1300 pounds, and for 1-inch diameter set-screws the safe holding force is 2500 pounds.

The power or torque that can be safely transmitted by a set-screw may be determined from the formulas,  $P = (DNd^{2.3}) \div 50$ ; or  $T = 1250Dd^{2.3}$  in which  $P$  is the horsepower transmitted;  $T$  is the torque in inch-pounds transmitted;  $D$  is the shaft diameter in inches;  $N$  is the speed of the shaft in revolutions per minute; and  $d$  is the diameter of the set-screw in inches.

*Example:* How many 1/2-inch diameter set-screws would be required to transmit 3 horsepower at a shaft speed of 1000 rpm if the shaft diameter is 1 inch?

Using the first formula given above, the power transmitted by a single 1/2-inch diameter set-screw is determined:  $P = [1 \times 1000 \times (1/2)^{2.3}] \div 50 = 4.1$  hp. Therefore a single 1/2-inch diameter set-screw is sufficient.

*Example:* In the previous example, how many 3/8-inch diameter set-screws would be required?  $P = [1 \times 1000 \times (3/8)^{2.3}] \div 50 = 2.1$  hp. Therefore two 3/8-inch diameter set-screws are required.

**Table 5. British Standard Whitworth (BSW) and British Standard Fine (BSF) Bright Square Head Set-Screws (With Flat Chamfered Ends)**

| Nominal Size and Max. Dia., Inches | Number of Threads per Inch |     | No. 1 Standard       |                 | No. 2 Standard       |                 | No. 3 Standard       |                 |
|------------------------------------|----------------------------|-----|----------------------|-----------------|----------------------|-----------------|----------------------|-----------------|
|                                    |                            |     | Width Across Flats A | Depth of Head B | Width Across Flats C | Depth of Head D | Width Across Flats E | Depth of Head F |
|                                    | BSW                        | BSF |                      |                 |                      |                 |                      |                 |
| 1/4                                | 20                         | 26  | 0.250                | 0.250           | 0.313                | 0.250           | 0.375                | 0.250           |
| 5/16                               | 18                         | 22  | 0.313                | 0.313           | 0.375                | 0.313           | 0.438                | 0.313           |
| 3/8                                | 16                         | 20  | 0.375                | 0.375           | 0.438                | 0.375           | 0.500                | 0.375           |
| 7/16                               | 14                         | 18  | 0.438                | 0.438           | 0.500                | 0.438           | 0.625                | 0.438           |
| 1/2                                | 12                         | 16  | 0.500                | 0.500           | 0.563                | 0.500           | 0.750                | 0.500           |
| 5/8                                | 11                         | 14  | 0.625                | 0.625           | 0.750                | 0.625           | 0.875                | 0.625           |
| 3/4                                | 10                         | 12  | 0.750                | 0.750           | 0.875                | 0.750           | 1.000                | 0.750           |
| 7/8                                | 9                          | 11  | 0.875                | 0.875           | 1.000                | 0.875           | 1.125                | 0.875           |
| 1                                  | 8                          | 10  | 1.000                | 1.000           | 1.125                | 1.000           | 1.250                | 1.000           |

\* Depth of Head B, D and F same as for Width Across Flats, No. 1 Standard. Dimensions A, B, C, D, E, and F are in inches.

## SELF-THREADING SCREWS

**ANSI Standard Sheet Metal, Self-Tapping, and Metallic Drive Screws.**—Table 1 shows the various types of “self-tapping” screw threads covered by the ANSI B18.6.4-1981 (R1991) standard. (Metric thread forming and thread cutting tapping screws are discussed beginning on page 1654). ANSI designations are also shown. Types A, AB, B, BP and C when turned into a hole of proper size form a thread by a displacing action. Types D, F, G, T, BF and BT when turned into a hole of proper size form a thread by a cutting action. Type U when driven into a hole of proper size forms a series of multiple threads by a displacing action. These screws have the following descriptions and applications:

*Type A:* Spaced-thread screw with gimlet point primarily for use in light sheet metal, resin-impregnated plywood, and asbestos compositions. This type is no longer recommended. Use Type AB in new designs and whenever possible substitute for Type A in existing designs.

*Type AB:* Spaced-thread screw with same pitches as Type B but with gimlet point, primarily for similar uses as for Type A.

*Type B:* Spaced-thread screw with a blunt point with pitches generally somewhat finer than Type A. Used for thin metal, non-ferrous castings, plastics, resin-impregnated plywood, and asbestos compositions.

*Type BP:* Spaced-thread screw, the same as Type B but having a conical point extending beyond incomplete entering threads. Used for piercing fabrics or in assemblies where holes are misaligned.

*Type C:* Screws having machine screw diameter-pitch combinations with threads approximately Unified Form and with blunt tapered points. Used where a machine screw thread is preferable to the spaced-thread types of thread forming screws. Also useful when chips from machine screw thread-cutting screws are objectionable. In view of the declining use of Type C screws, which in general require high driving torques, in favor of more efficient designs of thread tapping screws, they are not recommended for new designs.

*Types D, F, G, and T:* Thread-cutting screws with threads approximating machine screw threads, with blunt point, and with tapered entering threads having one or more cutting edges and chip cavities. The tapered threads of the Type F may be complete or incomplete at the producer's option; all other types have incomplete tapered threads. These screws can be used in materials such as aluminum, zinc, and lead die-castings; steel sheets and shapes; cast iron; brass; and plastics.

*Types BF and BT:* Thread-cutting screws with spaced threads as in Type B, with blunt points, and one or more cutting grooves. Used in plastics, asbestos, and other similar compositions.

*Type U:* Multiple-threaded drive screw with large helix angle, having a pilot point, for use in metal and plastics. This screw is forced into the work by pressure and is intended for making permanent fastenings.

*ANSI Standard Head Types for Tapping and Metallic Drive Screws:* Many of the head types used with “self-tapping” screw threads are similar to the head types of American National Standard machine screws shown in the section with that heading.

*Round Head:* The round head has a semi-elliptical top surface and a flat bearing surface. Because of the superior slot driving characteristics of pan head screws over round head screws, and the overlap in dimensions of cross recessed pan heads and round heads, it is recommended that pan head screws be used in new designs and wherever possible substituted in existing designs.

*Undercut Flat and Oval Countersunk Heads:* For short lengths, 82-degree and oval countersunk head tapping screws have heads undercut to 70 per cent of normal side height to afford greater length of thread on the screws.

*Flat Countersunk Head:* The flat countersunk head has a flat top surface and a conical bearing surface with a head angle for one design of approximately 82 degrees and for another design of approximately 100 degrees. Because of its limited usage and in the interest of curtailing product varieties, the 100-degree flat countersunk head is considered non-preferred.

*Oval Countersunk Head:* The oval countersunk head has a rounded top surface and a conical bearing surface with a head angle of approximately 82 degrees.

*Flat and Oval Countersunk Trim Heads:* Flat and oval countersunk trim heads are similar to the 82-degree flat and oval countersunk heads except that the size of head for a given size screw is one (large trim head) or two (small trim head) sizes smaller than the regular flat and oval countersunk head size. Oval countersunk trim heads have a definite radius where the curved top surface meets the conical bearing surface. Trim heads are furnished only in cross recessed types.

*Pan Head:* The slotted pan head has a flat top surface rounded into cylindrical sides and a flat bearing surface. The recessed pan head has a rounded top and a flat bearing surface. This head type is now preferred to the round head.

*Fillister Head:* The fillister head has a rounded top surface, cylindrical sides, and a flat bearing surface.

*Hex Head:* The hex head has a flat or indented top surface, six flat sides, and a flat bearing surface. Because the slotted hex head requires a secondary operation in manufacture which often results in burrs at the extremity of the slot that interfere with socket wrench engagement and the wrenching capability of the hex far exceeds that of the slot, it is not recommended for new designs.

*Hex Washer Head:* The hex washer head has an indented top surface and six flat sides formed integrally with a flat washer that projects beyond the sides and provides a flat bearing surface. Because the slotted hex washer head requires a secondary operation in manufacture which often results in burrs at the extremity of the slot that often interferes with socket wrench engagement and because the wrenching capability of the hex far exceeds that of the slot in the indented head, it is not recommended for new designs.

*Truss Head:* The truss head has a low rounded top surface with a flat bearing surface, the diameter of which for a given screw size is larger than the diameter of the corresponding round head. In the interest of product simplification and recognizing that the truss head is an inherently weak design, it is not recommended for new designs.

**Method of Designation.**—Tapping screws are designated by the following data in the sequence shown: Nominal size (number, fraction or decimal equivalent); threads per inch; nominal length (fraction or decimal equivalent); point type; product name, including head type and driving provision; material; and protective finish, if required.

Examples:

$\frac{1}{4}$ -14  $\times$  1 $\frac{1}{2}$  Type AB Slotted Pan Head Tapping Screw, Steel, Nickel Plated

6-32  $\times$   $\frac{3}{4}$  Type T, Type 1A Cross Recessed Pan Head Tapping Screw, Corrosion Resistant Steel

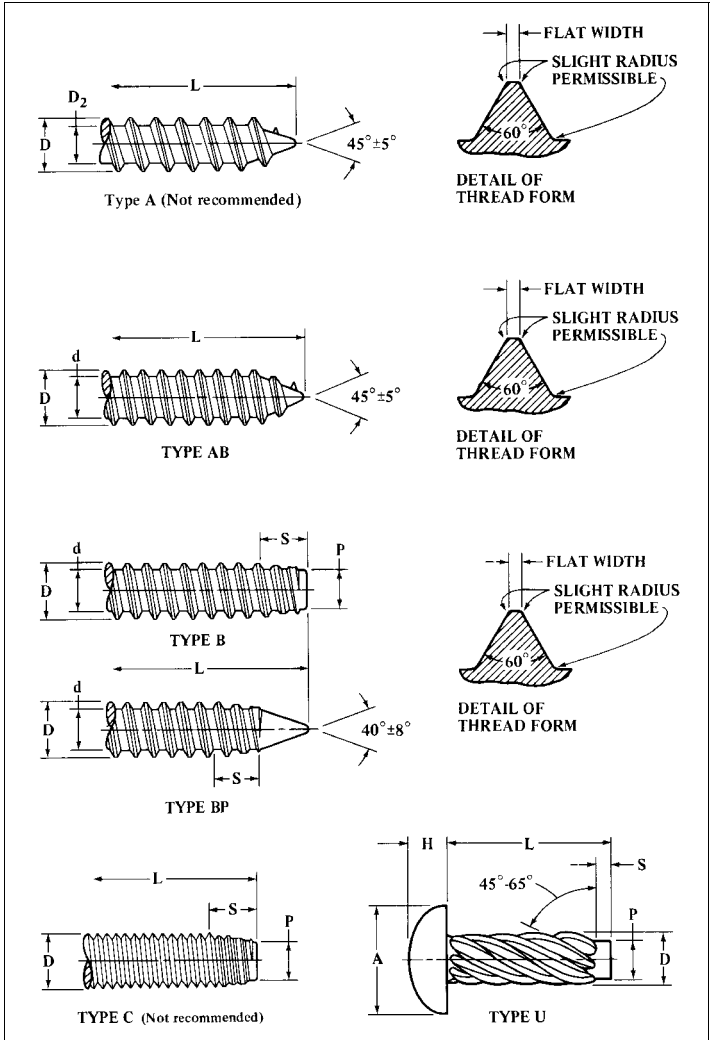
0.375-16  $\times$  1.50 Type D, Washer Head Tapping Screw, Steel

*Metallic Drive Screws:* Type U metallic drive screws are designated by the following data in the sequence shown: Nominal size (number, fraction, or decimal equivalent); nominal length (fraction or decimal equivalent); product name, including head type; material; and protective finish, if required. Examples:

10  $\times$   $\frac{5}{16}$  Round Head Metallic Drive Screw, Steel

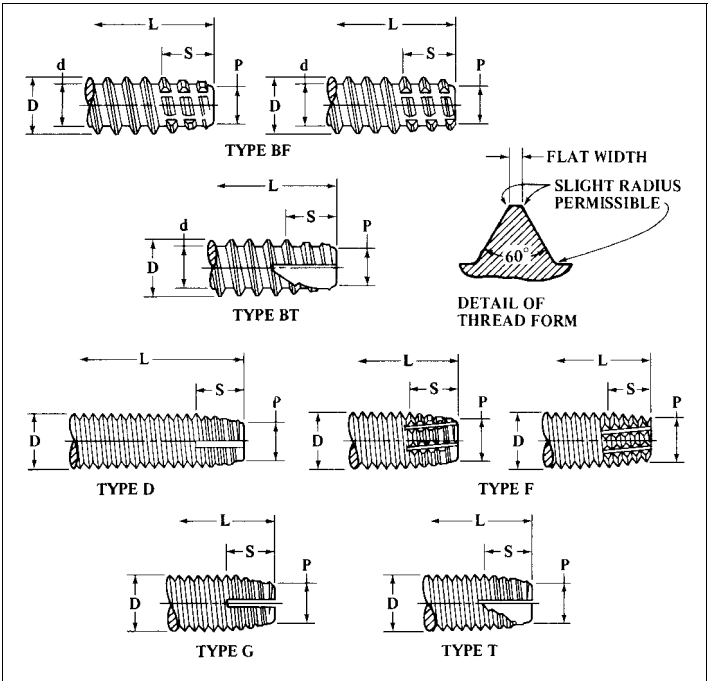
0.312  $\times$  0.50 Round Head Metallic Drive Screw, Steel, Zinc Plated

**Table 1. ANSI Standard Threads and Points for Thread Forming Self-Tapping Screws ANSI B18.6.4-1981 (R1991)**



See Tables 3, 5, and 6 for thread data.

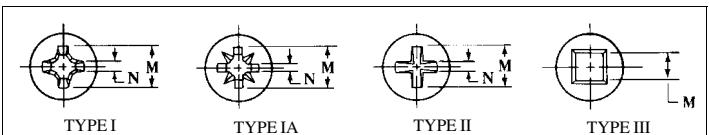
**Table 2. ANSI Standard Threads and Points for Thread Cutting Self-Tapping Screws ANSI B18.6.4-1981 (R1991)**



See Tables 5 and 7 for thread data.

**Cross Recesses.**—Type I cross recess has a large center opening, tapered wings, and blunt bottom, with all edges relieved or rounded. Type IA cross recess has a large center opening, wide straight wings, and blunt bottom, with all edges relieved or rounded. Type II consists of two intersecting slots with parallel sides converging to a slightly truncated apex at the bottom of the recess. Type III has a square center opening, slightly tapered side walls, and a conical bottom, with top edges relieved or rounded.

**Table 3. ANSI Standard Cross Recesses for Self-Tapping Screws ANSI B18.6.4-1981 (R1991) and Metric Thread Forming and Thread Cutting Tapping Screws ANSI/ASME B18.6.5M-1986**



**Table 4. ANSI Standard Thread and Point Dimensions for Types AB, A and U Thread Forming Tapping Screws ANSI B18.6.4-1981 (R1991)**

| Type AB (Formerly BA)                  |                  |                |              |                |              |                                 |                 |  |  |
|--|------------------|----------------|--------------|----------------|--------------|---------------------------------|-----------------|--|--|
| Nominal Size or Basic Screw Diameter   | Threads per inch | D              |              | d              |              | L                               |                 |  |  |
|  |                  | Major Diameter |              | Minor Diameter |              | Minimum Practical Screw Lengths |                 |  |  |
|  |                  | Max.           | Min.         | Max.           | Min.         | 90° Heads                       | Csk. Heads      |  |  |
| 0 0.0600                               | 48               | 0.060          | 0.054        | 0.036          | 0.033        | $\frac{1}{8}$                   | $\frac{3}{32}$  |  |  |
| 1 0.0730                               | 42               | 0.075          | 0.069        | 0.049          | 0.046        | $\frac{5}{32}$                  | $\frac{3}{16}$  |  |  |
| <b>2 0.0860</b>                        | <b>32</b>        | <b>0.088</b>   | <b>0.082</b> | <b>0.064</b>   | <b>0.060</b> | $\frac{3}{16}$                  | $\frac{7}{32}$  |  |  |
| 3 0.0990                               | 28               | 0.101          | 0.095        | 0.075          | 0.071        | $\frac{3}{16}$                  | $\frac{1}{4}$   |  |  |
| <b>4 0.1120</b>                        | <b>24</b>        | <b>0.114</b>   | <b>0.108</b> | <b>0.086</b>   | <b>0.082</b> | $\frac{7}{32}$                  | $\frac{9}{32}$  |  |  |
| 5 0.1250                               | 20               | 0.130          | 0.123        | 0.094          | 0.090        | $\frac{1}{4}$                   | $\frac{5}{16}$  |  |  |
| <b>6 0.1380</b>                        | <b>20</b>        | <b>0.139</b>   | <b>0.132</b> | <b>0.104</b>   | <b>0.099</b> | $\frac{9}{32}$                  | $\frac{11}{32}$ |  |  |
| 7 0.1510                               | 19               | 0.154          | 0.147        | 0.115          | 0.109        | $\frac{5}{16}$                  | $\frac{3}{8}$   |  |  |
| <b>8 0.1640</b>                        | <b>18</b>        | <b>0.166</b>   | <b>0.159</b> | <b>0.122</b>   | <b>0.116</b> | $\frac{5}{16}$                  | $\frac{3}{8}$   |  |  |
| <b>10 0.1900</b>                       | <b>16</b>        | <b>0.189</b>   | <b>0.182</b> | <b>0.141</b>   | <b>0.135</b> | $\frac{3}{8}$                   | $\frac{7}{16}$  |  |  |
| 12 0.2160                              | 14               | 0.215          | 0.208        | 0.164          | 0.157        | $\frac{7}{16}$                  | $\frac{21}{32}$ |  |  |
| <b><math>\frac{1}{4}</math> 0.2500</b> | <b>14</b>        | <b>0.246</b>   | <b>0.237</b> | <b>0.192</b>   | <b>0.185</b> | $\frac{1}{2}$                   | $\frac{19}{32}$ |  |  |
| $\frac{5}{16}$ 0.3125                  | 12               | 0.315          | 0.306        | 0.244          | 0.236        | $\frac{5}{8}$                   | $\frac{3}{4}$   |  |  |
| $\frac{3}{8}$ 0.3750                   | 12               | 0.380          | 0.371        | 0.309          | 0.299        | $\frac{3}{4}$                   | $\frac{29}{32}$ |  |  |
| $\frac{7}{16}$ 0.4375                  | 10               | 0.440          | 0.429        | 0.359          | 0.349        | $\frac{7}{8}$                   | $1\frac{1}{32}$ |  |  |
| $\frac{1}{2}$ 0.5000                   | 10               | 0.504          | 0.493        | 0.423          | 0.413        | 1                               | $1\frac{1}{32}$ |  |  |

| Type A                               |                  |                |       |                |       |                                       |                 |  |  |
|--------------------------------------|------------------|----------------|-------|----------------|-------|---------------------------------------|-----------------|--|--|
| Nominal Size or Basic Screw Diameter | Threads per inch | D              |       | d              |       | L                                     |                 |  |  |
|                                      |                  | Major Diameter |       | Minor Diameter |       | These Lengths or Shorter —Use Type AB |                 |  |  |
|                                      |                  | Max.           | Min.  | Max.           | Min.  | 90° Heads                             | Csk. Heads      |  |  |
| 0 0.0600                             | 40               | 0.060          | 0.057 | 0.042          | 0.039 | $\frac{1}{8}$                         | $\frac{3}{16}$  |  |  |
| 1 0.0730                             | 32               | 0.075          | 0.072 | 0.051          | 0.048 | $\frac{1}{8}$                         | $\frac{3}{16}$  |  |  |
| 2 0.0860                             | 32               | 0.088          | 0.084 | 0.061          | 0.056 | $\frac{5}{32}$                        | $\frac{3}{16}$  |  |  |
| 3 0.0990                             | 28               | 0.101          | 0.097 | 0.076          | 0.071 | $\frac{3}{16}$                        | $\frac{7}{32}$  |  |  |
| 4 0.1120                             | 24               | 0.114          | 0.110 | 0.083          | 0.078 | $\frac{3}{16}$                        | $\frac{1}{4}$   |  |  |
| 5 0.1250                             | 20               | 0.130          | 0.126 | 0.095          | 0.090 | $\frac{3}{16}$                        | $\frac{1}{4}$   |  |  |
| 6 0.1380                             | 18               | 0.141          | 0.136 | 0.102          | 0.096 | $\frac{1}{4}$                         | $\frac{5}{16}$  |  |  |
| 7 0.1510                             | 16               | 0.158          | 0.152 | 0.114          | 0.108 | $\frac{5}{16}$                        | $\frac{3}{8}$   |  |  |
| 8 0.1640                             | 15               | 0.168          | 0.162 | 0.123          | 0.116 | $\frac{3}{8}$                         | $\frac{7}{16}$  |  |  |
| 10 0.1900                            | 12               | 0.194          | 0.188 | 0.133          | 0.126 | $\frac{3}{8}$                         | $\frac{1}{2}$   |  |  |
| 12 0.2160                            | 11               | 0.221          | 0.215 | 0.162          | 0.155 | $\frac{7}{16}$                        | $\frac{9}{16}$  |  |  |
| 14 0.2420                            | 10               | 0.254          | 0.248 | 0.185          | 0.178 | $\frac{1}{2}$                         | $\frac{5}{8}$   |  |  |
| 16 0.2680                            | 10               | 0.280          | 0.274 | 0.197          | 0.189 | $\frac{9}{16}$                        | $\frac{3}{4}$   |  |  |
| 18 0.2940                            | 9                | 0.306          | 0.300 | 0.217          | 0.209 | $\frac{5}{8}$                         | $\frac{13}{16}$ |  |  |
| 20 0.3200                            | 9                | 0.333          | 0.327 | 0.234          | 0.226 | $\frac{11}{16}$                       | $\frac{13}{16}$ |  |  |
| 24 0.3720                            | 9                | 0.390          | 0.383 | 0.291          | 0.282 | $\frac{3}{4}$                         | 1               |  |  |

<sup>a</sup> Where specifying nominal size in decimals, zeros preceding decimal and in fourth place are omitted.

| Type U Metallic Drive Screws |               |           |       |            |       |                |               |           |       |            |       |
|------------------------------|---------------|-----------|-------|------------|-------|----------------|---------------|-----------|-------|------------|-------|
| Nom. Size                    | No. of Starts | Out. Dia. |       | Pilot Dia. |       | Nom. Size      | No. of Starts | Out. Dia. |       | Pilot Dia. |       |
|                              |               | Max.      | Min.  | Max.       | Min.  |                |               | Max.      | Min.  | Max.       | Min.  |
| 00                           | 6             | 0.060     | 0.057 | 0.049      | 0.046 | 8              | 8             | 0.167     | 0.162 | 0.136      | 0.132 |
| 0                            | 6             | 0.075     | 0.072 | 0.063      | 0.060 | 10             | 8             | 0.182     | 0.177 | 0.150      | 0.146 |
| 2                            | 8             | 0.100     | 0.097 | 0.083      | 0.080 | 12             | 8             | 0.212     | 0.206 | 0.177      | 0.173 |
| 4                            | 7             | 0.116     | 0.112 | 0.096      | 0.092 | 14             | 9             | 0.242     | 0.236 | 0.202      | 0.198 |
| 6                            | 7             | 0.140     | 0.136 | 0.116      | 0.112 | $\frac{5}{16}$ | 11            | 0.315     | 0.309 | 0.272      | 0.267 |
| 7                            | 8             | 0.154     | 0.150 | 0.126      | 0.122 | $\frac{3}{8}$  | 12            | 0.378     | 0.371 | 0.334      | 0.329 |

All dimensions are in inches. See Table 1 for thread diagrams.

Sizes shown in bold face type are preferred. Type A screws are no longer recommended.



**Table 5. ANSI Standard Thread and Point Dimensions for B and BP Thread Forming and BF and BT Thread Cutting Tapping Screws ANSI B18.6.4-1981 (R1991)**

| THREAD FORMING TYPES B AND BP                     |                            |                |       |                |       |                             |       |                                 |       |   |       |           |           |           |           |
|---|----------------------------|----------------|-------|----------------|-------|-----------------------------|-------|---------------------------------|-------|---|-------|-----------|-----------|-----------|-----------|
| Nominal Size <sup>a</sup> or Basic Screw Diameter | Thds per Inch <sup>b</sup> | D              |       | d              |       | P                           |       | S                               |       | L                                       |       |           |           |           |           |
|   |                            | Major Diameter |       | Minor Diameter |       | Point Diameter <sup>c</sup> |       | Point Taper Length <sup>d</sup> |       | Minimum Practical Nominal Screw Lengths |       |           |           |           |           |
|   |                            | Max            | Min   | Max            | Min   | Max                         | Min   | Max                             | Min   | Max                                     | Min   | Type B    |           | Type BP   |           |
|   |                            |                |       |                |       |                             |       |                                 |       |   |       | 90° Heads | Csk Heads | 90° Heads | Csk Heads |
| 0 0.0600  | 48                         | 0.060          | 0.054 | 0.036          | 0.033 | 0.031                       | 0.027 | 0.042                           | 0.031 | 1/8                                     | 1/8   | 5/32      | 3/16      |           |           |
| 1 0.0730  | 42                         | 0.075          | 0.069 | 0.049          | 0.046 | 0.044                       | 0.040 | 0.048                           | 0.036 | 1/8                                     | 5/32  | 3/16      | 7/32      |           |           |
| 2 0.0860  | 32                         | 0.088          | 0.082 | 0.064          | 0.060 | 0.058                       | 0.054 | 0.062                           | 0.047 | 5/32                                    | 3/16  | 1/4       | 9/32      |           |           |
| 3 0.0990  | 28                         | 0.101          | 0.095 | 0.075          | 0.071 | 0.068                       | 0.063 | 0.071                           | 0.054 | 5/32                                    | 3/16  | 9/32      | 5/16      |           |           |
| 4 0.1120  | 24                         | 0.114          | 0.108 | 0.086          | 0.082 | 0.079                       | 0.074 | 0.083                           | 0.063 | 3/16                                    | 1/4   | 5/16      | 11/32     |           |           |
| 5 0.1250  | 20                         | 0.130          | 0.123 | 0.094          | 0.090 | 0.087                       | 0.082 | 0.100                           | 0.075 | 7/32                                    | 9/32  | 11/32     | 13/32     |           |           |
| 6 0.1380  | 20                         | 0.139          | 0.132 | 0.104          | 0.099 | 0.095                       | 0.089 | 0.100                           | 0.075 | 1/4                                     | 9/32  | 3/8       | 7/16      |           |           |
| 7 0.1510  | 19                         | 0.154          | 0.147 | 0.115          | 0.109 | 0.105                       | 0.099 | 0.105                           | 0.079 | 1/4                                     | 5/16  | 13/32     | 15/32     |           |           |
| 8 0.1640  | 18                         | 0.166          | 0.159 | 0.122          | 0.116 | 0.112                       | 0.106 | 0.111                           | 0.083 | 9/32                                    | 11/32 | 7/16      | 1/2       |           |           |
| 10 0.1900   | 16                         | 0.189          | 0.182 | 0.141          | 0.135 | 0.130                       | 0.123 | 0.125                           | 0.094 | 5/16                                    | 3/8   | 1/2       | 19/32     |           |           |
| 12 0.2160   | 14                         | 0.215          | 0.208 | 0.164          | 0.157 | 0.152                       | 0.145 | 0.143                           | 0.107 | 11/32                                   | 7/16  | 9/16      | 21/32     |           |           |
| 1/4 0.2500  | 14                         | 0.246          | 0.237 | 0.192          | 0.185 | 0.179                       | 0.171 | 0.143                           | 0.107 | 3/8                                     | 1/2   | 21/32     | 3/4       |           |           |
| 5/16 0.3125                                       | 12                         | 0.315          | 0.306 | 0.244          | 0.236 | 0.230                       | 0.222 | 0.167                           | 0.125 | 15/32                                   | 19/32 | 27/32     | 31/32     |           |           |
| 3/8 0.3750  | 12                         | 0.380          | 0.371 | 0.309          | 0.299 | 0.293                       | 0.285 | 0.167                           | 0.125 | 17/32                                   | 11/16 | 15/16     | 1 1/8     |           |           |
| 7/16 0.4375                                       | 10                         | 0.440          | 0.429 | 0.359          | 0.349 | 0.343                       | 0.335 | 0.200                           | 0.150 | 5/8                                     | 25/32 | 11/8      | 1 1/4     |           |           |
| 1/2 0.5000  | 10                         | 0.504          | 0.493 | 0.423          | 0.413 | 0.407                       | 0.399 | 0.200                           | 0.150 | 11/16                                   | 27/32 | 1 1/4     | 1 13/32   |           |           |

<sup>a</sup> Where specifying nominal size in decimals, zeros preceding decimal and in the fourth decimal place shall be omitted.

<sup>b</sup> The width of flat at crest of thread shall not exceed 0.004 inch for sizes up to No. 8, inclusive, and 0.006 inch for larger sizes.

<sup>c</sup> Point diameters specified apply to screw threads before roll threading.

<sup>d</sup> Points of screws are tapered and fluted or slotted. The flute on Type BT screws has an included angle of 90 to 95 degrees and the thread cutting edge is located above the axis of the screw. Flutes and slots extend through first full form thread beyond taper except for Type BF screw on which tapered threads may be complete at manufacturer's option and flutes may be one pitch short of first full form thread.

| THREAD CUTTING TYPES BF AND BT <sup>d</sup>       |                            |                |       |                |       |                             |       |                                 |       |   |       |           |           |           |           |
|---|----------------------------|----------------|-------|----------------|-------|-----------------------------|-------|---------------------------------|-------|---|-------|-----------|-----------|-----------|-----------|
| Nominal Size <sup>a</sup> or Basic Screw Diameter | Thds per Inch <sup>b</sup> | D              |       | d              |       | P                           |       | S                               |       | L                                       |       |           |           |           |           |
|   |                            | Major Diameter |       | Minor Diameter |       | Point Diameter <sup>c</sup> |       | Point Taper Length <sup>d</sup> |       | Minimum Practical Nominal Screw Lengths |       |           |           |           |           |
|   |                            | Max            | Min   | Max            | Min   | Max                         | Min   | Max                             | Min   | Max                                     | Min   | 90° Heads |           | Csk Heads |           |
|   |                            |                |       |                |       |                             |       |                                 |       |   |       | 90° Heads | Csk Heads | 90° Heads | Csk Heads |
| 0 0.0600  | 48                         | 0.060          | 0.054 | 0.036          | 0.033 | 0.031                       | 0.027 | 0.042                           | 0.031 | 1/8                                     | 1/8   | 1/8       | 1/8       |           |           |
| 1 0.0730  | 42                         | 0.075          | 0.069 | 0.049          | 0.046 | 0.044                       | 0.040 | 0.048                           | 0.036 | 1/8                                     | 5/32  | 5/32      | 5/32      |           |           |
| 2 0.0860  | 32                         | 0.088          | 0.082 | 0.064          | 0.060 | 0.058                       | 0.054 | 0.062                           | 0.047 | 5/32                                    | 3/16  | 3/16      | 3/16      |           |           |
| 3 0.0990  | 28                         | 0.101          | 0.095 | 0.075          | 0.071 | 0.068                       | 0.063 | 0.071                           | 0.054 | 5/32                                    | 3/16  | 7/32      | 7/32      |           |           |
| 4 0.1120  | 24                         | 0.114          | 0.108 | 0.086          | 0.082 | 0.079                       | 0.074 | 0.083                           | 0.063 | 3/16                                    | 1/4   | 1/4       | 1/4       |           |           |
| 5 0.1250  | 20                         | 0.130          | 0.123 | 0.094          | 0.090 | 0.087                       | 0.082 | 0.100                           | 0.075 | 7/32                                    | 9/32  | 9/32      | 9/32      |           |           |
| 6 0.1380  | 20                         | 0.139          | 0.132 | 0.104          | 0.099 | 0.095                       | 0.089 | 0.100                           | 0.075 | 1/4                                     | 9/32  | 9/32      | 9/32      |           |           |
| 7 0.1510  | 19                         | 0.154          | 0.147 | 0.115          | 0.109 | 0.105                       | 0.099 | 0.105                           | 0.079 | 1/4                                     | 5/16  | 13/32     | 13/32     |           |           |
| 8 0.1640  | 18                         | 0.166          | 0.159 | 0.122          | 0.116 | 0.112                       | 0.106 | 0.111                           | 0.083 | 9/32                                    | 11/32 | 11/32     | 11/32     |           |           |
| 10 0.1900   | 16                         | 0.189          | 0.182 | 0.141          | 0.135 | 0.130                       | 0.123 | 0.125                           | 0.094 | 5/16                                    | 3/8   | 3/8       | 3/8       |           |           |
| 12 0.2160   | 14                         | 0.215          | 0.208 | 0.164          | 0.157 | 0.152                       | 0.145 | 0.143                           | 0.107 | 11/32                                   | 7/16  | 7/16      | 7/16      |           |           |
| 1/4 0.2500  | 14                         | 0.246          | 0.237 | 0.192          | 0.185 | 0.179                       | 0.171 | 0.143                           | 0.107 | 3/8                                     | 1/2   | 1/2       | 1/2       |           |           |
| 5/16 0.3125                                       | 12                         | 0.315          | 0.306 | 0.244          | 0.236 | 0.230                       | 0.222 | 0.167                           | 0.125 | 15/32                                   | 19/32 | 19/32     | 19/32     |           |           |
| 3/8 0.3750  | 12                         | 0.380          | 0.371 | 0.309          | 0.299 | 0.293                       | 0.285 | 0.167                           | 0.125 | 17/32                                   | 11/16 | 11/16     | 11/16     |           |           |
| 7/16 0.4375                                       | 10                         | 0.440          | 0.429 | 0.359          | 0.349 | 0.343                       | 0.335 | 0.200                           | 0.150 | 5/8                                     | 25/32 | 25/32     | 25/32     |           |           |
| 1/2 0.5000  | 10                         | 0.504          | 0.493 | 0.423          | 0.413 | 0.407                       | 0.399 | 0.200                           | 0.150 | 11/16                                   | 27/32 | 27/32     | 27/32     |           |           |

All dimensions are in inches. See Tables 1 and 2 for thread diagrams.

**Table 6. Thread and Point Dimensions for Type C Thread Forming Tapping Screws (ANSI B18.6.4–1981, R1991 Appendix)**

| Nominal Size <sup>a</sup> or Basic Screw Diameter | Threads per inch | D              |        | P                           |       | S                               |       |                 |       | L  |           |   |           |       |
|---|------------------|----------------|--------|-----------------------------|-------|---------------------------------|-------|-----------------|-------|--|-----------|---|-----------|-------|
|   |                  | Major Diameter |        | Point Diameter <sup>b</sup> |       | Point Taper Length <sup>c</sup> |       |                 |       | Determinant Lengths for Point Taper <sup>c</sup> |           | Minimum Practical Nominal Screw Lengths |           |       |
|   |                  | Max            | Min    | Max                         | Min   | For Short Screws                |       | For Long Screws |       | 90° Heads  | Csk Heads | 90° Heads                               | Csk Heads |       |
| 2   | 0.0860           | 56             | 0.0860 | 0.0813                      | 0.068 | 0.061                           | 0.062 | 0.045           | 0.080 | 0.062  | 5/32      | 3/16                                    | 5/32      | 3/16  |
| 2   | 0.0860           | 64             | 0.0860 | 0.0816                      | 0.070 | 0.064                           | 0.055 | 0.039           | 0.070 | 0.055  | 1/8       | 3/16                                    | 5/32      | 5/32  |
| 3   | 0.0990           | 48             | 0.0990 | 0.0938                      | 0.078 | 0.070                           | 0.073 | 0.052           | 0.094 | 0.073  | 5/32      | 5/32                                    | 5/32      | 5/32  |
| 3   | 0.0990           | 56             | 0.0990 | 0.0942                      | 0.081 | 0.074                           | 0.062 | 0.045           | 0.080 | 0.062  | 5/32      | 5/32                                    | 5/32      | 5/32  |
| 4   | 0.1120           | 40             | 0.1120 | 0.1061                      | 0.087 | 0.078                           | 0.088 | 0.062           | 0.112 | 0.088  | 5/32      | 1/4                                     | 5/32      | 1/4   |
| 4   | 0.1120           | 48             | 0.1120 | 0.1068                      | 0.091 | 0.083                           | 0.073 | 0.052           | 0.094 | 0.073  | 3/16      | 5/32                                    | 5/32      | 7/32  |
| 5   | 0.1250           | 40             | 0.1250 | 0.1191                      | 0.100 | 0.091                           | 0.088 | 0.062           | 0.112 | 0.088  | 5/32      | 5/32                                    | 5/32      | 1/4   |
| 5   | 0.1250           | 44             | 0.1250 | 0.1195                      | 0.102 | 0.094                           | 0.080 | 0.057           | 0.102 | 0.080  | 5/32      | 1/4                                     | 5/32      | 1/4   |
| 6   | 0.1380           | 32             | 0.1380 | 0.1312                      | 0.107 | 0.096                           | 0.109 | 0.078           | 0.141 | 0.109  | 1/4       | 5/16                                    | 1/4       | 5/16  |
| 6   | 0.1380           | 40             | 0.1380 | 0.1321                      | 0.113 | 0.104                           | 0.088 | 0.062           | 0.112 | 0.088  | 5/32      | 5/32                                    | 5/32      | 1/4   |
| 8   | 0.1640           | 32             | 0.1640 | 0.1571                      | 0.132 | 0.122                           | 0.109 | 0.078           | 0.141 | 0.109  | 1/4       | 5/16                                    | 1/4       | 5/16  |
| 8   | 0.1640           | 36             | 0.1640 | 0.1577                      | 0.136 | 0.126                           | 0.097 | 0.069           | 0.125 | 0.097  | 5/32      | 5/16                                    | 5/32      | 5/16  |
| 10  | 0.1900           | 24             | 0.1900 | 0.1818                      | 0.148 | 0.135                           | 0.146 | 0.104           | 0.188 | 0.146  | 1/2       | 5/16                                    | 5/32      | 5/16  |
| 10  | 0.1900           | 32             | 0.1900 | 0.1831                      | 0.158 | 0.148                           | 0.109 | 0.078           | 0.141 | 0.109  | 1/4       | 11/32                                   | 5/16      | 5/16  |
| 12  | 0.2160           | 24             | 0.2160 | 0.2078                      | 0.174 | 0.161                           | 0.146 | 0.104           | 0.188 | 0.146  | 11/32     | 7/16                                    | 5/16      | 13/32 |
| 12  | 0.2160           | 28             | 0.2160 | 0.2085                      | 0.180 | 0.168                           | 0.125 | 0.089           | 0.161 | 0.125  | 5/16      | 5/16                                    | 5/16      | 5/8   |
| 1/4   | 0.2500           | 20             | 0.2500 | 0.2408                      | 0.200 | 0.184                           | 0.175 | 0.125           | 0.225 | 0.175  | 13/32     | 17/32                                   | 5/8       | 1/2   |
| 1/4   | 0.2500           | 28             | 0.2500 | 0.2425                      | 0.214 | 0.202                           | 0.125 | 0.089           | 0.161 | 0.125  | 5/16      | 13/32                                   | 5/16      | 5/8   |
| 5/16  | 0.3125           | 18             | 0.3125 | 0.3026                      | 0.257 | 0.239                           | 0.194 | 0.139           | 0.250 | 0.194  | 15/32     | 17/32                                   | 5/16      | 5/16  |
| 5/16  | 0.3125           | 24             | 0.3125 | 0.3042                      | 0.271 | 0.257                           | 0.146 | 0.104           | 0.188 | 0.146  | 11/32     | 15/32                                   | 5/16      | 15/32 |
| 3/8   | 0.3750           | 16             | 0.3750 | 0.3643                      | 0.312 | 0.293                           | 0.219 | 0.156           | 0.281 | 0.219  | 1/2       | 17/16                                   | 5/8       | 5/8   |
| 3/8   | 0.3750           | 24             | 0.3750 | 0.3667                      | 0.333 | 0.319                           | 0.146 | 0.104           | 0.188 | 0.146  | 5/16      | 5/16                                    | 1/2       | 5/8   |
| 7/16  | 0.4375           | 14             | 0.4375 | 0.4258                      | 0.366 | 0.344                           | 0.250 | 0.179           | 0.321 | 0.250  | 19/32     | 3/4                                     | 9/16      | 23/32 |
| 7/16  | 0.4375           | 20             | 0.4375 | 0.4281                      | 0.387 | 0.371                           | 0.175 | 0.125           | 0.225 | 0.175  | 5/32      | 5/16                                    | 5/16      | 17/32 |
| 1/2   | 0.5000           | 13             | 0.5000 | 0.4876                      | 0.423 | 0.399                           | 0.269 | 0.192           | 0.346 | 0.269  | 5/8       | 19/32                                   | 5/8       | 3/4   |
| 1/2   | 0.5000           | 20             | 0.5000 | 0.4906                      | 0.450 | 0.433                           | 0.175 | 0.125           | 0.225 | 0.175  | 13/32     | 9/16                                    | 5/8       | 17/32 |

<sup>a</sup> Where specifying nominal size in decimals, zeros preceding decimal and in the fourth decimal place shall be omitted.

<sup>b</sup> The tabulated values apply to screw blanks before roll threading.

<sup>c</sup> Screws of these nominal lengths and shorter shall have point taper length specified above for short screws. Longer lengths shall have point taper length specified for long screws.

All dimensions are in inches. See [Table 1](#) for thread diagrams. Type C is not recommended for new designs.

Tapered threads shall have unfinished crests.

**Table 7. ANSI Standard Thread and Point Dimensions for Types D, F, G, and T  
Thread Cutting Tapping Screws ANSI B18.6.4-1981 (R1991)**

| Nominal Size <sup>a</sup> or Basic Screw Diameter | Threads per inch | D              |        | P                           |       | S                               |               |                 |       | L  |                 |   |                 |                 |                |
|---|------------------|----------------|--------|-----------------------------|-------|---------------------------------|---------------|-----------------|-------|--|-----------------|---|-----------------|-----------------|----------------|
|   |                  | Major Diameter |        | Point Diameter <sup>b</sup> |       | Point Taper Length <sup>c</sup> |               |                 |       | Determinant Lengths for Point Taper <sup>c</sup> |                 | Minimum Practical Nominal Screw Lengths |                 |                 |                |
|   |                  | Max            | Min    | Max                         | Min   | For Short Screws                |               | For Long Screws |       | 90° Heads  | Csk Heads       | 90° Heads                               | Csk Heads       |                 |                |
|   |                  |                |        |                             |       | Max                             | Min           | Max             | Min   |  |                 |   |                 |                 |                |
| 2   | 0.0860           | 56             | 0.0860 | 0.0813                      | 0.068 | 0.061                           | 0.062         | 0.045           | 0.080 | 0.062  | $\frac{5}{32}$  | $\frac{3}{16}$                          | $\frac{1}{2}$   | $\frac{3}{16}$  |                |
| 2   | 0.0860           | 64             | 0.0860 | 0.0816                      | 0.070 | 0.064                           | $\frac{1}{8}$ | 0.055           | 0.039 | 0.070  | 0.055           | $\frac{1}{8}$                           | $\frac{3}{16}$  | $\frac{5}{32}$  | $\frac{5}{32}$ |
| 3   | 0.0990           | 48             | 0.0990 | 0.0938                      | 0.078 | 0.070                           | 0.073         | 0.052           | 0.094 | 0.073  | $\frac{3}{16}$  | $\frac{7}{32}$                          | $\frac{5}{8}$   | $\frac{7}{32}$  |                |
| 3   | 0.0990           | 56             | 0.0990 | 0.0942                      | 0.081 | 0.074                           | 0.062         | 0.045           | 0.080 | 0.062  | $\frac{5}{32}$  | $\frac{3}{16}$                          | $\frac{5}{32}$  | $\frac{3}{16}$  |                |
| 4   | 0.1120           | 40             | 0.1120 | 0.1061                      | 0.087 | 0.078                           | 0.088         | 0.062           | 0.112 | 0.088  | $\frac{7}{32}$  | $\frac{3}{16}$                          | $\frac{1}{4}$   | $\frac{1}{4}$   |                |
| 4   | 0.1120           | 48             | 0.1120 | 0.1068                      | 0.091 | 0.083                           | 0.073         | 0.052           | 0.094 | 0.073  | $\frac{3}{16}$  | $\frac{7}{32}$                          | $\frac{5}{32}$  | $\frac{7}{32}$  |                |
| 5   | 0.1250           | 40             | 0.1250 | 0.1191                      | 0.100 | 0.091                           | 0.088         | 0.062           | 0.112 | 0.088  | $\frac{7}{32}$  | $\frac{3}{16}$                          | $\frac{1}{4}$   | $\frac{1}{4}$   |                |
| 5   | 0.1250           | 44             | 0.1250 | 0.1195                      | 0.102 | 0.094                           | 0.080         | 0.057           | 0.102 | 0.080  | $\frac{3}{16}$  | $\frac{1}{4}$                           | $\frac{3}{16}$  | $\frac{1}{4}$   |                |
| 6   | 0.1380           | 32             | 0.1380 | 0.1312                      | 0.107 | 0.096                           | 0.109         | 0.078           | 0.141 | 0.109  | $\frac{1}{4}$   | $\frac{5}{16}$                          | $\frac{1}{4}$   | $\frac{5}{16}$  |                |
| 6   | 0.1380           | 40             | 0.1380 | 0.1321                      | 0.113 | 0.104                           | 0.088         | 0.062           | 0.112 | 0.088  | $\frac{7}{32}$  | $\frac{9}{32}$                          | $\frac{1}{4}$   | $\frac{1}{4}$   |                |
| 8   | 0.1640           | 32             | 0.1640 | 0.1571                      | 0.132 | 0.122                           | 0.109         | 0.078           | 0.141 | 0.109  | $\frac{1}{4}$   | $\frac{11}{32}$                         | $\frac{1}{2}$   | $\frac{5}{16}$  |                |
| 8   | 0.1640           | 36             | 0.1640 | 0.1577                      | 0.136 | 0.126                           | 0.097         | 0.069           | 0.125 | 0.097  | $\frac{7}{32}$  | $\frac{5}{16}$                          | $\frac{1}{4}$   | $\frac{5}{16}$  |                |
| 10  | 0.1900           | 24             | 0.1900 | 0.1818                      | 0.148 | 0.135                           | 0.146         | 0.104           | 0.188 | 0.146  | $\frac{11}{32}$ | $\frac{7}{16}$                          | $\frac{1}{2}$   | $\frac{13}{32}$ |                |
| 10  | 0.1900           | 32             | 0.1900 | 0.1831                      | 0.158 | 0.148                           | 0.109         | 0.078           | 0.141 | 0.109  | $\frac{1}{4}$   | $\frac{11}{32}$                         | $\frac{1}{4}$   | $\frac{5}{16}$  |                |
| 12  | 0.2160           | 24             | 0.2160 | 0.2078                      | 0.174 | 0.161                           | 0.146         | 0.104           | 0.188 | 0.146  | $\frac{11}{32}$ | $\frac{11}{32}$                         | $\frac{1}{2}$   | $\frac{13}{32}$ |                |
| 12  | 0.2160           | 28             | 0.2160 | 0.2085                      | 0.180 | 0.168                           | 0.125         | 0.089           | 0.161 | 0.125  | $\frac{5}{16}$  | $\frac{11}{32}$                         | $\frac{5}{32}$  | $\frac{3}{8}$   |                |
| $\frac{1}{4}$                                     | 0.2500           | 20             | 0.2500 | 0.2408                      | 0.200 | 0.184                           | 0.175         | 0.125           | 0.225 | 0.175  | $\frac{13}{32}$ | $\frac{7}{16}$                          | $\frac{1}{2}$   | $\frac{1}{2}$   |                |
| $\frac{1}{4}$                                     | 0.2500           | 28             | 0.2500 | 0.2425                      | 0.214 | 0.202                           | 0.125         | 0.089           | 0.161 | 0.125  | $\frac{5}{16}$  | $\frac{13}{32}$                         | $\frac{9}{32}$  | $\frac{3}{8}$   |                |
| $\frac{5}{16}$                                    | 0.3125           | 18             | 0.3125 | 0.3026                      | 0.257 | 0.239                           | 0.194         | 0.139           | 0.250 | 0.194  | $\frac{15}{32}$ | $\frac{9}{16}$                          | $\frac{1}{2}$   | $\frac{9}{16}$  |                |
| $\frac{5}{16}$                                    | 0.3125           | 24             | 0.3125 | 0.3042                      | 0.271 | 0.257                           | 0.146         | 0.104           | 0.188 | 0.146  | $\frac{11}{32}$ | $\frac{15}{32}$                         | $\frac{5}{16}$  | $\frac{15}{32}$ |                |
| $\frac{3}{8}$                                     | 0.3750           | 16             | 0.3750 | 0.3643                      | 0.312 | 0.293                           | 0.219         | 0.156           | 0.281 | 0.219  | $\frac{1}{2}$   | $\frac{11}{16}$                         | $\frac{5}{32}$  | $\frac{5}{8}$   |                |
| $\frac{3}{8}$                                     | 0.3750           | 24             | 0.3750 | 0.3667                      | 0.333 | 0.319                           | 0.146         | 0.104           | 0.188 | 0.146  | $\frac{11}{32}$ | $\frac{1}{2}$                           | $\frac{1}{2}$   | $\frac{1}{2}$   |                |
| $\frac{7}{16}$                                    | 0.4375           | 14             | 0.4375 | 0.4258                      | 0.366 | 0.344                           | 0.250         | 0.179           | 0.321 | 0.250  | $\frac{19}{32}$ | $\frac{9}{16}$                          | $\frac{23}{32}$ | $\frac{23}{32}$ |                |
| $\frac{7}{16}$                                    | 0.4375           | 20             | 0.4375 | 0.4281                      | 0.387 | 0.371                           | 0.175         | 0.125           | 0.225 | 0.175  | $\frac{13}{32}$ | $\frac{9}{16}$                          | $\frac{17}{32}$ | $\frac{17}{32}$ |                |
| $\frac{1}{2}$                                     | 0.5000           | 13             | 0.5000 | 0.4876                      | 0.423 | 0.399                           | 0.269         | 0.192           | 0.346 | 0.269  | $\frac{5}{8}$   | $\frac{25}{32}$                         | $\frac{19}{32}$ | $\frac{3}{4}$   |                |
| $\frac{1}{2}$                                     | 0.5000           | 20             | 0.5000 | 0.4906                      | 0.450 | 0.433                           | 0.175         | 0.125           | 0.225 | 0.175  | $\frac{13}{32}$ | $\frac{9}{16}$                          | $\frac{3}{8}$   | $\frac{17}{32}$ |                |

<sup>a</sup> Where specifying nominal size in decimals, zeros preceding decimal and in the fourth decimal place shall be omitted.

<sup>b</sup> The tabulated values apply to screw blanks before roll threading.

<sup>c</sup> Screws of these nominal lengths and shorter shall have point taper length specified above for short screws. Longer lengths shall have point taper length specified for long screws.

All dimensions are in inches. See Table 2 for thread diagrams.

Type "Type D" otherwise designated "Type 1."

Type "Type T" otherwise designated "Type 23."

**Table 8. Approximate Hole Sizes for Type A Steel Thread Forming Screws**

| In Steel, Stainless Steel, Monel Metal, Brass, and Aluminum Sheet Metal |                 |                     |                          |            |            |                 |                     |                          |            |            |  |
|---|-----------------|---------------------|--------------------------|------------|------------|-----------------|---------------------|--------------------------|------------|------------|--|
| Screw Size  | Metal Thickness | Hole Size           |                          |            | Screw Size | Metal Thickness | Hole Size           |                          |            | Drill Size |  |
|   |                 | Pierced or Extruded | Drilled or Clean Punched | Drill Size |            |                 | Pierced or Extruded | Drilled or Clean Punched | Drill Size |            |  |
| 4   | 0.015           | ...                 | 0.086                    | 44         | 8          | 0.024           | 0.136               | 0.125                    | 1/8        |            |  |
|   | 0.018           | ...                 | 0.086                    | 44         |            | 0.030           | 0.136               | 0.125                    | 1/8        |            |  |
|   | 0.024           | 0.098               | 0.094                    | 42         |            | 0.036           | 0.136               | 0.125                    | 1/8        |            |  |
|   | 0.030           | 0.098               | 0.094                    | 42         |            | 0.048           | 0.136               | 0.128                    | 30         |            |  |
|   | 0.036           | 0.098               | 0.098                    | 40         |            | 0.018           | ...                 | 0.136                    | 29         |            |  |
| 6   | 0.015           | ...                 | 0.104                    | 37         | 10         | 0.024           | 0.157               | 0.136                    | 29         |            |  |
|   | 0.018           | ...                 | 0.104                    | 37         |            | 0.030           | 0.157               | 0.136                    | 29         |            |  |
|   | 0.024           | 0.111               | 0.104                    | 37         |            | 0.036           | 0.157               | 0.136                    | 29         |            |  |
|   | 0.030           | 0.111               | 0.104                    | 37         |            | 0.048           | 0.157               | 0.149                    | 25         |            |  |
|   | 0.036           | 0.111               | 0.106                    | 36         |            | 0.024           | ...                 | 0.161                    | 20         |            |  |
| 7   | 0.015           | ...                 | 0.116                    | 32         | 12         | 0.030           | 0.185               | 0.161                    | 20         |            |  |
|   | 0.018           | ...                 | 0.116                    | 32         |            | 0.036           | 0.185               | 0.161                    | 20         |            |  |
|   | 0.024           | 0.120               | 0.116                    | 32         |            | 0.048           | 0.185               | 0.161                    | 20         |            |  |
|   | 0.030           | 0.120               | 0.116                    | 32         |            | 0.024           | ...                 | 0.185                    | 13         |            |  |
|   | 0.036           | 0.120               | 0.116                    | 32         |            | 0.030           | 0.209               | 0.189                    | 12         |            |  |
| 8   | 0.048           | 0.120               | 0.120                    | 31         | 14         | 0.036           | 0.209               | 0.191                    | 11         |            |  |
|   | 0.018           | ...                 | 0.125                    | 1/8        |            | 0.048           | 0.209               | 0.196                    | 9          |            |  |

| In Plywood (Resin Impregnated) |           |            |                      |                            |       | In Asbestos Compositions |           |            |                      |                            |       |
|--------------------------------|-----------|------------|----------------------|----------------------------|-------|--------------------------|-----------|------------|----------------------|----------------------------|-------|
| Screw Size                     | Hole Size | Drill Size | Min. Mat'l Thickness | Penetration in Blind Holes |       | Screw Size               | Hole Size | Drill Size | Min. Mat'l Thickness | Penetration in Blind Holes |       |
|                                |           |            |                      | Min.                       | Max.  |                          |           |            |                      | Min.                       | Max.  |
| 4                              | 0.098     | 40         | 0.188                | 0.250                      | 0.750 | 4                        | 0.094     | 42         | 0.188                | 0.250                      | 0.750 |
| 6                              | 0.110     | 35         | 0.188                | 0.250                      | 0.750 | 6                        | 0.106     | 36         | 0.188                | 0.250                      | 0.750 |
| 7                              | 0.128     | 30         | 0.250                | 0.312                      | 0.750 | 7                        | 0.125     | 1/8        | 0.250                | 0.312                      | 0.750 |
| 8                              | 0.140     | 28         | 0.250                | 0.312                      | 0.750 | 8                        | 0.136     | 29         | 0.250                | 0.312                      | 0.750 |
| 10                             | 0.170     | 18         | 0.312                | 0.375                      | 1.000 | 10                       | 0.161     | 20         | 0.312                | 0.375                      | 1.000 |
| 12                             | 0.189     | 12         | 0.312                | 0.375                      | 1.000 | 12                       | 0.185     | 13         | 0.312                | 0.375                      | 1.000 |
| 14                             | 0.228     | 1          | 0.438                | 0.500                      | 1.000 | 14                       | 0.213     | 3          | 0.438                | 0.500                      | 1.000 |

Type A is not recommended, use Type AB.

See footnote at bottom of Table 9.

**Table 9. Approximate Hole Sizes for Type C Steel Thread Forming Screws**

| In Sheet Steel |                 |           |            |            |                 |           |            |            |                 |           |            |
|----------------|-----------------|-----------|------------|------------|-----------------|-----------|------------|------------|-----------------|-----------|------------|
| Screw Size     | Metal Thickness | Hole Size | Drill Size | Screw Size | Metal Thickness | Hole Size | Drill Size | Screw Size | Metal Thickness | Hole Size | Drill Size |
| 4-40           | 0.037           | 0.094     | 42         | 10-24      | 0.037           | 0.154     | 23         | 1/4-20     | 0.037           | 0.221     | 2          |
|                | 0.048           | 0.094     | 42         |            | 0.048           | 0.161     | 20         |            | 0.048           | 0.221     | 2          |
|                | 0.062           | 0.096     | 41         |            | 0.062           | 0.166     | 19         |            | 0.062           | 0.228     | 1          |
|                | 0.075           | 0.100     | 39         |            | 0.075           | 0.170     | 18         |            | 0.075           | 0.234     | A          |
|                | 0.105           | 0.102     | 38         |            | 0.105           | 0.173     | 17         |            | 0.105           | 0.234     | A          |
| 0.134          | 0.102           | 38        | 0.134      | 0.177      | 16              | 0.134     | 0.236      | 6mm        |                 |           |            |
| 6-32           | 0.037           | 0.113     | 33         | 10-32      | 0.037           | 0.170     | 18         | 1/4-28     | 0.037           | 0.224     | 5.7mm      |
|                | 0.048           | 0.116     | 32         |            | 0.048           | 0.170     | 18         |            | 0.048           | 0.228     | 1          |
|                | 0.062           | 0.116     | 32         |            | 0.062           | 0.170     | 18         |            | 0.062           | 0.232     | 5.9mm      |
|                | 0.075           | 0.122     | 3.1mm      |            | 0.075           | 0.173     | 17         |            | 0.075           | 0.234     | A          |
|                | 0.105           | 0.125     | 1/8        |            | 0.105           | 0.177     | 16         |            | 0.105           | 0.238     | B          |
| 0.134          | 0.125           | 1/8       | 0.134      | 0.177      | 16              | 0.134     | 0.238      | B          |                 |           |            |
| 8-32           | 0.037           | 0.136     | 29         | 12-24      | 0.037           | 0.189     | 12         | 5/16-18    | 0.037           | 0.290     | L          |
|                | 0.048           | 0.144     | 27         |            | 0.048           | 0.194     | 10         |            | 0.048           | 0.290     | L          |
|                | 0.062           | 0.144     | 27         |            | 0.062           | 0.194     | 10         |            | 0.062           | 0.290     | L          |
|                | 0.075           | 0.147     | 26         |            | 0.075           | 0.199     | 8          |            | 0.075           | 0.295     | M          |
|                | 0.105           | 0.150     | 25         |            | 0.105           | 0.199     | 8          |            | 0.105           | 0.295     | M          |
| 0.134          | 0.150           | 25        | 0.134      | 0.199      | 8               | 0.134     | 0.295      | M          |                 |           |            |

All dimensions are in inches except drill sizes. It may be necessary to vary the hole size to suit a particular application.

Type C is not recommended for new designs.

**Table 10. Approximate Pierced or Extruded Hole Sizes for Types AB, B, and BP Steel Thread Forming Screws**

| Screw Size  | Metal Thickness | Pierced or Extruded Hole Size | Screw Size | Metal Thickness | Pierced or Extruded Hole Size | Screw Size | Metal Thickness | Pierced or Extruded Hole Size |       |
|---|-----------------|-------------------------------|------------|-----------------|-------------------------------|------------|-----------------|-------------------------------|-------|
| In Steel, Stainless Steel, Monel Metal, and Brass Sheet Metal |                 |                               |            |                 |                               |            |                 |                               |       |
| 4   | 0.015           | 0.086                         | 7          | 0.024           | 0.120                         | 10         | 0.030           | 0.157                         |       |
|   | 0.018           | 0.086                         |            | 0.030           | 0.120                         |            | 0.036           | 0.157                         |       |
|   | 0.024           | 0.098                         |            | 0.036           | 0.120                         |            | 0.048           | 0.157                         |       |
|   | 0.030           | 0.098                         |            | 0.048           | 0.120                         |            | 12              | 0.024                         | 0.185 |
|   | 0.036           | 0.098                         |            | 0.018           | 0.136                         |            |                 | 0.030                         | 0.185 |
| 6   | 0.015           | 0.111                         | 8          | 0.024           | 0.136                         | ¼          | 0.036           | 0.209                         |       |
|   | 0.018           | 0.111                         |            | 0.030           | 0.136                         |            | 0.048           | 0.185                         |       |
|   | 0.024           | 0.111                         |            | 0.036           | 0.136                         |            | 0.030           | 0.209                         |       |
|   | 0.030           | 0.111                         |            | 0.048           | 0.136                         |            | 0.036           | 0.209                         |       |
| 7   | 0.036           | 0.111                         | 10         | 0.018           | 0.157                         | ...        | 0.048           | 0.209                         |       |
|   | 0.018           | 0.120                         |            | 0.024           | 0.157                         |            | ...             | ...                           |       |
| In Aluminum Alloy Sheet Metal                                 |                 |                               |            |                 |                               |            |                 |                               |       |
| 4   | 0.024           | 0.086                         | 6          | 0.048           | 0.111                         | 8          | 0.036           | 0.136                         |       |
|   | 0.030           | 0.086                         |            | 0.024           | 0.120                         |            | 0.048           | 0.136                         |       |
|   | 0.036           | 0.086                         | 7          | 0.030           | 0.120                         |            | 10              | 0.024                         | 0.157 |
|   | 0.048           | 0.086                         |            | 0.036           | 0.120                         |            |                 | 0.030                         | 0.157 |
| 6   | 0.024           | 0.111                         | 8          | 0.048           | 0.120                         | ...        | 0.036           | 0.157                         |       |
|   | 0.030           | 0.111                         |            | 0.024           | 0.136                         |            | 0.048           | 0.157                         |       |
|   | 0.036           | 0.111                         |            | 0.030           | 0.136                         |            | ...             | ...                           |       |

All dimensions are in inches except whole number screw and drill sizes.

Since conditions differ widely, it may be necessary to vary the hole size to suit a particular application.

**Table 11. Drilled Hole Sizes for Types AB, B, and BP Steel Thread Forming Screws**

| Screw Size  | Hole Size | Drill Size | Min. Mat'l Thickness | Penetration in Blind Holes |       | Screw Size                                   | Hole Size | Drill Size | Min. Mat'l Thickness | Penetration in Blind Holes |       |
|---|-----------|------------|----------------------|----------------------------|-------|--|-----------|------------|----------------------|----------------------------|-------|
|   |           |            |                      | Min.                       | Max.  |  |           |            |                      | Min.                       | Max.  |
| In Plywood (Resin Impregnated)  |           |            |                      |                            |       | In Asbestos Compositions                     |           |            |                      |                            |       |
| 2   | 0.073     | 49         | 0.125                | 0.188                      | 0.500 | 2  | 0.076     | 48         | 0.125                | 0.188                      | 0.500 |
| 4   | 0.100     | 39         | 0.188                | 0.250                      | 0.625 | 4  | 0.101     | 38         | 0.188                | 0.250                      | 0.625 |
| 6   | 0.125     | ⅝          | 0.188                | 0.250                      | 0.625 | 6  | 0.120     | 31         | 0.188                | 0.250                      | 0.625 |
| 7   | 0.136     | 29         | 0.188                | 0.250                      | 0.750 | 7  | 0.136     | 29         | 0.250                | 0.312                      | 0.750 |
| 8   | 0.144     | 27         | 0.188                | 0.250                      | 0.750 | 8  | 0.147     | 26         | 0.312                | 0.375                      | 0.750 |
| 10  | 0.173     | 17         | 0.250                | 0.312                      | 1.000 | 10   | 0.166     | 19         | 0.312                | 0.375                      | 1.000 |
| 12  | 0.194     | 10         | 0.312                | 0.375                      | 1.000 | 12   | 0.196     | 9          | 0.312                | 0.375                      | 1.000 |
| ¼   | 0.228     | 1          | 0.312                | 0.375                      | 1.000 | ¼  | 0.228     | 1          | 0.438                | 0.500                      | 1.000 |
| In Aluminum, Magnesium, Zinc, Brass, and Bronze Castings <sup>a</sup>         |           |            |                      |                            |       | In Phenol Formaldehyde Plastics <sup>a</sup> |           |            |                      |                            |       |
| 2   | 0.078     | 47         | ...                  | 0.125                      | ...   | 2  | 0.078     | 47         | ...                  | 0.188                      | ...   |
| 4   | 0.104     | 37         | ...                  | 0.188                      | ...   | 4  | 0.100     | 39         | ...                  | 0.250                      | ...   |
| 6   | 0.128     | 30         | ...                  | 0.250                      | ...   | 6  | 0.128     | 30         | ...                  | 0.250                      | ...   |
| 7   | 0.144     | 27         | ...                  | 0.250                      | ...   | 7  | 0.136     | 29         | ...                  | 0.250                      | ...   |
| 8   | 0.152     | 24         | ...                  | 0.250                      | ...   | 8  | 0.150     | 25         | ...                  | 0.312                      | ...   |
| 10  | 0.177     | 16         | ...                  | 0.250                      | ...   | 10   | 0.177     | 16         | ...                  | 0.312                      | ...   |
| 12  | 0.199     | 8          | ...                  | 0.281                      | ...   | 12   | 0.199     | 8          | ...                  | 0.375                      | ...   |
| ¼   | 0.234     | ⅝          | ...                  | 0.312                      | ...   | ¼  | 0.234     | ⅝          | ...                  | 0.375                      | ...   |
| In Cellulose Acetate and Nitrate, and Acrylic and Styrene Resins <sup>a</sup> |           |            |                      |                            |       |  |           |            |                      |                            |       |
| 2   | 0.078     | 47         | ...                  | 0.188                      | ...   | 8  | 0.144     | 27         | ...                  | 0.312                      | ...   |
| 4   | 0.094     | 42         | ...                  | 0.250                      | ...   | 10   | 0.170     | 18         | ...                  | 0.312                      | ...   |
| 6   | 0.120     | 31         | ...                  | 0.250                      | ...   | 12   | 0.191     | 11         | ...                  | 0.375                      | ...   |
| 7   | 0.128     | 30         | ...                  | 0.250                      | ...   | ¼  | 0.221     | 2          | ...                  | 0.375                      | ...   |

<sup>a</sup>Data below apply to Types B and BP only.

All dimensions are in inches except whole number screw and drill sizes.

Since conditions differ widely, it may be necessary to vary the hole size to suit a particular application.

**Table 12a. Approximate Drilled or Clean-Punched Hole Sizes for Types AB, B, and BP Steel Thread Forming Screws**

| Screw Size  | Metal Thickness | Hole Size | Drill Size | Screw Size | Metal Thickness | Hole Size          | Drill Size      | Screw Size      | Metal Thickness    | Hole Size          | Drill Size      |
|---|-----------------|-----------|------------|------------|-----------------|--------------------|-----------------|-----------------|--------------------|--------------------|-----------------|
| In Steel, Stainless Steel, Monel Metal, and Brass Sheet Metal |                 |           |            |            |                 |                    |                 |                 |                    |                    |                 |
| 2   | 0.015           | 0.064     | 52         | 7          | 0.018           | 0.116              | 32              | 10              | 0.125              | 0.170              | 18              |
|   | 0.018           | 0.064     | 52         |            | 0.024           | 0.116              | 32              |                 | 0.135              | 0.170              | 18              |
|   | 0.024           | 0.067     | 51         |            | 0.030           | 0.116              | 32              |                 | 0.164              | 0.173              | 17              |
|   | 0.030           | 0.070     | 50         |            | 0.036           | 0.116              | 32              | 12              | 0.024              | 0.166              | 19              |
|   | 0.036           | 0.073     | 49         |            | 0.048           | 0.120              | 31              |                 | 0.030              | 0.166              | 19              |
|   | 0.048           | 0.073     | 49         |            | 0.060           | 0.128              | 30              |                 | 0.036              | 0.166              | 19              |
| 0.060   | 0.076           | 48        | 0.075      | 0.136      | 29              | 0.048              | 0.170           |                 | 18                 |                    |                 |
| 4   | 0.015           | 0.086     | 44         | 8          | 0.105           | 0.140              | 28              |                 | 0.060              | 0.177              | 16              |
|   | 0.018           | 0.086     | 44         |            | 0.024           | 0.125              | $\frac{1}{8}$   |                 | 0.075              | 0.182              | 14              |
|   | 0.024           | 0.089     | 43         |            | 0.030           | 0.125              | $\frac{1}{8}$   | 0.105           | 0.185              | 13                 |                 |
|   | 0.030           | 0.094     | 42         |            | 0.036           | 0.125              | $\frac{1}{8}$   | 0.125           | 0.196              | 9                  |                 |
|   | 0.036           | 0.094     | 42         |            | 0.048           | 0.128              | $\frac{3}{8}$   | 0.135           | 0.196              | 9                  |                 |
|   | 0.048           | 0.096     | 41         |            | 0.060           | 0.136              | 29              | 0.164           | 0.201              | 7                  |                 |
|   | 0.060           | 0.100     | 39         |            | 0.075           | 0.140              | 28              | $\frac{1}{4}$   | 0.030              | 0.194 <sup>a</sup> | 10 <sup>a</sup> |
|   | 0.075           | 0.102     | 38         |            | 0.105           | 0.150              | 25              |                 | 0.036              | 0.194 <sup>a</sup> | 10 <sup>a</sup> |
| 6   | 0.015           | 0.104     | 37         | 10         | 0.125           | 0.150              | 25              |                 | 0.048              | 0.194 <sup>a</sup> | 10 <sup>a</sup> |
|   | 0.018           | 0.104     | 37         |            | 0.135           | 0.152              | 24              |                 | 0.060              | 0.199 <sup>a</sup> | 8 <sup>a</sup>  |
|   | 0.024           | 0.106     | 36         |            | 0.024           | 0.144              | 27              | 0.075           | 0.204 <sup>a</sup> | 6 <sup>a</sup>     |                 |
|   | 0.030           | 0.106     | 36         |            | 0.030           | 0.144              | 27              | 0.105           | 0.209              | 4                  |                 |
|   | 0.036           | 0.110     | 35         |            | 0.036           | 0.147              | 26              | 0.125           | 0.228              | 1                  |                 |
|   | 0.048           | 0.111     | 34         |            | 0.048           | 0.152 <sup>a</sup> | 24 <sup>a</sup> | 0.135           | 0.228              | 1                  |                 |
|   | 0.060           | 0.116     | 32         |            | 0.060           | 0.152 <sup>a</sup> | 24 <sup>a</sup> | 0.164           | 0.234              | $\frac{15}{64}$    |                 |
|   | 0.075           | 0.120     | 31         |            | 0.075           | 0.157              | 22              | 0.187           | 0.234              | $\frac{15}{64}$    |                 |
| 0.105   | 0.128           | 30        | 0.105      | 0.161      | 20              | 0.194              | 0.234           | $\frac{15}{64}$ |                    |                    |                 |
| In Aluminum Alloy Sheet Metal                                 |                 |           |            |            |                 |                    |                 |                 |                    |                    |                 |
| 2   | 0.024           | 0.064     | 52         | 7          | 0.060           | 0.120              | 31              | 10              | 0.164              | 0.159              | 21              |
|   | 0.030           | 0.064     | 52         |            | 0.075           | 0.128              | 30              |                 | 0.200              | 0.166              | 19              |
|   | 0.036           | 0.064     | 52         |            | 0.105           | 0.136              | 29              |                 | to                 |                    |                 |
|   | 0.048           | 0.067     | 51         |            | 0.128           | 0.136              | 29              | 0.375           | 0.048              | 0.161              | 20              |
|   | 0.060           | 0.070     | 50         |            | to              |                    |                 | 8               | 0.250              | 0.060              | 0.166           |
| 4   | 0.030           | 0.086     | 44         | 0.030      | 0.116           | 32                 | 12              |                 | 0.075              | 0.173              | 17              |
|   | 0.036           | 0.086     | 44         | 0.036      | 0.120           | 31                 |                 |                 | 0.105              | 0.180              | 15              |
|   | 0.048           | 0.086     | 44         | 0.048      | 0.128           | 30                 |                 |                 | 0.125              | 0.182              | 14              |
|   | 0.060           | 0.089     | 43         | 0.060      | 0.136           | 29                 |                 |                 | 0.135              | 0.182              | 14              |
|   | 0.075           | 0.089     | 43         | 0.075      | 0.140           | 28                 |                 |                 | 0.164              | 0.189              | 12              |
|   | 0.105           | 0.094     | 42         | 0.105      | 0.147           | 26                 |                 |                 | 0.200              | 0.196              | 9               |
| 6   | 0.030           | 0.104     | 37         | 0.125      | 0.147           | 26                 | to              |                 |                    |                    |                 |
|   | 0.036           | 0.104     | 37         | 0.135      | 0.149           | 25                 | 0.375           | 0.060           | 0.199              | 8                  |                 |
|   | 0.048           | 0.104     | 37         | 0.162      | 0.152           | 24                 | 0.075           | 0.201           | 7                  |                    |                 |
|   | 0.060           | 0.106     | 36         | to         |                 |                    | $\frac{1}{4}$   | 0.105           | 0.204              | 6                  |                 |
|   | 0.75            | 0.110     | 35         | 0.375      | 0.125           | 0.209              |                 | 4               |                    |                    |                 |
|   | 0.105           | 0.111     | 34         | 0.036      | 0.144           | 27                 |                 | 0.135           | 0.209              | 4                  |                 |
| 0.128   | 120             | 31        | 0.048      | 0.144      | 27              | 0.164              |                 | 0.213           | 3                  |                    |                 |
| to  |                 |           | 0.060      | 0.144      | 27              | 0.135              |                 | 0.213           | 3                  |                    |                 |
| 7   | 0.030           | 0.113     | 33         | 10         | 0.075           | 0.147              |                 | 26              | 0.187              | 0.213              | 3               |
|   | 0.036           | 0.113     | 33         |            | 0.105           | 0.147              | 26              | 0.194           | 0.221              | 2                  |                 |
|   | 0.048           | 0.116     | 32         |            | 0.125           | 0.154              | 23              | 0.200           | to                 | 228                |                 |
|   | 7               | 0.030     | 0.113      |            | 33              | 0.135              | 0.154           | 23              |                    |                    | 0.375           |
|   |                 | 0.048     | 0.116      |            | 32              |                    |                 |                 |                    |                    |                 |

<sup>a</sup>For Types B and BP only; for Type AB see concluded Table 12b following.

Since conditions differ widely, it may be necessary to vary the hole size to suit a particular application. Hole sizes for metal thicknesses above 0.075 inch are for Types B and BP only.

SELF-THREADING SCREWS

**Table 12b. Supplementary Data for Types AB Thread Forming Screws in Steel, Stainless Steel, Monel Metal, and Brass Sheet Metal**

| Screw Size  | Metal Thickness | Hole Size | Drill Size | Screw Size | Metal Thickness | Hole Size | Drill Size | Screw Size | Metal Thickness | Hole Size | Drill Size |
|---|-----------------|-----------|------------|------------|-----------------|-----------|------------|------------|-----------------|-----------|------------|
| In Steel, Stainless Steel, Monel Metal, and Brass Sheet Metal |                 |           |            |            |                 |           |            |            |                 |           |            |
| 10  | 0.018           | 0.144     | 27         | 1/4        | 0.018           | 0.196     | 9          | 1/4        | 0.048           | 0.205     | 5          |
| 10  | 0.048           | 0.149     | 25         | 1/4        | 0.024           | 0.196     | 9          | 1/4        | 0.060           | 0.228     | 1          |
| 10  | 0.060           | 0.154     | 23         | 1/4        | 0.030           | 0.196     | 9          | 1/4        | 0.075           | 0.232     | 5.9 mm     |
| ...   | ...             | ...       | ...        | 1/4        | 0.036           | 0.196     | 9          | ...        | ...             | ...       | ...        |

All dimensions are in inches except numbered screw and drill sizes.

**Table 13. Approximate Hole Sizes for Types D, F, G, and T Steel Thread Cutting Screws in Sheet Metals**

| Screw Size | Thick-ness | Steel     |            | Aluminum Alloy |            | Screw Size | Thick-ness | Steel     |            | Aluminum Alloy |            |       |    |
|------------|------------|-----------|------------|----------------|------------|------------|------------|-----------|------------|----------------|------------|-------|----|
|            |            | Hole Size | Drill Size | Hole Size      | Drill Size |            |            | Hole Size | Drill Size | Hole Size      | Drill Size |       |    |
| 2-56       | 0.050      | 0.073     | 49         | 0.070          | 50         | 8-32       | 0.187      | 0.150     | 25         | 0.147          | 26         |       |    |
|            | 0.060      | 0.073     | 49         | 0.073          | 49         |            | 0.250      | 0.150     | 25         | 0.150          | 25         |       |    |
|            | 0.083      | 0.073     | 49         | 0.073          | 49         |            | 0.312      | 0.150     | 25         | 0.150          | 25         |       |    |
|            | 0.109      | 0.073     | 49         | 0.073          | 49         | 10-24      | 0.050      | 0.152     | 24         | 0.150          | 25         |       |    |
|            | 0.125      | 0.076     | 48         | 0.073          | 49         |            | 0.060      | 0.154     | 23         | 0.152          | 24         |       |    |
|            | 0.140      | 0.076     | 48         | 0.073          | 49         |            | 0.083      | 0.161     | 20         | 0.154          | 23         |       |    |
| 3-48       | 0.050      | 0.081     | 46         | 0.078          | 5/64       |            | 0.109      | 0.161     | 20         | 0.157          | 22         |       |    |
|            | 0.060      | 0.081     | 46         | 0.081          | 46         |            | 0.125      | 0.166     | 19         | 0.159          | 21         |       |    |
|            | 0.083      | 0.082     | 45         | 0.082          | 45         |            | 0.140      | 0.170     | 18         | 0.161          | 20         |       |    |
|            | 0.109      | 0.086     | 44         | 0.082          | 45         | 0.187      | 0.173      | 17        | 0.166      | 19             |            |       |    |
|            | 0.125      | 0.086     | 44         | 0.082          | 45         | 0.250      | 0.173      | 17        | 0.172      | 19/64          |            |       |    |
|            | 0.140      | 0.086     | 44         | 0.086          | 44         | 0.312      | 0.173      | 17        | 0.173      | 17             |            |       |    |
| 4-40       | 0.050      | 0.089     | 43         | 0.089          | 43         | 10-32      | 0.050      | 0.159     | 21         | 0.161          | 20         |       |    |
|            | 0.060      | 0.089     | 43         | 0.089          | 43         |            | 0.060      | 0.166     | 19         | 0.161          | 20         |       |    |
|            | 0.083      | 0.094     | 42         | 0.089          | 43         |            | 0.083      | 0.166     | 19         | 0.161          | 20         |       |    |
|            | 0.109      | 0.096     | 41         | 0.094          | 42         |            | 0.109      | 0.170     | 18         | 0.166          | 19         |       |    |
|            | 0.125      | 0.098     | 40         | 0.094          | 42         |            | 0.125      | 0.170     | 18         | 0.166          | 19         |       |    |
|            | 0.140      | 0.098     | 40         | 0.094          | 42         |            | 0.140      | 0.170     | 18         | 0.166          | 19         |       |    |
| 5-40       | 0.187      | 0.102     | 38         | 0.098          | 40         | 0.187      | 0.177      | 16        | 0.172      | 19/64          |            |       |    |
|            | 6-32       | 0.050     | 0.106      | 36             | 0.102      | 38         | 12-24      | 0.250     | 0.177      | 16             | 0.177      | 16    |    |
|            |            | 0.060     | 0.106      | 36             | 0.102      | 38         |            | 0.312     | 0.177      | 16             | 0.177      | 16    |    |
|            |            | 0.083     | 0.106      | 36             | 0.104      | 37         |            | 0.375     | 0.177      | 16             | 0.177      | 16    |    |
|            |            | 0.109     | 0.106      | 36             | 0.104      | 37         |            | 10-24     | 0.060      | 0.180          | 15         | 0.177 | 16 |
|            |            | 0.125     | 0.109      | 35             | 0.106      | 36         |            |           | 0.083      | 0.182          | 14         | 0.180 | 15 |
| 0.140      |            | 0.110     | 35         | 0.106          | 36         | 0.109      |            |           | 0.188      | 3/16           | 0.182      | 14    |    |
| 0.187      | 0.116      | 32        | 0.110      | 35             | 0.125      | 0.191      | 11         |           | 0.185      | 13             |            |       |    |
| 0.250      | 0.116      | 32        | 0.113      | 33             | 0.140      | 0.191      | 11         |           | 0.188      | 3/16           |            |       |    |
| 8-32       | 0.050      | 0.110     | 35         | 0.109          | 3/64       | 1/4-20     | 0.187      |           | 0.199      | 8              | 0.191      | 11    |    |
|            | 0.060      | 0.113     | 33         | 0.109          | 3/64       |            | 0.250      | 0.199     | 8          | 0.199          | 8          |       |    |
|            | 0.083      | 0.116     | 32         | 0.111          | 34         |            | 0.312      | 0.199     | 8          | 0.199          | 8          |       |    |
|            | 0.109      | 0.116     | 32         | 0.113          | 33         |            | 0.375      | 0.199     | 8          | 0.199          | 8          |       |    |
|            | 0.125      | 0.116     | 32         | 0.116          | 32         |            | 0.500      | 0.199     | 8          | 0.199          | 8          |       |    |
|            | 0.140      | 0.120     | 31         | 0.116          | 32         |            | 1/4-20     | 0.083     | 0.213      | 3              | 0.206      | 5     |    |
| 0.187      | 0.125      | 1/8       | 0.120      | 31             | 0.109      | 0.219      |            | 3/32      | 0.209      | 4              |            |       |    |
| 0.250      | 0.125      | 1/8       | 0.125      | 1/8            | 0.125      | 0.221      |            | 2         | 0.213      | 3              |            |       |    |
| 8-32       | 0.050      | 0.136     | 29         | 0.136          | 29         | 0.140      |            | 0.221     | 2          | 0.213          | 3          |       |    |
|            | 0.060      | 0.140     | 28         | 0.136          | 29         | 0.187      |            | 0.228     | 1          | 0.221          | 2          |       |    |
|            | 0.083      | 0.140     | 28         | 0.136          | 29         | 0.250      |            | 0.228     | 1          | 0.228          | 1          |       |    |
|            | 0.109      | 0.144     | 27         | 0.140          | 28         | 0.312      | 0.228      | 1         | 0.228      | 1              |            |       |    |
|            | 0.125      | 0.144     | 27         | 0.140          | 28         | 0.375      | 0.228      | 1         | 0.228      | 1              |            |       |    |
|            | 0.140      | 0.147     | 26         | 0.144          | 27         | 0.500      | 0.228      | 1         | 0.228      | 1              |            |       |    |

**Table 13. (Continued) Approximate Hole Sizes for Types D, F, G, and T Steel Thread Cutting Screws in Sheet Metals**

| Screw Size | Thick-ness | Steel     |            | Aluminum Alloy |            | Screw Size | Thick-ness | Steel     |            | Aluminum Alloy |            |       |
|------------|------------|-----------|------------|----------------|------------|------------|------------|-----------|------------|----------------|------------|-------|
|            |            | Hole Size | Drill Size | Hole Size      | Drill Size |            |            | Hole Size | Drill Size | Hole Size      | Drill Size |       |
| 1/4-28     | 0.083      | 0.221     | 2          | 0.219          | 3/32       | 3/16-24    | 0.187      | 0.295     | M          | 0.290          | L          |       |
|            | 0.109      | 0.228     | 1          | 0.221          | 2          |            | 0.250      | 0.295     | M          | 0.295          | M          |       |
|            | 0.125      | 0.228     | 1          | 0.221          | 2          |            | 0.312      | 0.295     | M          | 0.295          | M          |       |
|            | 0.140      | 0.234     | A          | 0.221          | 2          |            | 0.375      | 0.295     | M          | 0.295          | M          |       |
|            | 0.187      | 0.234     | 15/64      | 0.228          | 1          |            | 0.500      | 0.295     | M          | 0.295          | M          |       |
|            | 0.250      | 0.234     | 15/64      | 0.234          | 15/64      |            | 3/8-16     | 0.125     | 0.339      | R              | 0.328      | 21/64 |
|            | 0.312      | 0.234     | 15/64      | 0.234          | 15/64      |            |            | 0.140     | 0.339      | R              | 0.332      | Q     |
|            | 0.375      | 0.234     | 15/64      | 0.234          | 15/64      |            |            | 0.187     | 0.348      | S              | 0.339      | R     |
| 0.500      | 0.234      | 15/64     | 0.234      | 15/64          | 0.250      | 0.358      |            | T         | 0.348      | S              |            |       |
| 5/16-18    | 0.109      | 0.277     | J          | 0.266          | H          | 0.312      |            | 0.358     | T          | 0.348          | S          |       |
|            | 0.125      | 0.277     | J          | 0.272          | I          | 0.375      |            | 0.358     | T          | 0.348          | S          |       |
|            | 0.140      | 0.281     | 3/32       | 0.272          | I          | 0.500      | 0.358      | T         | 0.348      | S              |            |       |
|            | 0.187      | 0.290     | L          | 0.281          | K          | 5/8-24     | 0.125      | 0.348     | S          | 0.344          | 11/32      |       |
|            | 0.250      | 0.290     | L          | 0.290          | L          |            | 0.140      | 0.348     | S          | 0.344          | 11/32      |       |
|            | 0.312      | 0.290     | L          | 0.290          | L          |            | 0.187      | 0.358     | T          | 0.348          | S          |       |
|            | 0.375      | 0.290     | L          | 0.290          | L          |            | 0.250      | 0.358     | T          | 0.358          | T          |       |
| 0.500      | 0.290      | L         | 0.290      | L              | 0.312      |            | 0.358      | T         | 0.358      | T              |            |       |
| 5/16-24    | 0.109      | 0.290     | L          | 0.281          | K          |            | 0.375      | 0.358     | T          | 0.358          | T          |       |
|            | 0.125      | 0.290     | L          | 0.281          | 3/32       | 0.500      | 0.358      | T         | 0.358      | T              |            |       |
|            | 0.140      | 0.290     | L          | 0.281          | 3/32       | ...        | ...        | ...       | ...        | ...            |            |       |

All dimensions are in inches except numbered drill and screw sizes. It may be necessary to vary the hole size to suit a particular application.

**Table 14. Approximate Hole Sizes for Types D, F, G, and T Steel Thread Cutting Screws in Cast Metals and Plastics**

| Screw Size | Thick-ness | Cast Iron |            | Zinc and Aluminum <sup>a</sup> |            | Screw Size | Thick-ness | Cast Iron |            | Zinc and Aluminum <sup>a</sup> |            |
|------------|------------|-----------|------------|--------------------------------|------------|------------|------------|-----------|------------|--------------------------------|------------|
|            |            | Hole Size | Drill Size | Hole Size                      | Drill Size |            |            | Hole Size | Drill Size | Hole Size                      | Drill Size |
| 2-56       | 0.050      | 0.076     | 48         | 0.073                          | 49         | 5-40       | 0.083      | 0.113     | 33         | 0.106                          | 36         |
|            | 0.060      | 0.076     | 48         | 0.073                          | 49         |            | 0.109      | 0.113     | 33         | 0.110                          | 35         |
|            | 0.083      | 0.076     | 48         | 0.076                          | 48         |            | 0.125      | 0.116     | 32         | 0.110                          | 35         |
|            | 0.109      | 0.078     | 5/64       | 0.076                          | 48         |            | 0.140      | 0.116     | 32         | 0.110                          | 35         |
|            | 0.125      | 0.078     | 5/64       | 0.076                          | 48         |            | 0.187      | 0.116     | 32         | 0.111                          | 34         |
|            | 0.140      | 0.078     | 5/64       | 0.076                          | 48         |            | 0.250      | 0.116     | 32         | 0.113                          | 33         |
| 3-48       | 0.050      | 0.089     | 43         | 0.082                          | 45         | 6-32       | 0.050      | 0.120     | 31         | 0.116                          | 32         |
|            | 0.060      | 0.089     | 43         | 0.082                          | 45         |            | 0.060      | 0.120     | 31         | 0.120                          | 31         |
|            | 0.083      | 0.089     | 43         | 0.082                          | 45         |            | 0.083      | 0.125     | 1/8        | 0.120                          | 31         |
|            | 0.109      | 0.089     | 43         | 0.086                          | 44         |            | 0.109      | 0.125     | 1/8        | 0.120                          | 31         |
|            | 0.125      | 0.089     | 43         | 0.089                          | 43         |            | 0.125      | 0.125     | 1/8        | 0.120                          | 31         |
|            | 0.140      | 0.094     | 42         | 0.089                          | 43         |            | 0.140      | 0.125     | 1/8        | 0.120                          | 31         |
|            | 0.187      | 0.094     | 42         | 0.089                          | 43         |            | 0.187      | 0.128     | 30         | 0.120                          | 31         |
| 4-40       | 0.050      | 0.100     | 39         | 0.090                          | 41         | 8-32       | 0.250      | 0.128     | 30         | 0.120                          | 31         |
|            | 0.060      | 0.100     | 39         | 0.096                          | 41         |            | 0.050      | 0.147     | 26         | 0.144                          | 27         |
|            | 0.083      | 0.102     | 38         | 0.096                          | 41         |            | 0.060      | 0.150     | 25         | 0.144                          | 27         |
|            | 0.109      | 0.102     | 38         | 0.096                          | 41         |            | 0.083      | 0.150     | 25         | 0.144                          | 27         |
|            | 0.125      | 0.102     | 38         | 0.100                          | 39         |            | 0.109      | 0.150     | 25         | 0.144                          | 27         |
|            | 0.140      | 0.102     | 38         | 0.100                          | 39         |            | 0.125      | 0.150     | 25         | 0.147                          | 26         |
|            | 0.187      | 0.104     | 37         | 0.100                          | 39         |            | 0.140      | 0.150     | 25         | 0.147                          | 26         |
| 5-40       | 0.050      | 0.111     | 34         | 0.106                          | 36         | 0.187      | 0.154      | 23        | 0.147      | 26                             |            |
|            | 0.060      | 0.111     | 34         | 0.106                          | 36         | 0.250      | 0.154      | 23        | 0.150      | 25                             |            |
|            |            |           |            |                                |            | 0.312      | 0.154      | 23        | 0.150      | 25                             |            |



**Table 14. (Continued) Approximate Hole Sizes for Types D, F, G, and T Steel Thread Cutting Screws in Cast Metals and Plastics**

| Screw Size | Thick-ness | Cast Iron |            | Zinc and Aluminum <sup>a</sup> |            | Screw Size | Thick-ness | Cast Iron |            | Zinc and Aluminum <sup>a</sup> |            |   |
|------------|------------|-----------|------------|--------------------------------|------------|------------|------------|-----------|------------|--------------------------------|------------|---|
|            |            | Hole Size | Drill Size | Hole Size                      | Drill Size |            |            | Hole Size | Drill Size | Hole Size                      | Drill Size |   |
| 10-24      | 0.050      | 0.170     | 18         | 0.161                          | 20         | 1/4-28     | 0.083      | 0.234     | A          | 0.228                          | 1          |   |
|            | 0.060      | 0.170     | 18         | 0.166                          | 19         |            | 0.109      | 0.234     | 15/64      | 0.228                          | 1          |   |
|            | 0.083      | 0.172     | 1 1/64     | 0.166                          | 19         |            | 0.125      | 0.234     | 15/64      | 0.228                          | 1          |   |
|            | 0.109      | 0.173     | 17         | 0.166                          | 19         |            | 0.140      | 0.234     | 15/64      | 0.228                          | 1          |   |
|            | 0.125      | 0.173     | 17         | 0.166                          | 19         |            | 0.187      | 0.238     | B          | 0.228                          | 1          |   |
|            | 0.140      | 0.173     | 17         | 0.166                          | 19         |            | 0.250      | 0.238     | B          | 0.234                          | A          |   |
|            | 0.187      | 0.177     | 16         | 0.170                          | 18         |            | 0.312      | 0.238     | B          | 0.234                          | A          |   |
|            | 0.250      | 0.177     | 16         | 0.170                          | 18         |            | 0.375      | 0.238     | B          | 0.234                          | 15/64      |   |
|            | 0.312      | 0.177     | 16         | 0.172                          | 1 1/64     |            | 0.500      | 0.238     | B          | 0.234                          | 15/64      |   |
|            | 0.375      | 0.177     | 16         | 0.172                          | 1 1/64     |            | 5/16-18    | 0.109     | 0.290      | L                              | 0.277      | J |
| 0.050      | 0.173      | 17        | 0.170      | 18                             | 0.125      | 0.290      |            | L         | 0.281      | K                              |            |   |
| 0.060      | 0.173      | 17        | 0.170      | 18                             | 0.140      | 0.290      |            | L         | 0.281      | K                              |            |   |
| 0.083      | 0.177      | 16        | 0.172      | 1 1/64                         | 0.187      | 0.295      |            | M         | 0.281      | 3/32                           |            |   |
| 0.109      | 0.177      | 16        | 0.172      | 1 1/64                         | 0.250      | 0.295      |            | M         | 0.281      | 3/32                           |            |   |
| 0.125      | 0.177      | 16        | 0.172      | 1 1/64                         | 0.312      | 0.295      |            | M         | 0.290      | L                              |            |   |
| 0.140      | 0.177      | 16        | 0.172      | 1 1/64                         | 0.375      | 0.295      |            | M         | 0.290      | L                              |            |   |
| 0.187      | 0.180      | 15        | 0.172      | 1 1/64                         | 0.500      | 0.295      |            | M         | 0.290      | L                              |            |   |
| 0.250      | 0.180      | 15        | 0.173      | 17                             | 3/16-24    | 0.109      |            | 0.295     | M          | 0.290                          | L          |   |
| 0.312      | 0.180      | 15        | 0.173      | 17                             |            | 0.125      |            | 0.295     | M          | 0.290                          | L          |   |
| 0.375      | 0.180      | 15        | 0.177      | 16                             |            | 0.140      | 0.295      | M         | 0.290      | L                              |            |   |
| 0.060      | 0.196      | 9         | 0.189      | 12                             |            | 0.187      | 0.302      | N         | 0.290      | L                              |            |   |
| 0.083      | 0.199      | 8         | 0.191      | 11                             |            | 0.250      | 0.302      | N         | 0.290      | L                              |            |   |
| 0.109      | 0.199      | 8         | 0.191      | 11                             |            | 0.312      | 0.302      | N         | 0.295      | M                              |            |   |
| 0.125      | 0.199      | 8         | 0.191      | 11                             |            | 0.375      | 0.302      | N         | 0.295      | M                              |            |   |
| 0.140      | 0.199      | 8         | 0.194      | 10                             |            | 0.500      | 0.302      | N         | 0.295      | M                              |            |   |
| 0.187      | 0.203      | 1 1/64    | 0.194      | 10                             |            | 3/8-16     | 0.125      | 0.348     | S          | 0.339                          | R          |   |
| 0.250      | 0.204      | 6         | 0.196      | 9                              |            |            | 0.140      | 0.348     | S          | 0.339                          | R          |   |
| 0.312      | 0.204      | 6         | 0.196      | 9                              | 0.187      |            | 0.348      | S         | 0.339      | R                              |            |   |
| 0.375      | 0.204      | 6         | 0.199      | 8                              | 0.250      |            | 0.348      | S         | 0.344      | 1/32                           |            |   |
| 0.500      | 0.204      | 6         | 0.199      | 8                              | 0.312      |            | 0.348      | S         | 0.344      | 1/32                           |            |   |
| 1/4-20     | 0.083      | 0.228     | 1          | 0.219                          | 3/32       |            | 0.375      | 0.348     | S          | 0.348                          | S          |   |
|            | 0.109      | 0.228     | 1          | 0.219                          | 3/32       |            | 0.500      | 0.348     | S          | 0.348                          | S          |   |
|            | 0.125      | 0.228     | 1          | 0.221                          | 2          |            | 5/8-24     | 0.125     | 0.358      | T                              | 0.348      | S |
|            | 0.140      | 0.228     | 1          | 0.221                          | 2          |            |            | 0.140     | 0.358      | T                              | 0.348      | S |
|            | 0.187      | 0.234     | 1 1/64     | 0.221                          | 2          |            |            | 0.187     | 0.358      | T                              | 0.348      | S |
|            | 0.250      | 0.234     | 1 1/64     | 0.228                          | 1          | 0.250      |            | 0.358     | T          | 0.358                          | T          |   |
|            | 0.312      | 0.234     | 1 1/64     | 0.228                          | 1          | 0.312      |            | 0.358     | T          | 0.358                          | T          |   |
|            | 0.375      | 0.234     | 1 1/64     | 0.228                          | 1          | 0.375      |            | 0.358     | T          | 0.358                          | T          |   |
|            | 0.500      | 0.234     | 1 1/64     | 0.228                          | 1          | 0.500      |            | 0.358     | T          | 0.358                          | T          |   |

<sup>a</sup> Die Castings

| Screw Size | Phenol Formaldehyde <sup>a</sup> |            |                      |       | Cellulose Acetate, Cellulose Nitrate, Acrylic Resin, and Styrene Resin <sup>a</sup> |            |                      |       |
|------------|----------------------------------|------------|----------------------|-------|---|------------|----------------------|-------|
|            | Hole Size                        | Drill Size | Depth of Penetration |       | Hole Size   | Drill Size | Depth of Penetration |       |
|            |                                  |            | Min                  | Max   |   |            | Min                  | Max   |
| 2-56       | 0.078                            | 5/64       | 0.219                | 0.375 | 0.076   | 48         | 0.219                | 0.375 |
| 3-48       | 0.089                            | 43         | 0.219                | 0.375 | 0.086   | 44         | 0.219                | 0.375 |
| 4-40       | 0.098                            | 40         | 0.250                | 0.312 | 0.093   | 42         | 0.250                | 0.312 |
| 5-40       | 0.113                            | 33         | 0.250                | 0.438 | 0.110   | 35         | 0.250                | 0.438 |
| 6-32       | 0.116                            | 32         | 0.250                | 0.312 | 0.116   | 32         | 0.250                | 0.312 |
| 8-32       | 0.144                            | 27         | 0.312                | 0.500 | 0.144   | 27         | 0.312                | 0.500 |
| 10-24      | 0.161                            | 20         | 0.375                | 0.500 | 0.161   | 20         | 0.375                | 0.500 |
| 10-32      | 0.166                            | 19         | 0.375                | 0.500 | 0.166   | 19         | 0.375                | 0.500 |
| 1/4-20     | 0.228                            | 1          | 0.375                | 0.625 | 0.228   | 1          | 0.375                | 1.000 |

<sup>a</sup> Plastics

For footnotes see Table 13.

**Table 15. Approximate Hole Sizes for Types BF and BT Steel Thread Cutting Screws in Cast Metals**

| In Die Cast Zinc and Aluminum |           |           |               |                |           |           |                  |
|-------------------------------|-----------|-----------|---------------|----------------|-----------|-----------|------------------|
| Screw Size                    | Thickness | Hole Size | Drill Size    | Screw Size     | Thickness | Hole Size | Drill Size       |
| 2                             | 0.060     | 0.073     | 49            | 10             | 0.125     | 0.166     | 19               |
|                               | 0.083     | 0.073     | 49            |                | 0.140     | 0.166     | 19               |
|                               | 0.109     | 0.076     | 48            |                | 0.188     | 0.166     | 19               |
|                               | 0.125     | 0.076     | 48            |                | 0.250     | 0.170     | 18               |
|                               | 0.140     | 0.076     | 48            |                | 0.312     | 0.172     | 1 $\frac{1}{64}$ |
| 3                             | 0.060     | 0.086     | 44            | 12             | 0.375     | 0.172     | 1 $\frac{1}{64}$ |
|                               | 0.083     | 0.086     | 44            |                | 0.125     | 0.191     | 11               |
|                               | 0.109     | 0.086     | 44            |                | 0.140     | 0.191     | 11               |
|                               | 0.125     | 0.086     | 44            |                | 0.188     | 0.191     | 11               |
|                               | 0.140     | 0.089     | 43            |                | 0.250     | 0.196     | 9                |
| 4                             | 0.188     | 0.089     | 43            | $\frac{1}{4}$  | 0.312     | 0.196     | 9                |
|                               | 0.109     | 0.098     | 40            |                | 0.375     | 0.196     | 9                |
|                               | 0.125     | 0.100     | 39            |                | 0.125     | 0.221     | 2                |
|                               | 0.140     | 0.100     | 39            |                | 0.140     | 0.221     | 2                |
|                               | 0.188     | 0.100     | 39            |                | 0.188     | 0.221     | 2                |
| 5                             | 0.250     | 0.102     | 38            | $\frac{5}{16}$ | 0.250     | 0.228     | 1                |
|                               | 0.109     | 0.111     | 34            |                | 0.312     | 0.228     | 1                |
|                               | 0.125     | 0.111     | 34            |                | 0.375     | 0.228     | 1                |
|                               | 0.140     | 0.113     | 33            |                | 0.125     | 0.281     | K                |
|                               | 0.188     | 0.113     | 33            |                | 0.140     | 0.281     | K                |
| 6                             | 0.250     | 0.116     | 32            | $\frac{3}{8}$  | 0.188     | 0.281     | K                |
|                               | 0.125     | 0.120     | 31            |                | 0.250     | 0.281     | K                |
|                               | 0.140     | 0.120     | 31            |                | 0.312     | 0.290     | L                |
|                               | 0.188     | 0.120     | 31            |                | 0.375     | 0.290     | L                |
|                               | 0.250     | 0.125     | $\frac{1}{8}$ |                | 0.125     | 0.344     | 1 $\frac{1}{32}$ |
| 8                             | 0.312     | 0.125     | $\frac{1}{8}$ | $\frac{7}{8}$  | 0.140     | 0.344     | 1 $\frac{1}{32}$ |
|                               | 0.125     | 0.149     | 25            |                | 0.188     | 0.344     | 1 $\frac{1}{32}$ |
|                               | 0.140     | 0.149     | 25            |                | 0.250     | 0.344     | 1 $\frac{1}{32}$ |
|                               | 0.188     | 0.149     | 25            |                | 0.312     | 0.348     | S                |
|                               | 0.250     | 0.152     | 24            |                | 0.375     | 0.348     | S                |
|                               | 0.312     | 0.152     | 24            |                | ...       | ...       | ...              |

All dimensions are in inches except numbered drill and screw sizes. It may be necessary to vary the hole size to suit a particular application.

**Table 16. Approximate Hole Size for Types BF and BT Steel Thread Cutting Screws in Plastics**

| Screw Size    | Phenol Formaldehyde |                |                      |       | Cellulose Acetate, Cellulose Nitrate, Acrylic Resin and Styrene Resin |            |                      |       |
|---------------|---------------------|----------------|----------------------|-------|---|------------|----------------------|-------|
|               | Hole Size           | Drill Size     | Depth of Penetration |       | Hole Size   | Drill Size | Depth of Penetration |       |
|               |                     |                | Min                  | Max   |   |            | Min                  | Max   |
| 2             | 0.078               | $\frac{5}{64}$ | 0.094                | 0.250 | 0.076   | 48         | 0.094                | 0.250 |
| 3             | 0.089               | 43             | 0.125                | 0.312 | 0.089   | 43         | 0.125                | 0.312 |
| 4             | 0.104               | 37             | 0.125                | 0.312 | 0.100   | 39         | 0.125                | 0.312 |
| 5             | 0.116               | 32             | 0.188                | 0.375 | 0.113   | 33         | 0.188                | 0.375 |
| 6             | 0.125               | $\frac{1}{8}$  | 0.188                | 0.375 | 0.120   | 31         | 0.188                | 0.375 |
| 8             | 0.147               | 26             | 0.250                | 0.500 | 0.144   | 27         | 0.250                | 0.500 |
| 10            | 0.170               | 18             | 0.312                | 0.625 | 0.166   | 19         | 0.312                | 0.625 |
| 12            | 0.194               | 10             | 0.375                | 0.625 | 0.189   | 12         | 0.375                | 0.625 |
| $\frac{1}{4}$ | 0.228               | 1              | 0.375                | 0.750 | 0.221   | 2          | 0.375                | 0.750 |

For footnotes see above table.

**Table 17. Approximate Hole Sizes for Type U Hardened Steel Metallic Drive Screws**

| In Ferrous and Non-Ferrous Castings, Sheet Metals, Plastics,<br>Plywood (Resin-Impregnated) and Fiber |           |            |            |           |            |                |           |            |
|---|-----------|------------|------------|-----------|------------|----------------|-----------|------------|
| Screw Size  | Hole Size | Drill Size | Screw Size | Hole Size | Drill Size | Screw Size     | Hole Size | Drill Size |
| 00  | .052      | 55         | 6          | .120      | 31         | 12             | .191      | 11         |
| 0   | .067      | 51         | 7          | .136      | 29         | 14             | .221      | 2          |
| 2   | .086      | 44         | 8          | .144      | 27         | $\frac{5}{16}$ | .295      | M          |
| 4   | .104      | 37         | 10         | .161      | 20         | $\frac{3}{8}$  | .358      | T          |

All dimensions are in inches except whole number screw and drill sizes and letter drill sizes.

**Table 18. ANSI Standard Torsional Strength Requirements for Tapping Screws  
ANSI B18.6.4-1981 (R1991)**

| Nom. Screw Size | Type A | Types AB, B, BF, BP, and BT | Types C, D, F, G, and T |             | Nom-Screw Size | Type A | Types AB, B, BF, BP, and BT | Types C, D, F, G, and T |             |
|-----------------|--------|-----------------------------|-------------------------|-------------|----------------|--------|-----------------------------|-------------------------|-------------|
|                 |        |                             | Coarse Thread           | Fine Thread |                |        |                             | Coarse Thread           | Fine Thread |
| 2               | 4      | 4                           | 5                       | 6           | $\frac{1}{4}$  | ...    | 142                         | 140                     | 179         |
| 3               | 9      | 9                           | 9                       | 10          | 16             | 152    | ...                         | ...                     | ...         |
| 4               | 12     | 13                          | 13                      | 15          | 18             | 196    | ...                         | ...                     | ...         |
| 5               | 18     | 18                          | 18                      | 20          | $\frac{5}{16}$ | ...    | 290                         | 306                     | 370         |
| 6               | 24     | 24                          | 23                      | 27          | 20             | 250    | ...                         | ...                     | ...         |
| 7               | 30     | 30                          | ...                     | ...         | 24             | 492    | ...                         | ...                     | ...         |
| 8               | 39     | 39                          | 42                      | 47          | $\frac{3}{8}$  | ...    | 590                         | 560                     | 710         |
| 10              | 48     | 56                          | 56                      | 74          | $\frac{7}{16}$ | ...    | 620                         | 700                     | 820         |
| 12              | 83     | 88                          | 93                      | 108         | $\frac{1}{2}$  | ...    | 1020                        | 1075                    | 1285        |
| 14              | 125    | ...                         | ...                     | ...         | ...            | ...    | ...                         | ...                     | ...         |

Torsional strength data are in pound-inches.

**Self-tapping Thread Inserts.**—Self-tapping screw thread inserts are essentially hard bushings with internal and external threads. The internal threads conform to Unified and American standard classes 2B and 3B, depending on the type of insert used. The external thread has cutting edges on the end that provide the self-tapping feature. These inserts may be used in magnesium, aluminum, cast iron, zinc, plastics, and other materials. Self-tapping inserts are made of case-hardened carbon steel, stainless steel, and brass, the brass type being designed specifically for installation in wood.

**Screw Thread Inserts.**—Screw thread inserts are helically formed coils of diamond-shaped stainless steel or phosphor bronze wire that screw into a threaded hole to form a mating internal thread for a screw or stud. These inserts provide a convenient means of repairing stripped-out threads and are also used to provide stronger threads in soft materials such as aluminum, zinc die castings, wood, magnesium, etc. than can be obtained by direct tapping of the base metal involved.

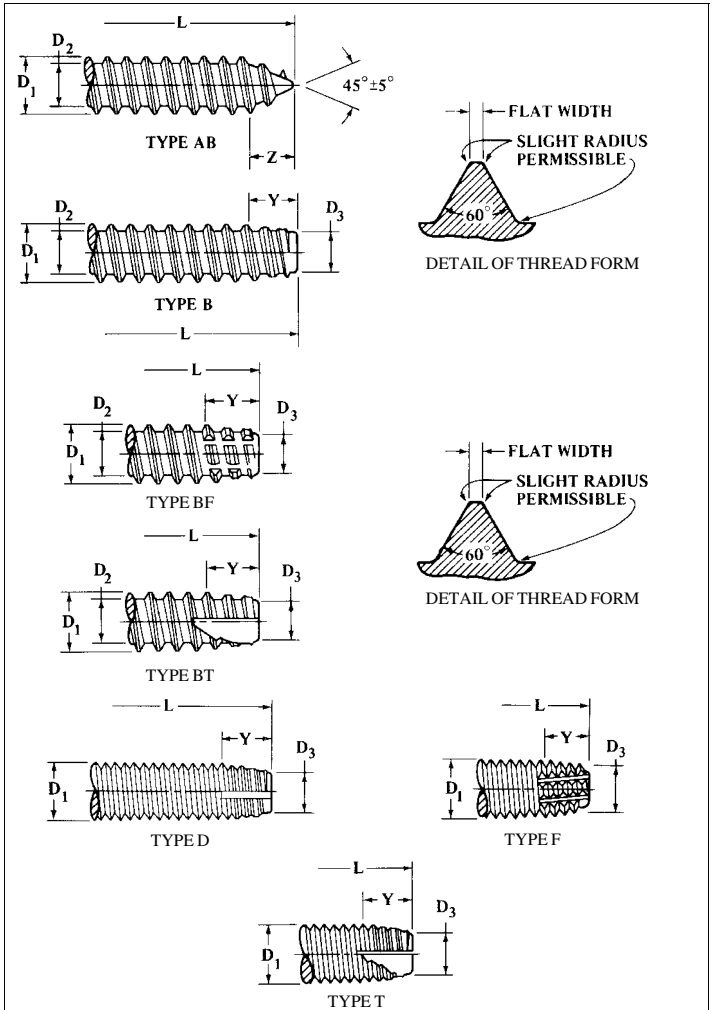
According to the Heli-Coil Corp., conventional design practice in specifying boss diameters or edge distances can usually be applied since the major diameter of a hole tapped to receive a thread insert is not much larger than the major diameter of thread the insert provides.

Screw thread inserts are available in thread sizes from 4–40 to  $1\frac{1}{2}$ –6 inch National and Unified Coarse Thread Series and in 6–40 to  $1\frac{1}{2}$ –12 sizes in the fine-thread series. When used in conjunction with appropriate taps and gages, screw thread inserts will meet requirements of 2, 2B, 3, and 3B thread classes.

**ANSI Standard Metric Thread Forming and Thread Cutting Tapping Screws.**—

Table 1 shows the various types of metric thread forming and thread cutting screw threads covered by the standard ANSI/ASME B18.6.5M-1986. The designations of the American National Standards Institute are shown.

**Table 1. ANSI Standard Threads and Points for Metric Thread Forming and Thread Cutting Tapping Screws ANSI/ASME B18.6.5M-1986**



See Tables 3 and 4 for thread data.

**Thread Forming Tapping Screws:** These types are generally for application in materials where large internal stresses are permissible or desirable, to increase resistance to loosening. These screws have the following descriptions and applications:

*Type AB:* Spaced thread screw with gimlet point primarily intended for use in thin metal, resin impregnated plywood, and asbestos compositions.

*Type B:* Spaced thread screw with a blunt point that has tapered entering threads with unfinished crests and same pitches as Type AB. Used for thin metal, nonferrous castings, resin impregnated plywood, certain resilient plastics, and asbestos compositions.

*Thread Cutting Tapping Screws:* These screws are generally for application in materials where disruptive internal stresses are undesirable or where excessive driving torques are encountered with thread forming tapping screws. These screws have the following descriptions and applications:

*Types BF and BT:* Spaced threads with blunt point and tapered entering threads having unfinished crests, as on Type B, with one or more cutting edges or chip cavities, intended for use in plastics, asbestos compositions, and other similar materials.

*Types D, F, and T:* Tapping screws with threads of machine screw diameter-pitch combinations (metric coarse thread series) approximating a 60 degree basic thread form (not necessarily conforming to any standard thread profile) with a blunt point and tapered entering threads with unfinished crests and having one or more cutting edges and chip cavities, intended for use in materials such as aluminum, zinc, and lead die castings; steel sheets and shapes; cast iron; brass; and plastics.

**ANSI Standard Head Types for Metric Thread Forming and Cutting Tapping Screws.**—The head types covered by ANSI/ASME B18.6.5M-1986 include those commonly applicable to metric tapping screws and are described as follows:

*Flat Countersunk Head:* The flat countersunk head has a flat top surface and a conical bearing surface with a head angle of 90 to 92 degrees.

*Oval Countersunk Head:* The oval countersunk head has a rounded top surface and a conical bearing surface with a head angle of 90 to 92 degrees.

*Pan Head:* The slotted pan head has a flat top surface rounding into cylindrical sides and a flat bearing surface. The recessed pan head has a rounded top surface blending into cylindrical sides and a flat bearing surface.

*Hex Head:* The hex head has a flat or indented top surface, six flat sides, and a flat bearing surface.

*Hex Flange Head:* The hex flange head has a flat or indented top surface and six flat sides formed integrally with a frustroconical or slightly rounded (convex) flange that projects beyond the sides and provides a flat bearing surface.

**Method of Designation.**—Metric tapping screws are designated with the following data, preferably in the sequence shown: Nominal size; thread pitch; nominal length; thread and point type; product name, including head style and driving provision; material; and protective finish, if required.

*Examples:*

6.3 × 1.8 × 30 Type AB, Slotted Pan Head Tapping Screw, Steel, Zinc Plated

6 × 1 × 20 Type T, Type 1A Cross Recessed Pan Head Tapping Screw, Corrosion Resistant Steel

4.2 × 1.4 × 13 Type BF, Type 1 Cross Recessed Oval Countersunk Head Tapping Screw, Steel, Chromium Plated

10 × 1.5 × 40 Type D, Hex Flange Head Tapping Screw, Steel

**Table 2. Recommended Nominal Screw Lengths for Metric Tapping Screws  
ANSI/ASME B18.6.5M-1986**

| Nominal Screw Length | Nominal Screw Size for Types AB, B, BF, and BT |     |     |     |     |     |     |     |    |     |
|----------------------|--|-----|-----|-----|-----|-----|-----|-----|----|-----|
|                      | 2.2  | -   | 2.9 | 3.5 | 4.2 | 4.8 | 5.5 | 6.3 | 8  | 9.5 |
|                      | Nominal Screw Size for Types D, F, and T       |     |     |     |     |     |     |     |    |     |
|                      | 2  | 2.5 | 3   | 3.5 | 4   | 5   | -   | 6   | 8  | 10  |
| 4                    | PH   | PH  |     |     |     |     |     |     |    |     |
| 5                    | PH   | PH  |     |     |     |     |     |     |    |     |
| 6                    | A  | A   | PH  |     |     |     |     |     |    |     |
| 8                    | A  | A   | A   | PH  | PH  |     |     |     |    |     |
| 10                   | A  | A   | A   | A   | A   | PH  |     |     |    |     |
| 13                   | A  | A   | A   | A   | A   | A   | A   | PH  |    |     |
| 16                   |  | A   | A   | A   | A   | A   | A   | A   | PH |     |
| 20                   |  |     |     | A   | A   | A   | A   | A   | A  | PH  |
| 25                   |  |     |     | A   | A   | A   | A   | A   | A  | A   |
| 30                   |  |     |     |     |     | A   | A   | A   | A  | A   |
| 35                   |  |     |     |     |     | A   | A   | A   | A  | A   |
| 40                   |  |     |     |     |     |     | A   | A   | A  | A   |
| 45                   |  |     |     |     |     |     |     | A   | A  | A   |
| 50                   |  |     |     |     |     |     |     |     | A  | A   |
| 55                   |  |     |     |     |     |     |     |     |    | A   |
| 60                   |  |     |     |     |     |     |     |     |    | A   |

**Table 3. ANSI Standard Thread and Point Dimensions for Types AB and B Metric Thread Forming Tapping Screws ANSI/ASME B18.6.5M-1986**

| Nominal Screw Size and Thread Pitch <sup>a</sup> | Basic Screw Diameter | Basic Thread Pitch | D <sub>1</sub>        |                  | D <sub>2</sub>        |      | D <sub>3</sub>              |      | Y                                      |     | Z                           | L  |                  |        |        |
|--|----------------------|--------------------|-----------------------|------------------|-----------------------|------|-----------------------------|------|--|-----|-----------------------------|--|------------------|--------|--------|
|  |                      |                    | Thread Major Diameter |                  | Thread Minor Diameter |      | Point Diameter <sup>b</sup> |      | Point Taper Length Type B <sup>c</sup> |     | Point Length Factor Type AB | Min. Practical Nominal Screw Length <sup>d</sup> |                  |        |        |
|  |                      |                    |                       |                  |                       |      |                             |      |  |     |                             | Type AB  |                  | Type B |        |
|  |                      |                    | Ref <sup>e</sup>      | Ref <sup>e</sup> | Max                   | Min  | Max                         | Min  | Max                                    | Min | Max                         | Min  | Ref <sup>f</sup> | Note 7 | Note 8 |
| 2.2 × 0.8  | 2.184                | 0.79               | 2.24                  | 2.10             | 1.63                  | 1.52 | 1.47                        | 1.37 | 1.6                                    | 1.2 | 2.0                         | 4  | 6                | 4      | 5      |
| 2.9 × 1  | 2.845                | 1.06               | 2.90                  | 2.76             | 2.18                  | 2.08 | 2.01                        | 1.88 | 2.1                                    | 1.6 | 2.6                         | 6  | 7                | 5      | 7      |
| 3.5 × 1.3  | 3.505                | 1.27               | 3.53                  | 3.35             | 2.64                  | 2.51 | 2.41                        | 2.26 | 2.5                                    | 1.9 | 3.2                         | 7  | 9                | 6      | 8      |
| 4.2 × 1.4  | 4.166                | 1.41               | 4.22                  | 4.04             | 3.10                  | 2.95 | 2.84                        | 2.69 | 2.8                                    | 2.1 | 3.7                         | 8  | 10               | 7      | 10     |
| 4.8 × 1.6  | 4.826                | 1.59               | 4.80                  | 4.62             | 3.58                  | 3.43 | 3.30                        | 3.12 | 3.2                                    | 2.4 | 4.3                         | 9  | 12               | 8      | 11     |
| 5.5 × 1.8  | 5.486                | 1.81               | 5.46                  | 5.28             | 4.17                  | 3.99 | 3.86                        | 3.68 | 3.6                                    | 2.7 | 5.0                         | 11   | 14               | 9      | 12     |
| 6.3 × 1.8  | 6.350                | 1.81               | 6.25                  | 6.03             | 4.88                  | 4.70 | 4.55                        | 4.34 | 3.6                                    | 2.7 | 6.0                         | 12   | 16               | 10     | 13     |
| 8 × 2.1  | 7.938                | 2.12               | 8.00                  | 7.78             | 6.20                  | 5.99 | 5.84                        | 5.64 | 4.2                                    | 3.2 | 7.5                         | 16   | 20               | 12     | 17     |
| 9.5 × 2.1  | 9.525                | 2.12               | 9.65                  | 9.43             | 7.85                  | 7.59 | 7.44                        | 7.24 | 4.2                                    | 3.2 | 8.0                         | 19   | 24               | 14     | 19     |

<sup>a</sup> The body diameter (unthreaded portion) is not less than the minimum minor diameter nor greater than the maximum major diameter of the thread.

<sup>b</sup> The tabulated values shall apply to screw blanks prior to roll threading.

<sup>c</sup> The tabulated maximum limits are equal to approximately two times the thread pitch.

<sup>d</sup> Lengths shown are theoretical minimums and are intended to assist the user in the selection of appropriate short screw lengths. Refer to Table 2 for recommended diameter-length combinations.

<sup>e</sup> Basic screw diameter and basic thread pitch shall be used for calculation purposes wherever these factors appear in formulations for dimensions.

<sup>f</sup> The minimum effective grip length on Type AB tapping screws shall be determined by subtracting the point length factor from the minimum screw length.

All dimensions are in millimeters. See Table 1 for thread diagrams.

<sup>7</sup> Pan, hex, and hex flange heads.

<sup>8</sup> Flat and oval countersunk heads.

**Table 4. ANSI Standard Thread and Point Dimensions for Types BF, BT, D, F, and T Metric Thread Cutting Tapping Screws ANSI/ASME B18.6.5M-1986**

| Types BF and BT                     |                      |                    |                       |                  |                       |      |                             |      |  |     |   |     |
|-------------------------------------|----------------------|--------------------|-----------------------|------------------|-----------------------|------|-----------------------------|------|--|-----|---|-----|
| Nominal Screw Size and Thread Pitch | Basic Screw Diameter | Basic Thread Pitch | D <sub>1</sub>        |                  | D <sub>2</sub>        |      | D <sub>3</sub>              |      | Y                                      |     | L   |     |
|                                     |                      |                    | Thread Major Diameter |                  | Thread Minor Diameter |      | Point Diameter <sup>a</sup> |      | Point Taper Length Type B <sup>b</sup> |     | Minimal Practical Nominal Screw Length <sup>c</sup> |     |
|                                     |                      |                    | Ref <sup>d</sup>      | Ref <sup>d</sup> | Max                   | Min  | Max                         | Min  | Max                                    | Min | Max   | Min |
| 2.2 × 0.8                           | 2.184                | 0.79               | 2.24                  | 2.10             | 1.63                  | 1.52 | 1.47                        | 1.37 | 1.6                                    | 1.2 | 4   | 5   |
| 2.9 × 1                             | 2.845                | 1.06               | 2.90                  | 2.76             | 2.18                  | 2.08 | 2.01                        | 1.88 | 2.1                                    | 1.6 | 5   | 7   |
| 3.5 × 1.3                           | 3.505                | 1.27               | 3.53                  | 3.35             | 2.64                  | 2.51 | 2.41                        | 2.26 | 2.5                                    | 1.9 | 6   | 8   |
| 4.2 × 1.4                           | 4.166                | 1.41               | 4.22                  | 4.04             | 3.10                  | 2.95 | 2.84                        | 2.69 | 2.8                                    | 2.1 | 7   | 10  |
| 4.8 × 1.6                           | 4.826                | 1.59               | 4.80                  | 4.62             | 3.58                  | 3.43 | 3.30                        | 3.12 | 3.2                                    | 2.4 | 8   | 11  |
| 5.5 × 1.8                           | 5.486                | 1.81               | 5.46                  | 5.28             | 4.17                  | 3.99 | 3.86                        | 3.68 | 3.6                                    | 2.7 | 9   | 12  |
| 6.3 × 1.8                           | 6.350                | 1.81               | 6.25                  | 6.03             | 4.88                  | 4.70 | 4.55                        | 4.34 | 3.6                                    | 2.7 | 10  | 13  |
| 8 × 2.1                             | 7.938                | 2.12               | 8.00                  | 7.78             | 6.20                  | 5.99 | 5.84                        | 5.64 | 4.2                                    | 3.2 | 12  | 17  |
| 9.5 × 2.1                           | 9.525                | 2.12               | 9.65                  | 9.43             | 7.85                  | 7.59 | 7.44                        | 7.24 | 4.2                                    | 3.2 | 14  | 19  |

<sup>a</sup> The tabulated values apply to screw blanks prior to roll threading.

<sup>b</sup> The tabulated maximum limits are equal to approximately two times the thread pitch.

<sup>c</sup> Lengths shown are theoretical minimums and are intended to assist in the selection of appropriate short screw lengths. See Table 2 for recommended length-diameter combinations. For Types D, F, and T, shorter screws are available with the point length reduced to the limits tabulated for short screws.

<sup>d</sup> Basic screw diameter and basic thread pitch are used for calculation purposes whenever these factors appear in formulations for dimensions.

| Types D, F, T                       |                       |      |                             |      |                |                    |                  |     |                              |   |                               |                           |
|-------------------------------------|-----------------------|------|-----------------------------|------|----------------|--------------------|------------------|-----|------------------------------|---|-------------------------------|---------------------------|
| Nominal Screw Size and Thread Pitch | D <sub>1</sub>        |      | D <sub>3</sub>              |      | D <sub>5</sub> | Y                  |                  |     |                              | L   |                               |                           |
|                                     | Thread Major Diameter |      | Point Diameter <sup>a</sup> |      |                | Point Taper Length |                  |     |                              | Minimum Practical Nominal Screw Length <sup>c</sup> |                               |                           |
|                                     | Max                   | Min  | Max                         | Min  |                | Min                | For Short Screws |     | For Long Screws <sup>b</sup> |   | Pan, Hex and Hex Flange Heads | Flat and Oval CsunK Heads |
| Max                                 | Min                   | Max  | Min                         | Min  | Max            | Min                | Max              | Min |                              |   |                               |                           |
| 2 × 0.4                             | 2.00                  | 1.88 | 1.45                        | 1.39 | 1.65           | 1.4                | 1.0              | 1.8 | 1.4                          | 4   | 5                             |                           |
| 2.5 × 0.45                          | 2.50                  | 2.37 | 1.88                        | 1.82 | 2.12           | 1.6                | 1.1              | 2.0 | 1.6                          | 4   | 6                             |                           |
| 3 × 0.5                             | 3.00                  | 2.87 | 2.32                        | 2.26 | 2.58           | 1.8                | 1.3              | 2.3 | 1.8                          | 5   | 6                             |                           |
| 3.5 × 0.6                           | 3.50                  | 3.35 | 2.68                        | 2.60 | 3.00           | 2.1                | 1.5              | 2.7 | 2.1                          | 5   | 8                             |                           |
| 4 × 0.7                             | 4.00                  | 3.83 | 3.07                        | 2.97 | 3.43           | 2.5                | 1.8              | 3.2 | 2.5                          | 6   | 9                             |                           |
| 5 × 0.8                             | 5.00                  | 4.82 | 3.94                        | 3.84 | 4.36           | 2.8                | 2.0              | 3.6 | 2.8                          | 7   | 10                            |                           |
| 6 × 1                               | 6.00                  | 5.79 | 4.69                        | 4.55 | 5.21           | 3.5                | 2.5              | 4.5 | 3.5                          | 9   | 12                            |                           |
| 8 × 1.25                            | 8.00                  | 7.76 | 6.40                        | 6.24 | 7.04           | 4.4                | 3.1              | 5.6 | 4.4                          | 11  | 16                            |                           |
| 10 × 1.5                            | 10.00                 | 9.73 | 8.08                        | 7.88 | 8.86           | 5.3                | 3.8              | 6.8 | 5.3                          | 13  | 18                            |                           |

<sup>a</sup> Minimum limits for body diameter (unthreaded portion) are tabulated for convenient reference. For Types BF and BT, the body diameter is not less than the minimum minor diameter nor greater than the maximum major diameter of the thread.

<sup>b</sup> Long screws are screws of nominal lengths equal to or longer than those listed under L.

All dimensions are in millimeters. See Table 1 for thread diagrams.

**Material and Heat Treatment.**—Tapping screws are normally fabricated from carbon steel and are suitably processed to meet the performance and test requirements outlined in the standard, B18.6.5M. Tapping screws may also be made from corrosion resistant steel, Monel, brass, and aluminum alloys. The materials, properties, and performance characteristics applicable to such screws should be mutually agreed upon between the manufacturer and the purchaser.

**Table 5. Clearance Holes for Metric Tapping Screws  
ANSI/ASME B18.6.5M-1986 Appendix**

| Nominal Screw Size and Thread Pitch | Basic Clearance Hole Diameter <sup>a</sup> |   |                              | Nominal Screw Size and Thread Pitch | Basic Clearance Hole Diameter <sup>a</sup> |   |                              |
|-------------------------------------|--|---|------------------------------|-------------------------------------|--|---|------------------------------|
|                                     | Close Clearance <sup>b</sup>               | Normal Clearance (Preferred) <sup>b</sup> | Loose Clearance <sup>b</sup> |                                     | Close Clearance <sup>b</sup>               | Normal Clearance (Preferred) <sup>b</sup> | Loose Clearance <sup>b</sup> |
| Types AB, B, BF, and BT             |  |   |                              | Types D, F, and T                   |  |   |                              |
| 2.2 × 0.8                           | 2.40                                       | 2.60                                      | 2.80                         | 2 × 0.4                             | 2.20                                       | 2.40                                      | 2.60                         |
| 2.9 × 1                             | 3.10                                       | 3.30                                      | 3.50                         | 2.5 × 0.45                          | 2.70                                       | 2.90                                      | 3.10                         |
| 3.5 × 1.3                           | 3.70                                       | 3.90                                      | 4.20                         | 3 × 0.5                             | 3.20                                       | 3.40                                      | 3.60                         |
| 4.2 × 1.4                           | 4.50                                       | 4.70                                      | 5.00                         | 3.5 × 0.6                           | 3.70                                       | 3.90                                      | 4.20                         |
| 4.8 × 1.6                           | 5.10                                       | 5.30                                      | 5.60                         | 4 × 0.7                             | 4.30                                       | 4.50                                      | 4.80                         |
| 5.5 × 1.8                           | 5.90                                       | 6.10                                      | 6.50                         | 5 × 0.8                             | 5.30                                       | 5.50                                      | 5.80                         |
| 6.3 × 1.8                           | 6.70                                       | 6.90                                      | 7.30                         | 6 × 1                               | 6.40                                       | 6.60                                      | 7.00                         |
| 8 × 2.1                             | 8.40                                       | 9.00                                      | 10.00                        | 8 × 1.25                            | 8.40                                       | 9.00                                      | 10.00                        |
| 9.5 × 2.1                           | 10.00                                      | 10.50                                     | 11.50                        | 10 × 1.5                            | 10.50                                      | 11.00                                     | 12.00                        |

<sup>a</sup> The values given in this table are minimum limits. The recommended plus tolerances are as follows: for clearance hole diameters over 1.70 to and including 5.80 mm, plus 0.12, 0.20, and 0.30 mm for close, normal, and loose clearances, respectively; over 5.80 to and including 14.50 mm, plus 0.18, 0.30, and 0.45 mm for close, normal, and loose clearances, respectively.

<sup>b</sup> Normal clearance hole sizes are preferred. Close clearance hole sizes are for situations such as critical alignment of assembled components, wall thickness, or other limitations that necessitate the use of a minimal hole. Countersinking or counterboring at the fastener entry side may be necessary for the proper seating of the head. Loose clearance hole sizes are for applications where maximum adjustment capability between the components being assembled is necessary.

All dimensions are in millimeters.

**Approximate Installation Hole Sizes for Metric Tapping Screws.**—The approximate hole sizes given in Tables 7 through 9 provide general guidance in selecting holes for installing the respective types of metric thread forming and thread cutting tapping screws in various commonly used materials. Types AB, B, BF, and BT metric tapping screws are covered in these tables; hole sizes for Types D, F, and T metric thread cutting tapping screws are still under development.

**Table 6. Approximate Pierced or Extruded Hole Sizes for Steel Types AB and B Metric Thread Forming Tapping Screws**

| Nominal Screw Size and Thread Pitch                     | Metal Thickness | Hole Size | Nominal Screw Size and Thread Pitch | Metal Thickness | Hole Size | Nominal Screw Size and Thread Pitch | Metal Thickness | Hole Size |
|---|-----------------|-----------|-------------------------------------|-----------------|-----------|-------------------------------------|-----------------|-----------|
| In Steel, Stainless Steel, Monel, and Brass Sheet Metal |                 |           |                                     |                 |           |                                     |                 |           |
| 2.9 × 1   | 0.38            | 2.18      | 4.2 × 1.4                           | 0.46            | 3.45      | 5.5 × 1.8                           | 0.61            | 4.70      |
|   | 0.46            | 2.18      |                                     | 0.61            | 3.45      |                                     | 0.76            | 4.70      |
|   | 0.61            | 2.49      |                                     | 0.76            | 3.45      |                                     | 0.91            | 4.70      |
|   | 0.76            | 2.49      |                                     | 0.91            | 3.45      |                                     | 1.22            | 4.70      |
|   | 0.91            | 2.49      |                                     | 1.22            | 3.45      |                                     | ...             | ...       |
| 3.5 × 1.3   | 0.38            | 2.82      | 4.8 × 1.6                           | 0.46            | 3.99      | 6.3 × 1.8                           | 0.76            | 5.31      |
|   | 0.46            | 2.82      |                                     | 0.61            | 3.99      |                                     | 0.91            | 5.31      |
|   | 0.61            | 2.82      |                                     | 0.76            | 3.99      |                                     | 1.22            | 5.31      |
|   | 0.76            | 2.82      |                                     | 0.91            | 3.99      |                                     | ...             | ...       |
|   | 0.91            | 2.82      |                                     | 1.22            | 3.99      |                                     | ...             | ...       |
| In Aluminum Alloy                                       |                 |           |                                     |                 |           |                                     |                 |           |
| 2.9 × 1   | 0.61            | 2.18      | 3.5 × 1.3                           | 0.91            | 2.82      | 4.8 × 1.6                           | 0.61            | 3.99      |
|   | 0.76            | 2.18      |                                     | 1.22            | 2.82      |                                     | 0.76            | 3.99      |
|   | 0.91            | 2.18      | 4.2 × 1.4                           | 0.61            | 3.45      |                                     | 0.91            | 3.99      |
|   | 1.22            | 2.18      |                                     | 0.76            | 3.45      |                                     | 1.22            | 3.99      |
| 3.5 × 1.3   | 0.61            | 2.82      | 4.2 × 1.4                           | 0.91            | 3.45      | ...                                 | ...             |           |
|   | 0.76            | 2.82      |                                     | 1.22            | 3.45      | ...                                 | ...             |           |

All dimensions are in millimeters.



**Table 7. Approximate Drilled or Clean-Punched Hole Sizes for Steel Type AB Metric Thread Forming Tapping Screws in Sheet Metal**

| Nominal Screw Size and Thread Pitch                     | Metal Thickness | Hole Size | Drill Size <sup>a</sup> | Nominal Screw Size and Thread Pitch | Metal Thickness | Hole Size | Drill Size <sup>a</sup> | Nominal Screw Size and Thread Pitch | Metal Thickness | Hole Size | Drill Size <sup>a</sup> |
|---|-----------------|-----------|-------------------------|-------------------------------------|-----------------|-----------|-------------------------|-------------------------------------|-----------------|-----------|-------------------------|
| In Steel, Stainless Steel, Monel, and Brass Sheet Metal |                 |           |                         |                                     |                 |           |                         |                                     |                 |           |                         |
| 2.2 × 0.8   | 0.38            | 1.63      | 52                      | 3.5 × 1.3                           | 0.61            | 2.69      | 36                      | 4.8 × 1.6                           | 1.22            | 3.78      | 25                      |
|   | 0.46            | 1.63      | 52                      |                                     | 0.76            | 2.69      | 36                      |                                     | 1.52            | 3.91      | 23                      |
|   | 0.61            | 1.70      | 51                      |                                     | 0.91            | 2.79      | 35                      |                                     | 1.90            | 3.99      | 22                      |
|   | 0.76            | 1.78      | 50                      |                                     | 1.22            | 2.82      | 34                      | 5.5 × 1.8                           | 0.46            | ...       | ...                     |
|   | 0.91            | 1.85      | 49                      |                                     | 1.52            | 2.95      | 32                      |                                     | 0.61            | 4.22      | 19                      |
|   | 1.22            | 1.85      | 49                      |                                     | 1.90            | 3.05      | 31                      |                                     | 0.76            | 4.22      | 19                      |
|   | 1.52            | 1.93      | 48                      |                                     | 0.46            | ...       | ...                     |                                     | 0.91            | 4.22      | 19                      |
| 2.9 × 1   | 0.38            | 2.18      | 44                      | 4.2 × 1.4                           | 0.61            | 3.18      | ...                     | 6.3 × 1.8                           | 1.22            | 4.32      | 18                      |
|   | 0.46            | 2.18      | 44                      |                                     | 0.76            | 3.18      | ...                     |                                     | 1.52            | 4.50      | 16                      |
|   | 0.61            | 2.26      | 43                      |                                     | 0.91            | 3.18      | ...                     |                                     | 1.90            | 4.62      | 14                      |
|   | 0.76            | 2.39      | 42                      |                                     | 1.22            | 3.25      | 30                      | 0.46                                | 4.98            | 9         |                         |
|   | 0.91            | 2.39      | 42                      |                                     | 1.52            | 3.45      | 29                      | 0.61                                | 4.98            | 9         |                         |
|   | 1.22            | 2.44      | 41                      | 1.90                                | 3.56            | 28        | 0.76                    | 4.98                                | 9               |           |                         |
|   | 1.52            | 2.54      | 39                      | 4.8 × 1.6                           | 0.46            | 3.66      | 27                      | 0.91                                | 4.98            | 9         |                         |
| 1.90  | 2.59            | 38        | 0.61                    |                                     | 3.66            | 27        | 1.22                    | 5.21                                | W               |           |                         |
| 3.5 × 1.3   | 0.38            | 2.64      | 37                      | 4.8 × 1.6                           | 0.76            | 3.66      | 27                      | 6.3 × 1.8                           | 1.52            | 5.79      | 1                       |
|   | 0.46            | 2.64      | 37                      |                                     | 0.91            | 3.73      | 26                      |                                     | 1.90            | 5.89      | ...                     |
| In Aluminum Alloy Sheet Metal                           |                 |           |                         |                                     |                 |           |                         |                                     |                 |           |                         |
| 2.2 × 0.8   | 0.38            | ...       | ...                     | 3.5 × 1.3                           | 0.61            | ...       | ...                     | 4.8 × 1.6                           | 1.22            | 3.66      | 27                      |
|   | 0.46            | ...       | ...                     |                                     | 0.76            | 2.64      | 37                      |                                     | 1.52            | 3.66      | 27                      |
|   | 0.61            | 1.63      | 52                      |                                     | 0.91            | 2.64      | 37                      |                                     | 1.90            | 3.73      | 26                      |
|   | 0.76            | 1.63      | 52                      |                                     | 1.22            | 2.64      | 37                      | 5.5 × 1.8                           | 0.46            | ...       | ...                     |
|   | 0.91            | 1.63      | 52                      |                                     | 1.52            | 2.69      | 36                      |                                     | 0.61            | ...       | ...                     |
|   | 1.22            | 1.70      | 51                      |                                     | 1.90            | 2.79      | 35                      |                                     | 0.76            | ...       | ...                     |
|   | 1.52            | 1.78      | 50                      |                                     | 0.46            | ...       | ...                     |                                     | 0.91            | ...       | ...                     |
| 2.9 × 1   | 0.38            | ...       | ...                     | 4.2 × 1.4                           | 0.61            | ...       | ...                     | 6.3 × 1.8                           | 1.22            | 4.09      | 20                      |
|   | 0.46            | ...       | ...                     |                                     | 0.76            | 2.95      | 32                      |                                     | 1.52            | 4.22      | 19                      |
|   | 0.61            | ...       | ...                     |                                     | 0.91            | 3.05      | 31                      |                                     | 1.90            | 4.39      | 17                      |
|   | 0.76            | 2.18      | 44                      |                                     | 1.22            | 3.25      | 30                      | 0.46                                | ...             | ...       |                         |
|   | 0.91            | 2.18      | 44                      |                                     | 1.52            | 3.45      | 29                      | 0.61                                | ...             | ...       |                         |
|   | 1.22            | 2.18      | 44                      | 1.90                                | 3.56            | 28        | 0.76                    | ...                                 | ...             |           |                         |
|   | 1.52            | 2.26      | 43                      | 4.8 × 1.6                           | 0.46            | ...       | ...                     | 0.91                                | ...             | ...       |                         |
| 1.90  | 2.26            | 43        | 0.61                    |                                     | ...             | ...       | 1.22                    | ...                                 | ...             |           |                         |
| 3.5 × 1.3   | 0.38            | ...       | ...                     | 4.8 × 1.6                           | 0.76            | ...       | ...                     | 6.3 × 1.8                           | 1.52            | 5.05      | 8                       |
|   | 0.46            | ...       | ...                     |                                     | 0.91            | 3.66      | 27                      |                                     | 1.90            | 5.11      | 7                       |

<sup>a</sup> Customary drill size references have been retained where the metric hole diameters are direct conversions of their decimal inch equivalents.

All dimensions are in millimeters except drill sizes.

**Table 8. Approximate Hole Sizes for Steel Type AB Metric Thread Forming Tapping Screws in Plywoods and Asbestos**

| Nominal Screw Size and Thread Pitch | Hole Size | Drill Size <sup>a</sup> | Min Mat'l Thickness | Penetration in Blind Holes |       | Hole Size                | Drill Size <sup>a</sup> | Min Mat'l Thickness | Penetration in Blind Holes |       |  |
|-------------------------------------|-----------|-------------------------|---------------------|----------------------------|-------|--------------------------|-------------------------|---------------------|----------------------------|-------|--|
|                                     |           |                         |                     | Min                        | Max   |                          |                         |                     | Min                        | Max   |  |
| In Plywood (Resin Impregnated)      |           |                         |                     |                            |       | In Asbestos Compositions |                         |                     |                            |       |  |
| 2.2 × 0.8                           | 1.85      | 49                      | 3.18                | 4.78                       | 12.70 | 1.93                     | 48                      | 3.18                | 4.78                       | 12.70 |  |
| 2.9 × 1                             | 2.54      | 39                      | 4.78                | 6.35                       | 15.88 | 2.57                     | 38                      | 4.78                | 6.35                       | 15.88 |  |
| 3.5 × 1.3                           | 3.18      | ...                     | 4.78                | 6.35                       | 15.88 | 3.05                     | 31                      | 4.78                | 6.35                       | 15.88 |  |
| 4.2 × 1.4                           | 3.66      | 27                      | 4.78                | 6.35                       | 19.05 | 3.73                     | 26                      | 7.92                | 9.52                       | 19.05 |  |
| 4.8 × 1.6                           | 4.39      | 17                      | 6.35                | 7.92                       | 25.40 | 4.22                     | 19                      | 7.92                | 9.52                       | 25.40 |  |
| 5.5 × 1.8                           | 4.93      | 10                      | 7.92                | 9.52                       | 25.40 | 4.98                     | 9                       | 7.92                | 9.52                       | 25.40 |  |
| 6.3 × 1.8                           | 5.79      | 1                       | 7.92                | 9.52                       | 25.40 | 5.79                     | 1                       | 11.13               | 12.70                      | 25.40 |  |

<sup>a</sup> Customary drill size references have been retained where the metric hole diameters are direct conversions of their decimal inch equivalents.

All dimensions are in millimeters except drill sizes.

**Table 9. Approximate Hole Sizes for Steel Type B Metric Thread Forming Tapping Screws in Plywoods, Asbestos, and Plastics**

| Nominal Screw Size and Thread Pitch | Hole Size | Drill Size <sup>a</sup> | Min Mat'l Thickness | Penetration in Blind Holes |       | Nominal Screw Size and Thread Pitch | Hole Size | Drill Size <sup>a</sup> | Min Mat'l Thickness | Penetration in Blind Holes |       |
|-------------------------------------|-----------|-------------------------|---------------------|----------------------------|-------|-------------------------------------|-----------|-------------------------|---------------------|----------------------------|-------|
|                                     |           |                         |                     | Min                        | Max   |                                     |           |                         |                     | Min                        | Max   |
| In Plywood (Resin Impregnated)      |           |                         |                     |                            |       |                                     |           |                         |                     |                            |       |
| 2.2 × 0.8                           | 1.85      | 49                      | 3.18                | 4.78                       | 12.70 | 4.8 × 1.6                           | 4.39      | 17                      | 6.35                | 7.92                       | 25.40 |
| 2.9 × 1                             | 2.54      | 39                      | 4.78                | 6.35                       | 15.88 | 5.5 × 1.8                           | 4.93      | 10                      | 7.92                | 9.52                       | 25.40 |
| 3.5 × 1.3                           | 3.18      | ...                     | 4.78                | 6.35                       | 15.88 | 6.3 × 1.8                           | 5.79      | 1                       | 7.92                | 9.52                       | 25.40 |
| 4.2 × 1.4                           | 3.66      | 27                      | 4.78                | 6.35                       | 19.05 | ...                                 | ...       | ...                     | ...                 | ...                        | ...   |

<sup>a</sup> Customary drill size references have been retained where the metric hole diameters are direct conversions of their decimal inch equivalents.

| Nominal Screw Size and Thread Pitch | Hole Size | Drill Size <sup>a</sup> | Min Mat'l Thickness | Penetration in Blind Holes |       |
|-------------------------------------|-----------|-------------------------|---------------------|----------------------------|-------|
|                                     |           |                         |                     | Min                        | Max   |
| In Asbestos Compositions            |           |                         |                     |                            |       |
| 2.2 × 0.8                           |           |                         | 1.93                | 48                         | 3.18  |
| 2.9 × 1                             |           |                         | 2.57                | 38                         | 4.78  |
| 3.5 × 1.3                           |           |                         | 3.05                | 31                         | 4.78  |
| 4.2 × 1.4                           |           |                         | 3.73                | 26                         | 7.92  |
| 4.8 × 1.6                           |           |                         | 4.22                | 19                         | 7.92  |
| 5.5 × 1.8                           |           |                         | 4.98                | 9                          | 7.92  |
| 6.3 × 1.8                           |           |                         | 5.79                | 1                          | 11.13 |
|                                     |           |                         |                     |                            | 12.70 |
|                                     |           |                         |                     |                            | 25.40 |

| Nominal Screw Size and Thread Pitch | Hole Size | Drill Size <sup>a</sup> | Min Penetration in Blind Holes | Hole Size | Drill Size <sup>a</sup> | Min Penetration in Blind Holes |
|-------------------------------------|-----------|-------------------------|--------------------------------|-----------|-------------------------|--------------------------------|
|                                     |           |                         |                                |           |                         |                                |
| In Phenol Formaldehyde              |           |                         |                                |           |                         |                                |
| 2.2 × 0.8                           | 1.98      | 47                      | 4.78                           | 1.98      | 47                      | 4.78                           |
| 2.9 × 1                             | 2.54      | 39                      | 6.35                           | 2.39      | 42                      | 6.35                           |
| 3.5 × 1.3                           | 3.25      | 30                      | 6.35                           | 3.05      | 32                      | 6.35                           |
| 4.2 × 1.4                           | 3.81      | 25                      | 7.92                           | 3.66      | 27                      | 7.92                           |
| 4.8 × 1.6                           | 4.50      | 16                      | 7.92                           | 4.32      | 18                      | 7.92                           |
| 5.5 × 1.8                           | 5.05      | 8                       | 9.52                           | 4.85      | 11                      | 9.52                           |
| 6.3 × 1.8                           | 5.94      | ...                     | 9.52                           | 5.61      | 2                       | 9.52                           |

All dimensions are in millimeters except drill sizes.

**Table 10. Approximate Drilled or Clean-Punched Hole Sizes for Steel Type B Metric Thread Forming Tapping Screws in Sheet Metal and Cast Metals**

| Nominal Screw Size and Thread Pitch                     | Metal Thickness               | Hole Size | Drill Size <sup>a</sup> | Nominal Screw Size and Thread Pitch | Metal Thickness | Hole Size | Drill Size <sup>a</sup> | Nominal Screw Size and Thread Pitch | Metal Thickness | Hole Size | Drill Size <sup>a</sup> |      |      |    |
|---|-------------------------------|-----------|-------------------------|-------------------------------------|-----------------|-----------|-------------------------|-------------------------------------|-----------------|-----------|-------------------------|------|------|----|
| In Steel, Stainless Steel, Monel, and Brass Sheet Metal |                               |           |                         |                                     |                 |           |                         |                                     |                 |           |                         |      |      |    |
| 2.2 × 0.8   | 0.38                          | 1.63      | 52                      | 3.5 × 1.3                           | 1.90            | 3.05      | 31                      | 5.5 × 1.8                           | 0.61            | 4.22      | 19                      |      |      |    |
|   | 0.46                          | 1.63      | 52                      |                                     | 2.67            | 3.25      | 30                      |                                     | 0.76            | 4.22      | 19                      |      |      |    |
|   | 0.61                          | 1.70      | 51                      | 4.2 × 1.4                           | 0.61            | 3.18      | ...                     |                                     | 0.91            | 4.22      | 19                      |      |      |    |
|   | 0.76                          | 1.78      | 50                      |                                     | 0.76            | 3.18      | ...                     |                                     | 1.22            | 4.32      | 18                      |      |      |    |
|   | 0.91                          | 1.85      | 49                      |                                     | 0.91            | 3.18      | ...                     |                                     | 1.52            | 4.50      | 16                      |      |      |    |
|   | 1.22                          | 1.85      | 49                      |                                     | 1.22            | 3.25      | 30                      |                                     | 1.90            | 4.62      | 14                      |      |      |    |
| 1.52  | 1.93                          | 48        | 1.52                    |                                     | 3.45            | 29        | 2.67                    | 4.70                                | 13              |           |                         |      |      |    |
| 2.9 × 1   | 0.38                          | 2.18      | 44                      |                                     | 4.8 × 1.6       | 1.90      | 3.56                    | 28                                  | 6.3 × 1.8       | 3.18      | 4.98                    | 9    |      |    |
|   | 0.46                          | 2.18      | 44                      | 2.67                                |                 | 3.81      | 25                      | 3.43                                |                 | 4.98      | 9                       |      |      |    |
|   | 0.61                          | 2.26      | 43                      | 3.18                                |                 | 3.81      | 25                      | 4.17                                |                 | 5.11      | 7                       |      |      |    |
|   | 0.76                          | 2.39      | 42                      | 3.43                                |                 | 3.86      | 24                      | 0.76                                |                 | 4.93      | 10                      |      |      |    |
|   | 0.91                          | 2.39      | 42                      | 0.61                                |                 | 3.66      | 27                      | 0.91                                |                 | 4.93      | 10                      |      |      |    |
|   | 1.22                          | 2.44      | 41                      | 0.76                                |                 | 3.66      | 27                      | 1.22                                |                 | 4.93      | 10                      |      |      |    |
| 3.5 × 1.3   | 1.52                          | 2.54      | 39                      | 4.8 × 1.6                           | 0.91            | 3.73      | 26                      | 6.3 × 1.8                           | 1.52            | 5.05      | 8                       |      |      |    |
|   | 1.90                          | 2.59      | 38                      |                                     | 1.22            | 3.86      | 24                      |                                     | 1.90            | 5.18      | 6                       |      |      |    |
|   | 0.38                          | 2.64      | 37                      |                                     | 1.52            | 3.86      | 24                      |                                     | 2.67            | 5.31      | 4                       |      |      |    |
|   | 0.46                          | 2.64      | 37                      |                                     | 1.90            | 3.99      | 22                      |                                     | 3.18            | 5.79      | 1                       |      |      |    |
|   | 0.61                          | 2.69      | 36                      |                                     | 2.67            | 4.09      | 20                      |                                     | 3.43            | 5.79      | 1                       |      |      |    |
|   | 0.76                          | 2.69      | 36                      |                                     | 3.18            | 4.32      | 18                      |                                     | 4.17            | 5.94      | ...                     |      |      |    |
| 3.5 × 1.3   | 0.91                          | 2.79      | 35                      | 4.8 × 1.6                           | 3.43            | 4.32      | 18                      | 6.3 × 1.8                           | 4.75            | 5.94      | ...                     |      |      |    |
|   | 1.22                          | 2.82      | 34                      |                                     | 4.17            | 4.39      | 17                      |                                     | 4.93            | 5.94      | ...                     |      |      |    |
|   | 1.52                          | 2.95      | 32                      |                                     |                 |           |                         |                                     |                 |           |                         |      |      |    |
|   | In Aluminum Alloy Sheet Metal |           |                         |                                     |                 |           |                         |                                     |                 |           |                         |      |      |    |
|   | 2.2 × 0.8                     | 0.61      | 1.63                    |                                     | 52              | 4.2 × 1.4 | 0.76                    |                                     | 2.95            | 32        | 5.5 × 1.8               | 1.22 | 4.09 | 20 |
|   |                               | 0.76      | 1.63                    |                                     | 52              |           | 0.91                    |                                     | 3.05            | 31        |                         | 1.52 | 4.22 | 19 |
| 0.91  |                               | 1.63      | 52                      | 1.22                                | 3.25            |           | 30                      | 1.90                                | 4.39            | 17        |                         |      |      |    |
| 1.22  |                               | 1.70      | 51                      | 1.52                                | 3.45            |           | 29                      | 2.67                                | 4.57            | 15        |                         |      |      |    |
| 1.52  |                               | 1.78      | 50                      | 1.90                                | 3.56            |           | 28                      | 3.18                                | 4.62            | 14        |                         |      |      |    |
| 2.9 × 1   | 0.76                          | 2.18      | 44                      | 4.8 × 1.6                           | 2.67            | 3.73      | 26                      | 6.3 × 1.8                           | 3.43            | 4.62      | 14                      |      |      |    |
|   | 0.91                          | 2.18      | 44                      |                                     | 3.18            | 3.73      | 26                      |                                     | 4.17            | 4.80      | 12                      |      |      |    |
|   | 1.22                          | 2.18      | 44                      |                                     | 3.43            | 3.78      | 25                      |                                     | 5.08            |           |                         |      |      |    |
|   | 1.52                          | 2.26      | 43                      |                                     | 4.11            |           |                         |                                     | to              |           |                         |      |      |    |
|   | 1.90                          | 2.26      | 43                      |                                     | to              |           |                         |                                     | 9.52            | 4.98      | 9                       |      |      |    |
|   | 2.67                          | 2.39      | 42                      |                                     | 9.52            | 3.86      | 24                      |                                     | 1.52            | 5.05      | 8                       |      |      |    |
| 3.5 × 1.3   | 0.76                          | 2.64      | 37                      | 4.8 × 1.6                           | 0.91            | 3.66      | 27                      | 6.3 × 1.8                           | 1.90            | 5.11      | 7                       |      |      |    |
|   | 0.91                          | 2.64      | 37                      |                                     | 1.22            | 3.66      | 27                      |                                     | 2.67            | 5.18      | 6                       |      |      |    |
|   | 1.22                          | 2.64      | 37                      |                                     | 1.52            | 3.66      | 27                      |                                     | 3.18            | 5.31      | 4                       |      |      |    |
|   | 1.52                          | 2.69      | 36                      |                                     | 1.90            | 3.73      | 26                      |                                     | 3.43            | 5.31      | 4                       |      |      |    |
|   | 1.90                          | 2.79      | 35                      |                                     | 2.67            | 3.73      | 26                      |                                     | 4.17            | 5.41      | 3                       |      |      |    |
|   | 2.67                          | 2.82      | 34                      |                                     | 3.18            | 3.91      | 23                      |                                     | 4.75            | 5.41      | 3                       |      |      |    |
|   | 3.25                          |           |                         |                                     | 3.43            | 3.91      | 23                      |                                     | 4.93            | 5.61      | 2                       |      |      |    |
|   | to<br>6.25                    | 3.05      | 31                      |                                     | 4.17            | 4.04      | 21                      |                                     | 5.08            |           |                         |      |      |    |
|   |                               |           | to<br>9.52              | 4.22                                | 19              | 9.52      | 5.79                    | 1                                   |                 |           |                         |      |      |    |

<sup>a</sup> Customary drill size references have been retained where the metric hole diameters are direct conversions of their decimal inch equivalents.

| In Aluminum, Magnesium, Zinc, Brass, and Bronze Cast Metals |           |                         |                                |                                     |           |                         |                                |
|---|-----------|-------------------------|--------------------------------|-------------------------------------|-----------|-------------------------|--------------------------------|
| Nominal Screw Size and Thread Pitch                         | Hole Size | Drill Size <sup>a</sup> | Min Penetration in Blind Holes | Nominal Screw Size and Thread Pitch | Hole Size | Drill Size <sup>a</sup> | Min Penetration in Blind Holes |
| 2.2 × 0.8   | 1.98      | 47                      | 3.18                           | 4.8 × 1.6                           | 4.50      | 16                      | 6.35                           |
| 2.9 × 1   | 2.64      | 37                      | 4.78                           | 5.5 × 1.8                           | 5.05      | 8                       | 7.14                           |
| 3.5 × 1.3   | 3.25      | 30                      | 6.35                           | 6.3 × 1.8                           | 5.94      | 4                       | 7.92                           |
| 4.2 × 1.4   | 3.86      | 24                      | 6.35                           | ...                                 | ...       | ...                     | ...                            |

All dimensions are in millimeters, except drill sizes.

**Table 11. Approximate Hole Sizes for Steel Types BF and BT  
Metric Thread Cutting Tapping Screws for Cast Metals and Plastics**

| Nominal<br>Screw Size and<br>Thread Pitch                    | Material<br>Thickness | Hole<br>Size               | Drill<br>Size <sup>a</sup> | Nominal<br>Screw Size and<br>Thread Pitch | Material<br>Thickness | Hole<br>Size | Drill<br>Size <sup>a</sup> |
|--|-----------------------|----------------------------|----------------------------|---|-----------------------|--------------|----------------------------|
| In Die Cast Zinc and Aluminum                                |                       |                            |                            |   |                       |              |                            |
| 2.2 × 0.8  | 1.52                  | 1.85                       | 49                         | 3.5 × 1.3                                 | 3.18                  | 3.05         | 31                         |
|  | 2.11                  | 1.85                       | 49                         |   | 3.56                  | 3.05         | 31                         |
|  | 2.77                  | 1.93                       | 48                         |   | 4.78                  | 3.05         | 31                         |
|  | 3.18                  | 1.93                       | 48                         |   | 6.35                  | 3.18         | ...                        |
|  | 3.56                  | 1.93                       | 48                         |   | 7.92                  | 3.18         | ...                        |
| 2.9 × 1  | 2.77                  | 2.49                       | 40                         | 4.2 × 1.4                                 | 3.18                  | 3.78         | 25                         |
|  | 3.18                  | 2.54                       | 39                         |   | 3.56                  | 3.78         | 25                         |
|  | 3.56                  | 2.54                       | 39                         |   | 4.78                  | 3.78         | 25                         |
|  | 4.78                  | 2.54                       | 39                         |   | 6.35                  | 3.86         | 24                         |
|  | 6.35                  | 2.59                       | 38                         |   | 7.92                  | 3.86         | 24                         |
| 4.8 × 1.6  | 3.18                  | 4.22                       | 19                         | 6.3 × 1.8                                 | 6.35                  | 5.79         | 1                          |
|  | 3.56                  | 4.22                       | 19                         |   | 7.92                  | 5.79         | 1                          |
|  | 4.78                  | 4.22                       | 19                         |   | 9.52                  | 5.79         | 1                          |
|  | 6.35                  | 4.32                       | 18                         | 8 × 2.1                                   | 3.18                  | 7.14         | K                          |
|  | 7.92                  | 4.37                       | ...                        |   | 3.56                  | 7.14         | K                          |
| 9.52   | 4.37                  | ...                        | 4.78                       |   | 7.14                  | K            |                            |
| 5.5 × 1.8  | 3.18                  | 4.85                       | 11                         |   | 6.35                  | 7.14         | K                          |
|  | 3.56                  | 4.85                       | 11                         |   | 7.92                  | 7.37         | L                          |
|  | 4.78                  | 4.85                       | 11                         | 9.52                                      | 7.37                  | L            |                            |
|  | 6.35                  | 4.98                       | 9                          | 9.5 × 2.1                                 | 3.18                  | 8.74         | ...                        |
|  | 7.92                  | 4.98                       | 9                          |   | 3.56                  | 8.74         | ...                        |
| 9.52   | 4.98                  | 9                          | 4.78                       |   | 8.74                  | ...          |                            |
| 6.3 × 1.8  | 3.18                  | 5.61                       | 2                          |   | 6.35                  | 8.74         | ...                        |
|  | 3.56                  | 5.61                       | 2                          |   | 7.92                  | 8.84         | S                          |
|  | 4.78                  | 5.61                       | 2                          | 9.52                                      | 8.84                  | S            |                            |
| Nominal Screw<br>Size and Thread Pitch                       | Hole<br>Size          | Drill<br>Size <sup>a</sup> | Depth of Penetration       |   |                       |              |                            |
|  |                       |                            | Min                        | Max                                       |                       |              |                            |
| In Phenol Formaldehyde                                       |                       |                            |                            |   |                       |              |                            |
| 2.2 × 0.8  | 1.98                  | ...                        | 2.39                       | 6.35                                      |                       |              |                            |
| 2.9 × 1.0  | 2.64                  | 37                         | 3.18                       | 7.92                                      |                       |              |                            |
| 3.5 × 1.3  | 3.18                  | ...                        | 4.78                       | 9.52                                      |                       |              |                            |
| 4.2 × 1.4  | 3.73                  | 26                         | 6.35                       | 12.70                                     |                       |              |                            |
| 4.8 × 1.6  | 4.32                  | 18                         | 7.92                       | 15.88                                     |                       |              |                            |
| 5.5 × 1.8  | 4.93                  | 10                         | 9.52                       | 15.88                                     |                       |              |                            |
| 6.3 × 1.8  | 5.79                  | 1                          | 9.52                       | 19.05                                     |                       |              |                            |
| In Cellulose Acetate and Nitrate, Acrylic and Styrene Resins |                       |                            |                            |   |                       |              |                            |
| 2.2 × 0.8  | 1.93                  | 48                         | 2.39                       | 6.35                                      |                       |              |                            |
| 2.9 × 1.0  | 2.54                  | 39                         | 3.18                       | 7.92                                      |                       |              |                            |
| 3.5 × 1.3  | 3.05                  | 31                         | 4.78                       | 9.52                                      |                       |              |                            |
| 4.2 × 1.4  | 3.66                  | 27                         | 6.35                       | 12.70                                     |                       |              |                            |
| 4.8 × 1.6  | 4.22                  | 19                         | 7.92                       | 15.88                                     |                       |              |                            |
| 5.5 × 1.8  | 4.80                  | 12                         | 9.52                       | 15.88                                     |                       |              |                            |
| 6.3 × 1.8  | 5.61                  | 2                          | 9.52                       | 19.05                                     |                       |              |                            |

<sup>a</sup> Customary drill size references have been retained where the metric hole sizes are direct conversions of their decimal inch equivalents.

All dimensions are in millimeters except drill sizes.

The finish (plating or coating) on metric tapping screws and the material composition and hardness of the mating component are factors that affect assembly torques in individual applications. Although the recommended installation hole sizes given in Tables 7 through 9 were based on the use of plain unfinished carbon steel metric tapping screws, experience has shown that the specified holes are also suitable for screws having most types of commercial finishes. However, owing to various finishes providing different degrees of lubricity, some adjustment of installation torques may be necessary to suit individual applications. Also, where exceptionally heavy finishes are involved or screws are to be assembled into materials of higher hardness, some deviation from the specified hole sizes may be required to provide optimum assembly. The necessity and extent of such deviations can best be determined by experiment in the particular assembly environment.

## T-SLOTS, BOLTS, AND NUTS

Table 1. American National Standard T-Slots ANSIA/SME B5.1M-1985 (R1998)

| T-SLOTS                             |    |                            |    |                          |       |      |      |                          |       |   |     |                       |       |     |     |  |              |              |              |              |              |
|-------------------------------------|----|----------------------------|----|--------------------------|-------|------|------|--------------------------|-------|---|-----|-----------------------|-------|-----|-----|--|--------------|--------------|--------------|--------------|--------------|
| Basic Dimensions                    |    |                            |    |                          |       |      |      |                          |       | Suggested Approximate Dimensions<br>For Rounding Or Breaking Of Corners |     |                       |       |     |     |  |              |              |              |              |              |
| Nominal<br>T-Bolt Size <sup>a</sup> |    | Width of<br>Throat $A_1^b$ |    | Width of Headspace $B_1$ |       |      |      | Depth of Headspace $C_1$ |       |   |     | Depth of Throat $D_1$ |       |     |     | Rounding or Breaking of Corners <sup>c</sup> |              |              |              |              |              |
|                                     |    |                            |    | inch                     |       | mm   |      | inch                     |       | mm  |     | inch                  |       | mm  |     | inch   |              | mm           |              |              |              |
| inch                                | mm | inch                       | mm | min                      | max   | min  | max  | min                      | max   | min   | max | min                   | max   | min | max | $R_1$<br>max                                 | $W_1$<br>max | $U_1$<br>max | $R_1$<br>max | $W_1$<br>max | $U_1$<br>max |
|                                     | 4  |                            | 5  |                          |       | 10   | 11   |                          |       | 3   | 3.5 |                       |       | 4.5 | 7   |  |              |              | 0.5          | 0.8          | 0.8          |
|                                     | 5  |                            | 6  |                          |       | 11   | 12.5 |                          |       | 5   | 6   |                       |       | 5   | 8   |  |              |              | 0.5          | 0.8          | 0.8          |
| 0.250                               | 6  | 0.282                      | 8  | 0.500                    | 0.562 | 14.5 | 16   | 0.203                    | 0.234 | 7   | 8   | 0.125                 | 0.375 | 7   | 11  | 0.02   | 0.02         | 0.03         | 0.5          | 0.8          | 0.8          |
| 0.312                               | 8  | 0.344                      | 10 | 0.594                    | 0.656 | 16   | 18   | 0.234                    | 0.266 | 7   | 8   | 0.156                 | 0.438 | 9   | 14  | 0.02   | 0.03         | 0.03         | 0.5          | 0.8          | 0.8          |
| 0.375                               | 10 | 0.438                      | 12 | 0.719                    | 0.781 | 19   | 21   | 0.297                    | 0.328 | 8   | 9   | 0.219                 | 0.562 | 11  | 17  | 0.02   | 0.03         | 0.03         | 0.5          | 0.8          | 0.8          |
| 0.500                               | 12 | 0.562                      | 14 | 0.906                    | 0.969 | 23   | 25   | 0.359                    | 0.391 | 9   | 11  | 0.312                 | 0.688 | 12  | 19  | 0.02   | 0.03         | 0.03         | 0.5          | 0.8          | 0.8          |
| 0.625                               | 16 | 0.688                      | 18 | 1.188                    | 1.250 | 30   | 32   | 0.453                    | 0.484 | 12  | 14  | 0.438                 | 0.875 | 16  | 24  | 0.03   | 0.03         | 0.05         | 0.8          | 0.8          | 1.3          |
| 0.750                               | 20 | 0.812                      | 22 | 1.375                    | 1.469 | 37   | 40   | 0.594                    | 0.625 | 16  | 18  | 0.562                 | 1.062 | 20  | 29  | 0.03   | 0.03         | 0.05         | 0.8          | 0.8          | 1.3          |
| 1.000                               | 24 | 1.062                      | 28 | 1.750                    | 1.844 | 46   | 50   | 0.781                    | 0.828 | 20  | 22  | 0.750                 | 1.250 | 26  | 36  | 0.03   | 0.06         | 0.05         | 0.8          | 1.5          | 1.3          |
| 1.250                               | 30 | 1.312                      | 36 | 2.125                    | 2.219 | 56   | 60   | 1.031                    | 1.094 | 25  | 28  | 1.000                 | 1.562 | 33  | 46  | 0.03   | 0.06         | 0.05         | 0.8          | 1.5          | 1.3          |
| 1.500                               | 36 | 1.562                      | 42 | 2.562                    | 2.656 | 68   | 72   | 1.281                    | 1.344 | 32  | 35  | 1.250                 | 1.938 | 39  | 53  | 0.03   | 0.06         | 0.05         | 0.8          | 1.5          | 1.3          |
|                                     | 42 |                            | 48 |                          |       | 80   | 85   |                          |       | 36  | 40  |                       |       | 44  | 59  |  |              |              | 1.5          | 2.5          | 2            |
|                                     | 48 |                            | 54 |                          |       | 90   | 95   |                          |       | 40  | 44  |                       |       | 50  | 66  |  |              |              | 1.5          | 2.5          | 2            |

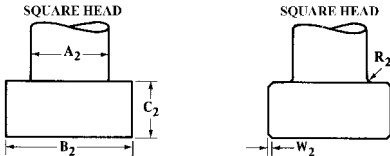
<sup>a</sup> Width of tongue (tenon) to be used with the above T-Slots will be found in the complete standard, B5.1M.

<sup>b</sup> Throat dimensions are basic. When slots are intended to be used for holding only, tolerances can be  $0.0 + 0.010$  inch or H12 Metric (ISO/R286); when intended for location, tolerance can be  $0.0 + 0.001$  inch or H8 Metric (see page 670).

<sup>c</sup> Corners of T-Slots may be square or may be rounded or broken to the indicated maximum dimensions at the manufacturer's option.

For the dimensions of tongue seats, inserted tongues, and solid tongues refer to the complete standard, B5.1M.

Table 2. American National Standard T-Bolts ANSI/ASME B5.1M-1985 (R1998)

| T-BOLTS                                      |                            |   |       |     |     |                      |           |              |       |     |      |                                  |           |             |           |
|--|----------------------------|---|-------|-----|-----|----------------------|-----------|--------------|-------|-----|------|----------------------------------|-----------|-------------|-----------|
|  |                            |  |       |     |     |                      |           |              |       |     |      |                                  |           |             |           |
| Nominal T-Bolt Size and Thread<br>$A_2^{ab}$ |                            | Bolt Head Dimensions  |       |     |     |                      |           |              |       |     |      | Rounding of Corners <sup>c</sup> |           |             |           |
|  |                            | Width Across Flats<br>$B_2$   |       |     |     | Width Across Corners |           | Height $C_2$ |       |     |      | $R_2$                            |           | $W_2$       |           |
| inch<br>UNC-2A                               | metric<br>ISO <sup>d</sup> | inch  |       | mm  |     | inch<br>max          | mm<br>max | inch         |       | mm  |      | inch<br>max                      | mm<br>max | inch<br>max | mm<br>max |
|  |                            | max   | min   | max | min |                      |           | max          | min   | max | min  |                                  |           |             |           |
|  | M4                         |   |       | 9   | 8.5 |                      | 12.7      |              |       | 2.5 | 2.1  |                                  | 0.3       |             | 0.5       |
|  | M5                         |   |       | 10  | 9.5 |                      | 14.1      |              |       | 4   | 3.6  |                                  | 0.3       |             | 0.5       |
| 0.250–20                                     | M6                         | 0.469   | 0.438 | 13  | 12  | 0.663                | 18.4      | 0.156        | 0.141 | 6   | 5.6  | 0.02                             | 0.5       | 0.03        | 0.8       |
| 0.312–18                                     | M8                         | 0.562   | 0.531 | 15  | 14  | 0.796                | 21.2      | 0.188        | 0.172 | 6   | 5.6  | 0.02                             | 0.5       | 0.03        | 0.8       |
| 0.375–16                                     | M10                        | 0.688   | 0.656 | 18  | 17  | 0.972                | 25.5      | 0.250        | 0.234 | 7   | 6.6  | 0.02                             | 0.5       | 0.03        | 0.8       |
| 0.500–13                                     | M12                        | 0.875   | 0.844 | 22  | 21  | 1.238                | 31.1      | 0.312        | 0.297 | 8   | 7.6  | 0.02                             | 0.5       | 0.06        | 1.5       |
| 0.625–11                                     | M16                        | 1.125   | 1.094 | 28  | 27  | 1.591                | 39.6      | 0.406        | 0.391 | 10  | 9.6  | 0.03                             | 0.8       | 0.06        | 1.5       |
| 0.750–10                                     | M20                        | 1.312   | 1.281 | 34  | 33  | 1.856                | 48.1      | 0.531        | 0.500 | 14  | 13.2 | 0.03                             | 0.8       | 0.06        | 1.5       |
| 1.000–8                                      | M24                        | 1.688   | 1.656 | 43  | 42  | 2.387                | 60.8      | 0.688        | 0.656 | 18  | 17.2 | 0.03                             | 0.8       | 0.06        | 1.5       |
| 1.250–7                                      | M30                        | 2.062   | 2.031 | 53  | 52  | 2.917                | 75        | 0.938        | 0.906 | 23  | 22.2 | 0.03                             | 0.8       | 0.06        | 1.5       |
| 1.500–6                                      | M36                        | 2.500   | 2.469 | 64  | 63  | 3.536                | 90.5      | 1.188        | 1.156 | 28  | 27.2 | 0.03                             | 0.8       | 0.06        | 1.5       |
|  | M42                        |   |       | 75  | 74  |                      | 106.1     |              |       | 32  | 30.5 |                                  | 1         |             | 2         |
|  | M48                        |   |       | 85  | 84  |                      | 120.2     |              |       | 36  | 34.5 |                                  | 1         |             | 2         |

<sup>a</sup>For inch tolerances for thread diameters of bolts or studs and for threads see page 1736.

<sup>b</sup>T-slots to be used with these bolts will be found in Table 1.

<sup>c</sup>Corners of T-bolts may be square or may be rounded or broken to the indicated maximum dimensions at the manufacturer's option.

<sup>d</sup>Metric thread grade and tolerance position is 5g 6g (see page 1790).

Table 3. American National Standard T-Nuts ANSI/ASME B5.1M-1985 (R1998)

| T-NUTS                                 |                          |       |       |       |                                    |          |                       |                  |       |     |                        |       |       |     |   |       |  |       |                     |      |       |      |     |     |
|--|--------------------------|-------|-------|-------|------------------------------------|----------|-----------------------|------------------|-------|-----|------------------------|-------|-------|-----|---|-------|--|-------|---------------------|------|-------|------|-----|-----|
|  |                          |       |       |       |                                    |          |                       |                  |       |     |                        |       |       |     |   |       |  |       |                     |      |       |      |     |     |
| Nominal<br>T-Bolt<br>Size <sup>a</sup> | Width of Tongue<br>$A_3$ |       |       |       | Tap for Stud <sup>b</sup><br>$E_3$ |          | Width of Nut<br>$B_3$ |                  |       |     | Height of Nut<br>$C_3$ |       |       |     | Total Thickness<br>Including<br>Tongue <sup>c</sup> $K_3$ |       | Length<br>of Nut <sup>c</sup><br>$L_3$ |       | Rounding of Corners |      |       |      |     |     |
|  | inch                     |       | mm    |       | inch                               | mm       | inch                  |                  | mm    |     | inch                   |       | mm    |     |   |       |  |       | $R_3$               |      | $W_3$ |      |     |     |
|  | inch                     | mm    | max   | min   | max                                | min      | UNC-3B                | ISO <sup>d</sup> | max   | min | max                    | min   | max   | min | max   | min   | inch                                   | mm    | inch                | mm   | max   | max  | max | max |
|  | 4                        |       |       |       |                                    |          |                       |                  |       |     |                        |       |       |     |   |       |  |       |                     |      |       |      |     |     |
|  | 5                        |       | ...   |       |                                    |          |                       |                  |       |     |                        |       |       |     |   |       |  |       |                     |      |       |      |     |     |
| 0.250                                  | 6                        | ...   | ...   | ...   | ...                                | ...      | ...                   | ...              | ...   | ... | ...                    | ...   | ...   | ... | ...   | ...   | ...                                    | ...   | ...                 | ...  | ...   | ...  | ... | ... |
| 0.312                                  | 8                        | 0.330 | 0.320 | 8.7   | 8.5                                | 0.250-20 | M6                    | 0.562            | 0.531 | 15  | 14                     | 0.188 | 0.172 | 6   | 5.6   | 0.281 | 9                                      | 0.562 | 18                  | 0.02 | 0.5   | 0.03 | 0.8 |     |
| 0.375                                  | 10                       | 0.418 | 0.408 | 11    | 10.75                              | 0.312-18 | M8                    | 0.688            | 0.656 | 18  | 17                     | 0.250 | 0.234 | 7   | 6.6   | 0.375 | 10.5                                   | 0.688 | 20                  | 0.02 | 0.5   | 0.03 | 0.8 |     |
| 0.500                                  | 12                       | 0.543 | 0.533 | 13.5  | 13.25                              | 0.375-1  | 6M10                  | 0.875            | 0.844 | 22  | 21                     | 0.312 | 0.297 | 8   | 7.6   | 0.531 | 12                                     | 0.875 | 23                  | 0.02 | 0.5   | 0.06 | 1.5 |     |
| 0.625                                  | 16                       | 0.668 | 0.658 | 17.25 | 17                                 | 0.500-13 | M12                   | 1.125            | 1.094 | 28  | 27                     | 0.406 | 0.391 | 10  | 9.6   | 0.625 | 15                                     | 1.125 | 27                  | 0.03 | 0.8   | 0.06 | 1.5 |     |
| 0.750                                  | 20                       | 0.783 | 0.773 | 20.5  | 20.25                              | 0.625-11 | M16                   | 1.312            | 1.281 | 34  | 33                     | 0.531 | 0.500 | 14  | 13.2  | 0.781 | 21                                     | 1.312 | 35                  | 0.03 | 0.8   | 0.06 | 1.5 |     |
| 1.000                                  | 24                       | 1.033 | 1.018 | 26.5  | 26                                 | 0.750-10 | M20                   | 1.688            | 1.656 | 43  | 42                     | 0.688 | 0.656 | 18  | 17.2  | 1.000 | 27                                     | 1.688 | 46                  | 0.03 | 0.8   | 0.06 | 1.5 |     |
| 1.250                                  | 30                       | 1.273 | 1.258 | 33    | 32.5                               | 1.000-8  | M24                   | 2.062            | 2.031 | 53  | 52                     | 0.938 | 0.906 | 23  | 22.2  | 1.312 | 34                                     | 2.062 | 53                  | 0.03 | 0.8   | 0.06 | 1.5 |     |
| 1.500                                  | 36                       | 1.523 | 1.508 | 39.25 | 38.75                              | 1.250-7  | M30                   | 2.500            | 2.469 | 64  | 63                     | 1.188 | 1.156 | 28  | 27.2  | 1.625 | 42                                     | 2.500 | 65                  | 0.03 | 0.8   | 0.06 | 1.5 |     |
|  | 42                       |       |       | 46.75 | 46.25                              |          | M36                   |                  |       | 75  | 74                     |       |       | 32  | 30.5  |       | 48                                     |       | 75                  |      | 1     |      | 2   |     |
|  | 48                       |       |       | 52.5  | 51.75                              |          | M42                   |                  |       | 85  | 84                     |       |       | 36  | 34.5  |       | 54                                     |       | 85                  |      | 1     |      | 2   |     |

<sup>a</sup>T-slot dimensions to fit the above nuts will be found in Table 1.

<sup>b</sup>For tolerances of inch threads see page 1736.

<sup>c</sup>No tolerances are given for "Total Thickness" or "Nut Length" as they need not be held to close limits.

<sup>d</sup>Metric tapped thread grade and tolerance position is 5H (see page 1790).

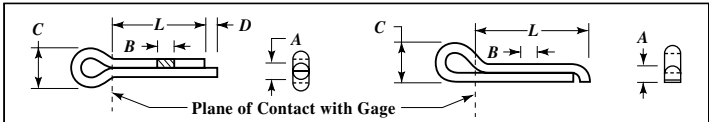
## PINS AND STUDS

**Dowel-Pins.**—Dowel-pins are used either to retain parts in a fixed position or to preserve alignment. Under normal conditions a properly fitted dowel-pin is subjected solely to shearing strain, and this strain occurs only at the junction of the surfaces of the two parts which are being held by the dowel-pin. It is seldom necessary to use more than two dowel-pins for holding two pieces together and frequently one is sufficient. For parts that have to be taken apart frequently, and where driving out of the dowel-pins would tend to wear the holes, and also for very accurately constructed tools and gages that have to be taken apart, or that require to be kept in absolute alignment, the taper dowel-pin is preferable. The taper dowel-pin is most commonly used for average machine work, but the straight type is given the preference on tool and gage work, except where extreme accuracy is required, or where the tool or gage is to be subjected to rough handling.

The size of the dowel-pin is governed by its application. For locating nests, gage plates, etc., pins from  $\frac{1}{8}$  to  $\frac{3}{16}$  inch in diameter are satisfactory. For locating dies, the diameter of the dowel-pin should never be less than  $\frac{1}{4}$  inch; the general rule is to use dowel-pins of the same size as the screws used in fastening the work. The length of the dowel-pin should be about one and one-half to two times its diameter in each plate or part to be doweled.

When hardened cylindrical dowel-pins are inserted in soft parts, ream the hole about 0.001 inch smaller than the dowel-pin. If the doweled parts are hardened, grind (or lap) the hole 0.0002 to 0.0003 inch under size. The hole should be ground or lapped straight, that is, without taper or "bell-mouth."

## American National Standard Cotter Pins ANSI B18.8.1-1972 (R1994)



The technical drawings show two types of cotter pins: a standard cotter pin on the left and a clevis pin on the right. Both drawings include side and end views. Dimensions are labeled as follows: C is the head diameter, L is the prong length, B is the wire width, D is the hole diameter, and A is the hole diameter for the clevis pin. A dashed line indicates the 'Plane of Contact with Gage'.

| Nom. Size      | Dia. A <sup>a</sup> & Width B Max. | Wire Width B Min. | Head Dia. C Min. | Prong Length D Min. | Hole Size | Nom. Size      | Dia. A <sup>a</sup> & Width B Max. | Wire Width B Min. | Head Dia. C Min. | Prong Length D Min. | Hole Size |
|----------------|------------------------------------|-------------------|------------------|---------------------|-----------|----------------|------------------------------------|-------------------|------------------|---------------------|-----------|
| $\frac{1}{32}$ | 0.032                              | 0.022             | 0.06             | 0.01                | 0.047     | $\frac{3}{16}$ | 0.176                              | 0.137             | 0.38             | 0.09                | 0.203     |
| $\frac{3}{64}$ | 0.048                              | 0.035             | 0.09             | 0.02                | 0.062     | $\frac{7}{32}$ | 0.207                              | 0.161             | 0.44             | 0.10                | 0.234     |
| $\frac{1}{16}$ | 0.060                              | 0.044             | 0.12             | 0.03                | 0.078     | $\frac{1}{4}$  | 0.225                              | 0.176             | 0.50             | 0.11                | 0.266     |
| $\frac{5}{64}$ | 0.076                              | 0.057             | 0.16             | 0.04                | 0.094     | $\frac{5}{16}$ | 0.280                              | 0.220             | 0.62             | 0.14                | 0.312     |
| $\frac{3}{32}$ | 0.090                              | 0.069             | 0.19             | 0.04                | 0.109     | $\frac{3}{8}$  | 0.335                              | 0.263             | 0.75             | 0.16                | 0.375     |
| $\frac{7}{64}$ | 0.104                              | 0.080             | 0.22             | 0.05                | 0.125     | $\frac{7}{16}$ | 0.406                              | 0.320             | 0.88             | 0.20                | 0.438     |
| $\frac{1}{8}$  | 0.120                              | 0.093             | 0.25             | 0.06                | 0.141     | $\frac{1}{2}$  | 0.473                              | 0.373             | 1.00             | 0.23                | 0.500     |
| $\frac{9}{64}$ | 0.134                              | 0.104             | 0.28             | 0.06                | 0.156     | $\frac{5}{8}$  | 0.598                              | 0.472             | 1.25             | 0.30                | 0.625     |
| $\frac{5}{32}$ | 0.150                              | 0.116             | 0.31             | 0.07                | 0.172     | $\frac{3}{4}$  | 0.723                              | 0.572             | 1.50             | 0.36                | 0.750     |

<sup>a</sup> Tolerances are: -0.004 inch for the  $\frac{1}{32}$ - to  $\frac{3}{16}$ -inch sizes, incl.; -0.005 inch for the  $\frac{7}{32}$ - to  $\frac{5}{16}$ -inch sizes, incl.; -0.006 inch for the  $\frac{3}{8}$ - to  $\frac{1}{2}$ -inch sizes, incl.; and -0.008 inch for the  $\frac{5}{8}$ - and  $\frac{3}{4}$ -inch sizes. Note: Tolerances for length are: up to 1 inch  $\pm 0.030$  inch, over 1 inch  $\pm 0.060$  inch.

All dimensions are in inches.



## American National Standard Clevis Pins ANSI B18.8.1-1972 (R1994)

| Nom. Size<br>(Basic<br>Pin Dia.) | Shank<br>Dia. A<br>Max. | Head<br>Dia. B<br>Max. <sup>a</sup> | Head<br>Hgt. C<br>Max. <sup>b</sup> | Head<br>Chamfer<br>D Nom. <sup>c</sup> | Hole<br>Dia. E<br>Max. <sup>d</sup> | Point<br>Dia. F<br>Max. <sup>e</sup> | Pin<br>Lgth. G<br>Basic <sup>f</sup> | Head to<br>Hole Center<br>H Max. <sup>g</sup> | Point Length L |       | Cotter<br>Pin Size<br>for Hole |
|----------------------------------|-------------------------|-------------------------------------|-------------------------------------|--|-------------------------------------|--------------------------------------|--------------------------------------|---|----------------|-------|--------------------------------|
|                                  |                         |                                     |                                     |  |                                     |                                      |                                      |   | Max.           | Min.  |                                |
| $\frac{3}{16}$                   | 0.186                   | 0.32                                | 0.07                                | 0.02                                   | 0.088                               | 0.15                                 | 0.58                                 | 0.504   | 0.055          | 0.035 | $\frac{1}{16}$                 |
| $\frac{1}{4}$                    | 0.248                   | 0.38                                | 0.10                                | 0.03                                   | 0.088                               | 0.21                                 | 0.77                                 | 0.692   | 0.055          | 0.035 | $\frac{1}{16}$                 |
| $\frac{5}{16}$                   | 0.311                   | 0.44                                | 0.10                                | 0.03                                   | 0.119                               | 0.26                                 | 0.94                                 | 0.832   | 0.071          | 0.049 | $\frac{3}{32}$                 |
| $\frac{3}{8}$                    | 0.373                   | 0.51                                | 0.13                                | 0.03                                   | 0.119                               | 0.33                                 | 1.06                                 | 0.958   | 0.071          | 0.049 | $\frac{3}{32}$                 |
| $\frac{7}{16}$                   | 0.436                   | 0.57                                | 0.16                                | 0.04                                   | 0.119                               | 0.39                                 | 1.19                                 | 1.082   | 0.071          | 0.049 | $\frac{3}{32}$                 |
| $\frac{1}{2}$                    | 0.496                   | 0.63                                | 0.16                                | 0.04                                   | 0.151                               | 0.44                                 | 1.36                                 | 1.223   | 0.089          | 0.063 | $\frac{1}{8}$                  |
| $\frac{5}{8}$                    | 0.621                   | 0.82                                | 0.21                                | 0.06                                   | 0.151                               | 0.56                                 | 1.61                                 | 1.473   | 0.089          | 0.063 | $\frac{1}{8}$                  |
| $\frac{3}{4}$                    | 0.746                   | 0.94                                | 0.26                                | 0.07                                   | 0.182                               | 0.68                                 | 1.91                                 | 1.739   | 0.110          | 0.076 | $\frac{5}{32}$                 |
| $\frac{7}{8}$                    | 0.871                   | 1.04                                | 0.32                                | 0.09                                   | 0.182                               | 0.80                                 | 2.16                                 | 1.989   | 0.110          | 0.076 | $\frac{5}{32}$                 |
| 1                                | 0.996                   | 1.19                                | 0.35                                | 0.10                                   | 0.182                               | 0.93                                 | 2.41                                 | 2.239   | 0.110          | 0.076 | $\frac{5}{32}$                 |

<sup>a</sup> Tolerance is  $-0.05$  inch.<sup>b</sup> Tolerance is  $-0.02$  inch.<sup>c</sup> Tolerance is  $\pm 0.01$  inch.<sup>d</sup> Tolerance is  $-0.015$  inch.<sup>e</sup> Tolerance is  $-0.01$  inch.<sup>f</sup> Lengths tabulated are intended for use with standard clevises, without spacers. When other lengths are required, it is recommended that they be limited wherever possible to nominal lengths in 0.06-inch increments.<sup>g</sup> Tolerance is  $-0.020$  inch.

All dimensions are in inches.

**British Standard for Metric Series Dowel Pins.**—Steel parallel dowel pins specified in British Standard 1804:Part 2:1968 are divided into three grades which provide different degrees of pin accuracy.

*Grade 1* is a precision ground pin made from En 32A or En 32B low carbon steel (BS 970) or from high carbon steel to BS 1407 or BS 1423. Pins below 4 mm diameter are unhardened. Those of 4 mm diameter and above are hardened to a minimum of 750 HV 30 in accordance with BS 427, but if they are made from steels to BS 1407 or BS 1423 then the hardness shall be within the range 600 to 700 HV 30, in accordance with BS 427. The values of other hardness scales may be used in accordance with BS 860.

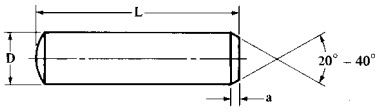
*Grade 2* is a ground pin made from any of the steels used for Grade 1. The pins are normally supplied unhardened, unless a different condition is agreed on between the purchaser and supplier.

*Grade 3* pins are made from En 1A free cutting steel (BS 970) and are supplied with a machined, bright rolled or drawn finish. They are normally supplied unhardened unless a different condition is agreed on between the purchaser and supplier.

Pins of any grade may be made from different steels in accordance with BS 970, by mutual agreement between the purchaser and manufacturer. If steels other than those in the

standard range are used, the hardness of the pins shall also be decided on by mutual agreement between purchaser and supplier. As shown in the illustration at the head of the accompanying table, one end of each pin is chamfered to provide a lead. The other end may be similarly chamfered, or domed.

**British Standard Parallel Steel Dowel Pins — Metric Series BS 1804: Part 2: 1968**



| Nom. Length L, mm | Nominal Diameter D, mm |     |     |     |      |     |      |     |     |     |     |     |    |    |
|-------------------|------------------------|-----|-----|-----|------|-----|------|-----|-----|-----|-----|-----|----|----|
|                   | 1                      | 1.5 | 2   | 2.5 | 3    | 4   | 5    | 6   | 8   | 10  | 12  | 16  | 20 | 25 |
|                   | Chamfer a max, mm      |     |     |     |      |     |      |     |     |     |     |     |    |    |
|                   | 0.3                    | 0.3 | 0.3 | 0.4 | 0.45 | 0.6 | 0.75 | 0.9 | 1.2 | 1.5 | 1.8 | 2.5 | 3  | 4  |
| Standard Sizes    |                        |     |     |     |      |     |      |     |     |     |     |     |    |    |
| 4                 | d                      | d   |     |     |      |     |      |     |     |     |     |     |    |    |
| 6                 | d                      | d   | d   | d   |      |     |      |     |     |     |     |     |    |    |
| 8                 | d                      | d   | d   | d   | d    |     |      |     |     |     |     |     |    |    |
| 10                |                        | d   | d   | d   | d    | d   |      |     |     |     |     |     |    |    |
| 12                |                        | d   | d   | d   | d    | d   | d    |     |     |     |     |     |    |    |
| 16                |                        |     | d   | d   | d    | d   | d    | d   |     |     |     |     |    |    |
| 20                |                        |     |     | d   | d    | d   | d    | d   | d   |     |     |     |    |    |
| 25                |                        |     |     |     | d    | d   | d    | d   | d   | d   |     |     |    |    |
| 30                |                        |     |     |     |      | d   | d    | d   | d   | d   | d   |     |    |    |
| 35                |                        |     |     |     |      |     | d    | d   | d   | d   | d   | d   |    |    |
| 40                |                        |     |     |     |      |     |      | d   | d   | d   | d   | d   | d  |    |
| 45                |                        |     |     |     |      |     |      |     | d   | d   | d   | d   | d  | d  |
| 50                |                        |     |     |     |      |     |      |     |     | d   | d   | d   | d  | d  |
| 60                |                        |     |     |     |      |     |      |     |     |     | d   | d   | d  | d  |
| 70                |                        |     |     |     |      |     |      |     |     |     |     | d   | d  | d  |
| 80                |                        |     |     |     |      |     |      |     |     |     |     |     | d  | d  |
| 90                |                        |     |     |     |      |     |      |     |     |     |     |     |    | d  |
| 100               |                        |     |     |     |      |     |      |     |     |     |     |     |    | d  |
| 110               |                        |     |     |     |      |     |      |     |     |     |     |     |    | d  |
| 120               |                        |     |     |     |      |     |      |     |     |     |     |     |    | d  |

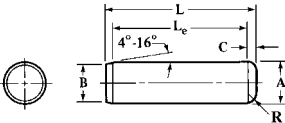
| Limits of Tolerance on Diameter |            |                               |    |    |                  |     |      |
|---------------------------------|------------|-------------------------------|----|----|------------------|-----|------|
| Grade <sup>a</sup>              |            | 1                             |    | 2  |                  | 3   |      |
| Tolerance Zone                  |            | m5                            |    | h7 |                  | h11 |      |
| Nom. Dia., mm                   |            | Limits of Tolerance, 0.001 mm |    |    |                  |     |      |
| Over                            | To & Incl. |                               |    |    |                  |     |      |
|                                 | 3          | +7                            | +2 | 0  | -12 <sup>b</sup> | 0   | -60  |
| 3                               | 6          | +9                            | +4 | 0  | -12              | 0   | -75  |
| 6                               | 10         | +12                           | +6 | 0  | -15              | 0   | -90  |
| 10                              | 14         | +15                           | +7 | 0  | -18              | 0   | -110 |
| 14                              | 18         | +15                           | +7 | 0  | -18              | 0   | -110 |
| 18                              | 24         | +17                           | +8 | 0  | -21              | 0   | -130 |
| 24                              | 30         | +17                           | +8 | 0  | -21              | 0   | -130 |

<sup>a</sup> The limits of tolerance for grades 1 and 2 dowel pins have been chosen to provide satisfactory assembly when used in standard reamed holes (H7 and H8 tolerance zones). If the assembly is not satisfactory, refer to B.S. 1916: Part 1, Limits and Fits for Engineering, and select a different class of fit.

<sup>b</sup> This tolerance is larger than that given in BS 1916, and has been included because the use of a closer tolerance would involve precision grinding by the manufacturer, which is uneconomic for a grade 2 dowel pin.

The tolerance limits on the overall length of all grades of dowel pin up to and including 50 mm long are +0.5, -0.0 mm, and for pins over 50 mm long are +0.8, -0.0 mm. The Standard specifies that the roughness of the cylindrical surface of grades 1 and 2 dowel pins, when assessed in accordance with BS 1134, shall not be greater than 0.4 μm CLA (16 CLA).

Table 1. American National Standard Hardened Ground Machine Dowel Pins ANS/ASME B18.8.2-1995



| Nominal Size <sup>a</sup><br>or Nominal Pin<br>Diameter | Pin Diameter, <i>A</i> |        |        |                      |        |        | Point<br>Diameter, <i>B</i> |       | Crown<br>Height, <i>C</i> | Crown<br>Radius, <i>R</i> | Range of<br>Preferred<br>Lengths, <sup>b</sup> <i>L</i> | Single Shear<br>Load, for Carbon<br>or Alloy Steel,<br>Calculated lb | Suggested<br>Hole Diameter <sup>c</sup> |        |        |
|---|------------------------|--------|--------|----------------------|--------|--------|-----------------------------|-------|---------------------------|---------------------------|---|--|---|--------|--------|
|   | Standard Series Pins   |        |        | Oversize Series Pins |        |        | Max                         | Min   | Max                       | Min                       |   |  | Max                                     | Min    |        |
|   | Basic                  | Max    | Min    | Basic                | Max    | Min    |                             |       |                           |                           |   |  |   |        |        |
| $\frac{1}{16}$  | 0.0625                 | 0.0627 | 0.0628 | 0.0626               | 0.0635 | 0.0636 | 0.0634                      | 0.058 | 0.048                     | 0.020                     | 0.008   | $\frac{3}{16}$ - $\frac{3}{4}$                                       | 400                                     | 0.0625 | 0.0620 |
| $\frac{5}{64}$ <sup>d</sup>                             | 0.0781                 | 0.0783 | 0.0784 | 0.0782               | 0.0791 | 0.0792 | 0.0790                      | 0.074 | 0.064                     | 0.026                     | 0.010   | ...  | 620                                     | 0.0781 | 0.0776 |
| $\frac{3}{32}$  | 0.0938                 | 0.0940 | 0.0941 | 0.0939               | 0.0948 | 0.0949 | 0.0947                      | 0.089 | 0.079                     | 0.031                     | 0.012   | $\frac{3}{16}$ -1  | 900                                     | 0.0937 | 0.0932 |
| $\frac{1}{8}$   | 0.1250                 | 0.1252 | 0.1253 | 0.1251               | 0.1260 | 0.1261 | 0.1259                      | 0.120 | 0.110                     | 0.041                     | 0.016   | $\frac{3}{8}$ -2   | 1,600                                   | 0.1250 | 0.1245 |
| $\frac{5}{32}$ <sup>d</sup>                             | 0.1562                 | 0.1564 | 0.1565 | 0.1563               | 0.1572 | 0.1573 | 0.1571                      | 0.150 | 0.140                     | 0.052                     | 0.020   | ...  | 2,500                                   | 0.1562 | 0.1557 |
| $\frac{3}{16}$  | 0.1875                 | 0.1877 | 0.1878 | 0.1876               | 0.1885 | 0.1886 | 0.1884                      | 0.180 | 0.170                     | 0.062                     | 0.023   | $\frac{1}{2}$ -2   | 3,600                                   | 0.1875 | 0.1870 |
| $\frac{1}{4}$   | 0.2500                 | 0.2502 | 0.2503 | 0.2501               | 0.2510 | 0.2511 | 0.2509                      | 0.240 | 0.230                     | 0.083                     | 0.031   | $\frac{1}{2}$ -2 $\frac{1}{2}$                                       | 6,400                                   | 0.2500 | 0.2495 |
| $\frac{5}{16}$  | 0.3125                 | 0.3127 | 0.3128 | 0.3126               | 0.3135 | 0.3136 | 0.3134                      | 0.302 | 0.290                     | 0.104                     | 0.039   | $\frac{1}{2}$ -2 $\frac{1}{2}$                                       | 10,000                                  | 0.3125 | 0.3120 |
| $\frac{3}{8}$   | 0.3750                 | 0.3752 | 0.3753 | 0.3751               | 0.3760 | 0.3761 | 0.3759                      | 0.365 | 0.350                     | 0.125                     | 0.047   | $\frac{1}{2}$ -3   | 14,350                                  | 0.3750 | 0.3745 |
| $\frac{7}{16}$  | 0.4375                 | 0.4377 | 0.4378 | 0.4376               | 0.4385 | 0.4386 | 0.4384                      | 0.424 | 0.409                     | 0.146                     | 0.055   | $\frac{3}{8}$ -3   | 19,550                                  | 0.4375 | 0.4370 |
| $\frac{1}{2}$   | 0.5000                 | 0.5002 | 0.5003 | 0.5001               | 0.5010 | 0.5011 | 0.5009                      | 0.486 | 0.471                     | 0.167                     | 0.063   | $\frac{3}{8}$ 1-4  | 25,500                                  | 0.5000 | 0.4995 |
| $\frac{5}{8}$   | 0.6250                 | 0.6252 | 0.6253 | 0.6251               | 0.6260 | 0.6261 | 0.6259                      | 0.611 | 0.595                     | 0.208                     | 0.078   | 1 $\frac{1}{2}$ -5   | 39,900                                  | 0.6250 | 0.6245 |
| $\frac{3}{4}$   | 0.7500                 | 0.7502 | 0.7503 | 0.7501               | 0.7510 | 0.7511 | 0.7509                      | 0.735 | 0.715                     | 0.250                     | 0.094   | 1 $\frac{1}{2}$ -6   | 57,000                                  | 0.7500 | 0.7495 |
| $\frac{7}{8}$   | 0.8750                 | 0.8752 | 0.8753 | 0.8751               | 0.8760 | 0.8761 | 0.8759                      | 0.860 | 0.840                     | 0.293                     | 0.109   | 2,2 $\frac{1}{2}$ -6   | 78,000                                  | 0.8750 | 0.8745 |
| 1   | 1.0000                 | 1.0002 | 1.0003 | 1.0001               | 1.0010 | 1.0011 | 1.0009                      | 0.980 | 0.960                     | 0.333                     | 0.125   | 2,2 $\frac{1}{2}$ -5.6   | 102,000                                 | 1.0000 | 0.9995 |

<sup>a</sup> Where specifying nominal size as basic diameter, zeros preceding decimal and in the fourth decimal place are omitted.

<sup>b</sup> Lengths increase in  $\frac{1}{16}$ -inch steps up to  $\frac{3}{8}$  inch, in  $\frac{1}{8}$ -inch steps from  $\frac{3}{8}$  inch to 1 inch, in  $\frac{1}{4}$ -inch steps from 1 inch to 2 $\frac{1}{2}$  inches, and in  $\frac{1}{2}$ -inch steps above 2 $\frac{1}{2}$  inches. Tolerance on length is  $\pm 0.010$  inch.

<sup>c</sup> These hole sizes have been commonly used for press fitting Standard Series machine dowel pins into materials such as mild steels and cast iron. In soft materials such as aluminum or zinc die castings, hole size limits are usually decreased by 0.0005 inch to increase the press fit.

<sup>d</sup> Nonpreferred sizes, not recommended for use in new designs.

All dimensions are in inches.

If a dowel pin is driven into a blind hole where no provision is made for releasing air, the worker assembling the pin may be endangered, and damage may be caused to the associated component, or stresses may be set up. The appendix of the Standard describes one method of overcoming this problem by providing a small flat surface along the length of a pin to permit the release of air.

For purposes of marking, the Standard states that each package or lot of dowel pins shall bear the manufacturer's name or trademark, the BS number, and the grade of pin.

**American National Standard Hardened Ground Machine Dowel Pins.**—Hardened ground machine dowel pins are furnished in two diameter series: Standard Series having basic diameters 0.0002 inch over the nominal diameter, intended for initial installations; and Oversize Series having basic diameters 0.001 inch over the nominal diameter, intended for replacement use.

*Preferred Lengths and Sizes:* The preferred lengths and sizes in which these pins are normally available are given in [Table 1](#). Other sizes and lengths are produced as required by the purchaser.

*Effective Length:* The effective length,  $L_e$ , must not be less than 75 per cent of the overall length of the pin.

*Shear Strength:* Single shear strength values are listed in [Table 1](#). Prior versions of ANSI/ASME B18.8.2-1995 had listed double shear load minimum values and had specified a minimum single shear strength of 130,000 psi. See ANSI/ASME B18.8.2-1995, Appendix B for a description of the double shear test.

*Designation:* These pins are designated by the following data in the sequence shown: Product name (noun first), including pin series, nominal pin diameter (fraction or decimal equivalent), length (fraction or decimal equivalent), material, and protective finish, if required.

*Examples:* Pins, Hardened Ground Machine Dowel — Standard Series,  $\frac{3}{8} \times 1\frac{1}{2}$ , Steel, Phosphate Coated.

Pins, Hardened Ground Machine Dowel — Oversize Series,  $0.625 \times 2.500$ , Steel

*Installation Precaution:* Pins should not be installed by striking or hammering and when installing with a press, a shield should be used and safety glasses worn.

**American National Standard Hardened Ground Production Dowel Pins.**—Hardened ground production dowel pins have basic diameters that are 0.0002 inch over the nominal pin diameter.

*Preferred Lengths and Sizes:* The preferred lengths and sizes in which these pins are available are given in [Table 2](#). Other sizes and lengths are produced as required by the purchaser.

*Shear Strength:* Single shear strength values are listed in [Table 2](#). Prior versions of ANSI/ASME B18.8.2-1995 had listed double shear load minimum values and had specified a minimum single shear strength of 102,000 psi. See ANSI/ASME B18.8.2-1995, Appendix B for a description of the double shear test.

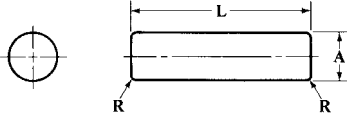
*Ductility:* These standard pins are sufficiently ductile to withstand being pressed into holes 0.0005 inch smaller than the nominal pin diameter in hardened steel without cracking or shattering.

*Designation:* These pins are designated by the following data in the sequence shown: Product name (noun first), nominal pin diameter (fraction or decimal equivalent), length (fraction or decimal equivalent), material, and protective finish, if required.

*Examples:* Pins, Hardened Ground Production Dowel,  $\frac{1}{8} \times \frac{3}{4}$ , Steel, Phosphate Coated

Pins, Hardened Ground Production Dowel,  $0.375 \times 1.500$ , Steel

**Table 2. American National Standard Hardened Ground Production Dowel Pins**  
ANSI/ASME B18.8.2-1995



| Nominal Size <sup>a</sup> or Nominal Pin Diameter | Pin Diameter, A |        |        | Corner Radius, R |       | Range of Preferred Lengths, <sup>b</sup> L | Single Shear Load, Calculated, lb | Suggested Hole Diameter <sup>c</sup> |        |        |
|---|-----------------|--------|--------|------------------|-------|--|-----------------------------------|--------------------------------------|--------|--------|
|   | Basic           | Max    | Min    | Max              | Min   |  |                                   | Max                                  | Min    |        |
| 1/16  | 0.0625          | 0.0627 | 0.0628 | 0.0626           | 0.020 | 0.010                                      | 3/16-1                            | 395                                  | 0.0625 | 0.0620 |
| 3/32  | 0.0938          | 0.0939 | 0.0940 | 0.0938           | 0.020 | 0.010                                      | 3/16-2                            | 700                                  | 0.0937 | 0.0932 |
| 7/64  | 0.1094          | 0.1095 | 0.1096 | 0.1094           | 0.020 | 0.010                                      | 3/16-2                            | 950                                  | 0.1094 | 0.1089 |
| 1/8   | 0.1250          | 0.1252 | 0.1253 | 0.1251           | 0.020 | 0.010                                      | 3/16-2                            | 1,300                                | 0.1250 | 0.1245 |
| 5/32  | 0.1562          | 0.1564 | 0.1565 | 0.1563           | 0.020 | 0.010                                      | 3/16-2                            | 2,050                                | 0.1562 | 0.1557 |
| 3/16  | 0.1875          | 0.1877 | 0.1878 | 0.1876           | 0.020 | 0.010                                      | 3/16-2                            | 2,950                                | 0.1875 | 0.1870 |
| 7/32  | 0.2188          | 0.2189 | 0.2190 | 0.2188           | 0.020 | 0.010                                      | 1/4-2                             | 3,800                                | 0.2188 | 0.2183 |
| 1/4   | 0.2500          | 0.2502 | 0.2503 | 0.2501           | 0.020 | 0.010                                      | 1/4-1 1/2, 1 3/8, 2-2 1/2         | 5,000                                | 0.2500 | 0.2495 |
| 5/16  | 0.3125          | 0.3127 | 0.3128 | 0.3126           | 0.020 | 0.010                                      | 5/16-1 1/2, 1 3/8, 2-2 1/2        | 8,000                                | 0.3125 | 0.3120 |
| 3/8   | 0.3750          | 0.3752 | 0.3753 | 0.3751           | 0.020 | 0.010                                      | 3/8-1 1/2, 1 3/4, 2-3             | 11,500                               | 0.3750 | 0.3745 |

<sup>a</sup> Where specifying nominal pin size in decimals, zeros preceding decimal and in the fourth decimal place are omitted.

<sup>b</sup> Lengths increase in 1/16-inch steps up to 1 inch, in 1/8-inch steps from 1 inch to 2 inches and then are 2/4, 2 1/2, and 3 inches.

<sup>c</sup> These hole sizes have been commonly used for press fitting production dowel pins into materials such as mild steels and cast iron. In soft materials such as aluminum or zinc die castings, hole size limits are usually decreased by 0.0005 inch to increase the press fit.

All dimensions are in inches.

**American National Standard Unhardened Ground Dowel Pins.**—Unhardened ground dowel pins are normally produced by grinding the outside diameter of commercial wire or rod material to size. Consequently, the maximum diameters of the pins, as specified in Table 3, are below the minimum commercial stock sizes by graduated amounts from 0.0005 inch on the 1/16-inch nominal pin size to 0.0028 inch on the 1-inch nominal pin size.

*Preferred Lengths and Sizes:* The preferred lengths and sizes in which unhardened ground pins are normally available are given in Table 3. Other sizes and lengths are produced as required by the purchaser.

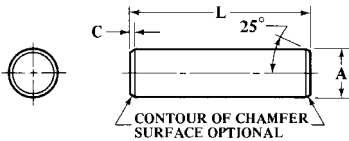
*Shear Strength:* These pins must have a single shear strength of 64,000 psi minimum for pins made from steel and 40,000 psi minimum for pins made from brass and must be capable of withstanding the minimum double shear loads given in Table 3 when tested in accordance with the procedure outlined in ANSI/ASME B18.8.2-1995, Appendix B.

*Designation:* These pins are designated by the following data in the order shown: Product name (noun first), nominal pin diameter (fraction or decimal equivalent), length (fraction or decimal equivalent), material, and protective finish, if required.

*Examples:* Pins, Unhardened Ground Dowel, 1/8 x 3/4, Steel

Pins, Unhardened Ground Dowel, 0.250 x 2.500, Steel, Zinc Plated

**Table 3. American National Standard Unhardened Ground Dowel Pins**  
ANSI/ASME B18.8.2-1995



| Nominal Size <sup>a</sup><br>or Basic Pin<br>Diameter | Pin<br>Diameter, A |        | Chamfer<br>Length, C |       | Range of<br>Preferred<br>Lengths, <sup>b</sup><br>L | Suggested<br>Hole Diameter <sup>c</sup>      |        | Double Shear Load<br>Min. lb. |        |        |
|---|--------------------|--------|----------------------|-------|---|--|--------|-------------------------------|--------|--------|
|   | Max                | Min    | Max                  | Min   |   | Max  | Min    | Carbon-<br>Steel              | Brass  |        |
| 1/16  | 0.0625             | 0.0600 | 0.0595               | 0.025 | 0.005   | 1/4-1  | 0.0595 | 0.0580                        | 350    | 220    |
| 3/32  | 0.0938             | 0.0912 | 0.0907               | 0.025 | 0.005   | 1/4-1 1/2                                    | 0.0907 | 0.0892                        | 820    | 510    |
| 7/64  | 0.1094             | 0.1068 | 0.1063               | 0.025 | 0.005   | ...  | 0.1062 | 0.1047                        | 1,130  | 710    |
| 1/8   | 0.1250             | 0.1223 | 0.1218               | 0.025 | 0.005   | 1/4-2  | 0.1217 | 0.1202                        | 1,490  | 930    |
| 5/32  | 0.1562             | 0.1535 | 0.1530               | 0.025 | 0.005   | 1/4-2  | 0.1528 | 0.1513                        | 2,350  | 1,470  |
| 3/16  | 0.1875             | 0.1847 | 0.1842               | 0.025 | 0.005   | 1/4-2  | 0.1840 | 0.1825                        | 3,410  | 2,130  |
| 7/32  | 0.2188             | 0.2159 | 0.2154               | 0.025 | 0.005   | 1/4-2  | 0.2151 | 0.2136                        | 4,660  | 2,910  |
| 1/4   | 0.2500             | 0.2470 | 0.2465               | 0.025 | 0.005   | 1/4-1 1/2, 1 3/4, 2-2 1/2                    | 0.2462 | 0.2447                        | 6,120  | 3,810  |
| 5/16  | 0.3125             | 0.3094 | 0.3089               | 0.040 | 0.020   | 5/16-1 1/2, 1 3/4, 2-2 1/2                   | 0.3085 | 0.3070                        | 9,590  | 5,990  |
| 3/8   | 0.3750             | 0.3717 | 0.3712               | 0.040 | 0.020   | 3/8-1 1/2, 1 3/4, 2-2 1/2                    | 0.3708 | 0.3693                        | 13,850 | 8,650  |
| 7/16  | 0.4375             | 0.4341 | 0.4336               | 0.040 | 0.020   | 7/16-5/8, 3/4, 7/8-1 1/2, 1 3/4, 2-2 1/2     | 0.4331 | 0.4316                        | 18,900 | 11,810 |
| 1/2   | 0.5000             | 0.4964 | 0.4959               | 0.040 | 0.020   | 1/2, 3/4, 7/8, 1-1 1/2, 1 3/4, 2-3           | 0.4954 | 0.4939                        | 24,720 | 15,450 |
| 5/8   | 0.6250             | 0.6211 | 0.6206               | 0.055 | 0.035   | 5/8, 3/4, 7/8, 1-1 1/2, 1 3/4, 2, 2 1/2-4    | 0.6200 | 0.6185                        | 38,710 | 24,190 |
| 3/4   | 0.7500             | 0.7458 | 0.7453               | 0.055 | 0.035   | 3/4, 7/8, 1, 1 1/4, 1 1/2, 1 3/4, 2, 2 1/2-4 | 0.7446 | 0.7431                        | 55,840 | 34,900 |
| 7/8   | 0.8750             | 0.8705 | 0.8700               | 0.070 | 0.050   | 7/8, 1, 1 1/4, 1 1/2, 1 3/4, 2, 2 1/2-4      | 0.8692 | 0.8677                        | 76,090 | 47,550 |
| 1   | 1.0000             | 0.9952 | 0.9947               | 0.070 | 0.050   | 1, 1 1/4, 1 1/2, 1 3/4, 2, 2 1/2-4           | 0.9938 | 0.9923                        | 99,460 | 62,160 |

<sup>a</sup> Where specifying pin size in decimals, zeros preceding decimal and in the fourth decimal place are omitted.

<sup>b</sup> Lengths increase in 1/16-inch increments from 1/4 to 1 inch, in 1/8-inch increments from 1 inch to 2 inches, and in 1/4-inch increments from 2 to 2 1/2 inches, and in 1/2-inch increments from 2 1/2 to 4 inches.

<sup>c</sup> These hole sizes have been found to be satisfactory for press fitting pins into mild steel and cast and malleable irons. In soft materials such as aluminum alloys or zinc die castings, hole size limits are usually decreased by 0.0005 inch to increase the press fit.

<sup>d</sup> Nonpreferred size, not recommended for use in new designs.

All dimensions are in inches.

**American National Standard Straight Pins.**—The diameter of both chamfered and square end straight pins is that of the commercial wire or rod from which the pins are made. The tolerances shown in Table 4 are applicable to carbon steel and some deviations in the diameter limits may be necessary for pins made from other materials.

**Table 4. American National Standard Chamfered and Square End Straight Pins**  
ANSI/ASME B18.8.2-1995

| CHAMFERED STRAIGHT PIN                          |                 |        |                   |       | SQUARE END STRAIGHT PIN                         |                 |       |                   |        |       |       |
|---|-----------------|--------|-------------------|-------|---|-----------------|-------|-------------------|--------|-------|-------|
| Nominal Size <sup>a</sup> or Basic Pin Diameter | Pin Diameter, A |        | Chamfer Length, C |       | Nominal Size <sup>b</sup> or Basic Pin Diameter | Pin Diameter, A |       | Chamfer Length, C |        |       |       |
|   | Max             | Min    | Max               | Min   |   | Max             | Min   | Max               | Min    |       |       |
| $\frac{1}{16}$                                  | 0.062           | 0.0625 | 0.0605            | 0.025 | 0.005   | $\frac{3}{16}$  | 0.312 | 0.3125            | 0.3105 | 0.040 | 0.020 |
| $\frac{3}{32}$                                  | 0.094           | 0.0937 | 0.0917            | 0.025 | 0.00  | $\frac{3}{8}$   | 0.375 | 0.3750            | 0.3730 | 0.040 | 0.020 |
| $\frac{7}{64}$                                  | 0.109           | 0.1094 | 0.1074            | 0.025 | 0.005   | $\frac{7}{16}$  | 0.438 | 0.4375            | 0.4355 | 0.040 | 0.020 |
| $\frac{1}{8}$                                   | 0.125           | 0.1250 | 0.1230            | 0.025 | 0.005   | $\frac{1}{2}$   | 0.500 | 0.5000            | 0.4980 | 0.040 | 0.020 |
| $\frac{5}{32}$                                  | 0.156           | 0.1562 | 0.1542            | 0.025 | 0.005   | $\frac{5}{8}$   | 0.625 | 0.6250            | 0.6230 | 0.055 | 0.035 |
| $\frac{3}{16}$                                  | 0.188           | 0.1875 | 0.1855            | 0.025 | 0.005   | $\frac{3}{4}$   | 0.750 | 0.7500            | 0.7480 | 0.055 | 0.035 |
| $\frac{1}{4}$                                   | 0.219           | 0.2187 | 0.2167            | 0.025 | 0.005   | $\frac{7}{8}$   | 0.875 | 0.8750            | 0.8730 | 0.055 | 0.035 |
| $\frac{1}{2}$                                   | 0.250           | 0.2500 | 0.2480            | 0.025 | 0.005   | 1               | 1.000 | 1.0000            | 0.9980 | 0.055 | 0.035 |

<sup>a</sup> Where specifying nominal size in decimals, zeros preceding decimal point are omitted.

<sup>b</sup> Where specifying nominal size in decimals, zeros preceding decimal point are omitted.

All dimensions are in inches.

**Length Increments:** Lengths are as specified by the purchaser; however, it is recommended that nominal pin lengths be limited to increments of not less than 0.062 inch.

**Material:** Straight pins are normally made from cold drawn steel wire or rod having a maximum carbon content of 0.28 per cent. Where required, pins may also be made from corrosion resistant steel, brass, or other metals.

**Designation:** Straight pins are designated by the following data, in the sequence shown: Product name (noun first), nominal size (fraction or decimal equivalent), material, and protective finish, if required.

**Examples:** Pin, Chamfered Straight,  $\frac{1}{8} \times 1.500$ , Steel

Pin, Square End Straight,  $0.250 \times 2.250$ , Steel, Zinc Plated

**American National Standard Taper Pins.**—Taper pins have a uniform taper over the pin length with both ends crowned. Most sizes are supplied in commercial and precision classes, the latter having generally tighter tolerances and being more closely controlled in manufacture.

**Diameters:** The major diameter of both commercial and precision classes of pins is the diameter of the large end and is the basis for pin size. The diameter at the small end is computed by multiplying the nominal length of the pin by the factor 0.02083 and subtracting the result from the basic pin diameter. See also [Table 5](#).

**Taper:** The taper on commercial class pins is  $0.250 \pm 0.006$  inch per foot and on the precision class pins is  $0.250 \pm 0.004$  inch per foot of length.

**Materials:** Unless otherwise specified, taper pins are made from SAE 1211 steel or cold drawn SAE 1212 or 1213 steel or equivalents, and no mechanical property requirements apply.

**Hole Sizes:** Under most circumstances, holes for taper pins require taper reaming. Sizes and lengths of taper pins for which standard reamers are available are given in [Table 6](#). Drilling specifications for taper pins are given below.

*Designation:* Taper pins are designated by the following data in the sequence shown: Product name (noun first), class, size number (or decimal equivalent), length (fraction or three-place decimal equivalent), material, and protective finish, if required.

*Examples:* Pin, Taper (Commercial Class) No. 0  $\times \frac{3}{4}$ , Steel

Pin, Taper (Precision Class) 0.219  $\times$  1.750, Steel, Zinc Plated

**Table 5. Nominal Diameter at Small Ends of Standard Taper Pins**

| Pin Length in inches | Pin Number and Small End Diameter for Given Length |       |       |       |       |       |       |       |       |       |       |
|----------------------|--|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                      | 0  | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
| $\frac{3}{4}$        | 0.140  | 0.156 | 0.177 | 0.203 | 0.235 | 0.273 | 0.325 | 0.393 | 0.476 | 0.575 | 0.690 |
| 1                    | 0.135  | 0.151 | 0.172 | 0.198 | 0.230 | 0.268 | 0.320 | 0.388 | 0.471 | 0.570 | 0.685 |
| $1\frac{1}{4}$       | 0.130  | 0.146 | 0.167 | 0.192 | 0.224 | 0.263 | 0.315 | 0.382 | 0.466 | 0.565 | 0.680 |
| $1\frac{1}{2}$       | 0.125  | 0.141 | 0.162 | 0.187 | 0.219 | 0.258 | 0.310 | 0.377 | 0.460 | 0.560 | 0.675 |
| $1\frac{3}{4}$       | 0.120  | 0.136 | 0.157 | 0.182 | 0.214 | 0.252 | 0.305 | 0.372 | 0.455 | 0.554 | 0.669 |
| 2                    | 0.114  | 0.130 | 0.151 | 0.177 | 0.209 | 0.247 | 0.299 | 0.367 | 0.450 | 0.549 | 0.664 |
| $2\frac{1}{4}$       | 0.109  | 0.125 | 0.146 | 0.172 | 0.204 | 0.242 | 0.294 | 0.362 | 0.445 | 0.544 | 0.659 |
| $2\frac{1}{2}$       | 0.104  | 0.120 | 0.141 | 0.166 | 0.198 | 0.237 | 0.289 | 0.356 | 0.440 | 0.539 | 0.654 |
| $2\frac{3}{4}$       | 0.099  | 0.115 | 0.136 | 0.161 | 0.193 | 0.232 | 0.284 | 0.351 | 0.434 | 0.534 | 0.649 |
| 3                    | 0.094  | 0.110 | 0.131 | 0.156 | 0.188 | 0.227 | 0.279 | 0.346 | 0.429 | 0.528 | 0.643 |
| $3\frac{1}{4}$       | ...  | ...   | ...   | 0.151 | 0.182 | 0.221 | 0.273 | 0.340 | 0.424 | 0.523 | 0.638 |
| $3\frac{1}{2}$       | ...  | ...   | ...   | 0.146 | 0.177 | 0.216 | 0.268 | 0.335 | 0.419 | 0.518 | 0.633 |
| $3\frac{3}{4}$       | ...  | ...   | ...   | 0.141 | 0.172 | 0.211 | 0.263 | 0.330 | 0.414 | 0.513 | 0.628 |
| 4                    | ...  | ...   | ...   | 0.136 | 0.167 | 0.206 | 0.258 | 0.326 | 0.409 | 0.508 | 0.623 |
| $4\frac{1}{4}$       | ...  | ...   | ...   | 0.131 | 0.162 | 0.201 | 0.253 | 0.321 | 0.403 | 0.502 | 0.617 |
| $4\frac{1}{2}$       | ...  | ...   | ...   | 0.125 | 0.156 | 0.195 | 0.247 | 0.315 | 0.398 | 0.497 | 0.612 |
| 5                    | ...  | ...   | ...   | ...   | 0.146 | 0.185 | 0.237 | 0.305 | 0.389 | 0.487 | 0.602 |
| $5\frac{1}{2}$       | ...  | ...   | ...   | ...   | ...   | ...   | ...   | 0.294 | 0.377 | 0.476 | 0.591 |
| 6                    | ...  | ...   | ...   | ...   | ...   | ...   | ...   | 0.284 | 0.367 | 0.466 | 0.581 |

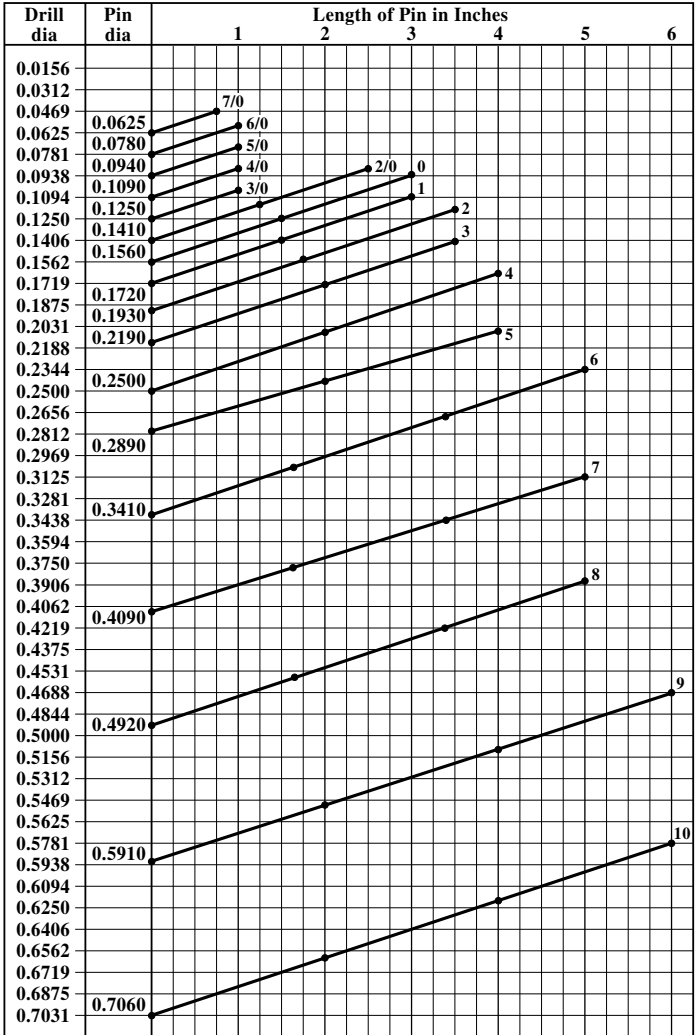
**Drilling Specifications for Taper Pins.**—When helically fluted taper pin reamers are used, the diameter of the through hole drilled prior to reaming is equal to the diameter at the small end of the taper pin. (See Table 5.) However, when straight fluted taper reamers are to be used, it may be necessary, for long pins, to step drill the hole before reaming, the number and sizes of the drills to be used depending on the depth of the hole (pin length).

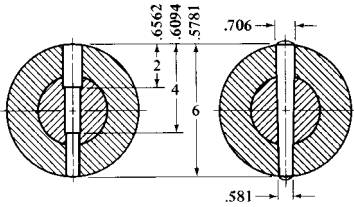
To determine the number and sizes of step drills required: Find the length of pin to be used at the top of the chart on page 1676 and follow this length down to the intersection with that heavy line which represents the size of taper pin (see taper pin numbers at the right-hand end of each heavy line). If the length of pin falls between the first and second dots, counting from the left, only one drill is required. Its size is indicated by following the nearest horizontal line from the point of intersection (of the pin length) on the heavy line over to the drill diameter values at the left. If the intersection of pin length comes between the second and third dots, then two drills are required. The size of the smaller drill then corresponds to the intersection of the pin length and the heavy line and the larger is the corresponding drill diameter for the intersection of one-half this length with the heavy line. Should the pin length fall between the third and fourth dots, three drills are required. The smallest drill will have a diameter corresponding to the intersection of the total pin length with the heavy line, the next in size will have a diameter corresponding to the intersection of two-thirds of this length with the heavy line and the largest will have a diameter corresponding to the intersection of one-third of this length with the heavy line. Where the intersection falls between two drill sizes, use the smaller.



TAPER-PIN REAMER DRILLS

Chart to Facilitate Selection of Number and Sizes of Drills for Step-Drilling Prior to Taper Reaming

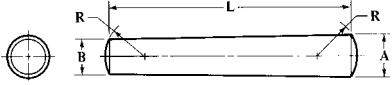




Examples: For a No. 10 taper pin 6-inches long, three drills would be used, of the sizes and for the depths shown in the accompanying diagram.

For a No. 10 taper pin 3-inches long, two drills would be used because the 3-inch length falls between the second and third dots. The first or through drill will be 0.6406 inch and the second drill, 0.6719 inch for a depth of 1½ inches.

Table 6. American National Standard Taper Pins ANSI/ASME B18.8.2-1995



| Pin Size Number and Basic Pin Dia. <sup>a</sup> | Major Diameter (Large End), A |        |                 |        | End Crown Radius, R |       | Range of Lengths, <sup>b</sup> L  |       |       |
|---|-------------------------------|--------|-----------------|--------|---------------------|-------|-----------------------------------|-------|-------|
|   | Commercial Class              |        | Precision Class |        | Max                 | Min   | Stand. Reamer Avail. <sup>c</sup> | Other |       |
|   | Max                           | Min    | Max             | Min    |                     |       |                                   |       |       |
| ⅜   | 0.0625                        | 0.0638 | 0.0618          | 0.0635 | 0.0625              | 0.072 | 0.052                             | ...   | ¼-1   |
| ⅝   | 0.0780                        | 0.0793 | 0.0773          | 0.0790 | 0.0780              | 0.088 | 0.068                             | ...   | ⅜-½   |
| ¾   | 0.0940                        | 0.0953 | 0.0933          | 0.0950 | 0.0940              | 0.104 | 0.084                             | ¼-1   | 1¼-1½ |
| ⅞   | 0.1090                        | 0.1103 | 0.1083          | 0.1100 | 0.1090              | 0.119 | 0.099                             | ⅜-1   | 1¼-2  |
| 1   | 0.1250                        | 0.1263 | 0.1243          | 0.1260 | 0.1250              | 0.135 | 0.115                             | ⅜-1   | 1½-2  |
| 1 ⅛   | 0.1410                        | 0.1423 | 0.1403          | 0.1420 | 0.1410              | 0.151 | 0.131                             | ½-1¼  | 1½-2½ |
| 1 ¼   | 0.1560                        | 0.1573 | 0.1553          | 0.1570 | 0.1560              | 0.166 | 0.146                             | ½-1¼  | 1½-3  |
| 1 ½   | 0.1720                        | 0.1733 | 0.1713          | 0.1730 | 0.1720              | 0.182 | 0.162                             | ¾-1¼  | 1½-3  |
| 1 ¾   | 0.1930                        | 0.1943 | 0.1923          | 0.1940 | 0.1930              | 0.203 | 0.183                             | ¾-1½  | 2-4   |
| 2   | 0.2190                        | 0.2203 | 0.2183          | 0.2200 | 0.2190              | 0.229 | 0.209                             | ¾-1¾  | 2¼-4  |
| 2 ¼   | 0.2500                        | 0.2513 | 0.2493          | 0.2510 | 0.2500              | 0.260 | 0.240                             | ¾-2   | 2¾-6  |
| 2 ½   | 0.2890                        | 0.2903 | 0.2883          | 0.2900 | 0.2890              | 0.299 | 0.279                             | 1-2½  | 2¾-6  |
| 2 ¾   | 0.3410                        | 0.3423 | 0.3403          | 0.3420 | 0.3410              | 0.351 | 0.331                             | 1¼-3  | 3¼-6  |
| 3   | 0.4090                        | 0.4103 | 0.4083          | 0.4100 | 0.4090              | 0.419 | 0.399                             | 1¼-3¾ | 4-8   |
| 3 ¼   | 0.4920                        | 0.4933 | 0.4913          | 0.4930 | 0.4920              | 0.502 | 0.482                             | 1¼-4½ | 4¾-8  |
| 3 ½   | 0.5910                        | 0.5923 | 0.5903          | 0.5920 | 0.5910              | 0.601 | 0.581                             | 1½-5¼ | 5½-8  |
| 3 ¾   | 0.7060                        | 0.7073 | 0.7053          | 0.7070 | 0.7060              | 0.716 | 0.696                             | 1½-6  | 6¼-8  |
| 4   | 0.8600                        | 0.8613 | 0.8593          | ...    | ...                 | 0.870 | 0.850                             | ...   | 2-8   |
| 4 ¼   | 1.0320                        | 1.0333 | 1.0313          | ...    | ...                 | 1.042 | 1.022                             | ...   | 2-9   |
| 4 ½   | 1.2410                        | 1.2423 | 1.2403          | ...    | ...                 | 1.251 | 1.231                             | ...   | 3-11  |
| 4 ¾   | 1.5210                        | 1.5223 | 1.5203          | ...    | ...                 | 1.531 | 1.511                             | ...   | 3-13  |

<sup>a</sup> When specifying nominal pin size in decimals, zeros preceding the decimal and in the fourth decimal place are omitted.

<sup>b</sup> Lengths increase in ⅛-inch steps up to 1 inch and in ¼-inch steps above 1 inch.

<sup>c</sup> Standard reamers are available for pin lengths in this column.

All dimensions are in inches.

For nominal diameters, B, see Table 5.

**American National Standard Grooved Pins.**—These pins have three equally spaced longitudinal grooves and an expanded diameter over the crests of the ridges formed by the material displaced when the grooves are produced. The grooves are aligned with the axes of the pins. There are seven types of grooved pins as shown in the illustration on page 1679.

*Standard Sizes and Lengths:* The standard sizes and lengths in which grooved pins are normally available are given in Table 7.

*Materials:* Grooved pins are normally made from cold drawn low carbon steel wire or rod. Where additional performance is required, carbon steel pins may be supplied surface hardened and heat treated to a hardness consistent with the performance requirements. Pins may also be made from alloy steel, corrosion resistant steel, brass, Monel and other non-ferrous metals having chemical properties as agreed upon between manufacturer and purchaser.

*Performance Requirements:* Grooved pins are required to withstand the minimum double shear loads given in [Table 7](#) for the respective materials shown, when tested in accordance with the Double Shear Testing of Pins as set forth in ANSI/ASME B18.8.2-1995, Appendix B.

*Hole Sizes:* To obtain maximum product retention under average conditions, it is recommended that holes for the installation of grooved pins be held as close as possible to the limits shown in [Table 7](#). The minimum limits correspond to the drill size, which is the same as the basic pin diameter. The maximum limits are generally suitable for length-diameter ratios of not less than 4 to 1 nor greater than 10 to 1. For smaller length-to-diameter ratios, the hole should be held closer to the minimum limits where retention is critical. Conversely for larger ratios where retention requirements are less important, it may be desirable to increase the hole diameters beyond the maximum limits shown.

*Designation:* Grooved pins are designated by the following data in the sequence shown: Product name (noun first) including type designation, nominal size (number, fraction or decimal equivalent), length (fraction or decimal equivalent), material, including specification or heat treatment where necessary, protective finish, if required.

*Examples:* Pin, Type A Grooved,  $\frac{3}{32} \times \frac{3}{4}$ , Steel, Zinc Plated

Pin, Type F Grooved, 0.250  $\times$  1.500, Corrosion Resistant Steel

**American National Standard Grooved T-Head Cotter Pins and Round Head Grooved Drive Studs.**—The cotter pins have a T-head and the studs a round head. Both pins and studs have three equally spaced longitudinal grooves and an expanded diameter over the crests of the raised ridges formed by the material displaced when the grooves are formed.

*Standard Sizes and Lengths:* The standard sizes and range of standard lengths are given in [Tables 8](#) and [9](#).

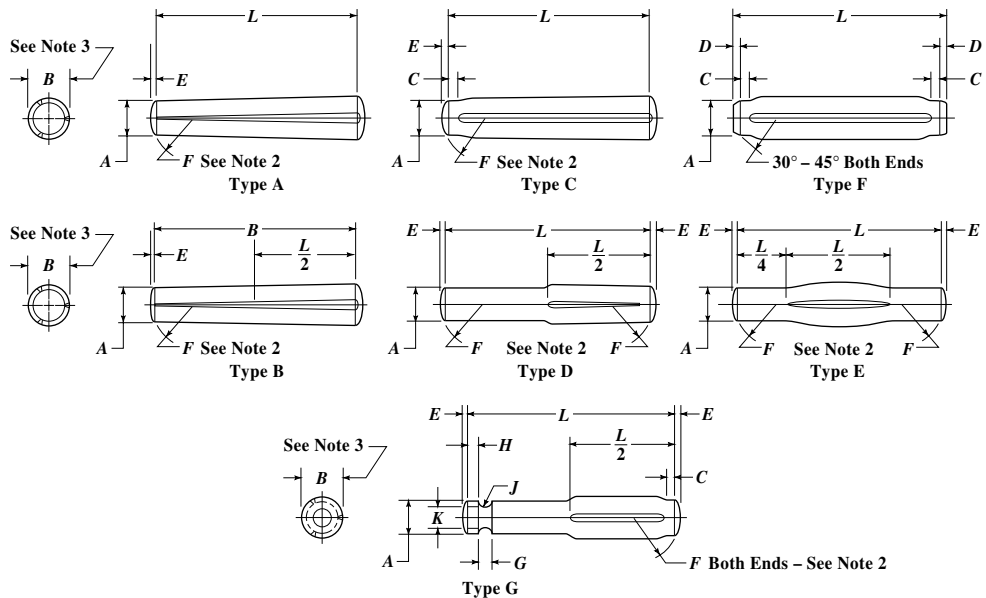
*Material:* Unless otherwise specified these pins are made from low carbon steel. Where so indicated by the purchaser they may be made from corrosion resistant steel, brass or other non-ferrous alloys.

*Hole Sizes:* To obtain optimum product retention under average conditions, it is recommended that holes for the installation of grooved T-head cotter pins and grooved drive studs be held as close as possible to the limits tabulated. The minimum limits given correspond to the drill size, which is equivalent to the basic shank diameter. The maximum limits shown are generally suitable for length-diameter ratios of not less than 4 to 1 and not greater than 10 to 1. For smaller length-to-diameter ratios, the holes should be held closer to minimum limits where retention is critical. Conversely, for larger length-to-diameter ratios or where retention requirements are not essential, it may be desirable to increase the hole diameter beyond the maximum limits shown.

*Designation:* Grooved T-head cotter pins and round head grooved drive studs are designated by the following data, in the order shown: Product name (noun first), nominal size (number, fraction or decimal equivalent), length (fraction or decimal equivalent), material including specification or heat treatment where necessary, and protective finish, if required.

*Examples:* Pin, Grooved T-Head Cotter,  $\frac{1}{4} \times 1\frac{1}{4}$ , Steel, Zinc Plated

Drive Stud, Round Head Grooved, No. 10  $\times$   $\frac{1}{2}$ , Corrosion Resistant Steel



Types of American National Standard Grooved Pins, ANSI/ASME B18.8.2-1995 (For notes see bottom of Table 7.)

**Table 7. American National Standard Grooved Pins ANSI/ASME B18.8.2-1995**

| Nominal Size or Basic Pin Diameter | Pin Diameter, <sup>a</sup> A |        | Pilot Length, C | Chamfer Length, <sup>b</sup> D | Crown Height, <sup>b</sup> E |        | Crown Radius, <sup>b</sup> F |       | Neck Width, G |       | Shoulder Length, H |       | Neck Radius, J | Neck Diameter, K |       | Range of Standard Lengths <sup>c</sup> |
|------------------------------------|------------------------------|--------|-----------------|--------------------------------|------------------------------|--------|------------------------------|-------|---------------|-------|--------------------|-------|----------------|------------------|-------|--|
|                                    | Max                          | Min    | Ref             | Min                            | Max                          | Min    | Max                          | Min   | Max           | Min   | Max                | Min   | Ref            | Max              | Min   |  |
| 1/32 <sup>d</sup>                  | 0.0312                       | 0.0302 | 0.015           | ...                            | ...                          | ...    | ...                          | ...   | ...           | ...   | ...                | ...   | ...            | ...              | ...   | 1/8-1/2                                |
| 3/64 <sup>d</sup>                  | 0.0469                       | 0.0459 | 0.031           | ...                            | ...                          | ...    | ...                          | ...   | ...           | ...   | ...                | ...   | ...            | ...              | ...   | 1/8-3/8                                |
| 1/16                               | 0.0625                       | 0.0615 | 0.031           | 0.016                          | 0.0115                       | 0.0015 | 0.088                        | 0.068 | ...           | ...   | ...                | ...   | ...            | ...              | ...   | 1/8-1                                  |
| 5/64 <sup>d</sup>                  | 0.0781                       | 0.0771 | 0.031           | 0.016                          | 0.0137                       | 0.0037 | 0.104                        | 0.084 | ...           | ...   | ...                | ...   | ...            | ...              | ...   | 1/4-1                                  |
| 3/32                               | 0.0938                       | 0.0928 | 0.031           | 0.016                          | 0.0141                       | 0.0041 | 0.135                        | 0.115 | 0.038         | 0.028 | 0.041              | 0.031 | 0.016          | 0.067            | 0.057 | 1/4-1 1/4                              |
| 7/64 <sup>d</sup>                  | 0.1094                       | 0.1074 | 0.031           | 0.016                          | 0.0160                       | 0.0060 | 0.150                        | 0.130 | 0.038         | 0.028 | 0.041              | 0.031 | 0.016          | 0.082            | 0.072 | 1/4-1 1/4                              |
| 1/8                                | 0.1250                       | 0.1230 | 0.031           | 0.016                          | 0.0180                       | 0.0080 | 0.166                        | 0.146 | 0.069         | 0.059 | 0.041              | 0.031 | 0.031          | 0.088            | 0.078 | 1/4-1 1/2                              |
| 5/32                               | 0.1563                       | 0.1543 | 0.062           | 0.031                          | 0.0220                       | 0.0120 | 0.198                        | 0.178 | 0.069         | 0.059 | 0.057              | 0.047 | 0.031          | 0.109            | 0.099 | 3/8-2                                  |
| 3/16                               | 0.1875                       | 0.1855 | 0.062           | 0.031                          | 0.0230                       | 0.0130 | 0.260                        | 0.240 | 0.069         | 0.059 | 0.057              | 0.047 | 0.031          | 0.130            | 0.120 | 3/8-2 1/4                              |
| 7/32                               | 0.2188                       | 0.2168 | 0.062           | 0.031                          | 0.0270                       | 0.0170 | 0.291                        | 0.271 | 0.101         | 0.091 | 0.072              | 0.062 | 0.047          | 0.151            | 0.141 | 1/2-3                                  |
| 1/4                                | 0.2500                       | 0.2480 | 0.062           | 0.031                          | 0.0310                       | 0.0210 | 0.322                        | 0.302 | 0.101         | 0.091 | 0.072              | 0.062 | 0.047          | 0.172            | 0.162 | 1/2-3 1/4                              |
| 5/16                               | 0.3125                       | 0.3105 | 0.094           | 0.047                          | 0.0390                       | 0.0290 | 0.385                        | 0.365 | 0.132         | 0.122 | 0.104              | 0.094 | 0.062          | 0.214            | 0.204 | 3/4-3 1/2                              |
| 3/8                                | 0.3750                       | 0.3730 | 0.094           | 0.047                          | 0.0440                       | 0.0340 | 0.479                        | 0.459 | 0.132         | 0.122 | 0.135              | 0.125 | 0.062          | 0.255            | 0.245 | 3/4-4 1/4                              |
| 7/16                               | 0.4375                       | 0.4355 | 0.094           | 0.047                          | 0.0520                       | 0.0420 | 0.541                        | 0.521 | 0.195         | 0.185 | 0.135              | 0.125 | 0.094          | 0.298            | 0.288 | 7/8-4 1/2                              |
| 1/2                                | 0.5000                       | 0.4980 | 0.094           | 0.047                          | 0.0570                       | 0.0470 | 0.635                        | 0.615 | 0.195         | 0.185 | 0.135              | 0.125 | 0.094          | 0.317            | 0.307 | 1-4 1/2                                |

<sup>a</sup> For expanded diameters, B, see ANSI/ASME B18.8.2-1995.

<sup>b</sup> Pins in 1/32- and 3/64-inch sizes of any length and all sizes of 1/4-inch nominal length or shorter are not crowned or chamfered.

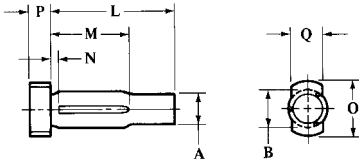
<sup>c</sup> Standard lengths increase in 1/8-inch steps from 1/8 to 1 inch, and in 1/4-inch steps above 1 inch. Standard lengths for the 1/32-, 3/64-, 1/16-, and 5/64-inch sizes and the 1/4-inch length for the 3/32-, 7/64-, and 1/8-inch sizes do not apply to Type G grooved pins.

<sup>d</sup> Non-stock items, not recommended for new designs.

| Pin Material                            | Nominal Pin Size   |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|---|--|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|   | 1/32   | 3/64   | 1/16   | 5/64   | 3/32   | 7/64   | 1/8    | 5/32   | 3/16   | 7/32   | 1/4    | 5/16   | 3/8    | 7/16   | 1/2    |
| Steels                                  | Double Shear Load, Min, lb   |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Low Carbon                              | 100  | 220    | 410    | 620    | 890    | 1,220  | 1,600  | 2,300  | 3,310  | 4,510  | 5,880  | 7,660  | 11,000 | 15,000 | 19,600 |
| Alloy (R <sub>c</sub> 40 - 48 hardness) | 180  | 400    | 720    | 1,120  | 1,600  | 2,180  | 2,820  | 4,520  | 6,440  | 8,770  | 11,500 | 17,900 | 26,000 | 35,200 | 46,000 |
| Corrosion Resistant                     | 140  | 300    | 540    | 860    | 1,240  | 1,680  | 2,200  | 3,310  | 4,760  | 6,480  | 8,460  | 12,700 | 18,200 | 24,800 | 32,400 |
| Brass                                   | 60   | 140    | 250    | 390    | 560    | 760    | 990    | 1,540  | 2,220  | 3,020  | 3,950  | 6,170  | 9,050  | 12,100 | 15,800 |
|   | Recommended Hole Sizes for Unplated Pins (The minimum drill size is the same as the pin size. See also text on page 1678.) |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Maximum Diameter                        | 0.0324   | 0.0482 | 0.0640 | 0.0798 | 0.0956 | 0.1113 | 0.1271 | 0.1587 | 0.1903 | 0.2219 | 0.2534 | 0.3166 | 0.3797 | 0.4428 | 0.5060 |
| Minimum Diameter                        | 0.0312   | 0.0469 | 0.0625 | 0.0781 | 0.0938 | 0.1094 | 0.1250 | 0.1563 | 0.1875 | 0.2188 | 0.2500 | 0.3125 | 0.3750 | 0.4375 | 0.5000 |

All dimensions are in inches.

**Table 8. American National Standard Grooved T-Head Cotter Pins**  
ANSI/ASME B18.8.2-1995



| Nominal Size <sup>a</sup> or Basic Shank Dia. | Shank Diameter, <i>A</i> |       | Length, <i>N</i> | Head Dia., <i>O</i> |      | Head Height, <i>P</i> |      | Head Width, <i>Q</i> |      | Range of Standard Lengths, <sup>b</sup> <i>L</i> | Recommended Hole Size          |       |                                |
|---|--------------------------|-------|------------------|---------------------|------|-----------------------|------|----------------------|------|--|--------------------------------|-------|--------------------------------|
|   | Max                      | Min   | Max              | Max                 | Min  | Max                   | Min  | Max                  | Min  |  | Max                            | Min   |                                |
|   | $\frac{5}{32}$           | 0.156 | 0.154            | 0.150               | 0.08 | 0.26                  | 0.24 | 0.11                 | 0.09 |  | 0.18                           | 0.15  | $\frac{3}{4}$ -1 $\frac{1}{8}$ |
| $\frac{3}{16}$                                | 0.187                    | 0.186 | 0.182            | 0.09                | 0.30 | 0.28                  | 0.13 | 0.11                 | 0.22 | 0.18   | $\frac{3}{4}$ -1 $\frac{1}{4}$ | 0.193 | 0.187                          |
| $\frac{1}{4}$                                 | 0.250                    | 0.248 | 0.244            | 0.12                | 0.40 | 0.38                  | 0.17 | 0.15                 | 0.28 | 0.24   | 1-1 $\frac{1}{2}$              | 0.257 | 0.250                          |
| $\frac{5}{16}$                                | 0.312                    | 0.310 | 0.305            | 0.16                | 0.51 | 0.48                  | 0.21 | 0.19                 | 0.34 | 0.30   | 1 $\frac{1}{8}$ -2             | 0.319 | 0.312                          |
| $\frac{3}{8}$                                 | 0.359                    | 0.358 | 0.353            | 0.18                | 0.57 | 0.54                  | 0.24 | 0.22                 | 0.38 | 0.35   | 1 $\frac{1}{4}$ -2             | 0.366 | 0.359                          |
| $\frac{1}{2}$                                 | 0.500                    | 0.498 | 0.493            | 0.25                | 0.79 | 0.76                  | 0.32 | 0.30                 | 0.54 | 0.49   | 2-3                            | 0.508 | 0.500                          |

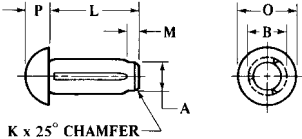
<sup>a</sup> When specifying nominal size in decimals, zeros preceding decimal point and in the fourth decimal place are omitted.

<sup>b</sup> Lengths increase in  $\frac{1}{8}$ -inch steps from  $\frac{3}{4}$  to 1 $\frac{1}{4}$  inch and in  $\frac{1}{4}$ -inch steps above 1 $\frac{1}{4}$  inches. For groove length, *M*, dimensions see ANSI/ASME B18.8.2-1995.

All dimensions are in inches.

For expanded diameter, *B*, dimensions, see ANSI/ASME B18.8.2-1995.

**Table 9. American National Standard Round Head Grooved Drive Studs**  
ANSI/ASME B18.8.2-1995



| Stud Size Number and Basic Shank Diameter <sup>a</sup> | Shank Diameter, <i>A</i> |       | Head Diameter, <i>O</i> |       | Head Height, <i>P</i> |       | Range of Standard Lengths, <sup>b</sup> <i>L</i> | Recommended Hole Size           |                               | Drill Size |               |
|--|--------------------------|-------|-------------------------|-------|-----------------------|-------|--|---------------------------------|-------------------------------|------------|---------------|
|  | Max                      | Min   | Max                     | Min   | Max                   | Min   |  | Max                             | Min                           |            |               |
|  | 0                        | 0.067 | 0.065                   | 0.130 | 0.120                 | 0.050 |  | 0.040                           | $\frac{1}{8}$ - $\frac{1}{4}$ |            | 0.0686        |
| 2  | 0.086                    | 0.086 | 0.162                   | 0.146 | 0.070                 | 0.059 | $\frac{1}{8}$ - $\frac{1}{4}$                    | 0.0877                          | 0.0860                        | 44         |               |
| 4  | 0.104                    | 0.104 | 0.102                   | 0.211 | 0.193                 | 0.086 | 0.075  | $\frac{3}{16}$ - $\frac{5}{16}$ | 0.1059                        | 0.1040     | 37            |
| 6  | 0.120                    | 0.120 | 0.118                   | 0.260 | 0.240                 | 0.103 | 0.091  | $\frac{1}{4}$ - $\frac{3}{8}$   | 0.1220                        | 0.1200     | 31            |
| 7  | 0.136                    | 0.136 | 0.134                   | 0.309 | 0.287                 | 0.119 | 0.107  | $\frac{5}{16}$ - $\frac{1}{2}$  | 0.1382                        | 0.1360     | 29            |
| 8  | 0.144                    | 0.144 | 0.142                   | 0.309 | 0.287                 | 0.119 | 0.107  | $\frac{3}{8}$ - $\frac{5}{8}$   | 0.1463                        | 0.1440     | 27            |
| 10   | 0.161                    | 0.161 | 0.159                   | 0.359 | 0.334                 | 0.136 | 0.124  | $\frac{3}{8}$ - $\frac{5}{8}$   | 0.1636                        | 0.1610     | 20            |
| 12   | 0.196                    | 0.196 | 0.194                   | 0.408 | 0.382                 | 0.152 | 0.140  | $\frac{1}{2}$ $\frac{1}{4}$     | 0.1990                        | 0.1960     | 9             |
| 14   | 0.221                    | 0.221 | 0.219                   | 0.457 | 0.429                 | 0.169 | 0.156  | $\frac{1}{2}$ - $\frac{3}{4}$   | 0.2240                        | 0.2210     | 2             |
| 16   | 0.250                    | 0.250 | 0.248                   | 0.472 | 0.443                 | 0.174 | 0.161  | $\frac{1}{2}$                   | 0.2534                        | 0.2500     | $\frac{1}{4}$ |

<sup>a</sup> Where specifying nominal size in decimals, zeros preceding decimal point and in the fourth decimal place are omitted.

<sup>b</sup> Lengths increase in  $\frac{1}{16}$ -inch steps from  $\frac{1}{8}$  to  $\frac{3}{8}$  inch and in  $\frac{1}{8}$ -inch steps above  $\frac{3}{8}$  inch.

All dimensions are in inches.

For pilot length, *M*, and expanded diameter, *B*, dimensions see ANSI/ASME B18.8.2-1995.

**Table 10. American National Standard Slotted Type Spring Pins**  
ANSI/ASME B18.8.2-1995

| Nominal Size <sup>a</sup> or Basic Pin Diameter | Average Pin Diameter, A    |       | Chamfer Dia., B | Chamfer Length, C |       | Stock Thickness, F | Recommended Hole Size |       | Material                    |                     |                  | Range of Practical Lengths <sup>b</sup> |  |
|---|----------------------------|-------|-----------------|-------------------|-------|--------------------|-----------------------|-------|-----------------------------|---------------------|------------------|---|--|
|   | Max                        | Min   |                 | Max               | Min   |                    | Max                   | Min   | SAE 1070-1095 and SAE 51420 | SAE 30302 and 30304 | Beryllium Copper |   |  |
|   | Double Shear Load, Min, lb |       |                 |                   |       |                    |                       |       |                             |                     |                  |   |  |
| $\frac{1}{16}$                                  | 0.062                      | 0.069 | 0.066           | 0.059             | 0.028 | 0.007              | 0.012                 | 0.065 | 0.062                       | 430                 | 250              | 270                                     | $\frac{3}{16}$ -1                                  |
| $\frac{5}{64}$                                  | 0.078                      | 0.086 | 0.083           | 0.075             | 0.032 | 0.008              | 0.018                 | 0.081 | 0.078                       | 800                 | 460              | 500                                     | $\frac{3}{16}$ -1½                                 |
| $\frac{3}{32}$                                  | 0.094                      | 0.103 | 0.099           | 0.091             | 0.038 | 0.008              | 0.022                 | 0.097 | 0.094                       | 1,150               | 670              | 710                                     | $\frac{3}{16}$ -1½                                 |
| $\frac{1}{8}$                                   | 0.125                      | 0.135 | 0.131           | 0.122             | 0.044 | 0.008              | 0.028                 | 0.129 | 0.125                       | 1,875               | 1,090            | 1,170                                   | $\frac{3}{16}$ -2                                  |
| $\frac{5}{64}$                                  | 0.141                      | 0.149 | 0.145           | 0.137             | 0.044 | 0.008              | 0.028                 | 0.144 | 0.140                       | 2,175               | 1,260            | 1,350                                   | $\frac{3}{16}$ -2                                  |
| $\frac{3}{32}$                                  | 0.156                      | 0.167 | 0.162           | 0.151             | 0.048 | 0.010              | 0.032                 | 0.160 | 0.156                       | 2,750               | 1,600            | 1,725                                   | $\frac{7}{16}$ -2½                                 |
| $\frac{3}{16}$                                  | 0.188                      | 0.199 | 0.194           | 0.182             | 0.055 | 0.011              | 0.040                 | 0.192 | 0.187                       | 4,150               | 2,425            | 2,600                                   | $\frac{1}{2}$ -2½                                  |
| $\frac{7}{32}$                                  | 0.219                      | 0.232 | 0.226           | 0.214             | 0.065 | 0.011              | 0.048                 | 0.224 | 0.219                       | 5,850               | 3,400            | 3,650                                   | $\frac{1}{2}$ -3                                   |
| $\frac{1}{4}$                                   | 0.250                      | 0.264 | 0.258           | 0.245             | 0.065 | 0.012              | 0.048                 | 0.256 | 0.250                       | 7,050               | 4,100            | 4,400                                   | $\frac{1}{2}$ -3½                                  |
| $\frac{5}{16}$                                  | 0.312                      | 0.330 | 0.321           | 0.306             | 0.080 | 0.014              | 0.062                 | 0.318 | 0.312                       | 10,800              | 6,300            | 6,750                                   | $\frac{3}{4}$ -4                                   |
| $\frac{3}{8}$                                   | 0.375                      | 0.395 | 0.385           | 0.368             | 0.095 | 0.016              | 0.077                 | 0.382 | 0.375                       | 16,300              | 9,500            | 10,200                                  | $\frac{3}{4}$ , $\frac{7}{8}$ , 1, 1½, 1½, 1¾, 2-4 |
| $\frac{7}{16}$                                  | 0.438                      | 0.459 | 0.448           | 0.430             | 0.095 | 0.017              | 0.077                 | 0.445 | 0.437                       | 19,800              | 11,500           | 12,300                                  | 1, 1¼, 1½, 1¾, 2-4                                 |
| $\frac{1}{2}$                                   | 0.500                      | 0.524 | 0.513           | 0.485             | 0.110 | 0.025              | 0.094                 | 0.510 | 0.500                       | 27,100              | 15,800           | 17,000                                  | 1½, 1½, 1¾, 2-4                                    |
| $\frac{5}{8}$                                   | 0.625                      | 0.653 | 0.640           | 0.608             | 0.125 | 0.030              | 0.125                 | 0.636 | 0.625                       | 46,000              | 18,800           | ...                                     | 2-6  |
| $\frac{3}{4}$                                   | 0.750                      | 0.784 | 0.769           | 0.730             | 0.150 | 0.030              | 0.150                 | 0.764 | 0.750                       | 66,000              | 23,200           | ...                                     | 2-6  |

<sup>a</sup> Where specifying nominal size in decimals, zeros preceding decimal point are omitted.

<sup>b</sup> Length increments are  $\frac{1}{16}$  inch from  $\frac{1}{8}$  to 1 inch;  $\frac{1}{8}$  from 1 inch to 2 inches; and  $\frac{1}{4}$  inch from 2 inches to 6 inches.

All dimensions are in inches.

**American National Standard Spring Pins.**—These pins are made in two types: one type has a slot throughout its length; the other is shaped into a coil.

**Preferred Lengths and Sizes:** The preferred lengths and sizes in which these pins are normally available are given in Tables 10 and 11.

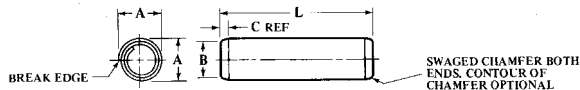
**Materials:** Spring pins are normally made from SAE 1070-1095 carbon steel, SAE 6150H alloy steel, SAE types 51410 through 51420, 30302 and 30304 corrosion resistant steels, and beryllium copper alloy, heat treated or cold worked to attain the hardness and performance characteristics set forth in ANSI/ASME B18.8.2-1995.

**Designation:** Spring pins are designated by the following data in the sequence shown:

**Examples:** Pin, Coiled Spring,  $\frac{1}{4} \times 1\frac{1}{4}$ , Standard Duty, Steel, Zinc Plated

Pin, Slotted Spring,  $\frac{1}{2} \times 3$ , Steel, Phosphate Coated

Table 11. American National Standard Coiled Type Spring Pins ANSI/ASME B18.8.2-1995



| Nominal Size or Basic Pin Diameter | Pin Diameter, A |       |            |       |            |       | Chamfer |           | Recommended Hole Size |       | SAE Material Number        |                     |                     |                     |                     |                 |       |
|------------------------------------|-----------------|-------|------------|-------|------------|-------|---------|-----------|-----------------------|-------|----------------------------|---------------------|---------------------|---------------------|---------------------|-----------------|-------|
|                                    | Standard Duty   |       | Heavy Duty |       | Light Duty |       | Dia., B | Length, C |                       |       | 1070-1095 and 51420        | 30302 and 30304     | 1070-1095 and 51420 | 30302 and 30304     | 1070-1095 and 51420 | 30302 and 30304 |       |
|                                    | Max             | Min   | Max        | Min   | Max        | Min   | Max     | Ref       | Max                   | Min   | Double Shear Load, Min, lb |                     | Standard Duty       | Heavy Duty          | Light Duty          |                 |       |
|                                    |                 |       |            |       |            |       |         |           |                       |       |                            |                     |                     |                     |                     |                 |       |
| $\frac{1}{32}$                     | 0.031           | 0.035 | 0.033      | ...   | ...        | ...   | ...     | 0.029     | 0.024                 | 0.032 | 0.031                      | 90 <sup>a</sup>     | 65                  | ...                 | ...                 | ...             | ...   |
|                                    | 0.039           | 0.044 | 0.041      | ...   | ...        | ...   | ...     | 0.037     | 0.024                 | 0.040 | 0.039                      | 135 <sup>a</sup>    | 100                 | ...                 | ...                 | ...             | ...   |
| $\frac{3}{64}$                     | 0.047           | 0.052 | 0.049      | ...   | ...        | ...   | ...     | 0.045     | 0.024                 | 0.048 | 0.046                      | 190 <sup>a</sup>    | 145                 | ...                 | ...                 | ...             | ...   |
|                                    | 0.052           | 0.057 | 0.054      | ...   | ...        | ...   | ...     | 0.050     | 0.024                 | 0.053 | 0.051                      | 250 <sup>a</sup>    | 190                 | ...                 | ...                 | ...             | ...   |
| $\frac{1}{16}$                     | 0.062           | 0.072 | 0.067      | 0.070 | 0.066      | 0.073 | 0.067   | 0.059     | 0.028                 | 0.065 | 0.061                      | 330                 | 265                 | 475                 | 360                 | 205             | 160   |
|                                    | 0.078           | 0.088 | 0.083      | 0.086 | 0.082      | 0.089 | 0.083   | 0.075     | 0.032                 | 0.081 | 0.077                      | 550                 | 425                 | 800                 | 575                 | 325             | 250   |
| $\frac{3}{32}$                     | 0.094           | 0.105 | 0.099      | 0.103 | 0.098      | 0.106 | 0.099   | 0.091     | 0.038                 | 0.097 | 0.093                      | 775                 | 600                 | 1,150               | 825                 | 475             | 360   |
|                                    | 0.109           | 0.120 | 0.114      | 0.118 | 0.113      | 0.121 | 0.114   | 0.106     | 0.038                 | 0.112 | 0.108                      | 1,050               | 825                 | 1,500               | 1,150               | 650             | 500   |
| $\frac{1}{8}$                      | 0.125           | 0.138 | 0.131      | 0.136 | 0.130      | 0.139 | 0.131   | 0.121     | 0.044                 | 0.129 | 0.124                      | 1,400               | 1,100               | 2,000               | 1,700               | 825             | 650   |
|                                    | 0.156           | 0.171 | 0.163      | 0.168 | 0.161      | 0.172 | 0.163   | 0.152     | 0.048                 | 0.160 | 0.155                      | 2,200               | 1,700               | 3,100               | 2,400               | 1,300           | 1,000 |
| $\frac{3}{16}$                     | 0.188           | 0.205 | 0.196      | 0.202 | 0.194      | 0.207 | 0.196   | 0.182     | 0.055                 | 0.192 | 0.185                      | 3,150               | 2,400               | 4,500               | 3,500               | 1,900           | 1,450 |
|                                    | 0.219           | 0.238 | 0.228      | 0.235 | 0.226      | 0.240 | 0.228   | 0.214     | 0.065                 | 0.224 | 0.217                      | 4,200               | 3,300               | 5,900               | 4,600               | 2,600           | 2,000 |
| $\frac{1}{4}$                      | 0.250           | 0.271 | 0.260      | 0.268 | 0.258      | 0.273 | 0.260   | 0.243     | 0.065                 | 0.256 | 0.247                      | 5,500               | 4,300               | 7,800               | 6,200               | 3,300           | 2,600 |
|                                    | 0.312           | 0.337 | 0.324      | 0.334 | 0.322      | 0.339 | 0.324   | 0.304     | 0.080                 | 0.319 | 0.308                      | 8,700               | 6,700               | 12,000              | 9,300               | 5,200           | 4,000 |
| $\frac{5}{16}$                     | 0.375           | 0.403 | 0.388      | 0.400 | 0.386      | 0.405 | 0.388   | 0.366     | 0.095                 | 0.383 | 0.370                      | 12,600              | 9,600               | 18,000              | 14,000              | ...             | ...   |
|                                    | 0.438           | 0.469 | 0.452      | 0.466 | 0.450      | 0.471 | 0.452   | 0.427     | 0.095                 | 0.446 | 0.431                      | 17,000              | 13,300              | 23,500              | 18,000              | ...             | ...   |
| $\frac{1}{2}$                      | 0.500           | 0.535 | 0.516      | 0.532 | 0.514      | 0.537 | 0.516   | 0.488     | 0.110                 | 0.510 | 0.493                      | 22,500              | 17,500              | 32,000              | 25,000              | ...             | ...   |
|                                    | 0.625           | 0.661 | 0.642      | 0.658 | 0.640      | ...   | ...     | 0.613     | 0.125                 | 0.635 | 0.618                      | 35,000 <sup>b</sup> | ...                 | 48,000 <sup>b</sup> | ...                 | ...             | ...   |
| $\frac{3}{4}$                      | 0.750           | 0.787 | 0.768      | 0.784 | 0.766      | ...   | ...     | 0.738     | 0.150                 | 0.760 | 0.743                      | 50,000 <sup>b</sup> | ...                 | 70,000 <sup>b</sup> | ...                 | ...             | ...   |

<sup>a</sup> Sizes  $\frac{1}{32}$  inch through 0.052 inch are not available in SAE 1070-1095 carbon steel.

<sup>b</sup> Sizes  $\frac{3}{8}$  inch and larger are produced from SAE 6150H alloy steel, not SAE 1070-1095 carbon steel. Practical lengths, L, for sizes  $\frac{1}{32}$  through 0.052 inch are  $\frac{1}{8}$  through  $\frac{3}{8}$  inch and for the  $\frac{1}{16}$  inch size,  $\frac{1}{4}$  through  $1\frac{1}{4}$  inches. For lengths of other sizes see Table 10.

All dimensions are in inches.



## RETAINING RINGS

**Retaining Rings.**—The purpose of a retaining ring is to act as an artificial shoulder that will retain an object in a housing (internal ring), as shown in Fig. 1, or on a shaft (external ring). Two types of retaining ring are common, the stamped ring and the spiral-wound ring. The stamped type of retaining ring, or snap ring, is stamped from tempered sheet metal and has a nonuniform cross-section. The typical spiral-wound retaining ring has a uniform cross-section and is made up of two or more turns of coiled, spring-tempered steel, although one-turn spiral-wound rings are common. Spiral-wound retaining rings provide a continuous gapless shoulder to a housing or shaft. Most stamped rings can only be installed at or near the end of a shaft or housing. The spiral-wound design generally requires installation from the end of a shaft or housing. Both types, stamped and spiral, are usually installed into grooves on the shaft or housing.

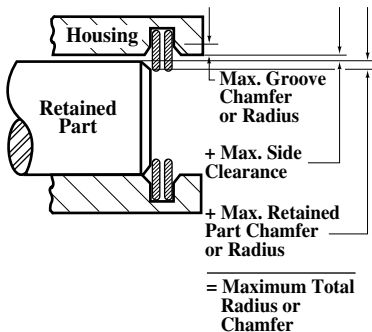
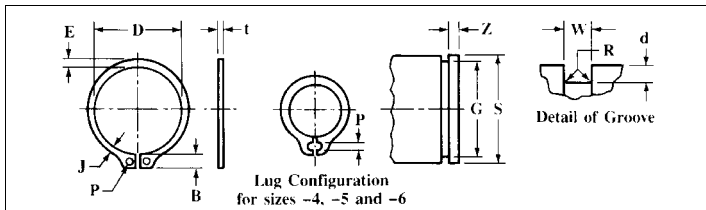


Fig. 1. Typical Retaining Ring Installation Showing Maximum Total Radius or Chamfer (Courtesy Spirolox Retaining Rings)

In the section that follows, Tables 1 through 6 give dimensions and data on general-purpose tapered and reduced cross-section metric retaining rings (stamped type) covered by ANSI B27.7-1977, R1993. Tables 1 and 4 cover Type 3AM1 tapered external retaining rings, Tables 2 and 5 cover Type 3BM1 tapered internal rings, and Tables 3 and 6 cover Type 3CM1 reduced cross-section external rings. Tables 7 through 10 cover inch sizes of internal and external spiral retaining rings corresponding to MIL-R-27426 Types A (external) and B (internal), Class 1 (medium duty) and Class 2 (heavy duty). Tables 11 through 17 cover stamped retaining rings in inch sizes.

**Table 1. American National Standard Metric Tapered Retaining Rings — Basic External Series — 3AM1 ANSI B27.7-1977, R1993**



**Table 1. (Continued) American National Standard Metric Tapered Retaining Rings — Basic External Series — 3AM1 ANSI B27.7-1977, R1993**

| Shaft Dia. | Ring      |           | Groove |       |       |             | Shaft Diam | Ring      |           | Groove |       |       |             |
|------------|-----------|-----------|--------|-------|-------|-------------|------------|-----------|-----------|--------|-------|-------|-------------|
|            | Free Dia. | Thickness | Dia.   | Width | Depth | Edge Margin |            | Free Dia. | Thickness | Dia.   | Width | Depth | Edge Margin |
| S          | D         | t         | G      | W     | d ref | Z min       | S          | D         | t         | G      | W     | d ref | Z min       |
| 4          | 3.60      | 0.25      | 3.80   | 0.32  | 0.1   | 0.3         | 36         | 33.25     | 1.3       | 33.85  | 1.4   | 1.06  | 3.2         |
| 5          | 4.55      | 0.4       | 4.75   | 0.5   | 0.13  | 0.4         | 38         | 35.20     | 1.3       | 35.8   | 1.4   | 1.10  | 3.3         |
| 6          | 5.45      | 0.4       | 5.70   | 0.5   | 0.15  | 0.5         | 40         | 36.75     | 1.6       | 37.7   | 1.75  | 1.15  | 3.4         |
| 7          | 6.35      | 0.6       | 6.60   | 0.7   | 0.20  | 0.6         | 42         | 38.80     | 1.6       | 39.6   | 1.75  | 1.20  | 3.6         |
| 8          | 7.15      | 0.6       | 7.50   | 0.7   | 0.25  | 0.8         | 43         | 39.65     | 1.6       | 40.5   | 1.75  | 1.25  | 3.8         |
| 9          | 8.15      | 0.6       | 8.45   | 0.7   | 0.28  | 0.8         | 45         | 41.60     | 1.6       | 42.4   | 1.75  | 1.30  | 3.9         |
| 10         | 9.00      | 0.6       | 9.40   | 0.7   | 0.30  | 0.9         | 46         | 42.55     | 1.6       | 43.3   | 1.75  | 1.35  | 4.0         |
| 11         | 10.00     | 0.6       | 10.35  | 0.7   | 0.33  | 1.0         | 48         | 44.40     | 1.6       | 45.2   | 1.75  | 1.40  | 4.2         |
| 12         | 10.85     | 0.6       | 11.35  | 0.7   | 0.33  | 1.0         | 50         | 46.20     | 1.6       | 47.2   | 1.75  | 1.40  | 4.2         |
| 13         | 11.90     | 0.9       | 12.30  | 1.0   | 0.35  | 1.0         | 52         | 48.40     | 2.0       | 49.1   | 2.15  | 1.45  | 4.3         |
| 14         | 12.90     | 0.9       | 13.25  | 1.0   | 0.38  | 1.2         | 54         | 49.9      | 2.0       | 51.0   | 2.15  | 1.50  | 4.5         |
| 15         | 13.80     | 0.9       | 14.15  | 1.0   | 0.43  | 1.3         | 55         | 50.6      | 2.0       | 51.8   | 2.15  | 1.60  | 4.8         |
| 16         | 14.70     | 0.9       | 15.10  | 1.0   | 0.45  | 1.4         | 57         | 52.9      | 2.0       | 53.8   | 2.15  | 1.60  | 4.8         |
| 17         | 15.75     | 0.9       | 16.10  | 1.0   | 0.45  | 1.4         | 58         | 53.6      | 2.0       | 54.7   | 2.15  | 1.65  | 4.9         |
| 18         | 16.65     | 1.1       | 17.00  | 1.2   | 0.50  | 1.5         | 60         | 55.8      | 2.0       | 56.7   | 2.15  | 1.65  | 4.9         |
| 19         | 17.60     | 1.1       | 17.95  | 1.2   | 0.53  | 1.6         | 62         | 57.3      | 2.0       | 58.6   | 2.15  | 1.70  | 5.1         |
| 20         | 18.35     | 1.1       | 18.85  | 1.2   | 0.58  | 1.7         | 65         | 60.4      | 2.0       | 61.6   | 2.15  | 1.70  | 5.1         |
| 21         | 19.40     | 1.1       | 19.80  | 1.2   | 0.60  | 1.8         | 68         | 63.1      | 2.0       | 64.5   | 2.15  | 1.75  | 5.3         |
| 22         | 20.30     | 1.1       | 20.70  | 1.2   | 0.65  | 1.9         | 70         | 64.6      | 2.4       | 66.4   | 2.55  | 1.80  | 5.4         |
| 23         | 21.25     | 1.1       | 21.65  | 1.2   | 0.67  | 2.0         | 72         | 66.6      | 2.4       | 68.3   | 2.55  | 1.85  | 5.5         |
| 24         | 22.20     | 1.1       | 22.60  | 1.2   | 0.70  | 2.1         | 75         | 69.0      | 2.4       | 71.2   | 2.55  | 1.90  | 5.7         |
| 25         | 23.10     | 1.1       | 23.50  | 1.2   | 0.75  | 2.3         | 78         | 72.0      | 2.4       | 74.0   | 2.55  | 2.00  | 6.0         |
| 26         | 24.05     | 1.1       | 24.50  | 1.2   | 0.75  | 2.3         | 80         | 74.2      | 2.4       | 75.9   | 2.55  | 2.05  | 6.1         |
| 27         | 24.95     | 1.3       | 25.45  | 1.4   | 0.78  | 2.3         | 82         | 76.4      | 2.4       | 77.8   | 2.55  | 2.10  | 6.3         |
| 28         | 25.80     | 1.3       | 26.40  | 1.4   | 0.80  | 2.4         | 85         | 78.6      | 2.4       | 80.6   | 2.55  | 2.20  | 6.6         |
| 30         | 27.90     | 1.3       | 28.35  | 1.4   | 0.83  | 2.5         | 88         | 81.4      | 2.8       | 83.5   | 2.95  | 2.25  | 6.7         |
| 32         | 29.60     | 1.3       | 30.20  | 1.4   | 0.90  | 2.7         | 90         | 83.2      | 2.8       | 85.4   | 2.95  | 2.30  | 6.9         |
| 34         | 31.40     | 1.3       | 32.00  | 1.4   | 1.00  | 3.0         | 95         | 88.1      | 2.8       | 90.2   | 2.95  | 2.40  | 7.2         |
| 35         | 32.30     | 1.3       | 32.90  | 1.4   | 1.05  | 3.1         | 100        | 92.5      | 2.8       | 95.0   | 2.95  | 2.50  | 7.5         |

All dimensions are in millimeters. Sizes -4, -5, and -6 are available in beryllium copper only.

These rings are designated by series symbol and shaft diameter, thus: for a 4 mm diameter shaft, 3AM1-4; for a 20 mm diameter shaft, 3AM1-20; etc.

**Ring Free Diameter Tolerances:** For ring sizes -4 through -6, +0.05, -0.10 mm; for sizes -7 through -12, +0.05, -0.15 mm; for sizes -13 through -26, +0.15, -0.25 mm; for sizes -27 through -38, +0.25, -0.40 mm; for sizes -40 through -50, +0.35, -0.50 mm; for sizes -52 through -62, +0.35, -0.65 mm; and for sizes -65 through -100, +0.50, -0.75 mm.

**Groove Diameter Tolerances:** For ring sizes -4 through -6, -0.08 mm; for sizes -7 through -10, -0.10 mm; for sizes -11 through -15, -0.12 mm; for sizes -16 through -26, -0.15 mm; for sizes -27 through -36, -0.20 mm; for sizes -38 through -55, -0.30 mm; and for sizes -57 through -100, -0.40 mm.

**Groove Diameter F.I.M. (full indicator movement)** or maximum allowable deviation of concentricity between groove and shaft: For ring sizes -4 through -6, 0.03 mm; for ring sizes -7 through -12, 0.05 mm; for sizes -13 through -28, 0.10 mm; for sizes -30 through -55, 0.15 mm; and for sizes -57 through -100, 0.20 mm.

**Groove Width Tolerances:** For ring size -4, +0.05 mm; for sizes -5 and -6, +0.10 mm, for sizes -7 through -38, +0.15 mm; and for sizes -40 through -100, +0.20 mm.

**Groove Maximum Bottom Radii, R:** For ring sizes -4 through -6, none; for sizes -7 through -18, 0.1 mm; for sizes -19 through -30, 0.2 mm; for sizes -32 through -50, 0.3 mm; and for sizes -52 through -100, 0.4 mm. For manufacturing details not shown, including materials, see ANSI B27.7-1977, R1993.

**Table 2. American National Standard Metric Tapered Retaining Rings — Basic Internal Series — 3BM1 ANSI B27.7-1977, R1993**

| Shaft Dia. | Ring      |           |       | Groove |       |             |           | Shaft Dia. | Ring      |       |       | Groove |             |  |  |
|------------|-----------|-----------|-------|--------|-------|-------------|-----------|------------|-----------|-------|-------|--------|-------------|--|--|
|            | Free Dia. | Thickness | Dia.  | Width  | Depth | Edge Margin | Free Dia. |            | Thickness | Dia.  | Width | Depth  | Edge Margin |  |  |
| S          | D         | t         | G     | W      | d ref | Z min       | S         | D          | t         | G     | W     | d ref  | Z min       |  |  |
| 8          | 8.80      | 0.4       | 8.40  | 0.5    | 0.2   | 0.6         | 65        | 72.2       | 2.4       | 69.0  | 2.55  | 2.00   | 6.0         |  |  |
| 9          | 10.00     | 0.6       | 9.45  | 0.7    | 0.23  | 0.7         | 68        | 75.7       | 2.4       | 72.2  | 2.55  | 2.10   | 6.3         |  |  |
| 10         | 11.10     | 0.6       | 10.50 | 0.7    | 0.25  | 0.8         | 70        | 77.5       | 2.4       | 74.4  | 2.55  | 2.20   | 6.6         |  |  |
| 11         | 12.20     | 0.6       | 11.60 | 0.7    | 0.3   | 0.9         | 72        | 79.6       | 2.4       | 76.5  | 2.55  | 2.25   | 6.7         |  |  |
| 12         | 13.30     | 0.6       | 12.65 | 0.7    | 0.33  | 1.0         | 75        | 83.3       | 2.4       | 79.7  | 2.55  | 2.35   | 7.1         |  |  |
| 13         | 14.25     | 0.9       | 13.70 | 1.0    | 0.35  | 1.1         | 78        | 86.8       | 2.8       | 82.8  | 2.95  | 2.40   | 7.2         |  |  |
| 14         | 15.45     | 0.9       | 14.80 | 1.0    | 0.40  | 1.2         | 80        | 89.1       | 2.8       | 85.0  | 2.95  | 2.50   | 7.5         |  |  |
| 15         | 16.60     | 0.9       | 15.85 | 1.0    | 0.43  | 1.3         | 82        | 91.1       | 2.8       | 87.2  | 2.95  | 2.60   | 7.8         |  |  |
| 16         | 17.70     | 0.9       | 16.90 | 1.0    | 0.45  | 1.4         | 85        | 94.4       | 2.8       | 90.4  | 2.95  | 2.70   | 8.1         |  |  |
| 17         | 18.90     | 0.9       | 18.00 | 1.0    | 0.50  | 1.5         | 88        | 97.9       | 2.8       | 93.6  | 2.95  | 2.80   | 8.4         |  |  |
| 18         | 20.05     | 0.9       | 19.05 | 1.0    | 0.53  | 1.6         | 90        | 100.0      | 2.80      | 95.7  | 2.95  | 2.85   | 8.6         |  |  |
| 19         | 21.10     | 0.9       | 20.10 | 1.0    | 0.55  | 1.7         | 92        | 102.2      | 2.8       | 97.8  | 2.95  | 2.90   | 8.7         |  |  |
| 20         | 22.25     | 0.9       | 21.15 | 1.0    | 0.57  | 1.7         | 95        | 105.6      | 2.8       | 101.0 | 2.95  | 3.00   | 9.0         |  |  |
| 21         | 23.30     | 0.9       | 22.20 | 1.0    | 0.60  | 1.8         | 98        | 109.0      | 2.8       | 104.2 | 2.95  | 3.10   | 9.3         |  |  |
| 22         | 24.40     | 1.1       | 23.30 | 1.2    | 0.65  | 1.9         | 100       | 110.7      | 2.8       | 106.3 | 2.95  | 3.15   | 9.5         |  |  |
| 23         | 25.45     | 1.1       | 24.35 | 1.2    | 0.67  | 2.0         | 102       | 112.4      | 2.8       | 108.4 | 2.95  | 3.20   | 9.6         |  |  |
| 24         | 26.55     | 1.1       | 25.4  | 1.2    | 0.70  | 2.1         | 105       | 115.8      | 2.8       | 111.5 | 2.95  | 3.25   | 9.8         |  |  |
| 25         | 27.75     | 1.1       | 26.6  | 1.2    | 0.80  | 2.4         | 108       | 119.2      | 2.8       | 114.6 | 2.95  | 3.30   | 9.9         |  |  |
| 26         | 28.85     | 1.1       | 27.7  | 1.2    | 0.85  | 2.6         | 110       | 120.8      | 2.8       | 116.7 | 2.95  | 3.35   | 10.1        |  |  |
| 27         | 29.95     | 1.3       | 28.8  | 1.4    | 0.90  | 2.7         | 115       | 126.0      | 2.8       | 121.9 | 2.95  | 3.45   | 10.4        |  |  |
| 28         | 31.10     | 1.3       | 29.8  | 1.4    | 0.90  | 2.7         | 120       | 132.4      | 2.8       | 127.0 | 2.95  | 3.50   | 10.5        |  |  |
| 30         | 33.40     | 1.3       | 31.9  | 1.4    | 0.95  | 2.9         | 125       | 137.1      | 2.8       | 132.1 | 2.95  | 3.55   | 10.7        |  |  |
| 32         | 35.35     | 1.3       | 33.9  | 1.4    | 0.95  | 2.9         | 130       | 142.5      | 2.8       | 137.2 | 2.95  | 3.60   | 10.8        |  |  |
| 34         | 37.75     | 1.3       | 36.1  | 1.4    | 1.05  | 3.2         | 135       | 148.5      | 3.2       | 142.3 | 3.40  | 3.65   | 11.0        |  |  |
| 35         | 38.75     | 1.3       | 37.2  | 1.4    | 1.10  | 3.3         | 140       | 154.1      | 3.2       | 147.4 | 3.40  | 3.70   | 11.1        |  |  |
| 36         | 40.00     | 1.3       | 38.3  | 1.4    | 1.15  | 3.5         | 145       | 159.5      | 3.2       | 152.5 | 3.40  | 3.75   | 11.3        |  |  |
| 37         | 41.05     | 1.3       | 39.3  | 1.4    | 1.15  | 3.5         | 150       | 164.5      | 3.2       | 157.6 | 3.40  | 3.80   | 11.4        |  |  |
| 38         | 42.15     | 1.3       | 40.4  | 1.4    | 1.20  | 3.6         | 155       | 168.8      | 3.2       | 162.7 | 3.40  | 3.85   | 11.6        |  |  |
| 40         | 44.25     | 1.6       | 42.4  | 1.75   | 1.20  | 3.6         | 160       | 175.1      | 4.0       | 167.8 | 4.25  | 3.90   | 11.7        |  |  |
| 42         | 46.60     | 1.6       | 44.5  | 1.75   | 1.25  | 3.7         | 165       | 180.3      | 4.0       | 172.9 | 4.25  | 3.95   | 11.9        |  |  |
| 45         | 49.95     | 1.6       | 47.6  | 1.75   | 1.30  | 3.9         | 170       | 185.6      | 4.0       | 178.0 | 4.25  | 4.00   | 12.0        |  |  |
| 46         | 51.05     | 1.6       | 48.7  | 1.75   | 1.35  | 4.0         | 175       | 191.3      | 4.0       | 183.2 | 4.25  | 4.10   | 12.3        |  |  |
| 47         | 52.15     | 1.6       | 49.8  | 1.75   | 1.40  | 4.2         | 180       | 196.6      | 4.0       | 188.4 | 4.25  | 4.20   | 12.6        |  |  |
| 48         | 53.30     | 1.6       | 50.9  | 1.75   | 1.45  | 4.3         | 185       | 202.7      | 4.8       | 193.6 | 5.10  | 4.30   | 12.9        |  |  |
| 50         | 55.35     | 1.6       | 53.1  | 1.75   | 1.55  | 4.6         | 190       | 207.7      | 4.8       | 198.8 | 5.10  | 4.40   | 13.2        |  |  |
| 52         | 57.90     | 2.0       | 55.3  | 2.15   | 1.65  | 5.0         | 200       | 217.8      | 4.8       | 209.0 | 5.10  | 4.50   | 13.5        |  |  |
| 55         | 61.10     | 2.0       | 58.4  | 2.15   | 1.70  | 5.1         | 210       | 230.3      | 4.8       | 219.4 | 5.10  | 4.70   | 14.1        |  |  |
| 57         | 63.25     | 2.0       | 60.5  | 2.15   | 1.75  | 5.3         | 220       | 240.5      | 4.8       | 230.0 | 5.10  | 5.00   | 15.0        |  |  |
| 58         | 64.4      | 2.0       | 61.6  | 2.15   | 1.80  | 5.4         | 230       | 251.4      | 4.8       | 240.6 | 5.10  | 5.30   | 15.9        |  |  |
| 60         | 66.8      | 2.0       | 63.8  | 2.15   | 1.90  | 5.7         | 240       | 262.3      | 4.8       | 251.0 | 5.10  | 5.50   | 16.5        |  |  |
| 62         | 68.6      | 2.0       | 65.8  | 2.15   | 1.90  | 5.7         | 250       | 273.3      | 4.8       | 261.4 | 5.10  | 5.70   | 17.1        |  |  |
| 63         | 69.9      | 2.0       | 66.9  | 2.15   | 1.95  | 5.9         | ...       | ...        | ...       | ...   | ...   | ...    | ...         |  |  |

All dimensions are in millimeters.

These rings are designated by series symbol and shaft diameter, thus: for a 9 mm diameter shaft, 3BM1-9; for a 22 mm diameter shaft, 3BM1-22; etc.

**Ring Free Diameter Tolerances:** For ring sizes -8 through -20, +0.25, -0.13 mm; for sizes -21 through -26, +0.40, -0.25 mm; for sizes -27 through -38, +0.65, -0.50 mm; for sizes -40 through -50, +0.90, -0.65 mm; for sizes -52 through -75, +1.00, -0.75 mm; for sizes -78 through -92, +1.40,

-1.40 mm; for sizes -95 through -155, +1.65, -1.65 mm; for sizes -160 through -180, +2.05, -2.05 mm; and for sizes -185 through -250, +2.30, -2.30 mm.

**Groove Diameter Tolerances:** For ring sizes -8 and -9, +0.06 mm; for sizes -10 through -18, +0.10 mm; for sizes -19 through -28, +0.15 mm; for sizes -30 through -50, +0.20 mm; for sizes -52 through -98, +0.30; for sizes -100 through -160, +0.40 mm; and for sizes -165 through -250, +0.50 mm.

**Groove Diameter F.I.M. (full indicator movement)** or maximum allowable deviation of concentricity between groove and shaft: For ring sizes -8 through -10, 0.03 mm; for sizes -11 through -15, 0.05 mm; for sizes -16 through -25, 0.10 mm; for sizes -26 through -45, 0.15 mm; for sizes -46 through -80, 0.20 mm; for sizes -82 through -150, 0.25 mm; and for sizes -155 through -250, 0.30 mm.

**Groove Width Tolerances:** For ring size -8, +0.10 mm; for sizes -9 through -38, +0.15 mm; for sizes -40 through -130, +0.20 mm; and for sizes -135 through -250, +0.25 mm.

**Groove Maximum Bottom Radii:** For ring sizes -8 through -17, 0.1 mm; for sizes -18 through -30, 0.2 mm; for sizes -32 through -55, 0.3 mm; and for sizes -56 through -250, 0.4 mm.

For manufacturing details not shown, including materials, see ANSI B27.7-1977, R1993.

**Table 3. American National Standard Metric Reduced Cross Section Retaining Rings — E Ring External Series — 3CM1 ANSI B27.7-1977, R1993**

| Shaft Dia. | Ring      |           |            |      | Groove |       |             |           | Shaft Dia. | Ring      |            |       |       | Groove |             |  |  |
|------------|-----------|-----------|------------|------|--------|-------|-------------|-----------|------------|-----------|------------|-------|-------|--------|-------------|--|--|
|            | Free Dia. | Thickness | Outer Dia. | Dia. | Width  | Depth | Edge Margin | Free Dia. |            | Thickness | Outer Dia. | Dia.  | Width | Depth  | Edge Margin |  |  |
| S          | D         | t         | Y nom      | G    | W      | d ref | Z min       | S         | D          | t         | Y nom      | G     | W     | d ref  | Z min       |  |  |
| 1          | 0.64      | 0.25      | 2.0        | 0.72 | 0.32   | 0.14  | 0.3         | 11        | 8.55       | 0.9       | 17.4       | 8.90  | 1.0   | 1.05   | 2.1         |  |  |
| 2          | 1.30      | 0.25      | 4.0        | 1.45 | 0.32   | 0.28  | 0.6         | 12        | 9.20       | 1.1       | 18.6       | 9.60  | 1.2   | 1.20   | 2.4         |  |  |
| 3          | 2.10      | 0.4       | 5.6        | 2.30 | 0.5    | 0.35  | 0.7         | 13        | 9.95       | 1.1       | 20.3       | 10.30 | 1.2   | 1.35   | 2.7         |  |  |
| 4          | 2.90      | 0.6       | 7.2        | 3.10 | 0.7    | 0.45  | 0.9         | 15        | 11.40      | 1.1       | 22.8       | 11.80 | 1.2   | 1.60   | 3.2         |  |  |
| 5          | 3.70      | 0.6       | 8.5        | 3.90 | 0.7    | 0.55  | 1.1         | 16        | 12.15      | 1.1       | 23.8       | 12.50 | 1.2   | 1.75   | 3.5         |  |  |
| 6          | 4.70      | 0.6       | 11.1       | 4.85 | 0.7    | 0.58  | 1.2         | 18        | 13.90      | 1.3       | 27.2       | 14.30 | 1.4   | 1.85   | 3.7         |  |  |
| 7          | 5.25      | 0.6       | 13.4       | 5.55 | 0.7    | 0.73  | 1.5         | 20        | 15.60      | 1.3       | 30.0       | 16.00 | 1.4   | 2.00   | 4.0         |  |  |
| 8          | 6.15      | 0.6       | 14.6       | 6.40 | 0.7    | 0.80  | 1.6         | 22        | 17.00      | 1.3       | 33.0       | 17.40 | 1.4   | 2.30   | 4.6         |  |  |
| 9          | 6.80      | 0.9       | 15.8       | 7.20 | 1.0    | 0.90  | 1.8         | 25        | 19.50      | 1.3       | 37.1       | 20.00 | 1.4   | 2.50   | 5.0         |  |  |
| 10         | 7.60      | 0.9       | 16.8       | 8.00 | 1.0    | 1.00  | 2.0         | ...       | ...        | ...       | ...        | ...   | ...   | ...    | ...         |  |  |

All dimensions are in millimeters. Size -1 is available in beryllium copper only.

These rings are designated by series symbol and shaft diameter, thus: for a 2 mm diameter shaft, 3CM1-2; for a 13 mm shaft, 3CM1-13; etc.

**Ring Free Diameter Tolerances:** For ring sizes -1 through -7, +0.03, -0.08 mm; for sizes -8 through -13, +0.05, -0.10 mm; and for sizes -15 through -25, +0.10, -0.15 mm.

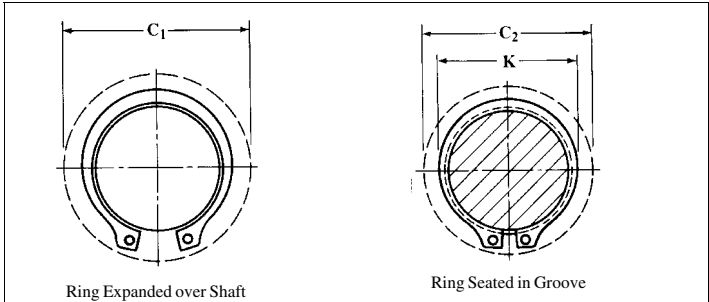
**Groove Diameter Tolerances:** For ring sizes -1 and -2, -0.05 mm; for sizes -3 through -6, -0.08; for sizes -7 through -11, -0.10 mm; for sizes -12 through -18, -0.15 mm; and for sizes -20 through -25, -0.20 mm.

**Groove Diameter F.I.M. (Full Indicator Movement)** or maximum allowable deviation of concentricity between groove and shaft: For ring sizes -1 through -3, 0.04 mm; for -4 through -6, 0.05 mm; for -7 through -10, 0.08 mm; for -11 through -25, 0.10 mm.

**Groove Width Tolerances:** For ring sizes -1 and -2, +0.05 mm; for size -3, +0.10 mm; and for sizes -4 through -25, +0.15 mm.

**Groove Maximum Bottom Radii:** For ring sizes -1 and -2, 0.05 mm; for -3 through -7, 0.15 mm; for -8 through -13, 0.25 mm; and for -15 through -25, 0.4 mm.

For manufacturing details not shown, including materials, see ANSI B27.7-1977, R1993.



**Table 4. American National Standard Metric Basic External Series 3AM1 Retaining Rings, Checking and Performance Data ANSI B27.7-1977, R1993**

| Ring Series and Size No. | Clearance Dia.  |                | Gaging Diameter <sup>a</sup> | Allowable Thrust Loads Sharp Corner Abutment |         | Maximum Allowable Corner Radii and Chamfers |          | Allowable Assembly Speed <sup>b</sup> |
|--------------------------|-----------------|----------------|------------------------------|--|---------|---|----------|---------------------------------------|
|                          | Ring Over Shaft | Ring in Groove |                              | $P_r^c$                                      | $P_g^d$ | $R$ max                                     | $Ch$ max |                                       |
| 3AM1                     | $C_1$           | $C_2$          | $K$ max                      | $P_r^c$                                      | $P_g^d$ | $R$ max                                     | $Ch$ max | ...                                   |
| No.                      | mm              | mm             | mm                           | kN   | kN      | mm  | mm       | rpm                                   |
| -4 <sup>a</sup>          | 7.0             | 6.8            | 4.90                         | 0.6  | 0.2     | 0.35  | 0.25     | 70 000                                |
| -5 <sup>a</sup>          | 8.2             | 7.9            | 5.85                         | 1.1  | 0.3     | 0.35  | 0.25     | 70 000                                |
| -6 <sup>a</sup>          | 9.1             | 8.8            | 6.95                         | 1.4  | 0.4     | 0.35  | 0.25     | 70 000                                |
| -7                       | 12.3            | 11.8           | 8.05                         | 2.6  | 0.7     | 0.45  | 0.3      | 60 000                                |
| -8                       | 13.6            | 13.0           | 9.15                         | 3.1  | 1.0     | 0.5   | 0.35     | 55 000                                |
| -9                       | 14.5            | 13.8           | 10.35                        | 3.5  | 1.2     | 0.6   | 0.35     | 48 000                                |
| -10                      | 15.5            | 14.7           | 11.50                        | 3.9  | 1.5     | 0.7   | 0.4      | 42 000                                |
| -11                      | 16.4            | 15.6           | 12.60                        | 4.3  | 1.8     | 0.75  | 0.45     | 38 000                                |
| -12                      | 17.4            | 16.6           | 13.80                        | 4.7  | 2.0     | 0.8   | 0.45     | 34 000                                |
| -13                      | 19.7            | 18.8           | 15.05                        | 7.5  | 2.2     | 0.8   | 0.5      | 31 000                                |
| -14                      | 20.7            | 19.7           | 15.60                        | 8.1  | 2.6     | 0.9   | 0.5      | 28 000                                |
| -15                      | 21.7            | 20.6           | 17.20                        | 8.7  | 3.2     | 1.0   | 0.6      | 27 000                                |
| -16                      | 22.7            | 21.6           | 18.35                        | 9.3  | 3.5     | 1.1   | 0.6      | 25 000                                |
| -17                      | 23.7            | 22.6           | 19.35                        | 9.9  | 4.0     | 1.1   | 0.6      | 24 000                                |
| -18                      | 26.2            | 25.0           | 20.60                        | 16.0   | 4.4     | 1.2   | 0.7      | 23 000                                |
| -19                      | 27.2            | 25.9           | 21.70                        | 16.9   | 4.9     | 1.2   | 0.7      | 21 500                                |
| -20                      | 28.2            | 26.8           | 22.65                        | 17.8   | 5.7     | 1.2   | 0.7      | 20 000                                |
| -21                      | 29.2            | 27.7           | 23.80                        | 18.6   | 6.2     | 1.3   | 0.7      | 19 000                                |
| -22                      | 30.3            | 28.7           | 24.90                        | 19.6   | 7.0     | 1.3   | 0.8      | 18 500                                |
| -23                      | 31.3            | 29.6           | 26.00                        | 20.5   | 7.6     | 1.3   | 0.8      | 18 000                                |
| -24                      | 34.1            | 32.4           | 27.15                        | 21.4   | 8.2     | 1.4   | 0.8      | 17 500                                |
| -25                      | 35.1            | 33.3           | 28.10                        | 22.3   | 9.2     | 1.4   | 0.8      | 17 000                                |
| -26                      | 36.0            | 34.2           | 29.25                        | 23.2   | 9.6     | 1.5   | 0.9      | 16 500                                |
| -27                      | 37.8            | 35.9           | 30.35                        | 28.4   | 10.3    | 1.5   | 0.9      | 16 300                                |
| -28                      | 38.8            | 36.9           | 31.45                        | 28.4   | 11.0    | 1.6   | 1.0      | 15 800                                |
| -30                      | 40.8            | 38.8           | 33.6                         | 31.6   | 12.3    | 1.6   | 1.0      | 15 000                                |
| -32                      | 42.8            | 40.7           | 35.9                         | 33.6   | 14.1    | 1.7   | 1.0      | 14 800                                |
| -34                      | 44.9            | 42.5           | 37.9                         | 36   | 16.7    | 1.7   | 1.1      | 14 000                                |

**Table 4. (Continued) American National Standard Metric Basic External Series 3AM1 Retaining Rings, Checking and Performance Data ANSI B27.7-1977, R1993**

| Ring Series and Size No. | Clearance Dia.  |                | Gaging Diameter <sup>a</sup> | Allowable Thrust Loads Sharp Corner Abutment |         | Maximum Allowable Corner Radii and Chamfers |          | Allowable Assembly Speed <sup>b</sup> |
|--------------------------|-----------------|----------------|------------------------------|--|---------|---|----------|---------------------------------------|
|                          | Ring Over Shaft | Ring in Groove |                              | $P_r^c$                                      | $P_g^d$ | $R$ max                                     | $Ch$ max |                                       |
| 3AM1                     | $C_1$           | $C_2$          | $K$ max                      | $P_r^c$                                      | $P_g^d$ | $R$ max                                     | $Ch$ max | ...                                   |
| No.                      | mm              | mm             | mm                           | kN   | kN      | mm  | mm       | rpm                                   |
| -35                      | 45.9            | 43.4           | 39.0                         | 37   | 18.1    | 1.8   | 1.1      | 13 500                                |
| -36                      | 48.6            | 46.1           | 40.2                         | 38   | 18.9    | 1.9   | 1.2      | 13 300                                |
| -38                      | 50.6            | 48.0           | 42.5                         | 40   | 20.5    | 2.0   | 1.2      | 12 700                                |
| -40                      | 54.0            | 51.3           | 44.5                         | 52   | 22.6    | 2.1   | 1.2      | 12 000                                |
| -42                      | 56.0            | 53.2           | 46.9                         | 54   | 24.8    | 2.2   | 1.3      | 11 000                                |
| -43                      | 57.0            | 54.0           | 47.9                         | 55   | 26.4    | 2.3   | 1.4      | 10 800                                |
| -45                      | 59.0            | 55.9           | 50.0                         | 58   | 28.8    | 2.3   | 1.4      | 10 000                                |
| -46                      | 60.0            | 56.8           | 50.9                         | 59   | 30.4    | 2.4   | 1.4      | 9 500                                 |
| -48                      | 62.4            | 59.1           | 53.0                         | 62   | 33      | 2.4   | 1.4      | 8 800                                 |
| -50                      | 64.4            | 61.1           | 55.2                         | 64   | 35      | 2.4   | 1.4      | 8 000                                 |
| -52                      | 67.6            | 64.1           | 57.4                         | 84   | 37      | 2.5   | 1.5      | 7 700                                 |
| -54                      | 69.6            | 66.1           | 59.5                         | 87   | 40      | 2.5   | 1.5      | 7 500                                 |
| -55                      | 70.6            | 66.9           | 60.4                         | 89   | 44      | 2.5   | 1.5      | 7 400                                 |
| -57                      | 72.6            | 68.9           | 62.7                         | 91   | 45      | 2.6   | 1.5      | 7 200                                 |
| -58                      | 73.6            | 69.8           | 63.6                         | 93   | 46      | 2.6   | 1.6      | 7 100                                 |
| -60                      | 75.6            | 71.8           | 65.8                         | 97   | 49      | 2.6   | 1.6      | 7 000                                 |
| -62                      | 77.6            | 73.6           | 67.9                         | 100  | 52      | 2.7   | 1.6      | 6 900                                 |
| -65                      | 80.6            | 76.6           | 71.2                         | 105  | 54      | 2.8   | 1.7      | 6 700                                 |
| -68                      | 83.6            | 79.5           | 74.5                         | 110  | 58      | 2.9   | 1.7      | 6 500                                 |
| -70                      | 88.1            | 83.9           | 76.4                         | 136  | 62      | 2.9   | 1.7      | 6 400                                 |
| -72                      | 90.1            | 85.8           | 78.5                         | 140  | 65      | 2.9   | 1.7      | 6 200                                 |
| -75                      | 93.1            | 88.7           | 81.7                         | 147  | 69      | 3.0   | 1.8      | 5 900                                 |
| -78                      | 95.4            | 92.1           | 84.6                         | 151  | 76      | 3.0   | 1.8      | 5 600                                 |
| -80                      | 97.9            | 93.1           | 87.0                         | 155  | 80      | 3.1   | 1.9      | 5 400                                 |
| -82                      | 100.0           | 95.1           | 89.0                         | 159  | 84      | 3.2   | 1.9      | 5 200                                 |
| -85                      | 103.0           | 97.9           | 92.1                         | 165  | 91      | 3.2   | 1.9      | 5 000                                 |
| -88                      | 107.0           | 100.8          | 95.1                         | 199  | 97      | 3.2   | 1.9      | 4 800                                 |
| -90                      | 109.0           | 103.6          | 97.1                         | 204  | 101     | 3.2   | 1.9      | 4 500                                 |
| -95                      | 114.0           | 108.6          | 102.7                        | 215  | 112     | 3.4   | 2.1      | 4 350                                 |
| -100                     | 119.5           | 113.7          | 108.0                        | 227  | 123     | 3.5   | 2.1      | 4 150                                 |

<sup>a</sup> For checking when ring is seated in groove.

<sup>b</sup> These values have been calculated for steel rings.

<sup>c</sup> These values apply to rings made from SAE 1060–1090 steels and PH 15-7 Mo stainless steel used on shafts hardened to  $R_c$  50 minimum, with the exception of sizes -4, -5, and -6 which are supplied in beryllium copper only. Values for other sizes made from beryllium copper can be calculated by multiplying the listed values by 0.75. The values listed include a safety factor of 4.

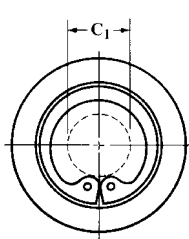
<sup>d</sup> These values are for all standard rings used on low carbon steel shafts. They include a safety factor of 2.

Maximum allowable assembly loads with  $R$  max or  $Ch$  max are: For rings sizes -4, 0.2 kN; for sizes -5 and -6, 0.5 kN; for sizes -7 through -12, 2.1 kN; for sizes -13 through -17, 4.0 kN; for sizes -18 through -26, 6.0 kN; for sizes -27 through -38, 8.6 kN; for sizes -40 through -50, 13.2 kN; for sizes -52 through -68, 22.0 kN; for sizes -70 through -85, 32 kN; and for sizes -88 through -100, 47 kN.

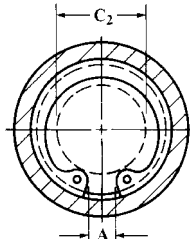
Source: Appendix to American National Standard ANSI B27.7-1977, R1993.

**Table 5. American National Standard Metric Basic Internal Series 3BMI Retaining Rings — Checking and Performance Data ANSI B27.7-1977, R1993**

| Ring Series and Size No. | Clearance Dia. |                | Gaging Diameter <sup>a</sup> | Allowable Thrust Loads Sharp Corner Abutment |         | Maximum Allowable Corner Radii and Chamfers |            |
|--------------------------|----------------|----------------|------------------------------|--|---------|---|------------|
|                          | Ring in Bore   | Ring in Groove |                              | $P_r^b$                                      | $P_g^c$ | $R_{max}$                                   | $Ch_{max}$ |
| 3BMI No.                 | $C_1$<br>mm    | $C_2$<br>mm    | $A$<br>mm                    | kN   | kN      | mm  | mm         |
| -8                       | 4.4            | 4.8            | 1.40                         | 2.4  | 1.0     | 0.4   | 0.3        |
| -9                       | 4.6            | 5.0            | 1.50                         | 4.4  | 1.2     | 0.5   | 0.35       |
| -10                      | 5.5            | 6.0            | 1.85                         | 4.9  | 1.5     | 0.5   | 0.35       |
| -11                      | 5.7            | 6.3            | 1.95                         | 5.4  | 2.0     | 0.6   | 0.4        |
| -12                      | 6.7            | 7.3            | 2.25                         | 5.8  | 2.4     | 0.6   | 0.4        |
| -13                      | 6.8            | 7.5            | 2.35                         | 8.9  | 2.6     | 0.7   | 0.5        |
| -14                      | 6.9            | 7.7            | 2.65                         | 9.7  | 3.2     | 0.7   | 0.5        |
| -15                      | 7.9            | 8.7            | 2.80                         | 10.4   | 3.7     | 0.7   | 0.5        |
| -16                      | 8.8            | 9.7            | 2.80                         | 11.0   | 4.2     | 0.7   | 0.5        |
| -17                      | 9.8            | 10.8           | 3.35                         | 11.7   | 4.9     | 0.75  | 0.6        |
| -18                      | 10.3           | 11.3           | 3.40                         | 12.3   | 5.5     | 0.75  | 0.6        |
| -19                      | 11.4           | 12.5           | 3.40                         | 13.1   | 6.0     | 0.8   | 0.65       |
| -20                      | 11.6           | 12.7           | 3.8                          | 13.7   | 6.6     | 0.9   | 0.7        |
| -21                      | 12.6           | 13.8           | 4.2                          | 14.5   | 7.3     | 0.9   | 0.7        |
| -22                      | 13.5           | 14.8           | 4.3                          | 22.5   | 8.3     | 0.9   | 0.7        |
| -23                      | 14.5           | 15.9           | 4.9                          | 23.5   | 8.9     | 1.0   | 0.8        |
| -24                      | 15.5           | 16.9           | 5.2                          | 24.8   | 9.7     | 1.0   | 0.8        |
| -25                      | 16.5           | 18.1           | 6.0                          | 25.7   | 11.6    | 1.0   | 0.8        |
| -26                      | 17.5           | 19.2           | 5.7                          | 26.8   | 12.7    | 1.2   | 1.0        |
| -27                      | 17.4           | 19.2           | 5.9                          | 33   | 14.0    | 1.2   | 1.0        |
| -28                      | 18.2           | 20.0           | 6.0                          | 34   | 14.6    | 1.2   | 1.0        |
| -30                      | 20.0           | 21.9           | 6.0                          | 37   | 16.5    | 1.2   | 1.0        |
| -32                      | 22.0           | 23.9           | 7.3                          | 39   | 17.6    | 1.2   | 1.0        |
| -34                      | 24.0           | 26.1           | 7.6                          | 42   | 20.6    | 1.2   | 1.0        |
| -35                      | 25.0           | 27.2           | 8.0                          | 43   | 22.3    | 1.2   | 1.0        |
| -36                      | 26.0           | 28.3           | 8.3                          | 44   | 23.9    | 1.2   | 1.0        |
| -37                      | 27.0           | 29.3           | 8.4                          | 45   | 24.6    | 1.2   | 1.0        |
| -38                      | 28.0           | 30.4           | 8.6                          | 46   | 26.4    | 1.2   | 1.0        |
| -40                      | 29.2           | 31.6           | 9.7                          | 62   | 27.7    | 1.7   | 1.3        |
| -42                      | 29.7           | 32.2           | 9.0                          | 65   | 30.2    | 1.7   | 1.3        |
| -45                      | 32.3           | 34.9           | 9.6                          | 69   | 33.8    | 1.7   | 1.3        |
| -46                      | 33.3           | 36.0           | 9.7                          | 71   | 36      | 1.7   | 1.3        |
| -47                      | 34.3           | 37.1           | 10.0                         | 72   | 38      | 1.7   | 1.3        |
| -48                      | 35.0           | 37.9           | 10.5                         | 74   | 40      | 1.7   | 1.3        |
| -50                      | 36.9           | 40.0           | 12.1                         | 77   | 45      | 1.7   | 1.3        |
| -52                      | 38.6           | 41.9           | 11.7                         | 99   | 50      | 2.0   | 1.6        |
| -55                      | 40.8           | 44.2           | 11.9                         | 105  | 54      | 2.0   | 1.6        |
| -57                      | 42.2           | 45.7           | 12.5                         | 109  | 58      | 2.0   | 1.6        |



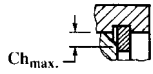
Ring Compressed in Bore



Ring Seated in Groove



Max Allowable Radius of Retained Part



Max Allowable Chamfer of Retained Part

**Table 5. (Continued) American National Standard Metric Basic Internal Series 3BBI**

|      |       |       |      |      |     |     |     |
|------|-------|-------|------|------|-----|-----|-----|
| -58  | 43.2  | 46.8  | 13.0 | 111  | 60  | 2.0 | 1.6 |
| -60  | 45.5  | 49.3  | 12.7 | 115  | 66  | 2.0 | 1.6 |
| -62  | 47.0  | 50.8  | 14.0 | 119  | 68  | 2.0 | 1.6 |
| -63  | 47.8  | 51.7  | 14.2 | 120  | 71  | 2.0 | 1.6 |
| -65  | 49.4  | 53.4  | 14.2 | 149  | 75  | 2.0 | 1.6 |
| -68  | 52.0  | 56.2  | 14.4 | 156  | 82  | 2.3 | 1.8 |
| -70  | 53.8  | 58.2  | 16.1 | 161  | 88  | 2.3 | 1.8 |
| -72  | 55.9  | 60.4  | 17.4 | 166  | 93  | 2.3 | 1.8 |
| -75  | 58.2  | 62.9  | 16.8 | 172  | 101 | 2.3 | 1.8 |
| -78  | 61.2  | 66.0  | 17.6 | 209  | 108 | 2.5 | 2.0 |
| -80  | 63.0  | 68.0  | 17.2 | 215  | 115 | 2.5 | 2.0 |
| -82  | 63.5  | 68.7  | 18.8 | 220  | 122 | 2.6 | 2.1 |
| -85  | 66.8  | 72.2  | 19.1 | 228  | 131 | 2.6 | 2.1 |
| -88  | 69.6  | 75.2  | 20.4 | 236  | 141 | 2.8 | 2.2 |
| -90  | 71.6  | 77.3  | 21.4 | 241  | 147 | 2.8 | 2.2 |
| -92  | 73.6  | 79.4  | 22.2 | 247  | 153 | 2.9 | 2.4 |
| -95  | 76.7  | 82.7  | 22.6 | 255  | 164 | 3.0 | 2.5 |
| -98  | 78.3  | 84.5  | 22.6 | 263  | 174 | 3.0 | 2.5 |
| -100 | 80.3  | 86.6  | 24.1 | 269  | 181 | 3.1 | 2.5 |
| -102 | 82.2  | 88.6  | 25.5 | 273  | 187 | 3.2 | 2.6 |
| -105 | 85.1  | 91.6  | 26.0 | 281  | 196 | 3.3 | 2.6 |
| -108 | 88.1  | 94.7  | 26.4 | 290  | 205 | 3.5 | 2.7 |
| -110 | 88.4  | 95.1  | 27.5 | 295  | 212 | 3.6 | 2.8 |
| -115 | 93.2  | 100.1 | 29.4 | 309  | 227 | 3.7 | 2.9 |
| -120 | 98.2  | 105.2 | 27.2 | 321  | 241 | 3.9 | 3.1 |
| -125 | 103.1 | 110.2 | 30.3 | 335  | 255 | 4.0 | 3.2 |
| -130 | 108.0 | 115.2 | 31.0 | 349  | 269 | 4.0 | 3.2 |
| -135 | 110.4 | 117.7 | 30.4 | 415  | 283 | 4.3 | 3.4 |
| -140 | 115.3 | 122.7 | 30.4 | 429  | 298 | 4.3 | 3.4 |
| -145 | 120.4 | 127.9 | 31.6 | 444  | 313 | 4.3 | 3.4 |
| -150 | 125.3 | 132.9 | 33.5 | 460  | 327 | 4.3 | 3.4 |
| -155 | 130.4 | 138.1 | 37.0 | 475  | 343 | 4.3 | 3.4 |
| -160 | 133.8 | 141.6 | 35.0 | 613  | 359 | 4.5 | 3.6 |
| -165 | 138.7 | 146.6 | 33.1 | 632  | 374 | 4.6 | 3.7 |
| -170 | 143.6 | 151.6 | 38.2 | 651  | 390 | 4.6 | 3.7 |
| -175 | 146.0 | 154.2 | 37.7 | 670  | 403 | 4.8 | 3.8 |
| -180 | 151.4 | 159.8 | 39.0 | 690  | 434 | 5.0 | 4.0 |
| -185 | 154.7 | 163.3 | 37.3 | 851  | 457 | 5.1 | 4.1 |
| -190 | 159.5 | 168.3 | 35.0 | 873  | 480 | 5.3 | 4.3 |
| -200 | 169.2 | 178.2 | 43.9 | 919  | 517 | 5.4 | 4.3 |
| -210 | 177.5 | 186.9 | 40.6 | 965  | 566 | 5.8 | 4.6 |
| -220 | 184.1 | 194.1 | 38.3 | 1000 | 608 | 6.1 | 4.9 |
| -230 | 194.0 | 204.6 | 49.0 | 1060 | 686 | 6.3 | 5.1 |
| -240 | 200.4 | 211.4 | 45.4 | 1090 | 725 | 6.6 | 5.3 |
| -250 | 210.0 | 221.4 | 53.0 | 1150 | 808 | 6.7 | 5.4 |

<sup>a</sup> For checking when ring is seated in groove.

<sup>b</sup> These values apply to rings made from SAE 1060-1090 steels and PH 15-7 Mo stainless steel used in bores hardened to  $R_c$  50 minimum. Values for rings made from beryllium copper can be calculated by multiplying the listed values by 0.75. The values listed include a safety factor of 4.

<sup>c</sup> These values are for standard rings used in low carbon steel bores. They include a safety factor of 2. Maximum allowable assembly loads for  $R$  max or  $Ch$  max are: For ring size -8, 0.8 kN; for sizes -9 through -12, 2.0 kN; for sizes -13 through -21, 4.0 kN; for sizes -22 through -26, 7.4 kN; for sizes -27 through -38, 10.8 kN; for sizes -40 through -50, 17.4 kN; for sizes -52 through -63, 27.4 kN; for size -65, 42.0 kN; for sizes -68 through -72, 39 kN; for sizes -75 through -130, 54 kN; for sizes -135 through -155, 67 kN; for sizes -160 through -180, 102 kN; and for sizes -185 through -250, 151 kN.

Source: Appendix to American National Standard ANSI B27.7-1977, R1993.



**Table 6. American National Standard Metric E-Type External Series 3CM1 Retaining Rings — Checking and Performance Data ANSI B27.7-1977, R1993**

| Ring Series and Size No. | Clearance Diameter | Allowable Thrust Loads Sharp Corner Abutment |         | Maximum Allowable Corner Radii and Chamfers |          | Allowable Assembly Speed <sup>a</sup> |
|--------------------------|--------------------|--|---------|---|----------|---------------------------------------|
|                          | Ring in Groove     |  |         | $R$ max                                     | $Ch$ max |                                       |
| 3CM1                     | $C_2$              | $P_r^b$                                      | $P_g^c$ | $R$ max                                     | $Ch$ max | ...                                   |
| No.                      | mm                 | kN   | kN      | mm  | mm       | rpm                                   |
| -1                       | 2.2                | 0.06   | 0.02    | 0.4   | 0.25     | 40 000                                |
| -2                       | 4.3                | 0.13   | 0.09    | 0.8   | 0.5      | 40 000                                |
| -3                       | 6.0                | 0.3  | 0.17    | 1.1   | 0.7      | 34 000                                |
| -4                       | 7.6                | 0.7  | 0.3     | 1.6   | 1.2      | 31 000                                |
| -5                       | 8.9                | 0.9  | 0.4     | 1.6   | 1.2      | 27 000                                |
| -6                       | 11.5               | 1.1  | 0.6     | 1.6   | 1.2      | 25 000                                |
| -7                       | 14.0               | 1.2  | 0.8     | 1.6   | 1.2      | 23 000                                |
| -8                       | 15.1               | 1.4  | 1.0     | 1.7   | 1.3      | 21 500                                |
| -9                       | 16.5               | 3.0  | 1.3     | 1.7   | 1.3      | 19 500                                |
| -10                      | 17.5               | 3.4  | 1.6     | 1.7   | 1.3      | 18 000                                |
| -11                      | 18.0               | 3.7  | 1.9     | 1.7   | 1.3      | 16 500                                |
| -12                      | 19.3               | 4.9  | 2.3     | 1.9   | 1.4      | 15 000                                |
| -13                      | 21.0               | 5.4  | 2.9     | 2.0   | 1.5      | 13 000                                |
| -15                      | 23.5               | 6.2  | 4.0     | 2.0   | 1.5      | 11 500                                |
| -16                      | 24.5               | 6.6  | 4.5     | 2.0   | 1.5      | 10 000                                |
| -18                      | 27.9               | 8.7  | 5.4     | 2.1   | 1.6      | 9 000                                 |
| -20                      | 30.7               | 9.8  | 6.5     | 2.2   | 1.7      | 8 000                                 |
| -22                      | 33.7               | 10.8   | 8.1     | 2.2   | 1.7      | 7 000                                 |
| -25                      | 37.9               | 12.2   | 10.1    | 2.4   | 1.9      | 5 000                                 |

<sup>a</sup>These values have been calculated for steel rings.

<sup>b</sup>These values apply to rings made from SAE 1060-1090 steels and PH 15-7 Mo stainless steel used on shafts hardened to  $R_c$  50 minimum, with the exception of size -1 which is supplied in beryllium copper only. Values for other sizes made from beryllium copper can be calculated by multiplying the listed values by 0.75. The values listed include a safety factor of 4.

<sup>c</sup>These values apply to all standard rings used on low carbon steel shafts. They include a safety factor of 2.

Maximum allowable assembly loads with  $R$  max or  $Ch$  max are as follows:

| Ring Size No. | Maximum Allowable Load, kN | Ring Size No. | Maximum Allowable Load, kN | Ring Size No. | Maximum Allowable Load, kN |
|---------------|----------------------------|---------------|----------------------------|---------------|----------------------------|
| -1            | 0.06                       | -8            | 1.4                        | -16           | 6.6                        |
| -2            | 0.13                       | -9            | 3.0                        | -18           | 8.7                        |
| -3            | 0.3                        | -10           | 3.4                        | -20           | 9.8                        |
| -4            | 0.7                        | -11           | 3.7                        | -22           | 10.8                       |
| -5            | 0.9                        | -12           | 4.9                        | -25           | 12.2                       |
| -6            | 1.1                        | -13           | 5.4                        | ...           | ...                        |
| -7            | 1.2                        | -15           | 6.2                        | ...           | ...                        |

Source: Appendix to American National Standard ANSI B27.7-1977, R1993.

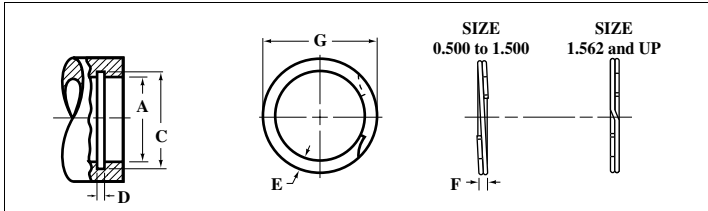


Table 7. Medium Duty Internal Spiral Retaining Rings MIL-R-27426

| Bore Dia. A | Ring   |        | Groove |         | Static Thrust Load (lb) |        | Bore Dia. A | Ring   |        | Groove |         | Static Thrust Load (lb) |        |
|-------------|--------|--------|--------|---------|-------------------------|--------|-------------|--------|--------|--------|---------|-------------------------|--------|
|             | Dia. G | Wall E | Dia. C | Width D | Ring                    | Groove |             | Dia. G | Wall E | Dia. C | Width D | Ring                    | Groove |
|             |        |        |        |         |                         |        |             |        |        |        |         |                         |        |
| 0.500       | 0.532  | 0.045  | 0.526  | 0.030   | 2000                    | 405    | 3.437       | 3.574  | 0.188  | 3.543  | 0.068   | 27660                   | 18240  |
| 0.512       | 0.544  | 0.045  | 0.538  | 0.030   | 2050                    | 420    | 3.500       | 3.636  | 0.188  | 3.606  | 0.068   | 28170                   | 18575  |
| 0.531       | 0.564  | 0.045  | 0.557  | 0.030   | 2130                    | 455    | 3.543       | 3.684  | 0.198  | 3.653  | 0.068   | 28520                   | 19515  |
| 0.562       | 0.594  | 0.045  | 0.588  | 0.030   | 2250                    | 495    | 3.562       | 3.703  | 0.198  | 3.672  | 0.068   | 28670                   | 19620  |
| 0.594       | 0.626  | 0.045  | 0.619  | 0.030   | 2380                    | 535    | 3.625       | 3.769  | 0.198  | 3.737  | 0.068   | 29180                   | 20330  |
| 0.625       | 0.658  | 0.045  | 0.651  | 0.030   | 2500                    | 610    | 3.687       | 3.832  | 0.198  | 3.799  | 0.068   | 29680                   | 20675  |
| 0.656       | 0.689  | 0.045  | 0.682  | 0.030   | 2630                    | 670    | 3.740       | 3.885  | 0.198  | 3.852  | 0.068   | 30100                   | 20975  |
| 0.687       | 0.720  | 0.045  | 0.713  | 0.030   | 2750                    | 725    | 3.750       | 3.894  | 0.198  | 3.862  | 0.068   | 30180                   | 21030  |
| 0.718       | 0.751  | 0.045  | 0.744  | 0.030   | 2870                    | 790    | 3.812       | 3.963  | 0.208  | 3.930  | 0.068   | 30680                   | 22525  |
| 0.750       | 0.790  | 0.065  | 0.782  | 0.036   | 3360                    | 800    | 4.437       | 4.611  | 0.238  | 4.573  | 0.068   | 35710                   | 30215  |
| 0.777       | 0.817  | 0.065  | 0.808  | 0.036   | 3480                    | 835    | 4.500       | 4.674  | 0.238  | 4.636  | 0.068   | 36220                   | 30645  |
| 0.781       | 0.821  | 0.065  | 0.812  | 0.036   | 3500                    | 840    | 4.527       | 4.701  | 0.238  | 4.663  | 0.068   | 36440                   | 30830  |
| 0.812       | 0.853  | 0.065  | 0.843  | 0.036   | 3640                    | 915    | 4.562       | 4.737  | 0.238  | 4.698  | 0.079   | 36720                   | 31065  |
| 0.843       | 0.889  | 0.065  | 0.880  | 0.036   | 3780                    | 1155   | 4.625       | 4.803  | 0.250  | 4.765  | 0.079   | 43940                   | 32420  |
| 0.866       | 0.913  | 0.065  | 0.903  | 0.036   | 3880                    | 1250   | 4.687       | 4.867  | 0.250  | 4.827  | 0.079   | 44530                   | 32855  |
| 0.875       | 0.922  | 0.065  | 0.912  | 0.036   | 3920                    | 1250   | 4.724       | 4.903  | 0.250  | 4.864  | 0.079   | 44880                   | 33115  |
| 0.906       | 0.949  | 0.065  | 0.939  | 0.036   | 4060                    | 1335   | 4.750       | 4.930  | 0.250  | 4.890  | 0.079   | 45130                   | 33300  |
| 0.938       | 0.986  | 0.065  | 0.975  | 0.036   | 4200                    | 1430   | 4.812       | 4.993  | 0.250  | 4.952  | 0.079   | 45710                   | 33735  |
| 0.968       | 1.025  | 0.075  | 1.015  | 0.042   | 4340                    | 1950   | 4.875       | 5.055  | 0.250  | 5.015  | 0.079   | 46310                   | 34175  |
| 0.987       | 1.041  | 0.075  | 1.030  | 0.042   | 4420                    | 1865   | 4.921       | 5.102  | 0.250  | 5.061  | 0.079   | 46750                   | 34495  |
| 1.000       | 1.054  | 0.075  | 1.043  | 0.042   | 4480                    | 1910   | 4.937       | 5.122  | 0.250  | 5.081  | 0.079   | 46900                   | 35595  |
| 1.023       | 1.078  | 0.075  | 1.066  | 0.042   | 5470                    | 1660   | 5.000       | 5.185  | 0.250  | 5.144  | 0.079   | 47500                   | 36050  |
| 1.031       | 1.084  | 0.075  | 1.074  | 0.042   | 5510                    | 1650   | 5.118       | 5.304  | 0.250  | 5.262  | 0.079   | 48620                   | 36905  |
| 1.062       | 1.117  | 0.075  | 1.104  | 0.042   | 5680                    | 1745   | 5.125       | 5.311  | 0.250  | 5.269  | 0.079   | 48690                   | 36955  |
| 1.093       | 1.147  | 0.075  | 1.135  | 0.042   | 5840                    | 1820   | 5.250       | 5.436  | 0.250  | 5.393  | 0.079   | 49880                   | 37590  |
| 1.125       | 1.180  | 0.075  | 1.167  | 0.042   | 6010                    | 1935   | 5.375       | 5.566  | 0.250  | 5.522  | 0.079   | 51050                   | 39565  |
| 1.156       | 1.210  | 0.075  | 1.198  | 0.042   | 6180                    | 2020   | 5.500       | 5.693  | 0.250  | 5.647  | 0.079   | 52250                   | 40485  |
| 1.188       | 1.249  | 0.085  | 1.236  | 0.048   | 7380                    | 2115   | 5.511       | 5.703  | 0.250  | 5.658  | 0.079   | 52350                   | 40565  |
| 1.218       | 1.278  | 0.085  | 1.266  | 0.048   | 7570                    | 2195   | 5.625       | 5.818  | 0.250  | 5.772  | 0.079   | 53440                   | 41405  |
| 1.250       | 1.312  | 0.085  | 1.298  | 0.048   | 7770                    | 2510   | 5.708       | 5.909  | 0.250  | 5.861  | 0.079   | 54230                   | 43730  |
| 1.281       | 1.342  | 0.085  | 1.329  | 0.048   | 7960                    | 2425   | 5.750       | 5.950  | 0.250  | 5.903  | 0.079   | 54630                   | 44050  |
| 1.312       | 1.374  | 0.085  | 1.360  | 0.048   | 8150                    | 2532   | 5.875       | 6.077  | 0.250  | 6.028  | 0.079   | 55810                   | 45010  |
| 1.343       | 1.408  | 0.085  | 1.395  | 0.048   | 8340                    | 2875   | 5.905       | 6.106  | 0.250  | 6.058  | 0.079   | 56100                   | 45240  |
| 1.375       | 1.442  | 0.095  | 1.427  | 0.048   | 8540                    | 3070   | 6.000       | 6.202  | 0.312  | 6.153  | 0.079   | 57000                   | 45965  |
| 1.406       | 1.472  | 0.095  | 1.458  | 0.048   | 8740                    | 3180   | 6.125       | 6.349  | 0.312  | 6.297  | 0.094   | 69500                   | 52750  |
| 1.437       | 1.504  | 0.095  | 1.489  | 0.048   | 8930                    | 3330   | 6.250       | 6.474  | 0.312  | 6.422  | 0.094   | 70920                   | 53825  |
| 1.456       | 1.523  | 0.095  | 1.508  | 0.048   | 9050                    | 3410   | 6.299       | 6.524  | 0.312  | 6.471  | 0.094   | 71480                   | 54250  |
| 1.468       | 1.535  | 0.095  | 1.520  | 0.048   | 9120                    | 3460   | 6.375       | 6.601  | 0.312  | 6.547  | 0.094   | 72340                   | 54905  |
| 1.500       | 1.567  | 0.095  | 1.552  | 0.048   | 9320                    | 3605   | 6.500       | 6.726  | 0.312  | 6.672  | 0.094   | 73760                   | 55980  |
| 1.562       | 1.634  | 0.108  | 1.617  | 0.056   | 10100                   | 3590   | 6.625       | 6.863  | 0.312  | 6.807  | 0.094   | 75180                   | 60375  |
| 1.574       | 1.649  | 0.108  | 1.633  | 0.056   | 10180                   | 3640   | 6.692       | 6.931  | 0.312  | 6.874  | 0.094   | 75940                   | 60985  |
| 1.625       | 1.701  | 0.108  | 1.684  | 0.056   | 10510                   | 3875   | 6.750       | 6.987  | 0.312  | 6.932  | 0.094   | 76590                   | 61515  |
| 1.653       | 1.730  | 0.108  | 1.712  | 0.056   | 10690                   | 4020   | 6.875       | 7.114  | 0.312  | 7.057  | 0.094   | 78010                   | 62655  |
| 1.687       | 1.768  | 0.118  | 1.750  | 0.056   | 10910                   | 4510   | 7.000       | 7.239  | 0.312  | 7.182  | 0.094   | 79430                   | 63790  |
| 1.750       | 1.834  | 0.118  | 1.813  | 0.056   | 11310                   | 4895   | 7.086       | 7.337  | 0.312  | 7.278  | 0.094   | 80410                   | 68125  |
| 1.813       | 1.894  | 0.118  | 1.875  | 0.056   | 11720                   | 5080   | 7.125       | 7.376  | 0.312  | 7.317  | 0.094   | 80850                   | 68500  |

**Table 7. (Continued) Medium Duty Internal Spiral Retaining Rings MIL-R-27426**

| Bore<br>Dia.<br>A | Ring      |           |           | Groove     |       | Static Thrust<br>Load (lb) |           | Bore<br>Dia.<br>A | Ring      |           |            | Groove |        | Static Thrust<br>Load (lb) |       |
|-------------------|-----------|-----------|-----------|------------|-------|----------------------------|-----------|-------------------|-----------|-----------|------------|--------|--------|----------------------------|-------|
|                   | Dia.<br>G | Wall<br>E | Dia.<br>C | Width<br>D | Ring  | Groove                     | Dia.<br>G |                   | Wall<br>E | Dia.<br>C | Width<br>D | Ring   | Groove |                            |       |
|                   |           |           |           |            |       |                            |           |                   |           |           |            |        |        | 1.850                      | 1.937 |
| 1.875             | 1.960     | 0.118     | 1.942     | 0.056      | 12120 | 5825                       | 7.375     | 7.628             | 0.312     | 7.567     | 0.094      | 83690  | 70900  |                            |       |
| 1.938             | 2.025     | 0.118     | 2.005     | 0.056      | 12530 | 6250                       | 7.480     | 7.734             | 0.312     | 7.672     | 0.094      | 84880  | 71910  |                            |       |
| 2.000             | 2.091     | 0.128     | 2.071     | 0.056      | 12930 | 7090                       | 7.500     | 7.754             | 0.312     | 7.692     | 0.094      | 85110  | 72105  |                            |       |
| 2.047             | 2.138     | 0.128     | 2.118     | 0.056      | 13230 | 7275                       | 7.625     | 7.890             | 0.312     | 7.827     | 0.094      | 86520  | 77125  |                            |       |
| 2.062             | 2.154     | 0.128     | 2.132     | 0.056      | 13330 | 7225                       | 7.750     | 8.014             | 0.312     | 7.952     | 0.094      | 87940  | 78390  |                            |       |
| 2.125             | 2.217     | 0.128     | 2.195     | 0.056      | 13740 | 7450                       | 7.875     | 8.131             | 0.312     | 8.077     | 0.094      | 89360  | 79655  |                            |       |
| 2.165             | 2.260     | 0.138     | 2.239     | 0.056      | 14000 | 8020                       | 8.000     | 8.266             | 0.312     | 8.202     | 0.094      | 90780  | 80920  |                            |       |
| 2.188             | 2.284     | 0.138     | 2.262     | 0.056      | 14150 | 8105                       | 8.250     | 8.528             | 0.375     | 8.462     | 0.094      | 93620  | 87575  |                            |       |
| 2.250             | 2.347     | 0.138     | 2.324     | 0.056      | 14550 | 8335                       | 8.267     | 8.546             | 0.375     | 8.479     | 0.094      | 93810  | 87755  |                            |       |
| 2.312             | 2.413     | 0.138     | 2.390     | 0.056      | 14950 | 9030                       | 8.464     | 8.744             | 0.375     | 8.676     | 0.094      | 96040  | 89850  |                            |       |
| 2.375             | 2.476     | 0.138     | 2.453     | 0.056      | 15350 | 9275                       | 8.500     | 8.780             | 0.375     | 8.712     | 0.094      | 96450  | 90230  |                            |       |
| 2.437             | 2.543     | 0.148     | 2.519     | 0.056      | 15760 | 10005                      | 8.750     | 9.041             | 0.375     | 8.972     | 0.094      | 99290  | 97265  |                            |       |
| 2.440             | 2.546     | 0.148     | 2.522     | 0.056      | 15780 | 10015                      | 8.858     | 9.151             | 0.375     | 9.080     | 0.094      | 100520 | 98465  |                            |       |
| 2.500             | 2.606     | 0.148     | 2.582     | 0.056      | 16160 | 10625                      | 9.000     | 9.293             | 0.375     | 9.222     | 0.094      | 102130 | 100045 |                            |       |
| 2.531             | 2.641     | 0.148     | 2.617     | 0.056      | 16360 | 10900                      | 9.055     | 9.359             | 0.375     | 9.287     | 0.094      | 102750 | 105190 |                            |       |
| 2.562             | 2.673     | 0.148     | 2.648     | 0.056      | 16560 | 11030                      | 9.250     | 9.555             | 0.375     | 9.482     | 0.094      | 104960 | 107455 |                            |       |
| 2.625             | 2.736     | 0.148     | 2.711     | 0.056      | 16970 | 11305                      | 9.448     | 9.755             | 0.375     | 9.680     | 0.094      | 107210 | 109755 |                            |       |
| 2.677             | 2.789     | 0.158     | 2.767     | 0.056      | 17310 | 12065                      | 9.500     | 9.806             | 0.375     | 9.732     | 0.094      | 107800 | 110360 |                            |       |
| 2.688             | 2.803     | 0.158     | 2.778     | 0.056      | 17380 | 12115                      | 9.750     | 10.068            | 0.375     | 9.992     | 0.094      | 110640 | 118145 |                            |       |
| 2.750             | 2.865     | 0.158     | 2.841     | 0.056      | 17780 | 12530                      | 10.000    | 10.320            | 0.375     | 10.242    | 0.094      | 113470 | 121175 |                            |       |
| 2.813             | 2.929     | 0.158     | 2.903     | 0.056      | 18190 | 12675                      | 10.250    | 10.582            | 0.375     | 10.502    | 0.094      | 116310 | 129340 |                            |       |
| 2.834             | 2.954     | 0.168     | 2.928     | 0.056      | 18320 | 13340                      | 10.500    | 10.834            | 0.375     | 10.752    | 0.094      | 119150 | 132490 |                            |       |
| 2.875             | 2.995     | 0.168     | 2.969     | 0.056      | 18590 | 13530                      | 10.750    | 11.095            | 0.375     | 11.012    | 0.094      | 121980 | 141030 |                            |       |
| 2.937             | 3.058     | 0.168     | 3.031     | 0.056      | 18990 | 13825                      | 11.000    | 11.347            | 0.375     | 11.262    | 0.094      | 124820 | 144310 |                            |       |
| 2.952             | 3.073     | 0.168     | 3.046     | 0.056      | 19090 | 13890                      | 3.875     | 4.025             | 0.208     | 3.993     | 0.068      | 30680  | 22525  |                            |       |
| 3.000             | 3.122     | 0.168     | 3.096     | 0.068      | 24150 | 14420                      | 3.938     | 4.089             | 0.208     | 4.056     | 0.068      | 31700  | 23265  |                            |       |
| 3.062             | 3.186     | 0.168     | 3.158     | 0.068      | 24640 | 14720                      | 4.000     | 4.157             | 0.218     | 5.124     | 0.068      | 32190  | 24835  |                            |       |
| 3.125             | 3.251     | 0.178     | 3.223     | 0.068      | 25150 | 15335                      | 4.063     | 4.222             | 0.218     | 4.187     | 0.068      | 32700  | 25225  |                            |       |
| 3.149             | 3.276     | 0.178     | 3.247     | 0.068      | 25340 | 15450                      | 4.125     | 4.284             | 0.218     | 4.249     | 0.068      | 33200  | 25610  |                            |       |
| 3.187             | 3.311     | 0.178     | 3.283     | 0.068      | 25650 | 15640                      | 4.188     | 4.347             | 0.218     | 4.311     | 0.068      | 33710  | 25795  |                            |       |
| 3.250             | 3.379     | 0.178     | 3.350     | 0.068      | 26160 | 16270                      | 4.250     | 4.416             | 0.228     | 4.380     | 0.068      | 34210  | 27665  |                            |       |
| 3.312             | 3.446     | 0.188     | 3.416     | 0.068      | 26660 | 17245                      | 4.312     | 4.479             | 0.228     | 4.442     | 0.068      | 34710  | 28065  |                            |       |
| 3.346             | 3.479     | 0.188     | 3.450     | 0.068      | 26930 | 17425                      | 4.330     | 4.497             | 0.228     | 4.460     | 0.068      | 34850  | 28185  |                            |       |
| 3.375             | 3.509     | 0.188     | 3.479     | 0.068      | 27160 | 17575                      | 4.375     | 4.543             | 0.228     | 4.505     | 0.068      | 35210  | 28475  |                            |       |

Source: Spirolox Retaining Rings, RR Series. All dimensions are in inches. Depth of groove  $d = (C - A)/2$ . Standard material: carbon spring steel (SAE 1070-1090).

**Ring Thickness, F:** For shaft sizes 0.500 through 0.718, 0.025; for sizes 0.750 through 0.938, 0.031; for sizes 0.968 through 1.156, 0.037; for sizes 1.188 through 1.500, 0.043; for sizes 1.562 through 2.952, 0.049; for sizes 3.000 through 4.562, 0.061; for sizes 4.625 through 6.000, 0.072; for sizes 6.125 through 11.000, 0.086.

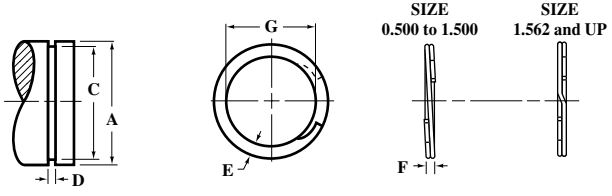
**Ring Free Diameter Tolerances:** For housing sizes 0.500 through 1.031, +0.013, -0.000; for sizes 1.062 through 1.500, +0.015, -0.000; for sizes 1.562 through 2.047, +0.020, -0.000; for sizes 2.062 through 3.000, +0.025, -0.000; for sizes 3.062 through 4.063, +0.030, -0.000; for sizes 4.125 through 5.125, +0.035, -0.000; for sizes 5.250 through 6.125, +0.045, -0.000; for sizes 6.250 through 7.125, +0.055, -0.000; for sizes 7.250 through 11.000, +0.065, -0.000.

**Ring Thickness Tolerances:** Thickness indicated is for unplated rings; add 0.002 to upper thickness tolerance for plated rings. For housing sizes 0.500 through 1.500,  $\pm 0.002$ ; for sizes 1.562 through 4.562,  $\pm 0.003$ ; for sizes 4.625 through 11.000,  $\pm 0.004$ .

**Groove Diameter Tolerances:** For housing sizes 0.500 through 0.750,  $\pm 0.002$ ; for sizes 0.777 through 1.031,  $\pm 0.003$ ; for sizes 1.062 through 1.500,  $\pm 0.004$ ; for sizes 1.562 through 2.047,  $\pm 0.005$ ; for sizes 2.062 through 5.125,  $\pm 0.006$ ; for sizes 5.250 through 6.000,  $\pm 0.007$ ; for sizes 6.125 through 11.000,  $\pm 0.008$ .

**Groove Width Tolerances:** For housing sizes 0.500 through 1.156, +0.003, -0.000; for sizes 1.188 through 2.952, +0.004, -0.000; for sizes 3.000 through 6.000, +0.005, -0.000; for sizes 6.125 through 11.000, +0.006, -0.000.

**Table 8. Medium Duty External Spiral Retaining Rings MIL-R-27426**



| Shaft Dia. A | Ring   |        | Groove |         | Static Thrust Load (lb) |        | Shaft Dia. A | Ring   |        | Groove |         | Static Thrust Load (lb) |        |
|--------------|--------|--------|--------|---------|-------------------------|--------|--------------|--------|--------|--------|---------|-------------------------|--------|
|              | Dia. G | Wall E | Dia. C | Width D | Ring                    | Groove |              | Dia. G | Wall E | Dia. C | Width D | Ring                    | Groove |
|              |        |        |        |         |                         |        |              |        |        |        |         |                         |        |
| 0.500        | 0.467  | 0.045  | 0.474  | 0.030   | 2000                    | 550    | 3.343        | 3.210  | 0.188  | 3.239  | 0.068   | 26910                   | 17410  |
| 0.531        | 0.498  | 0.045  | 0.505  | 0.030   | 2130                    | 640    | 3.375        | 3.242  | 0.188  | 3.271  | 0.068   | 27160                   | 17570  |
| 0.551        | 0.518  | 0.045  | 0.525  | 0.030   | 2210                    | 700    | 3.437        | 3.301  | 0.188  | 3.331  | 0.068   | 27660                   | 18240  |
| 0.562        | 0.529  | 0.045  | 0.536  | 0.030   | 2250                    | 730    | 3.500        | 3.363  | 0.188  | 3.394  | 0.068   | 28170                   | 18580  |
| 0.594        | 0.561  | 0.045  | 0.569  | 0.030   | 2380                    | 740    | 3.543        | 3.402  | 0.198  | 3.433  | 0.068   | 28520                   | 19510  |
| 0.625        | 0.585  | 0.055  | 0.594  | 0.030   | 2500                    | 970    | 3.562        | 3.422  | 0.198  | 3.452  | 0.068   | 28670                   | 19620  |
| 0.656        | 0.617  | 0.055  | 0.625  | 0.030   | 2630                    | 1020   | 3.625        | 3.483  | 0.198  | 3.515  | 0.068   | 29180                   | 19970  |
| 0.669        | 0.629  | 0.055  | 0.638  | 0.030   | 2680                    | 1040   | 3.687        | 3.543  | 0.198  | 3.575  | 0.068   | 29680                   | 20680  |
| 0.687        | 0.647  | 0.055  | 0.656  | 0.030   | 2750                    | 1060   | 3.740        | 3.597  | 0.198  | 3.628  | 0.068   | 30100                   | 20970  |
| 0.718        | 0.679  | 0.055  | 0.687  | 0.030   | 2870                    | 1110   | 3.750        | 3.606  | 0.198  | 3.638  | 0.068   | 30180                   | 21030  |
| 0.750        | 0.710  | 0.065  | 0.719  | 0.036   | 3360                    | 1100   | 3.812        | 3.668  | 0.198  | 3.700  | 0.068   | 30680                   | 21380  |
| 0.781        | 0.741  | 0.065  | 0.750  | 0.036   | 3500                    | 1210   | 3.875        | 3.724  | 0.208  | 3.757  | 0.068   | 31190                   | 22890  |
| 0.812        | 0.771  | 0.065  | 0.781  | 0.036   | 3640                    | 1260   | 3.938        | 3.784  | 0.208  | 3.820  | 0.068   | 31700                   | 23270  |
| 0.843        | 0.803  | 0.065  | 0.812  | 0.036   | 3780                    | 1310   | 4.000        | 3.842  | 0.218  | 3.876  | 0.068   | 32190                   | 24840  |
| 0.875        | 0.828  | 0.065  | 0.838  | 0.036   | 3920                    | 1620   | 4.063        | 3.906  | 0.218  | 3.939  | 0.068   | 32700                   | 25230  |
| 0.906        | 0.860  | 0.065  | 0.869  | 0.036   | 4060                    | 1680   | 4.125        | 3.967  | 0.218  | 4.000  | 0.068   | 33200                   | 25820  |
| 0.937        | 0.889  | 0.065  | 0.900  | 0.036   | 4200                    | 1740   | 4.134        | 3.975  | 0.218  | 4.010  | 0.068   | 33270                   | 25670  |
| 0.968        | 0.916  | 0.075  | 0.925  | 0.042   | 5180                    | 2080   | 4.188        | 4.030  | 0.218  | 4.058  | 0.068   | 33710                   | 27260  |
| 0.984        | 0.930  | 0.075  | 0.941  | 0.042   | 5260                    | 2120   | 4.250        | 4.084  | 0.228  | 4.120  | 0.068   | 34210                   | 27660  |
| 1.000        | 0.946  | 0.075  | 0.957  | 0.042   | 5350                    | 2150   | 4.312        | 4.147  | 0.218  | 4.182  | 0.068   | 34710                   | 28070  |
| 1.023        | 0.968  | 0.075  | 0.980  | 0.042   | 5470                    | 2200   | 4.331        | 4.164  | 0.218  | 4.200  | 0.068   | 34860                   | 28410  |
| 1.031        | 0.978  | 0.075  | 0.988  | 0.042   | 5510                    | 2220   | 4.375        | 4.208  | 0.218  | 4.245  | 0.068   | 35210                   | 28480  |
| 1.062        | 1.007  | 0.075  | 1.020  | 0.042   | 5680                    | 2230   | 4.437        | 4.271  | 0.218  | 4.307  | 0.068   | 35710                   | 28880  |
| 1.093        | 1.040  | 0.075  | 1.051  | 0.042   | 5840                    | 2300   | 4.500        | 4.326  | 0.238  | 4.364  | 0.068   | 36220                   | 30640  |
| 1.125        | 1.070  | 0.075  | 1.083  | 0.042   | 6010                    | 2370   | 4.562        | 4.384  | 0.250  | 4.422  | 0.079   | 43340                   | 31980  |
| 1.156        | 1.102  | 0.075  | 1.114  | 0.042   | 6180                    | 2430   | 4.625        | 4.447  | 0.250  | 4.485  | 0.079   | 43940                   | 32420  |
| 1.188        | 1.127  | 0.085  | 1.140  | 0.048   | 7380                    | 2850   | 4.687        | 4.508  | 0.250  | 4.457  | 0.079   | 44530                   | 32860  |
| 1.218        | 1.159  | 0.085  | 1.170  | 0.048   | 7570                    | 2930   | 4.724        | 4.546  | 0.250  | 4.584  | 0.079   | 44880                   | 33120  |
| 1.250        | 1.188  | 0.085  | 1.202  | 0.048   | 7770                    | 3000   | 4.750        | 4.571  | 0.250  | 4.610  | 0.079   | 45130                   | 33300  |
| 1.281        | 1.221  | 0.085  | 1.233  | 0.048   | 7960                    | 3080   | 4.812        | 4.633  | 0.250  | 4.672  | 0.079   | 45710                   | 33730  |
| 1.312        | 1.251  | 0.095  | 1.264  | 0.048   | 8150                    | 3150   | 4.875        | 4.695  | 0.250  | 4.735  | 0.079   | 46310                   | 34170  |
| 1.343        | 1.282  | 0.095  | 1.295  | 0.048   | 8340                    | 3230   | 4.937        | 4.757  | 0.250  | 4.797  | 0.079   | 46900                   | 34610  |
| 1.375        | 1.308  | 0.095  | 1.323  | 0.048   | 8540                    | 3580   | 5.000        | 4.820  | 0.250  | 4.856  | 0.079   | 47500                   | 36050  |
| 1.406        | 1.340  | 0.095  | 1.354  | 0.048   | 8740                    | 3660   | 5.118        | 4.934  | 0.250  | 4.974  | 0.079   | 48620                   | 36900  |
| 1.437        | 1.370  | 0.095  | 1.385  | 0.048   | 8930                    | 3740   | 5.125        | 4.939  | 0.250  | 4.981  | 0.079   | 48690                   | 36950  |
| 1.468        | 1.402  | 0.095  | 1.416  | 0.048   | 9120                    | 3820   | 5.250        | 5.064  | 0.250  | 5.107  | 0.079   | 49880                   | 37590  |
| 1.500        | 1.433  | 0.095  | 1.448  | 0.048   | 9320                    | 3910   | 5.375        | 5.187  | 0.250  | 5.228  | 0.079   | 51060                   | 39560  |
| 1.562        | 1.490  | 0.108  | 1.507  | 0.056   | 10100                   | 4300   | 5.500        | 5.308  | 0.250  | 5.353  | 0.079   | 52250                   | 40480  |
| 1.575        | 1.503  | 0.108  | 1.520  | 0.056   | 10190                   | 4340   | 5.511        | 5.320  | 0.250  | 5.364  | 0.079   | 52350                   | 40560  |
| 1.625        | 1.549  | 0.108  | 1.566  | 0.056   | 10510                   | 4800   | 5.625        | 5.433  | 0.250  | 5.478  | 0.079   | 53440                   | 41400  |

**Table 8. (Continued) Medium Duty External Spiral Retaining Rings MIL-R-27426**

|       |       |       |       |       |       |       |        |        |       |        |       |        |        |
|-------|-------|-------|-------|-------|-------|-------|--------|--------|-------|--------|-------|--------|--------|
| 1.687 | 1.610 | 0.118 | 1.628 | 0.056 | 10910 | 4980  | 5.750  | 5.550  | 0.250 | 5.597  | 0.079 | 54630  | 44050  |
| 1.750 | 1.673 | 0.118 | 1.691 | 0.056 | 11310 | 5170  | 5.875  | 5.674  | 0.250 | 5.722  | 0.079 | 55810  | 45010  |
| 1.771 | 1.690 | 0.118 | 1.708 | 0.056 | 11450 | 5590  | 5.905  | 5.705  | 0.250 | 5.752  | 0.079 | 56100  | 45240  |
| 1.813 | 1.730 | 0.118 | 1.749 | 0.056 | 11720 | 5810  | 6.000  | 5.798  | 0.250 | 5.847  | 0.079 | 57000  | 45970  |
| 1.875 | 1.789 | 0.128 | 1.808 | 0.056 | 12120 | 6290  | 6.125  | 5.903  | 0.312 | 5.953  | 0.094 | 69500  | 52750  |
| 1.938 | 1.844 | 0.128 | 1.861 | 0.056 | 12530 | 7470  | 6.250  | 6.026  | 0.312 | 6.078  | 0.094 | 70920  | 53830  |
| 1.969 | 1.882 | 0.128 | 1.902 | 0.056 | 12730 | 6610  | 6.299  | 6.076  | 0.312 | 6.127  | 0.094 | 71480  | 54250  |
| 2.000 | 1.909 | 0.128 | 1.992 | 0.056 | 12930 | 7110  | 6.375  | 6.152  | 0.312 | 6.203  | 0.094 | 72340  | 54900  |
| 2.062 | 1.971 | 0.128 | 2.051 | 0.056 | 13330 | 7870  | 6.500  | 6.274  | 0.312 | 6.328  | 0.094 | 73760  | 55980  |
| 2.125 | 2.029 | 0.128 | 2.082 | 0.056 | 13740 | 7990  | 6.625  | 6.390  | 0.312 | 6.443  | 0.094 | 75180  | 60380  |
| 2.156 | 2.060 | 0.138 | 2.091 | 0.056 | 13940 | 8020  | 6.750  | 6.513  | 0.312 | 6.568  | 0.094 | 76590  | 61515  |
| 2.188 | 2.070 | 0.138 | 2.113 | 0.056 | 14150 | 8220  | 6.875  | 6.638  | 0.312 | 6.693  | 0.094 | 78010  | 62650  |
| 2.250 | 2.092 | 0.138 | 2.176 | 0.056 | 14550 | 8340  | 7.000  | 6.761  | 0.312 | 6.818  | 0.094 | 79430  | 63790  |
| 2.312 | 2.153 | 0.138 | 2.234 | 0.056 | 14950 | 9030  | 7.125  | 6.877  | 0.312 | 6.933  | 0.094 | 80850  | 68500  |
| 2.362 | 2.211 | 0.138 | 2.284 | 0.056 | 15270 | 9230  | 7.250  | 6.999  | 0.312 | 7.058  | 0.094 | 82270  | 69700  |
| 2.375 | 2.273 | 0.138 | 2.297 | 0.056 | 15350 | 9280  | 7.375  | 7.125  | 0.312 | 7.183  | 0.094 | 83690  | 70900  |
| 2.437 | 2.331 | 0.148 | 2.355 | 0.056 | 15760 | 10000 | 7.500  | 7.250  | 0.312 | 7.308  | 0.094 | 85110  | 72100  |
| 2.500 | 2.394 | 0.148 | 2.418 | 0.056 | 16160 | 10260 | 7.625  | 7.363  | 0.312 | 7.423  | 0.094 | 86520  | 77120  |
| 2.559 | 2.449 | 0.148 | 2.473 | 0.056 | 16540 | 11020 | 7.750  | 7.486  | 0.312 | 7.548  | 0.094 | 87940  | 78390  |
| 2.562 | 2.452 | 0.148 | 2.476 | 0.056 | 16560 | 11030 | 7.875  | 7.611  | 0.312 | 7.673  | 0.094 | 89360  | 79650  |
| 2.625 | 2.514 | 0.148 | 2.539 | 0.056 | 16970 | 11300 | 8.000  | 7.734  | 0.312 | 7.798  | 0.094 | 90780  | 80920  |
| 2.688 | 2.572 | 0.158 | 2.597 | 0.056 | 17380 | 12250 | 8.250  | 7.972  | 0.375 | 8.038  | 0.094 | 93620  | 87580  |
| 2.750 | 2.635 | 0.158 | 2.660 | 0.056 | 17780 | 12390 | 8.500  | 8.220  | 0.375 | 8.288  | 0.094 | 96450  | 90230  |
| 2.813 | 2.696 | 0.168 | 2.722 | 0.056 | 18190 | 12820 | 8.750  | 8.459  | 0.375 | 8.528  | 0.094 | 99290  | 97270  |
| 2.875 | 2.755 | 0.168 | 2.781 | 0.056 | 18590 | 13530 | 9.000  | 8.707  | 0.375 | 8.778  | 0.094 | 102130 | 100050 |
| 2.937 | 2.817 | 0.168 | 2.843 | 0.056 | 18990 | 13820 | 9.250  | 8.945  | 0.375 | 9.018  | 0.094 | 104960 | 107560 |
| 2.952 | 2.831 | 0.168 | 2.858 | 0.056 | 19090 | 13890 | 9.500  | 9.194  | 0.375 | 9.268  | 0.094 | 107800 | 110360 |
| 3.000 | 2.877 | 0.168 | 2.904 | 0.068 | 24150 | 14420 | 9.750  | 9.432  | 0.375 | 9.508  | 0.094 | 110640 | 118150 |
| 3.062 | 2.938 | 0.168 | 2.966 | 0.068 | 24640 | 14720 | 10.000 | 9.680  | 0.375 | 9.758  | 0.094 | 113470 | 121180 |
| 3.125 | 3.000 | 0.178 | 3.027 | 0.068 | 25150 | 15335 | 10.250 | 9.918  | 0.375 | 9.998  | 0.094 | 116310 | 129340 |
| 3.149 | 3.023 | 0.178 | 3.051 | 0.068 | 25340 | 15450 | 10.500 | 10.166 | 0.375 | 10.248 | 0.094 | 119150 | 132490 |
| 3.187 | 3.061 | 0.178 | 3.089 | 0.068 | 25650 | 15640 | 10.750 | 10.405 | 0.375 | 10.488 | 0.094 | 121980 | 141030 |
| 3.250 | 3.121 | 0.178 | 3.150 | 0.068 | 26160 | 16270 | 11.000 | 10.653 | 0.375 | 10.738 | 0.094 | 124820 | 144310 |
| 3.312 | 3.180 | 0.188 | 3.208 | 0.068 | 26660 | 17250 |        |        |       |        |       |        |        |

Source: Spirolox Retaining Rings, RS Series. All dimensions are in inches. Depth of groove  $d = (A - C)/2$ . Standard material: carbon spring steel (SAE 1070–1090).

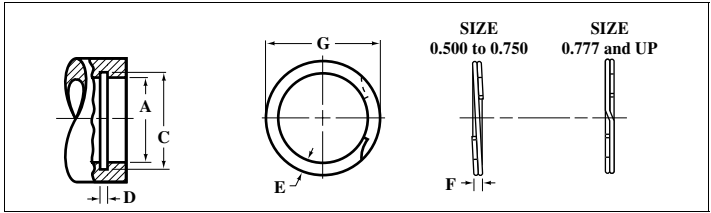
**Ring Thickness, F:** For shaft sizes 0.500 through 0.718, 0.025; for sizes 0.750 through 0.937, 0.031; for sizes 0.968 through 1.156, 0.037; for sizes 1.188 through 1.500, 0.043; for sizes 1.562 through 2.952, 0.049; for sizes 3.000 through 4.500, 0.061; for sizes 4.562 through 6.000, 0.072; for sizes 6.125 through 11.000, 0.086.

**Ring Free Diameter Tolerances:** For shaft sizes 0.500 through 1.031, +0.000, +0.000, -0.013; for sizes 1.062 through 1.500, +0.000, -0.015; for sizes 1.562 through 2.125, +0.000, -0.020; for sizes 2.156 through 2.688, +0.000, -0.025; for sizes 2.750 through 3.437, +0.000, -0.030; for sizes 3.500 through 5.125, +0.000, -0.040; for sizes 5.250 through 6.125, +0.000, -0.050; for sizes 6.250 through 7.375, +0.000, -0.060; for sizes 7.500 through 11.000, +0.000, -0.070.

**Ring Thickness Tolerances:** Thickness indicated is for unplated rings; add 0.002 to upper tolerance for plated rings. For shaft sizes 0.500 through 1.500,  $\pm 0.002$ ; for sizes 1.562 through 4.500,  $\pm 0.003$ ; for sizes 4.562 through 11.000,  $\pm 0.004$ .

**Groove Diameter Tolerances:** For shaft sizes 0.500 through 0.562,  $\pm 0.002$ ; for sizes 0.594 through 1.031,  $\pm 0.003$ ; for sizes 1.062 through 1.500,  $\pm 0.004$ ; for sizes 1.562 through 2.000,  $\pm 0.005$ ; for sizes 2.062 through 5.125,  $\pm 0.006$ ; for sizes 5.250 through 6.000,  $\pm 0.007$ ; for sizes 6.125 through 11.000,  $\pm 0.008$ .

**Groove Width Tolerances:** For shaft sizes 0.500 through 1.156, +0.003, -0.000; for sizes 1.188 through 2.952, +0.004, -0.000; for sizes 3.000 through 6.000, +0.005, -0.000; for sizes 6.125 through 11.000, +0.006, -0.000.



**Table 9. Heavy Duty Internal Spiral Retaining Rings MIL-R-27426**

| Bore Dia. A | Ring   |        | Groove |         | Static Thrust Load (lb) |        | Bore Dia. A | Ring   |        | Groove |         | Static Thrust Load (lb) |        |
|-------------|--------|--------|--------|---------|-------------------------|--------|-------------|--------|--------|--------|---------|-------------------------|--------|
|             | Dia. G | Wall E | Dia. C | Width D | Ring                    | Groove |             | Dia. G | Wall E | Dia. C | Width D | Ring                    | Groove |
|             |        |        |        |         |                         |        |             |        |        |        |         |                         |        |
| 0.500       | 0.538  | 0.045  | 0.530  | 0.039   | 2530                    | 310    | 3.543       | 3.781  | 0.281  | 3.755  | 0.120   | 49420                   | 28250  |
| 0.512       | 0.550  | 0.045  | 0.542  | 0.039   | 2590                    | 325    | 3.562       | 3.802  | 0.281  | 3.776  | 0.120   | 49680                   | 28815  |
| 0.562       | 0.605  | 0.055  | 0.596  | 0.039   | 2840                    | 455    | 3.625       | 3.868  | 0.281  | 3.841  | 0.120   | 50560                   | 30160  |
| 0.625       | 0.675  | 0.055  | 0.655  | 0.039   | 3160                    | 655    | 3.750       | 4.002  | 0.312  | 3.974  | 0.120   | 52310                   | 33720  |
| 0.688       | 0.743  | 0.065  | 0.732  | 0.039   | 3480                    | 965    | 3.875       | 4.136  | 0.312  | 4.107  | 0.120   | 54050                   | 37250  |
| 0.750       | 0.807  | 0.065  | 0.796  | 0.039   | 3790                    | 1065   | 3.938       | 4.203  | 0.312  | 4.174  | 0.120   | 54930                   | 39045  |
| 0.777       | 0.836  | 0.075  | 0.825  | 0.046   | 4720                    | 1026   | 4.000       | 4.270  | 0.312  | 4.240  | 0.120   | 55790                   | 41025  |
| 0.812       | 0.873  | 0.075  | 0.862  | 0.046   | 4930                    | 1150   | 4.125       | 4.369  | 0.312  | 4.339  | 0.120   | 57540                   | 38495  |
| 0.866       | 0.931  | 0.075  | 0.920  | 0.046   | 5260                    | 1395   | 4.250       | 4.501  | 0.312  | 4.470  | 0.120   | 59280                   | 41955  |
| 0.875       | 0.943  | 0.085  | 0.931  | 0.046   | 5310                    | 1520   | 4.330       | 4.588  | 0.312  | 4.556  | 0.120   | 60400                   | 44815  |
| 0.901       | 0.972  | 0.085  | 0.959  | 0.046   | 5470                    | 1675   | 4.500       | 4.768  | 0.312  | 4.735  | 0.120   | 62770                   | 50290  |
| 0.938       | 1.013  | 0.085  | 1.000  | 0.046   | 5690                    | 1925   | 4.625       | 4.899  | 0.312  | 4.865  | 0.120   | 64510                   | 54155  |
| 1.000       | 1.080  | 0.085  | 1.066  | 0.046   | 6070                    | 2310   | 4.750       | 5.030  | 0.312  | 4.995  | 0.120   | 66260                   | 58270  |
| 1.023       | 1.105  | 0.085  | 1.091  | 0.046   | 6210                    | 2480   | 5.000       | 5.297  | 0.312  | 5.260  | 0.120   | 69740                   | 65095  |
| 1.062       | 1.138  | 0.103  | 1.130  | 0.056   | 7010                    | 1940   | 5.250       | 5.559  | 0.350  | 5.520  | 0.139   | 83790                   | 68315  |
| 1.125       | 1.205  | 0.103  | 1.197  | 0.056   | 7420                    | 2280   | 5.375       | 5.690  | 0.350  | 5.650  | 0.139   | 85780                   | 72840  |
| 1.188       | 1.271  | 0.103  | 1.262  | 0.056   | 7840                    | 2615   | 5.500       | 5.810  | 0.350  | 5.770  | 0.139   | 87780                   | 74355  |
| 1.250       | 1.339  | 0.103  | 1.330  | 0.056   | 8250                    | 3110   | 5.750       | 6.062  | 0.350  | 6.020  | 0.139   | 91770                   | 77735  |
| 1.312       | 1.406  | 0.118  | 1.396  | 0.056   | 8650                    | 3650   | 6.000       | 6.314  | 0.350  | 6.270  | 0.139   | 95760                   | 81120  |
| 1.375       | 1.471  | 0.118  | 1.461  | 0.056   | 9070                    | 4075   | 6.250       | 6.576  | 0.380  | 6.530  | 0.174   | 122520                  | 80655  |
| 1.439       | 1.539  | 0.118  | 1.528  | 0.056   | 9490                    | 4670   | 6.500       | 6.838  | 0.380  | 6.790  | 0.174   | 127420                  | 90295  |
| 1.456       | 1.559  | 0.118  | 1.548  | 0.056   | 9600                    | 4890   | 6.625       | 6.974  | 0.380  | 6.925  | 0.174   | 129870                  | 92060  |
| 1.500       | 1.605  | 0.118  | 1.594  | 0.056   | 9900                    | 5275   | 6.750       | 7.105  | 0.380  | 7.055  | 0.174   | 132320                  | 102475 |
| 1.562       | 1.675  | 0.128  | 1.658  | 0.068   | 12780                   | 4840   | 7.000       | 7.366  | 0.380  | 7.315  | 0.174   | 137220                  | 110410 |
| 1.625       | 1.742  | 0.128  | 1.725  | 0.068   | 13290                   | 5415   | 7.250       | 7.628  | 0.418  | 7.575  | 0.209   | 170370                  | 103440 |
| 1.653       | 1.772  | 0.128  | 1.755  | 0.068   | 13520                   | 5695   | 7.500       | 7.895  | 0.418  | 7.840  | 0.209   | 176240                  | 115780 |
| 1.688       | 1.810  | 0.128  | 1.792  | 0.068   | 13810                   | 6070   | 7.750       | 8.157  | 0.418  | 8.100  | 0.209   | 182120                  | 127270 |
| 1.750       | 1.876  | 0.128  | 1.858  | 0.068   | 14320                   | 7635   | 8.000       | 8.419  | 0.418  | 8.360  | 0.209   | 187990                  | 139370 |
| 1.812       | 1.940  | 0.128  | 1.922  | 0.068   | 14820                   | 7305   | 8.250       | 8.680  | 0.437  | 8.620  | 0.209   | 193870                  | 152695 |
| 1.850       | 1.981  | 0.158  | 1.962  | 0.068   | 15130                   | 7960   | 8.500       | 8.942  | 0.437  | 8.880  | 0.209   | 199740                  | 161735 |
| 1.875       | 2.008  | 0.158  | 1.989  | 0.068   | 15340                   | 8305   | 8.750       | 9.209  | 0.437  | 9.145  | 0.209   | 205620                  | 173065 |
| 1.938       | 2.075  | 0.158  | 2.056  | 0.068   | 15850                   | 9125   | 9.000       | 9.471  | 0.437  | 9.405  | 0.209   | 211490                  | 182515 |
| 2.000       | 2.142  | 0.158  | 2.122  | 0.068   | 16360                   | 10040  | 9.250       | 9.737  | 0.437  | 9.669  | 0.209   | 217370                  | 194070 |
| 2.062       | 2.201  | 0.168  | 2.186  | 0.086   | 21220                   | 8280   | 9.500       | 10.000 | 0.500  | 9.930  | 0.209   | 223240                  | 204550 |

**Table 9. (Continued) Heavy Duty Internal Spiral Retaining Rings MIL-R-27426**

| Bore Dia. A | Ring   |        | Groove |         | Static Thrust Load (lb) |        | Bore Dia. A | Ring   |        | Groove |         | Static Thrust Load (lb) |        |
|-------------|--------|--------|--------|---------|-------------------------|--------|-------------|--------|--------|--------|---------|-------------------------|--------|
|             | Dia. G | Wall E | Dia. C | Width D | Ring                    | Groove |             | Dia. G | Wall E | Dia. C | Width D | Ring                    | Groove |
|             |        |        |        |         |                         |        |             |        |        |        |         |                         |        |
| 2.188       | 2.334  | 0.168  | 2.318  | 0.086   | 22520                   | 9745   | 10.000      | 10.523 | 0.500  | 10.450 | 0.209   | 234990                  | 225330 |
| 2.250       | 2.399  | 0.168  | 2.382  | 0.086   | 23160                   | 10455  | 10.250      | 10.786 | 0.500  | 10.711 | 0.209   | 240870                  | 236605 |
| 2.312       | 2.467  | 0.200  | 2.450  | 0.086   | 23790                   | 11700  | 10.500      | 11.047 | 0.500  | 10.970 | 0.209   | 246740                  | 247110 |
| 2.357       | 2.535  | 0.200  | 2.517  | 0.086   | 24440                   | 12715  | 10.750      | 11.313 | 0.500  | 11.234 | 0.209   | 252620                  | 260530 |
| 2.440       | 2.602  | 0.200  | 2.584  | 0.086   | 25110                   | 13550  | 11.000      | 11.575 | 0.500  | 11.495 | 0.209   | 258490                  | 272645 |
| 2.500       | 2.667  | 0.200  | 2.648  | 0.086   | 25730                   | 14640  | 11.250      | 11.838 | 0.500  | 11.756 | 0.209   | 264360                  | 285040 |
| 2.531       | 2.700  | 0.200  | 2.681  | 0.086   | 26050                   | 15185  | 11.500      | 12.102 | 0.562  | 12.018 | 0.209   | 270240                  | 298285 |
| 2.562       | 2.733  | 0.225  | 2.714  | 0.103   | 29940                   | 12775  | 11.750      | 12.365 | 0.562  | 12.279 | 0.209   | 276120                  | 311240 |
| 2.625       | 2.801  | 0.225  | 2.781  | 0.103   | 30680                   | 13780  | 12.000      | 12.628 | 0.562  | 12.540 | 0.209   | 281990                  | 324475 |
| 2.688       | 2.868  | 0.225  | 2.848  | 0.103   | 31410                   | 14775  | 12.250      | 12.891 | 0.562  | 12.801 | 0.209   | 287860                  | 337980 |
| 2.750       | 2.934  | 0.225  | 2.914  | 0.103   | 32140                   | 15790  | 12.500      | 13.154 | 0.562  | 13.063 | 0.209   | 293740                  | 352390 |
| 2.813       | 3.001  | 0.225  | 2.980  | 0.103   | 32870                   | 16845  | 12.750      | 13.417 | 0.562  | 13.324 | 0.209   | 299610                  | 366460 |
| 2.834       | 3.027  | 0.225  | 3.006  | 0.103   | 33120                   | 17595  | 13.000      | 13.680 | 0.662  | 13.585 | 0.209   | 305490                  | 380805 |
| 2.875       | 3.072  | 0.225  | 3.051  | 0.103   | 33600                   | 18505  | 13.250      | 13.943 | 0.662  | 13.846 | 0.209   | 311360                  | 395430 |
| 3.000       | 3.204  | 0.225  | 3.182  | 0.103   | 35060                   | 20795  | 13.500      | 14.207 | 0.662  | 14.108 | 0.209   | 317240                  | 411000 |
| 3.062       | 3.271  | 0.281  | 3.248  | 0.120   | 42710                   | 18735  | 13.750      | 14.470 | 0.662  | 14.369 | 0.209   | 323110                  | 426185 |
| 3.125       | 3.338  | 0.281  | 3.315  | 0.120   | 43590                   | 19865  | 14.000      | 14.732 | 0.662  | 14.630 | 0.209   | 328990                  | 441645 |
| 3.157       | 3.371  | 0.281  | 3.348  | 0.120   | 44020                   | 20345  | 14.250      | 14.995 | 0.662  | 14.891 | 0.209   | 334860                  | 457380 |
| 3.250       | 3.470  | 0.281  | 3.446  | 0.120   | 45330                   | 22120  | 14.500      | 15.259 | 0.750  | 15.153 | 0.209   | 340740                  | 474120 |
| 3.346       | 3.571  | 0.281  | 3.546  | 0.120   | 46670                   | 23905  | 14.750      | 15.522 | 0.750  | 15.414 | 0.209   | 346610                  | 490415 |
| 3.469       | 3.701  | 0.281  | 3.675  | 0.120   | 48390                   | 26405  | 15.000      | 15.785 | 0.750  | 15.675 | 0.209   | 352490                  | 506990 |
| 3.500       | 3.736  | 0.281  | 3.710  | 0.120   | 48820                   | 27370  |             |        |        |        |         |                         |        |

Source: Spirolox Retaining Rings, RRN Series. All dimensions are in inches. Depth of groove  $d = (C - A)/2$ . Thickness indicated is for unplated rings; add 0.002 to upper thickness tolerance for plated rings. Standard material: carbon spring steel (SAE 1070-1090).

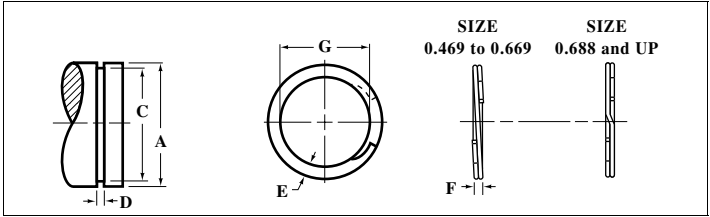
**Ring Thickness, F:** For housing sizes 0.500 through 0.750, 0.035; for sizes 0.777 through 1.023, 0.042; for sizes 1.062 through 1.500, 0.050; for sizes 1.562 through 2.000, 0.062; for sizes 2.062 through 2.531, 0.078; for sizes 2.562 through 3.000, 0.093; for sizes 3.062 through 5.000, 0.111; for sizes 5.250 through 7.000, 0.156; for sizes 7.250 through 15.000, 0.187.

**Ring Free Diameter Tolerances:** For housing sizes 0.500 through 1.500, +0.013, -0.000; for sizes 1.562 through 2.000, +0.020, -0.000; for sizes 2.062 through 2.531, +0.025, -0.000; for sizes 2.562 through 3.000, +0.030, -0.000; for sizes 3.062 through 5.000, +0.035, -0.000; for sizes 5.250 through 6.000, +0.050, -0.000; for sizes 6.250 through 7.000, +0.055, -0.000; for sizes 7.250 through 10.500, +0.070, -0.000; for sizes 10.750 through 12.750, +0.120, -0.000; for sizes 13.000 through 15.000, +0.140, -0.000.

**Ring Thickness Tolerances:** For housing sizes 0.500 through 1.500,  $\pm 0.002$ ; for sizes 1.562 through 5.000,  $\pm 0.003$ ; for sizes 5.250 through 6.000,  $\pm 0.004$ ; for sizes 6.250 through 15.000,  $\pm 0.005$ .

**Groove Diameter Tolerances:** For housing sizes 0.500 through 0.750,  $\pm 0.002$ ; for sizes 0.777 through 1.023,  $\pm 0.003$ ; for sizes 1.062 through 1.500,  $\pm 0.004$ ; for sizes 1.562 through 2.000,  $\pm 0.005$ ; for sizes 2.062 through 5.000,  $\pm 0.006$ ; for sizes 5.250 through 6.000,  $\pm 0.007$ ; for sizes 6.250 through 10.500,  $\pm 0.008$ ; for sizes 10.750 through 12.500,  $\pm 0.010$ ; for sizes 12.750 through 15.000,  $\pm 0.012$ .

**Groove Width Tolerances:** For housing sizes 0.500 through 1.023, +0.003, -0.000; for sizes 1.062 through 2.000, +0.004, -0.000; for sizes 2.062 through 5.000, +0.005, -0.000; for sizes 5.250 through 6.000, +0.006, -0.000; for sizes 6.250 through 7.000, +0.008, -0.000; for sizes 7.250 through 15.000, +0.008, -0.000.



**Table 10. Heavy Duty External Spiral Retaining Rings MIL-R-27426**

| Shaft Dia. A | Ring   |        | Groove |         | Static Thrust Load (lb) |        | Shaft Dia. A | Ring   |        | Groove |         | Static Thrust Load (lb) |        |
|--------------|--------|--------|--------|---------|-------------------------|--------|--------------|--------|--------|--------|---------|-------------------------|--------|
|              | Dia. G | Wall E | Dia. C | Width D | Ring                    | Groove |              | Dia. G | Wall E | Dia. C | Width D | Ring                    | Groove |
|              |        |        |        |         |                         |        |              |        |        |        |         |                         |        |
| 0.469        | 0.439  | 0.045  | 0.443  | 0.029   | 1880                    | 510    | 3.500        | 3.293  | 0.270  | 3.316  | 0.120   | 48820                   | 32250  |
| 0.500        | 0.464  | 0.050  | 0.468  | 0.039   | 2530                    | 440    | 3.543        | 3.333  | 0.270  | 3.357  | 0.120   | 49420                   | 33000  |
| 0.551        | 0.514  | 0.050  | 0.519  | 0.039   | 2790                    | 540    | 3.625        | 3.411  | 0.270  | 3.435  | 0.120   | 50560                   | 34490  |
| 0.562        | 0.525  | 0.050  | 0.530  | 0.039   | 2840                    | 560    | 3.687        | 3.469  | 0.270  | 3.493  | 0.120   | 51430                   | 35820  |
| 0.594        | 0.554  | 0.050  | 0.559  | 0.039   | 3000                    | 700    | 3.750        | 3.527  | 0.270  | 3.552  | 0.120   | 52310                   | 37180  |
| 0.625        | 0.583  | 0.055  | 0.588  | 0.039   | 3160                    | 820    | 3.875        | 3.647  | 0.270  | 3.673  | 0.120   | 54050                   | 39190  |
| 0.669        | 0.623  | 0.055  | 0.629  | 0.039   | 3380                    | 1070   | 3.938        | 3.708  | 0.270  | 3.734  | 0.120   | 54930                   | 40230  |
| 0.688        | 0.641  | 0.065  | 0.646  | 0.046   | 4170                    | 960    | 4.000        | 3.765  | 0.270  | 3.792  | 0.120   | 55790                   | 41660  |
| 0.750        | 0.698  | 0.065  | 0.704  | 0.046   | 4550                    | 1250   | 4.250        | 4.037  | 0.270  | 4.065  | 0.120   | 59280                   | 39370  |
| 0.781        | 0.727  | 0.065  | 0.733  | 0.046   | 4740                    | 1430   | 4.375        | 4.161  | 0.270  | 4.190  | 0.120   | 61020                   | 40530  |
| 0.812        | 0.756  | 0.065  | 0.762  | 0.046   | 4930                    | 1620   | 4.500        | 4.280  | 0.270  | 4.310  | 0.120   | 62770                   | 42810  |
| 0.875        | 0.814  | 0.075  | 0.821  | 0.046   | 5310                    | 2000   | 4.750        | 4.518  | 0.270  | 4.550  | 0.120   | 66260                   | 47570  |
| 0.938        | 0.875  | 0.075  | 0.882  | 0.046   | 5690                    | 2440   | 5.000        | 4.756  | 0.270  | 4.790  | 0.120   | 69740                   | 52580  |
| 0.984        | 0.919  | 0.085  | 0.926  | 0.046   | 5970                    | 2790   | 5.250        | 4.995  | 0.350  | 5.030  | 0.139   | 83790                   | 57830  |
| 1.000        | 0.932  | 0.085  | 0.940  | 0.046   | 6070                    | 2950   | 5.500        | 5.228  | 0.350  | 5.265  | 0.139   | 87780                   | 64720  |
| 1.023        | 0.953  | 0.085  | 0.961  | 0.046   | 6210                    | 3170   | 5.750        | 5.466  | 0.350  | 5.505  | 0.139   | 91770                   | 70540  |
| 1.062        | 0.986  | 0.103  | 0.998  | 0.056   | 7010                    | 2810   | 6.000        | 5.705  | 0.350  | 5.745  | 0.139   | 95760                   | 76610  |
| 1.125        | 1.047  | 0.103  | 1.059  | 0.056   | 7420                    | 2890   | 6.250        | 5.938  | 0.418  | 5.985  | 0.174   | 122520                  | 82930  |
| 1.188        | 1.105  | 0.103  | 1.118  | 0.056   | 7840                    | 3450   | 6.500        | 6.181  | 0.418  | 6.225  | 0.174   | 127420                  | 89510  |
| 1.250        | 1.163  | 0.103  | 1.176  | 0.056   | 8250                    | 4110   | 6.750        | 6.410  | 0.418  | 6.465  | 0.174   | 132320                  | 96330  |
| 1.312        | 1.218  | 0.118  | 1.232  | 0.056   | 8650                    | 4810   | 7.000        | 6.648  | 0.418  | 6.705  | 0.174   | 137220                  | 103400 |
| 1.375        | 1.277  | 0.118  | 1.291  | 0.056   | 9070                    | 5650   | 7.250        | 6.891  | 0.418  | 6.942  | 0.174   | 142130                  | 111810 |
| 1.438        | 1.336  | 0.118  | 1.350  | 0.056   | 9490                    | 6340   | 7.500        | 7.130  | 0.437  | 7.180  | 0.209   | 176240                  | 120170 |
| 1.500        | 1.385  | 0.118  | 1.406  | 0.056   | 9900                    | 7060   | 7.750        | 7.368  | 0.437  | 7.420  | 0.209   | 182120                  | 128060 |
| 1.562        | 1.453  | 0.128  | 1.468  | 0.068   | 12780                   | 6600   | 8.000        | 7.606  | 0.437  | 7.660  | 0.209   | 187990                  | 136200 |
| 1.625        | 1.513  | 0.128  | 1.529  | 0.068   | 13290                   | 7330   | 8.250        | 7.845  | 0.437  | 7.900  | 0.209   | 193870                  | 144590 |
| 1.687        | 1.573  | 0.128  | 1.589  | 0.068   | 13800                   | 8190   | 8.500        | 8.083  | 0.437  | 8.140  | 0.209   | 199740                  | 153220 |
| 1.750        | 1.633  | 0.128  | 1.650  | 0.068   | 14320                   | 8760   | 8.750        | 8.324  | 0.437  | 8.383  | 0.209   | 205620                  | 160800 |
| 1.771        | 1.651  | 0.128  | 1.669  | 0.068   | 14490                   | 9040   | 9.000        | 8.560  | 0.500  | 8.620  | 0.209   | 211490                  | 171250 |
| 1.812        | 1.690  | 0.128  | 1.708  | 0.068   | 14820                   | 9440   | 9.250        | 8.798  | 0.500  | 8.860  | 0.209   | 217370                  | 180640 |
| 1.875        | 1.751  | 0.158  | 1.769  | 0.068   | 15340                   | 9950   | 9.500        | 9.036  | 0.500  | 9.100  | 0.209   | 223240                  | 190280 |
| 1.969        | 1.838  | 0.158  | 1.857  | 0.068   | 16110                   | 11040  | 9.750        | 9.275  | 0.500  | 9.338  | 0.209   | 229120                  | 201140 |
| 2.000        | 1.867  | 0.158  | 1.886  | 0.068   | 16360                   | 11420  | 10.000       | 9.508  | 0.500  | 9.575  | 0.209   | 234990                  | 212810 |
| 2.062        | 1.932  | 0.168  | 1.946  | 0.086   | 21220                   | 11820  | 10.250       | 9.745  | 0.500  | 9.814  | 0.209   | 240870                  | 223780 |
| 2.125        | 1.989  | 0.168  | 2.003  | 0.086   | 21870                   | 12980  | 10.500       | 9.984  | 0.500  | 10.054 | 0.209   | 246740                  | 234490 |
| 2.156        | 2.018  | 0.168  | 2.032  | 0.086   | 22190                   | 13390  | 10.750       | 10.221 | 0.500  | 10.293 | 0.209   | 252620                  | 246000 |
| 2.250        | 2.105  | 0.168  | 2.120  | 0.086   | 23160                   | 14650  | 11.000       | 10.459 | 0.500  | 10.533 | 0.209   | 258490                  | 257230 |
| 2.312        | 2.163  | 0.168  | 2.178  | 0.086   | 23790                   | 15510  | 11.250       | 10.692 | 0.500  | 10.772 | 0.209   | 264360                  | 269270 |
| 2.375        | 2.223  | 0.200  | 2.239  | 0.086   | 24440                   | 16170  | 11.500       | 10.934 | 0.562  | 11.011 | 0.209   | 270240                  | 281590 |
| 2.437        | 2.283  | 0.200  | 2.299  | 0.086   | 25080                   | 16840  | 11.750       | 11.171 | 0.562  | 11.250 | 0.209   | 276120                  | 294180 |
| 2.500        | 2.343  | 0.200  | 2.360  | 0.086   | 25730                   | 17530  | 12.000       | 11.410 | 0.562  | 11.490 | 0.209   | 281990                  | 306450 |
| 2.559        | 2.402  | 0.200  | 2.419  | 0.086   | 26340                   | 17940  | 12.250       | 11.647 | 0.562  | 11.729 | 0.209   | 287860                  | 319580 |
| 2.625        | 2.464  | 0.200  | 2.481  | 0.086   | 27020                   | 18930  | 12.500       | 11.885 | 0.562  | 11.969 | 0.209   | 293740                  | 332360 |
| 2.687        | 2.523  | 0.200  | 2.541  | 0.086   | 27650                   | 19640  | 12.750       | 12.124 | 0.562  | 12.208 | 0.209   | 299610                  | 346030 |



**Table 10. (Continued) Heavy Duty External Spiral Retaining Rings MIL-R-27426**

| Shaft<br>Dia.<br>A | Ring      |           |           | Groove     |       | Static Thrust<br>Load (lb) |           | Shaft<br>Dia.<br>A | Ring      |           |            | Groove |        | Static Thrust<br>Load (lb) |  |
|--------------------|-----------|-----------|-----------|------------|-------|----------------------------|-----------|--------------------|-----------|-----------|------------|--------|--------|----------------------------|--|
|                    | Dia.<br>G | Wall<br>E | Dia.<br>C | Width<br>D | Ring  | Groove                     | Dia.<br>G |                    | Wall<br>E | Dia.<br>C | Width<br>D | Ring   | Groove |                            |  |
|                    |           |           |           |            |       |                            |           |                    |           |           |            |        |        |                            |  |
| 2.750              | 2.584     | 0.225     | 2.602     | 0.103      | 32140 | 20380                      | 13.000    | 12.361             | 0.662     | 12.448    | 0.209      | 305490 | 359330 |                            |  |
| 2.875              | 2.702     | 0.225     | 2.721     | 0.103      | 33600 | 22170                      | 13.250    | 12.598             | 0.662     | 12.687    | 0.209      | 311360 | 373530 |                            |  |
| 2.937              | 2.760     | 0.225     | 2.779     | 0.103      | 34320 | 23240                      | 13.500    | 12.837             | 0.662     | 12.927    | 0.209      | 317240 | 387340 |                            |  |
| 3.000              | 2.818     | 0.225     | 2.838     | 0.103      | 35060 | 24340                      | 13.750    | 13.074             | 0.662     | 13.166    | 0.209      | 323110 | 402090 |                            |  |
| 3.062              | 2.878     | 0.225     | 2.898     | 0.103      | 35780 | 25140                      | 14.000    | 13.311             | 0.662     | 13.405    | 0.209      | 328990 | 417110 |                            |  |
| 3.125              | 2.936     | 0.225     | 2.957     | 0.103      | 36520 | 26290                      | 14.250    | 13.548             | 0.662     | 13.644    | 0.209      | 334860 | 432410 |                            |  |
| 3.156              | 2.965     | 0.225     | 2.986     | 0.103      | 36880 | 26860                      | 14.500    | 13.787             | 0.750     | 13.884    | 0.209      | 340740 | 447250 |                            |  |
| 3.250              | 3.054     | 0.225     | 3.076     | 0.103      | 37980 | 28320                      | 14.750    | 14.024             | 0.750     | 14.123    | 0.209      | 346610 | 463090 |                            |  |
| 3.344              | 3.144     | 0.225     | 3.166     | 0.103      | 39080 | 29800                      | 15.000    | 14.262             | 0.750     | 14.363    | 0.209      | 352490 | 478450 |                            |  |
| 3.437              | 3.234     | 0.225     | 3.257     | 0.103      | 40170 | 30980                      |           |                    |           |           |            |        |        |                            |  |

*Source:* Spirolox Retaining Rings, RSN Series. All dimensions are in inches. Depth of groove  $d = (A - C)/2$ . Thickness indicated is for unplated rings; add 0.002 to upper tolerance for plated rings. Standard material: carbon spring steel (SAE 1070-1090).

*Ring Thickness, F:* For shaft size 0.469, 0.025; for sizes 0.500 through 0.669, 0.035; for sizes 0.688 through 1.023, 0.042; for sizes 1.062 through 1.500, 0.050; for sizes 1.562 through 2.000, 0.062; for sizes 2.062 through 2.687, 0.078; for sizes 2.750 through 3.437, 0.093; for sizes 3.500 through 5.000, 0.111; for sizes 5.250 through 6.000, 0.127; for sizes 6.250 through 7.250, 0.156; for sizes 7.500 through 15.000, 0.187.

*Ring Free Diameter Tolerances:* For shaft sizes 0.469 through 1.500, +0.000, -0.013; for sizes 1.562 through 2.000, +0.000, -0.020; for sizes 2.062 through 2.687, +0.000, -0.025; for sizes 2.750 through 3.437, +0.000, -0.030; for sizes 3.500 through 5.000, +0.000, -0.035; for sizes 5.250 through 6.000, +0.000, -0.050; for sizes 6.250 through 7.000, +0.000, -0.060; for sizes 7.250 through 10.000, +0.000, -0.070; for sizes 10.250 through 12.500, +0.000, -0.090; for sizes 12.750 through 15.000, +0.000, -0.110.

*Ring Thickness Tolerances:* For shaft sizes 0.469 through 1.500,  $\pm 0.002$ ; for sizes 1.562 through 5.000,  $\pm 0.003$ ; for sizes 5.250 through 6.000,  $\pm 0.004$ ; for sizes 6.250 through 15.000,  $\pm 0.005$ .

*Groove Diameter Tolerances:* For shaft sizes 0.469 through 0.562,  $\pm 0.002$ ; for sizes 0.594 through 1.023,  $\pm 0.003$ ; for sizes 1.062 through 1.500,  $\pm 0.004$ ; for sizes 1.562 through 2.000,  $\pm 0.005$ ; for sizes 2.062 through 5.000,  $\pm 0.006$ ; for sizes 5.250 through 6.000,  $\pm 0.007$ ; for sizes 6.250 through 10.000,  $\pm 0.008$ ; for sizes 10.250 through 12.500,  $\pm 0.010$ ; for sizes 12.750 through 15.000,  $\pm 0.012$ .

*Groove Width Tolerances:* For shaft sizes 0.469 through 1.023, +0.003, -0.000; for sizes 1.062 through 2.000, +0.004, -0.000; for sizes 2.062 through 5.000, +0.005, -0.000; for sizes 5.250 through 6.000, +0.006, -0.000; for sizes 6.250 through 7.250, +0.008, -0.000; for sizes 7.500 through 15.000, +0.008, -0.000.

*Thrust Load Capacity:* The most important criterion in determining which ring is best suited for a specific application is thrust load capacity. The strength of the retaining ring and groove must both be considered when analyzing the thrust load capacity of an application to determine whether the groove or the retaining ring is likely to fail first. When a retaining ring application fails, the fault will usually be with the groove, unless the groove material is of very high strength.

*Ring Material:* The standard materials for spiral-wound retaining rings are SAE 1070 to 1090 carbon spring steels and 18-8 type 302 stainless steels. The 1070 to 1090 carbon spring steels provide high-strength retaining rings at low cost. Type 302 stainless steel withstands ordinary rusting. Other materials are used for specialized applications, such as the type 316 stainless frequently used in the food industry. For high-temperature use, superalloy A286 rings can be used at up to 900°F and Inconel X-750 at up to 1200°F. Other materials, such as 316 stainless steel, 17-7PH and Inconel stainless steels are sometimes used for special-purpose and custom-made rings. Standard ring are typically supplied uncoated, however, special finishes such as cadmium, phosphate, zinc, or black oxide coatings for carbon spring steel rings and passivation of stainless steel rings are available.

**Table 11. Important Dimensions of Inch Series External Retaining Rings**  
MS 16624

Lugs: D = 0.125 to 0.236      Lugs: D = 4.25 to 8.00

| Shaft<br>Dia.<br>D | Ring   |          | Groove |         |          | Shaft<br>Dia.<br>D | Ring   |          | Groove |         |          |
|--------------------|--------|----------|--------|---------|----------|--------------------|--------|----------|--------|---------|----------|
|                    | Dia. A | Thick. T | Dia. G | Width W | Margin E |                    | Dia. A | Thick. T | Dia. G | Width W | Margin E |
| 0.125              | 0.112  | 0.010    | 0.117  | 0.012   | 0.012    | 1.812              | 1.675  | 0.062    | 1.708  | 0.068   | 0.156    |
| 0.156              | 0.142  | 0.010    | 0.146  | 0.012   | 0.015    | 1.875              | 1.735  | 0.062    | 1.769  | 0.068   | 0.159    |
| 0.188              | 0.168  | 0.015    | 0.175  | 0.018   | 0.018    | 1.969              | 1.819  | 0.062    | 1.857  | 0.068   | 0.168    |
| 0.197              | 0.179  | 0.015    | 0.185  | 0.018   | 0.018    | 2.000              | 1.850  | 0.062    | 1.886  | 0.068   | 0.171    |
| 0.219              | 0.196  | 0.015    | 0.205  | 0.018   | 0.021    | 2.062              | 1.906  | 0.078    | 1.946  | 0.086   | 0.174    |
| 0.236              | 0.215  | 0.015    | 0.222  | 0.018   | 0.021    | 2.125              | 1.964  | 0.078    | 2.003  | 0.086   | 0.183    |
| 0.250              | 0.225  | 0.025    | 0.230  | 0.029   | 0.030    | 2.156              | 1.993  | 0.078    | 2.032  | 0.086   | 0.186    |
| 0.276              | 0.250  | 0.025    | 0.255  | 0.029   | 0.030    | 2.250              | 2.081  | 0.078    | 2.120  | 0.086   | 0.195    |
| 0.281              | 0.256  | 0.025    | 0.261  | 0.029   | 0.030    | 2.312              | 2.139  | 0.078    | 2.178  | 0.086   | 0.201    |
| 0.312              | 0.281  | 0.025    | 0.290  | 0.029   | 0.033    | 2.375              | 2.197  | 0.078    | 2.239  | 0.086   | 0.204    |
| 0.344              | 0.309  | 0.025    | 0.321  | 0.029   | 0.033    | 2.438              | 2.255  | 0.078    | 2.299  | 0.086   | 0.207    |
| 0.354              | 0.320  | 0.025    | 0.330  | 0.029   | 0.036    | 2.500              | 2.313  | 0.078    | 2.360  | 0.086   | 0.210    |
| 0.375              | 0.338  | 0.025    | 0.352  | 0.029   | 0.036    | 2.559              | 2.377  | 0.078    | 2.419  | 0.086   | 0.210    |
| 0.394              | 0.354  | 0.025    | 0.369  | 0.029   | 0.036    | 2.625              | 2.428  | 0.078    | 2.481  | 0.086   | 0.216    |
| 0.406              | 0.366  | 0.025    | 0.382  | 0.029   | 0.036    | 2.688              | 2.485  | 0.078    | 2.541  | 0.086   | 0.219    |
| 0.438              | 0.395  | 0.025    | 0.412  | 0.029   | 0.039    | 2.750              | 2.543  | 0.093    | 2.602  | 0.103   | 0.222    |
| 0.469              | 0.428  | 0.025    | 0.443  | 0.029   | 0.039    | 2.875              | 2.659  | 0.093    | 2.721  | 0.103   | 0.231    |
| 0.500              | 0.461  | 0.035    | 0.468  | 0.039   | 0.048    | 2.938              | 2.717  | 0.093    | 2.779  | 0.103   | 0.237    |
| 0.551              | 0.509  | 0.035    | 0.519  | 0.039   | 0.048    | 3.000              | 2.775  | 0.093    | 2.838  | 0.103   | 0.243    |
| 0.562              | 0.521  | 0.035    | 0.530  | 0.039   | 0.048    | 3.062              | 2.832  | 0.093    | 2.898  | 0.103   | 0.246    |
| 0.594              | 0.550  | 0.035    | 0.559  | 0.039   | 0.051    | 3.125              | 2.892  | 0.093    | 2.957  | 0.103   | 0.252    |
| 0.625              | 0.579  | 0.035    | 0.588  | 0.039   | 0.054    | 3.156              | 2.920  | 0.093    | 2.986  | 0.103   | 0.255    |
| 0.669              | 0.621  | 0.035    | 0.629  | 0.039   | 0.060    | 3.250              | 3.006  | 0.093    | 3.076  | 0.103   | 0.261    |
| 0.672              | 0.621  | 0.035    | 0.631  | 0.039   | 0.060    | 3.346              | 3.092  | 0.093    | 3.166  | 0.103   | 0.270    |
| 0.688              | 0.635  | 0.042    | 0.646  | 0.046   | 0.063    | 3.438              | 3.179  | 0.093    | 3.257  | 0.103   | 0.270    |
| 0.750              | 0.693  | 0.042    | 0.704  | 0.046   | 0.069    | 3.500              | 3.237  | 0.109    | 3.316  | 0.120   | 0.276    |
| 0.781              | 0.722  | 0.042    | 0.733  | 0.046   | 0.072    | 3.543              | 3.277  | 0.109    | 3.357  | 0.120   | 0.279    |
| 0.812              | 0.751  | 0.042    | 0.762  | 0.046   | 0.075    | 3.625              | 3.352  | 0.109    | 3.435  | 0.120   | 0.285    |
| 0.844              | 0.780  | 0.042    | 0.791  | 0.046   | 0.080    | 3.688              | 3.410  | 0.109    | 3.493  | 0.120   | 0.291    |
| 0.875              | 0.810  | 0.042    | 0.821  | 0.046   | 0.081    | 3.750              | 3.468  | 0.109    | 3.552  | 0.120   | 0.297    |
| 0.938              | 0.867  | 0.042    | 0.882  | 0.046   | 0.084    | 3.875              | 3.584  | 0.109    | 3.673  | 0.120   | 0.303    |
| 0.984              | 0.910  | 0.042    | 0.926  | 0.046   | 0.087    | 3.938              | 3.642  | 0.109    | 3.734  | 0.120   | 0.306    |
| 1.000              | 0.925  | 0.042    | 0.940  | 0.046   | 0.090    | 4.000              | 3.700  | 0.109    | 3.792  | 0.120   | 0.312    |
| 1.023              | 0.946  | 0.042    | 0.961  | 0.046   | 0.093    | 4.250              | 3.989  | 0.109    | 4.065  | 0.120   | 0.276    |
| 1.062              | 0.982  | 0.050    | 0.998  | 0.056   | 0.096    | 4.375              | 4.106  | 0.109    | 4.190  | 0.120   | 0.276    |
| 1.125              | 1.041  | 0.050    | 1.059  | 0.056   | 0.099    | 4.500              | 4.223  | 0.109    | 4.310  | 0.120   | 0.285    |
| 1.188              | 1.098  | 0.050    | 1.118  | 0.056   | 0.105    | 4.750              | 4.458  | 0.109    | 4.550  | 0.120   | 0.300    |
| 1.250              | 1.156  | 0.050    | 1.176  | 0.056   | 0.111    | 5.000              | 4.692  | 0.109    | 4.790  | 0.120   | 0.315    |
| 1.312              | 1.214  | 0.050    | 1.232  | 0.056   | 0.120    | 5.250              | 4.927  | 0.125    | 5.030  | 0.139   | 0.330    |
| 1.375              | 1.272  | 0.050    | 1.291  | 0.056   | 0.126    | 5.500              | 5.162  | 0.125    | 5.265  | 0.139   | 0.351    |
| 1.438              | 1.333  | 0.050    | 1.350  | 0.056   | 0.132    | 5.750              | 5.396  | 0.125    | 5.505  | 0.139   | 0.366    |
| 1.500              | 1.387  | 0.050    | 1.406  | 0.056   | 0.141    | 6.000              | 5.631  | 0.125    | 5.745  | 0.139   | 0.381    |
| 1.562              | 1.446  | 0.062    | 1.468  | 0.068   | 0.141    | 6.250              | 5.866  | 0.156    | 5.985  | 0.174   | 0.396    |
| 1.625              | 1.503  | 0.062    | 1.529  | 0.068   | 0.144    | 6.500              | 6.100  | 0.156    | 6.225  | 0.174   | 0.411    |
| 1.687              | 1.560  | 0.062    | 1.589  | 0.068   | 0.147    | 6.750              | 6.335  | 0.156    | 6.465  | 0.174   | 0.426    |
| 1.750              | 1.618  | 0.062    | 1.650  | 0.068   | 0.150    | 7.000              | 6.570  | 0.156    | 6.705  | 0.174   | 0.441    |
| 1.772              | 1.637  | 0.062    | 1.669  | 0.068   | 0.153    | 7.500              | 7.009  | 0.187    | 7.180  | 0.209   | 0.480    |

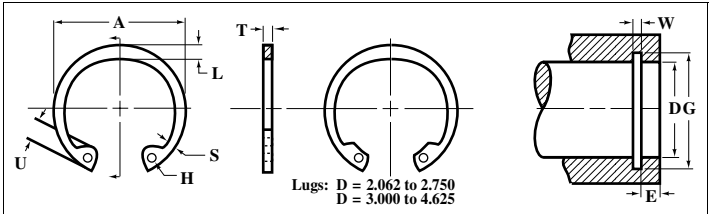
Source: Industrial Retaining Rings, 3100 Series. All dimensions are in inches. Depth of groove  $d = (D - G)/2$ . Thickness indicated is for unplated rings; for most plated rings, the maximum ring thickness will not exceed the minimum groove width (W) minus 0.0002 inch. Standard material: carbon spring steel (SAE 1060-1090).

**Ring Free Diameter Tolerances:** For shaft sizes 0.125 through 0.250, +0.002, -0.004; for sizes 0.276 through 0.500, +0.002, -0.005; for sizes 0.551 through 1.023, +0.005, -0.010; for sizes 1.062 through 1.500, +0.010, -0.015; for sizes 1.562 through 2.000, +0.013, -0.020; for sizes 2.062 through 2.500, +0.015, -0.025; for sizes 2.559 through 5.000, +0.020, -0.030; for sizes 5.250 through 6.000, +0.020, -0.040; for sizes 6.250 through 6.750, +0.020, -0.050; for sizes 7.000 and 7.500, +0.050, -0.130.

**Ring Thickness Tolerances:** For shaft sizes 0.125 and 0.156, ±0.001; for sizes 0.188 through 1.500, ±0.002; for sizes 1.562 through 5.000, ±0.003; for sizes 5.250 through 6.000, ±0.004; for sizes 6.250 through 7.500, ±0.005.

**Groove Diameter Tolerances:** For shaft sizes 0.125 through 0.250, ±0.0015; for sizes 0.276 through 0.562, ±0.002; for sizes 0.594 through 1.023, ±0.003; for sizes 1.062 through 1.500, ±0.004; for sizes 1.562 through 2.000, ±0.005; for sizes 2.062 through 5.000, ±0.006; for sizes 5.250 through 6.000, ±0.007; for sizes 6.250 through 7.500, ±0.008.

**Groove Width Tolerances:** For shaft sizes 0.125 through 0.236, +0.002, -0.000; for sizes 0.250 through 1.023, +0.003, -0.000; for sizes 1.062 through 2.000, +0.004, -0.000; for sizes 2.062 through 5.000, +0.005, -0.000; for sizes 5.250 through 6.000, +0.006, -0.000; for sizes 6.250 through 7.500, +0.008, -0.000.



**Table 12. Important Dimensions of Inch Series Internal Retaining Rings**

| Housing Dia. D | Ring   |          | Groove |         |          | Housing Dia. D | Ring   |          | Groove |         |          |
|----------------|--------|----------|--------|---------|----------|----------------|--------|----------|--------|---------|----------|
|                | Dia. A | Thick. T | Dia. G | Width W | Margin E |                | Dia. A | Thick. T | Dia. G | Width W | Margin E |
| 0.250          | 0.280  | 0.015    | 0.268  | 0.018   | 0.027    | 2.500          | 2.775  | 0.078    | 2.648  | 0.086   | 0.222    |
| 0.312          | 0.346  | 0.015    | 0.330  | 0.018   | 0.027    | 2.531          | 2.775  | 0.078    | 2.681  | 0.086   | 0.225    |
| 0.375          | 0.415  | 0.025    | 0.397  | 0.029   | 0.033    | 2.562          | 2.844  | 0.093    | 2.714  | 0.103   | 0.228    |
| 0.438          | 0.482  | 0.025    | 0.461  | 0.029   | 0.036    | 2.625          | 2.910  | 0.093    | 2.781  | 0.103   | 0.234    |
| 0.453          | 0.498  | 0.025    | 0.477  | 0.029   | 0.036    | 2.677          | 2.980  | 0.093    | 2.837  | 0.103   | 0.240    |
| 0.500          | 0.548  | 0.035    | 0.530  | 0.039   | 0.045    | 2.688          | 2.980  | 0.093    | 2.848  | 0.103   | 0.240    |
| 0.512          | 0.560  | 0.035    | 0.542  | 0.039   | 0.045    | 2.750          | 3.050  | 0.093    | 2.914  | 0.103   | 0.246    |
| 0.562          | 0.620  | 0.035    | 0.596  | 0.039   | 0.051    | 2.812          | 3.121  | 0.093    | 2.980  | 0.103   | 0.252    |
| 0.625          | 0.694  | 0.035    | 0.665  | 0.039   | 0.060    | 2.835          | 3.121  | 0.093    | 3.006  | 0.103   | 0.255    |
| 0.688          | 0.763  | 0.035    | 0.732  | 0.039   | 0.066    | 2.875          | 3.191  | 0.093    | 3.051  | 0.103   | 0.264    |
| 0.750          | 0.831  | 0.035    | 0.796  | 0.039   | 0.069    | 2.953          | 3.325  | 0.093    | 3.135  | 0.103   | 0.273    |
| 0.777          | 0.859  | 0.042    | 0.825  | 0.046   | 0.072    | 3.000          | 3.325  | 0.093    | 3.182  | 0.103   | 0.273    |
| 0.812          | 0.901  | 0.042    | 0.862  | 0.046   | 0.075    | 3.062          | 3.418  | 0.109    | 3.248  | 0.120   | 0.279    |
| 0.866          | 0.961  | 0.042    | 0.920  | 0.046   | 0.081    | 3.125          | 3.488  | 0.109    | 3.315  | 0.120   | 0.285    |
| 0.875          | 0.971  | 0.042    | 0.931  | 0.046   | 0.084    | 3.149          | 3.523  | 0.109    | 3.341  | 0.120   | 0.288    |
| 0.901          | 1.000  | 0.042    | 0.959  | 0.046   | 0.087    | 3.156          | 3.523  | 0.109    | 3.348  | 0.120   | 0.288    |
| 0.938          | 1.041  | 0.042    | 1.000  | 0.046   | 0.093    | 3.250          | 3.623  | 0.109    | 3.446  | 0.120   | 0.294    |
| 1.000          | 1.111  | 0.042    | 1.066  | 0.046   | 0.099    | 3.346          | 3.734  | 0.109    | 3.546  | 0.120   | 0.300    |
| 1.023          | 1.136  | 0.042    | 1.091  | 0.046   | 0.102    | 3.469          | 3.857  | 0.109    | 3.675  | 0.120   | 0.309    |
| 1.062          | 1.180  | 0.050    | 1.130  | 0.056   | 0.102    | 3.500          | 3.890  | 0.109    | 3.710  | 0.120   | 0.315    |

**Table 12. (Continued) Important Dimensions of Inch Series Internal Retaining Rings**

| Housing<br>Dia.<br>D | Ring      |             | Groove    |            |             | Housing<br>Dia.<br>D | Ring      |             | Groove    |            |             |
|----------------------|-----------|-------------|-----------|------------|-------------|----------------------|-----------|-------------|-----------|------------|-------------|
|                      | Dia.<br>A | Thick.<br>T | Dia.<br>G | Width<br>W | Margin<br>E |                      | Dia.<br>A | Thick.<br>T | Dia.<br>G | Width<br>W | Margin<br>E |
| 1.125                | 1.249     | 0.050       | 1.197     | 0.056      | 0.108       | 3.543                | 3.936     | 0.109       | 3.755     | 0.120      | 0.318       |
| 1.181                | 1.319     | 0.050       | 1.255     | 0.056      | 0.111       | 3.562                | 3.936     | 0.109       | 3.776     | 0.120      | 0.321       |
| 1.188                | 1.319     | 0.050       | 1.262     | 0.056      | 0.111       | 3.625                | 4.024     | 0.109       | 3.841     | 0.120      | 0.324       |
| 1.250                | 1.388     | 0.050       | 1.330     | 0.056      | 0.120       | 3.740                | 4.157     | 0.109       | 3.964     | 0.120      | 0.336       |
| 1.259                | 1.388     | 0.050       | 1.339     | 0.056      | 0.120       | 3.750                | 4.157     | 0.109       | 3.974     | 0.120      | 0.336       |
| 1.312                | 1.456     | 0.050       | 1.396     | 0.056      | 0.126       | 3.875                | 4.291     | 0.109       | 4.107     | 0.120      | 0.348       |
| 1.375                | 1.526     | 0.050       | 1.461     | 0.056      | 0.129       | 3.938                | 4.358     | 0.109       | 4.174     | 0.120      | 0.354       |
| 1.378                | 1.526     | 0.050       | 1.464     | 0.056      | 0.129       | 4.000                | 4.424     | 0.109       | 4.240     | 0.120      | 0.360       |
| 1.438                | 1.596     | 0.050       | 1.528     | 0.056      | 0.135       | 4.125                | 4.558     | 0.109       | 4.365     | 0.120      | 0.360       |
| 1.456                | 1.616     | 0.050       | 1.548     | 0.056      | 0.138       | 4.250                | 4.691     | 0.109       | 4.490     | 0.120      | 0.360       |
| 1.500                | 1.660     | 0.050       | 1.594     | 0.056      | 0.141       | 4.331                | 4.756     | 0.109       | 4.571     | 0.120      | 0.360       |
| 1.562                | 1.734     | 0.062       | 1.658     | 0.068      | 0.144       | 4.500                | 4.940     | 0.109       | 4.740     | 0.120      | 0.360       |
| 1.575                | 1.734     | 0.062       | 1.671     | 0.068      | 0.144       | 4.625                | 5.076     | 0.109       | 4.865     | 0.120      | 0.360       |
| 1.625                | 1.804     | 0.062       | 1.725     | 0.068      | 0.150       | 4.724                | 5.213     | 0.109       | 4.969     | 0.120      | 0.366       |
| 1.653                | 1.835     | 0.062       | 1.755     | 0.068      | 0.153       | 4.750                | 5.213     | 0.109       | 4.995     | 0.120      | 0.366       |
| 1.688                | 1.874     | 0.062       | 1.792     | 0.068      | 0.156       | 5.000                | 5.485     | 0.109       | 5.260     | 0.120      | 0.390       |
| 1.750                | 1.942     | 0.062       | 1.858     | 0.068      | 0.162       | 5.250                | 5.770     | 0.125       | 5.520     | 0.139      | 0.405       |
| 1.812                | 2.012     | 0.062       | 1.922     | 0.068      | 0.165       | 5.375                | 5.910     | 0.125       | 5.650     | 0.139      | 0.405       |
| 1.850                | 2.054     | 0.062       | 1.962     | 0.068      | 0.168       | 5.500                | 6.066     | 0.125       | 5.770     | 0.139      | 0.405       |
| 1.875                | 2.054     | 0.062       | 1.989     | 0.068      | 0.171       | 5.750                | 6.336     | 0.125       | 6.020     | 0.139      | 0.405       |
| 1.938                | 2.141     | 0.062       | 2.056     | 0.068      | 0.177       | 6.000                | 6.620     | 0.125       | 6.270     | 0.139      | 0.405       |
| 2.000                | 2.210     | 0.062       | 2.122     | 0.068      | 0.183       | 6.250                | 6.895     | 0.156       | 6.530     | 0.174      | 0.420       |
| 2.047                | 2.280     | 0.078       | 2.171     | 0.086      | 0.186       | 6.500                | 7.170     | 0.156       | 6.790     | 0.174      | 0.435       |
| 2.062                | 2.280     | 0.078       | 2.186     | 0.086      | 0.186       | 6.625                | 7.308     | 0.156       | 6.925     | 0.174      | 0.450       |
| 2.125                | 2.350     | 0.078       | 2.251     | 0.086      | 0.189       | 6.750                | 7.445     | 0.156       | 7.055     | 0.174      | 0.456       |
| 2.165                | 2.415     | 0.078       | 2.295     | 0.086      | 0.195       | 7.000                | 7.720     | 0.156       | 7.315     | 0.174      | 0.471       |
| 2.188                | 2.415     | 0.078       | 2.318     | 0.086      | 0.195       | 7.250                | 7.995     | 0.187       | 7.575     | 0.209      | 0.486       |
| 2.250                | 2.490     | 0.078       | 2.382     | 0.086      | 0.198       | 7.500                | 8.270     | 0.187       | 7.840     | 0.209      | 0.510       |
| 2.312                | 2.560     | 0.078       | 2.450     | 0.086      | 0.207       | 7.750                | 8.545     | 0.187       | 8.100     | 0.209      | 0.525       |
| 2.375                | 2.630     | 0.078       | 2.517     | 0.086      | 0.213       | 8.000                | 8.820     | 0.187       | 8.360     | 0.209      | 0.540       |
| 2.440                | 2.702     | 0.078       | 2.584     | 0.086      | 0.216       | 8.250                | 9.095     | 0.187       | 8.620     | 0.209      | 0.555       |

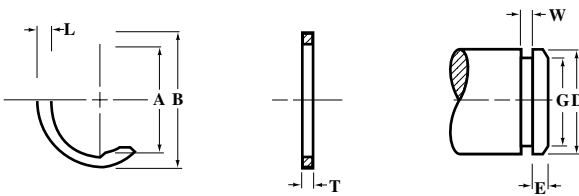
*Source:* Industrial Retaining Rings, 3000 Series. All dimensions are in inches. Depth of groove  $d = (G - D)/2$ . Thickness indicated is for unplated rings. Standard material: carbon spring steel (SAE 1060-1090).

*Ring Free Diameter Tolerances:* For housing sizes 0.250 through 0.777, +0.010, -0.005; for sizes 0.812 through 1.023, +0.015, -0.010; for sizes 1.062 through 1.500, +0.025, -0.020; for sizes 1.562 through 2.000, +0.035, -0.025; for sizes 2.047 through 3.000, +0.040, -0.030; for sizes 3.062 through 3.625,  $\pm 0.055$ ; for sizes 3.740 through 6.000,  $\pm 0.065$ ; for sizes 6.250 through 7.000,  $\pm 0.080$ ; for sizes 7.250 through 8.250,  $\pm 0.090$ .

*Ring Thickness Tolerances:* For housing sizes 0.250 through 1.500,  $\pm 0.002$ ; for sizes 1.562 through 5.000,  $\pm 0.003$ ; for sizes 5.250 through 6.000,  $\pm 0.004$ ; for sizes 6.250 through 8.250,  $\pm 0.005$ .

*Groove Diameter Tolerances:* For housing sizes 0.250 and 0.312,  $\pm 0.001$ ; for sizes 0.375 through 1.750,  $\pm 0.002$ ; for sizes 0.777 through 1.023  $\pm 0.003$ ; for sizes 1.062 through 1.500,  $\pm 0.004$ ; for sizes 1.562 through 2.000,  $\pm 0.005$ ; for sizes 2.047 through 5.000  $\pm 0.006$ ; for sizes 5.250 through 6.000,  $\pm 0.007$ ; for sizes 6.250 through 8.250,  $\pm 0.008$ .

*Groove Width Tolerances:* For housing sizes 0.250 and 0.312, +0.002, -0.000; for sizes 0.375 through 1.023, +0.003, -0.000; for sizes 1.062 through 2.000, +0.004, -0.000; for sizes 2.047 through 5.000, +0.005; -0.000; for sizes 5.250 through 6.000, +0.006, -0.000; for sizes 6.250 through 8.250, +0.008, -0.000.

**Table 13. Important Dimensions of Inch Series External Retaining Rings MS16632**


| Shaft Diameter<br>D | Ring           |                |               | Groove        |            |             | <sup>a</sup> Static Thrust Load (lb) |        |
|---------------------|----------------|----------------|---------------|---------------|------------|-------------|--------------------------------------|--------|
|                     | Free Dia.<br>A | Thickness<br>T | Diameter<br>B | Diameter<br>G | Width<br>W | Margin<br>E | Ring                                 | Groove |
|                     | 0.125          | 0.102          | 0.015         | 0.164         | 0.106      | 0.018       | 0.020                                | 85     |
| 0.156               | 0.131          | 0.015          | 0.205         | 0.135         | 0.018      | 0.020       | 110                                  | 55     |
| 0.188               | 0.161          | 0.015          | 0.245         | 0.165         | 0.018      | 0.022       | 130                                  | 70     |
| 0.219               | 0.187          | 0.025          | 0.275         | 0.193         | 0.029      | 0.026       | 260                                  | 100    |
| 0.236               | 0.203          | 0.025          | 0.295         | 0.208         | 0.029      | 0.028       | 280                                  | 115    |
| 0.250               | 0.211          | 0.025          | 0.311         | 0.220         | 0.029      | 0.030       | 295                                  | 130    |
| 0.281               | 0.242          | 0.025          | 0.344         | 0.247         | 0.029      | 0.034       | 330                                  | 170    |
| 0.312               | 0.270          | 0.025          | 0.376         | 0.276         | 0.029      | 0.036       | 370                                  | 200    |
| 0.375               | 0.328          | 0.025          | 0.448         | 0.335         | 0.029      | 0.040       | 440                                  | 265    |
| 0.406               | 0.359          | 0.025          | 0.485         | 0.364         | 0.029      | 0.042       | 480                                  | 300    |
| 0.437               | 0.386          | 0.025          | 0.516         | 0.393         | 0.029      | 0.044       | 515                                  | 340    |
| 0.500               | 0.441          | 0.035          | 0.581         | 0.450         | 0.039      | 0.050       | 825                                  | 440    |
| 0.562               | 0.497          | 0.035          | 0.653         | 0.507         | 0.039      | 0.056       | 930                                  | 550    |
| 0.625               | 0.553          | 0.035          | 0.715         | 0.563         | 0.039      | 0.062       | 1030                                 | 690    |
| 0.687               | 0.608          | 0.042          | 0.780         | 0.619         | 0.046      | 0.068       | 1700                                 | 820    |
| 0.750               | 0.665          | 0.042          | 0.845         | 0.676         | 0.046      | 0.074       | 1850                                 | 985    |
| 0.812               | 0.721          | 0.042          | 0.915         | 0.732         | 0.046      | 0.080       | 2010                                 | 1150   |
| 0.875               | 0.777          | 0.042          | 0.987         | 0.789         | 0.046      | 0.086       | 2165                                 | 1320   |
| 0.937               | 0.830          | 0.042          | 1.054         | 0.843         | 0.046      | 0.094       | 2320                                 | 1550   |
| 1.000               | 0.887          | 0.042          | 1.127         | 0.900         | 0.046      | 0.100       | 2480                                 | 1770   |
| 1.125               | 0.997          | 0.050          | 1.267         | 1.013         | 0.056      | 0.112       | 3300                                 | 2200   |
| 1.188               | 1.031          | 0.050          | 1.321         | 1.047         | 0.056      | 0.140       | 3500                                 | 2900   |
| 1.250               | 1.110          | 0.050          | 1.410         | 1.126         | 0.056      | 0.124       | 3600                                 | 2700   |
| 1.375               | 1.220          | 0.050          | 1.550         | 1.237         | 0.056      | 0.138       | 4000                                 | 3300   |
| 1.500               | 1.331          | 0.050          | 1.691         | 1.350         | 0.056      | 0.150       | 4400                                 | 4000   |
| 1.750               | 1.555          | 0.062          | 1.975         | 1.576         | 0.068      | 0.174       | 6400                                 | 5300   |
| 2.000               | 1.777          | 0.062          | 2.257         | 1.800         | 0.068      | 0.200       | 7300                                 | 7000   |

<sup>a</sup> *Thrust Load Safety Factors:* Ring, 4; groove, 2. Groove wall thrust loads are for grooves machined in cold-rolled steel with a tensile yield strength of 45,000 psi; for other shaft materials, the thrust load varies proportionally with the yield strength.

*Source:* Industrial Retaining Rings, 2000 Series. All dimensions are in inches. Depth of groove  $d = (D - G)/2$ . Standard material: carbon spring steel (SAE 1060-1090). Thickness indicated is for unplated rings; for most plated rings with shaft sizes less than 1.000 inch, the maximum thickness will not exceed the minimum groove width (W) minus 0.0002 inch; for larger rings, the ring thickness may increase by 0.002 inch.

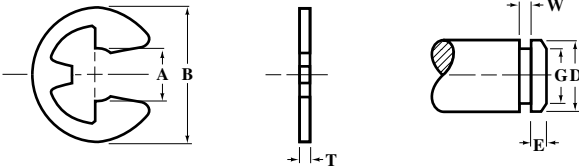
*Groove Maximum Bottom Radii:* For shaft diameters less than 0.500 inch, 0.005 inch; for shaft sizes 0.500 through 1.000 inch, 0.010 inch; all larger sizes, 0.015 inch.

*Ring Free Diameter Tolerances:* For shaft sizes 0.125 through 0.188, +0.002, -0.004; for sizes 0.219 through 0.437, +0.003, -0.005; for sizes 0.500 through 0.625,  $\pm 0.006$ ; for sizes 0.687 through 1.000,  $\pm 0.007$ ; for sizes 1.125 through 1.500,  $\pm 0.008$ ; for sizes 1.750 and 2.000,  $\pm 0.010$ .

*Ring Thickness Tolerances:* For shaft sizes 0.125 through 1.500,  $\pm 0.002$ ; for sizes 1.750 and 2.000,  $\pm 0.003$ .

*Groove Diameter Tolerances:* For shaft sizes 0.125 through 0.188,  $\pm 0.0015$ ; for sizes 0.219 through 0.437,  $\pm 0.002$ ; for sizes 0.500 through 1.000,  $\pm 0.003$ ; for sizes 1.125 through 1.500,  $\pm 0.004$ ; for sizes 1.750 and 2.000,  $\pm 0.005$ .

*Groove Width Tolerances:* For shaft sizes 0.125 through 0.188, +0.002, -0.000; for sizes 0.219 through 1.000, +0.003, -0.000; for sizes 1.125 through 2.000, +0.004, -0.000.

**Table 14. Important Dimensions of Inch Series External Retaining Rings MS16633**


| Shaft Diameter<br>D | Ring           |                |               | Groove        |            |             | Static Thrust Load (lb) |        |
|---------------------|----------------|----------------|---------------|---------------|------------|-------------|-------------------------|--------|
|                     | Free Dia.<br>A | Thickness<br>T | Diameter<br>B | Diameter<br>G | Width<br>W | Margin<br>E | Ring                    | Groove |
|                     | 0.040          | 0.025          | 0.010         | 0.079         | 0.026      | 0.012       | 0.014                   | 13     |
| 0.062               | 0.051          | 0.010          | 0.140         | 0.052         | 0.012      | 0.010       | 20                      | 7      |
| 0.062 <sup>a</sup>  | 0.051          | 0.010          | 0.156         | 0.052         | 0.012      | 0.010       | 20                      | 7      |
| 0.062 <sup>b</sup>  | 0.051          | 0.020          | 0.187         | 0.052         | 0.023      | 0.010       | 40                      | 7      |
| 0.094               | 0.073          | 0.015          | 0.187         | 0.074         | 0.018      | 0.020       | 45                      | 20     |
| 0.094               | 0.069          | 0.015          | 0.230         | 0.074         | 0.018      | 0.020       | 45                      | 20     |
| 0.110               | 0.076          | 0.015          | 0.375         | 0.079         | 0.018      | 0.030       | 55                      | 40     |
| 0.125               | 0.094          | 0.015          | 0.230         | 0.095         | 0.018      | 0.030       | 65                      | 45     |
| 0.140               | 0.100          | 0.015          | 0.203         | 0.102         | 0.018      | 0.038       | 70                      | 60     |
| 0.140 <sup>c</sup>  | 0.108          | 0.015          | 0.250         | 0.110         | 0.018      | 0.030       | 70                      | 45     |
| 0.140 <sup>d</sup>  | 0.102          | 0.025          | 0.270         | 0.105         | 0.029      | 0.034       | 150                     | 55     |
| 0.156               | 0.114          | 0.025          | 0.282         | 0.116         | 0.029      | 0.040       | 165                     | 70     |
| 0.172               | 0.125          | 0.025          | 0.312         | 0.127         | 0.029      | 0.044       | 180                     | 90     |
| 0.188               | 0.145          | 0.025          | 0.335         | 0.147         | 0.029      | 0.040       | 195                     | 90     |
| 0.188               | 0.122          | 0.025          | 0.375         | 0.125         | 0.029      | 0.062       | 195                     | 135    |
| 0.218               | 0.185          | 0.025          | 0.437         | 0.188         | 0.029      | 0.030       | 225                     | 75     |
| 0.250               | 0.207          | 0.025          | 0.527         | 0.210         | 0.029      | 0.040       | 260                     | 115    |
| 0.312               | 0.243          | 0.025          | 0.500         | 0.250         | 0.029      | 0.062       | 325                     | 225    |
| 0.375               | 0.300          | 0.035          | 0.660         | 0.303         | 0.039      | 0.072       | 685                     | 315    |
| 0.437               | 0.337          | 0.035          | 0.687         | 0.343         | 0.039      | 0.094       | 800                     | 485    |
| 0.437               | 0.375          | 0.035          | 0.600         | 0.380         | 0.039      | 0.058       | 800                     | 290    |
| 0.500               | 0.392          | 0.042          | 0.800         | 0.396         | 0.046      | 0.104       | 1100                    | 600    |
| 0.625               | 0.480          | 0.042          | 0.940         | 0.485         | 0.046      | 0.140       | 1370                    | 1040   |
| 0.744               | 0.616          | 0.050          | 1.000         | 0.625         | 0.056      | 0.118       | 1940                    | 1050   |
| 0.750               | 0.616          | 0.050          | 1.000         | 0.625         | 0.056      | 0.124       | 1960                    | 1100   |
| 0.750               | 0.574          | 0.050          | 1.120         | 0.580         | 0.056      | 0.170       | 1960                    | 1500   |
| 0.875               | 0.668          | 0.050          | 1.300         | 0.675         | 0.056      | 0.200       | 2200                    | 2050   |
| 0.985               | 0.822          | 0.050          | 1.500         | 0.835         | 0.056      | 0.148       | 2570                    | 1710   |
| 1.000               | 0.822          | 0.050          | 1.500         | 0.835         | 0.056      | 0.164       | 2620                    | 1900   |
| 1.188               | 1.066          | 0.062          | 1.626         | 1.079         | 0.068      | 0.108       | 3400                    | 1500   |
| 1.375               | 1.213          | 0.062          | 1.875         | 1.230         | 0.068      | 0.144       | 4100                    | 2300   |

<sup>a</sup> Thrust Load Safety Factors: Ring 3; groove, 2.

*Source:* Industrial Retaining Rings, 1000 Series. All dimensions are in inches. Depth of groove  $d = (D - G)/2$ . Standard material: carbon spring steel (SAE 1060–1090). Thickness indicated is for unplated rings; for most plated rings with shaft sizes less than 0.625, the maximum ring thickness will not exceed the minimum groove width (W) minus 0.0002 inch; for larger rings, the thickness may increase by 0.002 inch.

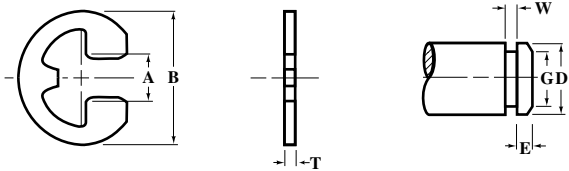
*Groove Maximum Bottom Radii:* For shaft sizes 0.040 and 0.062, 0.003 inch; for sizes 0.094 through 0.250, 0.005 inch; for sizes 0.312 through 0.437, 0.010 inch; for sizes 0.500 through 1.375, 0.015 inch.

*Ring Free Diameter Tolerances:* For shaft sizes 0.040 through 0.250, +0.001, -0.003; for sizes 0.312 through 0.500, +0.002, -0.004; for sizes 0.625 through 1.000, +0.003, -0.005; for sizes 1.188 and 1.375, +0.006, -0.010.

*Ring Thickness Tolerances:* For shaft sizes 0.040 and 0.062<sup>a</sup>, ±0.001; for sizes 0.062<sup>b</sup> through 1.000, ±0.002; for sizes 1.188 and 1.375, ±0.003.

*Groove Diameter Tolerances:* For shaft sizes 0.040 through 0.218, +0.002, -0.000; for sizes 0.250 through 1.000, +0.003, -0.000; for sizes 1.188 and 1.375, +0.005, -0.000.

*Groove Width Tolerances:* For shaft sizes 0.040 through 0.140<sup>c</sup>, +0.002, -0.000; for sizes 0.140<sup>d</sup> through 1.000, +0.003, -0.000; for sizes 1.188 and 1.375, +0.004, -0.000.

**Table 15. Dimensions of Inch Series External Retaining Rings MS3215**


| Shaft Diameter D | Ring        |             |            | Groove     |         |          | *Static Thrust Load (lb) |        |
|------------------|-------------|-------------|------------|------------|---------|----------|--------------------------|--------|
|                  | Free Dia. A | Thickness T | Diameter B | Diameter G | Width W | Margin E | Ring                     | Groove |
|                  |             |             |            |            |         |          |                          |        |
| 0.094            | 0.072       | 0.015       | 0.206      | 0.074      | 0.018   | 0.020    | 55                       | 13     |
| 0.125            | 0.093       | 0.015       | 0.270      | 0.095      | 0.018   | 0.030    | 75                       | 25     |
| 0.156            | 0.113       | 0.025       | 0.335      | 0.116      | 0.029   | 0.040    | 150                      | 40     |
| 0.188            | 0.143       | 0.025       | 0.375      | 0.147      | 0.029   | 0.040    | 180                      | 50     |
| 0.219            | 0.182       | 0.025       | 0.446      | 0.188      | 0.029   | 0.031    | 215                      | 50     |
| 0.250            | 0.204       | 0.025       | 0.516      | 0.210      | 0.029   | 0.040    | 250                      | 75     |
| 0.312            | 0.242       | 0.025       | 0.588      | 0.250      | 0.029   | 0.062    | 300                      | 135    |
| 0.312            | 0.242       | 0.035       | 0.588      | 0.250      | 0.039   | 0.062    | 420                      | 135    |
| 0.375            | 0.292       | 0.035       | 0.660      | 0.303      | 0.039   | 0.072    | 520                      | 190    |
| 0.438            | 0.332       | 0.035       | 0.746      | 0.343      | 0.039   | 0.096    | 600                      | 285    |
| 0.500            | 0.385       | 0.042       | 0.810      | 0.396      | 0.046   | 0.104    | 820                      | 360    |
| 0.562            | 0.430       | 0.042       | 0.870      | 0.437      | 0.046   | 0.124    | 930                      | 480    |

\*Thrust Load Safety Factors: Ring, 3; groove, 2.

Source: Industrial Retaining Rings, 1200 Series. All dimensions are in inches. Depth of groove  $d = (D - G)/2$ . Standard material: carbon spring steel (SAE 1060-1090). Thickness indicated is for unplated rings; for most plated rings the maximum thickness will not exceed the minimum groove width (W) minus 0.0002 inch.

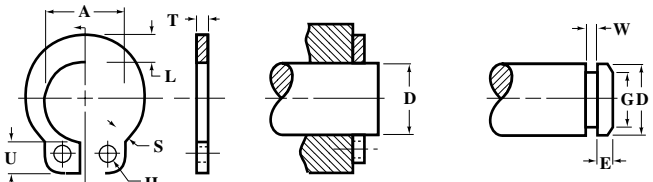
**Groove Maximum Bottom Radii:** For shaft sizes 0.250 and smaller, 0.005 inch; for sizes 0.312 through 0.438, 0.010 inch; for sizes 0.500 and 0.562, 0.015 inch. **Ring Free Diameter Tolerances:** For shaft sizes 0.094 through 0.156, +0.001, -0.003; for sizes 0.188 through 0.312,  $\pm 0.003$ ; for sizes 0.375 through 0.562,  $\pm 0.004$ . **Ring Thickness Tolerances:** For all shaft sizes,  $\pm 0.002$ . **Groove Diameter Tolerances:** For shaft sizes 0.094 through 0.188, +0.002, -0.000; for sizes 0.219 and 0.250,  $\pm 0.002$ ; for sizes 0.312 through 0.562,  $\pm 0.003$ . **Groove Width Tolerances:** For shaft sizes 0.094 and 0.125, +0.002, -0.000; for sizes 0.156 through 0.562, +0.003, -0.000.

The thrust load capacities shown in the tables of this section include safety factors. Usually, a safety factor of 2 is used for groove thrust load calculations when the load is applied through a retained part and groove with both having sharp corners and where the minimum side clearance exists between the retained part and the shaft or bore. Groove thrust load values in the tables of this section are based on these conditions. A safety factor of 3 is usual for calculations of thrust load capacity based on ring shear.

Ideally, the corner of a retained part in contact with a retaining ring should have square corners and contact the ring as closely as possible to the shaft or housing. The tabulated thrust capacities assume that minimum clearances exist between the retained part and shaft or housing, that the groove and retained part have square corners, and that contact between the retained part and the ring occurs close to the shaft or housing. If these conditions apply, the tabulated thrust loads apply. If the application does not meet the previous conditions but the side clearances, radii, and chamfers are less than the maximum total radius or chamfer of Fig. 1, then the thrust load capacity must be reduced by dividing the tabulated value by 2. The maximum total radius is given by  $0.5(b - d)$  and the maximum total chamfer by  $0.375(b - d)$ , where  $b$  is the radial wall thickness, and  $d$  is the groove depth. The recommended maximum total radius or chamfer specifications are intended to be used as guidelines by the designer, and to ensure the ring application will withstand published and calculated values of static thrust loads.

In analyzing the retaining ring loading conditions, a static, uniformly applied load is usually assumed. Dynamic and eccentric loads, however, are frequently encountered. Eccentric loading occurs when the load is concentrated on a small portion of the ring, such as may be caused by incorrectly machined surfaces, cocking of the retained part, and axial misalignment of parts. Conditions leading to eccentric loading on the ring should be avoided. In addition to the factors that affect the static thrust capacity, applications in which shock or impact loading occurs must be evaluated very carefully and tested in service to assess the effect of the mass and velocity of the retained part striking the ring. Vibration caused by impact loading can also cause the ring to fail if the resonant frequency of the system (retaining ring application) coincides with the resonant frequency of the retaining ring.

**Table 16. Dimensions of Inch Series Self-Locking External Retaining Rings**



| Shaft Diameter |        | Ring        |             | Optical Groove  |         |          | <sup>a</sup> Static Thrust Load (lb) |        |
|----------------|--------|-------------|-------------|---|---------|----------|--------------------------------------|--------|
| Min. D         | Max. D | Free Dia. A | Thickness T | Diameter G  | Width W | Margin E | Ring                                 | Groove |
| 0.078          | 0.080  | 0.074       | 0.025       | The use of grooves with these shaft sizes is not suggested. |         |          | 10                                   | 0      |
| 0.092          | 0.096  | 0.089       | 0.025       |   |         |          | 10                                   | 0      |
| 0.123          | 0.127  | 0.120       | 0.025       |   |         |          | 20                                   | 0      |
| 0.134          | 0.138  | 0.130       | 0.025       |   |         |          | 20                                   | 0      |
| 0.154          | 0.158  | 0.150       | 0.025       |   |         |          | 22                                   | 0      |
| 0.185          | 0.189  | 0.181       | 0.035       |   |         |          | 25                                   | 0      |
| 0.248          | 0.252  | 0.238       | 0.035       |   |         |          | 0.240                                | 0.041  |
| 0.310          | 0.316  | 0.298       | 0.042       | 0.303   | 0.048   | 0.030    | 50                                   | 110    |
| 0.373          | 0.379  | 0.354       | 0.042       | 0.361   | 0.048   | 0.030    | 55                                   | 185    |
| 0.434          | 0.440  | 0.412       | 0.050       | 0.419   | 0.056   | 0.030    | 60                                   | 280    |
| 0.497          | 0.503  | 0.470       | 0.050       | 0.478   | 0.056   | 0.040    | 65                                   | 390    |
| 0.622          | 0.628  | 0.593       | 0.062       | 0.599   | 0.069   | 0.045    | 85                                   | 570    |
| 0.745          | 0.755  | 0.706       | 0.062       | 0.718   | 0.069   | 0.050    | 90                                   | 845    |

<sup>a</sup>Thrust Load Safety Factors: Ring, 1; groove, 2.

*Source:* Industrial Retaining Rings, 7100 Series. All dimensions are in inches. Depth of groove  $d = (D - G)/2$ . Standard material: carbon spring steel (SAE 1060-1090). Thickness indicated is for unplated rings; for plated, phosphate coated, and stainless steel rings, the maximum ring thickness may be exceeded by 0.002 inch.

*Ring Free Diameter Tolerances:* For shaft sizes 0.078 through 0.138, +0.002, -0.003; for sizes 0.154 through 0.252, +0.002, -0.004; for sizes 0.310 through 0.440, +0.003, -0.005; for sizes 0.497 through 0.755, +0.004, -0.006. *Ring Thickness Tolerances:* For shaft sizes 0.078 through 0.158,  $\pm 0.002$ ; for sizes 0.185 through 0.503,  $\pm 0.003$ ; for sizes 0.622 through 0.755,  $\pm 0.004$ . *Groove Diameter Tolerances:* For shaft sizes less than 0.248, grooves are not recommended; for other sizes, grooves are optional. For shaft sizes 0.248 through 0.316, +0.005, -0.0015; for sizes 0.373 through 0.628, +0.001, -0.002; for sizes 0.745 and 0.755, +0.002, -0.003. *Groove Width Tolerances:* For shaft sizes 0.248 through 0.379, +0.003, -0.000; for sizes 0.434 through 0.755, +0.004, -0.000.



Table 17. Inch Series Internal and External Self-Locking Retaining Rings

| Internal |        |                 |        |          |                    | External |        |                 |        |          |                    |
|----------|--------|-----------------|--------|----------|--------------------|----------|--------|-----------------|--------|----------|--------------------|
| Housing  |        | Ring Dimensions |        |          | Static Thrust Load | Shaft    |        | Ring Dimensions |        |          | Static Thrust Load |
| Min. D   | Max. D | Thick. T        | Dia. D | Margin E |                    | Min. D   | Max. D | Thick. T        | Dia. D | Margin E |                    |
| 0.311    | 0.313  | 0.010           | 0.136  | 0.040    | 80                 | 0.093    | 0.095  | 0.010           | 0.250  | 0.040    | 15                 |
| 0.374    | 0.376  | 0.010           | 0.175  | 0.040    | 75                 | 0.124    | 0.126  | 0.010           | 0.325  | 0.040    | 20                 |
| 0.437    | 0.439  | 0.010           | 0.237  | 0.040    | 70                 | 0.155    | 0.157  | 0.010           | 0.356  | 0.040    | 25                 |
| 0.498    | 0.502  | 0.010           | 0.258  | 0.040    | 60                 | 0.187    | 0.189  | 0.010           | 0.387  | 0.040    | 35                 |
| 0.560    | 0.564  | 0.010           | 0.312  | 0.040    | 50                 | 0.218    | 0.220  | 0.010           | 0.418  | 0.040    | 35                 |
| 0.623    | 0.627  | 0.010           | 0.390  | 0.040    | 45                 | 0.239    | 0.241  | 0.015           | 0.460  | 0.060    | 35                 |
| 0.748    | 0.752  | 0.015           | 0.500  | 0.060    | 75                 | 0.249    | 0.251  | 0.010           | 0.450  | 0.040    | 40                 |
| 0.873    | 0.877  | 0.015           | 0.625  | 0.060    | 70                 | 0.311    | 0.313  | 0.010           | 0.512  | 0.040    | 40                 |
| 0.936    | 0.940  | 0.015           | 0.687  | 0.060    | 70                 | 0.374    | 0.376  | 0.010           | 0.575  | 0.040    | 40                 |
| 0.998    | 1.002  | 0.015           | 0.750  | 0.060    | 70                 | 0.437    | 0.440  | 0.015           | 0.638  | 0.060    | 50                 |
| 1.248    | 1.252  | 0.015           | 0.938  | 0.060    | 60                 | 0.498    | 0.502  | 0.015           | 0.750  | 0.060    | 50                 |
| 1.436    | 1.440  | 0.015           | 1.117  | 0.060    | 60                 | 0.560    | 0.564  | 0.015           | 0.812  | 0.060    | 50                 |
| 1.498    | 1.502  | 0.015           | 1.188  | 0.060    | 60                 | 0.623    | 0.627  | 0.015           | 0.875  | 0.060    | 50                 |
|          |        |                 |        |          |                    | 0.748    | 0.752  | 0.015           | 1.000  | 0.060    | 50                 |
|          |        |                 |        |          |                    | 0.873    | 0.877  | 0.015           | 1.125  | 0.060    | 55                 |
|          |        |                 |        |          |                    | 0.998    | 1.002  | 0.015           | 1.250  | 0.060    | 60                 |

Source: Industrial Retaining Rings, 6000 Series (internal) and 6100 Series (external). All dimensions are in inches, thrust loads are in pounds. Thickness indicated is for unplated rings. Standard material: carbon spring steel (SAE 1060-1090).

**Internal Rings:** Thrust loads are for rings made of standard material inserted into cold-rolled, low-carbon housing. **Ring Thickness Tolerances:** For housing sizes 0.311 through 0.627,  $\pm 0.001$ ; for sizes 0.748 through 1.502,  $\pm 0.002$ . **Ring Diameter Tolerances:** For housing sizes 0.311 through 0.439,  $\pm 0.005$ ; for sizes 0.498 through 1.502,  $\pm 0.010$ .

**External Rings:** Thrust loads are for rings made of standard material installed onto cold-rolled, low-carbon shafts. **Ring Thickness Tolerances:** For shaft sizes 0.093 through 0.220,  $\pm 0.001$ ; for size 0.239,  $\pm 0.002$ ; for sizes 0.249 through 0.376,  $\pm 0.001$ ; for sizes 0.437 through 1.002,  $\pm 0.002$ . **Ring Diameter Tolerances:** For shaft sizes 0.093 through 0.502,  $\pm 0.005$ ; for sizes 0.560 through 1.002,  $\pm 0.010$ .

**Centrifugal Capacity:** Proper functioning of a retaining ring depends on the ring remaining seated on the groove bottom. External rings "cling" to the groove bottom because the ring ID is slightly smaller than the diameter at the bottom of the groove. Ring speed should be kept below the allowable steady-state speed of the ring, or self-locking rings specially designed for high-speed applications should be used, otherwise an external ring can lose its grip on the groove. Applications of large retaining rings that tend to spin in their grooves when subjected to sudden acceleration or deceleration of the retained part can benefit from a ring with more "cling" (i.e., a smaller interior diameter) as long as the stress of installation is within permissible limits. Special rings are also available that lock into a hole in the bottom of the groove, thereby preventing rotation. The following equation can be used to determine the allowable steady-state speed  $N$  of an external spiral retaining ring:

$$N = \sqrt{\frac{0.466C_1E^3 \times 10^{12}}{R_n^3(1+C_1)(R_o^3-R_i^3)}} \quad (1)$$

where the speed  $N$  is in revolutions per minute,  $C_1$  is the minimum ring cling to groove bottom,  $E$  is the ring radial wall,  $R_n$  is the free neutral ring radius,  $R_o$  is the free outside ring radius, and  $R_i$  is the free inside ring radius, all in inches. For external spiral rings, the minimum ring cling is given by:  $C_1 = (C - G)/G$ , where  $C$  is the mean groove diameter in inches, and  $G$  is the maximum ring free ID in inches.

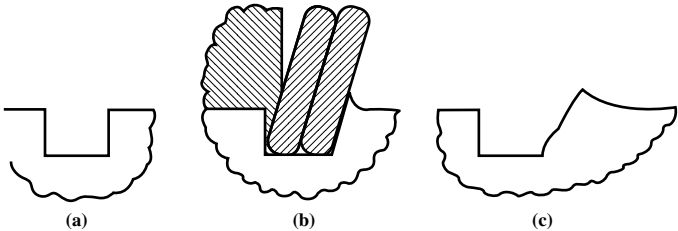


Fig. 2. Localized Groove Yielding under Load. (a) Groove Profile before Loading; (b) Localized Yielding of Retained Part and Groove under Load; (c) Groove Profile after Loading beyond Thrust Capacity (Courtesy Spirolox Retaining Rings)

**Rotation between Parts:** The use of spiral-wound rings to retain a rotating part should be limited to applications with rotation in only one direction. The ring should be matched so that the rotation tends to wind the spring into the groove. External rings should be wound in the direction of rotation of the retained part but internal rings should be wound against the direction of rotation of the rotating part. Failure to observe these precautions will cause the ring to wind out of the groove. Spiral-wound rings can be obtained with either right-hand (normal rotation) or left-hand (reverse rotation) wound configurations. Stamped retaining rings do not have these limitations, and may be used for applications that require rotation of the retained part, regardless of the direction of rotation.

**Retaining Ring Failure.**—Failure of a retaining ring application can result from failure of the ring itself, failure of the groove, or both. If a ring fails, the cause is likely to be from shearing of the ring. Shear failure occurs when a ring is installed in a groove and loaded by a retained part with both the groove and the retained part having a compressive yield strength greater than 45,000 psi; or when the load is applied through a retained part and groove, both having sharp corners and line-to-line contact; or when the ring is too thin in section compared with its diameter. To examine the possibility of ring shear, the allowable thrust  $P_s$ , based on the shear strength of the ring material, is given by

$$P_s = \frac{\pi D t S_s}{K} \quad (2)$$

where  $P_s$  is in lb<sub>f</sub>,  $D$  is the shaft or housing diameter in inches,  $t$  is the ring thickness in inches,  $S_s$  is the shear strength of the ring material in lb/in.<sup>2</sup>, and  $K$  is the factor of safety.

**Groove Failure:** The most common type of groove failure is yielding of the groove material that occurs when the thrust load, applied through the retaining ring against the corner of the groove, exceeds the compressive yield strength of the groove. This yielding of the groove results from a low compressive yield strength of the groove material, and allows the ring to tilt and come out of the groove, as illustrated in Fig. 2(b).

When dishing of a ring occurs as a result of yielding in the groove material, a bending moment across the cross-section of the ring generates a tensile stress that is highest at the

interior diameter of the ring. If the maximum stress is greater than the yield strength of the ring material, the ring ID will grow and the ring will become permanently dished in shape. To determine the thrust load capacity of a ring based on groove deformation, the allowable angle of ring deflection must be calculated, then the thrust load based on groove yield can be determined. However, for spiral-wound rings, the thrust load  $P_G$  that initiates the onset of groove deformation can be estimated from the following:

$$P_G = \frac{\pi D d S_y}{K} \quad (3)$$

where  $P_G$  is given in lb<sub>f</sub>,  $D$  is the shaft or housing diameter in inches,  $d$  is the groove depth in inches,  $S_y$  is the yield strength of the groove material, and  $K$  is the safety factor. For stamped rings, estimate  $P_G$  by multiplying Equation (3) by the fraction of the groove circumference that contacts the ring.

The thrust load capacity of a particular retaining ring application can be increased by changing the workpiece material that houses the groove. Increasing the yield strength of the groove material increases the thrust load capacity of the retaining ring application. However, increasing the strength of the groove material may cause the failure mechanism to shift from groove deformation to ring shear. Therefore, use the lower of the values obtained from Equations (2) and (3) for the allowable thrust load.

*Groove Design and Machining:* In most applications, grooves are located near the end of a shaft or housing bore to facilitate installation and removal of the rings. The groove is normally located a distance at least two to three times the groove depth from the end of the shaft or bore. If the groove is too close to the end of the shaft or bore, the groove may shear or yield. The following equation can be used to determine the minimum safe distance  $Y$  of a groove from the end of a shaft or housing:

$$Y = \frac{K P_t}{\pi D S_c} \quad (4)$$

where  $K$  is the factor of safety,  $P_t$  is the thrust load on the groove in pounds,  $S_c$  is the shear strength of the groove material in psi, and  $D$  is the shaft or housing diameter in inches.

A properly designed and machined groove is just as important in a retaining ring application as the ring itself. The walls of grooves should be perpendicular to the shaft or bore diameter; the grooves should have square corners on the top edges, and radii at the bottom, within the tolerances specified by the manufacturers, as shown in Fig. 1 (page 1684). Test data indicate that the ultimate thrust capacity for both static and dynamic loading conditions is greatly affected if these groove requirements are not met. For spiral-wound rings, the maximum bottom groove radius is 0.005 inch for rings up to 1.000 inch free diameter and 0.010 inch for larger rings, internal or external. For stamped rings, the maximum bottom groove radius varies with ring size and style.

**Table 18. Retaining Ring Standards**

| Military     |   |
|--------------|---|
| MIL-R-21248B | MS-16633 Open-type external uniform cross-section               |
|              | MS-16634 Open-type external uniform cross-section cylindrically |
|              | MS-3215 Open-type external tapered cross-section                |
|              | MS-16632 Crescent-type external                                 |
|              | MS-16625 Internal   |
|              | MS-16629 Internal cylindrically bowed                           |
|              | MS-16624 Closed-type external tapered cross-section             |

**Table 18. Retaining Ring Standards (Continued)**

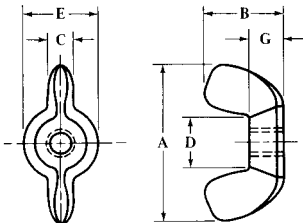
| Military                            |  |
|-------------------------------------|--|
| MIL-R-21248B                        | MS-16628 Closed-type external tapered cross-section cylindrically bowed                                      |
|                                     | MS-16627 Internal inverted   |
|                                     | MS-16626 Closed-type external tapered cross-section  |
|                                     | MS-90707 Self-locking external tapered cross-section   |
|                                     | MS-3217 External heavy-duty tapered cross-section  |
| MIL-R-27426                         | Uniform cross-section spiral retaining rings, Type 1-External, Type 2-Internal                               |
| Acrospace Standard                  |  |
| AS 3215                             | Ring, Retaining—Spiral, Internal, Heavy Duty, Stainless Steel  |
| AS 3216                             | Ring, Retaining—Spiral, External, Heavy Duty, Stainless Steel  |
| AS 3217                             | Ring, Retaining—Spiral, Internal, Light Duty, Stainless Steel  |
| AS 3218                             | Ring, Retaining—Spiral, External, Light Duty, Stainless Steel  |
| AS 3219                             | Ring, Wound, Dimensional and Acceptance Standard for Spiral Wound Retaining Rings                            |
| ANSI                                |  |
| B27.6-1972, R1983                   | General Purpose Uniform Cross-Section Spiral Retaining Rings   |
| B27.7-1977, R1983                   | General Purpose Tapered and Reduced Cross-Section Retaining Rings (Metric)                                   |
| B27.8M-1977, R1983                  | General Purpose Metric Tapered and Reduced Cross-Section Retaining Rings                                     |
|                                     | Type 3DM1—Heavy Duty External Rings  |
|                                     | Type 3EM1—Reinforced "E" Rings   |
|                                     | Type 3FM1—"C" Type Rings   |
| ANSI/SAE                            |  |
| MA4016                              | Ring, Retaining—External Spiral Wound, Heavy and Medium Duty, Crescent, Metric                               |
| MA4017                              | Ring, Retaining—External Spiral Wound, Heavy and Medium Duty, Crescent, Metric                               |
| MA4020                              | Ring, Retaining—External Tapered, Type 1, Class 2, AMS 5520, Metric  |
| MA4021                              | Ring, Retaining—Internal Tapered, Type 1, Class 1, AMS 5520, Metric  |
| MA4029                              | Ring, Retaining—Internal, Beveled, Tapered, Type 2, Class 1, AMS 5520, Metric                                |
| MA4030                              | Ring, Retaining—External, Reinforced E-Ring, Type 1, Class 3, AMS 5520, Metric                               |
| MA4035                              | Rings, Retaining—Spiral Wound, Uniform Section, Corrosion Resistant, Procurement Specification for, Metric   |
| MA4036                              | Ring, Retaining—Tapered Width, Uniform Thickness, Corrosion Resistant, Procurement Specification for, Metric |
| DIN                                 |  |
| DIN 471, 472, 6799, 984, 5417, 7993 | Standards for normal and heavy type, internal and external retaining rings and retaining washers             |
| LN 471, 472, 6799                   | Aerospace standards for internal and external retaining rings  |

WING NUTS, WING SCREWS, AND THUMB SCREWS

**Wing Nuts.**—A wing nut is a nut having wings designed for manual turning without driver or wrench. As covered by ANSI B18.17-1968 (R1983) wing nuts are classified first, by type on the basis of the method of manufacture; and second, by style on the basis of design characteristics. They consist of:

*Type A:* Type A wing nuts are cold forged or cold formed solid nuts having wings of moderate height. In some sizes they are produced in regular, light, and heavy series to best suit the requirements of specific applications. Dimensions are given in Table 1.

**Table 1. American National Standard Type A Wing Nuts**  
ANSI B18.17-1968, R1983



| Nominal Size or Basic Major Diameter of Thread <sup>a</sup> | Thds. per Inch | Series <sup>b</sup> | Nut Blank Size (Ref) | A           |             | B           |             | C           |             | D             |             | E           |             | G           |             |
|---|----------------|---------------------|----------------------|-------------|-------------|-------------|-------------|-------------|-------------|---------------|-------------|-------------|-------------|-------------|-------------|
|   |                |                     |                      | Wing Spread |             | Wing Height |             | Wing Thick. |             | Between Wings |             | Boss Dia.   |             | Boss Height |             |
|   |                |                     |                      | Max         | Min         | Max         | Min         | Max         | Min         | Max           | Min         | Max         | Min         | Max         | Min         |
| 3 (0.0990)  | 48, 56         | Hvy.                | AA                   | 0.72        | 0.59        | 0.41        | 0.28        | 0.11        | 0.07        | 0.21          | 0.17        | 0.33        | 0.29        | 0.14        | 0.10        |
| 4 (0.1120)  | 40, 38         | Hvy.                | AA                   | 0.72        | 0.59        | 0.41        | 0.28        | 0.11        | 0.07        | 0.21          | 0.17        | 0.33        | 0.29        | 0.14        | 0.10        |
| 5 (0.1250)  | 40, 44         | Lgt.                | AA                   | <b>0.72</b> | <b>0.59</b> | <b>0.41</b> | <b>0.28</b> | <b>0.11</b> | <b>0.07</b> | <b>0.21</b>   | <b>0.17</b> | <b>0.33</b> | <b>0.29</b> | <b>0.14</b> | <b>0.10</b> |
|   |                | Hvy.                | A                    | 0.91        | 0.78        | 0.47        | 0.34        | 0.14        | 0.10        | 0.27          | 0.22        | 0.43        | 0.39        | 0.18        | 0.14        |
| 6 (0.1380)  | 32, 40         | Lgt.                | AA                   | 0.72        | 0.59        | 0.41        | 0.28        | 0.11        | 0.07        | 0.21          | 0.17        | 0.33        | 0.29        | 0.14        | 0.10        |
|   |                | Hvy.                | A                    | <b>0.91</b> | <b>0.78</b> | <b>0.47</b> | <b>0.34</b> | <b>0.14</b> | <b>0.10</b> | <b>0.27</b>   | <b>0.22</b> | <b>0.43</b> | <b>0.39</b> | <b>0.18</b> | <b>0.14</b> |
| 8 (0.1640)  | 32, 36         | Lgt.                | A                    | <b>0.91</b> | <b>0.78</b> | <b>0.47</b> | <b>0.34</b> | <b>0.14</b> | <b>0.10</b> | <b>0.27</b>   | <b>0.22</b> | <b>0.43</b> | <b>0.39</b> | <b>0.18</b> | <b>0.14</b> |
|   |                | Hvy.                | B                    | 1.10        | 0.97        | 0.57        | 0.43        | 0.18        | 0.14        | 0.33          | 0.26        | 0.50        | 0.45        | 0.22        | 0.17        |
| 10 (0.1900)   | 24, 32         | Lgt.                | A                    | <b>0.91</b> | <b>0.78</b> | <b>0.47</b> | <b>0.34</b> | <b>0.14</b> | <b>0.10</b> | <b>0.27</b>   | <b>0.22</b> | <b>0.43</b> | <b>0.39</b> | <b>0.18</b> | <b>0.14</b> |
|   |                | Hvy.                | B                    | 1.10        | 0.97        | 0.57        | 0.43        | 0.18        | 0.14        | 0.33          | 0.26        | 0.50        | 0.45        | 0.22        | 0.17        |
| 12 (0.2160)   | 24, 28         | Lgt.                | B                    | <b>1.10</b> | <b>0.97</b> | <b>0.57</b> | <b>0.43</b> | <b>0.18</b> | <b>0.14</b> | <b>0.33</b>   | <b>0.26</b> | <b>0.50</b> | <b>0.45</b> | <b>0.22</b> | <b>0.17</b> |
|   |                | Hvy.                | C                    | 1.25        | 1.12        | 0.66        | 0.53        | 0.21        | 0.17        | 0.39          | 0.32        | 0.58        | 0.51        | 0.25        | 0.20        |
| ¼ (0.2500)  | 20, 28         | Lgt.                | B                    | <b>1.10</b> | <b>0.97</b> | <b>0.57</b> | <b>0.43</b> | <b>0.18</b> | <b>0.14</b> | <b>0.39</b>   | <b>0.26</b> | <b>0.50</b> | <b>0.45</b> | <b>0.22</b> | <b>0.17</b> |
|   |                | Reg.                | C                    | 1.25        | 1.12        | 0.66        | 0.53        | 0.21        | 0.17        | 0.39          | 0.32        | 0.58        | 0.51        | 0.25        | 0.20        |
| ⅜ (0.3125)  | 18, 24         | Lgt.                | C                    | <b>1.25</b> | <b>1.12</b> | <b>0.66</b> | <b>0.53</b> | <b>0.21</b> | <b>0.17</b> | <b>0.39</b>   | <b>0.32</b> | <b>0.58</b> | <b>0.51</b> | <b>0.25</b> | <b>0.20</b> |
|   |                | Reg.                | D                    | 1.44        | 1.31        | 0.79        | 0.65        | 0.24        | 0.20        | 0.48          | 0.42        | 0.70        | 0.64        | 0.30        | 0.26        |
| ½ (0.3750)  | 16, 24         | Lgt.                | D                    | <b>1.44</b> | <b>1.31</b> | <b>0.79</b> | <b>0.65</b> | <b>0.24</b> | <b>0.20</b> | <b>0.48</b>   | <b>0.42</b> | <b>0.70</b> | <b>0.64</b> | <b>0.30</b> | <b>0.26</b> |
|   |                | Reg.                | E                    | 1.94        | 1.81        | 1.00        | 0.87        | 0.33        | 0.26        | 0.65          | 0.54        | 0.93        | 0.86        | 0.39        | 0.35        |
| ¾ (0.4375)  | 14, 20         | Lgt.                | E                    | <b>1.94</b> | <b>1.81</b> | <b>1.00</b> | <b>0.87</b> | <b>0.33</b> | <b>0.26</b> | <b>0.65</b>   | <b>0.54</b> | <b>0.93</b> | <b>0.86</b> | <b>0.39</b> | <b>0.35</b> |
|   |                | Hvy.                | F                    | 2.76        | 2.62        | 1.44        | 1.31        | 0.40        | 0.34        | 0.90          | 0.80        | 1.19        | 1.13        | 0.55        | 0.51        |
| 1 (0.5000)  | 13, 20         | Lgt.                | E                    | <b>1.94</b> | <b>1.81</b> | <b>1.00</b> | <b>0.87</b> | <b>0.33</b> | <b>0.26</b> | <b>0.65</b>   | <b>0.54</b> | <b>0.93</b> | <b>0.86</b> | <b>0.39</b> | <b>0.35</b> |
|   |                | Hvy.                | F                    | 2.76        | 2.62        | 1.44        | 1.31        | 0.40        | 0.34        | 0.90          | 0.80        | 1.19        | 1.13        | 0.55        | 0.51        |
| 1 ¼ (0.5625)  | 12, 18         | Hvy.                | F                    | 2.76        | 2.62        | 1.44        | 1.31        | 0.40        | 0.34        | 0.90          | 0.80        | 1.19        | 1.13        | 0.55        | 0.51        |
|   |                | Hvy.                | F                    | 2.76        | 2.62        | 1.44        | 1.31        | 0.40        | 0.34        | 0.90          | 0.80        | 1.19        | 1.13        | 0.55        | 0.51        |
| 1 ½ (0.7500)  | 10, 16         | Hvy.                | F                    | 2.76        | 2.62        | 1.44        | 1.31        | 0.40        | 0.34        | 0.90          | 0.80        | 1.19        | 1.13        | 0.55        | 0.51        |

<sup>a</sup> Where specifying nominal size in decimals, zeros in the fourth decimal place are omitted.

<sup>b</sup> Lgt. = Light; Hvy. = Heavy; Reg. = Regular. Sizes shown in bold face are preferred.

All dimensions in inches.

Type B: Type B wing nuts are hot forged solid nuts available in two wing styles: Style 1, having wings of moderate height; and Style 2, having high wings. Dimensions are given in Table 2.

**Table 2. American National Standard Type B Wing Nuts**  
ANSI B18.17-1968, R1983

| Nominal Size or Basic Major Diameter of Thread <sup>a</sup> | Thds. per Inch | A           |      | B           |      | C           |      | D             |      | E         |      | G           |      |
|---|----------------|-------------|------|-------------|------|-------------|------|---------------|------|-----------|------|-------------|------|
|   |                | Wing Spread |      | Wing Height |      | Wing Thick. |      | Between Wings |      | Boss Dia. |      | Boss Height |      |
|   |                | Max         | Min  | Max         | Min  | Max         | Min  | Max           | Min  | Max       | Min  | Max         | Min  |
| <b>Type B, Style 1</b>                                      |                |             |      |             |      |             |      |               |      |           |      |             |      |
| 5 (0.1250)  | 40             | 0.78        | 0.72 | 0.36        | 0.30 | 0.13        | 0.10 | 0.28          | 0.22 | 0.31      | 0.28 | 0.22        | 0.16 |
| 10 (0.1900)   | 24             | 0.97        | 0.91 | 0.45        | 0.39 | 0.15        | 0.12 | 0.34          | 0.28 | 0.39      | 0.36 | 0.28        | 0.22 |
| ¼ (0.2500)  | 20             | 1.16        | 1.09 | 0.56        | 0.50 | 0.17        | 0.14 | 0.41          | 0.34 | 0.47      | 0.44 | 0.34        | 0.28 |
| ⅜ (0.3125)  | 18             | 1.44        | 1.38 | 0.67        | 0.61 | 0.18        | 0.15 | 0.50          | 0.44 | 0.55      | 0.52 | 0.41        | 0.34 |
| ⅝ (0.3750)  | 16             | 1.72        | 1.66 | 0.80        | 0.73 | 0.20        | 0.17 | 0.59          | 0.53 | 0.63      | 0.60 | 0.47        | 0.41 |
| ⅞ (0.4375)  | 14             | 2.00        | 1.94 | 0.91        | 0.84 | 0.21        | 0.18 | 0.69          | 0.62 | 0.71      | 0.68 | 0.53        | 0.47 |
| ½ (0.5000)  | 13             | 2.31        | 2.22 | 1.06        | 0.94 | 0.23        | 0.20 | 0.78          | 0.69 | 0.79      | 0.76 | 0.62        | 0.50 |
| ⅞ (0.5625)  | 12             | 2.59        | 2.47 | 1.17        | 1.05 | 0.25        | 0.21 | 0.88          | 0.78 | 0.88      | 0.84 | 0.69        | 0.56 |
| ⅝ (0.6250)  | 11             | 2.84        | 2.72 | 1.31        | 1.19 | 0.27        | 0.23 | 0.94          | 0.84 | 0.96      | 0.92 | 0.75        | 0.62 |
| ¾ (0.7500)  | 10             | 3.31        | 3.19 | 1.52        | 1.39 | 0.29        | 0.25 | 1.10          | 1.00 | 1.12      | 1.08 | 0.88        | 0.75 |
| <b>Type B, Style 2</b>                                      |                |             |      |             |      |             |      |               |      |           |      |             |      |
| 5 (0.1250)  | 40             | 0.81        | 0.75 | 0.62        | 0.56 | 0.12        | 0.09 | 0.28          | 0.22 | 0.31      | 0.28 | 0.22        | 0.16 |
| 10 (0.1900)   | 24             | 1.01        | 0.95 | 0.78        | 0.72 | 0.14        | 0.11 | 0.35          | 0.29 | 0.39      | 0.36 | 0.28        | 0.22 |
| ¼ (0.2500)  | 20             | 1.22        | 1.16 | 0.94        | 0.88 | 0.16        | 0.13 | 0.41          | 0.35 | 0.47      | 0.44 | 0.34        | 0.28 |
| ⅜ (0.3125)  | 18             | 1.43        | 1.37 | 1.09        | 1.03 | 0.17        | 0.14 | 0.48          | 0.42 | 0.55      | 0.52 | 0.41        | 0.34 |
| ⅝ (0.3750)  | 16             | 1.63        | 1.57 | 1.25        | 1.19 | 0.18        | 0.15 | 0.55          | 0.49 | 0.63      | 0.60 | 0.47        | 0.41 |
| ⅞ (0.4375)  | 14             | 1.90        | 1.84 | 1.42        | 1.36 | 0.19        | 0.16 | 0.62          | 0.56 | 0.71      | 0.68 | 0.53        | 0.47 |
| ½ (0.5000)  | 13             | 2.13        | 2.04 | 1.58        | 1.45 | 0.20        | 0.17 | 0.69          | 0.60 | 0.79      | 0.76 | 0.62        | 0.50 |
| ⅞ (0.5625)  | 12             | 2.40        | 2.28 | 1.75        | 1.62 | 0.22        | 0.18 | 0.76          | 0.67 | 0.88      | 0.84 | 0.69        | 0.56 |
| ⅝ (0.6250)  | 11             | 2.60        | 2.48 | 1.91        | 1.78 | 0.23        | 0.19 | 0.83          | 0.74 | 0.96      | 0.92 | 0.75        | 0.62 |
| ¾ (0.7500)  | 10             | 3.02        | 2.90 | 2.22        | 2.09 | 0.24        | 0.20 | 0.97          | 0.88 | 1.12      | 1.08 | 0.88        | 0.75 |

<sup>a</sup> Where specifying nominal size in decimals, zeros in the fourth decimal place are omitted.

All dimensions in inches.

**Table 3. American National Standard Type C Wing Nuts ANSI B18.17-1968, R1983**

| Nominal Size or Basic Major Diameter of Thread <sup>a</sup> | Thds. per Inch | Series           | Nut Blank Size (Ref) | A           |             | B           |             | C           |             | D             |             | E           |             | F           |             | G           |             |
|---|----------------|------------------|----------------------|-------------|-------------|-------------|-------------|-------------|-------------|---------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
|   |                |                  |                      | Wing Spread |             | Wing Height |             | Wing Thick. |             | Between Wings |             | Boss Dia.   |             | Boss Dia.   |             | Boss Height |             |
|   |                |                  |                      | Max         | Min         | Max         | Min         | Max         | Min         | Max           | Min         | Max         | Min         | Max         | Min         | Max         | Min         |
| <b>Type C, Style 1</b>                                      |                |                  |                      |             |             |             |             |             |             |               |             |             |             |             |             |             |             |
| 4 (0.1120)  | 40             | Reg.             | AA                   | 0.66        | 0.64        | 0.36        | 0.35        | 0.11        | 0.09        | 0.18          | 0.16        | 0.27        | 0.25        | 0.32        | 0.30        | 0.16        | 0.14        |
| 5 (0.1250)  | 40             | Reg.             | AA                   | 0.66        | 0.64        | 0.36        | 0.35        | 0.11        | 0.09        | 0.18          | 0.16        | 0.27        | 0.25        | 0.32        | 0.30        | 0.16        | 0.14        |
| 6 (0.1380)  | 32             | <b>Reg.-Hvy.</b> | <b>AA</b>            | <b>0.66</b> | <b>0.64</b> | <b>0.36</b> | <b>0.35</b> | <b>0.11</b> | <b>0.09</b> | <b>0.18</b>   | <b>0.16</b> | <b>0.27</b> | <b>0.25</b> | <b>0.32</b> | <b>0.30</b> | <b>0.16</b> | <b>0.14</b> |
|   |                | Reg.             | A                    | 0.85        | 0.83        | 0.43        | 0.42        | 0.14        | 0.12        | 0.29          | 0.27        | 0.38        | 0.36        | 0.41        | 0.40        | 0.20        | 0.18        |
| 8 (0.1640)  | 32             | Reg.             | A                    | 0.85        | 0.83        | 0.43        | 0.42        | 0.14        | 0.12        | 0.29          | 0.27        | 0.38        | 0.36        | 0.41        | 0.40        | 0.20        | 0.18        |
| 10 (0.1900)   | 24, 32         | Reg.             | A                    | 0.85        | 0.83        | 0.43        | 0.42        | 0.14        | 0.12        | 0.29          | 0.27        | 0.38        | 0.36        | 0.41        | 0.40        | 0.20        | 0.18        |
| 12 (0.2160)   | 24             | <b>Reg.-Hvy.</b> | <b>A</b>             | <b>0.85</b> | <b>0.83</b> | <b>0.43</b> | <b>0.42</b> | <b>0.14</b> | <b>0.12</b> | <b>0.29</b>   | <b>0.27</b> | <b>0.38</b> | <b>0.36</b> | <b>0.41</b> | <b>0.40</b> | <b>0.20</b> | <b>0.18</b> |
|   |                | Reg.             | B                    | 1.08        | 1.05        | 0.57        | 0.53        | 0.16        | 0.14        | 0.32          | 0.30        | 0.44        | 0.42        | 0.48        | 0.46        | 0.23        | 0.21        |
| ¼ (0.2500)  | 20, 28         | Reg.             | B                    | 1.08        | 1.05        | 0.57        | 0.53        | 0.16        | 0.14        | 0.32          | 0.30        | 0.44        | 0.42        | 0.48        | 0.46        | 0.23        | 0.21        |
| ⅜ (0.3125)  | 18, 24         | Reg.             | C                    | 1.23        | 1.20        | 0.64        | 0.62        | 0.20        | 0.18        | 0.39          | 0.35        | 0.50        | 0.49        | 0.57        | 0.55        | 0.26        | 0.24        |
| ½ (0.3750)  | 16, 24         | Reg.             | D                    | 1.45        | 1.42        | 0.74        | 0.72        | 0.23        | 0.21        | 0.46          | 0.42        | 0.62        | 0.60        | 0.69        | 0.67        | 0.29        | 0.27        |
| ⅝ (0.4375)  | 14, 20         | <b>Reg.-Hvy.</b> | <b>E</b>             | <b>1.89</b> | <b>1.86</b> | <b>0.91</b> | <b>0.90</b> | <b>0.29</b> | <b>0.28</b> | <b>0.67</b>   | <b>0.65</b> | <b>0.75</b> | <b>0.73</b> | <b>0.83</b> | <b>0.82</b> | <b>0.38</b> | <b>0.37</b> |
|   |                | Reg.             | EH                   | 1.89        | 1.86        | 0.93        | 0.91        | 0.34        | 0.33        | 0.63          | 0.62        | 0.81        | 0.79        | 0.89        | 0.87        | 0.42        | 0.40        |
| ¾ (0.5000)  | 13, 20         | <b>Reg.-Hvy.</b> | <b>E</b>             | <b>1.89</b> | <b>1.86</b> | <b>0.91</b> | <b>0.90</b> | <b>0.29</b> | <b>0.28</b> | <b>0.67</b>   | <b>0.65</b> | <b>0.75</b> | <b>0.73</b> | <b>0.83</b> | <b>0.82</b> | <b>0.38</b> | <b>0.37</b> |
|   |                | Reg.             | EH                   | 1.89        | 1.86        | 0.93        | 0.91        | 0.34        | 0.33        | 0.63          | 0.62        | 0.81        | 0.79        | 0.89        | 0.87        | 0.42        | 0.40        |
| <b>Type C, Style 2</b>                                      |                |                  |                      |             |             |             |             |             |             |               |             |             |             |             |             |             |             |
| 5 (0.1250)  | 40             | ...              | ...                  | 0.82        | 0.80        | 0.25        | 0.23        | 0.09        | 0.08        | 0.21          | 0.19        | 0.26        | 0.24        | ...         | ...         | 0.17        | 0.15        |
| 6 (0.1380)  | 32             | ...              | ...                  | 0.82        | 0.80        | 0.25        | 0.23        | 0.09        | 0.08        | 0.21          | 0.19        | 0.26        | 0.24        | ...         | ...         | 0.17        | 0.15        |
| 8 (0.1640)  | 32             | ...              | ...                  | 1.01        | 0.99        | 0.28        | 0.27        | 0.11        | 0.09        | 0.29          | 0.28        | 0.36        | 0.34        | ...         | ...         | 0.19        | 0.18        |
| 10 (0.1900)   | 24, 32         | ...              | ...                  | 1.01        | 0.99        | 0.28        | 0.27        | 0.11        | 0.09        | 0.29          | 0.28        | 0.36        | 0.34        | ...         | ...         | 0.19        | 0.18        |
| 12 (0.2160)   | 24             | ...              | ...                  | 1.20        | 1.18        | 0.32        | 0.31        | 0.12        | 0.11        | 0.38          | 0.37        | 0.44        | 0.43        | ...         | ...         | 0.22        | 0.20        |
| ¼ (0.2500)  | 20             | ...              | ...                  | 1.20        | 1.18        | 0.32        | 0.31        | 0.12        | 0.11        | 0.38          | 0.37        | 0.44        | 0.43        | ...         | ...         | 0.22        | 0.20        |
| ⅜ (0.3125)  | 18             | ...              | ...                  | 1.51        | 1.49        | 0.36        | 0.35        | 0.14        | 0.12        | 0.44          | 0.43        | 0.51        | 0.49        | ...         | ...         | 0.24        | 0.23        |
| ½ (0.3750)  | 16             | ...              | ...                  | 1.89        | 1.86        | 0.58        | 0.55        | 0.20        | 0.17        | 0.44          | 0.43        | 0.63        | 0.62        | ...         | ...         | 0.37        | 0.35        |
| <b>Type C, Style 3</b>                                      |                |                  |                      |             |             |             |             |             |             |               |             |             |             |             |             |             |             |
| 5 (0.1250)  | 40             | ...              | ...                  | 0.92        | 0.89        | 0.70        | 0.67        | 0.16        | 0.15        | 0.26          | 0.24        | 0.38        | 0.36        | ...         | ...         | 0.25        | 0.24        |
| 6 (0.1380)  | 32             | ...              | ...                  | 0.92        | 0.89        | 0.70        | 0.67        | 0.16        | 0.15        | 0.26          | 0.24        | 0.38        | 0.36        | ...         | ...         | 0.25        | 0.24        |
| 8 (0.1640)  | 32             | ...              | ...                  | 0.92        | 0.89        | 0.70        | 0.67        | 0.16        | 0.15        | 0.26          | 0.24        | 0.38        | 0.36        | ...         | ...         | 0.25        | 0.24        |
| 10 (0.1900)   | 24, 32         | ...              | ...                  | 1.14        | 1.12        | 0.85        | 0.83        | 0.19        | 0.17        | 0.32          | 0.30        | 0.44        | 0.42        | ...         | ...         | 0.29        | 0.27        |
| 12 (0.2160)   | 24             | ...              | ...                  | 1.14        | 1.12        | 0.85        | 0.83        | 0.19        | 0.17        | 0.32          | 0.30        | 0.44        | 0.42        | ...         | ...         | 0.29        | 0.27        |
| ¼ (0.2500)  | 20             | ...              | ...                  | 1.14        | 1.12        | 0.85        | 0.83        | 0.19        | 0.17        | 0.32          | 0.30        | 0.44        | 0.42        | ...         | ...         | 0.29        | 0.27        |
| ⅜ (0.3125)  | 18             | ...              | ...                  | 1.29        | 1.27        | 1.04        | 1.02        | 0.23        | 0.22        | 0.39          | 0.36        | 0.50        | 0.49        | ...         | ...         | 0.35        | 0.34        |
| ½ (0.3750)  | 16             | ...              | ...                  | 1.51        | 1.49        | 1.20        | 1.18        | 0.27        | 0.25        | 0.45          | 0.42        | 0.62        | 0.60        | ...         | ...         | 0.43        | 0.42        |

<sup>a</sup> Where specifying nominal size in decimals, zeros in the fourth decimal place are omitted.

All dimensions in inches. Sizes shown in **bold face** are preferred.

**Type C:** Type C wing nuts are die cast solid nuts and are available in three wing styles: Style 1, having wings of moderate height; Style 2, having low wings; and Style 3, having high wings. In some sizes, the Style 1 nuts are produced in regular, light, and heavy series to best suit the requirements of specific applications. Dimensions are given in [Table 3](#).

**Table 4. American National Standard Type D Wing Nuts ANSI B18.17-1968, R1983**

| Nominal Size or Basic Major Diameter of Thread <sup>a</sup> | Thds. per Inch | Series <sup>b</sup> | A           |      | B           |      | C           |      | D             | E         |      | G         | H         | T            |      |
|---|----------------|---------------------|-------------|------|-------------|------|-------------|------|---------------|-----------|------|-----------|-----------|--------------|------|
|   |                |                     | Wing Spread |      | Wing Height |      | Wing Thick. |      | Between Wings | Boss Dia. |      | Boss Hgt. | Wall Hgt. | Stock Thick. |      |
|   |                |                     | Max         | Min  | Max         | Min  | Max         | Min  | Min           | Max       | Min  | Min       | Min       | Max          | Min  |
| <b>Type D, Style 1</b>                                      |                |                     |             |      |             |      |             |      |               |           |      |           |           |              |      |
| 8 (0.1640)  | 32, 36         | ...                 | 0.78        | 0.72 | 0.40        | 0.34 | 0.18        | 0.14 | 0.25          | 0.41      | 0.35 | 0.08      | 0.12      | 0.04         | 0.03 |
| 10 (0.1900)   | 24, 32         | ...                 | 0.91        | 0.85 | 0.47        | 0.41 | 0.21        | 0.17 | 0.34          | 0.53      | 0.47 | 0.10      | 0.12      | 0.04         | 0.03 |
| 12 (0.2160)   | 24, 28         | ...                 | 1.09        | 1.03 | 0.47        | 0.41 | 0.21        | 0.17 | 0.34          | 0.53      | 0.47 | 0.10      | 0.12      | 0.05         | 0.04 |
| 1/4 (0.2500)  | 20, 28         | ...                 | 1.11        | 1.05 | 0.50        | 0.44 | 0.25        | 0.21 | 0.34          | 0.62      | 0.56 | 0.11      | 0.12      | 0.05         | 0.04 |
| 5/16 (0.3125)   | 18, 24         | ...                 | 1.30        | 1.24 | 0.59        | 0.53 | 0.30        | 0.26 | 0.46          | 0.73      | 0.67 | 0.14      | 0.18      | 0.06         | 0.05 |
| 3/8 (0.3750)  | 16, 24         | ...                 | 1.41        | 1.34 | 0.67        | 0.61 | 0.34        | 0.30 | 0.69          | 0.83      | 0.77 | 0.16      | 0.18      | 0.06         | 0.05 |
| <b>Type D, Style 2</b>                                      |                |                     |             |      |             |      |             |      |               |           |      |           |           |              |      |
| 5 (0.1250)  | 40             | Reg.                | 1.03        | 0.97 | 0.25        | 0.19 | 0.19        | 0.13 | 0.30          | 0.40      | 0.34 | 0.07      | 0.09      | 0.04         | 0.03 |
| 6 (0.1380)  | 32             | Reg.                | 1.03        | 0.97 | 0.25        | 0.19 | 0.19        | 0.13 | 0.30          | 0.40      | 0.34 | 0.08      | 0.09      | 0.04         | 0.03 |
| 8 (0.1640)  | 32             | Reg.                | 1.03        | 0.97 | 0.25        | 0.19 | 0.19        | 0.13 | 0.30          | 0.40      | 0.34 | 0.08      | 0.09      | 0.04         | 0.03 |
| 10 (0.1900)   | 24, 32         | Reg.<br>Hvy.        | 1.40        | 1.34 | 0.34        | 0.28 | 0.25        | 0.18 | 0.32          | 0.53      | 0.47 | 0.09      | 0.16      | 0.05         | 0.04 |
| 12 (0.2160)   | 24             | Reg.                | 1.21        | 1.16 | 0.28        | 0.26 | 0.31        | 0.25 | 0.60          | 0.61      | 0.55 | 0.09      | 0.13      | 0.05         | 0.04 |
| 1/4 (0.2500)  | 20             | Reg.                | 1.21        | 1.16 | 0.28        | 0.26 | 0.31        | 0.25 | 0.60          | 0.61      | 0.55 | 0.11      | 0.13      | 0.05         | 0.04 |
| <b>Type D, Style 3</b>                                      |                |                     |             |      |             |      |             |      |               |           |      |           |           |              |      |
| 10 (0.1900)   | 24, 32         | Lgt.<br>Reg.        | 1.31        | 1.25 | 0.48        | 0.42 | 0.29        | 0.23 | 0.47          | 0.65      | 0.59 | 0.08      | 0.12      | 0.04         | 0.03 |
| 12 (0.2160)   | 24             | Reg.                | 1.40        | 1.34 | 0.53        | 0.47 | 0.25        | 0.19 | 0.50          | 0.75      | 0.69 | 0.08      | 0.14      | 0.04         | 0.03 |
| 1/4 (0.2500)  | 20             | Lgt.                | 1.28        | 1.22 | 0.40        | 0.34 | 0.23        | 0.17 | 0.59          | 0.73      | 0.67 | 0.11      | 0.12      | 0.04         | 0.03 |
|   |                | Reg.                | 1.28        | 1.22 | 0.40        | 0.34 | 0.23        | 0.17 | 0.59          | 0.73      | 0.67 | 0.11      | 0.12      | 0.04         | 0.03 |
|   |                | Hvy.                | 1.78        | 1.72 | 0.66        | 0.60 | 0.31        | 0.25 | 0.70          | 1.03      | 0.97 | 0.14      | 0.17      | 0.06         | 0.04 |
| 5/16 (0.3125)   | 18             | Reg.                | 1.47        | 1.40 | 0.50        | 0.44 | 0.37        | 0.31 | 0.66          | 1.03      | 0.97 | 0.14      | 0.14      | 0.08         | 0.06 |
|   |                | Hvy.                | 1.78        | 1.72 | 0.66        | 0.60 | 0.31        | 0.25 | 0.70          | 1.03      | 0.97 | 0.14      | 0.17      | 0.06         | 0.04 |

<sup>a</sup> Where specifying nominal size in decimals, zeros in the fourth decimal place are omitted.

<sup>b</sup> Lgt. = Light; Hvy. = Heavy; Reg. = Regular.

All dimensions in inches.

**Type D:** Type D wing nuts are stamped sheet metal nuts and are available in three styles: Style 1, having wings of moderate height; Style 2, having low wings; and Style 3, having wings of moderate height and a larger bearing surface. In some sizes, Styles 2 and 3 are produced in regular, light, and heavy series to best suit the requirements of specific applications. Dimensions are given in Table 4.

**Specification of Wing Nuts.**—When specifying wing nuts, the following data should be included in the designation and should appear in the following sequence: nominal size (number, fraction or decimal equivalent), threads per inch, type, style and/or series, material, and finish.

*Examples:* 10—32 Type A Wing Nut, Regular Series, Steel, Zinc Plated.

0.250—20 Type C Wing Nut, Style 1, Zinc Alloy, Plain.

**Threads for Wing Nuts.**—Threads are in conformance with the ANSI Standard Unified Thread, Class 2B for all types of wing nuts except type D which have a modified Class 2B thread. Because of the method of manufacture, the minor diameter of the thread in type D



## 1716 WING NUTS, WING SCREWS AND THUMB SCREWS

nuts may be somewhat larger than the Unified Thread Class 2B maximum but shall in no case exceed the minimum pitch diameter.

**Materials and Finish for Wing Nuts.**—Types A, B, and D wing nuts are normally supplied as specified by the user in carbon steel, brass or corrosion resistant steel of good quality and adaptable to the manufacturing process. Type C wing nuts are made from die cast zinc alloy. Unless otherwise specified, wing nuts are supplied with a plain (unplated or uncoated) finish.

**Wing Screws.**—A wing screw is a screw having a wing-shaped head designed for manual turning without a driver or wrench. As covered by ANSI B18.17-1968 (R1983) wing screws are classified first, by type on the basis of the method of manufacture, and second, by style on the basis of design characteristics. They consist of the following:

*Type A:* Type A wing screws are of two-piece construction having cold formed or cold forged wing portions of moderate height. In some sizes they are produced in regular, light, and heavy series to best suit the requirements of specific applications. Dimensions are given in [Table 5](#).

*Type B:* Type B wing screws are of hot forged one-piece construction available in two wing styles: Style 1, having wings of moderate height; and Style 2, having high wings. Dimensions are given in [Table 5](#).

*Type C:* Type C wing screws are available in two styles: Style 1, of a one-piece die cast construction having wings of moderate height; and Style 2, of a two-piece construction having a die cast wing portion of moderate height. Dimensions are given in [Table 6](#).

*Type D:* Type D wing screws are of two-piece welded construction having stamped sheet metal wing portions of moderate height. Dimensions are given in [Table 6](#).

*Materials for Wing Screws and Thumb Screws:* Type A wing screws are normally supplied in carbon steel with the shank portion case hardened. When so specified, they also may be made from corrosion resistant steel, brass or other materials as agreed upon by the manufacturer and user.

Type B wing screws are normally made from carbon steel but also may be made from corrosion resistant steel, brass or other materials.

Type C, Style 1, wing screws are supplied only in die cast zinc alloy. Type C, Style 2, wing screws have the wing portion made from die cast zinc alloy with the shank portion normally made from carbon steel. Where so specified, the shank portion may be made from corrosion resistant steel, brass or other materials as agreed upon by the manufacturer and user.

Type D wing screws are normally supplied in carbon steel but also may be made from corrosion resistant steel, brass or other materials.

Thumb screws of all types are normally made from a good commercial quality of carbon steel having a maximum ultimate tensile strength of 48,000 psi. Where so specified, carbon steel thumb screws are case hardened. They are also made from corrosion resistant steel, brass, and other materials as agreed upon by the manufacturer and user.

Unless otherwise specified, wing screws and thumb screws are supplied with a plain (unplated or uncoated) finish.

**Thumb Screws.**—A thumb screw is a screw having a flattened head designed for manual turning without a driver or wrench. As covered by ANSI B18.17-1968 (R1983) thumb screws are classified by type on the basis of design characteristics. They consist of the following:

*Type A:* Type A thumb screws are forged one-piece screws having a shoulder under the head and are available in two series: regular and heavy. Dimensions are given in [Table 7](#).

*Type B:* Type B thumb screws are forged one-piece screws without a shoulder and are available in two series: regular and heavy. Dimensions are given in [Table 7](#).

**Table 5. American National Standard Types A and B Wing Screws**  
ANSI B18.17-1968, R1983

| Nominal Size or Basic Major Diameter <sup>a</sup> | Thds. per Inch | Series <sup>b</sup> | Head Blank size (Ref) | TYPE A      |             |             |             |              |                         |             |             |             |             |        |      |
|---|----------------|---------------------|-----------------------|-------------|-------------|-------------|-------------|--------------|-------------------------|-------------|-------------|-------------|-------------|--------|------|
|   |                |                     |                       | A           |             | B           |             | C            |                         | E           |             | G           |             | L      |      |
|   |                |                     |                       | Wing Spread | Wing Height | Wing Thick. | Boss Dia.   | Boss Height. | Practical Screw Lengths |             |             |             |             |        |      |
| Max   | Min            | Max                 | Min                   | Max         | Min         | Max         | Min         | Max          | Min                     | Max         | Min         | Max         | Min         |        |      |
| <b>Type A</b>                                     |                |                     |                       |             |             |             |             |              |                         |             |             |             |             |        |      |
| 4 (0.1120)  | 40             | Hvy.                | AA                    | 0.72        | 0.59        | 0.41        | 0.28        | 0.11         | 0.07                    | 0.33        | 0.29        | 0.14        | 0.10        | 0.75   | 0.25 |
| 6 (0.1380)  | 32             | Lgt.                | AA                    | 0.72        | 0.59        | 0.41        | 0.28        | 0.11         | 0.07                    | 0.33        | 0.29        | 0.14        | 0.10        | } 0.75 | 0.25 |
|   |                | Hvy.                | A                     | <b>0.91</b> | <b>0.78</b> | <b>0.47</b> | <b>0.34</b> | <b>0.14</b>  | <b>0.10</b>             | <b>0.43</b> | <b>0.39</b> | <b>0.18</b> | <b>0.14</b> |        |      |
| 8 (0.1640)  | 32             | Lgt.                | A                     | <b>0.91</b> | <b>0.78</b> | <b>0.47</b> | <b>0.34</b> | <b>0.14</b>  | <b>0.10</b>             | <b>0.43</b> | <b>0.39</b> | <b>0.18</b> | <b>0.14</b> | } 0.75 | 0.38 |
|   |                | Hvy.                | B                     | 1.10        | 0.97        | 0.57        | 0.43        | 0.18         | 0.14                    | 0.50        | 0.45        | 0.22        | 0.17        |        |      |
| 10 (0.1900)                                       | 24, 32         | Lgt.                | A                     | <b>0.91</b> | <b>0.78</b> | <b>0.47</b> | <b>0.34</b> | <b>0.14</b>  | <b>0.10</b>             | <b>0.43</b> | <b>0.39</b> | <b>0.18</b> | <b>0.14</b> | } 1.00 | 0.38 |
|   |                | Hvy.                | B                     | 1.10        | 0.97        | 0.57        | 0.43        | 0.18         | 0.14                    | 0.50        | 0.45        | 0.22        | 0.17        |        |      |
| 12 (0.2160)                                       | 24             | Lgt.                | B                     | <b>1.10</b> | <b>0.97</b> | <b>0.57</b> | <b>0.43</b> | <b>0.18</b>  | <b>0.14</b>             | <b>0.50</b> | <b>0.45</b> | <b>0.22</b> | <b>0.17</b> | } 1.00 | 0.38 |
|   |                | Hvy.                | C                     | 1.25        | 1.12        | 0.66        | 0.53        | 0.21         | 0.17                    | 0.58        | 0.51        | 0.25        | 0.20        |        |      |
| 1/4 (0.2500)                                      | 20             | Lgt.                | B                     | <b>1.10</b> | <b>0.97</b> | <b>0.57</b> | <b>0.43</b> | <b>0.18</b>  | <b>0.14</b>             | <b>0.50</b> | <b>0.45</b> | <b>0.22</b> | <b>0.17</b> | } 1.50 | 0.50 |
|   |                | Reg.                | C                     | 1.25        | 1.12        | 0.66        | 0.53        | 0.21         | 0.17                    | 0.58        | 0.51        | 0.25        | 0.20        |        |      |
| 1/8 (0.3125)                                      | 18             | Lgt.                | C                     | <b>1.25</b> | <b>1.12</b> | <b>0.66</b> | <b>0.53</b> | <b>0.21</b>  | <b>0.17</b>             | <b>0.58</b> | <b>0.51</b> | <b>0.25</b> | <b>0.20</b> | } 1.50 | 0.50 |
|   |                | Reg.                | D                     | 1.44        | 1.31        | 0.79        | 0.65        | 0.24         | 0.20                    | 0.70        | 0.64        | 0.30        | 0.26        |        |      |
| 3/16 (0.3750)                                     | 16             | Lgt.                | D                     | <b>1.44</b> | <b>1.31</b> | <b>0.79</b> | <b>0.65</b> | <b>0.24</b>  | <b>0.20</b>             | <b>0.70</b> | <b>0.64</b> | <b>0.30</b> | <b>0.26</b> | } 2.00 | 0.75 |
|   |                | Reg.                | E                     | 1.94        | 1.81        | 1.00        | 0.87        | 0.33         | 0.26                    | 0.93        | 0.86        | 0.39        | 0.35        |        |      |
| 7/16 (0.4375)                                     | 14             | Lgt.                | E                     | <b>1.94</b> | <b>1.81</b> | <b>1.00</b> | <b>0.87</b> | <b>0.33</b>  | <b>0.26</b>             | <b>0.93</b> | <b>0.86</b> | <b>0.39</b> | <b>0.35</b> | } 4.00 | 1.00 |
|   |                | Hvy.                | F                     | 2.76        | 2.62        | 1.44        | 1.31        | 0.40         | 0.34                    | 1.19        | 1.13        | 0.55        | 0.51        |        |      |
| 1/2 (0.5000)                                      | 13             | Lgt.                | E                     | <b>1.94</b> | <b>1.81</b> | <b>1.00</b> | <b>0.87</b> | <b>0.33</b>  | <b>0.26</b>             | <b>0.93</b> | <b>0.86</b> | <b>0.39</b> | <b>0.35</b> | } 4.00 | 1.00 |
|   |                | Hvy.                | F                     | 2.76        | 2.62        | 1.44        | 1.31        | 0.40         | 0.34                    | 1.19        | 1.13        | 0.55        | 0.51        |        |      |
| 5/8 (0.6250)                                      | 11             | Hvy.                | F                     | 2.76        | 2.62        | 1.44        | 1.31        | 0.40         | 0.34                    | 1.19        | 1.13        | 0.55        | 0.51        | 4.00   | 1.25 |
| <b>Type B, Style 1</b>                            |                |                     |                       |             |             |             |             |              |                         |             |             |             |             |        |      |
| 10 (0.1900)                                       | 24             | ...                 | ...                   | 0.97        | 0.91        | 0.45        | 0.39        | 0.15         | 0.12                    | 0.39        | 0.36        | 0.28        | 0.22        | 2.00   | 0.50 |
| 1/4 (0.2500)                                      | 20             | ...                 | ...                   | 1.16        | 1.09        | 0.56        | 0.50        | 0.17         | 0.14                    | 0.47        | 0.44        | 0.34        | 0.28        | 3.00   | 0.50 |
| 5/16 (0.3125)                                     | 18             | ...                 | ...                   | 1.44        | 1.38        | 0.67        | 0.61        | 0.18         | 0.15                    | 0.55        | 0.52        | 0.41        | 0.34        | 3.00   | 0.50 |
| 3/8 (0.3750)                                      | 16             | ...                 | ...                   | 1.72        | 1.66        | 0.80        | 0.73        | 0.20         | 0.17                    | 0.63        | 0.60        | 0.47        | 0.41        | 4.00   | 0.50 |
| 7/16 (0.4375)                                     | 14             | ...                 | ...                   | 2.00        | 1.94        | 0.91        | 0.84        | 0.21         | 0.18                    | 0.71        | 0.68        | 0.53        | 0.47        | 3.00   | 1.00 |
| 1/2 (0.5000)                                      | 13             | ...                 | ...                   | 2.31        | 2.22        | 1.06        | 0.94        | 0.23         | 0.20                    | 0.79        | 0.76        | 0.62        | 0.50        | 3.00   | 1.00 |
| 5/8 (0.6250)                                      | 11             | ...                 | ...                   | 2.84        | 2.72        | 1.31        | 1.19        | 0.27         | 0.23                    | 0.96        | 0.92        | 0.75        | 0.62        | 2.50   | 1.00 |
| <b>Type B, Style 2</b>                            |                |                     |                       |             |             |             |             |              |                         |             |             |             |             |        |      |
| 10 (0.1900)                                       | 24             | ...                 | ...                   | 1.01        | 0.95        | 0.78        | 0.72        | 0.14         | 0.11                    | 0.39        | 0.36        | 0.28        | 0.22        | 1.25   | 0.50 |
| 1/4 (0.2500)                                      | 20             | ...                 | ...                   | 1.22        | 1.16        | 0.94        | 0.88        | 0.16         | 0.13                    | 0.47        | 0.44        | 0.34        | 0.28        | 2.00   | 0.50 |
| 5/16 (0.3125)                                     | 18             | ...                 | ...                   | 1.43        | 1.37        | 1.09        | 1.03        | 0.17         | 0.14                    | 0.55        | 0.52        | 0.41        | 0.34        | 2.00   | 0.50 |
| 3/8 (0.3750)                                      | 16             | ...                 | ...                   | 1.63        | 1.57        | 1.25        | 1.19        | 0.18         | 0.15                    | 0.63        | 0.60        | 0.47        | 0.41        | 2.00   | 0.50 |

All dimensions in inches. Sizes shown in bold face are preferred.

<sup>1</sup>Plain point, unless alternate point from styles shown in Table 8 is specified by user.

<sup>a</sup> Where specifying nominal size in decimals, zeros in the fourth decimal place are omitted.

<sup>b</sup> Hvy. = Heavy; Lgt. = Light; Reg. = Regular.

**Table 6. American National Standard Types C and D Wing Screws**  
ANSI B18.17-1968, R1983

| Nominal Size or Basic Screw Diameter <sup>a</sup> | Thds. per Inch | A           |      | B           |      | C           |      | E         |      | F         |      | G      |      | L                       |      |
|---|----------------|-------------|------|-------------|------|-------------|------|-----------|------|-----------|------|--------|------|-------------------------|------|
|   |                | Wing Spread |      | Wing Height |      | Wing Thick. |      | Boss Dia. |      | Boss Dia. |      | Height |      | Practical Screw Lengths |      |
|   |                | Max         | Min  | Max         | Min  | Max         | Min  | Max       | Min  | Max       | Min  | Max    | Min  | Max                     | Min  |
| <b>Type C, Style 1</b>                            |                |             |      |             |      |             |      |           |      |           |      |        |      |                         |      |
| 6 (0.1380)  | 32             | 0.85        | 0.83 | 0.45        | 0.43 | 0.15        | 0.12 | ...       | ...  | 0.41      | 0.39 | 0.12   | 0.07 | 0.75                    | 0.25 |
| 8 (0.1640)  | 32             | 0.85        | 0.83 | 0.45        | 0.43 | 0.15        | 0.12 | ...       | ...  | 0.41      | 0.39 | 0.12   | 0.07 | 1.00                    | 0.38 |
| 10 (0.1900)                                       | 24, 32         | 0.85        | 0.83 | 0.45        | 0.43 | 0.15        | 0.12 | ...       | ...  | 0.41      | 0.39 | 0.12   | 0.07 | 1.25                    | 0.38 |
| ¼ (0.2500)  | 20             | 1.08        | 1.05 | 0.56        | 0.53 | 0.17        | 0.14 | ...       | ...  | 0.46      | 0.44 | 0.12   | 0.07 | 1.50                    | 0.50 |
| ⅕ (0.3125)  | 18             | 1.23        | 1.20 | 0.64        | 0.62 | 0.22        | 0.19 | ...       | ...  | 0.51      | 0.49 | 0.14   | 0.10 | 1.50                    | 0.50 |
| ⅜ (0.3750)  | 16             | 1.45        | 1.42 | 0.74        | 0.72 | 0.24        | 0.21 | ...       | ...  | 0.63      | 0.62 | 0.15   | 0.12 | 1.50                    | 0.50 |
| <b>Type C, Style 2</b>                            |                |             |      |             |      |             |      |           |      |           |      |        |      |                         |      |
| 6 (0.1380)  | 32             | 0.85        | 0.83 | 0.43        | 0.42 | 0.14        | 0.12 | 0.38      | 0.36 | 0.41      | 0.40 | 0.20   | 0.18 | 1.00                    | 0.25 |
| 8 (0.1640)  | 32             | 0.85        | 0.83 | 0.43        | 0.42 | 0.14        | 0.12 | 0.38      | 0.36 | 0.41      | 0.40 | 0.20   | 0.18 | 1.00                    | 0.38 |
| 10 (0.1900)                                       | 24, 32         | 0.85        | 0.83 | 0.43        | 0.42 | 0.14        | 0.12 | 0.38      | 0.36 | 0.41      | 0.40 | 0.20   | 0.18 | 2.00                    | 0.38 |
| ¼ (0.2500)  | 20             | 1.08        | 1.05 | 0.57        | 0.53 | 0.16        | 0.14 | 0.44      | 0.42 | 0.48      | 0.46 | 0.23   | 0.21 | 2.50                    | 0.50 |
| ⅕ (0.3125)  | 18             | 1.23        | 1.20 | 0.64        | 0.62 | 0.20        | 0.18 | 0.50      | 0.49 | 0.57      | 0.55 | 0.26   | 0.24 | 3.00                    | 0.50 |
| ⅜ (0.3750)  | 16             | 1.45        | 1.42 | 0.74        | 0.72 | 0.23        | 0.21 | 0.62      | 0.60 | 0.69      | 0.67 | 0.29   | 0.27 | 3.00                    | 0.75 |
| 7/16 (0.4375)                                     | 14             | 1.89        | 1.86 | 0.91        | 0.90 | 0.29        | 0.28 | 0.75      | 0.73 | 0.83      | 0.82 | 0.38   | 0.37 | 4.00                    | 1.00 |
| ½ (0.5000)  | 13             | 1.89        | 1.86 | 0.91        | 0.90 | 0.29        | 0.28 | 0.75      | 0.73 | 0.83      | 0.82 | 0.38   | 0.37 | 4.00                    | 1.00 |
| <b>Type D</b>                                     |                |             |      |             |      |             |      |           |      |           |      |        |      |                         |      |
| 6 (0.1380)  | 32             | 0.78        | 0.72 | 0.40        | 0.34 | 0.18        | 0.12 | 0.35      | 0.31 | 0.40      | 0.34 | 0.21   | 0.14 | 0.75                    | 0.25 |
| 8 (0.1640)  | 32             | 0.78        | 0.72 | 0.40        | 0.34 | 0.18        | 0.12 | 0.35      | 0.31 | 0.40      | 0.34 | 0.21   | 0.14 | 0.75                    | 0.38 |
| 10 (0.1900)                                       | 24             | 0.90        | 0.84 | 0.46        | 0.40 | 0.21        | 0.15 | 0.35      | 0.31 | 0.53      | 0.47 | 0.22   | 0.16 | 1.00                    | 0.38 |
| 12 (0.2160)                                       | 24             | 1.09        | 1.03 | 0.46        | 0.40 | 0.26        | 0.20 | 0.44      | 0.39 | 0.61      | 0.55 | 0.24   | 0.18 | 1.00                    | 0.38 |
| ¼ (0.2500)  | 20             | 1.09        | 1.03 | 0.46        | 0.40 | 0.26        | 0.20 | 0.47      | 0.43 | 0.61      | 0.55 | 0.24   | 0.18 | 1.50                    | 0.50 |
| ⅕ (0.3125)  | 18             | 1.31        | 1.25 | 0.62        | 0.56 | 0.29        | 0.23 | 0.57      | 0.53 | 0.68      | 0.62 | 0.29   | 0.23 | 1.50                    | 0.50 |
| ⅜ (0.3750)  | 16             | 1.31        | 1.25 | 0.62        | 0.56 | 0.29        | 0.23 | 0.63      | 0.59 | 0.68      | 0.62 | 0.29   | 0.23 | 2.00                    | 0.75 |

All dimensions in inches.

<sup>a</sup> Plain point, unless alternate point from styles shown in Table 8 is specified by user.

<sup>a</sup> Where specifying nominal size in decimals, zeros in the fourth decimal place are omitted.

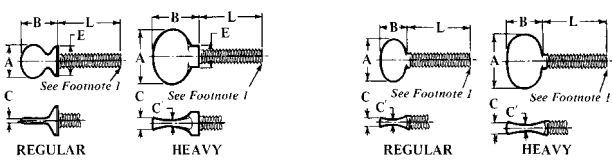
**Wing Screw and Thumb Screw Designation.**—When specifying wing and thumb screws, the following data should be included in the designation and should appear in the following sequence: nominal size (number, fraction or decimal equivalent), threads per inch, length (fractions or decimal equivalents), type, style and/or series, point (if other than plain point), materials, and finish.

Examples: 10—32 × 1¼, Thumb Screw, Type A, Regular, Steel, Zinc Plated.

0.375—16 × 2.00, Wing Screw, Type B, Style 2, Steel, Cadmium Plated.

0.250—20 × 1.50, Wing Screw, Type C, Style 2, Zinc Alloy Wings, Steel Shank, Brass Plated.

**Table 7. American National Standard Types A and B Thumb Screws**  
ANSI B18.17-1968, R1983



| Nominal Size or Basic Screw Diameter <sup>a</sup> | Thds. per Inch | A          |      | B           |      | C           |      | C'          |      | E                 |      | L                       |      |
|---|----------------|------------|------|-------------|------|-------------|------|-------------|------|-------------------|------|-------------------------|------|
|   |                | Head Width |      | Head Height |      | Head Thick. |      | Head Thick. |      | Shoulder Diameter |      | Practical Screw Lengths |      |
|   |                | Max        | Min  | Max         | Min  | Max         | Min  | Max         | Min  | Max               | Min  | Max                     | Min  |
| <b>Type A, Regular</b>                            |                |            |      |             |      |             |      |             |      |                   |      |                         |      |
| 6 (0.1380)  | 32             | 0.31       | 0.29 | 0.33        | 0.31 | 0.05        | 0.04 | ...         | ...  | 0.25              | 0.23 | 0.75                    | 0.25 |
| 8 (0.1640)  | 32             | 0.36       | 0.34 | 0.38        | 0.36 | 0.06        | 0.05 | ...         | ...  | 0.31              | 0.29 | 0.75                    | 0.38 |
| 10 (0.1900)                                       | 24, 32         | 0.42       | 0.40 | 0.48        | 0.46 | 0.06        | 0.05 | ...         | ...  | 0.35              | 0.32 | 1.00                    | 0.38 |
| 12 (0.2160)                                       | 24             | 0.48       | 0.46 | 0.54        | 0.52 | 0.06        | 0.05 | ...         | ...  | 0.40              | 0.38 | 1.00                    | 0.38 |
| ¼ (0.2500)  | 20             | 0.55       | 0.52 | 0.64        | 0.61 | 0.07        | 0.05 | ...         | ...  | 0.47              | 0.44 | 1.50                    | 0.50 |
| ⅜ (0.3125)  | 18             | 0.70       | 0.67 | 0.78        | 0.75 | 0.09        | 0.07 | ...         | ...  | 0.59              | 0.56 | 1.50                    | 0.50 |
| ½ (0.3750)  | 16             | 0.83       | 0.80 | 0.95        | 0.92 | 0.11        | 0.09 | ...         | ...  | 0.76              | 0.71 | 2.00                    | 0.75 |
| <b>Type A, Heavy</b>                              |                |            |      |             |      |             |      |             |      |                   |      |                         |      |
| 10 (0.1900)                                       | 24             | 0.89       | 0.83 | 0.84        | 0.72 | 0.18        | 0.16 | 0.10        | 0.08 | 0.33              | 0.31 | 2.00                    | 0.50 |
| ¼ (0.2500)  | 20             | 1.05       | 0.99 | 0.94        | 0.81 | 0.24        | 0.22 | 0.10        | 0.08 | 0.40              | 0.38 | 3.00                    | 0.50 |
| ⅜ (0.3125)  | 18             | 1.21       | 1.15 | 1.00        | 0.88 | 0.27        | 0.25 | 0.11        | 0.09 | 0.46              | 0.44 | 4.00                    | 0.50 |
| ½ (0.3750)  | 16             | 1.41       | 1.34 | 1.16        | 1.03 | 0.30        | 0.28 | 0.11        | 0.09 | 0.55              | 0.53 | 4.00                    | 0.50 |
| ⅞ (0.4375)  | 14             | 1.59       | 1.53 | 1.22        | 1.09 | 0.36        | 0.34 | 0.13        | 0.11 | 0.71              | 0.69 | 2.50                    | 1.00 |
| 1½ (0.5000)                                       | 13             | 1.81       | 1.72 | 1.28        | 1.16 | 0.40        | 0.38 | 0.14        | 0.12 | 0.83              | 0.81 | 3.00                    | 1.00 |
| <b>Type B, Regular</b>                            |                |            |      |             |      |             |      |             |      |                   |      |                         |      |
| 6 (0.1380)  | 32             | 0.45       | 0.43 | 0.28        | 0.26 | 0.08        | 0.06 | 0.03        | 0.02 | ...               | ...  | 1.00                    | 0.25 |
| 8 (0.1640)  | 32             | 0.51       | 0.49 | 0.32        | 0.30 | 0.09        | 0.07 | 0.04        | 0.02 | ...               | ...  | 1.00                    | 0.38 |
| 10 (0.1900)                                       | 24, 32         | 0.58       | 0.54 | 0.39        | 0.36 | 0.10        | 0.08 | 0.05        | 0.03 | ...               | ...  | 2.00                    | 0.38 |
| 12 (0.2160)                                       | 24             | 0.71       | 0.67 | 0.45        | 0.43 | 0.11        | 0.09 | 0.05        | 0.03 | ...               | ...  | 2.00                    | 0.38 |
| ¼ (0.2500)  | 20             | 0.83       | 0.80 | 0.52        | 0.48 | 0.16        | 0.14 | 0.06        | 0.03 | ...               | ...  | 2.50                    | 0.50 |
| ⅜ (0.3125)  | 18             | 0.96       | 0.91 | 0.64        | 0.60 | 0.17        | 0.14 | 0.09        | 0.06 | ...               | ...  | 3.00                    | 0.50 |
| ½ (0.3750)  | 16             | 1.09       | 1.03 | 0.71        | 0.67 | 0.22        | 0.18 | 0.11        | 0.08 | ...               | ...  | 3.00                    | 0.75 |
| ⅞ (0.4375)  | 14             | 1.40       | 1.35 | 0.96        | 0.91 | 0.27        | 0.24 | 0.14        | 0.11 | ...               | ...  | 4.00                    | 1.00 |
| 1½ (0.5000)                                       | 13             | 1.54       | 1.46 | 1.09        | 1.03 | 0.33        | 0.29 | 0.15        | 0.11 | ...               | ...  | 4.00                    | 1.00 |
| <b>Type B, Heavy</b>                              |                |            |      |             |      |             |      |             |      |                   |      |                         |      |
| 10 (0.1900)                                       | 24             | 0.89       | 0.83 | 0.78        | 0.66 | 0.18        | 0.16 | 0.08        | 0.06 | ...               | ...  | 2.00                    | 0.50 |
| ¼ (0.2500)  | 20             | 1.05       | 0.99 | 0.81        | 0.72 | 0.24        | 0.22 | 0.11        | 0.09 | ...               | ...  | 3.00                    | 0.50 |
| ⅜ (0.3125)  | 18             | 1.21       | 1.15 | 0.88        | 0.78 | 0.27        | 0.25 | 0.11        | 0.09 | ...               | ...  | 4.00                    | 0.50 |
| ½ (0.3750)  | 16             | 1.41       | 1.34 | 0.94        | 0.84 | 0.30        | 0.28 | 0.14        | 0.12 | ...               | ...  | 4.00                    | 0.50 |
| ⅞ (0.4375)  | 14             | 1.59       | 1.53 | 1.00        | 0.91 | 0.36        | 0.34 | 0.14        | 0.12 | ...               | ...  | 3.00                    | 1.00 |
| 1½ (0.5000)                                       | 13             | 1.81       | 1.72 | 1.09        | 0.97 | 0.40        | 0.38 | 0.18        | 0.16 | ...               | ...  | 3.00                    | 1.00 |

<sup>a</sup> Where specifying nominal size in decimals, zeroes in fourth decimal place are omitted. All dimensions in inches.

<sup>1</sup> Plain point, unless alternate point from styles shown in Table 8 is specified by user.

**Lengths of Wing and Thumb Screws.**—The length of wing or thumb screws is measured parallel to the axis of the screw from the intersection of the head or shoulder with the shank to the extreme point of the screw. Standard length increments are as follows: For

1720 WING NUTS, WING SCREWS AND THUMB SCREWS

sizes No. 4 through 1/4 inch and for nominal lengths of 0.25 to 0.75 inch, 0.12-inch increments; from 0.75- to 1.50-inch lengths, 0.25-inch increments; and for 1.50- to 3.00-inch lengths, 0.50-inch increments. For sizes 5/16 through 1/2 inch and for 0.50- to 1.50-inch lengths, 0.25-inch increments; for 1.50- to 3.00-inch lengths, 0.50-inch increments; and for 3.00- to 4.00-inch lengths, 1.00-inch increments.

**Threads for Wing Screws and Thumb Screws.**—Threads for all types of wing screws and thumb screws are in conformance with ANSI Standard Unified Thread, Class 2A. For threads with an additive finish the Class 2A maximum diameters apply to an unplated screw or to a screw before plating, whereas the basic diameters (Class 2A maximum diameters plus the allowance) apply to a screw after plating. All types of wing and thumb screws should have complete (full form) threads extending as close to the head or shoulder as practicable.

**Points for Wing and Thumb Screws.**—Wing and thumb screws are normally supplied with plain points (sheared ends). Where so specified, these screws may be obtained with cone, cup, dog, flat or oval points as shown in Table 8.

**Table 8. American National Standard Alternate Points for Wing and Thumb Screws**  
ANSI B18.17-1968, R1983

| Nominal Size or Basic Screw Diameter <sup>a</sup> | O                           |       | P                      |       | Q     |       | R                 |       |
|---|-----------------------------|-------|------------------------|-------|-------|-------|-------------------|-------|
|   | Cup and Flat Point Diameter |       | Dog Point <sup>b</sup> |       |       |       | Oval Point Radius |       |
|   | Max                         | Min   | Max                    | Min   | Max   | Min   | Max               | Min   |
| 4 (0.1120)  | 0.061                       | 0.051 | 0.075                  | 0.070 | 0.061 | 0.051 | 0.099             | 0.084 |
| 6 (0.1380)  | 0.074                       | 0.064 | 0.092                  | 0.087 | 0.075 | 0.065 | 0.140             | 0.109 |
| 8 (0.1640)  | 0.087                       | 0.076 | 0.109                  | 0.103 | 0.085 | 0.075 | 0.156             | 0.125 |
| 10 (0.1900)                                       | 0.102                       | 0.088 | 0.127                  | 0.120 | 0.095 | 0.085 | 0.172             | 0.141 |
| 12 (0.2160)                                       | 0.115                       | 0.101 | 0.144                  | 0.137 | 0.115 | 0.105 | 0.188             | 0.156 |
| 1/4 (0.2500)                                      | 0.132                       | 0.118 | 0.156                  | 0.149 | 0.130 | 0.120 | 0.219             | 0.188 |
| 5/16 (0.3125)                                     | 0.172                       | 0.156 | 0.203                  | 0.195 | 0.161 | 0.151 | 0.256             | 0.234 |
| 3/8 (0.3750)                                      | 0.212                       | 0.194 | 0.250                  | 0.241 | 0.193 | 0.183 | 0.312             | 0.281 |
| 7/16 (0.4375)                                     | 0.252                       | 0.232 | 0.297                  | 0.287 | 0.224 | 0.214 | 0.359             | 0.328 |
| 1/2 (0.5000)                                      | 0.291                       | 0.270 | 0.344                  | 0.334 | 0.255 | 0.245 | 0.406             | 0.375 |
| 5/8 (0.6250)                                      | 0.371                       | 0.347 | 0.469                  | 0.456 | 0.321 | 0.305 | 0.500             | 0.469 |

<sup>a</sup> Where specifying nominal size in decimals, zeros in the fourth decimal place are omitted.

<sup>b</sup> The axis of dog points shall not be eccentric with the axis of the screw by more than 3 per cent of the basic screw diameter or 0.005 in., whichever is the smaller.

All dimensions in inches.

<sup>1</sup> The external point angles specified shall apply to those portions of the angles which lie below the thread root diameter, it being recognized the angle within the thread profile may be varied due to the manufacturing processes.

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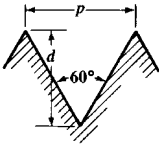
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## SCREW THREAD SYSTEMS

## Screw Thread Forms

Of the various screw thread forms which have been developed, the most used are those having symmetrical sides inclined at equal angles with a vertical center line through the thread apex. Present-day examples of such threads would include the Unified, the Whitworth and the Acme forms. One of the early forms was the Sharp V which is now used only occasionally. Symmetrical threads are relatively easy to manufacture and inspect and hence are widely used on mass-produced general-purpose threaded fasteners of all types. In addition to general-purpose fastener applications, certain threads are used to repeatedly move or translate machine parts against heavy loads. For these so-called translation threads a stronger form is required. The most widely used translation thread forms are the square, the Acme, and the buttress. Of these, the square thread is the most efficient, but it is also the most difficult to cut owing to its parallel sides and it cannot be adjusted to compensate for wear. Although less efficient, the Acme form of thread has none of the disadvantages of the square form and has the advantage of being somewhat stronger. The buttress form is used for translation of loads in one direction only because of its non-symmetrical form and combines the high efficiency and strength of the square thread with the ease of cutting and adjustment of the Acme thread.

**V-Thread, Sharp V-thread.**—The sides of the thread form an angle of 60 degrees with each other. The top and bottom or root of this thread form are theoretically sharp, but in actual practice the thread is made with a slight flat, owing to the difficulty of producing a perfectly sharp edge and because of the tendency of such an edge to wear away or become battered. This flat is usually equal to about one twenty-fifth of the pitch, although there is no generally recognized standard.



Owing to the difficulties connected with the V-thread, the tap manufacturers agreed in 1909 to discontinue the making of sharp V-thread taps, except when ordered. One advantage of the V-thread is that the same cutting tool may be used for all pitches, whereas, with the American Standard form, the width of the point or the flat varies according to the pitch.

The V-thread is regarded as a good form where a steam-tight joint is necessary, and many of the taps used on locomotive work have this form of thread. Some modified V-threads, for locomotive boiler taps particularly, have a depth of  $0.8 \times$  pitch.

The American Standard screw thread is used largely in preference to the sharp V-thread because it has several advantages; see *American Standard for Unified Screw Threads*. If  $p$  = pitch of thread, and  $d$  depth of thread, then

$$d = p \times \cos 30 \text{ deg.} = 0.866 \times p = \frac{0.866}{\text{No. of threads per inch}}$$

**United States Standard Screw Thread.**—William Sellers of Philadelphia, in a paper read before the Franklin Institute in 1864, originally proposed the screw thread system that later became known as the U. S. Standard system for screw threads. A report was made to the United States Navy in May, 1868, in which the Sellers system was recommended as a standard for the Navy Department, which accounts for the name of U. S. Standard. The American Standard Screw Thread system is a further development of the United States Standard. The thread form which is known as the American (National) form is the same as the United States Standard form. See *American Standard for Unified Screw Threads*.

**American National and Unified Screw Thread Forms.**—The American National form (formerly known as the United States Standard) was used for many years for most screws, bolts, and miscellaneous threaded products produced in the United States. The American

National Standard for Unified Screw Threads now in use includes certain modifications of the former standard as is explained below and on page 1732. The basic profile is shown in Fig. 1 and is identical for both UN and UNR screw threads. In this figure  $H$  is the height of a sharp V-thread,  $P$  is the pitch,  $D$  and  $d$  are the basic major diameters,  $D_2$  and  $d_2$  are the basic pitch diameters, and  $D_1$  and  $d_1$  are the basic minor diameters. Capital letters are used to designate the internal thread dimensions ( $D$ ,  $D_2$ ,  $D_1$ ), and lowercase letters to designate the external thread dimensions ( $d$ ,  $d_2$ ,  $d_1$ ). Definitions of *Basic Size* and *Basic Profile of Thread* are given on page 1727.

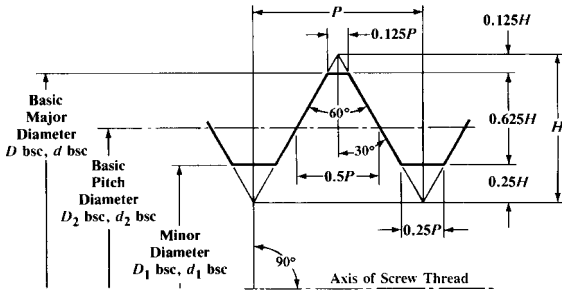


Fig. 1. Basic Profile of UN and UNF Screw Threads

In the past, other symbols were used for some of the thread dimensions illustrated above. These symbols were changed to conform with current practice in nomenclature as defined in ANSI/ASME B1.7M, "Nomenclature, Definitions, and Letter Symbols for Screw Threads." The symbols used above are also in accordance with terminology and symbols used for threads of the ISO metric thread system.

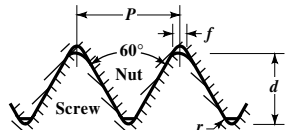
**International Metric Thread System.**—The *Système Internationale* (S.I.) Thread was adopted at the International Congress for the standardization of screw threads held in Zurich in 1898. The thread form is similar to the American standard (formerly U.S. Standard), excepting the depth which is greater. There is a clearance between the root and mating crest fixed at a maximum of  $\frac{1}{16}$  the height of the fundamental triangle or  $0.054 \times$  pitch. A rounded root profile is recommended. The angle in the plane of the axis is 60 degrees and the crest has a flat like the American standard equal to  $0.125 \times$  pitch. This system formed the basis of the normal metric series (ISO threads) of many European countries, Japan, and many other countries, including metric thread standards of the United States.

Depth  $d = 0.7035 P$  max.;  $0.6855 P$  min.

Flat  $f = 0.125 P$

Radius  $r = 0.0633 P$  max.;  $0.054 P$  min.

Tap drill dia = major dia. – pitch



**International Metric Fine Thread:** The International Metric Fine Thread form of thread is the same as the International system but the pitch for a given diameter is smaller.

**German Metric Thread Form:** The German metric thread form is like the International Standard but the thread depth =  $0.6945 P$ . The root radius is the same as the maximum for the International Standard or  $0.0633 P$ .

**ISO Metric Thread System.**—ISO refers to the International Organization for Standardization, a worldwide federation of national standards bodies (for example, the American National Standards Institute is the ISO national body representing the United States) that develops standards on a very wide variety of subjects.

The basic profile of ISO metric threads is specified in ISO 68 and shown in Fig. 2. The basic profile of this thread is very similar to that of the Unified thread, and as previously discussed,  $H$  is the height of a sharp V-thread,  $P$  is the pitch,  $D$  and  $d$  are the basic major diameters,  $D_2$  and  $d_2$  are the basic pitch diameters, and  $D_1$  and  $d_1$  are the basic minor diameters. Here also, capital letters designate the internal thread dimensions ( $D$ ,  $D_2$ ,  $D_1$ ), and lowercase letters designate the external thread dimensions ( $d$ ,  $d_2$ ,  $d_1$ ). This metric thread is discussed in detail in the section *METRIC SCREW THREADS* starting on page 1783.

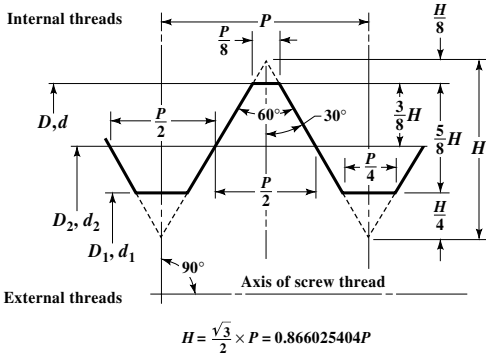


Fig. 2. ISO 68 Basic Profile

### Definitions of Screw Threads

The following definitions are based on American National Standard ANSI/ASME B1.7M-1984 (R2001) "Nomenclature, Definitions, and Letter Symbols for Screw Threads," and refer to both straight and taper threads.

**Actual Size:** An actual size is a measured size.

**Allowance:** An allowance is the prescribed difference between the design (maximum material) size and the basic size. It is numerically equal to the absolute value of the ISO term *fundamental deviation*.

**Axis of Thread:** Thread axis is coincident with the axis of its pitch cylinder or cone.

**Basic Profile of Thread:** The basic profile of a thread is the cyclical outline, in an axial plane, of the permanently established boundary between the provinces of the external and internal threads. All deviations are with respect to this boundary.

**Basic Size:** The basic size is that size from which the limits of size are derived by the application of allowances and tolerances.

**Bilateral Tolerance:** This is a tolerance in which variation is permitted in both directions from the specified dimension.

**Black Crest Thread:** This is a thread whose crest displays an unfinished cast, rolled, or forged surface.

**Blunt Start Thread:** "Blunt start" designates the removal of the incomplete thread at the starting end of the thread. This is a feature of threaded parts that are repeatedly assembled

by hand, such as hose couplings and thread plug gages, to prevent cutting of hands and crossing of threads. It was formerly known as a Higbee cut.

*Chamfer:* This is a conical surface at the starting end of a thread.

*Class of Thread:* The class of a thread is an alphanumeric designation to indicate the standard grade of tolerance and allowance specified for a thread.

*Clearance Fit:* This is a fit having limits of size so prescribed that a clearance always results when mating parts are assembled at their maximum material condition.

*Complete Thread:* The complete thread is that thread whose profile lies within the size limits. (See also *Effective Thread* and *Length of Complete Thread*.) *Note:* Formerly in pipe thread terminology this was referred to as "the perfect thread" but that term is no longer considered desirable.

*Crest:* This is that surface of a thread which joins the flanks of the thread and is farthest from the cylinder or cone from which the thread projects.

*Crest Truncation:* This is the radial distance between the sharp crest (crest apex) and the cylinder or cone that would bound the crest.

*Depth of Thread Engagement:* The depth (or height) of thread engagement between two coaxially assembled mating threads is the radial distance by which their thread forms overlap each other.

*Design Size:* This is the basic size with allowance applied, from which the limits of size are derived by the application of a tolerance. If there is no allowance, the design size is the same as the basic size.

*Deviation:* Deviation is a variation from an established dimension, position, standard, or value. In ISO usage, it is the algebraic difference between a size (actual, maximum, or minimum) and the corresponding basic size. The term deviation does not necessarily indicate an error. (See also *Error*.)

*Deviation, Fundamental (ISO term):* For standard threads, the fundamental deviation is the upper or lower deviation closer to the basic size. It is the upper deviation  $es$  for an external thread and the lower deviation  $EI$  for an internal thread. (See also *Allowance* and *Tolerance Position*.)

*Deviation, Lower (ISO term):* The algebraic difference between the minimum limit of size and the basic size. It is designated  $EI$  for internal and  $ei$  for external thread diameters.

*Deviation, Upper (ISO term):* The algebraic difference between the maximum limit of size and the basic size. It is designated  $ES$  for internal and  $es$  for external thread diameters.

*Dimension:* A numerical value expressed in appropriate units of measure and indicated on drawings along with lines, symbols, and notes to define the geometrical characteristic of an object.

*Effective Size:* See *Pitch Diameter*, *Functional Diameter*.

*Effective Thread:* The effective (or useful) thread includes the complete thread, and those portions of the incomplete thread which are fully formed at the root but not at the crest (in taper pipe threads it includes the so-called black crest threads); thus excluding the vanish thread.

*Error:* The algebraic difference between an observed or measured value beyond tolerance limits, and the specified value.

*External Thread:* A thread on a cylindrical or conical external surface.

*Fit:* Fit is the relationship resulting from the designed difference, before assembly, between the sizes of two mating parts which are to be assembled.

*Flank:* The flank of a thread is either surface connecting the crest with the root. The flank surface intersection with an axial plane is theoretically a straight line.

*Flank Angle:* The flank angles are the angles between the individual flanks and the perpendicular to the axis of the thread, measured in an axial plane. A flank angle of a symmetrical thread is commonly termed the half-angle of thread.

*Flank Diametral Displacement:* In a boundary profile defined system, flank diametral displacement is twice the radial distance between the straight thread flank segments of the

maximum and minimum boundary profiles. The value of flank diametral displacement is equal to pitch diameter tolerance in a pitch line reference thread system.

*Height of Thread:* The height (or depth) of thread is the distance, measured radially, between the major and minor cylinders or cones, respectively.

*Helix Angle:* On a straight thread, the helix angle is the angle made by the helix of the thread and its relation to the thread axis. On a taper thread, the helix angle at a given axial position is the angle made by the conical spiral of the thread with the axis of the thread. The helix angle is the complement of the lead angle. (See also page 1966 for diagram.)

*Higbee Cut:* See *Blunt Start Thread*.

*Imperfect Thread:* See *Incomplete Thread*.

*Included Angle:* This is the angle between the flanks of the thread measured in an axial plane.

*Incomplete Thread:* A threaded profile having either crests or roots or both, not fully formed, resulting from their intersection with the cylindrical or end surface of the work or the vanish cone. It may occur at either end of the thread.

*Interference Fit:* A fit having limits of size so prescribed that an interference always results when mating parts are assembled.

*Internal Thread:* A thread on a cylindrical or conical internal surface.

*Lead:* Lead is the axial distance between two consecutive points of intersection of a helix by a line parallel to the axis of the cylinder on which it lies, i.e., the axial movement of a threaded part rotated one turn in its mating thread.

*Lead Angle:* On a straight thread, the lead angle is the angle made by the helix of the thread at the pitch line with a plane perpendicular to the axis. On a taper thread, the lead angle at a given axial position is the angle made by the conical spiral of the thread with the perpendicular to the axis at the pitch line.

*Lead Thread:* That portion of the incomplete thread that is fully formed at the root but not fully formed at the crest that occurs at the entering end of either an external or internal thread.

*Left-hand Thread:* A thread is a left-hand thread if, when viewed axially, it winds in a counterclockwise and receding direction. Left-hand threads are designated LH.

*Length of Complete Thread:* The axial length of a thread section having full form at both crest and root but also including a maximum of two pitches at the start of the thread which may have a chamfer or incomplete crests.

*Length of Thread Engagement:* The length of thread engagement of two mating threads is the axial distance over which the two threads, each having full form at both crest and root, are designed to contact. (See also *Length of Complete Thread*.)

*Limits of Size:* The applicable maximum and minimum sizes.

*Major Clearance:* The radial distance between the root of the internal thread and the crest of the external thread of the coaxially assembled designed forms of mating threads.

*Major Cone:* The imaginary cone that would bound the crests of an external taper thread or the roots of an internal taper thread.

*Major Cylinder:* The imaginary cylinder that would bound the crests of an external straight thread or the roots of an internal straight thread.

*Major Diameter:* On a straight thread the major diameter is that of the major cylinder. On a taper thread the major diameter at a given position on the thread axis is that of the major cone at that position. (See also *Major Cylinder* and *Major Cone*.)

*Maximum Material Condition: (MMC):* The condition where a feature of size contains the maximum amount of material within the stated limits of size. For example, minimum internal thread size or maximum external thread size.

*Minimum Material Condition: (Least Material Condition (LMC)):* The condition where a feature of size contains the least amount of material within the stated limits of size. For example, maximum internal thread size or minimum external thread size.

*Minor Clearance:* The radial distance between the crest of the internal thread and the root of the external thread of the coaxially assembled design forms of mating threads.

*Minor Cone:* The imaginary cone that would bound the roots of an external taper thread or the crests of an internal taper thread.

*Minor Cylinder:* The imaginary cylinder that would bound the roots of an external straight thread or the crests of an internal straight thread.

*Minor Diameter:* On a straight thread the minor diameter is that of the minor cylinder. On a taper thread the minor diameter at a given position on the thread axis is that of the minor cone at that position. (See also *Minor Cylinder* and *Minor Cone*.)

*Multiple-Start Thread:* A thread in which the lead is an integral multiple, other than one, of the pitch.

*Nominal Size:* Designation used for general identification.

*Parallel Thread:* See *Screw Thread*.

*Partial Thread:* See *Vanish Thread*.

*Pitch:* The pitch of a thread having uniform spacing is the distance measured parallel with its axis between corresponding points on adjacent thread forms in the same axial plane and on the same side of the axis. Pitch is equal to the lead divided by the number of thread starts.

*Pitch Cone:* The pitch cone is an imaginary cone of such apex angle and location of its vertex and axis that its surface would pass through a taper thread in such a manner as to make the widths of the thread ridge and the thread groove equal. It is, therefore, located equidistantly between the sharp major and minor cones of a given thread form. On a theoretically perfect taper thread, these widths are equal to one-half the basic pitch. (See also *Axis of Thread* and *Pitch Diameter*.)

*Pitch Cylinder:* The pitch cylinder is an imaginary cylinder of such diameter and location of its axis that its surface would pass through a straight thread in such a manner as to make the widths of the thread ridge and groove equal. It is, therefore, located equidistantly between the sharp major and minor cylinders of a given thread form. On a theoretically perfect thread these widths are equal to one-half the basic pitch. (See also *Axis of Thread* and *Pitch Diameter*.)

*Pitch Diameter:* On a straight thread the pitch diameter is the diameter of the pitch cylinder. On a taper thread the pitch diameter at a given position on the thread axis is the diameter of the pitch cone at that position. *Note:* When the crest of a thread is truncated beyond the pitch line, the pitch diameter and pitch cylinder or pitch cone would be based on a theoretical extension of the thread flanks.

*Pitch Diameter, Functional Diameter:* The functional diameter is the pitch diameter of an enveloping thread with perfect pitch, lead, and flank angles and having a specified length of engagement. It includes the cumulative effect of variations in lead (pitch), flank angle, taper, straightness, and roundness. Variations at the thread crest and root are excluded. Other, nonpreferred terms are *virtual diameter*, *effective size*, *virtual effective diameter*, and *thread assembly diameter*.

*Pitch Line:* The generator of the cylinder or cone specified in *Pitch Cylinder* and *Pitch Cone*.

*Right-hand Thread:* A thread is a right-hand thread if, when viewed axially, it winds in a clockwise and receding direction. A thread is considered to be right-hand unless specifically indicated otherwise.

*Root:* That surface of the thread which joins the flanks of adjacent thread forms and is immediately adjacent to the cylinder or cone from which the thread projects.

*Root Truncation:* The radial distance between the sharp root (root apex) and the cylinder or cone that would bound the root. See also *Sharp Root (Root Apex)*.

*Runout:* As applied to screw threads, unless otherwise specified, runout refers to circular runout of major and minor cylinders with respect to the pitch cylinder. Circular runout, in accordance with ANSI Y14.5M, controls cumulative variations of circularity and coaxiality. Runout includes variations due to eccentricity and out-of-roundness. The amount of runout is usually expressed in terms of full indicator movement (FIM).

*Screw Thread:* A screw thread is a continuous and projecting helical ridge usually of uniform section on a cylindrical or conical surface.

*Sharp Crest (Crest Apex):* The apex formed by the intersection of the flanks of a thread when extended, if necessary, beyond the crest.

*Sharp Root (Root Apex):* The apex formed by the intersection of the adjacent flanks of adjacent threads when extended, if necessary, beyond the root.

*Standoff:* The axial distance between specified reference points on external and internal taper thread members or gages, when assembled with a specified torque or under other specified conditions.

*Straight Thread:* A straight thread is a screw thread projecting from a cylindrical surface.

*Taper Thread:* A taper thread is a screw thread projecting from a conical surface.

*Tensile Stress Area:* The tensile stress area is an arbitrarily selected area for computing the tensile strength of an externally threaded fastener so that the fastener strength is consistent with the basic material strength of the fastener. It is typically defined as a function of pitch diameter and/or minor diameter to calculate a circular cross section of the fastener correcting for the notch and helix effects of the threads.

*Thread:* A thread is a portion of a screw thread encompassed by one pitch. On a single-start thread it is equal to one turn. (See also *Threads per Inch* and *Turns per Inch*.)

*Thread Angle:* See *Included Angle*.

*Thread Runout:* See *Vanish Thread*.

*Thread Series:* Thread Series are groups of diameter/pitch combinations distinguished from each other by the number of threads per inch applied to specific diameters.

*Thread Shear Area:* The thread shear area is the total ridge cross-sectional area intersected by a specified cylinder with diameter and length equal to the mating thread engagement. Usually the cylinder diameter for external thread shearing is the minor diameter of the internal thread and for internal thread shearing it is the major diameter of the external thread.

*Threads per Inch:* The number of threads per inch is the reciprocal of the axial pitch in inches.

*Tolerance:* The total amount by which a specific dimension is permitted to vary. The tolerance is the difference between the maximum and minimum limits.

*Tolerance Class: (metric):* The tolerance class (metric) is the combination of a tolerance position with a tolerance grade. It specifies the allowance (fundamental deviation), pitch diameter tolerance (flank diametral displacement), and the crest diameter tolerance.

*Tolerance Grade: (metric):* The tolerance grade (metric) is a numerical symbol that designates the tolerances of crest diameters and pitch diameters applied to the design profiles.

*Tolerance Limit:* The variation, positive or negative, by which a size is permitted to depart from the design size.

*Tolerance Position: (metric):* The tolerance position (metric) is a letter symbol that designates the position of the tolerance zone in relation to the basic size. This position provides the allowance (fundamental deviation).

*Total Thread:* Includes the complete and all the incomplete thread, thus including the vanish thread and the lead thread.

*Transition Fit:* A fit having limits of size so prescribed that either a clearance or an interference may result when mating parts are assembled.

*Turns per Inch:* The number of turns per inch is the reciprocal of the lead in inches.

*Unilateral Tolerance:* A tolerance in which variation is permitted in one direction from the specified dimension.

*Vanish Thread: (Partial Thread, Washout Thread, or Thread Runout):* That portion of the incomplete thread which is not fully formed at the root or at crest and root. It is produced by the chamfer at the starting end of the thread forming tool.

*Virtual Diameter:* See *Pitch Diameter, Functional Diameter*.

*Washout Thread:* See *Vanish Thread*.



## UNIFIED SCREW THREADS

## American Standard for Unified Screw Threads

American Standard B1.1-1949 was the first American standard to cover those Unified Thread Series agreed upon by the United Kingdom, Canada, and the United States to obtain screw thread interchangeability among these three nations. These Unified threads are now the basic American standard for fastening types of screw threads. In relation to previous American practice, Unified threads have substantially the same thread form and are mechanically interchangeable with the former American National threads of the same diameter and pitch.

The principal differences between the two systems lie in: 1) application of allowances; 2) variation of tolerances with size; 3) difference in amount of pitch diameter tolerance on external and internal threads; and 4) differences in thread designation.

In the Unified system an allowance is provided on both the Classes 1A and 2A external threads whereas in the American National system only the Class I external thread has an allowance. Also, in the Unified system, the pitch diameter tolerance of an internal thread is 30 per cent greater than that of the external thread, whereas they are equal in the American National system.

**Revised Standard.**—The revised screw thread standard ANSI/ASME B1.1-1989 (R2001) is much the same as that of ANSI B1.1-1982. The latest symbols in accordance with ANSI/ASME B1.7M-1984 (R2001) Nomenclature, are used. Acceptability criteria are described in ANSI/ASME B1.3M-1992 (R2001), Screw Thread Gaging Systems for Dimensional Acceptability, Inch or Metric Screw Threads (UN, UNR, UNJ, M, and MJ).

Where the letters U, A or B do not appear in the thread designations, the threads conform to the outdated American National screw threads.

**Advantages of Unified Threads.**—The Unified standard is designed to correct certain production difficulties resulting from the former standard. Often, under the old system, the tolerances of the product were practically absorbed by the combined tool and gage tolerances, leaving little for a working tolerance in manufacture. Somewhat greater tolerances are now provided for nut threads. As contrasted with the old “classes of fit” 1, 2, and 3, for each of which the pitch diameter tolerance on the external and internal threads were equal, the Classes 1B, 2B, and 3B (internal) threads in the new standard have, respectively, a 30 per cent larger pitch diameter tolerance than the 1A, 2A, and 3A (external) threads. Relatively more tolerance is provided for fine threads than for coarse threads of the same pitch. Where previous tolerances were more liberal than required, they were reduced.

**Thread Form.**—The Design Profiles for Unified screw threads, shown on page 1733, define the maximum material condition for external and internal threads with no allowance and are derived from the Basic Profile, shown on page 1726.

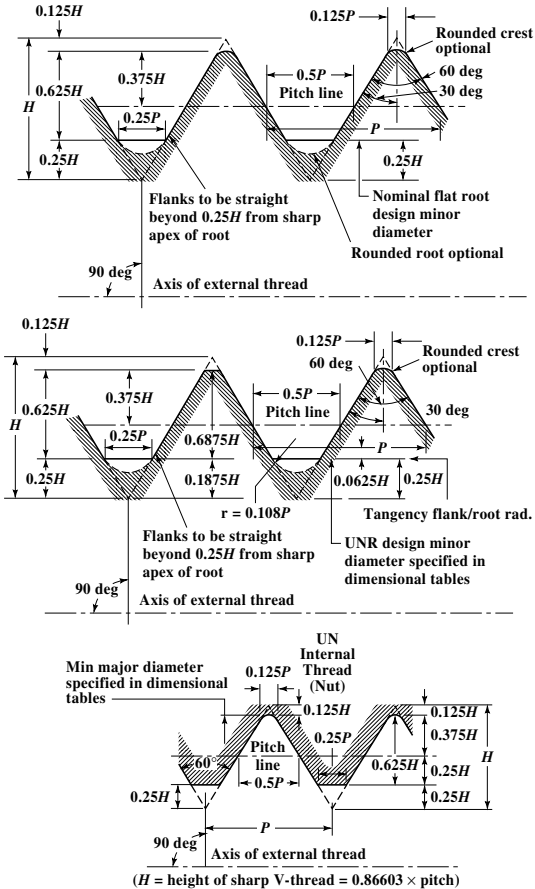
*UN External Screw Threads:* A flat root contour is specified, but it is necessary to provide for some threading tool crest wear, hence a rounded root contour cleared beyond the 0.25P flat width of the Basic Profile is optional.

*UNR External Screw Threads:* To reduce the rate of threading tool crest wear and to improve fatigue strength of a flat root thread, the Design Profile of the UNR thread has a smooth, continuous, non-reversing contour with a radius of curvature not less than 0.108P at any point and blends tangentially into the flanks and any straight segment. At the maximum material condition, the point of tangency is specified to be at a distance not less than 0.625H (where H is the height of a sharp V-thread) below the basic major diameter.

*UN and UNR External Screw Threads:* The Design Profiles of both UN and UNR external screw threads have flat crests. However, in practice, product threads are produced with partially or completely rounded crests. A rounded crest tangent at 0.125P flat is shown as an option on page 1733.

**UN Internal Screw Thread:** In practice it is necessary to provide for some threading tool crest wear, therefore the root of the Design Profile is rounded and cleared beyond the  $0.125P$  flat width of the Basic Profile. There is no internal UNR screw thread.

**American National Standard Unified Internal and External Screw Thread Design Profiles (Maximum Material Condition).—**



**Thread Series.**—Thread series are groups of diameter-pitch combinations distinguished from each other by the numbers of threads per inch applied to a specific diameter. The various diameter-pitch combinations of eleven standard series are shown in Table 2. The limits of size of threads in the eleven standard series together with certain selected combinations of diameter and pitch, as well as the symbols for designating the various threads, are given in Table 3. (Text continues on page 1763)

Table 1. American Standard Unified Inch Screw Thread Form Data

| Threads per Inch<br><i>n</i> | Pitch<br><i>P</i> | Depth of Sharp V-Thread<br>0.86603 <i>P</i> | Depth of Int. Thd. and UN Ext. Thd. <sup>a</sup><br>0.54127 <i>P</i> | Depth of UNR Ext. Thd.<br>0.59539 <i>P</i> | Truncation of Ext. Thd. Root<br>0.21651 <i>P</i> | Truncation of UNR Ext. Thd. Root <sup>b</sup><br>0.16238 <i>P</i> | Truncation of Ext. Thd. Crest<br>0.10825 <i>P</i> | Truncation of Int. Thd. Root<br>0.10825 <i>P</i> | Truncation of Int. Thd. Crest<br>0.2165 <i>P</i> | Flat at Ext. Thd. Crest and Int. Thd. Root<br>0.125 <i>P</i> | Basic Flat at Int. Thd. Crest <sup>c</sup><br>0.25 <i>P</i> | Maximum Ext. Thd. Root Radius<br>0.14434 <i>P</i> | Addendum of Ext. Thd.<br>0.32476 <i>P</i> |
|------------------------------|-------------------|---|--|--|--|---|---|--|--|--|---|---|---|
| 80                           | 0.01250           | 0.01083                                     | 0.00677  | 0.00744                                    | 0.00271  | 0.00203   | 0.00135   | 0.00135  | 0.00271  | 0.00156  | 0.00312   | 0.00180   | 0.00406                                   |
| 72                           | 0.01389           | 0.01203                                     | 0.00752  | 0.00827                                    | 0.00301  | 0.00226   | 0.00150   | 0.00150  | 0.00301  | 0.00174  | 0.00347   | 0.00200   | 0.00451                                   |
| 64                           | 0.01563           | 0.01353                                     | 0.00846  | 0.00930                                    | 0.00338  | 0.00254   | 0.00169   | 0.00169  | 0.00338  | 0.00195  | 0.00391   | 0.00226   | 0.00507                                   |
| 56                           | 0.01786           | 0.01546                                     | 0.00967  | 0.01063                                    | 0.00387  | 0.00290   | 0.00193   | 0.00193  | 0.00387  | 0.00223  | 0.00446   | 0.00258   | 0.00580                                   |
| 48                           | 0.02083           | 0.01804                                     | 0.01128  | 0.01240                                    | 0.00451  | 0.00338   | 0.00226   | 0.00226  | 0.00451  | 0.00260  | 0.00521   | 0.00301   | 0.00677                                   |
| 44                           | 0.02273           | 0.01968                                     | 0.01230  | 0.01353                                    | 0.00492  | 0.00369   | 0.00246   | 0.00246  | 0.00492  | 0.00284  | 0.00568   | 0.00328   | 0.00738                                   |
| 40                           | 0.02500           | 0.02165                                     | 0.01353  | 0.01488                                    | 0.00541  | 0.00406   | 0.00271   | 0.00271  | 0.00541  | 0.00312  | 0.00625   | 0.00361   | 0.00812                                   |
| 36                           | 0.02778           | 0.02406                                     | 0.01504  | 0.01654                                    | 0.00601  | 0.00451   | 0.00301   | 0.00301  | 0.00601  | 0.00347  | 0.00694   | 0.00401   | 0.00902                                   |
| 32                           | 0.03125           | 0.02706                                     | 0.01691  | 0.01861                                    | 0.00677  | 0.00507   | 0.00338   | 0.00338  | 0.00677  | 0.00391  | 0.00781   | 0.00451   | 0.01015                                   |
| 28                           | 0.03571           | 0.03093                                     | 0.01933  | 0.02126                                    | 0.00773  | 0.00580   | 0.00387   | 0.00387  | 0.00773  | 0.00446  | 0.00893   | 0.00515   | 0.01160                                   |
| 27                           | 0.03704           | 0.03208                                     | 0.02005  | 0.02205                                    | 0.00802  | 0.00601   | 0.00401   | 0.00401  | 0.00802  | 0.00463  | 0.00926   | 0.00535   | 0.01203                                   |
| 24                           | 0.04167           | 0.03608                                     | 0.02255  | 0.02481                                    | 0.00902  | 0.00677   | 0.00451   | 0.00451  | 0.00902  | 0.00521  | 0.01042   | 0.00601   | 0.01353                                   |
| 20                           | 0.05000           | 0.04330                                     | 0.02706  | 0.02977                                    | 0.01083  | 0.00812   | 0.00541   | 0.00541  | 0.01083  | 0.00625  | 0.01250   | 0.00722   | 0.01624                                   |
| 18                           | 0.05556           | 0.04811                                     | 0.03007  | 0.03308                                    | 0.01203  | 0.00902   | 0.00601   | 0.00601  | 0.01203  | 0.00694  | 0.01389   | 0.00802   | 0.01804                                   |
| 16                           | 0.06250           | 0.05413                                     | 0.03383  | 0.03721                                    | 0.01353  | 0.01015   | 0.00677   | 0.00677  | 0.01353  | 0.00781  | 0.01562   | 0.00902   | 0.02030                                   |
| 14                           | 0.07143           | 0.06186                                     | 0.03866  | 0.04253                                    | 0.01546  | 0.01160   | 0.00773   | 0.00773  | 0.01546  | 0.00893  | 0.01786   | 0.01031   | 0.02320                                   |
| 13                           | 0.07692           | 0.06662                                     | 0.04164  | 0.04580                                    | 0.01655  | 0.01249   | 0.00833   | 0.00833  | 0.01655  | 0.00962  | 0.01923   | 0.01110   | 0.02498                                   |
| 12                           | 0.08333           | 0.07217                                     | 0.04511  | 0.04962                                    | 0.01804  | 0.01353   | 0.00902   | 0.00902  | 0.01804  | 0.01042  | 0.02083   | 0.01203   | 0.02706                                   |
| 11½                          | 0.08696           | 0.07531                                     | 0.04707  | 0.05177                                    | 0.01883  | 0.01412   | 0.00941   | 0.00941  | 0.01883  | 0.01042  | 0.02174   | 0.01255   | 0.02824                                   |
| 11                           | 0.09091           | 0.07873                                     | 0.04921  | 0.05413                                    | 0.01968  | 0.01476   | 0.00984   | 0.00984  | 0.01968  | 0.01136  | 0.02273   | 0.01312   | 0.02952                                   |
| 10                           | 0.10000           | 0.08660                                     | 0.05413  | 0.05954                                    | 0.02165  | 0.01624   | 0.01083   | 0.01083  | 0.02165  | 0.01250  | 0.02500   | 0.01443   | 0.03248                                   |
| 9                            | 0.11111           | 0.09623                                     | 0.06014  | 0.06615                                    | 0.02406  | 0.01804   | 0.01203   | 0.01203  | 0.02406  | 0.01389  | 0.02778   | 0.01604   | 0.03608                                   |
| 8                            | 0.12500           | 0.10825                                     | 0.06766  | 0.07442                                    | 0.02706  | 0.02030   | 0.01353   | 0.01353  | 0.02706  | 0.01562  | 0.03125   | 0.01804   | 0.04059                                   |
| 7                            | 0.14286           | 0.12372                                     | 0.07732  | 0.08506                                    | 0.03093  | 0.02320   | 0.01546   | 0.01546  | 0.03093  | 0.01786  | 0.03571   | 0.02062   | 0.04639                                   |
| 6                            | 0.16667           | 0.14434                                     | 0.09021  | 0.09923                                    | 0.03608  | 0.02706   | 0.01804   | 0.01804  | 0.03608  | 0.02083  | 0.04167   | 0.02406   | 0.05413                                   |
| 5                            | 0.20000           | 0.17321                                     | 0.10825  | 0.11908                                    | 0.04330  | 0.03248   | 0.02165   | 0.02165  | 0.04330  | 0.02500  | 0.05000   | 0.02887   | 0.06495                                   |
| 4½                           | 0.22222           | 0.19245                                     | 0.12028  | 0.13231                                    | 0.04811  | 0.03608   | 0.02406   | 0.02406  | 0.04811  | 0.02780  | 0.05556   | 0.03208   | 0.07217                                   |
| 4                            | 0.25000           | 0.21651                                     | 0.13532  | 0.14885                                    | 0.05413  | 0.04059   | 0.02706   | 0.02706  | 0.05413  | 0.03125  | 0.06250   | 0.03608   | 0.08119                                   |

<sup>a</sup> Also depth of thread engagement.<sup>b</sup> Design profile.<sup>c</sup> Also basic flat at external UN thread root.

All dimensions are in inches.

**Table 2. Diameter-Pitch Combinations for Standard Series of Threads (UN/UNR)**

| Sizes <sup>a</sup><br>No. or<br>Inches | Basic<br>Major<br>Dia.<br>Inches | Threads per Inch           |                          |   |  |      |      |       |       |       |       |       |  |  |
|--|----------------------------------|----------------------------|--------------------------|---|--|------|------|-------|-------|-------|-------|-------|--|--|
|  |                                  | Series with Graded Pitches |                          |   | Series with Uniform (Constant) Pitches |      |      |       |       |       |       |       |  |  |
|  |                                  | Coarse<br>UNC              | Fine <sup>b</sup><br>UNF | Extra fine <sup>c</sup><br>UNEF   | 4-UN                                   | 6-UN | 8-UN | 12-UN | 16-UN | 20-UN | 28-UN | 32-UN |  |  |
| 0                                      | 0.0600                           | ...                        | 80                       | Series designation shown indicates the UN thread form; however, the UNR thread form may be specified by substituting UNR in place of UN in all designations for external threads. |  |      |      |       |       |       |       |       |  |  |
| (1)                                    | 0.0730                           | 64                         | 72                       |   |  |      |      |       |       |       |       |       |  |  |
| 2                                      | 0.0860                           | 56                         | 64                       |   |  |      |      |       |       |       |       |       |  |  |
| (3)                                    | 0.0990                           | 48                         | 56                       |   |  |      |      |       |       |       |       |       |  |  |
| 4                                      | 0.1120                           | 40                         | 48                       |   |  |      |      |       |       |       |       |       |  |  |
| 5                                      | 0.1250                           | 40                         | 44                       |   |  |      |      |       |       |       |       |       |  |  |
| 6                                      | 0.1380                           | 32                         | 40                       |   |  |      |      |       |       |       |       |       |  |  |
| 8                                      | 0.1640                           | 32                         | 36                       |   |  |      |      |       |       |       |       |       |  |  |
| 10                                     | 0.1900                           | 24                         | 32                       |   |  |      |      |       |       |       |       |       |  |  |
| (12)                                   | 0.2160                           | 24                         | 28                       |   |  |      |      |       |       |       |       |       |  |  |
| 1/4                                    | 0.2500                           | 20                         | 28                       | 32  | ...                                    | ...  | ...  | ...   | UNC   | UNC   | UNC   | UNC   |  |  |
| 5/16                                   | 0.3125                           | 18                         | 24                       | 32  | ...                                    | ...  | ...  | ...   | 20    | 28    | UNC   | UNC   |  |  |
| 3/8                                    | 0.3750                           | 16                         | 24                       | 32  | ...                                    | ...  | ...  | ...   | UNC   | 20    | 28    | UNC   |  |  |
| 7/16                                   | 0.4375                           | 14                         | 20                       | 28  | ...                                    | ...  | ...  | ...   | 16    | UNC   | UNC   | 32    |  |  |
| 1/2                                    | 0.5000                           | 13                         | 20                       | 28  | ...                                    | ...  | ...  | ...   | 16    | UNC   | UNC   | 32    |  |  |
| 9/16                                   | 0.5625                           | 12                         | 18                       | 24  | ...                                    | ...  | ...  | UNC   | 16    | 20    | 28    | 32    |  |  |
| 5/8                                    | 0.6250                           | 11                         | 18                       | 24  | ...                                    | ...  | ...  | 12    | 16    | 20    | 28    | 32    |  |  |
| (1 1/16)                               | 0.6875                           | ...                        | ...                      | 24  | ...                                    | ...  | ...  | 12    | 16    | 20    | 28    | 32    |  |  |
| 3/4                                    | 0.7500                           | 10                         | 16                       | 20  | ...                                    | ...  | ...  | 12    | UNC   | UNC   | 28    | 32    |  |  |
| (1 3/16)                               | 0.8125                           | ...                        | ...                      | 20  | ...                                    | ...  | ...  | 12    | 16    | UNC   | 28    | 32    |  |  |
| 7/8                                    | 0.8750                           | 9                          | 14                       | 20  | ...                                    | ...  | ...  | 12    | 16    | UNC   | 28    | 32    |  |  |
| (1 5/16)                               | 0.9375                           | ...                        | ...                      | 20  | ...                                    | ...  | ...  | 12    | 16    | UNC   | 28    | 32    |  |  |
| 1                                      | 1.0000                           | 8                          | 12                       | 20  | ...                                    | ...  | UNC  | UNC   | 16    | UNC   | 28    | 32    |  |  |
| (1 1/8)                                | 1.0625                           | ...                        | ...                      | 18  | ...                                    | ...  | 8    | 12    | 16    | 20    | 28    | ...   |  |  |
| 1 1/8                                  | 1.1250                           | 7                          | 12                       | 18  | ...                                    | ...  | 8    | UNC   | 16    | 20    | 28    | ...   |  |  |
| (1 3/8)                                | 1.1875                           | ...                        | ...                      | 18  | ...                                    | ...  | 8    | 12    | 16    | 20    | 28    | ...   |  |  |
| 1 1/4                                  | 1.2500                           | 7                          | 12                       | 18  | ...                                    | ...  | 8    | UNC   | 16    | 20    | 28    | ...   |  |  |
| 1 5/16                                 | 1.3125                           | ...                        | ...                      | 18  | ...                                    | ...  | 8    | 12    | 16    | 20    | 28    | ...   |  |  |
| 1 3/8                                  | 1.3750                           | 6                          | 12                       | 18  | ...                                    | UNC  | 8    | UNC   | 16    | 20    | 28    | ...   |  |  |
| (1 7/16)                               | 1.4375                           | ...                        | ...                      | 18  | ...                                    | ...  | 6    | 8     | 12    | 16    | 20    | 28    |  |  |
| 1 1/2                                  | 1.5000                           | 6                          | 12                       | 18  | ...                                    | UNC  | 8    | UNC   | 16    | 20    | 28    | ...   |  |  |
| (1 9/16)                               | 1.5625                           | ...                        | ...                      | 18  | ...                                    | ...  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| 1 5/8                                  | 1.6250                           | ...                        | ...                      | 18  | ...                                    | ...  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| (1 11/16)                              | 1.6875                           | ...                        | ...                      | 18  | ...                                    | ...  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| 1 3/4                                  | 1.7500                           | 5                          | ...                      | ...   | ...                                    | ...  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| (1 13/16)                              | 1.8125                           | ...                        | ...                      | ...   | ...                                    | ...  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| 1 7/8                                  | 1.8750                           | ...                        | ...                      | ...   | ...                                    | ...  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| (1 15/16)                              | 1.9375                           | ...                        | ...                      | ...   | ...                                    | ...  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| 2                                      | 2.0000                           | 4 1/2                      | ...                      | ...   | ...                                    | ...  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| (2 1/8)                                | 2.1250                           | ...                        | ...                      | ...   | ...                                    | ...  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| 2 1/4                                  | 2.2500                           | 4 1/2                      | ...                      | ...   | ...                                    | ...  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| (2 3/8)                                | 2.3750                           | ...                        | ...                      | ...   | ...                                    | ...  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| 2 1/2                                  | 2.5000                           | 4                          | ...                      | ...   | ...                                    | UNC  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| (2 5/8)                                | 2.6250                           | ...                        | ...                      | ...   | ...                                    | 4    | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| 2 3/4                                  | 2.7500                           | 4                          | ...                      | ...   | ...                                    | UNC  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| (2 7/8)                                | 2.8750                           | ...                        | ...                      | ...   | ...                                    | 4    | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| 3                                      | 3.0000                           | 4                          | ...                      | ...   | ...                                    | UNC  | 6    | 8     | 12    | 16    | 20    | ...   |  |  |
| (3 1/8)                                | 3.1250                           | ...                        | ...                      | ...   | ...                                    | 4    | 6    | 8     | 12    | 16    | ...   | ...   |  |  |
| 3 1/4                                  | 3.2500                           | 4                          | ...                      | ...   | ...                                    | UNC  | 6    | 8     | 12    | 16    | ...   | ...   |  |  |
| (3 3/8)                                | 3.3750                           | ...                        | ...                      | ...   | ...                                    | 4    | 6    | 8     | 12    | 16    | ...   | ...   |  |  |
| 3 1/2                                  | 3.5000                           | 4                          | ...                      | ...   | ...                                    | UNC  | 6    | 8     | 12    | 16    | ...   | ...   |  |  |
| (3 5/8)                                | 3.6250                           | ...                        | ...                      | ...   | ...                                    | 4    | 6    | 8     | 12    | 16    | ...   | ...   |  |  |
| 3 3/4                                  | 3.7500                           | 4                          | ...                      | ...   | ...                                    | UNC  | 6    | 8     | 12    | 16    | ...   | ...   |  |  |
| (3 7/8)                                | 3.8750                           | ...                        | ...                      | ...   | ...                                    | 4    | 6    | 8     | 12    | 16    | ...   | ...   |  |  |
| 4                                      | 4.0000                           | 4                          | ...                      | ...   | ...                                    | UNC  | 6    | 8     | 12    | 16    | ...   | ...   |  |  |

<sup>a</sup> Sizes shown in parentheses are secondary sizes. Primary sizes of 4 1/4, 4 1/2, 4 3/4, 5, 5 1/4, 5 1/2, 5 3/4 and 6 inches also are in the 4, 6, 8, 12, and 16 thread series; secondary sizes of 4 1/8, 4 3/8, 4 7/8, 5 1/8, 5 3/8, 5 7/8, and 5 7/16 also are in the 4, 6, 8, 12, and 16 thread series.

<sup>b</sup> For diameters over 1 1/2 inches, use 12-thread series.

<sup>c</sup> For diameters over 1 11/16 inches, use 16-thread series.

For UNR thread form substitute UNR for UN for external threads only.

Table 3. Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        |   | Internal <sup>b</sup> |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|---|-----------------------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class                 | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |   |                       | Min            | Max    | Min            | Max    |                   |
| 0–80 UNF   | 2A                    | 0.0005         | 0.0595           | 0.0563 | —                | 0.0514           | 0.0496 | 0.0446  | 2B                    | 0.0465         | 0.0514 | 0.0519         | 0.0542 | 0.0600            |
|  | 3A                    | 0.0000         | 0.0600           | 0.0568 | —                | 0.0519           | 0.0506 | 0.0451  | 3B                    | 0.0465         | 0.0514 | 0.0519         | 0.0536 | 0.0600            |
| 1–64 UNC   | 2A                    | 0.0006         | 0.0724           | 0.0686 | —                | 0.0623           | 0.0603 | 0.0538  | 2B                    | 0.0561         | 0.0623 | 0.0629         | 0.0655 | 0.0730            |
|  | 3A                    | 0.0000         | 0.0730           | 0.0692 | —                | 0.0629           | 0.0614 | 0.0544  | 3B                    | 0.0561         | 0.0623 | 0.0629         | 0.0648 | 0.0730            |
| 1–72 UNF   | 2A                    | 0.0006         | 0.0724           | 0.0689 | —                | 0.0634           | 0.0615 | 0.0559  | 2B                    | 0.0580         | 0.0635 | 0.0640         | 0.0665 | 0.0730            |
|  | 3A                    | 0.0000         | 0.0730           | 0.0695 | —                | 0.0640           | 0.0626 | 0.0565  | 3B                    | 0.0580         | 0.0635 | 0.0640         | 0.0659 | 0.0730            |
| 2–56 UNC   | 2A                    | 0.0006         | 0.0854           | 0.0813 | —                | 0.0738           | 0.0717 | 0.0642  | 2B                    | 0.0667         | 0.0737 | 0.0744         | 0.0772 | 0.0860            |
|  | 3A                    | 0.0000         | 0.0860           | 0.0819 | —                | 0.0744           | 0.0728 | 0.0648  | 3B                    | 0.0667         | 0.0737 | 0.0744         | 0.0765 | 0.0860            |
| 2–64 UNF   | 2A                    | 0.0006         | 0.0854           | 0.0816 | —                | 0.0753           | 0.0733 | 0.0668  | 2B                    | 0.0691         | 0.0753 | 0.0759         | 0.0786 | 0.0860            |
|  | 3A                    | 0.0000         | 0.0860           | 0.0822 | —                | 0.0759           | 0.0744 | 0.0674  | 3B                    | 0.0691         | 0.0753 | 0.0759         | 0.0779 | 0.0860            |
| 3–48 UNC   | 2A                    | 0.0007         | 0.0983           | 0.0938 | —                | 0.0848           | 0.0825 | 0.0734  | 2B                    | 0.0764         | 0.0845 | 0.0855         | 0.0885 | 0.0990            |
|  | 3A                    | 0.0000         | 0.0990           | 0.0945 | —                | 0.0855           | 0.0838 | 0.0741  | 3B                    | 0.0764         | 0.0845 | 0.0855         | 0.0877 | 0.0990            |
| 3–56 UNF   | 2A                    | 0.0007         | 0.0983           | 0.0942 | —                | 0.0867           | 0.0845 | 0.0771  | 2B                    | 0.0797         | 0.0865 | 0.0874         | 0.0902 | 0.0990            |
|  | 3A                    | 0.0000         | 0.0990           | 0.0949 | —                | 0.0874           | 0.0858 | 0.0778  | 3B                    | 0.0797         | 0.0865 | 0.0874         | 0.0895 | 0.0990            |
| 4–40 UNC   | 2A                    | 0.0008         | 0.1112           | 0.1061 | —                | 0.0950           | 0.0925 | 0.0814  | 2B                    | 0.0849         | 0.0939 | 0.0958         | 0.0991 | 0.1120            |
|  | 3A                    | 0.0000         | 0.1120           | 0.1069 | —                | 0.0958           | 0.0939 | 0.0822  | 3B                    | 0.0849         | 0.0939 | 0.0958         | 0.0982 | 0.1120            |
| 4–48 UNF   | 2A                    | 0.0007         | 0.1113           | 0.1068 | —                | 0.0978           | 0.0954 | 0.0864  | 2B                    | 0.0894         | 0.0968 | 0.0985         | 0.1016 | 0.1120            |
|  | 3A                    | 0.0000         | 0.1120           | 0.1075 | —                | 0.0985           | 0.0967 | 0.0871  | 3B                    | 0.0894         | 0.0968 | 0.0985         | 0.1008 | 0.1120            |
| 5–40 UNC   | 2A                    | 0.0008         | 0.1242           | 0.1191 | —                | 0.1080           | 0.1054 | 0.0944  | 2B                    | 0.0979         | 0.1062 | 0.1088         | 0.1121 | 0.1250            |
|  | 3A                    | 0.0000         | 0.1250           | 0.1199 | —                | 0.1088           | 0.1069 | 0.0952  | 3B                    | 0.0979         | 0.1062 | 0.1088         | 0.1113 | 0.1250            |
| 5–44 UNF   | 2A                    | 0.0007         | 0.1243           | 0.1195 | —                | 0.1095           | 0.1070 | 0.0972  | 2B                    | 0.1004         | 0.1079 | 0.1102         | 0.1134 | 0.1250            |
|  | 3A                    | 0.0000         | 0.1250           | 0.1202 | —                | 0.1102           | 0.1083 | 0.0979  | 3B                    | 0.1004         | 0.1079 | 0.1102         | 0.1126 | 0.1250            |
| 6–32 UNC   | 2A                    | 0.0008         | 0.1372           | 0.1312 | —                | 0.1169           | 0.1141 | 0.1000  | 2B                    | 0.104          | 0.114  | 0.1177         | 0.1214 | 0.1380            |
|  | 3A                    | 0.0000         | 0.1380           | 0.1320 | —                | 0.1177           | 0.1156 | 0.1008  | 3B                    | 0.1040         | 0.1140 | 0.1177         | 0.1204 | 0.1380            |
| 6–40 UNF   | 2A                    | 0.0008         | 0.1372           | 0.1321 | —                | 0.1210           | 0.1184 | 0.1074  | 2B                    | 0.111          | 0.119  | 0.1218         | 0.1252 | 0.1380            |
|  | 3A                    | 0.0000         | 0.1380           | 0.1329 | —                | 0.1218           | 0.1198 | 0.1082  | 3B                    | 0.1110         | 0.1186 | 0.1218         | 0.1243 | 0.1380            |
| 8–32 UNC   | 2A                    | 0.0009         | 0.1631           | 0.1571 | —                | 0.1428           | 0.1399 | 0.1259  | 2B                    | 0.130          | 0.139  | 0.1437         | 0.1475 | 0.1640            |
|  | 3A                    | 0.0000         | 0.1640           | 0.1580 | —                | 0.1437           | 0.1415 | 0.1268  | 3B                    | 0.1300         | 0.1389 | 0.1437         | 0.1465 | 0.1640            |
| 8–36 UNF   | 2A                    | 0.0008         | 0.1632           | 0.1577 | —                | 0.1452           | 0.1424 | 0.1301  | 2B                    | 0.134          | 0.142  | 0.1460         | 0.1496 | 0.1640            |
|  | 3A                    | 0.0000         | 0.1640           | 0.1585 | —                | 0.1460           | 0.1439 | 0.1309  | 3B                    | 0.1340         | 0.1416 | 0.1460         | 0.1487 | 0.1640            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  | Internal <sup>b</sup> |  |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|-----------------------|--|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |                       | UNR Minor<br>Dia. <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min                   |  |       | Min            | Max    | Min            | Max    |                   |
| 10–24 UNC  | 2A                    | 0.0010         | 0.1890           | 0.1818 | —                | 0.1619           | 0.1586                | 0.1394                                       | 2B    | 0.145          | 0.156  | 0.1629         | 0.1672 | 0.1900            |
|  | 3A                    | 0.0000         | 0.1900           | 0.1828 | —                | 0.1629           | 0.1604                | 0.1404                                       | 3B    | 0.1450         | 0.1555 | 0.1629         | 0.1661 | 0.1900            |
| 10–28 UNS  | 2A                    | 0.0010         | 0.1890           | 0.1825 | —                | 0.1658           | 0.1625                | 0.1464                                       | 2B    | 0.151          | 0.160  | 0.1668         | 0.1711 | 0.1900            |
| 10–32 UNF  | 2A                    | 0.0009         | 0.1891           | 0.1831 | —                | 0.1688           | 0.1658                | 0.1519                                       | 2B    | 0.156          | 0.164  | 0.1697         | 0.1736 | 0.1900            |
|  | 3A                    | 0.0000         | 0.1900           | 0.1840 | —                | 0.1697           | 0.1674                | 0.1528                                       | 3B    | 0.1560         | 0.1641 | 0.1697         | 0.1726 | 0.1900            |
| 10–36 UNS  | 2A                    | 0.0009         | 0.1891           | 0.1836 | —                | 0.1711           | 0.1681                | 0.1560                                       | 2B    | 0.160          | 0.166  | 0.1720         | 0.1759 | 0.1900            |
| 10–40 UNS  | 2A                    | 0.0009         | 0.1891           | 0.1840 | —                | 0.1729           | 0.1700                | 0.1592                                       | 2B    | 0.163          | 0.169  | 0.1738         | 0.1775 | 0.1900            |
| 10–48 UNS  | 2A                    | 0.0008         | 0.1892           | 0.1847 | —                | 0.1757           | 0.1731                | 0.1644                                       | 2B    | 0.167          | 0.172  | 0.1765         | 0.1799 | 0.1900            |
| 10–56 UNS  | 2A                    | 0.0007         | 0.1893           | 0.1852 | —                | 0.1777           | 0.1752                | 0.1681                                       | 2B    | 0.171          | 0.175  | 0.1784         | 0.1816 | 0.1900            |
| 12–24 UNC  | 2A                    | 0.0010         | 0.2150           | 0.2078 | —                | 0.1879           | 0.1845                | 0.1654                                       | 2B    | 0.171          | 0.181  | 0.1889         | 0.1933 | 0.2160            |
|  | 3A                    | 0.0000         | 0.2160           | 0.2088 | —                | 0.1889           | 0.1863                | 0.1664                                       | 3B    | 0.1710         | 0.1807 | 0.1889         | 0.1922 | 0.2160            |
| 12–28 UNF  | 2A                    | 0.0010         | 0.2150           | 0.2085 | —                | 0.1918           | 0.1886                | 0.1724                                       | 2B    | 0.177          | 0.186  | 0.1928         | 0.1970 | 0.2160            |
|  | 3A                    | 0.0000         | 0.2160           | 0.2095 | —                | 0.1928           | 0.1904                | 0.1734                                       | 3B    | 0.1770         | 0.1857 | 0.1928         | 0.1959 | 0.2160            |
| 12–32 UNEF   | 2A                    | 0.0009         | 0.2151           | 0.2091 | —                | 0.1948           | 0.1917                | 0.1779                                       | 2B    | 0.182          | 0.190  | 0.1957         | 0.1998 | 0.2160            |
|  | 3A                    | 0.0000         | 0.2160           | 0.2100 | —                | 0.1957           | 0.1933                | 0.1788                                       | 3B    | 0.1820         | 0.1895 | 0.1957         | 0.1988 | 0.2160            |
| 12–36 UNS  | 2A                    | 0.0009         | 0.2151           | 0.2096 | —                | 0.1971           | 0.1941                | 0.1821                                       | 2B    | 0.186          | 0.192  | 0.1980         | 0.2019 | 0.2160            |
| 12–40 UNS  | 2A                    | 0.0009         | 0.2151           | 0.2100 | —                | 0.1989           | 0.1960                | 0.1835                                       | 2B    | 0.189          | 0.195  | 0.1998         | 0.2035 | 0.2160            |
| 12–48 UNS  | 2A                    | 0.0008         | 0.2152           | 0.2107 | —                | 0.2017           | 0.1991                | 0.1904                                       | 2B    | 0.193          | 0.198  | 0.2025         | 0.2059 | 0.2160            |
| 12–56 UNS  | 2A                    | 0.0007         | 0.2153           | 0.2112 | —                | 0.2037           | 0.2012                | 0.1941                                       | 2B    | 0.197          | 0.201  | 0.2044         | 0.2076 | 0.2160            |
| 1/4–20 UNC   | 1A                    | 0.0011         | 0.2489           | 0.2367 | —                | 0.2164           | 0.2108                | 0.1894                                       | 1B    | 0.196          | 0.207  | 0.2175         | 0.2248 | 0.2500            |
|  | 2A                    | 0.0011         | 0.2489           | 0.2408 | 0.2367           | 0.2164           | 0.2127                | 0.1894                                       | 2B    | 0.196          | 0.207  | 0.2175         | 0.2224 | 0.2500            |
|  | 3A                    | 0.0000         | 0.2500           | 0.2419 | —                | 0.2175           | 0.2147                | 0.1905                                       | 3B    | 0.1960         | 0.2067 | 0.2175         | 0.2211 | 0.2500            |
| 1/4–24 UNS   | 2A                    | 0.0011         | 0.2489           | 0.2417 | —                | 0.2218           | 0.2181                | 0.1993                                       | 2B    | 0.205          | 0.215  | 0.2229         | 0.2277 | 0.2500            |
| 1/4–27 UNS   | 2A                    | 0.0010         | 0.2490           | 0.2423 | —                | 0.2249           | 0.2214                | 0.2049                                       | 2B    | 0.210          | 0.219  | 0.2259         | 0.2304 | 0.2500            |
| 1/4–28 UNF   | 1A                    | 0.0010         | 0.2490           | 0.2392 | —                | 0.2258           | 0.2208                | 0.2064                                       | 1B    | 0.211          | 0.220  | 0.2268         | 0.2333 | 0.2500            |
|  | 2A                    | 0.0010         | 0.2490           | 0.2425 | —                | 0.2258           | 0.2225                | 0.2064                                       | 2B    | 0.211          | 0.220  | 0.2268         | 0.2311 | 0.2500            |
|  | 3A                    | 0.0000         | 0.2500           | 0.2435 | —                | 0.2268           | 0.2243                | 0.2074                                       | 3B    | 0.2110         | 0.2190 | 0.2268         | 0.2300 | 0.2500            |
| 1/4–32 UNEF  | 2A                    | 0.0010         | 0.2490           | 0.2430 | —                | 0.2287           | 0.2255                | 0.2118                                       | 2B    | 0.216          | 0.224  | 0.2297         | 0.2339 | 0.2500            |
|  | 3A                    | 0.0000         | 0.2500           | 0.2440 | —                | 0.2297           | 0.2273                | 0.2128                                       | 3B    | 0.2160         | 0.2229 | 0.2297         | 0.2328 | 0.2500            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                         |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|---|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |   |       | Min            | Max    | Min            | Max    | Min               |
| $\frac{1}{4}$ -36 UNS  | 2A                    | 0.0009         | 0.2491           | 0.2436 | —                | 0.2311           | 0.2280 | 0.2161  | 2B    | 0.220          | 0.226  | 0.2320         | 0.2360 | 0.2500            |
| $\frac{1}{4}$ -40 UNS  | 2A                    | 0.0009         | 0.2491           | 0.2440 | —                | 0.2329           | 0.2300 | 0.2193  | 2B    | 0.223          | 0.229  | 0.2338         | 0.2376 | 0.2500            |
| $\frac{1}{4}$ -48 UNS  | 2A                    | 0.0008         | 0.2492           | 0.2447 | —                | 0.2357           | 0.2330 | 0.2243  | 2B    | 0.227          | 0.232  | 0.2365         | 0.2401 | 0.2500            |
| $\frac{1}{4}$ -56 UNS  | 2A                    | 0.0008         | 0.2492           | 0.2451 | —                | 0.2376           | 0.2350 | 0.2280  | 2B    | 0.231          | 0.235  | 0.2384         | 0.2417 | 0.2500            |
| $\frac{5}{16}$ -18 UNC   | 1A                    | 0.0012         | 0.3113           | 0.2982 | —                | 0.2752           | 0.2691 | 0.2452  | 1B    | 0.252          | 0.265  | 0.2764         | 0.2843 | 0.3125            |
|  | 2A                    | 0.0012         | 0.3113           | 0.3026 | 0.2982           | 0.2752           | 0.2712 | 0.2452  | 2B    | 0.252          | 0.265  | 0.2764         | 0.2817 | 0.3125            |
|  | 3A                    | 0.0000         | 0.3125           | 0.3038 | —                | 0.2764           | 0.2734 | 0.2464  | 3B    | 0.2520         | 0.2630 | 0.2764         | 0.2803 | 0.3125            |
| $\frac{5}{16}$ -20 UN  | 2A                    | 0.0012         | 0.3113           | 0.3032 | —                | 0.2788           | 0.2748 | 0.2518  | 2B    | 0.258          | 0.270  | 0.2800         | 0.2852 | 0.3125            |
|  | 3A                    | 0.0000         | 0.3125           | 0.3044 | —                | 0.2800           | 0.2770 | 0.2530  | 3B    | 0.2580         | 0.2680 | 0.2800         | 0.2839 | 0.3125            |
| $\frac{5}{16}$ -24 UNF   | 1A                    | 0.0011         | 0.3114           | 0.3006 | —                | 0.2843           | 0.2788 | 0.2618  | 1B    | 0.267          | 0.277  | 0.2854         | 0.2925 | 0.3125            |
|  | 2A                    | 0.0011         | 0.3114           | 0.3042 | —                | 0.2843           | 0.2806 | 0.2618  | 2B    | 0.267          | 0.277  | 0.2854         | 0.2902 | 0.3125            |
|  | 3A                    | 0.0000         | 0.3125           | 0.3053 | —                | 0.2854           | 0.2827 | 0.2629  | 3B    | 0.2670         | 0.2754 | 0.2854         | 0.2890 | 0.3125            |
| $\frac{5}{16}$ -27 UNS   | 2A                    | 0.0010         | 0.3115           | 0.3048 | —                | 0.2874           | 0.2839 | 0.2674  | 2B    | 0.272          | 0.281  | 0.2884         | 0.2929 | 0.3125            |
| $\frac{5}{16}$ -28 UN  | 2A                    | 0.0010         | 0.3115           | 0.3050 | —                | 0.2883           | 0.2849 | 0.2689  | 2B    | 0.274          | 0.282  | 0.2893         | 0.2937 | 0.3125            |
|  | 3A                    | 0.0000         | 0.3125           | 0.3060 | —                | 0.2893           | 0.2867 | 0.2699  | 3B    | 0.2740         | 0.2807 | 0.2893         | 0.2926 | 0.3125            |
| $\frac{5}{16}$ -32 UNEF  | 2A                    | 0.0010         | 0.3115           | 0.3055 | —                | 0.2912           | 0.2880 | 0.2743  | 2B    | 0.279          | 0.286  | 0.2922         | 0.2964 | 0.3125            |
|  | 3A                    | 0.0000         | 0.3125           | 0.3065 | —                | 0.2922           | 0.2898 | 0.2753  | 3B    | 0.2790         | 0.2847 | 0.2922         | 0.2953 | 0.3125            |
| $\frac{5}{16}$ -36 UNS   | 2A                    | 0.0009         | 0.3116           | 0.3061 | —                | 0.2936           | 0.2905 | 0.2785  | 2B    | 0.282          | 0.289  | 0.2945         | 0.2985 | 0.3125            |
| $\frac{5}{16}$ -40 UNS   | 2A                    | 0.0009         | 0.3116           | 0.3065 | —                | 0.2954           | 0.2925 | 0.2818  | 2B    | 0.285          | 0.291  | 0.2963         | 0.3001 | 0.3125            |
| $\frac{5}{16}$ -48 UNS   | 2A                    | 0.0008         | 0.3117           | 0.3072 | —                | 0.2982           | 0.2955 | 0.2869  | 2B    | 0.290          | 0.295  | 0.2990         | 0.3026 | 0.3125            |
| $\frac{3}{8}$ -16 UNC  | 1A                    | 0.0013         | 0.3737           | 0.3595 | —                | 0.3331           | 0.3266 | 0.2992  | 1B    | 0.307          | 0.321  | 0.3344         | 0.3429 | 0.3750            |
|  | 2A                    | 0.0013         | 0.3737           | 0.3643 | 0.3595           | 0.3331           | 0.3287 | 0.2992  | 2B    | 0.307          | 0.321  | 0.3344         | 0.3401 | 0.3750            |
|  | 3A                    | 0.0000         | 0.3750           | 0.3656 | —                | 0.3344           | 0.3311 | 0.3005  | 3B    | 0.3070         | 0.3182 | 0.3344         | 0.3387 | 0.3750            |
| $\frac{3}{8}$ -18 UNS  | 2A                    | 0.0013         | 0.3737           | 0.3650 | —                | 0.3376           | 0.3333 | 0.3076  | 2B    | 0.315          | 0.328  | 0.3389         | 0.3445 | 0.3750            |
| $\frac{3}{8}$ -20 UN   | 2A                    | 0.0012         | 0.3738           | 0.3657 | —                | 0.3413           | 0.3372 | 0.3143  | 2B    | 0.321          | 0.332  | 0.3425         | 0.3479 | 0.3750            |
|  | 3A                    | 0.0000         | 0.3750           | 0.3669 | —                | 0.3425           | 0.3394 | 0.3155  | 3B    | 0.3210         | 0.3297 | 0.3425         | 0.3465 | 0.3750            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |           |                  |        |                  |                  |        | Internal <sup>b</sup>                        |       |                |        |                |        |                   |
|--|-----------------------|-----------|------------------|--------|------------------|------------------|--------|--|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allowance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia. <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |           | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |  |       | Min            | Max    | Min            | Max    |                   |
| $\frac{3}{8}$ -24 UNF  | 1A                    | 0.0011    | 0.3739           | 0.3631 | —                | 0.3468           | 0.3411 | 0.3243                                       | 1B    | 0.330          | 0.340  | 0.3479         | 0.3553 | 0.3750            |
|  | 2A                    | 0.0011    | 0.3739           | 0.3667 | —                | 0.3468           | 0.3430 | 0.3243                                       | 2B    | 0.330          | 0.340  | 0.3479         | 0.3528 | 0.3750            |
| $\frac{3}{8}$ -24 UNF  | 3A                    | 0.0000    | 0.3750           | 0.3678 | —                | 0.3479           | 0.3450 | 0.3254                                       | 3B    | 0.3300         | 0.3372 | 0.3479         | 0.3516 | 0.3750            |
|  | 2A                    | 0.0011    | 0.3739           | 0.3672 | —                | 0.3498           | 0.3462 | 0.3298                                       | 2B    | 0.335          | 0.344  | 0.3509         | 0.3556 | 0.3750            |
| $\frac{3}{8}$ -27 UNS  | 2A                    | 0.0011    | 0.3739           | 0.3674 | —                | 0.3507           | 0.3471 | 0.3313                                       | 2B    | 0.336          | 0.345  | 0.3518         | 0.3564 | 0.3750            |
|  | 3A                    | 0.0000    | 0.3750           | 0.3685 | —                | 0.3518           | 0.3491 | 0.3324                                       | 3B    | 0.3360         | 0.3426 | 0.3518         | 0.3553 | 0.3750            |
| $\frac{3}{8}$ -32 UNEF   | 2A                    | 0.0010    | 0.3740           | 0.3680 | —                | 0.3537           | 0.3503 | 0.3368                                       | 2B    | 0.341          | 0.349  | 0.3547         | 0.3591 | 0.3750            |
|  | 3A                    | 0.0000    | 0.3750           | 0.3690 | —                | 0.3547           | 0.3522 | 0.3378                                       | 3B    | 0.3410         | 0.3469 | 0.3547         | 0.3580 | 0.3750            |
| $\frac{3}{8}$ -36 UNS  | 2A                    | 0.0010    | 0.3740           | 0.3685 | —                | 0.3560           | 0.3528 | 0.3409                                       | 2B    | 0.345          | 0.352  | 0.3570         | 0.3612 | 0.3750            |
|  | 2A                    | 0.0009    | 0.3741           | 0.3690 | —                | 0.3579           | 0.3548 | 0.3443                                       | 2B    | 0.348          | 0.354  | 0.3588         | 0.3628 | 0.3750            |
| 0.390-27 UNS   | 2A                    | 0.0011    | 0.3889           | 0.3822 | —                | 0.3648           | 0.3612 | 0.3448                                       | 2B    | 0.350          | 0.359  | 0.3659         | 0.3706 | 0.3900            |
|  | 1A                    | 0.0014    | 0.4361           | 0.4206 | —                | 0.3897           | 0.3826 | 0.3511                                       | 1B    | 0.360          | 0.376  | 0.3911         | 0.4003 | 0.4375            |
| $\frac{7}{16}$ -14 UNC   | 2A                    | 0.0014    | 0.4361           | 0.4258 | 0.4206           | 0.3897           | 0.3850 | 0.3511                                       | 2B    | 0.360          | 0.376  | 0.3911         | 0.3972 | 0.4375            |
|  | 3A                    | 0.0000    | 0.4375           | 0.4272 | —                | 0.3911           | 0.3876 | 0.3525                                       | 3B    | 0.3600         | 0.3717 | 0.3911         | 0.3957 | 0.4375            |
| $\frac{7}{16}$ -16 UN  | 2A                    | 0.0014    | 0.4361           | 0.4267 | —                | 0.3955           | 0.3909 | 0.3616                                       | 2B    | 0.370          | 0.384  | 0.3969         | 0.4028 | 0.4375            |
|  | 3A                    | 0.0000    | 0.4375           | 0.4281 | —                | 0.3969           | 0.3935 | 0.3630                                       | 3B    | 0.3700         | 0.3800 | 0.3969         | 0.4014 | 0.4375            |
| $\frac{7}{16}$ -18 UNS   | 2A                    | 0.0013    | 0.4362           | 0.4275 | —                | 0.4001           | 0.3958 | 0.3701                                       | 2B    | 0.377          | 0.390  | 0.4014         | 0.4070 | 0.4375            |
|  | 1A                    | 0.0013    | 0.4362           | 0.4240 | —                | 0.4037           | 0.3975 | 0.3767                                       | 1B    | 0.383          | 0.395  | 0.4050         | 0.4131 | 0.4375            |
| $\frac{7}{16}$ -20 UNF   | 2A                    | 0.0013    | 0.4362           | 0.4281 | —                | 0.4037           | 0.3995 | 0.3767                                       | 2B    | 0.383          | 0.395  | 0.4050         | 0.4104 | 0.4375            |
|  | 3A                    | 0.0000    | 0.4375           | 0.4294 | —                | 0.4050           | 0.4019 | 0.3780                                       | 3B    | 0.3830         | 0.3916 | 0.4050         | 0.4091 | 0.4375            |
| $\frac{7}{16}$ -24 UNS   | 2A                    | 0.0011    | 0.4364           | 0.4292 | —                | 0.4093           | 0.4055 | 0.3868                                       | 2B    | 0.392          | 0.402  | 0.4104         | 0.4153 | 0.4375            |
|  | 2A                    | 0.0011    | 0.4364           | 0.4297 | —                | 0.4123           | 0.4087 | 0.3923                                       | 2B    | 0.397          | 0.406  | 0.4134         | 0.4181 | 0.4375            |
| $\frac{7}{16}$ -27 UNS   | 2A                    | 0.0011    | 0.4364           | 0.4299 | —                | 0.4132           | 0.4096 | 0.3938                                       | 2B    | 0.399          | 0.407  | 0.4143         | 0.4189 | 0.4375            |
|  | 3A                    | 0.0000    | 0.4375           | 0.4310 | —                | 0.4143           | 0.4116 | 0.3949                                       | 3B    | 0.3990         | 0.4051 | 0.4143         | 0.4178 | 0.4375            |
| $\frac{7}{16}$ -28 UNEF  | 2A                    | 0.0010    | 0.4365           | 0.4305 | —                | 0.4162           | 0.4128 | 0.3993                                       | 2B    | 0.404          | 0.411  | 0.4172         | 0.4216 | 0.4375            |
|  | 3A                    | 0.0000    | 0.4375           | 0.4315 | —                | 0.4172           | 0.4147 | 0.4003                                       | 3B    | 0.4040         | 0.4094 | 0.4172         | 0.4205 | 0.4375            |



Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                        |       |                |        |                |        |                          |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|--|-------|----------------|--------|----------------|--------|--------------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia. <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter<br>Min |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |  |       | Min            | Max    | Min            | Max    |                          |
| $\frac{1}{2}$ -12 UNS  | 2A                    | 0.0016         | 0.4984           | 0.4870 | —                | 0.4443           | 0.4389 | 0.3992                                       | 2B    | 0.410          | 0.428  | 0.4459         | 0.4529 | 0.5000                   |
|  | 3A                    | 0.0000         | 0.5000           | 0.4886 | —                | 0.4459           | 0.4419 | 0.4008                                       | 3B    | 0.4100         | 0.4223 | 0.4459         | 0.4511 | 0.5000                   |
| $\frac{1}{2}$ -13 UNC  | 1A                    | 0.0015         | 0.4985           | 0.4822 | —                | 0.4485           | 0.4411 | 0.4069                                       | 1B    | 0.417          | 0.434  | 0.4500         | 0.4597 | 0.5000                   |
|  | 2A                    | 0.0015         | 0.4985           | 0.4876 | 0.4822           | 0.4485           | 0.4435 | 0.4069                                       | 2B    | 0.417          | 0.434  | 0.4500         | 0.4565 | 0.5000                   |
| $\frac{1}{2}$ -14 UNS  | 3A                    | 0.0000         | 0.5000           | 0.4891 | —                | 0.4500           | 0.4463 | 0.4084                                       | 3B    | 0.4170         | 0.4284 | 0.4500         | 0.4548 | 0.5000                   |
|  | 2A                    | 0.0015         | 0.4985           | 0.4882 | —                | 0.4521           | 0.4471 | 0.4135                                       | 2B    | 0.423          | 0.438  | 0.4536         | 0.4601 | 0.5000                   |
| $\frac{1}{2}$ -16 UN   | 2A                    | 0.0014         | 0.4986           | 0.4892 | —                | 0.4580           | 0.4533 | 0.4241                                       | 2B    | 0.432          | 0.446  | 0.4594         | 0.4655 | 0.5000                   |
|  | 3A                    | 0.0000         | 0.5000           | 0.4906 | —                | 0.4594           | 0.4559 | 0.4255                                       | 3B    | 0.4320         | 0.4419 | 0.4594         | 0.4640 | 0.5000                   |
| $\frac{1}{2}$ -18 UNS  | 2A                    | 0.0013         | 0.4987           | 0.4900 | —                | 0.4626           | 0.4582 | 0.4326                                       | 2B    | 0.440          | 0.453  | 0.4639         | 0.4697 | 0.5000                   |
|  | 1A                    | 0.0013         | 0.4987           | 0.4865 | —                | 0.4662           | 0.4598 | 0.4392                                       | 1B    | 0.446          | 0.457  | 0.4675         | 0.4759 | 0.5000                   |
| $\frac{1}{2}$ -20 UNF  | 2A                    | 0.0013         | 0.4987           | 0.4906 | —                | 0.4662           | 0.4619 | 0.4392                                       | 2B    | 0.446          | 0.457  | 0.4675         | 0.4731 | 0.5000                   |
|  | 3A                    | 0.0000         | 0.5000           | 0.4919 | —                | 0.4675           | 0.4643 | 0.4405                                       | 3B    | 0.4460         | 0.4537 | 0.4675         | 0.4717 | 0.5000                   |
| $\frac{1}{2}$ -24 UNS  | 2A                    | 0.0012         | 0.4988           | 0.4916 | —                | 0.4717           | 0.4678 | 0.4492                                       | 2B    | 0.455          | 0.465  | 0.4729         | 0.4780 | 0.5000                   |
|  | 2A                    | 0.0011         | 0.4989           | 0.4922 | —                | 0.4748           | 0.4711 | 0.4548                                       | 2B    | 0.460          | 0.469  | 0.4759         | 0.4807 | 0.5000                   |
| $\frac{1}{2}$ -27 UNS  | 2A                    | 0.0011         | 0.4989           | 0.4924 | —                | 0.4757           | 0.4720 | 0.4563                                       | 2B    | 0.461          | 0.470  | 0.4768         | 0.4816 | 0.5000                   |
|  | 3A                    | 0.0000         | 0.5000           | 0.4935 | —                | 0.4768           | 0.4740 | 0.4574                                       | 3B    | 0.4610         | 0.4676 | 0.4768         | 0.4804 | 0.5000                   |
| $\frac{1}{2}$ -28 UNEF   | 2A                    | 0.0010         | 0.4990           | 0.4930 | —                | 0.4787           | 0.4752 | 0.4618                                       | 2B    | 0.466          | 0.474  | 0.4797         | 0.4842 | 0.5000                   |
|  | 3A                    | 0.0000         | 0.5000           | 0.4940 | —                | 0.4797           | 0.4771 | 0.4628                                       | 3B    | 0.4660         | 0.4719 | 0.4797         | 0.4831 | 0.5000                   |
| $\frac{3}{16}$ -12 UNC   | 1A                    | 0.0016         | 0.5609           | 0.5437 | —                | 0.5068           | 0.4990 | 0.4617                                       | 1B    | 0.472          | 0.490  | 0.5084         | 0.5186 | 0.5625                   |
|  | 2A                    | 0.0016         | 0.5609           | 0.5495 | 0.5437           | 0.5068           | 0.5016 | 0.4617                                       | 2B    | 0.472          | 0.490  | 0.5084         | 0.5152 | 0.5625                   |
| $\frac{3}{16}$ -14 UNS   | 3A                    | 0.0000         | 0.5625           | 0.5511 | —                | 0.5084           | 0.5045 | 0.4633                                       | 3B    | 0.4720         | 0.4843 | 0.5084         | 0.5135 | 0.5625                   |
|  | 2A                    | 0.0015         | 0.5610           | 0.5507 | —                | 0.5146           | 0.5096 | 0.4760                                       | 2B    | 0.485          | 0.501  | 0.5161         | 0.5226 | 0.5625                   |
| $\frac{3}{16}$ -16 UN  | 2A                    | 0.0014         | 0.5611           | 0.5517 | —                | 0.5205           | 0.5158 | 0.4866                                       | 2B    | 0.495          | 0.509  | 0.5219         | 0.5280 | 0.5625                   |
|  | 3A                    | 0.0000         | 0.5625           | 0.5531 | —                | 0.5219           | 0.5184 | 0.4880                                       | 3B    | 0.4950         | 0.5040 | 0.5219         | 0.5265 | 0.5625                   |
| $\frac{3}{16}$ -18 UNF   | 1A                    | 0.0014         | 0.5611           | 0.5480 | —                | 0.5250           | 0.5182 | 0.4950                                       | 1B    | 0.502          | 0.515  | 0.5264         | 0.5353 | 0.5625                   |
|  | 2A                    | 0.0014         | 0.5611           | 0.5524 | —                | 0.5250           | 0.5205 | 0.4950                                       | 2B    | 0.502          | 0.515  | 0.5264         | 0.5323 | 0.5625                   |
|  | 3A                    | 0.0000         | 0.5625           | 0.5538 | —                | 0.5264           | 0.5230 | 0.4964                                       | 3B    | 0.5020         | 0.5106 | 0.5264         | 0.5308 | 0.5625                   |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                         |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|---|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |   |       | Min            | Max    | Min            | Max    |                   |
| $\frac{1}{16}$ -20 UN  | 2A                    | 0.0013         | 0.5612           | 0.5531 | —                | 0.5287           | 0.5245 | 0.5017  | 2B    | 0.508          | 0.520  | 0.5300         | 0.5355 | 0.5625            |
|  | 3A                    | 0.0000         | 0.5625           | 0.5544 | —                | 0.5300           | 0.5268 | 0.5030  | 3B    | 0.5080         | 0.5162 | 0.5300         | 0.5341 | 0.5625            |
| $\frac{1}{16}$ -24 UNEF  | 2A                    | 0.0012         | 0.5613           | 0.5541 | —                | 0.5342           | 0.5303 | 0.5117  | 2B    | 0.517          | 0.527  | 0.5354         | 0.5405 | 0.5625            |
|  | 3A                    | 0.0000         | 0.5625           | 0.5553 | —                | 0.5354           | 0.5325 | 0.5129  | 3B    | 0.5170         | 0.5244 | 0.5354         | 0.5392 | 0.5625            |
| $\frac{1}{16}$ -27 UNS   | 2A                    | 0.0011         | 0.5614           | 0.5547 | —                | 0.5373           | 0.5336 | 0.5173  | 2B    | 0.522          | 0.531  | 0.5384         | 0.5432 | 0.5625            |
| $\frac{1}{16}$ -28 UN  | 2A                    | 0.0011         | 0.5614           | 0.5549 | —                | 0.5382           | 0.5345 | 0.5188  | 2B    | 0.524          | 0.532  | 0.5393         | 0.5441 | 0.5625            |
|  | 3A                    | 0.0000         | 0.5625           | 0.5560 | —                | 0.5393           | 0.5365 | 0.5199  | 3B    | 0.5240         | 0.5301 | 0.5393         | 0.5429 | 0.5625            |
| $\frac{1}{16}$ -32 UN  | 2A                    | 0.0010         | 0.5615           | 0.5555 | —                | 0.5412           | 0.5377 | 0.5243  | 2B    | 0.529          | 0.536  | 0.5422         | 0.5467 | 0.5625            |
|  | 3A                    | 0.0000         | 0.5625           | 0.5565 | —                | 0.5422           | 0.5396 | 0.5253  | 3B    | 0.5290         | 0.5344 | 0.5422         | 0.5456 | 0.5625            |
| $\frac{5}{8}$ -11 UNC  | 1A                    | 0.0016         | 0.6234           | 0.6052 | —                | 0.5644           | 0.5561 | 0.5152  | 1B    | 0.527          | 0.546  | 0.5660         | 0.5767 | 0.6250            |
|  | 2A                    | 0.0016         | 0.6234           | 0.6113 | 0.6052           | 0.5644           | 0.5589 | 0.5152  | 2B    | 0.527          | 0.546  | 0.5660         | 0.5732 | 0.6250            |
|  | 3A                    | 0.0000         | 0.6250           | 0.6129 | —                | 0.5660           | 0.5619 | 0.5168  | 3B    | 0.5270         | 0.5391 | 0.5660         | 0.5714 | 0.6250            |
| $\frac{5}{8}$ -12 UN   | 2A                    | 0.0016         | 0.6234           | 0.6120 | —                | 0.5693           | 0.5639 | 0.5242  | 2B    | 0.535          | 0.553  | 0.5709         | 0.5780 | 0.6250            |
|  | 3A                    | 0.0000         | 0.6250           | 0.6136 | —                | 0.5709           | 0.5668 | 0.5258  | 3B    | 0.5350         | 0.5463 | 0.5709         | 0.5762 | 0.6250            |
| $\frac{5}{8}$ -14 UNS  | 2A                    | 0.0015         | 0.6235           | 0.6132 | —                | 0.5771           | 0.5720 | 0.5385  | 2B    | 0.548          | 0.564  | 0.5786         | 0.5852 | 0.6250            |
|  | 2A                    | 0.0014         | 0.6236           | 0.6142 | —                | 0.5830           | 0.5782 | 0.5491  | 2B    | 0.557          | 0.571  | 0.5844         | 0.5906 | 0.6250            |
| $\frac{5}{8}$ -16 UN   | 3A                    | 0.0000         | 0.6250           | 0.6156 | —                | 0.5844           | 0.5808 | 0.5505  | 3B    | 0.5570         | 0.5662 | 0.5844         | 0.5890 | 0.6250            |
|  | 1A                    | 0.0014         | 0.6236           | 0.6105 | —                | 0.5875           | 0.5805 | 0.5575  | 1B    | 0.565          | 0.578  | 0.5889         | 0.5980 | 0.6250            |
| $\frac{5}{8}$ -18 UNF  | 2A                    | 0.0014         | 0.6236           | 0.6149 | —                | 0.5875           | 0.5828 | 0.5575  | 2B    | 0.565          | 0.578  | 0.5889         | 0.5949 | 0.6250            |
|  | 3A                    | 0.0000         | 0.6250           | 0.6163 | —                | 0.5889           | 0.5854 | 0.5589  | 3B    | 0.5650         | 0.5730 | 0.5889         | 0.5934 | 0.6250            |
| $\frac{5}{8}$ -20 UN   | 2A                    | 0.0013         | 0.6237           | 0.6156 | —                | 0.5912           | 0.5869 | 0.5642  | 2B    | 0.571          | 0.582  | 0.5925         | 0.5981 | 0.6250            |
|  | 3A                    | 0.0000         | 0.6250           | 0.6169 | —                | 0.5925           | 0.5893 | 0.5655  | 3B    | 0.5710         | 0.5787 | 0.5925         | 0.5967 | 0.6250            |
| $\frac{5}{8}$ -24 UNEF   | 2A                    | 0.0012         | 0.6238           | 0.6166 | —                | 0.5967           | 0.5927 | 0.5742  | 2B    | 0.580          | 0.590  | 0.5979         | 0.6031 | 0.6250            |
|  | 3A                    | 0.0000         | 0.6250           | 0.6178 | —                | 0.5979           | 0.5949 | 0.5754  | 3B    | 0.5800         | 0.5869 | 0.5979         | 0.6018 | 0.6250            |
| $\frac{5}{8}$ -27 UNS  | 2A                    | 0.0011         | 0.6239           | 0.6172 | —                | 0.5998           | 0.5960 | 0.5798  | 2B    | 0.585          | 0.594  | 0.6009         | 0.6059 | 0.6250            |
| $\frac{5}{8}$ -28 UN   | 2A                    | 0.0011         | 0.6239           | 0.6174 | —                | 0.6007           | 0.5969 | 0.5813  | 2B    | 0.586          | 0.595  | 0.6018         | 0.6067 | 0.6250            |
|  | 3A                    | 0.0000         | 0.6250           | 0.6185 | —                | 0.6018           | 0.5990 | 0.5824  | 3B    | 0.5860         | 0.5926 | 0.6018         | 0.6055 | 0.6250            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                         |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|---|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |   |       | Min            | Max    | Min            | Max    | Min               |
| $\frac{5}{8}$ -32 UN   | 2A                    | 0.0011         | 0.6239           | 0.6179 | —                | 0.6036           | 0.6000 | 0.5867  | 2B    | 0.591          | 0.599  | 0.6047         | 0.6093 | 0.6250            |
|  | 3A                    | 0.0000         | 0.6250           | 0.6190 | —                | 0.6047           | 0.6020 | 0.5878  | 3B    | 0.5910         | 0.5969 | 0.6047         | 0.6082 | 0.6250            |
| $\frac{1}{2}$ -12 UN   | 2A                    | 0.0016         | 0.6859           | 0.6745 | —                | 0.6318           | 0.6264 | 0.5867  | 2B    | 0.597          | 0.615  | 0.6334         | 0.6405 | 0.6875            |
|  | 3A                    | 0.0000         | 0.6875           | 0.6761 | —                | 0.6334           | 0.6293 | 0.5883  | 3B    | 0.5970         | 0.6085 | 0.6334         | 0.6387 | 0.6875            |
| $\frac{1}{2}$ -16 UN   | 2A                    | 0.0014         | 0.6861           | 0.6767 | —                | 0.6455           | 0.6407 | 0.6116  | 2B    | 0.620          | 0.634  | 0.6469         | 0.6531 | 0.6875            |
|  | 3A                    | 0.0000         | 0.6875           | 0.6781 | —                | 0.6469           | 0.6433 | 0.6130  | 3B    | 0.6200         | 0.6284 | 0.6469         | 0.6515 | 0.6875            |
| $\frac{1}{2}$ -20 UN   | 2A                    | 0.0013         | 0.6862           | 0.6781 | —                | 0.6537           | 0.6494 | 0.6267  | 2B    | 0.633          | 0.645  | 0.6550         | 0.6606 | 0.6875            |
|  | 3A                    | 0.0000         | 0.6875           | 0.6794 | —                | 0.6550           | 0.6518 | 0.6280  | 3B    | 0.6330         | 0.6412 | 0.6550         | 0.6592 | 0.6875            |
| $\frac{1}{2}$ -24 UNEF   | 2A                    | 0.0012         | 0.6863           | 0.6791 | —                | 0.6592           | 0.6552 | 0.6367  | 2B    | 0.642          | 0.652  | 0.6604         | 0.6656 | 0.6875            |
|  | 3A                    | 0.0000         | 0.6875           | 0.6803 | —                | 0.6604           | 0.6574 | 0.6379  | 3B    | 0.6420         | 0.6494 | 0.6604         | 0.6643 | 0.6875            |
| $\frac{1}{2}$ -28 UN   | 2A                    | 0.0011         | 0.6864           | 0.6799 | —                | 0.6632           | 0.6594 | 0.6438  | 2B    | 0.649          | 0.657  | 0.6643         | 0.6692 | 0.6875            |
|  | 3A                    | 0.0000         | 0.6875           | 0.6810 | —                | 0.6643           | 0.6615 | 0.6449  | 3B    | 0.6490         | 0.6551 | 0.6643         | 0.6680 | 0.6875            |
| $\frac{1}{2}$ -32 UN   | 2A                    | 0.0011         | 0.6864           | 0.6804 | —                | 0.6661           | 0.6625 | 0.6492  | 2B    | 0.654          | 0.661  | 0.6672         | 0.6718 | 0.6875            |
|  | 3A                    | 0.0000         | 0.6875           | 0.6815 | —                | 0.6672           | 0.6645 | 0.6503  | 3B    | 0.6540         | 0.6594 | 0.6672         | 0.6707 | 0.6875            |
| $\frac{3}{4}$ -10 UNC  | 1A                    | 0.0018         | 0.7482           | 0.7288 | —                | 0.6832           | 0.6744 | 0.6291  | 1B    | 0.642          | 0.663  | 0.6850         | 0.6965 | 0.7500            |
|  | 2A                    | 0.0018         | 0.7482           | 0.7353 | 0.7288           | 0.6832           | 0.6773 | 0.6291  | 2B    | 0.642          | 0.663  | 0.6850         | 0.6927 | 0.7500            |
| $\frac{3}{4}$ -12 UN   | 3A                    | 0.0000         | 0.7500           | 0.7371 | —                | 0.6850           | 0.6806 | 0.6309  | 3B    | 0.6420         | 0.6545 | 0.6850         | 0.6907 | 0.7500            |
|  | 2A                    | 0.0017         | 0.7483           | 0.7369 | —                | 0.6942           | 0.6887 | 0.6491  | 2B    | 0.660          | 0.678  | 0.6959         | 0.7031 | 0.7500            |
| $\frac{3}{4}$ -14 UNS  | 3A                    | 0.0000         | 0.7500           | 0.7386 | —                | 0.6959           | 0.6918 | 0.6508  | 3B    | 0.6600         | 0.6707 | 0.6959         | 0.7013 | 0.7500            |
|  | 2A                    | 0.0015         | 0.7485           | 0.7382 | —                | 0.7021           | 0.6970 | 0.6635  | 2B    | 0.673          | 0.688  | 0.7036         | 0.7103 | 0.7500            |
| $\frac{3}{4}$ -16 UNF  | 1A                    | 0.0015         | 0.7485           | 0.7343 | —                | 0.7079           | 0.7004 | 0.6740  | 1B    | 0.682          | 0.696  | 0.7094         | 0.7192 | 0.7500            |
|  | 2A                    | 0.0015         | 0.7485           | 0.7391 | —                | 0.7079           | 0.7029 | 0.6740  | 2B    | 0.682          | 0.696  | 0.7094         | 0.7159 | 0.7500            |
| $\frac{3}{4}$ -18 UNS  | 3A                    | 0.0000         | 0.7500           | 0.7406 | —                | 0.7094           | 0.7056 | 0.6755  | 3B    | 0.6820         | 0.6908 | 0.7094         | 0.7143 | 0.7500            |
|  | 2A                    | 0.0014         | 0.7486           | 0.7399 | —                | 0.7125           | 0.7079 | 0.6825  | 2B    | 0.690          | 0.703  | 0.7139         | 0.7199 | 0.7500            |
| $\frac{3}{4}$ -20 UNEF   | 2A                    | 0.0013         | 0.7487           | 0.7406 | —                | 0.7162           | 0.7118 | 0.6892  | 2B    | 0.696          | 0.707  | 0.7175         | 0.7232 | 0.7500            |
|  | 3A                    | 0.0000         | 0.7500           | 0.7419 | —                | 0.7175           | 0.7142 | 0.6905  | 3B    | 0.6960         | 0.7037 | 0.7175         | 0.7218 | 0.7500            |
| $\frac{3}{4}$ -24 UNS  | 2A                    | 0.0012         | 0.7488           | 0.7416 | —                | 0.7217           | 0.7176 | 0.6992  | 2B    | 0.705          | 0.715  | 0.7229         | 0.7282 | 0.7500            |
|  | 2A                    | 0.0012         | 0.7488           | 0.7421 | —                | 0.7247           | 0.7208 | 0.7047  | 2B    | 0.710          | 0.719  | 0.7259         | 0.7310 | 0.7500            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |           |                  |        |                  |                  |        | Internal <sup>b</sup>                         |       |                |        |                |        |                   |
|--|-----------------------|-----------|------------------|--------|------------------|------------------|--------|---|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allowance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |           | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |   |       | Min            | Max    | Min            | Max    | Min               |
| $\frac{3}{8}$ -28 UN   | 2A                    | 0.0012    | 0.7488           | 0.7423 | —                | 0.7256           | 0.7218 | 0.7062  | 2B    | 0.711          | 0.720  | 0.7268         | 0.7318 | 0.7500            |
|  | 3A                    | 0.0000    | 0.7500           | 0.7435 | —                | 0.7268           | 0.7239 | 0.7074  | 3B    | 0.7110         | 0.7176 | 0.7268         | 0.7305 | 0.7500            |
| $\frac{3}{8}$ -32 UN   | 2A                    | 0.0011    | 0.7489           | 0.7429 | —                | 0.7286           | 0.7250 | 0.7117  | 2B    | 0.716          | 0.724  | 0.7297         | 0.7344 | 0.7500            |
|  | 3A                    | 0.0000    | 0.7500           | 0.7440 | —                | 0.7297           | 0.7270 | 0.7128  | 3B    | 0.7160         | 0.7219 | 0.7297         | 0.7333 | 0.7500            |
| $\frac{1}{2}$ -12 UN   | 2A                    | 0.0017    | 0.8108           | 0.7994 | —                | 0.7567           | 0.7512 | 0.7116  | 2B    | 0.722          | 0.740  | 0.7584         | 0.7656 | 0.8125            |
|  | 3A                    | 0.0000    | 0.8125           | 0.8011 | —                | 0.7584           | 0.7543 | 0.7133  | 3B    | 0.7220         | 0.7329 | 0.7584         | 0.7638 | 0.8125            |
| $\frac{1}{2}$ -16 UN   | 2A                    | 0.0015    | 0.8110           | 0.8016 | —                | 0.7704           | 0.7655 | 0.7365  | 2B    | 0.745          | 0.759  | 0.7719         | 0.7782 | 0.8125            |
|  | 3A                    | 0.0000    | 0.8125           | 0.8031 | —                | 0.7719           | 0.7683 | 0.7380  | 3B    | 0.7450         | 0.7533 | 0.7719         | 0.7766 | 0.8125            |
| $\frac{1}{2}$ -20 UNEF   | 2A                    | 0.0013    | 0.8112           | 0.8031 | —                | 0.7787           | 0.7743 | 0.7517  | 2B    | 0.758          | 0.770  | 0.7800         | 0.7857 | 0.8125            |
|  | 3A                    | 0.0000    | 0.8125           | 0.8044 | —                | 0.7800           | 0.7767 | 0.7530  | 3B    | 0.7580         | 0.7662 | 0.7800         | 0.7843 | 0.8125            |
| $\frac{1}{2}$ -28 UN   | 2A                    | 0.0012    | 0.8113           | 0.8048 | —                | 0.7881           | 0.7843 | 0.7687  | 2B    | 0.774          | 0.782  | 0.7893         | 0.7943 | 0.8125            |
|  | 3A                    | 0.0000    | 0.8125           | 0.8060 | —                | 0.7893           | 0.7864 | 0.7699  | 3B    | 0.7740         | 0.7801 | 0.7893         | 0.7930 | 0.8125            |
| $\frac{1}{2}$ -32 UN   | 2A                    | 0.0011    | 0.8114           | 0.8054 | —                | 0.7911           | 0.7875 | 0.7742  | 2B    | 0.779          | 0.786  | 0.7922         | 0.7969 | 0.8125            |
|  | 3A                    | 0.0000    | 0.8125           | 0.8065 | —                | 0.7922           | 0.7895 | 0.7753  | 3B    | 0.7790         | 0.7844 | 0.7922         | 0.7958 | 0.8125            |
| $\frac{7}{8}$ -9 UNC   | 1A                    | 0.0019    | 0.8731           | 0.8523 | —                | 0.8009           | 0.7914 | 0.7408  | 1B    | 0.755          | 0.778  | 0.8028         | 0.8151 | 0.8750            |
|  | 2A                    | 0.0019    | 0.8731           | 0.8592 | 0.8523           | 0.8009           | 0.7946 | 0.7408  | 2B    | 0.755          | 0.778  | 0.8028         | 0.8110 | 0.8750            |
| $\frac{7}{8}$ -10 UNS  | 3A                    | 0.0000    | 0.8750           | 0.8611 | —                | 0.8028           | 0.7981 | 0.7427  | 3B    | 0.7550         | 0.7681 | 0.8028         | 0.8089 | 0.8750            |
|  | 2A                    | 0.0018    | 0.8732           | 0.8603 | —                | 0.8082           | 0.8022 | 0.7542  | 2B    | 0.767          | 0.788  | 0.8100         | 0.8178 | 0.8750            |
| $\frac{7}{8}$ -12 UN   | 2A                    | 0.0017    | 0.8733           | 0.8619 | —                | 0.8192           | 0.8137 | 0.7741  | 2B    | 0.785          | 0.803  | 0.8209         | 0.8281 | 0.8750            |
|  | 3A                    | 0.0000    | 0.8750           | 0.8636 | —                | 0.8209           | 0.8168 | 0.7758  | 3B    | 0.7850         | 0.7948 | 0.8209         | 0.8263 | 0.8750            |
| $\frac{7}{8}$ -14 UNF  | 1A                    | 0.0016    | 0.8734           | 0.8579 | —                | 0.8270           | 0.8189 | 0.7884  | 1B    | 0.798          | 0.814  | 0.8286         | 0.8392 | 0.8750            |
|  | 2A                    | 0.0016    | 0.8734           | 0.8631 | —                | 0.8270           | 0.8216 | 0.7884  | 2B    | 0.798          | 0.814  | 0.8286         | 0.8356 | 0.8750            |
| $\frac{7}{8}$ -16 UN   | 3A                    | 0.0000    | 0.8750           | 0.8647 | —                | 0.8286           | 0.8245 | 0.7900  | 3B    | 0.7980         | 0.8068 | 0.8286         | 0.8339 | 0.8750            |
|  | 2A                    | 0.0015    | 0.8735           | 0.8641 | —                | 0.8329           | 0.8280 | 0.7900  | 2B    | 0.807          | 0.821  | 0.8344         | 0.8407 | 0.8750            |
| $\frac{7}{8}$ -18 UNS  | 3A                    | 0.0000    | 0.8750           | 0.8656 | —                | 0.8344           | 0.8308 | 0.8005  | 3B    | 0.8070         | 0.8158 | 0.8344         | 0.8391 | 0.8750            |
|  | 2A                    | 0.0014    | 0.8736           | 0.8649 | —                | 0.8375           | 0.8329 | 0.8075  | 2B    | 0.815          | 0.828  | 0.8389         | 0.8449 | 0.8750            |
| $\frac{7}{8}$ -20 UNEF   | 2A                    | 0.0013    | 0.8737           | 0.8656 | —                | 0.8412           | 0.8368 | 0.8142  | 2B    | 0.821          | 0.832  | 0.8425         | 0.8482 | 0.8750            |
|  | 3A                    | 0.0000    | 0.8750           | 0.8669 | —                | 0.8425           | 0.8392 | 0.8155  | 3B    | 0.8210         | 0.8287 | 0.8425         | 0.8468 | 0.8750            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                        |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|--|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia. <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |  |       | Min            | Max    | Min            | Max    |                   |
| $\frac{7}{8}$ -24 UNS  | 2A                    | 0.0012         | 0.8738           | 0.8666 | —                | 0.8467           | 0.8426 | 0.8242                                       | 2B    | 0.830          | 0.840  | 0.8479         | 0.8532 | 0.8750            |
| $\frac{7}{8}$ -27 UNS  | 2A                    | 0.0012         | 0.8738           | 0.8671 | —                | 0.8497           | 0.8458 | 0.8297                                       | 2B    | 0.835          | 0.844  | 0.8509         | 0.8560 | 0.8750            |
| $\frac{7}{8}$ -28 UN   | 2A                    | 0.0012         | 0.8738           | 0.8673 | —                | 0.8506           | 0.8468 | 0.8312                                       | 2B    | 0.836          | 0.845  | 0.8518         | 0.8568 | 0.8750            |
|  | 3A                    | 0.0000         | 0.8750           | 0.8685 | —                | 0.8518           | 0.8489 | 0.8324                                       | 3B    | 0.8360         | 0.8426 | 0.8518         | 0.8555 | 0.8750            |
| $\frac{7}{8}$ -32 UN   | 2A                    | 0.0011         | 0.8739           | 0.8679 | —                | 0.8536           | 0.8500 | 0.8367                                       | 2B    | 0.841          | 0.849  | 0.8547         | 0.8594 | 0.8750            |
|  | 3A                    | 0.0000         | 0.8750           | 0.8690 | —                | 0.8547           | 0.8520 | 0.8378                                       | 3B    | 0.8410         | 0.8469 | 0.8547         | 0.8583 | 0.8750            |
| $\frac{15}{16}$ -12 UN   | 2A                    | 0.0017         | 0.9358           | 0.9244 | —                | 0.8817           | 0.8760 | 0.8366                                       | 2B    | 0.847          | 0.865  | 0.8834         | 0.8908 | 0.9375            |
|  | 3A                    | 0.0000         | 0.9375           | 0.9261 | —                | 0.8834           | 0.8793 | 0.8383                                       | 3B    | 0.8470         | 0.8575 | 0.8834         | 0.8889 | 0.9375            |
| $\frac{15}{16}$ -16 UN   | 2A                    | 0.0015         | 0.9360           | 0.9266 | —                | 0.8954           | 0.8904 | 0.8615                                       | 2B    | 0.870          | 0.884  | 0.8969         | 0.9034 | 0.9375            |
|  | 3A                    | 0.0000         | 0.9375           | 0.9281 | —                | 0.8969           | 0.8932 | 0.8630                                       | 3B    | 0.8700         | 0.8783 | 0.8969         | 0.9018 | 0.9375            |
| $\frac{15}{16}$ -20 UNEF   | 2A                    | 0.0014         | 0.9361           | 0.9280 | —                | 0.9036           | 0.8991 | 0.8766                                       | 2B    | 0.883          | 0.895  | 0.9050         | 0.9109 | 0.9375            |
|  | 3A                    | 0.0000         | 0.9375           | 0.9294 | —                | 0.9050           | 0.9016 | 0.8780                                       | 3B    | 0.8830         | 0.8912 | 0.9050         | 0.9094 | 0.9375            |
| $\frac{15}{16}$ -28 UN   | 2A                    | 0.0012         | 0.9363           | 0.9298 | —                | 0.9131           | 0.9091 | 0.8937                                       | 2B    | 0.899          | 0.907  | 0.9143         | 0.9195 | 0.9375            |
|  | 3A                    | 0.0000         | 0.9375           | 0.9310 | —                | 0.9143           | 0.9113 | 0.8949                                       | 3B    | 0.8990         | 0.9051 | 0.9143         | 0.9182 | 0.9375            |
| $\frac{15}{16}$ -32 UN   | 2A                    | 0.0011         | 0.9364           | 0.9304 | —                | 0.9161           | 0.9123 | 0.8992                                       | 2B    | 0.904          | 0.911  | 0.9172         | 0.9221 | 0.9375            |
|  | 3A                    | 0.0000         | 0.9375           | 0.9315 | —                | 0.9172           | 0.9144 | 0.9003                                       | 3B    | 0.9040         | 0.9094 | 0.9172         | 0.9209 | 0.9375            |
| 1-8 UNC  | 1A                    | 0.0020         | 0.9980           | 0.9755 | —                | 0.9168           | 0.9067 | 0.8492                                       | 1B    | 0.865          | 0.890  | 0.9188         | 0.9320 | 1.0000            |
|  | 2A                    | 0.0020         | 0.9980           | 0.9830 | 0.9755           | 0.9168           | 0.9100 | 0.8492                                       | 2B    | 0.865          | 0.890  | 0.9188         | 0.9276 | 1.0000            |
|  | 3A                    | 0.0000         | 1.0000           | 0.9850 | —                | 0.9188           | 0.9137 | 0.8512                                       | 3B    | 0.8650         | 0.8797 | 0.9188         | 0.9254 | 1.0000            |
| 1-10 UNS   | 2A                    | 0.0018         | 0.9982           | 0.9853 | —                | 0.9332           | 0.9270 | 0.8792                                       | 2B    | 0.892          | 0.913  | 0.9350         | 0.9430 | 1.0000            |
| 1-12 UNF   | 1A                    | 0.0018         | 0.9982           | 0.9810 | —                | 0.9441           | 0.9353 | 0.8990                                       | 1B    | 0.910          | 0.928  | 0.9459         | 0.9573 | 1.0000            |
|  | 2A                    | 0.0018         | 0.9982           | 0.9868 | —                | 0.9441           | 0.9382 | 0.8990                                       | 2B    | 0.910          | 0.928  | 0.9459         | 0.9535 | 1.0000            |
|  | 3A                    | 0.0000         | 1.0000           | 0.9886 | —                | 0.9459           | 0.9415 | 0.9008                                       | 3B    | 0.9100         | 0.9198 | 0.9459         | 0.9516 | 1.0000            |
| 1-14 UNS <sup>f</sup>  | 1A                    | 0.0017         | 0.9983           | 0.9828 | —                | 0.9519           | 0.9435 | 0.9132                                       | 1B    | 0.923          | 0.938  | 0.9536         | 0.9645 | 1.0000            |
|  | 2A                    | 0.0017         | 0.9983           | 0.9880 | —                | 0.9519           | 0.9463 | 0.9132                                       | 2B    | 0.923          | 0.938  | 0.9536         | 0.9609 | 1.0000            |
|  | 3A                    | 0.0000         | 1.0000           | 0.9897 | —                | 0.9536           | 0.9494 | 0.9149                                       | 3B    | 0.9230         | 0.9315 | 0.9536         | 0.9590 | 1.0000            |
| 1-16 UN  | 2A                    | 0.0015         | 0.9985           | 0.9891 | —                | 0.9579           | 0.9529 | 0.9240                                       | 2B    | 0.932          | 0.946  | 0.9594         | 0.9659 | 1.0000            |
|  | 3A                    | 0.0000         | 1.0000           | 0.9906 | —                | 0.9594           | 0.9557 | 0.9255                                       | 3B    | 0.9320         | 0.9408 | 0.9594         | 0.9643 | 1.0000            |
| 1-18 UNS   | 2A                    | 0.0014         | 0.9986           | 0.9899 | —                | 0.9625           | 0.9578 | 0.9325                                       | 2B    | 0.940          | 0.953  | 0.9639         | 0.9701 | 1.0000            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  | Internal <sup>b</sup> |   |        |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|-----------------------|---|--------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |                       | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class  | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min                   |   |        | Min            | Max    | Min            | Max    | Min               |
| 1-20 UNEF  | 2A                    | 0.0014         | 0.9986           | 0.9905 | —                | 0.9661           | 0.9616                | 0.9391  | 2B     | 0.946          | 0.957  | 0.9675         | 0.9734 | 1.0000            |
|  | 3A                    | 0.0000         | 1.0000           | 0.9919 | —                | 0.9675           | 0.9641                | 0.9405  | 3B     | 0.9460         | 0.9537 | 0.9675         | 0.9719 | 1.0000            |
| 1-24 UNS   | 2A                    | 0.0013         | 0.9987           | 0.9915 | —                | 0.9716           | 0.9674                | 0.9491  | 2B     | 0.955          | 0.965  | 0.9729         | 0.9784 | 1.0000            |
| 1-27 UNS   | 2A                    | 0.0012         | 0.9988           | 0.9921 | —                | 0.9747           | 0.9707                | 0.9547  | 2B     | 0.960          | 0.969  | 0.9759         | 0.9811 | 1.0000            |
| 1-28 UN  | 2A                    | 0.0012         | 0.9988           | 0.9923 | —                | 0.9756           | 0.9716                | 0.9562  | 2B     | 0.961          | 0.970  | 0.9768         | 0.9820 | 1.0000            |
|  | 3A                    | 0.0000         | 1.0000           | 0.9935 | —                | 0.9768           | 0.9738                | 0.9574  | 3B     | 0.9610         | 0.9676 | 0.9768         | 0.9807 | 1.0000            |
| 1-32 UN  | 2A                    | 0.0011         | 0.9989           | 0.9929 | —                | 0.9786           | 0.9748                | 0.9617  | 2B     | 0.966          | 0.974  | 0.9797         | 0.9846 | 1.0000            |
|  | 3A                    | 0.0000         | 1.0000           | 0.9940 | —                | 0.9797           | 0.9769                | 0.9628  | 3B     | 0.9660         | 0.9719 | 0.9797         | 0.9834 | 1.0000            |
| 1 $\frac{1}{16}$ -8 UN   | 2A                    | 0.0020         | 1.0605           | 1.0455 | —                | 0.9793           | 0.9725                | 0.9117  | 2B     | 0.927          | 0.952  | 0.9813         | 0.9902 | 1.0625            |
|  | 3A                    | 0.0000         | 1.0625           | 1.0475 | —                | 0.9813           | 0.9762                | 0.9137  | 3B     | 0.9270         | 0.9422 | 0.9813         | 0.9880 | 1.0625            |
| 1 $\frac{1}{16}$ -12 UN  | 2A                    | 0.0017         | 1.0608           | 1.0494 | —                | 1.0067           | 1.0010                | 0.9616  | 2B     | 0.972          | 0.990  | 1.0084         | 1.0158 | 1.0625            |
|  | 3A                    | 0.0000         | 1.0625           | 1.0511 | —                | 1.0084           | 1.0042                | 0.9633  | 3B     | 0.9720         | 0.9823 | 1.0084         | 1.0139 | 1.0625            |
| 1 $\frac{1}{16}$ -16 UN  | 2A                    | 0.0015         | 1.0610           | 1.0516 | —                | 1.0204           | 1.0154                | 0.9865  | 2B     | 0.995          | 1.009  | 1.0219         | 1.0284 | 1.0625            |
|  | 3A                    | 0.0000         | 1.0625           | 1.0531 | —                | 1.0219           | 1.0182                | 0.9880  | 3B     | 0.9950         | 1.0033 | 1.0219         | 1.0268 | 1.0625            |
| 1 $\frac{1}{16}$ -18 UNEF  | 2A                    | 0.0014         | 1.0611           | 1.0524 | —                | 1.0250           | 1.0203                | 0.9950  | 2B     | 1.002          | 1.015  | 1.0264         | 1.0326 | 1.0625            |
|  | 3A                    | 0.0000         | 1.0625           | 1.0538 | —                | 1.0264           | 1.0228                | 0.9964  | 3B     | 1.0020         | 1.0105 | 1.0264         | 1.0310 | 1.0625            |
| 1 $\frac{1}{16}$ -20 UN  | 2A                    | 0.0014         | 1.0611           | 1.0530 | —                | 1.0286           | 1.0241                | 1.0016  | 2B     | 1.008          | 1.020  | 1.0300         | 1.0359 | 1.0625            |
|  | 3A                    | 0.0000         | 1.0625           | 1.0544 | —                | 1.0300           | 1.0266                | 1.0030  | 3B     | 1.0080         | 1.0162 | 1.0300         | 1.0344 | 1.0625            |
| 1 $\frac{1}{16}$ -28 UN  | 2A                    | 0.0012         | 1.0613           | 1.0548 | —                | 1.0381           | 1.0341                | 1.0187  | 2B     | 1.024          | 1.032  | 1.0393         | 1.0445 | 1.0625            |
|  | 3A                    | 0.0000         | 1.0625           | 1.0560 | —                | 1.0393           | 1.0363                | 1.0199  | 3B     | 1.0240         | 1.0301 | 1.0393         | 1.0432 | 1.0625            |
| 1 $\frac{1}{8}$ -7 UNC   | 1A                    | 0.0022         | 1.1228           | 1.0982 | —                | 1.0300           | 1.0191                | 0.9527  | 1B     | 0.970          | 0.998  | 1.0322         | 1.0463 | 1.1250            |
|  | 2A                    | 0.0022         | 1.1228           | 1.1064 | 1.0982           | 1.0300           | 1.0228                | 0.9527  | 2B     | 0.970          | 0.998  | 1.0322         | 1.0416 | 1.1250            |
| 1 $\frac{1}{8}$ -8 UN  | 3A                    | 0.0000         | 1.1250           | 1.1086 | —                | 1.0322           | 1.0268                | 0.9549  | 3B     | 0.9700         | 0.9875 | 1.0322         | 1.0393 | 1.1250            |
|  | 2A                    | 0.0021         | 1.1229           | 1.1079 | 1.1004           | 1.0417           | 1.0348                | 0.9741  | 2B     | 0.990          | 1.015  | 1.0438         | 1.0528 | 1.1250            |
| 1 $\frac{1}{8}$ -10 UNS  | 3A                    | 0.0000         | 1.1250           | 1.1100 | —                | 1.0438           | 1.0386                | 0.9762  | 3B     | 0.9900         | 1.0047 | 1.0438         | 1.0505 | 1.1250            |
|  | 2A                    | 0.0018         | 1.1232           | 1.1103 | —                | 1.0582           | 1.0520                | 1.0042  | 2B     | 1.017          | 1.038  | 1.0600         | 1.0680 | 1.1250            |
| 1 $\frac{1}{8}$ -12 UNF  | 1A                    | 0.0018         | 1.1232           | 1.1060 | —                | 1.0691           | 1.0601                | 1.0240  | 1B     | 1.035          | 1.053  | 1.0709         | 1.0826 | 1.1250            |
|  | 2A                    | 0.0018         | 1.1232           | 1.1118 | —                | 1.0691           | 1.0631                | 1.0240  | 2B     | 1.035          | 1.053  | 1.0709         | 1.0787 | 1.1250            |
| 3A   | 0.0000                | 1.1250         | 1.1136           | —      | 1.0709           | 1.0664           | 1.0258                | 3B  | 1.0350 | 1.0448         | 1.0709 | 1.0768         | 1.1250 |                   |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                        |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|--|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia. <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |  |       | Min            | Max    | Min            | Max    | Min               |
| 1 $\frac{1}{8}$ -14 UNS  | 2A                    | 0.0016         | 1.1234           | 1.1131 | —                | 1.0770           | 1.0717 | 1.0384                                       | 2B    | 1.048          | 1.064  | 1.0786         | 1.0855 | 1.1250            |
| 1 $\frac{1}{8}$ -16 UN   | 2A                    | 0.0015         | 1.1235           | 1.1141 | —                | 1.0829           | 1.0779 | 1.0490                                       | 2B    | 1.057          | 1.071  | 1.0844         | 1.0909 | 1.1250            |
|  | 3A                    | 0.0000         | 1.1250           | 1.1156 | —                | 1.0844           | 1.0807 | 1.0505                                       | 3B    | 1.0570         | 1.0658 | 1.0844         | 1.0893 | 1.1250            |
|  | 2A                    | 0.0014         | 1.1236           | 1.1149 | —                | 1.0875           | 1.0828 | 1.0575                                       | 2B    | 1.065          | 1.078  | 1.0889         | 1.0951 | 1.1250            |
| 1 $\frac{1}{8}$ -18 UNEF   | 3A                    | 0.0000         | 1.1250           | 1.1163 | —                | 1.0889           | 1.0853 | 1.0589                                       | 3B    | 1.0650         | 1.0730 | 1.0889         | 1.0935 | 1.1250            |
|  | 2A                    | 0.0014         | 1.1236           | 1.1155 | —                | 1.0911           | 1.0866 | 1.0641                                       | 2B    | 1.071          | 1.082  | 1.0925         | 1.0984 | 1.1250            |
|  | 3A                    | 0.0000         | 1.1250           | 1.1169 | —                | 1.0925           | 1.0891 | 1.0655                                       | 3B    | 1.0710         | 1.0787 | 1.0925         | 1.0969 | 1.1250            |
| 1 $\frac{1}{8}$ -20 UN   | 2A                    | 0.0013         | 1.1237           | 1.1165 | —                | 1.0966           | 1.0924 | 1.0742                                       | 2B    | 1.080          | 1.090  | 1.0979         | 1.1034 | 1.1250            |
| 1 $\frac{1}{8}$ -24 UNS  | 2A                    | 0.0012         | 1.1238           | 1.1173 | —                | 1.1006           | 1.0966 | 1.0812                                       | 2B    | 1.086          | 1.095  | 1.1018         | 1.1070 | 1.1250            |
|  | 3A                    | 0.0000         | 1.1250           | 1.1185 | —                | 1.1018           | 1.0988 | 1.0824                                       | 3B    | 1.0860         | 1.0926 | 1.1018         | 1.1057 | 1.1250            |
|  | 2A                    | 0.0021         | 1.1854           | 1.1704 | —                | 1.1042           | 1.0972 | 1.0366                                       | 2B    | 1.052          | 1.077  | 1.1063         | 1.1154 | 1.1875            |
| 1 $\frac{3}{16}$ -8 UN   | 3A                    | 0.0000         | 1.1875           | 1.1725 | —                | 1.1063           | 1.1011 | 1.0387                                       | 3B    | 1.0520         | 1.0672 | 1.1063         | 1.1131 | 1.1875            |
|  | 2A                    | 0.0017         | 1.1858           | 1.1744 | —                | 1.1317           | 1.1259 | 1.0866                                       | 2B    | 1.097          | 1.115  | 1.1334         | 1.1409 | 1.1875            |
|  | 3A                    | 0.0000         | 1.1875           | 1.1761 | —                | 1.1334           | 1.1291 | 1.0883                                       | 3B    | 1.0970         | 1.1073 | 1.1334         | 1.1390 | 1.1875            |
| 1 $\frac{3}{16}$ -16 UN  | 2A                    | 0.0015         | 1.1860           | 1.1766 | —                | 1.1454           | 1.1403 | 1.1115                                       | 2B    | 1.120          | 1.134  | 1.1469         | 1.1535 | 1.1875            |
|  | 3A                    | 0.0000         | 1.1875           | 1.1781 | —                | 1.1469           | 1.1431 | 1.1130                                       | 3B    | 1.1200         | 1.1283 | 1.1469         | 1.1519 | 1.1875            |
|  | 2A                    | 0.0015         | 1.1860           | 1.1773 | —                | 1.1499           | 1.1450 | 1.1199                                       | 2B    | 1.127          | 1.140  | 1.1514         | 1.1577 | 1.1875            |
| 1 $\frac{3}{16}$ -18 UNEF  | 3A                    | 0.0000         | 1.1875           | 1.1788 | —                | 1.1514           | 1.1478 | 1.1214                                       | 3B    | 1.1270         | 1.1355 | 1.1514         | 1.1561 | 1.1875            |
|  | 2A                    | 0.0014         | 1.1861           | 1.1780 | —                | 1.1536           | 1.1489 | 1.1266                                       | 2B    | 1.133          | 1.145  | 1.1550         | 1.1611 | 1.1875            |
|  | 3A                    | 0.0000         | 1.1875           | 1.1794 | —                | 1.1550           | 1.1515 | 1.1280                                       | 3B    | 1.1330         | 1.1412 | 1.1550         | 1.1595 | 1.1875            |
| 1 $\frac{3}{16}$ -28 UN  | 2A                    | 0.0012         | 1.1863           | 1.1798 | —                | 1.1631           | 1.1590 | 1.1437                                       | 2B    | 1.149          | 1.157  | 1.1643         | 1.1696 | 1.1875            |
|  | 3A                    | 0.0000         | 1.1875           | 1.1810 | —                | 1.1643           | 1.1612 | 1.1449                                       | 3B    | 1.1490         | 1.1551 | 1.1643         | 1.1683 | 1.1875            |
|  | 1A                    | 0.0022         | 1.2478           | 1.2332 | —                | 1.1550           | 1.1439 | 1.0777                                       | 1B    | 1.095          | 1.123  | 1.1572         | 1.1716 | 1.2500            |
| 1 $\frac{1}{4}$ -7 UNC   | 2A                    | 0.0022         | 1.2478           | 1.2314 | 1.2232           | 1.1550           | 1.1476 | 1.0777                                       | 2B    | 1.095          | 1.123  | 1.1572         | 1.1668 | 1.2500            |
|  | 3A                    | 0.0000         | 1.2500           | 1.2336 | —                | 1.1572           | 1.1517 | 1.0799                                       | 3B    | 1.0950         | 1.1125 | 1.1572         | 1.1644 | 1.2500            |
|  | 2A                    | 0.0021         | 1.2479           | 1.2329 | 1.2254           | 1.1667           | 1.1597 | 1.0991                                       | 2B    | 1.115          | 1.140  | 1.1688         | 1.1780 | 1.2500            |
| 1 $\frac{1}{4}$ -8 UN  | 3A                    | 0.0000         | 1.2500           | 1.2350 | —                | 1.1688           | 1.1635 | 1.1012                                       | 3B    | 1.1150         | 1.1297 | 1.1688         | 1.1757 | 1.2500            |
|  | 2A                    | 0.0019         | 1.2481           | 1.2352 | —                | 1.1831           | 1.1768 | 1.1291                                       | 2B    | 1.142          | 1.163  | 1.1850         | 1.1932 | 1.2500            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  | Internal <sup>b</sup> |   |        |                |        |                |        |                   |        |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|-----------------------|---|--------|----------------|--------|----------------|--------|-------------------|--------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |                       | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class  | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |        |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min                   |   |        | Min            | Max    | Min            | Max    | Min               |        |
| 1¼-12 UNF  | 1A                    | 0.0018         | 1.2482           | 1.2310 | —                | 1.1941           | 1.1849                | 1.1490  | 1B     | 1.160          | 1.178  | 1.1959         | 1.2079 | 1.2500            |        |
|  | 2A                    | 0.0018         | 1.2482           | 1.2368 | —                | 1.1941           | 1.1879                | 1.1490  | 2B     | 1.160          | 1.178  | 1.1959         | 1.2039 | 1.2500            |        |
|  | 3A                    | 0.0000         | 1.2500           | 1.2386 | —                | 1.1959           | 1.1913                | 1.1508  | 3B     | 1.1600         | 1.1698 | 1.1959         | 1.2019 | 1.2500            |        |
| 1¼-14 UNS  | 2A                    | 0.0016         | 1.2484           | 1.2381 | —                | 1.2020           | 1.1966                | 1.1634  | 2B     | 1.173          | 1.188  | 1.2036         | 1.2106 | 1.2500            |        |
|  | 1¼-16 UN              | 2A             | 0.0015           | 1.2485 | 1.2391           | —                | 1.2079                | 1.2028  | 1.1740 | 2B             | 1.182  | 1.196          | 1.2094 | 1.2160            | 1.2500 |
| 3A   |                       | 0.0000         | 1.2500           | 1.2406 | —                | 1.2094           | 1.2056                | 1.1755  | 3B     | 1.1820         | 1.1908 | 1.2094         | 1.2144 | 1.2500            |        |
| 2A   |                       | 0.0015         | 1.2485           | 1.2398 | —                | 1.2124           | 1.2075                | 1.1824  | 2B     | 1.190          | 1.203  | 1.2139         | 1.2202 | 1.2500            |        |
| 1¼-18 UNEF   | 3A                    | 0.0000         | 1.2500           | 1.2413 | —                | 1.2139           | 1.2103                | 1.1839  | 3B     | 1.1900         | 1.1980 | 1.2139         | 1.2186 | 1.2500            |        |
|  | 1¼-20 UN              | 2A             | 0.0014           | 1.2486 | 1.2405           | —                | 1.2161                | 1.2114  | 1.1891 | 2B             | 1.196  | 1.207          | 1.2175 | 1.2236            | 1.2500 |
| 3A   |                       | 0.0000         | 1.2500           | 1.2419 | —                | 1.2175           | 1.2140                | 1.1905  | 3B     | 1.1960         | 1.2037 | 1.2175         | 1.2220 | 1.2500            |        |
| 2A   |                       | 0.0013         | 1.2487           | 1.2415 | —                | 1.2216           | 1.2173                | 1.1991  | 2B     | 1.205          | 1.215  | 1.2229         | 1.2285 | 1.2500            |        |
| 1¼-24 UNS  | 2A                    | 0.0012         | 1.2488           | 1.2423 | —                | 1.2256           | 1.2215                | 1.2062  | 2B     | 1.211          | 1.220  | 1.2268         | 1.2321 | 1.2500            |        |
|  | 1¼-28 UN              | 3A             | 0.0000           | 1.2500 | 1.2435           | —                | 1.2268                | 1.2237  | 1.2074 | 3B             | 1.2110 | 1.2176         | 1.2268 | 1.2308            | 1.2500 |
| 2A   |                       | 0.0021         | 1.3104           | 1.2954 | —                | 1.2292           | 1.2221                | 1.1616  | 2B     | 1.177          | 1.202  | 1.2313         | 1.2405 | 1.3125            |        |
| 3A   |                       | 0.0000         | 1.3125           | 1.2975 | —                | 1.2313           | 1.2260                | 1.1637  | 3B     | 1.1770         | 1.1922 | 1.2313         | 1.2382 | 1.3125            |        |
| 1½-8 UN  | 2A                    | 0.0017         | 1.3108           | 1.2994 | —                | 1.2567           | 1.2509                | 1.2116  | 2B     | 1.222          | 1.240  | 1.2584         | 1.2659 | 1.3125            |        |
|  | 1½-12 UN              | 3A             | 0.0000           | 1.3125 | 1.3011           | —                | 1.2584                | 1.2541  | 1.2133 | 3B             | 1.2220 | 1.2323         | 1.2584 | 1.2640            | 1.3125 |
| 2A   |                       | 0.0015         | 1.3110           | 1.3016 | —                | 1.2704           | 1.2653                | 1.2365  | 2B     | 1.245          | 1.259  | 1.2719         | 1.2785 | 1.3125            |        |
| 3A   |                       | 0.0000         | 1.3125           | 1.3031 | —                | 1.2719           | 1.2681                | 1.2380  | 3B     | 1.2450         | 1.2533 | 1.2719         | 1.2769 | 1.3125            |        |
| 1½-16 UN   | 2A                    | 0.0015         | 1.3110           | 1.3023 | —                | 1.2749           | 1.2700                | 1.2449  | 2B     | 1.252          | 1.265  | 1.2764         | 1.2827 | 1.3125            |        |
|  | 3A                    | 0.0000         | 1.3125           | 1.3038 | —                | 1.2764           | 1.2728                | 1.2464  | 3B     | 1.2520         | 1.2605 | 1.2764         | 1.2811 | 1.3125            |        |
|  | 2A                    | 0.0014         | 1.3111           | 1.3030 | —                | 1.2786           | 1.2739                | 1.2516  | 2B     | 1.258          | 1.270  | 1.2800         | 1.2861 | 1.3125            |        |
| 1½-20 UN   | 3A                    | 0.0000         | 1.3125           | 1.3044 | —                | 1.2800           | 1.2765                | 1.2530  | 3B     | 1.2580         | 1.2662 | 1.2800         | 1.2845 | 1.3125            |        |
|  | 2A                    | 0.0012         | 1.3113           | 1.3048 | —                | 1.2881           | 1.2840                | 1.2687  | 2B     | 1.274          | 1.282  | 1.2893         | 1.2946 | 1.3125            |        |
| 1½-28 UN   | 3A                    | 0.0000         | 1.3125           | 1.3060 | —                | 1.2893           | 1.2862                | 1.2699  | 3B     | 1.2740         | 1.2801 | 1.2893         | 1.2933 | 1.3125            |        |
|  | 1¾-6 UNC              | 1A             | 0.0024           | 1.3726 | 1.3453           | —                | 1.2643                | 1.2523  | 1.1742 | 1B             | 1.195  | 1.225          | 1.2667 | 1.2822            | 1.3750 |
|  |                       | 2A             | 0.0024           | 1.3726 | 1.3544           | 1.3453           | 1.2643                | 1.2563  | 1.1742 | 2B             | 1.195  | 1.225          | 1.2667 | 1.2771            | 1.3750 |
| 3A   |                       | 0.0000         | 1.3750           | 1.3568 | —                | 1.2667           | 1.2607                | 1.1766  | 3B     | 1.1950         | 1.2146 | 1.2667         | 1.2745 | 1.3750            |        |



Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                         |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|---|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |   |       | Min            | Max    | Min            | Max    | Min               |
| 1 $\frac{3}{8}$ -8 UN  | 2A                    | 0.0022         | 1.3728           | 1.3578 | 1.3503           | 1.2916           | 1.2844 | 1.2240  | 2B    | 1.240          | 1.265  | 1.2938         | 1.3031 | 1.3750            |
|  | 3A                    | 0.0000         | 1.3750           | 1.3600 | —                | 1.2938           | 1.2884 | 1.2262  | 3B    | 1.2400         | 1.2547 | 1.2938         | 1.3008 | 1.3750            |
| 1 $\frac{3}{8}$ -10 UNS  | 2A                    | 0.0019         | 1.3731           | 1.3602 | —                | 1.3081           | 1.3018 | 1.2541  | 2B    | 1.267          | 1.288  | 1.3100         | 1.3182 | 1.3750            |
| 1 $\frac{3}{8}$ -12 UNF  | 1A                    | 0.0019         | 1.3731           | 1.3559 | —                | 1.3190           | 1.3096 | 1.2739  | 1B    | 1.285          | 1.303  | 1.3209         | 1.3332 | 1.3750            |
|  | 2A                    | 0.0019         | 1.3731           | 1.3617 | —                | 1.3190           | 1.3127 | 1.2739  | 2B    | 1.285          | 1.303  | 1.3209         | 1.3291 | 1.3750            |
|  | 3A                    | 0.0000         | 1.3750           | 1.3636 | —                | 1.3209           | 1.3162 | 1.2758  | 3B    | 1.2850         | 1.2948 | 1.3209         | 1.3270 | 1.3750            |
| 1 $\frac{3}{8}$ -14 UNS  | 2A                    | 0.0016         | 1.3734           | 1.3631 | —                | 1.3270           | 1.3216 | 1.2884  | 2B    | 1.298          | 1.314  | 1.3286         | 1.3356 | 1.3750            |
|  | 2A                    | 0.0015         | 1.3735           | 1.3641 | —                | 1.3329           | 1.3278 | 1.2990  | 2B    | 1.307          | 1.321  | 1.3344         | 1.3410 | 1.3750            |
| 1 $\frac{3}{8}$ -16 UN   | 3A                    | 0.0000         | 1.3750           | 1.3656 | —                | 1.3344           | 1.3306 | 1.3005  | 3B    | 1.3070         | 1.3158 | 1.3344         | 1.3394 | 1.3750            |
|  | 2A                    | 0.0015         | 1.3735           | 1.3648 | —                | 1.3374           | 1.3325 | 1.3074  | 2B    | 1.315          | 1.328  | 1.3389         | 1.3452 | 1.3750            |
| 1 $\frac{3}{8}$ -18 UNEF   | 3A                    | 0.0000         | 1.3750           | 1.3663 | —                | 1.3389           | 1.3353 | 1.3089  | 3B    | 1.3150         | 1.3230 | 1.3389         | 1.3436 | 1.3750            |
|  | 2A                    | 0.0014         | 1.3736           | 1.3655 | —                | 1.3411           | 1.3364 | 1.3141  | 2B    | 1.321          | 1.332  | 1.3425         | 1.3486 | 1.3750            |
| 1 $\frac{3}{8}$ -20 UN   | 3A                    | 0.0000         | 1.3750           | 1.3669 | —                | 1.3425           | 1.3390 | 1.3155  | 3B    | 1.3210         | 1.3287 | 1.3425         | 1.3470 | 1.3750            |
|  | 2A                    | 0.0013         | 1.3737           | 1.3665 | —                | 1.3466           | 1.3423 | 1.3241  | 2B    | 1.330          | 1.340  | 1.3479         | 1.3535 | 1.3750            |
| 1 $\frac{3}{8}$ -28 UN   | 2A                    | 0.0012         | 1.3738           | 1.3673 | —                | 1.3506           | 1.3465 | 1.3312  | 2B    | 1.336          | 1.345  | 1.3518         | 1.3571 | 1.3750            |
|  | 3A                    | 0.0000         | 1.3750           | 1.3685 | —                | 1.3518           | 1.3487 | 1.3324  | 3B    | 1.3360         | 1.3426 | 1.3518         | 1.3558 | 1.3750            |
| 1 $\frac{7}{16}$ -6 UN   | 2A                    | 0.0024         | 1.4351           | 1.4169 | —                | 1.3268           | 1.3188 | 1.2367  | 2B    | 1.257          | 1.288  | 1.3292         | 1.3396 | 1.4375            |
|  | 3A                    | 0.0000         | 1.4375           | 1.4193 | —                | 1.3292           | 1.3232 | 1.2391  | 3B    | 1.2570         | 1.2771 | 1.3292         | 1.3370 | 1.4375            |
| 1 $\frac{7}{16}$ -8 UN   | 2A                    | 0.0022         | 1.4353           | 1.4203 | —                | 1.3541           | 1.3469 | 1.2865  | 2B    | 1.302          | 1.327  | 1.3563         | 1.3657 | 1.4375            |
|  | 3A                    | 0.0000         | 1.4375           | 1.4225 | —                | 1.3563           | 1.3509 | 1.2887  | 3B    | 1.3020         | 1.3172 | 1.3563         | 1.3634 | 1.4375            |
| 1 $\frac{7}{16}$ -12 UN  | 2A                    | 0.0018         | 1.4357           | 1.4243 | —                | 1.3816           | 1.3757 | 1.3365  | 2B    | 1.347          | 1.365  | 1.3834         | 1.3910 | 1.4375            |
|  | 3A                    | 0.0000         | 1.4375           | 1.4261 | —                | 1.3834           | 1.3790 | 1.3383  | 3B    | 1.3470         | 1.3573 | 1.3834         | 1.3891 | 1.4375            |
|  | 2A                    | 0.0016         | 1.4359           | 1.4265 | —                | 1.3953           | 1.3901 | 1.3614  | 2B    | 1.370          | 1.384  | 1.3969         | 1.4037 | 1.4375            |
| 1 $\frac{7}{16}$ -16 UN  | 3A                    | 0.0000         | 1.4375           | 1.4281 | —                | 1.3969           | 1.3930 | 1.3630  | 3B    | 1.3700         | 1.3783 | 1.3969         | 1.4020 | 1.4375            |
|  | 2A                    | 0.0015         | 1.4360           | 1.4273 | —                | 1.3999           | 1.3949 | 1.3699  | 2B    | 1.377          | 1.390  | 1.4014         | 1.4079 | 1.4375            |
| 1 $\frac{7}{16}$ -18 UNEF  | 3A                    | 0.0000         | 1.4375           | 1.4288 | —                | 1.4014           | 1.3977 | 1.3714  | 3B    | 1.3770         | 1.3855 | 1.4014         | 1.4062 | 1.4375            |
|  | 2A                    | 0.0014         | 1.4361           | 1.4280 | —                | 1.4036           | 1.3988 | 1.3766  | 2B    | 1.383          | 1.395  | 1.4050         | 1.4112 | 1.4375            |
| 1 $\frac{7}{16}$ -20 UN  | 3A                    | 0.0000         | 1.4375           | 1.4294 | —                | 1.4050           | 1.4014 | 1.3780  | 3B    | 1.3830         | 1.3912 | 1.4050         | 1.4096 | 1.4375            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  | Internal <sup>b</sup> |  |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|-----------------------|--|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |                       | UNR Minor<br>Dia. <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min                   |  |       | Min            | Max    | Min            | Max    | Min               |
| 1 $\frac{1}{16}$ -28 UN  | 2A                    | 0.0013         | 1.4362           | 1.4297 | —                | 1.4130           | 1.4088                | 1.3936                                       | 2B    | 1.399          | 1.407  | 1.4143         | 1.4198 | 1.4375            |
|  | 3A                    | 0.0000         | 1.4375           | 1.4310 | —                | 1.4143           | 1.4112                | 1.3949                                       | 3B    | 1.3990         | 1.4051 | 1.4143         | 1.4184 | 1.4375            |
| 1 $\frac{1}{2}$ -6   | 1A                    | 0.0024         | 1.4976           | 1.4703 | —                | 1.3893           | 1.3772                | 1.2992                                       | 1B    | 1.320          | 1.350  | 1.3917         | 1.4075 | 1.5000            |
|  | 2A                    | 0.0024         | 1.4976           | 1.4794 | 1.4703           | 1.3893           | 1.3812                | 1.2992                                       | 2B    | 1.320          | 1.350  | 1.3917         | 1.4022 | 1.5000            |
| 1 $\frac{1}{2}$ -8 UN  | 3A                    | 0.0000         | 1.5000           | 1.4818 | —                | 1.3917           | 1.3856                | 1.3016                                       | 3B    | 1.3200         | 1.3396 | 1.3917         | 1.3996 | 1.5000            |
|  | 2A                    | 0.0022         | 1.4978           | 1.4828 | 1.4753           | 1.4166           | 1.4093                | 1.3490                                       | 2B    | 1.365          | 1.390  | 1.4188         | 1.4283 | 1.5000            |
| 1 $\frac{1}{2}$ -10 UNS  | 3A                    | 0.0000         | 1.5000           | 1.4850 | —                | 1.4188           | 1.4133                | 1.3512                                       | 3B    | 1.3650         | 1.3797 | 1.4188         | 1.4259 | 1.5000            |
|  | 2A                    | 0.0019         | 1.4981           | 1.4852 | —                | 1.4331           | 1.4267                | 1.3791                                       | 2B    | 1.392          | 1.413  | 1.4350         | 1.4433 | 1.5000            |
| 1 $\frac{1}{2}$ -12 UNF  | 1A                    | 0.0019         | 1.4981           | 1.4809 | —                | 1.4440           | 1.4344                | 1.3989                                       | 1B    | 1.410          | 1.428  | 1.4459         | 1.4584 | 1.5000            |
|  | 2A                    | 0.0019         | 1.4981           | 1.4867 | —                | 1.4440           | 1.4376                | 1.3989                                       | 2B    | 1.410          | 1.428  | 1.4459         | 1.4542 | 1.5000            |
| 1 $\frac{1}{2}$ -14 UNS  | 3A                    | 0.0000         | 1.5000           | 1.4886 | —                | 1.4459           | 1.4411                | 1.4008                                       | 3B    | 1.4100         | 1.4198 | 1.4459         | 1.4522 | 1.5000            |
|  | 2A                    | 0.0017         | 1.4983           | 1.4880 | —                | 1.4519           | 1.4464                | 1.4133                                       | 2B    | 1.423          | 1.438  | 1.4536         | 1.4608 | 1.5000            |
| 1 $\frac{1}{2}$ -16 UN   | 2A                    | 0.0016         | 1.4984           | 1.4890 | —                | 1.4578           | 1.4526                | 1.4239                                       | 2B    | 1.432          | 1.446  | 1.4594         | 1.4662 | 1.5000            |
|  | 3A                    | 0.0000         | 1.5000           | 1.4906 | —                | 1.4594           | 1.4555                | 1.4255                                       | 3B    | 1.4320         | 1.4408 | 1.4594         | 1.4645 | 1.5000            |
| 1 $\frac{1}{2}$ -18 UNEF   | 2A                    | 0.0015         | 1.4985           | 1.4898 | —                | 1.4624           | 1.4574                | 1.4324                                       | 2B    | 1.440          | 1.452  | 1.4639         | 1.4704 | 1.5000            |
|  | 3A                    | 0.0000         | 1.5000           | 1.4913 | —                | 1.4639           | 1.4602                | 1.4339                                       | 3B    | 1.4400         | 1.4480 | 1.4639         | 1.4687 | 1.5000            |
| 1 $\frac{1}{2}$ -20 UN   | 2A                    | 0.0014         | 1.4986           | 1.4905 | —                | 1.4661           | 1.4613                | 1.4391                                       | 2B    | 1.446          | 1.457  | 1.4675         | 1.4737 | 1.5000            |
|  | 3A                    | 0.0000         | 1.5000           | 1.4919 | —                | 1.4675           | 1.4639                | 1.4405                                       | 3B    | 1.4460         | 1.4537 | 1.4675         | 1.4721 | 1.5000            |
| 1 $\frac{1}{2}$ -24 UNS  | 2A                    | 0.0013         | 1.4987           | 1.4915 | —                | 1.4716           | 1.4672                | 1.4491                                       | 2B    | 1.455          | 1.465  | 1.4729         | 1.4787 | 1.5000            |
|  | 2A                    | 0.0013         | 1.4987           | 1.4922 | —                | 1.4755           | 1.4713                | 1.4561                                       | 2B    | 1.461          | 1.470  | 1.4768         | 1.4823 | 1.5000            |
| 1 $\frac{1}{16}$ -6 UN   | 3A                    | 0.0000         | 1.5000           | 1.4935 | —                | 1.4768           | 1.4737                | 1.4574                                       | 3B    | 1.4610         | 1.4676 | 1.4768         | 1.4809 | 1.5000            |
|  | 2A                    | 0.0024         | 1.5601           | 1.5419 | —                | 1.4518           | 1.4436                | 1.3617                                       | 2B    | 1.382          | 1.413  | 1.4542         | 1.4648 | 1.5625            |
| 1 $\frac{1}{16}$ -8 UN   | 3A                    | 0.0000         | 1.5625           | 1.5443 | —                | 1.4542           | 1.4481                | 1.3641                                       | 3B    | 1.3820         | 1.4021 | 1.4542         | 1.4622 | 1.5625            |
|  | 2A                    | 0.0022         | 1.5603           | 1.5453 | —                | 1.4791           | 1.4717                | 1.4115                                       | 2B    | 1.427          | 1.452  | 1.4813         | 1.4909 | 1.5625            |
| 1 $\frac{1}{16}$ -12 UN  | 3A                    | 0.0000         | 1.5625           | 1.5475 | —                | 1.4813           | 1.4758                | 1.4137                                       | 3B    | 1.4270         | 1.4422 | 1.4813         | 1.4885 | 1.5625            |
|  | 2A                    | 0.0018         | 1.5607           | 1.5493 | —                | 1.5066           | 1.5007                | 1.4615                                       | 2B    | 1.472          | 1.490  | 1.5084         | 1.5160 | 1.5625            |
|  | 3A                    | 0.0000         | 1.5625           | 1.5511 | —                | 1.5084           | 1.5040                | 1.4633                                       | 3B    | 1.4720         | 1.4823 | 1.5084         | 1.5141 | 1.5625            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                        |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|--|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia. <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |  |       | Min            | Max    | Min            | Max    | Min               |
| 1 $\frac{1}{16}$ -16 UN  | 2A                    | 0.0016         | 1.5609           | 1.5515 | —                | 1.5203           | 1.5151 | 1.4864                                       | 2B    | 1.495          | 1.509  | 1.5219         | 1.5287 | 1.5625            |
|  | 3A                    | 0.0000         | 1.5625           | 1.5531 | —                | 1.5219           | 1.5180 | 1.4880                                       | 3B    | 1.4950         | 1.5033 | 1.5219         | 1.5270 | 1.5625            |
| 1 $\frac{1}{16}$ -18 UNEF  | 2A                    | 0.0015         | 1.5610           | 1.5523 | —                | 1.5249           | 1.5199 | 1.4949                                       | 2B    | 1.502          | 1.515  | 1.5264         | 1.5329 | 1.5625            |
|  | 3A                    | 0.0000         | 1.5625           | 1.5538 | —                | 1.5264           | 1.5227 | 1.4964                                       | 3B    | 1.5020         | 1.5105 | 1.5264         | 1.5312 | 1.5625            |
| 1 $\frac{9}{16}$ -20 UN  | 2A                    | 0.0014         | 1.5611           | 1.5530 | —                | 1.5286           | 1.5238 | 1.5016                                       | 2B    | 1.508          | 1.520  | 1.5300         | 1.5362 | 1.5625            |
|  | 3A                    | 0.0000         | 1.5625           | 1.5544 | —                | 1.5300           | 1.5264 | 1.5030                                       | 3B    | 1.5080         | 1.5162 | 1.5300         | 1.5346 | 1.5625            |
| 1 $\frac{5}{8}$ -6 UN  | 2A                    | 0.0025         | 1.6225           | 1.6043 | —                | 1.5142           | 1.5060 | 1.4246                                       | 2B    | 1.445          | 1.475  | 1.5167         | 1.5274 | 1.6250            |
|  | 3A                    | 0.0000         | 1.6250           | 1.6068 | —                | 1.5167           | 1.5105 | 1.4271                                       | 3B    | 1.4450         | 1.4646 | 1.5167         | 1.5247 | 1.6250            |
| 1 $\frac{5}{8}$ -8 UN  | 2A                    | 0.0022         | 1.6228           | 1.6078 | 1.6003           | 1.5416           | 1.5342 | 1.4784                                       | 2B    | 1.490          | 1.515  | 1.5438         | 1.5535 | 1.6250            |
|  | 3A                    | 0.0000         | 1.6250           | 1.6100 | —                | 1.5438           | 1.5382 | 1.4806                                       | 3B    | 1.4900         | 1.5047 | 1.5438         | 1.5510 | 1.6250            |
| 1 $\frac{5}{8}$ -10 UNS  | 2A                    | 0.0019         | 1.6231           | 1.6102 | —                | 1.5581           | 1.5517 | 1.5041                                       | 2B    | 1.517          | 1.538  | 1.5600         | 1.5683 | 1.6250            |
|  | 2A                    | 0.0018         | 1.6232           | 1.6118 | —                | 1.5691           | 1.5632 | 1.5240                                       | 2B    | 1.535          | 1.553  | 1.5709         | 1.5785 | 1.6250            |
| 1 $\frac{5}{8}$ -12 UN   | 3A                    | 0.0000         | 1.6250           | 1.6136 | —                | 1.5709           | 1.5665 | 1.5258                                       | 3B    | 1.5350         | 1.5448 | 1.5709         | 1.5766 | 1.6250            |
|  | 2A                    | 0.0017         | 1.6233           | 1.6130 | —                | 1.5769           | 1.5714 | 1.5383                                       | 2B    | 1.548          | 1.564  | 1.5786         | 1.5858 | 1.6250            |
| 1 $\frac{5}{8}$ -16 UN   | 2A                    | 0.0016         | 1.6234           | 1.6140 | —                | 1.5828           | 1.5776 | 1.5489                                       | 2B    | 1.557          | 1.571  | 1.5844         | 1.5912 | 1.6250            |
|  | 3A                    | 0.0000         | 1.6250           | 1.6156 | —                | 1.5844           | 1.5805 | 1.5505                                       | 3B    | 1.5570         | 1.5658 | 1.5844         | 1.5895 | 1.6250            |
| 1 $\frac{5}{8}$ -18 UNEF   | 2A                    | 0.0015         | 1.6235           | 1.6148 | —                | 1.5874           | 1.5824 | 1.5574                                       | 2B    | 1.565          | 1.578  | 1.5889         | 1.5954 | 1.6250            |
|  | 3A                    | 0.0000         | 1.6250           | 1.6163 | —                | 1.5889           | 1.5852 | 1.5589                                       | 3B    | 1.5650         | 1.5730 | 1.5889         | 1.5937 | 1.6250            |
| 1 $\frac{5}{8}$ -20 UN   | 2A                    | 0.0014         | 1.6236           | 1.6155 | —                | 1.5911           | 1.5863 | 1.5641                                       | 2B    | 1.571          | 1.582  | 1.5925         | 1.5987 | 1.6250            |
|  | 3A                    | 0.0000         | 1.6250           | 1.6169 | —                | 1.5925           | 1.5889 | 1.5655                                       | 3B    | 1.5710         | 1.5787 | 1.5925         | 1.5971 | 1.6250            |
| 1 $\frac{5}{8}$ -24 UNS  | 2A                    | 0.0013         | 1.6237           | 1.6165 | —                | 1.5966           | 1.5922 | 1.5741                                       | 2B    | 1.580          | 1.590  | 1.5979         | 1.6037 | 1.6250            |
|  | 2A                    | 0.0025         | 1.6850           | 1.6668 | —                | 1.5767           | 1.5684 | 1.4866                                       | 2B    | 1.507          | 1.538  | 1.5792         | 1.5900 | 1.6875            |
| 1 $\frac{11}{16}$ -6 UN  | 3A                    | 0.0000         | 1.6875           | 1.6693 | —                | 1.5792           | 1.5730 | 1.4891                                       | 3B    | 1.5070         | 1.5271 | 1.5792         | 1.5873 | 1.6875            |
|  | 2A                    | 0.0022         | 1.6853           | 1.6703 | —                | 1.6041           | 1.5966 | 1.5365                                       | 2B    | 1.552          | 1.577  | 1.6063         | 1.6160 | 1.6875            |
| 1 $\frac{11}{16}$ -8 UN  | 3A                    | 0.0000         | 1.6875           | 1.6725 | —                | 1.6063           | 1.6007 | 1.5387                                       | 3B    | 1.5520         | 1.5672 | 1.6063         | 1.6136 | 1.6875            |
|  | 2A                    | 0.0018         | 1.6857           | 1.6743 | —                | 1.6316           | 1.6256 | 1.5865                                       | 2B    | 1.597          | 1.615  | 1.6334         | 1.6412 | 1.6875            |
| 1 $\frac{11}{16}$ -12 UN   | 3A                    | 0.0000         | 1.6875           | 1.6761 | —                | 1.6334           | 1.6289 | 1.5883                                       | 3B    | 1.5970         | 1.6073 | 1.6334         | 1.6392 | 1.6875            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                        |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|--|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia. <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |  |       | Min            | Max    | Min            | Max    | Min               |
| 1 <sup>1</sup> / <sub>16</sub> -16 UN  | 2A                    | 0.0016         | 1.6859           | 1.6765 | —                | 1.6453           | 1.6400 | 1.6114                                       | 2B    | 1.620          | 1.634  | 1.6469         | 1.6538 | 1.6875            |
|  | 3A                    | 0.0000         | 1.6875           | 1.6781 | —                | 1.6469           | 1.6429 | 1.6130                                       | 3B    | 1.6200         | 1.6283 | 1.6469         | 1.6521 | 1.6875            |
|  | 2A                    | 0.0015         | 1.6860           | 1.6773 | —                | 1.6499           | 1.6448 | 1.6199                                       | 2B    | 1.627          | 1.640  | 1.6514         | 1.6580 | 1.6875            |
| 1 <sup>1</sup> / <sub>16</sub> -18 UNEF                                      | 3A                    | 0.0000         | 1.6875           | 1.6788 | —                | 1.6514           | 1.6476 | 1.6214                                       | 3B    | 1.6270         | 1.6355 | 1.6514         | 1.6563 | 1.6875            |
|  | 2A                    | 0.0015         | 1.6860           | 1.6779 | —                | 1.6535           | 1.6487 | 1.6265                                       | 2B    | 1.633          | 1.645  | 1.6550         | 1.6613 | 1.6875            |
|  | 3A                    | 0.0000         | 1.6875           | 1.6794 | —                | 1.6550           | 1.6514 | 1.6280                                       | 3B    | 1.6330         | 1.6412 | 1.6550         | 1.6597 | 1.6875            |
| 1 <sup>3</sup> / <sub>4</sub> -5 UNC   | 1A                    | 0.0027         | 1.7473           | 1.7165 | —                | 1.6174           | 1.6040 | 1.5092                                       | 1B    | 1.534          | 1.568  | 1.6201         | 1.6375 | 1.7500            |
|  | 2A                    | 0.0027         | 1.7473           | 1.7268 | 1.7165           | 1.6174           | 1.6085 | 1.5092                                       | 2B    | 1.534          | 1.568  | 1.6201         | 1.6317 | 1.7500            |
|  | 3A                    | 0.0000         | 1.7500           | 1.7295 | —                | 1.6201           | 1.6134 | 1.5119                                       | 3B    | 1.5340         | 1.5575 | 1.6201         | 1.6288 | 1.7500            |
| 1 <sup>3</sup> / <sub>4</sub> -6 UN  | 2A                    | 0.0025         | 1.7475           | 1.7293 | —                | 1.6392           | 1.6309 | 1.5491                                       | 2B    | 1.570          | 1.600  | 1.6417         | 1.6525 | 1.7500            |
|  | 3A                    | 0.0000         | 1.7500           | 1.7318 | —                | 1.6417           | 1.6354 | 1.5516                                       | 3B    | 1.5700         | 1.5896 | 1.6417         | 1.6498 | 1.7500            |
|  | 2A                    | 0.0023         | 1.7477           | 1.7327 | 1.7252           | 1.6665           | 1.6590 | 1.5989                                       | 2B    | 1.615          | 1.640  | 1.6688         | 1.6786 | 1.7500            |
| 1 <sup>3</sup> / <sub>4</sub> -8 UN  | 3A                    | 0.0000         | 1.7500           | 1.7350 | —                | 1.6688           | 1.6632 | 1.6012                                       | 3B    | 1.6150         | 1.6297 | 1.6688         | 1.6762 | 1.7500            |
|  | 2A                    | 0.0019         | 1.7481           | 1.7352 | —                | 1.6831           | 1.6766 | 1.6291                                       | 2B    | 1.642          | 1.663  | 1.6850         | 1.6934 | 1.7500            |
|  | 3A                    | 0.0000         | 1.7500           | 1.7386 | —                | 1.6941           | 1.6881 | 1.6490                                       | 2B    | 1.660          | 1.678  | 1.6959         | 1.7037 | 1.7500            |
| 1 <sup>3</sup> / <sub>4</sub> -10 UNS  | 2A                    | 0.0019         | 1.7481           | 1.7386 | —                | 1.6959           | 1.6914 | 1.6508                                       | 3B    | 1.6600         | 1.6698 | 1.6959         | 1.7017 | 1.7500            |
|  | 3A                    | 0.0000         | 1.7500           | 1.7386 | —                | 1.6959           | 1.6914 | 1.6508                                       | 2B    | 1.673          | 1.688  | 1.7036         | 1.7109 | 1.7500            |
|  | 2A                    | 0.0017         | 1.7483           | 1.7380 | —                | 1.7019           | 1.6963 | 1.6632                                       | 2B    | 1.673          | 1.688  | 1.7036         | 1.7109 | 1.7500            |
| 1 <sup>3</sup> / <sub>4</sub> -12 UN   | 2A                    | 0.0016         | 1.7484           | 1.7390 | —                | 1.7078           | 1.7025 | 1.6739                                       | 2B    | 1.682          | 1.696  | 1.7094         | 1.7163 | 1.7500            |
|  | 3A                    | 0.0000         | 1.7500           | 1.7406 | —                | 1.7094           | 1.7054 | 1.6755                                       | 3B    | 1.6820         | 1.6908 | 1.7094         | 1.7146 | 1.7500            |
|  | 2A                    | 0.0015         | 1.7485           | 1.7398 | —                | 1.7124           | 1.7073 | 1.6824                                       | 2B    | 1.690          | 1.703  | 1.7139         | 1.7205 | 1.7500            |
| 1 <sup>3</sup> / <sub>4</sub> -14 UNS  | 2A                    | 0.0016         | 1.7484           | 1.7390 | —                | 1.7078           | 1.7025 | 1.6739                                       | 2B    | 1.682          | 1.696  | 1.7094         | 1.7163 | 1.7500            |
|  | 3A                    | 0.0000         | 1.7500           | 1.7406 | —                | 1.7094           | 1.7054 | 1.6755                                       | 3B    | 1.6820         | 1.6908 | 1.7094         | 1.7146 | 1.7500            |
|  | 2A                    | 0.0015         | 1.7485           | 1.7398 | —                | 1.7124           | 1.7073 | 1.6824                                       | 2B    | 1.690          | 1.703  | 1.7139         | 1.7205 | 1.7500            |
| 1 <sup>3</sup> / <sub>4</sub> -16 UN   | 2A                    | 0.0015         | 1.7485           | 1.7404 | —                | 1.7160           | 1.7112 | 1.6890                                       | 2B    | 1.696          | 1.707  | 1.7175         | 1.7238 | 1.7500            |
|  | 3A                    | 0.0000         | 1.7500           | 1.7419 | —                | 1.7175           | 1.7139 | 1.6905                                       | 3B    | 1.6960         | 1.7037 | 1.7175         | 1.7222 | 1.7500            |
|  | 2A                    | 0.0025         | 1.8100           | 1.7918 | —                | 1.7017           | 1.6933 | 1.6116                                       | 2B    | 1.632          | 1.663  | 1.7042         | 1.7151 | 1.8125            |
| 1 <sup>13</sup> / <sub>16</sub> -6 UN  | 3A                    | 0.0000         | 1.8125           | 1.7943 | —                | 1.7042           | 1.6979 | 1.6141                                       | 3B    | 1.6320         | 1.6521 | 1.7042         | 1.7124 | 1.8125            |
|  | 2A                    | 0.0023         | 1.8102           | 1.7952 | —                | 1.7290           | 1.7214 | 1.6614                                       | 2B    | 1.677          | 1.702  | 1.7313         | 1.7412 | 1.8125            |
|  | 3A                    | 0.0000         | 1.8125           | 1.7975 | —                | 1.7313           | 1.7256 | 1.6637                                       | 3B    | 1.6770         | 1.6922 | 1.7313         | 1.7387 | 1.8125            |
| 1 <sup>13</sup> / <sub>16</sub> -8 UN  | 2A                    | 0.0018         | 1.8107           | 1.7993 | —                | 1.7566           | 1.7506 | 1.7115                                       | 2B    | 1.722          | 1.740  | 1.7584         | 1.7662 | 1.8125            |
|  | 3A                    | 0.0000         | 1.8125           | 1.8011 | —                | 1.7584           | 1.7539 | 1.7133                                       | 3B    | 1.7220         | 1.7323 | 1.7584         | 1.7642 | 1.8125            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  | Internal <sup>b</sup> |  |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|-----------------------|--|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |                       | UNR Minor<br>Dia. <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min                   |  |       | Min            | Max    | Min            | Max    |                   |
| 1 <sup>3</sup> / <sub>16</sub> -16 UN  | 2A                    | 0.0016         | 1.8109           | 1.8015 | —                | 1.7703           | 1.7650                | 1.7364                                       | 2B    | 1.745          | 1.759  | 1.7719         | 1.7788 | 1.8125            |
|  | 3A                    | 0.0000         | 1.8125           | 1.8031 | —                | 1.7719           | 1.7679                | 1.7380                                       | 3B    | 1.7450         | 1.7533 | 1.7719         | 1.7771 | 1.8125            |
| 1 <sup>3</sup> / <sub>16</sub> -20 UN  | 2A                    | 0.0015         | 1.8110           | 1.8029 | —                | 1.7785           | 1.7737                | 1.7515                                       | 2B    | 1.758          | 1.770  | 1.7800         | 1.7863 | 1.8125            |
|  | 3A                    | 0.0000         | 1.8125           | 1.8044 | —                | 1.7800           | 1.7764                | 1.7530                                       | 3B    | 1.7580         | 1.7662 | 1.7800         | 1.7847 | 1.8125            |
| 1 <sup>7</sup> / <sub>8</sub> -6 UN  | 2A                    | 0.0025         | 1.8725           | 1.8543 | —                | 1.7642           | 1.7558                | 1.6741                                       | 2B    | 1.695          | 1.725  | 1.7667         | 1.7777 | 1.8750            |
|  | 3A                    | 0.0000         | 1.8750           | 1.8568 | —                | 1.7667           | 1.7604                | 1.6766                                       | 3B    | 1.6950         | 1.7146 | 1.7667         | 1.7749 | 1.8750            |
| 1 <sup>7</sup> / <sub>8</sub> -8 UN  | 2A                    | 0.0023         | 1.8727           | 1.8577 | 1.8502           | 1.7915           | 1.7838                | 1.7239                                       | 2B    | 1.740          | 1.765  | 1.7938         | 1.8038 | 1.8750            |
|  | 3A                    | 0.0000         | 1.8750           | 1.8600 | —                | 1.7938           | 1.7881                | 1.7262                                       | 3B    | 1.7400         | 1.7547 | 1.7938         | 1.8013 | 1.8750            |
| 1 <sup>7</sup> / <sub>8</sub> -10 UNS  | 2A                    | 0.0019         | 1.8731           | 1.8602 | —                | 1.8081           | 1.8016                | 1.7541                                       | 2B    | 1.767          | 1.788  | 1.8100         | 1.8184 | 1.8750            |
|  | 3A                    | 0.0000         | 1.8732           | 1.8618 | —                | 1.8191           | 1.8131                | 1.7740                                       | 2B    | 1.785          | 1.803  | 1.8209         | 1.8287 | 1.8750            |
| 1 <sup>7</sup> / <sub>8</sub> -12 UN   | 2A                    | 0.0018         | 1.8732           | 1.8618 | —                | 1.8191           | 1.8131                | 1.7740                                       | 2B    | 1.785          | 1.803  | 1.8209         | 1.8287 | 1.8750            |
|  | 3A                    | 0.0000         | 1.8750           | 1.8636 | —                | 1.8209           | 1.8164                | 1.7758                                       | 3B    | 1.7850         | 1.7948 | 1.8209         | 1.8267 | 1.8750            |
| 1 <sup>7</sup> / <sub>8</sub> -14 UNS  | 2A                    | 0.0017         | 1.8733           | 1.8630 | —                | 1.8269           | 1.8213                | 1.7883                                       | 2B    | 1.798          | 1.814  | 1.8286         | 1.8359 | 1.8750            |
|  | 3A                    | 0.0000         | 1.8734           | 1.8640 | —                | 1.8328           | 1.8275                | 1.7989                                       | 2B    | 1.807          | 1.821  | 1.8344         | 1.8413 | 1.8750            |
| 1 <sup>7</sup> / <sub>8</sub> -16 UN   | 2A                    | 0.0016         | 1.8734           | 1.8640 | —                | 1.8328           | 1.8275                | 1.7989                                       | 2B    | 1.807          | 1.821  | 1.8344         | 1.8413 | 1.8750            |
|  | 3A                    | 0.0000         | 1.8750           | 1.8656 | —                | 1.8344           | 1.8304                | 1.8005                                       | 3B    | 1.8070         | 1.8158 | 1.8344         | 1.8396 | 1.8750            |
| 1 <sup>7</sup> / <sub>8</sub> -18 UNS  | 2A                    | 0.0015         | 1.8735           | 1.8648 | —                | 1.8374           | 1.8323                | 1.8074                                       | 2B    | 1.815          | 1.828  | 1.8389         | 1.8455 | 1.8750            |
|  | 3A                    | 0.0000         | 1.8735           | 1.8654 | —                | 1.8410           | 1.8362                | 1.8140                                       | 2B    | 1.821          | 1.832  | 1.8425         | 1.8488 | 1.8750            |
| 1 <sup>7</sup> / <sub>8</sub> -20 UN   | 2A                    | 0.0015         | 1.8735           | 1.8654 | —                | 1.8410           | 1.8362                | 1.8140                                       | 2B    | 1.821          | 1.832  | 1.8425         | 1.8488 | 1.8750            |
|  | 3A                    | 0.0000         | 1.8750           | 1.8669 | —                | 1.8425           | 1.8389                | 1.8155                                       | 3B    | 1.8210         | 1.8287 | 1.8425         | 1.8472 | 1.8750            |
| 1 <sup>5</sup> / <sub>16</sub> -6 UN   | 2A                    | 0.0026         | 1.9349           | 1.9167 | —                | 1.8266           | 1.8181                | 1.7365                                       | 2B    | 1.757          | 1.788  | 1.8292         | 1.8403 | 1.9375            |
|  | 3A                    | 0.0000         | 1.9375           | 1.9193 | —                | 1.8292           | 1.8228                | 1.7391                                       | 3B    | 1.7570         | 1.7771 | 1.8292         | 1.8375 | 1.9375            |
| 1 <sup>5</sup> / <sub>16</sub> -8 UN   | 2A                    | 0.0023         | 1.9352           | 1.9202 | —                | 1.8540           | 1.8463                | 1.7864                                       | 2B    | 1.802          | 1.827  | 1.8563         | 1.8663 | 1.9375            |
|  | 3A                    | 0.0000         | 1.9375           | 1.9225 | —                | 1.8563           | 1.8505                | 1.7887                                       | 3B    | 1.8020         | 1.8172 | 1.8563         | 1.8638 | 1.9375            |
| 1 <sup>5</sup> / <sub>16</sub> -12 UN  | 2A                    | 0.0018         | 1.9357           | 1.9243 | —                | 1.8816           | 1.8755                | 1.8365                                       | 2B    | 1.847          | 1.865  | 1.8834         | 1.8913 | 1.9375            |
|  | 3A                    | 0.0000         | 1.9375           | 1.9261 | —                | 1.8834           | 1.8789                | 1.8383                                       | 3B    | 1.8470         | 1.8573 | 1.8834         | 1.8893 | 1.9375            |
| 1 <sup>5</sup> / <sub>16</sub> -16 UN  | 2A                    | 0.0016         | 1.9359           | 1.9265 | —                | 1.8953           | 1.8899                | 1.8614                                       | 2B    | 1.870          | 1.884  | 1.8969         | 1.9039 | 1.9375            |
|  | 3A                    | 0.0000         | 1.9375           | 1.9281 | —                | 1.8969           | 1.8929                | 1.8630                                       | 3B    | 1.8700         | 1.8783 | 1.8969         | 1.9021 | 1.9375            |
| 1 <sup>5</sup> / <sub>16</sub> -20 UN  | 2A                    | 0.0015         | 1.9360           | 1.9279 | —                | 1.9035           | 1.8986                | 1.8765                                       | 2B    | 1.883          | 1.895  | 1.9050         | 1.9114 | 1.9375            |
|  | 3A                    | 0.0000         | 1.9375           | 1.9294 | —                | 1.9050           | 1.9013                | 1.8780                                       | 3B    | 1.8830         | 1.8912 | 1.9050         | 1.9098 | 1.9375            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  | Internal <sup>b</sup> |   |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|-----------------------|---|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |                       | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min                   |   |       | Min            | Max    | Min            | Max    |                   |
| 2-4½ UNC   | 1A                    | 0.0029         | 1.9971           | 1.9641 | —                | 1.8528           | 1.8385                | 1.7324  | 1B    | 1.759          | 1.795  | 1.8557         | 1.8743 | 2.0000            |
|  | 2A                    | 0.0029         | 1.9971           | 1.9751 | 1.9641           | 1.8528           | 1.8433                | 1.7324  | 2B    | 1.759          | 1.795  | 1.8557         | 1.8681 | 2.0000            |
|  | 3A                    | 0.0000         | 2.0000           | 1.9780 | —                | 1.8557           | 1.8486                | 1.7353  | 3B    | 1.7590         | 1.7861 | 1.8557         | 1.8650 | 2.0000            |
| 2-6 UN   | 2A                    | 0.0026         | 1.9974           | 1.9792 | —                | 1.8891           | 1.8805                | 1.7990  | 2B    | 1.820          | 1.850  | 1.8917         | 1.9028 | 2.0000            |
|  | 3A                    | 0.0000         | 2.0000           | 1.9818 | —                | 1.8917           | 1.8853                | 1.8016  | 3B    | 1.8200         | 1.8396 | 1.8917         | 1.9000 | 2.0000            |
| 2-8 UN   | 2A                    | 0.0023         | 1.9977           | 1.9827 | 1.9752           | 1.9165           | 1.9087                | 1.8489  | 2B    | 1.865          | 1.890  | 1.9188         | 1.9289 | 2.0000            |
|  | 3A                    | 0.0000         | 2.0000           | 1.9850 | —                | 1.9188           | 1.9130                | 1.8512  | 3B    | 1.8650         | 1.8797 | 1.9188         | 1.9264 | 2.0000            |
| 2-10 UNS   | 2A                    | 0.0020         | 1.9980           | 1.9851 | —                | 1.9330           | 1.9265                | 1.8790  | 2B    | 1.892          | 1.913  | 1.9350         | 1.9435 | 2.0000            |
| 2-12 UN  | 2A                    | 0.0018         | 1.9982           | 1.9868 | —                | 1.9441           | 1.9380                | 1.8990  | 2B    | 1.910          | 1.928  | 1.9459         | 1.9538 | 2.0000            |
|  | 3A                    | 0.0000         | 2.0000           | 1.9886 | —                | 1.9459           | 1.9414                | 1.9008  | 3B    | 1.9100         | 1.9198 | 1.9459         | 1.9518 | 2.0000            |
| 2-14 UNS   | 2A                    | 0.0017         | 1.9983           | 1.9880 | —                | 1.9519           | 1.9462                | 1.9133  | 2B    | 1.923          | 1.938  | 1.9536         | 1.9610 | 2.0000            |
| 2-16 UN  | 2A                    | 0.0016         | 1.9984           | 1.9890 | —                | 1.9578           | 1.9524                | 1.9239  | 2B    | 1.932          | 1.946  | 1.9594         | 1.9664 | 2.0000            |
|  | 3A                    | 0.0000         | 2.0000           | 1.9906 | —                | 1.9594           | 1.9554                | 1.9255  | 3B    | 1.9320         | 1.9408 | 1.9594         | 1.9646 | 2.0000            |
| 2-18 UNS   | 2A                    | 0.0015         | 1.9985           | 1.9898 | —                | 1.9624           | 1.9573                | 1.9324  | 2B    | 1.940          | 1.953  | 1.9639         | 1.9706 | 2.0000            |
| 2-20 UN  | 2A                    | 0.0015         | 1.9985           | 1.9904 | —                | 1.9660           | 1.9611                | 1.9390  | 2B    | 1.946          | 1.957  | 1.9675         | 1.9739 | 2.0000            |
|  | 3A                    | 0.0000         | 2.0000           | 1.9919 | —                | 1.9675           | 1.9638                | 1.9405  | 3B    | 1.9460         | 1.9537 | 1.9675         | 1.9723 | 2.0000            |
| 2½/16-16 UNS   | 2A                    | 0.0016         | 2.0609           | 2.0515 | —                | 2.0203           | 2.0149                | 1.9864  | 2B    | 1.995          | 2.009  | 2.0219         | 2.0289 | 2.0625            |
|  | 3A                    | 0.0000         | 2.0625           | 2.0531 | —                | 2.0219           | 2.0179                | 1.9880  | 3B    | 1.9950         | 2.0033 | 2.0219         | 2.0271 | 2.0625            |
|  | 2A                    | 0.0026         | 2.1224           | 2.1042 | —                | 2.0141           | 2.0054                | 1.9240  | 2B    | 1.945          | 1.975  | 2.0167         | 2.0280 | 2.1250            |
| 2½/8-6 UN  | 3A                    | 0.0000         | 2.1250           | 2.1068 | —                | 2.0167           | 2.0102                | 1.9266  | 3B    | 1.9450         | 1.9646 | 2.0167         | 2.0251 | 2.1250            |
|  | 2A                    | 0.0024         | 2.1226           | 2.1076 | 2.1001           | 2.0414           | 2.0335                | 1.9738  | 2B    | 1.990          | 2.015  | 2.0438         | 2.0540 | 2.1250            |
| 2½/8-8 UN  | 3A                    | 0.0000         | 2.1250           | 2.1100 | —                | 2.0438           | 2.0379                | 1.9762  | 3B    | 1.9900         | 2.0047 | 2.0438         | 2.0515 | 2.1250            |
|  | 2A                    | 0.0018         | 2.1232           | 2.1118 | —                | 2.0691           | 2.0630                | 2.0240  | 2B    | 2.035          | 2.053  | 2.0709         | 2.0788 | 2.1250            |
| 2½/8-12 UN   | 3A                    | 0.0000         | 2.1250           | 2.1136 | —                | 2.0709           | 2.0664                | 2.0258  | 3B    | 2.0350         | 2.0448 | 2.0709         | 2.0768 | 2.1250            |
|  | 2A                    | 0.0016         | 2.1234           | 2.1140 | —                | 2.0828           | 2.0774                | 2.0489  | 2B    | 2.057          | 2.071  | 2.0844         | 2.0914 | 2.1250            |
| 2½/8-16 UN   | 3A                    | 0.0000         | 2.1250           | 2.1156 | —                | 2.0844           | 2.0803                | 2.0505  | 3B    | 2.0570         | 2.0658 | 2.0844         | 2.0896 | 2.1250            |
|  | 2A                    | 0.0015         | 2.1235           | 2.1154 | —                | 2.0910           | 2.0861                | 2.0640  | 2B    | 2.071          | 2.082  | 2.0925         | 2.0989 | 2.1250            |
| 2½/8-20 UN   | 3A                    | 0.0000         | 2.1250           | 2.1169 | —                | 2.0925           | 2.0888                | 2.0655  | 3B    | 2.0710         | 2.0787 | 2.0925         | 2.0973 | 2.1250            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  | Internal <sup>b</sup> |   |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|-----------------------|---|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |                       | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min                   |   |       | Min            | Max    | Min            | Max    | Min               |
| 2 $\frac{3}{16}$ -16 UNS   | 2A                    | 0.0016         | 2.1859           | 2.1765 | —                | 2.1453           | 2.1399                | 2.1114  | 2B    | 2.120          | 2.134  | 2.1469         | 2.1539 | 2.1875            |
|  | 3A                    | 0.0000         | 2.1875           | 2.1781 | —                | 2.1469           | 2.1428                | 2.1130  | 3B    | 2.1200         | 2.1283 | 2.1469         | 2.1521 | 2.1875            |
| 2 $\frac{1}{4}$ -4 $\frac{1}{2}$ UNC   | 1A                    | 0.0029         | 2.2471           | 2.2141 | —                | 2.1028           | 2.0882                | 1.9824  | 1B    | 2.009          | 2.045  | 2.1057         | 2.1247 | 2.2500            |
|  | 2A                    | 0.0029         | 2.2471           | 2.2251 | 2.2141           | 2.1028           | 2.0931                | 1.9824  | 2B    | 2.009          | 2.045  | 2.1057         | 2.1183 | 2.2500            |
|  | 3A                    | 0.0000         | 2.2500           | 2.2280 | —                | 2.1057           | 2.0984                | 1.9853  | 3B    | 2.0090         | 2.0361 | 2.1057         | 2.1152 | 2.2500            |
| 2 $\frac{1}{4}$ -6 UN  | 2A                    | 0.0026         | 2.2474           | 2.2292 | —                | 2.1391           | 2.1303                | 2.0490  | 2B    | 2.070          | 2.100  | 2.1417         | 2.1531 | 2.2500            |
|  | 3A                    | 0.0000         | 2.2500           | 2.2318 | —                | 2.1417           | 2.1351                | 2.0516  | 3B    | 2.0700         | 2.0896 | 2.1417         | 2.1502 | 2.2500            |
| 2 $\frac{1}{4}$ -8 UN  | 2A                    | 0.0024         | 2.2476           | 2.2326 | 2.2251           | 2.1664           | 2.1584                | 2.0988  | 2B    | 2.115          | 2.140  | 2.1688         | 2.1792 | 2.2500            |
|  | 3A                    | 0.0000         | 2.2500           | 2.2350 | —                | 2.1688           | 2.1628                | 2.1012  | 3B    | 2.1150         | 2.1297 | 2.1688         | 2.1766 | 2.2500            |
| 2 $\frac{1}{4}$ -10 UNS  | 2A                    | 0.0020         | 2.2480           | 2.2351 | —                | 2.1830           | 2.1765                | 2.1290  | 2B    | 2.142          | 2.163  | 2.1850         | 2.1935 | 2.2500            |
|  | 3A                    | 0.0018         | 2.2482           | 2.2368 | —                | 2.1941           | 2.1880                | 2.1490  | 2B    | 2.160          | 2.178  | 2.1959         | 2.2038 | 2.2500            |
| 2 $\frac{1}{4}$ -12 UN   | 2A                    | 0.0000         | 2.2500           | 2.2386 | —                | 2.1959           | 2.1914                | 2.1508  | 3B    | 2.1600         | 2.1698 | 2.1959         | 2.2018 | 2.2500            |
|  | 2A                    | 0.0017         | 2.2483           | 2.2380 | —                | 2.2019           | 2.1962                | 2.1633  | 2B    | 2.173          | 2.188  | 2.2036         | 2.2110 | 2.2500            |
| 2 $\frac{1}{4}$ -16 UN   | 2A                    | 0.0016         | 2.2484           | 2.2390 | —                | 2.2078           | 2.2024                | 2.1739  | 2B    | 2.182          | 2.196  | 2.2094         | 2.2164 | 2.2500            |
|  | 3A                    | 0.0000         | 2.2500           | 2.2406 | —                | 2.2094           | 2.2053                | 2.1755  | 3B    | 2.1820         | 2.1908 | 2.2094         | 2.2146 | 2.2500            |
| 2 $\frac{1}{4}$ -18 UNS  | 2A                    | 0.0015         | 2.2485           | 2.2398 | —                | 2.2124           | 2.2073                | 2.1824  | 2B    | 2.190          | 2.203  | 2.2139         | 2.2206 | 2.2500            |
|  | 2A                    | 0.0015         | 2.2485           | 2.2404 | —                | 2.2160           | 2.2111                | 2.1890  | 2B    | 2.196          | 2.207  | 2.2175         | 2.2239 | 2.2500            |
| 2 $\frac{1}{4}$ -20 UN   | 3A                    | 0.0000         | 2.2500           | 2.2419 | —                | 2.2175           | 2.2137                | 2.1905  | 3B    | 2.1960         | 2.2037 | 2.2175         | 2.2223 | 2.2500            |
|  | 2A                    | 0.0017         | 2.3108           | 2.3014 | —                | 2.2702           | 2.2647                | 2.2363  | 2B    | 2.245          | 2.259  | 2.2719         | 2.2791 | 2.3125            |
|  | 3A                    | 0.0000         | 2.3125           | 2.3031 | —                | 2.2719           | 2.2678                | 2.2380  | 3B    | 2.2450         | 2.2533 | 2.2719         | 2.2773 | 2.3125            |
| 2 $\frac{3}{8}$ -6 UN  | 2A                    | 0.0027         | 2.3723           | 2.3541 | —                | 2.2640           | 2.2551                | 2.1739  | 2B    | 2.195          | 2.226  | 2.2667         | 2.2782 | 2.3750            |
|  | 3A                    | 0.0000         | 2.3750           | 2.3568 | —                | 2.2667           | 2.2601                | 2.1766  | 3B    | 2.1950         | 2.2146 | 2.2667         | 2.2753 | 2.3750            |
| 2 $\frac{3}{8}$ -8 UN  | 2A                    | 0.0024         | 2.3726           | 2.3576 | —                | 2.2914           | 2.2833                | 2.2238  | 2B    | 2.240          | 2.265  | 2.2938         | 2.3043 | 2.3750            |
|  | 3A                    | 0.0000         | 2.3750           | 2.3600 | —                | 2.2938           | 2.2878                | 2.2262  | 3B    | 2.2400         | 2.2547 | 2.2938         | 2.3017 | 2.3750            |
| 2 $\frac{3}{8}$ -12 UN   | 2A                    | 0.0019         | 2.3731           | 2.3617 | —                | 2.3190           | 2.3128                | 2.2739  | 2B    | 2.285          | 2.303  | 2.3209         | 2.3290 | 2.3750            |
|  | 3A                    | 0.0000         | 2.3750           | 2.3636 | —                | 2.3209           | 2.3163                | 2.2758  | 3B    | 2.2850         | 2.2948 | 2.3209         | 2.3269 | 2.3750            |
| 2 $\frac{3}{8}$ -16 UN   | 2A                    | 0.0017         | 2.3733           | 2.3639 | —                | 2.3327           | 2.3272                | 2.2988  | 2B    | 2.307          | 2.321  | 2.3344         | 2.3416 | 2.3750            |
|  | 3A                    | 0.0000         | 2.3750           | 2.3656 | —                | 2.3344           | 2.3303                | 2.3005  | 3B    | 2.3070         | 2.3158 | 2.3344         | 2.3398 | 2.3750            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                        |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|--|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia. <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |  |       | Min            | Max    | Min            | Max    |                   |
| 2 $\frac{3}{8}$ -20 UN   | 2A                    | 0.0015         | 2.3735           | 2.3654 | —                | 2.3410           | 2.3359 | 2.3140                                       | 2B    | 2.321          | 2.332  | 2.3425         | 2.3491 | 2.3750            |
|  | 3A                    | 0.0000         | 2.3750           | 2.3669 | —                | 2.3425           | 2.3387 | 2.3155                                       | 3B    | 2.3210         | 2.3287 | 2.3425         | 2.3475 | 2.3750            |
| 2 $\frac{7}{16}$ -16 UNS   | 2A                    | 0.0017         | 2.4358           | 2.4264 | —                | 2.3952           | 2.3897 | 2.3613                                       | 2B    | 2.370          | 2.384  | 2.3969         | 2.4041 | 2.4375            |
|  | 3A                    | 0.0000         | 2.4375           | 2.4281 | —                | 2.3969           | 2.3928 | 2.3630                                       | 3B    | 2.3700         | 2.3783 | 2.3969         | 2.4023 | 2.4375            |
| 2 $\frac{1}{2}$ -4 UNC   | 1A                    | 0.0031         | 2.4969           | 2.4612 | —                | 2.3345           | 2.3190 | 2.1992                                       | 1B    | 2.229          | 2.267  | 2.3376         | 2.3578 | 2.5000            |
|  | 2A                    | 0.0031         | 2.4969           | 2.4731 | 2.4612           | 2.3345           | 2.3241 | 2.1992                                       | 2B    | 2.229          | 2.267  | 2.3376         | 2.3511 | 2.5000            |
| 2 $\frac{1}{2}$ -6 UN  | 3A                    | 0.0000         | 2.5000           | 2.4762 | —                | 2.3376           | 2.3298 | 2.2023                                       | 3B    | 2.2290         | 2.2594 | 2.3376         | 2.3477 | 2.5000            |
|  | 2A                    | 0.0027         | 2.4973           | 2.4791 | —                | 2.3890           | 2.3800 | 2.2989                                       | 2B    | 2.320          | 2.350  | 2.3917         | 2.4033 | 2.5000            |
| 2 $\frac{1}{2}$ -8 UN  | 3A                    | 0.0000         | 2.5000           | 2.4818 | —                | 2.3917           | 2.3850 | 2.3016                                       | 3B    | 2.3200         | 2.3396 | 2.3917         | 2.4004 | 2.5000            |
|  | 2A                    | 0.0024         | 2.4976           | 2.4826 | 2.4751           | 2.4164           | 2.4082 | 2.3488                                       | 2B    | 2.365          | 2.390  | 2.4188         | 2.4294 | 2.5000            |
| 2 $\frac{1}{2}$ -10 UNS  | 3A                    | 0.0000         | 2.5000           | 2.4850 | —                | 2.4188           | 2.4127 | 2.3512                                       | 3B    | 2.3650         | 2.3797 | 2.4188         | 2.4268 | 2.5000            |
|  | 2A                    | 0.0020         | 2.4980           | 2.4851 | —                | 2.4330           | 2.4263 | 2.3790                                       | 2B    | 2.392          | 2.413  | 2.4350         | 2.4437 | 2.5000            |
| 2 $\frac{1}{2}$ -12 UN   | 2A                    | 0.0019         | 2.4981           | 2.4867 | —                | 2.4440           | 2.4378 | 2.3989                                       | 2B    | 2.410          | 2.428  | 2.4459         | 2.4540 | 2.5000            |
|  | 3A                    | 0.0000         | 2.5000           | 2.4886 | —                | 2.4459           | 2.4413 | 2.4008                                       | 3B    | 2.4100         | 2.4198 | 2.4459         | 2.4519 | 2.5000            |
| 2 $\frac{1}{2}$ -14 UNS  | 2A                    | 0.0017         | 2.4983           | 2.4880 | —                | 2.4519           | 2.4461 | 2.4133                                       | 2B    | 2.423          | 2.438  | 2.4536         | 2.4612 | 2.5000            |
|  | 2A                    | 0.0017         | 2.4983           | 2.4889 | —                | 2.4577           | 2.4522 | 2.4238                                       | 2B    | 2.432          | 2.446  | 2.4594         | 2.4666 | 2.5000            |
| 2 $\frac{1}{2}$ -16 UN   | 3A                    | 0.0000         | 2.5000           | 2.4906 | —                | 2.4594           | 2.4553 | 2.4255                                       | 3B    | 2.4320         | 2.4408 | 2.4594         | 2.4648 | 2.5000            |
|  | 2A                    | 0.0016         | 2.4984           | 2.4897 | —                | 2.4623           | 2.4570 | 2.4323                                       | 2B    | 2.440          | 2.453  | 2.4639         | 2.4708 | 2.5000            |
| 2 $\frac{1}{2}$ -20 UN   | 2A                    | 0.0015         | 2.4985           | 2.4904 | —                | 2.4660           | 2.4609 | 2.4390                                       | 2B    | 2.446          | 2.457  | 2.4675         | 2.4741 | 2.5000            |
|  | 3A                    | 0.0000         | 2.5000           | 2.4919 | —                | 2.4675           | 2.4637 | 2.4405                                       | 3B    | 2.4460         | 2.4537 | 2.4675         | 2.4725 | 2.5000            |
| 2 $\frac{5}{8}$ -6 UN  | 2A                    | 0.0027         | 2.6223           | 2.6041 | —                | 2.5140           | 2.5050 | 2.4239                                       | 2B    | 2.445          | 2.475  | 2.5167         | 2.5285 | 2.6250            |
|  | 3A                    | 0.0000         | 2.6250           | 2.6068 | —                | 2.5167           | 2.5099 | 2.4266                                       | 3B    | 2.4450         | 2.4646 | 2.5167         | 2.5255 | 2.6250            |
| 2 $\frac{5}{8}$ -8 UN  | 2A                    | 0.0025         | 2.6225           | 2.6075 | —                | 2.5413           | 2.5331 | 2.4737                                       | 2B    | 2.490          | 2.515  | 2.5438         | 2.5545 | 2.6250            |
|  | 3A                    | 0.0000         | 2.6250           | 2.6100 | —                | 2.5438           | 2.5376 | 2.4762                                       | 3B    | 2.4900         | 2.5047 | 2.5438         | 2.5518 | 2.6250            |
| 2 $\frac{5}{8}$ -12 UN   | 2A                    | 0.0019         | 2.6231           | 2.6117 | —                | 2.5690           | 2.5628 | 2.5239                                       | 2B    | 2.535          | 2.553  | 2.5709         | 2.5790 | 2.6250            |
|  | 3A                    | 0.0000         | 2.6250           | 2.6136 | —                | 2.5709           | 2.5663 | 2.5258                                       | 3B    | 2.5350         | 2.5448 | 2.5709         | 2.5769 | 2.6250            |
| 2 $\frac{5}{8}$ -16 UN   | 2A                    | 0.0017         | 2.6233           | 2.6139 | —                | 2.5827           | 2.5772 | 2.5488                                       | 2B    | 2.557          | 2.571  | 2.5844         | 2.5916 | 2.6250            |
|  | 3A                    | 0.0000         | 2.6250           | 2.6156 | —                | 2.5844           | 2.5803 | 2.5505                                       | 3B    | 2.5570         | 2.5658 | 2.5844         | 2.5898 | 2.6250            |



Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  | Internal <sup>b</sup> |   |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|-----------------------|---|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |                       | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min                   |   |       | Min            | Max    | Min            | Max    |                   |
| 2 $\frac{3}{8}$ -20 UN   | 2A                    | 0.0015         | 2.6235           | 2.6154 | —                | 2.5910           | 2.5859                | 2.5640  | 2B    | 2.571          | 2.582  | 2.5925         | 2.5991 | 2.6250            |
|  | 3A                    | 0.0000         | 2.6250           | 2.6169 | —                | 2.5925           | 2.5887                | 2.5655  | 3B    | 2.5710         | 2.5787 | 2.5925         | 2.5975 | 2.6250            |
| 2 $\frac{3}{4}$ -4 UNC   | 1A                    | 0.0032         | 2.7468           | 2.7111 | —                | 2.5844           | 2.5686                | 2.4491  | 1B    | 2.479          | 2.517  | 2.5876         | 2.6082 | 2.7500            |
|  | 2A                    | 0.0032         | 2.7468           | 2.7230 | 2.7111           | 2.5844           | 2.5739                | 2.4491  | 2B    | 2.479          | 2.517  | 2.5876         | 2.6013 | 2.7500            |
|  | 3A                    | 0.0000         | 2.7500           | 2.7262 | —                | 2.5876           | 2.5797                | 2.4523  | 3B    | 2.4790         | 2.5094 | 2.5876         | 2.5979 | 2.7500            |
| 2 $\frac{3}{4}$ -6 UN  | 2A                    | 0.0027         | 2.7473           | 2.7291 | —                | 2.6390           | 2.6299                | 2.5489  | 2B    | 2.570          | 2.600  | 2.6417         | 2.6536 | 2.7500            |
|  | 3A                    | 0.0000         | 2.7500           | 2.7318 | —                | 2.6417           | 2.6349                | 2.5516  | 3B    | 2.5700         | 2.5896 | 2.6417         | 2.6506 | 2.7500            |
| 2 $\frac{3}{4}$ -8 UN  | 2A                    | 0.0025         | 2.7475           | 2.7325 | 2.7250           | 2.6663           | 2.6580                | 2.5987  | 2B    | 2.615          | 2.640  | 2.6688         | 2.6796 | 2.7500            |
|  | 3A                    | 0.0000         | 2.7500           | 2.7350 | —                | 2.6688           | 2.6625                | 2.6012  | 3B    | 2.6150         | 2.6297 | 2.6688         | 2.6769 | 2.7500            |
| 2 $\frac{3}{4}$ -10 UNS  | 2A                    | 0.0020         | 2.7480           | 2.7351 | —                | 2.6830           | 2.6763                | 2.6290  | 2B    | 2.642          | 2.663  | 2.6850         | 2.6937 | 2.7500            |
|  | 2A                    | 0.0019         | 2.7481           | 2.7367 | —                | 2.6940           | 2.6878                | 2.6489  | 2B    | 2.660          | 2.678  | 2.6959         | 2.7040 | 2.7500            |
| 2 $\frac{3}{4}$ -12 UN   | 3A                    | 0.0000         | 2.7500           | 2.7386 | —                | 2.6959           | 2.6913                | 2.6508  | 3B    | 2.6600         | 2.6698 | 2.6959         | 2.7019 | 2.7500            |
|  | 2A                    | 0.0017         | 2.7483           | 2.7380 | —                | 2.7019           | 2.6961                | 2.6633  | 2B    | 2.673          | 2.688  | 2.7036         | 2.7112 | 2.7500            |
| 2 $\frac{3}{4}$ -14 UNS  | 2A                    | 0.0017         | 2.7483           | 2.7389 | —                | 2.7077           | 2.7022                | 2.6738  | 2B    | 2.682          | 2.696  | 2.7094         | 2.7166 | 2.7500            |
|  | 3A                    | 0.0000         | 2.7500           | 2.7406 | —                | 2.7094           | 2.7053                | 2.6755  | 3B    | 2.6820         | 2.6908 | 2.7094         | 2.7148 | 2.7500            |
| 2 $\frac{3}{4}$ -16 UN   | 2A                    | 0.0016         | 2.7484           | 2.7397 | —                | 2.7123           | 2.7070                | 2.6823  | 2B    | 2.690          | 2.703  | 2.7139         | 2.7208 | 2.7500            |
|  | 2A                    | 0.0015         | 2.7485           | 2.7404 | —                | 2.7160           | 2.7109                | 2.6890  | 2B    | 2.696          | 2.707  | 2.7175         | 2.7241 | 2.7500            |
| 2 $\frac{3}{4}$ -18 UNS  | 3A                    | 0.0000         | 2.7500           | 2.7419 | —                | 2.7175           | 2.7137                | 2.6905  | 3B    | 2.6960         | 2.7037 | 2.7175         | 2.7225 | 2.7500            |
|  | 2A                    | 0.0028         | 2.8722           | 2.8540 | —                | 2.7639           | 2.7547                | 2.6738  | 2B    | 2.695          | 2.725  | 2.7667         | 2.7787 | 2.8750            |
| 2 $\frac{7}{8}$ -6 UN  | 3A                    | 0.0000         | 2.8750           | 2.8568 | —                | 2.7667           | 2.7598                | 2.6766  | 3B    | 2.6950         | 2.7146 | 2.7667         | 2.7757 | 2.8750            |
|  | 2A                    | 0.0025         | 2.8725           | 2.8575 | —                | 2.7913           | 2.7829                | 2.7237  | 2B    | 2.740          | 2.765  | 2.7938         | 2.8048 | 2.8750            |
| 2 $\frac{7}{8}$ -8 UN  | 3A                    | 0.0000         | 2.8750           | 2.8600 | —                | 2.7938           | 2.7875                | 2.7262  | 3B    | 2.7400         | 2.7547 | 2.7938         | 2.8020 | 2.8750            |
|  | 2A                    | 0.0019         | 2.8731           | 2.8617 | —                | 2.8190           | 2.8127                | 2.7739  | 2B    | 2.785          | 2.803  | 2.8209         | 2.8291 | 2.8750            |
| 2 $\frac{7}{8}$ -12 UN   | 3A                    | 0.0000         | 2.8750           | 2.8636 | —                | 2.8209           | 2.8162                | 2.7758  | 3B    | 2.7850         | 2.7948 | 2.8209         | 2.8271 | 2.8750            |
|  | 2A                    | 0.0017         | 2.8733           | 2.8639 | —                | 2.8327           | 2.8271                | 2.7988  | 2B    | 2.807          | 2.821  | 2.8344         | 2.8417 | 2.8750            |
| 2 $\frac{7}{8}$ -16 UN   | 3A                    | 0.0000         | 2.8750           | 2.8656 | —                | 2.8344           | 2.8302                | 2.8005  | 3B    | 2.8070         | 2.8158 | 2.8344         | 2.8399 | 2.8750            |
|  | 2A                    | 0.0016         | 2.8734           | 2.8653 | —                | 2.8409           | 2.8357                | 2.8139  | 2B    | 2.821          | 2.832  | 2.8425         | 2.8493 | 2.8750            |
| 2 $\frac{7}{8}$ -20 UN   | 3A                    | 0.0000         | 2.8750           | 2.8669 | —                | 2.8425           | 2.8386                | 2.8155  | 3B    | 2.8210         | 2.8287 | 2.8425         | 2.8476 | 2.8750            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                         |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|---|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |   |       | Min            | Max    | Min            | Max    | Min               |
| 3-4 UNC  | 1A                    | 0.0032         | 2.9968           | 2.9611 | —                | 2.8344           | 2.8183 | 2.6991  | 1B    | 2.729          | 2.767  | 2.8376         | 2.8585 | 3.0000            |
|  | 2A                    | 0.0032         | 2.9968           | 2.9730 | 2.9611           | 2.8344           | 2.8237 | 2.6991  | 2B    | 2.729          | 2.767  | 2.8376         | 2.8515 | 3.0000            |
|  | 3A                    | 0.0000         | 3.0000           | 2.9762 | —                | 2.8376           | 2.8296 | 2.7023  | 3B    | 2.7290         | 2.7594 | 2.8376         | 2.8480 | 3.0000            |
| 3-6 UN   | 2A                    | 0.0028         | 2.9972           | 2.9790 | —                | 2.8889           | 2.8796 | 2.7988  | 2B    | 2.820          | 2.850  | 2.8917         | 2.9038 | 3.0000            |
|  | 3A                    | 0.0000         | 3.0000           | 2.9818 | —                | 2.8917           | 2.8847 | 2.8016  | 3B    | 2.8200         | 2.8396 | 2.8917         | 2.9008 | 3.0000            |
|  | 2A                    | 0.0026         | 2.9974           | 2.9824 | 2.9749           | 2.9162           | 2.9077 | 2.8486  | 2B    | 2.865          | 2.890  | 2.9188         | 2.9299 | 3.0000            |
| 3-8 UN   | 3A                    | 0.0000         | 3.0000           | 2.9850 | —                | 2.9188           | 2.9124 | 2.8512  | 3B    | 2.8650         | 2.8797 | 2.9188         | 2.9271 | 3.0000            |
|  | 2A                    | 0.0020         | 2.9980           | 2.9851 | —                | 2.9330           | 2.9262 | 2.8790  | 2B    | 2.892          | 2.913  | 2.9350         | 2.9439 | 3.0000            |
|  | 2A                    | 0.0019         | 2.9981           | 2.9867 | —                | 2.9440           | 2.9377 | 2.8989  | 2B    | 2.910          | 2.928  | 2.9459         | 2.9541 | 3.0000            |
| 3-12 UN  | 3A                    | 0.0000         | 3.0000           | 2.9886 | —                | 2.9459           | 2.9412 | 2.9008  | 3B    | 2.9100         | 2.9198 | 2.9459         | 2.9521 | 3.0000            |
|  | 2A                    | 0.0018         | 2.9982           | 2.9879 | —                | 2.9518           | 2.9459 | 2.9132  | 2B    | 2.923          | 2.938  | 2.9536         | 2.9613 | 3.0000            |
|  | 2A                    | 0.0017         | 2.9983           | 2.9889 | —                | 2.9577           | 2.9521 | 2.9238  | 2B    | 2.932          | 2.946  | 2.9594         | 2.9667 | 3.0000            |
| 3-16 UN  | 3A                    | 0.0000         | 3.0000           | 2.9906 | —                | 2.9594           | 2.9552 | 2.9255  | 3B    | 2.9320         | 2.9408 | 2.9594         | 2.9649 | 3.0000            |
|  | 2A                    | 0.0016         | 2.9984           | 2.9897 | —                | 2.9623           | 2.9569 | 2.9323  | 2B    | 2.940          | 2.953  | 2.9639         | 2.9709 | 3.0000            |
|  | 2A                    | 0.0016         | 2.9984           | 2.9903 | —                | 2.9659           | 2.9607 | 2.9389  | 2B    | 2.946          | 2.957  | 2.9675         | 2.9743 | 3.0000            |
| 3-20 UN  | 3A                    | 0.0000         | 3.0000           | 2.9919 | —                | 2.9675           | 2.9636 | 2.9405  | 3B    | 2.9460         | 2.9537 | 2.9675         | 2.9726 | 3.0000            |
|  | 2A                    | 0.0028         | 3.1222           | 3.1040 | —                | 3.0139           | 3.0045 | 2.9238  | 2B    | 2.945          | 2.975  | 3.0167         | 3.0289 | 3.1250            |
|  | 3A                    | 0.0000         | 3.1250           | 3.1068 | —                | 3.0167           | 3.0097 | 2.9266  | 3B    | 2.9450         | 2.9646 | 3.0167         | 3.0259 | 3.1250            |
| 3½-8 UN  | 2A                    | 0.0026         | 3.1224           | 3.1074 | —                | 3.0412           | 3.0326 | 2.9736  | 2B    | 2.990          | 3.015  | 3.0438         | 3.0550 | 3.1250            |
|  | 3A                    | 0.0000         | 3.1250           | 3.1100 | —                | 3.0438           | 3.0374 | 2.9762  | 3B    | 2.9900         | 3.0047 | 3.0438         | 3.0522 | 3.1250            |
|  | 2A                    | 0.0019         | 3.1231           | 3.1117 | —                | 3.0690           | 3.0627 | 3.0239  | 2B    | 3.035          | 3.053  | 3.0709         | 3.0791 | 3.1250            |
| 3½-12 UN   | 3A                    | 0.0000         | 3.1250           | 3.1136 | —                | 3.0709           | 3.0662 | 3.0258  | 3B    | 3.0350         | 3.0448 | 3.0709         | 3.0771 | 3.1250            |
|  | 2A                    | 0.0017         | 3.1233           | 3.1139 | —                | 3.0827           | 3.0771 | 3.0488  | 2B    | 3.057          | 3.071  | 3.0844         | 3.0917 | 3.1250            |
|  | 3A                    | 0.0000         | 3.1250           | 3.1156 | —                | 3.0844           | 3.0802 | 3.0505  | 3B    | 3.0570         | 3.0658 | 3.0844         | 3.0899 | 3.1250            |
| 3½-16 UN   | 1A                    | 0.0033         | 3.2467           | 3.2110 | —                | 3.0843           | 3.0680 | 2.9490  | 1B    | 2.979          | 3.017  | 3.0876         | 3.1088 | 3.2500            |
|  | 2A                    | 0.0033         | 3.2467           | 3.2229 | 3.2110           | 3.0843           | 3.0734 | 2.9490  | 2B    | 2.979          | 3.017  | 3.0876         | 3.1017 | 3.2500            |
|  | 3A                    | 0.0000         | 3.2500           | 3.2262 | —                | 3.0876           | 3.0794 | 2.9523  | 3B    | 2.9790         | 3.0094 | 3.0876         | 3.0982 | 3.2500            |
| 3¾-6 UN  | 2A                    | 0.0028         | 3.2472           | 3.2290 | —                | 3.1389           | 3.1294 | 3.0488  | 2B    | 3.070          | 3.100  | 3.1417         | 3.1540 | 3.2500            |
|  | 3A                    | 0.0000         | 3.2500           | 3.2318 | —                | 3.1417           | 3.1346 | 3.0516  | 3B    | 3.0700         | 3.0896 | 3.1417         | 3.1509 | 3.2500            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  | Internal <sup>b</sup> |  |        |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|-----------------------|--|--------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |                       | UNR Minor<br>Dia. <sup>c</sup> Max<br>(Ref.) | Class  | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min                   |  |        | Min            | Max    | Min            | Max    | Min               |
| 3/4-8 UN   | 2A                    | 0.0026         | 3.2474           | 3.2324 | 3.2249           | 3.1662           | 3.1575                | 3.0986                                       | 2B     | 3.115          | 3.140  | 3.1688         | 3.1801 | 3.2500            |
|  | 3A                    | 0.0000         | 3.2500           | 3.2350 | —                | 3.1688           | 3.1623                | 3.1012                                       | 3B     | 3.1150         | 3.1297 | 3.1688         | 3.1773 | 3.2500            |
| 3/4-10 UNS   | 2A                    | 0.0020         | 3.2480           | 3.2351 | —                | 3.1830           | 3.1762                | 3.1290                                       | 2B     | 3.142          | 3.163  | 3.1850         | 3.1939 | 3.2500            |
|  | 2A                    | 0.0019         | 3.2481           | 3.2367 | —                | 3.1940           | 3.1877                | 3.1489                                       | 2B     | 3.160          | 3.178  | 3.1959         | 3.2041 | 3.2500            |
| 3/4-12 UN  | 3A                    | 0.0000         | 3.2500           | 3.2386 | —                | 3.1959           | 3.1912                | 3.1508                                       | 3B     | 3.1600         | 3.1698 | 3.1959         | 3.2041 | 3.2500            |
|  | 2A                    | 0.0018         | 3.2482           | 3.2379 | —                | 3.2018           | 3.1959                | 3.1632                                       | 2B     | 3.173          | 3.188  | 3.2036         | 3.2113 | 3.2500            |
| 3/4-16 UN  | 2A                    | 0.0017         | 3.2483           | 3.2389 | —                | 3.2077           | 3.2021                | 3.1738                                       | 2B     | 3.182          | 3.196  | 3.2094         | 3.2167 | 3.2500            |
|  | 3A                    | 0.0000         | 3.2500           | 3.2406 | —                | 3.2094           | 3.2052                | 3.1755                                       | 3B     | 3.1820         | 3.1908 | 3.2094         | 3.2149 | 3.2500            |
| 3/4-18 UNS   | 2A                    | 0.0016         | 3.2484           | 3.2397 | —                | 3.2123           | 3.2069                | 3.1823                                       | 2B     | 3.190          | 3.203  | 3.2139         | 3.2209 | 3.2500            |
|  | 3/8-6 UN              | 2A             | 0.0029           | 3.3721 | 3.3539           | —                | 3.2638                | 3.2543                                       | 3.1737 | 2B             | 3.195  | 3.225          | 3.2667 | 3.2791            |
| 3A   |                       | 0.0000         | 3.3750           | 3.3568 | —                | 3.2667           | 3.2595                | 3.1766                                       | 3B     | 3.1950         | 3.2146 | 3.2667         | 3.2760 | 3.3750            |
| 3/8-8 UN   | 2A                    | 0.0026         | 3.3724           | 3.3574 | —                | 3.2912           | 3.2824                | 3.2236                                       | 2B     | 3.240          | 3.265  | 3.2938         | 3.3052 | 3.3750            |
|  | 3A                    | 0.0000         | 3.3750           | 3.3600 | —                | 3.2938           | 3.2872                | 3.2262                                       | 3B     | 3.2400         | 3.2547 | 3.2938         | 3.3023 | 3.3750            |
| 3/8-12 UN  | 2A                    | 0.0019         | 3.3731           | 3.3617 | —                | 3.3190           | 3.3126                | 3.2739                                       | 2B     | 3.285          | 3.303  | 3.3209         | 3.3293 | 3.3750            |
|  | 3A                    | 0.0000         | 3.3750           | 3.3636 | —                | 3.3209           | 3.3161                | 3.2758                                       | 3B     | 3.2850         | 3.2948 | 3.3209         | 3.3272 | 3.3750            |
| 3/8-16 UN  | 2A                    | 0.0017         | 3.3733           | 3.3639 | —                | 3.3327           | 3.3269                | 3.2988                                       | 2B     | 3.307          | 3.321  | 3.3344         | 3.3419 | 3.3750            |
|  | 3A                    | 0.0000         | 3.3750           | 3.3656 | —                | 3.3344           | 3.3301                | 3.3005                                       | 3B     | 3.3070         | 3.3158 | 3.3344         | 3.3400 | 3.3750            |
| 3/2-4 UNC  | 1A                    | 0.0033         | 3.4967           | 3.4610 | —                | 3.3343           | 3.3177                | 3.1990                                       | 1B     | 3.229          | 3.267  | 3.3376         | 3.3591 | 3.5000            |
|  | 2A                    | 0.0033         | 3.4967           | 3.4729 | 3.4610           | 3.3343           | 3.3233                | 3.1990                                       | 2B     | 3.229          | 3.267  | 3.3376         | 3.3519 | 3.5000            |
| 3/2-6 UN   | 3A                    | 0.0000         | 3.5000           | 3.4762 | —                | 3.3376           | 3.3293                | 3.2023                                       | 3B     | 3.2290         | 3.2594 | 3.3376         | 3.3484 | 3.5000            |
|  | 2A                    | 0.0029         | 3.4971           | 3.4789 | —                | 3.3888           | 3.3792                | 3.2987                                       | 2B     | 3.320          | 3.350  | 3.3917         | 3.4042 | 3.5000            |
| 3/2-8 UN   | 3A                    | 0.0000         | 3.5000           | 3.4818 | —                | 3.3917           | 3.3845                | 3.3016                                       | 3B     | 3.3200         | 3.3396 | 3.3917         | 3.4011 | 3.5000            |
|  | 2A                    | 0.0026         | 3.4974           | 3.4824 | 3.4749           | 3.4162           | 3.4074                | 3.3486                                       | 2B     | 3.365          | 3.390  | 3.4188         | 3.4303 | 3.5000            |
| 3/2-10 UNS   | 3A                    | 0.0000         | 3.5000           | 3.4850 | —                | 3.4188           | 3.4122                | 3.3512                                       | 3B     | 3.3650         | 3.3797 | 3.4188         | 3.4274 | 3.5000            |
|  | 2A                    | 0.0021         | 3.4979           | 3.4850 | —                | 3.4329           | 3.4260                | 3.3789                                       | 2B     | 3.392          | 3.413  | 3.4350         | 3.4440 | 3.5000            |
| 3/2-12 UN  | 2A                    | 0.0019         | 3.4981           | 3.4867 | —                | 3.4440           | 3.4376                | 3.3989                                       | 2B     | 3.410          | 3.428  | 3.4459         | 3.4543 | 3.5000            |
|  | 3A                    | 0.0000         | 3.5000           | 3.4886 | —                | 3.4459           | 3.4411                | 3.4008                                       | 3B     | 3.4100         | 3.4198 | 3.4459         | 3.4522 | 3.5000            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  | Internal <sup>b</sup> |   |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|-----------------------|---|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |                       | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min                   |   |       | Min            | Max    | Min            | Max    | Min               |
| 3½-14 UNS  | 2A                    | 0.0018         | 3.4982           | 3.4879 | —                | 3.4518           | 3.4457                | 3.4132  | 2B    | 3.423          | 3.438  | 3.4536         | 3.4615 | 3.5000            |
| 3½-16 UN   | 2A                    | 0.0017         | 3.4983           | 3.4889 | —                | 3.4577           | 3.4519                | 3.4238  | 2B    | 3.432          | 3.446  | 3.4594         | 3.4669 | 3.5000            |
|  | 3A                    | 0.0000         | 3.5000           | 3.4906 | —                | 3.4594           | 3.4551                | 3.4255  | 3B    | 3.4320         | 3.4408 | 3.4594         | 3.4650 | 3.5000            |
|  | 2A                    | 0.0017         | 3.4983           | 3.4896 | —                | 3.4622           | 3.4567                | 3.4322  | 2B    | 3.440          | 3.453  | 3.4639         | 3.4711 | 3.5000            |
| 3½-18 UNS  | 2A                    | 0.0029         | 3.6221           | 3.6039 | —                | 3.5138           | 3.5041                | 3.4237  | 2B    | 3.445          | 3.475  | 3.5167         | 3.5293 | 3.6250            |
|  | 3A                    | 0.0000         | 3.6250           | 3.6068 | —                | 3.5167           | 3.5094                | 3.4266  | 3B    | 3.4450         | 3.4646 | 3.5167         | 3.5262 | 3.6250            |
|  | 2A                    | 0.0027         | 3.6223           | 3.6073 | —                | 3.5411           | 3.5322                | 3.4735  | 2B    | 3.490          | 3.515  | 3.5438         | 3.5554 | 3.6250            |
| 3½-8 UN  | 3A                    | 0.0000         | 3.6250           | 3.6100 | —                | 3.5438           | 3.5371                | 3.4762  | 3B    | 3.4900         | 3.5047 | 3.5438         | 3.5525 | 3.6250            |
|  | 2A                    | 0.0019         | 3.6231           | 3.6117 | —                | 3.5690           | 3.5626                | 3.5239  | 2B    | 3.535          | 3.553  | 3.5709         | 3.5793 | 3.6250            |
|  | 3A                    | 0.0000         | 3.6250           | 3.6136 | —                | 3.5709           | 3.5661                | 3.5258  | 3B    | 3.5350         | 3.5448 | 3.5709         | 3.5772 | 3.6250            |
| 3½-16 UN   | 2A                    | 0.0017         | 3.6233           | 3.6139 | —                | 3.5827           | 3.5769                | 3.5488  | 2B    | 3.557          | 3.571  | 3.5844         | 3.5919 | 3.6250            |
|  | 3A                    | 0.0000         | 3.6250           | 3.6156 | —                | 3.5844           | 3.5801                | 3.5505  | 3B    | 3.5570         | 3.5658 | 3.5844         | 3.5900 | 3.6250            |
|  | 1A                    | 0.0034         | 3.7466           | 3.7109 | —                | 3.5842           | 3.5674                | 3.4489  | 1B    | 3.479          | 3.517  | 3.5876         | 3.6094 | 3.7500            |
| 3¾-4 UNC   | 2A                    | 0.0034         | 3.7466           | 3.7228 | 3.7109           | 3.5842           | 3.5730                | 3.4489  | 2B    | 3.479          | 3.517  | 3.5876         | 3.6021 | 3.7500            |
|  | 3A                    | 0.0000         | 3.7500           | 3.7262 | —                | 3.5876           | 3.5792                | 3.4523  | 3B    | 3.4790         | 3.5094 | 3.5876         | 3.5985 | 3.7500            |
|  | 2A                    | 0.0029         | 3.7471           | 3.7289 | —                | 3.6388           | 3.6290                | 3.5487  | 2B    | 3.570          | 3.600  | 3.6417         | 3.6544 | 3.7500            |
| 3¾-6 UN  | 3A                    | 0.0000         | 3.7500           | 3.7318 | —                | 3.6417           | 3.6344                | 3.5516  | 3B    | 3.5700         | 3.5896 | 3.6417         | 3.6512 | 3.7500            |
|  | 2A                    | 0.0027         | 3.7473           | 3.7323 | 3.7248           | 3.6661           | 3.6571                | 3.5985  | 2B    | 3.615          | 3.640  | 3.6688         | 3.6805 | 3.7500            |
|  | 3A                    | 0.0000         | 3.7500           | 3.7350 | —                | 3.6688           | 3.6621                | 3.6012  | 3B    | 3.6150         | 3.6297 | 3.6688         | 3.6776 | 3.7500            |
| 3¾-10 UNS  | 2A                    | 0.0021         | 3.7479           | 3.7350 | —                | 3.6829           | 3.6760                | 3.6289  | 2B    | 3.642          | 3.663  | 3.6850         | 3.6940 | 3.7500            |
|  | 2A                    | 0.0019         | 3.7481           | 3.7367 | —                | 3.6940           | 3.6876                | 3.6489  | 2B    | 3.660          | 3.678  | 3.6959         | 3.7043 | 3.7500            |
|  | 3A                    | 0.0000         | 3.7500           | 3.7386 | —                | 3.6959           | 3.6911                | 3.6508  | 3B    | 3.6600         | 3.6698 | 3.6959         | 3.7022 | 3.7500            |
| 3¾-14 UNS  | 2A                    | 0.0018         | 3.7482           | 3.7379 | —                | 3.7018           | 3.6957                | 3.6632  | 2B    | 3.673          | 3.688  | 3.7036         | 3.7115 | 3.7500            |
|  | 2A                    | 0.0017         | 3.7483           | 3.7389 | —                | 3.7077           | 3.7019                | 3.6738  | 2B    | 3.682          | 3.696  | 3.7094         | 3.7169 | 3.7500            |
|  | 3A                    | 0.0000         | 3.7500           | 3.7406 | —                | 3.7094           | 3.7051                | 3.6755  | 3B    | 3.6820         | 3.6908 | 3.7094         | 3.7150 | 3.7500            |
| 3¾-18 UNS  | 2A                    | 0.0017         | 3.7483           | 3.7396 | —                | 3.7122           | 3.7067                | 3.6822  | 2B    | 3.690          | 3.703  | 3.7139         | 3.7211 | 3.7500            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                        |       |                |        |                |                   |        |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|--|-------|----------------|--------|----------------|-------------------|--------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia. <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter | Major<br>Diameter |        |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |  |       | Min            | Max    | Min            | Max               | Min    |
| 3 $\frac{3}{8}$ -6 UN  | 2A                    | 0.0030         | 3.8720           | 3.8538 | —                | 3.7637           | 3.7538 | 3.6736                                       | 2B    | 3.695          | 3.725  | 3.7667         | 3.7795            | 3.8750 |
|  | 3A                    | 0.0000         | 3.8750           | 3.8568 | —                | 3.7667           | 3.7593 | 3.6766                                       | 3B    | 3.6950         | 3.7146 | 3.7667         | 3.7763            | 3.8750 |
| 3 $\frac{3}{8}$ -8 UN  | 2A                    | 0.0027         | 3.8723           | 3.8573 | —                | 3.7911           | 3.7820 | 3.7235                                       | 2B    | 3.740          | 3.765  | 3.7938         | 3.8056            | 3.8750 |
|  | 3A                    | 0.0000         | 3.8750           | 3.8600 | —                | 3.7938           | 3.7870 | 3.7262                                       | 3B    | 3.7400         | 3.7547 | 3.7938         | 3.8026            | 3.8750 |
| 3 $\frac{3}{8}$ -12 UN   | 2A                    | 0.0020         | 3.8730           | 3.8616 | —                | 3.8189           | 3.8124 | 3.7738                                       | 2B    | 3.785          | 3.803  | 3.8209         | 3.8294            | 3.8750 |
|  | 3A                    | 0.0000         | 3.8750           | 3.8636 | —                | 3.8209           | 3.8160 | 3.7758                                       | 3B    | 3.7850         | 3.7948 | 3.8209         | 3.8273            | 3.8750 |
| 3 $\frac{3}{8}$ -16 UN   | 2A                    | 0.0018         | 3.8732           | 3.8638 | —                | 3.8326           | 3.8267 | 3.7987                                       | 2B    | 3.807          | 3.821  | 3.8344         | 3.8420            | 3.8750 |
|  | 3A                    | 0.0000         | 3.8750           | 3.8656 | —                | 3.8344           | 3.8300 | 3.8005                                       | 3B    | 3.8070         | 3.8158 | 3.8344         | 3.8401            | 3.8750 |
| 4-4 UNC  | 1A                    | 0.0034         | 3.9966           | 3.9609 | —                | 3.8342           | 3.8172 | 3.6989                                       | 1B    | 3.729          | 3.767  | 3.8376         | 3.8597            | 4.0000 |
|  | 2A                    | 0.0034         | 3.9966           | 3.9728 | 3.9609           | 3.8342           | 3.8229 | 3.6989                                       | 2B    | 3.729          | 3.767  | 3.8376         | 3.8523            | 4.0000 |
| 4-6 UN   | 3A                    | 0.0000         | 4.0000           | 3.9762 | —                | 3.8376           | 3.8291 | 3.7023                                       | 3B    | 3.7290         | 3.7594 | 3.8376         | 3.8487            | 4.0000 |
|  | 2A                    | 0.0030         | 3.9970           | 3.9788 | —                | 3.8887           | 3.8788 | 3.7986                                       | 2B    | 3.820          | 3.850  | 3.8917         | 3.9046            | 4.0000 |
| 4-8 UN   | 3A                    | 0.0000         | 4.0000           | 3.9818 | —                | 3.8917           | 3.8843 | 3.8016                                       | 3B    | 3.8200         | 3.8396 | 3.8917         | 3.9014            | 4.0000 |
|  | 2A                    | 0.0027         | 3.9973           | 3.9823 | 3.9748           | 3.9161           | 3.9070 | 3.8485                                       | 2B    | 3.865          | 3.890  | 3.9188         | 3.9307            | 4.0000 |
| 4-10 UNS   | 3A                    | 0.0000         | 4.0000           | 3.9850 | —                | 3.9188           | 3.9120 | 3.8512                                       | 3B    | 3.8650         | 3.8797 | 3.9188         | 3.9277            | 4.0000 |
|  | 2A                    | 0.0021         | 3.9979           | 3.9850 | —                | 3.9329           | 3.9259 | 3.8768                                       | 2B    | 3.892          | 3.913  | 3.9350         | 3.9441            | 4.0000 |
| 4-12 UN  | 2A                    | 0.0020         | 3.9980           | 3.9866 | —                | 3.9439           | 3.9374 | 3.8988                                       | 2B    | 3.910          | 3.928  | 3.9459         | 3.9544            | 4.0000 |
|  | 3A                    | 0.0000         | 4.0000           | 3.9886 | —                | 3.9459           | 3.9410 | 3.9008                                       | 3B    | 3.9100         | 3.9198 | 3.9459         | 3.9523            | 4.0000 |
| 4-14 UNS   | 2A                    | 0.0018         | 3.9982           | 3.9879 | —                | 3.9518           | 3.9456 | 3.9132                                       | 2B    | 3.923          | 3.938  | 3.9536         | 3.9616            | 4.0000 |
|  | 2A                    | 0.0018         | 3.9982           | 3.9888 | —                | 3.9576           | 3.9517 | 3.9237                                       | 2B    | 3.932          | 3.946  | 3.9594         | 3.9670            | 4.0000 |
| 4-16 UN  | 3A                    | 0.0000         | 4.0000           | 3.9906 | —                | 3.9594           | 3.9550 | 3.9255                                       | 3B    | 3.9320         | 3.9408 | 3.9594         | 3.9651            | 4.0000 |
|  | 2A                    | 0.0021         | 4.2479           | 4.2350 | —                | 4.1829           | 4.1759 | 4.1289                                       | 2B    | 4.142          | 4.163  | 4.1850         | 4.1941            | 4.2500 |
| 4 $\frac{1}{2}$ -10 UNS  | 2A                    | 0.0018         | 4.2482           | 4.2379 | —                | 4.2018           | 4.1956 | 4.1632                                       | 2B    | 4.173          | 4.188  | 4.2036         | 4.2116            | 4.2500 |
|  | 2A                    | 0.0020         | 4.2480           | 4.2366 | —                | 4.1939           | 4.1874 | 4.1488                                       | 2B    | 4.160          | 4.178  | 4.1959         | 4.2044            | 4.2500 |
| 4 $\frac{1}{2}$ -12 UN   | 3A                    | 0.0000         | 4.2500           | 4.2386 | —                | 4.1959           | 4.1910 | 4.1508                                       | 3B    | 4.1600         | 4.1698 | 4.1959         | 4.2023            | 4.2500 |
|  | 2A                    | 0.0018         | 4.2482           | 4.2388 | —                | 4.2076           | 4.2017 | 4.1737                                       | 2B    | 4.182          | 4.196  | 4.2094         | 4.2170            | 4.2500 |
| 4 $\frac{1}{2}$ -16 UN   | 3A                    | 0.0000         | 4.2500           | 4.2406 | —                | 4.2094           | 4.2050 | 4.1755                                       | 3B    | 4.1820         | 4.1900 | 4.2094         | 4.2151            | 4.2500 |
|  | 2A                    | 0.0021         | 4.4979           | 4.4850 | —                | 4.4329           | 4.4259 | 4.3789                                       | 2B    | 4.392          | 4.413  | 4.4350         | 4.4441            | 4.5000 |
| 4 $\frac{1}{2}$ -14 UNS  | 2A                    | 0.0018         | 4.4982           | 4.4879 | —                | 4.4518           | 4.4456 | 4.4132                                       | 2B    | 4.423          | 4.438  | 4.4536         | 4.4616            | 4.5000 |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        | Internal <sup>b</sup>                         |       |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|---|-------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |   |       | Min            | Max    | Min            | Max    | Min               |
| 4½-12 UN   | 2A                    | 0.0020         | 4.4980           | 4.4866 | —                | 4.4439           | 4.4374 | 4.3988  | 2B    | 4.410          | 4.428  | 4.4459         | 4.4544 | 4.5000            |
|  | 3A                    | 0.0000         | 4.5000           | 4.4886 | —                | 4.4459           | 4.4410 | 4.4008  | 3B    | 4.4100         | 4.4198 | 4.4459         | 4.4523 | 4.5000            |
| 4½-16 UN   | 2A                    | 0.0018         | 4.4982           | 4.4888 | —                | 4.4576           | 4.4517 | 4.4237  | 2B    | 4.432          | 4.446  | 4.4594         | 4.4670 | 4.5000            |
|  | 3A                    | 0.0000         | 4.5000           | 4.4906 | —                | 4.4594           | 4.4550 | 4.4255  | 3B    | 4.4320         | 4.4408 | 4.4594         | 4.4651 | 4.5000            |
| 4¾-10 UNS  | 2A                    | 0.0022         | 4.7478           | 4.7349 | —                | 4.6828           | 4.6756 | 4.6288  | 2B    | 4.642          | 4.663  | 4.6850         | 4.6944 | 4.7500            |
| 4¾-14 UNS  | 2A                    | 0.0019         | 4.7481           | 4.7378 | —                | 4.7017           | 4.6953 | 4.6631  | 2B    | 4.673          | 4.688  | 4.7036         | 4.7119 | 4.7500            |
| 4¾-12 UN   | 2A                    | 0.0020         | 4.7480           | 4.7366 | —                | 4.6939           | 4.6872 | 4.6488  | 2B    | 4.660          | 4.678  | 4.6959         | 4.7046 | 4.7500            |
|  | 3A                    | 0.0000         | 4.7500           | 4.7386 | —                | 4.6959           | 4.6909 | 4.6508  | 3B    | 4.6600         | 4.6698 | 4.6959         | 4.7025 | 4.7500            |
|  | 2A                    | 0.0018         | 4.7482           | 4.7388 | —                | 4.7076           | 4.7015 | 4.6737  | 2B    | 4.682          | 4.696  | 4.7094         | 4.7173 | 4.7500            |
| 4¾-16 UN   | 3A                    | 0.0000         | 4.7500           | 4.7406 | —                | 4.7094           | 4.7049 | 4.6755  | 3B    | 4.6820         | 4.6908 | 4.7094         | 4.7153 | 4.7500            |
|  | 2A                    | 0.0022         | 4.9978           | 4.9849 | —                | 4.9328           | 4.9256 | 4.8788  | 2B    | 4.892          | 4.913  | 4.9350         | 4.9444 | 5.0000            |
| 5.00-10 UNS  | 2A                    | 0.0019         | 4.9981           | 4.9878 | —                | 4.9517           | 4.9453 | 4.9131  | 2B    | 4.923          | 4.938  | 4.9536         | 4.9619 | 5.0000            |
| 5.00-14 UNS  | 2A                    | 0.0020         | 4.9980           | 4.9866 | —                | 4.9439           | 4.9372 | 4.8988  | 2B    | 4.910          | 4.928  | 4.9459         | 4.9546 | 5.0000            |
|  | 3A                    | 0.0000         | 5.0000           | 4.9886 | —                | 4.9459           | 4.9409 | 4.9008  | 3B    | 4.9100         | 4.9198 | 4.9459         | 4.9525 | 5.0000            |
| 5.00-16 UN   | 2A                    | 0.0018         | 4.9982           | 4.9888 | —                | 4.9576           | 4.9515 | 4.9237  | 2B    | 4.932          | 4.946  | 4.9594         | 4.9673 | 5.0000            |
|  | 3A                    | 0.0000         | 5.0000           | 4.9906 | —                | 4.9594           | 4.9549 | 4.9255  | 3B    | 4.9320         | 4.9408 | 4.9594         | 4.9653 | 5.0000            |
| 5¼-10 UNS  | 2A                    | 0.0022         | 5.2478           | 5.2349 | —                | 5.1829           | 5.1756 | 5.1288  | 2B    | 5.142          | 5.163  | 5.1850         | 5.1944 | 5.2500            |
| 5¼-14 UNS  | 2A                    | 0.0019         | 5.2481           | 5.2378 | —                | 5.2017           | 5.1953 | 5.1631  | 2B    | 5.173          | 5.188  | 5.2036         | 5.2119 | 5.2500            |
|  | 2A                    | 0.0020         | 5.2480           | 5.2366 | —                | 5.1939           | 5.1872 | 5.1488  | 2B    | 5.160          | 5.178  | 5.1959         | 5.2046 | 5.2500            |
| 5¼-12 UN   | 3A                    | 0.0000         | 5.2500           | 5.2386 | —                | 5.1959           | 5.1909 | 5.1508  | 3B    | 5.1600         | 5.1698 | 5.1959         | 5.2025 | 5.2500            |
|  | 2A                    | 0.0018         | 5.2482           | 5.2388 | —                | 5.2076           | 5.2015 | 5.1737  | 2B    | 5.182          | 5.196  | 5.2094         | 5.2173 | 5.2500            |
| 5¼-16 UN   | 3A                    | 0.0000         | 5.2500           | 5.2406 | —                | 5.2094           | 5.2049 | 5.1755  | 3B    | 5.1820         | 5.1908 | 5.2094         | 5.2153 | 5.2500            |
|  | 2A                    | 0.0022         | 5.4978           | 5.4849 | —                | 5.4328           | 5.4256 | 5.3788  | 2B    | 5.392          | 5.413  | 5.4350         | 5.4444 | 5.5000            |
| 5½-14 UNS  | 2A                    | 0.0019         | 5.4981           | 5.4878 | —                | 5.4517           | 5.4453 | 5.4131  | 2B    | 5.423          | 5.438  | 5.4536         | 5.4619 | 5.5000            |
|  | 2A                    | 0.0020         | 5.4980           | 5.4866 | —                | 5.4439           | 5.4372 | 5.3988  | 2B    | 5.410          | 5.428  | 5.4459         | 5.4546 | 5.5000            |
| 5½-12 UN   | 3A                    | 0.0000         | 5.5000           | 5.4886 | —                | 5.4459           | 5.4409 | 5.4008  | 3B    | 5.4100         | 5.4198 | 5.4459         | 5.4525 | 5.5000            |
|  | 2A                    | 0.0018         | 5.4982           | 5.4888 | —                | 5.4576           | 5.4515 | 5.4237  | 2B    | 5.432          | 5.446  | 5.4594         | 5.4673 | 5.5000            |
| 5½-16 UN   | 3A                    | 0.0000         | 5.5000           | 5.4906 | —                | 5.4594           | 5.4549 | 5.4255  | 3B    | 5.4320         | 5.4408 | 5.4594         | 5.4653 | 5.5000            |

Table 3. (Continued) Standard Series and Selected Combinations — Unified Screw Threads

| Nominal Size,<br>Threads per Inch,<br>and Series<br>Designation <sup>a</sup> | External <sup>b</sup> |                |                  |        |                  |                  |        |   | Internal <sup>b</sup> |                |        |                |        |                   |
|--|-----------------------|----------------|------------------|--------|------------------|------------------|--------|---|-----------------------|----------------|--------|----------------|--------|-------------------|
|  | Class                 | Allow-<br>ance | Major Diameter   |        |                  | Pitch Diameter   |        | UNR Minor<br>Dia., <sup>c</sup> Max<br>(Ref.) | Class                 | Minor Diameter |        | Pitch Diameter |        | Major<br>Diameter |
|  |                       |                | Max <sup>d</sup> | Min    | Min <sup>e</sup> | Max <sup>d</sup> | Min    |   |                       | Min            | Max    | Min            | Max    |                   |
| 5 $\frac{3}{4}$ -10 UNS  | 2A                    | 0.0022         | 5.7478           | 5.7349 | —                | 5.6828           | 5.6754 | 5.6288  | 2B                    | 5.642          | 5.663  | 5.6850         | 5.6946 | 5.7500            |
| 5 $\frac{3}{4}$ -14 UNS  | 2A                    | 0.0020         | 5.7480           | 5.7377 | —                | 5.7016           | 5.6951 | 5.6630  | 2B                    | 5.673          | 5.688  | 5.7036         | 5.7121 | 5.7500            |
| 5 $\frac{3}{4}$ -12 UN   | 2A                    | 0.0021         | 5.7479           | 5.7365 | —                | 5.6938           | 5.6869 | 5.6487  | 2B                    | 5.660          | 5.678  | 5.6959         | 5.7049 | 5.7500            |
|  | 3A                    | 0.0000         | 5.7500           | 5.7386 | —                | 5.6959           | 5.6907 | 5.6508  | 3B                    | 5.6600         | 5.6698 | 5.6959         | 5.7026 | 5.7500            |
| 5 $\frac{3}{4}$ -16 UN   | 2A                    | 0.0019         | 5.7481           | 5.7387 | —                | 5.7075           | 5.7013 | 5.6736  | 2B                    | 5.682          | 5.696  | 5.7094         | 5.7175 | 5.7500            |
|  | 3A                    | 0.0000         | 5.7500           | 5.7406 | —                | 5.7094           | 5.7047 | 5.6755  | 3B                    | 5.6820         | 5.6908 | 5.7094         | 5.7155 | 5.7500            |
| 6-10 UNS   | 2A                    | 0.0022         | 5.9978           | 5.9849 | —                | 5.9328           | 5.9254 | 5.8788  | 2B                    | 5.892          | 5.913  | 5.9350         | 5.9446 | 6.0000            |
| 6-14 UNS   | 2A                    | 0.0020         | 5.9980           | 5.9877 | —                | 5.9516           | 5.9451 | 5.9130  | 2B                    | 5.923          | 5.938  | 5.9536         | 5.9621 | 6.0000            |
| 6-12 UN  | 2A                    | 0.0021         | 5.9979           | 5.9865 | —                | 5.9438           | 5.9369 | 5.8987  | 2B                    | 5.910          | 5.928  | 5.9459         | 5.9549 | 6.0000            |
|  | 3A                    | 0.0000         | 6.0000           | 5.9886 | —                | 5.9459           | 5.9407 | 5.9008  | 3B                    | 5.9100         | 5.9198 | 5.9459         | 5.9526 | 6.0000            |
| 6-16 UN  | 2A                    | 0.0019         | 5.9981           | 5.9887 | —                | 5.9575           | 5.9513 | 5.9236  | 2B                    | 5.932          | 5.946  | 5.9594         | 5.9675 | 6.0000            |
|  | 3A                    | 0.0000         | 6.0000           | 5.9906 | —                | 5.9594           | 5.9547 | 5.9255  | 3B                    | 5.9320         | 5.9408 | 5.9594         | 5.9655 | 6.0000            |

<sup>a</sup> Use UNR designation instead of UN wherever UNR thread form is desired for external use.

<sup>b</sup> Regarding combinations of thread classes, see text on page 1773.

<sup>c</sup> UN series external thread maximum minor diameter is basic for Class 3A and basic minus allowance for Classes 1A and 2A.

<sup>d</sup> For Class 2A threads having an additive finish the maximum is increased, by the allowance, to the basic size, the value being the same as for Class 3A.

<sup>e</sup> For unfinished hot-rolled material not including standard fasteners with rolled threads.

<sup>f</sup> Formerly NF, tolerances and allowances are based on one diameter length of engagement.

All dimensions in inches.

Use UNS threads only if Standard Series do not meet requirements (see pages 1733, 1765, and 1776). For additional sizes above 4 inches see ASME/ANSI B1.1-1989 (R2001).

*Coarse-Thread Series:* This series, UNC/UNRC, is the one most commonly used in the bulk production of bolts, screws, nuts and other general engineering applications. It is also used for threading into lower tensile strength materials such as cast iron, mild steel and softer materials (bronze, brass, aluminum, magnesium and plastics) to obtain the optimum resistance to stripping of the internal thread. It is applicable for rapid assembly or disassembly, or if corrosion or slight damage is possible.

**Table 4a. Coarse-Thread Series, UNC and UNRC — Basic Dimensions**

| Sizes<br>No. or<br>Inches | Basic<br>Major<br>Dia.,<br><i>D</i><br>Inches | Thds.<br>per<br>Inch,<br><i>n</i> | Basic<br>Pitch<br>Dia., <sup>a</sup><br><i>D</i> <sub>2</sub><br>Inches | Minor Diameter  |  | Lead<br>Angle $\lambda$<br>at Basic<br>P.D. |     | Area of<br>Minor<br>Dia. at<br><i>D</i> -2 <i>h</i> <sub>b</sub><br>Sq. In. | Tensile<br>Stress<br>Area <sup>b</sup><br>Sq. In. |
|---------------------------|---|-----------------------------------|---|---|--|---|-----|---|---|
|                           |   |                                   |   | Ext.<br>Thds., <sup>c</sup><br><i>d</i> <sub>3</sub> (Ref.)<br>Inches | Int.<br>Thds., <sup>d</sup><br><i>D</i> <sub>1</sub><br>Inches | Deg.  | Min |   |   |
|                           |   |                                   |   |   |  |   |     |   |   |
| 1 (0.073) <sup>e</sup>    | 0.0730  | 64                                | 0.0629  | 0.0544  | 0.0561   | 4   | 31  | 0.00218   | 0.00263   |
| 2 (0.086)                 | 0.0860  | 56                                | 0.0744  | 0.0648  | 0.0667   | 4   | 22  | 0.00310   | 0.00370   |
| 3 (0.099) <sup>e</sup>    | 0.0990  | 48                                | 0.0855  | 0.0741  | 0.0764   | 4   | 26  | 0.00406   | 0.00487   |
| 4 (0.112)                 | 0.1120  | 40                                | 0.0958  | 0.0822  | 0.0849   | 4   | 45  | 0.00496   | 0.00604   |
| 5 (0.125)                 | 0.1250  | 40                                | 0.1088  | 0.0952  | 0.0979   | 4   | 11  | 0.00672   | 0.00796   |
| 6 (0.138)                 | 0.1380  | 32                                | 0.1177  | 0.1008  | 0.1042   | 4   | 50  | 0.00745   | 0.00909   |
| 8 (0.164)                 | 0.1640  | 32                                | 0.1437  | 0.1268  | 0.1302   | 3   | 58  | 0.01196   | 0.0140  |
| 10 (0.190)                | 0.1900  | 24                                | 0.1629  | 0.1404  | 0.1449   | 4   | 39  | 0.01450   | 0.0175  |
| 12 (0.216) <sup>e</sup>   | 0.2160  | 24                                | 0.1889  | 0.1664  | 0.1709   | 4   | 1   | 0.0206  | 0.0242  |
| 1/4                       | 0.2500  | 20                                | 0.2175  | 0.1905  | 0.1959   | 4   | 11  | 0.0269  | 0.0318  |
| 5/16                      | 0.3125  | 18                                | 0.2764  | 0.2464  | 0.2524   | 3   | 40  | 0.0454  | 0.0524  |
| 3/8                       | 0.3750  | 16                                | 0.3344  | 0.3005  | 0.3073   | 3   | 24  | 0.0678  | 0.0775  |
| 7/16                      | 0.4375  | 14                                | 0.3911  | 0.3525  | 0.3602   | 3   | 20  | 0.0933  | 0.1063  |
| 1/2                       | 0.5000  | 13                                | 0.4500  | 0.4084  | 0.4167   | 3   | 7   | 0.1257  | 0.1419  |
| 9/16                      | 0.5625  | 12                                | 0.5084  | 0.4633  | 0.4723   | 2   | 59  | 0.162   | 0.182   |
| 5/8                       | 0.6250  | 11                                | 0.5660  | 0.5168  | 0.5266   | 2   | 56  | 0.202   | 0.226   |
| 3/4                       | 0.7500  | 10                                | 0.6850  | 0.6309  | 0.6417   | 2   | 40  | 0.302   | 0.334   |
| 7/8                       | 0.8750  | 9                                 | 0.8028  | 0.7427  | 0.7547   | 2   | 31  | 0.419   | 0.462   |
| 1                         | 1.0000  | 8                                 | 0.9188  | 0.8512  | 0.8647   | 2   | 29  | 0.551   | 0.606   |
| 1 1/8                     | 1.1250  | 7                                 | 1.0322  | 0.9549  | 0.9704   | 2   | 31  | 0.693   | 0.763   |
| 1 1/4                     | 1.2500  | 7                                 | 1.1572  | 1.0799  | 1.0954   | 2   | 15  | 0.890   | 0.969   |
| 1 3/8                     | 1.3750  | 6                                 | 1.2667  | 1.1766  | 1.1946   | 2   | 24  | 1.054   | 1.155   |
| 1 1/2                     | 1.5000  | 6                                 | 1.3917  | 1.3016  | 1.3196   | 2   | 11  | 1.294   | 1.405   |
| 1 3/4                     | 1.7500  | 5                                 | 1.6201  | 1.5119  | 1.5335   | 2   | 15  | 1.74  | 1.90  |
| 2                         | 2.0000  | 4 1/2                             | 1.8557  | 1.7353  | 1.7594   | 2   | 11  | 2.30  | 2.50  |
| 2 1/4                     | 2.2500  | 4 1/2                             | 2.1057  | 1.9853  | 2.0094   | 1   | 55  | 3.02  | 3.25  |
| 2 1/2                     | 2.5000  | 4                                 | 2.3376  | 2.2023  | 2.2294   | 1   | 57  | 3.72  | 4.00  |
| 2 3/4                     | 2.7500  | 4                                 | 2.5876  | 2.4523  | 2.4794   | 1   | 46  | 4.62  | 4.93  |
| 3                         | 3.0000  | 4                                 | 2.8376  | 2.7023  | 2.7294   | 1   | 36  | 5.62  | 5.97  |
| 3 1/4                     | 3.2500  | 4                                 | 3.0876  | 2.9523  | 2.9794   | 1   | 29  | 6.72  | 7.10  |
| 3 1/2                     | 3.5000  | 4                                 | 3.3376  | 3.2023  | 3.2294   | 1   | 22  | 7.92  | 8.33  |
| 3 3/4                     | 3.7500  | 4                                 | 3.5876  | 3.4523  | 3.4794   | 1   | 16  | 9.21  | 9.66  |
| 4                         | 4.0000  | 4                                 | 3.8376  | 3.7023  | 3.7294   | 1   | 11  | 10.61   | 11.08   |

<sup>a</sup> British: Effective Diameter.

<sup>b</sup> See formula, pages 1502 and 1510.

<sup>c</sup> Design form for UNR threads. (See figure on page 1733.)

<sup>d</sup> Basic minor diameter.

<sup>e</sup> Secondary sizes.

*Fine-Thread Series:* This series, UNF/UNRF, is suitable for the production of bolts, screws, and nuts and for other applications where the Coarse series is not applicable. External threads of this series have greater tensile stress area than comparable sizes of the Coarse series. The Fine series is suitable when the resistance to stripping of both external



and mating internal threads equals or exceeds the tensile load carrying capacity of the externally threaded member (see page 1510). It is also used where the length of engagement is short, where a smaller lead angle is desired, where the wall thickness demands a fine pitch, or where finer adjustment is needed.

**Table 4b. Fine-Thread Series, UNF and UNRF — Basic Dimensions**

| Sizes<br>No. or<br>Inches | Basic<br>Major<br>Dia.,<br><i>D</i><br>Inches | Thds.<br>per<br>Inch,<br><i>n</i> | Basic<br>Pitch<br>Dia., <sup>a</sup><br><i>D</i> <sub>2</sub><br>Inches | Minor Diameter  |  | Lead<br>Angle $\lambda$<br>at Basic<br>P.D. |     | Area of<br>Minor<br>Dia. at<br><i>D-2h<sub>b</sub></i><br>Sq. In. | Tensile<br>Stress<br>Area <sup>b</sup><br>Sq. In. |
|---------------------------|---|-----------------------------------|---|---|--|---|-----|---|---|
|                           |   |                                   |   | Ext.<br>Thds., <sup>c</sup><br><i>d</i> <sub>3</sub> (Ref.)<br>Inches | Int.<br>Thds., <sup>d</sup><br><i>D</i> <sub>1</sub><br>Inches | Deg.  | Min |   |   |
|                           |   |                                   |   |   |  |   |     |   |   |
| 0 (0.060)                 | 0.0600  | 80                                | 0.0519  | 0.0451  | 0.0465   | 4   | 23  | 0.00151   | 0.00180   |
| 1 (0.073) <sup>e</sup>    | 0.0730  | 72                                | 0.0640  | 0.0565  | 0.0580   | 3   | 57  | 0.00237   | 0.00278   |
| 2 (0.086)                 | 0.0860  | 64                                | 0.0759  | 0.0674  | 0.0691   | 3   | 45  | 0.00339   | 0.00394   |
| 3 (0.099) <sup>e</sup>    | 0.0990  | 56                                | 0.0874  | 0.0778  | 0.0797   | 3   | 43  | 0.00451   | 0.00523   |
| 4 (0.112)                 | 0.1120  | 48                                | 0.0985  | 0.0871  | 0.0894   | 3   | 51  | 0.00566   | 0.00661   |
| 5 (0.125)                 | 0.1250  | 44                                | 0.1102  | 0.0979  | 0.1004   | 3   | 45  | 0.00716   | 0.00830   |
| 6 (0.138)                 | 0.1380  | 40                                | 0.1218  | 0.1082  | 0.1109   | 3   | 44  | 0.00874   | 0.01015   |
| 8 (0.164)                 | 0.1640  | 36                                | 0.1460  | 0.1309  | 0.1339   | 3   | 28  | 0.01285   | 0.01474   |
| 10 (0.190)                | 0.1900  | 32                                | 0.1697  | 0.1528  | 0.1562   | 3   | 21  | 0.0175  | 0.0200  |
| 12 (0.216) <sup>e</sup>   | 0.2160  | 28                                | 0.1928  | 0.1734  | 0.1773   | 3   | 22  | 0.0226  | 0.258   |
| 1/4                       | 0.2500  | 28                                | 0.2268  | 0.2074  | 0.2113   | 2   | 52  | 0.0326  | 0.0364  |
| 5/16                      | 0.3125  | 24                                | 0.2854  | 0.2629  | 0.2674   | 2   | 40  | 0.0524  | 0.0580  |
| 3/8                       | 0.3750  | 24                                | 0.3479  | 0.3254  | 0.3299   | 2   | 11  | 0.0809  | 0.0878  |
| 7/16                      | 0.4375  | 20                                | 0.4050  | 0.3780  | 0.3834   | 2   | 15  | 0.1090  | 0.1187  |
| 1/2                       | 0.5000  | 20                                | 0.4675  | 0.4405  | 0.4459   | 1   | 57  | 0.1486  | 0.1599  |
| 9/16                      | 0.5625  | 18                                | 0.5264  | 0.4964  | 0.5024   | 1   | 55  | 0.189   | 0.203   |
| 5/8                       | 0.6250  | 18                                | 0.5889  | 0.5589  | 0.5649   | 1   | 43  | 0.240   | 0.256   |
| 3/4                       | 0.7500  | 16                                | 0.7094  | 0.6763  | 0.6823   | 1   | 36  | 0.351   | 0.373   |
| 7/8                       | 0.8750  | 14                                | 0.8286  | 0.7900  | 0.7977   | 1   | 34  | 0.480   | 0.509   |
| 1                         | 1.0000  | 12                                | 0.9459  | 0.9001  | 0.9098   | 1   | 36  | 0.625   | 0.663   |
| 1 1/8                     | 1.1250  | 12                                | 1.0709  | 1.0258  | 1.0348   | 1   | 25  | 0.812   | 0.856   |
| 1 1/4                     | 1.2500  | 12                                | 1.1959  | 1.1508  | 1.1598   | 1   | 16  | 1.024   | 1.073   |
| 1 3/8                     | 1.3750  | 12                                | 1.3209  | 1.2758  | 1.2848   | 1   | 9   | 1.260   | 1.315   |
| 1 1/2                     | 1.5000  | 12                                | 1.4459  | 1.4008  | 1.4098   | 1   | 3   | 1.521   | 1.581   |

<sup>a</sup> British: Effective Diameter.

<sup>b</sup> See formula, pages 1502 and 1510.

<sup>c</sup> Design form for UNR threads. (See figure on page 1733.)

<sup>d</sup> Basic minor diameter.

<sup>e</sup> Secondary sizes.

*Extra-Fine-Thread Series:* This series, UNEF/UNREF, is applicable where even finer pitches of threads are desirable, as for short lengths of engagement and for thin-walled tubes, nuts, ferrules, or couplings. It is also generally applicable under the conditions stated above for the fine threads. See Table 4c.

*Fine Threads for Thin-Wall Tubing:* Dimensions for a 27-thread series, ranging from 1/4- to 1-inch nominal size, also are included in Table 3. These threads are recommended for general use on thin-wall tubing. The minimum length of complete thread is one-third of the basic major diameter plus 5 threads (+ 0.185 in.).

*Selected Combinations:* Thread data are tabulated in Table 3 for certain additional selected special combinations of diameter and pitch, with pitch diameter tolerances based on a length of thread engagement of 9 times the pitch. The pitch diameter limits are applicable to a length of engagement of from 5 to 15 times the pitch. (This provision should not be confused with the lengths of thread on mating parts, as they may exceed the length of engagement by a considerable amount.) Thread symbols are UNS and UNRS.

**Table 4c. Extra-Fine-Thread Series, UNEF and UNREF — Basic Dimensions**

| Sizes<br>No. or<br>Inches     | Basic<br>Major<br>Dia.,<br><i>D</i> | Thds.<br>per<br>Inch,<br><i>n</i> | Basic<br>Pitch<br>Dia., <sup>a</sup><br><i>D</i> <sub>2</sub> | Minor Diameter  |  | Lead<br>Angle $\lambda$<br>at Basic<br>P.D. | Area of<br>Minor<br>Dia. at<br>$D - 2h_b$ | Tensile<br>Stress<br>Area <sup>b</sup> |
|-------------------------------|-------------------------------------|-----------------------------------|---|---|--|---|---|--|
|                               |                                     |                                   |   | Ext.<br>Thds., <sup>c</sup><br><i>d</i> <sub>3</sub> (Ref.) | Int.<br>Thds., <sup>d</sup><br><i>D</i> <sub>1</sub> |   |   |  |
|                               |                                     |                                   |   | Inches  | Inches   |   |   |  |
| <b>12 (0.216)<sup>e</sup></b> | <b>0.2160</b>                       | <b>32</b>                         | <b>0.1957</b>   | <b>0.1788</b>   | <b>0.1822</b>  | <b>2 55</b>                                 | 0.0242                                    | 0.0270                                 |
| $\frac{1}{4}$                 | <b>0.2500</b>                       | <b>32</b>                         | <b>0.2297</b>   | <b>0.2128</b>   | <b>0.2162</b>  | <b>2 29</b>                                 | 0.0344                                    | 0.0379                                 |
| $\frac{5}{16}$                | <b>0.3125</b>                       | <b>32</b>                         | <b>0.2922</b>   | <b>0.2753</b>   | <b>0.2787</b>  | <b>1 57</b>                                 | 0.0581                                    | 0.0625                                 |
| $\frac{3}{8}$                 | <b>0.3750</b>                       | <b>32</b>                         | <b>0.3547</b>   | <b>0.3378</b>   | <b>0.3412</b>  | <b>1 36</b>                                 | 0.0878                                    | 0.0932                                 |
| $\frac{7}{16}$                | <b>0.4375</b>                       | <b>28</b>                         | <b>0.4143</b>   | <b>0.3949</b>   | <b>0.3988</b>  | <b>1 34</b>                                 | 0.1201                                    | 0.1274                                 |
| $\frac{1}{2}$                 | <b>0.5000</b>                       | <b>28</b>                         | <b>0.4768</b>   | <b>0.4574</b>   | <b>0.4613</b>  | <b>1 22</b>                                 | 0.162                                     | 0.170                                  |
| $\frac{9}{16}$                | <b>0.5625</b>                       | <b>24</b>                         | <b>0.5354</b>   | <b>0.5129</b>   | <b>0.5174</b>  | <b>1 25</b>                                 | 0.203                                     | 0.214                                  |
| $\frac{5}{8}$                 | <b>0.6250</b>                       | <b>24</b>                         | <b>0.5979</b>   | <b>0.5754</b>   | <b>0.5799</b>  | <b>1 16</b>                                 | 0.256                                     | 0.268                                  |
| $\frac{11}{16}^e$             | <b>0.6875</b>                       | <b>24</b>                         | <b>0.6604</b>   | <b>0.6379</b>   | <b>0.6424</b>  | <b>1 9</b>                                  | 0.315                                     | 0.329                                  |
| $\frac{3}{4}$                 | <b>0.7500</b>                       | <b>20</b>                         | <b>0.7175</b>   | <b>0.6905</b>   | <b>0.6959</b>  | <b>1 16</b>                                 | 0.369                                     | 0.386                                  |
| $\frac{13}{16}^e$             | <b>0.8125</b>                       | <b>20</b>                         | <b>0.7800</b>   | <b>0.7530</b>   | <b>0.7584</b>  | <b>1 10</b>                                 | 0.439                                     | 0.458                                  |
| $\frac{7}{8}$                 | <b>0.8750</b>                       | <b>20</b>                         | <b>0.8425</b>   | <b>0.8155</b>   | <b>0.8209</b>  | <b>1 5</b>                                  | 0.515                                     | 0.536                                  |
| $\frac{15}{16}^e$             | <b>0.9375</b>                       | <b>20</b>                         | <b>0.9050</b>   | <b>0.8780</b>   | <b>0.8834</b>  | <b>1 0</b>                                  | 0.598                                     | 0.620                                  |
| <b>1</b>                      | <b>1.0000</b>                       | <b>20</b>                         | <b>0.9675</b>   | <b>0.9405</b>   | <b>0.9459</b>  | <b>0 57</b>                                 | 0.687                                     | 0.711                                  |
| $\frac{1}{16}^e$              | <b>1.0625</b>                       | <b>18</b>                         | <b>1.0264</b>   | <b>0.9964</b>   | <b>1.0024</b>  | <b>0 59</b>                                 | 0.770                                     | 0.799                                  |
| $\frac{1}{8}$                 | <b>1.1250</b>                       | <b>18</b>                         | <b>1.0889</b>   | <b>1.0589</b>   | <b>1.0649</b>  | <b>0 56</b>                                 | 0.871                                     | 0.901                                  |
| $\frac{3}{16}^e$              | <b>1.1875</b>                       | <b>18</b>                         | <b>1.1514</b>   | <b>1.1214</b>   | <b>1.1274</b>  | <b>0 53</b>                                 | 0.977                                     | 1.009                                  |
| $\frac{1}{4}$                 | <b>1.2500</b>                       | <b>18</b>                         | <b>1.2139</b>   | <b>1.1839</b>   | <b>1.1899</b>  | <b>0 50</b>                                 | 1.090                                     | 1.123                                  |
| $\frac{5}{16}^e$              | <b>1.3125</b>                       | <b>18</b>                         | <b>1.2764</b>   | <b>1.2464</b>   | <b>1.2524</b>  | <b>0 48</b>                                 | 1.208                                     | 1.244                                  |
| $\frac{3}{8}$                 | <b>1.3750</b>                       | <b>18</b>                         | <b>1.3389</b>   | <b>1.3089</b>   | <b>1.3149</b>  | <b>0 45</b>                                 | 1.333                                     | 1.370                                  |
| $\frac{7}{16}^e$              | <b>1.4375</b>                       | <b>18</b>                         | <b>1.4014</b>   | <b>1.3714</b>   | <b>1.3774</b>  | <b>0 43</b>                                 | 1.464                                     | 1.503                                  |
| $\frac{1}{2}$                 | <b>1.5000</b>                       | <b>18</b>                         | <b>1.4639</b>   | <b>1.4339</b>   | <b>1.4399</b>  | <b>0 42</b>                                 | 1.60                                      | 1.64                                   |
| $\frac{9}{16}^e$              | <b>1.5625</b>                       | <b>18</b>                         | <b>1.5264</b>   | <b>1.4964</b>   | <b>1.5024</b>  | <b>0 40</b>                                 | 1.74                                      | 1.79                                   |
| $\frac{5}{8}$                 | <b>1.6250</b>                       | <b>18</b>                         | <b>1.5889</b>   | <b>1.5589</b>   | <b>1.5649</b>  | <b>0 38</b>                                 | 1.89                                      | 1.94                                   |
| $\frac{11}{16}^e$             | <b>1.6875</b>                       | <b>18</b>                         | <b>1.6514</b>   | <b>1.6214</b>   | <b>1.6274</b>  | <b>0 37</b>                                 | 2.05                                      | 2.10                                   |

<sup>a</sup> British: Effective Diameter.<sup>b</sup> See formula, pages 1502 and 1510.<sup>c</sup> Design form for UNR threads. (See figure on page 1733.)<sup>d</sup> Basic minor diameter.<sup>e</sup> Secondary sizes.

*Other Threads of Special Diameters, Pitches, and Lengths of Engagement:* Thread data for special combinations of diameter, pitch, and length of engagement not included in selected combinations are also given in the Standard but are not given here. Also, when design considerations require non-standard pitches or extreme conditions of engagement not covered by the tables, the allowance and tolerances should be derived from the formulas in the Standard. The thread symbol for such special threads is UNS.

**Constant Pitch Series.**—The various constant-pitch series, UN, with 4, 6, 8, 12, 16, 20, 28 and 32 threads per inch, given in Table 3, offer a comprehensive range of diameter-pitch combinations for those purposes where the threads in the Coarse, Fine, and Extra-Fine series do not meet the particular requirements of the design.

When selecting threads from these constant-pitch series, preference should be given wherever possible to those tabulated in the 8-, 12-, or 16-thread series.

*8-Thread Series:* The 8-thread series (8-UN) is a uniform-pitch series for large diameters. Although originally intended for high-pressure-joint bolts and nuts, it is now widely used as a substitute for the Coarse-Thread Series for diameters larger than 1 inch.

**12-Thread Series:** The 12-thread series (12-UN) is a uniform pitch series for large diameters requiring threads of medium-fine pitch. Although originally intended for boiler practice, it is now used as a continuation of the Fine-Thread Series for diameters larger than  $1\frac{1}{2}$  inches.

**16-Thread Series:** The 16-thread series (16-UN) is a uniform pitch series for large diameters requiring fine-pitch threads. It is suitable for adjusting collars and retaining nuts, and also serves as a continuation of the Extra-fine Thread Series for diameters larger than  $1\frac{11}{16}$  inches.

**4-, 6-, 20-, 28-, and 32-Thread Series:** These thread series have been used more or less widely in industry for various applications where the Standard Coarse, Fine or Extra-fine Series were not as applicable. They are now recognized as Standard Unified Thread Series in a specified selection of diameters for each pitch (see Table 2).

Whenever a thread in a constant-pitch series also appears in the UNC, UNF, or UNEF series, the symbols and tolerances for limits of size of UNC, UNF, or UNEF series are applicable, as will be seen in Tables 2 and 3.

**Table 5a. 4-Thread Series, 4-UN and 4-UNR — Basic Dimensions**

| Sizes          |                | Basic Major Dia.,<br>$D$ | Basic Pitch Dia., <sup>a</sup><br>$D_2$ | Minor Diameter                              |                                   | Lead Angle $\lambda$ at Basic P.D. |      | Area of Minor Dia. at $D - 2h_b$ | Tensile Stress Area <sup>b</sup> |
|----------------|----------------|--------------------------|---|---|-----------------------------------|------------------------------------|------|----------------------------------|----------------------------------|
| Primary        | Secondary      |                          |   | Ext. Thds., <sup>c</sup><br>$d_{3s}$ (Ref.) | Int. Thds., <sup>d</sup><br>$D_1$ | Deg.                               | Min. |                                  |                                  |
| Inches         | Inches         | Inches                   | Inches                                  | Inches                                      | Inches                            | Deg.                               | Min. | Sq. In.                          | Sq. In.                          |
| $2\frac{1}{2}$ |                | 2.5000                   | 2.3376                                  | 2.2023                                      | 2.2294                            | 1                                  | 57   | 3.72                             | 4.00                             |
|                | $2\frac{5}{8}$ | 2.6250                   | 2.4626                                  | 2.3273                                      | 2.3544                            | 1                                  | 51   | 4.16                             | 4.45                             |
| $2\frac{3}{4}$ |                | 2.7500                   | 2.5876                                  | 2.4523                                      | 2.4794                            | 1                                  | 46   | 4.62                             | 4.93                             |
|                | $2\frac{7}{8}$ | 2.8750                   | 2.7126                                  | 2.5773                                      | 2.6044                            | 1                                  | 41   | 5.11                             | 5.44                             |
| 3              |                | 3.0000                   | 2.8376                                  | 2.7023                                      | 2.7294                            | 1                                  | 36   | 5.62                             | 5.97                             |
|                | $3\frac{1}{8}$ | 3.1250                   | 2.9626                                  | 2.8273                                      | 2.8544                            | 1                                  | 32   | 6.16                             | 6.52                             |
| $3\frac{1}{4}$ |                | 3.2500                   | 3.0876                                  | 2.9523                                      | 2.9794                            | 1                                  | 29   | 6.72                             | 7.10                             |
|                | $3\frac{3}{8}$ | 3.3750                   | 3.2126                                  | 3.0773                                      | 3.1044                            | 1                                  | 25   | 7.31                             | 7.70                             |
| $3\frac{1}{2}$ |                | 3.5000                   | 3.3376                                  | 3.2023                                      | 3.2294                            | 1                                  | 22   | 7.92                             | 8.33                             |
|                | $3\frac{5}{8}$ | 3.6250                   | 3.4626                                  | 3.3273                                      | 3.3544                            | 1                                  | 19   | 8.55                             | 9.00                             |
| $3\frac{3}{4}$ |                | 3.7500                   | 3.5876                                  | 3.4523                                      | 3.4794                            | 1                                  | 16   | 9.21                             | 9.66                             |
|                | $3\frac{7}{8}$ | 3.8750                   | 3.7126                                  | 3.5773                                      | 3.6044                            | 1                                  | 14   | 9.90                             | 10.36                            |
| 4              |                | 4.0000                   | 3.8376                                  | 3.7023                                      | 3.7294                            | 1                                  | 11   | 10.61                            | 11.08                            |
|                | $4\frac{1}{8}$ | 4.1250                   | 3.9626                                  | 3.8273                                      | 3.8544                            | 1                                  | 9    | 11.34                            | 11.83                            |
| $4\frac{1}{4}$ |                | 4.2500                   | 4.0876                                  | 3.9523                                      | 3.9794                            | 1                                  | 7    | 12.10                            | 12.61                            |
|                | $4\frac{3}{8}$ | 4.3750                   | 4.2126                                  | 4.0773                                      | 4.1044                            | 1                                  | 5    | 12.88                            | 13.41                            |
| $4\frac{1}{2}$ |                | 4.5000                   | 4.3376                                  | 4.2023                                      | 4.2294                            | 1                                  | 3    | 13.69                            | 14.23                            |
|                | $4\frac{5}{8}$ | 4.6250                   | 4.4626                                  | 4.3273                                      | 4.3544                            | 1                                  | 1    | 14.52                            | 15.1                             |
| $4\frac{3}{4}$ |                | 4.7500                   | 4.5876                                  | 4.4523                                      | 4.4794                            | 1                                  | 0    | 15.4                             | 15.9                             |
|                | $4\frac{7}{8}$ | 4.8750                   | 4.7126                                  | 4.5773                                      | 4.6044                            | 0                                  | 58   | 16.3                             | 16.8                             |
| 5              |                | 5.0000                   | 4.8376                                  | 4.7023                                      | 4.7294                            | 0                                  | 57   | 17.2                             | 17.8                             |
|                | $5\frac{1}{8}$ | 5.1250                   | 4.9626                                  | 4.8273                                      | 4.8544                            | 0                                  | 55   | 18.1                             | 18.7                             |
| $5\frac{1}{4}$ |                | 5.2500                   | 5.0876                                  | 4.9523                                      | 4.9794                            | 0                                  | 54   | 19.1                             | 19.7                             |
|                | $5\frac{3}{8}$ | 5.3750                   | 5.2126                                  | 5.0773                                      | 5.1044                            | 0                                  | 52   | 20.0                             | 20.7                             |
| $5\frac{1}{2}$ |                | 5.5000                   | 5.3376                                  | 5.2023                                      | 5.2294                            | 0                                  | 51   | 21.0                             | 21.7                             |
|                | $5\frac{5}{8}$ | 5.6250                   | 5.4626                                  | 5.3273                                      | 5.3544                            | 0                                  | 50   | 22.1                             | 22.7                             |
| $5\frac{3}{4}$ |                | 5.7500                   | 5.5876                                  | 5.4523                                      | 5.4794                            | 0                                  | 49   | 23.1                             | 23.8                             |
|                | $5\frac{7}{8}$ | 5.8750                   | 5.7126                                  | 5.5773                                      | 5.6044                            | 0                                  | 48   | 24.2                             | 24.9                             |
| 6              |                | 6.0000                   | 5.8376                                  | 5.7023                                      | 5.7294                            | 0                                  | 47   | 25.3                             | 26.0                             |

<sup>a</sup> British: Effective Diameter.

<sup>b</sup> See formula, pages 1502 and 1510.

<sup>c</sup> Design form for UNR threads. (See figure on page 1733).

<sup>d</sup> Basic minor diameter.

<sup>e</sup> These are standard sizes of the UNC series.

Table 5b. 6-Thread Series, 6-UN and 6-UNR—Basic Dimensions

| Sizes                        |                   | Basic Major Dia.,<br>$D$ | Basic Pitch Dia., <sup>a</sup><br>$D_2$ | Minor Diameter                           |                                   | Lead Angle $\lambda$ at Basic P.D. |      | Area of Minor Dia. at $D - 2h_b$ | Tensile Stress Area <sup>b</sup> |
|------------------------------|-------------------|--------------------------|---|--|-----------------------------------|------------------------------------|------|----------------------------------|----------------------------------|
| Primary                      | Secondary         |                          |   | Ext. Thds., <sup>c</sup><br>$d_3$ (Ref.) | Int. Thds., <sup>d</sup><br>$D_1$ | Deg.                               | Min. |                                  |                                  |
| Inches                       | Inches            | Inches                   | Inches                                  | Inches                                   | Inches                            | Deg.                               | Min. | Sq. In.                          | Sq. In.                          |
| 1 $\frac{3}{8}$ <sup>e</sup> |                   | 1.3750                   | 1.2667                                  | 1.1766                                   | 1.1946                            | 2                                  | 24   | 1.054                            | 1.155                            |
|                              | 1 $\frac{7}{16}$  | 1.4375                   | 1.3292                                  | 1.2391                                   | 1.2571                            | 2                                  | 17   | 1.171                            | 1.277                            |
| 1 $\frac{1}{2}$ <sup>e</sup> |                   | 1.5000                   | 1.3917                                  | 1.3016                                   | 1.3196                            | 2                                  | 11   | 1.294                            | 1.405                            |
|                              | 1 $\frac{9}{16}$  | 1.5625                   | 1.4542                                  | 1.3641                                   | 1.3821                            | 2                                  | 5    | 1.423                            | 1.54                             |
| 1 $\frac{5}{8}$              |                   | 1.6250                   | 1.5167                                  | 1.4271                                   | 1.4446                            | 2                                  | 0    | 1.56                             | 1.68                             |
|                              | 1 $\frac{11}{16}$ | 1.6875                   | 1.5792                                  | 1.4891                                   | 1.5071                            | 1                                  | 55   | 1.70                             | 1.83                             |
| 1 $\frac{3}{4}$              |                   | 1.7500                   | 1.6417                                  | 1.5516                                   | 1.5696                            | 1                                  | 51   | 1.85                             | 1.98                             |
|                              | 1 $\frac{13}{16}$ | 1.8125                   | 1.7042                                  | 1.6141                                   | 1.6321                            | 1                                  | 47   | 2.00                             | 2.14                             |
| 1 $\frac{7}{8}$              |                   | 1.8750                   | 1.7667                                  | 1.6766                                   | 1.6946                            | 1                                  | 43   | 2.16                             | 2.30                             |
|                              | 1 $\frac{15}{16}$ | 1.9375                   | 1.8292                                  | 1.7391                                   | 1.7571                            | 1                                  | 40   | 2.33                             | 2.47                             |
| 2                            |                   | 2.0000                   | 1.8917                                  | 1.8016                                   | 1.8196                            | 1                                  | 36   | 2.50                             | 2.65                             |
|                              | 2 $\frac{1}{8}$   | 2.1250                   | 2.0167                                  | 1.9266                                   | 1.9446                            | 1                                  | 30   | 2.86                             | 3.03                             |
| 2 $\frac{1}{4}$              |                   | 2.2500                   | 2.1417                                  | 2.0516                                   | 2.0696                            | 1                                  | 25   | 3.25                             | 3.42                             |
|                              | 2 $\frac{3}{8}$   | 2.3750                   | 2.2667                                  | 2.1766                                   | 2.1946                            | 1                                  | 20   | 3.66                             | 3.85                             |
| 2 $\frac{1}{2}$              |                   | 2.5000                   | 2.3917                                  | 2.3016                                   | 2.3196                            | 1                                  | 16   | 4.10                             | 4.29                             |
|                              | 2 $\frac{5}{8}$   | 2.6250                   | 2.5167                                  | 2.4266                                   | 2.4446                            | 1                                  | 12   | 4.56                             | 4.76                             |
| 2 $\frac{3}{4}$              |                   | 2.7500                   | 2.6417                                  | 2.5516                                   | 2.5696                            | 1                                  | 9    | 5.04                             | 5.26                             |
|                              | 2 $\frac{7}{8}$   | 2.8750                   | 2.7667                                  | 2.6766                                   | 2.6946                            | 1                                  | 6    | 5.55                             | 5.78                             |
| 3                            |                   | 3.0000                   | 2.8917                                  | 2.8016                                   | 2.8196                            | 1                                  | 3    | 6.09                             | 6.33                             |
|                              | 3 $\frac{1}{8}$   | 3.1250                   | 3.0167                                  | 2.9266                                   | 2.9446                            | 1                                  | 0    | 6.64                             | 6.89                             |
| 3 $\frac{1}{4}$              |                   | 3.2500                   | 3.1417                                  | 3.0516                                   | 3.0696                            | 0                                  | 58   | 7.23                             | 7.49                             |
|                              | 3 $\frac{3}{8}$   | 3.3750                   | 3.2667                                  | 3.1766                                   | 3.1946                            | 0                                  | 56   | 7.84                             | 8.11                             |
| 3 $\frac{1}{2}$              |                   | 3.5000                   | 3.3917                                  | 3.3016                                   | 3.3196                            | 0                                  | 54   | 8.47                             | 8.75                             |
|                              | 3 $\frac{5}{8}$   | 3.6250                   | 3.5167                                  | 3.4266                                   | 3.4446                            | 0                                  | 52   | 9.12                             | 9.42                             |
| 3 $\frac{3}{4}$              |                   | 3.7500                   | 3.6417                                  | 3.5516                                   | 3.5696                            | 0                                  | 50   | 9.81                             | 10.11                            |
|                              | 3 $\frac{7}{8}$   | 3.8750                   | 3.7667                                  | 3.6766                                   | 3.6946                            | 0                                  | 48   | 10.51                            | 10.83                            |
| 4                            |                   | 4.0000                   | 3.8917                                  | 3.8016                                   | 3.8196                            | 0                                  | 47   | 11.24                            | 11.57                            |
|                              | 4 $\frac{1}{8}$   | 4.1250                   | 4.0167                                  | 3.9266                                   | 3.9446                            | 0                                  | 45   | 12.00                            | 12.33                            |
| 4 $\frac{1}{4}$              |                   | 4.2500                   | 4.1417                                  | 4.0516                                   | 4.0696                            | 0                                  | 44   | 12.78                            | 13.12                            |
|                              | 4 $\frac{3}{8}$   | 4.3750                   | 4.2667                                  | 4.1766                                   | 4.1946                            | 0                                  | 43   | 13.58                            | 13.94                            |
| 4 $\frac{1}{2}$              |                   | 4.5000                   | 4.3917                                  | 4.3016                                   | 4.3196                            | 0                                  | 42   | 14.41                            | 14.78                            |
|                              | 4 $\frac{5}{8}$   | 4.6250                   | 4.5167                                  | 4.4266                                   | 4.4446                            | 0                                  | 40   | 15.3                             | 15.6                             |
| 4 $\frac{3}{4}$              |                   | 4.7500                   | 4.6417                                  | 4.5516                                   | 4.5696                            | 0                                  | 39   | 16.1                             | 16.5                             |
|                              | 4 $\frac{7}{8}$   | 4.8750                   | 4.7667                                  | 4.6766                                   | 4.6946                            | 0                                  | 38   | 17.0                             | 17.5                             |
| 5                            |                   | 5.0000                   | 4.8917                                  | 4.8016                                   | 4.8196                            | 0                                  | 37   | 18.0                             | 18.4                             |
|                              | 5 $\frac{1}{8}$   | 5.1250                   | 5.0167                                  | 4.9266                                   | 4.9446                            | 0                                  | 36   | 18.9                             | 19.3                             |
| 5 $\frac{1}{4}$              |                   | 5.2500                   | 5.1417                                  | 5.0516                                   | 5.0696                            | 0                                  | 35   | 19.9                             | 20.3                             |
|                              | 5 $\frac{3}{8}$   | 5.3750                   | 5.2667                                  | 5.1766                                   | 5.1946                            | 0                                  | 35   | 20.9                             | 21.3                             |
| 5 $\frac{1}{2}$              |                   | 5.5000                   | 5.3917                                  | 5.3016                                   | 5.3196                            | 0                                  | 34   | 21.9                             | 22.4                             |
|                              | 5 $\frac{5}{8}$   | 5.6250                   | 5.5167                                  | 5.4266                                   | 5.4446                            | 0                                  | 33   | 23.0                             | 23.4                             |
| 5 $\frac{3}{4}$              |                   | 5.7500                   | 5.6417                                  | 5.5516                                   | 5.5696                            | 0                                  | 32   | 24.0                             | 24.5                             |
|                              | 5 $\frac{7}{8}$   | 5.8750                   | 5.7667                                  | 5.6766                                   | 5.6946                            | 0                                  | 32   | 25.1                             | 25.6                             |
| 6                            |                   | 6.0000                   | 5.8917                                  | 5.8016                                   | 5.8196                            | 0                                  | 31   | 26.3                             | 26.8                             |

<sup>a</sup> British: Effective Diameter.<sup>b</sup> See formula, pages 1502 and 1510.<sup>c</sup> Design form for UNR threads. (See figure on page 1733).<sup>d</sup> Basic minor diameter.<sup>e</sup> These are standard sizes of the UNC series.

Table 5c. 8-Thread Series, 8-UN and 8-UNR—Basic Dimensions

| Sizes           |                   | Basic Major Dia., $D$ | Basic Pitch Dia., $^a D_2$ | Minor Diameter                        |                                | Lead Angle $\lambda$ at Basic P.D. |      | Area of Minor Dia. at $D - 2h_b$ | Tensile Stress Area <sup>b</sup> |
|-----------------|-------------------|-----------------------|----------------------------|---------------------------------------|--------------------------------|------------------------------------|------|----------------------------------|----------------------------------|
| Primary         | Secondary         |                       |                            | Ext. Thds., <sup>c</sup> $d_3$ (Ref.) | Int. Thds., <sup>d</sup> $D_1$ | Deg.                               | Min. |                                  |                                  |
| Inches          | Inches            | Inches                | Inches                     | Inches                                | Inches                         | Deg.                               | Min. | Sq. In.                          | Sq. In.                          |
| 1 <sup>e</sup>  |                   | 1.0000                | 0.9188                     | 0.8512                                | 0.8647                         | 2                                  | 29   | 0.551                            | 0.606                            |
|                 | 1 $\frac{1}{16}$  | 1.0625                | 0.9813                     | 0.9137                                | 0.9272                         | 2                                  | 19   | 0.636                            | 0.695                            |
| 1 $\frac{1}{8}$ |                   | 1.1250                | 1.0438                     | 0.9792                                | 0.9897                         | 2                                  | 11   | 0.728                            | 0.790                            |
|                 | 1 $\frac{3}{16}$  | 1.1875                | 1.1063                     | 1.0387                                | 1.0522                         | 2                                  | 4    | 0.825                            | 0.892                            |
| 1 $\frac{1}{4}$ |                   | 1.2500                | 1.1688                     | 1.1012                                | 1.1147                         | 1                                  | 57   | 0.929                            | 1.000                            |
|                 | 1 $\frac{5}{16}$  | 1.3125                | 1.2313                     | 1.1637                                | 1.1772                         | 1                                  | 51   | 1.039                            | 1.114                            |
| 1 $\frac{3}{8}$ |                   | 1.3750                | 1.2938                     | 1.2262                                | 1.2397                         | 1                                  | 46   | 1.155                            | 1.233                            |
|                 | 1 $\frac{7}{16}$  | 1.4375                | 1.3563                     | 1.2887                                | 1.3022                         | 1                                  | 41   | 1.277                            | 1.360                            |
| 1 $\frac{1}{2}$ |                   | 1.5000                | 1.4188                     | 1.3512                                | 1.3647                         | 1                                  | 36   | 1.405                            | 1.492                            |
|                 | 1 $\frac{9}{16}$  | 1.5625                | 1.4813                     | 1.4137                                | 1.4272                         | 1                                  | 32   | 1.54                             | 1.63                             |
| 1 $\frac{5}{8}$ |                   | 1.6250                | 1.5438                     | 1.4806                                | 1.4897                         | 1                                  | 29   | 1.68                             | 1.78                             |
|                 | 1 $\frac{11}{16}$ | 1.6875                | 1.6063                     | 1.5387                                | 1.5522                         | 1                                  | 25   | 1.83                             | 1.93                             |
| 1 $\frac{3}{4}$ |                   | 1.7500                | 1.6688                     | 1.6012                                | 1.6147                         | 1                                  | 22   | 1.98                             | 2.08                             |
|                 | 1 $\frac{13}{16}$ | 1.8125                | 1.7313                     | 1.6637                                | 1.6772                         | 1                                  | 19   | 2.14                             | 2.25                             |
| 1 $\frac{7}{8}$ |                   | 1.8750                | 1.7938                     | 1.7262                                | 1.7397                         | 1                                  | 16   | 2.30                             | 2.41                             |
|                 | 1 $\frac{15}{16}$ | 1.9375                | 1.8563                     | 1.7887                                | 1.8022                         | 1                                  | 14   | 2.47                             | 2.59                             |
| 2               |                   | 2.0000                | 1.9188                     | 1.8512                                | 1.8647                         | 1                                  | 11   | 2.65                             | 2.77                             |
|                 | 2 $\frac{1}{8}$   | 2.1250                | 2.0438                     | 1.9762                                | 1.9897                         | 1                                  | 7    | 3.03                             | 3.15                             |
| 2 $\frac{1}{4}$ |                   | 2.2500                | 2.1688                     | 2.1012                                | 2.1147                         | 1                                  | 3    | 3.42                             | 3.56                             |
|                 | 2 $\frac{3}{8}$   | 2.3750                | 2.2938                     | 2.2262                                | 2.2397                         | 1                                  | 0    | 3.85                             | 3.99                             |
| 2 $\frac{1}{2}$ |                   | 2.5000                | 2.4188                     | 2.3512                                | 2.3647                         | 0                                  | 57   | 4.29                             | 4.44                             |
|                 | 2 $\frac{5}{8}$   | 2.6250                | 2.5438                     | 2.4762                                | 2.4897                         | 0                                  | 54   | 4.76                             | 4.92                             |
| 2 $\frac{3}{4}$ |                   | 2.7500                | 2.6688                     | 2.6012                                | 2.6147                         | 0                                  | 51   | 5.26                             | 5.43                             |
|                 | 2 $\frac{7}{8}$   | 2.8750                | 2.7938                     | 2.7262                                | 2.7397                         | 0                                  | 49   | 5.78                             | 5.95                             |
| 3               |                   | 3.0000                | 2.9188                     | 2.8512                                | 2.8647                         | 0                                  | 47   | 6.32                             | 6.51                             |
|                 | 3 $\frac{1}{8}$   | 3.1250                | 3.0438                     | 2.9762                                | 2.9897                         | 0                                  | 45   | 6.89                             | 7.08                             |
| 3 $\frac{1}{4}$ |                   | 3.2500                | 3.1688                     | 3.1012                                | 3.1147                         | 0                                  | 43   | 7.49                             | 7.69                             |
|                 | 3 $\frac{3}{8}$   | 3.3750                | 3.2938                     | 3.2262                                | 3.2397                         | 0                                  | 42   | 8.11                             | 8.31                             |
| 3 $\frac{1}{2}$ |                   | 3.5000                | 3.4188                     | 3.3512                                | 3.3647                         | 0                                  | 40   | 8.75                             | 8.96                             |
|                 | 3 $\frac{5}{8}$   | 3.6250                | 3.5438                     | 3.4762                                | 3.4897                         | 0                                  | 39   | 9.42                             | 9.64                             |
| 3 $\frac{3}{4}$ |                   | 3.7500                | 3.6688                     | 3.6012                                | 3.6147                         | 0                                  | 37   | 10.11                            | 10.34                            |
|                 | 3 $\frac{7}{8}$   | 3.8750                | 3.7938                     | 3.7262                                | 3.7397                         | 0                                  | 36   | 10.83                            | 11.06                            |
| 4               |                   | 4.0000                | 3.9188                     | 3.8512                                | 3.8647                         | 0                                  | 35   | 11.57                            | 11.81                            |
|                 | 4 $\frac{1}{8}$   | 4.1250                | 4.0438                     | 3.9762                                | 3.9897                         | 0                                  | 34   | 12.34                            | 12.59                            |
| 4 $\frac{1}{4}$ |                   | 4.2500                | 4.1688                     | 4.1012                                | 4.1147                         | 0                                  | 33   | 13.12                            | 13.38                            |
|                 | 4 $\frac{3}{8}$   | 4.3750                | 4.2938                     | 4.2262                                | 4.2397                         | 0                                  | 32   | 13.94                            | 14.21                            |
| 4 $\frac{1}{2}$ |                   | 4.5000                | 4.4188                     | 4.3512                                | 4.3647                         | 0                                  | 31   | 14.78                            | 15.1                             |
|                 | 4 $\frac{5}{8}$   | 4.6250                | 4.5438                     | 4.4762                                | 4.4897                         | 0                                  | 30   | 15.6                             | 15.9                             |
| 4 $\frac{3}{4}$ |                   | 4.7500                | 4.6688                     | 4.6012                                | 4.6147                         | 0                                  | 29   | 16.5                             | 16.8                             |
|                 | 4 $\frac{7}{8}$   | 4.8750                | 4.7938                     | 4.7262                                | 4.7397                         | 0                                  | 29   | 17.4                             | 17.7                             |
| 5               |                   | 5.0000                | 4.9188                     | 4.8512                                | 4.8647                         | 0                                  | 28   | 18.4                             | 18.7                             |
|                 | 5 $\frac{1}{8}$   | 5.1250                | 5.0438                     | 4.9762                                | 4.9897                         | 0                                  | 27   | 19.3                             | 19.7                             |
| 5 $\frac{1}{4}$ |                   | 5.2500                | 5.1688                     | 5.1012                                | 5.1147                         | 0                                  | 26   | 20.3                             | 20.7                             |
|                 | 5 $\frac{3}{8}$   | 5.3750                | 5.2938                     | 5.2262                                | 5.2397                         | 0                                  | 26   | 21.3                             | 21.7                             |
| 5 $\frac{1}{2}$ |                   | 5.5000                | 5.4188                     | 5.3512                                | 5.3647                         | 0                                  | 25   | 22.4                             | 22.7                             |
|                 | 5 $\frac{5}{8}$   | 5.6250                | 5.5438                     | 5.4762                                | 5.4897                         | 0                                  | 25   | 23.4                             | 23.8                             |
| 5 $\frac{3}{4}$ |                   | 5.7500                | 5.6688                     | 5.6012                                | 5.6147                         | 0                                  | 24   | 24.5                             | 24.9                             |
|                 | 5 $\frac{7}{8}$   | 5.8750                | 5.7938                     | 5.7262                                | 5.7397                         | 0                                  | 24   | 25.6                             | 26.0                             |
| 6               |                   | 6.0000                | 5.9188                     | 5.8512                                | 5.8647                         | 0                                  | 23   | 26.8                             | 27.1                             |

<sup>a</sup> British: Effective Diameter.<sup>b</sup> See formula, pages 1502 and 1510.<sup>c</sup> Design form for UNR threads. (See figure on page 1733).<sup>d</sup> Basic minor diameter.<sup>e</sup> This is a standard size of the UNC series.

Table 5d. 12-Thread series, 12-UN and 12-UNR—Basic Dimensions

| Sizes              |           | Basic Major Dia.,<br>D | Basic Pitch Dia., <sup>a</sup><br>D <sub>2</sub> | Minor Diameter                                    |  | Lead Angle λ at Basic P.D. |      | Area of Minor Dia. at D - 2h <sub>t</sub><br>Sq. In. | Tensile Stress Area <sup>b</sup><br>Sq. In. |
|--------------------|-----------|------------------------|--|---|--|----------------------------|------|--|---|
| Primary            | Secondary |                        |  | Ext. Thds., <sup>c</sup><br>d <sub>3</sub> (Ref.) | Int. Thds., <sup>d</sup><br>D <sub>1</sub> | Deg.                       | Min. |  |   |
| Inches             | Inches    | Inches                 | Inches   | Inches  | Inches                                     | Deg.                       | Min. | Sq. In.  | Sq. In.                                     |
| 9/16 <sup>e</sup>  |           | 0.5625                 | 0.5084   | 0.4633  | 0.4723                                     | 2                          | 59   | 0.162  | 0.182                                       |
| 5/8                |           | 0.6250                 | 0.5709   | 0.5258  | 0.5348                                     | 2                          | 40   | 0.210  | 0.232                                       |
|                    | 11/16     | 0.6875                 | 0.6334   | 0.5883  | 0.5973                                     | 2                          | 24   | 0.264  | 0.289                                       |
| 3/4                |           | 0.7500                 | 0.6959   | 0.6508  | 0.6598                                     | 2                          | 11   | 0.323  | 0.351                                       |
|                    | 13/16     | 0.8125                 | 0.7584   | 0.7133  | 0.7223                                     | 2                          | 0    | 0.390  | 0.420                                       |
| 7/8                |           | 0.8750                 | 0.8209   | 0.7758  | 0.7848                                     | 1                          | 51   | 0.462  | 0.495                                       |
|                    | 15/16     | 0.9375                 | 0.8834   | 0.8383  | 0.8473                                     | 1                          | 43   | 0.540  | 0.576                                       |
| 1 <sup>e</sup>     |           | 1.0000                 | 0.9459   | 0.9008  | 0.9098                                     | 1                          | 36   | 0.625  | 0.663                                       |
|                    | 1 1/16    | 1.0625                 | 1.0084   | 0.9633  | 0.9723                                     | 1                          | 30   | 0.715  | 0.756                                       |
| 1 1/8 <sup>e</sup> |           | 1.1250                 | 1.0709   | 1.0258  | 1.0348                                     | 1                          | 25   | 0.812  | 0.856                                       |
|                    | 1 3/16    | 1.1875                 | 1.1334   | 1.0883  | 1.0973                                     | 1                          | 20   | 0.915  | 0.961                                       |
| 1 1/4 <sup>e</sup> |           | 1.2500                 | 1.1959   | 1.1508  | 1.1598                                     | 1                          | 16   | 1.024  | 1.073                                       |
|                    | 1 5/16    | 1.3125                 | 1.2584   | 1.2133  | 1.2223                                     | 1                          | 12   | 1.139  | 1.191                                       |
| 1 3/8              |           | 1.3750                 | 1.3209   | 1.2758  | 1.2848                                     | 1                          | 9    | 1.260  | 1.315                                       |
|                    | 1 7/16    | 1.4375                 | 1.3834   | 1.3383  | 1.3473                                     | 1                          | 6    | 1.388  | 1.445                                       |
| 1 1/2 <sup>e</sup> |           | 1.5000                 | 1.4459   | 1.4008  | 1.4098                                     | 1                          | 3    | 1.52   | 1.58  |
|                    | 1 9/16    | 1.5625                 | 1.5084   | 1.4633  | 1.4723                                     | 1                          | 0    | 1.66   | 1.72  |
| 1 5/8              |           | 1.6250                 | 1.5709   | 1.5258  | 1.5348                                     | 0                          | 58   | 1.81   | 1.87  |
|                    | 1 11/16   | 1.6875                 | 1.6334   | 1.5883  | 1.5973                                     | 0                          | 56   | 1.96   | 2.03  |
| 1 3/4              |           | 1.7500                 | 1.6959   | 1.6508  | 1.6598                                     | 0                          | 54   | 2.12   | 2.19  |
|                    | 1 13/16   | 1.8125                 | 1.7584   | 1.7133  | 1.7223                                     | 0                          | 52   | 2.28   | 2.35  |
| 1 7/8              |           | 1.8750                 | 1.8209   | 1.7758  | 1.7848                                     | 0                          | 50   | 2.45   | 2.53  |
|                    | 1 15/16   | 1.9375                 | 1.8834   | 1.8383  | 1.8473                                     | 0                          | 48   | 2.63   | 2.71  |
| 2                  |           | 2.0000                 | 1.9459   | 1.9008  | 1.9098                                     | 0                          | 47   | 2.81   | 2.89  |
|                    | 2 1/8     | 2.1250                 | 2.0709   | 2.0258  | 2.0348                                     | 0                          | 44   | 3.19   | 3.28  |
| 2 1/4              |           | 2.2500                 | 2.1959   | 2.1508  | 2.1598                                     | 0                          | 42   | 3.60   | 3.69  |
|                    | 2 3/8     | 2.3750                 | 2.3209   | 2.2758  | 2.2848                                     | 0                          | 39   | 4.04   | 4.13  |
| 2 1/2              |           | 2.5000                 | 2.4459   | 2.4008  | 2.4098                                     | 0                          | 37   | 4.49   | 4.60  |
|                    | 2 5/8     | 2.6250                 | 2.5709   | 2.5258  | 2.5348                                     | 0                          | 35   | 4.97   | 5.08  |
| 2 3/4              |           | 2.7500                 | 2.6959   | 2.6508  | 2.6598                                     | 0                          | 34   | 5.48   | 5.59  |
|                    | 2 7/8     | 2.8750                 | 2.8209   | 2.7758  | 2.7848                                     | 0                          | 32   | 6.01   | 6.13  |
| 3                  |           | 3.0000                 | 2.9459   | 2.9008  | 2.9098                                     | 0                          | 31   | 6.57   | 6.69  |
|                    | 3 1/8     | 3.1250                 | 3.0709   | 3.0258  | 3.0348                                     | 0                          | 30   | 7.15   | 7.28  |
| 3 1/4              |           | 3.2500                 | 3.1959   | 3.1508  | 3.1598                                     | 0                          | 29   | 7.75   | 7.89  |
|                    | 3 3/8     | 3.3750                 | 3.3209   | 3.2758  | 3.2848                                     | 0                          | 27   | 8.38   | 8.52  |
| 3 1/2              |           | 3.5000                 | 3.4459   | 3.4008  | 3.4098                                     | 0                          | 26   | 9.03   | 9.18  |
|                    | 3 5/8     | 3.6250                 | 3.5709   | 3.5258  | 3.5348                                     | 0                          | 26   | 9.71   | 9.86  |
| 3 3/4              |           | 3.7500                 | 3.6959   | 3.6508  | 3.6598                                     | 0                          | 25   | 10.42  | 10.57                                       |
|                    | 3 7/8     | 3.8750                 | 3.8209   | 3.7758  | 3.7848                                     | 0                          | 24   | 11.14  | 11.30                                       |
| 4                  |           | 4.0000                 | 3.9459   | 3.9008  | 3.9098                                     | 0                          | 23   | 11.90  | 12.06                                       |
|                    | 4 1/8     | 4.1250                 | 4.0709   | 4.0258  | 4.0348                                     | 0                          | 22   | 12.67  | 12.84                                       |
| 4 1/4              |           | 4.2500                 | 4.1959   | 4.1508  | 4.1598                                     | 0                          | 22   | 13.47  | 13.65                                       |
|                    | 4 3/8     | 4.3750                 | 4.3209   | 4.2758  | 4.2848                                     | 0                          | 21   | 14.30  | 14.48                                       |
| 4 1/2              |           | 4.5000                 | 4.4459   | 4.4008  | 4.4098                                     | 0                          | 21   | 15.1   | 15.3  |
|                    | 4 5/8     | 4.6250                 | 4.5709   | 4.5258  | 4.5348                                     | 0                          | 20   | 16.0   | 16.2  |
| 4 3/4              |           | 4.7500                 | 4.6959   | 4.6508  | 4.6598                                     | 0                          | 19   | 16.9   | 17.1  |
|                    | 4 7/8     | 4.8750                 | 4.8209   | 4.7758  | 4.7848                                     | 0                          | 19   | 17.8   | 18.0  |
| 5                  |           | 5.0000                 | 4.9459   | 4.9008  | 4.9098                                     | 0                          | 18   | 18.8   | 19.0  |
|                    | 5 1/8     | 5.1250                 | 5.0709   | 5.0258  | 5.0348                                     | 0                          | 18   | 19.8   | 20.0  |
| 5 1/4              |           | 5.2500                 | 5.1959   | 5.1508  | 5.1598                                     | 0                          | 18   | 20.8   | 21.0  |
|                    | 5 3/8     | 5.3750                 | 5.3209   | 5.2758  | 5.2848                                     | 0                          | 17   | 21.8   | 22.0  |
| 5 1/2              |           | 5.5000                 | 5.4459   | 5.4008  | 5.4098                                     | 0                          | 17   | 22.8   | 23.1  |
|                    | 5 5/8     | 5.6250                 | 5.5709   | 5.5258  | 5.5348                                     | 0                          | 16   | 23.9   | 24.1  |
| 5 3/4              |           | 5.7500                 | 5.6959   | 5.6508  | 5.6598                                     | 0                          | 16   | 25.0   | 25.2  |
|                    | 5 7/8     | 5.8750                 | 5.8209   | 5.7758  | 5.7848                                     | 0                          | 16   | 26.1   | 26.4  |
| 6                  |           | 6.0000                 | 5.9459   | 5.9008  | 5.9098                                     | 0                          | 15   | 27.3   | 27.5  |

<sup>a</sup> British: Effective Diameter.<sup>b</sup> See formula, pages 1502 and 1510.<sup>c</sup> Design form for UNR threads. (See figure on page 1733.)<sup>d</sup> Basic minor diameter.<sup>e</sup> These are standard sizes of the UNC or UNF Series.

UNIFIED SCREW THREADS

**Table 5e. 16-Thread Series, 16-UN and 16-UNR—Basic Dimensions**

| Sizes   |           | Basic Major Dia., $D$ | Basic Pitch Dia., $D_2$ | Minor Diameter                           |                                   | Lead Angle $\lambda$ at Basic P.D. |      | Area of Minor Dia. at $D - 2h_b$ | Tensile Stress Area <sup>b</sup> |
|---------|-----------|-----------------------|-------------------------|--|-----------------------------------|------------------------------------|------|----------------------------------|----------------------------------|
| Primary | Secondary |                       |                         | Ext. Thds., <sup>c</sup><br>$d_3$ (Ref.) | Int. Thds., <sup>d</sup><br>$D_1$ | Deg.                               | Min. |                                  |                                  |
| Inches  | Inches    | Inches                | Inches                  | Inches                                   | Inches                            |                                    |      | Sq. In.                          | Sq. In.                          |
| 3/8     |           | 0.3750                | 0.3344                  | 0.3005                                   | 0.3073                            | 3                                  | 24   | 0.0678                           | 0.0775                           |
| 7/16    |           | 0.4375                | 0.3969                  | 0.3630                                   | 0.3698                            | 2                                  | 52   | 0.0997                           | 0.1114                           |
| 1/2     |           | 0.5000                | 0.4594                  | 0.4255                                   | 0.4323                            | 2                                  | 29   | 0.1378                           | 0.151                            |
| 9/16    |           | 0.5625                | 0.5219                  | 0.4880                                   | 0.4948                            | 2                                  | 11   | 0.182                            | 0.198                            |
| 5/8     |           | 0.6250                | 0.5844                  | 0.5505                                   | 0.5573                            | 1                                  | 57   | 0.232                            | 0.250                            |
|         | 11/16     | 0.6875                | 0.6469                  | 0.6130                                   | 0.6198                            | 1                                  | 46   | 0.289                            | 0.308                            |
| 3/4     |           | 0.7500                | 0.7094                  | 0.6755                                   | 0.6823                            | 1                                  | 36   | 0.351                            | 0.373                            |
|         | 13/16     | 0.8125                | 0.7719                  | 0.7380                                   | 0.7448                            | 1                                  | 29   | 0.420                            | 0.444                            |
| 7/8     |           | 0.8750                | 0.8344                  | 0.8005                                   | 0.8073                            | 1                                  | 22   | 0.495                            | 0.521                            |
|         | 15/16     | 0.9375                | 0.8969                  | 0.8630                                   | 0.8698                            | 1                                  | 16   | 0.576                            | 0.604                            |
| 1       |           | 1.0000                | 0.9594                  | 0.9255                                   | 0.9323                            | 1                                  | 11   | 0.663                            | 0.693                            |
|         | 11/16     | 1.0625                | 1.0219                  | 0.9880                                   | 0.9948                            | 1                                  | 7    | 0.756                            | 0.788                            |
| 1 1/8   |           | 1.1250                | 1.0844                  | 1.0505                                   | 1.0573                            | 1                                  | 3    | 0.856                            | 0.889                            |
|         | 13/16     | 1.1875                | 1.1469                  | 1.1130                                   | 1.1198                            | 1                                  | 0    | 0.961                            | 0.997                            |
| 1 1/4   |           | 1.2500                | 1.2094                  | 1.1755                                   | 1.1823                            | 0                                  | 57   | 1.073                            | 1.111                            |
|         | 15/16     | 1.3125                | 1.2719                  | 1.2380                                   | 1.2448                            | 0                                  | 54   | 1.191                            | 1.230                            |
| 1 3/8   |           | 1.3750                | 1.3344                  | 1.3005                                   | 1.3073                            | 0                                  | 51   | 1.315                            | 1.356                            |
|         | 17/16     | 1.4375                | 1.3969                  | 1.3630                                   | 1.3698                            | 0                                  | 49   | 1.445                            | 1.488                            |
| 1 1/2   |           | 1.5000                | 1.4594                  | 1.4255                                   | 1.4323                            | 0                                  | 47   | 1.58                             | 1.63                             |
|         | 19/16     | 1.5625                | 1.5219                  | 1.4880                                   | 1.4948                            | 0                                  | 45   | 1.72                             | 1.77                             |
| 1 5/8   |           | 1.6250                | 1.5844                  | 1.5505                                   | 1.5573                            | 0                                  | 43   | 1.87                             | 1.92                             |
|         | 111/16    | 1.6875                | 1.6469                  | 1.6130                                   | 1.6198                            | 0                                  | 42   | 2.03                             | 2.08                             |
| 1 3/4   |           | 1.7500                | 1.7094                  | 1.6755                                   | 1.6823                            | 0                                  | 40   | 2.19                             | 2.24                             |
|         | 113/16    | 1.8125                | 1.7719                  | 1.7380                                   | 1.7448                            | 0                                  | 39   | 2.35                             | 2.41                             |
| 1 7/8   |           | 1.8750                | 1.8344                  | 1.8005                                   | 1.8073                            | 0                                  | 37   | 2.53                             | 2.58                             |
|         | 115/16    | 1.9375                | 1.8969                  | 1.8630                                   | 1.8698                            | 0                                  | 36   | 2.71                             | 2.77                             |
| 2       |           | 2.0000                | 1.9594                  | 1.9255                                   | 1.9323                            | 0                                  | 35   | 2.89                             | 2.95                             |
|         | 21/8      | 2.1250                | 2.0844                  | 2.0505                                   | 2.0573                            | 0                                  | 33   | 3.28                             | 3.35                             |
| 2 1/4   |           | 2.2500                | 2.2094                  | 2.1755                                   | 2.1823                            | 0                                  | 31   | 3.69                             | 3.76                             |
|         | 23/8      | 2.3750                | 2.3344                  | 2.3005                                   | 2.3073                            | 0                                  | 29   | 4.13                             | 4.21                             |
| 2 1/2   |           | 2.5000                | 2.4594                  | 2.4255                                   | 2.4323                            | 0                                  | 28   | 4.60                             | 4.67                             |
|         | 25/8      | 2.6250                | 2.5844                  | 2.5505                                   | 2.5573                            | 0                                  | 26   | 5.08                             | 5.16                             |
| 2 3/4   |           | 2.7500                | 2.7094                  | 2.6755                                   | 2.6823                            | 0                                  | 25   | 5.59                             | 5.68                             |
|         | 27/8      | 2.8750                | 2.8344                  | 2.8005                                   | 2.8073                            | 0                                  | 24   | 6.13                             | 6.22                             |
| 3       |           | 3.0000                | 2.9594                  | 2.9255                                   | 2.9323                            | 0                                  | 23   | 6.69                             | 6.78                             |
|         | 31/8      | 3.1250                | 3.0844                  | 3.0505                                   | 3.0573                            | 0                                  | 22   | 7.28                             | 7.37                             |
| 3 1/4   |           | 3.2500                | 3.2094                  | 3.1755                                   | 3.1823                            | 0                                  | 21   | 7.89                             | 7.99                             |
|         | 33/8      | 3.3750                | 3.3344                  | 3.3005                                   | 3.3073                            | 0                                  | 21   | 8.52                             | 8.63                             |
| 3 1/2   |           | 3.5000                | 3.4594                  | 3.4255                                   | 3.4323                            | 0                                  | 20   | 9.18                             | 9.29                             |
|         | 35/8      | 3.6250                | 3.5844                  | 3.5505                                   | 3.5573                            | 0                                  | 19   | 9.86                             | 9.98                             |
| 3 3/4   |           | 3.7500                | 3.7094                  | 3.6755                                   | 3.6823                            | 0                                  | 18   | 10.57                            | 10.69                            |
|         | 37/8      | 3.8750                | 3.8344                  | 3.8005                                   | 3.8073                            | 0                                  | 18   | 11.30                            | 11.43                            |
| 4       |           | 4.0000                | 3.9594                  | 3.9255                                   | 3.9323                            | 0                                  | 17   | 12.06                            | 12.19                            |
|         | 41/8      | 4.1250                | 4.0844                  | 4.0505                                   | 4.0573                            | 0                                  | 17   | 12.84                            | 12.97                            |
| 4 1/4   |           | 4.2500                | 4.2094                  | 4.1755                                   | 4.1823                            | 0                                  | 16   | 13.65                            | 13.78                            |
|         | 43/8      | 4.3750                | 4.3344                  | 4.3005                                   | 4.3073                            | 0                                  | 16   | 14.48                            | 14.62                            |
| 4 1/2   |           | 4.5000                | 4.4594                  | 4.4255                                   | 4.4323                            | 0                                  | 15   | 15.34                            | 15.5                             |
|         | 45/8      | 4.6250                | 4.5844                  | 4.5505                                   | 4.5573                            | 0                                  | 15   | 16.2                             | 16.4                             |
| 4 3/4   |           | 4.7500                | 4.7094                  | 4.6755                                   | 4.6823                            | 0                                  | 15   | 17.1                             | 17.3                             |
|         | 47/8      | 4.8750                | 4.8344                  | 4.8005                                   | 4.8073                            | 0                                  | 14   | 18.0                             | 18.2                             |
| 5       |           | 5.0000                | 4.9594                  | 4.9255                                   | 4.9323                            | 0                                  | 14   | 19.0                             | 19.2                             |
|         | 51/8      | 5.1250                | 5.0844                  | 5.0505                                   | 5.0573                            | 0                                  | 13   | 20.0                             | 20.1                             |
| 5 1/4   |           | 5.2500                | 5.2094                  | 5.1755                                   | 5.1823                            | 0                                  | 13   | 21.0                             | 21.1                             |
|         | 53/8      | 5.3750                | 5.3344                  | 5.3005                                   | 5.3073                            | 0                                  | 13   | 22.0                             | 22.2                             |

**Table 5e. (Continued) 16-Thread Series, 16-UN and 16-UNR—Basic Dimensions**

| Sizes   |           | Basic Major Dia., $D$ | Basic Pitch Dia., $^a D_2$ | Minor Diameter                           |                                   | Lead Angle $\lambda$ at Basic P.D. |      | Area of Minor Dia. at $D - 2h_b$ | Tensile Stress Area <sup>b</sup> |
|---------|-----------|-----------------------|----------------------------|--|-----------------------------------|------------------------------------|------|----------------------------------|----------------------------------|
| Primary | Secondary |                       |                            | Ext. Thds., <sup>c</sup><br>$d_3$ (Ref.) | Int. Thds., <sup>d</sup><br>$D_1$ | Deg.                               | Min. |                                  |                                  |
| Inches  | Inches    | Inches                | Inches                     | Inches                                   | Inches                            | Deg.                               | Min. | Sq. In.                          | Sq. In.                          |
| 5½      | 5⅝        | 5.5000                | 5.4594                     | 5.4255                                   | 5.4323                            | 0                                  | 13   | 23.1                             | 23.2                             |
|         |           | 5.6250                | 5.5844                     | 5.5505                                   | 5.5573                            | 0                                  | 12   | 24.1                             | 24.3                             |
| 5¾      | 5⅞        | 5.7500                | 5.7094                     | 5.6755                                   | 5.6823                            | 0                                  | 12   | 25.2                             | 25.4                             |
|         |           | 5.8750                | 5.8344                     | 5.8005                                   | 5.8073                            | 0                                  | 12   | 26.4                             | 26.5                             |
| 6       |           | 6.0000                | 5.9594                     | 5.9255                                   | 5.9323                            | 0                                  | 11   | 27.5                             | 27.7                             |

<sup>a</sup> British: Effective Diameter.

<sup>b</sup> See formula, pages 1502 and 1510.

<sup>c</sup> Design form for UNR threads. (See figure on page 1733.)

<sup>d</sup> Basic minor diameter.

<sup>e</sup> These are standard sizes of the UNC or UNF Series.

**Table 5f. 20-Thread Series, 20-UN and 20-UNR—Basic Dimensions**

| Sizes          |           | Basic Major Dia., $D$ | Basic Pitch Dia., $^a D_2$ | Minor Diameter                           |                                   | Lead Angle $\lambda$ at Basic P.D. |      | Area of Minor Dia. at $D - 2h_b$ | Tensile Stress Area <sup>b</sup> |
|----------------|-----------|-----------------------|----------------------------|--|-----------------------------------|------------------------------------|------|----------------------------------|----------------------------------|
| Primary        | Secondary |                       |                            | Ext. Thds., <sup>c</sup><br>$d_3$ (Ref.) | Int. Thds., <sup>d</sup><br>$D_1$ | Deg.                               | Min. |                                  |                                  |
| Inches         | Inches    | Inches                | Inches                     | Inches                                   | Inches                            | Deg.                               | Min. | Sq. In.                          | Sq. In.                          |
| ¼ <sup>e</sup> | ⅝         | 0.2500                | 0.2175                     | 0.1905                                   | 0.1959                            | 4                                  | 11   | 0.0269                           | 0.0318                           |
|                |           | 0.3125                | 0.2800                     | 0.2530                                   | 0.2584                            | 3                                  | 15   | 0.0481                           | 0.0547                           |
| ⅜              | ⅞         | 0.3750                | 0.3425                     | 0.3155                                   | 0.3209                            | 2                                  | 40   | 0.0755                           | 0.0836                           |
|                |           | 0.4375                | 0.4050                     | 0.3780                                   | 0.3834                            | 2                                  | 15   | 0.1090                           | 0.1187                           |
| ½ <sup>e</sup> | 1⅞        | 0.5000                | 0.4675                     | 0.4405                                   | 0.4459                            | 1                                  | 57   | 0.1486                           | 0.160                            |
|                |           | 0.5625                | 0.5300                     | 0.5030                                   | 0.5084                            | 1                                  | 43   | 0.194                            | 0.207                            |
| ¾              | 2⅞        | 0.6250                | 0.5925                     | 0.5655                                   | 0.5709                            | 1                                  | 32   | 0.246                            | 0.261                            |
|                |           | 0.6875                | 0.6550                     | 0.6280                                   | 0.6334                            | 1                                  | 24   | 0.304                            | 0.320                            |
| ¾              | 3⅞        | 0.7500                | 0.7175                     | 0.6905                                   | 0.6959                            | 1                                  | 16   | 0.369                            | 0.386                            |
|                |           | 0.8125                | 0.7800                     | 0.7530                                   | 0.7584                            | 1                                  | 10   | 0.439                            | 0.458                            |
| 7⁄8            | 4⅞        | 0.8750                | 0.8425                     | 0.8155                                   | 0.8209                            | 1                                  | 5    | 0.515                            | 0.536                            |
|                |           | 0.9375                | 0.9050                     | 0.8780                                   | 0.8834                            | 1                                  | 0    | 0.0.598                          | 0.620                            |
| 1 <sup>e</sup> | 5⅞        | 1.0000                | 0.9675                     | 0.9405                                   | 0.9459                            | 0                                  | 57   | 0.687                            | 0.711                            |
|                |           | 1.0625                | 1.0300                     | 1.0030                                   | 1.0084                            | 0                                  | 53   | 0.782                            | 0.807                            |
| 1⅛             | 6⅞        | 1.1250                | 1.0925                     | 1.0655                                   | 1.0709                            | 0                                  | 50   | 0.882                            | 0.910                            |
|                |           | 1.1875                | 1.1550                     | 1.1280                                   | 1.1334                            | 0                                  | 47   | 0.990                            | 1.018                            |
| 1¼             | 7⅞        | 1.2500                | 1.2175                     | 1.1905                                   | 1.1959                            | 0                                  | 45   | 1.103                            | 1.133                            |
|                |           | 1.3125                | 1.2800                     | 1.2530                                   | 1.2584                            | 0                                  | 43   | 1.222                            | 1.254                            |
| 1⅜             | 8⅞        | 1.3750                | 1.3425                     | 1.3155                                   | 1.3209                            | 0                                  | 41   | 1.348                            | 1.382                            |
|                |           | 1.4375                | 1.4050                     | 1.3780                                   | 1.3834                            | 0                                  | 39   | 1.479                            | 1.51                             |
| 1½             | 9⅞        | 1.5000                | 1.4675                     | 1.4405                                   | 1.4459                            | 0                                  | 37   | 1.62                             | 1.65                             |
|                |           | 1.5625                | 1.5300                     | 1.5030                                   | 1.5084                            | 0                                  | 36   | 1.76                             | 1.80                             |
| 1⅝             | 10⅞       | 1.6250                | 1.5925                     | 1.5655                                   | 1.5709                            | 0                                  | 34   | 1.91                             | 1.95                             |
|                |           | 1.6875                | 1.6550                     | 1.6280                                   | 1.6334                            | 0                                  | 33   | 2.07                             | 2.11                             |
| 1¾             | 11⅞       | 1.7500                | 1.7175                     | 1.6905                                   | 1.6959                            | 0                                  | 32   | 2.23                             | 2.27                             |
|                |           | 1.8125                | 1.7800                     | 1.7530                                   | 1.7584                            | 0                                  | 31   | 2.40                             | 2.44                             |
| 1⅞             | 12⅞       | 1.8750                | 1.8425                     | 1.8155                                   | 1.8209                            | 0                                  | 30   | 2.57                             | 2.62                             |
|                |           | 1.9375                | 1.9050                     | 1.8780                                   | 1.8834                            | 0                                  | 29   | 2.75                             | 2.80                             |
| 2              | 13⅞       | 2.0000                | 1.9675                     | 1.9405                                   | 1.9459                            | 0                                  | 28   | 2.94                             | 2.99                             |
|                |           | 2.1250                | 2.0925                     | 2.0655                                   | 2.0709                            | 0                                  | 26   | 3.33                             | 3.39                             |
| 2¼             | 14⅞       | 2.2500                | 2.2175                     | 2.1905                                   | 2.1959                            | 0                                  | 25   | 3.75                             | 3.81                             |
|                |           | 2.3750                | 2.3425                     | 2.3155                                   | 2.3209                            | 0                                  | 23   | 4.19                             | 4.25                             |
| 2½             | 15⅞       | 2.5000                | 2.4675                     | 2.4405                                   | 2.4459                            | 0                                  | 22   | 4.66                             | 4.72                             |
|                |           | 2.6250                | 2.5925                     | 2.5655                                   | 2.5709                            | 0                                  | 21   | 5.15                             | 5.21                             |
| 2¾             | 16⅞       | 2.7500                | 2.7175                     | 2.6905                                   | 2.6959                            | 0                                  | 20   | 5.66                             | 5.73                             |
|                |           | 2.8750                | 2.8425                     | 2.8155                                   | 2.8209                            | 0                                  | 19   | 6.20                             | 6.27                             |
| 3              |           | 3.0000                | 2.9675                     | 2.9405                                   | 2.9459                            | 0                                  | 18   | 6.77                             | 6.84                             |

<sup>a</sup> British: Effective Diameter.

<sup>b</sup> See formula, pages 1502 and 1510.

<sup>c</sup> Design form for UNR threads. (See figure on page 1733.)

<sup>d</sup> Basic minor diameter.

<sup>e</sup> These are standard sizes of the UNC, UNF, or UNEF Series.



UNIFIED SCREW THREADS

**Table 5g. 28-Thread Series, 28-UN and 28-UNR — Basic Dimensions**

| Sizes             |                               | Basic Major Dia.,<br>D | Basic Pitch Dia., <sup>a</sup><br>D <sub>2</sub> | Minor Diameter                                    |  | Lead Angel λ at Basic P.D. |           | Area of Minor Dia. at D-2h <sub>b</sub> | Tensile Stress Area <sup>b</sup> |
|-------------------|-------------------------------|------------------------|--|---|--|----------------------------|-----------|---|----------------------------------|
| Primary           | Secondary                     |                        |  | Ext. Thds., <sup>c</sup><br>d <sub>3</sub> (Ref.) | Int. Thds., <sup>d</sup><br>D <sub>1</sub> | Deg.                       | Min.      |   |                                  |
| Inches            | Inches                        | Inches                 | Inches   | Inches  | Inches                                     | Deg.                       | Min.      | Sq. In.                                 | Sq. In.                          |
|                   | <b>12 (0.216)<sup>e</sup></b> | <b>0.2160</b>          | <b>0.1928</b>                                    | <b>0.1734</b>                                     | <b>0.1773</b>                              | <b>3</b>                   | <b>22</b> | 0.0226                                  | 0.0258                           |
| 1/4               |                               | <b>0.2500</b>          | <b>0.2268</b>                                    | <b>0.2074</b>                                     | <b>0.2113</b>                              | <b>2</b>                   | <b>52</b> | 0.0326                                  | 0.0364                           |
| 5/16              |                               | <b>0.3125</b>          | <b>0.2893</b>                                    | <b>0.2699</b>                                     | <b>0.2738</b>                              | <b>2</b>                   | <b>15</b> | 0.0556                                  | 0.0606                           |
| 3/8               |                               | <b>0.3750</b>          | <b>0.3518</b>                                    | <b>0.3324</b>                                     | <b>0.3363</b>                              | <b>1</b>                   | <b>51</b> | 0.0848                                  | 0.0909                           |
| 7/16 <sup>e</sup> |                               | <b>0.4375</b>          | <b>0.4143</b>                                    | <b>0.3949</b>                                     | <b>0.3988</b>                              | <b>1</b>                   | <b>34</b> | 0.1201                                  | 0.1274                           |
| 1/2               |                               | <b>0.5000</b>          | <b>0.4768</b>                                    | <b>0.4574</b>                                     | <b>0.4613</b>                              | <b>1</b>                   | <b>22</b> | 0.162                                   | 0.170                            |
| 9/16              |                               | <b>0.5625</b>          | <b>0.5393</b>                                    | <b>0.5199</b>                                     | <b>0.5238</b>                              | <b>1</b>                   | <b>12</b> | 0.209                                   | 0.219                            |
| 5/8               |                               | <b>0.6250</b>          | <b>0.6018</b>                                    | <b>0.5824</b>                                     | <b>0.5863</b>                              | <b>1</b>                   | <b>5</b>  | 0.263                                   | 0.274                            |
|                   | 11/16                         | <b>0.6875</b>          | <b>0.6643</b>                                    | <b>0.6449</b>                                     | <b>0.6488</b>                              | <b>0</b>                   | <b>59</b> | 0.323                                   | 0.335                            |
| 3/4               |                               | <b>0.7500</b>          | <b>0.7268</b>                                    | <b>0.7074</b>                                     | <b>0.7113</b>                              | <b>0</b>                   | <b>54</b> | 0.389                                   | 0.402                            |
|                   | 13/16                         | <b>0.8125</b>          | <b>0.7893</b>                                    | <b>0.7699</b>                                     | <b>0.7738</b>                              | <b>0</b>                   | <b>50</b> | 0.461                                   | 0.475                            |
| 7/8               |                               | <b>0.8750</b>          | <b>0.8518</b>                                    | <b>0.8324</b>                                     | <b>0.8363</b>                              | <b>0</b>                   | <b>46</b> | 0.539                                   | 0.554                            |
|                   | 15/16                         | <b>0.9375</b>          | <b>0.9143</b>                                    | <b>0.8949</b>                                     | <b>0.8988</b>                              | <b>0</b>                   | <b>43</b> | 0.624                                   | 0.640                            |
| <b>1</b>          |                               | <b>1.0000</b>          | <b>0.9768</b>                                    | <b>0.9574</b>                                     | <b>0.9613</b>                              | <b>0</b>                   | <b>40</b> | 0.714                                   | 0.732                            |
|                   | 1 1/16                        | <b>1.0625</b>          | <b>1.0393</b>                                    | <b>1.0199</b>                                     | <b>1.0238</b>                              | <b>0</b>                   | <b>38</b> | 0.811                                   | 0.830                            |
| 1 1/8             |                               | <b>1.1250</b>          | <b>1.1018</b>                                    | <b>1.0824</b>                                     | <b>1.0863</b>                              | <b>0</b>                   | <b>35</b> | 0.914                                   | 0.933                            |
|                   | 1 3/16                        | <b>1.1875</b>          | <b>1.1643</b>                                    | <b>1.1449</b>                                     | <b>1.1488</b>                              | <b>0</b>                   | <b>34</b> | 1.023                                   | 1.044                            |
| 1 1/4             |                               | <b>1.2500</b>          | <b>1.2268</b>                                    | <b>1.2074</b>                                     | <b>1.2113</b>                              | <b>0</b>                   | <b>32</b> | 1.138                                   | 1.160                            |
|                   | 1 5/16                        | <b>1.3125</b>          | <b>1.2893</b>                                    | <b>1.2699</b>                                     | <b>1.2738</b>                              | <b>0</b>                   | <b>30</b> | 1.259                                   | 1.282                            |
| 1 3/8             |                               | <b>1.3750</b>          | <b>1.3518</b>                                    | <b>1.3324</b>                                     | <b>1.3363</b>                              | <b>0</b>                   | <b>29</b> | 1.386                                   | 1.411                            |
|                   | 1 7/16                        | <b>1.4375</b>          | <b>1.4143</b>                                    | <b>1.3949</b>                                     | <b>1.3988</b>                              | <b>0</b>                   | <b>28</b> | 1.52                                    | 1.55                             |
| 1 1/2             |                               | <b>1.5000</b>          | <b>1.4768</b>                                    | <b>1.4574</b>                                     | <b>1.4613</b>                              | <b>0</b>                   | <b>26</b> | 1.66                                    | 1.69                             |

- <sup>a</sup> British: Effective Diameter.
- <sup>b</sup> See formula, pages 1502 and 1510.
- <sup>c</sup> Design form for UNR threads. (See figure on page 1733.)
- <sup>d</sup> Basic minor diameter.
- <sup>e</sup> These are standard sizes of the UNF or UNEF Series.

**Table 5h. 32-Thread Series, 32-UN and 32-UNR — Basic Dimensions**

| Sizes                         |                               | Basic Major Dia.,<br>D | Basic Pitch Dia., <sup>a</sup><br>D <sub>2</sub> | Minor Diameter                                    |  | Lead Angel λ at Basic P.D. |           | Area of Minor Dia. at D-2h <sub>b</sub> | Tensile Stress Area <sup>b</sup> |
|-------------------------------|-------------------------------|------------------------|--|---|--|----------------------------|-----------|---|----------------------------------|
| Primary                       | Secondary                     |                        |  | Ext. Thds., <sup>c</sup><br>d <sub>3</sub> (Ref.) | Int. Thds., <sup>d</sup><br>D <sub>1</sub> | Deg.                       | Min.      |   |                                  |
| Inches                        | Inches                        | Inches                 | Inches   | Inches  | Inches                                     | Deg.                       | Min.      | Sq. In.                                 | Sq. In.                          |
| <b>6 (0.138)<sup>e</sup></b>  |                               | <b>0.1380</b>          | <b>0.1177</b>                                    | <b>0.1008</b>                                     | <b>0.1042</b>                              | <b>4</b>                   | <b>50</b> | 0.00745                                 | 0.00909                          |
| <b>8 (0.164)<sup>e</sup></b>  |                               | <b>0.1640</b>          | <b>0.1437</b>                                    | <b>0.1268</b>                                     | <b>0.1302</b>                              | <b>3</b>                   | <b>58</b> | 0.01196                                 | 0.0140                           |
| <b>10 (0.190)<sup>e</sup></b> |                               | <b>0.1900</b>          | <b>0.1697</b>                                    | <b>0.1528</b>                                     | <b>0.1562</b>                              | <b>3</b>                   | <b>21</b> | 0.01750                                 | 0.0200                           |
|                               | <b>12 (0.216)<sup>e</sup></b> | <b>0.2160</b>          | <b>0.1957</b>                                    | <b>0.1788</b>                                     | <b>0.1822</b>                              | <b>2</b>                   | <b>55</b> | 0.0242                                  | 0.0270                           |
| 1/4                           |                               | <b>0.2500</b>          | <b>0.2297</b>                                    | <b>0.2128</b>                                     | <b>0.2162</b>                              | <b>2</b>                   | <b>29</b> | 0.0344                                  | 0.0379                           |
| 5/16                          |                               | <b>0.3125</b>          | <b>0.2922</b>                                    | <b>0.2753</b>                                     | <b>0.2787</b>                              | <b>1</b>                   | <b>57</b> | 0.0581                                  | 0.0625                           |
| 3/8                           |                               | <b>0.3750</b>          | <b>0.3547</b>                                    | <b>0.3378</b>                                     | <b>0.3412</b>                              | <b>1</b>                   | <b>36</b> | 0.0878                                  | 0.0932                           |
| 7/16                          |                               | <b>0.4375</b>          | <b>0.4172</b>                                    | <b>0.4003</b>                                     | <b>0.4037</b>                              | <b>1</b>                   | <b>22</b> | 0.1237                                  | 0.1301                           |
| 1/2                           |                               | <b>0.5000</b>          | <b>0.4797</b>                                    | <b>0.4628</b>                                     | <b>0.4662</b>                              | <b>1</b>                   | <b>11</b> | 0.166                                   | 0.173                            |
| 9/16                          |                               | <b>0.5625</b>          | <b>0.5422</b>                                    | <b>0.5253</b>                                     | <b>0.5287</b>                              | <b>1</b>                   | <b>3</b>  | 0.214                                   | 0.222                            |
| 5/8                           |                               | <b>0.6250</b>          | <b>0.6047</b>                                    | <b>0.5878</b>                                     | <b>0.5912</b>                              | <b>0</b>                   | <b>57</b> | 0.268                                   | 0.278                            |
|                               | 11/16                         | <b>0.6875</b>          | <b>0.6672</b>                                    | <b>0.6503</b>                                     | <b>0.6537</b>                              | <b>0</b>                   | <b>51</b> | 0.329                                   | 0.339                            |
| 3/4                           |                               | <b>0.7500</b>          | <b>0.7297</b>                                    | <b>0.7128</b>                                     | <b>0.7162</b>                              | <b>0</b>                   | <b>47</b> | 0.395                                   | 0.407                            |
|                               | 13/16                         | <b>0.8125</b>          | <b>0.7922</b>                                    | <b>0.7753</b>                                     | <b>0.7787</b>                              | <b>0</b>                   | <b>43</b> | 0.468                                   | 0.480                            |
| 7/8                           |                               | <b>0.8750</b>          | <b>0.8547</b>                                    | <b>0.8378</b>                                     | <b>0.8412</b>                              | <b>0</b>                   | <b>40</b> | 0.547                                   | 0.560                            |
|                               | 15/16                         | <b>0.9375</b>          | <b>0.9172</b>                                    | <b>0.9003</b>                                     | <b>0.9037</b>                              | <b>0</b>                   | <b>37</b> | 0.632                                   | 0.646                            |
| <b>1</b>                      |                               | <b>1.0000</b>          | <b>0.9797</b>                                    | <b>0.9628</b>                                     | <b>0.9662</b>                              | <b>0</b>                   | <b>35</b> | 0.723                                   | 0.738                            |

- <sup>a</sup> British: Effective Diameter.
- <sup>b</sup> See formula, pages 1502 and 1510.
- <sup>c</sup> Design form for UNR threads. (See figure on page 1733.)
- <sup>d</sup> Basic minor diameter.
- <sup>e</sup> These are standard sizes of the UNC, UNF, or UNEF Series.

**Thread Classes.**—Thread classes are distinguished from each other by the amounts of tolerance and allowance. Classes identified by a numeral followed by the letters A and B are derived from certain Unified formulas (not shown here) in which the pitch diameter tolerances are based on increments of the basic major (nominal) diameter, the pitch, and the length of engagement. These formulas and the class identification or symbols apply to all of the Unified threads.

Classes 1A, 2A, and 3A apply to external threads only, and Classes 1B, 2B, and 3B apply to internal threads only. The disposition of the tolerances, allowances, and crest clearances for the various classes is illustrated on pages 1774 and 1774.

*Classes 2A and 2B:* Classes 2A and 2B are the most commonly used for general applications, including production of bolts, screws, nuts, and similar fasteners.

The maximum diameters of Class 2A (external) uncoated threads are less than basic by the amount of the allowance. The allowance minimizes galling and seizing in high-cycle wrench assembly, or it can be used to accommodate plated finishes or other coating. However, for threads with additive finish, the maximum diameters of Class 2A may be exceeded by the amount of the allowance, for example, the 2A maximum diameters apply to an unplated part or to a part before plating whereas the basic diameters (the 2A maximum diameter plus allowance) apply to a part after plating. The minimum diameters of Class 2B (internal) threads, whether or not plated or coated, are basic, affording no allowance or clearance in assembly at maximum metal limits.

*Class 2AG:* Certain applications require an allowance for rapid assembly to permit application of the proper lubricant or for residual growth due to high-temperature expansion. In these applications, when the thread is coated and the 2A allowance is not permitted to be consumed by such coating, the thread class symbol is qualified by G following the class symbol.

*Classes 3A and 3B:* Classes 3A and 3B may be used if closer tolerances are desired than those provided by Classes 2A and 2B. The maximum diameters of Class 3A (external) threads and the minimum diameters of Class 3B (internal) threads, whether or not plated or coated, are basic, affording no allowance or clearance for assembly of maximum metal components.

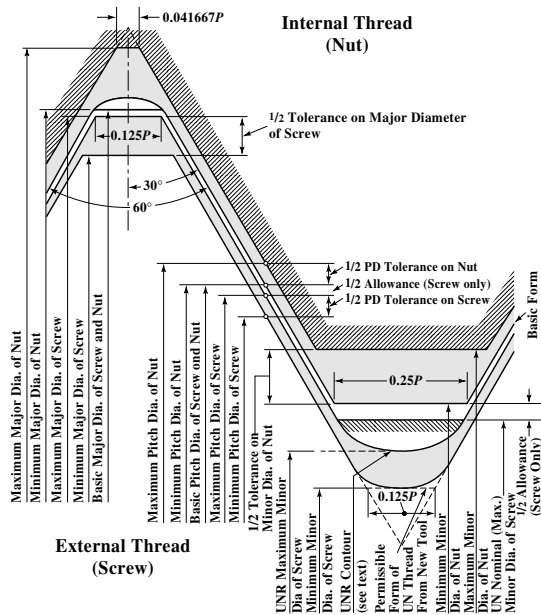
*Classes 1A and 1B:* Classes 1A and 1B threads replaced American National Class 1. These classes are intended for ordnance and other special uses. They are used on threaded components where quick and easy assembly is necessary and where a liberal allowance is required to permit ready assembly, even with slightly bruised or dirty threads.

Maximum diameters of Class 1A (external) threads are less than basic by the amount of the same allowance as applied to Class 2A. For the intended applications in American practice the allowance is not available for plating or coating. Where the thread is plated or coated, special provisions are necessary. The minimum diameters of Class 1B (internal) threads, whether or not plated or coated, are basic, affording no allowance or clearance for assembly with maximum metal external thread components having maximum diameters which are basic.

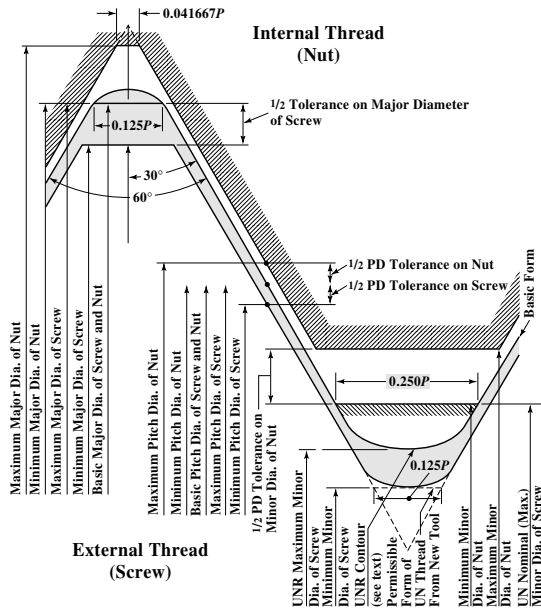
**Coated 60-deg. Threads.**—Although the Standard does not make recommendations for thicknesses of, or specify limits for coatings, it does outline certain principles that will aid mechanical interchangeability if followed whenever conditions permit.

To keep finished threads within the limits of size established in the Standard, external threads should not exceed basic size after plating and internal threads should not be below basic size after plating. This recommendation does not apply to threads coated by certain commonly used processes such as hot-dip galvanizing where it may not be required to maintain these limits.

Class 2A provides both a tolerance and an allowance. Many thread requirements call for coatings such as those deposited by electro-plating processes and, in general, the 2A allow-



Limits of Size Showing Tolerances, Allowances (Neutral Space), and Crest Clearances for Unified Classes 1A, 2A, 1B, and 2B



Limits of Size Showing Tolerances and Crest Clearances for Unified Classes 3A and 3B and American National Classes 2 and 3

ance provides adequate undercut for such coatings. There may be variations in thickness and symmetry of coating resulting from commercial processes but after plating the threads should be accepted by a basic Class 3A size GO gage and a Class 2A gage as a NOT-GO gage. Class 1A provides an allowance which is maintained for both coated and uncoated product, i.e., it is not available for coating.

Class 3A does not include an allowance so it is suggested that the limits of size before plating be reduced by the amount of the 2A allowance whenever that allowance is adequate.

No provision is made for overcutting internal threads as coatings on such threads are not generally required. Further, it is very difficult to deposit a significant thickness of coating on the flanks of internal threads. Where a specific thickness of coating is required on an internal thread, it is suggested that the thread be overcut so that the thread as coated will be accepted by a GO thread plug gage of basic size.

This Standard ASME/ANSI B1.1-1989 (R2001) specifies limits of size that pertain whether threads are coated or uncoated. Only in Class 2A threads is an allowance available to accommodate coatings. Thus, in all classes of internal threads and in all Class 1A, 2AG, and 3A external threads, limits of size must be adjusted to provide suitable provision for the desired coating.

For further information concerning dimensional accommodation of coating or plating for 60-degree threads, see Section 7, ASME/ANSI B1.1-1989 (R2001).

**Screw Thread Selection — Combination of Classes.**—Whenever possible, selection should be made from [Table 2](#), Standard Series Unified Screw Threads, preference being given to the Coarse- and Fine- thread Series. If threads in the standard series do not meet the requirements of design, reference should be made to the selected combinations in [Table 3](#). The third expedient is to compute the limits of size from the tolerance tables or tolerance increment tables given in the Standard. The fourth and last resort is calculation by the formulas given in the Standard.

The requirements for screw thread fits for specific applications depend on end use and can be met by specifying the proper combinations of thread classes for the components. For example, a Class 2A external thread may be used with a Class 1B, 2B, or 3B internal thread.

**Pitch Diameter Tolerances, All Classes.**—The pitch diameter tolerances in [Table 3](#) for all classes of the UNC, UNF, 4-UN, 6-UN, and 8-UN series are based on a length of engagement equal to the basic major (nominal) diameter and are applicable for lengths of engagement up to  $1\frac{1}{2}$  diameters.

The pitch diameter tolerances used in [Table 3](#) for all classes of the UNEF, 12-UN, 16-UN, 20-UN, 28-UN, and 32-UN series and the UNS series, are based on a length of engagement of 9 pitches and are applicable for lengths of engagement of from 5 to 15 pitches.

**Screw Thread Designation.**—The basic method of designating a screw thread is used where the standard tolerances or limits of size based on the standard length of engagement are applicable. The designation specifies in sequence the nominal size, number of threads per inch, thread series symbol, thread class symbol, and the gaging system number per ASME/ANSI B1.3M. The nominal size is the basic major diameter and is specified as the fractional diameter, screw number, or their decimal equivalent. Where decimal equivalents are used for size callout, they shall be interpreted as being nominal size designations only and shall have no dimensional significance beyond the fractional size or number designation. The symbol LH is placed after the thread class symbol to indicate a left-hand thread:

*Examples:*

$\frac{1}{4}$ -20 UNC-2A (21) or 0.250-20 UNC-2A (21)

10–32 UNF-2A (22) or 0.190–32 UNF-2A (22)

$\frac{7}{16}$ –20 UNRF-2A (23) or 0.4375–20 UNRF-2A (23)

2–12 UN-2A (21) or 2.000–12 UN-2A (21)

$\frac{1}{4}$ –20 UNC-3A-LH (21) or 0.250–20 UNC-3A-LH (21)

For uncoated standard series threads these designations may optionally be supplemented by the addition of the pitch diameter limits of size.

*Example:*

$\frac{1}{4}$ –20 UNC-2A (21)

PD 0.2164–0.2127 (Optional for uncoated threads)

**Designating Coated Threads.**—For coated (or plated) Class 2A external threads, the basic (max) major and basic (max) pitch diameters are given followed by the words AFTER COATING. The major and pitch diameter limits of size before coating are also given followed by the words BEFORE COATING.

*Example:*

$\frac{3}{4}$ –10 UNC-2A (21)

<sup>a</sup>Major dia 0.7500 max  
PD 0.6850 max

} AFTER COATING

<sup>b</sup>Major dia 0.7482–0.7353  
PD 0.6832–0.6773

} BEFORE COATING

<sup>a</sup> Major and PD values are equal to basic and correspond to those in Table 3 for Class 3A.

<sup>b</sup> Major and PD limits are those in Table 3 for Class 2A.

Certain applications require an allowance for rapid assembly, to permit application of a proper lubricant, or for residual growth due to high-temperature expansion. In such applications where the thread is to be coated and the 2A allowance is not permitted to be consumed by such coating, the thread class symbol is qualified by the addition of the letter G (symbol for allowance) following the class symbol, and the maximum major and maximum pitch diameters are reduced below basic size by the amount of the 2A allowance and followed by the words AFTER COATING. This arrangement ensures that the allowance is maintained. The major and pitch diameter limits of size before coating are also given followed by SPL and BEFORE COATING. For information concerning the designating of this and other special coating conditions reference should be made to American National Standard ASME/ANSI B1.1-1989 (R2001).

**Designating UNS Threads.**—UNS screw threads that have special combinations of diameter and pitch with tolerance to Unified formulation have the basic form designation set out first followed always by the limits of size.

**Designating Multiple Start Threads.**—If a screw thread is of multiple start, it is designated by specifying in sequence the nominal size, pitch (in decimals or threads per inch) and lead (in decimals or fractions).

**Other Special Designations.**—For other special designations including threads with modified limits of size or with special lengths of engagement, reference should be made to American National Standard ASME/ANSI B1.1-1989 (R2001).

**Hole Sizes for Tapping.**—Hole size limits for tapping Classes 1B, 2B, and 3B threads of various lengths of engagement are given in Table 2 on page 1925.

**Internal Thread Minor Diameter Tolerances.**—Internal thread minor diameter tolerances in Table 3 are based on a length of engagement equal to the nominal diameter. For general applications these tolerances are suitable for lengths of engagement up to  $1\frac{1}{2}$  diameters. However, some thread applications have lengths of engagement which are greater than  $1\frac{1}{2}$  diameters or less than the nominal diameter. For such applications it may be advantageous to increase or decrease the tolerance, respectively, as explained in the Tapping Section.

### American Standard for Unified Miniature Screw Threads

This American Standard (B1.10-1958, R1988) introduces a new series to be known as Unified Miniature Screw Threads and intended for general purpose fastening screws and similar uses in watches, instruments, and miniature mechanisms. Use of this series is recommended on all new products in place of the many improvised and unsystematized sizes now in existence which have never achieved broad acceptance nor recognition by standardization bodies. The series covers a diameter range from 0.30 to 1.40 millimeters (0.0118 to 0.0551 inch) and thus supplements the Unified and American thread series which begins at 0.060 inch (number 0 of the machine screw series). It comprises a total of fourteen sizes which, together with their respective pitches, are those endorsed by the American-British-Canadian Conference of April 1955 as the basis for a Unified standard among the inch-using countries, and coincide with the corresponding range of sizes in ISO (International Organization for Standardization) Recommendation No. 68. Additionally, it utilizes thread forms which are compatible in all significant respects with both the Unified and ISO basic thread profiles. Thus, threads in this series are interchangeable with the corresponding sizes in both the American-British-Canadian and ISO standardization programs.

**Basic Form of Thread.**—The basic profile by which the design forms of the threads covered by this standard are governed is shown in Table 1. The thread angle is 60 degrees and except for basic height and depth of engagement which are  $0.52p$ , instead of  $0.54127p$ , the basic profile for this thread standard is identical with the Unified and American basic thread form. The selection of 0.52 as the exact value of the coefficient for the height of this basic form is based on practical manufacturing considerations and a plan evolved to simplify calculations and achieve more precise agreement between the metric and inch dimensional tables.

Products made to this standard will be interchangeable with products made to other standards which allow a maximum depth of engagement (or combined addendum height) of  $0.54127p$ . The resulting difference is negligible (only 0.00025 inch for the coarsest pitch) and is completely offset by practical considerations in tapping, since internal thread heights exceeding  $0.52p$  are avoided in these (Unified Miniature) small thread sizes in order to reduce excessive tap breakage.

**Design Forms of Threads.**—The design (maximum material) forms of the external and internal threads are shown in Table 2. These forms are derived from the basic profile shown in Table 1 by the application of clearances for the crests of the addenda at the roots of the mating dedendum forms. Basic and design form dimensions are given in Table 3.

**Nominal Sizes:** The thread sizes comprising this series and their respective pitches are shown in the first two columns of Table 5. The fourteen sizes shown in Table 5 have been systematically distributed to provide a uniformly proportioned selection over the entire range. They are separated alternately into two categories: The sizes shown in bold type are selections made in the interest of simplification and are those to which it is recommended that usage be confined wherever the circumstances of design permit. Where these sizes do not meet requirements the intermediate sizes shown in light type are available.

**Table 1. Unified Miniature Screw Threads — Basic Thread Form**

| Formulas for Basic Thread Form                      |           |            |  |
|---|-----------|------------|--|
| Metric units (millimeters) are used in all formulas |           |            |  |
| Thread Element                                      | Symbol    | Formula    |  |
| Angle of thread                                     | $2\alpha$ | 60°        |  |
| Half angle of thread                                | $\alpha$  | 30°        |  |
| Pitch of thread                                     | $p$       |            |  |
| No. of threads per inch                             | $n$       | $25.4/p$   |  |
| Height of sharp V thread                            | $H$       | $0.86603p$ |  |
| Addendum of basic thread                            | $h_{db}$  | $0.32476p$ |  |
| Height of basic thread                              | $h_b$     | $0.52p$    |  |

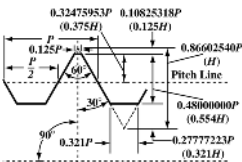


Table 2. Unified Miniature Screw Threads — Design Thread Form

Formulas for Design Thread Form (maximum material)<sup>a</sup>

| External Thread |          |                      | Internal Thread      |          |                      |
|-----------------|----------|----------------------|----------------------|----------|----------------------|
| Thread Element  | Symbol   | Formula              | Thread Element       | Symbol   | Formula              |
| Addendum        | $h_{as}$ | $0.32476p$           | Height of engagement | $h_e$    | $0.52p$              |
| Height          | $h_s$    | $0.60p$              | Height of thread     | $h_n$    | $0.556p$             |
| Flat at crest   | $F_{cs}$ | $0.125p$             | Flat at crest        | $F_{cn}$ | $0.27456p$           |
| Radius at root  | $r_{rs}$ | $0.158p$<br>(approx) | Radius at root       | $r_m$    | $0.072p$<br>(approx) |

<sup>a</sup> Metric units (millimeters) are used in all formulas.

**Table 3. Unified Miniature Screw Threads—Basic and Design Form Dimensions**

| Threads per inch<br>$n^a$    | Basic Thread Form |                                     |                         |  | External Thread Design Form |                                    |                                     | Internal Thread Design Form |                                      |                                     |
|------------------------------|-------------------|-------------------------------------|-------------------------|--|-----------------------------|------------------------------------|-------------------------------------|-----------------------------|--------------------------------------|-------------------------------------|
|                              | Pitch<br>$p$      | Height of Sharp V<br>$H = 0.86603p$ | Height<br>$h_b = 0.52p$ | Addendum<br>$h_{ub} = h_{bs} = 0.32476p$ | Height<br>$h_s = 0.60p$     | Flat at Crest<br>$F_{cs} = 0.125p$ | Radius at Root<br>$r_{rs} = 0.158p$ | Height<br>$h_b = 0.556p$    | Flat at Crest<br>$F_{cs} = 0.27456p$ | Radius at Root<br>$r_{rs} = 0.072p$ |
| <b>Millimeter Dimensions</b> |                   |                                     |                         |  |                             |                                    |                                     |                             |                                      |                                     |
| ...                          | .080              | .0693                               | .0416                   | .0260                                    | .048                        | .0100                              | .0126                               | .0445                       | .0220                                | .0058                               |
| ...                          | .090              | .0779                               | .0468                   | .0292                                    | .054                        | .0112                              | .0142                               | .0500                       | .0247                                | .0065                               |
| ...                          | .100              | .0866                               | .0520                   | .0325                                    | .060                        | .0125                              | .0158                               | .0556                       | .0275                                | .0072                               |
| ...                          | .125              | .1083                               | .0650                   | .0406                                    | .075                        | .0156                              | .0198                               | .0695                       | .0343                                | .0090                               |
| ...                          | .150              | .1299                               | .0780                   | .0487                                    | .090                        | .0188                              | .0237                               | .0834                       | .0412                                | .0108                               |
| ...                          | .175              | .1516                               | .0910                   | .0568                                    | .105                        | .0219                              | .0277                               | .0973                       | .0480                                | .0126                               |
| ...                          | .200              | .1732                               | .1040                   | .0650                                    | .120                        | .0250                              | .0316                               | .1112                       | .0549                                | .0144                               |
| ...                          | .225              | .1949                               | .1170                   | .0731                                    | .135                        | .0281                              | .0356                               | .1251                       | .0618                                | .0162                               |
| ...                          | .250              | .2165                               | .1300                   | .0812                                    | .150                        | .0312                              | .0395                               | .1390                       | .0686                                | .0180                               |
| ...                          | .300              | .2598                               | .1560                   | .0974                                    | .180                        | .0375                              | .0474                               | .1668                       | .0824                                | .0216                               |
| <b>Inch Dimensions</b>       |                   |                                     |                         |  |                             |                                    |                                     |                             |                                      |                                     |
| 317½                         | .003150           | .00273                              | .00164                  | .00102                                   | .00189                      | .00039                             | .00050                              | .00175                      | .00086                               | .00023                              |
| 282⅝                         | .003543           | .00307                              | .00184                  | .00115                                   | .00213                      | .00044                             | .00056                              | .00197                      | .00097                               | .00026                              |
| 254                          | .003937           | .00341                              | .00205                  | .00128                                   | .00236                      | .00049                             | .00062                              | .00219                      | .00108                               | .00028                              |
| 203⅓                         | .004921           | .00426                              | .00256                  | .00160                                   | .00295                      | .00062                             | .00078                              | .00274                      | .00135                               | .00035                              |
| 169⅓                         | .005906           | .00511                              | .00307                  | .00192                                   | .00354                      | .00074                             | .00093                              | .00328                      | .00162                               | .00043                              |
| 145⅓                         | .006890           | .00597                              | .00358                  | .00224                                   | .00413                      | .00086                             | .00109                              | .00383                      | .00189                               | .00050                              |
| 127                          | .007874           | .00682                              | .00409                  | .00256                                   | .00472                      | .00098                             | .00124                              | .00438                      | .00216                               | .00057                              |
| 112⅝                         | .008858           | .00767                              | .00461                  | .00288                                   | .00531                      | .00111                             | .00140                              | .00493                      | .00243                               | .00064                              |
| 101⅓                         | .009843           | .00852                              | .00512                  | .00320                                   | .00591                      | .00123                             | .00156                              | .00547                      | .00270                               | .00071                              |
| 84⅔                          | .011811           | .01023                              | .00614                  | .00384                                   | .00709                      | .00148                             | .00187                              | .00657                      | .00324                               | .00085                              |

<sup>a</sup>In Tables 5 and 6 these values are shown rounded to the nearest whole number.

**Table 4. Unified Miniature Screw Threads — Formulas for Basic and Design Dimensions and Tolerances**

| Formulas for Basic Dimensions  |  |
|--|--|
| D = Basic Major Diameter and Nominal Size in millimeters; $p$ = Pitch in millimeters; $E$ = Basic Pitch Diameter in millimeters = $D - 0.64952p$ ; and $K$ = Basic Minor Diameter in millimeters = $D - 1.04p$ |  |
| Formulas for Design Dimensions (Maximum Material)  |  |
| External Thread  | Internal Thread                                    |
| $D_s$ = Major Diameter = $D$   | $D_n$ = Major Diameter = $D + 0.072p$              |
| $E_s$ = Pitch Diameter = $E$   | $E_n$ = Pitch Diameter = $E$                       |
| $K_s$ = Minor Diameter = $D - 1.20p$   | $K_n$ = Minor Diameter = $K$                       |
| Formulas for Tolerances on Design Dimensions <sup>a</sup>  |  |
| External Thread (-)  | Internal Thread (+)                                |
| Major Diameter Tol., $0.12p + 0.006$   | <sup>b</sup> Major Diameter Tol., $0.168p + 0.008$ |
| Pitch Diameter Tol., $0.08p + 0.008$   | Pitch Diameter Tol., $0.08p + 0.008$               |
| <sup>c</sup> Minor Diameter Tol., $0.16p + 0.008$  | Minor Diameter Tol., $0.32p + 0.012$               |

<sup>a</sup>These tolerances are based on lengths of engagement of  $\frac{2}{3}D$  to  $1\frac{1}{2}D$ .

<sup>b</sup>This tolerance establishes the maximum limit of the major diameter of the internal thread. In practice, this limit is applied to the threading tool (tap) and not gaged on the product. Values for this tolerance are, therefore, not given in Table 5.

<sup>c</sup>This tolerance establishes the minimum limit of the minor diameter of the external thread. In practice, this limit is applied to the threading tool and only gaged on the product in confirming new tools. Values for this tolerance are, therefore, not given in Table 5.

Metric units (millimeters) apply in all formulas. Inch tolerances are not derived by direct conversion of the metric values. They are the differences between the rounded off limits of size in inch units.



Table 5. Unified Miniature Screw Threads — Limits of Size and Tolerances

| Size Designation <sup>a</sup> | External Threads |                        |               |                        |               |                        |                        |                        | Internal Threads |                        |               |                        | Lead Angle at Basic Pitch Diam. |          | Sectional Area at Minor Diam. at D — 1.28p |                  |
|-------------------------------|------------------|------------------------|---------------|------------------------|---------------|------------------------|------------------------|------------------------|------------------|------------------------|---------------|------------------------|---------------------------------|----------|--|------------------|
|                               | Major Diam.      |                        | Pitch Diam.   |                        | Minor Diam.   |                        | Minor Diam.            |                        | Pitch Diam.      |                        | Major Diam.   |                        |                                 |          |  |                  |
|                               | mm               | Max <sup>b</sup><br>mm | Min<br>mm     | Max <sup>b</sup><br>mm | Min<br>mm     | Max <sup>c</sup><br>mm | Min <sup>d</sup><br>mm | Min <sup>e</sup><br>mm | Max<br>mm        | Min <sup>b</sup><br>mm | Max<br>mm     | Min <sup>e</sup><br>mm | Max <sup>d</sup><br>mm          | deg      | min  | sq mm            |
| <b>0.30 UNM</b>               | <b>0.080</b>     | <b>0.300</b>           | <b>0.284</b>  | <b>0.248</b>           | <b>0.234</b>  | <b>0.204</b>           | <b>0.183</b>           | <b>0.217</b>           | <b>0.254</b>     | <b>0.248</b>           | <b>0.262</b>  | <b>0.306</b>           | <b>0.327</b>                    | <b>5</b> | <b>52</b>                                  | <b>0.0307</b>    |
| 0.35 UNM                      | 0.090            | 0.350                  | 0.333         | 0.292                  | 0.277         | 0.242                  | 0.220                  | 0.256                  | 0.297            | 0.292                  | 0.307         | 0.356                  | 0.380                           | 5        | 37   | 0.0433           |
| <b>0.40 UNM</b>               | <b>0.100</b>     | <b>0.400</b>           | <b>0.382</b>  | <b>0.335</b>           | <b>0.319</b>  | <b>0.280</b>           | <b>0.256</b>           | <b>0.296</b>           | <b>0.340</b>     | <b>0.335</b>           | <b>0.351</b>  | <b>0.407</b>           | <b>0.432</b>                    | <b>5</b> | <b>26</b>                                  | <b>0.0581</b>    |
| 0.45 UNM                      | 0.100            | 0.450                  | 0.432         | 0.385                  | 0.369         | 0.330                  | 0.306                  | 0.346                  | 0.390            | 0.385                  | 0.401         | 0.457                  | 0.482                           | 4        | 44   | 0.0814           |
| <b>0.50 UNM</b>               | <b>0.125</b>     | <b>0.500</b>           | <b>0.479</b>  | <b>0.419</b>           | <b>0.401</b>  | <b>0.350</b>           | <b>0.322</b>           | <b>0.370</b>           | <b>0.422</b>     | <b>0.419</b>           | <b>0.437</b>  | <b>0.509</b>           | <b>0.538</b>                    | <b>5</b> | <b>26</b>                                  | <b>0.0908</b>    |
| 0.55 UNM                      | 0.125            | 0.550                  | 0.529         | 0.469                  | 0.451         | 0.400                  | 0.372                  | 0.420                  | 0.472            | 0.469                  | 0.487         | 0.559                  | 0.588                           | 4        | 51   | 0.1195           |
| <b>0.60 UNM</b>               | <b>0.150</b>     | <b>0.600</b>           | <b>0.576</b>  | <b>0.503</b>           | <b>0.483</b>  | <b>0.420</b>           | <b>0.388</b>           | <b>0.444</b>           | <b>0.504</b>     | <b>0.503</b>           | <b>0.523</b>  | <b>0.611</b>           | <b>0.644</b>                    | <b>5</b> | <b>26</b>                                  | <b>0.1307</b>    |
| 0.70 UNM                      | 0.175            | 0.700                  | 0.673         | 0.586                  | 0.564         | 0.490                  | 0.454                  | 0.518                  | 0.586            | 0.586                  | 0.608         | 0.713                  | 0.750                           | 5        | 26   | 0.1780           |
| <b>0.80 UNM</b>               | <b>0.200</b>     | <b>0.800</b>           | <b>0.770</b>  | <b>0.670</b>           | <b>0.646</b>  | <b>0.560</b>           | <b>0.520</b>           | <b>0.592</b>           | <b>0.668</b>     | <b>0.670</b>           | <b>0.694</b>  | <b>0.814</b>           | <b>0.856</b>                    | <b>5</b> | <b>26</b>                                  | <b>0.232</b>     |
| 0.90 UNM                      | 0.225            | 0.900                  | 0.867         | 0.754                  | 0.728         | 0.630                  | 0.586                  | 0.666                  | 0.750            | 0.754                  | 0.780         | 0.916                  | 0.962                           | 5        | 26   | 0.294            |
| <b>1.00 UNM</b>               | <b>0.250</b>     | <b>1.000</b>           | <b>0.964</b>  | <b>0.838</b>           | <b>0.810</b>  | <b>0.700</b>           | <b>0.652</b>           | <b>0.740</b>           | <b>0.832</b>     | <b>0.838</b>           | <b>0.866</b>  | <b>1.018</b>           | <b>1.068</b>                    | <b>5</b> | <b>26</b>                                  | <b>0.363</b>     |
| 1.10 UNM                      | 0.250            | 1.100                  | 1.064         | 0.938                  | 0.910         | 0.800                  | 0.752                  | 0.840                  | 0.932            | 0.938                  | 0.966         | 1.118                  | 1.168                           | 4        | 51   | 0.478            |
| <b>1.20 UNM</b>               | <b>0.250</b>     | <b>1.200</b>           | <b>1.164</b>  | <b>1.038</b>           | <b>1.010</b>  | <b>0.900</b>           | <b>0.852</b>           | <b>0.940</b>           | <b>1.032</b>     | <b>1.038</b>           | <b>1.066</b>  | <b>1.218</b>           | <b>1.268</b>                    | <b>4</b> | <b>23</b>                                  | <b>0.608</b>     |
| 1.40 UNM                      | 0.300            | 1.400                  | 1.358         | 1.205                  | 1.173         | 1.040                  | 0.984                  | 1.088                  | 1.196            | 1.205                  | 1.237         | 1.422                  | 1.480                           | 4        | 32   | 0.811            |
|                               | Thds. per in.    | inch                   | inch          | inch                   | inch          | inch                   | inch                   | inch                   | inch             | inch                   | inch          | inch                   | inch                            | deg      | min  | sq in            |
| <b>0.30 UNM</b>               | <b>318</b>       | <b>0.0118</b>          | <b>0.0112</b> | <b>0.0098</b>          | <b>0.0092</b> | <b>0.0080</b>          | <b>0.0072</b>          | <b>0.0085</b>          | <b>0.0100</b>    | <b>0.0098</b>          | <b>0.0104</b> | <b>0.0120</b>          | <b>0.0129</b>                   | <b>5</b> | <b>52</b>                                  | <b>0.0000475</b> |
| 0.35 UNM                      | 282              | 0.0138                 | 0.0131        | 0.0115                 | 0.0109        | 0.0095                 | 0.0086                 | 0.0101                 | 0.0117           | 0.0115                 | 0.0121        | 0.0140                 | 0.0149                          | 5        | 37   | 0.0000671        |
| <b>0.40 UNM</b>               | <b>254</b>       | <b>0.0157</b>          | <b>0.0150</b> | <b>0.0132</b>          | <b>0.0126</b> | <b>0.0110</b>          | <b>0.0101</b>          | <b>0.0117</b>          | <b>0.0134</b>    | <b>0.0132</b>          | <b>0.0138</b> | <b>0.0160</b>          | <b>0.0170</b>                   | <b>5</b> | <b>26</b>                                  | <b>0.0000901</b> |
| 0.45 UNM                      | 254              | 0.0177                 | 0.0170        | 0.0152                 | 0.0145        | 0.0130                 | 0.0120                 | 0.0136                 | 0.0154           | 0.0152                 | 0.0158        | 0.0180                 | 0.0190                          | 4        | 44   | 0.0001262        |
| <b>0.50 UNM</b>               | <b>203</b>       | <b>0.0197</b>          | <b>0.0189</b> | <b>0.0165</b>          | <b>0.0158</b> | <b>0.0138</b>          | <b>0.0127</b>          | <b>0.0146</b>          | <b>0.0166</b>    | <b>0.0165</b>          | <b>0.0172</b> | <b>0.0200</b>          | <b>0.0212</b>                   | <b>5</b> | <b>26</b>                                  | <b>0.0001407</b> |
| 0.55 UNM                      | 203              | 0.0217                 | 0.0208        | 0.0185                 | 0.0177        | 0.0157                 | 0.0146                 | 0.0165                 | 0.0186           | 0.0185                 | 0.0192        | 0.0220                 | 0.0231                          | 4        | 51   | 0.0001852        |
| <b>0.60 UNM</b>               | <b>169</b>       | <b>0.0236</b>          | <b>0.0227</b> | <b>0.0198</b>          | <b>0.0190</b> | <b>0.0165</b>          | <b>0.0153</b>          | <b>0.0175</b>          | <b>0.0198</b>    | <b>0.0198</b>          | <b>0.0206</b> | <b>0.0240</b>          | <b>0.0254</b>                   | <b>5</b> | <b>26</b>                                  | <b>0.000203</b>  |
| 0.70 UNM                      | 145              | 0.0276                 | 0.0265        | 0.0231                 | 0.0222        | 0.0193                 | 0.0179                 | 0.0204                 | 0.0231           | 0.0231                 | 0.0240        | 0.0281                 | 0.0295                          | 5        | 26   | 0.000276         |
| <b>0.80 UNM</b>               | <b>127</b>       | <b>0.0315</b>          | <b>0.0303</b> | <b>0.0264</b>          | <b>0.0254</b> | <b>0.0220</b>          | <b>0.0205</b>          | <b>0.0233</b>          | <b>0.0263</b>    | <b>0.0264</b>          | <b>0.0273</b> | <b>0.0321</b>          | <b>0.0337</b>                   | <b>5</b> | <b>26</b>                                  | <b>0.000360</b>  |
| 0.90 UNM                      | 113              | 0.0354                 | 0.0341        | 0.0297                 | 0.0287        | 0.0248                 | 0.0231                 | 0.0262                 | 0.0295           | 0.0297                 | 0.0307        | 0.0361                 | 0.0379                          | 5        | 26   | 0.000456         |
| <b>1.00 UNM</b>               | <b>102</b>       | <b>0.0394</b>          | <b>0.0380</b> | <b>0.0330</b>          | <b>0.0319</b> | <b>0.0276</b>          | <b>0.0257</b>          | <b>0.0291</b>          | <b>0.0327</b>    | <b>0.0330</b>          | <b>0.0341</b> | <b>0.0401</b>          | <b>0.0420</b>                   | <b>5</b> | <b>26</b>                                  | <b>0.000563</b>  |
| 1.10 UNM                      | 102              | 0.0433                 | 0.0419        | 0.0369                 | 0.0358        | 0.0315                 | 0.0296                 | 0.0331                 | 0.0367           | 0.0369                 | 0.0380        | 0.0440                 | 0.0460                          | 4        | 51   | 0.000741         |
| <b>1.20 UNM</b>               | <b>102</b>       | <b>0.0472</b>          | <b>0.0458</b> | <b>0.0409</b>          | <b>0.0397</b> | <b>0.0354</b>          | <b>0.0335</b>          | <b>0.0370</b>          | <b>0.0406</b>    | <b>0.0409</b>          | <b>0.0420</b> | <b>0.0480</b>          | <b>0.0499</b>                   | <b>4</b> | <b>23</b>                                  | <b>0.000943</b>  |
| 1.40 UNM                      | 85               | 0.0551                 | 0.0535        | 0.0474                 | 0.0462        | 0.0409                 | 0.0387                 | 0.0428                 | 0.0471           | 0.0474                 | 0.0487        | 0.0560                 | 0.0583                          | 4        | 32   | 0.001257         |

<sup>a</sup> Sizes shown in bold type are preferred.

<sup>b</sup> This is also the basic dimension.

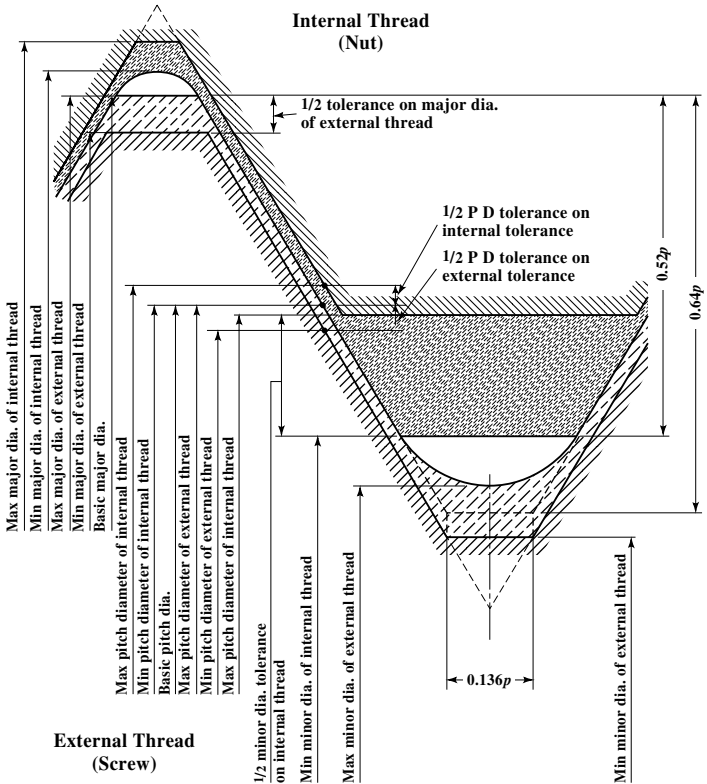
<sup>c</sup> This limit, in conjunction with root form shown in Table 2, is advocated for use when optical projection methods of gaging are employed. For mechanical gaging the minimum minor diameter of the internal thread is applied.

<sup>d</sup> This limit is provided for reference only. In practice, the form of the threading tool is relied upon for this limit.

<sup>e</sup> This limit is provided for reference only, and is not gaged. For gaging, the maximum major diameter of the external thread is applied.

**Table 6. Unified Miniature Screw Threads—  
Minimum Root Flats for External Threads**

| Pitch<br>mm | No. of<br>Threads<br>Per Inch | Thread Height for Min. Flat at Root<br>$0.64p$ |         | Minimum Flat at Root<br>$F_{rs} = 0.136p$ |         |
|-------------|-------------------------------|--|---------|---|---------|
|             |                               | mm   | Inch    | mm  | Inch    |
| 0.080       | 318                           | 0.0512   | 0.00202 | 0.0109                                    | 0.00043 |
| 0.090       | 282                           | 0.0576   | 0.00227 | 0.0122                                    | 0.00048 |
| 0.100       | 254                           | 0.0640   | 0.00252 | 0.0136                                    | 0.00054 |
| 0.125       | 203                           | 0.0800   | 0.00315 | 0.0170                                    | 0.00067 |
| 0.150       | 169                           | 0.0960   | 0.00378 | 0.0204                                    | 0.00080 |
| 0.175       | 145                           | 0.1120   | 0.00441 | 0.0238                                    | 0.00094 |
| 0.200       | 127                           | 0.1280   | 0.00504 | 0.0272                                    | 0.00107 |
| 0.225       | 113                           | 0.1440   | 0.00567 | 0.0306                                    | 0.00120 |
| 0.250       | 102                           | 0.1600   | 0.00630 | 0.0340                                    | 0.00134 |
| 0.300       | 85                            | 0.1920   | 0.00756 | 0.0408                                    | 0.00161 |



Limits of Size Showing Tolerances and Crest Clearances for UNM Threads

*Limits of Size:* Formulas used to determine limits of size are given in [Table 4](#); the limits of size are given in [Table 5](#). The diagram on page [1781](#) illustrates the limits of size and [Table 6](#) gives values for the minimum flat at the root of the external thread shown on the diagram.

*Classes of Threads:* The standard establishes one class of thread with zero allowance on all diameters. When coatings of a measurable thickness are required, they should be included within the maximum material limits of the threads since these limits apply to both coated and uncoated threads.

*Hole Sizes for Tapping:* Suggested hole sizes are given in the Tapping Section.

#### **British Standard Unified Screw Threads of UNJ Basic Profile**

This British Standard B.S. 4084: 1978 arises from a request originating from within the British aircraft industry and is based upon specifications for Unified screw threads and American military standard MIL-S-8879.

These UNJ threads, having an enlarged root radius, were introduced for applications requiring high fatigue strength where working stress levels are high, in order to minimize size and weight, as in aircraft engines, airframes, missiles, space vehicles and similar designs where size and weight are critical. To meet these requirements the root radius of external Unified threads is controlled between appreciably enlarged limits, the minor diameter of the mating internal threads being appropriately increased to insure the necessary clearance. The requirement for high strength is further met by restricting the tolerances for UNJ threads to the highest classes, Classes 3A and 3B, of Unified screw threads.

The standard, not described further here, contains both a coarse and a fine pitch series of threads.

## METRIC SCREW THREADS

### American National Standard Metric Screw Threads M Profile

American National Standard ANSI/ASME B1.13M-1983 (R1995) describes a system of metric threads for general fastening purposes in mechanisms and structures. The standard is in basic agreement with ISO screw standards and resolutions, as of the date of publication, and features detailed information for diameter-pitch combinations selected as to preferred standard sizes. This Standard contains general metric standards for a 60-degree symmetrical screw thread with a basic ISO 68 designated profile.

**Application Comparison with Inch Threads.**—The metric M profile threads of tolerance class 6H/6g (see page 1790) are intended for metric applications where the inch class 2A/2B have been used. At the minimum material limits, the 6H/6g results in a looser fit than the 2A/2B. Tabular data are also provided for a tighter tolerance fit external thread of class 4g6g which is approximately equivalent to the inch class 3A but with an allowance applied. It may be noted that a 4H5H/4h6h fit is approximately equivalent to class 3A/3B fit in the inch system.

**Interchangeability with Other System Threads.**—Threads produced to this Standard ANSI/ASME B1.13M are fully interchangeable with threads conforming to other National Standards that are based on ISO 68 basic profile and ISO 965/1 tolerance practices.

Threads produced to this Standard should be mechanically interchangeable with those produced to ANSI B1.18M-1982 (R1987) "Metric Screw Threads for Commercial Mechanical Fasteners—Boundary Profile Defined," of the same size and tolerance class. However, there is a possibility that some parts may be accepted by conventional gages used for threads made to ANSI/ASME B1.13M and rejected by the Double-NOT-GO gages required for threads made to ANSI B1.18M.

Threads produced in accordance with M profile and MJ profile ANSI/ASME B1.21M design data will assemble with each other. However, external MJ threads will encounter interference on the root radii with internal M thread crests when both threads are at maximum material condition.

**Definitions.**—The following definitions apply to metric screw threads — M profile.

*Allowance:* The minimum nominal clearance between a prescribed dimension and its basic dimension. Allowance is not an ISO metric screw thread term but it is numerically equal to the absolute value of the ISO term *fundamental deviation*.

*Basic Thread Profile:* The cyclical outline in an axial plane of the permanently established boundary between the provinces of the external and internal threads. All deviations are with respect to this boundary. (See Figs. 1 and 5.)

*Bolt Thread (External Thread):* The term used in ISO metric thread standards to describe all external threads. All symbols associated with external threads are designated with lower case letters. This Standard uses the term external threads in accordance with United States practice.

*Clearance:* The difference between the size of the internal thread and the size of the external thread when the latter is smaller.

*Crest Diameter:* The major diameter of an external thread and the minor diameter of an internal thread.

*Design Profiles:* The maximum material profiles permitted for external and internal threads for a specified tolerance class. (See Figs. 2 and 3.)

*Deviation:* An ISO term for the algebraic difference between a given size (actual, measured, maximum, minimum, etc.) and the corresponding basic size. The term deviation does not necessarily indicate an error.

**Fit:** The relationship existing between two corresponding external and internal threads with respect to the amount of clearance or interference which is present when they are assembled.

**Fundamental Deviation:** For Standard threads, the deviation (upper or lower) closer to the basic size. It is the upper deviation,  $es$ , for an external thread and the lower deviation,  $ei$ , for an internal thread. (See Fig. 5.)

**Limiting Profiles:** The limiting M profile for internal threads is shown in Fig. 6. The limiting M profile for external threads is shown in Fig. 7.

**Lower Deviation:** The algebraic difference between the minimum limit of size and the corresponding basic size.

**Nut Thread (Internal Thread):** A term used in ISO metric thread standards to describe all internal threads. All symbols associated with internal threads are designated with upper case letters. This Standard uses the term *internal thread* in accordance with United States practice.

**Tolerance:** The total amount of variation permitted for the size of a dimension. It is the difference between the maximum limit of size and the minimum limit of size (i.e., the algebraic difference between the upper deviation and the lower deviation). The tolerance is an absolute value without sign. Tolerance for threads is applied to the design size in the direction of the minimum material. On external threads the tolerance is applied negatively. On internal threads the tolerance is applied positively.

**Tolerance Class:** The combination of a tolerance position with a tolerance grade. It specifies the allowance (fundamental deviation) and tolerance for the pitch and major diameters of external threads and pitch and minor diameters of internal threads.

**Tolerance Grade:** A numerical symbol that designates the tolerances of crest diameters and pitch diameters applied to the design profiles.

**Tolerance Position:** A letter symbol that designates the position of the tolerance zone in relation to the basic size. This position provides the allowance (fundamental deviation).

**Upper Deviation:** The algebraic difference between the maximum limit of size and the corresponding basic size.

**Basic M Profile.**—The basic M thread profile also known as ISO 68 basic profile for metric screw threads is shown in Fig. 1 with associated dimensions listed in Table 3.

**Design M Profile for Internal Thread.**—The design M profile for the internal thread at maximum material condition is the basic ISO 68 profile. It is shown in Fig. 2 with associated thread data listed in Table 3.

**Design M Profile for External Thread.**—The design M profile for the external thread at the no allowance maximum material condition is the basic ISO 68 profile except where a rounded root is required. For the standard  $0.125P$  minimum radius, the ISO 68 profile is modified at the root with a  $0.17783H$  truncation blending into two arcs with radii of  $0.125P$  tangent to the thread flanks as shown in Fig. 3 with associated thread data in Table 3.

**M Crest and Root Form.**—The form of crest at the major diameter of the external thread is flat, permitting corner rounding. The external thread is truncated  $0.125H$  from a sharp crest. The form of the crest at the minor diameter of the internal thread is flat. It is truncated  $0.25H$  from a sharp crest.

The crest and root tolerance zones at the major and minor diameters will permit rounded crest and root forms in both external and internal threads.

The root profile of the external thread must lie within the "section lined" tolerance zone shown in Fig. 4. For the rounded root thread, the root profile must lie within the "section lined" rounded root tolerance zone shown in Fig. 4. The profile must be a continuous, smoothly blended non-reversing curve, no part of which has a radius of less than  $0.125P$ , and which is tangential to the thread flank. The profile may comprise tangent flank arcs that are joined by a tangential flat at the root.

The root profile of the internal thread must not be smaller than the basic profile. The maximum major diameter must not be sharp.

**General Symbols.**—The general symbols used to describe the metric screw thread forms are shown in Table 1.

**Table 1. American National Standard Symbols for Metric Threads  
ANSI/ASME B1.13M-1983 (R1995)**

| Symbol           | Explanation   |
|------------------|---|
| $D$              | Major Diameter Internal Thread  |
| $D_1$            | Minor Diameter Internal Thread  |
| $D_2$            | Pitch Diameter Internal Thread  |
| $d$              | Major Diameter External Thread  |
| $d_1$            | Minor Diameter External Thread  |
| $d_2$            | Pitch Diameter External Thread  |
| $d_3$            | Rounded Form Minor Diameter External Thread   |
| $P$              | Pitch   |
| $r$              | External Thread Root Radius   |
| $T$              | Tolerance   |
| $T_{D1}, T_{D2}$ | Tolerances for $D_1, D_2$   |
| $T_d, T_{d2}$    | Tolerances for $d, d_2$   |
| $ES$             | Upper Deviation, Internal Thread [Equals the Allowance (Fundamental Deviation) Plus the Tolerance]. See Fig. 5.   |
| $EI$             | Lower Deviation, Internal Thread Allowance (Fundamental Deviation). See Fig. 5.   |
| $G, H$           | Letter Designations for Tolerance Positions for Lower Deviation, Internal Thread  |
| $g, h$           | Letter Designations for Tolerance Positions for Upper Deviation, External Thread  |
| $es$             | Upper Deviation, External Thread Allowance (Fundamental Deviation). See Fig. 5. In the ISO system $es$ is always negative for an allowance fit or zero for no allowance.        |
| $ei$             | Lower Deviation, External Thread [Equals the Allowance (Fundamental Deviation) Plus the Tolerance]. See Fig. 5. In the ISO system $ei$ is always negative for an allowance fit. |
| $H$              | Height of Fundamental Triangle  |
| $LE$             | Length of Engagement  |
| $LH$             | Left Hand Thread  |

**Standard M Profile Screw Thread Series.**—The standard metric screw thread series for general purpose equipment's threaded components design and mechanical fasteners is a *coarse thread* series. Their diameter/pitch combinations are shown in Table 4. These diameter/pitch combinations are the preferred sizes and should be the first choice as applicable. Additional *fine pitch* diameter/pitch combinations are shown in Table 5.

**Table 2. American National Standard General Purpose and Mechanical Fastener  
Coarse Pitch Metric Thread—M Profile Series ANSI/ASME B1.13M-1983 (R1995)**

| Nom.Size | Pitch | Nom.Size | Pitch | Nom.Size | Pitch            | Nom.Size | Pitch |
|----------|-------|----------|-------|----------|------------------|----------|-------|
| 1.6      | 0.35  | 6        | 1     | 22       | 2.5 <sup>a</sup> | 56       | 5.5   |
| 2        | 0.4   | 8        | 1.25  | 24       | 3                | 64       | 6     |
| 2.5      | 0.45  | 10       | 1.5   | 27       | 3 <sup>a</sup>   | 72       | 6     |
| 3        | 0.5   | 12       | 1.75  | 30       | 3.5              | 80       | 6     |
| 3.5      | 0.6   | 14       | 2     | 36       | 4                | 90       | 6     |
| 4        | 0.7   | 16       | 2     | 42       | 4.5              | 100      | 6     |
| 5        | 0.8   | 20       | 2.5   | 48       | 5                | ...      | ...   |

<sup>a</sup> For high strength structural steel fasteners only.

All dimensions are in millimeters.

Table 3. American National Standard Metric Thread — M Profile Data ANSI/ASME B1.13M-1983 (R1995)

| Pitch<br>$P$ | Truncation of<br>Internal Thread and<br>External<br>Thread Crest<br>$\frac{H}{8}$ | Addendum of<br>Internal Thread and<br>Truncation of<br>Internal Thread<br>$\frac{H}{4}$ | DEDENDUM OF<br>INTERNAL THREAD AND<br>ADDENDUM EXTERNAL<br>THREAD<br>$\frac{3}{8}H$ | Difference <sup>a</sup><br>$\frac{H}{2}$ | Height of Internal Thread<br>and<br>Depth of Thread<br>Engagement<br>$\frac{5}{8}H$ | Difference <sup>b</sup><br>$0.711325H$ | Twice the<br>External Thread<br>Addendum<br>$\frac{3}{4}H$ | Difference <sup>c</sup><br>$\frac{11}{12}H$ | Height of<br>Sharp<br>V-Thread<br>$\frac{H}{4}$ | Double<br>Height of<br>Internal Thread<br>$\frac{5}{4}H$ |
|--------------|---|---|---|--|---|--|--|---|---|--|
|              | 0.108253P   | 0.216506P   | 0.324760P   | 0.433013P                                | 0.541266P   | 0.616025P                              | 0.649519P  | 0.793857P                                   | 0.8660254P                                      | 1.082532P  |
| 0.2          | 0.02165   | 0.04330   | 0.06495   | 0.08660                                  | 0.10825   | 0.12321                                | 0.12990  | 0.15877                                     | 0.17321   | 0.21651  |
| 0.25         | 0.02706   | 0.05413   | 0.08119   | 0.10825                                  | 0.13532   | 0.15401                                | 0.16238  | 0.19846                                     | 0.21651   | 0.27063  |
| 0.3          | 0.03248   | 0.06495   | 0.09743   | 0.12990                                  | 0.16238   | 0.18481                                | 0.19486  | 0.23816                                     | 0.25981   | 0.32476  |
| 0.35         | 0.03789   | 0.07578   | 0.11367   | 0.15155                                  | 0.18944   | 0.21561                                | 0.22733  | 0.27785                                     | 0.30311   | 0.37889  |
| 0.4          | 0.04330   | 0.08660   | 0.12990   | 0.17321                                  | 0.21651   | 0.24541                                | 0.25981  | 0.31754                                     | 0.34641   | 0.43301  |
| 0.45         | 0.04871   | 0.09743   | 0.14614   | 0.19486                                  | 0.24357   | 0.27721                                | 0.29228  | 0.35724                                     | 0.38971   | 0.48714  |
| 0.5          | 0.05413   | 0.10825   | 0.16238   | 0.21651                                  | 0.27063   | 0.30801                                | 0.32476  | 0.39693                                     | 0.43301   | 0.64952  |
| 0.6          | 0.06495   | 0.12990   | 0.19486   | 0.25981                                  | 0.32476   | 0.36962                                | 0.38971  | 0.47631                                     | 0.51962   | 0.64952  |
| 0.7          | 0.07578   | 0.15155   | 0.22733   | 0.30311                                  | 0.37889   | 0.43122                                | 0.45466  | 0.55570                                     | 0.60622   | 0.75777  |
| 0.75         | 0.08119   | 0.16238   | 0.24357   | 0.32476                                  | 0.40595   | 0.46202                                | 0.48714  | 0.59539                                     | 0.64952   | 0.81190  |
| 0.8          | 0.08660   | 0.17321   | 0.25981   | 0.34641                                  | 0.43301   | 0.49282                                | 0.51962  | 0.63509                                     | 0.69282   | 0.86603  |
| 1            | 0.10825   | 0.21651   | 0.32476   | 0.43301                                  | 0.54127   | 0.61603                                | 0.64952  | 0.79386                                     | 0.86603   | 1.08253  |
| 1.25         | 0.13532   | 0.27063   | 0.40595   | 0.54127                                  | 0.67658   | 0.77003                                | 0.81190  | 0.99232                                     | 1.08253   | 1.35316  |
| 1.5          | 0.16238   | 0.32476   | 0.48714   | 0.64952                                  | 0.81190   | 0.92404                                | 0.97428  | 1.19078                                     | 1.29904   | 1.62380  |
| 1.75         | 0.18944   | 0.37889   | 0.56833   | 0.75777                                  | 0.94722   | 1.07804                                | 1.13666  | 1.38925                                     | 1.51554   | 1.89443  |
| 2            | 0.21651   | 0.43301   | 0.64952   | 0.86603                                  | 1.08253   | 1.23205                                | 1.29904  | 1.58771                                     | 1.73205   | 2.16506  |
| 2.5          | 0.27063   | 0.54127   | 0.81190   | 1.08253                                  | 1.35316   | 1.54006                                | 1.62380  | 1.98464                                     | 2.16506   | 2.70633  |
| 3            | 0.32476   | 0.64652   | 0.97428   | 1.29904                                  | 1.62380   | 1.84808                                | 1.94856  | 2.38157                                     | 2.59808   | 3.24760  |
| 3.5          | 0.37889   | 0.75777   | 1.13666   | 1.51554                                  | 1.89443   | 2.15609                                | 2.27332  | 2.77850                                     | 3.03109   | 3.78886  |
| 4            | 0.43301   | 0.86603   | 1.29904   | 1.73205                                  | 2.16506   | 2.46410                                | 2.59808  | 3.17543                                     | 3.64410   | 4.33013  |
| 4.5          | 0.48714   | 0.97428   | 1.46142   | 1.94856                                  | 2.43570   | 2.77211                                | 2.92284  | 3.57235                                     | 3.89711   | 4.87139  |
| 5            | 0.54127   | 1.08253   | 1.62380   | 2.16506                                  | 2.70633   | 3.08013                                | 3.24760  | 3.96928                                     | 4.33013   | 5.41266  |
| 5.5          | 0.59539   | 1.19078   | 1.78618   | 2.38157                                  | 2.97696   | 3.38814                                | 3.57235  | 4.36621                                     | 4.76314   | 5.95392  |
| 6            | 0.64952   | 1.29904   | 1.94856   | 2.59808                                  | 3.24760   | 3.69615                                | 3.89711  | 4.76314                                     | 5.19615   | 6.49519  |
| 8            | 0.86603   | 1.73205   | 2.59808   | 3.46410                                  | 4.33013   | 4.92820                                | 5.19615  | 6.35085                                     | 6.92820   | 8.66025  |

<sup>a</sup> Difference between max theoretical pitch diameter and max minor diameter of external thread and between min theoretical pitch diameter and min minor diameter of internal thread.

<sup>b</sup> Difference between min theoretical pitch diameter and min design minor diameter of external thread for 0.125P root radius.

<sup>c</sup> Difference between max major diameter and max theoretical pitch diameter of internal thread.

All dimensions are in millimeters.

**Table 4. American National Standard General Purpose and Mechanical Fastener Coarse Pitch Metric Thread—M Profile Series ANSI/ASME B1.13M-1983 (R1995)**

| Nom. Size | Pitch | Nom. Size | Pitch | Nom. Size | Pitch            | Nom. Size | Pitch |
|-----------|-------|-----------|-------|-----------|------------------|-----------|-------|
| 1.6       | 0.35  | 6         | 1     | 22        | 2.5 <sup>a</sup> | 56        | 5.5   |
| 2         | 0.4   | 8         | 1.25  | 24        | 3                | 64        | 6     |
| 2.5       | 0.45  | 10        | 1.5   | 27        | 3 <sup>a</sup>   | 72        | 6     |
| 3         | 0.5   | 12        | 1.75  | 30        | 3.5              | 80        | 6     |
| 3.5       | 0.6   | 14        | 2     | 36        | 4                | 90        | 6     |
| 4         | 0.7   | 16        | 2     | 42        | 4.5              | 100       | 6     |
| 5         | 0.8   | 20        | 2.5   | 48        | 5                | ...       | ...   |

<sup>a</sup> For high strength structural steel fasteners only.

All dimensions are in millimeters.

**Table 5. American National Standard Fine Pitch Metric Thread—M Profile Series ANSI/ASME B1.13M-1983 (R1995)**

| Nom. Size | Pitch |                  | Nom. Size | Pitch |     | Nom. Size | Pitch |     | Nom. Size | Pitch |
|-----------|-------|------------------|-----------|-------|-----|-----------|-------|-----|-----------|-------|
| 8         | 1     | ...              | 27        | ...   | 2   | 56        | ...   | 2   | 105       | 2     |
| 10        | 0.75  | 1.25             | 30        | 1.5   | 2   | 60        | 1.5   | ... | 110       | 2     |
| 12        | 1     | 1.5 <sup>a</sup> | 33        | ...   | 2   | 64        | ...   | 2   | 120       | 2     |
| 14        | ...   | 1.5              | 35        | 1.5   | ... | 65        | 1.5   | ... | 130       | 2     |
| 15        | 1     | ...              | 36        | ...   | 2   | 70        | 1.5   | ... | 140       | 2     |
| 16        | ...   | 1.5              | 39        | ...   | 2   | 72        | ...   | 2   | 150       | 2     |
| 17        | 1     | ...              | 40        | 1.5   | ... | 75        | 1.5   | ... | 160       | 3     |
| 18        | ...   | 1.5              | 42        | ...   | 2   | 80        | 1.5   | 2   | 170       | 3     |
| 20        | 1     | 1.5              | 45        | 1.5   | ... | 85        | ...   | 2   | 180       | 3     |
| 22        | ...   | 1.5              | 48        | ...   | 2   | 90        | ...   | 2   | 190       | 3     |
| 24        | ...   | 2                | 50        | 1.5   | ... | 95        | ...   | 2   | 200       | 3     |
| 25        | 1.5   | ...              | 55        | 1.5   | ... | 100       | ...   | 2   |           |       |

<sup>a</sup> Only for wheel studs and nuts.

All dimensions are in millimeters.

**Limits and Fits for Metric Screw Threads — M Profile.**—The International (ISO) metric tolerance system is based on a system of limits and fits. The limits of the tolerances on the mating parts together with their allowances (fundamental deviations) determine the fit of the assembly. For simplicity the system is described for cylindrical parts (see *British Standard for Metric ISO Limits and Fits* starting on page 679) but in this Standard it is applied to screw threads. Holes are equivalent to internal threads and shafts to external threads.

**Basic Size:** This is the zero line or surface at assembly where the interface of the two mating parts have a common reference.\*

**Upper Deviation:** This is the algebraic difference between the maximum limit of size and the basic size. It is designated by the French term “écart supérieur” (ES for internal and es for external threads).

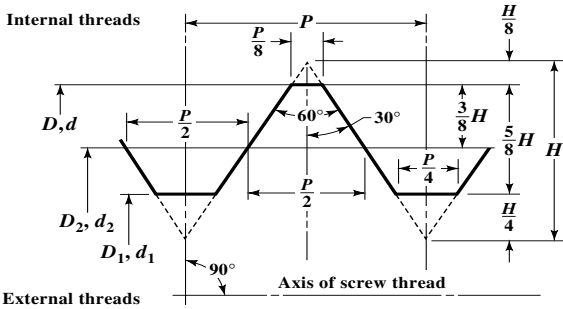
**Lower Deviation:** This is the algebraic difference between the minimum limit of size and the basic size. It is designated by the French term “écart inférieur” (EI for internal and ei for external threads).

\* Basic,” when used to identify a particular dimension in this Standard, such as basic major diameter, refers to the h/H tolerance position (zero fundamental deviation) value.



*Fundamental Deviations (Allowances):* These are the deviations which are closest to the basic size. In the accompanying figure they would be *EI* and *es*.

*Fits:* Fits are determined by the fundamental deviations assigned to the mating parts and may be positive or negative. The selected fits can be clearance, transition, or interference. To illustrate the fits schematically, a zero line is drawn to represent the basic size as shown in Fig. 5. By convention, the external thread lies below the zero line and the internal thread lies above it (except for interference fits). This makes the fundamental deviation negative for the external thread and equal to its upper deviation (*es*). The fundamental deviation is positive for the internal thread and equal to its lower deviation (*EI*).



$$H = \frac{\sqrt{3}}{2} \times P = 0.866025P$$

$$0.125H = 0.108253P \quad 0.250H = 0.216506P \quad 0.375H = 0.324760P \quad 0.625H = 0.541266P$$

Fig. 1. Basic M Thread Profile (ISO 68 Basic Profile)

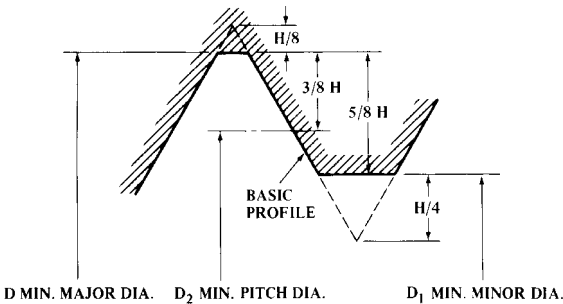


Fig. 2. Internal Thread Design M Profile with No Allowance (Fundamental Deviation) (Maximum Material Condition). For Dimensions see Table 3

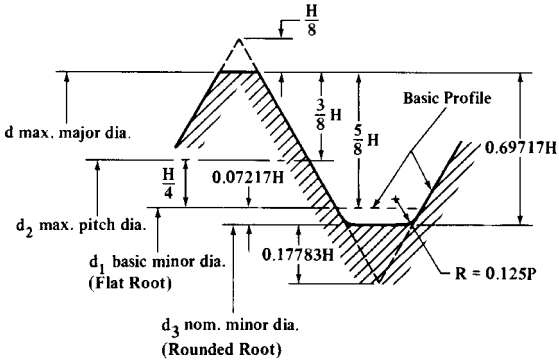


Fig. 3. External Thread Design M Profile with No Allowance (Fundamental Deviation) (Flanks at Maximum Material Condition). For Dimensions see Table 3

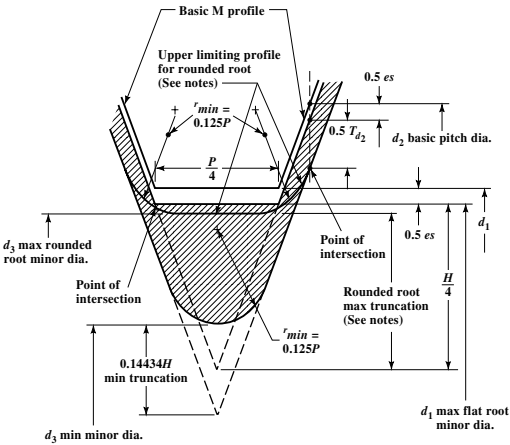


Fig. 4. M Profile, External Thread Root, Upper and Lower Limiting Profiles for  $r_{min} = 0.125P$  and for Flat Root (Shown for Tolerance Position g)

Notes:

- 1) "Section lined" portions identify tolerance zone and unshaded portions identify allowance (fundamental deviation).
- 2) The upper limiting profile for rounded root is not a design profile; rather it indicates the limiting acceptable condition for the rounded root which will pass a GO thread gage.
- 3) Max truncation =  $\frac{H}{4} - r_{min} \left( 1 - \cos \left[ 60^\circ - \arccos \left( 1 - \frac{T_{d2}}{4r_{min}} \right) \right] \right)$

where

$H$  = Height of fundamental triangle  
 $r_{min}$  = Minimum external thread root radius  
 $T_{d2}$  = Tolerance on pitch diameter of external thread

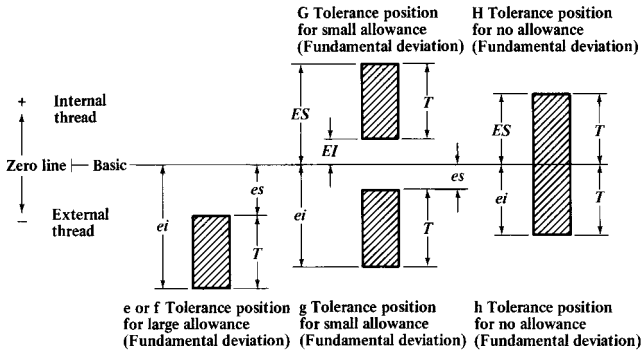


Fig. 5. Metric Tolerance System for Screw Threads

**Tolerance:** The tolerance is defined by a series of numerical grades. Each grade provides numerical values for the various nominal sizes corresponding to the standard tolerance for that grade.

In the schematic diagram the tolerance for the external thread is shown as negative. Thus the tolerance plus the fit define the lower deviation ( $ei$ ). The tolerance for the mating internal thread is shown as positive. Thus the tolerance plus the fit defines the upper deviation ( $ES$ ).

**Tolerance Grade:** This is indicated by a number. The system provides for a series of tolerance grades for each of the four screw thread parameters: minor diameter, internal thread,  $D_1$ ; major diameter, external thread,  $d$ ; pitch diameter, internal thread,  $D_2$ ; and pitch diameter, external thread,  $d_2$ . The tolerance grades for this Standard ANSI B1.13M were selected from those given in ISO 965/1.

| Dimension | Tolerance Grades                    | Table                    |
|-----------|-------------------------------------|--------------------------|
| $D_1$     | 4, 5, <u>6</u> , 7, 8               | <a href="#">Table 8</a>  |
| $d$       | 4, <u>6</u> , 8                     | <a href="#">Table 9</a>  |
| $D_2$     | 4, 5, <u>6</u> , 7, 8               | <a href="#">Table 10</a> |
| $d_2$     | 3, <u>4</u> , 5, <u>6</u> , 7, 8, 9 | <a href="#">Table 11</a> |

*Note:* The underlined tolerance grades are used with normal length of thread engagement.

**Tolerance Position:** This position is the allowance (fundamental deviation) and is indicated by a letter. A capital letter is used for internal threads and a lower case letter for external threads. The system provides a series of tolerance positions for internal and external threads. The underlined letters are used in this Standard:

|                  |                    |                         |
|------------------|--------------------|-------------------------|
| Internal threads | G, <u>H</u>        | <a href="#">Table 6</a> |
| External threads | e, f, <u>g</u> , h | <a href="#">Table 6</a> |

**Designations of Tolerance Grade, Tolerance Position, and Tolerance Class:** The tolerance grade is given first followed by the tolerance position, thus: 4g or 5H. To designate the tolerance class the grade and position of the pitch diameter is shown first followed by that for the major diameter in the case of the external thread or that for the minor diameter in the case of the internal thread, thus 4g6g for an external thread and 5H6H for an internal thread. If the two grades and positions are identical, it is not necessary to repeat the symbols, thus 4g, alone, stands for 4g4g and 5H, alone, stands for 5H5H.

**Table 6. American National Standard Allowance (Fundamental Deviation) for Internal and External Metric Threads**  
*ISO 965/1 ANSI/ASME B1.13M-1983 (R1995)*

| Pitch<br><i>P</i> | Allowance (Fundamental Deviation) <sup>a</sup>                   |           |   |           |           |           |
|-------------------|--|-----------|---|-----------|-----------|-----------|
|                   | Internal Thread<br><i>D</i> <sub>2</sub> , <i>D</i> <sub>1</sub> |           | External Thread<br><i>d</i> , <i>d</i> <sub>2</sub> |           |           |           |
|                   | G  | H         | e   | f         | g         | h         |
|                   | <i>EI</i>  | <i>EI</i> | <i>es</i>   | <i>es</i> | <i>es</i> | <i>es</i> |
| 0.2               | +0.017   | 0         | ...   | ...       | -0.017    | 0         |
| 0.25              | +0.018   | 0         | ...   | ...       | -0.018    | 0         |
| 0.3               | +0.018   | 0         | ...   | ...       | -0.018    | 0         |
| 0.35              | +0.019   | 0         | ...   | -0.034    | -0.019    | 0         |
| 0.4               | +0.019   | 0         | ...   | -0.034    | -0.019    | 0         |
| 0.45              | +0.020   | 0         | ...   | -0.035    | -0.020    | 0         |
| 0.5               | +0.020   | 0         | -0.050  | -0.036    | -0.020    | 0         |
| 0.6               | +0.021   | 0         | -0.053  | -0.036    | -0.021    | 0         |
| 0.7               | +0.022   | 0         | -0.056  | -0.038    | -0.022    | 0         |
| 0.75              | +0.022   | 0         | -0.056  | -0.038    | -0.022    | 0         |
| 0.8               | +0.024   | 0         | -0.060  | -0.038    | -0.024    | 0         |
| 1                 | +0.026   | 0         | -0.060  | -0.040    | -0.026    | 0         |
| 1.25              | +0.028   | 0         | -0.063  | -0.042    | -0.028    | 0         |
| 1.5               | +0.032   | 0         | -0.067  | -0.045    | -0.032    | 0         |
| 1.75              | +0.034   | 0         | -0.071  | -0.048    | -0.034    | 0         |
| 2                 | +0.038   | 0         | -0.071  | -0.052    | -0.038    | 0         |
| 2.5               | +0.042   | 0         | -0.080  | -0.058    | -0.042    | 0         |
| 3                 | +0.048   | 0         | -0.085  | -0.063    | -0.048    | 0         |
| 3.5               | +0.053   | 0         | -0.090  | -0.070    | -0.053    | 0         |
| 4                 | +0.060   | 0         | -0.095  | -0.075    | -0.060    | 0         |
| 4.5               | +0.063   | 0         | -0.100  | -0.080    | -0.063    | 0         |
| 5                 | +0.071   | 0         | -0.106  | -0.085    | -0.071    | 0         |
| 5.5               | +0.075   | 0         | -0.112  | -0.090    | -0.075    | 0         |
| 6                 | +0.080   | 0         | -0.118  | -0.095    | -0.080    | 0         |

All dimensions are in millimeters.

<sup>a</sup> Allowance is the absolute value of fundamental deviation.

**Lead and Flank Angle Tolerances:** For acceptance of lead and flank angles of product screw threads, see Section 10 of ANSI/ASME B1.13M-1983 (R1995).

**Short and Long Lengths of Thread Engagement when Gaged with Normal Length Contacts:** For short lengths of thread engagement, LE, reduce the pitch diameter tolerance of the external thread by one tolerance grade number. For long lengths of thread engagement, LE, increase the allowance (fundamental deviation) at the pitch diameter of the external thread. Examples of tolerance classes required for normal, short, and long gage length contacts are given in the following table.

| Normal LE         | Short LE | Long LE |
|-------------------|----------|---------|
| 6g                | 5g6g     | 6e6g    |
| 4g6g              | 3g6g     | 4e6g    |
| 6h <sup>a</sup>   | 5h6h     | 6g6h    |
| 4h6h <sup>a</sup> | 3h6h     | 4g6h    |

<sup>a</sup> Applies to maximum material functional size (GO thread gage) for plated 6g and 4g6g class threads, respectively.

For lengths of thread engagement classified as normal, short, and long, see [Table 7](#).

**Coated or Plated Threads:** Coating is one or more applications of additive material to the threads, including dry-film lubricants, but excluding soft or liquid lubricants that are readily displaced in assembly or gaging. Plating is included as coating in the Standard.

**Table 7. American National Standard Length of Metric Thread Engagement**  
*ISO 965/1 and ANSI/ASME B1.13M-1983 (R1995)*

| Basic Major Diameter $d_{\text{bsc}}$ |                 | Pitch<br>$P$ | Length of Thread Engagement |           |                 |         |
|---------------------------------------|-----------------|--------------|-----------------------------|-----------|-----------------|---------|
|                                       |                 |              | Short LE                    | Normal LE |                 | Long LE |
| Over                                  | Up to and incl. |              | Up to and incl.             | Over      | Up to and incl. | Over    |
| 1.5                                   | 2.8             | 0.2          | 0.5                         | 0.5       | 1.5             | 1.5     |
|                                       |                 | 0.25         | 0.6                         | 0.6       | 1.9             | 1.9     |
|                                       |                 | 0.35         | 0.8                         | 0.8       | 2.6             | 2.6     |
|                                       |                 | 0.4          | 1                           | 1         | 3               | 3       |
|                                       |                 | 0.45         | 1.3                         | 1.3       | 3.8             | 3.8     |
| 2.8                                   | 5.6             | 0.35         | 1                           | 1         | 3               | 3       |
|                                       |                 | 0.5          | 1.5                         | 1.5       | 4.5             | 4.5     |
|                                       |                 | 0.6          | 1.7                         | 1.7       | 5               | 5       |
|                                       |                 | 0.7          | 2                           | 2         | 6               | 6       |
|                                       |                 | 0.75         | 2.2                         | 2.2       | 6.7             | 6.7     |
| 5.6                                   | 11.2            | 0.8          | 2.5                         | 2.5       | 7.5             | 7.5     |
|                                       |                 | 0.75         | 2.4                         | 2.4       | 7.1             | 7.1     |
|                                       |                 | 1            | 3                           | 3         | 9               | 9       |
|                                       |                 | 1.25         | 4                           | 4         | 12              | 12      |
| 11.2                                  | 22.4            | 1.5          | 5                           | 5         | 15              | 15      |
|                                       |                 | 1            | 3.8                         | 3.8       | 11              | 11      |
|                                       |                 | 1.25         | 4.5                         | 4.5       | 13              | 13      |
|                                       |                 | 1.5          | 5.6                         | 5.6       | 16              | 16      |
|                                       |                 | 1.75         | 6                           | 6         | 18              | 18      |
| 22.4                                  | 45              | 2            | 8                           | 8         | 24              | 24      |
|                                       |                 | 2.5          | 10                          | 10        | 30              | 30      |
|                                       |                 | 1            | 4                           | 4         | 12              | 12      |
|                                       |                 | 1.5          | 6.3                         | 6.3       | 19              | 19      |
|                                       |                 | 2            | 8.5                         | 8.5       | 25              | 25      |
|                                       |                 | 3            | 12                          | 12        | 36              | 36      |
| 45                                    | 90              | 3.5          | 15                          | 15        | 45              | 45      |
|                                       |                 | 4            | 18                          | 18        | 53              | 53      |
|                                       |                 | 4.5          | 21                          | 21        | 63              | 63      |
|                                       |                 | 1.5          | 7.5                         | 7.5       | 22              | 22      |
|                                       |                 | 2            | 9.5                         | 9.5       | 28              | 28      |
|                                       |                 | 3            | 15                          | 15        | 45              | 45      |
| 90                                    | 180             | 4            | 19                          | 19        | 56              | 56      |
|                                       |                 | 5            | 24                          | 24        | 71              | 71      |
|                                       |                 | 5.5          | 28                          | 28        | 85              | 85      |
|                                       |                 | 6            | 32                          | 32        | 95              | 95      |
|                                       |                 | 2            | 12                          | 12        | 36              | 36      |
| 180                                   | 355             | 3            | 18                          | 18        | 53              | 53      |
|                                       |                 | 4            | 24                          | 24        | 71              | 71      |
|                                       |                 | 6            | 36                          | 36        | 106             | 106     |
|                                       |                 | 3            | 20                          | 20        | 60              | 60      |
|                                       |                 | 4            | 26                          | 26        | 80              | 80      |
|                                       |                 | 6            | 40                          | 40        | 118             | 118     |

All dimensions are in millimeters.

Unless otherwise specified, size limits for standard external tolerance classes 6g and 4g6g apply prior to coating. The external thread allowance may thus be used to accommodate the coating thickness on coated parts, provided that the maximum coating thickness is no more than one-quarter of the allowance. Thus, the thread after coating is subject to acceptance using a basic (tolerance position h) size GO thread gage and tolerance position g thread gage for either minimum material, LO, or NOT-GO. Where the external thread has no allowance or the allowance must be maintained after coating, and for standard internal

threads, sufficient allowance must be provided prior to coating to ensure that finished product threads do not exceed the maximum material limits specified. For thread classes with tolerance position H or h, coating allowances in accordance with Table 6 for position G or g, respectively, should be applied wherever possible.

**Dimensional Effect of Coating.**—On a cylindrical surface, the effect of coating is to change the diameter by twice the coating thickness. On a 60-degree thread, however, since the coating thickness is measured perpendicular to the thread surface while the pitch diameter is measured perpendicular to the thread axis, the effect of a uniformly coated flank on the pitch diameter is to change it by four times the thickness of the coating on the flank.

*External Thread with No Allowance for Coating:* To determine gaging limits before coating for a uniformly coated thread, decrease: 1) maximum pitch diameter by four times maximum coating thickness; 2) minimum pitch diameter by four times minimum coating thickness; 3) maximum major diameter by two times maximum coating thickness; and

4) minimum major diameter by two times minimum coating thickness.

*External Thread with Only Nominal or Minimum Thickness Coating:* If no coating thickness tolerance is given, it is recommended that a tolerance of plus 50 per cent of the nominal or minimum thickness be assumed.

Then, to determine before coating gaging limits for a uniformly coated thread, decrease:

1) maximum pitch diameter by six times coating thickness; 2) minimum pitch diameter by four times coating thickness; 3) maximum major diameter by three times coating thickness; and 4) minimum major diameter by two times coating thickness.

*Adjusted Size Limits:* It should be noted that the before coating material limit tolerances are less than the tolerance after coating. This is because the coating tolerance consumes some of the product tolerance. In cases there may be insufficient pitch diameter tolerance available in the before coating condition so that additional adjustments and controls will be necessary.

*Strength:* On small threads (5 mm and smaller) there is a possibility that coating thickness adjustments will cause base material minimum material conditions which may significantly affect strength of externally threaded parts. Limitations on coating thickness or part redesign may then be necessary.

*Internal Threads:* Standard internal threads provide no allowance for coating thickness.

To determine before coating, gaging limits for a uniformly coated thread, increase:

1) minimum pitch diameter by four times maximum coating thickness, if specified, or by six times minimum or nominal coating thickness when a tolerance is not specified; 2) maximum pitch diameter by four times minimum or nominal coating thickness; 3) minimum minor diameter by two times maximum coating thickness, if specified, or by three times minimum or nominal coating thickness; and 4) maximum minor diameter by two times minimum or nominal coating thickness.

**Other Considerations.**—It is essential to review all possibilities adequately and consider limitations in the threading and coating production processes before finally deciding on the coating process and the allowance required to accommodate the coating. A no-allowance thread after coating must not transgress the basic profile and is, therefore, subject to acceptance using a basic (tolerance position H/h) size GO thread gage.

**Formulas for M Profile Screw Thread Limiting Dimensions.**—The limiting dimensions for M profile screw threads are calculated from the following formulas.

**Internal Threads:**

*Min major dia.* = basic major dia. +  $EI$  (Table 6)

*Min pitch dia.* = basic major dia. -  $0.649519P$  (Table 3) +  $EI$  for  $D_2$  (Table 6)

*Max pitch dia.* = min pitch dia. +  $T_{D_2}$  (Table 10)

*Max major dia.* = max pitch dia. +  $0.793857P$  (Table 3)

*Min minor dia.* = min major dia. -  $1.082532P$  (Table 3)

*Max minor dia.* = min minor dia. +  $T_{D_1}$  (Table 8)

**External Threads:**

*Max major dia.* = basic major dia. -  $es$  (Table 6) (Note that  $es$  is an absolute value.)

*Min major dia.* = max major dia. -  $T_d$  (Table 9)

*Max pitch dia.* = basic major dia. -  $0.649519P$  (Table 3) -  $es$  for  $d_2$  (Table 6)

*Min pitch dia.* = max pitch dia. -  $T_{d_2}$  (Table 11)

*Max flat form minor dia.* = max pitch dia. -  $0.433013P$  (Table 3)

*Max rounded root minor dia.* = max pitch dia. -  $2 \times$  max trunc. (See Fig. 4)

*Min rounded root minor dia.* = min pitch dia. -  $0.616025P$  (Table 3)

*Min root radius* =  $0.125P$

**Table 8. ANSI Standard Minor Diameter Tolerances of Internal Metric Threads  $T_{D1}$  ISO 965/1 ANSI/ASME B1.13M-1983 (R1995)**

| Pitch<br>$P$ | Tolerance Grade |       |       |       |       |
|--------------|-----------------|-------|-------|-------|-------|
|              | 4               | 5     | 6     | 7     | 8     |
| 0.2          | 0.038           | ...   | ...   | ...   | ...   |
| 0.25         | 0.045           | 0.056 | ...   | ...   | ...   |
| 0.3          | 0.053           | 0.067 | 0.085 | ...   | ...   |
| 0.35         | 0.063           | 0.080 | 0.100 | ...   | ...   |
| 0.4          | 0.071           | 0.090 | 0.112 | ...   | ...   |
| 0.45         | 0.080           | 0.100 | 0.125 | ...   | ...   |
| 0.5          | 0.090           | 0.112 | 0.140 | 0.180 | ...   |
| 0.6          | 0.100           | 0.125 | 0.160 | 0.200 | ...   |
| 0.7          | 0.112           | 0.140 | 0.180 | 0.224 | ...   |
| 0.75         | 0.118           | 0.150 | 0.190 | 0.236 | ...   |
| 0.8          | 0.125           | 0.160 | 0.200 | 0.250 | 0.315 |
| 1            | 0.150           | 0.190 | 0.236 | 0.300 | 0.375 |
| 1.25         | 0.170           | 0.212 | 0.265 | 0.335 | 0.425 |
| 1.5          | 0.190           | 0.236 | 0.300 | 0.375 | 0.475 |
| 1.75         | 0.212           | 0.265 | 0.335 | 0.425 | 0.530 |
| 2            | 0.236           | 0.300 | 0.375 | 0.475 | 0.600 |
| 2.5          | 0.280           | 0.355 | 0.450 | 0.560 | 0.710 |
| 3            | 0.315           | 0.400 | 0.500 | 0.630 | 0.800 |
| 3.5          | 0.355           | 0.450 | 0.560 | 0.710 | 0.900 |
| 4            | 0.375           | 0.475 | 0.600 | 0.750 | 0.950 |
| 4.5          | 0.425           | 0.530 | 0.670 | 0.850 | 1.060 |
| 5            | 0.450           | 0.560 | 0.710 | 0.900 | 1.120 |
| 5.5          | 0.475           | 0.600 | 0.750 | 0.950 | 1.180 |
| 6            | 0.500           | 0.630 | 0.800 | 1.000 | 1.250 |

All dimensions are in millimeters.

**Table 9. ANSI Standard Major Diameter Tolerances of External Metric Threads,  $T_d$  ISO 965/1 ANSI/ASME B1.13M-1983 (R1995)**

| Pitch<br>$P$ | Tolerance Grade |       |       | Pitch<br>$P$ | Tolerance Grade |       |       |
|--------------|-----------------|-------|-------|--------------|-----------------|-------|-------|
|              | 4               | 6     | 8     |              | 4               | 6     | 8     |
| 0.2          | 0.036           | 0.056 | ...   | 1.25         | 0.132           | 0.212 | 0.335 |
| 0.25         | 0.042           | 0.067 | ...   | 1.5          | 0.150           | 0.236 | 0.375 |
| 0.3          | 0.048           | 0.075 | ...   | 1.75         | 0.170           | 0.265 | 0.425 |
| 0.35         | 0.053           | 0.085 | ...   | 2            | 0.180           | 0.280 | 0.450 |
| 0.4          | 0.060           | 0.095 | ...   | 2.5          | 0.212           | 0.335 | 0.530 |
| 0.45         | 0.063           | 0.100 | ...   | 3            | 0.236           | 0.375 | 0.600 |
| 0.5          | 0.067           | 0.106 | ...   | 3.5          | 0.265           | 0.425 | 0.670 |
| 0.6          | 0.080           | 0.125 | ...   | 4            | 0.300           | 0.475 | 0.750 |
| 0.7          | 0.090           | 0.140 | ...   | 4.5          | 0.315           | 0.500 | 0.800 |
| 0.75         | 0.090           | 0.140 | ...   | 5            | 0.335           | 0.530 | 0.850 |
| 0.8          | 0.095           | 0.150 | 0.236 | 5.5          | 0.355           | 0.560 | 0.900 |
| 1            | 0.112           | 0.180 | 0.280 | 6            | 0.375           | 0.600 | 0.950 |

All dimensions are in millimeters.

**Table 10. ANSI Standard Pitch-Diameter Tolerances of Internal Metric Threads,  $T_{D2}$  ISO 965/1 ANSI/ASME B1.13M-1983 (R1995)**

| Basic Major Diameter, $D$ |                 | Pitch<br>$P$ | Tolerance Grade |       |       |       |       |
|---------------------------|-----------------|--------------|-----------------|-------|-------|-------|-------|
| Over                      | Up to and incl. |              | 4               | 5     | 6     | 7     | 8     |
| 1.5                       | 2.8             | 0.2          | 0.042           | ...   | ...   | ...   | ...   |
|                           |                 | 0.25         | 0.048           | 0.060 | ...   | ...   | ...   |
|                           |                 | 0.35         | 0.053           | 0.067 | 0.085 | ...   | ...   |
|                           |                 | 0.4          | 0.056           | 0.071 | 0.090 | ...   | ...   |
|                           |                 | 0.45         | 0.060           | 0.075 | 0.095 | ...   | ...   |
| 2.8                       | 5.6             | 0.35         | 0.056           | 0.071 | 0.090 | ...   | ...   |
|                           |                 | 0.5          | 0.063           | 0.080 | 0.100 | 0.125 | ...   |
|                           |                 | 0.6          | 0.071           | 0.090 | 0.112 | 0.140 | ...   |
|                           |                 | 0.7          | 0.075           | 0.095 | 0.118 | 0.150 | ...   |
|                           |                 | 0.75         | 0.075           | 0.095 | 0.118 | 0.150 | ...   |
|                           |                 | 0.8          | 0.080           | 0.100 | 0.125 | 0.160 | 0.200 |
| 5.6                       | 11.2            | 0.75         | 0.085           | 0.106 | 0.132 | 0.170 | ...   |
|                           |                 | 1            | 0.095           | 0.118 | 0.150 | 0.190 | 0.236 |
|                           |                 | 1.25         | 0.100           | 0.125 | 0.160 | 0.200 | 0.250 |
|                           |                 | 1.5          | 0.112           | 0.140 | 0.180 | 0.224 | 0.280 |
| 11.2                      | 22.4            | 1            | 0.100           | 0.125 | 0.160 | 0.200 | 0.250 |
|                           |                 | 1.25         | 0.112           | 0.140 | 0.180 | 0.224 | 0.280 |
|                           |                 | 1.5          | 0.118           | 0.150 | 0.190 | 0.236 | 0.300 |
|                           |                 | 1.75         | 0.125           | 0.160 | 0.200 | 0.250 | 0.315 |
|                           |                 | 2            | 0.132           | 0.170 | 0.212 | 0.265 | 0.335 |
|                           |                 | 2.5          | 0.140           | 0.180 | 0.224 | 0.280 | 0.355 |
| 22.4                      | 45              | 1            | 0.106           | 0.132 | 0.170 | 0.212 | ...   |
|                           |                 | 1.5          | 0.125           | 0.160 | 0.200 | 0.250 | 0.315 |
|                           |                 | 2            | 0.140           | 0.180 | 0.224 | 0.280 | 0.355 |
|                           |                 | 3            | 0.170           | 0.212 | 0.265 | 0.335 | 0.425 |
|                           |                 | 3.5          | 0.180           | 0.224 | 0.280 | 0.355 | 0.450 |
|                           |                 | 4            | 0.190           | 0.236 | 0.300 | 0.375 | 0.475 |
|                           |                 | 4.5          | 0.200           | 0.250 | 0.315 | 0.400 | 0.500 |
| 45                        | 90              | 1.5          | 0.132           | 0.170 | 0.212 | 0.265 | 0.335 |
|                           |                 | 2            | 0.150           | 0.190 | 0.236 | 0.300 | 0.375 |
|                           |                 | 3            | 0.180           | 0.224 | 0.280 | 0.355 | 0.450 |
|                           |                 | 4            | 0.200           | 0.250 | 0.315 | 0.400 | 0.500 |
|                           |                 | 5            | 0.212           | 0.265 | 0.335 | 0.425 | 0.530 |
|                           |                 | 5.5          | 0.224           | 0.280 | 0.355 | 0.450 | 0.560 |
|                           |                 | 6            | 0.236           | 0.300 | 0.375 | 0.475 | 0.600 |



**Table 10. (Continued) ANSI Standard Pitch-Diameter Tolerances of Internal Metric Threads,  $T_{D2}$  ISO 965/1 ANSI/ASME B1.13M-1983 (R1995)**

| Basic Major Diameter, $D$ |                 | Pitch $P$ | Tolerance Grade |       |       |       |       |
|---------------------------|-----------------|-----------|-----------------|-------|-------|-------|-------|
| Over                      | Up to and incl. |           | 4               | 5     | 6     | 7     | 8     |
| 90                        | 180             | 2         | 0.160           | 0.200 | 0.250 | 0.315 | 0.400 |
|                           |                 | 3         | 0.190           | 0.236 | 0.300 | 0.375 | 0.475 |
|                           |                 | 4         | 0.212           | 0.265 | 0.335 | 0.425 | 0.530 |
|                           |                 | 6         | 0.250           | 0.315 | 0.400 | 0.500 | 0.630 |
| 180                       | 355             | 3         | 0.212           | 0.265 | 0.335 | 0.425 | 0.530 |
|                           |                 | 4         | 0.236           | 0.300 | 0.375 | 0.475 | 0.600 |
|                           |                 | 6         | 0.265           | 0.335 | 0.425 | 0.530 | 0.670 |

All dimensions are in millimeters.

**Table 11. ANSI Standard Pitch-Diameter Tolerances of External Metric Threads,  $T_{d2}$  ISO 965/1 ANSI/ASME B1.13M-1983 (R1995)**

| Basic Major Diameter, $d$ |                 | Pitch $P$ | Tolerance Grade |       |       |       |       |       |       |
|---------------------------|-----------------|-----------|-----------------|-------|-------|-------|-------|-------|-------|
| Over                      | Up to and incl. |           | 3               | 4     | 5     | 6     | 7     | 8     | 9     |
| 1.5                       | 2.8             | 0.2       | 0.025           | 0.032 | 0.040 | 0.050 | ...   | ...   | ...   |
|                           |                 | 0.25      | 0.028           | 0.036 | 0.045 | 0.056 | ...   | ...   | ...   |
|                           |                 | 0.35      | 0.032           | 0.040 | 0.050 | 0.063 | 0.080 | ...   | ...   |
|                           |                 | 0.4       | 0.034           | 0.042 | 0.053 | 0.067 | 0.085 | ...   | ...   |
|                           |                 | 0.45      | 0.036           | 0.045 | 0.056 | 0.071 | 0.090 | ...   | ...   |
| 2.8                       | 5.6             | 0.35      | 0.034           | 0.042 | 0.053 | 0.067 | 0.085 | ...   | ...   |
|                           |                 | 0.5       | 0.038           | 0.048 | 0.060 | 0.075 | 0.095 | ...   | ...   |
|                           |                 | 0.6       | 0.042           | 0.053 | 0.067 | 0.085 | 0.106 | ...   | ...   |
|                           |                 | 0.7       | 0.045           | 0.056 | 0.071 | 0.090 | 0.112 | ...   | ...   |
|                           |                 | 0.75      | 0.045           | 0.056 | 0.071 | 0.090 | 0.112 | ...   | ...   |
| 5.6                       | 11.2            | 0.8       | 0.048           | 0.060 | 0.075 | 0.095 | 0.118 | 0.150 | 0.190 |
|                           |                 | 0.75      | 0.050           | 0.063 | 0.080 | 0.100 | 0.125 | ...   | ...   |
|                           |                 | 1         | 0.056           | 0.071 | 0.090 | 0.112 | 0.140 | 0.180 | 0.224 |
|                           |                 | 1.25      | 0.060           | 0.075 | 0.095 | 0.118 | 0.150 | 0.190 | 0.236 |
| 11.2                      | 22.4            | 1.5       | 0.067           | 0.085 | 0.106 | 0.132 | 0.170 | 0.212 | 0.265 |
|                           |                 | 1         | 0.060           | 0.075 | 0.095 | 0.118 | 0.150 | 0.190 | 0.236 |
|                           |                 | 1.25      | 0.067           | 0.085 | 0.106 | 0.132 | 0.170 | 0.212 | 0.265 |
|                           |                 | 1.5       | 0.071           | 0.090 | 0.112 | 0.140 | 0.180 | 0.224 | 0.280 |
| 22.4                      | 45              | 1.75      | 0.075           | 0.095 | 0.118 | 0.150 | 0.190 | 0.236 | 0.300 |
|                           |                 | 2         | 0.080           | 0.100 | 0.125 | 0.160 | 0.200 | 0.250 | 0.315 |
|                           |                 | 2.5       | 0.085           | 0.106 | 0.132 | 0.170 | 0.212 | 0.265 | 0.335 |
|                           |                 | 1         | 0.063           | 0.080 | 0.100 | 0.125 | 0.160 | 0.200 | 0.250 |
|                           |                 | 1.5       | 0.075           | 0.095 | 0.118 | 0.150 | 0.190 | 0.236 | 0.300 |
| 45                        | 90              | 2         | 0.085           | 0.106 | 0.132 | 0.170 | 0.212 | 0.265 | 0.335 |
|                           |                 | 3         | 0.100           | 0.125 | 0.160 | 0.200 | 0.250 | 0.315 | 0.400 |
|                           |                 | 3.5       | 0.106           | 0.132 | 0.170 | 0.212 | 0.265 | 0.335 | 0.425 |
|                           |                 | 4         | 0.112           | 0.140 | 0.180 | 0.224 | 0.280 | 0.355 | 0.450 |
|                           |                 | 4.5       | 0.118           | 0.150 | 0.190 | 0.236 | 0.300 | 0.375 | 0.475 |
| 90                        | 180             | 1.5       | 0.080           | 0.100 | 0.125 | 0.160 | 0.200 | 0.250 | 0.315 |
|                           |                 | 2         | 0.090           | 0.112 | 0.140 | 0.180 | 0.224 | 0.280 | 0.355 |
|                           |                 | 3         | 0.106           | 0.132 | 0.170 | 0.212 | 0.265 | 0.335 | 0.425 |
|                           |                 | 4         | 0.118           | 0.150 | 0.190 | 0.236 | 0.300 | 0.375 | 0.475 |
|                           |                 | 5         | 0.125           | 0.160 | 0.200 | 0.250 | 0.315 | 0.400 | 0.500 |
|                           |                 | 5.5       | 0.132           | 0.170 | 0.212 | 0.265 | 0.335 | 0.425 | 0.530 |
| 180                       | 355             | 6         | 0.140           | 0.180 | 0.224 | 0.280 | 0.355 | 0.450 | 0.560 |
|                           |                 | 2         | 0.095           | 0.118 | 0.150 | 0.190 | 0.236 | 0.300 | 0.375 |
|                           |                 | 3         | 0.112           | 0.140 | 0.180 | 0.224 | 0.280 | 0.355 | 0.450 |
|                           |                 | 4         | 0.125           | 0.160 | 0.200 | 0.250 | 0.315 | 0.400 | 0.500 |
| 180                       | 355             | 6         | 0.150           | 0.190 | 0.236 | 0.300 | 0.375 | 0.475 | 0.600 |
|                           |                 | 3         | 0.125           | 0.160 | 0.200 | 0.250 | 0.315 | 0.400 | 0.500 |
|                           |                 | 4         | 0.140           | 0.180 | 0.224 | 0.280 | 0.355 | 0.450 | 0.560 |
| 180                       | 355             | 6         | 0.160           | 0.200 | 0.250 | 0.315 | 0.400 | 0.500 | 0.630 |

All dimensions are in millimeters.

**Tolerance Grade Comparisons.**—The approximate ratios of the tolerance grades shown in Tables 8, 9, 10, and 11 in terms of Grade 6 are as follows:

*Minor Diameter Tolerance of Internal Thread:*  $T_{D_1}$  (Table 8): Grade 4 is  $0.63 T_{D_1}$  (6); Grade 5 is  $0.8 T_{D_1}$  (6); Grade 7 is  $1.25 T_{D_1}$  (6); and Grade 8 is  $1.6 T_{D_1}$  (6).

*Pitch Diameter Tolerance of Internal Thread:*  $T_{D_2}$  (Table 10): Grade 4 is  $0.85 T_{D_2}$  (6); Grade 5 is  $1.06 T_{D_2}$  (6); Grade 6 is  $1.32 T_{D_2}$  (6); Grade 7 is  $1.7 T_{D_2}$  (6); and Grade 8 is  $2.12 T_{D_2}$  (6). It should be noted that these ratios are in terms of the Grade 6 pitch diameter tolerance for the external thread.

*Major Diameter Tolerance of External Thread:*  $T_d$  (Table 9): Grade 4 is  $0.63 T_d$  (6); and Grade 8 is  $1.6 T_d$  (6).

*Pitch Diameter Tolerance of External Thread:*  $T_{d_2}$  (Table 11): Grade 3 is  $0.5 T_{d_2}$  (6); Grade 4 is  $0.63 T_{d_2}$  (6); Grade 5 is  $0.8 T_{d_2}$  (6); Grade 7 is  $1.25 T_{d_2}$  (6); Grade 8 is  $1.6 T_{d_2}$  (6); and Grade 9 is  $2 T_{d_2}$  (6).

**Standard M Profile Screw Threads, Limits of Size.**—The limiting M profile for internal threads is shown in Fig. 6 with associated dimensions for standard sizes in Table 12. The limiting M profiles for external threads are shown in Fig. 7 with associated dimensions for standard sizes in Table 13.

If the required values are not listed in these tables, they may be calculated using the data in Tables 3, 6, 7, 8, 9, 10, and 11 together with the preceding formulas. If the required data are not included in any of the tables listed above, reference should be made to Sections 6 and 9.3 of ANSI/ASME B1.13M, which gives design formulas.

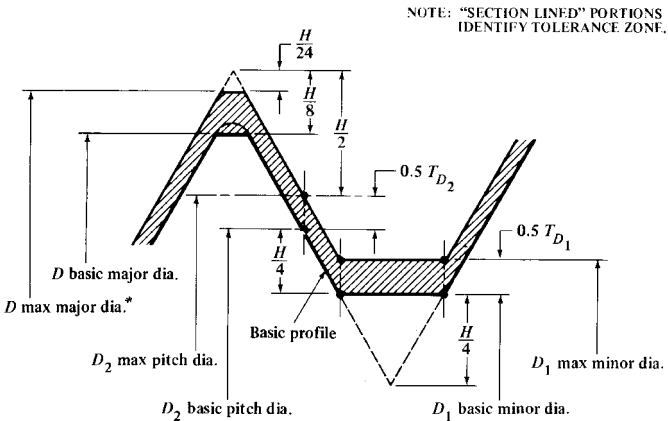
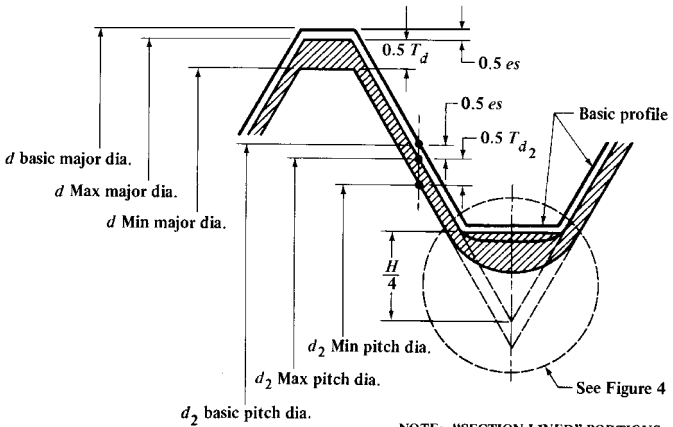


Fig. 6. Internal Thread—Limiting M Profile. Tolerance Position H

\*This dimension is used in the design of tools, etc. For internal threads it is not normally specified. Generally, major diameter acceptance is based on maximum material condition gaging.

METRIC SCREW THREADS M PROFILE



NOTE: "SECTION LINED" PORTIONS IDENTIFY TOLERANCE ZONE AND UNSHADED PORTIONS IDENTIFY ALLOWANCE (FUNDAMENTAL DEVIATION)

Fig. 7. External Thread — Limiting M Profile. Tolerance Position g

**Table 12. Internal Metric Thread - M Profile Limiting Dimensions, ANSI/ASME B1.13M-1983 (R1995)**

| Basic Thread Designation | Toler. Class | Minor Diameter $D_1$ |        | Pitch Diameter $D_2$ |        |       | Major Diameter $D$ |                  |
|--------------------------|--------------|----------------------|--------|----------------------|--------|-------|--------------------|------------------|
|                          |              | Min                  | Max    | Min                  | Max    | Tol   | Min                | Max <sup>a</sup> |
| M1.6 × 0.35              | 6H           | 1.221                | 1.321  | 1.373                | 1.458  | 0.085 | 1.600              | 1.736            |
| M2 × 0.4                 | 6H           | 1.567                | 1.679  | 1.740                | 1.830  | 0.090 | 2.000              | 2.148            |
| M2.5 × 0.45              | 6H           | 2.013                | 2.138  | 2.208                | 2.303  | 0.095 | 2.500              | 2.660            |
| M3 × 0.5                 | 6H           | 2.459                | 2.599  | 2.675                | 2.775  | 0.100 | 3.000              | 3.172            |
| M3.5 × 0.6               | 6H           | 2.850                | 3.010  | 3.110                | 3.222  | 0.112 | 3.500              | 3.699            |
| M4 × 0.7                 | 6H           | 3.242                | 3.422  | 3.545                | 3.663  | 0.118 | 4.000              | 4.219            |
| M5 × 0.8                 | 6H           | 4.134                | 4.334  | 4.480                | 4.605  | 0.125 | 5.000              | 5.240            |
| M6 × 1                   | 6H           | 4.917                | 5.153  | 5.350                | 5.500  | 0.150 | 6.000              | 6.294            |
| M8 × 1.25                | 6H           | 6.647                | 6.912  | 7.188                | 7.348  | 0.160 | 8.000              | 8.340            |
| M8 × 1                   | 6H           | 6.917                | 7.153  | 7.350                | 7.500  | 0.150 | 8.000              | 8.294            |
| M10 × 1.5                | 6H           | 8.376                | 8.676  | 9.026                | 9.206  | 0.180 | 10.000             | 10.396           |
| M10 × 1.25               | 6H           | 8.647                | 8.912  | 9.188                | 9.348  | 0.160 | 10.000             | 10.340           |
| M10 × 0.75               | 6H           | 9.188                | 9.378  | 9.513                | 9.645  | 0.132 | 10.000             | 10.240           |
| M12 × 1.75               | 6H           | 10.106               | 10.441 | 10.863               | 11.063 | 0.200 | 12.000             | 12.453           |
| M12 × 1.5                | 6H           | 10.376               | 10.676 | 11.026               | 11.216 | 0.190 | 12.000             | 12.406           |
| M12 × 1.25               | 6H           | 10.647               | 10.912 | 11.188               | 11.368 | 0.180 | 12.000             | 12.360           |
| M12 × 1                  | 6H           | 10.917               | 11.153 | 11.350               | 11.510 | 0.160 | 12.000             | 12.304           |
| M14 × 2                  | 6H           | 11.835               | 12.210 | 12.701               | 12.913 | 0.212 | 14.000             | 14.501           |
| M14 × 1.5                | 6H           | 12.376               | 12.676 | 13.026               | 13.216 | 0.190 | 14.000             | 14.406           |
| M15 × 1                  | 6H           | 13.917               | 14.153 | 14.350               | 14.510 | 0.160 | 15.000             | 15.304           |
| M16 × 2                  | 6H           | 13.835               | 14.210 | 14.701               | 14.913 | 0.212 | 16.000             | 16.501           |
| M16 × 1.5                | 6H           | 14.376               | 14.676 | 15.026               | 15.216 | 0.190 | 16.000             | 16.406           |
| M17 × 1                  | 6H           | 15.917               | 16.153 | 16.350               | 16.510 | 0.160 | 17.000             | 17.304           |
| M18 × 1.5                | 6H           | 16.376               | 16.676 | 17.026               | 17.216 | 0.190 | 18.000             | 18.406           |
| M20 × 2.5                | 6H           | 17.294               | 17.744 | 18.376               | 18.600 | 0.224 | 20.000             | 20.585           |
| M20 × 1.5                | 6H           | 18.376               | 18.676 | 19.026               | 19.216 | 0.190 | 20.000             | 20.406           |
| M20 × 1                  | 6H           | 18.917               | 19.153 | 19.350               | 19.510 | 0.160 | 20.000             | 20.304           |

**Table 12. (Continued) Internal Metric Thread - M Profile Limiting Dimensions, ANSI/ASME B1.13M-1983 (R1995)**

| Basic Thread Designation | Toler. Class | Minor Diameter $D_1$ |         | Pitch Diameter $D_2$ |         |       | Major Diameter $D$ |                  |
|--------------------------|--------------|----------------------|---------|----------------------|---------|-------|--------------------|------------------|
|                          |              | Min                  | Max     | Min                  | Max     | Tol   | Min                | Max <sup>a</sup> |
| M22 × 2.5                | 6H           | 19.294               | 19.744  | 20.376               | 20.600  | 0.224 | 22.000             | 22.585           |
| M22 × 1.5                | 6H           | 20.376               | 20.676  | 21.026               | 21.216  | 0.190 | 22.000             | 22.406           |
| M24 × 3                  | 6H           | 20.752               | 21.252  | 22.051               | 22.316  | 0.265 | 24.000             | 24.698           |
| M24 × 2                  | 6H           | 21.835               | 22.210  | 22.701               | 22.925  | 0.224 | 24.000             | 24.513           |
| M25 × 1.5                | 6H           | 23.376               | 23.676  | 24.026               | 24.226  | 0.200 | 25.000             | 25.416           |
| M27 × 3                  | 6H           | 23.752               | 24.252  | 25.051               | 25.316  | 0.265 | 27.000             | 27.698           |
| M27 × 2                  | 6H           | 24.835               | 25.210  | 25.701               | 25.925  | 0.224 | 27.000             | 27.513           |
| M30 × 3.5                | 6H           | 26.211               | 26.771  | 27.727               | 28.007  | 0.280 | 30.000             | 30.785           |
| M30 × 2                  | 6H           | 27.835               | 28.210  | 28.701               | 28.925  | 0.224 | 30.000             | 30.513           |
| M30 × 1.5                | 6H           | 28.376               | 28.676  | 29.026               | 29.226  | 0.200 | 30.000             | 30.416           |
| M33 × 2                  | 6H           | 30.835               | 31.210  | 31.701               | 31.925  | 0.224 | 33.000             | 33.513           |
| M35 × 1.5                | 6H           | 33.376               | 33.676  | 34.026               | 34.226  | 0.200 | 35.000             | 35.416           |
| M36 × 4                  | 6H           | 31.670               | 32.270  | 33.402               | 33.702  | 0.300 | 36.000             | 36.877           |
| M36 × 2                  | 6H           | 33.835               | 34.210  | 34.701               | 34.925  | 0.224 | 36.000             | 36.513           |
| M39 × 2                  | 6H           | 36.835               | 37.210  | 37.701               | 37.925  | 0.224 | 39.000             | 39.513           |
| M40 × 1.5                | 6H           | 38.376               | 38.676  | 39.026               | 39.226  | 0.200 | 40.000             | 40.416           |
| M42 × 4.5                | 6H           | 37.129               | 37.799  | 39.077               | 39.392  | 0.315 | 42.000             | 42.965           |
| M42 × 2                  | 6H           | 39.835               | 40.210  | 40.701               | 40.925  | 0.224 | 42.000             | 42.513           |
| M45 × 1.5                | 6H           | 43.376               | 43.676  | 44.026               | 44.226  | 0.200 | 45.000             | 45.416           |
| M48 × 5                  | 6H           | 42.587               | 43.297  | 44.752               | 45.087  | 0.335 | 48.000             | 49.057           |
| M48 × 2                  | 6H           | 45.835               | 46.210  | 46.701               | 46.937  | 0.236 | 48.000             | 48.525           |
| M50 × 1.5                | 6H           | 48.376               | 48.676  | 49.026               | 49.238  | 0.212 | 50.000             | 50.428           |
| M55 × 1.5                | 6H           | 53.376               | 53.676  | 54.026               | 54.238  | 0.212 | 55.000             | 55.428           |
| M56 × 5.5                | 6H           | 50.046               | 50.796  | 52.428               | 52.783  | 0.355 | 56.000             | 57.149           |
| M56 × 2                  | 6H           | 53.835               | 54.210  | 54.701               | 54.937  | 0.236 | 56.000             | 56.525           |
| M60 × 1.5                | 6H           | 58.376               | 58.676  | 59.026               | 59.238  | 0.212 | 60.000             | 60.428           |
| M64 × 6                  | 6H           | 57.505               | 58.305  | 60.103               | 60.478  | 0.375 | 64.000             | 65.241           |
| M64 × 2                  | 6H           | 61.835               | 62.210  | 62.701               | 62.937  | 0.236 | 64.000             | 64.525           |
| M65 × 1.5                | 6H           | 63.376               | 63.676  | 64.026               | 64.238  | 0.212 | 65.000             | 65.428           |
| M70 × 1.5                | 6H           | 68.376               | 68.676  | 69.026               | 69.238  | 0.212 | 70.000             | 70.428           |
| M72 × 6                  | 6H           | 65.505               | 66.305  | 68.103               | 68.478  | 0.375 | 72.000             | 73.241           |
| M72 × 2                  | 6H           | 69.835               | 70.210  | 70.701               | 70.937  | 0.236 | 72.000             | 72.525           |
| M75 × 1.5                | 6H           | 73.376               | 73.676  | 74.026               | 74.238  | 0.212 | 75.000             | 75.428           |
| M80 × 6                  | 6H           | 73.505               | 74.305  | 76.103               | 76.478  | 0.375 | 80.000             | 81.241           |
| M80 × 2                  | 6H           | 77.835               | 78.210  | 78.701               | 78.937  | 0.236 | 80.000             | 80.525           |
| M80 × 1.5                | 6H           | 78.376               | 78.676  | 79.026               | 79.238  | 0.212 | 80.000             | 80.428           |
| M85 × 2                  | 6H           | 82.835               | 83.210  | 83.701               | 83.937  | 0.236 | 85.000             | 85.525           |
| M90 × 6                  | 6H           | 83.505               | 84.305  | 86.103               | 86.478  | 0.375 | 90.000             | 91.241           |
| M90 × 2                  | 6H           | 87.835               | 88.210  | 88.701               | 88.937  | 0.236 | 90.000             | 90.525           |
| M95 × 2                  | 6H           | 92.835               | 93.210  | 93.701               | 93.951  | 0.250 | 95.000             | 95.539           |
| M100 × 6                 | 6H           | 93.505               | 94.305  | 96.103               | 96.503  | 0.400 | 100.000            | 101.266          |
| M100 × 2                 | 6H           | 97.835               | 98.210  | 98.701               | 98.951  | 0.250 | 100.000            | 100.539          |
| M105 × 2                 | 6H           | 102.835              | 103.210 | 103.701              | 103.951 | 0.250 | 105.000            | 105.539          |
| M110 × 2                 | 6H           | 107.835              | 108.210 | 108.701              | 108.951 | 0.250 | 110.000            | 110.539          |
| M120 × 2                 | 6H           | 117.835              | 118.210 | 118.701              | 118.951 | 0.250 | 120.000            | 120.539          |
| M130 × 2                 | 6H           | 127.835              | 128.210 | 128.701              | 128.951 | 0.250 | 130.000            | 130.539          |
| M140 × 2                 | 6H           | 137.835              | 138.210 | 138.701              | 138.951 | 0.250 | 140.000            | 140.539          |
| M150 × 2                 | 6H           | 147.835              | 148.210 | 148.701              | 148.951 | 0.250 | 150.000            | 150.539          |
| M160 × 3                 | 6H           | 156.752              | 157.252 | 158.051              | 158.351 | 0.300 | 160.000            | 160.733          |
| M170 × 3                 | 6H           | 166.752              | 167.252 | 168.051              | 168.351 | 0.300 | 170.000            | 170.733          |
| M180 × 3                 | 6H           | 176.752              | 177.252 | 178.051              | 178.351 | 0.300 | 180.000            | 180.733          |
| M190 × 3                 | 6H           | 186.752              | 187.252 | 188.051              | 188.386 | 0.335 | 190.000            | 190.768          |
| M200 × 3                 | 6H           | 196.752              | 197.252 | 198.051              | 198.386 | 0.335 | 200.000            | 200.768          |

<sup>a</sup> This reference dimension is used in design of tools, etc., and is not normally specified. Generally, major diameter acceptance is based upon maximum material condition gaging.

All dimensions are in millimeters.

**Table 13. External Metric Thread—M Profile Limiting Dimensions ANSI/ASME B1.13M-1983 (R1995)**

| Basic Thread Desig. | Toler. Class | Allow. $es^a$ | Major Diam. <sup>b</sup><br>$d$ |        | Pitch Diam. <sup>b</sup><br>$d_2$ |        |       | Minor-Diam. <sup>b</sup><br>$d_1$ | Minor Diam. <sup>c</sup><br>$d_3$ |
|---------------------|--------------|---------------|---------------------------------|--------|-----------------------------------|--------|-------|-----------------------------------|-----------------------------------|
|                     |              |               | Max                             | Min    | Max                               | Min    | Tol.  | Max                               | Min                               |
| M1.6 × 0.35         | 6g           | 0.019         | 1.581                           | 1.496  | 1.354                             | 1.291  | 0.063 | 1.202                             | 1.075                             |
| M1.6 × 0.35         | 4g6g         | 0.019         | 1.581                           | 1.496  | 1.354                             | 1.314  | 0.040 | 1.202                             | 1.098                             |
| M2 × 0.4            | 6g           | 0.019         | 1.981                           | 1.886  | 1.721                             | 1.654  | 0.067 | 1.548                             | 1.408                             |
| M2 × 0.4            | 4g6g         | 0.019         | 1.981                           | 1.886  | 1.721                             | 1.679  | 0.042 | 1.548                             | 1.433                             |
| M2.5 × 0.45         | 6g           | 0.020         | 2.480                           | 2.380  | 2.188                             | 2.117  | 0.071 | 1.993                             | 1.840                             |
| M2.5 × 0.45         | 4g6g         | 0.020         | 2.480                           | 2.380  | 2.188                             | 2.143  | 0.045 | 1.993                             | 1.866                             |
| M3 × 0.5            | 6g           | 0.020         | 2.980                           | 2.874  | 2.655                             | 2.580  | 0.075 | 2.439                             | 2.272                             |
| M3 × 0.5            | 4g6g         | 0.020         | 2.980                           | 2.874  | 2.655                             | 2.607  | 0.048 | 2.439                             | 2.299                             |
| M3.5 × 0.6          | 6g           | 0.021         | 3.479                           | 3.354  | 3.089                             | 3.004  | 0.085 | 2.829                             | 2.635                             |
| M3.5 × 0.6          | 4g6g         | 0.021         | 3.479                           | 3.354  | 3.089                             | 3.036  | 0.053 | 2.829                             | 2.667                             |
| M4 × 0.7            | 6g           | 0.022         | 3.978                           | 3.838  | 3.523                             | 3.433  | 0.090 | 3.220                             | 3.002                             |
| M4 × 0.7            | 4g6g         | 0.022         | 3.978                           | 3.838  | 3.523                             | 3.467  | 0.056 | 3.220                             | 3.036                             |
| M5 × 0.8            | 6g           | 0.024         | 4.976                           | 4.826  | 4.456                             | 4.361  | 0.095 | 4.110                             | 3.869                             |
| M5 × 0.8            | 4g6g         | 0.024         | 4.976                           | 4.826  | 4.456                             | 4.396  | 0.060 | 4.110                             | 3.904                             |
| M6 × 1              | 6g           | 0.026         | 5.974                           | 5.794  | 5.324                             | 5.212  | 0.112 | 4.891                             | 4.596                             |
| M6 × 1              | 4g6g         | 0.026         | 5.974                           | 5.794  | 5.324                             | 5.253  | 0.071 | 4.891                             | 4.637                             |
| M8 × 1.25           | 6g           | 0.028         | 7.972                           | 7.760  | 7.160                             | 7.042  | 0.118 | 6.619                             | 6.272                             |
| M8 × 1.25           | 4g6g         | 0.028         | 7.972                           | 7.760  | 7.160                             | 7.085  | 0.075 | 6.619                             | 6.315                             |
| M8 × 1              | 6g           | 0.026         | 7.974                           | 7.794  | 7.324                             | 7.212  | 0.112 | 6.891                             | 6.596                             |
| M8 × 1              | 4g6g         | 0.026         | 7.974                           | 7.794  | 7.324                             | 7.253  | 0.071 | 6.891                             | 6.637                             |
| M10 × 1.5           | 6g           | 0.032         | 9.968                           | 9.732  | 8.994                             | 8.862  | 0.132 | 8.344                             | 7.938                             |
| M10 × 1.5           | 4g6g         | 0.032         | 9.968                           | 9.732  | 8.994                             | 8.909  | 0.085 | 8.344                             | 7.985                             |
| M10 × 1.25          | 6g           | 0.028         | 9.972                           | 9.760  | 9.160                             | 9.042  | 0.118 | 8.619                             | 8.272                             |
| M10 × 1.25          | 4g6g         | 0.028         | 9.972                           | 9.760  | 9.160                             | 9.085  | 0.075 | 8.619                             | 8.315                             |
| M10 × 0.75          | 6g           | 0.022         | 9.978                           | 9.838  | 9.491                             | 9.391  | 0.100 | 9.166                             | 8.929                             |
| M10 × 0.75          | 4g6g         | 0.022         | 9.978                           | 9.838  | 9.491                             | 9.428  | 0.063 | 9.166                             | 8.966                             |
| M12 × 1.75          | 6g           | 0.034         | 11.966                          | 11.701 | 10.829                            | 10.679 | 0.150 | 10.072                            | 9.601                             |
| M12 × 1.75          | 4g6g         | 0.034         | 11.966                          | 11.701 | 10.829                            | 10.734 | 0.095 | 10.072                            | 9.656                             |
| M12 × 1.5           | 6g           | 0.032         | 11.968                          | 11.732 | 10.994                            | 10.854 | 0.140 | 10.344                            | 9.930                             |
| M12 × 1.25          | 6g           | 0.028         | 11.972                          | 11.760 | 11.160                            | 11.028 | 0.132 | 10.619                            | 10.258                            |
| M12 × 1.25          | 4g6g         | 0.028         | 11.972                          | 11.760 | 11.160                            | 11.075 | 0.085 | 10.619                            | 10.305                            |
| M12 × 1             | 6g           | 0.026         | 11.974                          | 11.794 | 11.324                            | 11.206 | 0.118 | 10.891                            | 10.590                            |
| M12 × 1             | 4g6g         | 0.026         | 11.974                          | 11.794 | 11.324                            | 11.249 | 0.075 | 10.891                            | 10.633                            |
| M14 × 2             | 6g           | 0.038         | 13.962                          | 13.682 | 12.663                            | 12.563 | 0.100 | 11.797                            | 11.271                            |
| M14 × 2             | 4g6g         | 0.038         | 13.962                          | 13.682 | 12.663                            | 12.663 | 0.100 | 11.797                            | 11.331                            |
| M14 × 1.5           | 6g           | 0.032         | 13.968                          | 13.732 | 12.994                            | 12.854 | 0.140 | 12.344                            | 11.930                            |
| M14 × 1.5           | 4g6g         | 0.032         | 13.968                          | 13.732 | 12.994                            | 12.904 | 0.090 | 12.344                            | 11.980                            |
| M15 × 1             | 6g           | 0.026         | 14.974                          | 14.794 | 14.324                            | 14.206 | 0.118 | 13.891                            | 13.590                            |
| M15 × 1             | 4g6g         | 0.026         | 14.974                          | 14.794 | 14.324                            | 14.249 | 0.075 | 13.891                            | 13.633                            |
| M16 × 2             | 6g           | 0.038         | 15.962                          | 15.682 | 14.663                            | 14.503 | 0.160 | 13.797                            | 13.271                            |
| M16 × 2             | 4g6g         | 0.038         | 15.962                          | 15.682 | 14.663                            | 14.563 | 0.100 | 13.797                            | 13.331                            |
| M16 × 1.5           | 6g           | 0.032         | 15.968                          | 15.732 | 14.994                            | 14.854 | 0.140 | 14.344                            | 13.930                            |
| M16 × 1.5           | 4g6g         | 0.032         | 15.968                          | 15.732 | 14.994                            | 14.904 | 0.090 | 14.344                            | 13.980                            |
| M17 × 1             | 6g           | 0.026         | 16.974                          | 16.794 | 16.324                            | 16.206 | 0.118 | 15.891                            | 15.590                            |
| M17 × 1             | 4g6g         | 0.026         | 16.974                          | 16.794 | 16.324                            | 16.249 | 0.075 | 15.891                            | 15.633                            |
| M18 × 1.5           | 6g           | 0.032         | 17.968                          | 17.732 | 16.994                            | 16.854 | 0.140 | 16.344                            | 15.930                            |
| M18 × 1.5           | 4g6g         | 0.032         | 17.968                          | 17.732 | 16.994                            | 16.904 | 0.090 | 16.344                            | 15.980                            |
| M20 × 2.5           | 6g           | 0.042         | 19.958                          | 19.623 | 18.334                            | 18.164 | 0.170 | 17.252                            | 16.624                            |
| M20 × 2.5           | 4g6g         | 0.042         | 19.958                          | 19.623 | 18.334                            | 18.228 | 0.106 | 17.252                            | 16.688                            |
| M20 × 1.5           | 6g           | 0.032         | 19.968                          | 19.732 | 18.994                            | 18.854 | 0.140 | 18.344                            | 17.930                            |
| M20 × 1.5           | 4g6g         | 0.032         | 19.968                          | 19.732 | 18.994                            | 18.904 | 0.090 | 18.344                            | 17.980                            |
| M20 × 1             | 6g           | 0.026         | 19.974                          | 19.794 | 19.324                            | 19.206 | 0.118 | 18.891                            | 18.590                            |
| M20 × 1             | 4g6g         | 0.026         | 19.974                          | 19.794 | 19.324                            | 19.249 | 0.075 | 18.891                            | 18.633                            |
| M22 × 2.5           | 6g           | 0.042         | 21.9587                         | 21.623 | 20.334                            | 20.164 | 0.170 | 19.252                            | 18.624                            |
| M22 × 1.5           | 6g           | 0.032         | 21.968                          | 21.732 | 20.994                            | 20.854 | 0.140 | 20.344                            | 19.930                            |
| M22 × 1.5           | 4g6g         | 0.032         | 21.968                          | 21.732 | 20.994                            | 20.904 | 0.090 | 20.344                            | 19.980                            |

**Table 13. (Continued) External Metric Thread—M Profile Limiting Dimensions ANSI/ASME B1.13M-1983 (R1995)**

| Basic Thread Desig. | Toler. Class | Allow. $e_s^a$ | Major Diam. <sup>b</sup> |        | Pitch Diam. <sup>b</sup> |        |       | Minor-Diam. <sup>a,d</sup> <sup>b</sup> | Minor Diam. <sup>d</sup> <sup>c</sup> |
|---------------------|--------------|----------------|--------------------------|--------|--------------------------|--------|-------|---|---------------------------------------|
|                     |              |                | $d$                      |        | $d_2$                    |        | Tol.  | Max <sub>1</sub>                        | Min                                   |
|                     |              |                | Max                      | Min    | Max                      | Min    |       |   |                                       |
| M24 × 3             | 6g           | 0.048          | 23.952                   | 23.577 | 22.003                   | 21.803 | 0.200 | 20.704                                  | 19.955                                |
| M24 × 3             | 4g6g         | 0.048          | 23.952                   | 23.557 | 22.003                   | 21.878 | 0.125 | 20.704                                  | 20.030                                |
| M24 × 2             | 6g           | 0.038          | 23.962                   | 23.682 | 22.663                   | 22.493 | 0.170 | 21.797                                  | 21.261                                |
| M24 × 2             | 4g6g         | 0.038          | 23.962                   | 23.682 | 22.663                   | 22.557 | 0.106 | 21.797                                  | 21.325                                |
| M25 × 1.5           | 6g           | 0.032          | 24.968                   | 24.732 | 23.994                   | 23.844 | 0.150 | 23.344                                  | 22.920                                |
| M25 × 1.5           | 4g6g         | 0.032          | 24.968                   | 24.732 | 23.994                   | 23.899 | 0.095 | 23.344                                  | 22.975                                |
| M27 × 3             | 6g           | 0.048          | 26.952                   | 26.577 | 25.003                   | 24.803 | 0.200 | 23.704                                  | 22.955                                |
| M27 × 2             | 6g           | 0.038          | 26.962                   | 26.682 | 25.663                   | 25.493 | 0.170 | 24.797                                  | 24.261                                |
| M27 × 2             | 4g6g         | 0.038          | 26.962                   | 26.682 | 25.663                   | 25.557 | 0.106 | 24.797                                  | 24.325                                |
| M30 × 3.5           | 6g           | 0.053          | 29.947                   | 29.522 | 27.674                   | 27.462 | 0.212 | 26.158                                  | 25.306                                |
| M30 × 3.5           | 4g6g         | 0.053          | 29.947                   | 29.522 | 27.674                   | 27.542 | 0.132 | 26.158                                  | 25.386                                |
| M30 × 2             | 6g           | 0.038          | 29.962                   | 29.682 | 28.663                   | 28.493 | 0.170 | 27.797                                  | 27.261                                |
| M30 × 2             | 4g6g         | 0.038          | 29.962                   | 29.682 | 28.663                   | 28.557 | 0.106 | 27.797                                  | 27.325                                |
| M30 × 1.5           | 6g           | 0.032          | 29.968                   | 29.732 | 28.994                   | 28.844 | 0.150 | 28.344                                  | 27.920                                |
| M30 × 1.5           | 4g6g         | 0.032          | 29.968                   | 29.732 | 28.994                   | 28.899 | 0.095 | 28.344                                  | 27.975                                |
| M33 × 2             | 6g           | 0.038          | 32.962                   | 32.682 | 31.663                   | 31.493 | 0.170 | 30.797                                  | 30.261                                |
| M33 × 2             | 4g6g         | 0.038          | 32.962                   | 32.682 | 31.663                   | 31.557 | 0.106 | 30.797                                  | 30.325                                |
| M35 × 1.5           | 6g           | 0.032          | 34.968                   | 34.732 | 33.994                   | 33.844 | 0.150 | 33.344                                  | 33.920                                |
| M36 × 4             | 6g           | 0.060          | 35.940                   | 35.465 | 33.342                   | 33.118 | 0.224 | 31.610                                  | 30.654                                |
| M36 × 4             | 4g6g         | 0.060          | 35.940                   | 35.465 | 33.342                   | 33.202 | 0.140 | 31.610                                  | 30.738                                |
| M36 × 2             | 6g           | 0.038          | 35.962                   | 35.682 | 34.663                   | 34.493 | 0.170 | 33.797                                  | 33.261                                |
| M36 × 2             | 4g6g         | 0.038          | 35.962                   | 35.682 | 34.663                   | 34.557 | 0.106 | 33.797                                  | 33.325                                |
| M39 × 2             | 6g           | 0.038          | 38.962                   | 38.682 | 37.663                   | 37.493 | 0.170 | 36.797                                  | 36.261                                |
| M39 × 2             | 4g6g         | 0.038          | 38.962                   | 38.682 | 37.663                   | 37.557 | 0.106 | 36.797                                  | 36.325                                |
| M40 × 1.5           | 6g           | 0.032          | 39.968                   | 39.732 | 38.994                   | 38.844 | 0.150 | 38.344                                  | 37.920                                |
| M40 × 1.5           | 4g6g         | 0.032          | 39.968                   | 39.732 | 38.994                   | 38.899 | 0.095 | 38.344                                  | 37.975                                |
| M42 × 4.5           | 6g           | 0.063          | 41.937                   | 41.437 | 39.014                   | 38.778 | 0.236 | 37.066                                  | 36.006                                |
| M42 × 4.5           | 4g6g         | 0.063          | 41.937                   | 41.437 | 39.014                   | 38.864 | 0.150 | 37.066                                  | 36.092                                |
| M42 × 2             | 6g           | 0.038          | 41.962                   | 41.682 | 40.663                   | 40.493 | 0.170 | 39.797                                  | 39.261                                |
| M42 × 2             | 4g6g         | 0.038          | 41.962                   | 41.682 | 40.663                   | 40.557 | 0.106 | 39.797                                  | 39.325                                |
| M45 × 1.5           | 6g           | 0.032          | 44.968                   | 44.732 | 43.994                   | 43.844 | 0.150 | 43.344                                  | 42.920                                |
| M45 × 1.5           | 4g6g         | 0.032          | 44.968                   | 44.732 | 43.994                   | 43.899 | 0.095 | 43.344                                  | 42.975                                |
| M48 × 5             | 6g           | 0.071          | 47.929                   | 47.399 | 44.681                   | 44.431 | 0.250 | 42.516                                  | 41.351                                |
| M48 × 5             | 4g6g         | 0.071          | 47.929                   | 47.399 | 44.681                   | 44.521 | 0.160 | 42.516                                  | 41.441                                |
| M48 × 2             | 6g           | 0.038          | 47.962                   | 47.682 | 46.663                   | 46.483 | 0.180 | 45.797                                  | 45.251                                |
| M48 × 2             | 4g6g         | 0.038          | 47.962                   | 47.682 | 46.663                   | 46.551 | 0.112 | 45.797                                  | 45.319                                |
| M50 × 1.5           | 6g           | 0.032          | 49.968                   | 49.732 | 48.994                   | 48.834 | 0.160 | 48.344                                  | 47.910                                |
| M50 × 1.5           | 4g6g         | 0.032          | 49.968                   | 49.732 | 48.994                   | 48.894 | 0.100 | 48.344                                  | 47.970                                |
| M55 × 1.5           | 6g           | 0.032          | 54.968                   | 54.732 | 53.994                   | 53.834 | 0.160 | 53.344                                  | 52.910                                |
| M55 × 1.5           | 4g6g         | 0.032          | 54.968                   | 54.732 | 53.994                   | 53.894 | 0.100 | 53.344                                  | 52.970                                |
| M56 × 5.5           | 6g           | 0.075          | 55.925                   | 55.365 | 52.353                   | 52.088 | 0.265 | 49.971                                  | 48.700                                |
| M56 × 5.5           | 4g6g         | 0.075          | 55.925                   | 55.365 | 52.353                   | 52.183 | 0.170 | 49.971                                  | 48.795                                |
| M56 × 2             | 6g           | 0.038          | 55.962                   | 55.682 | 54.663                   | 54.483 | 0.180 | 53.797                                  | 53.251                                |
| M56 × 2             | 4g6g         | 0.038          | 55.962                   | 55.682 | 54.663                   | 54.551 | 0.112 | 53.797                                  | 53.319                                |
| M60 × 1.5           | 6g           | 0.032          | 59.968                   | 59.732 | 58.994                   | 58.834 | 0.160 | 58.344                                  | 57.910                                |
| M60 × 1.5           | 4g6g         | 0.032          | 59.968                   | 59.732 | 58.994                   | 58.894 | 0.100 | 58.344                                  | 57.970                                |
| M64 × 6             | 6g           | 0.080          | 63.920                   | 63.320 | 60.023                   | 59.743 | 0.280 | 57.425                                  | 56.047                                |
| M64 × 6             | 4g6g         | 0.080          | 63.920                   | 63.320 | 60.023                   | 59.843 | 0.180 | 57.425                                  | 56.147                                |
| M64 × 2             | 6g           | 0.038          | 63.962                   | 63.682 | 62.663                   | 62.483 | 0.180 | 61.797                                  | 61.251                                |
| M64 × 2             | 4g6g         | 0.038          | 63.962                   | 63.682 | 62.663                   | 62.551 | 0.112 | 61.797                                  | 61.319                                |
| M65 × 1.5           | 6g           | 0.032          | 64.968                   | 64.732 | 63.994                   | 63.834 | 0.160 | 63.344                                  | 62.910                                |
| M65 × 1.5           | 4g6g         | 0.032          | 64.968                   | 64.732 | 63.994                   | 63.894 | 0.100 | 63.344                                  | 62.970                                |
| M70 × 1.5           | 6g           | 0.032          | 69.968                   | 69.732 | 68.994                   | 68.834 | 0.160 | 68.344                                  | 67.910                                |
| M70 × 1.5           | 4g6g         | 0.032          | 69.968                   | 69.732 | 68.994                   | 68.894 | 0.100 | 68.344                                  | 67.970                                |
| M72 × 6             | 6g           | 0.080          | 71.920                   | 71.320 | 68.023                   | 67.743 | 0.280 | 65.425                                  | 64.047                                |
| M72 × 6             | 4g6g         | 0.080          | 71.920                   | 71.320 | 68.023                   | 67.843 | 0.180 | 65.425                                  | 64.147                                |

**Table 13. (Continued) External Metric Thread—M Profile Limiting Dimensions ANSI/ASME B1.13M-1983 (R1995)**

| Basic Thread Desig. | Toler. Class | Allow. $e_s^a$ | Major Diam. <sup>b</sup><br>$d$ |         | Pitch Diam. <sup>b</sup><br>$d_2$ |         |       | Minor-Diam.. <sup>a,b</sup><br>$d_1$ | Minor Diam.. <sup>a,c</sup><br>$d_2$ |
|---------------------|--------------|----------------|---------------------------------|---------|-----------------------------------|---------|-------|--------------------------------------|--------------------------------------|
|                     |              |                | Max                             | Min     | Max                               | Min     | Tol.  | Max                                  | Min                                  |
| M72 × 2             | 6g           | 0.038          | 71.962                          | 71.682  | 70.663                            | 70.483  | 0.180 | 69.797                               | 69.251                               |
| M72 × 2             | 4g6g         | 0.038          | 71.962                          | 71.682  | 70.663                            | 70.551  | 0.112 | 69.797                               | 69.319                               |
| M75 × 1.5           | 6g           | 0.032          | 74.968                          | 74.732  | 73.994                            | 73.834  | 0.160 | 73.344                               | 72.910                               |
| M75 × 1.5           | 4g6g         | 0.032          | 74.968                          | 74.732  | 73.994                            | 73.894  | 0.100 | 73.344                               | 72.970                               |
| M80 × 6             | 6g           | 0.080          | 79.920                          | 79.320  | 76.023                            | 75.743  | 0.280 | 73.425                               | 72.047                               |
| M80 × 6             | 4g6g         | 0.080          | 79.920                          | 79.320  | 76.023                            | 75.843  | 0.180 | 73.425                               | 72.147                               |
| M80 × 2             | 6g           | 0.038          | 79.962                          | 79.682  | 78.663                            | 78.483  | 0.180 | 77.797                               | 77.251                               |
| M80 × 2             | 4g6g         | 0.038          | 79.962                          | 79.682  | 78.663                            | 78.551  | 0.112 | 77.797                               | 77.319                               |
| M80 × 1.5           | 6g           | 0.032          | 79.968                          | 79.732  | 78.994                            | 78.834  | 0.160 | 78.344                               | 77.910                               |
| M80 × 1.5           | 4g6g         | 0.032          | 79.968                          | 79.732  | 78.994                            | 78.894  | 0.100 | 78.344                               | 77.970                               |
| M85 × 2             | 6g           | 0.038          | 84.962                          | 84.682  | 83.663                            | 83.483  | 0.180 | 82.797                               | 82.251                               |
| M85 × 2             | 4g6g         | 0.038          | 84.962                          | 84.682  | 83.663                            | 83.551  | 0.112 | 82.797                               | 82.319                               |
| M90 × 6             | 6g           | 0.080          | 89.920                          | 89.320  | 86.023                            | 85.743  | 0.280 | 83.425                               | 82.047                               |
| M90 × 6             | 4g6g         | 0.080          | 89.920                          | 89.320  | 86.023                            | 85.843  | 0.180 | 83.425                               | 82.147                               |
| M90 × 2             | 6g           | 0.038          | 89.962                          | 89.682  | 88.663                            | 88.483  | 0.180 | 87.797                               | 87.251                               |
| M90 × 2             | 4g6g         | 0.038          | 89.962                          | 89.682  | 88.663                            | 88.551  | 0.112 | 87.797                               | 87.319                               |
| M95 × 2             | 6g           | 0.038          | 94.962                          | 94.682  | 93.663                            | 93.473  | 0.190 | 92.797                               | 92.241                               |
| M95 × 2             | 4g6g         | 0.038          | 94.962                          | 94.682  | 93.663                            | 93.545  | 0.118 | 92.797                               | 92.313                               |
| M100 × 6            | 6g           | 0.080          | 99.920                          | 99.320  | 96.023                            | 95.723  | 0.300 | 93.425                               | 92.027                               |
| M100 × 6            | 4g6g         | 0.080          | 99.920                          | 99.320  | 96.023                            | 95.833  | 0.190 | 93.425                               | 92.137                               |
| M100 × 2            | 6g           | 0.038          | 99.962                          | 99.682  | 98.663                            | 98.473  | 0.190 | 97.797                               | 97.241                               |
| M100 × 2            | 4g6g         | 0.038          | 99.962                          | 99.682  | 98.663                            | 98.545  | 0.118 | 97.797                               | 97.313                               |
| M105 × 2            | 6g           | 0.038          | 104.962                         | 104.682 | 103.663                           | 103.473 | 0.190 | 102.797                              | 102.241                              |
| M105 × 2            | 4g6g         | 0.038          | 104.962                         | 104.682 | 103.663                           | 103.545 | 0.118 | 102.797                              | 102.313                              |
| M110 × 2            | 6g           | 0.038          | 109.962                         | 109.682 | 108.663                           | 108.473 | 0.190 | 107.797                              | 107.241                              |
| M110 × 2            | 4g6g         | 0.038          | 109.962                         | 109.682 | 108.663                           | 108.545 | 0.118 | 107.797                              | 107.313                              |
| M120 × 2            | 6g           | 0.038          | 119.962                         | 119.682 | 118.663                           | 118.473 | 0.190 | 117.797                              | 117.241                              |
| M120 × 2            | 4g6g         | 0.038          | 119.962                         | 119.682 | 118.663                           | 118.545 | 0.118 | 117.797                              | 117.313                              |
| M130 × 2            | 6g           | 0.038          | 129.962                         | 129.682 | 128.663                           | 128.473 | 0.190 | 127.797                              | 127.241                              |
| M130 × 2            | 4g6g         | 0.038          | 129.962                         | 129.682 | 128.663                           | 128.545 | 0.118 | 127.797                              | 127.313                              |
| M140 × 2            | 6g           | 0.038          | 139.962                         | 139.682 | 138.663                           | 138.473 | 0.190 | 137.797                              | 137.241                              |
| M140 × 2            | 4g6g         | 0.038          | 139.962                         | 139.682 | 138.663                           | 138.545 | 0.118 | 137.797                              | 137.313                              |
| M150 × 2            | 6g           | 0.038          | 149.962                         | 149.682 | 148.663                           | 148.473 | 0.190 | 147.797                              | 147.241                              |
| M150 × 2            | 4g6g         | 0.038          | 149.962                         | 149.682 | 148.663                           | 148.545 | 0.118 | 147.797                              | 147.313                              |
| M160 × 3            | 6g           | 0.048          | 159.952                         | 159.577 | 158.003                           | 157.779 | 0.224 | 156.704                              | 155.931                              |
| M160 × 3            | 4g6g         | 0.048          | 159.952                         | 159.577 | 158.003                           | 157.863 | 0.140 | 156.704                              | 156.015                              |
| M170 × 3            | 6g           | 0.048          | 169.952                         | 169.577 | 168.003                           | 167.779 | 0.224 | 166.704                              | 165.931                              |
| M170 × 3            | 4g6g         | 0.048          | 169.952                         | 169.577 | 168.003                           | 167.863 | 0.140 | 166.704                              | 166.015                              |
| M180 × 3            | 6g           | 0.048          | 179.952                         | 179.577 | 178.003                           | 177.779 | 0.224 | 176.704                              | 175.931                              |
| M180 × 3            | 4g6g         | 0.048          | 179.952                         | 179.577 | 178.003                           | 177.863 | 0.140 | 176.704                              | 176.015                              |
| M190 × 3            | 6g           | 0.048          | 189.952                         | 189.577 | 188.003                           | 187.753 | 0.250 | 186.704                              | 185.905                              |
| M190 × 3            | 4g6g         | 0.048          | 189.952                         | 189.577 | 188.003                           | 187.843 | 0.160 | 186.704                              | 185.995                              |
| M200 × 3            | 6g           | 0.048          | 199.952                         | 199.577 | 198.003                           | 197.753 | 0.250 | 196.704                              | 195.905                              |
| M200 × 3            | 4g6g         | 0.048          | 199.952                         | 199.577 | 198.003                           | 197.843 | 0.160 | 196.704                              | 195.995                              |

<sup>a</sup>  $e_s$  is an absolute value.<sup>b</sup> (Flat form) For screw threads at maximum limits of tolerance position  $h$ , add the absolute value  $e_s$  to the maximum diameters required. For maximum major diameter this value is the basic thread size listed in Table 12 as Minimum Major Diameter ( $D_{1min}$ ); for maximum pitch diameter this value is the same as listed in Table 12 as Minimum Pitch Diameter ( $D_{2min}$ ); and for maximum minor diameter this value is the same as listed in Table 12 as Minimum Minor Diameter ( $D_{1min}$ ).<sup>c</sup> (Rounded form) This reference dimension is used in the design of tools, etc. In dimensioning external threads it is not normally specified. Generally minor diameter acceptance is based upon maximum material condition gaging.

All dimensions are in millimeters.

**Metric Screw Thread Designations.**—Metric screw threads are identified by the letter (M) for the thread form profile, followed by the nominal diameter size and the pitch expressed in millimeters, separated by the sign (×) and followed by the tolerance class separated by a dash (–) from the pitch.

The simplified international practice for designating coarse pitch M profile metric screw threads is to leave off the pitch. Thus a M14 × 2 thread is designated just M14. However, to prevent misunderstanding, it is mandatory to use the value for pitch in all designations.

Thread acceptability gaging system requirements of ANSI B1.3M may be added to the thread size designation as noted in the examples (numbers in parentheses) or as specified in pertinent documentation, such as the drawing or procurement document.

Unless otherwise specified in the designation, the screw thread is right hand.

*Examples:* External thread of M profile, right hand: M6 × 1 – 4g6g (22)  
Internal thread of M profile, right hand: M6 × 1 – 5H6H (21)

*Designation of Left Hand Thread:* When a left hand thread is specified, the tolerance class designation is followed by a dash and LH.

*Example:* M6 × 1 – 5H6H – LH (23)

*Designation for Identical Tolerance Classes:* If the two tolerance class designations for a thread are identical, it is not necessary to repeat the symbols.

*Example:* M6 × 1 – 6H (21)

*Designation Using All Capital Letters:* When computer and teletype thread designations use all capital letters, the external or internal thread may need further identification. Thus the tolerance class is followed by the abbreviations EXT or INT in capital letters.

*Examples:* M6 × 1 – 4G6G EXT; M6 × 1 – 6H INT

*Designation for Thread Fit:* A fit between mating threads is indicated by the internal thread tolerance class followed by the external thread tolerance class and separated by a slash.

*Examples:* M6 × 1 – 6H/6g; M6 × 1 – 6H/4g6g

*Designation for Rounded Root External Thread:* The M profile with a minimum root radius of 0.125P on the external thread is desirable for all threads but is mandatory for threaded mechanical fasteners of ISO 898/I property class 8.8 (minimum tensile strength 800 MPa) and stronger. No special designation is required for these threads. Other parts requiring a 0.125P root radius must have that radius specified.

When a special rounded root is required, its external thread designation is suffixed by the minimum root radius value in millimeters and the letter R.

*Example:* M42 × 4.5 – 6g – 0.63R

*Designation of Threads Having Modified Crests:* Where the limits of size of the major diameter of an external thread or the minor diameter of an internal thread are modified, the thread designation is suffixed by the letters MOD followed by the modified diameter limits.

*Examples:*

|   |   |
|---|---|
| External thread M profile, major diameter reduced 0.075 mm.<br>M6 × 1 – 4h6h MOD<br>Major dia = 5.745 – 5.925 MOD | Internal thread M profile, minor diameter increased 0.075 mm.<br>M6 × 1 – 4H5H MOD<br>Minor dia = 5.101 – 5.291 MOD |
|---|---|

*Designation of Special Threads:* Special diameter-pitch threads developed in accordance with this Standard ANSI/ASME B1.13M are identified by the letters SPL following the tolerance class. The limits of size for the major diameter, pitch diameter, and minor diameter are specified below this designation.



*Examples:*

| External thread            | Internal thread            |
|----------------------------|----------------------------|
| M6.5 × 1 – 4h6h – SPL (22) | M6.5 × 1 – 4H5H – SPL (23) |
| Major dia = 6.320 – 6.500  | Major dia = 6.500 min      |
| Pitch dia = 5.779 – 5.850  | Pitch dia = 5.850 – 5.945  |
| Minor dia = 5.163 – 5.386  | Minor dia = 5.417 – 5.607  |

*Designation of Multiple Start Threads:* When a thread is required with a multiple start, it is designated by specifying sequentially: M for metric thread, nominal diameter size, × L for lead, lead value, dash, P for pitch, pitch value, dash, tolerance class, parenthesis, script number of starts, and the word starts, close parenthesis.

*Examples:* M16 × L4 – P2 – 4h6h (TWO STARTS)  
M14 × L6 – P2 – 6H (THREE STARTS)

*Designation of Coated or Plated Threads:* In designating coated or plated M threads the tolerance class should be specified as after coating or after plating. If no designation of after coating or after plating is specified, the tolerance class applies before coating or plating in accordance with ISO practice. After plating, the thread must not transgress the maximum material limits for the tolerance position H/h.

*Examples:* M6 × 1 – 6h AFTER COATING or AFTER PLATING  
M6 × 1 – 6g AFTER COATING or AFTER PLATING

Where the tolerance position G/g is insufficient relief for the application to hold the threads within product limits, the coating or plating allowance may be specified as the maximum and minimum limits of size for minor and pitch diameters of internal threads or major and pitch diameters for external threads before coating or plating.

*Example:* Allowance on external thread M profile based on 0.010 mm minimum coating thickness.

M6 × 1 – 4h6h – AFTER COATING  
BEFORE COATING  
Major dia = 5.780 – 5.940  
Pitch dia = 5.239 – 5.290

**Metric Screw Threads—MJ Profile**

The MJ screw thread is intended for aerospace metric threaded parts and for other highly stressed applications requiring high temperature or high fatigue strength, or for “no allowance” applications. The MJ profile thread is a hard metric version similar to the UNJ inch standards, ANSI/ASME B1.15 and MIL-S-8879. The MJ profile thread has a 0.15011P to 0.180424P controlled root radius in the external thread and the internal thread minor diameter truncated to accommodate the external thread maximum root radius.

First issued in 1978, the American National Standard ANSI/ASME B1.21M-1997 establishes the basic triangular profile for the MJ form of thread; gives a system of designations; lists the standard series of diameter-pitch combinations for diameters from 1.6 to 200 mm; and specifies limiting dimensions and tolerances. Changes included in the 1997 revision are the addition of tolerance class 4G6G and 4G5G/4g6g comparable to ANSI/ASME B1.15 (UNJ thread); the addition of tolerance class 6H/6g comparable to ANSI/ASME B1.13M; and changes in the rounding procedure as set forth in ANSI/ASME B1.30M.

**Diameter-Pitch Combinations.**—This Standard includes a selected series of diameter-pitch combinations of threads taken from International Standard ISO 261 plus some additional sizes in the constant pitch series. These are given in [Table 1](#). It also includes the standard series of diameter-pitch combinations for aerospace screws, bolts, nuts, and fluid system fittings as shown in [Table 2](#).

**Table 1. ANSI Standard Metric Screw Threads MJ Profile Diameter-Pitch Combinations ANSI/ASME B1.21M-1997**

| Nominal Diameter |     | Pitches |                             | Nominal Diameter |     | Pitches |                                      |
|------------------|-----|---------|-----------------------------|------------------|-----|---------|--------------------------------------|
| Choices          |     | Coarse  | Fine                        | Choices          |     | Coarse  | Fine                                 |
| 1st              | 2nd |         |                             | 1st              | 2nd |         |                                      |
| 1.6              | ... | 0.35    | ...                         | ...              | 52  | ...     | 3, 2, 1.5                            |
| ...              | 1.8 | 0.35    | ...                         | 55               | ... | ...     | 3, 2, 1.5                            |
| 2.0              | ... | 0.4     | ...                         | ...              | 56  | 5.5     | 3, 2, 1.5                            |
| ...              | 2.2 | 0.45    | ...                         | ...              | 58  | ...     | 3, 2, 1.5                            |
| 2.5              | ... | 0.45    | ...                         | 60               | ... | ...     | 3, 2, 1.5                            |
| 3                | ... | 0.5     | ...                         | ...              | 62  | ...     | 3, 2, 1.5                            |
| 3.5              | ... | 0.6     | ...                         | ...              | 64  | 6       | 3, 2, 1.5                            |
| 4                | ... | 0.7     | ...                         | 65               | ... | ...     | 3, 2, 1.5                            |
| ...              | 4.5 | 0.75    | ...                         | ...              | 68  | ...     | 3, 2, 1.5                            |
| 5                | ... | 0.8     | ...                         | 70               | ... | ...     | 3, 2, 1.5                            |
| 6                | ... | 1       | 0.75                        | ...              | 72  | 6       | 3, 2, 1.5                            |
| 7                | ... | 1       | 0.75                        | 75               | ... | ...     | 3, 2, 1.5                            |
| 8                | ... | 1.25    | 1, 0.75                     | ...              | 76  | ...     | 3, 2, 1.5                            |
| ...              | 9   | 1.25    | 1, 0.75                     | ...              | 78  | ...     | 3 <sup>a</sup> , 2, 1.5 <sup>a</sup> |
| 10               | ... | 1.5     | 1.25, 1, 0.75               | 80               | ... | 6       | 3, 2, 1.5                            |
| ...              | 11  | 1.5     | 1.25 <sup>b</sup> , 1, 0.75 | ...              | 82  | ...     | 3 <sup>a</sup> , 2, 1.5 <sup>a</sup> |
| 12               | ... | 1.75    | 1.5, 1.25, 1                | 85               | ... | ...     | 3, 2, 1.5 <sup>a</sup>               |
| 14               | ... | 2       | 1.5, 1.25 <sup>c</sup> , 1  | 90               | ... | 6       | 3, 2, 1.5 <sup>a</sup>               |
| ...              | 15  | ...     | 1.5, 1                      | 95               | ... | ...     | 3, 2, 1.5 <sup>a</sup>               |
| 16               | ... | 2       | 1.5, 1                      | 100              | ... | 6       | 3, 2, 1.5 <sup>a</sup>               |
| ...              | 17  | ...     | 1.5, 1                      | 105              | ... | ...     | 3, 2, 1.5 <sup>a</sup>               |
| 18               | ... | 2.5     | 2, 1.5, 1                   | 110              | ... | ...     | 3, 2, 1.5 <sup>a</sup>               |
| 20               | ... | 2.5     | 2, 1.5, 1                   | ...              | 115 | ...     | 3, 2, 1.5 <sup>a</sup>               |
| 22               | ... | 2.5     | 2, 1.5, 1                   | 120              | ... | ...     | 3, 2, 1.5 <sup>a</sup>               |
| 24               | ... | 3       | 2, 1.5, 1                   | ...              | 125 | ...     | 3, 2, 1.5 <sup>a</sup>               |
| ...              | 25  | ...     | 2, 1.5, 1                   | 130              | ... | ...     | 3, 2, 1.5 <sup>a</sup>               |
| ...              | 26  | ...     | 1.5                         | ...              | 135 | ...     | 3, 2, 1.5 <sup>a</sup>               |
| 27               | ... | 3       | 2, 1.5, 1                   | 140              | ... | ...     | 3, 2, 1.5 <sup>a</sup>               |
| ...              | 28  | ...     | 2, 1.5, 1                   | ...              | 145 | ...     | 3, 2, 1.5 <sup>a</sup>               |
| 30               | ... | 3.5     | 3, 2, 1.5, 1                | 150              | ... | ...     | 3, 2, 1.5 <sup>a</sup>               |
| ...              | 32  | ...     | 2, 1.5                      | ...              | 155 | ...     | 3                                    |
| 33               | ... | ...     | 3, 2, 1.5                   | 160              | ... | ...     | 3                                    |
| ...              | 35  | ...     | 1.5                         | ...              | 165 | ...     | 3                                    |
| 36               | ... | 4       | 3, 2, 1.5                   | 170              | ... | ...     | 3                                    |
| ...              | 38  | ...     | 1.5                         | ...              | 175 | ...     | 3                                    |
| 39               | ... | ...     | 3, 2, 1.5                   | 180              | ... | ...     | 3                                    |
| ...              | 40  | ...     | 3, 2, 1.5                   | ...              | 185 | ...     | 3                                    |
| ...              | 42  | 4.5     | 3, 2, 1.5                   | 190              | ... | ...     | 3                                    |
| 45               | ... | ...     | 3, 2, 1.5                   | ...              | 195 | ...     | 3                                    |
| ...              | 48  | 5       | 3, 2, 1.5                   | 200              | ... | ...     | 3                                    |
| 50               | ... | ...     | 3, 2, 1.5                   | ...              | ... | ...     | ...                                  |

<sup>a</sup>Not included in ISO 261.<sup>b</sup>Only for aircraft control cable fittings.<sup>c</sup>Only for spark plugs for engines.

All dimensions are in millimeters. Pitches in parentheses ( ) are to be avoided as far as possible.

**Table 2. ANSI Standard Metric Screw Threads MJ Profile, Diameter-Pitch Combinations for Aerospace ANSI/ASME B1.21M-1997**

| Aerospace Screws, Bolts and Nuts |       |           |       |           |       |           |       | Aerospace Fluid System Fittings |       |           |       |           |       |
|----------------------------------|-------|-----------|-------|-----------|-------|-----------|-------|---------------------------------|-------|-----------|-------|-----------|-------|
| Nom. Size <sup>a</sup>           | Pitch | Nom. Size | Pitch | Nom. Size | Pitch | Nom. Size | Pitch | Nom. Size                       | Pitch | Nom. Size | Pitch | Nom. Size | Pitch |
| 1.6                              | 0.35  | 5         | 0.8   | 14        | 1.5   | 27        | 2     | 8                               | 1     | 20        | 1.5   | 36        | 1.5   |
| 2                                | 0.4   | 6         | 1     | 16        | 1.5   | 30        | 2     | 10                              | 1     | 22        | 1.5   | 39        | 1.5   |
| 2.5                              | 0.45  | 7         | 1     | 18        | 1.5   | 33        | 2     | 12                              | 1.25  | 24        | 1.5   | 42        | 2     |
| 3                                | 0.5   | 8         | 1     | 20        | 1.5   | 36        | 2     | 14                              | 1.5   | 27        | 1.5   | 48        | 2     |
| 3.5                              | 0.6   | 10        | 1.25  | 22        | 1.5   | 39        | 2     | 16                              | 1.5   | 30        | 1.5   | 50        | 2     |
| 4                                | 0.7   | 12        | 1.25  | 24        | 2     | ...       | ...   | 18                              | 1.5   | 33        | 1.5   | ...       | ...   |

All dimensions are in millimeters.

<sup>a</sup>For threads smaller than 1.6 mm nominal size, use miniature screw threads (ANSI B1.10M).

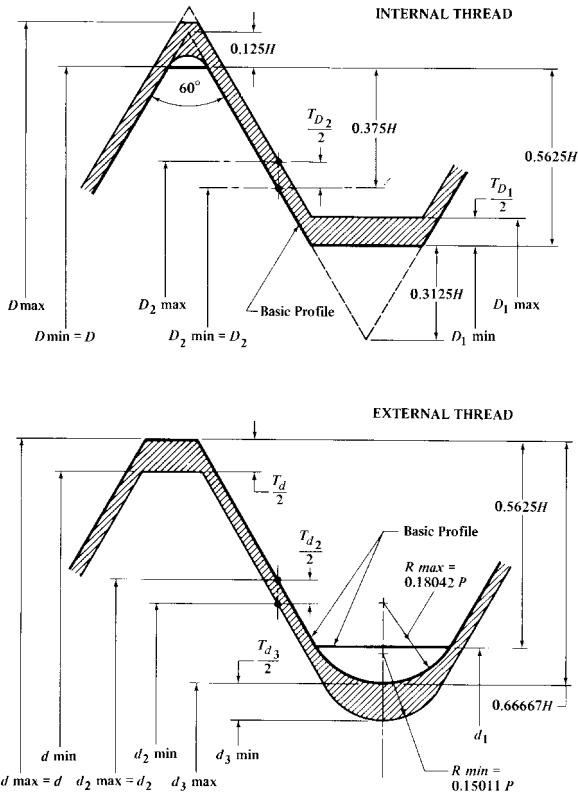


Fig. 1. Internal MJ Thread Basic and Design Profiles (Top) and External MJ Thread Basic and Design Profiles (Bottom) Showing Tolerance Zones

*Tolerances:* The thread tolerance system is based on ISO 965/1, *Metric Screw thread System of Tolerance Positions and Grades*. Tolerances are positive for internal threads and negative for external threads, that is, in the direction of minimum material.

For aerospace applications, except for fluid fittings, tolerance classes 4H5H or 4G6G and 4g6g should be used. These classes approximate classes 3B/3A in the inch system. Aerospace fluid fittings use classes 4H5H or 4H6H and 4g6g.

Tolerance classes 4G5G or 4G6G and 4g6g are provided for use when thread allowances are required. These classes provide a slightly tighter fit than the inch classes 2B/2A at minimum material condition.

Additional tolerance classes 6H/6g are included in this Standard to provide appropriate product selection based on general applications. These classes and the selection of standard diameter/pitch combinations are the same as those provided for the M profile metric screw threads in ANSI/ASME B1.13M. Classes 6H/6g result in a slightly looser fit than inch classes 2B/2A at minimum material condition.

*Symbols:* Standard symbols appearing in Fig. 1 are:

$D$  = Basic major diameter of internal thread

$D_2$  = Basic pitch diameter of internal thread

$D_1$  = Basic minor diameter of internal thread

$d$  = Basic major diameter of external thread

$d_2$  = Basic pitch diameter of external thread

$d_1$  = Basic minor diameter of internal thread

$d_3$  = Diameter to bottom of external thread root radius

$H$  = Height of fundamental triangle

$P$  = Pitch

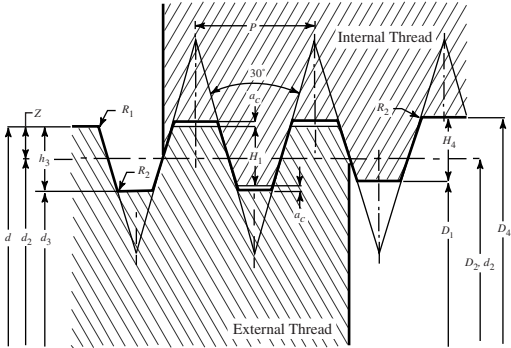
*Basic Designations:* The aerospace metric screw thread is designated by the letters "MJ" to identify the metric J thread form, followed by the nominal size and pitch in millimeters (separated by the sign "×") and followed by the tolerance class (separated by a dash from the pitch). Unless otherwise specified in the designation, the thread helix is right hand.

*Example:* MJ6 × 1 – 4h6h

For further details concerning limiting dimensions, allowances for coating and plating, modified and special threads, etc., reference should be made to the Standard.

### Trapezoidal Metric Thread

**Comparison of ISO and DIN Standards.**—ISO metric trapezoidal screw threads standard, ISO 2904-1977, describes the system of general purpose metric threads for use in mechanisms and structures. The standard is in basic agreement with trapezoidal metric thread DIN 103. The DIN 103 standard applies a particular pitch for a particular diameter of thread, but the ISO standard applies a variety of pitches for a particular diameter. In ISO 2904-1977, the same clearance is applied to both the major diameter and minor diameter, but in DIN 103 the clearance in the minor diameter is two or three times greater than clearance in the major diameter. A comparison of ISO 2904 and DIN 103 is given in Table 1.



Metric Trapezoidal Thread, ISO 2904

**Terminology:** The term "bolt threads" is used for external screw threads, the term "nut threads" for internal screw threads.

**Calculation:** The value given in the International standards have been calculated by using the following formulas:

$$\begin{aligned}
 H_1 &= 0.5P & H_4 &= H_1 + a_c = 0.5P + a_c & H_3 &= H_1 + a_c = 0.5P + a_c \\
 D_4 &= d + 2a_c & Z &= 0.25P = H_1/2 & D_1 &= d - 2H_1 = d - p \\
 D_3 &= D - 2h_3 & d_2 &= D_2 = d - 2Z = d - 0.5P & R_{1max.} &= 0.5a_c & R_{2max.} &= a_c
 \end{aligned}$$

where  $a_c$  = clearance on the crest;  $D$  = major diameter for nut threads;  $D_2$  = pitch diameter for nut threads;  $D_1$  = minor diameter for nut threads;  $d$  = major diameter for bolt threads = nominal diameter;  $d_2$  = pitch diameter for bolt threads;  $d_3$  = minor diameter for bolt threads;  $h_1$  = Height of overlapping;  $h_4$  = height of nut threads;  $h_3$  = height of bolt threads; and,  $P$  = pitch.

**Table 1. Comparison of ISO Metric Trapezoidal Screw Thread ISO 2904-1977 and Trapezoidal Metric Screw Thread DIN 103**

|                                     | ISO 2904            | DIN 103            | Comment  |
|-------------------------------------|---------------------|--------------------|----------|
| Nominal Diameter                    | $D$                 | $D_S$              |          |
| Pitch                               | $p$                 | $p$                | Same     |
| Clearances (Bolt Circle)            | $a_c$               | $b$                | Same     |
| Clearances (Nut Circle)             | $a_c$               | $a$                | Not same |
| Height of Overlapping               | $h_1$               | $h_e$              | Same     |
| Bolt Circle                         |                     |                    |          |
|                                     | $h_3 = 0.50P + a_c$ | $h_s = 0.50P + a$  | Same     |
|                                     | $h_{as} = 0.25p$    | $z = 0.25p$        | Same     |
| Minor diameter for external thread  | $D_3 = d - 2h_3$    | $k_s = d - 2h_s$   | Same     |
| Pitch diameter for external thread  | $D_2 = d - 2h_{as}$ | $d_2 = d - 2z$     | Same     |
| Nut Circle                          |                     |                    |          |
| Basic major diameter for nut thread | $D_4 = d + 2a_c$    | $d_n = d + a + b$  | Not same |
| Height of internal thread           | $h_4 = h_3$         | $h_n = h_3 + a$    | Not same |
| Minor diameter of internal thread   | $D_1 = D - 2h_1$    | $K_n = D_n - 2h_n$ | Not same |

**Table 2. ISO Metric Trapezoidal Screw Thread ISO 2904-1977**

| Nominal Diameter, $d$ |    |  | Pitch, $P$ | Pitch Diam.<br>$d_2 = D_2$ | Major Diam.<br>$D_4$ | Minor Diameter |        |
|-----------------------|----|--|------------|----------------------------|----------------------|----------------|--------|
|                       |    |  |            |                            |                      | $d_3$          | $D_1$  |
| 8                     |    |  | 1.5        | 7.250                      | 8.300                | 6.200          | 6.500  |
|                       |    |  | 2          | 8.000                      | 9.500                | 6.500          | 7.000  |
| 10                    |    |  | 1.5        | 9.250                      | 10.300               | 8.200          | 8.500  |
|                       |    |  | 2          | 9.000                      | 10.500               | 7.500          | 8.000  |
|                       | 11 |  | 2          | 10.000                     | 11.500               | 8.500          | 9.000  |
|                       |    |  | 3          | 9.500                      | 11.500               | 7.500          | 8.000  |
| 12                    |    |  | 2          | 11.000                     | 12.500               | 9.500          | 10.000 |
|                       |    |  | 3          | 10.500                     | 12.500               | 8.500          | 9.000  |
|                       | 14 |  | 2          | 13.000                     | 14.500               | 11.500         | 12.000 |
|                       |    |  | 3          | 12.500                     | 14.500               | 10.500         | 11.000 |
| 16                    |    |  | 2          | 15.000                     | 16.500               | 13.500         | 14.000 |
|                       |    |  | 3          | 14.500                     | 16.500               | 12.500         | 13.000 |
|                       | 18 |  | 2          | 17.000                     | 18.500               | 15.500         | 16.000 |
|                       |    |  | 4          | 16.000                     | 18.500               | 13.500         | 14.000 |
| 20                    |    |  | 2          | 19.000                     | 20.500               | 17.500         | 18.000 |
|                       |    |  | 4          | 18.000                     | 20.500               | 15.500         | 16.000 |
|                       | 22 |  | 3          | 20.500                     | 22.500               | 18.500         | 19.000 |
|                       |    |  | 5          | 19.500                     | 22.500               | 16.500         | 17.000 |
|                       |    |  | 8          | 18.000                     | 23.000               | 13.000         | 14.000 |
| 24                    |    |  | 3          | 22.500                     | 24.500               | 20.500         | 21.000 |
|                       |    |  | 5          | 21.500                     | 24.500               | 18.500         | 19.000 |
|                       |    |  | 8          | 20.000                     | 25.000               | 15.000         | 16.000 |
|                       | 26 |  | 3          | 24.500                     | 26.500               | 22.500         | 23.000 |
|                       |    |  | 5          | 23.500                     | 26.500               | 20.500         | 21.000 |
|                       |    |  | 8          | 22.000                     | 27.000               | 17.000         | 18.000 |
| 28                    |    |  | 3          | 26.500                     | 28.500               | 24.500         | 25.000 |
|                       |    |  | 5          | 25.500                     | 28.500               | 22.500         | 23.000 |
|                       |    |  | 8          | 24.000                     | 29.000               | 19.000         | 20.000 |
|                       | 30 |  | 3          | 28.500                     | 30.500               | 26.500         | 27.000 |
|                       |    |  | 6          | 27.000                     | 31.000               | 23.000         | 24.000 |
|                       |    |  | 10         | 25.000                     | 31.000               | 19.000         | 20.000 |
| 32                    |    |  | 3          | 30.500                     | 32.500               | 28.500         | 29.000 |
|                       |    |  | 6          | 29.000                     | 33.000               | 25.000         | 26.000 |
|                       |    |  | 10         | 27.000                     | 33.000               | 21.000         | 22.000 |
|                       | 34 |  | 3          | 32.500                     | 34.500               | 30.500         | 31.000 |
|                       |    |  | 6          | 31.000                     | 35.000               | 27.000         | 28.000 |
|                       |    |  | 10         | 29.000                     | 35.000               | 23.000         | 24.000 |
| 36                    |    |  | 3          | 34.500                     | 36.500               | 32.500         | 33.000 |
|                       |    |  | 6          | 33.000                     | 37.000               | 29.000         | 30.000 |
|                       |    |  | 10         | 31.000                     | 37.000               | 25.000         | 26.000 |
|                       | 38 |  | 3          | 36.500                     | 38.500               | 34.500         | 35.000 |
|                       |    |  | 7          | 34.500                     | 39.000               | 30.000         | 31.000 |
|                       |    |  | 10         | 33.000                     | 39.000               | 27.000         | 28.000 |
| 40                    |    |  | 3          | 38.500                     | 40.500               | 36.500         | 37.000 |
|                       |    |  | 7          | 36.500                     | 41.000               | 32.000         | 33.000 |
|                       |    |  | 10         | 35.000                     | 41.000               | 29.000         | 30.000 |

**Table 2. (Continued) ISO Metric Trapezoidal Screw Thread ISO 2904-1977**

| Nominal Diameter, $d$ |  |  | Pitch, $P$ | Pitch Diam.<br>$d_2 = D_2$ | Major Diam.<br>$D_4$ | Minor Diameter |        |
|-----------------------|--|--|------------|----------------------------|----------------------|----------------|--------|
|                       |  |  |            |                            |                      | $d_3$          | $D_1$  |
| 42                    |  |  | 3          | 40.500                     | 42.500               | 38.500         | 39.000 |
|                       |  |  | 7          | 38.500                     | 43.000               | 34.000         | 35.000 |
|                       |  |  | 10         | 37.000                     | 43.000               | 31.000         | 32.000 |
| 44                    |  |  | 3          | 42.500                     | 44.500               | 40.500         | 41.000 |
|                       |  |  | 7          | 40.500                     | 45.000               | 36.000         | 37.000 |
|                       |  |  | 12         | 38.000                     | 45.000               | 31.000         | 32.000 |
| 46                    |  |  | 3          | 44.500                     | 46.500               | 42.500         | 43.000 |
|                       |  |  | 8          | 42.000                     | 47.000               | 37.000         | 38.000 |
|                       |  |  | 12         | 40.000                     | 47.000               | 33.000         | 34.000 |
| 48                    |  |  | 3          | 46.500                     | 48.500               | 44.500         | 45.000 |
|                       |  |  | 8          | 44.000                     | 49.000               | 39.000         | 40.000 |
|                       |  |  | 12         | 42.000                     | 49.000               | 35.000         | 36.000 |
| 50                    |  |  | 3          | 48.500                     | 50.500               | 46.500         | 47.000 |
|                       |  |  | 8          | 46.000                     | 51.000               | 41.000         | 42.000 |
|                       |  |  | 12         | 44.000                     | 51.000               | 37.000         | 38.000 |
| 52                    |  |  | 3          | 50.500                     | 52.500               | 48.500         | 49.000 |
|                       |  |  | 8          | 48.000                     | 53.000               | 43.000         | 44.000 |
|                       |  |  | 12         | 46.000                     | 53.000               | 39.000         | 40.000 |
| 55                    |  |  | 3          | 53.500                     | 55.500               | 51.500         | 52.000 |
|                       |  |  | 9          | 50.500                     | 56.000               | 45.000         | 46.000 |
|                       |  |  | 14         | 48.000                     | 57.000               | 39.000         | 41.000 |
| 60                    |  |  | 3          | 58.500                     | 60.500               | 56.500         | 57.000 |
|                       |  |  | 9          | 55.500                     | 61.000               | 50.000         | 51.000 |
|                       |  |  | 14         | 53.000                     | 62.000               | 44.000         | 46.000 |
| 65                    |  |  | 4          | 63.000                     | 65.500               | 60.500         | 61.000 |
|                       |  |  | 10         | 60.000                     | 66.000               | 54.000         | 55.000 |
|                       |  |  | 16         | 57.000                     | 67.000               | 47.000         | 49.000 |
| 70                    |  |  | 4          | 68.000                     | 70.500               | 65.500         | 66.000 |
|                       |  |  | 10         | 65.000                     | 71.000               | 59.000         | 60.000 |
|                       |  |  | 16         | 62.000                     | 72.000               | 52.000         | 54.000 |
| 75                    |  |  | 4          | 73.000                     | 75.500               | 70.500         | 71.000 |
|                       |  |  | 10         | 70.000                     | 76.000               | 64.000         | 65.000 |
|                       |  |  | 16         | 67.000                     | 77.000               | 57.000         | 59.000 |
| 80                    |  |  | 4          | 78.000                     | 80.500               | 75.500         | 76.000 |
|                       |  |  | 10         | 75.000                     | 81.000               | 69.000         | 70.000 |
|                       |  |  | 16         | 72.000                     | 82.000               | 62.000         | 64.000 |
| 85                    |  |  | 4          | 83.000                     | 85.500               | 80.500         | 81.000 |
|                       |  |  | 12         | 79.000                     | 86.000               | 72.000         | 73.000 |
|                       |  |  | 18         | 76.000                     | 87.000               | 65.000         | 67.000 |
| 90                    |  |  | 4          | 88.000                     | 90.500               | 85.500         | 86.000 |
|                       |  |  | 12         | 84.000                     | 91.000               | 77.000         | 78.000 |
|                       |  |  | 18         | 81.000                     | 92.000               | 70.000         | 72.000 |
| 95                    |  |  | 4          | 93.000                     | 95.500               | 90.500         | 91.000 |
|                       |  |  | 12         | 89.000                     | 96.000               | 82.000         | 83.000 |
| 95                    |  |  | 18         | 86.000                     | 97.000               | 75.000         | 77.000 |
|                       |  |  | 4          | 98.000                     | 100.500              | 95.500         | 96.000 |
| 100                   |  |  | 12         | 94.000                     | 101.000              | 87.000         | 88.000 |
|                       |  |  | 20         | 90.000                     | 102.000              | 78.000         | 80.000 |

**Table 2. (Continued) ISO Metric Trapezoidal Screw Thread ISO 2904-1977**

| Nominal Diameter, $d$ |     |    | Pitch, $P$ | Pitch Diam.<br>$d_2 = D_2$ | Major Diam.<br>$D_4$ | Minor Diameter |         |
|-----------------------|-----|----|------------|----------------------------|----------------------|----------------|---------|
|                       |     |    |            |                            |                      | $d_3$          | $D_1$   |
|                       | 105 | 4  | 4          | 103.000                    | 105.500              | 100.500        | 101.000 |
|                       |     | 12 | 12         | 103.000                    | 106.000              | 92.000         | 93.000  |
|                       |     | 20 | 20         | 95.000                     | 107.000              | 83.000         | 85.000  |
|                       | 110 | 4  | 4          | 108.000                    | 110.500              | 105.500        | 106.000 |
|                       |     | 12 | 12         | 104.000                    | 111.000              | 97.000         | 98.000  |
|                       |     | 20 | 20         | 100.000                    | 112.000              | 88.000         | 90.000  |
|                       | 115 | 6  | 6          | 112.000                    | 116.000              | 108.000        | 109.000 |
|                       |     | 14 | 14         | 112.000                    | 117.000              | 99.000         | 101.000 |
|                       |     | 22 | 22         | 104.000                    | 117.000              | 91.000         | 93.000  |
| 120                   |     | 6  | 6          | 117.000                    | 121.000              | 113.000        | 114.000 |
|                       |     | 14 | 14         | 113.000                    | 122.000              | 104.000        | 106.000 |
|                       |     | 22 | 22         | 109.000                    | 122.000              | 96.000         | 98.000  |
|                       | 125 | 6  | 6          | 122.000                    | 126.000              | 118.000        | 119.000 |
|                       |     | 14 | 14         | 122.000                    | 127.000              | 109.000        | 111.000 |
|                       |     | 22 | 22         | 114.000                    | 127.000              | 101.000        | 103.000 |
|                       | 130 | 6  | 6          | 127.000                    | 131.000              | 123.000        | 124.000 |
|                       |     | 14 | 14         | 123.000                    | 132.000              | 114.000        | 116.000 |
|                       |     | 22 | 22         | 119.000                    | 132.000              | 106.000        | 108.000 |
|                       | 135 | 6  | 6          | 132.000                    | 136.000              | 128.000        | 129.000 |
|                       |     | 14 | 14         | 132.000                    | 137.000              | 119.000        | 121.000 |
|                       |     | 24 | 24         | 123.000                    | 137.000              | 109.000        | 111.000 |
| 140                   |     | 6  | 6          | 137.000                    | 141.000              | 133.000        | 134.000 |
|                       |     | 14 | 14         | 133.000                    | 142.000              | 124.000        | 126.000 |
|                       |     | 24 | 24         | 128.000                    | 142.000              | 114.000        | 116.000 |
|                       | 145 | 6  | 6          | 142.000                    | 146.000              | 138.000        | 139.000 |
|                       |     | 14 | 14         | 142.000                    | 147.000              | 129.000        | 131.000 |
|                       |     | 24 | 24         | 133.000                    | 147.000              | 119.000        | 121.000 |
|                       | 150 | 6  | 6          | 147.000                    | 151.000              | 143.000        | 144.000 |
|                       |     | 16 | 16         | 142.000                    | 152.000              | 132.000        | 134.000 |
|                       |     | 24 | 24         | 138.000                    | 152.000              | 124.000        | 126.000 |
|                       | 155 | 6  | 6          | 152.000                    | 156.000              | 148.000        | 149.000 |
|                       |     | 16 | 16         | 152.000                    | 157.000              | 137.000        | 139.000 |
|                       |     | 24 | 24         | 143.000                    | 157.000              | 129.000        | 131.000 |
| 160                   |     | 6  | 6          | 157.000                    | 161.000              | 153.000        | 154.000 |
|                       |     | 16 | 16         | 152.000                    | 162.000              | 142.000        | 144.000 |
|                       |     | 28 | 28         | 146.000                    | 162.000              | 130.000        | 132.000 |
|                       | 165 | 6  | 6          | 162.000                    | 166.000              | 158.000        | 159.000 |
|                       |     | 16 | 16         | 162.000                    | 167.000              | 147.000        | 149.000 |
|                       |     | 28 | 28         | 151.000                    | 167.000              | 135.000        | 137.000 |
|                       | 170 | 6  | 6          | 167.000                    | 171.000              | 163.000        | 164.000 |
|                       |     | 16 | 16         | 162.000                    | 172.000              | 152.000        | 154.000 |
|                       |     | 28 | 28         | 156.000                    | 172.000              | 140.000        | 142.000 |
|                       | 175 | 8  | 8          | 171.000                    | 176.000              | 166.000        | 167.000 |
|                       |     | 16 | 16         | 171.000                    | 177.000              | 157.000        | 159.000 |
|                       |     | 28 | 28         | 161.000                    | 177.000              | 145.000        | 147.000 |
| 180                   |     | 8  | 8          | 176.000                    | 181.000              | 171.000        | 172.000 |
|                       |     | 18 | 18         | 171.000                    | 182.000              | 160.000        | 162.000 |
|                       |     | 28 | 28         | 166.000                    | 182.000              | 150.000        | 152.000 |



**Table 2. (Continued) ISO Metric Trapezoidal Screw Thread ISO 2904-1977**

| Nominal Diameter, $d$ |  |  | Pitch, $P$ | Pitch Diam.<br>$d_2 = D_2$ | Major Diam.<br>$D_4$ | Minor Diameter |         |
|-----------------------|--|--|------------|----------------------------|----------------------|----------------|---------|
|                       |  |  |            |                            |                      | $d_3$          | $D_1$   |
| 185                   |  |  | 8          | 181.000                    | 186.000              | 176.000        | 177.000 |
|                       |  |  | 18         | 181.000                    | 187.000              | 165.000        | 167.000 |
|                       |  |  | 32         | 169.000                    | 187.000              | 151.000        | 153.000 |
| 190                   |  |  | 8          | 186.000                    | 191.000              | 181.000        | 182.000 |
|                       |  |  | 18         | 181.000                    | 192.000              | 170.000        | 172.000 |
|                       |  |  | 32         | 174.000                    | 192.000              | 156.000        | 158.000 |
| 195                   |  |  | 8          | 191.000                    | 196.000              | 186.000        | 187.000 |
|                       |  |  | 18         | 191.000                    | 197.000              | 175.000        | 177.000 |
|                       |  |  | 32         | 179.000                    | 197.000              | 161.000        | 163.000 |
| 200                   |  |  | 8          | 196.000                    | 201.000              | 191.000        | 192.000 |
|                       |  |  | 18         | 191.000                    | 202.000              | 180.000        | 182.000 |
|                       |  |  | 32         | 184.000                    | 202.000              | 166.000        | 168.000 |
| 210                   |  |  | 8          | 206.000                    | 211.000              | 201.000        | 202.000 |
|                       |  |  | 20         | 200.000                    | 212.000              | 188.000        | 190.000 |
|                       |  |  | 36         | 192.000                    | 212.000              | 172.000        | 174.000 |
| 220                   |  |  | 8          | 216.000                    | 221.000              | 211.000        | 212.000 |
|                       |  |  | 20         | 210.000                    | 222.000              | 198.000        | 200.000 |
|                       |  |  | 36         | 202.000                    | 222.000              | 182.000        | 184.000 |
| 230                   |  |  | 8          | 226.000                    | 231.000              | 221.000        | 222.000 |
|                       |  |  | 20         | 220.000                    | 232.000              | 208.000        | 210.000 |
|                       |  |  | 36         | 212.000                    | 232.000              | 192.000        | 194.000 |
| 240                   |  |  | 8          | 236.000                    | 241.000              | 231.000        | 232.000 |
|                       |  |  | 22         | 229.000                    | 242.000              | 216.000        | 218.000 |
|                       |  |  | 36         | 222.000                    | 242.000              | 202.000        | 204.000 |
| 250                   |  |  | 12         | 244.000                    | 251.000              | 237.000        | 238.000 |
|                       |  |  | 22         | 239.000                    | 252.000              | 226.000        | 228.000 |
|                       |  |  | 40         | 230.000                    | 252.000              | 208.000        | 210.000 |
| 260                   |  |  | 12         | 254.000                    | 261.000              | 247.000        | 248.000 |
|                       |  |  | 22         | 249.000                    | 262.000              | 236.000        | 238.000 |
|                       |  |  | 40         | 240.000                    | 262.000              | 218.000        | 220.000 |
| 270                   |  |  | 12         | 264.000                    | 271.000              | 257.000        | 258.000 |
|                       |  |  | 24         | 258.000                    | 272.000              | 244.000        | 246.000 |
|                       |  |  | 40         | 250.000                    | 272.000              | 228.000        | 230.000 |
| 280                   |  |  | 12         | 274.000                    | 281.000              | 267.000        | 268.000 |
|                       |  |  | 24         | 268.000                    | 282.000              | 254.000        | 256.000 |
|                       |  |  | 40         | 260.000                    | 282.000              | 238.000        | 240.000 |
| 290                   |  |  | 12         | 284.000                    | 291.000              | 277.000        | 278.000 |
|                       |  |  | 24         | 278.000                    | 292.000              | 264.000        | 266.000 |
|                       |  |  | 44         | 268.000                    | 292.000              | 244.000        | 246.000 |
| 300                   |  |  | 12         | 294.000                    | 301.000              | 287.000        | 288.000 |
|                       |  |  | 24         | 288.000                    | 302.000              | 274.000        | 276.000 |
|                       |  |  | 44         | 278.000                    | 302.000              | 254.000        | 256.000 |

All dimensions in millimeters

Trapezoidal Metric Thread — Preferred Basic Sizes DIN 103

$H = 1.866P$   
 $h_e = 0.5P + a$   
 $h_n = 0.5P + a - b$   
 $h_{as} = 0.5P + 2a - b$   
 $h_{as} = 0.25P$

| Nom. & Major Diam. of Bolt, $D_s$ | Pitch, $P$ | Pitch Diam., $E$ | Depth of Engagement, $h_e$ | Clearance |      | Bolt               |                        | Nut                |                    |                        |
|-----------------------------------|------------|------------------|----------------------------|-----------|------|--------------------|------------------------|--------------------|--------------------|------------------------|
|                                   |            |                  |                            | $a$       | $b$  | Minor Diam., $K_s$ | Depth of Thread, $h_s$ | Major Diam., $D_n$ | Minor Diam., $K_n$ | Depth of Thread, $h_n$ |
|                                   |            |                  |                            |           |      |                    |                        |                    |                    |                        |
| 10                                | 3          | 8.5              | 1.25                       | 0.25      | 0.5  | 6.5                | 1.75                   | 10.5               | 7.5                | 1.50                   |
| 12                                | 3          | 10.5             | 1.25                       | 0.25      | 0.5  | 8.5                | 1.75                   | 12.5               | 9.5                | 1.50                   |
| 14                                | 4          | 12               | 1.75                       | 0.25      | 0.5  | 9.5                | 2.25                   | 14.5               | 10.5               | 2.00                   |
| 16                                | 4          | 14               | 1.75                       | 0.25      | 0.5  | 11.5               | 2.25                   | 16.5               | 12.5               | 2.00                   |
| 18                                | 4          | 16               | 1.75                       | 0.25      | 0.5  | 13.5               | 2.25                   | 18.5               | 14.5               | 2.00                   |
| 20                                | 4          | 18               | 1.75                       | 0.25      | 0.5  | 15.5               | 2.25                   | 20.5               | 16.5               | 2.00                   |
| 22                                | 5          | 19.5             | 2                          | 0.25      | 0.75 | 16.5               | 2.75                   | 22.5               | 18                 | 2.00                   |
| 24                                | 5          | 21.5             | 2                          | 0.25      | 0.75 | 18.5               | 2.75                   | 24.5               | 20                 | 2.25                   |
| 26                                | 5          | 23.5             | 2                          | 0.25      | 0.75 | 20.5               | 2.75                   | 26.5               | 22                 | 2.25                   |
| 28                                | 5          | 25.5             | 2                          | 0.25      | 0.75 | 22.5               | 2.75                   | 28.5               | 24                 | 2.25                   |
| 30                                | 6          | 27               | 2.5                        | 0.25      | 0.75 | 23.5               | 3.25                   | 30.5               | 25                 | 2.75                   |
| 32                                | 6          | 29               | 2.5                        | 0.25      | 0.75 | 25.5               | 3.25                   | 32.5               | 27                 | 2.75                   |
| 36                                | 6          | 33               | 2.5                        | 0.25      | 0.75 | 29.5               | 3.25                   | 36.5               | 31                 | 2.75                   |
| 40                                | 7          | 36.5             | 3                          | 0.25      | 0.75 | 32.5               | 3.75                   | 40.5               | 34                 | 3.25                   |
| 44                                | 7          | 40.5             | 3                          | 0.25      | 0.75 | 36.5               | 3.75                   | 44.5               | 38                 | 3.25                   |
| 48                                | 8          | 44               | 3.5                        | 0.25      | 0.75 | 39.5               | 4.25                   | 48.5               | 41                 | 3.75                   |
| 50                                | 8          | 46               | 3.5                        | 0.25      | 0.75 | 41.5               | 4.25                   | 50.5               | 43                 | 3.75                   |
| 52                                | 8          | 48               | 3.5                        | 0.25      | 0.75 | 43.5               | 4.25                   | 52.5               | 45                 | 3.75                   |
| 55                                | 9          | 50.5             | 4                          | 0.25      | 0.75 | 45.5               | 4.75                   | 55.5               | 47                 | 4.25                   |
| 60                                | 9          | 55.5             | 4                          | 0.25      | 0.75 | 50.5               | 4.75                   | 60.5               | 52                 | 4.25                   |
| 65                                | 10         | 60               | 4.5                        | 0.25      | 0.75 | 54.5               | 5.25                   | 65.5               | 56                 | 4.75                   |
| 70                                | 10         | 65               | 4.5                        | 0.25      | 0.75 | 59.5               | 5.25                   | 70.5               | 61                 | 4.75                   |
| 75                                | 10         | 70               | 4.5                        | 0.25      | 0.75 | 64.5               | 5.25                   | 75.5               | 66                 | 4.75                   |
| 80                                | 10         | 75               | 4.5                        | 0.25      | 0.75 | 69.5               | 5.25                   | 80.5               | 71                 | 4.75                   |
| 85                                | 12         | 79               | 5.5                        | 0.25      | 0.75 | 72.5               | 6.25                   | 85.5               | 74                 | 5.75                   |
| 90                                | 12         | 84               | 5.5                        | 0.25      | 0.75 | 77.5               | 6.25                   | 90.5               | 79                 | 5.75                   |
| 95                                | 12         | 89               | 5.5                        | 0.25      | 0.75 | 82.5               | 6.25                   | 95.5               | 84                 | 5.75                   |
| 100                               | 12         | 94               | 5.5                        | 0.25      | 0.75 | 87.5               | 6.25                   | 100.5              | 89                 | 5.75                   |
| 110                               | 12         | 104              | 5.5                        | 0.25      | 0.75 | 97.5               | 6.25                   | 110.5              | 99                 | 5.75                   |
| 120                               | 14         | 113              | 6                          | 0.5       | 1.5  | 105                | 7.5                    | 121                | 108                | 6.5                    |
| 130                               | 14         | 123              | 6                          | 0.5       | 1.5  | 115                | 7.5                    | 131                | 118                | 6.5                    |
| 140                               | 14         | 133              | 6                          | 0.5       | 1.5  | 125                | 7.5                    | 141                | 128                | 6.5                    |
| 150                               | 16         | 142              | 7                          | 0.5       | 1.5  | 133                | 8.5                    | 151                | 136                | 7.5                    |
| 160                               | 16         | 152              | 7                          | 0.5       | 1.5  | 143                | 8.5                    | 161                | 146                | 7.5                    |
| 170                               | 16         | 162              | 7                          | 0.5       | 1.5  | 153                | 8.5                    | 171                | 156                | 7.5                    |
| 180                               | 18         | 171              | 8                          | 0.5       | 1.5  | 161                | 9.5                    | 181                | 164                | 8.5                    |
| 190                               | 18         | 181              | 8                          | 0.5       | 1.5  | 171                | 9.5                    | 191                | 174                | 8.5                    |
| 200                               | 18         | 191              | 8                          | 0.5       | 1.5  | 181                | 9.5                    | 201                | 184                | 8.5                    |
| 210                               | 20         | 200              | 9                          | 0.5       | 1.5  | 189                | 10.5                   | 211                | 192                | 9.5                    |
| 220                               | 20         | 210              | 9                          | 0.5       | 1.5  | 199                | 10.5                   | 221                | 202                | 9.5                    |
| 230                               | 20         | 220              | 9                          | 0.5       | 1.5  | 209                | 10.5                   | 231                | 212                | 9.5                    |
| 240                               | 22         | 229              | 10                         | 0.5       | 1.5  | 217                | 11.5                   | 241                | 220                | 10.5                   |
| 250                               | 22         | 239              | 10                         | 0.5       | 1.5  | 227                | 11.5                   | 251                | 230                | 10.5                   |
| 260                               | 22         | 249              | 10                         | 0.5       | 1.5  | 237                | 11.5                   | 261                | 240                | 10.5                   |
| 270                               | 24         | 258              | 11                         | 0.5       | 1.5  | 245                | 12.5                   | 271                | 248                | 11.5                   |
| 280                               | 24         | 268              | 11                         | 0.5       | 1.5  | 255                | 12.5                   | 281                | 258                | 11.5                   |
| 290                               | 24         | 278              | 11                         | 0.5       | 1.5  | 265                | 12.5                   | 291                | 268                | 11.5                   |
| 300                               | 26         | 287              | 12                         | 0.5       | 1.5  | 273                | 13.5                   | 301                | 276                | 12.5                   |

All dimensions are in millimeters.

\*Roots are rounded to a radius,  $r$ , equal to 0.25 mm for pitches of from 3 to 12 mm inclusive and 0.5 mm for pitches of from 14 to 26 mm inclusive for power transmission.

## ISO Miniature Screw Threads

## ISO Miniature Screw Threads, Basic Form ISO/R 1501:1970

| Pitch<br>$P$ | $H = 0.866025P$ | $0.554256H = 0.48P$ | $0.375H = 0.324760P$ | $0.320744H = 0.320744P$ | $0.125H = 0.108253P$ |
|--------------|-----------------|---------------------|----------------------|-------------------------|----------------------|
| 0.08         | 0.069282        | 0.038400            | 0.025981             | 0.022222                | 0.008660             |
| 0.09         | 0.077942        | 0.043200            | 0.029228             | 0.024999                | 0.009743             |
| 0.1          | 0.086603        | 0.048000            | 0.032476             | 0.027777                | 0.010825             |
| 0.125        | 0.108253        | 0.060000            | 0.040595             | 0.034722                | 0.013532             |
| 0.15         | 0.129904        | 0.072000            | 0.048714             | 0.041666                | 0.016238             |
| 0.175        | 0.151554        | 0.084000            | 0.056833             | 0.048610                | 0.018944             |
| 0.2          | 0.173205        | 0.096000            | 0.064952             | 0.055554                | 0.021651             |
| 0.225        | 0.194856        | 0.108000            | 0.073071             | 0.062499                | 0.024357             |
| 0.25         | 0.216506        | 0.120000            | 0.081190             | 0.069443                | 0.027063             |
| 0.3          | 0.259808        | 0.144000            | 0.097428             | 0.083332                | 0.032476             |

## ISO Miniature Screw Threads, Basic Dimensions ISO/R 1501:1970

| Nominal Diameter | Pitch<br>$P$ | Major Diameter<br>$D, d$ | Pitch Diameter<br>$D_2, d_2$ | Minor Diameter<br>$D_1, d_1$ |
|------------------|--------------|--------------------------|------------------------------|------------------------------|
| 0.30             | 0.080        | 0.300000                 | 0.248039                     | 0.223200                     |
| 0.35             | 0.090        | 0.350000                 | 0.291543                     | 0.263600                     |
| 0.40             | 0.100        | 0.400000                 | 0.335048                     | 0.304000                     |
| 0.45             | 0.100        | 0.450000                 | 0.385048                     | 0.354000                     |
| 0.50             | 0.125        | 0.500000                 | 0.418810                     | 0.380000                     |
| 0.55             | 0.125        | 0.550000                 | 0.468810                     | 0.430000                     |
| 0.60             | 0.150        | 0.600000                 | 0.502572                     | 0.456000                     |
| 0.70             | 0.175        | 0.700000                 | 0.586334                     | 0.532000                     |
| 0.80             | 0.200        | 0.800000                 | 0.670096                     | 0.608000                     |
| 0.90             | 0.225        | 0.900000                 | 0.753858                     | 0.684000                     |
| 1.00             | 0.250        | 1.000000                 | 0.837620                     | 0.760000                     |
| 1.10             | 0.250        | 1.100000                 | 0.937620                     | 0.860000                     |
| 1.20             | 0.250        | 1.200000                 | 1.037620                     | 0.960000                     |
| 1.40             | 0.300        | 1.400000                 | 1.205144                     | 1.112000                     |

$D$  and  $d$  dimensions refer to the nut (internal) and screw (external) threads, respectively.

## British Standard ISO Metric Screw Threads

BS 3643:Part 1:1981 (1998) provides principles and basic data for ISO metric screw threads. It covers single-start, parallel screw threads of from 1 to 300 millimeters in diameter. Part 2 of the Standard gives the specifications for selected limits of size.

**Basic Profile.**—The ISO basic profile for triangular screw threads is shown in Fig. 1, and basic dimensions of this profile are given in Table 1.

**Table 1. British Standard ISO Metric Screw Threads  
Basic Profile Dimensions BS 3643:1981 (1998)**

| Pitch<br>$P$ | $H = 0.86603P$ | $\frac{5}{8}H = 0.54127P$ | $\frac{3}{8}H = 0.32476P$ | $H/4 = 0.21651P$ | $H/8 = 0.10825P$ |
|--------------|----------------|---------------------------|---------------------------|------------------|------------------|
| 0.2          | 0.173 205      | 0.108 253                 | 0.064 952                 | 0.043 301        | 0.021 651        |
| 0.25         | 0.216 506      | 0.135 316                 | 0.081 190                 | 0.054 127        | 0.027 063        |
| 0.3          | 0.259 808      | 0.162 380                 | 0.097 428                 | 0.064 952        | 0.032 476        |
| 0.35         | 0.303 109      | 0.189 443                 | 0.113 666                 | 0.075 777        | 0.037 889        |
| 0.4          | 0.346 410      | 0.216 506                 | 0.129 904                 | 0.086 603        | 0.043 301        |
| 0.45         | 0.389 711      | 0.243 570                 | 0.146 142                 | 0.097 428        | 0.048 714        |
| 0.5          | 0.433 013      | 0.270 633                 | 0.162 380                 | 0.108 253        | 0.054 127        |
| 0.6          | 0.519 615      | 0.324 760                 | 0.194 856                 | 0.129 904        | 0.064 952        |

**Table 1. (Continued) British Standard ISO Metric Screw Threads  
Basic Profile Dimensions BS 3643:1981 (1998)**

| Pitch<br><i>P</i> | <i>H</i> =<br>0.086603 <i>P</i> | $\frac{5}{8}H$ =<br>0.54127 <i>P</i> | $\frac{3}{8}H$ =<br>0.32476 <i>P</i> | <i>H</i> /4 =<br>0.21651 <i>P</i> | <i>H</i> /8 =<br>0.10825 <i>P</i> |
|-------------------|---------------------------------|--------------------------------------|--------------------------------------|-----------------------------------|-----------------------------------|
| 0.7               | 0.606 218                       | 0.378 886                            | 0.227 322                            | 0.151 554                         | 0.075 777                         |
| 0.75              | 0.649 519                       | 0.405 949                            | 0.243 570                            | 0.162 380                         | 0.081 190                         |
| 0.8               | 0.692 820                       | 0.433 013                            | 0.259 808                            | 0.173 205                         | 0.086 603                         |
| 1                 | 0.866 025                       | 0.541 266                            | 0.324 760                            | 0.216 506                         | 0.108 253                         |
| 1.25              | 1.082 532                       | 0.676 582                            | 0.405 949                            | 0.270 633                         | 0.135 316                         |
| 1.5               | 1.299 038                       | 0.811 899                            | 0.487 139                            | 0.324 760                         | 0.162 380                         |
| 1.75              | 1.515 544                       | 0.947 215                            | 0.568 329                            | 0.378 886                         | 0.189 443                         |
| 2                 | 1.732 051                       | 1.082 532                            | 0.649 519                            | 0.433 013                         | 0.216 506                         |
| 2.5               | 2.165 063                       | 1.353 165                            | 0.811 899                            | 0.541 266                         | 0.270 633                         |
| 3                 | 2.598 076                       | 1.623 798                            | 0.974 279                            | 0.649 519                         | 0.324 760                         |
| 3.5               | 3.031 089                       | 1.894 431                            | 1.136 658                            | 0.757 772                         | 0.378 886                         |
| 4                 | 3.464 102                       | 2.165 063                            | 1.299 038                            | 0.866 025                         | 0.433 013                         |
| 4.5               | 3.897 114                       | 2.435 696                            | 1.461 418                            | 0.974 279                         | 0.487 139                         |
| 5                 | 4.330 127                       | 2.706 329                            | 1.623 798                            | 1.082 532                         | 0.541 266                         |
| 5.5               | 4.763 140                       | 2.976 962                            | 1.786 177                            | 1.190 785                         | 0.595 392                         |
| 6                 | 5.196 152                       | 3.247 595                            | 1.948 557                            | 1.299 038                         | 0.649 519                         |
| 8 <sup>a</sup>    | 6.928 203                       | 4.330 127                            | 2.598 076                            | 1.732 051                         | 0.866 025                         |

<sup>a</sup>This pitch is not used in any of the ISO metric standard series.  
All dimensions are given in millimeters.

**Tolerance System.**—The tolerance system defines *tolerance classes* in terms of a combination of a *tolerance grade* (figure) and a *tolerance position* (letter). The tolerance position is defined by the distance between the basic size and the nearest end of the tolerance zone, this distance being known as the *fundamental deviation*, EI, in the case of internal threads, and es in the case of external threads. These tolerance positions with respect to the basic size (zero line) are shown in Fig. 2 and fundamental deviations for nut and bolt threads are given in Table 2.

**Table 2. Fundamental Deviations for Nut Threads and Bolt Threads**

| Pitch<br><i>P</i><br>mm | Nut Thread<br><i>D</i> <sub>2</sub> , <i>D</i> <sub>1</sub> |    | Bolt Thread<br><i>d</i> , <i>d</i> <sub>2</sub> |     |     |    | Pitch<br><i>P</i><br>mm | Nut Thread<br><i>D</i> <sub>2</sub> , <i>D</i> <sub>1</sub> |    | Bolt Thread<br><i>d</i> , <i>d</i> <sub>2</sub> |     |     |    |
|-------------------------|---|----|---|-----|-----|----|-------------------------|---|----|---|-----|-----|----|
|                         | Tolerance Position  |    |   |     |     |    |                         | Tolerance Position  |    |   |     |     |    |
|                         | G   | H  | e   | f   | g   | h  |                         | G   | H  | e   | f   | g   | h  |
|                         | Fundamental Deviation                                       |    |   |     |     |    |                         | Fundamental Deviation                                       |    |   |     |     |    |
|                         | EI  | EI | es  | es  | es  | es |                         | EI  | EI | es  | es  | es  | es |
| μm                      | μm  | μm | μm  | μm  | μm  | μm | μm                      | μm  | μm | μm  | μm  |     |    |
| 0.2                     | +17   | 0  | ...   | ... | -17 | 0  | 1.25                    | +28   | 0  | -63   | -42 | -28 | 0  |
| 0.25                    | +18   | 0  | ...   | ... | -18 | 0  | 1.5                     | +32   | 0  | -67   | -45 | -32 | 0  |
| 0.3                     | +18   | 0  | ...   | ... | -18 | 0  | 1.75                    | +34   | 0  | -71   | -48 | -34 | 0  |
| 0.35                    | +19   | 0  | ...   | -34 | -19 | 0  | 2                       | +38   | 0  | -71   | -52 | -38 | 0  |
| 0.4                     | +19   | 0  | ...   | -34 | -19 | 0  | 2.5                     | +42   | 0  | -80   | -58 | -42 | 0  |
| 0.45                    | +20   | 0  | ...   | -35 | -20 | 0  | 3                       | +48   | 0  | -85   | -63 | -48 | 0  |
| 0.5                     | +20   | 0  | -50   | -36 | -20 | 0  | 3.5                     | +53   | 0  | -90   | -70 | -53 | 0  |
| 0.6                     | +21   | 0  | -53   | -36 | -21 | 0  | 4                       | +60   | 0  | -95   | -75 | -60 | 0  |
| 0.7                     | +22   | 0  | -56   | -38 | -22 | 0  | 4.5                     | +63   | 0  | -100  | -80 | -63 | 0  |
| 0.75                    | +22   | 0  | -56   | -38 | -22 | 0  | 5                       | +71   | 0  | -106  | -85 | -71 | 0  |
| 0.8                     | +24   | 0  | -60   | -38 | -24 | 0  | 5.5                     | +75   | 0  | -112  | -90 | -75 | 0  |
| 1                       | +26   | 0  | -60   | -40 | -26 | 0  | 6                       | +80   | 0  | -118  | -95 | -80 | 0  |

See Figs. 1 and 2 for meaning of symbols.

**Tolerance Grades.**—Tolerance grades specified in the Standard for each of the four main screw thread diameters are as follows:

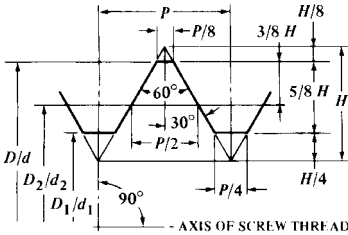
Minor diameter of nut threads ( $D_1$ ): tolerance grades 4, 5, 6, 7, and 8.

Major diameter of bolt threads ( $d$ ): tolerance grades 4, 6, and 8.

Pitch diameter of nut threads ( $D_2$ ): tolerance grades 4, 5, 6, 7, and 8.

Pitch diameter of bolt threads ( $d_2$ ): tolerance grades 3, 4, 5, 6, 7, 8, and 9.

**Tolerance Positions.**—Tolerance positions are G and H for nut threads and e, f, g, and h for bolt threads. The relationship of these tolerance position identifying letters to the amount of fundamental deviation is shown in Table 2.



- $D$  = maj. diam. of internal thread;
- $d$  = maj. diam. of external th
- $D_2$  = pitch diam. of internal thread;
- $d_2$  = pitch diam. of internal thread;
- $D_1$  = minor diam. of internal thread;
- $d_1$  = minor diam. of external thread;
- $P$  = Pitch;
- $H$  = height of fundamental angle;

Fig. 1. Basic Profile of ISO Metric Thread

**Tolerance Classes.**—To reduce the number of gages and tools, the Standard specifies that the tolerance positions and classes shall be chosen from those listed in Table 3 for short, normal, and long lengths of thread engagement. The following rules apply for the choice of tolerance quality: *Fine*: for precision threads when little variation of fit character is needed; *Medium*: for general use; and *Coarse*: for cases where manufacturing difficulties can arise as, for example, when threading hot-rolled bars and long blind holes. If the actual length of thread engagement is unknown, as in the manufacturing of standard bolts, normal is recommended.

Table 3. Tolerance Classes<sup>a,b,c</sup> for Nuts and Bolts

| Tolerance Classes for Nuts  |                      |                 |                   |                      |                   |                 |                      |                   |                   |                      |                 |                   |
|-----------------------------|----------------------|-----------------|-------------------|----------------------|-------------------|-----------------|----------------------|-------------------|-------------------|----------------------|-----------------|-------------------|
| Tolerance Quality           | Tolerance Position G |                 |                   | Tolerance Position H |                   |                 |                      |                   |                   |                      |                 |                   |
|                             | Short                | Normal          | Long              | Short                | Normal            | Long            |                      |                   |                   |                      |                 |                   |
| Fine                        | ...                  | ...             | ...               | 4H <sup>b</sup>      | 5H <sup>b</sup>   | 6H <sup>b</sup> |                      |                   |                   |                      |                 |                   |
| Medium                      | 5G <sup>a</sup>      | 6G <sup>c</sup> | 7G <sup>c</sup>   | 5H <sup>a</sup>      | 6H <sup>a,d</sup> | 7H <sup>a</sup> |                      |                   |                   |                      |                 |                   |
| Coarse                      | ...                  | 7G <sup>c</sup> | 8G <sup>c</sup>   | ...                  | 7H <sup>b</sup>   | 8H <sup>b</sup> |                      |                   |                   |                      |                 |                   |
| Tolerance Classes for Bolts |                      |                 |                   |                      |                   |                 |                      |                   |                   |                      |                 |                   |
| Tolerance Quality           | Tolerance Position e |                 |                   | Tolerance Position f |                   |                 | Tolerance Position g |                   |                   | Tolerance Position h |                 |                   |
|                             | Short                | Normal          | Long              | Short                | Normal            | Long            | Short                | Normal            | Long              | Short                | Normal          | Long              |
| Fine                        | ...                  | ...             | ...               | ...                  | ...               | ...             | ...                  | ...               | ...               | 3h4h <sup>c</sup>    | 4h <sup>a</sup> | 5h4h <sup>c</sup> |
| Medium                      | ...                  | 6e <sup>a</sup> | 7e6e <sup>c</sup> | ...                  | 6f <sup>a</sup>   | ...             | 5g6g <sup>c</sup>    | 6g <sup>a,d</sup> | 7g6g <sup>c</sup> | 5h6h <sup>c</sup>    | 6h <sup>b</sup> | 7h6h <sup>c</sup> |
| Coarse                      | ...                  | ...             | ...               | ...                  | ...               | ...             | ...                  | 8g <sup>b</sup>   | 9g8g <sup>c</sup> | ...                  | ...             | ...               |

<sup>a</sup> First choice.

<sup>b</sup> Second choice.

<sup>c</sup> Third choice; these are to be avoided.

<sup>d</sup> For commercial nut and bolt threads.

*Note:* See Table 4 for short, normal, and long categories. Any of the recommended tolerance classes for nuts can be combined with any of the recommended tolerance classes for bolts with the exception of sizes M1.4 and smaller for which the combination 5H/6h or finer shall be chosen. However, to guarantee a sufficient overlap, the finished components should preferably be made to form the fits H/g, H/h, or G/h.

**Table 4. Lengths of Thread Engagements for Short, Normal, and Long Categories**

| Basic Major Diameter $d$ |                 |                             | Pitch $P$ | Short | Normal          |      | Long            | Basic Major Diameter $d$ |                 |                             | Pitch $P$ | Short           | Normal |                 | Long |    |    |     |     |
|--------------------------|-----------------|-----------------------------|-----------|-------|-----------------|------|-----------------|--------------------------|-----------------|-----------------------------|-----------|-----------------|--------|-----------------|------|----|----|-----|-----|
| Over                     | Up to and Incl. | Length of Thread Engagement |           |       |                 |      |                 | Over                     | Up to and Incl. | Length of Thread Engagement |           |                 |        |                 |      |    |    |     |     |
|                          |                 | Up to and Incl.             |           | Over  | Up to and Incl. | Over | Up to and Incl. |                          |                 | Over                        |           | Up to and Incl. | Over   | Up to and Incl. | Over |    |    |     |     |
| 0.99                     | 1.4             | 0.2                         | 0.5       | 0.5   | 1.4             | 1.4  | 22.4            | 45                       | 1               | 4                           | 4         | 12              | 12     | 22.4            | 45   |    |    |     |     |
|                          |                 | 0.25                        | 0.6       | 0.6   | 1.7             | 1.7  |                 |                          | 1.5             | 6.3                         | 6.3       | 19              | 19     |                 |      |    |    |     |     |
|                          |                 | 0.3                         | 0.7       | 0.7   | 2               | 2    |                 |                          | 2               | 8.5                         | 8.5       | 25              | 25     |                 |      |    |    |     |     |
| 1.4                      | 2.8             | 0.2                         | 0.5       | 0.5   | 1.5             | 1.5  |                 |                          | 45              | 90                          | 3         | 12              | 12     | 36              | 36   | 45 | 90 |     |     |
|                          |                 | 0.25                        | 0.6       | 0.6   | 1.9             | 1.9  |                 |                          |                 |                             | 3.5       | 15              | 15     | 45              | 45   |    |    |     |     |
|                          |                 | 0.35                        | 0.8       | 0.8   | 2.6             | 2.6  |                 |                          |                 |                             | 4         | 18              | 18     | 53              | 53   |    |    |     |     |
|                          |                 | 0.4                         | 1         | 1     | 3               | 3    |                 |                          |                 |                             | 4.5       | 21              | 21     | 63              | 63   |    |    |     |     |
| 2.8                      | 5.6             | 0.45                        | 1.3       | 1.3   | 3.8             | 3.8  |                 |                          |                 |                             | 90        | 180             | 1.5    | 7.5             | 7.5  | 22 | 22 | 90  | 180 |
|                          |                 | 0.35                        | 1         | 1     | 3               | 3    |                 |                          |                 |                             |           |                 | 2      | 9.5             | 9.5  | 28 | 28 |     |     |
|                          |                 | 0.5                         | 1.5       | 1.5   | 4.5             | 4.5  |                 |                          |                 |                             |           |                 | 3      | 15              | 15   | 45 | 45 |     |     |
|                          |                 | 0.6                         | 1.7       | 1.7   | 5               | 5    | 4               | 19                       |                 |                             |           |                 | 19     | 56              | 56   |    |    |     |     |
|                          |                 | 0.7                         | 2         | 2     | 6               | 6    | 5               | 24                       |                 |                             |           |                 | 24     | 71              | 71   |    |    |     |     |
| 5.6                      | 11.2            | 0.75                        | 2.2       | 2.2   | 6.7             | 6.7  | 180             | 300                      |                 |                             |           |                 | 5.5    | 28              | 28   | 85 | 85 | 180 | 300 |
|                          |                 | 0.8                         | 2.5       | 2.5   | 7.5             | 7.5  |                 |                          | 6               | 32                          |           |                 | 32     | 95              | 95   |    |    |     |     |
|                          |                 | 1                           | 3         | 3     | 9               | 9    |                 |                          | 2               | 12                          |           |                 | 12     | 36              | 36   |    |    |     |     |
|                          |                 | 1.25                        | 4         | 4     | 12              | 12   |                 |                          | 3               | 18                          |           |                 | 18     | 53              | 53   |    |    |     |     |
| 11.2                     | 22.4            | 1.5                         | 5         | 5     | 15              | 15   |                 |                          | 300             | 600                         |           |                 | 4      | 24              | 24   | 71 | 71 | 300 | 600 |
|                          |                 | 1                           | 3.8       | 3.8   | 11              | 11   |                 |                          |                 |                             | 6         | 36              | 36     | 106             | 106  |    |    |     |     |
|                          |                 | 1.25                        | 4.5       | 4.5   | 13              | 13   |                 |                          |                 |                             | 3         | 20              | 20     | 60              | 60   |    |    |     |     |
|                          |                 | 1.5                         | 5.6       | 5.6   | 16              | 16   |                 |                          |                 |                             | 4         | 26              | 26     | 80              | 80   |    |    |     |     |
|                          |                 | 1.75                        | 6         | 6     | 18              | 18   |                 |                          |                 |                             | 6         | 40              | 40     | 118             | 118  |    |    |     |     |
| 2                        | 8               | 8                           | 24        | 24    |                 |      |                 |                          |                 |                             |           |                 |        |                 |      |    |    |     |     |
| 2.5                      | 10              | 10                          | 30        | 30    |                 |      |                 |                          |                 |                             |           |                 |        |                 |      |    |    |     |     |

All dimensions are given in millimeters

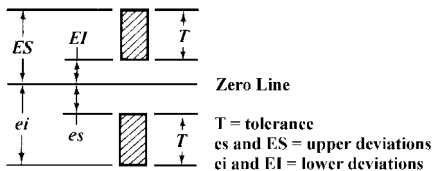


Fig. 2. Tolerance Positions with Respect to Zero Line (Basic Size)

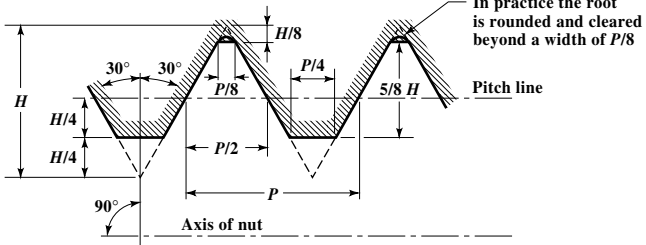
**Design Profiles.**—The design profiles for ISO metric internal and external screw threads are shown in Fig. 3. These represent the profiles of the threads at their maximum metal condition. It may be noted that the root of each thread is deepened so as to clear the basic flat crest of the other thread. The contact between the thread is thus confined to their sloping flanks. However, for nut threads as well as bolt threads, the actual root contours shall not at any point violate the basic profile.

**Designation.**—Screw threads complying with the requirements of the Standard shall be designated by the letter M followed by values of the nominal diameter and of the pitch, expressed in millimeters, and separated by the sign  $\times$ . *Example:* M6  $\times$  0.75. The absence of the indication of pitch means that a coarse pitch is specified.

The complete designation of a screw thread consists of a designation for the thread system and size, and a designation for the crest diameter tolerance. Each class designation consists of: a figure indicating the tolerance grade; and a letter indicating the tolerance

position, capital for nuts, lower case for bolts. If the two class designations for a thread are the same (one for the pitch diameter and one for the crest diameter), it is not necessary to repeat the symbols. As examples, a bolt thread designated M10-6g signifies a thread of 10 mm nominal diameter in the Coarse Thread Series having a tolerance class 6g for both pitch and major diameters. A designation M10 × 1-5g6g signifies a bolt thread of 10 mm nominal diameter having a pitch of 1 mm, a tolerance class 5g for pitch diameter, and a tolerance class 6g for major diameter. A designation M10-6H signifies a nut thread of 10 mm diameter in the Coarse Thread Series having a tolerance class 6H for both pitch and minor diameters.

## Nut (Internal Thread)



## Bolt (External Thread)

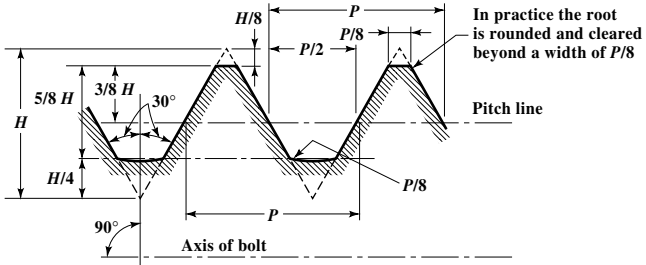


Fig. 3. Maximum Material Profiles for Internal and External Threads

A fit between mating parts is indicated by the nut thread tolerance class followed by the bolt thread tolerance class separated by an oblique stroke. *Examples:* M6-6H/6g and M20 × 2-6H/5g6g. For coated threads, the tolerances apply to the parts before coating, unless otherwise specified. After coating, the actual thread profile shall not at any point exceed the maximum material limits for either tolerance position H or h.

**Fundamental Deviation Formulas.**—The formulas used to calculate the fundamental deviations in Table 2 are:

$$EI_G = + (15 + 11P)$$

$$EI_H = 0$$

$$es_e = -(50 + 11P) \text{ except for threads with } P \leq 0.45 \text{ mm}$$

$$es_f = -(30 + 11P)$$

$$es_g = -(15 + 11P)$$

$$es_h = 0$$

In these formulas, EI and es are expressed in micrometers and P is in millimeters.

**Crest Diameter Tolerance Formulas.**—The tolerances for the major diameter of bolt threads ( $T_d$ ), grade 6, in Table 5, were calculated from the formula:

$$T_d(6) = 180 \sqrt[3]{P^2} - \frac{3.15}{\sqrt{P}}$$

In this formula,  $T_d(6)$  is in micrometers and  $P$  is in millimeters. For tolerance grades 4 and 8:  $T_d(4) = 0.63 T_d(6)$  and  $T_d(8) = 1.6 T_d(6)$ , respectively.

The tolerances for the minor diameter of nut threads ( $T_{D1}$ ), grade 6, in Table 5, were calculated as follows:

For pitches 0.2 to 0.8 mm,  $T_{D1}(6) = 433P - 190P^{1.22}$ .

For pitches 1 mm and coarser,  $T_{D1}(6) = 230P^{0.7}$ .

In these formulas,  $T_{D1}(6)$  is in micrometers and  $P$  is in millimeters. For tolerance grades 4, 5, 7, and 8:  $T_{D1}(4) = 0.63 T_{D1}(6)$ ;  $T_{D1}(5) = 0.8 T_{D1}(6)$ ;  $T_{D1}(7) = 1.25 T_{D1}(6)$ ; and  $T_{D1}(8) = 1.6 T_{D1}(6)$ , respectively.

**Table 5. British Standard ISO Metric Screw Threads: Limits and Tolerances for Finished Uncoated Threads for Normal Lengths of Engagement BS 3643: Part 2: 1981**

| Nominal Diameter <sup>a</sup> | Pitch  |      | External Threads (Bolts) |            |            |        |            |        | Internal Threads (Nuts) <sup>b</sup> |            |            |       |            |       |           |       |
|-------------------------------|--------|------|--------------------------|------------|------------|--------|------------|--------|--------------------------------------|------------|------------|-------|------------|-------|-----------|-------|
|                               | Course | Fine | Tol. Class               | Fund. dev. | Major Dia. |        | Pitch Dia. |        | Minor Dia                            | Tol. Class | Major Dia. |       | Pitch Dia. |       | Minor Dia |       |
|                               |        |      |                          |            | Max        | Tol(-) | Max        | Tol(-) | Min                                  |            | Min        | Max   | Tol(-)     | Max   | Tol(-)    |       |
|                               |        |      |                          |            |            |        |            |        |                                      |            |            |       |            |       |           |       |
| 1                             | 0.2    |      | 4h                       | 0          | 1.000      | 0.036  | 0.870      | 0.030  | 0.717                                | 4H         | 1.000      | 0.910 | 0.040      | 0.821 | 0.038     |       |
|                               |        |      | 6g                       | 0.017      | 0.983      | 0.056  | 0.853      | 0.048  | 0.682                                |            |            |       |            |       |           |       |
|                               | 0.25   |      | 4h                       | 0          | 1.000      | 0.042  | 0.838      | 0.034  | 0.649                                | 4H         | 1.000      | 0.883 | 0.045      | 0.774 | 0.045     |       |
|                               |        |      | 6g                       | 0.018      | 0.982      | 0.067  | 0.820      | 0.053  | 0.613                                | 5H         | 1.000      | 0.894 | 0.056      | 0.785 | 0.056     |       |
|                               | 1.1    | 0.2  |                          | 4h         | 0          | 1.100  | 0.036      | 0.970  | 0.030                                | 0.817      | 4H         | 1.100 | 1.010      | 0.040 | 0.921     | 0.038 |
|                               |        |      |                          | 6g         | 0.017      | 1.083  | 0.056      | 0.953  | 0.048                                | 0.782      |            |       |            |       |           |       |
| 0.25                          |        |      | 4h                       | 0          | 1.100      | 0.042  | 0.938      | 0.034  | 0.750                                | 4H         | 1.100      | 0.983 | 0.045      | 0.874 | 0.045     |       |
|                               |        |      | 6g                       | 0.018      | 1.082      | 0.067  | 0.920      | 0.053  | 0.713                                | 5H         | 1.100      | 0.994 | 0.056      | 0.885 | 0.056     |       |
| 1.2                           | 0.2    |      | 4h                       | 0          | 1.200      | 0.036  | 1.070      | 0.030  | 0.917                                | 4H         | 1.200      | 1.110 | 0.040      | 1.021 | 0.038     |       |
|                               |        |      | 6g                       | 0.017      | 1.183      | 0.056  | 1.053      | 0.048  | 0.882                                |            |            |       |            |       |           |       |
|                               | 0.25   |      | 4h                       | 0          | 1.200      | 0.042  | 1.038      | 0.034  | 0.850                                | 4H         | 1.200      | 1.083 | 0.045      | 0.974 | 0.045     |       |
|                               |        |      | 6g                       | 0.018      | 1.182      | 0.067  | 1.020      | 0.053  | 0.813                                | 5H         | 1.200      | 1.094 | 0.056      | 0.985 | 0.056     |       |
| 1.4                           | 0.2    |      | 4h                       | 0          | 1.400      | 0.036  | 1.270      | 0.030  | 1.117                                | 4H         | 1.400      | 1.310 | 0.040      | 1.221 | 0.038     |       |
|                               |        |      | 6g                       | 0.017      | 1.383      | 0.056  | 1.253      | 0.048  | 1.082                                |            |            |       |            |       |           |       |
|                               | 0.3    |      | 4h                       | 0          | 1.400      | 0.048  | 1.205      | 0.036  | 0.984                                | 4H         | 1.400      | 1.253 | 0.048      | 1.128 | 0.053     |       |
|                               |        |      | 6g                       | 0.018      | 1.382      | 0.075  | 1.187      | 0.056  | 0.946                                | 5H         | 1.400      | 1.265 | 0.060      | 1.142 | 0.067     |       |
| 1.6                           | 0.2    |      | 4h                       | 0          | 1.600      | 0.036  | 1.470      | 0.032  | 1.315                                | 4H         | 1.600      | 1.512 | 0.042      | 1.421 | 0.038     |       |
|                               |        |      | 6g                       | 0.017      | 1.583      | 0.056  | 1.453      | 0.050  | 1.280                                |            |            |       |            |       |           |       |
|                               | 0.35   |      | 4h                       | 0          | 1.600      | 0.053  | 1.373      | 0.040  | 1.117                                | 4H         | 1.600      | 1.426 | 0.053      | 1.284 | 0.063     |       |
|                               |        |      | 6g                       | 0.019      | 1.581      | 0.085  | 1.354      | 0.063  | 1.075                                | 5H         | 1.600      | 1.440 | 0.067      | 1.301 | 0.080     |       |
|                               | 1.8    | 0.2  |                          | 4h         | 0          | 1.800  | 0.036      | 1.670  | 0.032                                | 1.515      | 4H         | 1.800 | 1.712      | 0.042 | 1.621     | 0.038 |
|                               |        |      |                          | 6g         | 0.017      | 1.783  | 0.056      | 1.653  | 0.050                                | 1.480      |            |       |            |       |           |       |
| 0.35                          |        |      | 4h                       | 0          | 1.800      | 0.053  | 1.573      | 0.040  | 1.317                                | 4H         | 1.800      | 1.626 | 0.053      | 1.484 | 0.063     |       |
|                               |        |      | 6g                       | 0.019      | 1.781      | 0.085  | 1.554      | 0.063  | 1.275                                | 5H         | 1.800      | 1.640 | 0.067      | 1.501 | 0.080     |       |
| 2                             | 0.25   |      | 4h                       | 0          | 2.000      | 0.042  | 1.838      | 0.036  | 1.648                                | 4H         | 2.000      | 1.886 | 0.048      | 1.774 | 0.045     |       |
|                               |        |      | 6g                       | 0.018      | 1.982      | 0.067  | 1.820      | 0.056  | 1.610                                | 5H         | 2.000      | 1.898 | 0.060      | 1.785 | 0.056     |       |
|                               | 0.4    |      | 4h                       | 0          | 2.000      | 0.060  | 1.740      | 0.042  | 1.452                                | 4H         | 2.000      | 1.796 | 0.056      | 1.638 | 0.071     |       |
|                               |        |      | 6g                       | 0.019      | 1.981      | 0.095  | 1.721      | 0.067  | 1.408                                | 5H         | 2.000      | 1.811 | 0.071      | 1.657 | 0.090     |       |
|                               | 2.2    | 0.25 |                          | 4h         | 0          | 2.200  | 0.042      | 2.038  | 0.036                                | 1.848      | 4H         | 2.200 | 2.086      | 0.048 | 1.974     | 0.045 |
|                               |        |      |                          | 6g         | 0.018      | 2.182  | 0.067      | 2.020  | 0.056                                | 1.810      | 5H         | 2.200 | 2.098      | 0.060 | 1.985     | 0.056 |
| 0.45                          |        |      | 4h                       | 0          | 2.200      | 0.063  | 1.908      | 0.045  | 1.585                                | 4H         | 2.200      | 1.968 | 0.060      | 1.793 | 0.080     |       |
|                               |        |      | 6g                       | 0.020      | 2.180      | 0.100  | 1.888      | 0.071  | 1.539                                | 5H         | 2.200      | 1.983 | 0.075      | 1.813 | 0.100     |       |
|                               |        |      |                          |            |            |        |            | 6H     | 2.000                                | 2.003      | 0.095      | 1.838 | 0.125      |       |           |       |



**Table 5. (Continued) British Standard ISO Metric Screw Threads: Limits and Tolerances for Finished Uncoated Threads for Normal Lengths of Engagement BS 3643: Part 2: 1981**

| Nominal Diameter <sup>a</sup> | Pitch  |      | External Threads (Bolts) |            |            |        |            |        | Internal Threads (Nuts) <sup>b</sup> |            |            |       |            |        |           |        |
|-------------------------------|--------|------|--------------------------|------------|------------|--------|------------|--------|--------------------------------------|------------|------------|-------|------------|--------|-----------|--------|
|                               | Coarse | Fine | Tol. Class               | Fund. dev. | Major Dia. |        | Pitch Dia. |        | Minor Dia                            | Tol. Class | Major Dia. |       | Pitch Dia. |        | Minor Dia |        |
|                               |        |      |                          |            | Max        | Tol(-) | Max        | Tol(-) |                                      |            | Min        | Min   | Max        | Tol(-) | Max       | Tol(-) |
|                               |        |      |                          |            |            |        |            |        |                                      |            |            |       |            |        |           |        |
| 2.5                           | 0.35   |      | 4h                       | 0          | 2.500      | 0.053  | 2.273      | 0.040  | 2.017                                | 4H         | 2.500      | 2.326 | 0.053      | 2.184  | 0.063     |        |
|                               |        |      | 6g                       | 0.019      | 2.481      | 0.085  | 2.254      | 0.063  | 1.975                                | 5H         | 2.500      | 2.340 | 0.067      | 2.201  | 0.080     |        |
|                               |        |      | 6H                       |            |            |        |            |        |                                      | 6H         | 2.500      | 2.358 | 0.085      | 2.221  | 0.100     |        |
|                               | 0.45   |      | 4h                       | 0          | 2.500      | 0.063  | 2.208      | 0.045  | 1.885                                | 4H         | 2.500      | 2.268 | 0.060      | 2.093  | 0.080     |        |
|                               |        |      | 6g                       | 0.020      | 2.480      | 0.100  | 2.188      | 0.071  | 1.839                                | 5H         | 2.500      | 2.283 | 0.075      | 2.113  | 0.100     |        |
|                               |        |      | 6H                       |            |            |        |            |        |                                      | 6H         | 2.500      | 2.303 | 0.095      | 2.138  | 0.125     |        |
| 3                             | 0.35   |      | 4h                       | 0          | 3.000      | 0.053  | 2.773      | 0.042  | 2.515                                | 4H         | 3.000      | 2.829 | 0.056      | 2.684  | 0.063     |        |
|                               |        |      | 6g                       | 0.019      | 2.981      | 0.085  | 2.754      | 0.067  | 2.471                                | 5H         | 3.000      | 2.844 | 0.071      | 2.701  | 0.080     |        |
|                               |        |      | 6H                       |            |            |        |            |        |                                      | 6H         | 3.000      | 2.863 | 0.090      | 2.721  | 0.100     |        |
|                               | 0.5    |      | 4h                       | 0          | 3.000      | 0.067  | 2.675      | 0.048  | 2.319                                | 5H         | 3.000      | 2.755 | 0.080      | 2.571  | 0.112     |        |
|                               |        |      | 6g                       | 0.020      | 2.980      | 0.106  | 2.655      | 0.075  | 2.272                                | 6H         | 3.000      | 2.775 | 0.100      | 2.599  | 0.140     |        |
|                               |        |      | 7H                       |            |            |        |            |        |                                      | 7H         | 3.000      | 2.800 | 0.125      | 2.639  | 0.180     |        |
| 3.5                           | 0.35   |      | 4h                       | 0          | 3.500      | 0.053  | 3.273      | 0.042  | 3.015                                | 4H         | 3.500      | 3.329 | 0.056      | 3.184  | 0.063     |        |
|                               |        |      | 6g                       | 0.019      | 3.481      | 0.085  | 3.254      | 0.067  | 2.971                                | 5H         | 3.500      | 3.344 | 0.071      | 3.201  | 0.080     |        |
|                               |        |      | 6H                       |            |            |        |            |        |                                      | 6H         | 3.500      | 3.363 | 0.090      | 3.221  | 0.100     |        |
|                               | 0.6    |      | 4h                       | 0          | 3.500      | 0.080  | 3.110      | 0.053  | 2.688                                | 5H         | 3.500      | 3.200 | 0.090      | 2.975  | 0.125     |        |
|                               |        |      | 6g                       | 0.021      | 3.479      | 0.125  | 3.089      | 0.085  | 2.635                                | 6H         | 3.500      | 3.222 | 0.112      | 3.010  | 0.160     |        |
|                               |        |      | 7H                       |            |            |        |            |        |                                      | 7H         | 3.500      | 3.250 | 0.140      | 3.050  | 0.200     |        |
| 4                             | 0.5    |      | 4h                       | 0          | 4.000      | 0.067  | 3.675      | 0.048  | 3.319                                | 5H         | 4.000      | 3.755 | 0.080      | 3.571  | 0.112     |        |
|                               |        |      | 6g                       | 0.020      | 3.980      | 0.106  | 3.655      | 0.075  | 3.272                                | 6H         | 4.000      | 3.775 | 0.100      | 3.599  | 0.140     |        |
|                               |        |      | 7H                       |            |            |        |            |        |                                      | 7H         | 4.000      | 3.800 | 0.125      | 3.639  | 0.180     |        |
|                               | 0.7    |      | 4h                       | 0          | 4.000      | 0.090  | 3.545      | 0.056  | 3.058                                | 5H         | 4.000      | 3.640 | 0.095      | 3.382  | 0.140     |        |
|                               |        |      | 6g                       | 0.022      | 3.978      | 0.140  | 3.523      | 0.090  | 3.002                                | 6H         | 4.000      | 3.663 | 0.118      | 3.422  | 0.180     |        |
|                               |        |      | 7H                       |            |            |        |            |        |                                      | 7H         | 4.000      | 3.695 | 0.150      | 3.466  | 0.224     |        |
| 4.5                           | 0.5    |      | 4h                       | 0          | 4.500      | 0.067  | 4.175      | 0.048  | 3.819                                | 5H         | 4.500      | 4.255 | 0.080      | 4.071  | 0.112     |        |
|                               |        |      | 6g                       | 0.020      | 4.480      | 0.106  | 4.155      | 0.075  | 3.772                                | 6H         | 4.500      | 4.275 | 0.100      | 4.099  | 0.140     |        |
|                               |        |      | 7H                       |            |            |        |            |        |                                      | 7H         | 4.500      | 4.300 | 0.125      | 4.139  | 0.180     |        |
|                               | 0.75   |      | 4h                       | 0          | 4.500      | 0.090  | 4.013      | 0.056  | 3.495                                | 5H         | 4.500      | 4.108 | 0.095      | 3.838  | 0.150     |        |
|                               |        |      | 6g                       | 0.022      | 4.478      | 0.140  | 3.991      | 0.090  | 3.439                                | 6H         | 4.500      | 4.131 | 0.118      | 3.878  | 0.190     |        |
|                               |        |      | 7H                       |            |            |        |            |        |                                      | 7H         | 4.500      | 4.163 | 0.150      | 3.924  | 0.236     |        |
| 5                             | 0.5    |      | 4h                       | 0          | 5.000      | 0.067  | 4.675      | 0.048  | 4.319                                | 5H         | 5.000      | 4.755 | 0.080      | 4.571  | 0.112     |        |
|                               |        |      | 6g                       | 0.020      | 4.980      | 0.106  | 4.655      | 0.075  | 4.272                                | 6H         | 5.000      | 4.775 | 0.100      | 4.599  | 0.140     |        |
|                               |        |      | 7H                       |            |            |        |            |        |                                      | 7H         | 5.000      | 4.800 | 0.125      | 4.639  | 0.180     |        |
|                               | 0.8    |      | 4h                       | 0          | 5.000      | 0.095  | 4.480      | 0.060  | 3.927                                | 5H         | 5.000      | 4.580 | 0.100      | 4.294  | 0.160     |        |
|                               |        |      | 6g                       | 0.024      | 4.976      | 0.150  | 4.456      | 0.095  | 3.868                                | 6H         | 5.000      | 4.605 | 0.125      | 4.334  | 0.200     |        |
|                               |        |      | 7H                       |            |            |        |            |        |                                      | 7H         | 5.000      | 4.640 | 0.160      | 4.384  | 0.250     |        |
| 5.5                           | 0.5    |      | 4h                       | 0          | 5.500      | 0.067  | 5.175      | 0.048  | 4.819                                | 5H         | 5.500      | 5.255 | 0.080      | 5.071  | 0.112     |        |
|                               |        |      | 6g                       | 0.020      | 5.480      | 0.106  | 5.155      | 0.075  | 4.772                                | 6H         | 5.500      | 5.275 | 0.100      | 5.099  | 0.140     |        |
|                               |        |      | 7H                       |            |            |        |            |        |                                      | 7H         | 5.500      | 5.300 | 0.125      | 5.139  | 0.180     |        |
|                               | 0.75   |      | 4h                       | 0          | 6.000      | 0.090  | 5.513      | 0.063  | 4.988                                | 5H         | 6.000      | 5.619 | 0.106      | 5.338  | 0.150     |        |
|                               |        |      | 6g                       | 0.022      | 5.978      | 0.140  | 5.491      | 0.100  | 4.929                                | 6H         | 6.000      | 5.645 | 0.132      | 5.378  | 0.190     |        |
|                               |        |      | 7H                       |            |            |        |            |        |                                      | 7H         | 6.000      | 5.683 | 0.170      | 5.424  | 0.236     |        |
| 6                             | 1      |      | 4h                       | 0          | 6.000      | 0.112  | 5.350      | 0.071  | 4.663                                | 5H         | 6.000      | 5.468 | 0.118      | 5.107  | 0.190     |        |
|                               |        |      | 6g                       | 0.026      | 5.974      | 0.180  | 5.324      | 0.112  | 4.597                                | 6H         | 6.000      | 5.500 | 0.150      | 5.153  | 0.236     |        |
|                               |        |      | 8g                       | 0.026      | 5.974      | 0.280  | 5.324      | 0.180  | 4.528                                | 7H         | 6.000      | 5.540 | 0.190      | 5.217  | 0.300     |        |
|                               | 0.75   |      | 4h                       | 0          | 7.000      | 0.090  | 6.513      | 0.063  | 5.988                                | 5H         | 7.000      | 6.619 | 0.106      | 6.338  | 0.150     |        |
|                               |        |      | 6g                       | 0.022      | 6.978      | 0.140  | 6.491      | 0.100  | 5.929                                | 6H         | 7.000      | 6.645 | 0.132      | 6.378  | 0.190     |        |
|                               |        |      | 7H                       |            |            |        |            |        |                                      | 7H         | 7.000      | 6.683 | 0.170      | 6.424  | 0.236     |        |
| 1                             |        | 4h   | 0                        | 7.000      | 0.112      | 6.350  | 0.071      | 5.663  | 5H                                   | 7.000      | 6.468      | 0.118 | 6.107      | 0.190  |           |        |
|                               |        | 6g   | 0.026                    | 6.974      | 0.180      | 6.324  | 0.112      | 5.596  | 6H                                   | 7.000      | 6.500      | 0.150 | 6.153      | 0.236  |           |        |
|                               |        | 8g   | 0.026                    | 6.974      | 0.280      | 6.324  | 0.180      | 5.528  | 7H                                   | 7.000      | 6.540      | 0.190 | 6.217      | 0.300  |           |        |
| 8                             | 1      |      | 4h                       | 0          | 8.000      | 0.112  | 7.350      | 0.071  | 6.663                                | 5H         | 8.000      | 7.468 | 0.118      | 7.107  | 0.190     |        |
|                               |        |      | 6g                       | 0.026      | 7.974      | 0.180  | 7.324      | 0.112  | 6.596                                | 6H         | 8.000      | 7.500 | 0.150      | 7.153  | 0.236     |        |
|                               |        |      | 8g                       | 0.026      | 7.974      | 0.280  | 7.324      | 0.180  | 6.528                                | 7H         | 8.000      | 7.540 | 0.190      | 7.217  | 0.300     |        |
|                               | 1.25   |      | 4h                       | 0          | 8.000      | 0.132  | 7.188      | 0.075  | 6.343                                | 5H         | 8.000      | 7.313 | 0.125      | 6.859  | 0.212     |        |
|                               |        |      | 6g                       | 0.028      | 7.972      | 0.212  | 7.160      | 0.118  | 6.272                                | 6H         | 8.000      | 7.348 | 0.160      | 6.912  | 0.265     |        |
|                               |        |      | 8g                       | 0.028      | 7.972      | 0.335  | 7.160      | 0.190  | 6.200                                | 7H         | 8.000      | 7.388 | 0.200      | 6.982  | 0.335     |        |



**Table 5. (Continued) British Standard ISO Metric Screw Threads: Limits and Tolerances for Finished Uncoated Threads for Normal Lengths of Engagement BS 3643: Part 2: 1981**

| Nominal Diameter <sup>a</sup> | Pitch  |      | External Threads (Bolts) |            |            |        |            |        | Internal Threads (Nuts) <sup>b</sup> |            |            |        |            |       |           |  |
|-------------------------------|--------|------|--------------------------|------------|------------|--------|------------|--------|--------------------------------------|------------|------------|--------|------------|-------|-----------|--|
|                               | Coarse | Fine | Tol. Class               | Fund. dev. | Major Dia. |        | Pitch Dia. |        | Minor Dia                            | Tol. Class | Major Dia. |        | Pitch Dia. |       | Minor Dia |  |
|                               |        |      |                          |            | Max        | Tol(-) | Max        | Tol(-) | Min                                  |            | Min        | Max    | Tol(-)     | Max   | Tol(-)    |  |
|                               | 4h     | 0    | 30.000                   | 0.180      | 28.701     | 0.106  | 27.363     | 5H     | 30.000                               | 28.881     | 0.180      | 28.135 | 0.300      |       |           |  |
| 30                            | 2      | 6g   | 0.038                    | 29.962     | 0.280      | 28.663 | 0.170      | 27.261 | 6H                                   | 30.000     | 27.925     | 0.224  | 28.210     | 0.375 |           |  |
|                               |        | 8g   | 0.038                    | 29.962     | 0.450      | 28.663 | 0.265      | 27.166 | 7H                                   | 30.000     | 28.981     | 0.280  | 28.310     | 0.475 |           |  |
|                               |        | 4h   | 0                        | 30.000     | 0.265      | 27.727 | 0.132      | 25.439 | 5H                                   | 30.000     | 27.951     | 0.224  | 26.661     | 0.450 |           |  |
|                               | 3.5    | 6g   | 0.053                    | 29.947     | 0.425      | 27.674 | 0.212      | 25.305 | 6H                                   | 30.000     | 28.007     | 0.280  | 26.771     | 0.560 |           |  |
|                               |        | 8g   | 0.053                    | 29.947     | 0.670      | 27.674 | 0.335      | 25.183 | 7H                                   | 30.000     | 28.082     | 0.355  | 26.921     | 0.710 |           |  |
|                               |        | 4h   | 0                        | 33.000     | 0.180      | 31.701 | 0.106      | 30.363 | 5H                                   | 33.000     | 31.881     | 0.180  | 31.135     | 0.300 |           |  |
| 33                            | 2      | 6g   | 0.038                    | 32.962     | 0.280      | 31.663 | 0.170      | 30.261 | 6H                                   | 33.000     | 31.925     | 0.224  | 31.210     | 0.375 |           |  |
|                               |        | 8g   | 0.038                    | 32.962     | 0.450      | 30.663 | 0.265      | 30.166 | 7H                                   | 33.000     | 31.981     | 0.280  | 31.310     | 0.475 |           |  |
|                               |        | 4h   | 0                        | 33.000     | 0.265      | 30.727 | 0.132      | 28.438 | 5H                                   | 33.000     | 30.951     | 0.224  | 29.661     | 0.450 |           |  |
|                               | 3.5    | 6g   | 0.053                    | 32.947     | 0.425      | 30.674 | 0.212      | 28.305 | 6H                                   | 33.000     | 31.007     | 0.280  | 29.771     | 0.560 |           |  |
|                               |        | 8g   | 0.053                    | 32.947     | 0.670      | 30.674 | 0.335      | 28.182 | 7H                                   | 33.000     | 31.082     | 0.355  | 29.921     | 0.710 |           |  |
|                               |        | 4h   | 0                        | 36.000     | 0.300      | 33.402 | 0.140      | 30.798 | 5H                                   | 36.000     | 33.638     | 0.236  | 32.145     | 0.475 |           |  |
| 36                            | 4      | 6g   | 0.060                    | 35.940     | 0.475      | 33.342 | 0.224      | 30.654 | 6H                                   | 36.000     | 33.702     | 0.300  | 32.270     | 0.600 |           |  |
|                               |        | 8g   | 0.060                    | 35.940     | 0.750      | 33.342 | 0.355      | 30.523 | 7H                                   | 36.000     | 33.777     | 0.375  | 32.420     | 0.750 |           |  |
|                               |        | 4h   | 0                        | 39.000     | 0.300      | 36.402 | 0.140      | 33.798 | 5H                                   | 39.000     | 36.638     | 0.236  | 35.145     | 0.475 |           |  |
| 39                            | 4      | 6g   | 0.060                    | 38.940     | 0.475      | 36.342 | 0.224      | 33.654 | 6H                                   | 39.000     | 36.702     | 0.300  | 35.270     | 0.600 |           |  |
|                               |        | 8g   | 0.060                    | 38.940     | 0.750      | 36.342 | 0.355      | 33.523 | 7H                                   | 39.000     | 36.777     | 0.375  | 35.420     | 0.750 |           |  |

<sup>a</sup> This table provides coarse- and fine-pitch series data for threads listed in Table 6 for first, second, and third choices. For constant-pitch series and for larger sizes than are shown, refer to the Standard.

<sup>b</sup> The fundamental deviation for internal threads (nuts) is zero for threads in this table.

All dimensions are in millimeters.

**Diameter/Pitch Combinations.**—Part 1 of BS 3643 provides a choice of diameter/pitch combinations shown here in Table 6. The use of first-choice items is preferred but if necessary, second, then third choice combinations may be selected. If pitches finer than those given in Table 6 are necessary, only the following pitches should be used: 3, 2, 1.5, 1, 0.75, 0.5, 0.35, 0.25, and 0.2 mm. When selecting such pitches it should be noted that there is increasing difficulty in meeting tolerance requirements as the diameter is increased for a given pitch. It is suggested that diameters greater than the following should not be used with the pitches indicated:

|                      |     |      |    |     |     |     |
|----------------------|-----|------|----|-----|-----|-----|
| Pitch, mm            | 0.5 | 0.75 | 1  | 1.5 | 2   | 3   |
| Maximum Diameter, mm | 22  | 33   | 80 | 150 | 200 | 300 |

In cases where it is necessary to use a thread with a pitch larger than 6 mm, in the diameter range of 150 to 300 mm, the 8 mm pitch should be used.

**Limits and Tolerances for Finished Uncoated Threads.**—Part 2 of BS 3643 specifies the fundamental deviations, tolerances, and limits of size for the tolerance classes 4H, 5H, 6H, and 7H for internal threads (nuts) and 4h, 6g, and 8g for external threads (bolts) for coarse-pitch series within the range of 1 to 68 mm; fine-pitch series within the range of 1 to 33 mm; and constant pitch series within the range of 8 to 300 mm diameter.

The data in Table 5 provide the first, second, and third choice combinations shown in Table 6 except that constant-pitch series threads are omitted. For diameters larger than shown in Table 5, and for constant-pitch series data, refer to the Standard.

**Table 6. British Standard ISO Metric Screw Threads — Diameter/Pitch Combinations BS 3643:Part 1:1981 (1998)**

| Nominal Diameter |     |                 | Coarse Pitch | Fine Pitch | Constant Pitch        | Nominal Diameter |     |                 | Constant Pitch |
|------------------|-----|-----------------|--------------|------------|-----------------------|------------------|-----|-----------------|----------------|
| Choices          |     |                 |              |            |                       | Choices          |     |                 |                |
| 1st              | 2nd | 3rd             |              |            |                       | 1st              | 2nd | 3rd             |                |
| 1                | ... | ...             | 0.25         | 0.2        | ...                   | ...              | 70  | 6, 4, 3, 2, 1.5 |                |
| ...              | 1.1 | ...             | 0.25         | 0.2        | ...                   | 72               | ... | 6, 4, 3, 2, 1.5 |                |
| 1.2              | ... | ...             | 0.25         | 0.2        | ...                   | ...              | 75  | 4, 3, 2, 1.5    |                |
| ...              | 1.4 | ...             | 0.3          | 0.2        | ...                   | ...              | 76  | 6, 4, 3, 2, 1.5 |                |
| 1.6              | ... | ...             | 0.35         | 0.2        | ...                   | ...              | 78  | 2               |                |
| ...              | 1.8 | ...             | 0.35         | 0.2        | ...                   | 80               | ... | 6, 4, 3, 2, 1.5 |                |
| 2.0              | ... | ...             | 0.4          | 0.25       | ...                   | ...              | 82  | 2               |                |
| ...              | 2.2 | ...             | 0.45         | 0.25       | ...                   | ...              | 85  | 6, 4, 3, 2      |                |
| 2.5              | ... | ...             | 0.45         | 0.35       | ...                   | 90               | ... | 6, 4, 3, 2      |                |
| 3                | ... | ...             | 0.5          | 0.35       | ...                   | ...              | 95  | 6, 4, 3, 2      |                |
| ...              | 3.5 | ...             | 0.6          | 0.35       | ...                   | 100              | ... | 6, 4, 3, 2      |                |
| 4                | ... | ...             | 0.7          | 0.5        | ...                   | ...              | 105 | 6, 4, 3, 2      |                |
| ...              | 4.5 | ...             | 0.75         | 0.5        | ...                   | 110              | ... | 6, 4, 3, 2      |                |
| 5                | ... | ...             | 0.8          | 0.5        | ...                   | ...              | 115 | 6, 4, 3, 2      |                |
| ...              | ... | 5.5             | ...          | (0.5)      | ...                   | ...              | 120 | 6, 4, 3, 2      |                |
| 6                | ... | ...             | 1            | 0.75       | ...                   | 125              | ... | 6, 4, 3, 2      |                |
| ...              | 7   | ...             | 1            | 0.75       | ...                   | ...              | 130 | 6, 4, 3, 2      |                |
| 8                | ... | ...             | 1.25         | 1          | 0.75                  | ...              | 135 | 6, 4, 3, 2      |                |
| ...              | ... | 9               | 1.25         | ...        | 1, 0.75               | 140              | ... | 6, 4, 3, 2      |                |
| 10               | ... | ...             | 1.5          | 1.25       | 1, 0.75               | ...              | 145 | 6, 4, 3, 2      |                |
| ...              | ... | 11              | 1.5          | ...        | 1, 0.75               | ...              | 150 | 6, 4, 3, 2      |                |
| 12               | ... | ...             | 1.75         | 1.25       | 1.5, 1                | ...              | 155 | 6, 4, 3         |                |
| ...              | 14  | ...             | 2            | 1.5        | 1.25 <sup>a</sup> , 1 | 160              | ... | 6, 4, 3         |                |
| ...              | ... | 15              | ...          | ...        | 1.5, 1                | ...              | 165 | 6, 4, 3         |                |
| 16               | ... | ...             | 2            | 1.5        | 1                     | ...              | 170 | 6, 4, 3         |                |
| ...              | ... | 17              | ...          | ...        | 1.5, 1                | ...              | 175 | 6, 4, 3         |                |
| ...              | 18  | ...             | 2.5          | 1.5        | 2, 1                  | 180              | ... | 6, 4, 3         |                |
| 20               | ... | ...             | 2.5          | 1.5        | 2, 1                  | ...              | 185 | 6, 4, 3         |                |
| ...              | 22  | ...             | 2.5          | 1.5        | 2, 1                  | ...              | 190 | 6, 4, 3         |                |
| 24               | ... | ...             | 3            | 2          | 1.5, 1                | ...              | 195 | 6, 4, 3         |                |
| ...              | ... | 25              | ...          | ...        | 2, 1.5, 1             | 200              | ... | 6, 4, 3         |                |
| ...              | ... | 26              | ...          | ...        | 1.5                   | ...              | 205 | 6, 4, 3         |                |
| ...              | 27  | ...             | 3            | 2          | 1.5, 1                | ...              | 210 | 6, 4, 3         |                |
| ...              | ... | 28              | ...          | ...        | 2, 1.5, 1             | ...              | 215 | 6, 4, 3         |                |
| 30               | ... | ...             | 3.5          | 2          | (3), 1.5, 1           | 220              | ... | 6, 4, 3         |                |
| ...              | ... | 32              | ...          | ...        | 2, 1.5                | ...              | 225 | 6, 4, 3         |                |
| ...              | 33  | ...             | 3.5          | 2          | (3), 1.5              | ...              | 230 | 6, 4, 3         |                |
| ...              | ... | 35 <sup>b</sup> | ...          | ...        | 1.5                   | ...              | 235 | 6, 4, 3         |                |
| 36               | ... | ...             | 4            | ...        | 3, 2, 1.5             | ...              | 240 | 6, 4, 3         |                |
| ...              | ... | 38              | ...          | ...        | 1.5                   | ...              | 245 | 6, 4, 3         |                |
| ...              | 39  | ...             | 4            | ...        | 3, 2, 1.5             | 250              | ... | 6, 4, 3         |                |
| ...              | ... | 40              | ...          | ...        | 3, 2, 1.5             | ...              | 255 | 6, 4            |                |
| 42               | 45  | ...             | 4.5          | ...        | 4, 3, 2, 1.5          | ...              | 260 | 6, 4            |                |
| 48               | ... | ...             | 5            | ...        | 4, 3, 2, 1.5          | ...              | 265 | 6, 4            |                |
| ...              | ... | 50              | ...          | ...        | 3, 2, 1.5             | ...              | 270 | 6, 4            |                |
| ...              | 52  | ...             | 5            | ...        | 4, 3, 2, 1.5          | ...              | 275 | 6, 4            |                |
| ...              | ... | 55              | ...          | ...        | 4, 3, 2, 1.5          | 280              | ... | 6, 4            |                |
| 56               | ... | ...             | 5.5          | ...        | 4, 3, 2, 1.5          | ...              | 285 | 6, 4            |                |
| ...              | ... | 58              | ...          | ...        | 4, 3, 2, 1.5          | ...              | 290 | 6, 4            |                |
| ...              | 60  | ...             | 5.5          | ...        | 4, 3, 2, 1.5          | ...              | 295 | 6, 4            |                |
| ...              | ... | 62              | ...          | ...        | 4, 3, 2, 1.5          | 300              | ... | 6, 4            |                |
| 64               | ... | ...             | 6            | ...        | 4, 3, 2, 1.5          | ...              | ... | ...             |                |
| ...              | ... | 65              | ...          | ...        | 4, 3, 2, 1.5          | ...              | ... | ...             |                |
| ...              | 68  | ...             | 6            | ...        | 4, 3, 2, 1.5          | ...              | ... | ...             |                |

<sup>a</sup>Only for spark plugs for engines.<sup>b</sup>Only for locking nuts for bearings.

All dimensions are in millimeters. Pitches in parentheses ( ) are to be avoided as far as possible.

## Comparison of Various Metric Thread Systems

**Metric Series Threads — A comparison of Maximum Metal Dimensions of British (BS 1095), French (NF E03-104), German (DIN 13), and Swiss (VSM 12003) Systems**

| Nominal Size and Major Bolt Diam. | Pitch | Pitch Diam. | Bolt           |        |        |       | Nut              |        |        |                        |         |
|-----------------------------------|-------|-------------|----------------|--------|--------|-------|------------------|--------|--------|------------------------|---------|
|                                   |       |             | Minor Diameter |        |        |       | Major Diameter   |        |        | Minor Diameter         |         |
|                                   |       |             | British        | French | German | Swiss | British & German | French | Swiss  | French, German & Swiss | British |
| 6                                 | 1     | 5.350       | 4.863          | 4.59   | 4.700  | 4.60  | 6.000            | 6.108  | 6.100  | 4.700                  | 4.863   |
| 7                                 | 1     | 6.350       | 5.863          | 5.59   | 5.700  | 5.60  | 7.000            | 7.108  | 7.100  | 5.700                  | 5.863   |
| 8                                 | 1.25  | 7.188       | 6.579          | 6.24   | 6.376  | 6.25  | 8.000            | 8.135  | 8.124  | 6.376                  | 6.579   |
| 9                                 | 1.25  | 8.188       | 7.579          | 7.24   | 7.376  | 7.25  | 9.000            | 9.135  | 9.124  | 7.376                  | 7.579   |
| 10                                | 1.5   | 9.026       | 8.295          | 7.89   | 8.052  | 7.90  | 10.000           | 10.162 | 10.150 | 8.052                  | 8.295   |
| 11                                | 1.5   | 10.026      | 9.295          | 8.89   | 9.052  | 8.90  | 11.000           | 11.162 | 11.150 | 9.052                  | 9.295   |
| 12                                | 1.75  | 10.863      | 10.011         | 9.54   | 9.726  | 9.55  | 12.000           | 12.189 | 12.174 | 9.726                  | 10.011  |
| 14                                | 2     | 12.701      | 11.727         | 11.19  | 11.402 | 11.20 | 14.000           | 14.216 | 14.200 | 11.402                 | 11.727  |
| 16                                | 2     | 14.701      | 13.727         | 13.19  | 13.402 | 13.20 | 16.000           | 16.216 | 16.200 | 13.402                 | 13.727  |
| 18                                | 2.5   | 16.376      | 15.158         | 14.48  | 14.752 | 14.50 | 18.000           | 18.270 | 18.250 | 14.752                 | 15.158  |
| 20                                | 2.5   | 18.376      | 17.158         | 16.48  | 16.752 | 16.50 | 20.000           | 20.270 | 20.250 | 16.752                 | 17.158  |
| 22                                | 2.5   | 20.376      | 19.158         | 18.48  | 18.752 | 18.50 | 22.000           | 22.270 | 22.250 | 18.752                 | 19.158  |
| 24                                | 3     | 22.051      | 20.590         | 19.78  | 20.102 | 19.80 | 24.000           | 24.324 | 24.300 | 20.102 <sup>a</sup>    | 20.590  |
| 27                                | 3     | 25.051      | 23.590         | 22.78  | 23.102 | 22.80 | 27.000           | 27.324 | 27.300 | 23.102 <sup>b</sup>    | 23.590  |
| 30                                | 3.5   | 27.727      | 26.022         | 25.08  | 25.454 | 25.10 | 30.000           | 30.378 | 30.350 | 25.454                 | 26.022  |
| 33                                | 3.5   | 30.727      | 29.022         | 28.08  | 28.454 | 28.10 | 33.000           | 33.378 | 33.350 | 28.454                 | 29.022  |
| 36                                | 4     | 33.402      | 31.453         | 30.37  | 30.804 | 30.40 | 36.000           | 36.432 | 36.400 | 30.804                 | 31.453  |
| 39                                | 4     | 36.402      | 34.453         | 33.37  | 33.804 | 33.40 | 39.000           | 39.432 | 39.400 | 33.804                 | 34.453  |
| 42                                | 4.5   | 39.077      | 36.885         | 35.67  | 36.154 | 35.70 | 42.000           | 42.486 | 42.450 | 36.154                 | 36.885  |
| 45                                | 4.5   | 42.077      | 39.885         | 38.67  | 39.154 | 38.70 | 45.000           | 45.486 | 45.450 | 39.154                 | 39.885  |
| 48                                | 5     | 41.752      | 42.316         | 40.96  | 41.504 | 41.00 | 48.000           | 48.540 | 48.500 | 41.504                 | 42.316  |
| 52                                | 5     | 48.752      | 46.316         | 44.96  | 45.504 | 45.00 | 52.000           | 52.540 | 52.500 | 45.504                 | 46.316  |
| 56                                | 5.5   | 52.428      | 49.748         | 48.26  | 48.856 | 48.30 | 56.000           | 56.594 | 56.550 | 48.856                 | 49.748  |
| 60                                | 5.5   | 56.428      | 53.748         | 52.26  | 52.856 | 52.30 | 60.000           | 60.594 | 60.550 | 52.856                 | 53.748  |

<sup>a</sup>The value shown is given in the German Standard; the value in the French Standard is 20.002; and in the Swiss Standard, 20.104.

<sup>b</sup>The value shown is given in the German Standard; the value in the French Standard is 23.002; and in the Swiss Standard, 23.104.

All dimensions are in mm.

## ACME SCREW THREADS

### American National Standard Acme Screw Threads

This American National Standard ASME/ANSI B1.5-1997 is a revision of American Standard ANSI B1.5-1988 and provides for two general applications of Acme threads, namely, General Purpose and Centralizing.

The limits and tolerances in this standard relate to single-start Acme threads, and may be used, if considered suitable, for multi-start Acme threads, which provide fast relative traversing motion when this is necessary. For information on additional allowances for multi-start Acme threads, see later section on page 1827.

**General Purpose Acme Threads.**—Three classes of General Purpose threads, 2G, 3G, and 4G, are provided in the standard, each having clearance on all diameters for free movement, and may be used in assemblies with the internal thread rigidly fixed and movement of the external thread in a direction perpendicular to its axis limited by its bearing or bearings. It is suggested that external and internal threads of the same class be used together for general purpose assemblies, Class 2G being the preferred choice. If less backlash or end play is desired, Classes 3G and 4G are provided. Class 5G is not recommended for new designs.

**Thread Form:** The accompanying Fig. 1 shows the thread form of these General Purpose threads, and the formulas accompanying the figure determine their basic dimensions. Table 1 gives the basic dimensions for the most generally used pitches.

**Angle of Thread:** The angle between the sides of the thread, measured in an axial plane, is 29 degrees. The line bisecting this 29-degree angle shall be perpendicular to the axis of the screw thread.

**Thread Series:** A series of diameters and associated pitches is recommended in the Standard as preferred. These diameters and pitches have been chosen to meet present needs with the fewest number of items in order to reduce to a minimum the inventory of both tools and gages. This series of diameters and associated pitches is given in Table 3.

**Chamfers and Fillets:** General Purpose external threads may have the crest corner chamfered to an angle of 45 degrees with the axis to a maximum width of  $P/15$ , where  $P$  is the pitch. This corresponds to a maximum depth of chamfer flat of  $0.0945P$ .

**Basic Diameters:** The max major diameter of the external thread is basic and is the nominal major diameter for all classes. The min pitch diameter of the internal thread is basic and is equal to the basic major diameter minus the basic height of the thread,  $h$ . The basic minor diameter is the min minor diameter of the internal thread. It is equal to the basic major diameter minus twice the basic thread height,  $2h$ .

**Length of Engagement:** The tolerances specified in this standard are applicable to lengths of engagement not exceeding twice the nominal major diameter.

**Major and Minor Diameter Allowances:** A minimum diametral clearance is provided at the minor diameter of all external threads by establishing the maximum minor diameter 0.020 inch below the basic minor diameter of the nut for pitches of 10 threads per inch and coarser, and 0.10 inch for finer pitches. A minimum diametral clearance at the major diameter is obtained by establishing the minimum major diameter of the internal thread 0.020 inch above the basic major diameter of the screw for pitches of 10 threads per inch and coarser, and 0.010 inch for finer pitches.

**Major and Minor Diameter Tolerances:** The tolerance on the external thread major diameter is  $0.05P$ , where  $P$  is the pitch, with a minimum of 0.005 inch. The tolerance on the internal thread major diameter is 0.020 inch for 10 threads per inch and coarser and 0.010 for finer pitches. The tolerance on the external thread minor diameter is  $1.5 \times$  pitch diameter tolerance. The tolerance on the internal thread minor diameter is  $0.05P$  with a minimum of 0.005 inch.

**ANSI General Purpose Acme Thread Form ASME/ANSI B1.5-1997,  
and Stub Acme Screw Thread Form ASME/ANSI B1.8-1988 (R2001)**

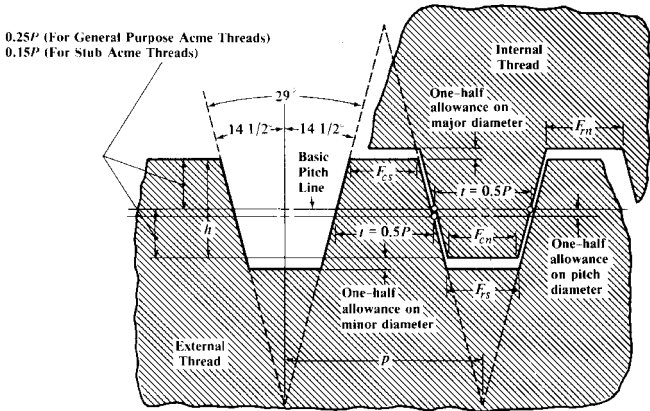


Fig. 1. General Purpose and Stub Acme Thread Forms

**Formulas for Basic Dimensions of General Purpose and Stub Acme Screw Threads**

| General Purpose   | Stub Acme Threads   |
|---|---|
| Pitch = $P = 1 \div$ No. threads per inch, $n$  | Pitch = $P = 1 \div$ No. threads per inch, $n$  |
| Basic thread height $h = 0.5P$  | Basic thread height $h = 0.3P$  |
| Basic thread thickness $t = 0.5P$   | Basic thread thickness $t = 0.5P$   |
| Basic flat at crest $F_{cn} = 0.3707P$ (internal thread)  | Basic flat at crest $F_{cn} = 0.4224P$ (internal thread)  |
| Basic flat at crest $F_{cs} = 0.3707P - 0.259 \times$<br>(pitch dia. allowance on ext. thd.)                        | Basic flat at crest $F_{cs} = 0.4224P - 0.259 \times$<br>(pitch dia. allowance on ext. thread)                      |
| $F_{rn} = 0.3707P - 0.259 \times$ (major dia. allowance<br>on internal thread)                                      | $F_{rn} = 0.4224P - 0.259 \times$ (major dia. allowance<br>on internal thread)                                      |
| $F_{rs} = 0.3707P - 0.259 \times$ (minor dia. allowance<br>on ext. thread - pitch dia.<br>allowance on ext. thread) | $F_{rs} = 0.4224P - 0.259 \times$ (minor dia. allowance<br>on ext. thread - pitch dia. allowance<br>on ext. thread) |

**Pitch Diameter Allowances and Tolerances:** Allowances on the pitch diameter of General Purpose Acme threads are given in Table 4. Pitch diameter tolerances are given in Table 5. The ratios of the pitch diameter tolerances of Classes 2G, 3G, and 4G, General Purpose threads are 3.0, 1.4, and 1, respectively.

An increase of 10 per cent in the allowance is recommended for each inch, or fraction thereof, that the length of engagement exceeds two diameters.

**Application of Tolerances:** The tolerances specified are designed to ensure interchangeability and maintain a high grade of product. The tolerances on diameters of the internal thread are plus, being applied from minimum sizes to above the minimum sizes. The tolerances on diameters of the external thread are minus, being applied from the maximum sizes to below the maximum sizes. The pitch diameter (or thread thickness) tolerances for an external or internal thread of a given class are the same. The thread thickness tolerance is 0.259 times the pitch diameter tolerance.

*Limiting Dimensions:* Limiting dimensions of General Purpose Acme screw threads in the recommended series are given in Table 2b. These limits are based on the formulas in Table 2a.

For combinations of pitch and diameter other than those in the recommended series, the formulas in Table 2a and the data in Tables 4 and 5 make it possible to readily determine the limiting dimensions required.

A diagram showing the disposition of allowances, tolerances, and crest clearances for General Purpose Acme threads appears on page 1826.

*Stress Area of General Purpose Acme Threads:* For computing the tensile strength of the thread section, the minimum stress area based on the mean of the minimum pitch diameter  $d_2$  min. and the minimum minor diameter  $d_1$  max. of the external thread is used:

$$\text{Stress Area} = 3.1416 \left( \frac{d_2 \text{ min.} + d_1 \text{ max.}}{4} \right)^2$$

where  $d_2$  min. and  $d_1$  max. may be computed by Formulas 4 and 6, Table 2a or taken from Table 2b.

*Shear Area of General Purpose Acme Threads:* For computing the shear area per inch length of engagement of the external thread, the maximum minor diameter of the internal thread  $D_1$  max., and the minimum pitch diameter of the external thread  $D_2$  min., Table 2b or Formulas 12 and 4, Table 2a, are used:

$$\text{Shear Area} = 3.1416 D_1 \text{ max.} [0.5 + n \tan 14\frac{1}{2}^\circ (D_2 \text{ min.} - D_1 \text{ max.})]$$

**Acme Thread Abbreviations.**—The following abbreviations are recommended for use on drawings and in specifications, and on tools and gages:

ACME = Acme threads  
 G = General Purpose  
 C = Centralizing  
 P = pitch  
 L = lead  
 LH = left hand

**Designation of General Purpose Acme Threads.**—The examples listed below are given here to show how General Purpose Acme threads are designated on drawings and tools:

1.750-4 ACME-2G indicates a General Purpose Class 2G Acme thread of 1.750-inch major diameter, 4 threads per inch, single thread, right hand. The same thread, but left hand, is designated 1.750-4 ACME-2G-LH.

2.875-0.4P-0.8L-ACME-3G indicates a General Purpose Class 3G Acme thread of 2.875-inch major diameter, pitch 0.4 inch, lead 0.8 inch, double thread, right hand.

**Multiple Start Acme Threads.**—The tabulated diameter-pitch data with allowances and tolerances relate to single-start threads. These data, as tabulated, may be and often are used for two-start Class 2G threads but this usage generally requires reduction of the full working tolerances to provide a greater allowance or clearance zone between the mating threads to assure satisfactory assembly.

When the class of thread requires smaller working tolerances than the 2G class or when threads with 3, 4, or more starts are required, some additional allowances or increased tolerances or both may be needed to ensure adequate working tolerances and satisfactory assembly of mating parts.

It is suggested that the allowances shown in Table 4 be used for all external threads and that allowances be applied to internal threads in the following ratios: for two-start threads, 50 per cent of the allowances shown in the Class 2G, 3G and 4G columns of Table 4; for



**Table 1. American National Standard General Purpose Acme Screw Thread Form — Basic Dimensions ASME/ANSI B1.5-1997**

| Thds. per Inch<br><i>n</i> | Pitch,<br>$P = 1/n$ | Height of Thread (Basic),<br>$h = P/2$ | Total Height of Thread,<br>$h_s = P/2 + \frac{1}{2}$ allowance <sup>a</sup> | Thread Thickness (Basic),<br>$t = P/2$ | Width of Flat   |   |
|----------------------------|---------------------|--|---|--|---|---|
|                            |                     |  |   |  | Crest of Internal Thread (Basic),<br>$F_{cn} = 0.3707P$ | Root of Internal Thread, $F_m$<br>$0.3707P - 0.259 \times$ allowance <sup>a</sup> |
| 16                         | 0.06250             | 0.03125                                | 0.0362  | 0.03125                                | 0.0232  | 0.0206  |
| 14                         | 0.07143             | 0.03571                                | 0.0407  | 0.03571                                | 0.0265  | 0.0239  |
| 12                         | 0.08333             | 0.04167                                | 0.0467  | 0.04167                                | 0.0309  | 0.0283  |
| 10                         | 0.010000            | 0.05000                                | 0.0600  | 0.05000                                | 0.0371  | 0.0319  |
| 8                          | 0.12500             | 0.06250                                | 0.0725  | 0.06250                                | 0.0463  | 0.0411  |
| 6                          | 0.16667             | 0.08333                                | 0.0933  | 0.08333                                | 0.0618  | 0.0566  |
| 5                          | 0.20000             | 0.10000                                | 0.1100  | 0.10000                                | 0.0741  | 0.0689  |
| 4                          | 0.25000             | 0.12500                                | 0.1350  | 0.12500                                | 0.0927  | 0.0875  |
| 3                          | 0.33333             | 0.16667                                | 0.1767  | 0.16667                                | 0.1236  | 0.1184  |
| 2½                         | 0.40000             | 0.20000                                | 0.2100  | 0.20000                                | 0.1483  | 0.1431  |
| 2                          | 0.50000             | 0.25000                                | 0.2600  | 0.25000                                | 0.1853  | 0.1802  |
| 1½                         | 0.66667             | 0.33333                                | 0.3433  | 0.33333                                | 0.2471  | 0.2419  |
| 1⅓                         | 0.75000             | 0.37500                                | 0.3850  | 0.37500                                | 0.2780  | 0.2728  |
| 1                          | 1.00000             | 0.50000                                | 0.5100  | 0.50000                                | 0.3707  | 0.3655  |

All dimensions are in inches.

<sup>a</sup> Allowance is 0.020 inch for 10 threads per inch and coarser, and 0.010 inch for finer threads.

**Table 2a. American National Standard General Purpose Acme Single-Start Screw Threads — Formulas for Determining Diameters ASME/ANSI B1.5-1997**

| <p><math>D</math> = Basic Major Diameter and Nominal Size, in Inches.<br/> <math>P</math> = Pitch = <math>1 \div</math> Number of Threads per Inch.<br/> <math>E</math> = Basic Pitch Diameter = <math>D - 0.5P</math><br/> <math>K</math> = Basic Minor Diameter = <math>D - P</math></p> |   |
|--|---|
| No.  | External Threads (Screws)   |
| 1  | Major Dia., Max. = $D$  |
| 2  | Major Dia., Min. = $D$ minus $0.05P^a$ but not less than 0.005.   |
| 3  | Pitch Dia., Max. = $E$ minus allowance from Table 4.  |
| 4  | Pitch Dia., Min. = Pitch Dia., Max. (Formula 3) minus tolerance from Table 5.   |
| 5  | Minor Dia., Max. = $K$ minus 0.020 for 10 threads per inch and coarser and 0.010 for finer-pitches.                         |
| 6  | Minor Dia., Min. = Minor Dia., Max. (Formula 5) minus $1.5 \times$ pitch diameter tolerance from Table 5.                   |
| Internal Threads (Nuts)  |   |
| 7  | Major Dia., Min. = $D$ plus 0.020 for 10 threads per inch and coarser and 0.010 for finer pitches.                          |
| 8  | Major Dia., Max. = Major Dia., Min. (Formula 7) plus 0.020 for 10 threads per inch and coarser and 0.010 for finer pitches. |
| 9  | Pitch Dia., Min. = $E$  |
| 10   | Pitch Dia., Max. = Pitch Dia., Min. (Formula 9) plus tolerance from Table 5.  |
| 11   | Minor Dia., Min. = $K$  |
| 12   | Minor Dia., Max. = Minor Dia., Min. (Formula 11) plus $0.05P^a$ but not less than 0.005.                                    |

<sup>a</sup> If  $P$  is between two recommended pitches listed in Table 3, use the coarser of the two pitches in this formula instead of the actual value of  $P$ .

**Table 2b. Limiting Dimensions of ANSI General Purpose Acme Single-Start Screw Threads ASME/ANSI B1.5-1988**

| Nominal Diameter, $D$                    |             | $\frac{1}{4}$                 | $\frac{5}{16}$ | $\frac{3}{8}$ | $\frac{7}{16}$ | $\frac{1}{2}$ | $\frac{5}{8}$ | $\frac{3}{4}$ | $\frac{7}{8}$ | 1      | $1\frac{1}{8}$ | $1\frac{1}{4}$ | $1\frac{3}{8}$ |
|--|-------------|-------------------------------|----------------|---------------|----------------|---------------|---------------|---------------|---------------|--------|----------------|----------------|----------------|
|  |             | Threads per Inch <sup>a</sup> |                |               |                |               |               |               |               |        |                |                |                |
| Limiting Diameters                       |             | 16                            | 14             | 12            | 12             | 10            | 8             | 6             | 6             | 5      | 5              | 5              | 4              |
|  |             | External Threads              |                |               |                |               |               |               |               |        |                |                |                |
| Classes 2G, 3G, and 4G<br>Major Diameter | Max ( $D$ ) | 0.2500                        | 0.3125         | 0.3750        | 0.4375         | 0.5000        | 0.6250        | 0.7500        | 0.8750        | 1.0000 | 1.1250         | 1.2500         | 1.3750         |
|  | Min         | 0.2450                        | 0.3075         | 0.3700        | 0.4325         | 0.4950        | 0.6188        | 0.7417        | 0.8667        | 0.9900 | 1.1150         | 1.2400         | 1.3625         |
| Classes 2G, 3G, and 4G<br>Minor Diameter | Max         | 0.1775                        | 0.2311         | 0.2817        | 0.3442         | 0.3800        | 0.4800        | 0.5633        | 0.6883        | 0.7800 | 0.9050         | 1.0300         | 1.1050         |
|  | Min         | 0.1618                        | 0.2140         | 0.2632        | 0.3253         | 0.3594        | 0.4570        | 0.5372        | 0.6615        | 0.7509 | 0.8753         | 0.9998         | 1.0720         |
| Class 2G, Minor Diameter                 | Min         | 0.1702                        | 0.2231         | 0.2730        | 0.3354         | 0.3704        | 0.4693        | 0.5511        | 0.6758        | 0.7664 | 0.8912         | 1.0159         | 1.0896         |
| Class 3G, Minor Diameter                 | Min         | 0.1722                        | 0.2254         | 0.2755        | 0.3379         | 0.3731        | 0.4723        | 0.5546        | 0.6794        | 0.7703 | 0.8951         | 1.0199         | 1.0940         |
| Class 4G, Minor Diameter                 | Min         | 0.1722                        | 0.2254         | 0.2755        | 0.3379         | 0.3731        | 0.4723        | 0.5546        | 0.6794        | 0.7703 | 0.8951         | 1.0199         | 1.0940         |
| Class 2G, Pitch Diameter                 | Max         | 0.2148                        | 0.2728         | 0.3284        | 0.3909         | 0.4443        | 0.5562        | 0.6598        | 0.7842        | 0.8920 | 1.0165         | 1.1411         | 1.2406         |
|  | Min         | 0.2043                        | 0.2614         | 0.3161        | 0.3783         | 0.4306        | 0.5408        | 0.6424        | 0.7663        | 0.8726 | 0.9967         | 1.1210         | 1.2188         |
| Class 3G, Pitch Diameter                 | Max         | 0.2158                        | 0.2738         | 0.3296        | 0.3921         | 0.4458        | 0.5578        | 0.6615        | 0.7861        | 0.8940 | 1.0186         | 1.1433         | 1.2430         |
|  | Min         | 0.2109                        | 0.2685         | 0.3238        | 0.3862         | 0.4394        | 0.5506        | 0.6534        | 0.7778        | 0.8849 | 1.0094         | 1.1339         | 1.2327         |
| Class 4G, Pitch Diameter                 | Max         | 0.2168                        | 0.2748         | 0.3309        | 0.3934         | 0.4472        | 0.5593        | 0.6632        | 0.7880        | 0.8960 | 1.0208         | 1.1455         | 1.2453         |
|  | Min         | 0.2133                        | 0.2710         | 0.3268        | 0.3892         | 0.4426        | 0.5542        | 0.6574        | 0.7820        | 0.8895 | 1.0142         | 1.1388         | 1.2380         |
|  |             | Internal Threads              |                |               |                |               |               |               |               |        |                |                |                |
| Classes 2G, 3G, and 4G<br>Major Diameter | Min         | 0.2600                        | 0.3225         | 0.3850        | 0.4475         | 0.5200        | 0.6450        | 0.7700        | 0.8950        | 1.0200 | 1.1450         | 1.2700         | 1.3950         |
|  | Max         | 0.2700                        | 0.3325         | 0.3950        | 0.4575         | 0.5400        | 0.6650        | 0.7900        | 0.9150        | 1.0400 | 1.1650         | 1.2900         | 1.4150         |
| Classes 2G, 3G, and 4G<br>Minor Diameter | Min         | 0.1875                        | 0.2411         | 0.2917        | 0.3542         | 0.4000        | 0.5000        | 0.5833        | 0.7083        | 0.8000 | 0.9250         | 1.0500         | 1.1250         |
|  | Max         | 0.1925                        | 0.2461         | 0.2967        | 0.3592         | 0.4050        | 0.5062        | 0.5916        | 0.7166        | 0.8100 | 0.9350         | 1.0600         | 1.1375         |
| Class 2G, Pitch Diameter                 | Min         | 0.2188                        | 0.2768         | 0.3333        | 0.3958         | 0.4500        | 0.5625        | 0.6667        | 0.7917        | 0.9000 | 1.0250         | 1.1500         | 1.2500         |
|  | Max         | 0.2293                        | 0.2882         | 0.3456        | 0.4084         | 0.4637        | 0.5779        | 0.6841        | 0.8096        | 0.9194 | 1.0448         | 1.1701         | 1.2720         |
| Class 3G, Pitch Diameter                 | Min         | 0.2188                        | 0.2768         | 0.3333        | 0.3958         | 0.4500        | 0.5625        | 0.6667        | 0.7917        | 0.9000 | 1.0250         | 1.1500         | 1.2500         |
|  | Max         | 0.2237                        | 0.2821         | 0.3391        | 0.4017         | 0.4564        | 0.5697        | 0.6748        | 0.8000        | 0.9091 | 1.0342         | 1.1594         | 1.2603         |
| Class 4G, Pitch Diameter                 | Min         | 0.2188                        | 0.2768         | 0.3333        | 0.3958         | 0.4500        | 0.5625        | 0.6667        | 0.7917        | 0.9000 | 1.0250         | 1.1500         | 1.2500         |
|  | Max         | 0.2223                        | 0.2806         | 0.3374        | 0.4000         | 0.4546        | 0.5676        | 0.6725        | 0.7977        | 0.9065 | 1.0316         | 1.1567         | 1.2573         |

**Table 2b. (Continued) Limiting Dimensions of ANSI General Purpose Acme Single-Start Screw Threads ASME/ANSI B1.5-1988**

| Nominal Diameter, $D$    |                          | $1\frac{1}{2}$                | $1\frac{3}{4}$ | 2      | $2\frac{1}{4}$ | $2\frac{1}{2}$ | $2\frac{3}{4}$ | 3      | $3\frac{1}{2}$ | 4      | $4\frac{1}{2}$ | 5      |
|--------------------------|--------------------------|-------------------------------|----------------|--------|----------------|----------------|----------------|--------|----------------|--------|----------------|--------|
|                          |                          | Threads per Inch <sup>a</sup> |                |        |                |                |                |        |                |        |                |        |
| Limiting Dimensions      |                          | External Threads              |                |        |                |                |                |        |                |        |                |        |
| Classes 2G, 3G, and 4G   | Max ( $D$ )              | 1.5000                        | 1.7500         | 2.0000 | 2.2500         | 2.5000         | 2.7500         | 3.0000 | 3.5000         | 4.0000 | 4.5000         | 5.0000 |
|                          | Major Diameter           | 1.4875                        | 1.7375         | 1.9875 | 2.2333         | 2.4833         | 2.7333         | 2.9750 | 3.4750         | 3.9750 | 4.4750         | 4.9750 |
| Classes 2G, 3G, and 4G   | Minor Diameter           | 1.2300                        | 1.4800         | 1.7300 | 1.8967         | 2.1467         | 2.3967         | 2.4800 | 2.9800         | 3.4800 | 3.9800         | 4.4800 |
|                          | Class 2G, Minor Diameter | 1.1965                        | 1.4456         | 1.6948 | 1.8572         | 2.1065         | 2.3558         | 2.4326 | 2.9314         | 3.4302 | 3.9291         | 4.4281 |
| Class 3G, Minor Diameter | Min                      | 1.2144                        | 1.4640         | 1.7136 | 1.8783         | 2.1279         | 2.3776         | 2.4579 | 2.9574         | 3.4568 | 3.9563         | 4.4558 |
|                          | Class 4G, Minor Diameter | 1.2189                        | 1.4686         | 1.7183 | 1.8835         | 2.1333         | 2.3831         | 2.4642 | 2.9638         | 3.4634 | 3.9631         | 4.4627 |
| Class 2G, Pitch Diameter | Max                      | 1.3652                        | 1.6145         | 1.8637 | 2.0713         | 2.3207         | 2.5700         | 2.7360 | 3.2350         | 3.7340 | 4.2330         | 4.7319 |
|                          | Min                      | 1.3429                        | 1.5916         | 1.8402 | 2.0450         | 2.2939         | 2.5427         | 2.7044 | 3.2026         | 3.7008 | 4.1991         | 4.6973 |
| Class 3G, Pitch Diameter | Max                      | 1.3677                        | 1.6171         | 1.8665 | 2.0743         | 2.3238         | 2.5734         | 2.7395 | 3.2388         | 3.7380 | 4.2373         | 4.7364 |
|                          | Min                      | 1.3573                        | 1.6064         | 1.8555 | 2.0620         | 2.3113         | 2.5607         | 2.7248 | 3.2237         | 3.7225 | 4.2215         | 4.7202 |
| Class 4G, Pitch Diameter | Max                      | 1.3701                        | 1.6198         | 1.8693 | 2.0773         | 2.3270         | 2.5767         | 2.7430 | 3.2425         | 3.7420 | 4.2415         | 4.7409 |
|                          | Min                      | 1.3627                        | 1.6122         | 1.8615 | 2.0685         | 2.3181         | 2.5676         | 2.7325 | 3.2317         | 3.7309 | 4.2302         | 4.7294 |
|                          |                          | Internal Threads              |                |        |                |                |                |        |                |        |                |        |
| Classes 2G, 3G, and 4G   | Min                      | 1.5200                        | 1.7700         | 2.0200 | 2.2700         | 2.5200         | 2.7700         | 3.0200 | 3.5200         | 4.0200 | 4.5200         | 5.0200 |
|                          | Major Diameter           | 1.5400                        | 1.7900         | 2.0400 | 2.2900         | 2.5400         | 2.7900         | 3.0400 | 3.5400         | 4.0400 | 4.5400         | 5.0400 |
| Classes 2G, 3G, and 4G   | Minor Diameter           | 1.2500                        | 1.5000         | 1.7500 | 1.9167         | 2.1667         | 2.4167         | 2.5000 | 3.0000         | 3.5000 | 4.0000         | 4.5000 |
|                          | Max                      | 1.2625                        | 1.5125         | 1.7625 | 1.9334         | 2.1834         | 2.4334         | 2.5250 | 3.0250         | 3.5250 | 4.0250         | 4.5250 |
| Class 2G, Pitch Diameter | Min                      | 1.3750                        | 1.6250         | 1.8750 | 2.0833         | 2.3333         | 2.5833         | 2.7500 | 3.2500         | 3.7500 | 4.2500         | 4.7500 |
|                          | Max                      | 1.3973                        | 1.6479         | 1.8985 | 2.1096         | 2.3601         | 2.6106         | 2.7816 | 3.2824         | 3.7832 | 4.2839         | 4.7846 |
| Class 3G, Pitch Diameter | Min                      | 1.3750                        | 1.6250         | 1.8750 | 2.0833         | 2.3333         | 2.5833         | 2.7500 | 3.2500         | 3.7500 | 4.2500         | 4.7500 |
|                          | Max                      | 1.3854                        | 1.6357         | 1.8860 | 2.0956         | 2.3458         | 2.5960         | 2.7647 | 3.2651         | 3.7655 | 4.2658         | 4.7662 |
| Class 4G, Pitch Diameter | Min                      | 1.3750                        | 1.6250         | 1.8750 | 2.0833         | 2.3333         | 2.5833         | 2.7500 | 3.2500         | 3.7500 | 4.2500         | 4.7500 |
|                          | Max                      | 1.3824                        | 1.6326         | 1.8828 | 2.0921         | 2.3422         | 2.5924         | 2.7605 | 3.2608         | 3.7611 | 4.2613         | 4.7615 |

<sup>a</sup> All other dimensions are given in inches. The selection of threads per inch is arbitrary and for the purpose of establishing a standard.

**Table 3. General Purpose Acme Single-Start Screw Thread Data ASME/ANSI B1.5-1988**

| Identification              |  | Basic Diameters             |   |  | Thread Data        |  |   |  |   |     |                                     |                                      |
|-----------------------------|--|-----------------------------|---|--|--------------------|--|---|--|---|-----|-------------------------------------|--------------------------------------|
| Nominal Sizes (All Classes) | Threads per Inch, <sup>a</sup><br><i>n</i> | Classes 2G, 3G, and 4G      |   |  | Pitch,<br><i>P</i> | Thickness at Pitch Line,<br><i>t = P/2</i> | Basic Height of Thread,<br><i>h = P/2</i> | Basic Width of Flat,<br><i>F = 0.3707P</i> | Lead Angle $\lambda$ at Basic Pitch Diameter <sup>b</sup><br>Classes 2G, 3G, and 4G |     | Shear Area <sup>b</sup><br>Class 3G | Stress Area <sup>c</sup><br>Class 3G |
|                             |  | Major Diameter,<br><i>D</i> | Pitch Diameter,<br><i>D<sub>2</sub> = D - h</i> | Minor Diameter,<br><i>D<sub>1</sub> = D - 2h</i> |                    |  |   |  | Deg   | Min |                                     |                                      |
|                             |  |                             |   |  |                    |  |   |  |   |     |                                     |                                      |
| 1/4                         | 16   | 0.2500                      | 0.2188  | 0.1875   | 0.06250            | 0.03125                                    | 0.03125                                   | 0.0232                                     | 5   | 12  | 0.350                               | 0.0285                               |
| 5/16                        | 14   | 0.3125                      | 0.2768  | 0.2411   | 0.07143            | 0.03571                                    | 0.03571                                   | 0.0265                                     | 4   | 42  | 0.451                               | 0.0474                               |
| 3/8                         | 12   | 0.3750                      | 0.3333  | 0.2917   | 0.08333            | 0.04167                                    | 0.04167                                   | 0.0309                                     | 4   | 33  | 0.545                               | 0.0699                               |
| 7/16                        | 12   | 0.4375                      | 0.3958  | 0.3542   | 0.08333            | 0.04167                                    | 0.04167                                   | 0.0309                                     | 3   | 50  | 0.660                               | 0.1022                               |
| 1/2                         | 10   | 0.5000                      | 0.4500  | 0.4000   | 0.10000            | 0.05000                                    | 0.05000                                   | 0.0371                                     | 4   | 3   | 0.749                               | 0.1287                               |
| 5/8                         | 8  | 0.6250                      | 0.5625  | 0.5000   | 0.12500            | 0.06250                                    | 0.06250                                   | 0.0463                                     | 4   | 3   | 0.941                               | 0.2043                               |
| 3/4                         | 6  | 0.7500                      | 0.6667  | 0.5833   | 0.16667            | 0.08333                                    | 0.08333                                   | 0.0618                                     | 4   | 33  | 1.108                               | 0.2848                               |
| 7/8                         | 6  | 0.8750                      | 0.7917  | 0.7083   | 0.16667            | 0.08333                                    | 0.08333                                   | 0.0618                                     | 3   | 50  | 1.339                               | 0.4150                               |
| 1                           | 5  | 1.0000                      | 0.9000  | 0.8000   | 0.20000            | 0.10000                                    | 0.10000                                   | 0.0741                                     | 4   | 3   | 1.519                               | 0.5354                               |
| 1 1/8                       | 5  | 1.1250                      | 1.0250  | 0.9250   | 0.20000            | 0.10000                                    | 0.10000                                   | 0.0741                                     | 3   | 33  | 1.751                               | 0.709                                |
| 1 1/4                       | 5  | 1.2500                      | 1.1500  | 1.0500   | 0.20000            | 0.10000                                    | 0.10000                                   | 0.0741                                     | 3   | 10  | 1.983                               | 0.907                                |
| 1 3/8                       | 4  | 1.3750                      | 1.2500  | 1.1250   | 0.25000            | 0.12500                                    | 0.12500                                   | 0.0927                                     | 3   | 39  | 2.139                               | 1.059                                |
| 1 1/2                       | 4  | 1.5000                      | 1.3750  | 1.2500   | 0.25000            | 0.12500                                    | 0.12500                                   | 0.0927                                     | 3   | 19  | 2.372                               | 1.298                                |
| 1 3/4                       | 4  | 1.7500                      | 1.6250  | 1.5000   | 0.25000            | 0.12500                                    | 0.12500                                   | 0.0927                                     | 2   | 48  | 2.837                               | 1.851                                |
| 2                           | 4  | 2.0000                      | 1.8750  | 1.7500   | 0.25000            | 0.12500                                    | 0.12500                                   | 0.0927                                     | 2   | 26  | 3.301                               | 2.501                                |
| 2 1/4                       | 3  | 2.2500                      | 2.0833  | 1.9167   | 0.33333            | 0.16667                                    | 0.16667                                   | 0.1236                                     | 2   | 55  | 3.643                               | 3.049                                |
| 2 1/2                       | 3  | 2.5000                      | 2.3333  | 2.1667   | 0.33333            | 0.16667                                    | 0.16667                                   | 0.1236                                     | 2   | 36  | 4.110                               | 3.870                                |
| 2 3/4                       | 3  | 2.7500                      | 2.5833  | 2.4167   | 0.33333            | 0.16667                                    | 0.16667                                   | 0.1236                                     | 2   | 21  | 4.577                               | 4.788                                |
| 3                           | 2  | 3.0000                      | 2.7500  | 2.5000   | 0.50000            | 0.25000                                    | 0.25000                                   | 0.1853                                     | 3   | 19  | 4.786                               | 5.27                                 |
| 3 1/2                       | 2  | 3.5000                      | 3.2500  | 3.0000   | 0.50000            | 0.25000                                    | 0.25000                                   | 0.1853                                     | 2   | 48  | 5.73                                | 7.50                                 |
| 4                           | 2  | 4.0000                      | 3.7500  | 3.5000   | 0.50000            | 0.25000                                    | 0.25000                                   | 0.1853                                     | 2   | 26  | 6.67                                | 10.12                                |
| 4 1/2                       | 2  | 4.5000                      | 4.2500  | 4.0000   | 0.50000            | 0.25000                                    | 0.25000                                   | 0.1853                                     | 2   | 9   | 7.60                                | 13.13                                |
| 5                           | 2  | 5.0000                      | 4.7500  | 4.5000   | 0.50000            | 0.25000                                    | 0.25000                                   | 0.1853                                     | 1   | 55  | 8.54                                | 16.53                                |

<sup>a</sup> All other dimensions are given in inches.<sup>b</sup> Per inch length of engagement of the external thread in line with the minor diameter crests of the internal thread. Figures given are the minimum shear area based on max  $D_1$  and min  $d_2$ .<sup>c</sup> Figures given are the minimum stress area based on the mean of the minimum minor and pitch diameters of the external thread. See formulas for shear area and stress area on page 1827.

**Table 4. American National Standard General Purpose Acme Single-Start Screw Threads — Pitch Diameter Allowances ASME/ANSI B1.5-1988**

| Nominal Size Range <sup>a</sup> |                  | Allowances on External Threads <sup>b</sup> |                               |                               | Nominal Size Range <sup>a</sup> |                  | Allowances on External Threads <sup>b</sup> |                               |                               |
|---------------------------------|------------------|---|-------------------------------|-------------------------------|---------------------------------|------------------|---|-------------------------------|-------------------------------|
| Above                           | To and Including | Class 2G,<br>0.008 $\sqrt{D}$               | Class 3G,<br>0.006 $\sqrt{D}$ | Class 4G,<br>0.004 $\sqrt{D}$ | Above                           | To and Including | Class 2G,<br>0.008 $\sqrt{D}$               | Class 3G,<br>0.006 $\sqrt{D}$ | Class 4G,<br>0.004 $\sqrt{D}$ |
| 0                               | $\frac{3}{16}$   | 0.0024                                      | 0.0018                        | 0.0012                        | $1\frac{7}{16}$                 | $1\frac{9}{16}$  | 0.0098                                      | 0.0073                        | 0.0049                        |
| $\frac{3}{16}$                  | $\frac{5}{16}$   | 0.0040                                      | 0.0030                        | 0.0020                        | $1\frac{1}{8}$                  | $1\frac{7}{8}$   | 0.0105                                      | 0.0079                        | 0.0052                        |
| $\frac{5}{16}$                  | $\frac{7}{16}$   | 0.0049                                      | 0.0037                        | 0.0024                        | $1\frac{3}{8}$                  | $2\frac{1}{8}$   | 0.0113                                      | 0.0085                        | 0.0057                        |
| $\frac{7}{16}$                  | $\frac{9}{16}$   | 0.0057                                      | 0.0042                        | 0.0028                        | $2\frac{1}{8}$                  | $2\frac{3}{8}$   | 0.0120                                      | 0.0090                        | 0.0060                        |
| $\frac{9}{16}$                  | $1\frac{1}{16}$  | 0.0063                                      | 0.0047                        | 0.0032                        | $2\frac{3}{8}$                  | $2\frac{5}{8}$   | 0.0126                                      | 0.0095                        | 0.0063                        |
| $1\frac{1}{16}$                 | $1\frac{3}{16}$  | 0.0069                                      | 0.0052                        | 0.0035                        | $2\frac{5}{8}$                  | $2\frac{7}{8}$   | 0.0133                                      | 0.0099                        | 0.0066                        |
| $1\frac{3}{16}$                 | $1\frac{5}{16}$  | 0.0075                                      | 0.0056                        | 0.0037                        | $2\frac{7}{8}$                  | $3\frac{1}{4}$   | 0.0140                                      | 0.0105                        | 0.0070                        |
| $1\frac{5}{16}$                 | $1\frac{7}{16}$  | 0.0080                                      | 0.0060                        | 0.0040                        | $3\frac{1}{4}$                  | $3\frac{3}{4}$   | 0.0150                                      | 0.0112                        | 0.0075                        |
| $1\frac{7}{16}$                 | $1\frac{9}{16}$  | 0.0085                                      | 0.0064                        | 0.0042                        | $3\frac{3}{4}$                  | $4\frac{1}{4}$   | 0.0160                                      | 0.0120                        | 0.0080                        |
| $1\frac{9}{16}$                 | $1\frac{11}{16}$ | 0.0089                                      | 0.0067                        | 0.0045                        | $4\frac{1}{4}$                  | $4\frac{3}{4}$   | 0.0170                                      | 0.0127                        | 0.0085                        |
| $1\frac{11}{16}$                | $1\frac{13}{16}$ | 0.0094                                      | 0.0070                        | 0.0047                        | $4\frac{3}{4}$                  | $5\frac{1}{2}$   | 0.0181                                      | 0.0136                        | 0.0091                        |

All dimensions in inches. It is recommended that the sizes given in Table 3 be used whenever possible.

<sup>a</sup> The values in columns for Classes 2G, 3G, and 4G are to be used for any size within the nominal size range shown. These values are calculated from the mean of the range.

<sup>b</sup> An increase of 10 per cent in the allowance is recommended for each inch, or fraction thereof, that the length of engagement exceeds two diameters.

<sup>c</sup> Allowances for the 2G Class of thread in this table also apply to American National Standard Stub Acme threads ASME/ANSI B 1.8-1988.

three-start threads, 75 per cent of these allowances; and for four-start threads, 100 per cent of these same values.

These values will provide for a 0.25-16 ACME-2G thread size, 0.002, 0.003, and 0.004 inch additional clearance for 2-, 3-, and 4-start threads, respectively. For a 5-2 ACME-3G thread size the additional clearances would be 0.0091, 0.0136, and 0.0181 inch, respectively. GO thread plug gages and taps would be increased by these same values. To maintain the same working tolerances on multi-start threads, the pitch diameter of the NOT GO thread plug gage would also be increased by these same values.

For multi-start threads with more than four starts, it is believed that the 100 per cent allowance provided by the above procedures would be adequate as index spacing variables would generally be no greater than on a four-start thread.

In general, for multi-start threads of Classes 2G, 3G, and 4G the percentages would be applied, usually, to allowances for the same class, respectively. However, where exceptionally good control over lead, angle, and spacing variables would produce close to theoretical values in the product, it is conceivable that these percentages could be applied to Class 3G or Class 4G allowances used on Class 2G internally threaded product. Also, these percentages could be applied to Class 4G allowances used on Class 3G internally threaded product. It is not advocated that any change be made in externally threaded products.

Designations for gages or tools for internal threads could cover allowance requirements as follows:

GO and NOT GO thread plug gages for: 2.875-0.4P-0.8L-ACME-2G with 50 per cent of the 4G internal thread allowance.

**Centralizing Acme Threads.**—The three classes of Centralizing Acme threads in American National Standard ASME/ANSI B1.5-1988, designated as 2C, 3C, and 4C, have limited clearance at the major diameters of internal and external threads so that a bearing at the major diameters maintains approximate alignment of the thread axis and prevents wedging

**Table 5. American National Standard General Purpose Acme Single-Start Screw Threads — Pitch Diameter Tolerances ASME/ANSI B1.5-1988**

| Nom. Dia., <sup>a</sup><br><i>D</i>       | Class of Thread    |                   |                   | Nom. Dia., <sup>a</sup><br><i>D</i>       | Class of Thread    |                   |                   |
|---|--------------------|-------------------|-------------------|---|--------------------|-------------------|-------------------|
|   | 2G <sup>b</sup>    | 3G                | 4G                |   | 2G <sup>b</sup>    | 3G                | 4G                |
|   | Diameter Increment |                   |                   |   | Diameter Increment |                   |                   |
|   | $0.006\sqrt{D}$    | $0.0028\sqrt{D}$  | $0.002\sqrt{D}$   |   | $0.006\sqrt{D}$    | $0.0028\sqrt{D}$  | $0.002\sqrt{D}$   |
| ¼   | .00300             | .00140            | .00100            | 1½  | .00735             | .00343            | .00245            |
| ⅜   | .00335             | .00157            | .00112            | 1¾  | .00794             | .00370            | .00265            |
| ½   | .00367             | .00171            | .00122            | 2   | .00849             | .00396            | .00283            |
| ⅝   | .00397             | .00185            | .00132            | 2¼  | .00900             | .00420            | .00300            |
| ¾   | .00424             | .00198            | .00141            | 2½  | .00949             | .00443            | .00316            |
| ⅞   | .00474             | .00221            | .00158            | 2¾  | .00995             | .00464            | .00332            |
| 1   | .00520             | .00242            | .00173            | 3   | .01039             | .00485            | .00346            |
| 1¼  | .00561             | .00262            | .00187            | 3½  | .01122             | .00524            | .00374            |
| 1½  | .00600             | .00280            | .00200            | 4   | .01200             | .00560            | .00400            |
| 1¾  | .00636             | .00297            | .00212            | 4½  | .01273             | .00594            | .00424            |
| 1⅞  | .00671             | .00313            | .00224            | 5   | .01342             | .00626            | .00447            |
| 2   | .00704             | .00328            | .00235            | ...                                       | ...                | ...               | ...               |
| Thds. per Inch <sup>c</sup> ,<br><i>n</i> | Class of Thread    |                   |                   | Thds. per Inch <sup>c</sup> ,<br><i>n</i> | Class of Thread    |                   |                   |
|   | 2G <sup>b</sup>    | 3G                | 4G                |   | 2G <sup>b</sup>    | 3G                | 4G                |
|   | Pitch Increment    |                   |                   |   | Pitch Increment    |                   |                   |
|   | $0.030\sqrt{1/n}$  | $0.014\sqrt{1/n}$ | $0.010\sqrt{1/n}$ |   | $0.030\sqrt{1/n}$  | $0.014\sqrt{1/n}$ | $0.010\sqrt{1/n}$ |
| 16  | .00750             | .00350            | .00250            | 4   | .01500             | .00700            | .00500            |
| 14  | .00802             | .00374            | .00267            | 3   | .01732             | .00808            | .00577            |
| 12  | .00866             | .00404            | .00289            | 2½  | .01897             | .00885            | .00632            |
| 10  | .00949             | .00443            | .00316            | 2   | .02121             | .00990            | .00707            |
| 8   | .01061             | .00495            | .00354            | 1½  | .02449             | .01143            | .00816            |
| 6   | .01225             | .00572            | .00408            | 1⅓  | .02598             | .01212            | .00866            |
| 5   | .01342             | .00626            | .00447            | 1   | .03000             | .01400            | .01000            |

For any particular size of thread, the pitch diameter tolerance is obtained by adding the *diameter increment* from the upper half of the table to the *pitch increment* from the lower half of the table. *Example:* A ¼-16 Acme-2G thread has a pitch diameter tolerance of  $0.00300 + 0.00750 = 0.0105$  inch.

The equivalent tolerance on thread thickness is 0.259 times the pitch diameter tolerance.

<sup>a</sup> For a nominal diameter between any two tabulated nominal diameters, use the diameter increment for the larger of the two tabulated nominal diameters.

<sup>b</sup> Columns for the 2G Class of thread in this table also apply to American National Standard Stub Acme threads, ASME/ANSI B1.8-1988 (R2001).

<sup>c</sup> All other dimensions are given in inches.

on the flanks of the thread. An alternative series having centralizing control on the *minor* diameter is described on page 1843. For any combination of the three classes of threads covered in this standard some end play or backlash will result. Classes 5C and 6C are not recommended for new designs.

*Application:* These three classes together with the accompanying specifications are for the purpose of ensuring the interchangeable manufacture of Centralizing Acme threaded parts. Each user is free to select the classes best adapted to his particular needs. It is suggested that external and internal threads of the same class be used together for centralizing assemblies, Class 2C providing the maximum end play or backlash. If less backlash or end play is desired, Classes 3C and 4C are provided. The requirement for a centralizing fit is that the sum of the major diameter tolerance plus the major diameter allowance on the internal thread, and the major diameter tolerance on the external thread shall equal or be less than the pitch diameter allowance on the external thread. A Class 2C external thread, which has a larger pitch diameter allowance than either a Class 3C or 4C, can be used inter-

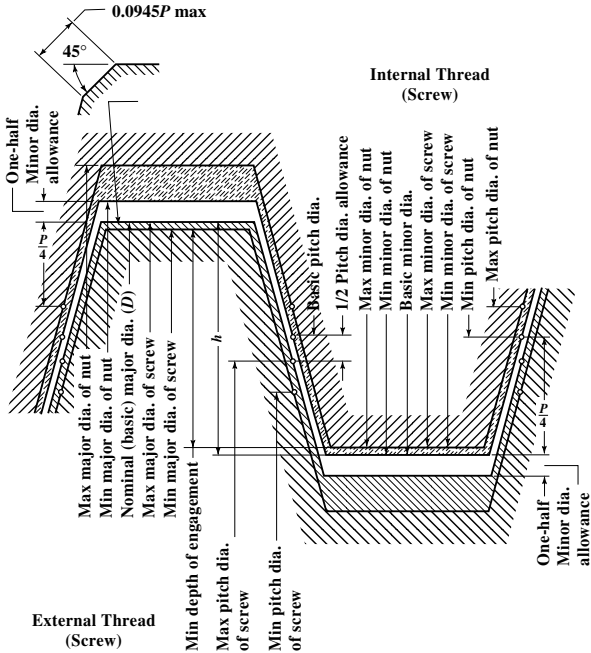


Fig. 2. Disposition of Allowances, Tolerances, and Crest Clearances for General Purpose Single-start Acme Threads (All Classes)

changeably with a Class 2C, 3C, or 4C internal thread and fulfill this requirement. Similarly, a Class 3C external thread can be used interchangeably with a Class 3C or 4C internal thread, but only a Class 4C internal thread can be used with a Class 4C external thread.

**Thread Form:** The thread form is the same as the General Purpose Acme Thread and is shown in Fig. 3. The formulas in Table 7 determine the basic dimensions, which are given in Table 6 for the most generally used pitches.

**Angle of Thread:** The angle between the sides of the thread measured in an axial plane is 29 degrees. The line bisecting this 29-degree angle shall be perpendicular to the axis of the thread.

**Chamfers and Fillets:** External threads have the crest corners chamfered at an angle of 45 degrees with the axis to a minimum depth of  $P/20$  and a maximum depth of  $P/15$ . These modifications correspond to a minimum width of chamfer flat of  $0.0707P$  and a maximum width of  $0.0945P$  (see Table 6, columns 6 and 7).

External threads for Classes 2C, 3C, and 4C may have a fillet at the minor diameter not greater than  $0.1P$

**Thread Series:** A series of diameters and pitches is recommended in the Standard as preferred. These diameters and pitches have been chosen to meet present needs with the few-

**Table 6. American National Standard Centralizing Acme Screw Thread Form — Basic Dimensions ASME/ANSI B1.5-1988**

| Thds per Inch, $n$ | Pitch, $P$ | Height of Thread (Basic), $h = P/2$ | Total Height of Thread (All External Threads) $h_t = h + \frac{1}{2}$ allowance <sup>a</sup> | Thread Thickness (Basic), $t = P/2$ | 45-Deg Chamfer Crest of External Threads |                                      | Max Fillet Radius, Root of Tapped Hole, $0.06P$ | Fillet Radius at Min or Diameter of Screws Max (All) $0.10P$ |
|--------------------|------------|-------------------------------------|--|-------------------------------------|--|--------------------------------------|---|--|
|                    |            |                                     |  |                                     | Min Depth, $0.05P$                       | Min Width of Chamfer Flat, $0.0707P$ |   |  |
| 16                 | 0.06250    | 0.03125                             | 0.0362   | 0.03125                             | 0.0031                                   | 0.0044                               | 0.0038  | 0.0062   |
| 14                 | 0.07143    | 0.03571                             | 0.0407   | 0.03571                             | 0.0036                                   | 0.0050                               | 0.0038  | 0.0071   |
| 12                 | 0.08333    | 0.04167                             | 0.0467   | 0.04167                             | 0.0042                                   | 0.0059                               | 0.0050  | 0.0083   |
| 10                 | 0.10000    | 0.05000                             | 0.0600   | 0.05000                             | 0.0050                                   | 0.0071                               | 0.0060  | 0.0100   |
| 8                  | 0.12500    | 0.06250                             | 0.0725   | 0.06250                             | 0.0062                                   | 0.0088                               | 0.0075  | 0.0125   |
| 6                  | 0.16667    | 0.08333                             | 0.0933   | 0.08333                             | 0.0083                                   | 0.0119                               | 0.0100  | 0.0167   |
| 5                  | 0.20000    | 0.10000                             | 0.1100   | 0.10000                             | 0.0100                                   | 0.0141                               | 0.0120  | 0.0200   |
| 4                  | 0.25000    | 0.12500                             | 0.1350   | 0.12500                             | 0.0125                                   | 0.0177                               | 0.0150  | 0.0250   |
| 3                  | 0.33333    | 0.16667                             | 0.1767   | 0.16667                             | 0.0167                                   | 0.0236                               | 0.0200  | 0.0333   |
| 2½                 | 0.40000    | 0.20000                             | 0.2100   | 0.20000                             | 0.0200                                   | 0.0283                               | 0.0240  | 0.0400   |
| 2                  | 0.50000    | 0.25000                             | 0.2600   | 0.25000                             | 0.0250                                   | 0.0354                               | 0.0300  | 0.0500   |
| 1½                 | 0.66667    | 0.33333                             | 0.3433   | 0.33333                             | 0.0330                                   | 0.0471                               | 0.0400  | 0.0667   |
| 1⅓                 | 0.75000    | 0.37500                             | 0.3850   | 0.37500                             | 0.0380                                   | 0.0530                               | 0.0450  | 0.0750   |
| 1                  | 1.00000    | 0.50000                             | 0.5100   | 0.50000                             | 0.0500                                   | 0.0707                               | 0.0600  | 0.1000   |

All dimensions in inches. See Fig. 3.

<sup>a</sup> Allowance is 0.020 inch for 10 or less threads per inch and 0.010 inch for more than 10 threads per inch.

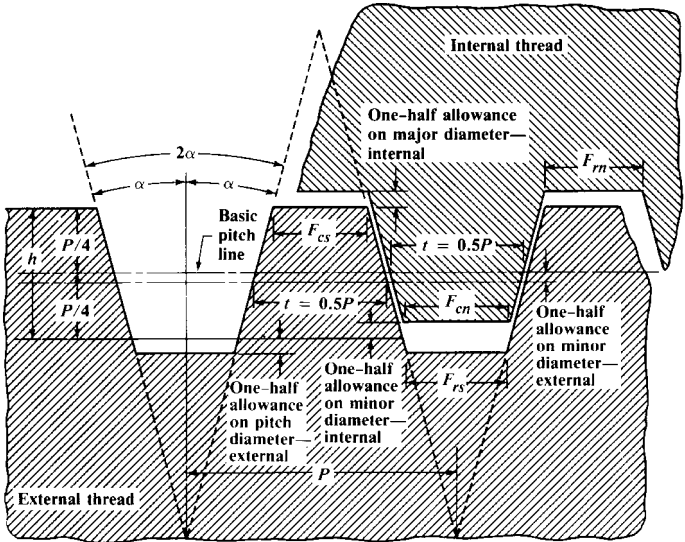


Fig. 3. Centralizing Acme Screw Thread Form



**Table 7. Formulas for Finding Basic Dimensions of Centralizing Acme Screw Threads**

|   |                                |
|---|--------------------------------|
| Pitch = $P = 1 \div \text{No. threads per inch, } n$ :  | Basic thread height $h = 0.5P$ |
| Basic thread thickness $t = 0.5P$   |                                |
| Basic flat at crest $F_{cn} = 0.3707P + 0.259 \times (\text{minor diameter allowance on internal threads})$ (internal thread)       |                                |
| Basic flat at crest $F_{cs} = 0.3707P - 0.259 \times (\text{pitch diameter allowance on external thread})$ (external thread)        |                                |
| $F_m = 0.3707P - 0.259 \times (\text{major dia. allowance on internal thread})$   |                                |
| $F_{rs} = 0.3707P - 0.259 \times (\text{minor dia. allowance on external thread} - \text{pitch dia. allowance on external thread})$ |                                |

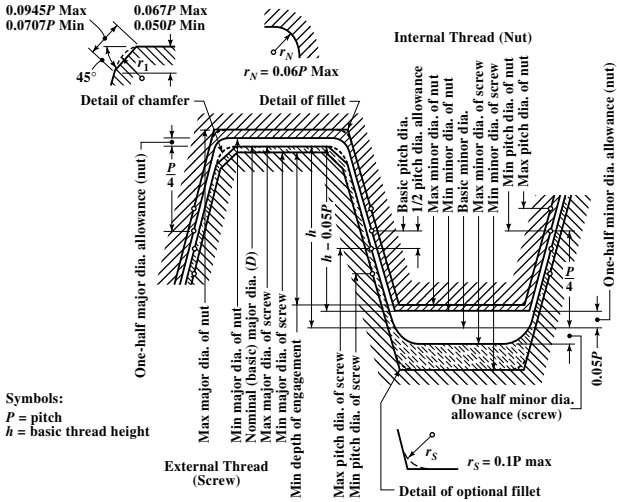


Fig. 4. Disposition of Allowances, Tolerances, and Crest Clearances for Centralizing Single-Start Acme Threads—Classes 2C, 3C, and 4C

est number of items in order to reduce to a minimum the inventory of both tools and gages. This series of diameters and associated pitches is given in [Table 9](#).

**Basic Diameters:** The maximum major diameter of the external thread is basic and is the nominal major diameter for all classes.

The minimum pitch diameter of the internal thread is basic for all classes and is equal to the basic major diameter  $D$  minus the basic height of thread,  $h$ . The minimum minor diameter of the internal thread for all classes is  $0.1P$  above basic.

**Length of Engagement:** The tolerances specified in this Standard are applicable to lengths of engagement not exceeding twice the nominal major diameter.

**Pitch Diameter Allowances:** Allowances applied to the pitch diameter of the external thread for all classes are given in [Table 10](#).

**Major and Minor Diameter Allowances:** A minimum diametral clearance is provided at the minor diameter of all external threads by establishing the maximum minor diameter  $0.020$  inch below the basic minor diameter for 10 threads per inch and coarser, and  $0.010$  inch for finer pitches and by establishing the minimum minor diameter of the internal thread  $0.1P$  greater than the basic minor diameter.

**Table 8a. American National Standard Centralizing Acme Single-Start Screw Threads — Formulas for Determining Diameters ASME/ANSI B1.5-1988**

| $D$ = Nominal Size or Diameter in Inches<br>$P$ = Pitch = $1 \div$ Number of Threads per Inch |   |
|---|---|
| No.   | Classes 2C, 3C, and 4C External Threads (Screws)  |
| 1   | Major Dia., Max = $D$ (Basic).  |
| 2   | Major Dia., Min = $D$ minus tolerance from Table 12, columns 7, 8, or 10.   |
| 3   | Pitch Dia., Max = Int. Pitch Dia., Min (Formula 9) minus allowance from the appropriate Class 2C, 3C, or 4C column of Table 10. |
| 4   | Pitch Dia., Min = Ext. Pitch Dia., Max (Formula 3) minus tolerance from Table 11.   |
| 5   | Minor Dia., Max = $D$ minus $P$ minus allowance from Table 12, column 3.  |
| 6   | Minor Dia., Min = Ext. Minor Dia., Max (Formula 5) minus $1.5 \times$ Pitch Dia. tolerance from Table 11.                       |
| Classes 2C, 3C, and 4C Internal Threads (Nuts)  |   |
| 7   | Major Dia., Min = $D$ plus allowance from Table 12, column 4.   |
| 8   | Major Dia., Max = Int. Major Dia., Min (Formula 7) plus tolerance from Table 12, columns 7, 9, or 11.                           |
| 9   | Pitch Dia., Min = $D$ minus $P/2$ (Basic).  |
| 10  | Pitch Dia., Max = Int. Pitch Dia., Min (Formula 9) plus tolerance from Table 11.  |
| 11  | Minor Dia., Min = $D$ minus $0.9P$ .  |
| 12  | Minor Dia., Max = Int. Minor Dia., Min (Formula 11) plus tolerance from Table 12, column 6.                                     |

A minimum diametral clearance at the major diameter is obtained by establishing the minimum major diameter of the internal thread  $0.001\sqrt{D}$  above the basic major diameter. These allowances are shown in Table 12.

**Major and Minor Diameter Tolerances:** The tolerances on the major and minor diameters of the external and internal threads are listed in Table 12 and are based upon the formulas given in the column headings.

An increase of 10 per cent in the allowance is recommended for each inch or fraction thereof that the length of engagement exceeds two diameters.

For information on gages for Centralizing Acme threads the Standard ASME/ANSI B1.5 should be consulted.

**Pitch Diameter Tolerances:** Pitch diameter tolerances for Classes 2C, 3C and 4C for various practicable combinations of diameter and pitch are given in Table 11. The ratios of the pitch diameter tolerances of Classes 2C, 3C, and 4C are 3.0, 1.4, and 1, respectively.

**Application of Tolerances:** The tolerances specified are such as to insure interchangeability and maintain a high grade of product. The tolerances on the diameters of internal threads are plus, being applied from the minimum sizes to above the minimum sizes. The tolerances on the diameters of external threads are minus, being applied from the maximum sizes to below the maximum sizes. The pitch diameter tolerances for an external or internal thread of a given class are the same.

**Limiting Dimensions:** Limiting dimensions for Centralizing Acme threads in the preferred series of diameters and pitches are given in Tables 8b and 8c. These limits are based on the formulas in Table 8a.

For combinations of pitch and diameter other than those in the preferred series the formulas in Tables 8b and 8c and the data in the tables referred to therein make it possible to readily determine the limiting dimension required.

**Table 8b. Limiting Dimensions of American National Standard Centralizing Acme Single-Start Screw Threads, Classes 2C, 3C, and 4C ASME/ANSI B1.5-1988**

| Nominal Diameter, $D$<br>Threads per Inch <sup>a</sup> |     | $\frac{1}{2}$           | $\frac{5}{8}$ | $\frac{3}{4}$ | $\frac{7}{8}$ | 1      | $1\frac{1}{8}$ | $1\frac{1}{4}$ | $1\frac{3}{8}$ | $1\frac{1}{2}$ |
|--|-----|-------------------------|---------------|---------------|---------------|--------|----------------|----------------|----------------|----------------|
|  |     | 10                      | 8             | 6             | 6             | 5      | 5              | 5              | 4              | 4              |
| Limiting Dimensions                                    |     | <b>External Threads</b> |               |               |               |        |                |                |                |                |
| Classes 2C, 3C, and 4C, Major Diameter                 | Max | 0.5000                  | 0.6250        | 0.7500        | 0.8750        | 1.0000 | 1.1250         | 1.2500         | 1.3750         | 1.5000         |
| Class 2C, Major Diameter                               | Min | 0.4975                  | 0.6222        | 0.7470        | 0.8717        | 0.9965 | 1.1213         | 1.2461         | 1.3709         | 1.4957         |
| Class 3C, Major Diameter                               | Min | 0.4989                  | 0.6238        | 0.7487        | 0.8736        | 0.9985 | 1.1234         | 1.2483         | 1.3732         | 1.4982         |
| Class 4C, Major Diameter                               | Min | 0.4993                  | 0.6242        | 0.7491        | 0.8741        | 0.9990 | 1.1239         | 1.2489         | 1.3738         | 1.4988         |
| Classes 2C, 3C, and 4C, Minor Diameter                 | Max | 0.3800                  | 0.4800        | 0.5633        | 0.6883        | 0.7800 | 0.9050         | 1.0300         | 1.1050         | 1.2300         |
| Class 2C, Minor Diameter                               | Min | 0.3594                  | 0.4570        | 0.5371        | 0.6615        | 0.7509 | 0.8753         | 0.9998         | 1.0719         | 1.1965         |
| Class 3C, Minor Diameter                               | Min | 0.3704                  | 0.4693        | 0.5511        | 0.6758        | 0.7664 | 0.8912         | 1.0159         | 1.0896         | 1.2144         |
| Class 4C, Minor Diameter                               | Min | 0.3731                  | 0.4723        | 0.5546        | 0.6794        | 0.7703 | 0.8951         | 1.0199         | 1.0940         | 1.2188         |
| Class 2C, Pitch Diameter                               | Max | 0.4443                  | 0.5562        | 0.6598        | 0.7842        | 0.8920 | 1.0165         | 1.1411         | 1.2406         | 1.3652         |
|  | Min | 0.4306                  | 0.5408        | 0.6424        | 0.7663        | 0.8726 | 0.9967         | 1.1210         | 1.2186         | 1.3429         |
| Class 3C, Pitch Diameter                               | Max | 0.4458                  | 0.5578        | 0.6615        | 0.7861        | 0.8940 | 1.0186         | 1.1433         | 1.2430         | 1.3677         |
|  | Min | 0.4394                  | 0.5506        | 0.6534        | 0.7778        | 0.8849 | 1.0094         | 1.1339         | 1.2327         | 1.3573         |
| Class 4C, Pitch Diameter                               | Max | 0.4472                  | 0.5593        | 0.6632        | 0.7880        | 0.8960 | 1.0208         | 1.1455         | 1.2453         | 1.3701         |
|  | Min | 0.4426                  | 0.5542        | 0.6574        | 0.7820        | 0.8895 | 1.0142         | 1.1388         | 1.2380         | 1.3627         |
|  |     | <b>Internal Threads</b> |               |               |               |        |                |                |                |                |
| Classes 2C, 3C, and 4C, Major Diameter                 | Min | 0.5007                  | 0.6258        | 0.7509        | 0.8759        | 1.0010 | 1.1261         | 1.2511         | 1.3762         | 1.5012         |
| Classes 2C and 3C, Major Diameter                      | Max | 0.5032                  | 0.6286        | 0.7539        | 0.8792        | 1.0045 | 1.1298         | 1.2550         | 1.3803         | 1.5055         |
| Class 4C, Major Diameter                               | Max | 0.5021                  | 0.6274        | 0.7526        | 0.8778        | 1.0030 | 0.1282         | 1.2533         | 1.3785         | 1.5036         |
| Classes 2C, 3C, and 4C, Minor Diameter                 | Min | 0.4100                  | 0.5125        | 0.6000        | 0.7250        | 0.8200 | 0.9450         | 0.0700         | 1.1500         | 1.2750         |
|  | Max | 0.04150                 | 0.5187        | 0.6083        | 0.7333        | 0.8300 | 0.9550         | 1.0800         | 1.1625         | 1.2875         |
| Class 2C, Pitch Diameter                               | Min | 0.4500                  | 0.5625        | 0.6667        | 0.7917        | 0.9000 | 1.0250         | 1.1500         | 1.2500         | 1.3750         |
|  | Max | 0.4637                  | 0.5779        | 0.6841        | 0.8096        | 0.9194 | 1.0448         | 1.1701         | 1.2720         | 1.3973         |
| Class 3C, Pitch Diameter                               | Min | 0.4500                  | 0.5625        | 0.6667        | 0.7917        | 0.9000 | 1.0250         | 1.1500         | 1.2500         | 1.3750         |
|  | Max | 0.4564                  | 0.5697        | 0.6748        | 0.8000        | 0.9091 | 1.0342         | 1.1594         | 1.2603         | 1.3854         |
| Class 4C, Pitch Diameter                               | Min | 0.4500                  | 0.5625        | 0.6667        | 0.7917        | 0.9000 | 1.0250         | 1.1500         | 1.2500         | 1.3750         |
|  | Max | 0.4546                  | 0.5676        | 0.6725        | 0.7977        | 0.9065 | 1.0316         | 1.1567         | 1.2573         | 1.3824         |

**Table 8c. Limiting Dimensions of American National Standard Centralizing Acme Single-Start Screw Threads, Classes 2C, 3C, and 4C ASME/ANSI B1.5-1988**

| Nominal Diameter, $D$                  |     | $1\frac{3}{4}$   | 2      | $2\frac{1}{4}$ | $2\frac{1}{2}$ | $2\frac{3}{4}$ | 3      | $3\frac{1}{2}$ <sub>212</sub> | 4      | $4\frac{1}{2}$ | 5      |
|--|-----|------------------|--------|----------------|----------------|----------------|--------|-------------------------------|--------|----------------|--------|
| Threads per Inch <sup>a</sup>          |     | 4                | 4      | 3              | 3              | 3              | 2      | 2                             | 2      | 2              | 2      |
| Limiting Dimensions                    |     | External Threads |        |                |                |                |        |                               |        |                |        |
| Classes 2C, 3C, and 4C, Major Diameter | Max | 1.7500           | 2.0000 | 2.2500         | 2.5000         | 2.7500         | 3.0000 | 3.5000                        | 4.0000 | 4.5000         | 5.0000 |
| Class 2C, Major Diameter               | Min | 1.7454           | 1.9951 | 2.2448         | 2.4945         | 2.7442         | 2.9939 | 3.4935                        | 3.9930 | 4.4926         | 4.9922 |
| Class 3C, Major Diameter               | Min | 1.7480           | 1.9979 | 2.2478         | 2.4976         | 2.7475         | 2.9974 | 3.4972                        | 3.9970 | 4.4968         | 4.9966 |
| Class 4C, Major Diameter               | Min | 1.7487           | 1.9986 | 2.2485         | 2.4984         | 2.7483         | 2.9983 | 3.4981                        | 3.9980 | 4.4979         | 4.9978 |
| Classes 2C, 3C, and 4C, Minor Diameter | Max | 1.4800           | 1.7300 | 1.8967         | 2.1467         | 2.3967         | 2.4800 | 2.9800                        | 3.4800 | 3.9800         | 4.4800 |
| Class 2C, Minor Diameter               | Min | 1.4456           | 1.6948 | 1.8572         | 2.1065         | 2.3558         | 2.4326 | 2.9314                        | 3.4302 | 3.9291         | 4.4281 |
| Class 3C, Minor Diameter               | Min | 1.4640           | 1.7136 | 1.8783         | 2.1279         | 2.3776         | 2.4579 | 2.9574                        | 3.4568 | 3.9563         | 4.4558 |
| Class 4C, Minor Diameter               | Min | 1.4685           | 1.7183 | 1.8835         | 2.1333         | 2.3831         | 2.4642 | 2.9638                        | 3.4634 | 3.9631         | 4.4627 |
| Class 2C, Pitch Diameter               | Max | 1.6145           | 1.8637 | 2.0713         | 2.3207         | 2.5700         | 2.7360 | 3.2350                        | 3.7340 | 4.2330         | 4.7319 |
|  | Min | 1.5916           | 1.8402 | 2.0450         | 2.2939         | 2.5427         | 2.7044 | 3.2026                        | 3.7008 | 4.1991         | 4.6973 |
| Class 3C, Pitch Diameter               | Max | 1.6171           | 1.8665 | 2.0743         | 2.3238         | 2.5734         | 2.7395 | 3.2388                        | 3.7380 | 4.2373         | 4.7364 |
|  | Min | 1.6064           | 1.8555 | 2.0620         | 2.3113         | 2.5607         | 2.7248 | 3.2237                        | 3.7225 | 4.2215         | 4.7202 |
| Class 4C, Pitch Diameter               | Max | 1.6198           | 1.8693 | 2.0773         | 2.3270         | 2.5767         | 2.7430 | 3.2425                        | 3.7420 | 4.2415         | 4.7409 |
|  | Min | 1.6122           | 1.8615 | 2.0685         | 2.3181         | 2.5676         | 2.7325 | 3.2317                        | 3.7309 | 4.2302         | 4.7294 |
|  |     | Internal Threads |        |                |                |                |        |                               |        |                |        |
| Classes 2C, 3C, and 4C, Major Diameter | Min | 1.7513           | 2.0014 | 2.2515         | 2.5016         | 2.7517         | 3.0017 | 3.5019                        | 4.0020 | 4.5021         | 5.0022 |
| Classes 2C and 3C, Major Diameter      | Max | 1.7559           | 2.0063 | 2.2567         | 2.5071         | 2.7575         | 3.0078 | 3.5084                        | 4.0090 | 4.5095         | 5.0100 |
| Class 4C, Major Diameter               | Max | 1.7539           | 2.0042 | 2.2545         | 2.5048         | 2.7550         | 3.0052 | 3.5056                        | 4.0060 | 4.5063         | 5.0067 |
| Classes 2C, 3C, and 4C, Minor Diameter | Min | 1.5250           | 1.7750 | 1.9500         | 2.2000         | 2.4500         | 2.5500 | 3.0500                        | 3.5500 | 4.0500         | 4.5500 |
|  | Max | 1.5375           | 1.7875 | 1.9667         | 2.2167         | 2.4667         | 2.5750 | 3.0750                        | 3.5750 | 4.0750         | 4.5750 |
| Class 2C, Pitch Diameter               | Min | 1.6250           | 1.8750 | 2.0833         | 2.3333         | 2.5833         | 2.7500 | 3.2500                        | 3.7500 | 4.2500         | 4.7500 |
|  | Max | 1.6479           | 1.8985 | 2.1096         | 2.3601         | 2.6106         | 2.7816 | 3.2824                        | 3.7832 | 4.2839         | 4.7846 |
| Class 3C, Pitch Diameter               | Min | 1.6250           | 1.8750 | 2.0833         | 2.3333         | 2.5833         | 2.7500 | 3.2500                        | 3.7500 | 4.2500         | 4.7500 |
|  | Max | 1.6357           | 1.8860 | 2.0956         | 2.3458         | 2.5960         | 2.7647 | 3.2651                        | 3.7655 | 4.2658         | 4.7662 |
| Class 4C Pitch Diameter                | Min | 1.6250           | 1.8750 | 2.0833         | 2.3333         | 2.5833         | 2.7500 | 3.2500                        | 3.7500 | 4.2500         | 4.7500 |
|  | Max | 1.6326           | 1.8828 | 2.0921         | 2.3422         | 2.5924         | 2.7605 | 3.2608                        | 3.7611 | 4.2613         | 4.7615 |

<sup>a</sup> All other dimensions are in inches. The selection of threads per inch is arbitrary and for the purpose of establishing a standard.

**Table 9. American National Standard Centralizing Acme Single-Start Screw Thread Data ASME/ANSI B1.5-1988**

| Identification                 |  | Diameters                            |  |   | Thread Data        |   |   |   |   |     |
|--------------------------------|--|--------------------------------------|--|---|--------------------|---|---|---|---|-----|
| Nominal Sizes<br>(All Classes) | Threads<br>per<br>Inch, <sup>a</sup><br><i>n</i> | Centralizing, Classes 2C, 3C, and 4C |  |   | Pitch,<br><i>P</i> | Thickness at<br>Pitch Line,<br><i>t = P/2</i> | Basic<br>Height of<br>Thread,<br><i>h = P/2</i> | Basic Width<br>of Flat,<br><i>F = 0.3707P</i> | Lead Angle $\lambda$ at Basic Pitch Diameter <sup>a</sup> |     |
|                                |  | Basic Major<br>Diameter,<br><i>D</i> | Pitch<br>Diameter,<br><i>D<sub>2</sub> = (D - h)</i> | Minor<br>Diameter,<br><i>D<sub>1</sub> = (D - 2h)</i> |                    |   |   |   | Centralizing Classes 2C, 3C, and 4C,                      |     |
|                                |  |                                      |  |   |                    |   |   |   | Deg   | Min |
| 1/4                            | 16   | 0.2500                               | 0.2188   | 0.1875  | 0.06250            | 0.03125                                       | 0.03125   | 0.0232  | 5   | 12  |
| 5/16                           | 14   | 0.3125                               | 0.2768   | 0.2411  | 0.07143            | 0.03571                                       | 0.03571   | 0.0265  | 4   | 42  |
| 3/8                            | 12   | 0.3750                               | 0.3333   | 0.2917  | 0.08333            | 0.04167                                       | 0.04167   | 0.0309  | 4   | 33  |
| 7/16                           | 12   | 0.4375                               | 0.3958   | 0.3542  | 0.08333            | 0.04167                                       | 0.04167   | 0.0309  | 3   | 50  |
| 1/2                            | 10   | 0.5000                               | 0.4500   | 0.4000  | 0.10000            | 0.05000                                       | 0.05000   | 0.0371  | 4   | 3   |
| 5/8                            | 8  | 0.6250                               | 0.5625   | 0.5000  | 0.12500            | 0.06250                                       | 0.06250   | 0.0463  | 4   | 3   |
| 3/4                            | 6  | 0.7500                               | 0.6667   | 0.5833  | 0.16667            | 0.08333                                       | 0.08333   | 0.0618  | 4   | 33  |
| 7/8                            | 6  | 0.8750                               | 0.7917   | 0.7083  | 0.16667            | 0.08333                                       | 0.08333   | 0.0618  | 3   | 50  |
| 1                              | 5  | 1.0000                               | 0.9000   | 0.8000  | 0.20000            | 0.10000                                       | 0.10000   | 0.0741  | 4   | 3   |
| 1 1/8                          | 5  | 1.1250                               | 1.0250   | 0.9250  | 0.20000            | 0.10000                                       | 0.10000   | 0.0741  | 3   | 33  |
| 1 1/4                          | 5  | 1.2500                               | 1.1500   | 1.0500  | 0.20000            | 0.10000                                       | 0.10000   | 0.0741  | 3   | 10  |
| 1 3/8                          | 4  | 1.3750                               | 1.2500   | 1.1250  | 0.25000            | 0.12500                                       | 0.12500   | 0.0927  | 3   | 39  |
| 1 1/2                          | 4  | 1.5000                               | 1.3750   | 1.2500  | 0.25000            | 0.12500                                       | 0.12500   | 0.0927  | 3   | 19  |
| 1 3/4                          | 4  | 1.7500                               | 1.6250   | 1.5000  | 0.25000            | 0.12500                                       | 0.12500   | 0.0927  | 2   | 48  |
| 2                              | 4  | 2.0000                               | 1.8750   | 1.7500  | 0.25000            | 0.12500                                       | 0.12500   | 0.0927  | 2   | 26  |
| 2 1/4                          | 3  | 2.2500                               | 2.0833   | 1.9167  | 0.33333            | 0.16667                                       | 0.16667   | 0.1236  | 2   | 55  |
| 2 1/2                          | 3  | 2.5000                               | 2.3333   | 2.1667  | 0.33333            | 0.16667                                       | 0.16667   | 0.1236  | 2   | 36  |
| 2 3/4                          | 3  | 2.7500                               | 2.5833   | 2.4167  | 0.33333            | 0.16667                                       | 0.16667   | 0.1236  | 2   | 21  |
| 3                              | 2  | 3.0000                               | 2.7500   | 2.5000  | 0.50000            | 0.25000                                       | 0.25000   | 0.1853  | 3   | 19  |
| 3 1/2                          | 2  | 3.5000                               | 3.2500   | 3.0000  | 0.50000            | 0.25000                                       | 0.25000   | 0.1853  | 2   | 48  |
| 4                              | 2  | 4.0000                               | 3.7500   | 3.5000  | 0.50000            | 0.25000                                       | 0.25000   | 0.1853  | 2   | 26  |
| 4 1/2                          | 2  | 4.5000                               | 4.2500   | 4.0000  | 0.50000            | 0.25000                                       | 0.25000   | 0.1853  | 2   | 9   |
| 5                              | 2  | 5.0000                               | 4.7500   | 4.5000  | 0.50000            | 0.25000                                       | 0.25000   | 0.1853  | 1   | 55  |

<sup>a</sup>All other dimensions are given in inches.

**Table 10. American National Standard Centralizing Acme Single-Start Screw Threads — Pitch Diameter Allowances ASME/ANSI B1.5-1988**

| Nominal Size Range <sup>a</sup> |                  | Allowances on External Threads <sup>b</sup> |                               |                               | Nominal Size Range <sup>a</sup> |                  | Allowances on External Threads <sup>b</sup> |                               |                               |
|---------------------------------|------------------|---|-------------------------------|-------------------------------|---------------------------------|------------------|---|-------------------------------|-------------------------------|
| Above                           | To and Including | Centralizing                                |                               |                               | Above                           | To and Including | Centralizing                                |                               |                               |
|                                 |                  | Class 2C,<br>0.008 $\sqrt{D}$               | Class 3C,<br>0.006 $\sqrt{D}$ | Class 4C,<br>0.004 $\sqrt{D}$ |                                 |                  | Class 2C,<br>0.008 $\sqrt{D}$               | Class 3C,<br>0.006 $\sqrt{D}$ | Class 4C,<br>0.004 $\sqrt{D}$ |
| 0                               | 3/16             | 0.0024                                      | 0.0018                        | 0.0012                        | 1 7/16                          | 1 9/16           | 0.0098                                      | 0.0073                        | 0.0049                        |
| 3/16                            | 5/16             | 0.0040                                      | 0.0030                        | 0.0020                        | 1 7/16                          | 1 7/8            | 0.0105                                      | 0.0079                        | 0.0052                        |
| 5/16                            | 7/16             | 0.0049                                      | 0.0037                        | 0.0024                        | 1 7/8                           | 2 1/8            | 0.0113                                      | 0.0085                        | 0.0057                        |
| 7/16                            | 9/16             | 0.0057                                      | 0.0042                        | 0.0028                        | 2 1/8                           | 2 3/8            | 0.0120                                      | 0.0090                        | 0.0060                        |
| 9/16                            | 11/16            | 0.0063                                      | 0.0047                        | 0.0032                        | 2 3/8                           | 2 5/8            | 0.0126                                      | 0.0095                        | 0.0063                        |
| 11/16                           | 13/16            | 0.0069                                      | 0.0052                        | 0.0035                        | 2 5/8                           | 2 7/8            | 0.0133                                      | 0.0099                        | 0.0066                        |
| 13/16                           | 15/16            | 0.0075                                      | 0.0056                        | 0.0037                        | 2 7/8                           | 3 1/4            | 0.0140                                      | 0.0105                        | 0.0070                        |
| 15/16                           | 1 1/16           | 0.0080                                      | 0.0060                        | 0.0040                        | 3 1/4                           | 3 3/4            | 0.0150                                      | 0.0110                        | 0.0075                        |
| 1 1/16                          | 1 3/16           | 0.0085                                      | 0.0064                        | 0.0042                        | 3 3/4                           | 4 1/4            | 0.0160                                      | 0.0120                        | 0.0080                        |
| 1 3/16                          | 1 5/16           | 0.0089                                      | 0.0067                        | 0.0045                        | 4 1/4                           | 4 3/4            | 0.0170                                      | 0.0127                        | 0.0085                        |
| 1 5/16                          | 1 7/16           | 0.0094                                      | 0.0070                        | 0.0047                        | 4 3/4                           | 5 1/2            | 0.0181                                      | 0.0136                        | 0.0091                        |

All dimensions are given in inches.

It is recommended that the sizes given in Table 9 be used whenever possible.

<sup>a</sup>The values in columns for Classes 2C, 3C, and 4C are to be used for any size within the nominal size range columns. These values are calculated from the mean of the range.

<sup>b</sup>An increase of 10 per cent in the allowance is recommended for each inch, or fraction thereof, that the length of engagement exceeds two diameters.

**Table 11. American National Standard Centralizing Acme Single-Start Screw Threads — Pitch Diameter Tolerances ASME/ANSI B1.5-1988**

| Nom. Dia., <sup>a</sup><br>D | Class of Thread and Diameter Increment |                          |                          | Nom. Dia., <sup>a</sup><br>D | Class of Thread and Diameter Increment |                          |                          |
|------------------------------|--|--------------------------|--------------------------|------------------------------|--|--------------------------|--------------------------|
|                              | 2C<br>0.006 $\sqrt{D}$                 | 3C<br>0.0028 $\sqrt{D}$  | 4C<br>0.002 $\sqrt{D}$   |                              | 2C<br>0.006 $\sqrt{D}$                 | 3C<br>0.0028 $\sqrt{D}$  | 4C<br>0.002 $\sqrt{D}$   |
| 1/4                          | .00300                                 | .00140                   | .00100                   | 1 1/2                        | .00735                                 | .00343                   | .00245                   |
| 5/16                         | .00335                                 | .00157                   | .00112                   | 1 3/4                        | .00794                                 | .00370                   | .00265                   |
| 3/8                          | .00367                                 | .00171                   | .00122                   | 2                            | .00849                                 | .00396                   | .00283                   |
| 7/16                         | .00397                                 | .00185                   | .00132                   | 2 1/4                        | .00900                                 | .00420                   | .00300                   |
| 1/2                          | .00424                                 | .00198                   | .00141                   | 2 1/2                        | .00949                                 | .00443                   | .00316                   |
| 5/8                          | .00474                                 | .00221                   | .00158                   | 2 3/4                        | .00995                                 | .00464                   | .00332                   |
| 3/4                          | .00520                                 | .00242                   | .00173                   | 3                            | .01039                                 | .00485                   | .00346                   |
| 7/8                          | .00561                                 | .00262                   | .00187                   | 3 1/2                        | .01122                                 | .00524                   | .00374                   |
| 1                            | .00600                                 | .00280                   | .00200                   | 4                            | .01200                                 | .00560                   | .00400                   |
| 1 1/8                        | .00636                                 | .00297                   | .00212                   | 4 1/2                        | .01273                                 | .00594                   | .00424                   |
| 1 1/4                        | .00671                                 | .00313                   | .00224                   | 5                            | .01342                                 | .00626                   | .00447                   |
| 1 3/8                        | .00704                                 | .00328                   | .00235                   | ...                          | ...                                    | ...                      | ...                      |
| Thds. per Inch,<br>n         | Class of Thread and Pitch Increment    |                          |                          | Thds. per Inch,<br>n         | Class of Thread and Pitch Increment    |                          |                          |
|                              | 2C<br>0.030 $\sqrt{1/n}$               | 3C<br>0.014 $\sqrt{1/n}$ | 4C<br>0.010 $\sqrt{1/n}$ |                              | 2C<br>0.030 $\sqrt{1/n}$               | 3C<br>0.014 $\sqrt{1/n}$ | 4C<br>0.010 $\sqrt{1/n}$ |
| 16                           | .00750                                 | .00350                   | .00250                   | 4                            | .01500                                 | .00700                   | .00500                   |
| 14                           | .00802                                 | .00374                   | .00267                   | 3                            | .01732                                 | .00808                   | .00577                   |
| 12                           | .00866                                 | .00404                   | .00289                   | 2 1/2                        | .01897                                 | .00885                   | .00632                   |
| 10                           | .00949                                 | .00443                   | .00316                   | 2                            | .02121                                 | .00990                   | .00707                   |
| 8                            | .01061                                 | .00495                   | .00354                   | 1 1/2                        | .02449                                 | .01143                   | .00816                   |
| 6                            | .01225                                 | .00572                   | .00408                   | 1 1/3                        | .02598                                 | .01212                   | .00866                   |
| 5                            | .01342                                 | .00626                   | .00447                   | 1                            | .03000                                 | .01400                   | .01000                   |

All dimensions are given in inches.

For any particular size of thread, the pitch diameter tolerance is obtained by adding the diameter increment from the upper half of the table to the pitch increment from the lower half of the table. Example: A 0.250-16-ACME-2C thread has a pitch diameter tolerance of 0.00300 + 0.00750 = 0.0105 inch.

The equivalent tolerance on thread thickness is 0.259 times the pitch diameter tolerance.

<sup>a</sup>For a nominal diameter between any two tabulated nominal diameters, use the diameter increment for the larger of the two tabulated nominal diameters.

**Table 12. American National Standard Centralizing Acme Single-Start Screw Threads — Tolerances and Allowances for Major and Minor Diameters ASME/ANSI B1.5-1988**

| Size<br>(Nom.) | Thds <sup>a</sup><br>per<br>Inch | Allowance From Basic Major and<br>Minor Diameters (All Classes) |  |   | Tolerance<br>on Minor Diam., <sup>b,c</sup><br>All Internal<br>Threads,<br>(Plus 0.05P) | Tolerance on Major Diameter Plus on Internal, Minus on External Threads |   |   |   |   |
|----------------|----------------------------------|---|--|---|---|---|---|---|---|---|
|                |                                  | Minor Diam., <sup>d</sup><br>All External<br>Threads<br>(Minus) | Internal Thread  |   |   | Class 2C  | Class 3C  |   | Class 4C                                |   |
|                |                                  |   | Major Diam., <sup>e</sup><br>(Plus<br>$0.0010\sqrt{D}$ ) | Minor<br>Diam., <sup>d</sup><br>(Plus 0.1P) |   |   | External and<br>Internal Threads,<br>$0.0035\sqrt{D}$ | External<br>Thread,<br>$0.0015\sqrt{D}$ | Internal<br>Thread,<br>$0.0035\sqrt{D}$ | External<br>Thread,<br>$0.0010\sqrt{D}$ |
| 1/4            | 16                               | 0.010   | 0.0005   | 0.0062                                      | 0.0050  | 0.0017  | 0.0007  | 0.0017                                  | 0.0005                                  | 0.0010                                  |
| 5/16           | 14                               | 0.010   | 0.0006   | 0.0071                                      | 0.0050  | 0.0020  | 0.0008  | 0.0020                                  | 0.0006                                  | 0.0011                                  |
| 3/8            | 12                               | 0.010   | 0.0006   | 0.0083                                      | 0.0050  | 0.0021  | 0.0009  | 0.0021                                  | 0.0006                                  | 0.0012                                  |
| 7/16           | 12                               | 0.010   | 0.0007   | 0.0083                                      | 0.0050  | 0.0023  | 0.0010  | 0.0023                                  | 0.0007                                  | 0.0013                                  |
| 1/2            | 10                               | 0.020   | 0.0007   | 0.0100                                      | 0.0050  | 0.0025  | 0.0011  | 0.0025                                  | 0.0007                                  | 0.0014                                  |
| 5/8            | 8                                | 0.020   | 0.0008   | 0.0125                                      | 0.0062  | 0.0028  | 0.0012  | 0.0028                                  | 0.0008                                  | 0.0016                                  |
| 3/4            | 6                                | 0.020   | 0.0009   | 0.0167                                      | 0.0083  | 0.0030  | 0.0013  | 0.0030                                  | 0.0009                                  | 0.0017                                  |
| 7/8            | 6                                | 0.020   | 0.0009   | 0.0167                                      | 0.0083  | 0.0033  | 0.0014  | 0.0033                                  | 0.0009                                  | 0.0019                                  |
| 1              | 5                                | 0.020   | 0.0010   | 0.0200                                      | 0.0100  | 0.0035  | 0.0015  | 0.0035                                  | 0.0010                                  | 0.0020                                  |
| 1 1/8          | 5                                | 0.020   | 0.0011   | 0.0200                                      | 0.0100  | 0.0037  | 0.0016  | 0.0037                                  | 0.0011                                  | 0.0021                                  |
| 1 1/4          | 5                                | 0.020   | 0.0011   | 0.0200                                      | 0.0100  | 0.0039  | 0.0017  | 0.0039                                  | 0.0011                                  | 0.0022                                  |
| 1 3/8          | 4                                | 0.020   | 0.0012   | 0.0250                                      | 0.0125  | 0.0041  | 0.0018  | 0.0041                                  | 0.0012                                  | 0.0023                                  |
| 1 1/2          | 4                                | 0.020   | 0.0012   | 0.0250                                      | 0.0125  | 0.0043  | 0.0018  | 0.0043                                  | 0.0012                                  | 0.0024                                  |
| 1 3/4          | 4                                | 0.020   | 0.0013   | 0.0250                                      | 0.0125  | 0.0046  | 0.0020  | 0.0046                                  | 0.0013                                  | 0.0026                                  |
| 2              | 4                                | 0.020   | 0.0014   | 0.0250                                      | 0.0125  | 0.0049  | 0.0021  | 0.0049                                  | 0.0014                                  | 0.0028                                  |
| 2 1/4          | 3                                | 0.020   | 0.0015   | 0.0333                                      | 0.0167  | 0.0052  | 0.0022  | 0.0052                                  | 0.0015                                  | 0.0030                                  |
| 2 1/2          | 3                                | 0.020   | 0.0016   | 0.0333                                      | 0.0167  | 0.0055  | 0.0024  | 0.0055                                  | 0.0016                                  | 0.0032                                  |
| 2 3/4          | 3                                | 0.020   | 0.0017   | 0.0333                                      | 0.0167  | 0.0058  | 0.0025  | 0.0058                                  | 0.0017                                  | 0.0033                                  |
| 3              | 2                                | 0.020   | 0.0017   | 0.0500                                      | 0.0250  | 0.0061  | 0.0026  | 0.0061                                  | 0.0017                                  | 0.0035                                  |
| 3 1/2          | 2                                | 0.020   | 0.0019   | 0.0500                                      | 0.0250  | 0.0065  | 0.0028  | 0.0065                                  | 0.0019                                  | 0.0037                                  |
| 4              | 2                                | 0.020   | 0.0020   | 0.0500                                      | 0.0250  | 0.0070  | 0.0030  | 0.0070                                  | 0.0020                                  | 0.0040                                  |
| 4 1/2          | 2                                | 0.020   | 0.0021   | 0.0500                                      | 0.0250  | 0.0074  | 0.0032  | 0.0074                                  | 0.0021                                  | 0.0042                                  |
| 5              | 2                                | 0.020   | 0.0022   | 0.0500                                      | 0.0250  | 0.0078  | 0.0034  | 0.0078                                  | 0.0022                                  | 0.0045                                  |

<sup>a</sup> All other dimensions are given in inches. Intermediate pitches take the values of the next coarser pitch listed. Values for intermediate diameters should be calculated from the formulas in column headings, but ordinarily may be interpolated.

<sup>b</sup> To avoid a complicated formula and still provide an adequate tolerance, the pitch factor is used as a basis, with the minimum tolerance set at 0.005 in.

<sup>c</sup> Tolerance on minor diameter of all external threads is  $1.5 \times$  pitch diameter tolerance.

<sup>d</sup> The minimum clearance at the minor diameter between the internal and external thread is the sum of the values in columns 3 and 5.

<sup>e</sup> The minimum clearance at the major diameter between the internal and external thread is equal to column 4.

**Designation of Centralizing Acme Threads.**—The following examples are given to show how these Acme threads are designated on drawings, in specifications, and on tools and gages:

*Example, 1.750-6-ACME-4C:* Indicates a Centralizing Class 4C Acme thread of 1.750-inch major diameter, 0.1667-inch pitch, single thread, right-hand.

*Example, 1.750-6-ACME-4C-LH:* Indicates the same thread left-hand.

*Example, 2.875-0.4P-0.8L-ACME-3C (Two Start):* Indicates a Centralizing Class 3C Acme thread with 2.875-inch major diameter, 0.4-inch pitch, 0.8-inch lead, double thread, right-hand.

*Example, 2.500-0.3333P-0.6667L-ACME-4C (Two Start):* Indicates a Centralizing Class 4C Acme thread with 2.500-inch nominal major diameter (basic major diameter 2.500 inches), 0.3333-inch pitch, 0.6667-inch lead, double thread, right-hand. The same thread left-hand would have LH at the end of the designation.

**Acme Centralizing Threads—Alternative Series with Minor Diameter Centralizing Control.**—When Acme centralizing threads are produced in single units or in very small quantities (and principally in sizes larger than the range of commercial taps and dies) where the manufacturing process employs cutting tools (such as lathe cutting), it may be economically advantageous and therefore desirable to have the centralizing control of the mating threads located at the *minor diameters*.

Particularly under the above-mentioned type of manufacturing, the two advantages cited for minor diameter centralizing control over centralizing control at the major diameters of the mating threads are: 1) Greater ease and faster checking of machined thread dimensions. It is much easier to measure the minor diameter (root) of the external thread and the mating minor diameter (crest or bore) of the internal thread than it is to determine the major diameter (root) of the internal thread and the major diameter (crest or turn) of the external thread; and 2) better manufacturing control of the machined size due to greater ease of checking.

In the event that minor diameter centralizing is necessary, recalculate all thread dimensions, reversing major and minor diameter allowances, tolerances, radii, and chamfer.

**American National Standard Stub Acme Threads.**—This American National Standard ASME/ANSI B1.8-1988 (R2001) provides a Stub Acme screw thread for those unusual applications where, due to mechanical or metallurgical considerations, a coarse-pitch thread of shallow depth is required. The fit of Stub Acme threads corresponds to the Class 2G General Purpose Acme thread in American National Standard ANSI B1.5-1988. For a fit having less backlash, the tolerances and allowances for Classes 3G or 4G General Purpose Acme threads may be used.

*Thread Form:* The thread form and basic formulas for Stub Acme threads are given on page 1826 and the basic dimensions in Table 13.

*Allowances and Tolerances:* The major and minor diameter allowances for Stub Acme threads are the same as those given for General Purpose Acme threads on page 1825.

Pitch diameter allowances for Stub Acme threads are the same as for Class 2G General Purpose Acme threads and are given in Table 4. Pitch diameter tolerances for Stub Acme threads are the same as for Class 2G General Purpose Acme threads given in Table 5.

*Limiting Dimensions:* Limiting dimensions of American Standard Stub Acme threads may be determined by using the formulas given in Table 14a, or directly from Table 14b. The diagram below shows the limits of size for Stub Acme threads.

*Thread Series:* A preferred series of diameters and pitches for General Purpose Acme threads (Table 15) is recommended for Stub Acme threads.



**Table 13. American National Standard Stub Acme Screw Thread Form — Basic Dimensions ASME/ANSI B1.8-1988 (R2001)**

| Thds. per Inch <sup>a</sup><br><i>n</i> | Pitch,<br>$P = 1/n$ | Height of Thread (Basic),<br>$0.3P$ | Total Height of Thread,<br>$0.3P + \frac{1}{2}$ allowance <sup>b</sup> | Thread Thickness (Basic),<br>$P/2$ | Width of Flat                                  |   |
|---|---------------------|-------------------------------------|--|------------------------------------|--|---|
|   |                     |                                     |  |                                    | Crest of Internal Thread (Basic),<br>$0.4224P$ | Root of Internal Thread,<br>$0.4224P - 0.259 \times$ allowance <sup>b</sup> |
| 16                                      | 0.06250             | 0.01875                             | 0.0238   | 0.03125                            | 0.0264   | 0.0238  |
| 14                                      | 0.07143             | 0.02143                             | 0.0264   | 0.03571                            | 0.0302   | 0.0276  |
| 12                                      | 0.08333             | 0.02500                             | 0.0300   | 0.04167                            | 0.0352   | 0.0326  |
| 10                                      | 0.10000             | 0.03000                             | 0.0400   | 0.05000                            | 0.0422   | 0.0370  |
| 9                                       | 0.11111             | 0.03333                             | 0.0433   | 0.05556                            | 0.0469   | 0.0417  |
| 8                                       | 0.12500             | 0.03750                             | 0.0475   | 0.06250                            | 0.0528   | 0.0476  |
| 7                                       | 0.14286             | 0.04285                             | 0.0529   | 0.07143                            | 0.0603   | 0.0551  |
| 6                                       | 0.16667             | 0.05000                             | 0.0600   | 0.08333                            | 0.0704   | 0.0652  |
| 5                                       | 0.20000             | 0.06000                             | 0.0700   | 0.10000                            | 0.0845   | 0.0793  |
| 4                                       | 0.25000             | 0.07500                             | 0.0850   | 0.12500                            | 0.1056   | 0.1004  |
| 3½                                      | 0.28571             | 0.08571                             | 0.0957   | 0.14286                            | 0.1207   | 0.1155  |
| 3                                       | 0.33333             | 0.10000                             | 0.1100   | 0.16667                            | 0.1408   | 0.1356  |
| 2½                                      | 0.40000             | 0.12000                             | 0.1300   | 0.20000                            | 0.1690   | 0.1638  |
| 2                                       | 0.50000             | 0.15000                             | 0.1600   | 0.25000                            | 0.2112   | 0.2060  |
| 1½                                      | 0.66667             | 0.20000                             | 0.2100   | 0.33333                            | 0.2816   | 0.2764  |
| 1¼                                      | 0.75000             | 0.22500                             | 0.2350   | 0.37500                            | 0.3168   | 0.3116  |
| 1                                       | 1.00000             | 0.30000                             | 0.3100   | 0.50000                            | 0.4224   | 0.4172  |

<sup>a</sup> All other dimensions in inches. See Fig. 1, page 1826.

<sup>b</sup> Allowance is 0.020 inch for 10 or less threads per inch and 0.010 inch for more than 10 threads per inch.

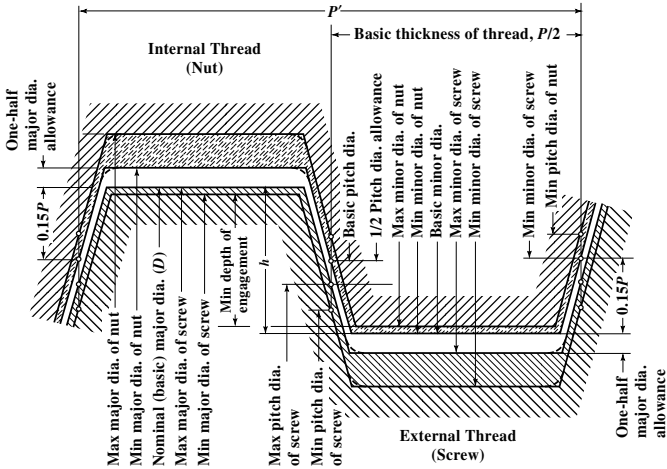
**Table 14a. American National Standard Stub Acme Single-Start Screw Threads — Formulas for Determining Diameters ASME/ANSI B1.8-1988 (R2001)**

| $D$ = Basic Major Diameter and Nominal Size in Inches<br>$D_2$ = Basic Pitch Diameter = $D - 0.3P$<br>$D_1$ = Basic Minor Diameter = $D - 0.6P$ |   |
|---|---|
| No.   | External Threads (Screws)   |
| 1   | Major Dia., Max = $D$ .   |
| 2   | Major Dia., Min. = $D$ minus $0.05P$ .  |
| 3   | Pitch Dia., Max. = $D_2$ minus allowance from the appropriate Class 2G column, Table 4.               |
| 4   | Pitch Dia., Min. = Pitch Dia., Max. (Formula 3) minus Class 2G tolerance from Table 5.                |
| 5   | Minor Dia., Max. = $D_1$ minus 0.020 for 10 threads per inch and coarser and 0.010 for finer pitches. |
| 6   | Minor Dia., Min. = Minor Dia., Max. (Formula 5) minus Class 2G pitch diameter tolerance from Table 5. |
| Internal Threads (Nuts)   |   |
| 7   | Major Dia., Min. = $D$ plus 0.020 for 10 threads per inch and coarser and 0.010 for finer pitches.    |
| 8   | Major Dia., Max. = Major Dia., Min. (Formula 7) plus Class 2G pitch diameter tolerance from Table 5.  |
| 9   | Pitch Dia., Min. = $D_2 = D - 0.3P$   |
| 10  | Pitch Dia., Max. = Pitch Dia., Min. (Formula 9) plus Class 2G tolerance from Table 5.                 |
| 11  | Minor Dia., Min. = $D_1 = D - 0.6P$   |
| 12  | Minor Dia., Max. = Minor Dia., Min. (Formula 11) plus $0.05P$ .                                       |

**Table 14b. Limiting Dimensions for American National Standard Stub Acme Single-Start Screw Threads ASME/ANSI B1.8-1988 (R2001)**

| Nominal Diameter, $D$<br>Threads per Inch <sup>a</sup> |               | $\frac{1}{4}$    | $\frac{3}{16}$ | $\frac{3}{8}$ | $\frac{7}{16}$ | $\frac{1}{2}$  | $\frac{5}{8}$  | $\frac{3}{4}$ | $\frac{7}{8}$  | 1      | $1\frac{1}{8}$ | $1\frac{1}{4}$ | $1\frac{3}{8}$ |
|--|---------------|------------------|----------------|---------------|----------------|----------------|----------------|---------------|----------------|--------|----------------|----------------|----------------|
|  |               | 16               | 14             | 12            | 12             | 10             | 8              | 6             | 6              | 5      | 5              | 5              | 4              |
| Limiting Dimensions                                    |               | External Threads |                |               |                |                |                |               |                |        |                |                |                |
| Major Dia.   | { Max ( $D$ ) | 0.2500           | 0.3125         | 0.3750        | 0.4375         | 0.5000         | 0.6250         | 0.7500        | 0.8750         | 1.0000 | 1.1250         | 1.2500         | 1.3750         |
|  | { Min         | 0.2469           | 0.3089         | 0.3708        | 0.4333         | 0.4950         | 0.6188         | 0.7417        | 0.8667         | 0.9900 | 1.1150         | 1.2400         | 1.3625         |
| Pitch Dia.   | { Max         | 0.2272           | 0.2871         | 0.3451        | 0.4076         | 0.4643         | 0.5812         | 0.6931        | 0.8175         | 0.9320 | 1.0565         | 1.1811         | 1.2906         |
|  | { Min         | 0.2167           | 0.2757         | 0.3328        | 0.3950         | 0.4506         | 0.5658         | 0.6757        | 0.7996         | 0.9126 | 1.0367         | 1.1610         | 1.2686         |
| Minor Dia.   | { Max         | 0.2024           | 0.2597         | 0.3150        | 0.3775         | 0.4200         | 0.5300         | 0.6300        | 0.7550         | 0.8600 | 0.9850         | 1.1100         | 1.2050         |
|  | { Min         | 0.1919           | 0.2483         | 0.3027        | 0.3649         | 0.4063         | 0.5146         | 0.6126        | 0.7371         | 0.8406 | 0.9652         | 1.0899         | 1.1830         |
|  |               | Internal Threads |                |               |                |                |                |               |                |        |                |                |                |
| Major Dia.   | { Min         | 0.2600           | 0.3225         | 0.3850        | 0.4475         | 0.5200         | 0.6450         | 0.7700        | 0.8950         | 1.0200 | 1.1450         | 1.2700         | 1.3950         |
|  | { Max         | 0.2705           | 0.3339         | 0.3973        | 0.4601         | 0.5337         | 0.6604         | 0.7874        | 0.9129         | 1.0394 | 1.1648         | 1.2901         | 1.4170         |
| Pitch Dia.   | { Min         | 0.2312           | 0.2911         | 0.3500        | 0.4125         | 0.4700         | 0.5875         | 0.7000        | 0.8250         | 0.9400 | 1.0650         | 1.1900         | 1.3000         |
|  | { Max         | 0.2417           | 0.3025         | 0.3623        | 0.4251         | 0.4837         | 0.6029         | 0.7174        | 0.8429         | 0.9594 | 1.0848         | 1.2101         | 1.3220         |
| Minor Dia.   | { Min         | 0.2125           | 0.2696         | 0.3250        | 0.3875         | 0.4400         | 0.5500         | 0.6500        | 0.7750         | 0.8800 | 1.0050         | 1.1300         | 1.2250         |
|  | { Max         | 0.2156           | 0.2732         | 0.3292        | 0.3917         | 0.4450         | 0.5562         | 0.6583        | 0.7833         | 0.8900 | 1.0150         | 1.1400         | 1.2375         |
| Nominal Diameter, $D$<br>Threads per Inch <sup>a</sup> |               | $1\frac{1}{2}$   | $1\frac{3}{4}$ | 2             | $2\frac{1}{4}$ | $2\frac{1}{2}$ | $2\frac{3}{4}$ | 3             | $3\frac{1}{2}$ | 4      | $4\frac{1}{2}$ | 5              |                |
|  |               | 4                | 4              | 4             | 3              | 3              | 3              | 2             | 2              | 2      | 2              | 2              |                |
| Limiting Dimensions                                    |               | External Threads |                |               |                |                |                |               |                |        |                |                |                |
| Major Dia.   | { Max ( $D$ ) | 1.5000           | 1.7500         | 2.0000        | 2.2500         | 2.5000         | 2.7500         | 3.0000        | 3.5000         | 4.0000 | 4.5000         | 5.0000         |                |
|  | { Min         | 1.4875           | 1.7375         | 1.9875        | 2.2333         | 2.4833         | 2.7333         | 2.9750        | 3.4750         | 3.9750 | 4.4750         | 4.9750         |                |
| Pitch Dia.   | { Max         | 1.4152           | 1.6645         | 1.9137        | 2.1380         | 2.3874         | 2.6367         | 2.8360        | 3.3350         | 3.8340 | 4.3330         | 4.8319         |                |
|  | { Min         | 1.3929           | 1.6416         | 1.8902        | 2.1117         | 2.3606         | 2.6094         | 2.8044        | 3.3026         | 3.8008 | 4.2991         | 4.7973         |                |
| Minor Dia.   | { Max         | 1.3300           | 1.5800         | 1.8300        | 2.0300         | 2.2800         | 2.5300         | 2.6800        | 3.1800         | 3.6800 | 4.1800         | 4.6800         |                |
|  | { Min         | 1.3077           | 1.5571         | 1.8065        | 2.0037         | 2.2532         | 2.5027         | 2.6484        | 3.1476         | 3.6468 | 4.1461         | 4.6454         |                |
|  |               | Internal Threads |                |               |                |                |                |               |                |        |                |                |                |
| Major Dia.   | { Min         | 1.5200           | 1.7700         | 2.0200        | 2.2700         | 2.5200         | 2.7700         | 3.0200        | 3.5200         | 4.0200 | 4.5200         | 5.0200         |                |
|  | { Max         | 1.5423           | 1.7929         | 2.0435        | 2.2963         | 2.5468         | 2.7973         | 3.0516        | 3.5524         | 4.0532 | 4.5539         | 5.0546         |                |
| Pitch Dia.   | { Min         | 1.4250           | 1.6750         | 1.9250        | 2.1500         | 2.4000         | 2.6500         | 2.8500        | 3.3500         | 3.8500 | 4.3500         | 4.8500         |                |
|  | { Max         | 1.4473           | 1.6979         | 1.9485        | 2.1763         | 2.4268         | 2.6773         | 2.8816        | 3.3824         | 3.8832 | 4.3839         | 4.8846         |                |
| Minor Dia.   | { Min         | 1.3500           | 1.6000         | 1.8500        | 2.0500         | 2.3000         | 2.5500         | 2.7000        | 3.2000         | 3.7000 | 4.2000         | 4.7000         |                |
|  | { Max         | 1.3625           | 1.6125         | 1.8625        | 2.0667         | 2.3167         | 2.5667         | 2.7250        | 3.2250         | 3.7250 | 4.2250         | 4.7250         |                |

<sup>a</sup> All other dimensions are given in inches.



Limits of Size, Allowances, Tolerances, and Crest Clearances for American National Standard Stub Acme Threads

**Stub Acme Thread Designations.**—The method of designation for Standard Stub Acme threads is illustrated in the following examples: 0.500-20 Stub Acme indicates a  $\frac{1}{2}$ -inch major diameter, 20 threads per inch, right hand, single thread, Standard Stub Acme thread. The designation 0.500-20 Stub Acme-LH indicates the same thread except that it is left hand.

**Alternative Stub Acme Threads.**—Since one Stub Acme thread form may not meet the requirements of all applications, basic data for two of the other commonly used forms are included in the appendix of the American Standard for Stub Acme Threads. These so-called Modified Form 1 and Modified Form 2 threads utilize the same tolerances and allowances as Standard Stub Acme threads and have the same major diameter and basic thread thickness at the pitchline ( $0.5P$ ). The basic height of Form 1 threads,  $h$ , is  $0.375P$ ; for Form 2 it is  $0.250P$ . The basic width of flat at the crest of the internal thread is  $0.4030P$  for Form 1 and  $0.4353P$  for Form 2.

The pitch diameter and minor diameter for Form 1 threads will be smaller than similar values for the Standard Stub Acme Form and for Form 2 they will be larger owing to the differences in basic thread height  $h$ . Therefore, in calculating the dimensions of Form 1 and Form 2 threads using Formulas 1 through 12 in Table 14a, it is only necessary to substitute the following values in applying the formulas: For Form 1,  $D_2 = D - 0.375P$ ,  $D_1 = D - 0.75P$ ; for Form 2,  $D_2 = D - 0.25P$ ,  $D_1 = D - 0.5P$ .

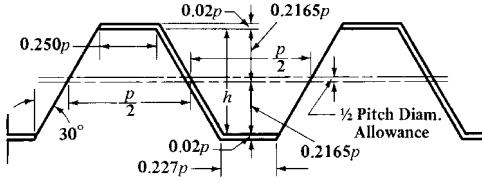
**Thread Designation:** These threads are designated in the same manner as Standard Stub Acme threads except for the insertion of either M1 or M2 after "Acme." Thus, 0.500-20 Stub Acme M1 for a Form 1 thread; and 0.500-20 Stub Acme M2 for a Form 2 thread.

**Former 60-Degree Stub Thread.**—Former American Standard B1.3-1941 included a 60-degree stub thread for use where design or operating conditions could be better satisfied by the use of this thread, or other modified threads, than by Acme threads. Data for 60-Degree Stub thread form are given in the accompanying diagram.

Table 15. Stub Acme Screw Thread Data ASME/ANSI B1.8-1988 (R2001)

| Identification |  | Basic Diameters             |  |  | Thread Data        |   |   |   |                                     |     |
|----------------|--|-----------------------------|--|--|--------------------|---|---|---|-------------------------------------|-----|
| Nominal Sizes  | Threads per Inch, <sup>a</sup><br><i>n</i> | Major Diameter,<br><i>D</i> | Pitch Diameter,<br><i>D</i> <sub>2</sub> = <i>D</i> - <i>h</i> | Minor Diameter,<br><i>D</i> <sub>1</sub> = <i>D</i> - 2 <i>h</i> | Pitch,<br><i>P</i> | Thread Thickness at Pitch Line,<br><i>t</i> = <i>P</i> /2 | Basic Thread Height,<br><i>h</i> = 0.3 <i>P</i> | Basic Width of Flat,<br>0.4224 <i>P</i> | Lead Anglet<br>Basic Pitch Diameter |     |
|                |  |                             |  |  |                    |   |   |   | Deg                                 | Min |
| 1/4            | 16   | 0.2500                      | 0.2312   | 0.2125   | 0.06250            | 0.03125   | 0.01875   | 0.0264                                  | 4                                   | 54  |
| 5/16           | 14   | 0.3125                      | 0.2911   | 0.2696   | 0.07143            | 0.03572   | 0.02143   | 0.0302                                  | 4                                   | 28  |
| 3/8            | 12   | 0.3750                      | 0.3500   | 0.3250   | 0.08333            | 0.04167   | 0.02500   | 0.0352                                  | 4                                   | 20  |
| 7/16           | 12   | 0.4375                      | 0.4125   | 0.3875   | 0.08333            | 0.04167   | 0.02500   | 0.0352                                  | 3                                   | 41  |
| 1/2            | 10   | 0.5000                      | 0.4700   | 0.4400   | 0.10000            | 0.05000   | 0.03000   | 0.0422                                  | 3                                   | 52  |
| 5/8            | 8  | 0.6250                      | 0.5875   | 0.5500   | 0.12500            | 0.06250   | 0.03750   | 0.0528                                  | 3                                   | 52  |
| 3/4            | 6  | 0.7500                      | 0.7000   | 0.6500   | 0.16667            | 0.08333   | 0.05000   | 0.0704                                  | 4                                   | 20  |
| 7/8            | 6  | 0.8750                      | 0.8250   | 0.7750   | 0.16667            | 0.08333   | 0.05000   | 0.0704                                  | 3                                   | 41  |
| 1              | 5  | 1.0000                      | 0.9400   | 0.8800   | 0.20000            | 0.10000   | 0.06000   | 0.0845                                  | 3                                   | 52  |
| 1 1/8          | 5  | 1.1250                      | 1.0650   | 1.0050   | 0.20000            | 0.10000   | 0.06000   | 0.0845                                  | 3                                   | 25  |
| 1 1/4          | 5  | 1.2500                      | 1.1900   | 1.1300   | 0.20000            | 0.10000   | 0.06000   | 0.0845                                  | 3                                   | 4   |
| 1 3/8          | 4  | 1.3750                      | 1.3000   | 1.2250   | 0.25000            | 0.12500   | 0.07500   | 0.1056                                  | 3                                   | 30  |
| 1 1/2          | 4  | 1.5000                      | 1.4250   | 1.3500   | 0.25000            | 0.12500   | 0.07500   | 0.1056                                  | 3                                   | 12  |
| 1 3/4          | 4  | 1.7500                      | 1.6750   | 1.6000   | 0.25000            | 0.12500   | 0.07500   | 0.1056                                  | 2                                   | 43  |
| 2              | 4  | 2.0000                      | 1.9250   | 1.8500   | 0.25000            | 0.12500   | 0.07500   | 0.1056                                  | 2                                   | 22  |
| 2 1/4          | 3  | 2.2500                      | 2.1500   | 2.0500   | 0.33333            | 0.16667   | 0.10000   | 0.1408                                  | 2                                   | 50  |
| 2 1/2          | 3  | 2.5000                      | 2.4000   | 2.3000   | 0.33333            | 0.16667   | 0.10000   | 0.1408                                  | 2                                   | 32  |
| 2 3/4          | 3  | 2.7500                      | 2.6500   | 2.5500   | 0.33333            | 0.16667   | 0.10000   | 0.1408                                  | 2                                   | 18  |
| 3              | 2  | 3.0000                      | 2.8500   | 2.7000   | 0.50000            | 0.25000   | 0.15000   | 0.2112                                  | 3                                   | 12  |
| 3 1/2          | 2  | 3.5000                      | 3.3500   | 3.2000   | 0.50000            | 0.25000   | 0.15000   | 0.2112                                  | 2                                   | 43  |
| 4              | 2  | 4.0000                      | 3.8500   | 3.7000   | 0.50000            | 0.25000   | 0.15000   | 0.2112                                  | 2                                   | 22  |
| 4 1/2          | 2  | 4.5000                      | 4.3500   | 4.2000   | 0.50000            | 0.25000   | 0.15000   | 0.2112                                  | 2                                   | 6   |
| 5              | 2  | 5.0000                      | 4.8500   | 4.7000   | 0.50000            | 0.25000   | 0.15000   | 0.2112                                  | 1                                   | 53  |

<sup>a</sup> All other dimensions are given in inches.



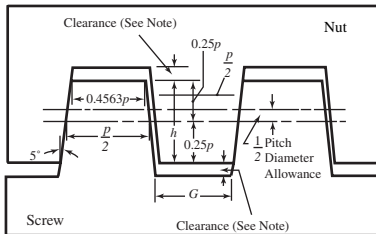
60-Degree Stub Thread

A clearance of at least  $0.02 \times$  pitch is added to depth  $h$  to produce extra depth, thus avoiding interference with threads of mating part at minor or major diameters.

Basic thread thickness at pitch line =  $0.5 \times$  pitch  $p$ ; basic depth  $h = 0.433 \times$  pitch; basic width of flat at crest =  $0.25 \times$  pitch; width of flat at root of screw thread =  $0.227 \times$  pitch; basic pitch diameter = basic major diameter -  $0.433 \times$  pitch; basic minor diameter = basic major diameter -  $0.866 \times$  pitch.

**Square Thread.**—The square thread is so named because the section is square, the depth, in the case of a screw, being equal to the width or one-half the pitch. The thread groove in a square-threaded nut is made a little greater than one-half the pitch in order to provide a slight clearance for the screw; hence, the tools used for threading square-threaded taps are a little less in width at the point than one-half the pitch. The pitch of a square thread is usually twice the pitch of an American Standard thread of corresponding diameter. The square thread has been superseded quite largely by the Acme form which has several advantages. See *ACME SCREW THREADS*.

**10-Degree Modified Square Thread:** The included angle between the sides of the thread is 10 degrees (see accompanying diagram). The angle of 10 degrees results in a thread which is the practical equivalent of a "square thread," and yet is capable of economical production. Multiple thread milling cutters and ground thread taps should not be specified for modified square threads of the larger lead angles without consulting the cutting tool manufacturer.



In the following formulas,  $D$  = basic major diameter;  $E$  = basic pitch diameter;  $K$  = basic minor diameter;  $p$  = pitch;  $h$  = basic depth of thread on screw depth when there is no clearance between root of screw and crest of thread on nut;  $t$  = basic thickness of thread at pitch line;  $F$  = basic width of flat at crest of screw thread;  $G$  = basic width of flat at root of screw thread;  $C$  = clearance between root of screw and crest of thread on nut:  $E = D - 0.5p$ ;  $K = D - p$ ;  $h = 0.5p$  (see Note);  $t = 0.5p$ ;  $F = 0.4563p$ ;  $G = 0.4563p - (0.17 \times C)$ .

*Note:* A clearance should be added to depth  $h$  to avoid interference with threads of mating parts at minor or major diameters.

## BUTTRESS THREADS

## Threads of Buttress Form

The buttress form of thread has certain advantages in applications involving exceptionally high stresses along the thread axis in one direction only. The contacting flank of the thread, which takes the thrust, is referred to as the *pressure flank* and is so nearly perpendicular to the thread axis that the radial component of the thrust is reduced to a minimum. Because of the small radial thrust, this form of thread is particularly applicable where tubular members are screwed together, as in the case of breech mechanisms of large guns and airplane propeller hubs.

Fig. 1a shows a common form. The front or load-resisting face is perpendicular to the axis of the screw and the thread angle is 45 degrees. According to one rule, the pitch  $P = 2 \times$  screw diameter  $\div 15$ . The thread depth  $d$  may equal  $\frac{3}{4} \times$  pitch, making the flat  $f = \frac{1}{8} \times$  pitch. Sometimes depth  $d$  is reduced to  $\frac{2}{3} \times$  pitch, making  $f = \frac{1}{6} \times$  pitch.

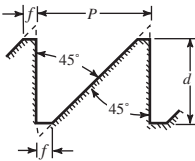


Fig. 1a.

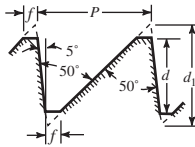


Fig. 1b.

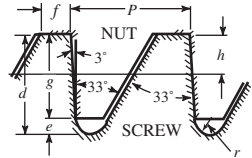


Fig. 1c.

The load-resisting side or flank may be inclined an amount (Fig. 1b) ranging usually from 1 to 5 degrees to avoid cutter interference in milling the thread. With an angle of 5 degrees and an included thread angle of 50 degrees, if the width of the flat  $f$  at both crest and root equals  $\frac{1}{8} \times$  pitch, then the thread depth equals  $0.69 \times$  pitch or  $\frac{3}{4} d_1$ .

The saw-tooth form of thread illustrated by Fig. 1c is known in Germany as the "Sägewinde" and in Italy as the "Filettatura a dente di Sega." Pitches are standardized from 2 millimeters up to 48 millimeters in the German and Italian specifications. The front face inclines 3 degrees from the perpendicular and the included angle is 33 degrees.

The thread depth  $d$  for the screw =  $0.86777 \times$  pitch  $P$ . The thread depth  $g$  for the nut =  $0.75 \times$  pitch. Dimension  $h = 0.341 \times P$ . The width  $f$  of flat at the crest of the thread on the screw =  $0.26384 \times$  pitch. Radius  $r$  at the root =  $0.12427 \times$  pitch. The clearance space  $e = 0.11777 \times$  pitch.

**British Standard Buttress Threads BS 1657: 1950.**—Specifications for buttress threads in this standard are similar to those in the American Standard (see page 1850) except: 1) A basic depth of thread of  $0.4p$  is used instead of  $0.6p$ ; 2) Sizes below 1 inch are not included; 3) Tolerances on major and minor diameters are the same as the pitch diameter tolerances, whereas in the American Standard separate tolerances are provided; however, provision is made for smaller major and minor diameter tolerances when crest surfaces of screws or nuts are used as datum surfaces, or when the resulting reduction in depth of engagement must be limited; and 4) Certain combinations of large diameters with fine pitches are provided that are not encouraged in the American Standard.

**Lowenherz or Löwenherz Thread.**—The Lowenherz thread is intended for the fine screws of instruments and is based on the metric system. The Löwenherz thread has flats at the top and bottom the same as the U.S. standard buttress form, but the angle is 53 degrees 8 minutes. The depth equals  $0.75 \times$  the pitch, and the width of the flats at the top and bottom is equal to  $0.125 \times$  the pitch. This screw thread used for measuring instruments, optical apparatus, etc., especially in Germany.

## Löwenherz Thread

| Diameter    |        | Pitch,<br>Millimeters | Approximate<br>No. of Threads<br>per Inch | Diameter    |        | Pitch,<br>Millimeters | Approximate<br>No. of Threads<br>per Inch |
|-------------|--------|-----------------------|---|-------------|--------|-----------------------|---|
| Millimeters | Inches |                       |   | Millimeters | Inches |                       |   |
| 1.0         | 0.0394 | 0.25                  | 101.6                                     | 9.0         | 0.3543 | 1.30                  | 19.5                                      |
| 1.2         | 0.0472 | 0.25                  | 101.6                                     | 10.0        | 0.3937 | 1.40                  | 18.1                                      |
| 1.4         | 0.0551 | 0.30                  | 84.7                                      | 12.0        | 0.4724 | 1.60                  | 15.9                                      |
| 1.7         | 0.0669 | 0.35                  | 72.6                                      | 14.0        | 0.5512 | 1.80                  | 14.1                                      |
| 2.0         | 0.0787 | 0.40                  | 63.5                                      | 16.0        | 0.6299 | 2.00                  | 12.7                                      |
| 2.3         | 0.0905 | 0.40                  | 63.5                                      | 18.0        | 0.7087 | 2.20                  | 11.5                                      |
| 2.6         | 0.1024 | 0.45                  | 56.4                                      | 20.0        | 0.7874 | 2.40                  | 10.6                                      |
| 3.0         | 0.1181 | 0.50                  | 50.8                                      | 22.0        | 0.8661 | 2.80                  | 9.1                                       |
| 3.5         | 0.1378 | 0.60                  | 42.3                                      | 24.0        | 0.9450 | 2.80                  | 9.1                                       |
| 4.0         | 0.1575 | 0.70                  | 36.3                                      | 26.0        | 1.0236 | 3.20                  | 7.9                                       |
| 4.5         | 0.1772 | 0.75                  | 33.9                                      | 28.0        | 1.1024 | 3.20                  | 7.9                                       |
| 5.0         | 0.1968 | 0.80                  | 31.7                                      | 30.0        | 1.1811 | 3.60                  | 7.1                                       |
| 5.5         | 0.2165 | 0.90                  | 28.2                                      | 32.0        | 1.2599 | 3.60                  | 7.1                                       |
| 6.0         | 0.2362 | 1.00                  | 25.4                                      | 36.0        | 1.4173 | 4.00                  | 6.4                                       |
| 7.0         | 0.2756 | 1.10                  | 23.1                                      | 40.0        | 1.5748 | 4.40                  | 5.7                                       |
| 8.0         | 0.3150 | 1.20                  | 21.1                                      | ...         | ...    | ...                   | ...                                       |

## American National Standard Buttress Inch Screw Threads

The buttress form of thread has certain advantages in applications involving exceptionally high stresses along the thread axis in one direction only. As the thrust side (load flank) of the standard buttress thread is made very nearly perpendicular to the thread axis, the radial component of the thrust is reduced to a minimum. On account of the small radial thrust, the buttress form of thread is particularly applicable when tubular members are screwed together. Examples of actual applications are the breech assemblies of large guns, airplane propeller hubs, and columns for hydraulic presses.

**7°/45° Buttress Thread Form.**—In selecting the form of thread recommended as standard, ANSI B1.9-1973 (R1992), manufacture by milling, grinding, rolling, or other suitable means, has been taken into consideration. All dimensions are in inches.

*Form of Thread:* The form of the buttress thread is shown in the accompanying Figs. 2a and 2b, and has the following characteristics:

- A load flank angle, measured in an axial plane, of 7 degrees from the normal to the axis.
- A clearance flank angle, measured in an axial plane, of 45 degrees from the normal to the axis.
- Equal truncations at the crests of the external and internal threads such that the basic height of thread engagement (assuming no allowance) is equal to 0.6 of the pitch
- Equal radii, at the roots of the external and internal basic thread forms tangential to the load flank and the clearance flank. (There is, in practice, almost no chance that the thread forms will be achieved strictly as basically specified, that is, as true radii.) When specified, equal flat roots of the external and internal thread may be supplied.

**Table 1. American National Standard Diameter—Pitch Combinations for 7°/45° Buttress Threads ANSI B1.9-1973 (R1992)**

| Preferred Nominal Major Diameters, Inches | Threads per Inch <sup>a</sup> | Preferred Nominal Major Diameters, Inches | Threads per Inch <sup>a</sup>          |
|---|-------------------------------|---|--|
| 0.5, 0.625, 0.75                          | (20, 16, 12)                  | 4.5, 5, 5.5, 6                            | 12, 10, 8, (6, 5, 4), 3                |
| 0.875, 1.0                                | (16, 12, 10)                  | 7, 8, 9, 10                               | 10, 8, 6, (5, 4, 3), 2.5, 2            |
| 1.25, 1.375, 1.5                          | 16, (12, 10, 8), 6            | 11, 12, 14, 16                            | 10, 8, 6, 5, (4, 3, 2.5), 2, 1.5, 1.25 |
| 1.75, 2, 2.25, 2.5                        | 16, 12, (10, 8, 6), 5, 4      | 18, 20, 22, 24                            | 8, 6, 5, 4, (3, 2.5, 2), 1.5, 1.25, 1  |
| 2.75, 3, 3.5, 4                           | 16, 12, 10, (8, 6, 5), 4      |   |  |

<sup>a</sup> Preferred threads per inch are in parentheses.

**Table 2. American National Standard Inch Buttress Screw Threads—  
Basic Dimensions ANSI B1.9-1973 (R1992)**

| Thds. <sup>a</sup><br>per<br>Inch | Pitch,<br>$p$ | Basic<br>Height of<br>Thread,<br>$h = 0.6p$ | Height of<br>Sharp-V<br>Thread, $H =$<br>$0.89064p$ | Crest<br>Truncation,<br>$f =$<br>$0.14532p$ | Height of<br>Thread,<br>$h_s$ or $h_n =$<br>$0.66271p$ | Max.<br>Root<br>Trunca-<br>tion, <sup>b</sup><br>$s =$<br>$0.0826p$ | Max.<br>Root<br>Radius, <sup>c</sup><br>$r =$<br>$0.0714p$ | Width of<br>Flat at<br>Crest, $F =$<br>$0.16316p$ |
|-----------------------------------|---------------|---|---|---|--|---|--|---|
| 20                                | 0.0500        | 0.0300                                      | 0.0445  | 0.0073                                      | 0.0331   | 0.0041  | 0.0036   | 0.0082  |
| 16                                | 0.0625        | 0.0375                                      | 0.0557  | 0.0091                                      | 0.0414   | 0.0052  | 0.0045   | 0.0102  |
| 12                                | 0.0833        | 0.0500                                      | 0.0742  | 0.0121                                      | 0.0552   | 0.0069  | 0.0059   | 0.0136  |
| 10                                | 0.1000        | 0.0600                                      | 0.0891  | 0.0145                                      | 0.0663   | 0.0083  | 0.0071   | 0.0163  |
| 8                                 | 0.1250        | 0.0750                                      | 0.1113  | 0.0182                                      | 0.0828   | 0.0103  | 0.0089   | 0.0204  |
| 6                                 | 0.1667        | 0.1000                                      | 0.1484  | 0.0242                                      | 0.1105   | 0.0138  | 0.0119   | 0.0271  |
| 5                                 | 0.2000        | 0.1200                                      | 0.1781  | 0.0291                                      | 0.1325   | 0.0165  | 0.0143   | 0.0326  |
| 4                                 | 0.2500        | 0.1500                                      | 0.2227  | 0.0363                                      | 0.1657   | 0.0207  | 0.0179   | 0.0408  |
| 3                                 | 0.3333        | 0.2000                                      | 0.2969  | 0.0484                                      | 0.2209   | 0.0275  | 0.0238   | 0.0543  |
| 2½                                | 0.4000        | 0.2400                                      | 0.3563  | 0.0581                                      | 0.2651   | 0.0330  | 0.0286   | 0.0653  |
| 2                                 | 0.5000        | 0.3000                                      | 0.4453  | 0.0727                                      | 0.3314   | 0.0413  | 0.0357   | 0.0816  |
| 1½                                | 0.6667        | 0.4000                                      | 0.5938  | 0.0969                                      | 0.4418   | 0.0551  | 0.0476   | 0.1088  |
| 1¼                                | 0.8000        | 0.4800                                      | 0.7125  | 0.1163                                      | 0.5302   | 0.0661  | 0.0572   | 0.1305  |
| 1                                 | 1.0000        | 0.6000                                      | 0.8906  | 0.1453                                      | 0.6627   | 0.0826  | 0.0714   | 0.1632  |

<sup>a</sup> All other dimensions are in inches.

<sup>b</sup> Minimum root truncation is one-half of maximum.

<sup>c</sup> Minimum root radius is one-half of maximum.

**Buttress Thread Tolerances.**—Tolerances from basic size on external threads are applied in a minus direction and on internal threads in a plus direction.

**Pitch Diameter Tolerances:** The following formula is used for determining the pitch diameter product tolerance for Class 2 (standard grade) external or internal threads:

$$\text{PD tolerance} = 0.002 \sqrt[3]{D} + 0.00278 \sqrt{L_e} + 0.00854 \sqrt{p}$$

where  $D$  = basic major diameter of external thread (assuming no allowance)

$L_e$  = length of engagement

$p$  = pitch of thread

When the length of engagement is taken as  $10p$ , the formula reduces to

$$0.002 \sqrt[3]{D} + 0.0173 \sqrt{p}$$

It is to be noted that this formula relates specifically to Class 2 (standard grade) PD tolerances. Class 3 (precision grade) PD tolerances are two-thirds of Class 2 PD tolerances. Pitch diameter tolerances based on this latter formula, for various diameter pitch combinations, are given in [Table 4](#).

**Functional Size:** Deviations in lead and flank angle of product threads increase the functional size of an external thread and decrease the functional size of an internal thread by the cumulative effect of the diameter equivalents of these deviations. The functional size of all buttress product threads shall not exceed the maximum-material limit.

**Tolerances on Major Diameter of External Thread and Minor Diameter of Internal Thread:** Unless otherwise specified, these tolerances should be the same as the pitch diameter tolerance for the class used.

**Tolerances on Minor Diameter of External Thread and Major Diameter of Internal Thread:** It will be sufficient in most instances to state only the maximum minor diameter of the external thread and the minimum major diameter of the internal thread without any tol-



Form of American National Standard 7°/45° Buttress Thread with 0.6p Basic Height of Thread Engagement

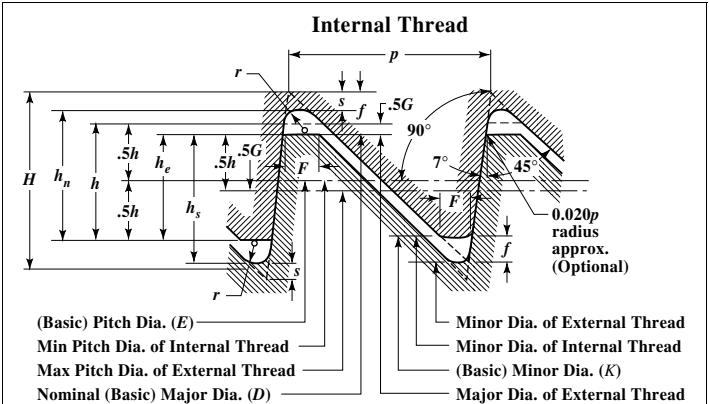


Fig. 2a. Round Root External Thread

Heavy Line Indicates Basic Form

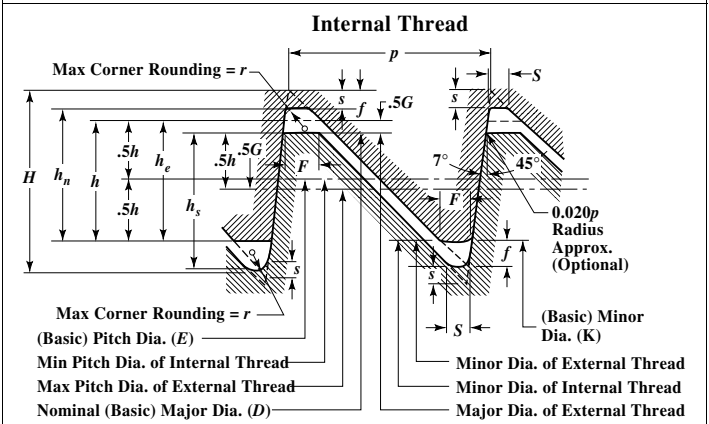


Fig. 2b. Flat Root External Thread

Heavy Line Indicates Basic Form

erance. However, the root truncation from a sharp V should not be greater than  $0.0826p$  nor less than  $0.0413p$ .

**Lead and Flank Angle Deviations for Class 2:** The deviations in lead and flank angles may consume the entire tolerance zone between maximum and minimum material product limits given in Table 4.

**Diameter Equivalents for Variations in Lead and Flank Angles for Class 3:** The combined diameter equivalents of variations in lead (including helix deviations), and flank

**Table 3. American National Standard Buttress Inch Screw Thread Symbols and Form**

| Thread Element   | Max. Material (Basic)    | Min. Material   |
|--|--------------------------|---|
| Pitch  | $p$                      |   |
| Height of sharp-V thread                                       | $H = 0.89064p$           |   |
| Basic height of thread engagement                              | $h = 0.6p$               |   |
| Root radius (theoretical)(see footnote <sup>a</sup> )          | $r = 0.07141p$           | Min. $r = 0.0357p$  |
| Root truncation  | $s = 0.0826p$            | Min. $s = 0.5$ ; Max. $s = 0.0413p$   |
| Root truncation for flat root form                             | $s = 0.0826p$            | Min. $s = 0.5$ ; Max. $s = 0.0413p$   |
| Flat width for flat root form                                  | $S = 0.0928p$            | Min. $S = 0.0464p$  |
| Allowance  | $G$ (see text)           |   |
| Height of thread engagement                                    | $h_e = h - 0.5G$         | Min. $h_e = \text{Max. } h_e - [0.5 \text{ tol. on major dia. external thread} + 0.5 \text{ tol. on minor dia. internal thread}]$ |
| Crest truncation   | $f = 0.14532p$           |   |
| Crest width  | $F = 0.16316p$           |   |
| Major diameter   | $D$                      |   |
| Major diameter of internal thread                              | $D_n = D + 0.12542p$     | Max. $D_n = \text{Max. pitch dia. of internal thread} + 0.80803p$   |
| Major diameter of external thread                              | $D_s = D - G$            | Min. $D_s = D - G - D \text{ tol.}$   |
| Pitch diameter   | $E$                      |   |
| Pitch diameter of internal thread (see footnote <sup>b</sup> ) | $E_n = D - h$            | Max. $E_n = D - h + PD \text{ tol.}$  |
| Pitch diameter of external thread (see footnote <sup>c</sup> ) | $E_s = D - h - G$        | Min. $E_s = D - h - G - PD \text{ tol.}$  |
| Minor diameter   | $K$                      |   |
| Minor diameter of external thread                              | $K_s = D - 1.32542p - G$ | Min. $K_s = \text{Min. pitch dia. of external thread} - 0.80803p$   |
| Minor diameter of internal thread                              | $K_n = D - 2h$           | Min. $K_n = D - 2h + K \text{ tol.}$  |
| Height of thread of internal thread                            | $h_n = 0.66271p$         |   |
| Height of thread of external thread                            | $h_s = 0.66271p$         |   |
| Pitch diameter increment for lead                              | $\Delta EI$              |   |
| Pitch diameter increment for 45° clearance flank angle         | $\Delta E\alpha_1$       |   |
| Pitch diameter increment for 7° load flank angle               | $\Delta E\alpha_2$       |   |
| Length of engagement   | $L_e$                    |   |

<sup>a</sup>Unless the flat root form is specified, the rounded root form of the external and internal thread shall be a continuous, smoothly blended curve within the zone defined by 0.07141*p* maximum to 0.0357*p* minimum radius. The resulting curve shall have no reversals or sudden angular variations, and shall be tangent to the flanks of the thread. There is, in practice, almost no chance that the rounded thread form will be achieved strictly as basically specified, that is, as a true radius.

<sup>b</sup>The pitch diameter *X* tolerances for GO and NOT GO threaded plug gages are applied to the internal product limits for  $E_n$  and Max.  $E_n$ .

<sup>c</sup>The pitch diameter *W* tolerances for GO and NOT GO threaded setting plug gages are applied to the external product limits for  $E_s$  and Min.  $E_s$ .

**Table 4. American National Standard Buttress Inch Screw Threads Tolerances Class 2 (Standard Grade) and Class 3 (Precision Grade) ANSI B1.9-1973 (R1992)**

| Thds. per Inch   | Pitch, <sup>a</sup><br><i>p</i><br>Inch | Basic Major Diameter, Inch   |                   |                   |                   |                 |               |                |                 |                 | Pitch <sup>b</sup><br>Increment,<br>$0.0173\sqrt{p}$<br>Inch |
|--|---|--|-------------------|-------------------|-------------------|-----------------|---------------|----------------|-----------------|-----------------|--|
|  |   | From 0.5 thru 0.7  | Over 0.7 thru 1.0 | Over 1.0 thru 1.5 | Over 1.5 thru 2.5 | Over 2.5 thru 4 | Over 4 thru 6 | Over 6 thru 10 | Over 10 thru 16 | Over 16 thru 24 |  |
|  |   | Tolerance on Major Diameter of External Thread, Pitch Diameter of External and Internal Threads, and Minor Diameter of Internal Thread, Inch |                   |                   |                   |                 |               |                |                 |                 |  |
| <b>Class 2, Standard Grade</b>                         |   |  |                   |                   |                   |                 |               |                |                 |                 |  |
| 20   | 0.0500                                  | .0056  | ....              | ....              | ....              | ....            | ....          | ....           | ....            | ....            | .00387   |
| 16   | 0.0625                                  | .0060  | .0062             | .0065             | .0068             | .0073           | ....          | ....           | ....            | ....            | .00432   |
| 12   | 0.0833                                  | .0067  | .0069             | .0071             | .0075             | .0080           | .0084         | ....           | ....            | ....            | .00499   |
| 10   | 0.1000                                  | ....   | .0074             | .0076             | .0080             | .0084           | .0089         | .0095          | .0102           | ....            | .00547   |
| 8  | 0.1250                                  | ....   | ....              | .0083             | .0086             | .0091           | .0095         | .0101          | .0108           | .0115           | .00612   |
| 6  | 0.1667                                  | ....   | ....              | .0092             | .0096             | .0100           | .0105         | .0111          | .0118           | .0125           | .00706   |
| 5  | 0.2000                                  | ....   | ....              | ....              | .0103             | .0107           | .0112         | .0117          | .0124           | .0132           | .00774   |
| 4  | 0.2500                                  | ....   | ....              | ....              | .0112             | .0116           | .0121         | .0127          | .0134           | .0141           | .00865   |
| 3  | 0.3333                                  | ....   | ....              | ....              | ....              | ....            | .0134         | .0140          | .0147           | .0154           | .00999   |
| 2.5  | 0.4000                                  | ....   | ....              | ....              | ....              | ....            | ....          | .0149          | .0156           | .0164           | .01094   |
| 2.0  | 0.5000                                  | ....   | ....              | ....              | ....              | ....            | ....          | .0162          | .0169           | .0177           | .01223   |
| 1.5  | 0.6667                                  | ....   | ....              | ....              | ....              | ....            | ....          | ....           | .0188           | .0196           | .01413   |
| 1.25   | 0.8000                                  | ....   | ....              | ....              | ....              | ....            | ....          | ....           | .0202           | .0209           | .01547   |
| 1.0  | 1.0000                                  | ....   | ....              | ....              | ....              | ....            | ....          | ....           | ....            | .0227           | .01730   |
| Diameter Increment, <sup>c</sup><br>$0.002\sqrt[3]{D}$ |   | .00169   | .00189            | .00215            | .00252            | .00296          | .00342        | .00400         | .00470          | .00543          |  |
| <b>Class 3, Precision Grade</b>                        |   |  |                   |                   |                   |                 |               |                |                 |                 |  |
| 20   | 0.0500                                  | .0037  | ....              | ....              | ....              | ....            | ....          | ....           | ....            | ....            |  |
| 16   | 0.0625                                  | .0040  | .0042             | .0043             | .0046             | .0049           | ....          | ....           | ....            | ....            |  |
| 12   | 0.0833                                  | .0044  | .0046             | .0048             | .0050             | .0053           | .0056         | ....           | ....            | ....            |  |
| 10   | 0.1000                                  | ....   | .0049             | .0051             | .0053             | .0056           | .0059         | .0063          | .0068           | ....            |  |
| 8  | 0.1250                                  | ....   | ....              | .0055             | .0058             | .0061           | .0064         | .0067          | .0072           | .0077           |  |
| 6  | 0.1667                                  | ....   | ....              | .0061             | .0064             | .0067           | .0070         | .0074          | .0078           | .0083           |  |
| 5  | .02000                                  | ....   | ....              | ....              | .0068             | .0071           | .0074         | .0078          | .0083           | .0088           |  |
| 4  | 0.2500                                  | ....   | ....              | ....              | .0074             | .0077           | .0080         | .0084          | .0089           | .0094           |  |
| 3  | .03333                                  | ....   | ....              | ....              | ....              | ....            | .0089         | .0093          | .0098           | .0103           |  |
| 2.5  | 0.4000                                  | ....   | ....              | ....              | ....              | ....            | ....          | .0100          | .0104           | .0109           |  |
| 2.0  | 0.5000                                  | ....   | ....              | ....              | ....              | ....            | ....          | .0108          | .0113           | .0118           |  |
| 1.5  | 0.6667                                  | ....   | ....              | ....              | ....              | ....            | ....          | ....           | .0126           | .0130           |  |
| 1.25   | 0.8000                                  | ....   | ....              | ....              | ....              | ....            | ....          | ....           | .0135           | .0139           |  |
| 1.0  | 1.0000                                  | ....   | ....              | ....              | ....              | ....            | ....          | ....           | ....            | .0152           |  |

<sup>a</sup> For threads with pitches not shown in this table, pitch increment to be used in tolerance formula is to be determined by use of formula  $PD \text{ Tolerance} = 0.002\sqrt[3]{D} + 0.00278\sqrt{L_e} + 0.00854\sqrt{p}$ , where:  $D$  = basic major diameter of external thread (assuming no allowance),  $L_e$  = length of engagement, and  $p$  = pitch of thread. This formula relates specifically to Class 2 (standard grade) PD tolerances. Class 3 (precision grade) PD tolerances are two-thirds of Class 2 PD tolerances. See text

<sup>b</sup> When the length of engagement is taken as  $10p$ , the formula reduces to:  $0.002\sqrt[3]{D} + 0.0173\sqrt{p}$

<sup>c</sup> Diameter  $D$ , used in diameter increment formula, is based on the average of the range.

angle for Class 3, shall not exceed 50 percent of the Class 2 pitch diameter tolerances given in Table 4.

*Tolerances on Taper and Roundness:* There are no requirements for taper and roundness for Class 2 buttress screw threads.

The major and minor diameters of Class 3 buttress threads shall not taper nor be out of round to the extent that specified limits for major and minor diameter are exceeded. The taper and out-of-roundness of the pitch diameter for Class 3 buttress threads shall not exceed 50 per cent of the pitch-diameter tolerances.

**Allowances for Easy Assembly.**—An allowance (clearance) should be provided on all external threads to secure easy assembly of parts. The amount of the allowance is deducted from the nominal major, pitch, and minor diameters of the external thread when the maximum material condition of the external thread is to be determined.

The minimum internal thread is basic.

The amount of the allowance is the same for both classes and is equal to the Class 3 pitch-diameter tolerance as calculated by the formulas previously given. The allowances for various diameter-pitch combinations are given in [Table 5](#).

**Table 5. American National Standard External Thread Allowances for Classes 2 and 3 Buttress Inch Screw Threads ANSI B1.9-1973 (R1992)**

| Threads per Inch | Pitch, <i>p</i> Inch | Basic Major Diameter, Inch   |                   |                   |                   |                 |               |                |                 |                 |
|------------------|----------------------|--|-------------------|-------------------|-------------------|-----------------|---------------|----------------|-----------------|-----------------|
|                  |                      | From 0.5 thru 0.7  | Over 0.7 thru 1.0 | Over 1.0 thru 1.5 | Over 1.5 thru 2.5 | Over 2.5 thru 4 | Over 4 thru 6 | Over 6 thru 10 | Over 10 thru 16 | Over 16 thru 24 |
|                  |                      | Allowance on Major, Minor and Pitch Diameters of External Thread, Inch |                   |                   |                   |                 |               |                |                 |                 |
| 20               | 0.0500               | .0037  | ....              | ....              | ....              | ....            | ....          | ....           | ....            | ....            |
| 16               | 0.0625               | .0040  | .0042             | .0043             | .0046             | .0049           | ....          | ....           | ....            | ....            |
| 12               | 0.0833               | .0044  | .0046             | .0048             | .0050             | .0053           | .0056         | ....           | ....            | ....            |
| 10               | 0.1000               | ....   | .0049             | .0051             | .0053             | .0056           | .0059         | .0063          | .0068           | ....            |
| 8                | 0.1250               | ....   | ....              | .0055             | .0058             | .0061           | .0064         | .0067          | .0072           | .0077           |
| 6                | 0.1667               | ....   | ....              | .0061             | .0064             | .0067           | .0070         | .0074          | .0078           | .0083           |
| 5                | 0.2000               | ....   | ....              | ....              | .0068             | .0071           | .0074         | .0078          | .0083           | .0088           |
| 4                | 0.2500               | ....   | ....              | ....              | .0074             | .0077           | .0080         | .0084          | .0089           | .0094           |
| 3                | 0.3333               | ....   | ....              | ....              | ....              | ....            | .0089         | .0093          | .0098           | .0103           |
| 2.5              | 0.4000               | ....   | ....              | ....              | ....              | ....            | ....          | .0100          | .0104           | .0109           |
| 2.0              | 0.5000               | ....   | ....              | ....              | ....              | ....            | ....          | .0108          | .0113           | .0118           |
| 1.5              | 0.6667               | ....   | ....              | ....              | ....              | ....            | ....          | ....           | .0126           | .0130           |
| 1.25             | 0.8000               | ....   | ....              | ....              | ....              | ....            | ....          | ....           | .0135           | .0139           |
| 1.0              | 1.0000               | ....   | ....              | ....              | ....              | ....            | ....          | ....           | ....            | .0152           |

**Example Showing Dimensions for a Typical Buttress Thread.**—The dimensions for a 2-inch diameter, 4 threads per inch, Class 2 buttress thread with flank angles of 7 degrees and 45 degrees are

$$h = \text{basic thread height} = 0.1500 \text{ (Table 2)}$$

$$h_s = h_n = \text{height of thread in external and internal threads} = 0.1657 \text{ (Table 2)}$$

$$G = \text{pitch-diameter allowance on external thread} = 0.0074 \text{ (Table 5)}$$

Tolerance on PD of external and internal threads = 0.0112 (Table 4)

Tolerance on major diameter of external thread and minor diameter of internal thread = 0.0112 (Table 4)

**Internal Thread:**

Basic Major Diameter:  $D = 2.0000$

Min. Major Diameter:  $D - 2h + 2h_n = 2.0314$  (see [Table 2](#))

Min. Pitch Diameter:  $D - h = 1.8500$  (see [Table 2](#))

Max. Pitch Diameter:  $D - h + PD \text{ Tolerance} = 1.8612$  (see [Table 4](#))

Min. Minor Diameter:  $D - 2h = 1.7000$  (see [Table 2](#))

Max. Minor Diameter:  $D - 2h + \text{Minor Diameter Tolerance} = 1.7112$  (see [Table 4](#))

**External Thread:**

*Max. Major Diameter:*  $D - G = 1.9926$  (see Table 5)

*Min. Major Diameter:*  $D - G - \text{Major Diameter Tolerance} = 1.9814$  (see Tables 4 and 5)

*Max. Pitch Diameter:*  $D - h - G = 1.8426$  (see Tables 2 and 5)

*Min. Pitch Diameter:*  $D - h - G - PD \text{ Tolerance} = 1.8314$  (see Table 4)

*Max. Minor Diameter:*  $D - G - 2h_s = 1.6612$  (see Tables 2 and 5)

**Buttress Thread Designations.**—When only the designation, BUTT is used, the thread is “pull” type buttress (external thread pulls) with the clearance flank leading and the 7-degree pressure flank following. When the designation, PUSH-BUTT is used, the thread is a push type buttress (external thread pushes) with the 7-degree load flank leading and the 45-degree clearance flank following. Whenever possible this description should be confirmed by a simplified view showing thread angles on the drawing of the product that has the buttress thread.

*Standard Buttress Threads:* A buttress thread is considered to be standard when: 1) opposite flank angles are 7-degrees and 45-degrees; 2) basic thread height is  $0.6p$ ; 3) tolerances and allowances are as shown in Tables 4 and 5; and 4) length of engagement is  $10p$  or less.

*Thread Designation Abbreviations:* In thread designations on drawings, tools, gages, and in specifications, the following abbreviations and letters are to be used:

|           |  |   |
|-----------|--|---|
| BUTT      | for buttress thread, pull type   |   |
| PUSH-BUTT | for buttress thread, push type   |   |
| LH        | for left-hand thread (Absence of LH indicates that the thread is a right-hand thread.) |   |
| P         | for pitch  |   |
| L         | for lead   |   |
| A         | for external thread  | <i>Note:</i> Absence of A or B after thread class indicates that designation covers both the external and internal threads. |
| B         | for internal thread  |   |
| Le        | for length of thread engagement  |   |
| SPL       | for special  |   |
| FL        | for flat root thread   |   |
| E         | for pitch diameter   |   |
| TPI       | for threads per inch   |   |
| THD       | for thread   |   |

**Designation Sequence for Buttress Inch Screw Threads.**—When designating single-start standard buttress threads the nominal size is given first, the threads per inch next, then PUSH if the internal member is to push, but nothing if it is to pull, then the class of thread (2 or 3), then whether external (A) or internal (B), then LH if left-hand, but nothing if right-hand, and finally FL if a flat root thread, but nothing if a radiused root thread; thus, 2.5-8 BUTT-2A indicates a 2.5 inch, 8 threads per inch buttress thread, Class 2 external, right-hand, internal member to pull, with radiused root of thread. The designation 2.5-8 PUSH-BUTT-2A-LH-FL signifies a 2.5 inch size, 8 threads per inch buttress thread with internal member to push, Class 2 external, left-hand, and flat root.

A multiple-start standard buttress thread is similarly designated but the pitch is given instead of the threads per inch, followed by the lead and the number of starts is indicated in parentheses after the class of thread. Thus, 10-0.25P-0.5L - BUTT-3B (2 start) indicates a 10-inch thread with 4 threads per inch, 0.5 inch lead, buttress form with internal member to pull, Class 3 internal, 2 starts, with radiused root of thread.

## WHITWORTH THREADS

**British Standard Whitworth (BSW) and British Standard Fine (BSF) Threads**

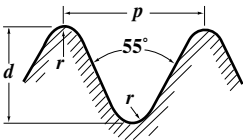
The BSW is the Coarse Thread series and the BSF is the Fine Thread series of British Standard 84:1956—Parallel Screw Threads of Whitworth Form. The dimensions given in the tables on the following pages for the major, effective, and minor diameters are, respectively, the maximum limits of these diameters for bolts and the minimum limits for nuts. Formulas for the tolerances on these diameters are given in the table below.

**Whitworth Standard Thread Form.**—This thread form is used for the British Standard Whitworth (BSW) and British Standard Fine (BSF) screw threads. More recently, both threads have been known as parallel screw threads of Whitworth form.

With standardization of the Unified thread, the Whitworth thread form is expected to be used only for replacements or spare parts. Tables of British Standard Parallel Screw Threads of Whitworth Form will be found on the following pages; tolerance formulas are given in the table below. The form of the thread is shown by the diagram. If  $p$  = pitch,  $d$  = depth of thread,  $r$  = radius at crest and root, and  $n$  = number of threads per inch, then

$$d = \frac{1}{2}p \times \cot 27^{\circ}30' = 0.640327p = 0.640327 \div n$$

$$r = 0.137329p = 0.137329 \div n$$



It is recommended that stainless steel bolts of nominal size  $\frac{3}{4}$  inch and below should not be made to Close Class limits but rather to Medium or Free Class limits. Nominal sizes above  $\frac{3}{4}$  inch should have maximum and minimum limits 0.001 inch smaller than the values obtained from the table.

**Tolerance Classes :** *Close Class bolts.* Applies to screw threads requiring a fine snug fit, and should be used only for special work where refined accuracy of pitch and thread form are particularly required. *Medium Class bolts and nuts.* Applies to the better class of ordinary interchangeable screw threads. *Free Class bolts.* Applies to the majority of bolts of ordinary commercial quality. *Normal Class nuts.* Applies to ordinary commercial quality nuts; this class is intended for use with Medium or Free Class bolts.

**Table 1. Tolerance Formulas for BSW and BSF Threads**

|       | Class or Fit | Tolerance in inches <sup>a</sup> (+ for nuts, - for bolts) |                |  |
|-------|--------------|--|----------------|--|
|       |              | Major Dia.   | Effective Dia. | Minor Dia.   |
| Bolts | Close        | $\frac{2}{3}T + 0.01\sqrt{p}$                              | $\frac{2}{3}T$ | $\frac{2}{3}T + 0.013\sqrt{p}$   |
|       | Medium       | $T + 0.01\sqrt{p}$   | $T$            | $T + 0.02\sqrt{p}$   |
|       | Free         | $\frac{3}{2}T + 0.01\sqrt{p}$                              | $\frac{3}{2}T$ | $\frac{3}{2}T + 0.02\sqrt{p}$  |
| Nuts  | Close        | ...  | $\frac{2}{3}T$ | } {<br>0.2p + 0.004 <sup>b</sup><br>0.2p + 0.005 <sup>c</sup><br>0.2p + 0.007 <sup>d</sup> |
|       | Medium       | ...  | $T$            |  |
|       | Normal       | ...  | $\frac{3}{2}T$ |  |

<sup>a</sup> The symbol  $T = 0.002\sqrt[3]{D} + 0.003\sqrt{L} + 0.005\sqrt{p}$ , where  $D$  = major diameter of thread in inches;  $L$  = length of engagement in inches;  $p$  = pitch in inches. The symbol  $p$  signifies pitch.

<sup>b</sup> For 26 threads per inch and finer.

<sup>c</sup> For 24 and 22 threads per inch.

<sup>d</sup> For 20 threads per inch and coarser.

WHITWORTH THREADS

Table 2. Threads of Whitworth Form—Basic Dimensions

$p = 1 \div n$   
 $H = 0.960491p$   
 $H/6 = 0.160082p$   
 $h = 0.640327p$   
 $e = 0.0739176p$   
 $r = 0.137329p$

| Threads per Inch | Pitch    | Triangular Height | Shortening | Depth of Thread | Depth of Rounding | Radius   |
|------------------|----------|-------------------|------------|-----------------|-------------------|----------|
| <i>n</i>         | <i>p</i> | <i>H</i>          | <i>H/6</i> | <i>h</i>        | <i>e</i>          | <i>r</i> |
| 72               | 0.013889 | 0.013340          | 0.002223   | 0.008894        | 0.001027          | 0.001907 |
| 60               | 0.016667 | 0.016009          | 0.002668   | 0.010672        | 0.001232          | 0.002289 |
| 56               | 0.017857 | 0.017151          | 0.002859   | 0.011434        | 0.001320          | 0.002452 |
| 48               | 0.020833 | 0.020010          | 0.003335   | 0.013340        | 0.001540          | 0.002861 |
| 40               | 0.025000 | 0.024012          | 0.004002   | 0.016008        | 0.0011848         | 0.003433 |
| 36               | 0.027778 | 0.026680          | 0.004447   | 0.017787        | 0.002053          | 0.003815 |
| 32               | 0.031250 | 0.030015          | 0.005003   | 0.020010        | 0.002310          | 0.004292 |
| 28               | 0.035714 | 0.034303          | 0.005717   | 0.022869        | 0.002640          | 0.004905 |
| 26               | 0.038462 | 0.036942          | 0.006157   | 0.024628        | 0.002843          | 0.005282 |
| 24               | 0.041667 | 0.040020          | 0.006670   | 0.026680        | 0.003080          | 0.005722 |
| 22               | 0.045455 | 0.043659          | 0.007276   | 0.029106        | 0.003366          | 0.006242 |
| 20               | 0.050000 | 0.048025          | 0.008004   | 0.032016        | 0.003696          | 0.006866 |
| 19               | 0.052632 | 0.050553          | 0.008425   | 0.033702        | 0.003890          | 0.007228 |
| 18               | 0.055556 | 0.053361          | 0.008893   | 0.035574        | 0.004107          | 0.007629 |
| 16               | 0.062500 | 0.060031          | 0.010005   | 0.040020        | 0.004620          | 0.008583 |
| 14               | 0.071429 | 0.068607          | 0.011434   | 0.045738        | 0.005280          | 0.009809 |
| 12               | 0.083333 | 0.080041          | 0.013340   | 0.053361        | 0.006160          | 0.011444 |
| 11               | 0.090909 | 0.087317          | 0.014553   | 0.058212        | 0.006720          | 0.012484 |
| 10               | 0.100000 | 0.096049          | 0.016008   | 0.064033        | 0.007392          | 0.013733 |
| 9                | 0.111111 | 0.106721          | 0.017787   | 0.071147        | 0.008213          | 0.015259 |
| 8                | 0.125000 | 0.120061          | 0.020010   | 0.080041        | 0.009240          | 0.017166 |
| 7                | 0.142857 | 0.137213          | 0.022869   | 0.091475        | 0.010560          | 0.019618 |
| 6                | 0.166667 | 0.160082          | 0.026680   | 0.106721        | 0.012320          | 0.022888 |
| 5                | 0.200000 | 0.192098          | 0.032016   | 0.128065        | 0.014784          | 0.027466 |
| 4.5              | 0.222222 | 0.213442          | 0.035574   | 0.142295        | 0.016426          | 0.030518 |
| 4                | 0.250000 | 0.240123          | 0.040020   | 0.160082        | 0.018479          | 0.034332 |
| 3.5              | 0.285714 | 0.274426          | 0.045738   | 0.182951        | 0.021119          | 0.039237 |
| 3.25             | 0.307692 | 0.295536          | 0.049256   | 0.197024        | 0.022744          | 0.042255 |
| 3                | 0.333333 | 0.320164          | 0.053361   | 0.213442        | 0.024639          | 0.045776 |
| 2.875            | 0.347826 | 0.334084          | 0.055681   | 0.222722        | 0.025710          | 0.047767 |
| 2.75             | 0.363636 | 0.349269          | 0.058212   | 0.232846        | 0.026879          | 0.049938 |
| 2.625            | 0.380952 | 0.365901          | 0.060984   | 0.243934        | 0.028159          | 0.052316 |
| 2.5              | 0.400000 | 0.384196          | 0.064033   | 0.256131        | 0.029567          | 0.054932 |

Dimensions are in inches.

*Allowances:* Only Free Class and Medium Class bolts have an allowance. For nominal sizes of 3/4 inch down to 1/4 inch, the allowance is 30 per cent of the Medium Class bolt effective-diameter tolerance (0.3T); for sizes less than 1/4 inch, the allowance for the 1/4-inch size applies. Allowances are applied minus from the basic bolt dimensions; the tolerances are then applied to the reduced dimensions.

**Table 3. British Standard Whitworth (BSW) and British Standard Fine (BSF) Screw Thread Series—Basic Dimensions BS 84:1956 (obsolescent)**

| Nominal Size, Inches              | Threads per Inch | Pitch, Inches | Depth of Thread, Inches | Major Diameter, Inches | Effective Diameter, Inches | Minor Diameter, Inches | Area at Bottom of Thread, Sq. in. | Tap Drill Dia.   |
|-----------------------------------|------------------|---------------|-------------------------|------------------------|----------------------------|------------------------|-----------------------------------|--|
| <b>Coarse Thread Series (BSW)</b> |                  |               |                         |                        |                            |                        |                                   |  |
| $\frac{1}{8}$ <sup>a</sup>        | 40               | 0.02500       | 0.0160                  | 0.1250                 | 0.1090                     | 0.9030                 | 0.0068                            | 2.55 mm  |
| $\frac{3}{16}$                    | 24               | 0.04167       | 0.0267                  | 0.1875                 | 0.1608                     | 0.1341                 | 0.0141                            | 3.70 mm  |
| $\frac{1}{4}$                     | 20               | 0.05000       | 0.0320                  | 0.2500                 | 0.2180                     | 0.1860                 | 0.0272                            | 5.10 mm  |
| $\frac{5}{16}$                    | 18               | 0.05556       | 0.0356                  | 0.3125                 | 0.2769                     | 0.2413                 | 0.0457                            | 6.50 mm  |
| $\frac{3}{8}$                     | 16               | 0.06250       | 0.0400                  | 0.3750                 | 0.3350                     | 0.2950                 | 0.0683                            | 7.90 mm  |
| $\frac{7}{16}$                    | 14               | 0.07143       | 0.0457                  | 0.4375                 | 0.3918                     | 0.3461                 | 0.0941                            | 9.30 mm  |
| $\frac{1}{2}$                     | 12               | 0.08333       | 0.0534                  | 0.5000                 | 0.4466                     | 0.3932                 | 0.1214                            | 10.50 mm   |
| $\frac{5}{16}$ <sup>a</sup>       | 12               | 0.08333       | 0.0534                  | 0.5625                 | 0.5091                     | 0.4557                 | 0.1631                            | 12.10 mm   |
| $\frac{5}{8}$                     | 11               | 0.09091       | 0.0582                  | 0.6250                 | 0.5668                     | 0.5086                 | 0.2032                            | 13.50 mm   |
| $\frac{11}{16}$ <sup>a</sup>      | 11               | 0.09091       | 0.0582                  | 0.6875                 | 0.6293                     | 0.5711                 | 0.2562                            | 15.00 mm   |
| $\frac{3}{4}$                     | 10               | 0.10000       | 0.0640                  | 0.7500                 | 0.6860                     | 0.6220                 | 0.3039                            | 16.25 mm   |
| $\frac{7}{8}$                     | 9                | 0.11111       | 0.0711                  | 0.8750                 | 0.8039                     | 0.7328                 | 0.4218                            | 19.25 mm   |
| 1                                 | 8                | 0.12500       | 0.0800                  | 1.0000                 | 0.9200                     | 0.8400                 | 0.5542                            | 22.00 mm   |
| $1\frac{1}{8}$                    | 7                | 0.14286       | 0.0915                  | 1.1250                 | 1.0335                     | 0.9420                 | 0.6969                            | 24.75 mm   |
| $1\frac{1}{4}$                    | 7                | 0.14286       | 0.0915                  | 1.2500                 | 1.1585                     | 1.0670                 | 0.8942                            | 28.00 mm   |
| $1\frac{1}{2}$                    | 6                | 0.16667       | 0.1067                  | 1.5000                 | 1.3933                     | 1.2866                 | 1.3000                            | 33.50 mm   |
| $1\frac{3}{4}$                    | 5                | 0.20000       | 0.1281                  | 1.7500                 | 1.6219                     | 1.4938                 | 1.7530                            | 39.00 mm   |
| 2                                 | 4.5              | 0.22222       | 0.1423                  | 2.0000                 | 1.8577                     | 1.7154                 | 2.3110                            | 44.50 mm   |
| $2\frac{1}{4}$                    | 4                | 0.25000       | 0.1601                  | 2.2500                 | 2.0899                     | 1.9298                 | 2.9250                            |  |
| $2\frac{1}{2}$                    | 4                | 0.25000       | 0.1601                  | 2.5000                 | 2.3399                     | 2.1798                 | 3.7320                            |  |
| $2\frac{3}{4}$                    | 3.5              | 0.28571       | 0.1830                  | 2.7500                 | 2.5670                     | 2.3840                 | 4.4640                            | Tap drill diameters shown in this column are recommended sizes listed in BS 1157:1975 and provide from 77 to 87% of full thread. |
| 3                                 | 3.5              | 0.28571       | 0.1830                  | 3.0000                 | 2.8170                     | 2.6340                 | 5.4490                            |  |
| $3\frac{1}{2}$ <sup>a</sup>       | 3.25             | 0.30769       | 0.1970                  | 3.2500                 | 3.0530                     | 2.8560                 | 6.4060                            |  |
| $3\frac{1}{2}$                    | 3.25             | 0.30769       | 0.1970                  | 3.5000                 | 3.3030                     | 3.1060                 | 7.5770                            |  |
| $3\frac{3}{4}$ <sup>a</sup>       | 3                | 0.33333       | 0.2134                  | 3.7500                 | 3.5366                     | 3.3232                 | 8.6740                            |  |
| 4                                 | 3                | 0.33333       | 0.2134                  | 4.0000                 | 3.7866                     | 3.5732                 | 10.0300                           |  |
| $4\frac{1}{2}$                    | 2.875            | 0.34783       | 0.2227                  | 4.5000                 | 4.2773                     | 4.0546                 | 12.9100                           |  |
| 5                                 | 2.75             | 0.36364       | 0.2328                  | 5.0000                 | 4.7672                     | 4.5344                 | 16.1500                           |  |
| $5\frac{1}{2}$                    | 2.625            | 0.38095       | 0.2439                  | 5.5000                 | 5.2561                     | 5.0122                 | 19.7300                           |  |
| 6                                 | 2.5              | 0.40000       | 0.2561                  | 6.0000                 | 5.7439                     | 5.4878                 | 23.6500                           |  |
| <b>Fine Thread Series (BSF)</b>   |                  |               |                         |                        |                            |                        |                                   |  |
| $\frac{3}{16}$ <sup>a b</sup>     | 32               | 0.03125       | 0.0200                  | 0.1875                 | 0.1675                     | 0.1475                 | 0.0171                            | 4.00 mm  |
| $\frac{7}{32}$ <sup>a</sup>       | 28               | 0.03571       | 0.0229                  | 0.2188                 | 0.1959                     | 0.1730                 | 0.0235                            | 4.60 mm  |
| $\frac{1}{4}$                     | 26               | 0.03846       | 0.0246                  | 0.2500                 | 0.2254                     | 0.2008                 | 0.0317                            | 5.30 mm  |
| $\frac{9}{32}$ <sup>a</sup>       | 26               | 0.03846       | 0.0246                  | 0.2812                 | 0.2566                     | 0.2320                 | 0.0423                            | 6.10 mm  |
| $\frac{5}{16}$                    | 22               | 0.04545       | 0.0291                  | 0.3125                 | 0.2834                     | 0.2543                 | 0.0508                            | 6.80 mm  |
| $\frac{3}{8}$                     | 20               | 0.05000       | 0.0320                  | 0.3750                 | 0.3430                     | 0.3110                 | 0.0760                            | 8.30 mm  |
| $\frac{7}{16}$                    | 18               | 0.05556       | 0.0356                  | 0.4375                 | 0.4019                     | 0.3363                 | 0.1054                            | 9.70 mm  |
| $\frac{1}{2}$                     | 16               | 0.06250       | 0.0400                  | 0.5000                 | 0.4600                     | 0.4200                 | 0.1385                            | 11.10 mm   |
| $\frac{9}{16}$                    | 16               | 0.06250       | 0.0400                  | 0.5625                 | 0.5225                     | 0.4825                 | 0.1828                            | 12.70 mm   |
| $\frac{5}{8}$                     | 14               | 0.07143       | 0.0457                  | 0.6250                 | 0.5793                     | 0.5336                 | 0.2236                            | 14.00 mm   |
| $\frac{11}{16}$ <sup>a</sup>      | 14               | 0.07143       | 0.0457                  | 0.6875                 | 0.6418                     | 0.5961                 | 0.2791                            | 15.50 mm   |
| $\frac{3}{4}$                     | 12               | 0.08333       | 0.0534                  | 0.7500                 | 0.6966                     | 0.6432                 | 0.3249                            | 16.75 mm   |
| $\frac{7}{8}$                     | 11               | 0.09091       | 0.0582                  | 0.8750                 | 0.8168                     | 0.7586                 | 0.4520                            | 19.75 mm   |
| 1                                 | 10               | 0.10000       | 0.0640                  | 1.0000                 | 0.9360                     | 0.8720                 | 0.5972                            | 22.75 mm   |
| $1\frac{1}{8}$                    | 9                | 0.11111       | 0.0711                  | 1.1250                 | 1.0539                     | 0.9828                 | 0.7586                            | 25.50 mm   |
| $1\frac{1}{4}$                    | 9                | 0.11111       | 0.0711                  | 1.2500                 | 1.1789                     | 1.1078                 | 0.9639                            | 28.50 mm   |
| $1\frac{3}{8}$ <sup>a</sup>       | 8                | 0.12500       | 0.0800                  | 1.3750                 | 1.2950                     | 1.2150                 | 1.1590                            | 31.50 mm   |
| $1\frac{1}{2}$                    | 8                | 0.12500       | 0.0800                  | 1.5000                 | 1.4200                     | 1.3400                 | 1.4100                            | 34.50 mm   |
| $1\frac{5}{8}$ <sup>a</sup>       | 8                | 0.12500       | 0.0800                  | 1.6250                 | 1.5450                     | 1.4650                 | 1.6860                            |  |
| $1\frac{3}{4}$                    | 7                | 0.14286       | 0.0915                  | 1.7500                 | 1.6585                     | 1.5670                 | 1.9280                            |  |
| 2                                 | 7                | 0.14286       | 0.0915                  | 2.0000                 | 1.9085                     | 1.8170                 | 2.5930                            |  |
| $2\frac{1}{4}$                    | 6                | 0.16667       | 0.1067                  | 2.2500                 | 2.1433                     | 2.0366                 | 3.2580                            |  |
| $2\frac{1}{2}$                    | 6                | 0.16667       | 0.1067                  | 2.5000                 | 2.3933                     | 2.2866                 | 4.1060                            |  |
| $2\frac{3}{4}$                    | 6                | 0.16667       | 0.1067                  | 2.7500                 | 2.6433                     | 2.5366                 | 5.0540                            | Tap drill sizes listed in this column are recommended sizes shown in BS 1157:1975 and provide from 78 to 88% of full thread.     |
| 3                                 | 5                | 0.20000       | 0.1281                  | 3.0000                 | 2.8719                     | 2.7438                 | 5.9130                            |  |
| $3\frac{1}{4}$                    | 5                | 0.20000       | 0.1281                  | 3.2500                 | 3.1219                     | 2.9938                 | 7.0390                            |  |
| $3\frac{1}{2}$                    | 4.5              | 0.22222       | 0.1423                  | 3.5000                 | 3.3577                     | 3.2154                 | 8.1200                            |  |
| $3\frac{3}{4}$                    | 4.5              | 0.22222       | 0.1423                  | 3.7500                 | 3.6077                     | 3.4654                 | 9.4320                            |  |
| 4                                 | 4.5              | 0.22222       | 0.1423                  | 4.0000                 | 3.8577                     | 3.7154                 | 10.8400                           |  |
| $4\frac{1}{4}$                    | 4                | 0.25000       | 0.1601                  | 4.2500                 | 4.0899                     | 3.9298                 | 12.1300                           |  |

<sup>a</sup>To be dispensed with wherever possible.<sup>b</sup>The use of number 2 BA threads is recommended in place of 3/16-inch BSF thread, see page 1885.



## PIPE AND HOSE THREADS

The types of threads used on pipe and pipe fittings may be classed according to their intended use: 1) threads that when assembled with a sealer will produce a pressure-tight joint; 2) threads that when assembled without a sealer will produce a pressure-tight joint; 3) threads that provide free- and loose-fitting mechanical joints without pressure tightness; and 4) threads that produce rigid mechanical joints without pressure tightness.

## American National Standard Pipe Threads

American National Standard pipe threads described in the following paragraphs provide taper and straight pipe threads for use in various combinations and with certain modifications to meet these specific needs.

**Thread Designation and Notation.**—American National Standard Pipe Threads are designated by specifying in sequence the nominal size, number of threads per inch, and the symbols for the thread series and form, as:  $\frac{3}{8}$ —18 NPT. The symbol designations are as follows: NPT—American National Standard Taper Pipe Thread; NPTR—American National Standard Taper Pipe Thread for Railing Joints; NPSC—American National Standard Straight Pipe Thread for Couplings; NPSM—American National Standard Straight Pipe Thread for Free-fitting Mechanical Joints; NPSL—American National Standard Straight Pipe Thread for Loose-fitting Mechanical Joints with Locknuts; and NPSH—American National Standard Straight Pipe Thread for Hose Couplings.

**American National Standard Taper Pipe Threads.**—The basic dimensions of the ANSI Standard taper pipe thread are given in [Table 1a](#).

*Form of Thread:* The angle between the sides of the thread is 60 degrees when measured in an axial plane, and the line bisecting this angle is perpendicular to the axis. The depth of the truncated thread is based on factors entering into the manufacture of cutting tools and the making of tight joints and is given by the formulas in [Table 1a](#) or the data in [Table 2](#) obtained from these formulas. Although the standard shows flat surfaces at the crest and root of the thread, some rounding may occur in commercial practice, and it is intended that the pipe threads of product shall be acceptable when crest and root of the tools or chasers lie within the limits shown in [Table 2](#).

*Pitch Diameter Formulas:* In the following formulas, which apply to the ANSI Standard taper pipe thread,  $E_0$  = pitch diameter at end of pipe;  $E_1$  = pitch diameter at the large end of the internal thread and at the gaging notch;  $D$  = outside diameter of pipe;  $L_1$  = length of hand-tight or normal engagement between external and internal threads;  $L_2$  = basic length of effective external taper thread; and  $p$  = pitch =  $1 \div$  number of threads per inch.

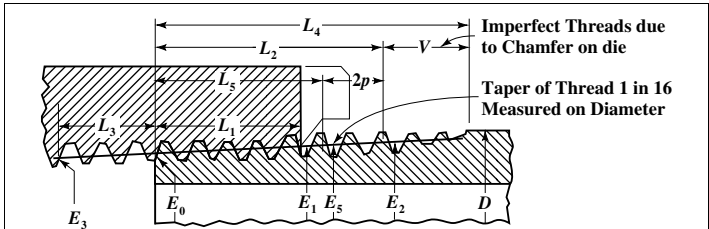
$$E_0 = D - (0.05D + 1.1)p$$

$$E_1 = E_0 + 0.0625L_1$$

*Thread Length:* The formula for  $L_2$  determines the length of the effective thread and includes approximately two usable threads that are slightly imperfect at the crest. The normal length of engagement,  $L_1$ , between external and internal taper threads, when assembled by hand, is controlled by the use of the gages.

$$L_2 = (0.80D + 6.8)p$$

*Taper:* The taper of the thread is 1 in 16, or 0.75 inch per foot, measured on the diameter and along the axis. The corresponding half-angle of taper or angle with the center line is 1 degree, 47 minutes.

**Table 1a. Basic Dimensions, American National Standard Taper Pipe Threads, NPT  
ANSI/ASME B1.20.1-1983 (R2001)**

For all dimensions, see corresponding reference letter in table.

Angle between sides of thread is 60 degrees. Taper of thread, on diameter, is  $\frac{3}{4}$  inch per foot. Angle of taper with center line is  $1^{\circ}47'$ .

The basic maximum thread height,  $h$ , of the truncated thread is  $0.8 \times$  pitch of thread. The crest and root are truncated a minimum of  $0.033 \times$  pitch for all pitches. For maximum depth of truncation, see Table 2.

| Nominal Pipe Size | Outside Dia. of Pipe, $D$ | Threads per Inch, $n$ | Pitch of Thread, $p$ | Pitch Diameter at Beginning of External Thread, $E_0$ | Handtight Engagement       |                          | Effective Thread, External |             |
|-------------------|---------------------------|-----------------------|----------------------|---|----------------------------|--------------------------|----------------------------|-------------|
|                   |                           |                       |                      |   | Length, <sup>a</sup> $L_1$ | Dia., <sup>b</sup> $E_1$ | Length, <sup>c</sup> $L_2$ | Dia., $E_2$ |
|                   |                           |                       |                      |   | Inch                       |                          | Inch                       |             |
| $\frac{1}{16}$    | 0.3125                    | 27                    | 0.03704              | 0.27118   | 0.160                      | 0.28118                  | 0.2611                     | 0.28750     |
| $\frac{1}{8}$     | 0.405                     | 27                    | 0.03704              | 0.36351   | 0.1615                     | 0.37360                  | 0.2639                     | 0.38000     |
| $\frac{1}{4}$     | 0.540                     | 18                    | 0.05556              | 0.47739   | 0.2278                     | 0.49163                  | 0.4018                     | 0.50250     |
| $\frac{3}{8}$     | 0.675                     | 18                    | 0.05556              | 0.61201   | 0.240                      | 0.62701                  | 0.4078                     | 0.63750     |
| $\frac{1}{2}$     | 0.840                     | 14                    | 0.07143              | 0.75843   | 0.320                      | 0.77843                  | 0.5337                     | 0.79179     |
| $\frac{3}{4}$     | 1.050                     | 14                    | 0.07143              | 0.96768   | 0.339                      | 0.98887                  | 0.5457                     | 1.00179     |
| 1                 | 1.315                     | $11\frac{1}{2}$       | 0.08696              | 1.21363   | 0.400                      | 1.23863                  | 0.6828                     | 1.25630     |
| $1\frac{1}{4}$    | 1.660                     | $11\frac{1}{2}$       | 0.08696              | 1.55713   | 0.420                      | 1.58338                  | 0.7068                     | 1.60130     |
| $1\frac{1}{2}$    | 1.900                     | $11\frac{1}{2}$       | 0.08696              | 1.79609   | 0.420                      | 1.82234                  | 0.7235                     | 1.84130     |
| 2                 | 2.375                     | $11\frac{1}{2}$       | 0.08696              | 2.26902   | 0.436                      | 2.29627                  | 0.7565                     | 2.31630     |
| $2\frac{1}{2}$    | 2.875                     | 8                     | 0.12500              | 2.71953   | 0.682                      | 2.76216                  | 1.1375                     | 2.79062     |
| 3                 | 3.500                     | 8                     | 0.12500              | 3.34062   | 0.766                      | 3.38850                  | 1.2000                     | 3.41562     |
| $3\frac{1}{2}$    | 4.000                     | 8                     | 0.12500              | 3.83750   | 0.821                      | 3.88881                  | 1.2500                     | 3.91562     |
| 4                 | 4.500                     | 8                     | 0.12500              | 4.33438   | 0.844                      | 4.38712                  | 1.3000                     | 4.41562     |
| 5                 | 5.563                     | 8                     | 0.12500              | 5.39073   | 0.937                      | 5.44929                  | 1.4063                     | 5.47862     |
| 6                 | 6.625                     | 8                     | 0.12500              | 6.44609   | 0.958                      | 6.50597                  | 1.5125                     | 6.54062     |
| 8                 | 8.625                     | 8                     | 0.12500              | 8.43359   | 1.063                      | 8.50003                  | 1.7125                     | 8.54062     |
| 10                | 10.750                    | 8                     | 0.12500              | 10.54531  | 1.210                      | 10.62094                 | 1.9250                     | 10.66562    |
| 12                | 12.750                    | 8                     | 0.12500              | 12.53281  | 1.360                      | 12.61781                 | 2.1250                     | 12.66562    |
| 14 OD             | 14.000                    | 8                     | 0.12500              | 13.77500  | 1.562                      | 13.87262                 | 2.2500                     | 13.91562    |
| 16 OD             | 16.000                    | 8                     | 0.12500              | 15.76250  | 1.812                      | 15.87575                 | 2.4500                     | 15.91562    |
| 18 OD             | 18.000                    | 8                     | 0.12500              | 17.75000  | 2.000                      | 17.87500                 | 2.6500                     | 17.91562    |
| 20 OD             | 20.000                    | 8                     | 0.12500              | 19.73750  | 2.125                      | 19.87031                 | 2.8500                     | 19.91562    |
| 24 OD             | 24.000                    | 8                     | 0.12500              | 23.71250  | 2.375                      | 23.86094                 | 3.2500                     | 23.91562    |

<sup>a</sup> Also length of thin ring gage and length from gaging notch to small end of plug gage.

<sup>b</sup> Also pitch diameter at gaging notch (handtight plane).

<sup>c</sup> Also length of plug gage.

**Table 1b. Basic Dimensions, American National Standard Taper Pipe Threads, NPT  
ANSI/ASME B1.20.1-1983 (R2001)**

| Nominal<br>Pipe<br>Size | Wrench Makeup Length<br>for Internal Thread |                | Vanish<br>Thread,<br>(3.47 thds.),<br>$V$ | Overall Length<br>External<br>Thread,<br>$L_4$ | Nominal Perfect<br>External Threads <sup>a</sup> |                | Height<br>of<br>Thread,<br>$h$ | Basic Minor<br>Dia. at Small<br>End of Pipe, <sup>b</sup><br>$K_0$ |
|-------------------------|---|----------------|---|--|--|----------------|--------------------------------|--|
|                         | Length, <sup>c</sup><br>$L_3$               | Dia.,<br>$E_3$ |   |  | Length,<br>$L_5$                                 | Dia.,<br>$E_5$ |                                |  |
| 1/16                    | 0.1111                                      | 0.26424        | 0.1285                                    | 0.3896   | 0.1870   | 0.28287        | 0.02963                        | 0.2416   |
| 1/8                     | 0.1111                                      | 0.35656        | 0.1285                                    | 0.3924   | 0.1898   | 0.37537        | 0.02963                        | 0.3339   |
| 1/4                     | 0.1667                                      | 0.46697        | 0.1928                                    | 0.5946   | 0.2907   | 0.49556        | 0.04444                        | 0.4329   |
| 3/8                     | 0.1667                                      | 0.60160        | 0.1928                                    | 0.6006   | 0.2967   | 0.63056        | 0.04444                        | 0.5676   |
| 1/2                     | 0.2143                                      | 0.74504        | 0.2478                                    | 0.7815   | 0.3909   | 0.78286        | 0.05714                        | 0.7013   |
| 3/4                     | 0.2143                                      | 0.95429        | 0.2478                                    | 0.7935   | 0.4029   | 0.99286        | 0.05714                        | 0.9105   |
| 1                       | 0.2609                                      | 1.19733        | 0.3017                                    | 0.9845   | 0.5089   | 1.24543        | 0.06957                        | 1.1441   |
| 1 1/4                   | 0.2609                                      | 1.54083        | 0.3017                                    | 1.0085   | 0.5329   | 1.59043        | 0.06957                        | 1.4876   |
| 1 1/2                   | 0.2609                                      | 1.77978        | 0.3017                                    | 1.0252   | 0.5496   | 1.83043        | 0.06957                        | 1.7265   |
| 2                       | 0.2609                                      | 2.25272        | 0.3017                                    | 1.0582   | 0.5826   | 2.30543        | 0.06957                        | 2.1995   |
| 2 1/2                   | 0.2500 <sup>d</sup>                         | 2.70391        | 0.4337                                    | 1.5712   | 0.8875   | 2.77500        | 0.100000                       | 2.6195   |
| 3                       | 0.2500 <sup>d</sup>                         | 3.32500        | 0.4337                                    | 1.6337   | 0.9500   | 3.40000        | 0.100000                       | 3.2406   |
| 3 1/2                   | 0.2500                                      | 3.82188        | 0.4337                                    | 1.6837   | 1.0000   | 3.90000        | 0.100000                       | 3.7375   |
| 4                       | 0.2500                                      | 4.31875        | 0.4337                                    | 1.7337   | 1.0500   | 4.40000        | 0.100000                       | 4.2344   |
| 5                       | 0.2500                                      | 5.37511        | 0.4337                                    | 1.8400   | 1.1563   | 5.46300        | 0.100000                       | 5.2907   |
| 6                       | 0.2500                                      | 6.43047        | 0.4337                                    | 1.9462   | 1.2625   | 6.52500        | 0.100000                       | 6.3461   |
| 8                       | 0.2500                                      | 8.41797        | 0.4337                                    | 2.1462   | 1.4625   | 8.52500        | 0.100000                       | 8.3336   |
| 10                      | 0.2500                                      | 10.52969       | 0.4337                                    | 2.3587   | 1.6750   | 10.65000       | 0.100000                       | 10.4453  |
| 12                      | 0.2500                                      | 12.51719       | 0.4337                                    | 2.5587   | 1.8750   | 12.65000       | 0.100000                       | 12.4328  |
| 14 OD                   | 0.2500                                      | 13.75938       | 0.4337                                    | 2.6837   | 2.0000   | 13.90000       | 0.100000                       | 13.6750  |
| 16 OD                   | 0.2500                                      | 15.74688       | 0.4337                                    | 2.8837   | 2.2000   | 15.90000       | 0.100000                       | 15.6625  |
| 18 OD                   | 0.2500                                      | 17.73438       | 0.4337                                    | 3.0837   | 2.4000   | 17.90000       | 0.100000                       | 17.6500  |
| 20 OD                   | 0.2500                                      | 19.72188       | 0.4337                                    | 3.2837   | 2.6000   | 19.90000       | 0.100000                       | 19.6375  |
| 24 OD                   | 0.2500                                      | 23.69688       | 0.4337                                    | 3.6837   | 3.0000   | 23.90000       | 0.100000                       | 23.6125  |

<sup>a</sup>The length  $L_5$  from the end of the pipe determines the plane beyond which the thread form is imperfect at the crest. The next two threads are perfect at the root. At this plane the cone formed by the crests of the thread intersects the cylinder forming the external surface of the pipe.  $L_5 = L_2 - 2p$ .

<sup>b</sup>Given as information for use in selecting tap drills.

<sup>c</sup>Three threads for 2-inch size and smaller; two threads for larger sizes.

<sup>d</sup>Military Specification MIL—P—7105 gives the wrench makeup as three threads for 3 in. and smaller. The  $E_3$  dimensions are then as follows: Size 2 1/2 in., 2.69609 and size 3 in., 3.31719.

All dimensions given in inches.

Increase in diameter per thread is equal to  $0.0625/n$ .

The basic dimensions of the ANSI Standard Taper Pipe Thread are given in inches to four or five decimal places. While this implies a greater degree of precision than is ordinarily attained, these dimensions are the basis of gage dimensions and are so expressed for the purpose of eliminating errors in computations.

**Engagement Between External and Internal Taper Threads.**—The normal length of engagement between external and internal taper threads when screwed together handtight is shown as  $L_1$  in Table 1a. This length is controlled by the construction and use of the pipe thread gages. It is recognized that in special applications, such as flanges for high-pressure work, longer thread engagement is used, in which case the pitch diameter  $E_1$  (Table 1a) is maintained and the pitch diameter  $E_0$  at the end of the pipe is proportionately smaller.

**Tolerances on Thread Elements.**—The maximum allowable variation in the commercial product (manufacturing tolerance) is one turn large or small from the basic dimensions.

The permissible variations in thread elements on steel products and all pipe made of steel, wrought iron, or brass, exclusive of butt-weld pipe, are given in Table 3. This table is a

guide for establishing the limits of the thread elements of taps, dies, and thread chasers. These limits may be required on product threads.

On pipe fittings and valves (not steel) for steam pressures 300 pounds and below, it is intended that plug and ring gage practice as set up in the Standard ANSI/ASME B1.20.1 will provide for a satisfactory check of accumulated variations of taper, lead, and angle in such product. Therefore, no tolerances on thread elements have been established for this class.

For service conditions where a more exact check is required, procedures have been developed by industry to supplement the regulation plug and ring method of gaging.

**Table 2. Limits on Crest and Root of American National Standard External and Internal Taper Pipe Threads, NPT ANSI/ASME B1.20.1-1983 (R2001)**

| INTERNAL THREAD  |                               |                            |         |                 |        |   |        |
|------------------|-------------------------------|----------------------------|---------|-----------------|--------|---|--------|
|                  |                               |                            |         |                 |        |   |        |
| EXTERNAL THREAD  |                               |                            |         |                 |        |   |        |
| Threads per Inch | Height of Sharp V Thread, $H$ | Height of Pipe Thread, $h$ |         | Truncation, $f$ |        | Width of Flat, $F$ , Equivalent to Truncation |        |
|                  |                               | Max.                       | Min.    | Min.            | Max.   | Min.  | Max.   |
| 27               | 0.03208                       | 0.02963                    | 0.02496 | 0.0012          | 0.0036 | 0.0014  | 0.0041 |
| 18               | 0.04811                       | 0.04444                    | 0.03833 | 0.0018          | 0.0049 | 0.0021  | 0.0057 |
| 14               | 0.06186                       | 0.05714                    | 0.05071 | 0.0024          | 0.0056 | 0.0027  | 0.0064 |
| 11½              | 0.07531                       | 0.06957                    | 0.06261 | 0.0029          | 0.0063 | 0.0033  | 0.0073 |
| 8                | 0.10825                       | 0.10000                    | 0.09275 | 0.0041          | 0.0078 | 0.0048  | 0.0090 |

All dimensions are in inches and are given to four or five decimal places only to avoid errors in computations, not to indicate required precision.

**Table 3. Tolerances on Taper, Lead, and Angle of Pipe Threads of Steel Products and All Pipe of Steel, Wrought Iron, or Brass ANSI/ASME B1.20.1-1983 (R2001) (Exclusive of Butt-Weld Pipe)**

| Nominal Pipe Size            | Threads per Inch | Taper on Pitch Line ( $\frac{1}{4}$ in./ft) |                 | Lead in Length of Effective Threads | 60 Degree Angle of Threads, Degrees |
|------------------------------|------------------|---|-----------------|-------------------------------------|-------------------------------------|
|                              |                  | Max.  | Min.            |                                     |                                     |
| $\frac{1}{16}$ $\frac{1}{8}$ | 27               | $+\frac{1}{8}$                              | $-\frac{1}{16}$ | $\pm 0.003$                         | $\pm 2\frac{1}{2}$                  |
| $\frac{1}{4}$ $\frac{3}{8}$  | 18               | $+\frac{1}{8}$                              | $-\frac{1}{16}$ | $\pm 0.003$                         | $\pm 2$                             |
| $\frac{1}{2}$ $\frac{3}{4}$  | 14               | $+\frac{1}{8}$                              | $-\frac{1}{16}$ | $\pm 0.003^a$                       | $\pm 2$                             |
| 1, 1¼, 1½, 2                 | 11½              | $+\frac{1}{8}$                              | $-\frac{1}{16}$ | $\pm 0.003^a$                       | $\pm 1\frac{1}{2}$                  |
| 2½ and larger                | 8                | $+\frac{1}{8}$                              | $-\frac{1}{16}$ | $\pm 0.003^a$                       | $\pm 1\frac{1}{2}$                  |

<sup>a</sup>The tolerance on lead shall be  $\pm 0.003$  in. per inch on any size threaded to an effective thread length greater than 1 in.

For tolerances on height of thread, see Table 2.

The limits specified in this table are intended to serve as a guide for establishing limits of the thread elements of taps, dies, and thread chasers. These limits may be required on product threads.

**Table 4. Internal Threads in Pipe Couplings, NPSC for Pressure-tight Joints with Lubricant or Sealer ANSI/ASME B1.20.1-1983 (R2001)**

| Nom. Pipe-Size | Thds. per Inch | Minor <sup>a</sup> Dia. | Pitch Diameter <sup>b</sup> |        | Nom. Pipe | Thds. per Inch | Minor <sup>a</sup> Dia. | Pitch Diameter <sup>b</sup> |        |
|----------------|----------------|-------------------------|-----------------------------|--------|-----------|----------------|-------------------------|-----------------------------|--------|
|                |                |                         | Min.                        | Max.   |           |                |                         | Min.                        | Max.   |
| 1/8            | 27             | 0.340                   | 0.3701                      | 0.3771 | 1 1/2     | 11 1/2         | 1.745                   | 1.8142                      | 1.8305 |
| 1/4            | 18             | 0.442                   | 0.4864                      | 0.4968 | 2         | 11 1/2         | 2.219                   | 2.2881                      | 2.3044 |
| 3/8            | 18             | 0.577                   | 0.6218                      | 0.6322 | 2 1/2     | 8              | 2.650                   | 2.7504                      | 2.7739 |
| 1/2            | 14             | 0.715                   | 0.7717                      | 0.7851 | 3         | 8              | 3.277                   | 3.3768                      | 3.4002 |
| 3/4            | 14             | 0.925                   | 0.9822                      | 0.9956 | 3 1/2     | 8              | 3.777                   | 3.8771                      | 3.9005 |
| 1              | 11 1/2         | 1.161                   | 1.2305                      | 1.2468 | 4         | 8              | 4.275                   | 4.3754                      | 4.3988 |
| 1 1/4          | 11 1/2         | 1.506                   | 1.5752                      | 1.5915 | ...       | ...            | ...                     | ...                         | ...    |

<sup>a</sup> As the ANSI Standard Pipe Thread form is maintained, the major and minor diameters of the internal thread vary with the pitch diameter. All dimensions are given in inches.

<sup>b</sup> The actual pitch diameter of the straight tapped hole will be slightly smaller than the value given when gaged with a taper plug gage as called for in ANSI/ASME B1.20.1.

**Railing Joint Taper Pipe Threads, NPTR.**—Railing joints require a rigid mechanical thread joint with external and internal taper threads. The external thread is basically the same as the ANSI Standard Taper Pipe Thread, except that sizes 1/2 through 2 inches are shortened by 3 threads and sizes 2 1/2 through 4 inches are shortened by 4 threads to permit the use of the larger end of the pipe thread. A recess in the fitting covers the last scratch or imperfect threads on the pipe.

**Straight Pipe Threads in Pipe Couplings, NPSC.**—Threads in pipe couplings made in accordance with the ANSI/ASME B1.20.1 specifications are straight (parallel) threads of the same thread form as the ANSI Standard Taper Pipe Thread. They are used to form pressure-tight joints when assembled with an ANSI Standard external taper pipe thread and made up with lubricant or sealant. These joints are recommended for comparatively low pressures only.

**Straight Pipe Threads for Mechanical Joints, NPSM, NPSL, and NPSH.**—While external and internal taper pipe threads are recommended for pipe joints in practically every service, there are mechanical joints where straight pipe threads are used to advantage. Three types covered by ANSI/ASME B1.20.1 are:

*Loose-fitting Mechanical Joints With Locknuts (External and Internal), NPSL:* This thread is designed to produce a pipe thread having the largest diameter that it is possible to cut on standard pipe. The dimensions of these threads are given in Table 5. It will be noted that the maximum major diameter of the external thread is slightly greater than the nominal outside diameter of the pipe. The normal manufacturer's variation in pipe diameter provides for this increase.

*Loose-fitting Mechanical Joints for Hose Couplings (External and Internal), NPSH:*

Hose coupling joints are ordinarily made with straight internal and external loose-fitting threads. There are several standards of hose threads having various diameters and pitches. One of these is based on the ANSI Standard pipe thread and by the use of this thread series, it is possible to join small hose couplings in sizes 1/2 to 4 inches, inclusive, to ends of standard pipe having ANSI Standard External Pipe Threads, using a gasket to seal the joints. For the hose coupling thread dimensions see *ANSI Standard Hose Coupling Screw Threads* starting on page 1872.

*Free-fitting Mechanical Joints for Fixtures (External and Internal), NPSM:* Standard iron, steel, and brass pipe are often used for special applications where there are no internal pressures. Where straight thread joints are required for mechanical assemblies, straight pipe threads are often found more suitable or convenient. Dimensions of these threads are given in Table 5.

**Table 5. American National Standard Straight Pipe Threads for Mechanical Joints, NPSM and NPSL ANSI/ASME B1.20.1-1983 (R2001)**

| Nominal Pipe Size  | Threads per Inch | Allowance | External Thread   |       |                |         | Internal Thread   |       |                   |         |
|--|------------------|-----------|-------------------|-------|----------------|---------|-------------------|-------|-------------------|---------|
|  |                  |           | Major Diameter    |       | Pitch Diameter |         | Minor Diameter    |       | Pitch Diameter    |         |
|  |                  |           | Max. <sup>a</sup> | Min.  | Max.           | Min.    | Min. <sup>a</sup> | Max.  | Min. <sup>b</sup> | Max.    |
| Free-fitting Mechanical Joints for Fittings—NPSM             |                  |           |                   |       |                |         |                   |       |                   |         |
| 1/8  | 27               | 0.0011    | 0.397             | 0.390 | 0.3725         | 0.3689  | 0.358             | 0.364 | 0.3736            | 0.3783  |
| 1/4  | 18               | 0.0013    | 0.526             | 0.517 | 0.4903         | 0.4859  | 0.468             | 0.481 | 0.4916            | 0.4974  |
| 3/8  | 18               | 0.0014    | 0.662             | 0.653 | 0.6256         | 0.6211  | 0.603             | 0.612 | 0.6270            | 0.6329  |
| 1/2  | 14               | 0.0015    | 0.823             | 0.813 | 0.7769         | 0.7718  | 0.747             | 0.759 | 0.7784            | 0.7851  |
| 3/4  | 14               | 0.0016    | 1.034             | 1.024 | 0.9873         | 0.9820  | 0.958             | 0.970 | 0.9889            | 0.9958  |
| 1  | 11 1/2           | 0.0017    | 1.293             | 1.281 | 1.2369         | 1.2311  | 1.201             | 1.211 | 1.2386            | 1.2462  |
| 1 1/4  | 11 1/2           | 0.0018    | 1.638             | 1.626 | 1.5816         | 1.5756  | 1.546             | 1.555 | 1.5834            | 1.5912  |
| 1 1/2  | 11 1/2           | 0.0018    | 1.877             | 1.865 | 1.8205         | 1.8144  | 1.785             | 1.794 | 1.8223            | 1.8302  |
| 2  | 11 1/2           | 0.0019    | 2.351             | 2.339 | 2.2944         | 2.2882  | 2.259             | 2.268 | 2.2963            | 2.3044  |
| 2 1/2  | 8                | 0.0022    | 2.841             | 2.826 | 2.7600         | 2.7526  | 2.708             | 2.727 | 2.7622            | 2.7720  |
| 3  | 8                | 0.0023    | 3.467             | 3.452 | 3.3862         | 3.3786  | 3.334             | 3.353 | 3.3885            | 3.3984  |
| 3 1/2  | 8                | 0.0023    | 3.968             | 3.953 | 3.8865         | 3.8788  | 3.835             | 3.848 | 3.8888            | 3.8988  |
| 4  | 8                | 0.0023    | 4.466             | 4.451 | 4.3848         | 4.3771  | 4.333             | 4.346 | 4.3871            | 4.3971  |
| 5  | 8                | 0.0024    | 5.528             | 5.513 | 5.4469         | 5.4390  | 5.395             | 5.408 | 5.4493            | 5.4598  |
| 6  | 8                | 0.0024    | 6.585             | 6.570 | 6.5036         | 6.4955  | 6.452             | 6.464 | 6.5060            | 6.5165  |
| Loose-fitting Mechanical Joints for Locknut Connections—NPSL |                  |           |                   |       |                |         |                   |       |                   |         |
| 1/8  | 27               | ...       | 0.409             | ...   | 0.3840         | 0.3805  | 0.362             | ...   | 0.3863            | 0.3898  |
| 1/4  | 18               | ...       | 0.541             | ...   | 0.5038         | 0.4986  | 0.470             | ...   | 0.5073            | 0.5125  |
| 3/8  | 18               | ...       | 0.678             | ...   | 0.6409         | 0.6357  | 0.607             | ...   | 0.6444            | 0.6496  |
| 1/2  | 14               | ...       | 0.844             | ...   | 0.7963         | 0.7896  | 0.753             | ...   | 0.8008            | 0.8075  |
| 3/4  | 14               | ...       | 1.054             | ...   | 1.0067         | 1.0000  | 0.964             | ...   | 1.0112            | 1.0179  |
| 1  | 11 1/2           | ...       | 1.318             | ...   | 1.2604         | 1.2523  | 1.208             | ...   | 1.2658            | 1.2739  |
| 1 1/4  | 11 1/2           | ...       | 1.663             | ...   | 1.6051         | 1.5970  | 1.553             | ...   | 1.6106            | 1.6187  |
| 1 1/2  | 11 1/2           | ...       | 1.902             | ...   | 1.8441         | 1.8360  | 1.792             | ...   | 1.8495            | 1.8576  |
| 2  | 11 1/2           | ...       | 2.376             | ...   | 2.3180         | 2.3099  | 2.265             | ...   | 2.3234            | 2.3315  |
| 2 1/2  | 8                | ...       | 2.877             | ...   | 2.7934         | 2.7817  | 2.718             | ...   | 2.8012            | 2.8129  |
| 3  | 8                | ...       | 3.503             | ...   | 3.4198         | 3.4081  | 3.344             | ...   | 3.4276            | 3.4393  |
| 3 1/2  | 8                | ...       | 4.003             | ...   | 3.9201         | 3.9084  | 3.845             | ...   | 3.9279            | 3.9396  |
| 4  | 8                | ...       | 4.502             | ...   | 4.4184         | 4.4067  | 4.343             | ...   | 4.4262            | 4.4379  |
| 5  | 8                | ...       | 5.564             | ...   | 5.4805         | 5.4688  | 5.405             | ...   | 5.4884            | 5.5001  |
| 6  | 8                | ...       | 6.620             | ...   | 6.5372         | 6.5255  | 6.462             | ...   | 6.5450            | 6.5567  |
| 8  | 8                | ...       | 8.615             | ...   | 8.5313         | 8.5196  | 8.456             | ...   | 8.5391            | 8.5508  |
| 10   | 8                | ...       | 10.735            | ...   | 10.6522        | 10.6405 | 10.577            | ...   | 10.6600           | 10.6717 |
| 12   | 8                | ...       | 12.732            | ...   | 12.6491        | 12.6374 | 12.574            | ...   | 12.6569           | 12.6686 |

<sup>a</sup> As the ANSI Standard Straight Pipe Thread form of thread is maintained, the major and the minor diameters of the internal thread and the minor diameter of the external thread vary with the pitch diameter. The major diameter of the external thread is usually determined by the diameter of the pipe. These theoretical diameters result from adding the depth of the truncated thread ( $0.666025 \times p$ ) to the maximum pitch diameters, and it should be understood that commercial pipe will not always have these maximum major diameters.

<sup>b</sup> This is the same as the pitch diameter at end of internal thread,  $E_1$  Basic. (See Table 1a.)

All dimensions are given in inches.

*Notes for Free-fitting Fixture Threads:* The minor diameters of external threads and major diameters of internal threads are those as produced by commercial straight pipe dies and commercial ground straight pipe taps.

The major diameter of the external thread has been calculated on the basis of a truncation of  $0.10825p$ , and the minor diameter of the internal thread has been calculated on the basis of a truncation of  $0.21651p$ , to provide no interference at crest and root when product is gaged with gages made in accordance with the Standard.

*Notes for Loose-fitting Locknut Threads:* The locknut thread is established on the basis of retaining the greatest possible amount of metal thickness between the bottom of the thread and the inside of the pipe. In order that a locknut may fit loosely on the externally threaded part, an allowance equal to the "increase in pitch diameter per turn" is provided, with a tolerance of  $1\frac{1}{2}$  turns for both external and internal threads.

**American National Standard Dryseal Pipe Threads for Pressure-Tight Joints.—**

Dryseal pipe threads are based on the USA (American) pipe thread; however, they differ in that they are designed to seal pressure-tight joints without the necessity of using sealing compounds. To accomplish this, some modification of thread form and greater accuracy in manufacture is required. The roots of both the external and internal threads are truncated slightly more than the crests, i.e., roots have wider flats than crests so that metal-to-metal contact occurs at the crests and roots coincident with, or prior to, flank contact. Thus, as the threads are assembled by wrenching, the roots of the threads crush the sharper crests of the mating threads. This sealing action at both major and minor diameters tends to prevent spiral leakage and makes the joints pressure-tight without the necessity of using sealing compounds, provided that the threads are in accordance with standard specifications and tolerances and are not damaged by galling in assembly. The control of crest and root truncation is simplified by the use of properly designed threading tools. Also, it is desirable that both external and internal threads have full thread height for the length of hand engagement. Where not functionally objectionable, the use of a compatible lubricant or sealant is permissible to minimize the possibility of galling. This is desirable in assembling Dryseal pipe threads in refrigeration and other systems to effect a pressure-tight seal. The crest and root of Dryseal pipe threads may be slightly rounded, but are acceptable if they lie within the truncation limits given in Table 6.

**Table 6. American National Standard Dryseal Pipe Threads—Limits on Crest and Root Truncation ANSI B1.20.3-1976 (R1998)**

| Threads Per Inch | Height of Sharp V Thread ( $H$ ) | Truncation |        |           |        |           |        |           |        |
|------------------|----------------------------------|------------|--------|-----------|--------|-----------|--------|-----------|--------|
|                  |                                  | Minimum    |        |           |        | Maximum   |        |           |        |
|                  |                                  | At Crest   |        | At Root   |        | At Crest  |        | At Root   |        |
|                  |                                  | Formula    | Inch   | Formula   | Inch   | Formula   | Inch   | Formula   | Inch   |
| 27               | 0.03208                          | 0.047 $p$  | 0.0017 | 0.094 $p$ | 0.0035 | 0.094 $p$ | 0.0035 | 0.140 $p$ | 0.0052 |
| 18               | 0.04811                          | 0.047 $p$  | 0.0026 | 0.078 $p$ | 0.0043 | 0.078 $p$ | 0.0043 | 0.109 $p$ | 0.0061 |
| 14               | 0.06180                          | 0.036 $p$  | 0.0026 | 0.060 $p$ | 0.0043 | 0.060 $p$ | 0.0043 | 0.085 $p$ | 0.0061 |
| 11½              | 0.07531                          | 0.040 $p$  | 0.0035 | 0.060 $p$ | 0.0052 | 0.060 $p$ | 0.0052 | 0.090 $p$ | 0.0078 |
| 8                | 0.10825                          | 0.042 $p$  | 0.0052 | 0.055 $p$ | 0.0069 | 0.055 $p$ | 0.0069 | 0.076 $p$ | 0.0095 |

All dimensions are given in inches. In the formulas,  $p$  = pitch.

**Types of Dryseal Pipe Thread.—**American National Standard ANSI B1.20.3-1976 (R1998) covers four types of standard Dryseal pipe threads:

NPTF, Dryseal USA (American) Standard Taper Pipe Thread

PTF-SAE SHORT, Dryseal SAE Short Taper Pipe Thread

NPSF, Dryseal USA (American) Standard Fuel Internal Straight Pipe Thread

NPSI, Dryseal USA (American) Standard Intermediate Internal Straight Pipe Thread

**Table 7. Recommended Limitation of Assembly among the Various Types of Dryseal Threads**

| External Dryseal Thread |                                 | For Assembly with Internal Dryseal Thread |                                  |
|-------------------------|---------------------------------|---|----------------------------------|
| Type                    | Description                     | Type                                      | Description                      |
| 1                       | NPTF (tapered), ext thd         | 1   | NPTF (tapered), int thd          |
|                         |                                 | 2 <sup>a,b</sup>                          | PTF-SAE SHORT (tapered), int thd |
|                         |                                 | 3 <sup>a,c</sup>                          | NPSF (straight), int thd         |
|                         |                                 | 4 <sup>a,c,d</sup>                        | NPSI (straight), int thd         |
| 2 <sup>a,c</sup>        | PTF-SAE SHORT (tapered) ext thd | 4   | NPSI (straight), int thd         |
|                         |                                 | 1   | NPTF (tapered), int thd          |

<sup>a</sup> Pressure-tight joints without the use of a sealant can best be ensured where both components are threaded with NPTF (full length threads), since theoretically interference (sealing) occurs at all threads, but there are two less threads engaged than for NPTF assemblies. When straight internal threads are used, there is interference only at one thread depending on ductility of materials.

<sup>b</sup>PTF-SAE SHORT internal threads are primarily intended for assembly with type 1-NPTF external threads. They are not designed for, and at extreme tolerance limits may not assemble with, type 2-PTF-SAE SHORT external threads.

<sup>c</sup>There is no external straight Dryseal thread.

<sup>d</sup>NPSI internal threads are primarily intended for assembly with type 2-PTF-SAE SHORT external threads but will also assemble with full length type 1 NPTF external threads.

<sup>e</sup>PTF-SAE SHORT external threads are primarily intended for assembly with type 4-NPSI internal threads but can also be used with type 1-NPTF internal threads. They are not designed for, and at extreme tolerance limits may not assemble with, type 2-PTF-SAE SHORT internal threads or type 3-NPSF internal threads.

An assembly with straight internal pipe threads and taper external pipe threads is frequently more advantageous than an all taper thread assembly, particularly in automotive and other allied industries where economy and rapid production are major considerations. Dryseal threads are not used in assemblies in which both components have straight pipe threads.

*NPTF Threads:* This type applies to both external and internal threads and is suitable for pipe joints in practically every type of service. Of all Dryseal pipe threads, NPTF external and internal threads mated are generally conceded to be superior for strength and seal since they have the longest length of thread and, theoretically, interference (sealing) occurs at every engaged thread root and crest. Use of tapered internal threads, such as NPTF or PTF-SAE SHORT in hard or brittle materials having thin sections will minimize the possibility of fracture.

There are two classes of NPTF threads. Class 1 threads are made to interfere (seal) at root and crest when mated, but inspection of crest and root truncation is not required. Consequently, Class 1 threads are intended for applications where close control of tooling is required for conformance of truncation or where sealing is accomplished by means of a sealant applied to the threads.

Class 2 threads are theoretically identical to those made to Class 1, however, inspection of root and crest truncation is required. Consequently, where a sealant is not used, there is more assurance of a pressure-tight seal for Class 2 threads than for Class 1 threads.

*PTF-SAE SHORT Threads:* External threads of this type conform in all respects with NPTF threads except that the thread length has been shortened by eliminating one thread from the small (entering) end. These threads are designed for applications where clearance is not sufficient for the full length of the NPTF threads or for economy of material where the full thread length is not necessary.

Internal threads of this type conform in all respects with NPTF threads, except that the thread length has been shortened by eliminating one thread from the large (entry) end. These threads are designed for thin materials where thickness is not sufficient for the full thread length of the NPTF threads or for economy in tapping where the full thread length is not necessary.

Pressure-tight joints without the use of lubricant or sealer can best be ensured where mating components are both threaded with NPTF threads. This should be considered before specifying PTF-SAE SHORT external or internal threads.

*NPSF Threads:* Threads of this type are straight (cylindrical) instead of tapered and are internal only. They are more economical to produce than tapered internal threads, but when assembled do not offer as strong a guarantee of sealing since root and crest interference will not occur for all threads. NPSF threads are generally used with soft or ductile materials which will tend to adjust at assembly to the taper of external threads, but may be used in hard or brittle materials where the section is thick.

*NPSI Threads:* Threads of this type are straight (cylindrical) instead of tapered, are internal only and are slightly larger in diameter than NPSF threads but have the same tolerance and thread length. They are more economical to produce than tapered threads and may be used in hard or brittle materials where the section is thick or where there is little expansion at assembly with external taper threads. As with NPSF threads, NPSI threads when assembled do not offer as strong a guarantee of sealing as do tapered internal threads.



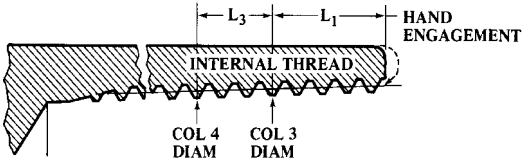
DRYSEAL PIPE THREADS

For more complete specifications for production and acceptance of Dryseal pipe threads, see ANSI B1.20.3 (Inch) and ANSI B1.20.4 (Metric Translation), and for gaging and inspection, see ANSI B1.20.5 (Inch) and ANSI B1.20.6M (Metric Translation).

*Designation of Dryseal Pipe Threads:* The standard Dryseal pipe threads are designated by specifying in sequence nominal size, thread series symbol, and class:

*Examples:* 1/8-27 NPTF-1; 1/8-27 PTF-SAE SHORT; and 3/8-18 NPTF-1 AFTER PLATING.

**Table 8. Suggested Tap Drill Sizes for Internal Dryseal Pipe Threads**



| Size         | Probable Drill Oversize Cut (Mean) | Taper Pipe Thread             |  |                         |                 | Straight Pipe Thread |        |                         |
|--------------|------------------------------------|-------------------------------|--|-------------------------|-----------------|----------------------|--------|-------------------------|
|              |                                    | Minor Diameter At Distance    |  | Drill Size <sup>a</sup> |                 | Minor Diameter       |        | Drill Size <sup>a</sup> |
|              |                                    | L <sub>1</sub> From Large End | L <sub>1</sub> + L <sub>3</sub> From Large End | Without Reamer          | With Reamer     | NPSF                 | NPSI   |                         |
| 1/16-27      | 0.0038                             | 0.2443                        | 0.2374   | "C" (0.242)             | "A" (0.234)     | 0.2482               | 0.2505 | "D" (0.246)             |
| 1/8-27       | 0.0044                             | 0.3367                        | 0.3298   | "Q" (0.332)             | 21/64 (0.328)   | 0.3406               | 0.3429 | "R" (0.339)             |
| 1/4-18       | 0.0047                             | 0.4362                        | 0.4258   | 7/16 (0.438)            | 27/64 (0.422)   | 0.4422               | 0.4457 | 7/16 (0.438)            |
| 3/8-18       | 0.0049                             | 0.5708                        | 0.5604   | 9/16 (0.562)            | 9/16 (0.563)    | 0.5776               | 0.5811 | 37/64 (0.578)           |
| 1/2-14       | 0.0051                             | 0.7034                        | 0.6901   | 45/64 (0.703)           | 11/16 (0.688)   | 0.7133               | 0.7180 | 45/64 (0.703)           |
| 3/4-14       | 0.0060                             | 0.9127                        | 0.8993   | 29/32 (0.906)           | 57/64 (0.891)   | 0.9238               | 0.9283 | 59/64 (0.922)           |
| 1-11 1/2     | 0.0080                             | 1.1470                        | 1.1307   | 1 1/64 (1.141)          | 1 1/8 (1.125)   | 1.1600               | 1.1655 | 1 5/32 (1.156)          |
| 1 1/4-11 1/2 | 0.0100                             | 1.4905                        | 1.4742   | 1 31/64 (1.484)         | 1 15/32 (1.469) | ...                  | ...    | ...                     |
| 1 1/2-11 1/2 | 0.0120                             | 1.7295                        | 1.7132   | 1 23/32 (1.719)         | 1 45/64 (1.703) | ...                  | ...    | ...                     |
| 2-11 1/2     | 0.0160                             | 2.2024                        | 2.1861   | 2 3/16 (2.188)          | 2 11/64 (2.172) | ...                  | ...    | ...                     |
| 2 1/2-8      | 0.0180                             | 2.6234                        | 2.6000   | 2 39/64 (2.609)         | 2 27/64 (2.578) | ...                  | ...    | ...                     |
| 3-8          | 0.0200                             | 3.2445                        | 3.2211   | 3 15/64 (3.234)         | 3 13/64 (3.203) | ...                  | ...    | ...                     |

<sup>a</sup> Some drill sizes listed may not be standard drills.

All dimensions are given in inches.

**Special Dryseal Threads.**—Where design limitations, economy of material, permanent installation, or other limiting conditions prevail, consideration may be given to using a special Dryseal thread series.

*Dryseal Special Short Taper Pipe Thread, PTF-SPL SHORT:* Threads of this series conform in all respects to PTF-SAE SHORT threads except that the full thread length has been further shortened by eliminating one thread at the small end of internal threads or one thread at the large end of external threads.

*Dryseal Special Extra Short Taper Pipe Thread, PTF-SPL EXTRA SHORT:* Threads of this series conform in all respects to PTF-SAE SHORT threads except that the full thread length has been further shortened by eliminating two threads at the small end of internal threads or two threads at the large end of external threads.

*Limitations of Assembly:* Table 9 applies where Dryseal Special Short or Extra Short Taper Pipe Threads are to be assembled as special combinations.

**Table 9. Assembly Limitations for Special Combinations of Dryseal Threads**

| Thread   | May Assemble with <sup>a</sup>  | May Assemble with <sup>b</sup> |
|--|---|--------------------------------|
| PTF SPL SHORT EXTERNAL<br>PTF SPL EXTRA SHORT EXTERNAL | PTF-SAE SHORT INTERNAL<br>NPSF INTERNAL<br>PTF SPL SHORT INTERNAL<br>PTF SPL EXTRA SHORT INTERNAL | NPTF or NPSI INTERNAL          |
| PTF SPL SHORT INTERNAL<br>PTF SPL EXTRA SHORT INTERNAL | PTF-SAE SHORT EXTERNAL  | NPTF EXTERNAL                  |

<sup>a</sup> Only when the external thread or the internal thread or both are held closer than the standard tolerance, the external thread toward the minimum and the internal thread toward the maximum pitch diameter to provide a minimum of one turn hand engagement. At extreme tolerance limits the shortened full-thread lengths reduce hand engagement and the threads may not start to assemble.

<sup>b</sup> Only when the internal thread or the external thread or both are held closer than the standard tolerance, the internal thread toward the minimum and the external thread toward the maximum pitch diameter to provide a minimum of two turns for wrench make-up and sealing. At extreme tolerance limits the shortened full-thread lengths reduce wrench make-up and the threads may not seal.

*Dryseal Fine Taper Thread Series, F-PTF:* The need for finer pitches for nominal pipe sizes has brought into use applications of 27 threads per inch to  $\frac{1}{4}$ - and  $\frac{3}{8}$ -inch pipe sizes. There may be other needs that require finer pitches for larger pipe sizes. It is recommended that the existing threads per inch be applied to the next larger pipe size for a fine thread series, thus:  $\frac{1}{4}$ -27,  $\frac{3}{8}$ -27,  $\frac{1}{2}$ -18,  $\frac{3}{4}$ -18, 1-14,  $1\frac{1}{4}$ -14,  $1\frac{1}{2}$ -14, and 2-14. This series applies to external and internal threads of full length and is suitable for applications where threads finer than NPTF are required.

*Dryseal Special Diameter-Pitch Combination Series, SPL-PTF:* Other applications of diameter-pitch combinations have come into use where taper pipe threads are applied to nominal size thin wall tubing. These combinations are:  $\frac{1}{2}$ -27,  $\frac{5}{8}$ -27,  $\frac{3}{4}$ -27,  $\frac{7}{8}$ -27, and 1-27. This series applies to external and internal threads of full length and is applicable to thin wall nominal diameter outside tubing.

*Designation of Special Dryseal Pipe Threads:* The designations used for these special dryseal pipe threads are as follows:

$\frac{1}{8}$ -27 PTF-SPL SHORT

$\frac{1}{8}$ -27 PTF-SPL EXTRA SHORT

$\frac{1}{2}$ -27 SPL PTF, OD 0.500

Note that in the last designation the OD of tubing is given.

### British Standard Pipe Threads

**British Standard Pipe Threads for Non-pressure-tight Joints.**—The threads in BS 2779:1973, “Specifications for Pipe Threads where Pressure-tight Joints are not Made on the Threads”, are Whitworth form parallel fastening threads that are generally used for fastening purposes such as the mechanical assembly of component parts of fittings, cocks and valves. They are not suitable where pressure-tight joints are made on the threads.

The crests of the basic Whitworth thread form may be truncated to certain limits of size given in the Standard except on internal threads, when they are likely to be assembled with external threads conforming to the requirements of BS 21 “British Standard Pipe Threads for Pressure-tight Joints” (see page 1870).

For external threads two classes of tolerance are provided and for internal, one class. The two classes of tolerance for external threads are Class A and Class B. For economy of manufacture the class B fit should be chosen whenever possible. The class A is reserved for those applications where the closer tolerance is essential. Class A tolerance is an entirely negative value, equivalent to the internal thread tolerance. Class B tolerance is an entirely negative value twice that of class A tolerance. Tables showing limits and dimensions are given in the Standard.

The thread series specified in this Standard shall be designated by the letter "G". A typical reference on a drawing might be "G $\frac{1}{2}$ ", for internal thread; "G $\frac{1}{2}$ A", for external thread, class A; and "G  $\frac{1}{2}$  B", for external thread, class B. Where no class reference is stated for external threads, that of class B will be assumed. The designation of truncated threads shall have the addition of the letter "T" to the designation, i.e., G  $\frac{1}{2}$ T and G  $\frac{1}{2}$ BT.

**British Standard Pipe Threads (Non-pressure-tight Joints)  
Metric and Inch Basic Sizes BS 2779:1973**

| Nominal Size, Inches | Threads per Inch <sup>a</sup> | Depth of Thread | Major Diameter | Pitch Diameter | Minor Diameter | Nominal Size, Inches | Threads per Inch <sup>a</sup> | Depth of Thread | Major Diameter | Pitch Diameter | Minor Diameter |
|----------------------|-------------------------------|-----------------|----------------|----------------|----------------|----------------------|-------------------------------|-----------------|----------------|----------------|----------------|
| $\frac{1}{16}$       | 28 {                          | 0.581           | 7.723          | 7.142          | 6.561          | $1\frac{3}{4}$       | 11 {                          | 1.479           | 53.746         | 52.267         | 50.788         |
|                      |                               | <i>0.0229</i>   | <i>0.3041</i>  | <i>0.2812</i>  | <i>0.2583</i>  |                      |                               | <i>0.0582</i>   | <i>2.1160</i>  | <i>2.0578</i>  | <i>1.9996</i>  |
| $\frac{1}{8}$        | 28 {                          | 0.581           | 9.728          | 9.147          | 8.566          | 2                    | 11 {                          | 1.479           | 59.614         | 58.135         | 56.656         |
|                      |                               | <i>0.0229</i>   | <i>0.3830</i>  | <i>0.3601</i>  | <i>0.3372</i>  |                      |                               | <i>0.0582</i>   | <i>2.3470</i>  | <i>2.2888</i>  | <i>2.2306</i>  |
| $\frac{1}{4}$        | 19 {                          | 0.856           | 13.157         | 12.301         | 11.445         | $2\frac{1}{4}$       | 11 {                          | 1.479           | 65.710         | 64.231         | 62.752         |
|                      |                               | <i>0.0337</i>   | <i>0.5180</i>  | <i>0.4843</i>  | <i>0.4506</i>  |                      |                               | <i>0.0582</i>   | <i>2.5870</i>  | <i>2.5288</i>  | <i>2.4706</i>  |
| $\frac{3}{8}$        | 19 {                          | 0.856           | 16.662         | 15.806         | 14.950         | $2\frac{1}{2}$       | 11 {                          | 1.479           | 75.184         | 73.705         | 72.226         |
|                      |                               | <i>0.0337</i>   | <i>0.6560</i>  | <i>0.6223</i>  | <i>0.5886</i>  |                      |                               | <i>0.0582</i>   | <i>2.9600</i>  | <i>2.9018</i>  | <i>2.8436</i>  |
| $\frac{1}{2}$        | 14 {                          | 1.162           | 20.955         | 19.793         | 18.631         | $2\frac{3}{4}$       | 11 {                          | 1.479           | 81.534         | 80.055         | 78.576         |
|                      |                               | <i>0.0457</i>   | <i>0.8250</i>  | <i>0.7793</i>  | <i>0.7336</i>  |                      |                               | <i>0.0582</i>   | <i>3.2100</i>  | <i>3.1518</i>  | <i>3.0936</i>  |
| $\frac{3}{4}$        | 14 {                          | 1.162           | 22.911         | 21.749         | 20.587         | 3                    | 11 {                          | 1.479           | 87.884         | 86.405         | 84.926         |
|                      |                               | <i>0.0457</i>   | <i>0.9020</i>  | <i>0.8563</i>  | <i>0.8106</i>  |                      |                               | <i>0.0582</i>   | <i>3.4600</i>  | <i>3.4018</i>  | <i>3.3436</i>  |
| $\frac{7}{8}$        | 14 {                          | 1.162           | 26.441         | 25.279         | 24.117         | $3\frac{1}{2}$       | 11 {                          | 1.479           | 100.330        | 98.851         | 97.372         |
|                      |                               | <i>0.0457</i>   | <i>1.0410</i>  | <i>0.9953</i>  | <i>0.9496</i>  |                      |                               | <i>0.0582</i>   | <i>3.9500</i>  | <i>3.8918</i>  | <i>3.8336</i>  |
| $1$                  | 11 {                          | 1.479           | 30.201         | 29.039         | 27.877         | 4                    | 11 {                          | 1.479           | 113.030        | 111.551        | 110.072        |
|                      |                               | <i>0.0582</i>   | <i>1.1890</i>  | <i>1.1433</i>  | <i>1.0976</i>  |                      |                               | <i>0.0582</i>   | <i>4.4500</i>  | <i>4.3918</i>  | <i>4.3336</i>  |
| $1\frac{1}{8}$       | 11 {                          | 1.479           | 33.249         | 31.770         | 30.291         | $4\frac{1}{2}$       | 11 {                          | 1.479           | 125.730        | 124.251        | 122.772        |
|                      |                               | <i>0.0582</i>   | <i>1.3090</i>  | <i>1.2508</i>  | <i>1.1926</i>  |                      |                               | <i>0.0582</i>   | <i>4.9500</i>  | <i>4.8918</i>  | <i>4.8336</i>  |
| $1\frac{1}{4}$       | 11 {                          | 1.479           | 37.897         | 36.418         | 34.939         | 5                    | 11 {                          | 1.479           | 138.430        | 136.951        | 135.472        |
|                      |                               | <i>0.0582</i>   | <i>1.4920</i>  | <i>1.4338</i>  | <i>1.3756</i>  |                      |                               | <i>0.0582</i>   | <i>5.4500</i>  | <i>5.3918</i>  | <i>5.3336</i>  |
| $1\frac{3}{4}$       | 11 {                          | 1.479           | 41.910         | 40.431         | 38.952         | $5\frac{1}{2}$       | 11 {                          | 1.479           | 151.130        | 149.651        | 148.172        |
|                      |                               | <i>0.0582</i>   | <i>1.6500</i>  | <i>1.5918</i>  | <i>1.5336</i>  |                      |                               | <i>0.0582</i>   | <i>5.9500</i>  | <i>5.8918</i>  | <i>5.8336</i>  |
| $1\frac{1}{2}$       | 11 {                          | 1.479           | 47.803         | 46.324         | 44.845         | 6                    | 11 {                          | 1.479           | 163.830        | 162.351        | 160.872        |
|                      |                               | <i>0.0582</i>   | <i>1.8820</i>  | <i>1.8238</i>  | <i>1.7656</i>  |                      |                               | <i>0.0582</i>   | <i>6.4500</i>  | <i>6.3918</i>  | <i>6.3336</i>  |

<sup>a</sup>The thread pitches in millimeters are as follows: 0.907 for 28 threads per inch. 1.337 for 19 threads per inch, 1.814 for 14 threads per inch, and 2.309 for 11 threads per inch.

Each basic metric dimension is given in roman figures (nominal sizes excepted) and each basic inch dimension is shown in italics directly beneath it.

**British Standard Pipe Threads for Pressure-tight Joints.**—The threads in BS 21:1973, "Specification for Pipe Threads where Pressure-tight Joints are Made on the Threads", are based on the Whitworth thread form and are specified as:

1) *Jointing threads:* These relate to pipe threads for joints made pressure-tight by the mating of the threads; they include taper external threads for assembly with either taper or parallel internal threads (parallel external pipe threads are not suitable as jointing threads)

2) *Longscrew threads:* These relate to parallel external pipe threads used for longscrews (connectors) specified in BS 1387 where a pressure-tight joint is achieved by the compression of a soft material onto the surface of the external thread by tightening a back nut against a socket

**British Standard External and Internal Pipe Threads (Pressure-tight Joints)  
Metric and Inch Dimensions and Limits of Size BS 21:1973**

| Nominal Size | No. of Threads per Inch <sup>a</sup> |   | Basic Diameters at Gage Plane |               |               | Gage Length |                     | Number of Useful Threads on Pipe for Basic Gage Length <sup>b</sup> | Tolerance + and -                       |                                      |
|--------------|--------------------------------------|---|-------------------------------|---------------|---------------|-------------|---------------------|---|---|--------------------------------------|
|              |                                      |   | Major                         | Pitch         | Minor         | Basic       | Tolerance (+ and -) |   | Gage Plane to Face of Int. Taper Thread | On Diameter of Parallel Int. Threads |
| 1/16         | 28                                   | { | 7.723                         | 7.142         | 6.561         | (4 3/8)     | (1)                 | (7 1/8)   | (1 1/4)                                 | 0.071                                |
|              |                                      |   | <i>0.304</i>                  | <i>0.2812</i> | <i>0.2583</i> | 4.0         | 0.9                 | 6.5   | 1.1                                     | <i>0.0028</i>                        |
| 1/8          | 28                                   | { | 9.728                         | 9.147         | 8.566         | (4 3/8)     | (1)                 | (7 1/8)   | (1 1/4)                                 | 0.071                                |
|              |                                      |   | <i>0.383</i>                  | <i>0.3601</i> | <i>0.3372</i> | 4.0         | 0.9                 | 6.5   | 1.1                                     | <i>0.0028</i>                        |
| 1/4          | 19                                   | { | 13.157                        | 12.301        | 11.445        | (4 1/2)     | (1)                 | (7 1/4)   | (1 1/4)                                 | 0.104                                |
|              |                                      |   | <i>0.518</i>                  | <i>0.4843</i> | <i>0.4506</i> | 6.0         | 1.3                 | 9.7   | 1.7                                     | <i>0.0041</i>                        |
| 3/8          | 19                                   | { | 16.662                        | 15.806        | 14.950        | (4 3/4)     | (1)                 | (7 1/2)   | (1 1/4)                                 | 0.104                                |
|              |                                      |   | <i>0.656</i>                  | <i>0.6223</i> | <i>0.5886</i> | 6.4         | 1.3                 | 10.1  | 1.7                                     | <i>0.0041</i>                        |
| 1/2          | 14                                   | { | 20.955                        | 19.793        | 18.631        | (4 1/2)     | (1)                 | (7 1/4)   | (1 1/4)                                 | 0.142                                |
|              |                                      |   | <i>0.825</i>                  | <i>0.7793</i> | <i>0.7336</i> | 8.2         | 1.8                 | 13.2  | 2.3                                     | <i>0.0056</i>                        |
| 3/4          | 14                                   | { | 26.441                        | 25.279        | 24.117        | (5 1/4)     | (1)                 | (8)   | (1 1/4)                                 | 0.142                                |
|              |                                      |   | <i>1.041</i>                  | <i>0.9953</i> | <i>0.9496</i> | 9.5         | 1.8                 | 14.5  | 2.3                                     | <i>0.0056</i>                        |
| 1            | 11                                   | { | 33.249                        | 31.770        | 30.291        | (4 1/2)     | (1)                 | (7 1/4)   | (1 1/4)                                 | 0.180                                |
|              |                                      |   | <i>1.309</i>                  | <i>1.2508</i> | <i>1.1926</i> | 10.4        | 2.3                 | 16.8  | 2.9                                     | <i>0.0071</i>                        |
| 1 1/4        | 11                                   | { | 41.910                        | 40.431        | 38.952        | (5 1/2)     | (1)                 | (8 1/4)   | (1 1/4)                                 | 0.180                                |
|              |                                      |   | <i>1.650</i>                  | <i>1.5918</i> | <i>1.5336</i> | 12.7        | 2.3                 | 19.1  | 2.9                                     | <i>0.0071</i>                        |
| 1 1/2        | 11                                   | { | 47.803                        | 46.324        | 44.845        | (5 1/2)     | (1)                 | (8 1/4)   | (1 1/4)                                 | 0.180                                |
|              |                                      |   | <i>1.882</i>                  | <i>1.8238</i> | <i>1.7656</i> | 12.7        | 2.3                 | 19.1  | 2.9                                     | <i>0.0071</i>                        |
| 2            | 11                                   | { | 59.614                        | 58.135        | 56.656        | (6 3/8)     | (1)                 | (10 1/8)  | (1 1/4)                                 | 0.180                                |
|              |                                      |   | <i>2.347</i>                  | <i>2.2888</i> | <i>2.2306</i> | 15.9        | 2.3                 | 23.4  | 2.9                                     | <i>0.0071</i>                        |
| 2 1/2        | 11                                   | { | 75.184                        | 73.705        | 72.226        | (7 9/16)    | (1 1/2)             | (11 9/16)   | (1 1/2)                                 | 0.216                                |
|              |                                      |   | <i>2.960</i>                  | <i>2.9018</i> | <i>2.8436</i> | 17.5        | 3.5                 | 26.7  | 3.5                                     | <i>0.0085</i>                        |
| 3            | 11                                   | { | 87.884                        | 86.405        | 84.926        | (8 15/16)   | (1 1/2)             | (12 15/16)  | (1 1/2)                                 | 0.216                                |
|              |                                      |   | <i>3.460</i>                  | <i>3.4018</i> | <i>3.3436</i> | 20.6        | 3.5                 | 29.8  | 3.5                                     | <i>0.0085</i>                        |
| 4            | 11                                   | { | 113.030                       | 111.551       | 110.072       | (11)        | (1 1/2)             | (15 1/2)  | (1 1/2)                                 | 0.216                                |
|              |                                      |   | <i>4.450</i>                  | <i>4.3918</i> | <i>4.3336</i> | 25.4        | 3.5                 | 35.8  | 3.5                                     | <i>0.0085</i>                        |
| 5            | 11                                   | { | 138.430                       | 136.951       | 135.472       | (12 3/8)    | (1 1/2)             | (17 3/8)  | (1 1/2)                                 | 0.216                                |
|              |                                      |   | <i>5.450</i>                  | <i>5.3918</i> | <i>5.3336</i> | 28.6        | 3.5                 | 40.1  | 3.5                                     | <i>0.0085</i>                        |
| 6            | 11                                   | { | 163.830                       | 162.351       | 160.872       | (12 3/8)    | (1 1/2)             | (17 3/8)  | (1 1/2)                                 | 0.216                                |
|              |                                      |   | <i>6.450</i>                  | <i>6.3918</i> | <i>6.3336</i> | 28.6        | 3.5                 | 40.1  | 3.5                                     | <i>0.0085</i>                        |

<sup>a</sup>In the Standard BS 21:1973 the thread pitches in millimeters are as follows: 0.907 for 28 threads per inch, 1.337 for 19 threads per inch, 1.814 for 14 threads per inch, and 2.309 for 11 threads per inch.

<sup>b</sup>This is the minimum number of useful threads on the pipe for the basic gage length; for the maximum and minimum gage lengths, the minimum numbers of useful threads are, respectively, greater and less by the amount of tolerance in the column to the left. The design of internally threaded parts shall make allowance for receiving pipe ends of up to the minimum number of useful threads corresponding to the maximum gage length; the minimum number of useful *internal* threads shall be no less than 80 per cent of the minimum number of useful external threads for the minimum gage length.

Each basic metric dimension is given in roman figures (nominal sizes excepted) and each basic inch dimension is shown in italics directly beneath it. Figures in ( ) are numbers of turns of thread with metric linear equivalents given beneath. Taper of taper thread is 1 in 16 on diameter.

## Hose Coupling Screw Threads

**ANSI Standard Hose Coupling Screw Threads.**—Threads for hose couplings, valves, and all other fittings used in direct connection with hose intended for domestic, industrial, and general service in sizes  $\frac{1}{2}$ ,  $\frac{5}{8}$ ,  $\frac{3}{4}$ , 1,  $1\frac{1}{4}$ ,  $1\frac{1}{2}$ , 2,  $2\frac{1}{2}$ , 3,  $3\frac{1}{2}$ , and 4 inches are covered by American National Standard ANSI/ASME B1.20.7-1991. These threads are designated as follows:

NH — Standard hose coupling threads of full form as produced by cutting or rolling.

NHR — Standard hose coupling threads for garden hose applications where the design utilizes thin walled material which is formed to the desired thread.

NPSH — Standard straight hose coupling thread series in sizes  $\frac{1}{2}$  to 4 inches for joining to American National Standard taper pipe threads using a gasket to seal the joint.

Thread dimensions are given in [Table 1](#) and thread lengths in [Table 2](#).

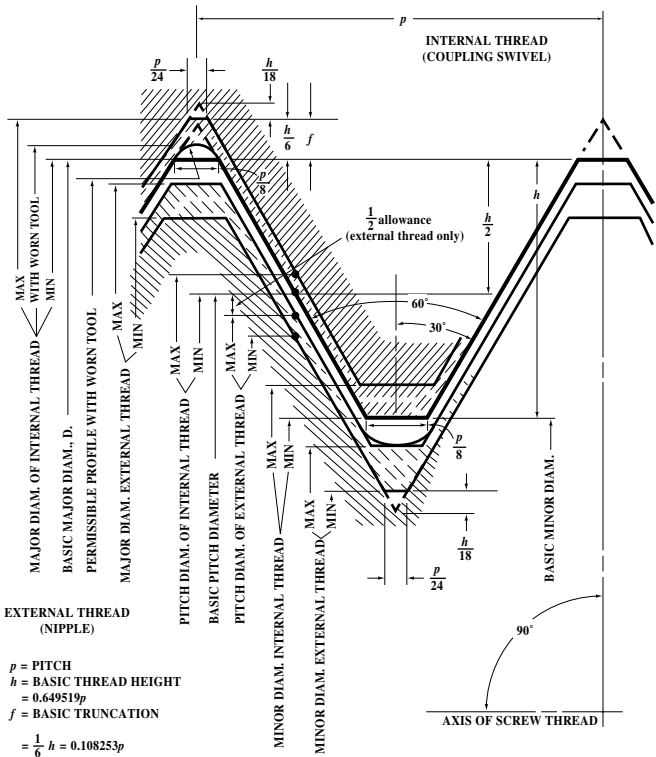


Fig. 1. Thread Form for ANSI Standard Hose Coupling Threads, NPSH, NH, and NHR. Heavy Line Shows Basic Size.

**Table 1. ANSI Standard Hose Coupling Threads for NPSH, NH, and NHR Nipples and Coupling Swivels ANSI/ASME B1.20.7-1991**

| Nominal Size of Hose                          | Threads per Inch | Thread Designation | Pitch  | Basic Height of Thread | Nipple (External) Thread |        |            |        |            | Coupling (Internal) Thread |        |            |        |            |
|---|------------------|--------------------|--------|------------------------|--------------------------|--------|------------|--------|------------|----------------------------|--------|------------|--------|------------|
|   |                  |                    |        |                        | Major Dia.               |        | Pitch Dia. |        | Minor Dia. | Minor Dia.                 |        | Pitch Dia. |        | Major Dia. |
|   |                  |                    |        |                        | Max.                     | Min.   | Max.       | Min.   | Max.       | Min.                       | Max.   | Min.       | Max.   | Min.       |
| $\frac{1}{2}$ , $\frac{5}{8}$ , $\frac{3}{4}$ | 11.5             | .75-11.5NH         | .08696 | .05648                 | 1.0625                   | 1.0455 | 1.0060     | 0.9975 | 0.9495     | 0.9595                     | 0.9765 | 1.0160     | 1.0245 | 1.0725     |
| $\frac{1}{2}$ , $\frac{5}{8}$ , $\frac{3}{4}$ | 11.5             | .75-11.5NHR        | .08696 | .05648                 | 1.0520                   | 1.0350 | 1.0100     | 0.9930 | 0.9495     | 0.9720                     | 0.9930 | 1.0160     | 1.0280 | 1.0680     |
| $\frac{1}{2}$                                 | 14               | .5-14NPSH          | .07143 | .04639                 | 0.8248                   | 0.8108 | 0.7784     | 0.7714 | 0.7320     | 0.7395                     | 0.7535 | 0.7859     | 0.7929 | 0.8323     |
| $\frac{3}{4}$                                 | 14               | .75-14NPSH         | .07143 | .04639                 | 1.0353                   | 1.0213 | 0.9889     | 0.9819 | 0.9425     | 0.9500                     | 0.9640 | 0.9964     | 1.0034 | 1.0428     |
| 1   | 11.5             | 1-11.5NPSH         | .08696 | .05648                 | 1.2951                   | 1.2781 | 1.2396     | 1.2301 | 1.1821     | 1.1921                     | 1.2091 | 1.2486     | 1.2571 | 1.3051     |
| $1\frac{1}{4}$                                | 11.5             | 1.25-11.5NPSH      | .08696 | .05648                 | 1.6399                   | 1.6229 | 1.5834     | 1.5749 | 1.5269     | 1.5369                     | 1.5539 | 1.5934     | 1.6019 | 1.6499     |
| $1\frac{1}{2}$                                | 11.5             | 1.5-11.5 NPSH      | .08696 | .05648                 | 1.8788                   | 1.8618 | 1.8223     | 1.8138 | 1.7658     | 1.7758                     | 1.7928 | 1.8323     | 1.8408 | 1.8888     |
| 2   | 11.5             | 2-11.5NPSH         | .08696 | .05648                 | 2.3528                   | 2.3358 | 2.2963     | 2.2878 | 2.2398     | 2.2498                     | 2.2668 | 2.3063     | 2.3148 | 2.3628     |
| $2\frac{1}{2}$                                | 8                | 2.5-8NPSH          | .12500 | .08119                 | 2.8434                   | 2.8212 | 2.7622     | 2.7511 | 2.6810     | 2.6930                     | 2.7152 | 2.7742     | 2.7853 | 2.8554     |
| 3   | 8                | 3-8NPSH            | .12500 | .08119                 | 3.4697                   | 3.4475 | 3.3885     | 3.3774 | 3.3073     | 3.3193                     | 3.3415 | 3.4005     | 3.4116 | 3.4817     |
| $3\frac{1}{2}$                                | 8                | 3.5-8NPSH          | .12500 | .08119                 | 3.9700                   | 3.9478 | 3.8888     | 3.8777 | 3.8076     | 3.8196                     | 3.8418 | 3.9008     | 3.9119 | 3.9820     |
| 4   | 8                | 4-8NPSH            | .12500 | .08119                 | 4.4683                   | 4.4461 | 4.3871     | 4.3760 | 4.3059     | 4.3179                     | 4.3401 | 4.3991     | 4.4102 | 4.4803     |
| 4   | 6                | 4-6NH (SPL)        | .16667 | .10825                 | 4.9082                   | 4.8722 | 4.7999     | 4.7819 | 4.6916     | 4.7117                     | 4.7477 | 4.8200     | 4.8380 | 4.9283     |

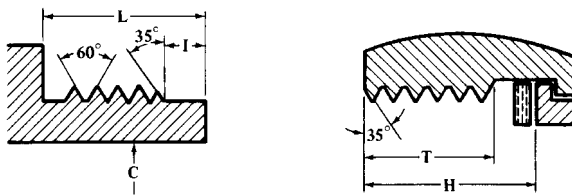
All dimensions are given in inches.

Dimensions given for the maximum minor diameter of the nipple are figured to the intersection of the worn tool arc with a centerline through crest and root. The minimum minor diameter of the nipple shall be that corresponding to a flat at the minor diameter of the minimum nipple equal to  $\frac{1}{2}p$ , and may be determined by subtracting  $0.7939p$  from the minimum pitch diameter of the nipple. (See Fig. 1)

Dimensions given for the minimum major diameter of the coupling correspond to the basic flat,  $\frac{1}{2}p$ , and the profile at the major diameter produced by a worn tool must not fall below the basic outline. The maximum major diameter of the coupling shall be that corresponding to a flat at the major diameter of the maximum coupling equal to  $\frac{1}{2}p$  and may be determined by adding  $0.7939p$  to the maximum pitch diameter of the coupling. (See Fig. 1)

NH and NHR threads are used for garden hose applications. NPSH threads are used for steam, air and all other hose connections to be made up with standard pipe threads. NH (SPL) threads are used for marine applications.

**Table 2. ANSI Standard Hose Coupling Screw Thread Lengths**  
ANSI/ASME B1.20.7-1991



| Nominal Size of Hose                          | Threads per Inch | I.D. of Nipple, C | Approx. O.D. of Ext. Thd. | Length of Nipple, L | Length of Pilot, I | Depth of Coupl., H | Coupl. Thd. Length, T | Approx. No. Thds. in Length T |
|---|------------------|-------------------|---------------------------|---------------------|--------------------|--------------------|-----------------------|-------------------------------|
| $\frac{1}{2}$ , $\frac{5}{8}$ , $\frac{3}{4}$ | 11.5             | $\frac{25}{32}$   | $1\frac{1}{16}$           | $\frac{9}{16}$      | $\frac{1}{8}$      | $\frac{17}{32}$    | $\frac{3}{8}$         | $4\frac{1}{4}$                |
| $\frac{1}{2}$ , $\frac{5}{8}$ , $\frac{3}{4}$ | 11.5             | $\frac{25}{32}$   | $1\frac{1}{16}$           | $\frac{9}{16}$      | $\frac{1}{8}$      | $\frac{17}{32}$    | $\frac{3}{8}$         | $4\frac{1}{4}$                |
| $\frac{1}{2}$                                 | 14               | $\frac{17}{32}$   | $\frac{13}{16}$           | $\frac{1}{2}$       | $\frac{1}{8}$      | $\frac{15}{32}$    | $\frac{5}{16}$        | $4\frac{1}{4}$                |
| $\frac{3}{4}$                                 | 14               | $\frac{25}{32}$   | $1\frac{1}{32}$           | $\frac{9}{16}$      | $\frac{1}{8}$      | $\frac{17}{32}$    | $\frac{3}{8}$         | $5\frac{1}{4}$                |
| 1   | 11.5             | $1\frac{1}{32}$   | $1\frac{9}{32}$           | $\frac{9}{16}$      | $\frac{5}{32}$     | $\frac{17}{32}$    | $\frac{3}{8}$         | $4\frac{1}{4}$                |
| $1\frac{1}{4}$                                | 11.5             | $1\frac{9}{32}$   | $1\frac{5}{8}$            | $\frac{5}{8}$       | $\frac{5}{32}$     | $\frac{19}{32}$    | $\frac{15}{32}$       | $5\frac{1}{2}$                |
| $1\frac{1}{2}$                                | 11.5             | $1\frac{17}{32}$  | $1\frac{7}{8}$            | $\frac{5}{8}$       | $\frac{5}{32}$     | $\frac{19}{32}$    | $\frac{15}{32}$       | $5\frac{1}{2}$                |
| 2   | 11.5             | $2\frac{1}{32}$   | $2\frac{11}{32}$          | $\frac{3}{4}$       | $\frac{3}{16}$     | $\frac{23}{32}$    | $\frac{19}{32}$       | $6\frac{3}{4}$                |
| $2\frac{1}{2}$                                | 8                | $2\frac{17}{32}$  | $2\frac{27}{32}$          | 1                   | $\frac{1}{4}$      | $\frac{15}{16}$    | $\frac{11}{16}$       | $5\frac{1}{2}$                |
| 3   | 8                | $3\frac{3}{32}$   | $3\frac{15}{32}$          | $1\frac{1}{8}$      | $\frac{1}{4}$      | $1\frac{1}{16}$    | $\frac{13}{16}$       | $6\frac{1}{2}$                |
| $3\frac{1}{2}$                                | 8                | $3\frac{17}{32}$  | $3\frac{31}{32}$          | $1\frac{1}{8}$      | $\frac{1}{4}$      | $1\frac{1}{16}$    | $\frac{13}{16}$       | $6\frac{1}{2}$                |
| 4   | 8                | $4\frac{3}{32}$   | $4\frac{15}{32}$          | $1\frac{1}{8}$      | $\frac{1}{4}$      | $1\frac{1}{16}$    | $\frac{13}{16}$       | $6\frac{1}{2}$                |
| 4   | 6                | 4                 | $4\frac{29}{32}$          | $1\frac{1}{8}$      | $\frac{5}{16}$     | $1\frac{1}{16}$    | $\frac{3}{4}$         | $4\frac{1}{2}$                |

All dimensions are given in inches. For thread designation see Table 1.

**American National Fire Hose Connection Screw Thread.**—This thread is specified in the National Fire Protection Association's Standard NFPA No. 194-1974. It covers the dimensions for screw thread connections for fire hose couplings, suction hose couplings, relay supply hose couplings, fire pump suction, discharge valves, fire hydrants, nozzles, adaptors, reducers, caps, plugs, wyes, siamese connections, standpipe connections, and sprinkler connections.

**Form of Thread:** The basic form of thread is as shown in Fig. 1. It has an included angle of 60 degrees and is truncated top and bottom. The flat at the root and crest of the basic thread form is equal to  $\frac{1}{8}$  (0.125) times the pitch in inches. The height of the thread is equal to 0.649519 times the pitch. The outer ends of both external and internal threads are terminated by the blunt start or "Higbee Cut" on full thread to avoid crossing and mutilation of thread.

**Thread Designation:** The thread is designated by specifying in sequence the nominal size of the connection, number of threads per inch followed by the thread symbol NH.

Thus, .75-8NH indicates a nominal size connection of 0.75 inch diameter with 8 threads per inch.

*Basic Dimensions:* The basic dimensions of the thread are as given in [Table 1](#).

**Table 1. Basic Dimensions of NH Threads NFPA 1963–1993 Edition**

| Nom. Size      | Threads per Inch (tpi) | Thread Designation | Pitch, $p$ | Basic Thread Height, $h$            | Minimum Internal Thread Dimensions |                  |                  |
|----------------|------------------------|--------------------|------------|-------------------------------------|------------------------------------|------------------|------------------|
|                |                        |                    |            |                                     | Min. Minor Dia.                    | Basic Pitch Dia. | Basic Major Dia. |
| $\frac{3}{4}$  | 8                      | 0.75-8 NH          | 0.12500    | 0.08119                             | 1.2246                             | 1.3058           | 1.3870           |
| 1              | 8                      | 1-8 NH             | 0.12500    | 0.08119                             | 1.2246                             | 1.3058           | 1.3870           |
| $1\frac{1}{2}$ | 9                      | 1.5-9 NH           | 0.11111    | 0.07217                             | 1.8577                             | 1.9298           | 2.0020           |
| $2\frac{1}{2}$ | 7.5                    | 2.5-7.5 NH         | 0.13333    | 0.08660                             | 2.9104                             | 2.9970           | 3.0836           |
| 3              | 6                      | 3-6 NH             | 0.16667    | 0.10825                             | 3.4223                             | 3.5306           | 3.6389           |
| $3\frac{1}{2}$ | 6                      | 3.5-6 NH           | 0.16667    | 0.10825                             | 4.0473                             | 4.1556           | 4.2639           |
| 4              | 4                      | 4-4 NH             | 0.25000    | 0.16238                             | 4.7111                             | 4.8735           | 5.0359           |
| $4\frac{1}{2}$ | 4                      | 4.5-4 NH           | 0.25000    | 0.16238                             | 5.4611                             | 5.6235           | 5.7859           |
| 5              | 4                      | 5-4 NH             | 0.25000    | 0.16238                             | 5.9602                             | 6.1226           | 6.2850           |
| 6              | 4                      | 6-4 NH             | 0.25000    | 0.16238                             | 6.7252                             | 6.8876           | 7.0500           |
| Nom. Size      | Threads per Inch (tpi) | Thread Designation | Pitch, $p$ | External Thread Dimensions (Nipple) |                                    |                  |                  |
|                |                        |                    |            | Allowance                           | Max. Major Dia.                    | Max. Pitch Dia.  | Max. Minor Dia.  |
| $\frac{3}{4}$  | 8                      | 0.75-8 NH          | 0.12500    | 0.0120                              | 1.3750                             | 1.2938           | 1.2126           |
| 1              | 8                      | 1-8 NH             | 0.12500    | 0.0120                              | 1.3750                             | 1.2938           | 1.2126           |
| $1\frac{1}{2}$ | 9                      | 1.5-9 NH           | 0.11111    | 0.0120                              | 1.9900                             | 1.9178           | 1.8457           |
| $2\frac{1}{2}$ | 7.5                    | 2.5-7.5 NH         | 0.13333    | 0.0150                              | 3.0686                             | 2.9820           | 2.8954           |
| 3              | 6                      | 3-6 NH             | 0.16667    | 0.0150                              | 3.6239                             | 3.5156           | 3.4073           |
| $3\frac{1}{2}$ | 6                      | 3.5-6 NH           | 0.16667    | 0.0200                              | 4.2439                             | 4.1356           | 4.0273           |
| 4              | 4                      | 4-4 NH             | 0.25000    | 0.0250                              | 5.0109                             | 4.8485           | 4.6861           |
| $4\frac{1}{2}$ | 4                      | 4.5-4 NH           | 0.25000    | 0.0250                              | 5.7609                             | 5.5985           | 5.4361           |
| 5              | 4                      | 5-4 NH             | 0.25000    | 0.0250                              | 6.2600                             | 6.0976           | 5.9352           |
| 6              | 4                      | 6-4 NH             | 0.25000    | 0.0250                              | 7.0250                             | 6.8626           | 6.7002           |

All dimensions are in inches.

*Thread Limits of Size:* Limits of size for NH external threads are given in [Table 2](#). Limits of size for NH internal threads are given in [Table 3](#).

*Tolerances:* The pitch-diameter tolerances for mating external and internal threads are the same. Pitch-diameter tolerances include lead and half-angle deviations. Lead deviations consuming one-half of the pitch-diameter tolerance are 0.0032 inch for  $\frac{3}{4}$ -, 1-, and  $1\frac{1}{2}$ -inch sizes; 0.0046 inch for  $2\frac{1}{2}$ -inch size; 0.0052 inch for 3-, and  $3\frac{1}{2}$ -inch sizes; and 0.0072 inch for 4-,  $4\frac{1}{2}$ -, 5-, and 6-inch sizes. Half-angle deviations consuming one-half of the pitch-diameter tolerance are 1 degree, 42 minutes for  $\frac{3}{4}$ - and 1-inch sizes; 1 degree, 54 minutes for  $1\frac{1}{2}$ -inch size; 2 degrees, 17 minutes for  $2\frac{1}{2}$ -inch size; 2 degrees, 4 minutes for 3- and  $3\frac{1}{2}$ -inch size; and 1 degree, 55 minutes for 4-,  $4\frac{1}{2}$ -, 5-, and 6-inch sizes.

Tolerances for the external threads are:

Major diameter tolerance =  $2 \times$  pitch-diameter tolerance

Minor diameter tolerance = pitch-diameter tolerance +  $2h/9$

The minimum minor diameter of the external thread is such as to result in a flat equal to one-third of the  $p/8$  basic flat, or  $p/24$ , at the root when the pitch diameter of the external thread is at its minimum value. The maximum minor diameter is basic, but may be such as results from the use of a worn or rounded threading tool. The maximum minor diameter is shown in [Fig. 1](#) and is the diameter upon which the minor diameter tolerance formula shown above is based.

Tolerances for the internal threads are:



Minor diameter tolerance =  $2 \times$  pitch-diameter tolerance

The minimum minor diameter of the internal thread is such as to result in a basic flat,  $p/8$ , at the crest when the pitch diameter of the thread is at its minimum value.

Major diameter tolerance = pitch-diameter tolerance -  $2h/9$

**Table 2. Limits of Size and Tolerances for NH External Threads (Nipples)**  
*NFPA 1963, 1993 Edition*

| Nom. Size      | Threads per Inch (tpi) | External Thread (Nipple) |        |        |                |        |        |                         |
|----------------|------------------------|--------------------------|--------|--------|----------------|--------|--------|-------------------------|
|                |                        | Major Diameter           |        |        | Pitch Diameter |        |        | Minor <sup>a</sup> Dia. |
|                |                        | Max.                     | Min.   | Toler. | Max.           | Min.   | Toler. | Max.                    |
| $\frac{3}{4}$  | 8                      | 1.3750                   | 1.3528 | 0.0222 | 1.2938         | 1.2827 | 0.0111 | 1.2126                  |
| 1              | 8                      | 1.3750                   | 1.3528 | 0.0222 | 1.2938         | 1.2827 | 0.0111 | 1.2126                  |
| $1\frac{1}{2}$ | 9                      | 1.9900                   | 1.9678 | 0.0222 | 1.9178         | 1.9067 | 0.0111 | 1.8457                  |
| $2\frac{1}{2}$ | 7.5                    | 3.0686                   | 3.0366 | 0.0320 | 2.9820         | 2.9660 | 0.0160 | 2.8954                  |
| 3              | 6                      | 3.6239                   | 3.5879 | 0.0360 | 3.5156         | 3.4976 | 0.0180 | 3.4073                  |
| $3\frac{1}{2}$ | 6                      | 4.2439                   | 4.2079 | 0.0360 | 4.1356         | 4.1176 | 0.0180 | 4.0273                  |
| 4              | 4                      | 5.0109                   | 4.9609 | 0.0500 | 4.8485         | 4.8235 | 0.0250 | 4.6861                  |
| $4\frac{1}{2}$ | 4                      | 5.7609                   | 5.7109 | 0.0500 | 5.5985         | 5.5735 | 0.0250 | 5.4361                  |
| 5              | 4                      | 6.2600                   | 6.2100 | 0.0500 | 6.0976         | 6.0726 | 0.0250 | 5.9352                  |
| 6              | 4                      | 7.0250                   | 6.9750 | 0.0500 | 6.8626         | 6.8376 | 0.0250 | 6.7002                  |

<sup>a</sup>Dimensions given for the maximum minor diameter of the nipple are figured to the intersection of the worn tool arc with a center line through crest and root. The minimum minor diameter of the nipple shall be that corresponding to a flat at the minor diameter of the minimum nipple equal to  $p/24$  and may be determined by subtracting  $11h/9$  (or  $0.7939p$ ) from the minimum pitch diameter of the nipple.

All dimensions are in inches.

**Table 3. Limits of Size and Tolerances for NH Internal Threads (Couplings)**  
*NFPA 1963, 1993 Edition*

| Nom. Size      | Threads per Inch (tpi) | Internal Thread (Coupling) |        |        |                |        |        |                         |
|----------------|------------------------|----------------------------|--------|--------|----------------|--------|--------|-------------------------|
|                |                        | Minor Diameter             |        |        | Pitch Diameter |        |        | Major <sup>a</sup> Dia. |
|                |                        | Min.                       | Max.   | Toler. | Min.           | Max.   | Toler. | Min.                    |
| $\frac{3}{4}$  | 8                      | 1.2246                     | 1.2468 | 0.0222 | 1.3058         | 1.3169 | 0.0111 | 1.3870                  |
| 1              | 8                      | 1.2246                     | 1.2468 | 0.0222 | 1.3058         | 1.3169 | 0.0111 | 1.3870                  |
| $1\frac{1}{2}$ | 9                      | 1.8577                     | 1.8799 | 0.0222 | 1.9298         | 1.9409 | 0.0111 | 2.0020                  |
| $2\frac{1}{2}$ | 7.5                    | 2.9104                     | 2.9424 | 0.0320 | 2.9970         | 3.0130 | 0.0160 | 3.0836                  |
| 3              | 6                      | 3.4223                     | 3.4583 | 0.0360 | 3.5306         | 3.5486 | 0.0180 | 3.6389                  |
| $3\frac{1}{2}$ | 6                      | 4.0473                     | 4.0833 | 0.0360 | 4.1556         | 4.1736 | 0.0180 | 4.2639                  |
| 4              | 4                      | 4.7111                     | 4.7611 | 0.0500 | 4.8735         | 4.8985 | 0.0250 | 5.0359                  |
| $4\frac{1}{2}$ | 4                      | 5.4611                     | 5.5111 | 0.0500 | 5.6235         | 5.6485 | 0.0250 | 5.7859                  |
| 5              | 4                      | 5.9602                     | 6.0102 | 0.0500 | 6.1226         | 6.1476 | 0.0250 | 6.2850                  |
| 6              | 4                      | 6.7252                     | 6.7752 | 0.0500 | 6.8876         | 6.9126 | 0.0250 | 7.0500                  |

<sup>a</sup>Dimensions for the minimum major diameter of the coupling correspond to the basic flat ( $p/8$ ), and the profile at the major diameter produced by a worn tool must not fall below the basic outline. The maximum major diameter of the coupling shall be that corresponding to a flat at the major diameter of the maximum coupling equal to  $p/24$  and may be determined by adding  $11h/9$  (or  $0.7939p$ ) to the maximum pitch diameter of the coupling.

All dimensions are in inches.

**Gages and Gaging:** Full information on gage dimensions and the use of gages in checking the NH thread are given in NFPA Standard No. 1963, 1993 Edition, published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269.

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## OTHER THREADS

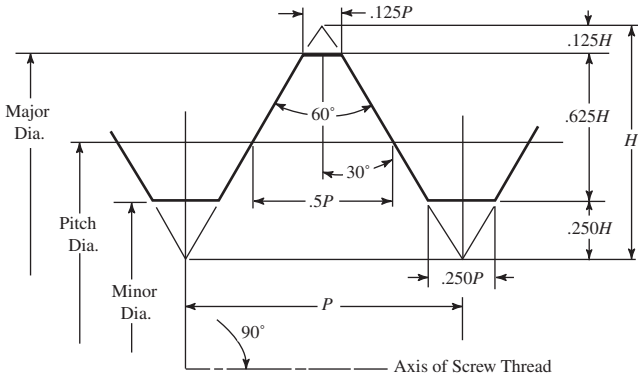
### Interference-Fit Threads

**Interference-Fit Threads.**—Interference-fit threads are threads in which the externally threaded member is larger than the internally threaded member when both members are in the free state and that, when assembled, become the same size and develop a holding torque through elastic compression, plastic movement of material, or both. By custom, these threads are designated Class 5.

The data in [Tables 1, 2, and 3](#), which are based on years of research, testing and field study, represent an American standard for interference-fit threads that overcomes the difficulties experienced with previous interference-fit recommendations such as are given in Federal Screw Thread Handbook H28. These data were adopted as American Standard ASA B1.12-1963. Subsequently, the standard was revised and issued as American National Standard ANSI B1.12-1972. More recent research conducted by the Portsmouth Naval Shipyard has led to the current revision ASME/ANSI B1.12-1987 (R1998).

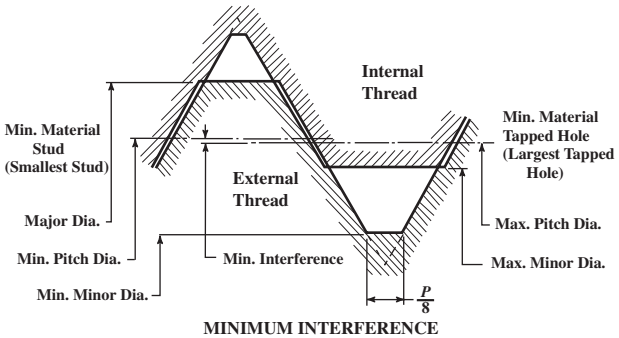
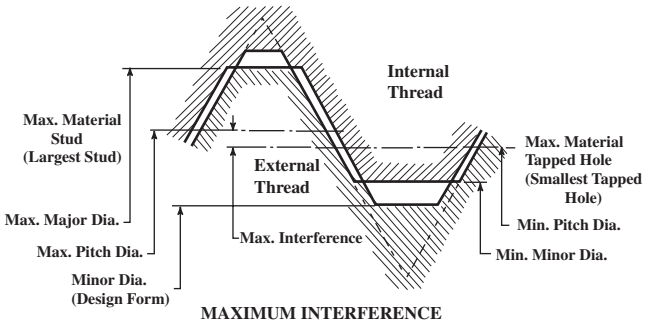
The data in [Tables 1, 2, and 3](#) provide dimensions for external and internal interference-fit (Class 5) threads of modified American National form in the Coarse Thread series, sizes  $\frac{1}{4}$  inch to  $1\frac{1}{2}$  inches. It is intended that interference-fit threads conforming with this standard will provide adequate torque conditions which fall within the limits shown in [Table 3](#). The minimum torques are intended to be sufficient to ensure that externally threaded members will not loosen in service; the maximum torques establish a ceiling below which seizing, galling, or torsional failure of the externally threaded components is reduced.

[Tables 1 and 2](#) give external and internal thread dimensions and are based on engagement lengths, external thread lengths, and tapping hole depths specified in [Table 3](#) and in compliance with the design and application data given in the following paragraphs. [Table 4](#) gives the allowances and [Table 5](#) gives the tolerances for pitch, major, and minor diameters for the Coarse Thread Series.



Basic Profile of American National Standard Class 5 Interference Fit Thread

## INTERFERENCE FIT THREADS



Note: Plastic flow of interference metal into cavities at major and minor diameters is not illustrated.

Maximum and Minimum Material Limits for Class 5 Interference-Fit Thread

**Design and Application Data for Class 5 Interference-Fit Threads.**—Following are conditions of usage and inspection on which satisfactory application of products made to dimensions in [Tables 1, 2, and 3](#) are based.

*Thread Designations:* The following thread designations provide a means of distinguishing the American Standard Class 5 Threads from the tentative Class 5 and alternate Class 5 threads, specified in Handbook H28. They also distinguish between external and internal American Standard Class 5 Threads.

Class 5 External Threads are designated as follows:

NC-5 HF—For driving in hard ferrous material of hardness over 160 BHN.

NC-5 CSF—For driving in copper alloy and soft ferrous material of 160 BHN or less.

NC-5 ONF—For driving in other nonferrous material (nonferrous materials other than copper alloys), any hardness.

Class 5 Internal Threads are designated as follows:

NC-5 IF—Entire ferrous material range.

NC-5 INF—Entire nonferrous material range.

**Table 1. External Thread Dimensions for Class 5 Interference-Fit Threads  
ANSI/ASME B1.12-1987 (R1998)**

| Nominal Size | Major Diameter, Inches   |        |  |        |  |        | Pitch Diameter, Inches |        | Minor Diameter, Inches |
|--------------|--|--------|--|--------|--|--------|------------------------|--------|------------------------|
|              | NC-5 HF<br>for driving in<br>ferrous material<br>with hardness greater<br>than 160 BHN<br>$L_e = 1\frac{1}{4}$ Diam. |        | NC-5 CSF<br>for driving in brass and<br>ferrous material<br>with hardness equal to<br>or less than 160 BHN<br>$L_e = 1\frac{1}{4}$ Diam. |        | NC-5 ONF<br>for driving in<br>nonferrous<br>except brass<br>(any hardness)<br>$L_e = 2\frac{1}{2}$ Diam. |        |                        |        |                        |
|              | Max  | Min    | Max  | Min    | Max  | Min    | Max                    | Min    | Max                    |
| 0.2500-20    | 0.2470   | 0.2418 | 0.2470   | 0.2418 | 0.2470   | 0.2418 | 0.2230                 | 0.2204 | 0.1932                 |
| 0.3125-18    | 0.3080   | 0.3020 | 0.3090   | 0.3030 | 0.3090   | 0.3030 | 0.2829                 | 0.2799 | 0.2508                 |
| 0.3750-16    | 0.3690   | 0.3626 | 0.3710   | 0.3646 | 0.3710   | 0.3646 | 0.3414                 | 0.3382 | 0.3053                 |
| 0.4375-14    | 0.4305   | 0.4233 | 0.4330   | 0.4258 | 0.4330   | 0.4258 | 0.3991                 | 0.3955 | 0.3579                 |
| 0.5000-13    | 0.4920   | 0.4846 | 0.4950   | 0.4876 | 0.4950   | 0.4876 | 0.4584                 | 0.4547 | 0.4140                 |
| 0.5625-12    | 0.5540   | 0.5460 | 0.5575   | 0.5495 | 0.5575   | 0.5495 | 0.5176                 | 0.5136 | 0.4695                 |
| 0.6250-11    | 0.6140   | 0.6056 | 0.6195   | 0.6111 | 0.6195   | 0.6111 | 0.5758                 | 0.5716 | 0.5233                 |
| 0.7500-10    | 0.7360   | 0.7270 | 0.7440   | 0.7350 | 0.7440   | 0.7350 | 0.6955                 | 0.6910 | 0.6378                 |
| 0.8750- 9    | 0.8600   | 0.8502 | 0.8685   | 0.8587 | 0.8685   | 0.8587 | 0.8144                 | 0.8095 | 0.7503                 |
| 1.0000- 8    | 0.9835   | 0.9727 | 0.9935   | 0.9827 | 0.9935   | 0.9827 | 0.9316                 | 0.9262 | 0.8594                 |
| 1.1250- 7    | 1.1070   | 1.0952 | 1.1180   | 1.1062 | 1.1180   | 1.1062 | 1.0465                 | 1.0406 | 0.9640                 |
| 1.2500- 7    | 1.2320   | 1.2200 | 1.2430   | 1.2312 | 1.2430   | 1.2312 | 1.1715                 | 1.1656 | 1.0890                 |
| 1.3750- 6    | 1.3560   | 1.3410 | 1.3680   | 1.3538 | 1.3680   | 1.3538 | 1.2839                 | 1.2768 | 1.1877                 |
| 1.5000- 6    | 1.4810   | 1.4670 | 1.4930   | 1.4788 | 1.4930   | 1.4788 | 1.4089                 | 1.4018 | 1.3127                 |

Based on external threaded members being steel ASTM A-325 (SAE Grade 5) or better.  $L_e$  = length of engagement.

**Table 2. Internal Thread Dimensions for Class 5 Interference-Fit Threads  
ANSI/ASME B1.12-1987 (R1998)**

| Nominal Size | NC-5 IF<br>Ferrous Material |       |           | NC-5 INF<br>Nonferrous Material |       |           | Pitch Diameter |        | Major Diam. |
|--------------|-----------------------------|-------|-----------|---------------------------------|-------|-----------|----------------|--------|-------------|
|              | Minor Diam. <sup>a</sup>    |       | Tap Drill | Minor Diam. <sup>a</sup>        |       | Tap Drill |                |        |             |
|              | Min                         | Max   |           | Min                             | Max   |           | Min            | Max    |             |
| 0.2500-20    | 0.196                       | 0.206 | 0.2031    | 0.196                           | 0.206 | 0.2031    | 0.2175         | 0.2201 | 0.2532      |
| 0.3125-18    | 0.252                       | 0.263 | 0.2610    | 0.252                           | 0.263 | 0.2610    | 0.2764         | 0.2794 | 0.3161      |
| 0.3750-16    | 0.307                       | 0.318 | 0.3160    | 0.307                           | 0.318 | 0.3160    | 0.3344         | 0.3376 | 0.3790      |
| 0.4375-14    | 0.374                       | 0.381 | 0.3750    | 0.360                           | 0.372 | 0.3680    | 0.3911         | 0.3947 | 0.4421      |
| 0.5000-13    | 0.431                       | 0.440 | 0.4331    | 0.417                           | 0.429 | 0.4219    | 0.4500         | 0.4537 | 0.5050      |
| 0.5625-12    | 0.488                       | 0.497 | 0.4921    | 0.472                           | 0.485 | 0.4844    | 0.5084         | 0.5124 | 0.5679      |
| 0.6250-11    | 0.544                       | 0.554 | 0.5469    | 0.527                           | 0.540 | 0.5313    | 0.5660         | 0.5702 | 0.6309      |
| 0.7500-10    | 0.667                       | 0.678 | 0.6719    | 0.642                           | 0.655 | 0.6496    | 0.6850         | 0.6895 | 0.7565      |
| 0.8750- 9    | 0.777                       | 0.789 | 0.7812    | 0.755                           | 0.769 | 0.7656    | 0.8028         | 0.8077 | 0.8822      |
| 1.0000- 8    | 0.890                       | 0.904 | 0.8906    | 0.865                           | 0.880 | 0.8750    | 0.9188         | 0.9242 | 1.0081      |
| 1.1250- 7    | 1.000                       | 1.015 | 1.0000    | 0.970                           | 0.986 | 0.9844    | 1.0322         | 1.0381 | 1.1343      |
| 1.2500- 7    | 1.125                       | 1.140 | 1.1250    | 1.095                           | 1.111 | 1.1094    | 1.1572         | 1.1631 | 1.2593      |
| 1.3750- 6    | 1.229                       | 1.247 | 1.2344    | 1.195                           | 1.213 | 1.2031    | 1.2667         | 1.2738 | 1.3858      |
| 1.5000- 6    | 1.354                       | 1.372 | 1.3594    | 1.320                           | 1.338 | 1.3281    | 1.3917         | 1.3988 | 1.5108      |

<sup>a</sup> Fourth decimal place is 0 for all sizes.

All dimensions are in inches, unless otherwise specified.

*Externally Threaded Products:* Points of externally threaded components should be chamfered or otherwise reduced to a diameter below the minimum minor diameter of the thread. The limits apply to bare or metallic coated parts. The threads should be free from excessive nicks, burrs, chips, grit or other extraneous material before driving.

**Table 3. Torques, Interferences, and Engagement Lengths for Class 5 Interference-Fit Threads ANSI/ASME B1.12-1987 (R1998)**

| Nominal Size | Interference on Pitch Diameter |       | Engagement Lengths, External Thread Lengths and Tapped Hole Depths <sup>a</sup> |                  |           |                            |                  |           | Torque at $1\frac{1}{2}D$ Engagement in Ferrous Material |            |
|--------------|--------------------------------|-------|---|------------------|-----------|----------------------------|------------------|-----------|--|------------|
|              |                                |       | In Brass and Ferrous  |                  |           | In Nonferrous Except Brass |                  |           |  |            |
|              | Max                            | Min   | $L_e$   | $T_s$            | $T_h$ min | $L_e$                      | $T_s$            | $T_h$ min | Max, lb-ft   | Min, lb-ft |
| 0.2500-20    | .0055                          | .0003 | 0.312   | 0.375 + .125 - 0 | 0.375     | 0.625                      | 0.688 + .125 - 0 | 0.688     | 12   | 3          |
| 0.3125-18    | .0065                          | .0005 | 0.391   | 0.469 + .139 - 0 | 0.469     | 0.781                      | 0.859 + .139 - 0 | 0.859     | 19   | 6          |
| 0.3750-16    | .0070                          | .0006 | 0.469   | 0.562 + .156 - 0 | 0.562     | 0.938                      | 1.031 + .156 - 0 | 1.031     | 35   | 10         |
| 0.4375-14    | .0080                          | .0008 | 0.547   | 0.656 + .179 - 0 | 0.656     | 1.094                      | 1.203 + .179 - 0 | 1.203     | 45   | 15         |
| 0.5000-13    | .0084                          | .0010 | 0.625   | 0.750 + .192 - 0 | 0.750     | 1.250                      | 1.375 + .192 - 0 | 1.375     | 75   | 20         |
| 0.5625-12    | .0092                          | .0012 | 0.703   | 0.844 + .208 - 0 | 0.844     | 1.406                      | 1.547 + .208 - 0 | 1.547     | 90   | 30         |
| 0.6250-11    | .0098                          | .0014 | 0.781   | 0.938 + .227 - 0 | 0.938     | 1.562                      | 1.719 + .227 - 0 | 1.719     | 120  | 37         |
| 0.7500-10    | .0105                          | .0015 | 0.938   | 1.125 + .250 - 0 | 1.125     | 1.875                      | 2.062 + .250 - 0 | 2.062     | 190  | 60         |
| 0.8750-9     | .0016                          | .0018 | 1.094   | 1.312 + .278 - 0 | 1.312     | 2.188                      | 2.406 + .278 - 0 | 2.406     | 250  | 90         |
| 1.0000-8     | .0128                          | .0020 | 1.250   | 1.500 + .312 - 0 | 1.500     | 2.500                      | 2.750 + .312 - 0 | 2.750     | 400  | 125        |
| 1.1250-7     | .0143                          | .0025 | 1.406   | 1.688 + .357 - 0 | 1.688     | 2.812                      | 3.094 + .357 - 0 | 3.095     | 470  | 155        |
| 1.2500-7     | .0143                          | .0025 | 1.562   | 1.875 + .357 - 0 | 1.875     | 3.125                      | 3.438 + .357 - 0 | 3.438     | 580  | 210        |
| 1.3750-6     | .0172                          | .0030 | 1.719   | 2.062 + .419 - 0 | 2.062     | 3.438                      | 3.781 + .419 - 0 | 3.781     | 705  | 250        |
| 1.5000-6     | .0172                          | .0030 | 1.875   | 2.250 + .419 - 0 | 2.250     | 3.750                      | 4.125 + .419 - 0 | 4.125     | 840  | 325        |

<sup>a</sup> $L_e$  = Length of engagement.  $T_s$  = External thread length of full form thread.  $T_h$  = Minimum depth of full form thread in hole.

All dimensions are inches.

**Materials for Externally Threaded Products:** The length of engagement, depth of thread engagement and pitch diameter in Tables 1, 2, and 3 are designed to produce adequate torque conditions when heat-treated medium-carbon steel products, ASTM A-325 (SAE Grade 5) or better, are used. In many applications, case-carburized and nonheat-treated medium-carbon steel products of SAE Grade 4 are satisfactory. SAE Grades 1 and 2, may be usable under certain conditions. This standard is not intended to cover the use of products made of stainless steel, silicon bronze, brass or similar materials. When such materials are used, the tabulated dimensions will probably require adjustment based on pilot experimental work with the materials involved.

**Lubrication:** For driving in ferrous material, a good lubricant sealer should be used, particularly in the hole. A non-carbonizing type of lubricant (such as a rubber-in-water dispersion) is suggested. The lubricant must be applied to the hole and it may be applied to the male member. In applying it to the hole, care must be taken so that an excess amount of lubricant will not cause the male member to be impeded by hydraulic pressure in a blind hole. Where sealing is involved, the lubricant selected should be insoluble in the medium being sealed.

For driving, in nonferrous material, lubrication may not be needed. The use of medium gear oil for driving in aluminum is recommended. American research has observed that the minor diameter of lubricated tapped holes in non-ferrous materials may tend to close in, that is, be reduced in driving; whereas with an unlubricated hole the minor diameter may tend to open up.

**Driving Speed:** This standard makes no recommendation for driving speed. Some opinion has been advanced that careful selection and control of driving speed is desirable to obtain optimum results with various combinations of surface hardness and roughness. Experience with threads made to this standard may indicate what limitations should be placed on driving speeds.

**Table 4. Allowances for Coarse Thread Series ANSI/ASME B1.12-1987 (R1998)**

| TPI | Difference between Nom. Size and Max Major Diam of NC-5 HF <sup>a</sup> | Difference between Nom. Size and Max Major Diam. of NC-5 CSF or NC-5 ONF <sup>a</sup> | Difference between Basic Minor Diam. and Min Minor Diam. of NC-5 IF <sup>a</sup> | Difference between Basic Minor Diam. and Min Minor Diam. of NC-5 INF | Max PD Inteferece or Neg Allowance, Ext Thread <sup>b</sup> | Difference between Max Minor Diam. and Basic Minor Diam., Ext Thread |
|-----|---|---|--|--|---|--|
| 20  | 0.0030  | 0.0030  | 0.000  | 0.000  | 0.0055  | 0.0072   |
| 18  | 0.0045  | 0.0035  | 0.000  | 0.000  | 0.0065  | 0.0080   |
| 16  | 0.0060  | 0.0040  | 0.000  | 0.000  | 0.0070  | 0.0090   |
| 14  | 0.0070  | 0.0045  | 0.014  | 0.000  | 0.0080  | 0.0103   |
| 13  | 0.0080  | 0.0050  | 0.014  | 0.000  | 0.0084  | 0.0111   |
| 12  | 0.0085  | 0.0050  | 0.016  | 0.000  | 0.0092  | 0.0120   |
| 11  | 0.0110  | 0.0055  | 0.017  | 0.000  | 0.0098  | 0.0131   |
| 10  | 0.0140  | 0.0060  | 0.019  | 0.000  | 0.0105  | 0.0144   |
| 9   | 0.0150  | 0.0065  | 0.022  | 0.000  | 0.0116  | 0.0160   |
| 8   | 0.0165  | 0.0065  | 0.025  | 0.000  | 0.0128  | 0.0180   |
| 7   | 0.0180  | 0.0070  | 0.030  | 0.000  | 0.0143  | 0.0206   |
| 6   | 0.0190  | 0.0070  | 0.034  | 0.000  | 0.0172  | 0.0241   |

<sup>a</sup>The allowances in these columns were obtained from industrial research data.

<sup>b</sup>Negative allowance is the difference between the basic pitch diameter and pitch diameter value at maximum material condition.

All dimensions are in inches.

The difference between basic major diameter and internal thread minimum major diameter is  $0.075H$  and is tabulated in Table 5.

**Table 5. Tolerances for Pitch Diameter, Major Diameter, and Minor Diameter for Coarse Thread Series ANSI/ASME B1.12-1987 (R1998)**

| TPI | PD Tolerance for Ext and Int Threads <sup>a</sup> | Major Diam. Tolerance for Ext Thread <sup>b</sup> | Minor Diam. Tolerance for Int Thread NC-5 IF | Minor Diam. Tolerance for Int Thread NC-5 INF <sup>c</sup> | Tolerance $0.075H$ or $0.065P$ for Tap Major Diam. |
|-----|---|---|--|--|--|
| 20  | 0.0026  | 0.0052  | 0.010  | 0.010  | 0.0032   |
| 18  | 0.0030  | 0.0060  | 0.011  | 0.011  | 0.0036   |
| 16  | 0.0032  | 0.0064  | 0.011  | 0.011  | 0.0041   |
| 14  | 0.0036  | 0.0072  | 0.008  | 0.012  | 0.0046   |
| 13  | 0.0037  | 0.0074  | 0.008  | 0.012  | 0.0050   |
| 12  | 0.0040  | 0.0080  | 0.009  | 0.013  | 0.0054   |
| 11  | 0.0042  | 0.0084  | 0.010  | 0.013  | 0.0059   |
| 10  | 0.0045  | 0.0090  | 0.011  | 0.014  | 0.0065   |
| 9   | 0.0049  | 0.0098  | 0.012  | 0.014  | 0.0072   |
| 8   | 0.0054  | 0.0108  | 0.014  | 0.015  | 0.0093   |
| 7   | 0.0059  | 0.0118  | 0.015  | 0.015  | 0.0093   |
| 6   | 0.0071  | 0.0142  | 0.018  | 0.018  | 0.0108   |

<sup>a</sup>National Class 3 pitch diameter tolerance from ASA B1.1-1960.

<sup>b</sup>Twice the NC-3 pitch diameter tolerance.

<sup>c</sup>National Class 3 minor diameter tolerance from ASA B1.1-1960.

All dimensions are in inches.

**Relation of Driving Torque to Length of Engagement:** Torques increase directly as the length of engagement and this increase is proportionately more rapid as size increases. The standard does not establish recommended breakloose torques.

**Surface Roughness:** Surface roughness is not a required measurement. Roughness between 63 and 125  $\mu\text{in}$ . Ra is recommended. Surface roughness greater than 125  $\mu\text{in}$ . Ra may encourage galling and tearing of threads. Surfaces with roughness less than 63  $\mu\text{in}$ . Ra may hold insufficient lubricant and wring or weld together.

**Lead and Angle Variations:** The lead variation values tabulated in Table 6 are the maximum variations from specified lead between any two points not farther apart than the length of the standard GO thread gage. Flank angle variation values tabulated in Table 7 are maximum variations from the basic 30° angle between thread flanks and perpendiculars to the thread axis. The application of these data in accordance with ANSI/ASME B1.3M, the screw thread gaging system for dimensional acceptability, is given in the Standard. Lead variation does not change the volume of displaced metal, but it exerts a cumulative unilateral stress on the pressure side of the thread flank. Control of the difference between pitch diameter size and functional diameter size to within one-half the pitch diameter tolerance will hold lead and angle variables to within satisfactory limits. Both the variations may produce unacceptable torque and faulty assemblies.

**Table 6. Maximum Allowable Variations in Lead and Maximum Equivalent Change in Functional Diameter ANSI/ASME B1.12-1987 (R1998)**

| Nominal Size | External and Internal Threads                     |   |
|--------------|---|---|
|              | Allowable Variation in Axial Lead (Plus or Minus) | Max Equivalent Change in Functional Diam. (Plus for Ext, Minus for Int) |
| 0.2500–20    | 0.0008  | 0.0013  |
| 0.3125–18    | 0.0009  | 0.0015  |
| 0.3750–16    | 0.0009  | 0.0016  |
| 0.4375–14    | 0.0010  | 0.0018  |
| 0.5000–13    | 0.0011  | 0.0018  |
| 0.5625–12    | 0.0012  | 0.0020  |
| 0.6250–11    | 0.0012  | 0.0021  |
| 0.7500–10    | 0.0013  | 0.0022  |
| 0.8750– 9    | 0.0014  | 0.0024  |
| 1.0000– 8    | 0.0016  | 0.0027  |
| 1.1250– 7    | 0.0017  | 0.0030  |
| 1.2500– 7    | 0.0017  | 0.0030  |
| 1.3750– 6    | 0.0020  | 0.0036  |
| 1.5000– 6    | 0.0020  | 0.0036  |

All dimensions are in inches.

Note: The equivalent change in functional diameter applies to total effect of form errors.

Maximum allowable variation in lead is permitted only when all other form variations are zero.

For sizes not tabulated, maximum allowable variation in lead is equal to 0.57735 times one-half the pitch diameter tolerance.

**Table 7. Maximum Allowable Variation in 30° Basic Half-Angle of External and Internal Screw Threads ANSI/ASME B1.12-1987 (R1998)**

| TPI | Allowable Variation in Half-Angle of Thread (Plus or Minus) | TPI | Allowable Variation in Half-Angle of Thread (Plus or Minus) | TPI | Allowable Variation in Half-Angle of Thread (Plus or Minus) |
|-----|---|-----|---|-----|---|
| 32  | 1° 30'  | 14  | 0° 55'  | 8   | 0° 45'  |
| 28  | 1° 20'  | 13  | 0° 55'  | 7   | 0° 45'  |
| 27  | 1° 20'  | 12  | 0° 50'  | 6   | 0° 40'  |
| 24  | 1° 15'  | 11½ | 0° 50'  | 5   | 0° 40'  |
| 20  | 1° 10'  | 11  | 0° 50'  | 4½  | 0° 40'  |
| 18  | 1° 05'  | 10  | 0° 50'  | 4   | 0° 40'  |
| 16  | 1° 00'  | 9   | 0° 50'  | ... | ...   |

## Spark Plug Threads

**British Standard for Spark Plugs BS 45:1972 (withdrawn).**—This revised British Standard refers solely to spark plugs used in automobiles and industrial spark ignition internal combustion engines. The basic thread form is that of the ISO metric (see page 1816). In assigning tolerances to the threads of the spark plug and the tapped holes, full consideration has been given to the desirability of achieving the closest possible measure of interchangeability between British spark plugs and engines, and those made to the standards of other ISO Member Bodies.

## Basic Thread Dimensions for Spark Plug and Tapped Hole in Cylinder Head

| Nom. Size | Pitch | Thread | Major Dia.          |        | Pitch Dia. |        | Minor Dia. |        |
|-----------|-------|--------|---------------------|--------|------------|--------|------------|--------|
|           |       |        | Max.                | Min.   | Max.       | Min.   | Max.       | Min.   |
| 14        | 1.25  | Plug   | 13.937 <sup>a</sup> | 13.725 | 13.125     | 12.993 | 12.402     | 12.181 |
| 14        | 1.25  | Hole   |                     | 14.00  | 13.368     | 13.188 | 12.912     | 12.647 |
| 18        | 1.5   | Plug   | 17.933 <sup>a</sup> | 17.697 | 16.959     | 16.819 | 16.092     | 15.845 |
| 18        | 1.5   | Hole   |                     | 18.00  | 17.216     | 17.026 | 16.676     | 16.376 |

<sup>a</sup> Not specified

All dimensions are given in millimeters.

The tolerance grades for finished spark plugs and corresponding tapped holes in the cylinder head are: for 14 mm size, 6e for spark plugs and 6H for tapped holes which gives a minimum clearance of 0.063 mm; and for 18 mm size, 6e for spark plugs and 6H for tapped holes which gives a minimum clearance of 0.067 mm.

These minimum clearances are intended to prevent the possibility of seizure, as a result of combustion deposits on the bare threads, when removing the spark plugs and applies to both ferrous and non-ferrous materials. These clearances are also intended to enable spark plugs with threads in accordance with this standard to be fitted into existing holes.

**SAE Spark-Plug Screw Threads.**—The SAE Standard includes the following sizes:  $\frac{7}{8}$ -inch nominal diameter with 18 threads per inch; 18-millimeter nominal diameter with a 18-millimeter nominal diameter with a 1.5-millimeter pitch; 14-millimeter nominal diameter with a 1.25-millimeter pitch; 10-millimeter nominal diameter with a 1.0 millimeter pitch;  $\frac{3}{8}$ -inch nominal diameter with 24 threads per inch; and  $\frac{1}{4}$ -inch nominal diameter with 32 threads per inch. During manufacture, in order to keep the wear on the threading tools within permissible limits, the threads in the spark plug GO (ring) gage should be truncated to the maximum minor diameter of the spark plug; and in the tapped hole GO (plug) gage to the minimum major diameter of the tapped hole.

## SAE Standard Threads for Spark Plugs

| Size <sup>a</sup><br>Nom. × Pitch | Major Diameter      |                    | Pitch Diameter     |                    | Minor Diameter     |      |
|-----------------------------------|---------------------|--------------------|--------------------|--------------------|--------------------|------|
|                                   | Max.                | Min.               | Max.               | Min.               | Max.               | Min. |
| Spark Plug Threads, mm (inches)   |                     |                    |                    |                    |                    |      |
| M18 × 1.5                         | 17.933<br>(0.07060) | 17.803<br>(0.7009) | 16.959<br>(0.6677) | 16.853<br>(0.6635) | 16.053<br>(0.6320) | ...  |
| M14 × 1.25                        | 13.868<br>(0.5460)  | 13.741<br>(0.5410) | 13.104<br>(0.5159) | 12.997<br>(0.5117) | 12.339<br>(0.4858) | ...  |
| M12 × 1.25                        | 11.862<br>(0.4670)  | 11.735<br>(0.4620) | 11.100<br>(0.4370) | 10.998<br>(0.4330) | 10.211<br>(0.4020) | ...  |
| M10 × 1.0                         | 9.974<br>(0.3927)   | 9.794<br>(0.3856)  | 9.324<br>(0.3671)  | 9.212<br>(0.3627)  | 8.747<br>(0.3444)  | ...  |



**SAE Standard Threads for Spark Plugs (Continued)**

| Size <sup>a</sup><br>Nom. × Pitch | Major Diameter |                    | Pitch Diameter     |                    | Minor Diameter     |                    |
|-----------------------------------|----------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|                                   | Max.           | Min.               | Max.               | Min.               | Max.               | Min.               |
| Tapped Hole Threads, mm (inches)  |                |                    |                    |                    |                    |                    |
| M18 × 1.5                         | ...            | 18.039<br>(0.7102) | 17.153<br>(0.6753) | 17.026<br>(0.6703) | 16.426<br>(0.6467) | 16.266<br>(0.6404) |
| M14 × 1.25                        | ...            | 14.034<br>(0.5525) | 13.297<br>(0.5235) | 13.188<br>(0.5192) | 12.692<br>(0.4997) | 12.499<br>(0.4921) |
| M12 × 1.25                        | ...            | 12.000<br>(0.4724) | 11.242<br>(0.4426) | 11.188<br>(0.4405) | 10.559<br>(0.4157) | 10.366<br>(0.4081) |
| M10 × 1.0                         | ...            | 10.000<br>(0.3937) | 9.500<br>(0.3740)  | 9.350<br>(0.3681)  | 9.153<br>(0.3604)  | 8.917<br>(0.3511)  |

<sup>a</sup> M14 and M18 are preferred for new applications.

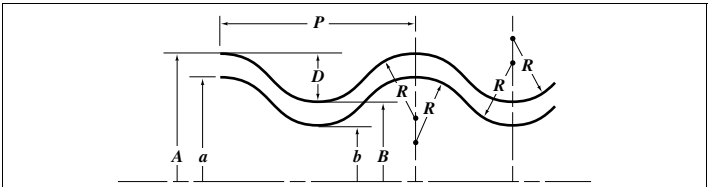
In order to keep the wear on the threading tools within permissible limits, the threads in the spark plug GO (ring) gage shall be truncated to the maximum minor diameter of the spark plug, and in the tapped hole GO (plug) gage to the minimum major diameter of the tapped hole. The plain plug gage for checking the minor diameter of the tapped hole shall be the minimum specified. The thread form is that of the ISO metric (see page 1816).

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**Lamp Base and Electrical Fixture Threads**

**Lamp Base and Socket Shell Threads.**—The “American Standard” threads for lamp base and socket shells are sponsored by the American Society of Mechanical Engineers, the National Electrical Manufacturers’ Association and by most of the large manufacturers of products requiring rolled threads on sheet metal shells or parts, such as lamp bases, fuse plugs, attachment plugs, etc. There are five sizes, designated as the “miniature size,” the “candelabra size,” the “intermediate size,” the “medium size” and the “mogul size.”

**Rolled Threads for Screw Shells of Electric Sockets and Lamp Bases— American Standard**



Male or Base Screw Shells Before Assembly

| Size         | Threads per Inch | Pitch <i>P</i> | Depth of Thread <i>D</i> | Radius Crest Root <i>R</i> | Major Dia.    |               | Minor Diam.   |               |
|--------------|------------------|----------------|--------------------------|----------------------------|---------------|---------------|---------------|---------------|
|              |                  |                |                          |                            | Max. <i>A</i> | Min. <i>a</i> | Max. <i>B</i> | Min. <i>b</i> |
| Miniature    | 14               | 0.07143        | 0.020                    | 0.0210                     | 0.375         | 0.370         | 0.335         | 0.330         |
| Candelabra   | 10               | 0.10000        | 0.025                    | 0.0312                     | 0.465         | 0.460         | 0.415         | 0.410         |
| Intermediate | 9                | 0.11111        | 0.027                    | 0.0353                     | 0.651         | 0.645         | 0.597         | 0.591         |
| Medium       | 7                | 0.14286        | 0.033                    | 0.0470                     | 1.037         | 1.031         | 0.971         | 0.965         |
| Mogul        | 4                | 0.25000        | 0.050                    | 0.0906                     | 1.555         | 1.545         | 1.455         | 1.445         |

Socket Screw Shells Before Assembly

|              |    |         |       |        |        |        |        |        |
|--------------|----|---------|-------|--------|--------|--------|--------|--------|
| Miniature    | 14 | 0.07143 | 0.020 | 0.0210 | 0.3835 | 0.3775 | 0.3435 | 0.3375 |
| Candelabra   | 10 | 0.10000 | 0.025 | 0.0312 | 0.476  | 0.470  | 0.426  | 0.420  |
| Intermediate | 9  | 0.11111 | 0.027 | 0.0353 | 0.664  | 0.657  | 0.610  | 0.603  |
| Medium       | 7  | 0.14286 | 0.033 | 0.0470 | 1.053  | 1.045  | 0.987  | 0.979  |
| Mogul        | 4  | 0.25000 | 0.050 | 0.0906 | 1.577  | 1.565  | 1.477  | 1.465  |

All dimensions are in inches.

*Base Screw Shell Gage Tolerances:* Threaded ring gages—"Go," Max. thread size to minus 0.0003 inch; "Not Go," Min. thread size to plus 0.0003 inch. Plain ring gages—"Go," Max. thread O.D. to minus 0.0002 inch; "Not Go," Min. thread O.D. to plus 0.0002 inch.

*Socket Screw Shell Gages:* Threaded plug gages—"Go," Min. thread size to plus 0.0003 inch; "Not Go," Max. thread size to minus 0.0003 inch. Plain plug gages—"Go," Min. minor dia. to plus 0.0002 inch; "Not Go," Max. minor dia. to minus 0.0002 inch.

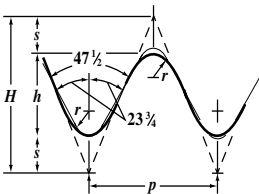
*Check Gages for Base Screw Shell Gages:* Threaded plugs for checking threaded ring gages—"Go," Max. thread size to minus 0.0003 inch; "Not Go," Min. thread size to plus 0.0003 inch.

**Electric Fixture Thread.**—The special straight electric fixture thread consists of a straight thread of the same pitches as the American standard pipe thread, and having the regular American or U. S. standard form; it is used for caps, etc. The male thread is smaller, and the female thread larger than those of the special straight-fixture pipe threads. The male thread assembles with a standard taper female thread, while the female thread assembles with a standard taper male thread. This thread is used when it is desired to have the joint "make up" on a shoulder. The gages used are straight-threaded limit gages.

### Instrument and Microscope Threads

**British Association Standard Thread (BA).**—This form of thread is similar to the Whitworth thread in that the root and crest are rounded (see illustration). The angle, however, is only 47 degrees 30 minutes and the radius of the root and crest are proportionately larger. This thread is used in Great Britain and, to some extent, in other European countries for very small screws. Its use in the United States is practically confined to the manufacture of tools for export. This thread system was originated in Switzerland as a standard for watch and clock screws, and it is sometimes referred to as the "Swiss small screw thread standard." See also *Swiss Screw Thread*.

This screw thread system is recommended by the British Standards Institution for use in preference to the BSW and BSF systems for all screws smaller than  $\frac{1}{4}$  inch except that the use of the "0" BA thread be discontinued in favor of the  $\frac{1}{4}$ -in. BSF. It is further recommended that in the selection of sizes, preference be given to even numbered BA sizes. The thread form is shown by the diagram.



British Association Thread

$$H = 1.13634 \times p$$

$$h = 0.60000 \times p$$

$$r = 0.18083 \times p$$

$$s = 0.26817 \times p$$

It is a symmetrical V-thread, of  $47\frac{1}{2}$  degree included angle, having its crests and roots rounded with equal radii, such that the basic depth of the thread is 0.6000 of the pitch. Where  $p$  = pitch of thread,  $H$  = depth of V-thread,  $h$  = depth of BA thread,  $r$  = radius at root and crest of thread, and  $s$  = root and crest truncation.

**British Association (BA) Standard Thread, Basic Dimensions**  
**BS 93:1951 (obsolescent)**

| Designation Number | Pitch, mm | Depth of Thread, mm | Bolt and Nut       |                        |                    | Radius, mm | Threads per Inch (approx.) |
|--------------------|-----------|---------------------|--------------------|------------------------|--------------------|------------|----------------------------|
|                    |           |                     | Major Diameter, mm | Effective Diameter, mm | Minor Diameter, mm |            |                            |
| 0                  | 1.0000    | 0.600               | 6.00               | 5.400                  | 4.80               | 0.1808     | 25.4                       |
| 1                  | 0.9000    | 0.540               | 5.30               | 4.760                  | 4.22               | 0.1627     | 28.2                       |
| 2                  | 0.8100    | 0.485               | 4.70               | 4.215                  | 3.73               | 0.1465     | 31.4                       |
| 3                  | 0.7300    | 0.440               | 4.10               | 3.660                  | 3.22               | 0.1320     | 34.8                       |
| 4                  | 0.6600    | 0.395               | 3.60               | 3.205                  | 2.81               | 0.1193     | 38.5                       |
| 5                  | 0.5900    | 0.355               | 3.20               | 2.845                  | 2.49               | 0.1067     | 43.0                       |
| 6                  | 0.5300    | 0.320               | 2.80               | 2.480                  | 2.16               | 0.0958     | 47.9                       |
| 7                  | 0.4800    | 0.290               | 2.50               | 2.210                  | 1.92               | 0.0868     | 52.9                       |
| 8                  | 0.4300    | 0.260               | 2.20               | 1.940                  | 1.68               | 0.0778     | 59.1                       |
| 9                  | 0.3900    | 0.235               | 1.90               | 1.665                  | 1.43               | 0.0705     | 65.1                       |
| 10                 | 0.3500    | 0.210               | 1.70               | 1.490                  | 1.28               | 0.0633     | 72.6                       |
| 11                 | 0.3100    | 0.185               | 1.50               | 1.315                  | 1.13               | 0.0561     | 82.0                       |
| 12                 | 0.2800    | 0.170               | 1.30               | 1.130                  | 0.96               | 0.0506     | 90.7                       |
| 13                 | 0.2500    | 0.150               | 1.20               | 1.050                  | 0.90               | 0.0452     | 102                        |
| 14                 | 0.2300    | 0.140               | 1.00               | 0.860                  | 0.72               | 0.0416     | 110                        |
| 15                 | 0.2100    | 0.125               | 0.90               | 0.775                  | 0.65               | 0.0380     | 121                        |
| 16                 | 0.1900    | 0.115               | 0.79               | 0.675                  | 0.56               | 0.0344     | 134                        |

**Tolerances and Allowances:** Two classes of bolts and one for nuts are provided: *Close Class bolts* are intended for precision parts subject to stress, no allowance being provided between maximum bolt and minimum nut sizes. *Normal Class bolts* are intended for general commercial production and general engineering use; for sizes 0 to 10 BA, an allowance of 0.025 mm is provided.

**Tolerance Formulas for British Association (BA) Screw Threads**

|       | Class or Fit                   | Tolerance (+ for nuts, - for bolts) |                          |                         |
|-------|--------------------------------|-------------------------------------|--------------------------|-------------------------|
|       |                                | Major Dia.                          | Effective Dia.           | Minor Dia.              |
| Bolts | Close Class 0 to 10 BA incl.   | 0.15 <i>p</i> mm                    | 0.08 <i>p</i> + 0.02 mm  | 0.16 <i>p</i> + 0.04 mm |
|       | Normal Class 0 to 10 BA incl.  | 0.20 <i>p</i> mm                    | 0.10 <i>p</i> + 0.025 mm | 0.20 <i>p</i> + 0.05 mm |
|       | Normal Class 11 to 16 BA incl. | 0.25 <i>p</i> mm                    | 0.10 <i>p</i> + 0.025 mm | 0.20 <i>p</i> + 0.05 mm |
| Nuts  | All Classes                    |                                     | 0.12 <i>p</i> + 0.03 mm  | 0.375 <i>p</i> mm       |

In these formulas, *p* = pitch in millimeters.

**Instrument Makers' Screw Thread System.**—The standard screw system of the Royal Microscopical Society of London, also known as the "Society Thread," is employed for microscope objectives and the nose pieces of the microscope into which these objectives screw. The form of the thread is the standard Whitworth form. The number of threads per inch is 36. There is one size only. The maximum pitch diameter of the objective is 0.7804 inch and the minimum pitch diameter of the nose-piece is 0.7822 inch. The dimensions are as follows:

|               |                |                   |                   |
|---------------|----------------|-------------------|-------------------|
| Male thread   | outside dia.   | max., 0.7982 inch | min., 0.7952 inch |
|               | root dia.      | max., 0.7626 inch | min., 0.7596 inch |
| Female thread | root of thread | max., 0.7674 inch | min., 0.7644 inch |
|               | top of thread  | max., 0.8030 inch | min., 0.8000 inch |

The Royal Photographic Society Standard Screw Thread ranges from 1-inch diameter upward. For screws less than 1 inch, the Microscopical Society Standard is used. The British Association thread is another thread system employed on instruments abroad.

**American Microscope Objective Thread (AMO).**—The standard, ANSI B1.11-1958 (R2001), describes the American microscope objective thread, AMO, the screw thread form used for mounting a microscope objective assembly to the body or lens turret of a microscope. This screw thread is also recommended for other microscope optical assem-

bles as well as related applications such as photomicrographic equipment. It is based on, and intended to be interchangeable with, the screw thread produced and adopted many years ago by the Royal Microscopical Society of Great Britain, generally known as the RMS thread. While the standard is almost universally accepted as the basic standard for microscope objective mountings, formal recognition has been extremely limited.

The basic thread possesses the overall British Standard Whitworth form. (See *Whitworth Standard Thread Form* starting on page 1857). However, the actual design thread form implementation is based on the WWII era ASA B1.6-1944 "Truncated Whitworth Form" in which the rounded crests and roots are removed. ASA B1.6-1944 was withdrawn in 1951, however, ANSI B1.11-1958 (R2001) is still active for new design.

*Design Requirements of Microscope Objective Threads:* Due to the inherent longevity of optical equipment and the repeated use to which the objective threads are subjected, the following factors should be considered when designing microscope objective threads:

Adequate clearance to afford protection against binding due to the presence of foreign particles or minor crest damage.

Sufficient depth of thread engagement to assure security in the short lengths of engagement commonly encountered.

Allowances for limited eccentricities so that centralization and squareness of the objective are not influenced by such errors in manufacture.

*Deviation from the Truncated Whitworth Thread Form:* Although ANSI B1.11-1958 (R2001) is based on the withdrawn ASA B1.6-1944 truncated Whitworth standard, the previously described design requirements necessitate a deviation from the truncated Whitworth thread form. Some of the more significant modifications are:

A larger allowance on the pitch diameter of the external thread.

Smaller tolerances on the major diameter of the external thread and minor diameter of the internal thread.

The provision of allowances on the major and minor diameters of the external thread.

*Thread Overview:* The thread is a single start type. There is only one class of thread based on a basic major diameter of 0.800 in. and a pitch,  $p$ , of 0.027778 inch (36 threads per inch). The AMO thread shall be designated on drawings, tools and gages as "0.800–36 AMO." Thread nomenclature, definitions and terminology are based on ANSI B1.7-1965 (R1972), "Nomenclature, Threads, and Letter Symbols for Screw Threads."

It should also be noted that ISO 8038-1:1997 "Screw threads for objectives and related nosepieces" is also based on the 0.800 inch, 36 tpi RMS thread form.

*Tolerances and Allowances:* Tolerances are given in Table 2. A positive allowance (minimum clearance) of 0.0018 in. is provided for the pitch diameter  $E$ , major diameter  $D$ , and minor diameter,  $K$

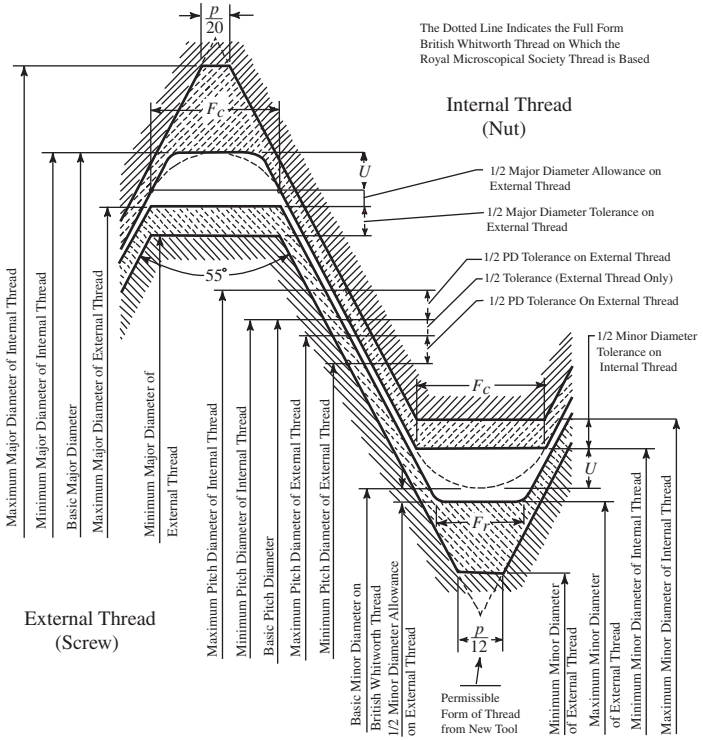
If interchangeability with full-form Whitworth threads is not required, the allowances for the major and minor diameters are not necessary, because the forms at the root and crest are truncated. In these cases, either both limits or only the maximum limit of the major and minor diameters may be increased by the amount of the allowance, 0.0018 inch.

*Lengths of Engagement:* The tolerances specified in Table 2 are applicable to lengths of engagement ranging from  $\frac{1}{8}$  in. to  $\frac{3}{8}$  inch, approximately 15% to 50% of the basic diameter. Microscope objective assemblies generally have a length of engagement of  $\frac{1}{8}$  inch. Lengths exceeding these limits are seldom employed and not covered in this standard.

*Gage testing:* Recommended ring and plug testing gage dimensions for the 0.800–36 AMO thread size can be found in ANSI B1.11–1958 (R2001), Appendix.

*Dimensional Terminology:* Because the active standard ANSI B1.11–1958 (R2001) is based on the withdrawn ASA Truncated Whitworth standard, dimensional nomenclature is described below.

MICROSCOPE OBJECTIVE THREAD



Tolerances, Allowances and Crest Clearances for Microscope Objective Thread (AMO) ANSI B1.11-1958 (R2001)

**Table 1. Definitions, Formulas, Basic and Design Dimensions**  
ANSI B1.11-1958 (R1994)

| Symbol            | Property   | Formula     | Dimension |
|-------------------|--|-------------|-----------|
| Basic Thread Form |  |             |           |
| $\alpha$          | Half angle of thread   | ...         | 27°30'    |
| $2\alpha$         | Included angle of thread   | ...         | 55°00'    |
| $n$               | Number of threads per inch   | ...         | 36        |
| $p$               | Pitch  | $1/n$       | 0.027778  |
| $H$               | Height of fundamental triangle   | $0.960491p$ | 0.026680  |
| $h_b$             | Height of basic thread   | $0.640327p$ | 0.0178    |
| $r$               | Radius at crest and root of British Standard Whitworth basic thread (not used) | $0.137329p$ | 0.0038    |

**Table 1. (Continued) Definitions, Formulas, Basic and Design Dimensions**  
*ANSI B1.11-1958 (R1994)*

| Symbol                 | Property   | Formula               | Dimension |
|------------------------|--|-----------------------|-----------|
| Design Thread Form     |  |                       |           |
| $k$                    | Height of truncated Whitworth thread                       | $h_b - U = 0.566410p$ | 0.0157    |
| $F_c$                  | Width of flat at crest                                     | $0.243624p$           | 0.0068    |
| $F_r$                  | Width of flat at root                                      | $0.166667p$           | 0.0046    |
| $U$                    | Basic truncation of crest from basic Whitworth form        | $0.073917p$           | 0.00205   |
| Basic and Design Sizes |  |                       |           |
| $D$                    | Major diameter, nominal and basic                          | ...                   | 0.800     |
| $D_n$                  | Major diameter of internal thread                          | $D$                   | 0.800     |
| $D_s$                  | Major diameter of external thread <sup>a</sup>             | $D - 2U - G$          | 0.7941    |
| $E$                    | Pitch (effective) diameter, basic                          | $D - h_b$             | 0.7822    |
| $E_n$                  | Pitch (effective) diameter of internal thread              | $D - h_b$             | 0.7822    |
| $E_s$                  | Pitch (effective) diameter of external thread <sup>b</sup> | $D - h_b - G$         | 0.7804    |
| $K$                    | Minor diameter, basic                                      | $D - 2h_b$            | 0.7644    |
| $K_n$                  | Minor diameter of internal thread                          | $D - 2k$              | 0.7685    |
| $K_s$                  | Minor diameter of external thread <sup>a</sup>             | $D - 2h_b - G$        | 0.7626    |
| $G$                    | Allowance at pitch (effective) diameter <sup>a, b</sup>    | ...                   | 0.0018    |

<sup>a</sup> An allowance equal to that on the pitch diameter is also provided on the major and minor diameters of the external thread for additional clearance and centralizing.

<sup>b</sup> Allowance (minimum clearance) on pitch (effective) diameter is the same as the British RMS thread.

All dimensions are in inches.

**Table 2. Limits of Size and Tolerances — 0.800–36 AMO Thread**  
*ANSI B1.11-1958 (R2001)*

| Element         | Major Diameter, $D$ |        |        | Pitch Diameter, $E$ |        |        | Minor Diameter, $K$ |                     |        |
|-----------------|---------------------|--------|--------|---------------------|--------|--------|---------------------|---------------------|--------|
|                 | Max.                | Min.   | Tol.   | Max.                | Min.   | Tol.   | Max.                | Min.                | Tol.   |
| External thread | 0.7941              | 0.7911 | 0.0030 | 0.7804              | 0.7774 | 0.0030 | 0.7626              | 0.7552 <sup>a</sup> | ...    |
| Internal thread | 0.8092 <sup>b</sup> | 0.8000 | ...    | 0.7852              | 0.7822 | 0.0030 | 0.7715              | 0.7865              | 0.0030 |

<sup>a</sup> Extreme minimum minor diameter produced by a new threading tool having a minimum flat of  $p/12 = 0.0023$  inch. This minimum diameter is not controlled by gages but by the form of the threading tool.

<sup>b</sup> Extreme maximum major diameter produced by a new threading tool having a minimum flat of  $p/20 = 0.0014$  inch. This maximum diameter is not controlled by gages but by the form of the threading tool.

Tolerances on the internal thread are applied in a plus direction from the basic and design size and tolerances on the external thread are applied in a minus direction from its design (maximum material) size.

All dimensions are in inches.

**Swiss Screw Thread.**—This is a thread system originated in Switzerland as a standard for screws used in watch and clock making. The angle between the two sides of the thread is 47 degrees 30 minutes, and the top and bottom of the thread are rounded. This system has been adopted by the British Association as a standard for small screws, and is known as the British Association thread. See *British Association Standard Thread (BA)* on page 1885.

### Historical and Miscellaneous Threads

**Aero-Thread.**—The name “Aero-thread” has been applied to a patented screw thread system that is specially applicable in cases where the nut or internally threaded part is made from a soft material, such as aluminum or magnesium alloy, for the sake of obtaining lightness, as in aircraft construction, and where the screw is made from a high-strength steel to provide strength and good wearing qualities. The nut or part containing the internal thread has a 60-degree truncated form of thread. See Fig. 1. The screw, or stud, is provided with a semi-circular thread form, as shown. Between the screw and the nut there is an intermediary part known as a thread lining or insert, which is made in the form of a helical spring, so that it can be screwed into the nut. The stud, in turn, is then screwed into the thread formed by the semicircular part of the thread insert. When the screw is provided with a V-form of thread, like the American Standard, frequent loosening and tightening of the screw would cause rapid wear of the softer metal from which the nut is made; furthermore, all the threads might not have an even bearing on the mating threads. By using a thread insert which is screwed into the nut permanently, and which is made from a reasonably hard material like phosphor bronze, good wearing qualities are obtained. Also, the bearing or load is evenly distributed over all the threads of the nut since the insert, being in the form of a spring, can adjust itself to bear on all of the thread surfaces.

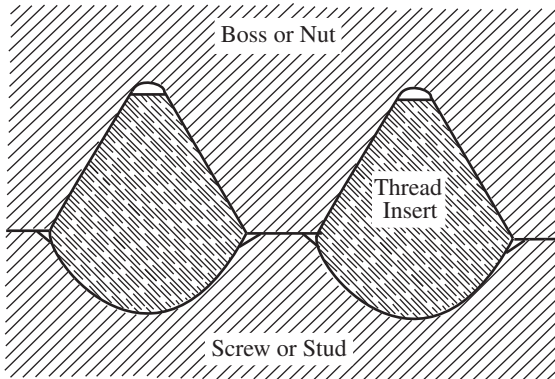


Fig. 1. The Basic Thread Form Used in the Aero-Thread System

**Briggs Pipe Thread.**—The Briggs pipe thread (now known as the American Standard) is used for threaded pipe joints and is the standard for this purpose in the United States. It derives its name from Robert Briggs.

**Casing Thread.**—The standard casing thread of the American Petroleum Institute has an included angle of 60 degrees and a taper of  $\frac{3}{4}$  inch per foot.

The fourteen casing sizes listed in the 1942 revision have outside diameters ranging from  $4\frac{1}{2}$  to 20 inches. All sizes have 8 threads per inch.

**Rounded Thread Form:** Threads for casing sizes up to  $13\frac{3}{8}$  inches, inclusive, have rounded crests and roots, and the depth, measured perpendicular to the axis of the pipe, equals  $0.626 \times \text{pitch} - 0.007 = 0.07125$  inch.

**Truncated Form:** Threads for the 16- and 20-inch casing sizes have flat crests and roots. The depth equals  $0.760 \times \text{pitch} = 0.0950$  inch. This truncated form is designated in the A.P.I. Standard as a “sharp thread.”

**Cordeaux Thread.**—The Cordeaux screw thread derives its name from John Henry Cordeaux, an English telegraph inspector who obtained a patent for this thread in 1877. This thread is used for connecting porcelain insulators with their stalks by means of a screw thread on the stalk and a corresponding thread in the insulator. The thread is approximately a Whitworth thread, 6 threads per inch, the diameters most commonly used being  $\frac{5}{8}$  or  $\frac{3}{4}$  inch outside diameter of thread;  $\frac{5}{8}$  inch is almost universally used for telegraph purposes, while a limited number of  $\frac{3}{4}$ -inch sizes are used for large insulators.

**Dardelet Thread.**—The Dardelet patented self-locking thread is designed to resist vibrations and remain tight without auxiliary locking devices. The locking surfaces are the tapered root of the bolt thread and the tapered crest of the nut thread. The nut is free to turn until seated tightly against a resisting surface, thus causing it to shift from the free position (indicated by dotted lines) to the locking position. The locking is due to a wedging action between the tapered crest of the nut thread and the tapered root or binding surface of the bolt thread. This self-locking thread is also applied to set-screws and cap-screws. The holes must, of course, be threaded with Dardelet taps. The abutment sides of the Dardelet thread carry the major part of the tensile load. The nut is unlocked simply by turning it backward with a wrench. The Dardelet thread can either be cut or rolled, using standard equipment provided with tools, taps, dies, or rolls made to suit the Dardelet thread profile. The included thread angle is 29 degrees; depth  $E = 0.3P$ ; maximum axial movement =  $0.28P$ . The major internal thread diameter (standard series) equals major external thread diameter plus 0.003 inch except for  $\frac{1}{4}$ -inch size which is plus 0.002 inch. The width of both external and internal threads at pitch line equals  $0.36P$ .

**"Drunken" Thread.**—A "drunken" thread, according to prevalent usage of this expression by machinists, etc., is a thread that does not coincide with a true helix or advance uniformly. This irregularity in a taper thread may be due to the fact that in taper turning with the tailstock set over, the work does not turn with a uniform angular velocity, while the cutting tool is advancing along the work longitudinally with a uniform linear velocity. The change in the pitch and the irregularity of the thread is so small as to be imperceptible to the eye, if the taper is slight, but as the tapers increase to, say,  $\frac{3}{4}$  inch per foot or more, the errors become more pronounced. To avoid this defect, a taper attachment should be used for taper thread cutting.

**Echols Thread.**—Chip room is of great importance in machine taps and taper taps where the cutting speed is high and always in one direction. The tap as well as the nut to be threaded is liable to be injured, if ample space for the chips to pass away from the cutting edges is not provided. A method of decreasing the number of cutting edges, as well as increasing the amount of chip room, is embodied in the "Echols thread," where every alternate tooth is removed. If a tap has an even number of flutes, the removal of every other tooth in the lands will be equivalent to the removal of the teeth of a continuous thread. It is, therefore, necessary that taps provided with this thread be made with an odd number of lands, so that removing the tooth in alternate lands may result in removing every other tooth in each individual land. Machine taps are often provided with the Echols thread.

**French Thread (S.F.).**—The French thread has the same form and proportions as the American Standard (formerly U. S. Standard). This French thread is being displaced gradually by the International Metric Thread System.

**Harvey Grip Thread.**—The characteristic feature of this thread is that one side inclines 44 degrees from a line at right angles to the axis, whereas the other side has an inclination of only 1 degree. This form of thread is sometimes used when there is considerable resistance or pressure in an axial direction and when it is desirable to reduce the radial or bursting pressure on the nut as much as possible. See *BUTTRESS THREADS*.



**Lloyd & Lloyd Thread.**—The Lloyd & Lloyd screw thread is the same as the regular Whitworth screw thread in which the sides of the thread form an angle of 55 degrees with one another. The top and bottom of the thread are rounded.

**Lock-Nut Pipe Thread.**—The lock-nut pipe thread is a straight thread of the largest diameter which can be cut on a pipe. Its form is identical with that of the American or Briggs standard taper pipe thread. In general, “Go” gages only are required. These consist of a straight-threaded plug representing the minimum female lock-nut thread, and a straight-threaded ring representing the maximum male lock-nut thread. This thread is used only to hold parts together, or to retain a collar on the pipe. It is never used where a tight threaded joint is required.

**Philadelphia Carriage Bolt Thread.**—This is a screw thread for carriage bolts which is somewhat similar to a square thread, but having rounded corners at the top and bottom. The sides of the thread are inclined to an inclusive angle of  $3\frac{1}{2}$  degrees. The width of the thread at the top is 0.53 times the pitch.

**SAE Standard Screw Thread.**—The screw thread standard of the Society of Automotive Engineers (SAE) is intended for use in the automotive industries of the United States. The SAE Standard includes a Coarse series, a Fine series, an 8-thread series, a 12-thread series, a 16-thread series, an Extra-fine series, and a Special-pitch series. The Coarse and Fine series, and also the 8-, 12- and 16-thread series, are exactly the same as corresponding series in the American Standard. The Extra-fine and Special-pitch series are SAE Standards only.

The American Standard thread *form* (or the form previously known as the U. S. Standard) is applied to all SAE Standard screw threads. The Extra-fine series has a total of six pitches ranging from 32 down to 16 threads per inch. The 16 threads per inch in the Extra-fine series, applies to all diameters from  $1\frac{3}{4}$  up to 6 inches. This Extra-fine series is intended for use on relatively light sections; on parts requiring fine adjustment; where jar and vibration are important factors; when the thickness of a threaded section is relatively small as in tubing, and where assembly is made without the use of wrenches.

The SAE Special pitches include some which are finer than any in the Extra-fine series. The special pitches apply to a range of diameters extending from No. 10 (0.1900 inch) up to 6 inches. Each diameter has a range of pitches varying from five to eight. For example, a  $\frac{1}{4}$ -inch diameter has six pitches ranging from 24 to 56 threads per inch, whereas a 6-inch diameter has eight pitches ranging from 4 to 16 threads per inch. These various SAE Standard series are intended to provide adequate screw thread specifications for all uses in the automotive industries.

**Sellers Screw Thread.**—The Sellers screw thread, later known as the “United States standard thread,” and now as the “American Standard,” is the most commonly used screw thread in the United States. It was originated by William Sellers, of Philadelphia, and first proposed by him in a paper read before the Franklin Institute, in April, 1864. In 1868, it was adopted by the United States Navy and has since become the generally accepted standard screw thread in the United States.

## MEASURING SCREW THREADS

### Measuring Screw Threads

**Pitch and Lead of Screw Threads.**—The *pitch* of a screw thread is the distance from the center of one thread to the center of the next thread. This applies no matter whether the screw has a single, double, triple or quadruple thread. The *lead* of a screw thread is the distance the nut will move forward on the screw if it is turned around one full revolution. In a single-threaded screw, the pitch and lead are equal, because the nut would move forward the distance from one thread to the next, if turned around once. In a double-threaded screw, the nut will move forward two threads, or twice the pitch, so that in this case the lead equals twice the pitch. In a triple-threaded screw, the lead equals three times the pitch, and so on.

The word “pitch” is often, although improperly, used to denote the *number of threads per inch*. Screws are spoken of as having a 12-pitch thread, when twelve threads per inch is what is really meant. The number of threads per inch equals 1 divided by the pitch, or expressed as a formula:

$$\text{Number of threads per inch} = \frac{1}{\text{pitch}}$$

The pitch of a screw equals 1 divided by the number of threads per inch, or:

$$\text{Pitch} = \frac{1}{\text{number of threads per inch}}$$

If the number of threads per inch equals 16, the pitch =  $\frac{1}{16}$ . If the pitch equals 0.05, the number of threads equals  $1 \div 0.05 = 20$ . If the pitch is  $\frac{2}{5}$  inch, the number of threads per inch equals  $1 \div \frac{2}{5} = 2\frac{1}{2}$ .

Confusion is often caused by the indefinite designation of multiple-thread screws (double, triple, quadruple, etc.). The expression, “four threads per inch, triple,” for example, is not to be recommended. It means that the screw is cut with four triple threads or with twelve threads per inch, if the threads are counted by placing a scale alongside the screw. To cut this screw, the lathe would be geared to cut four threads per inch, but they would be cut only to the depth required for twelve threads per inch. The best expression, when a multiple-thread is to be cut, is to say, in this case, “ $\frac{1}{4}$  inch lead,  $\frac{1}{12}$  inch pitch, triple thread.” For single-threaded screws, only the number of threads per inch and the form of the thread are specified. The word “single” is not required.

**Measuring Screw Thread Pitch Diameters by Thread Micrometers.**—As the pitch or angle diameter of a tap or screw is the most important dimension, it is necessary that the pitch diameter of screw threads be measured, in addition to the outside diameter.

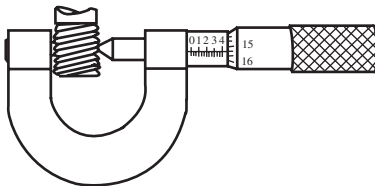


Fig. 1.

One method of measuring in the angle of a thread is by means of a special screw thread micrometer, as shown in the accompanying engraving, Fig. 1. The fixed anvil is W-shaped to engage two thread flanks, and the movable point is cone-shaped so as to enable it to enter the space between two threads, and at the same time be at liberty to revolve. The contact points are on the sides of the thread, as they necessarily must be in order that the pitch diam-

eter may be determined. The cone-shaped point of the measuring screw is slightly rounded so that it will not bear in the bottom of the thread. There is also sufficient clearance at the bottom of the V-shaped anvil to prevent it from bearing on the top of the thread. The movable point is adapted to measuring all pitches, but the fixed anvil is limited in its capacity. To cover the whole range of pitches, from the finest to the coarsest, a number of fixed anvils are therefore required.

To find the theoretical pitch diameter, which is measured by the micrometer, subtract twice the addendum of the thread from the standard outside diameter. The addendum of the thread for the American and other standard threads is given in the section on screw thread systems.

**Ball-point Micrometers.**—If standard plug gages are available, it is not necessary to actually measure the pitch diameter, but merely to compare it with the standard gage. In this case, a ball-point micrometer, as shown in Fig. 2, may be employed. Two types of ball-point micrometers are ordinarily used. One is simply a regular plain micrometer with ball points made to slip over both measuring points. (See B, Fig. 2.) This makes a kind of combination plain and ball-point micrometer, the ball points being easily removed. These ball points, however, do not fit solidly on their seats, even if they are split, as shown, and are apt to cause errors in measurements. The best, and, in the long run, the cheapest, method is to use a regular micrometer arranged as shown at A. Drill and ream out both the end of the measuring screw or spindle and the anvil, and fit ball points into them as shown. Care should be taken to have the ball point in the spindle run true. The holes in the micrometer spindle and anvil and the shanks on the points are tapered to insure a good fit. The hole *H* in spindle *G* is provided so that the ball point can be easily driven out when a change for a larger or smaller size of ball point is required.

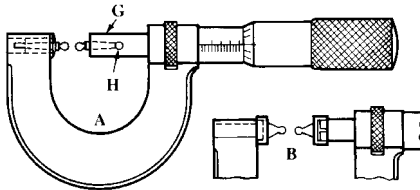


Fig. 2.

A ball-point micrometer may be used for comparing the *angle* of a screw thread, with that of a gage. This can be done by using different sizes of ball points, comparing the size first near the root of the thread, then (using a larger ball point) at about the point of the pitch diameter, and finally near the top of the thread (using in the latter case, of course, a much larger ball point). If the gage and thread measurements are the same at each of the three points referred to, this indicates that the thread angle is correct.

**Measuring Screw Threads by Three-wire Method.**—The *effective* or *pitch diameter* of a screw thread may be measured very accurately by means of some form of micrometer and three wires of equal diameter. This method is extensively used in checking the accuracy of threaded plug gages and other precision screw threads. Two of the wires are placed in contact with the thread on one side and the third wire in a position diametrically opposite as illustrated by the diagram, (see table "Formulas for Checking Pitch Diameters of Screw Threads") and the dimension over the wires is determined by means of a micrometer. An ordinary micrometer is commonly used but some form of "floating micrometer" is preferable, especially for measuring thread gages and other precision work. The floating micrometer is mounted upon a compound slide so that it can move freely in directions parallel or at right angles to the axis of the screw, which is held in a horizontal position between adjustable centers. With this arrangement the micrometer is held constantly at

right angles to the axis of the screw so that only one wire on each side may be used instead of having two on one side and one on the other, as is necessary when using an ordinary micrometer. The pitch diameter may be determined accurately if the correct micrometer reading for wires of a given size is known.

**Classes of Formulas for Three-Wire Measurement.**—Various formulas have been established for checking the pitch diameters of screw threads by measurement over wires of known size. These formulas differ with regard to their simplicity or complexity and resulting accuracy. They also differ in that some show what measurement  $M$  over the wires should be to obtain a given pitch diameter  $E$ , whereas others show the value of the pitch diameter  $E$  for a given measurement  $M$ .

*Formulas for Finding Measurement  $M$ :* In using a formula for finding the value of measurement  $M$ , the required pitch diameter  $E$  is inserted in the formula. Then, in cutting or grinding a screw thread, the actual measurement  $M$  is made to conform to the calculated value of  $M$ . Formulas for finding measurement  $M$  may be modified so that the basic major or outside diameter is inserted in the formula instead of the pitch diameter; however, the pitch-diameter type of formula is preferable because the pitch diameter is a more important dimension than the major diameter.

*Formulas for Finding Pitch Diameters  $E$ :* Some formulas are arranged to show the value of the pitch diameter  $E$  when measurement  $M$  is known. Thus, the value of  $M$  is first determined by measurement and then is inserted in the formula for finding the corresponding pitch diameter  $E$ . This type of formula is useful for determining the pitch diameter of an existing thread gage or other screw thread in connection with inspection work. The formula for finding measurement  $M$  is more convenient to use in the shop or tool room in cutting or grinding new threads, because the pitch diameter is specified on the drawing and the problem is to find the value of measurement  $M$  for obtaining that pitch diameter.

**General Classes of Screw Thread Profiles.**—Thread profiles may be divided into three general classes or types as follows:

*Screw Helicoid:* Represented by a screw thread having a straight-line profile in the axial plane. Such a screw thread may be cut in a lathe by using a straight-sided single-point tool, provided the top surface lies in the axial plane.

*Involute Helicoid:* Represented either by a screw thread or a helical gear tooth having an involute profile in a plane perpendicular to the axis. A rolled screw thread, theoretically at least, is an exact involute helicoid.

*Intermediate Profiles:* An intermediate profile that lies somewhere between the screw helicoid and the involute helicoid will be formed on a screw thread either by milling or grinding with a straight-sided wheel set in alignment with the thread groove. The resulting form will approach closely the involute helicoid form. In milling or grinding a thread, the included cutter or wheel angle may either equal the standard thread angle (which is always measured in the axial plane) or the cutter or wheel angle may be reduced to approximate, at least, the thread angle in the normal plane. In practice, all these variations affect the three-wire measurement.

**Accuracy of Formulas for Checking Pitch Diameters by Three-Wire Method.**—The exact measurement  $M$  for a given pitch diameter depends upon the lead angle, the thread angle, and the profile or cross-sectional shape of the thread. As pointed out in the preceding paragraph, the profile depends upon the method of cutting or forming the thread. In a milled or ground thread, the profile is affected not only by the cutter or wheel angle, but also by the diameter of the cutter or wheel; hence, because of these variations, an absolutely exact and reasonably simple general formula for measurement  $M$  cannot be established; however, if the lead angle is low, as with a standard single-thread screw, and especially if the thread angle is high like a 60-degree thread, simple formulas that are not arranged to compensate for the lead angle are used ordinarily and meet most practical requirements, particularly in measuring 60-degree threads. If lead angles are large enough

to greatly affect the result, as with most multiple threads (especially Acme or 29-degree worm threads), a formula should be used that compensates for the lead angle sufficiently to obtain the necessary accuracy.

The formulas that follow include 1) a very simple type in which the effect of the lead angle on measurement  $M$  is entirely ignored. This simple formula usually is applicable to the measurement of 60-degree single-thread screws, except possibly when gage-making accuracy is required; 2) formulas that do include the effect of the lead angle but, nevertheless, are approximations and not always suitable for the higher lead angles when extreme accuracy is required; and 3) formulas for the higher lead angles and the most precise classes of work.

Where approximate formulas are applied consistently in the measurement of both thread plug gages and the thread "setting plugs" for ring gages, interchangeability might be secured, assuming that such approximate formulas were universally employed.

**Wire Sizes for Checking Pitch Diameters of Screw Threads.**—In checking screw threads by the 3-wire method, the general practice is to use measuring wires of the so-called "best size." The "best-size" wire is one that contacts at the pitch line or midslope of the thread because then the measurement of the pitch diameter is least affected by an error in the thread angle. In the following formula for determining approximately the "best-size" wire or the diameter for pitch-line contact,  $A$  = one-half included angle of thread in the axial plane.

$$\text{Best-size wire} = \frac{0.5 \text{ pitch}}{\cos A} = 0.5 \text{ pitch} \times \sec A$$

For 60-degree threads, this formula reduces to

$$\text{Best-size wire} = 0.57735 \times \text{pitch}$$

### Diameters of Wires for Measuring American Standard and British Standard Whitworth Screw Threads

| Threads per Inch | Pitch, Inch | Wire Diameters for American Standard Threads |        |                    | Wire Diameters for Whitworth Standard Threads |        |                    |
|------------------|-------------|--|--------|--------------------|---|--------|--------------------|
|                  |             | Max.   | Min.   | Pitch-Line Contact | Max.  | Min.   | Pitch-Line Contact |
| 4                | 0.2500      | 0.2250                                       | 0.1400 | 0.1443             | 0.1900  | 0.1350 | 0.1409             |
| 4½               | 0.2222      | 0.2000                                       | 0.1244 | 0.1283             | 0.1689  | 0.1200 | 0.1253             |
| 5                | 0.2000      | 0.1800                                       | 0.1120 | 0.1155             | 0.1520  | 0.1080 | 0.1127             |
| 5½               | 0.1818      | 0.1636                                       | 0.1018 | 0.1050             | 0.1382  | 0.0982 | 0.1025             |
| 6                | 0.1667      | 0.1500                                       | 0.0933 | 0.0962             | 0.1267  | 0.0900 | 0.0939             |
| 7                | 0.1428      | 0.1283                                       | 0.0800 | 0.0825             | 0.1086  | 0.0771 | 0.0805             |
| 8                | 0.1250      | 0.1125                                       | 0.0700 | 0.0722             | 0.0950  | 0.0675 | 0.0705             |
| 9                | 0.1111      | 0.1000                                       | 0.0622 | 0.0641             | 0.0844  | 0.0600 | 0.0626             |
| 10               | 0.1000      | 0.0900                                       | 0.0560 | 0.0577             | 0.0760  | 0.0540 | 0.0564             |
| 11               | 0.0909      | 0.0818                                       | 0.0509 | 0.0525             | 0.0691  | 0.0491 | 0.0512             |
| 12               | 0.0833      | 0.0750                                       | 0.0467 | 0.0481             | 0.0633  | 0.0450 | 0.0470             |
| 13               | 0.0769      | 0.0692                                       | 0.0431 | 0.0444             | 0.0585  | 0.0415 | 0.0434             |
| 14               | 0.0714      | 0.0643                                       | 0.0400 | 0.0412             | 0.0543  | 0.0386 | 0.0403             |
| 16               | 0.0625      | 0.0562                                       | 0.0350 | 0.0361             | 0.0475  | 0.0337 | 0.0352             |
| 18               | 0.0555      | 0.0500                                       | 0.0311 | 0.0321             | 0.0422  | 0.0300 | 0.0313             |
| 20               | 0.0500      | 0.0450                                       | 0.0280 | 0.0289             | 0.0380  | 0.0270 | 0.0282             |
| 22               | 0.0454      | 0.0409                                       | 0.0254 | 0.0262             | 0.0345  | 0.0245 | 0.0256             |
| 24               | 0.0417      | 0.0375                                       | 0.0233 | 0.0240             | 0.0317  | 0.0225 | 0.0235             |
| 28               | 0.0357      | 0.0321                                       | 0.0200 | 0.0206             | 0.0271  | 0.0193 | 0.0201             |
| 32               | 0.0312      | 0.0281                                       | 0.0175 | 0.0180             | 0.0237  | 0.0169 | 0.0176             |
| 36               | 0.0278      | 0.0250                                       | 0.0156 | 0.0160             | 0.0211  | 0.0150 | 0.0156             |
| 40               | 0.0250      | 0.0225                                       | 0.0140 | 0.0144             | 0.0190  | 0.0135 | 0.0141             |

These formulas are based upon a thread groove of zero lead angle because ordinary variations in the lead angle have little effect on the wire diameter and it is desirable to use one wire size for a given pitch regardless of the lead angle. A theoretically correct solution for finding the *exact* size for pitch-line contact involves the use of cumbersome indeterminate equations with solution by successive trials. The accompanying table gives the wire sizes for both American Standard (formerly, U.S. Standard) and the Whitworth Standard Threads. The following formulas for determining wire diameters do not give the extreme theoretical limits, but the smallest and largest practicable sizes. The diameters in the table are based upon these approximate formulas.

|                   |   |
|-------------------|---|
|                   | Smallest wire diameter = $0.56 \times \text{pitch}$             |
| American Standard | Largest wire diameter = $0.90 \times \text{pitch}$              |
|                   | Diameter for pitch-line contact = $0.57735 \times \text{pitch}$ |
|                   | Smallest wire diameter = $0.54 \times \text{pitch}$             |
| Whitworth         | Largest wire diameter = $0.76 \times \text{pitch}$              |
|                   | Diameter for pitch-line contact = $0.56369 \times \text{pitch}$ |

**Measuring Wire Accuracy.**—A set of three measuring wires should have the same diameter within 0.0002 inch. To measure the pitch diameter of a screw-thread gage to an accuracy of 0.0001 inch by means of wires, it is necessary to know the wire diameters to 0.00002 inch. If the diameters of the wires are known only to an accuracy of 0.0001 inch, an accuracy better than 0.0003 inch in the measurement of pitch diameter cannot be expected. The wires should be accurately finished hardened steel cylinders of the maximum possible hardness without being brittle. The hardness should not be less than that corresponding to a Knoop indentation number of 630. A wire of this hardness can be cut with a file only with difficulty. The surface should not be rougher than the equivalent of a deviation of 3 microinches from a true cylindrical surface.

**Measuring or Contact Pressure.**—In measuring screw threads or screw-thread gages by the 3-wire method, variations in contact pressure will result in different readings. The effect of a variation in contact pressure in measuring threads of fine pitches is indicated by the difference in readings obtained with pressures of 2 and 5 pounds in checking a thread plug gage having 24 threads per inch. The reading over the wires with 5 pounds pressure was 0.00013 inch less than with 2 pounds pressure. For pitches finer than 20 threads per inch, a pressure of 16 ounces is recommended by the National Bureau of Standards, now National Institute of Standards and Technology (NIST). For pitches of 20 threads per inch and coarser, a pressure of  $2 \frac{1}{2}$  pounds is recommended.

For Acme threads, the wire presses against the sides of the thread with a pressure of approximately twice that of the measuring instrument. To limit the tendency of the wires to wedge in between the sides of an Acme thread, it is recommended that pitch-diameter measurements be made at 1 pound on 8 threads per inch and finer, and at  $2 \frac{1}{2}$  pounds for pitches coarser than 8 threads per inch.

**Approximate Three-Wire Formulas That Do Not Compensate for Lead Angle.**—A general formula in which the effect of lead angle is ignored is as follows (see accompanying notation used in formulas):

$$M = E - T \cot A + W(1 + \csc A) \quad (1)$$

This formula can be simplified for any given thread angle and pitch. To illustrate, because  $T = 0.5P$ ,  $M = E - 0.5P \cot 30^\circ + W(1 + 2)$ , for a 60-degree thread, such as the American Standard,

$$M = E - 0.866025P + 3W$$

The accompanying table contains these simplified formulas for different standard threads. Two formulas are given for each. The upper one is used when the measurement over wires,  $M$ , is known and the corresponding pitch diameter,  $E$ , is required; the lower formula gives the measurement  $M$  for a specified value of pitch diameter. These formulas are sufficiently accurate for checking practically all standard 60-degree single-thread screws because of the low lead angles, which vary from  $1^\circ 11'$  to  $4^\circ 31'$  in the American Standard Coarse-Thread Series.

**Bureau of Standards (now NIST) General Formula.**—**Formula (2)**, which follows, compensates quite largely for the effect of the lead angle. It is from the National Bureau of Standards Handbook H 28 (1944), now FED-STD-H28. The formula, however, as here given has been arranged for finding the value of  $M$  (instead of  $E$ ).

$$M = E - T \cot A + W(1 + \csc A + 0.5 \tan^2 B \cos A \cot A) \quad (2)$$

This expression is also found in ANSI/ASME B1.2-1983 (R2001). The Bureau of Standards uses **Formula (2)** in preference to **Formula (1)** when the value of  $0.5W \tan^2 B \cos A \cot A$  exceeds 0.00015, with the larger lead angles. If this test is applied to American Standard 60-degree threads, it will show that **Formula (1)** is generally applicable; but for 29-degree Acme or worm threads, **Formula (2)** (or some other that includes the effect of lead angle) should be employed.

#### Notation Used in Formulas for Checking Pitch Diameters by Three-Wire Method

$A$  = one-half included thread angle in the axial plane

$A_n$  = one-half included thread angle in the normal plane or in plane perpendicular to sides of thread = one-half included angle of cutter when thread is milled ( $\tan A_n = \tan A \times \cos B$ ). (Note: Included angle of milling cutter or grinding wheel may equal the nominal included angle of thread, or may be reduced to whatever normal angle is required to make the thread angle standard in the axial plane. In either case,  $A_n$  = one-half cutter angle.)

$B$  = lead angle at pitch diameter = helix angle of thread as measured from a plane perpendicular to the axis,  $\tan B = L \div 3.1416E$

$D$  = basic major or outside diameter

$E$  = pitch diameter (basic, maximum, or minimum) for which  $M$  is required, or pitch diameter corresponding to measurement  $M$

$F$  = angle required in **Formulas (4b)**, **(4d)**, and **(4e)**

$G$  = angle required in **Formula (4)**

$H$  = helix angle at pitch diameter and measured from axis =  $90^\circ - B$  or  $\tan H = \cot B$

$H_b$  = helix angle at  $R_b$  measured from axis

$L$  = lead of thread = pitch  $P \times$  number of threads  $S$

$M$  = dimension over wires

$P$  = pitch =  $1 \div$  number of threads per inch

$R_b$  = radius required in **Formulas (4)** and **(4e)**

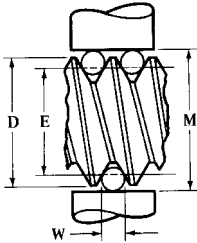
$S$  = number of "starts" or threads on a multiple-threaded worm or screw

$T = 0.5 P$  = width of thread in axial plane at diameter  $E$

$T_a$  = arc thickness on pitch cylinder in plane perpendicular to axis

$W$  = wire or pin diameter

## Formulas for Checking Pitch Diameters of Screw Threads



The formulas below do not compensate for the effect of the lead angle upon measurement  $M$ , but they are sufficiently accurate for checking standard single-thread screws unless exceptional accuracy is required. See accompanying information on effect of lead angle; also matter relating to measuring wire sizes, accuracy required for such wires, and contact or measuring pressure.

The approximate best wire size for pitch-line contact may be obtained by the formula

$$W = 0.5 \times \text{pitch} \times \sec \frac{1}{2} \text{ included thread angle}$$

For 60-degree threads,  $W = 0.57735 \times \text{pitch}$ .

| Form of Thread                     | Formulas for determining measurement $M$ corresponding to correct pitch diameter and the pitch diameter $E$ corresponding to a given measurement over wires. <sup>a</sup>                     |
|------------------------------------|---|
| American National Standard Unified | When measurement $M$ is known, $E = M + 0.866025P - 3W$<br>When pitch diameter $E$ is used in formula, $M = E - 0.866025P + 3W$<br>The American Standard formerly was known as U.S. Standard. |
| British Standard Whitworth         | When measurement $M$ is known, $E = M + 0.9605P - 3.1657W$<br>When pitch diameter $E$ is used in formula, $M = E - 0.9605P + 3.1657W$   |
| British Association Standard       | When measurement $M$ is known, $E = M + 1.1363P - 3.4829W$<br>When pitch diameter $E$ is used in formula, $M = E - 1.1363P + 3.4829W$   |
| Lowenherz Thread                   | When measurement $M$ is known, $E = M + P - 3.2359W$<br>When pitch diameter $E$ is used in formula, $M = E - P + 3.2359W$   |
| Sharp V-Thread                     | When measurement $M$ is known, $E = M + 0.866025P - 3W$<br>When pitch diameter $E$ is used in formula, $M = E - 0.866025P + 3W$   |
| International Standard             | Use the formula above for the American National Standard Unified Thread.  |
| Pipe Thread                        | See accompanying paragraph on <i>Buckingham Exact Involute Helicoid Formula Applied to Screw Threads</i> .  |
| Acme and Worm Threads              | See Buckingham Formulas page 1903; also <i>Three-wire Measurement of Acme and Stub Acme Thread Pitch Diameter</i> .   |
| Buttress Form of Thread            | Different forms of buttress threads are used. See paragraph on <i>Three-Wire Method Applied to Buttress Threads</i> .   |

<sup>a</sup>The wires must be lapped to a uniform diameter and it is very important to insert in the rule or formula the wire diameter as determined by precise means of measurement. Any error will be multiplied. See paragraph on *Wire Sizes for Checking Pitch Diameters of Screw Threads* on page 1896.

**Why Small Thread Angle Affects Accuracy of Three-Wire Measurement.**—In measuring or checking Acme threads, or any others having a comparatively small thread angle  $A$ , it is particularly important to use a formula that compensates largely, if not entirely, for the effect of the lead angle, especially in all gage and precision work. The effect of the lead angle on the position of the wires and upon the resulting measurement  $M$  is much greater in a 29-degree thread than in a higher thread angle such, for example, as a 60-degree thread. This effect results from an increase in the cotangent of the thread angle as this angle becomes smaller. The reduction in the width of the thread groove in the normal plane due



to the lead angle causes a wire of given size to rest higher in the groove of a thread having a small thread angle  $A$  (like a 29-degree thread) than in the groove of a thread with a larger angle (like a 60-degree American Standard).

*Acme Threads:* Three-wire measurements of high accuracy require the use of [Formula \(4\)](#). For most measurements, however, [Formula \(2\)](#) or [\(3\)](#) gives satisfactory results. The table on page [1906](#) lists suitable wire sizes for use in [Formulas \(2\)](#) and [\(4\)](#).

### Values of Constants Used in Formulas for Measuring Pitch Diameters of Screws by the Three-wire System

| No. of Threads per Inch | American Standard Unified and Sharp V-Thread<br>0.866025P | Whitworth Thread<br>0.9605P | No. of Threads per Inch | American Standard Unified and Sharp V-Thread<br>0.866025P | Whitworth Thread<br>0.9605P |
|-------------------------|---|-----------------------------|-------------------------|---|-----------------------------|
| 2¼                      | 0.38490   | 0.42689                     | 18                      | 0.04811   | 0.05336                     |
| 2⅜                      | 0.36464   | 0.40442                     | 20                      | 0.04330   | 0.04803                     |
| 2½                      | 0.34641   | 0.38420                     | 22                      | 0.03936   | 0.04366                     |
| 2⅝                      | 0.32992   | 0.36590                     | 24                      | 0.03608   | 0.04002                     |
| 2¾                      | 0.31492   | 0.34927                     | 26                      | 0.03331   | 0.03694                     |
| 2⅞                      | 0.30123   | 0.33409                     | 28                      | 0.03093   | 0.03430                     |
| 3                       | 0.28868   | 0.32017                     | 30                      | 0.02887   | 0.03202                     |
| 3¼                      | 0.26647   | 0.29554                     | 32                      | 0.02706   | 0.03002                     |
| 3½                      | 0.24744   | 0.27443                     | 34                      | 0.02547   | 0.02825                     |
| 4                       | 0.21651   | 0.24013                     | 36                      | 0.02406   | 0.02668                     |
| 4½                      | 0.19245   | 0.21344                     | 38                      | 0.02279   | 0.02528                     |
| 5                       | 0.17321   | 0.19210                     | 40                      | 0.02165   | 0.02401                     |
| 5½                      | 0.15746   | 0.17464                     | 42                      | 0.02062   | 0.02287                     |
| 6                       | 0.14434   | 0.16008                     | 44                      | 0.01968   | 0.02183                     |
| 7                       | 0.12372   | 0.13721                     | 46                      | 0.01883   | 0.02088                     |
| 8                       | 0.10825   | 0.12006                     | 48                      | 0.01804   | 0.02001                     |
| 9                       | 0.09623   | 0.10672                     | 50                      | 0.01732   | 0.01921                     |
| 10                      | 0.08660   | 0.09605                     | 52                      | 0.01665   | 0.01847                     |
| 11                      | 0.07873   | 0.08732                     | 56                      | 0.01546   | 0.01715                     |
| 12                      | 0.07217   | 0.08004                     | 60                      | 0.01443   | 0.01601                     |
| 13                      | 0.06662   | 0.07388                     | 64                      | 0.01353   | 0.01501                     |
| 14                      | 0.06186   | 0.06861                     | 68                      | 0.01274   | 0.01412                     |
| 15                      | 0.05774   | 0.06403                     | 72                      | 0.01203   | 0.01334                     |
| 16                      | 0.05413   | 0.06003                     | 80                      | 0.01083   | 0.01201                     |

### Constants Used for Measuring Pitch Diameters of Metric Screws by the Three-wire System

| Pitch in mm | 0.866025P in Inches | W in Inches | Pitch in mm | 0.866025P in Inches | W in Inches | Pitch in mm | 0.866025P in Inches | W in Inches |
|-------------|---------------------|-------------|-------------|---------------------|-------------|-------------|---------------------|-------------|
| 0.2         | 0.00682             | 0.00455     | 0.75        | 0.02557             | 0.01705     | 3.5         | 0.11933             | 0.07956     |
| 0.25        | 0.00852             | 0.00568     | 0.8         | 0.02728             | 0.01818     | 4           | 0.13638             | 0.09092     |
| 0.3         | 0.01023             | 0.00682     | 1           | 0.03410             | 0.02273     | 4.5         | 0.15343             | 0.10229     |
| 0.35        | 0.01193             | 0.00796     | 1.25        | 0.04262             | 0.02841     | 5           | 0.17048             | 0.11365     |
| 0.4         | 0.01364             | 0.00909     | 1.5         | 0.05114             | 0.03410     | 5.5         | 0.18753             | 0.12502     |
| 0.45        | 0.01534             | 0.01023     | 1.75        | 0.05967             | 0.03978     | 6           | 0.20457             | 0.13638     |
| 0.5         | 0.01705             | 0.01137     | 2           | 0.06819             | 0.04546     | 8           | 0.30686             | 0.18184     |
| 0.6         | 0.02046             | 0.01364     | 2.5         | 0.08524             | 0.05683     | ...         | ...                 | ...         |
| 0.7         | 0.02387             | 0.01591     | 3           | 0.10229             | 0.06819     | ...         | ...                 | ...         |

This table may be used for American National Standard Metric Threads. The formulas for American Standard Unified Threads on page [1899](#) are used. In the table above, the values of  $0.866025P$  and  $W$  are in inches so that the values for  $E$  and  $M$  calculated from the formulas on page [1899](#) are also in inches.

**Dimensions Over Wires of Given Diameter for Checking Screw Threads  
of American National Form (U.S. Standard) and the V-Form**

| Dia. of Thread | No. of Threads per Inch | Wire Dia. Used | Dimension over Wires |             | Dia. of Thread | No. of Threads per Inch | Wire Dia. Used | Dimension over Wires |             |
|----------------|-------------------------|----------------|----------------------|-------------|----------------|-------------------------|----------------|----------------------|-------------|
|                |                         |                | V-Thread             | U.S. Thread |                |                         |                | V-Thread             | U.S. Thread |
| 1/4            | 18                      | 0.035          | 0.2588               | 0.2708      | 7/8            | 8                       | 0.090          | 0.9285               | 0.9556      |
| 1/4            | 20                      | 0.035          | 0.2684               | 0.2792      | 7/8            | 9                       | 0.090          | 0.9525               | 0.9766      |
| 1/4            | 22                      | 0.035          | 0.2763               | 0.2861      | 7/8            | 10                      | 0.090          | 0.9718               | 0.9935      |
| 1/4            | 24                      | 0.035          | 0.2828               | 0.2919      | 15/16          | 8                       | 0.090          | 0.9910               | 1.0181      |
| 5/16           | 18                      | 0.035          | 0.3213               | 0.3333      | 15/16          | 9                       | 0.090          | 1.0150               | 1.0391      |
| 5/16           | 20                      | 0.035          | 0.3309               | 0.3417      | 1              | 8                       | 0.090          | 1.0535               | 1.0806      |
| 5/16           | 22                      | 0.035          | 0.3388               | 0.3486      | 1              | 9                       | 0.090          | 1.0775               | 1.1016      |
| 5/16           | 24                      | 0.035          | 0.3453               | 0.3544      | 1 1/8          | 7                       | 0.090          | 1.1476               | 1.1785      |
| 3/8            | 16                      | 0.040          | 0.3867               | 0.4003      | 1 1/4          | 7                       | 0.090          | 1.2726               | 1.3035      |
| 3/8            | 18                      | 0.040          | 0.3988               | 0.4108      | 1 3/8          | 6                       | 0.150          | 1.5363               | 1.5724      |
| 3/8            | 20                      | 0.040          | 0.4084               | 0.4192      | 1 1/2          | 6                       | 0.150          | 1.6613               | 1.6974      |
| 7/16           | 14                      | 0.050          | 0.4638               | 0.4793      | 1 5/8          | 5 1/2                   | 0.150          | 1.7601               | 1.7995      |
| 7/16           | 16                      | 0.050          | 0.4792               | 0.4928      | 1 3/4          | 5                       | 0.150          | 1.8536               | 1.8969      |
| 1/2            | 12                      | 0.050          | 0.5057               | 0.5237      | 1 7/8          | 5                       | 0.150          | 1.9786               | 2.0219      |
| 1/2            | 13                      | 0.050          | 0.5168               | 0.5334      | 2              | 4 1/2                   | 0.150          | 2.0651               | 2.1132      |
| 1/2            | 14                      | 0.050          | 0.5263               | 0.5418      | 2 1/4          | 4 1/2                   | 0.150          | 2.3151               | 2.3632      |
| 9/16           | 12                      | 0.050          | 0.5682               | 0.5862      | 2 1/2          | 4                       | 0.150          | 2.5170               | 2.5711      |
| 9/16           | 14                      | 0.050          | 0.5888               | 0.6043      | 2 3/4          | 4                       | 0.150          | 2.7670               | 2.8211      |
| 5/8            | 10                      | 0.070          | 0.6618               | 0.6835      | 3              | 3 1/2                   | 0.200          | 3.1051               | 3.1670      |
| 5/8            | 11                      | 0.070          | 0.6775               | 0.6972      | 3 1/4          | 3 1/2                   | 0.200          | 3.3551               | 3.4170      |
| 5/8            | 12                      | 0.070          | 0.6907               | 0.7087      | 3 1/2          | 3 1/4                   | 0.250          | 3.7171               | 3.7837      |
| 11/16          | 10                      | 0.070          | 0.7243               | 0.7460      | 3 3/4          | 3                       | 0.250          | 3.9226               | 3.9948      |
| 11/16          | 11                      | 0.070          | 0.7400               | 0.7597      | 4              | 3                       | 0.250          | 4.1726               | 4.2448      |
| 3/4            | 10                      | 0.070          | 0.7868               | 0.8085      | 4 1/4          | 2 3/8                   | 0.250          | 4.3975               | 4.4729      |
| 3/4            | 11                      | 0.070          | 0.8025               | 0.8222      | 4 1/2          | 2 3/4                   | 0.250          | 4.6202               | 4.6989      |
| 3/4            | 12                      | 0.070          | 0.8157               | 0.8337      | 4 3/4          | 2 5/8                   | 0.250          | 4.8402               | 4.9227      |
| 13/16          | 9                       | 0.070          | 0.8300               | 0.8541      | 5              | 2 1/2                   | 0.250          | 5.0572               | 5.1438      |
| 13/16          | 10                      | 0.070          | 0.8493               | 0.8710      | ...            | ...                     | ...            | ...                  | ...         |

**Buckingham Simplified Formula which Includes Effect of Lead Angle.**—The **Formula (3)** which follows gives very accurate results for the lower lead angles in determining measurement  $M$ . However, if extreme accuracy is essential, it may be advisable to use the involute helicoid formulas as explained later.

$$M = E + W(1 + \sin A_n) \quad (3) \quad \text{where} \quad W = \frac{T \times \cos B}{\cos A_n} \quad (3a)$$

Theoretically correct equations for determining measurement  $M$  are complex and cumbersome to apply. **Formula (3)** combines simplicity with a degree of accuracy which meets all but the most exacting requirements, particularly for lead angles below 8 or 10 degrees and the higher thread angles. However, the wire diameter used in **Formula (3)** must conform to that obtained by **Formula (3a)** to permit a direct solution or one not involving indeterminate equations and successive trials.

**Application of Buckingham Formula:** In the application of **Formula (3)** to screw or worm threads, two general cases are to be considered.

**Case 1:** The screw thread or worm is to be milled with a cutter having an included angle equal to the nominal or standard thread angle that is assumed to be the angle in the axial plane. For example, a 60-degree cutter is to be used for milling a thread. In this case, the

**Table for Measuring Whitworth Standard Threads by the Three-wire Method**

| Dia. of Thread   | No. of Threads per Inch | Dia. of Wire Used | Dia. Measured over Wires | Dia. of Thread | No. of Threads per Inch | Dia. of Wire Used | Dia. Measured over Wires |
|------------------|-------------------------|-------------------|--------------------------|----------------|-------------------------|-------------------|--------------------------|
| $\frac{1}{8}$    | 40                      | 0.018             | 0.1420                   | $2\frac{1}{4}$ | 4                       | 0.150             | 2.3247                   |
| $\frac{3}{16}$   | 24                      | 0.030             | 0.2158                   | $2\frac{3}{8}$ | 4                       | 0.150             | 2.4497                   |
| $\frac{1}{4}$    | 20                      | 0.035             | 0.2808                   | $2\frac{1}{2}$ | 4                       | 0.150             | 2.5747                   |
| $\frac{5}{16}$   | 18                      | 0.040             | 0.3502                   | $2\frac{5}{8}$ | 4                       | 0.150             | 2.6997                   |
| $\frac{3}{8}$    | 16                      | 0.040             | 0.4015                   | $2\frac{3}{4}$ | $3\frac{1}{2}$          | 0.200             | 2.9257                   |
| $\frac{7}{16}$   | 14                      | 0.050             | 0.4815                   | $2\frac{7}{8}$ | $3\frac{1}{2}$          | 0.200             | 3.0507                   |
| $\frac{1}{2}$    | 12                      | 0.050             | 0.5249                   | 3              | $3\frac{1}{2}$          | 0.200             | 3.1757                   |
| $\frac{9}{16}$   | 12                      | 0.050             | 0.5874                   | $3\frac{1}{8}$ | $3\frac{1}{2}$          | 0.200             | 3.3007                   |
| $\frac{5}{8}$    | 11                      | 0.070             | 0.7011                   | $3\frac{1}{4}$ | $3\frac{1}{4}$          | 0.200             | 3.3905                   |
| $\frac{11}{16}$  | 11                      | 0.070             | 0.7636                   | $3\frac{3}{8}$ | $3\frac{1}{4}$          | 0.200             | 3.5155                   |
| $\frac{3}{4}$    | 10                      | 0.070             | 0.8115                   | $3\frac{1}{2}$ | $3\frac{1}{4}$          | 0.200             | 3.6405                   |
| $\frac{13}{16}$  | 10                      | 0.070             | 0.8740                   | $3\frac{5}{8}$ | $3\frac{1}{4}$          | 0.200             | 3.7655                   |
| $\frac{7}{8}$    | 9                       | 0.070             | 0.9187                   | $3\frac{3}{4}$ | 3                       | 0.200             | 3.8495                   |
| $\frac{15}{16}$  | 9                       | 0.070             | 0.9812                   | $3\frac{7}{8}$ | 3                       | 0.200             | 3.9745                   |
| 1                | 8                       | 0.090             | 1.0848                   | 4              | 3                       | 0.200             | 4.0995                   |
| $1\frac{1}{16}$  | 8                       | 0.090             | 1.1473                   | $4\frac{1}{8}$ | 3                       | 0.200             | 4.2245                   |
| $1\frac{1}{8}$   | 7                       | 0.090             | 1.1812                   | $4\frac{1}{4}$ | $2\frac{7}{8}$          | 0.250             | 4.4846                   |
| $1\frac{3}{16}$  | 7                       | 0.090             | 1.2437                   | $4\frac{3}{8}$ | $2\frac{7}{8}$          | 0.250             | 4.6096                   |
| $1\frac{1}{4}$   | 7                       | 0.090             | 1.3062                   | $4\frac{1}{2}$ | $2\frac{7}{8}$          | 0.250             | 4.7346                   |
| $1\frac{5}{16}$  | 7                       | 0.090             | 1.3687                   | $4\frac{5}{8}$ | $2\frac{7}{8}$          | 0.250             | 4.8596                   |
| $1\frac{3}{8}$   | 6                       | 0.120             | 1.4881                   | $4\frac{3}{4}$ | $2\frac{3}{4}$          | 0.250             | 4.9593                   |
| $1\frac{7}{16}$  | 6                       | 0.120             | 1.5506                   | $4\frac{7}{8}$ | $2\frac{3}{4}$          | 0.250             | 5.0843                   |
| $1\frac{1}{2}$   | 6                       | 0.120             | 1.6131                   | 5              | $2\frac{3}{4}$          | 0.250             | 5.2093                   |
| $1\frac{9}{16}$  | 6                       | 0.120             | 1.6756                   | $5\frac{1}{8}$ | $2\frac{3}{4}$          | 0.250             | 5.3343                   |
| $1\frac{5}{8}$   | 5                       | 0.120             | 1.6847                   | $5\frac{1}{4}$ | $2\frac{5}{8}$          | 0.250             | 5.4316                   |
| $1\frac{11}{16}$ | 5                       | 0.120             | 1.7472                   | $5\frac{3}{8}$ | $2\frac{5}{8}$          | 0.250             | 5.5566                   |
| $1\frac{3}{4}$   | 5                       | 0.120             | 1.8097                   | $5\frac{1}{2}$ | $2\frac{5}{8}$          | 0.250             | 5.6816                   |
| $1\frac{13}{16}$ | 5                       | 0.120             | 1.8722                   | $5\frac{5}{8}$ | $2\frac{5}{8}$          | 0.250             | 5.8066                   |
| $1\frac{7}{8}$   | $4\frac{1}{2}$          | 0.150             | 1.9942                   | $5\frac{3}{4}$ | $2\frac{1}{2}$          | 0.250             | 5.9011                   |
| $1\frac{15}{16}$ | $4\frac{1}{2}$          | 0.150             | 2.0567                   | $5\frac{7}{8}$ | $2\frac{1}{2}$          | 0.250             | 6.0261                   |
| 2                | $4\frac{1}{2}$          | 0.150             | 2.1192                   | 6              | $2\frac{1}{2}$          | 0.250             | 6.1511                   |
| $2\frac{1}{8}$   | $4\frac{1}{2}$          | 0.150             | 2.2442                   | ...            | ...                     | ...               | ...                      |

All dimensions are given in inches.

thread angle in the plane of the axis will exceed 60 degrees by an amount increasing with the lead angle. This variation from the standard angle may be of little or no practical importance if the lead angle is small or if the mating nut (or teeth in worm gearing) is formed to suit the thread as milled.

*Case 2:* The screw thread or worm is to be milled with a cutter reduced to whatever normal angle is equivalent to the standard thread angle in the axial plane. For example, a 29-degree Acme thread is to be milled with a cutter having some angle smaller than 29 degrees (the reduction increasing with the lead angle) to make the thread angle standard in the plane of the axis. Theoretically, the milling cutter angle should always be corrected to suit the normal angle; but if the lead angle is small, such correction may be unnecessary.

If the thread is cut in a lathe to the standard angle as measured in the axial plane, Case 2 applies in determining the pin size  $W$  and the overall measurement  $M$ .

In solving all problems under Case 1, angle  $A_n$  used in Formulas (3) and (3a) equals one-half the included angle of the milling cutter.

When Case 2 applies, angle  $A_n$  for milled threads also equals one-half the included angle of the cutter, but the cutter angle is reduced and is determined as follows:

$$\tan A_n = \tan A \times \cos B$$

The included angle of the cutter or the normal included angle of the thread groove =  $2A_n$ . Examples 1 and 2, which follow, illustrate Cases 1 and 2.

*Example 1 (Case 1):* Take, for example, an Acme screw thread that is milled with a cutter having an included angle of 29 degrees; consequently, the angle of the thread exceeds 29 degrees in the axial section.

The outside or major diameter is 3 inches; the pitch,  $\frac{1}{2}$  inch; the lead, 1 inch; the number of threads or "starts," 2. Find pin size  $W$  and measurement  $M$ .

Pitch diameter  $E = 2.75$ ;  $T = 0.25$ ;  $L = 1.0$ ;  $A_n = 14.50^\circ$   $\tan A_n = 0.258618$ ;  $\sin A_n = 0.25038$ ; and  $\cos A_n = 0.968148$ .

$$\tan B = \frac{1.0}{3.1416 \times 2.75} = 0.115749 \quad B = 6.6025^\circ$$

$$W = \frac{0.25 \times 0.993368}{0.968148} = 0.25651 \text{ inch}$$

$$M = 2.75 + 0.25651 \times (1 + 0.25038) = 3.0707 \text{ inches}$$

*Note:* This value of  $M$  is only 0.0001 inch larger than that obtained by using the very accurate involute helicoid Formula (4) discussed on the following page.

*Example 2 (Case 2):* A triple-threaded worm has a pitch diameter of 2.481 inches, pitch of 1.5 inches, lead of 4.5 inches, lead angle of 30 degrees, and nominal thread angle of 60 degrees in the axial plane. Milling cutter angle is to be reduced.  $T = 0.75$  inch;  $\cos B = 0.866025$ ; and  $\tan A = 0.57735$ . Again use Formula (3) to see if it is applicable.

$\tan A_n = \tan A \times \cos B = 0.57735 \times 0.866025 = 0.5000$ ; hence  $A_n = 26.565^\circ$ , making the included cutter angle  $53.13^\circ$ , thus  $\cos A_n = 0.89443$  and  $\sin A_n = 0.44721$ .

$$W = \frac{0.75 \times 0.866025}{0.89443} = 0.72618 \text{ inch}$$

$$M = 2.481 + 0.72618 \times (1 + 0.44721) = 3.532 \text{ inches}$$

*Note:* If the value of measurement  $M$  is determined by using the following Formula (4) it will be found that  $M = 3.515$  inches; hence the error equals  $3.532 - 3.515 = 0.017$  inch approximately, which indicates that Formula (3) is not accurate enough here. The application of this simpler Formula (3) will depend upon the lead angle and thread angle (as previously explained) and upon the class of work.

**Buckingham Exact Involute Helicoid Formula Applied to Screw Threads.**—When extreme accuracy is required in finding measurement  $M$  for obtaining a given pitch diameter, the equations that follow, although somewhat cumbersome to apply, have the merit of providing a direct and very accurate solution; consequently, they are preferable to the indeterminate equations and successive trial solutions heretofore employed when extreme precision is required. These equations are exact for involute helical gears and, consequently, give theoretically correct results when applied to a screw thread of the involute helicoidal form; they also give very close approximations for threads having intermediate profiles.

*Helical Gear Equation Applied to Screw Thread Measurement:* In applying the helical gear equations to a screw thread, use either the axial or normal thread angle and the lead

angle of the helix. To keep the solution on a practical basis, either thread angle  $A$  or  $A_n$ , as the case may be, is assumed to equal the cutter angle of a milled thread. Actually, the profile of a milled thread will have some curvature in both axial and normal sections; hence angles  $A$  and  $A_n$  represent the angular approximations of these slightly curved profiles. The equations that follow give the values needed to solve the screw thread problem as a helical gear problem.

$$M = \frac{2R_b}{\cos G} + W \quad (4)$$

$$\tan F = \frac{\tan A}{\tan B} = \frac{\tan A_n}{\sin B} \quad (4a) \quad R_b = \frac{E}{2} \cos F \quad (4b)$$

$$T_a = \frac{T}{\tan B} \quad (4c) \quad \tan H_b = \cos F \times \tan H \quad (4d)$$

$$\text{inv } G = \frac{T_a}{E} + \text{inv } F + \frac{W}{2R_b \cos H_b} - \frac{\pi}{S} \quad (4e)$$

The tables of involute functions starting on page 104 provide values for angles from 14 to 51 degrees, used for gear calculations. The formula for involute functions on page 103 may be used to extend this table as required.

*Example 3:* To illustrate the application of [Formula \(4\)](#) and the supplementary formulas, assume that the number of starts  $S = 6$ ; pitch diameter  $E = 0.6250$ ; normal thread angle  $A_n = 20^\circ$ ; lead of thread  $L = 0.864$  inch;  $T = 0.072$ ;  $W = 0.07013$  inch.

$$\tan B = \frac{L}{\pi E} = \frac{0.864}{1.9635} = 0.44003 \quad B = 23.751^\circ$$

$$\text{Helix angle } H = 90^\circ - 23.751^\circ = 66.249^\circ$$

$$\tan F = \frac{\tan A_n}{\sin B} = \frac{0.36397}{0.40276} = 0.90369 \quad F = 42.104^\circ$$

$$R_b = \frac{E}{2} \cos F = \frac{0.6250}{2} \times 0.74193 = 0.23185$$

$$T_a = \frac{T}{\tan B} = \frac{0.072}{0.44003} = 0.16362$$

$$\tan H_b = \cos F \tan H = 0.74193 \times 2.27257 = 1.68609 \quad H_b = 59.328^\circ$$

The involute function of  $G$  is found next by [Formula \(4e\)](#).

$$\text{inv } G = \frac{0.16362}{0.625} + 0.16884 + \frac{0.07013}{2 \times 0.23185 \times 0.51012} - \frac{3.1416}{6} = 0.20351$$

Since 0.20351 is outside the values for involute functions given in the tables on pages 104 through 107 use the formula for involute functions on page 103 to extend these tables as required. It will be found that 44 deg. 21 min. or 44.350 degrees is the angular equivalent of 0.20351; hence,  $G = 44.350$  degrees.

$$M = \frac{2R_b}{\cos G} + W = \frac{2 \times 0.23185}{0.71508} + 0.07013 = 0.71859 \text{ inch}$$

**Accuracy of Formulas (3) and (4) Compared.**—With the involute helicoid [Formula \(4\)](#) any wire size that makes contact with the flanks of the thread may be used; however, in the preceding example, the wire diameter  $W$  was obtained by [Formula \(3a\)](#) in order to compare [Formula \(4\)](#) with (3). If [Example \(3\)](#) is solved by [Formula \(3\)](#),  $M = 0.71912$ ; hence

the difference between the values of  $M$  obtained with Formulas (3) and (4) equals  $0.71912 - 0.71859 = 0.00053$  inch. The included thread angle in this case is 40 degrees. If Formulas (3) and (4) are applied to a 29-degree thread, the difference in measurements  $M$  or the error resulting from the use of Formula (3) will be larger. For example, with an Acme thread having a lead angle of about 34 degrees, the difference in values of  $M$  obtained by the two formulas equals 0.0008 inch.

**Three-wire Measurement of Acme and Stub Acme Thread Pitch Diameter.**—For single- and multiple-start Acme and Stub Acme threads having lead angles of less than 5 degrees, the approximate three-wire formula given on page 1897 and the best wire size taken from the table on page 1906 may be used.

Multiple-start Acme and Stub Acme threads commonly have a lead angle of greater than 5 degrees. For these, a direct determination of the actual pitch diameter is obtained by using the formula:  $E = M - (C + c)$  in conjunction with the table on page 1907. To enter the table, the lead angle  $B$  of the thread to be measured must be known. It is found by the formula:  $\tan B = L \div 3.1416E_1$  where  $L$  is the lead of the thread and  $E_1$  is the nominal pitch diameter. The best wire size is now found by taking the value of  $w_1$  as given in the table for lead angle  $B$ , with interpolation, and dividing it by the number of threads per inch. The value of  $(C + c)_1$  given in the table for lead angle  $B$  is also divided by the number of threads per inch to get  $(C + c)$ . Using the best size wires, the actual measurement over wires  $M$  is made and the actual pitch diameter  $E$  found by using the formula:  $E = M - (C + c)$ .

*Example:* For a 5 tpi, 4-start Acme thread with a  $13.952^\circ$  lead angle, using three 0.10024-inch wires,  $M = 1.1498$  inches, hence  $E = 1.1498 - 0.1248 = 1.0250$  inches.

Under certain conditions, a wire may contact one thread flank at two points, and it is then advisable to substitute balls of the same diameter as the wires.

**Checking Thickness of Acme Screw Threads.**—In some instances it may be preferable to check the thread thickness instead of the pitch diameter, especially if there is a thread thickness tolerance.

A direct method, applicable to the larger pitches, is to use a vernier gear-tooth caliper for measuring the thickness in the normal plane of the thread. This measurement, for an American Standard General Purpose Acme thread, should be made at a distance below the basic outside diameter equal to  $p/4$ . The thickness at this basic pitch-line depth and in the axial plane should be  $p/2 - 0.259 \times$  the pitch diameter allowance from the table on page 1827 with a tolerance of *minus*  $0.259 \times$  the pitch diameter tolerance from the table on page 1832. The thickness in the normal plane or plane of measurement is equal to the thickness in the axial plane multiplied by the cosine of the helix angle. The helix angle may be determined from the formula:

$$\text{tangent of helix angle} = \text{lead of thread} \div (3.1416 \times \text{pitch diameter})$$

**Three-Wire Method for Checking Thickness of Acme Threads.**—The application of the 3-wire method of checking the thickness of an Acme screw thread is included in the Report of the National Screw Thread Commission. In applying the 3-wire method for checking thread thickness, the procedure is the same as in checking pitch diameter (see *Three-wire Measurement of Acme and Stub Acme Thread Pitch Diameter*), although a different formula is required. Assume that  $D$  = basic major diameter of screw;  $M$  = measurement over wires;  $W$  = diameter of wires;  $S$  = tangent of helix angle at pitch line;  $P$  = pitch;  $T$  = thread thickness at depth equal to  $0.25P$ .

$$T = 1.12931 \times P + 0.25862 \times (M - D) - W \times (1.29152 + 0.48407S^2)$$

This formula transposed to show the correct measurement  $M$  equivalent to a given required thread thickness is as follows:

$$M = D + \frac{W \times (1.29152 + 0.48407S^2) + T - 1.12931 \times P}{0.25862}$$

**Wire Sizes for Three-Wire Measurement of Acme Threads  
with Lead Angles of Less than 5 Degrees**

| Threads per Inch | Best Size | Max.    | Min.    | Threads per Inch | Best Size | Max.    | Min.    |
|------------------|-----------|---------|---------|------------------|-----------|---------|---------|
| 1                | 0.51645   | 0.65001 | 0.48726 | 5                | 0.10329   | 0.13000 | 0.09745 |
| 1½               | 0.38734   | 0.48751 | 0.36545 | 6                | 0.08608   | 0.10834 | 0.08121 |
| 1½               | 0.34430   | 0.43334 | 0.32484 | 8                | 0.06456   | 0.08125 | 0.06091 |
| 2                | 0.25822   | 0.32501 | 0.24363 | 10               | 0.05164   | 0.06500 | 0.04873 |
| 2½               | 0.20658   | 0.26001 | 0.19491 | 12               | 0.04304   | 0.05417 | 0.04061 |
| 3                | 0.17215   | 0.21667 | 0.16242 | 14               | 0.03689   | 0.04643 | 0.03480 |
| 4                | 0.12911   | 0.16250 | 0.12182 | 16               | 0.03228   | 0.04063 | 0.03045 |

Wire sizes are based upon zero helix angle. Best size =  $0.51645 \times \text{pitch}$ ; maximum size =  $0.650013 \times \text{pitch}$ ; minimum size =  $0.487263 \times \text{pitch}$ .

*Example:* An Acme General Purpose thread, Class 2G, has a 5-inch basic major diameter, 0.5-inch pitch, and 1-inch lead (double thread). Assume the wire size is 0.258 inch. Determine measurement  $M$  for a thread thickness  $T$  at the basic pitch line of 0.2454 inch. ( $T$  is the maximum thickness at the basic pitch line and equals  $0.5P$ , the basic thickness,  $-0.259 \times$  allowance from Table 4, page 1832.)

$$M = 5 + \frac{0.258 \times [1.29152 + 0.48407 \times (0.06701)^2] + 0.2454 - 1.12931 \times 0.5}{0.25862}$$

$$= 5.056 \text{ inches}$$

**Testing Angle of Thread by Three-Wire Method.**—The error in the angle of a thread may be determined by using sets of wires of two diameters, the measurement over the two sets of wires being followed by calculations to determine the amount of error, assuming that the angle cannot be tested by comparison with a standard plug gage, known to be correct. The diameter of the small wires for the American Standard thread is usually about 0.6 times the pitch and the diameter of the large wires, about 0.9 times the pitch. The total difference between the measurements over the large and small sets of wires is first determined. If the thread is an American Standard or any other form having an included angle of 60 degrees, the difference between the two measurements should equal three times the difference between the diameters of the wires used. Thus, if the wires are 0.116 and 0.076 inch in diameter, respectively, the difference equals  $0.116 - 0.076 = 0.040$  inch. Therefore, the difference between the micrometer readings for a standard angle of 60 degrees equals  $3 \times 0.040 = 0.120$  inch for this example. If the angle is incorrect, the amount of error may be determined by the following formula, which applies to any thread regardless of angle:

$$\sin a = \frac{A}{B - A}$$

where  $A$  = difference in diameters of the large and small wires used

$B$  = total difference between the measurements over the large and small wires

$a$  = one-half the included thread angle

*Example:* The diameter of the large wires used for testing the angle of a thread is 0.116 inch and of the small wires 0.076 inch. The measurement over the two sets of wires shows a total difference of 0.122 inch instead of the correct difference, 0.120 inch, for a standard angle of 60 degrees when using the sizes of wires mentioned. The amount of error is determined as follows:

$$\sin a = \frac{0.040}{0.122 - 0.040} = \frac{0.040}{0.082} = 0.4878$$

A table of sines shows that this value (0.4878) is the sine of 29 degrees 12 minutes, approximately. Therefore, the angle of the thread is 58 degrees 24 minutes or 1 degree 36 minutes less than the standard angle.

**Best Wire Diameters and Constants for Three-wire Measurement of Acme and Stub  
Acme Threads with Large Lead Angles, 1-inch Axial Pitch**

| Lead angle, $B$ , deg. | 1-start threads |             | 2-start threads |             | Lead angle, $B$ , deg. | 2-start threads |             | 3-start threads |             |
|------------------------|-----------------|-------------|-----------------|-------------|------------------------|-----------------|-------------|-----------------|-------------|
|                        | $w_1$           | $(C + c)_1$ | $w_1$           | $(C + c)_1$ |                        | $w_1$           | $(C + c)_1$ | $w_1$           | $(C + c)_1$ |
| 5.0                    | 0.51450         | 0.64311     | 0.51443         | 0.64290     | 10.0                   | 0.50864         | 0.63518     | 0.50847         | 0.63463     |
| 5.1                    | 0.51442         | 0.64301     | 0.51435         | 0.64279     | 10.1                   | 0.50849         | 0.63498     | 0.50381         | 0.63442     |
| 5.2                    | 0.51435         | 0.64291     | 0.51427         | 0.64268     | 10.2                   | 0.50834         | 0.63478     | 0.50815         | 0.63420     |
| 5.3                    | 0.51427         | 0.64282     | 0.51418         | 0.64256     | 10.3                   | 0.50818         | 0.63457     | 0.50800         | 0.63399     |
| 5.4                    | 0.51419         | 0.64272     | 0.51410         | 0.64245     | 10.4                   | 0.50802         | 0.63436     | 0.50784         | 0.63378     |
| 5.5                    | 0.51411         | 0.64261     | 0.51401         | 0.64233     | 10.5                   | 0.40786         | 0.63416     | 0.50768         | 0.63356     |
| 5.6                    | 0.51403         | 0.64251     | 0.51393         | 0.64221     | 10.6                   | 0.50771         | 0.63395     | 0.50751         | 0.63333     |
| 5.7                    | 0.51395         | 0.64240     | 0.51384         | 0.64209     | 10.7                   | 0.50755         | 0.63375     | 0.50735         | 0.63311     |
| 5.8                    | 0.51386         | 0.64229     | 0.51375         | 0.64196     | 10.8                   | 0.50739         | 0.53354     | 0.50718         | 0.63288     |
| 5.9                    | 0.51377         | 0.64218     | 0.51366         | 0.64184     | 10.9                   | 0.50723         | 0.63333     | 0.50701         | 0.63265     |
| 6.0                    | 0.51368         | 0.64207     | 0.51356         | 0.64171     | 11.0                   | 0.50707         | 0.63313     | 0.50684         | 0.63242     |
| 6.1                    | 0.51359         | 0.64195     | 0.51346         | 0.64157     | 11.1                   | 0.50691         | 0.63292     | 0.50667         | 0.63219     |
| 6.2                    | 0.51350         | 0.64184     | 0.51336         | 0.64144     | 11.2                   | 0.50674         | 0.63271     | 0.50649         | 0.63195     |
| 6.3                    | 0.51340         | 0.64172     | 0.41327         | 0.64131     | 11.3                   | 0.50658         | 0.63250     | 0.50632         | 0.63172     |
| 6.4                    | 0.51330         | 0.64160     | 0.51317         | 0.64117     | 11.4                   | 0.50641         | 0.63228     | 0.50615         | 0.63149     |
| 6.5                    | 0.51320         | 0.64147     | 0.51306         | 0.64103     | 11.5                   | 0.50623         | 0.63206     | 0.50597         | 0.63126     |
| 6.6                    | 0.51310         | 0.64134     | 0.51296         | 0.64089     | 11.6                   | 0.50606         | 0.63184     | 0.50579         | 0.63102     |
| 6.7                    | 0.51300         | 0.64122     | 0.51285         | 0.64075     | 11.7                   | 0.50589         | 0.63162     | 0.50561         | 0.63078     |
| 6.8                    | 0.51290         | 0.64110     | 0.51275         | 0.64061     | 11.8                   | 0.50571         | 0.63140     | 0.50544         | 0.63055     |
| 6.9                    | 0.51280         | 0.64097     | 0.51264         | 0.64046     | 11.9                   | 0.50553         | 0.63117     | 0.50526         | 0.63031     |
| 7.0                    | 0.51270         | 0.64085     | 0.51254         | 0.64032     | 12.0                   | 0.50535         | 0.63095     | 0.50507         | 0.63006     |
| 7.1                    | 0.51259         | 0.64072     | 0.51243         | 0.64017     | 12.1                   | 0.50517         | 0.63072     | 0.50488         | 0.62981     |
| 7.2                    | 0.51249         | 0.64060     | 0.51232         | 0.64002     | 12.2                   | 0.50500         | 0.63050     | 0.50470         | 0.62956     |
| 7.3                    | 0.51238         | 0.64047     | 0.51221         | 0.63987     | 12.3                   | 0.50482         | 0.63027     | 0.50451         | 0.62931     |
| 7.4                    | 0.51227         | 0.64034     | 0.51209         | 0.63972     | 12.4                   | 0.50464         | 0.63004     | 0.50432         | 0.62906     |
| 7.5                    | 0.51217         | 0.64021     | 0.51198         | 0.63957     | 12.5                   | 0.50445         | 0.62981     | 0.50413         | 0.62881     |
| 7.6                    | 0.51206         | 0.64008     | 0.51186         | 0.63941     | 12.6                   | 0.50427         | 0.62958     | 0.50394         | 0.62856     |
| 7.7                    | 0.51196         | 0.63996     | 0.51174         | 0.63925     | 12.7                   | 0.50408         | 0.62934     | 0.50375         | 0.62830     |
| 7.8                    | 0.51186         | 0.63983     | 0.51162         | 0.63909     | 12.8                   | 0.50389         | 0.62911     | 0.50356         | 0.62805     |
| 7.9                    | 0.51175         | 0.63970     | 0.51150         | 0.63892     | 12.9                   | 0.50371         | 0.62888     | 0.50336         | 0.62779     |
| 8.0                    | 0.51164         | 0.63957     | 0.51138         | 0.63876     | 13.0                   | 0.50352         | 0.62865     |                 |             |
| 8.1                    | 0.51153         | 0.63944     | 0.51125         | 0.63859     | 13.1                   | 0.50333         | 0.62841     |                 |             |
| 8.2                    | 0.51142         | 0.63930     | 0.51113         | 0.63843     | 13.2                   | 0.50313         | 0.62817     |                 |             |
| 8.3                    | 0.51130         | 0.63916     | 0.51101         | 0.63827     | 13.3                   | 0.50293         | 0.62792     |                 |             |
| 8.4                    | 0.51118         | 0.63902     | 0.51088         | 0.63810     | 13.4                   | 0.50274         | 0.62778     |                 |             |
| 8.5                    | 0.51105         | 0.63887     | 0.51075         | 0.63793     | 13.5                   | 0.50254         | 0.62743     |                 |             |
| 8.6                    | 0.51093         | 0.63873     | 0.51062         | 0.63775     | 13.6                   | 0.50234         | 0.62718     |                 |             |
| 8.7                    | 0.51081         | 0.63859     | 0.51049         | 0.63758     | 13.7                   | 0.50215         | 0.62694     |                 |             |
| 8.8                    | 0.51069         | 0.63845     | 0.51035         | 0.63740     | 13.8                   | 0.50195         | 0.62670     |                 |             |
| 8.9                    | 0.51057         | 0.63831     | 0.51022         | 0.63722     | 13.9                   | 0.50175         | 0.62645     |                 |             |
| 9.0                    | 0.51044         | 0.63817     | 0.51008         | 0.63704     | 14.0                   | 0.50155         | 0.62621     |                 |             |
| 9.1                    | 0.51032         | 0.63802     | 0.50993         | 0.63685     | 14.1                   | 0.50135         | 0.62596     |                 |             |
| 9.2                    | 0.51019         | 0.63788     | 0.50979         | 0.63667     | 14.2                   | 0.50115         | 0.62571     |                 |             |
| 9.3                    | 0.51006         | 0.63774     | 0.50965         | 0.63649     | 14.3                   | 0.50094         | 0.62546     |                 |             |
| 9.4                    | 0.50993         | 0.63759     | 0.50951         | 0.63630     | 14.4                   | 0.50073         | 0.62520     |                 |             |
| 9.5                    | 0.50981         | 0.63744     | 0.50937         | 0.63612     | 14.5                   | 0.50051         | 0.62494     |                 |             |
| 9.6                    | 0.50968         | 0.63730     | 0.50922         | 0.63593     | 14.6                   | 0.50030         | 0.62468     |                 |             |
| 9.7                    | 0.50955         | 0.63715     | 0.50908         | 0.63574     | 14.7                   | 0.50009         | 0.62442     |                 |             |
| 9.8                    | 0.50941         | 0.63700     | 0.50893         | 0.63555     | 14.8                   | 0.49988         | 0.62417     |                 |             |
| 9.9                    | 0.50927         | 0.63685     | 0.50879         | 0.63537     | 14.9                   | 0.49966         | 0.62391     |                 |             |
| 10.0                   | 0.50913         | 0.63670     | 0.50864         | 0.63518     | 15.0                   | 0.49945         | 0.62365     |                 |             |

All dimensions are in inches.

Values given for  $w_1$  and  $(C + c)_1$  in table are for 1-inch pitch axial threads. For other pitches, divide table values by number of threads per inch.

*Courtesy of Van Keuren Co.*



**Best Wire Diameters and Constants for Three-wire Measurement of Acme and Stub Acme Threads with Large Lead Angles—1-inch Axial Pitch**

| Lead angle, $B$ , deg. | 3-start threads |             | 4-start threads |             | Lead angle, $B$ , deg. | 3-start threads |             | 4-start threads |             |
|------------------------|-----------------|-------------|-----------------|-------------|------------------------|-----------------|-------------|-----------------|-------------|
|                        | $w_1$           | $(C + c)_1$ | $w_1$           | $(C + c)_1$ |                        | $w_1$           | $(C + c)_1$ | $w_1$           | $(C + c)_1$ |
| 13.0                   | 0.50316         | 0.62752     | 0.50297         | 0.62694     | 18.0                   | 0.49154         | 0.61250     | 0.49109         | 0.61109     |
| 13.1                   | 0.50295         | 0.62725     | 0.50277         | 0.62667     | 18.1                   | 0.49127         | 0.61216     | 0.49082         | 0.61073     |
| 13.2                   | 0.50275         | 0.62699     | 0.50256         | 0.62639     | 18.2                   | 0.49101         | 0.61182     | 0.49054         | 0.61037     |
| 13.3                   | 0.50255         | 0.62672     | 0.50235         | 0.62611     | 18.3                   | 0.49074         | 0.61148     | 0.49027         | 0.61001     |
| 13.4                   | 0.50235         | 0.62646     | 0.50215         | 0.62583     | 18.4                   | 0.49047         | 0.61114     | 0.48999         | 0.60964     |
| 13.5                   | 0.50214         | 0.62619     | 0.50194         | 0.62555     | 18.5                   | 0.49020         | 0.61080     | 0.48971         | 0.60928     |
| 13.6                   | 0.50194         | 0.62592     | 0.50173         | 0.62526     | 18.6                   | 0.48992         | 0.61045     | 0.48943         | 0.60981     |
| 13.7                   | 0.50173         | 0.62564     | 0.50152         | 0.62498     | 18.7                   | 0.48965         | 0.61011     | 0.48915         | 0.60854     |
| 13.8                   | 0.50152         | 0.62537     | 0.50131         | 0.62469     | 18.8                   | 0.48938         | 0.60976     | 0.48887         | 0.60817     |
| 13.9                   | 0.50131         | 0.62509     | 0.50109         | 0.62440     | 18.9                   | 0.48910         | 0.60941     | 0.48859         | 0.60780     |
| 14.0                   | 0.50110         | 0.62481     | 0.50087         | 0.62411     | 19.0                   | 0.48882         | 0.60906     | 0.48830         | 0.60742     |
| 14.1                   | 0.50089         | 0.62453     | 0.50065         | 0.62381     | 19.1                   | 0.48854         | 0.60871     | 0.48800         | 0.60704     |
| 14.2                   | 0.50068         | 0.62425     | 0.50043         | 0.62351     | 19.2                   | 0.48825         | 0.60835     | 0.48771         | 0.60666     |
| 14.3                   | 0.50046         | 0.62397     | 0.50021         | 0.62321     | 19.3                   | 0.48797         | 0.60799     | 0.48742         | 0.60628     |
| 14.4                   | 0.50024         | 0.62368     | 0.49999         | 0.62291     | 19.4                   | 0.48769         | 0.60764     | 0.48713         | 0.60590     |
| 14.5                   | 0.50003         | 0.62340     | 0.49977         | 0.62262     | 19.5                   | 0.48741         | 0.60729     | 0.48684         | 0.60552     |
| 14.6                   | 0.49981         | 0.62312     | 0.49955         | 0.62232     | 19.6                   | 0.48712         | 0.60693     | 0.48655         | 0.60514     |
| 14.7                   | 0.49959         | 0.62283     | 0.49932         | 0.62202     | 19.7                   | 0.48683         | 0.60657     | 0.48625         | 0.60475     |
| 14.8                   | 0.49936         | 0.62253     | 0.49910         | 0.62172     | 19.8                   | 0.48655         | 0.60621     | 0.48596         | 0.60437     |
| 14.9                   | 0.49914         | 0.62224     | 0.49887         | 0.62141     | 19.9                   | 0.48626         | 0.60585     | 0.48566         | 0.60398     |
| 15.0                   | 0.49891         | 0.62195     | 0.49864         | 0.62110     | 20.0                   | 0.48597         | 0.60549     | 0.48536         | 0.60359     |
| 15.1                   | 0.49869         | 0.62166     | 0.49842         | 0.62080     | 20.1                   | ...             | ...         | 0.48506         | 0.60320     |
| 15.2                   | 0.49846         | 0.62137     | 0.49819         | 0.62049     | 20.2                   | ...             | ...         | 0.48476         | 0.60281     |
| 15.3                   | 0.49824         | 0.62108     | 0.49795         | 0.62017     | 20.3                   | ...             | ...         | 0.48445         | 0.60241     |
| 15.4                   | 0.42801         | 0.62078     | 0.49771         | 0.61985     | 20.4                   | ...             | ...         | 0.48415         | 0.60202     |
| 15.5                   | 0.49778         | 0.62048     | 0.49747         | 0.61953     | 20.5                   | ...             | ...         | 0.48384         | 0.60162     |
| 15.6                   | 0.49754         | 0.62017     | 0.49723         | 0.61921     | 20.6                   | ...             | ...         | 0.48354         | 0.60123     |
| 15.7                   | 0.49731         | 0.61987     | 0.49699         | 0.61889     | 20.7                   | ...             | ...         | 0.48323         | 0.60083     |
| 15.8                   | 0.49707         | 0.61956     | 0.49675         | 0.61857     | 20.8                   | ...             | ...         | 0.48292         | 0.60044     |
| 15.9                   | 0.49683         | 0.61926     | 0.49651         | 0.61825     | 20.9                   | ...             | ...         | 0.48261         | 0.60002     |
| 16.0                   | 0.49659         | 0.61895     | 0.49627         | 0.61793     | 21.0                   | ...             | ...         | 0.48230         | 0.59961     |
| 16.1                   | 0.49635         | 0.61864     | 0.49602         | 0.61760     | 21.1                   | ...             | ...         | 0.48198         | 0.49920     |
| 16.2                   | 0.49611         | 0.61833     | 0.49577         | 0.61727     | 21.2                   | ...             | ...         | 0.48166         | 0.59879     |
| 16.3                   | 0.49586         | 0.61801     | 0.49552         | 0.61694     | 21.3                   | ...             | ...         | 0.48134         | 0.59838     |
| 16.4                   | 0.49562         | 0.61770     | 0.49527         | 0.61661     | 21.4                   | ...             | ...         | 0.48103         | 0.59797     |
| 16.5                   | 0.49537         | 0.61738     | 0.49502         | 0.61628     | 21.5                   | ...             | ...         | 0.48071         | 0.59756     |
| 16.6                   | 0.49512         | 0.61706     | 0.49476         | 0.61594     | 21.6                   | ...             | ...         | 0.48040         | 0.59715     |
| 16.7                   | 0.49488         | 0.61675     | 0.49451         | 0.61560     | 21.7                   | ...             | ...         | 0.48008         | 0.59674     |
| 16.8                   | 0.40463         | 0.61643     | 0.49425         | 0.61526     | 21.8                   | ...             | ...         | 0.47975         | 0.59632     |
| 16.9                   | 0.49438         | 0.61611     | 0.49400         | 0.61492     | 21.9                   | ...             | ...         | 0.47943         | 0.59590     |
| 17.0                   | 0.49414         | 0.61580     | 0.49375         | 0.61458     | 22.0                   | ...             | ...         | 0.47910         | 0.59548     |
| 17.1                   | 0.49389         | 0.61548     | 0.49349         | 0.61424     | 22.1                   | ...             | ...         | 0.47878         | 0.59507     |
| 17.2                   | 0.49363         | 0.61515     | 0.49322         | 0.61389     | 22.2                   | ...             | ...         | 0.47845         | 0.59465     |
| 17.3                   | 0.49337         | 0.61482     | 0.49296         | 0.61354     | 22.3                   | ...             | ...         | 0.47812         | 0.59422     |
| 17.4                   | 0.49311         | 0.61449     | 0.49269         | 0.61319     | 22.4                   | ...             | ...         | 0.47778         | 0.59379     |
| 17.5                   | 0.49285         | 0.61416     | 0.49243         | 0.61284     | 22.5                   | ...             | ...         | 0.47745         | 0.59336     |
| 17.6                   | 0.49259         | 0.61383     | 0.49217         | 0.61250     | 22.6                   | ...             | ...         | 0.47711         | 0.59293     |
| 17.7                   | 0.49233         | 0.61350     | 0.49191         | 0.61215     | 22.7                   | ...             | ...         | 0.47677         | 0.59250     |
| 17.8                   | 0.49206         | 0.61316     | 0.49164         | 0.61180     | 22.8                   | ...             | ...         | 0.47643         | 0.59207     |
| 17.9                   | 0.49180         | 0.61283     | 0.49137         | 0.61144     | 22.9                   | ...             | ...         | 0.47610         | 0.59164     |
| ...                    | ...             | ...         | ...             | ...         | 23.0                   | ...             | ...         | 0.47577         | 0.59121     |

All dimensions are in inches.

Values given for  $w_1$  and  $(C + c)_1$  in table are for 1-inch pitch axial threads. For other pitches divide table values by number of threads per inch.

*Courtesy of Van Keuren Co.*

**Measuring Taper Screw Threads by Three-Wire Method.**—When the 3-wire method is used in measuring a taper screw thread, the measurement is along a line that is not perpendicular to the axis of the screw thread, the inclination from the perpendicular equaling one-half the included angle of the taper. The formula that follows compensates for this inclination resulting from contact of the measuring instrument surfaces, with two wires on one side and one on the other. The taper thread is measured over the wires in the usual manner except that the single wire must be located in the thread at a point where the effective diameter is to be checked (as described more fully later). The formula shows the dimension equivalent to the correct pitch diameter at this given point. The general formula for taper screw threads follows:

$$M = \frac{E - (\cot a)/2N + W(1 + \csc a)}{\sec b}$$

where  $M$  = measurement over the 3 wires

$E$  = pitch diameter

$a$  = one-half the angle of the thread

$N$  = number of threads per inch

$W$  = diameter of wires; and

$b$  = one-half the angle of taper.

This formula is not theoretically correct but it is accurate for screw threads having tapers of  $\frac{3}{4}$  inch per foot or less. This general formula can be simplified for a given thread angle and taper. The simplified formula following (in which  $P$  = pitch) is for an American National Standard pipe thread:

$$M = \frac{E - (0.866025 \times P) + 3 \times W}{1.00049}$$

Standard pitch diameters for pipe threads will be found in the section "American Pipe Threads," which also shows the location, or distance, of this pitch diameter from the end of the pipe. In using the formula for finding dimension  $M$  over the wires, the single wire is placed in whatever part of the thread groove locates it at the point where the pitch diameter is to be checked. The wire must be accurately located at this point. The other wires are then placed on each side of the thread that is diametrically opposite the single wire. If the pipe thread is straight or without taper,

$$M = E - (0.866025 \times P) + 3 \times W$$

*Application of Formula to Taper Pipe Threads:* To illustrate the use of the formula for taper threads, assume that dimension  $M$  is required for an American Standard 3-inch pipe thread gage. Table 1a starting on page 1861 shows that the 3-inch size has 8 threads per inch, or a pitch of 0.125 inch, and a pitch diameter at the gaging notch of 3.3885 inches. Assume that the wire diameter is 0.07217 inch: Then when the pitch diameter is correct

$$M = \frac{3.3885 - (0.866025 \times 0.125) + 3 \times 0.07217}{1.00049} = 3.495 \text{ inches}$$

*Pitch Diameter Equivalent to a Given Measurement Over the Wires:* The formula following may be used to check the pitch diameter at any point along a tapering thread when measurement  $M$  over wires of a given diameter is known. In this formula,  $E$  = the effective or pitch diameter at the position occupied by the single wire. The formula is not theoretically correct but gives very accurate results when applied to tapers of  $\frac{3}{4}$  inch per foot or less.

$$E = 1.00049 \times M + (0.866025 \times P) - 3 \times W$$

*Example:* Measurement  $M$  = 3.495 inches at the gaging notch of a 3-inch pipe thread and the wire diameter = 0.07217 inch. Then

$$E = 1.00049 \times 3.495 + (0.866025 \times 0.125) - 3 \times 0.07217 = 3.3885 \text{ inches}$$

**Pitch Diameter at Any Point Along Taper Screw Thread:** When the pitch diameter in any position along a tapering thread is known, the pitch diameter at any other position may be determined as follows:

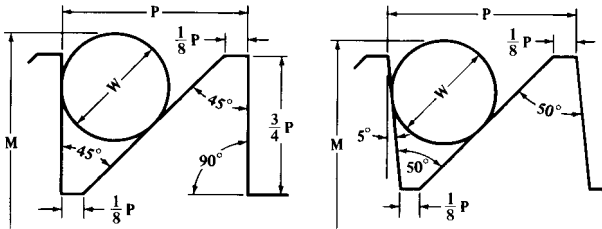
Multiply the distance (measured along the axis) between the location of the known pitch diameter and the location of the required pitch diameter, by the taper per inch or by 0.0625 for American National Standard pipe threads. Add this product to the known diameter, if the required diameter is at a large part of the taper, or subtract if the required diameter is smaller.

**Example:** The pitch diameter of a 3-inch American National Standard pipe thread is 3.3885 at the gaging notch. Determine the pitch diameter at the small end. The table starting on page 1861 shows that the distance between the gaging notch and the small end of a 3-inch pipe is 0.77 inch. Hence the pitch diameter at the small end =  $3.3885 - (0.77 \times 0.0625) = 3.3404$  inches.

#### Three-Wire Method Applied to Buttress Threads

The angles of buttress threads vary somewhat, especially on the front or load-resisting side. **Formula (1)**, which follows, may be applied to any angles required. In this formula,  $M$  = measurement over wires when *pitch diameter*  $E$  is correct;  $A$  = included angle of thread and thread groove;  $a$  = angle of front face or load-resisting side, measured from a line perpendicular to screw thread axis;  $P$  = pitch of thread; and  $W$  = wire diameter.

$$M = E - \left[ \frac{P}{\tan a + \tan(A - a)} \right] + W \left[ 1 + \cos\left(\frac{A}{2} - a\right) \times \csc\frac{A}{2} \right] \quad (1)$$



For given angles  $A$  and  $a$ , this general formula may be simplified as shown by **Formulas (3)** and **(4)**. These simplified formulas contain constants with values depending upon angles  $A$  and  $a$ .

**Wire Diameter:** The wire diameter for obtaining pitch-line contact at the back of a buttress thread may be determined by the following general **Formula (2)**:

$$W = P \left( \frac{\cos a}{1 + \cos A} \right) \quad (2)$$

**45-Degree Buttress Thread:** The buttress thread shown by the diagram at the left, has a front or load-resisting side that is perpendicular to the axis of the screw. Measurement  $M$  equivalent to a correct pitch diameter  $E$  may be determined by **Formula (3)**:

$$M = E - P + (W \times 3.4142) \quad (3)$$

Wire diameter  $W$  for pitch-line contact at back of thread =  $0.586 \times$  pitch.

*50-Degree Buttress Thread with Front-face Inclination of 5 Degrees:* This buttress thread form is illustrated by the diagram at the right. Measurement  $M$  equivalent to the correct pitch diameter  $E$  may be determined by [Formula \(4\)](#):

$$M = E - (P \times 0.91955) + (W \times 3.2235) \quad (4)$$

Wire diameter  $W$  for pitch-line contact at back of thread =  $0.606 \times$  pitch. If the width of flat at crest and root =  $\frac{1}{8} \times$  pitch, depth =  $0.69 \times$  pitch.

*American National Standard Buttress Threads ANSI B1.9-1973:* This buttress screw thread has an included thread angle of 52 degrees and a front face inclination of 7 degrees. Measurements  $M$  equivalent to a pitch diameter  $E$  may be determined by [Formula \(5\)](#):

$$M = E - 0.89064P + 3.15689W + c \quad (5)$$

The wire angle correction factor  $c$  is less than 0.0004 inch for recommended combinations of thread diameters and pitches and may be neglected. Use of wire diameter  $W = 0.54147P$  is recommended.

**Measurement of Pitch Diameter of Thread Ring Gages.**—The application of direct methods of measurement to determine the pitch diameter of thread ring gages presents serious difficulties, particularly in securing proper contact pressure when a high degree of precision is required. The usual practice is to fit the ring gage to a master setting plug. When the thread ring gage is of correct lead, angle, and thread form, within close limits, this method is quite satisfactory and represents standard American practice. It is the only method available for small sizes of threads. For the larger sizes, various more or less satisfactory methods have been devised, but none of these have found wide application.

**Screw Thread Gage Classification.**—Screw thread gages are classified by their degree of accuracy, that is, by the amount of tolerance afforded the gage manufacturer and the wear allowance, if any.

There are also three classifications according to use: 1) Working gages for controlling production; 2) inspection gages for rejection or acceptance of the finished product; and 3) reference gages for determining the accuracy of the working and inspection gages.

**American National Standard for Gages and Gaging for Unified Inch Screw Threads ANSI/ASME B1.2-1983 (R2001).**—This standard covers gaging methods for conformance of Unified Screw threads and provides the essential specifications for applicable gages required for unified inch screw threads.

The standard includes the following gages for *Product Internal Thread*:

*GO Working Thread Plug Gage* for inspecting the maximum-material GO functional limit.

*NOT GO (HI) Thread Plug Gage* for inspecting the NOT GO (HI) functional diameter limit.

*Thread Snap Gage—GO Segments or Rolls* for inspecting the maximum-material GO functional limit.

*Thread Snap Gage—NOT GO (HI) Segments or Rolls* for inspecting the NOT GO (HI) functional diameter limit.

*Thread Snap Gages—Minimum Material: Pitch Diameter Cone Type and Vee and Thread Groove Diameter Type* for inspecting the minimum-material limit pitch diameter.

*Thread-Setting Solid Ring Gage* for setting internal thread indicating and snap gages.

*Plain Plug, Snap, and Indicating Gages* for checking the minor diameter of internal threads.

*Snap and Indicating Gages* for checking the major diameter of internal threads.

*Functional Indicating Thread Gage* for inspecting the maximum-material GO functional limit and size and the NOT GO (HI) functional diameter limit and size.

*Minimum-Material Indicating Thread Gage* for inspecting the minimum-material limit and size.

*Indicating Runout Thread Gage* for inspecting runout of the minor diameter to pitch diameter.

In addition to these gages for product internal threads, the Standard also covers differential gaging and such instruments as pitch micrometers, thread-measuring balls, optical comparator and toolmaker's microscope, profile tracing instrument, surface roughness measuring instrument, and roundness measuring equipment.

The Standard includes the following gages for *Product External Thread*:

*GO Working Thread Ring Gage* for inspecting the maximum-material GO functional limit.

*NOT GO (LO) Thread Ring Gage* for inspecting the NOT GO (LO) functional diameter limit.

*Thread Snap Gage—GO Segments or Rolls* for inspecting the maximum-material GO functional limit.

*Thread Snap Gage—NOT GO (LO) Segments or Rolls* for inspecting the NOT GO (LO) functional diameter limit.

*Thread Snap Gages—Cone and Vee Type and Minimum Material Thread Groove Diameter Type* for inspecting the minimum-material pitch diameter limit.

*Plain Ring and Snap Gages* for checking the major diameter.

*Snap Gage* for checking the minor diameter.

*Functional Indicating Thread Gage* for inspecting the maximum-material GO functional limit and size and the NOT GO (LO) functional diameter limit and size.

*Minimum-Material Indicating Thread Gage* for inspecting the minimum-material limit and size.

*Indicating Runout Gage* for inspecting the runout of the major diameter to the pitch diameter.

*WTolerance Thread-Setting Plug Gage* for setting adjustable thread ring gages, checking solid thread ring gages, setting thread snap limit gages, and setting indicating thread gages.

*Plain Check Plug Gage for Thread Ring Gage* for verifying the minor diameter limits of thread ring gages after the thread rings have been properly set with the applicable thread-setting plug gages.

*Indicating Plain Diameter Gage* for checking the major diameter.

*Indicating Gage* for checking the minor diameter.

In addition to these gages for product external threads, the Standard also covers differential gaging and such instruments as thread micrometers, thread-measuring wires, optical comparator and toolmaker's microscope, profile tracing instrument, electromechanical lead tester, helical path attachment used with GO type thread indicating gage, helical path analyzer, surface roughness measuring equipment, and roundness measuring equipment.

The standard lists the following for use of Threaded and Plain Gages for verification of product internal threads:

*Tolerance:* Unless otherwise specified all thread gages which directly check the product thread shall be X tolerance for all classes.

*GO Thread Plug Gages:* GO thread plug gages must enter and pass through the full threaded length of the product freely. The GO thread plug gage is a cumulative check of all thread elements except the minor diameter.

*NOT GO (HI) Thread Plug Gages:* NOT GO (HI) thread plug gages when applied to the product internal thread may engage only the end threads (which may not be representative of the complete thread). Entering threads on product are incomplete and permit gage to start. Starting threads on NOT GO (HI) plugs are subject to greater wear than the remaining threads. Such wear in combination with the incomplete product threads permits further entry of the gage. NOT GO (HI) functional diameter is acceptable when the NOT GO (HI) thread plug gage applied to the product internal thread does not enter more than three complete turns. The gage should not be forced. Special requirements such as exceptionally thin or ductile material, small number of threads, etc., may necessitate modification of this practice.

*GO and NOT GO Plain Plug Gages for Minor Diameter of Product Internal Thread:* (Recommended in Class Z tolerance.) GO plain plug gages must completely enter and pass through the length of the product without force. NOT GO cylindrical plug gage must not enter.

The standard lists the following for use of Thread Gages for verification of product external threads:

*GO Thread Ring Gages:* Adjustable GO thread ring gages must be set to the applicable W tolerance setting plugs to assure they are within specified limits. The product thread must freely enter the GO thread ring gage for the entire length of the threaded portion. The GO thread ring gage is a cumulative check of all thread elements except the major diameter.

*NOT GO (LO) Thread Ring Gages:* NOT GO (LO) thread ring gages must be set to the applicable W tolerance setting plugs to assure that they are within specified limits. NOT GO (LO) thread ring gages when applied to the product external thread may engage only the end threads (which may not be representative of the complete product thread)

Starting threads on NOT GO (LO) rings are subject to greater wear than the remaining threads. Such wear in combination with the incomplete threads at the end of the product thread permit further entry in the gage. NOT GO (LO) functional diameter is acceptable when the NOT GO (LO) thread ring gage applied to the product external thread does not pass over the thread more than three complete turns. The gage should not be forced. Special requirements such as exceptionally thin or ductile material, small number of threads, etc., may necessitate modification of this practice.

*GO and NOT GO Plain Ring and Snap Gages for Checking Major Diameter of Product External Thread:* The GO gage must completely receive or pass over the major diameter of the product external thread to ensure that the major diameter does not exceed the maximum-material-limit. The NOT GO gage must not pass over the major diameter of the product external thread to ensure that the major diameter is not less than the minimum-material-limit.

Limitations concerning the use of gages are given in the standard as follows:

*Product threads* accepted by a gage of one type may be verified by other types. It is possible, however, that parts which are near either rejection limit may be accepted by one type and rejected by another. Also, it is possible for two individual limit gages of the same type to be at the opposite extremes of the gage tolerances permitted, and borderline product threads accepted by one gage could be rejected by another. For these reasons, a product screw thread is considered acceptable when it passes a test by any of the permissible gages in ANSI B1.3 for the gaging system that are within the tolerances.

*Gaging large product external and internal threads* equal to above 6.25-inch nominal size with plain and threaded plug and ring gages presents problems for technical and economic reasons. In these instances, verification may be based on use of modified snap or indicating gages or measurement of thread elements. Various types of gages or measuring

devices in addition to those defined in the Standard are available and acceptable when properly correlated to this Standard. Producer and user should agree on the method and equipment used.

**Thread Forms of Gages.**—Thread forms of gages for product internal and external threads are given in [Table 1](#). The Standard ANSI/ASME B1.2-1983 (R2001) also gives illustrations of the thread forms of truncated thread setting plug gages, the thread forms of full-form thread setting plug gages, the thread forms of solid thread setting ring gages, and an illustration that shows the chip groove and removal of partial thread.

**Thread Gage Tolerances.**—Gage tolerances of thread plug and ring gages, thread setting plugs, and setting rings for Unified screw threads, designated as W and X tolerances, are given in [Table 4](#). W tolerances represent the highest commercial grade of accuracy and workmanship, and are specified for thread setting gages; X tolerances are larger than W tolerances and are used for product inspection gages. Tolerances for plain gages are given in [Table 2](#).

*Determining Size of Gages:* The three-wire method of determining pitch diameter size of plug gages is recommended for gages covered by American National Standard B1.2, described in Appendix B of the 1983 issue of that Standard.

Size limit adjustments of thread ring and external thread snap gages are determined by their fit on their respective calibrated setting plugs. Indicating gages and thread gages for product external threads are controlled by reference to appropriate calibrated setting plugs.

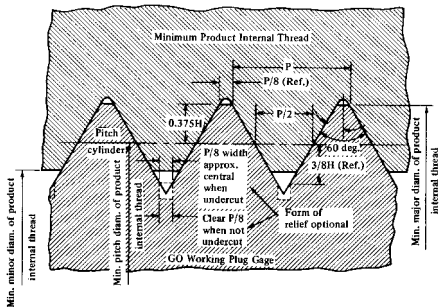
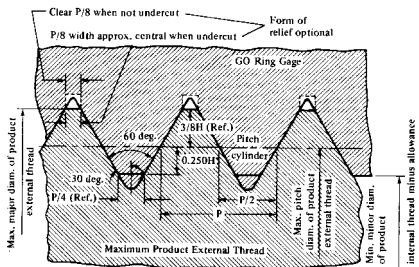
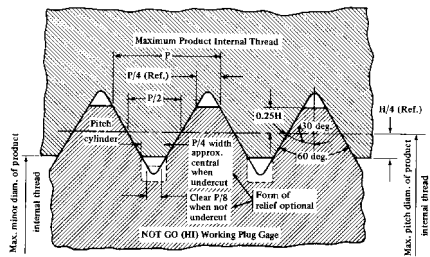
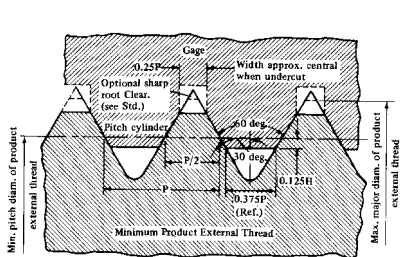
Size limit adjustments of internal thread snap gages are determined by their fit on their respective calibrated setting rings. Indicating gages and other adjustable thread gages for product internal threads are controlled by reference to appropriate calibrated setting rings or by direct measuring methods.

*Interpretation of Tolerances:* Tolerances on lead, half-angle, and pitch diameter are variations which may be taken independently for each of these elements and may be taken to the extent allowed by respective tabulated dimensional limits. The tabulated tolerance on any one element must not be exceeded, even though variations in the other two elements are smaller than the respective tabulated tolerances.

*Direction of Tolerance on Gages:* At the maximum-material limit (GO), the dimensions of all gages used for final conformance gaging are to be within limits of size of the product thread. At the functional diameter limit, using NOT GO (HI and LO) thread gages, the standard practice is to have the gage tolerance within the limits of size of the product thread.

*Formulas for Limits of Gages:* Formulas for limits of American National Standard Gages for Unified screw threads are given in [Table 5](#). Some constants which are required to determine gage dimensions are tabulated in [Table 3](#).

Table 1. Thread Forms of Gages for Product Internal and External Threads





**Table 2. American National Standard Tolerances for Plain Cylindrical Gages  
ANSI/ASME B1.2-1983 (R2001)**

| Size Range |                  | Tolerance Class <sup>a</sup> |        |        |        |        |
|------------|------------------|------------------------------|--------|--------|--------|--------|
| Above      | To and Including | XX                           | X      | Y      | Z      | ZZ     |
|            |                  | Tolerance                    |        |        |        |        |
| 0.020      | 0.825            | .00002                       | .00004 | .00007 | .00010 | .00020 |
| 0.825      | 1.510            | .00003                       | .00006 | .00009 | .00012 | .00024 |
| 1.510      | 2.510            | .00004                       | .00008 | .00012 | .00016 | .00032 |
| 2.510      | 4.510            | .00005                       | .00010 | .00015 | .00020 | .00040 |
| 4.510      | 6.510            | .000065                      | .00013 | .00019 | .00025 | .00050 |
| 6.510      | 9.010            | .00008                       | .00016 | .00024 | .00032 | .00064 |
| 9.010      | 12.010           | .00010                       | .00020 | .00030 | .00040 | .00080 |

<sup>a</sup> Tolerances apply to actual diameter of plug or ring. Apply tolerances as specified in the Standard. Symbols XX, X, Y, Z, and ZZ are standard gage tolerance classes.

All dimensions are given in inches.

**Table 3. Constants for Computing Thread Gage Dimensions  
ANSI/ASME B1.2-1983 (R2001)**

| Threads per Inch | Pitch, $p$ | $0.060\sqrt[3]{p^2} + 0.017p$ | $.05p$ | $.087p$ | Height of Sharp V-Thread, $H = .866025p$ | $H/2 = .43301p$ | $H/4 = .216506p$ |
|------------------|------------|-------------------------------|--------|---------|--|-----------------|------------------|
| 80               | .012500    | .0034                         | .00063 | .00109  | .010825                                  | .00541          | .00271           |
| 72               | .013889    | .0037                         | .00069 | .00122  | .012028                                  | .00601          | .00301           |
| 64               | .015625    | .0040                         | .00078 | .00136  | .013532                                  | .00677          | .00338           |
| 56               | .017857    | .0044                         | .00089 | .00155  | .015465                                  | .00773          | .00387           |
| 48               | .020833    | .0049                         | .00104 | .00181  | .018042                                  | .00902          | .00451           |
| 44               | .022727    | .0052                         | .00114 | .00198  | .019682                                  | .00984          | .00492           |
| 40               | .025000    | .0056                         | .00125 | .00218  | .021651                                  | .01083          | .00541           |
| 36               | .027778    | .0060                         | .00139 | .00242  | .024056                                  | .01203          | .00601           |
| 32               | .031250    | .0065                         | .00156 | .00272  | .027063                                  | .01353          | .00677           |
| 28               | .035714    | .0071                         | .00179 | .00311  | .030929                                  | .01546          | .00773           |
| 27               | .037037    | .0073                         | .00185 | .00322  | .032075                                  | .01604          | .00802           |
| 24               | .041667    | .0079                         | .00208 | .00361  | .036084                                  | .01804          | .00902           |
| 20               | .050000    | .0090                         | .00250 | .00435  | .043301                                  | .02165          | .01083           |
| 18               | .055556    | .0097                         | .00278 | .00483  | .048113                                  | .02406          | .01203           |
| 16               | .062500    | .0105                         | .00313 | .00544  | .054127                                  | .02706          | .01353           |
| 14               | .071429    | .0115                         | .00357 | .00621  | .061859                                  | .03093          | .01546           |
| 13               | .076923    | .0122                         | .00385 | .00669  | .066617                                  | .03331          | .01665           |
| 12               | .083333    | .0129                         | .00417 | .00725  | .072169                                  | .03608          | .01804           |
| 11½              | .086957    | .0133                         | .00435 | .00757  | .075307                                  | .03765          | .01883           |
| 11               | .090909    | .0137                         | .00451 | .00791  | .078730                                  | .03936          | .01968           |
| 10               | .100000    | .0146                         | .00500 | .00870  | .086603                                  | .04330          | .02165           |
| 9                | .111111    | .0158                         | .00556 | .00967  | .096225                                  | .04811          | .02406           |
| 8                | .125000    | .0171                         | .00625 | .01088  | .108253                                  | .05413          | .02706           |
| 7                | .142857    | .0188                         | .00714 | .01243  | .123718                                  | .06186          | .03093           |
| 6                | .166667    | .0210                         | .00833 | .01450  | .144338                                  | .07217          | .03608           |
| 5                | .200000    | .0239                         | .01000 | .01740  | .173205                                  | .08660          | .04330           |
| 4½               | .222222    | .0258                         | .01111 | .01933  | .192450                                  | .09623          | .04811           |
| 4                | .250000    | .0281                         | .01250 | .02175  | .216506                                  | .10825          | .05413           |

All dimensions are given in inches unless otherwise specified.

**Table 4. American National Standard Tolerance for GO, HI, and LO Thread Gages for Unified Inch Screw Thread**

| Thds. per Inch | Tolerance on Lead <sup>a</sup> |                    | Tol. on Thread Half-angle (±), minutes | Tol. on Major and Minor Diam. <sup>b</sup> |                         |                  | Tolerance on Pitch Diameter <sup>b</sup> |                             |                           |                       |                                     |
|----------------|--------------------------------|--------------------|--|--|-------------------------|------------------|--|-----------------------------|---------------------------|-----------------------|-------------------------------------|
|                | To & incl. 1/2 in. Dia.        | Above 1/2 in. Dia. |  | To & incl. 1/2 in. Dia.                    | Above 1/2 to 4 in. Dia. | Above 4 in. Dia. | To & incl. 1/2 in. Dia.                  | Above 1/2 to 1 1/2 in. Dia. | Above 1 1/2 to 4 in. Dia. | Above 4 to 8 in. Dia. | Above 8 to 12 in. <sup>c</sup> Dia. |
| <b>W GAGES</b> |                                |                    |  |  |                         |                  |  |                             |                           |                       |                                     |
| 80, 72         | .0001                          | .00015             | 20                                     | .0003                                      | .0003                   | ...              | .0001                                    | .00015                      | ...                       | ...                   | ...                                 |
| 64             | .0001                          | .00015             | 20                                     | .0003                                      | .0004                   | ...              | .0001                                    | .00015                      | ...                       | ...                   | ...                                 |
| 56             | .0001                          | .00015             | 20                                     | .0003                                      | .0004                   | ...              | .0001                                    | .00015                      | .0002                     | ...                   | ...                                 |
| 48             | .0001                          | .00015             | 18                                     | .0003                                      | .0004                   | ...              | .0001                                    | .00015                      | .0002                     | ...                   | ...                                 |
| 44, 40         | .0001                          | .00015             | 15                                     | .0003                                      | .0004                   | ...              | .0001                                    | .00015                      | .0002                     | ...                   | ...                                 |
| 36             | .0001                          | .00015             | 12                                     | .0003                                      | .0004                   | ...              | .0001                                    | .00015                      | .0002                     | ...                   | ...                                 |
| 32             | .0001                          | .00015             | 12                                     | .0003                                      | .0005                   | .0007            | .0001                                    | .00015                      | .0002                     | .00025                | .0003                               |
| 28, 27         | .00015                         | .00015             | 8                                      | .0005                                      | .0005                   | .0007            | .0001                                    | .00015                      | .0002                     | .00025                | .0003                               |
| 24, 20         | .00015                         | .00015             | 8                                      | .0005                                      | .0005                   | .0007            | .0001                                    | .00015                      | .0002                     | .00025                | .0003                               |
| 18             | .00015                         | .00015             | 8                                      | .0005                                      | .0005                   | .0007            | .0001                                    | .00015                      | .0002                     | .00025                | .0003                               |
| 16             | .00015                         | .00015             | 8                                      | .0006                                      | .0006                   | .0009            | .0001                                    | .0002                       | .00025                    | .0003                 | .0004                               |
| 14, 13         | .0002                          | .0002              | 6                                      | .0006                                      | .0006                   | .0009            | .00015                                   | .0002                       | .00025                    | .0003                 | .0004                               |
| 12             | .0002                          | .0002              | 6                                      | .0006                                      | .0006                   | .0009            | .00015                                   | .0002                       | .00025                    | .0003                 | .0004                               |
| 11 1/2         | .0002                          | .0002              | 6                                      | .0006                                      | .0006                   | .0009            | .00015                                   | .0002                       | .00025                    | .0003                 | .0004                               |
| 11             | .0002                          | .0002              | 6                                      | .0006                                      | .0006                   | .0009            | .00015                                   | .0002                       | .00025                    | .0003                 | .0004                               |
| 10             | ...                            | .00025             | 6                                      | ...  | .0006                   | .0009            | ...                                      | .0002                       | .00025                    | .0003                 | .0004                               |
| 9              | ...                            | .00025             | 6                                      | ...  | .0007                   | .0011            | ...                                      | .0002                       | .00025                    | .0003                 | .0004                               |
| 8              | ...                            | .00025             | 5                                      | ...  | .0007                   | .0011            | ...                                      | .0002                       | .00025                    | .0003                 | .0004                               |
| 7              | ...                            | .0003              | 5                                      | ...  | .0007                   | .0011            | ...                                      | .0002                       | .00025                    | .0003                 | .0004                               |
| 6              | ...                            | .0003              | 5                                      | ...  | .0008                   | .0013            | ...                                      | .0002                       | .00025                    | .0003                 | .0004                               |
| 5              | ...                            | .0003              | 4                                      | ...  | .0008                   | .0013            | ...                                      | ...                         | .00025                    | .0003                 | .0004                               |
| 4 1/2          | ...                            | .0003              | 4                                      | ...  | .0008                   | .0013            | ...                                      | ...                         | .00025                    | .0003                 | .0004                               |
| 4              | ...                            | .0003              | 4                                      | ...  | .0009                   | .0015            | ...                                      | ...                         | .00025                    | .0003                 | .0004                               |
| <b>X GAGES</b> |                                |                    |  |  |                         |                  |  |                             |                           |                       |                                     |
| 80, 72         | .0002                          | .0002              | 30                                     | .0003                                      | .0003                   | ...              | .0002                                    | .0002                       | ...                       | ...                   | ...                                 |
| 64             | .0002                          | .0002              | 30                                     | .0004                                      | .0004                   | ...              | .0002                                    | .0002                       | ...                       | ...                   | ...                                 |
| 56, 48         | .0002                          | .0002              | 30                                     | .0004                                      | .0004                   | ...              | .0002                                    | .0002                       | .0003                     | ...                   | ...                                 |
| 44, 40         | .0002                          | .0002              | 20                                     | .0004                                      | .0004                   | ...              | .0002                                    | .0002                       | .0003                     | ...                   | ...                                 |
| 36             | .0002                          | .0002              | 20                                     | .0004                                      | .0004                   | ...              | .0002                                    | .0002                       | .0003                     | ...                   | ...                                 |
| 32, 28         | .0003                          | .0003              | 15                                     | .0005                                      | .0005                   | .0007            | .0003                                    | .0003                       | .0004                     | .0005                 | .0006                               |
| 27, 24         | .0003                          | .0003              | 15                                     | .0005                                      | .0005                   | .0007            | .0003                                    | .0003                       | .0004                     | .0005                 | .0006                               |
| 20             | .0003                          | .0003              | 15                                     | .0005                                      | .0005                   | .0007            | .0003                                    | .0003                       | .0004                     | .0005                 | .0006                               |
| 18             | .0003                          | .0003              | 10                                     | .0005                                      | .0005                   | .0007            | .0003                                    | .0003                       | .0004                     | .0005                 | .0006                               |
| 16, 14         | .0003                          | .0003              | 10                                     | .0006                                      | .0006                   | .0009            | .0003                                    | .0003                       | .0004                     | .0006                 | .0008                               |
| 13, 12         | .0003                          | .0003              | 10                                     | .0006                                      | .0006                   | .0009            | .0003                                    | .0003                       | .0004                     | .0006                 | .0008                               |
| 11 1/2         | .0003                          | .0003              | 10                                     | .0006                                      | .0006                   | .0009            | .0003                                    | .0003                       | .0004                     | .0006                 | .0008                               |
| 11, 10         | .0003                          | .0003              | 10                                     | .0006                                      | .0006                   | .0009            | .0003                                    | .0003                       | .0004                     | .0006                 | .0008                               |
| 9              | .0003                          | .0003              | 10                                     | .0007                                      | .0007                   | .0011            | .0003                                    | .0003                       | .0004                     | .0006                 | .0008                               |
| 8, 7           | .0004                          | .0004              | 5                                      | .0007                                      | .0007                   | .0011            | .0004                                    | .0004                       | .0005                     | .0006                 | .0008                               |
| 6              | .0004                          | .0004              | 5                                      | .0008                                      | .0008                   | .0013            | .0004                                    | .0004                       | .0005                     | .0006                 | .0008                               |
| 5, 4 1/2       | .0004                          | .0004              | 5                                      | .0008                                      | .0008                   | .0013            | ...                                      | ...                         | .0005                     | .0006                 | .0008                               |
| 4              | .0004                          | .0004              | 5                                      | .0009                                      | .0009                   | .0015            | ...                                      | ...                         | .0005                     | .0006                 | .0008                               |

<sup>a</sup> Allowable variation in lead between any two threads not farther apart than the length of the standard gage as shown in ANSI B47.1. The tolerance on lead establishes the width of a zone, measured parallel to the axis of the thread, within which the actual helical path must lie for the specified length of the thread. Measurements are taken from a fixed reference point, located at the start of the first full thread, to a sufficient number of positions along the entire helix to detect all types of lead variations. The amounts that these positions vary from their basic (theoretical) positions are recorded with due respect to sign. The greatest variation in each direction (±) is selected, and the sum of their values, disregarding sign, must not exceed the tolerance limits specified for W gages.

<sup>b</sup> Tolerances apply to designated size of thread. The application of the tolerances is specified in the Standard.

<sup>c</sup> Above 12 in. the tolerance is directly proportional to the tolerance given in this column below, in the ratio of the diameter to 12 in.

All dimensions are given in inches unless otherwise specified.

**Table 5. Formulas for Limits of American National Standard Gages for Unified Inch Screw Threads ANSI/ASME B1.2-1983 (R2001)**

| No.  | Thread Gages for External Threads   |
|--|---|
| 1  | GO Pitch Diameter = Maximum pitch diameter of external thread. Gage tolerance is <i>minus</i> .   |
| 2  | GO Minor Diameter = Maximum pitch diameter of external thread minus $H/2$ . Gage tolerance is <i>minus</i> .  |
| 3  | NOT GO (LO) Pitch Diameter (for plus tolerance gage) = Minimum pitch diameter of external thread. Gage tolerance is <i>plus</i> .   |
| 4  | NOT GO (LO) Minor Diameter = Minimum pitch diameter of external thread minus $H/4$ . Gage tolerance is <i>plus</i> .  |
| Plain Gages for Major Diameter of External Threads       |   |
| 5  | GO = Maximum major diameter of external thread. Gage tolerance is <i>minus</i> .  |
| 6  | NOT GO = Minimum major diameter of external thread. Gage tolerance is <i>plus</i> .   |
| Thread Gages for Internal Threads                        |   |
| 7  | GO Major Diameter = Minimum major diameter of internal thread. Gage tolerance is <i>plus</i> .  |
| 8  | GO Pitch Diameter = Minimum pitch diameter of internal thread. Gage tolerance is <i>plus</i> .  |
| 9  | NOT GO (HI) Major Diameter = Maximum pitch diameter of internal thread plus $H/2$ . Gage tolerance is <i>minus</i> .  |
| 10   | NOT GO (HI) Pitch Diameter = Maximum pitch diameter of internal thread. Gage tolerance is <i>minus</i> .  |
| Plain Gages for Minor Diameter of Internal Threads       |   |
| 11   | GO = Minimum minor diameter of internal thread. Gage tolerance is <i>plus</i> .   |
| 12   | NOT GO = Maximum minor diameter of internal thread. Gage tolerance is <i>minus</i> .  |
| Full Form and Truncated Setting Plugs                    |   |
| 13   | GO Major Diameter (Truncated Portion) = Maximum major diameter of external thread (= minimum major diameter of full portion of GO setting plug) minus $(0.060\sqrt[3]{p^2} + 0.017p)$ . Gage tolerance is <i>minus</i> .  |
| 14   | GO Major Diameter (Full Portion) = Maximum major diameter of external thread. Gage tolerance is <i>plus</i> .   |
| 15   | GO Pitch Diameter = Maximum pitch diameter of external thread. Gage tolerance is <i>minus</i> .   |
| 16   | <sup>a</sup> NOT GO (LO) Major Diameter (Truncated Portion) = Minimum pitch diameter of external thread plus $H/2$ . Gage tolerance is <i>minus</i> .   |
| 17   | NOT GO (LO) Major Diameter (Full Portion) = Maximum major diameter of external thread provided major diameter crest width shall not be less than 0.001 in. (0.0009 in. truncation). Apply $W$ tolerance <i>plus</i> for maximum size except that for 0.001 in. crest width apply tolerance <i>minus</i> . For the 0.001 in. crest width, major diameter is equal to maximum major diameter of external thread plus $0.216506p$ minus the sum of external thread pitch diameter tolerance and 0.0017 in. |
| 18   | NOT GO (LO) Pitch Diameter = Minimum pitch diameter of external thread. Gage tolerance is <i>plus</i> .   |
| Solid Thread-setting Rings for Snap and Indicating Gages |   |
| 19   | <sup>b</sup> GO Pitch Diameter = Minimum pitch diameter of internal thread. $W$ gage tolerance is <i>plus</i> .   |
| 20   | GO Minor Diameter = Minimum minor diameter of internal thread. $W$ gage tolerance is <i>minus</i> .   |
| 21   | <sup>b</sup> NOT GO (HI) Pitch Diameter = Maximum pitch diameter of internal thread. $W$ gage tolerance is <i>minus</i> .   |
| 22   | NOT GO (HI) Minor Diameter = Maximum minor diameter of internal thread. $W$ gage tolerance is <i>minus</i> .  |

<sup>a</sup>Truncated portion is required when optional sharp root profile is used.

<sup>b</sup>Tolerances greater than  $W$  tolerance for pitch diameter are acceptable when internal indicating or snap gage can accommodate a greater tolerance and when agreed upon by supplier and user.

See data in Screw Thread Systems section for symbols and dimensions of Unified Screw Threads.

## TAPPING AND THREAD CUTTING

**Selection of Taps.**—For most applications, a standard tap supplied by the manufacturer can be used, but some jobs may require special taps. A variety of standard taps can be obtained. In addition to specifying the size of the tap it is necessary to be able to select the one most suitable for the application at hand.

The elements of standard taps that are varied are: the number of flutes; the type of flute, whether straight, spiral pointed, or spiral fluted; the chamfer length; the relief of the land, if any; the tool steel used to make the tap; and the surface treatment of the tap.

Details regarding the nomenclature of tap elements are given in the section *TAPS AND THREADING DIES* starting on page 892, along with a listing of the standard sizes available.

Factors to consider in selecting a tap include: the method of tapping, by hand or by machine; the material to be tapped and its heat treatment; the length of thread, or depth of the tapped hole; the required tolerance or class of fit; and the production requirement and the type of machine to be used.

The diameter of the hole must also be considered, although this action is usually only a matter of design and the specification of the tap drill size.

*Method of Tapping:* The term *hand tap* is used for both hand and machine taps, and almost all taps can be applied by the hand or machine method. While any tap can be used for hand tapping, those having a concentric land without the relief are preferable. In hand tapping the tool is reversed periodically to break the chip, and the heel of the land of a tap with a concentric land (without relief) will cut the chip off cleanly or any portion of it that is attached to the work, whereas a tap with an eccentric or con-eccentric relief may leave a small burr that becomes wedged between the relieved portion of the land and the work. This wedging creates a pressure towards the cutting face of the tap that may cause it to chip; it tends to roughen the threads in the hole, and it increases the overall torque required to turn the tool. When tapping by machine, however, the tap is usually turned only in one direction until the operation is complete, and an eccentric or con-eccentric relief is often an advantage.

*Chamfer Length:* Three types of hand taps, used both for hand and machine tapping, are available, and they are distinguished from each other by the length of chamfer. *Taper taps* have a chamfer angle that reduces the height about 8–10 teeth; *plug taps* have a chamfer angle with 3–5 threads reduced in height; and *bottoming taps* have a chamfer angle with  $1\frac{1}{2}$  threads reduced in height. Since the teeth that are reduced in height do practically all the cutting, the chip load or chip thickness per tooth will be least for a taper tap, greater for a plug tap, and greatest for a bottoming tap.

For most through hole tapping applications it is necessary to use only a plug type tap, which is also most suitable for blind holes where the tap drill hole is deeper than the required thread. If the tap must bottom in a blind hole, the hole is usually threaded first with a plug tap and then finished with a bottoming tap to catch the last threads in the bottom of the hole. Taper taps are used on materials where the chip load per tooth must be kept to a minimum. However, taper taps should not be used on materials that have a strong tendency to work harden, such as the austenitic stainless steels.

*Spiral Point Taps:* Spiral point taps offer a special advantage when machine tapping through holes in ductile materials because they are designed to handle the long continuous chips that form and would otherwise cause a disposal problem. An angular gash is ground at the point or end of the tap along the face of the chamfered threads or lead teeth of the tap. This gash forms a left-hand helix in the flutes adjacent to the lead teeth which causes the chips to flow ahead of the tap and through the hole. The gash is usually formed to produce a rake angle on the cutting face that increases progressively toward the end of the tool. Since the flutes are used primarily to provide a passage for the cutting fluid, they are usu-

ally made narrower and shallower thereby strengthening the tool. For tapping thin workpieces short fluted spiral point taps are recommended. They have a spiral point gash along the cutting teeth; the remainder of the threaded portion of the tap has no flute. Most spiral pointed taps are of plug type; however, spiral point bottoming taps are also made.

*Spiral Fluted Taps:* Spiral fluted taps have a helical flute; the helix angle of the flute may be between 15 and 52 degrees and the hand of the helix is the same as that of the threads on the tap. The spiral flute and the rake that it forms on the cutting face of the tap combine to induce the chips to flow backward along the helix and out of the hole. Thus, they are ideally suited for tapping blind holes and they are available as plug and bottoming types. A higher spiral angle should be specified for tapping very ductile materials; when tapping harder materials, chipping at the cutting edge may result and the spiral angle must be reduced.

Holes having a pronounced interruption such as a groove or a keyway can be tapped with spiral fluted taps. The land bridges the interruption and allows the tap to cut relatively smoothly.

*Serial Taps and Close Tolerance Threads:* For tapping holes to close tolerances a set of serial taps is used.

They are usually available in sets of three: the No. 1 tap is undersize and is the first rougher; the No. 2 tap is of intermediate size and is the second rougher; and the No. 3 tap is used for finishing.

The different taps are identified by one, two, and three annular grooves in the shank adjacent to the square. For some applications involving finer pitches only two serial taps are required. Sets are also used to tap hard or tough materials having a high tensile strength, deep blind holes in normal materials, and large coarse threads. A set of more than three taps is sometimes required to produce threads of coarse pitch. Threads to some commercial tolerances, such as American Standard Unified 2B, or ISO Metric 6H, can be produced in one cut using a ground tap; sometimes even closer tolerances can be produced with a single tap. Ground taps are recommended for all close tolerance tapping operations. For much ordinary work, cut taps are satisfactory and more economical than ground taps.

*Tap Steels:* Most taps are made from high speed steel. The type of tool steel used is determined by the tap manufacturer and is usually satisfactory when correctly applied except in a few exceptional cases. Typical grades of high speed steel used to make taps are M-1, M-2, M-3, M-42, etc. Carbon tool steel taps are satisfactory where the operating temperature of the tap is low and where a high resistance to abrasion is not required as in some types of hand tapping.

*Surface Treatment:* The life of high speed steel taps can sometimes be increased significantly by treating the surface of the tap. A very common treatment is oxide coating, which forms a thin metallic oxide coating on the tap that has lubricity and is somewhat porous to absorb and retain oil. This coating reduces the friction between the tap and the work and it makes the surface virtually impervious to rust. It does not increase the hardness of the surface but it significantly reduces or prevents entirely galling, or the tendency of the work material to weld or stick to the cutting edge and to other areas on the tap with which it is in contact. For this reason oxide coated taps are recommended for metals that tend to gall and stick such as non-free cutting low carbon steels and soft copper. It is also useful for tapping other steels having higher strength properties.

Nitriding provides a very hard and wear resistant case on high speed steel. Nitrided taps are especially recommended for tapping plastics; they have also been used successfully on a variety of other materials including high strength high alloy steels. However, some caution must be used in specifying nitrided taps because the nitride case is very brittle and may have a tendency to chip.

Chrome plating has been used to increase the wear resistance of taps but its application has been limited because of the high cost and the danger of hydrogen embrittlement which can cause cracks to form in the tool. A flash plate of about .0001 in. or less in thickness is

applied to the tap. Chrome-plated taps have been used successfully to tap a variety of ferrous and nonferrous materials including plastics, hard rubber, mild steel, and tool steel. Other surface treatments that have been used successfully to a limited extent are vapor blasting and liquid honing.

**Rake Angle:** For the majority of applications in both ferrous and nonferrous materials the rake angle machined on the tap by the manufacturer is satisfactory. This angle is approximately 5 to 7 degrees. In some instances it may be desirable to alter the rake angle of the tap to obtain beneficial results and Table 1 provides a guide that can be used. In selecting a rake angle from this table, consideration must be given to the size of the tap and the strength of the land. Most standard taps are made with a curved face with the rake angle measured as a chord between the crest and root of the thread. The resulting shape is called a hook angle.

**Table 1. Tap Rake Angles for Tapping Different Materials**

| Material  | Rake Angle, Degrees | Material          | Rake Angle, Degrees |
|---|---------------------|-------------------|---------------------|
| Cast Iron   | 0-3                 | Aluminum          | 8-20                |
| Malleable Iron                                      | 5-8                 | Brass             | 2-7                 |
| Steel   |                     | Naval Brass       | 5-8                 |
| AISI 1100 Series                                    | 5-12                | Phosphor Bronze   | 5-12                |
| Low Carbon (up to .25 per cent)                     | 5-12                | Tobin Bronze      | 5-8                 |
| Medium Carbon, Annealed (.30 to .60 per cent)       | 5-10                | Manganese Bronze  | 5-12                |
| Heat Treated, 225-283 Brinell (.30 to .60 per cent) | 0-8                 | Magnesium         | 10-20               |
| High Carbon and High Speed                          | 0-5                 | Monel             | 9-12                |
| Stainless   | 8-15                | Copper            | 10-18               |
| Titanium  | 5-10                | Zinc Die Castings | 10-15               |
|   |                     | Plastic           |                     |
|   |                     | Thermoplastic     | 5-8                 |
|   |                     | Thermosetting     | 0-3                 |
|   |                     | Hard Rubber       | 0-3                 |

**Cutting Speed.**—The cutting speed for machine tapping is treated in detail on page 1072. It suffices to say here that many variables must be considered in selecting this cutting speed and any tabulation may have to be modified greatly. Where cutting speeds are mentioned in the following section, they are intended only to provide a guideline to show the possible range of speeds that could be used.

**Tapping Specific Materials.**—The work material has a great influence on the ease with which a hole can be tapped. For production work, in many instances, modified taps are recommended; however, for toolroom or short batch work, standard hand taps can be used on most jobs, providing reasonable care is taken when tapping. The following concerns the tapping of metallic materials; information on the tapping of plastics is given on page 623.

**Low Carbon Steel (Less than 0.15% C):** These steels are very soft and ductile resulting in a tendency for the work material to tear and to weld to the tap. They produce a continuous chip that is difficult to break and spiral pointed taps are recommended for tapping through holes; for blind holes a spiral fluted tap is recommended. To prevent galling and welding, a liberal application of a sulfur base or other suitable cutting fluid is essential and the selection of an oxide coated tap is very helpful.

**Low Carbon Steels (0.15 to 0.30% C):** The additional carbon in these steels is beneficial as it reduces the tendency to tear and to weld; their machinability is further improved by cold drawing. These steels present no serious problems in tapping provided a suitable cut-

ting fluid is used. An oxide coated tap is recommended, particularly in the lower carbon range.

*Medium Carbon Steels (0.30 to 0.60% C):* These steels can be tapped without too much difficulty, although a lower cutting speed must be used in machine tapping. The cutting speed is dependent on the carbon content and the heat treatment. Steels that have a higher carbon content must be tapped more slowly, especially if the heat treatment has produced a pearlitic microstructure. The cutting speed and ease of tapping is significantly improved by heat treating to produce a spheroidized microstructure. A suitable cutting fluid must be used.

*High Carbon Steels (More than 0.6% C):* Usually these materials are tapped in the annealed or normalized condition although sometimes tapping is done after hardening and tempering to a hardness below 55 Rc. Recommendations for tapping after hardening and tempering are given under High Tensile Strength Steels. In the annealed and normalized condition these steels have a higher strength and are more abrasive than steels with a lower carbon content; thus, they are more difficult to tap. The microstructure resulting from the heat treatment has a significant effect on the ease of tapping and the tap life, a spheroidite structure being better in this respect than a pearlitic structure. The rake angle of the tap should not exceed 5 degrees and for the harder materials a concentric tap is recommended. The cutting speed is considerably lower for these steels and an activated sulfur-chlorinated cutting fluid is recommended.

*Alloy Steels:* This classification includes a wide variety of steels, each of which may be heat treated to have a wide range of properties. When annealed and normalized they are similar to medium to high carbon steels and usually can be tapped without difficulty, although for some alloy steels a lower tapping speed may be required. Standard taps can be used and for machine tapping a con-eccentric relief may be helpful. A suitable cutting fluid must be used.

*High-Tensile Strength Steels:* Any steel that must be tapped after being heat treated to a hardness range of 40–55 Rc is included in this classification. Low tap life and excessive tap breakage are characteristics of tapping these materials; those that have a high chromium content are particularly troublesome. Best results are obtained with taps that have concentric lands, a rake angle that is at or near zero degrees, and 6 to 8 chamfered threads on the end to reduce the chip load per tooth. The chamfer relief should be kept to a minimum. The load on the tap should be kept to a minimum by every possible means, including using the largest possible tap drill size; keeping the hole depth to a minimum; avoidance of bottoming holes; and, in the larger sizes, using fine instead of coarse pitches. Oxide coated taps are recommended although a nitrided tap can sometimes be used to reduce tap wear. An active sulfur-chlorinated oil is recommended as a cutting fluid and the tapping speed should not exceed about 10 feet per minute.

*Stainless Steels:* Ferritic and martensitic type stainless steels are somewhat like alloy steels that have a high chromium content, and they can be tapped in a similar manner, although a slightly slower cutting speed may have to be used. Standard rake angle oxide coated taps are recommended and a cutting fluid containing molybdenum disulphide is helpful to reduce the friction in tapping. Austenitic stainless steels are very difficult to tap because of their high resistance to cutting and their great tendency to work harden. A work-hardened layer is formed by a cutting edge of the tap and the depth of this layer depends on the severity of the cut and the sharpness of the tool. The next cutting edge must penetrate below the work-hardened layer, if it is to be able to cut. Therefore, the tap must be kept sharp and each succeeding cutting edge on the tool must penetrate below the work-hardened layer formed by the preceding cutting edge. For this reason, a taper tap should not be used, but rather a plug tap having 3–5 chamfered threads. To reduce the rubbing of the lands, an eccentric or con-eccentric relieved land should be used and a 10–15 degree rake angle is recommended. A tough continuous chip is formed that is difficult to break. To con-

trol this chip, spiral pointed taps are recommended for through holes and low-helix angle spiral fluted taps for blind holes. An oxide coating on the tap is very helpful and a sulfur-chlorinated mineral lard oil is recommended, although heavy duty soluble oils have also been used successfully.

*Free Cutting Steels:* There are large numbers of free cutting steels, including free cutting stainless steels, which are also called free machining steels. Sulfur, lead, or phosphorus are added to these steels to improve their machinability. Free machining steels are always easier to tap than their counterparts that do not have the free machining additives. Tool life is usually increased and a somewhat higher cutting speed can be used. The type of tap recommended depends on the particular type of free machining steel and the nature of the tapping operation; usually a standard tap can be used.

*High Temperature Alloys:* These are cobalt or nickel base nonferrous alloys that cut like austenitic stainless steel, but are often even more difficult to machine. The recommendations given for austenitic stainless steel also apply to tapping these alloys but the rake angle should be 0 to 10 degrees to strengthen the cutting edge. For most applications a nitrided tap or one made from M41, M42, M43, or M44 steel is recommended. The tapping speed is usually in the range of 5 to 10 feet per minute.

*Titanium and Titanium Alloys:* Titanium and its alloys have a low specific heat and a pronounced tendency to weld on to the tool material; therefore, oxide coated taps are recommended to minimize galling and welding. The rake angle of the tap should be from 6 to 10 degrees. To minimize the contact between the work and the tap an eccentric or con-eccentric relief land should be used. Taps having interrupted threads are sometimes helpful. Pure titanium is comparatively easy to tap but the alloys are very difficult. The cutting speed depends on the composition of the alloy and may vary from 40 to 10 feet per minute. Special cutting oils are recommended for tapping titanium.

*Gray Cast Iron:* The microstructure of gray cast iron can vary, even within a single casting, and compositions are used that vary in tensile strength from about 20,000 to 60,000 psi (160 to 250 Bhn). Thus, cast iron is not a single material, although in general it is not difficult to tap. The cutting speed may vary from 90 feet per minute for the softer grades to 30 feet per minute for the harder grades. The chip is discontinuous and straight fluted taps should be used for all applications. Oxide coated taps are helpful and gray cast iron can usually be tapped dry, although water soluble oils and chemical emulsions are sometimes used.

*Malleable Cast Iron:* Commercial malleable cast irons are also available having a rather wide range of properties, although within a single casting they tend to be quite uniform. They are relatively easy to tap and standard taps can be used. The cutting speed for ferritic cast irons is 60–90 feet per minute, for pearlitic malleable irons 40–50 feet per minute, and for martensitic malleable irons 30–35 feet per minute. A soluble oil cutting fluid is recommended except for martensitic malleable iron where a sulfur base oil may work better.

*Ductile or Nodular Cast Iron:* Several classes of nodular iron are used having a tensile strength varying from 60,000 to 120,000 psi. Moreover, the microstructure in a single casting and in castings produced at different times vary rather widely. The chips are easily controlled but have some tendency to weld to the faces and flanks of cutting tools. For this reason oxide coated taps are recommended. The cutting speed may vary from 15 fpm for the harder martensitic ductile irons to 60 fpm for the softer ferritic grades. A suitable cutting fluid should be used.

*Aluminum:* Aluminum and aluminum alloys are relatively soft materials that have little resistance to cutting. The danger in tapping these alloys is that the tap will ream the hole instead of cutting threads, or that it will cut a thread eccentric to the hole. For these reasons, extra care must be taken when aligning the tap and starting the thread. For production tapping a spiral pointed tap is recommended for through holes and a spiral fluted tap for blind holes; preferably these taps should have a 10 to 15 degree rake angle. A lead screw tapping



machine is helpful in cutting accurate threads. A heavy duty soluble oil or a light base mineral oil should be used as a cutting fluid.

**Copper Alloys:** Most copper alloys are not difficult to tap, except beryllium copper and a few other hard alloys. Pure copper offers some difficulty because of its ductility and the ductile continuous chip formed, which can be difficult to control. However, with reasonable care and the use of medium heavy duty mineral lard oil it can be tapped successfully. Red brass, yellow brass, and similar alloys containing not more than 35 per cent zinc produce a continuous chip. While straight fluted taps can be used for hand tapping these alloys, machine tapping should be done with spiral pointed or spiral fluted taps for through and blind holes respectively. Naval brass, leaded brass, and cast brasses produce a discontinuous chip and a straight fluted tap can be used for machine tapping. These alloys exhibit a tendency to close in on the tap and sometimes an interrupted thread tap is used to reduce the resulting jamming effect. Beryllium copper and the silicon bronzes are the strongest of the copper alloys. Their strength combined with their ability to work harden can cause difficulties in tapping. For these alloys plug type taps should be used and the taps should be kept as sharp as possible. A medium or heavy duty water soluble oil is recommended as a cutting fluid.

**Diameter of Tap Drill.**—Tapping troubles are sometimes caused by tap drills that are too small in diameter. The tap drill should not be smaller than is necessary to give the required strength to the thread as even a very small decrease in the diameter of the drill will increase the torque required and the possibility of broken taps. Tests have shown that any increase in the percentage of full thread over 60 per cent does not significantly increase the strength of the thread. Often, a 55 to 60 per cent thread is satisfactory, although 75 per cent threads are commonly used to provide an extra measure of safety. The present thread specifications do not always allow the use of the smaller thread depths. However, the specification given on a part drawing must be adhered to and may require smaller minor diameters than might otherwise be recommended.

The depth of the thread in the tapped hole is dependent on the length of thread engagement and on the material. In general, when the engagement length is more than one and one-half times the nominal diameter a 50 or 55 per cent thread is satisfactory. Soft ductile materials may permit use of a slightly larger tapping hole than brittle materials such as gray cast iron.

It must be remembered that a twist drill is a roughing tool that may be expected to drill slightly oversize and that some variations in the size of the tapping holes are almost inevitable. When a closer control of the hole size is required it must be reamed. Reaming is recommended for the larger thread diameters and for some fine pitch threads.

For threads of Unified form (see *American National and Unified Screw Thread Forms* on page 1725) the selection of tap drills is covered in the following section, Factors Influencing Minor Diameter Tolerances of Tapped Holes and the hole size limits are given in [Table 2](#). [Tables 3](#) and [4](#) give tap drill sizes for American National Form threads based on 75 per cent of full thread depth. For smaller-size threads the use of slightly larger drills, if permissible, will reduce tap breakage. The selection of tap drills for these threads also may be based on the hole size limits given in [Table 2](#) for Unified threads that take lengths of engagement into account.

**Table 2. Recommended Hole Size Limits Before Tapping Unified Threads**

| Thread Size                     | Classes 1B and 2B                                    |         |  |                      |   |         |                               |                      | Class 3B                        |         |  |                      |   |         |                               |        |
|---------------------------------|--|---------|--|----------------------|---|---------|-------------------------------|----------------------|---------------------------------|---------|--|----------------------|---|---------|-------------------------------|--------|
|                                 | Length of Engagement ( $D =$ Nominal Size of Thread) |         |  |                      |   |         |                               |                      |                                 |         |  |                      |   |         |                               |        |
|                                 | To and Including $\frac{1}{2}D$                      |         | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |                      | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |         | Above $1\frac{1}{2}D$ to $3D$ |                      | To and Including $\frac{1}{2}D$ |         | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |                      | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |         | Above $1\frac{1}{2}D$ to $3D$ |        |
|                                 | Recommended Hole Size Limits                         |         |  |                      |   |         |                               |                      |                                 |         |  |                      |   |         |                               |        |
| Min <sup>a</sup> Max            |  | Min Max |  | Min Max <sup>b</sup> |   | Min Max |                               | Min <sup>a</sup> Max |                                 | Min Max |  | Min Max <sup>b</sup> |   | Min Max |                               |        |
| 0-80                            | 0.0465   | 0.0500  | 0.0479                                 | 0.0514               | 0.0479                                  | 0.0514  | 0.0479                        | 0.0514               | 0.0465                          | 0.0500  | 0.0479                                 | 0.0514               | 0.0479                                  | 0.0514  | 0.0479                        | 0.0514 |
| 1-64                            | 0.0561   | 0.0599  | 0.0585                                 | 0.0623               | 0.0585                                  | 0.0623  | 0.0585                        | 0.0623               | 0.0561                          | 0.0599  | 0.0585                                 | 0.0623               | 0.0585                                  | 0.0623  | 0.0585                        | 0.0623 |
| 1-72                            | 0.0580   | 0.0613  | 0.0596                                 | 0.0629               | 0.0602                                  | 0.0635  | 0.0602                        | 0.0635               | 0.0580                          | 0.0613  | 0.0596                                 | 0.0629               | 0.0602                                  | 0.0635  | 0.0602                        | 0.0635 |
| 2-56                            | 0.0667   | 0.0705  | 0.0686                                 | 0.0724               | 0.0699                                  | 0.0737  | 0.0699                        | 0.0737               | 0.0667                          | 0.0705  | 0.0686                                 | 0.0724               | 0.0699                                  | 0.0737  | 0.0699                        | 0.0737 |
| 2-64                            | 0.0691   | 0.0724  | 0.0707                                 | 0.0740               | 0.0720                                  | 0.0753  | 0.0720                        | 0.0753               | 0.0691                          | 0.0724  | 0.0707                                 | 0.0740               | 0.0720                                  | 0.0753  | 0.0720                        | 0.0753 |
| 3-48                            | 0.0764   | 0.0804  | 0.0785                                 | 0.0825               | 0.0805                                  | 0.0845  | 0.0806                        | 0.0846               | 0.0764                          | 0.0804  | 0.0785                                 | 0.0825               | 0.0805                                  | 0.0845  | 0.0806                        | 0.0846 |
| 3-56                            | 0.0797   | 0.0831  | 0.0814                                 | 0.0848               | 0.0831                                  | 0.0865  | 0.0833                        | 0.0867               | 0.0797                          | 0.0831  | 0.0814                                 | 0.0848               | 0.0831                                  | 0.0865  | 0.0833                        | 0.0867 |
| 4-40                            | 0.0849   | 0.0894  | 0.0871                                 | 0.0916               | 0.0894                                  | 0.0939  | 0.0902                        | 0.0947               | 0.0849                          | 0.0894  | 0.0871                                 | 0.0916               | 0.0894                                  | 0.0939  | 0.0902                        | 0.0947 |
| 4-48                            | 0.0894   | 0.0931  | 0.0912                                 | 0.0949               | 0.0931                                  | 0.0968  | 0.0939                        | 0.0976               | 0.0894                          | 0.0931  | 0.0912                                 | 0.0949               | 0.0931                                  | 0.0968  | 0.0939                        | 0.0976 |
| 5-40                            | 0.0979   | 0.1020  | 0.1000                                 | 0.1041               | 0.1021                                  | 0.1062  | 0.1036                        | 0.1077               | 0.0979                          | 0.1020  | 0.1000                                 | 0.1041               | 0.1021                                  | 0.1062  | 0.1036                        | 0.1077 |
| 5-44                            | 0.1004   | 0.1042  | 0.1023                                 | 0.1060               | 0.1042                                  | 0.1079  | 0.1060                        | 0.1097               | 0.1004                          | 0.1042  | 0.1023                                 | 0.1060               | 0.1042                                  | 0.1079  | 0.1060                        | 0.1097 |
| 6-32                            | 0.104  | 0.109   | 0.106                                  | 0.112                | 0.109                                   | 0.114   | 0.112                         | 0.117                | 0.1040                          | 0.1091  | 0.1066                                 | 0.1115               | 0.1091                                  | 0.1140  | 0.1115                        | 0.1164 |
| 6-40                            | 0.111  | 0.115   | 0.113                                  | 0.117                | 0.115                                   | 0.119   | 0.117                         | 0.121                | 0.1110                          | 0.1148  | 0.1128                                 | 0.1167               | 0.1147                                  | 0.1186  | 0.1166                        | 0.1205 |
| 8-32                            | 0.130  | 0.134   | 0.132                                  | 0.137                | 0.134                                   | 0.139   | 0.137                         | 0.141                | 0.1300                          | 0.1345  | 0.1324                                 | 0.1367               | 0.1346                                  | 0.1389  | 0.1367                        | 0.1410 |
| 8-36                            | 0.134  | 0.138   | 0.136                                  | 0.140                | 0.138                                   | 0.142   | 0.140                         | 0.144                | 0.1340                          | 0.1377  | 0.1359                                 | 0.1397               | 0.1378                                  | 0.1416  | 0.1397                        | 0.1435 |
| 10-24                           | 0.145  | 0.150   | 0.148                                  | 0.154                | 0.150                                   | 0.156   | 0.152                         | 0.159                | 0.1450                          | 0.1502  | 0.1475                                 | 0.1528               | 0.1502                                  | 0.1555  | 0.1528                        | 0.1581 |
| 10-32                           | 0.156  | 0.160   | 0.158                                  | 0.162                | 0.160                                   | 0.164   | 0.162                         | 0.166                | 0.1560                          | 0.1601  | 0.1581                                 | 0.1621               | 0.1601                                  | 0.1641  | 0.1621                        | 0.1661 |
| 12-24                           | 0.171  | 0.176   | 0.174                                  | 0.179                | 0.176                                   | 0.181   | 0.178                         | 0.184                | 0.1710                          | 0.1758  | 0.1733                                 | 0.1782               | 0.1758                                  | 0.1807  | 0.1782                        | 0.1831 |
| 12-28                           | 0.177  | 0.182   | 0.179                                  | 0.184                | 0.182                                   | 0.186   | 0.184                         | 0.188                | 0.1770                          | 0.1815  | 0.1794                                 | 0.1836               | 0.1815                                  | 0.1857  | 0.1836                        | 0.1878 |
| 12-32                           | 0.182  | 0.186   | 0.184                                  | 0.188                | 0.186                                   | 0.190   | 0.188                         | 0.192                | 0.1820                          | 0.1858  | 0.1837                                 | 0.1877               | 0.1855                                  | 0.1895  | 0.1873                        | 0.1913 |
| $\frac{1}{4}$ -20               | 0.196  | 0.202   | 0.199                                  | 0.204                | 0.202                                   | 0.207   | 0.204                         | 0.210                | 0.1960                          | 0.2013  | 0.1986                                 | 0.2040               | 0.2013                                  | 0.2067  | 0.2040                        | 0.2094 |
| $\frac{1}{4}$ -28               | 0.211  | 0.216   | 0.213                                  | 0.218                | 0.216                                   | 0.220   | 0.218                         | 0.222                | 0.2110                          | 0.2152  | 0.2131                                 | 0.2171               | 0.2150                                  | 0.2190  | 0.2169                        | 0.2209 |
| $\frac{1}{4}$ -32               | 0.216  | 0.220   | 0.218                                  | 0.222                | 0.220                                   | 0.224   | 0.222                         | 0.226                | 0.2160                          | 0.2196  | 0.2172                                 | 0.2212               | 0.2189                                  | 0.2229  | 0.2206                        | 0.2246 |
| $\frac{1}{4}$ -36               | 0.220  | 0.224   | 0.221                                  | 0.225                | 0.224                                   | 0.226   | 0.225                         | 0.228                | 0.2200                          | 0.2243  | 0.2199                                 | 0.2243               | 0.2214                                  | 0.2258  | 0.2229                        | 0.2273 |
| $\frac{3}{8}$ <sub>IE</sub> -18 | 0.252  | 0.259   | 0.255                                  | 0.262                | 0.259                                   | 0.265   | 0.262                         | 0.268                | 0.2520                          | 0.2577  | 0.2551                                 | 0.2604               | 0.2577                                  | 0.2630  | 0.2604                        | 0.2657 |
| $\frac{3}{8}$ <sub>IE</sub> -24 | 0.267  | 0.272   | 0.270                                  | 0.275                | 0.272                                   | 0.277   | 0.275                         | 0.280                | 0.2670                          | 0.2714  | 0.2694                                 | 0.2734               | 0.2714                                  | 0.2754  | 0.2734                        | 0.2774 |
| $\frac{3}{8}$ <sub>IE</sub> -32 | 0.279  | 0.283   | 0.281                                  | 0.285                | 0.283                                   | 0.286   | 0.285                         | 0.289                | 0.2790                          | 0.2817  | 0.2792                                 | 0.2832               | 0.2807                                  | 0.2847  | 0.2822                        | 0.2862 |
| $\frac{3}{8}$ <sub>IE</sub> -36 | 0.282  | 0.286   | 0.284                                  | 0.288                | 0.285                                   | 0.289   | 0.287                         | 0.291                | 0.2820                          | 0.2863  | 0.2824                                 | 0.2863               | 0.2837                                  | 0.2877  | 0.2850                        | 0.2890 |
| $\frac{3}{8}$ <sub>IE</sub> -16 | 0.307  | 0.314   | 0.311                                  | 0.318                | 0.314                                   | 0.321   | 0.318                         | 0.325                | 0.3070                          | 0.3127  | 0.3101                                 | 0.3155               | 0.3128                                  | 0.3182  | 0.3155                        | 0.3209 |

Table 2. (Continued) Recommended Hole Size Limits Before Tapping Unified Threads

| Thread Size        | Classes 1B and 2B                                    |       |  |       |   |       |                               |       | Class 3B                        |                  |  |        |   |        |                               |        |     |
|--------------------|--|-------|--|-------|---|-------|-------------------------------|-------|---------------------------------|------------------|--|--------|---|--------|-------------------------------|--------|-----|
|                    | Length of Engagement ( $D$ = Nominal Size of Thread) |       |  |       |   |       |                               |       |                                 |                  |  |        |   |        |                               |        |     |
|                    | To and Including $\frac{1}{2}D$                      |       | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |       | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |       | Above $1\frac{1}{2}D$ to $3D$ |       | To and Including $\frac{1}{2}D$ |                  | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |        | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |        | Above $1\frac{1}{2}D$ to $3D$ |        |     |
|                    | Recommended Hole Size Limits                         |       |  |       |   |       |                               |       |                                 |                  |  |        |   |        |                               |        |     |
| Min <sup>a</sup>   | Max  | Min   | Max                                    | Min   | Max <sup>b</sup>                        | Min   | Max                           | Min   | Max                             | Min <sup>a</sup> | Max                                    | Min    | Max                                     | Min    | Max <sup>b</sup>              | Min    | Max |
| $\frac{3}{8}$ -24  | 0.330  | 0.335 | 0.333                                  | 0.338 | 0.335                                   | 0.340 | 0.338                         | 0.343 | 0.330                           | 0.3336           | 0.3314                                 | 0.3354 | 0.3332                                  | 0.3372 | 0.3351                        | 0.3391 |     |
| $\frac{3}{8}$ -32  | 0.341  | 0.345 | 0.343                                  | 0.347 | 0.345                                   | 0.349 | 0.347                         | 0.351 | 0.3410                          | 0.3441           | 0.3415                                 | 0.3455 | 0.3429                                  | 0.3469 | 0.3444                        | 0.3484 |     |
| $\frac{3}{8}$ -36  | 0.345  | 0.349 | 0.346                                  | 0.350 | 0.347                                   | 0.352 | 0.349                         | 0.353 | 0.3450                          | 0.3488           | 0.3449                                 | 0.3488 | 0.3461                                  | 0.3501 | 0.3474                        | 0.3514 |     |
| $\frac{7}{16}$ -14 | 0.360  | 0.368 | 0.364                                  | 0.372 | 0.368                                   | 0.376 | 0.372                         | 0.380 | 0.3600                          | 0.3660           | 0.3630                                 | 0.3688 | 0.3659                                  | 0.3717 | 0.3688                        | 0.3746 |     |
| $\frac{7}{16}$ -20 | 0.383  | 0.389 | 0.386                                  | 0.391 | 0.389                                   | 0.395 | 0.391                         | 0.397 | 0.3830                          | 0.3875           | 0.3855                                 | 0.3896 | 0.3875                                  | 0.3916 | 0.3896                        | 0.3937 |     |
| $\frac{7}{16}$ -28 | 0.399  | 0.403 | 0.401                                  | 0.406 | 0.403                                   | 0.407 | 0.406                         | 0.410 | 0.3990                          | 0.4020           | 0.3995                                 | 0.4035 | 0.4011                                  | 0.4051 | 0.4017                        | 0.4067 |     |
| $\frac{1}{2}$ -13  | 0.417  | 0.426 | 0.421                                  | 0.430 | 0.426                                   | 0.434 | 0.430                         | 0.438 | 0.4170                          | 0.4225           | 0.4196                                 | 0.4254 | 0.4226                                  | 0.4284 | 0.4255                        | 0.4313 |     |
| $\frac{1}{2}$ -12  | 0.410  | 0.414 | 0.414                                  | 0.424 | 0.414                                   | 0.428 | 0.424                         | 0.433 | 0.4100                          | 0.4161           | 0.4129                                 | 0.4192 | 0.4160                                  | 0.4223 | 0.4192                        | 0.4255 |     |
| $\frac{1}{2}$ -20  | 0.446  | 0.452 | 0.449                                  | 0.454 | 0.452                                   | 0.457 | 0.454                         | 0.460 | 0.4460                          | 0.4498           | 0.4477                                 | 0.4517 | 0.4497                                  | 0.4537 | 0.4516                        | 0.4556 |     |
| $\frac{1}{2}$ -28  | 0.461  | 0.467 | 0.463                                  | 0.468 | 0.466                                   | 0.470 | 0.468                         | 0.472 | 0.4610                          | 0.4645           | 0.4620                                 | 0.4660 | 0.4636                                  | 0.4676 | 0.4652                        | 0.4692 |     |
| $\frac{9}{16}$ -12 | 0.472  | 0.476 | 0.476                                  | 0.486 | 0.476                                   | 0.490 | 0.486                         | 0.495 | 0.4720                          | 0.4783           | 0.4753                                 | 0.4813 | 0.4783                                  | 0.4843 | 0.4813                        | 0.4873 |     |
| $\frac{9}{16}$ -18 | 0.502  | 0.509 | 0.505                                  | 0.512 | 0.509                                   | 0.515 | 0.512                         | 0.518 | 0.5020                          | 0.5065           | 0.5045                                 | 0.5086 | 0.5065                                  | 0.5106 | 0.5086                        | 0.5127 |     |
| $\frac{9}{16}$ -24 | 0.517  | 0.522 | 0.520                                  | 0.525 | 0.522                                   | 0.527 | 0.525                         | 0.530 | 0.5170                          | 0.5209           | 0.5186                                 | 0.5226 | 0.5204                                  | 0.5244 | 0.5221                        | 0.5261 |     |
| $\frac{9}{16}$ -28 | 0.524  | 0.528 | 0.526                                  | 0.531 | 0.528                                   | 0.532 | 0.531                         | 0.535 | 0.5240                          | 0.5270           | 0.5245                                 | 0.5285 | 0.5261                                  | 0.5301 | 0.5277                        | 0.5317 |     |
| $\frac{3}{8}$ -11  | 0.527  | 0.536 | 0.532                                  | 0.541 | 0.536                                   | 0.546 | 0.541                         | 0.551 | 0.5270                          | 0.5328           | 0.5298                                 | 0.5360 | 0.5329                                  | 0.5391 | 0.5360                        | 0.5422 |     |
| $\frac{3}{8}$ -12  | 0.535  | 0.544 | 0.540                                  | 0.549 | 0.544                                   | 0.553 | 0.549                         | 0.558 | 0.5350                          | 0.5406           | 0.5377                                 | 0.5435 | 0.5405                                  | 0.5463 | 0.5434                        | 0.5492 |     |
| $\frac{3}{8}$ -18  | 0.565  | 0.572 | 0.568                                  | 0.575 | 0.572                                   | 0.578 | 0.575                         | 0.581 | 0.5650                          | 0.5690           | 0.5670                                 | 0.5711 | 0.5690                                  | 0.5730 | 0.5711                        | 0.5752 |     |
| $\frac{3}{8}$ -24  | 0.580  | 0.585 | 0.583                                  | 0.588 | 0.585                                   | 0.590 | 0.588                         | 0.593 | 0.5800                          | 0.5834           | 0.5811                                 | 0.5851 | 0.5829                                  | 0.5869 | 0.5846                        | 0.5886 |     |
| $\frac{3}{8}$ -28  | 0.586  | 0.591 | 0.588                                  | 0.593 | 0.591                                   | 0.595 | 0.593                         | 0.597 | 0.5860                          | 0.5895           | 0.5870                                 | 0.5910 | 0.5886                                  | 0.5926 | 0.5902                        | 0.5942 |     |
| $\frac{1}{2}$ -12  | 0.597  | 0.606 | 0.602                                  | 0.611 | 0.606                                   | 0.615 | 0.611                         | 0.620 | 0.5970                          | 0.6029           | 0.6001                                 | 0.6057 | 0.6029                                  | 0.6085 | 0.6057                        | 0.6113 |     |
| $\frac{1}{2}$ -24  | 0.642  | 0.647 | 0.645                                  | 0.650 | 0.647                                   | 0.652 | 0.650                         | 0.655 | 0.6420                          | 0.6459           | 0.6436                                 | 0.6476 | 0.6454                                  | 0.6494 | 0.6471                        | 0.6511 |     |
| $\frac{3}{4}$ -10  | 0.642  | 0.653 | 0.647                                  | 0.658 | 0.653                                   | 0.663 | 0.658                         | 0.668 | 0.6420                          | 0.6481           | 0.6449                                 | 0.6513 | 0.6481                                  | 0.6545 | 0.6513                        | 0.6577 |     |
| $\frac{3}{4}$ -12  | 0.660  | 0.669 | 0.665                                  | 0.674 | 0.669                                   | 0.678 | 0.674                         | 0.683 | 0.6600                          | 0.6652           | 0.6626                                 | 0.6680 | 0.6653                                  | 0.6707 | 0.6680                        | 0.6734 |     |
| $\frac{3}{4}$ -16  | 0.682  | 0.689 | 0.686                                  | 0.693 | 0.689                                   | 0.696 | 0.693                         | 0.700 | 0.6820                          | 0.6866           | 0.6844                                 | 0.6887 | 0.6865                                  | 0.6908 | 0.6886                        | 0.6929 |     |
| $\frac{3}{4}$ -20  | 0.696  | 0.702 | 0.699                                  | 0.704 | 0.702                                   | 0.707 | 0.704                         | 0.710 | 0.6960                          | 0.6998           | 0.6977                                 | 0.7017 | 0.6997                                  | 0.7037 | 0.7016                        | 0.7056 |     |
| $\frac{3}{4}$ -28  | 0.711  | 0.716 | 0.713                                  | 0.718 | 0.716                                   | 0.720 | 0.718                         | 0.722 | 0.7110                          | 0.7145           | 0.7120                                 | 0.7160 | 0.7136                                  | 0.7176 | 0.7152                        | 0.7192 |     |
| $\frac{1}{2}$ -12  | 0.722  | 0.731 | 0.727                                  | 0.736 | 0.731                                   | 0.740 | 0.736                         | 0.745 | 0.7220                          | 0.7276           | 0.7250                                 | 0.7303 | 0.7276                                  | 0.7329 | 0.7303                        | 0.7356 |     |

**Table 2. (Continued) Recommended Hole Size Limits Before Tapping Unified Threads**

| Thread Size         | Classes 1B and 2B  |       |  |       |   |       |                               |                  | Class 3B                        |        |  |        |   |        |                               |        |
|---------------------|--|-------|--|-------|---|-------|-------------------------------|------------------|---------------------------------|--------|--|--------|---|--------|-------------------------------|--------|
|                     | Length of Engagement ( $D = \text{Nominal Size of Thread}$ ) |       |  |       |   |       |                               |                  |                                 |        |  |        |   |        |                               |        |
|                     | To and Including $\frac{1}{2}D$                              |       | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |       | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |       | Above $1\frac{1}{2}D$ to $3D$ |                  | To and Including $\frac{1}{2}D$ |        | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |        | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |        | Above $1\frac{1}{2}D$ to $3D$ |        |
|                     | Recommended Hole Size Limits                                 |       |  |       |   |       |                               |                  |                                 |        |  |        |   |        |                               |        |
| Min <sup>a</sup>    | Max  | Min   | Max                                    | Min   | Max <sup>b</sup>                        | Min   | Max                           | Min <sup>a</sup> | Max                             | Min    | Max                                    | Min    | Max <sup>b</sup>                        | Min    | Max                           |        |
| $\frac{1}{16}$ -16  | 0.745  | 0.752 | 0.749                                  | 0.756 | 0.752                                   | 0.759 | 0.756                         | 0.763            | 0.7450                          | 0.7491 | 0.7469                                 | 0.7512 | 0.7490                                  | 0.7533 | 0.7511                        | 0.7554 |
| $\frac{1}{16}$ -20  | 0.758  | 0.764 | 0.761                                  | 0.766 | 0.764                                   | 0.770 | 0.766                         | 0.772            | 0.7580                          | 0.7623 | 0.7602                                 | 0.7642 | 0.7622                                  | 0.7662 | 0.7641                        | 0.7681 |
| $\frac{7}{8}$ -9    | 0.755  | 0.767 | 0.761                                  | 0.773 | 0.767                                   | 0.778 | 0.773                         | 0.785            | 0.7550                          | 0.7614 | 0.7580                                 | 0.7647 | 0.7614                                  | 0.7681 | 0.7647                        | 0.7714 |
| $\frac{7}{8}$ -12   | 0.785  | 0.794 | 0.790                                  | 0.799 | 0.794                                   | 0.803 | 0.799                         | 0.808            | 0.7850                          | 0.7900 | 0.7874                                 | 0.7926 | 0.7900                                  | 0.7952 | 0.7926                        | 0.7978 |
| $\frac{7}{8}$ -14   | 0.798  | 0.806 | 0.802                                  | 0.810 | 0.806                                   | 0.814 | 0.810                         | 0.818            | 0.7980                          | 0.8022 | 0.8000                                 | 0.8045 | 0.8023                                  | 0.8068 | 0.8045                        | 0.8090 |
| $\frac{7}{8}$ -16   | 0.807  | 0.814 | 0.811                                  | 0.818 | 0.814                                   | 0.821 | 0.818                         | 0.825            | 0.8070                          | 0.8116 | 0.8094                                 | 0.8137 | 0.8115                                  | 0.8158 | 0.8136                        | 0.8179 |
| $\frac{7}{8}$ -20   | 0.821  | 0.827 | 0.824                                  | 0.829 | 0.827                                   | 0.832 | 0.829                         | 0.835            | 0.8210                          | 0.8248 | 0.8227                                 | 0.8267 | 0.8247                                  | 0.8287 | 0.8266                        | 0.8306 |
| $\frac{7}{8}$ -28   | 0.836  | 0.840 | 0.838                                  | 0.843 | 0.840                                   | 0.845 | 0.843                         | 0.847            | 0.8360                          | 0.8395 | 0.8370                                 | 0.8410 | 0.8386                                  | 0.8426 | 0.8402                        | 0.8442 |
| $\frac{15}{16}$ -12 | 0.847  | 0.856 | 0.852                                  | 0.861 | 0.856                                   | 0.865 | 0.861                         | 0.870            | 0.8470                          | 0.8524 | 0.8499                                 | 0.8550 | 0.8524                                  | 0.8575 | 0.8550                        | 0.8601 |
| $\frac{15}{16}$ -16 | 0.870  | 0.877 | 0.874                                  | 0.881 | 0.877                                   | 0.884 | 0.881                         | 0.888            | 0.8700                          | 0.8741 | 0.8719                                 | 0.8762 | 0.8740                                  | 0.8783 | 0.8761                        | 0.8804 |
| $\frac{15}{16}$ -20 | 0.883  | 0.889 | 0.886                                  | 0.891 | 0.889                                   | 0.895 | 0.891                         | 0.897            | 0.8830                          | 0.8873 | 0.8852                                 | 0.8892 | 0.8872                                  | 0.8912 | 0.8891                        | 0.8931 |
| 1-8                 | 0.865  | 0.878 | 0.871                                  | 0.884 | 0.878                                   | 0.890 | 0.884                         | 0.896            | 0.8650                          | 0.8722 | 0.8684                                 | 0.8759 | 0.8722                                  | 0.8797 | 0.8760                        | 0.8835 |
| 1-12                | 0.910  | 0.919 | 0.915                                  | 0.924 | 0.919                                   | 0.928 | 0.924                         | 0.933            | 0.9100                          | 0.9148 | 0.9123                                 | 0.9173 | 0.9148                                  | 0.9198 | 0.9173                        | 0.9223 |
| 1-14                | 0.923  | 0.931 | 0.927                                  | 0.934 | 0.931                                   | 0.938 | 0.934                         | 0.942            | 0.9230                          | 0.9271 | 0.9249                                 | 0.9293 | 0.9271                                  | 0.9315 | 0.9293                        | 0.9337 |
| 1-16                | 0.932  | 0.939 | 0.936                                  | 0.943 | 0.939                                   | 0.946 | 0.943                         | 0.950            | 0.9320                          | 0.9366 | 0.9344                                 | 0.9387 | 0.9365                                  | 0.9408 | 0.9386                        | 0.9429 |
| 1-20                | 0.946  | 0.952 | 0.949                                  | 0.954 | 0.952                                   | 0.957 | 0.954                         | 0.960            | 0.9460                          | 0.9498 | 0.9477                                 | 0.9517 | 0.9497                                  | 0.9537 | 0.9516                        | 0.9556 |
| 1-28                | 0.961  | 0.966 | 0.963                                  | 0.968 | 0.966                                   | 0.970 | 0.968                         | 0.972            | 0.9610                          | 0.9645 | 0.9620                                 | 0.9660 | 0.9636                                  | 0.9676 | 0.9652                        | 0.9692 |
| $1\frac{1}{16}$ -12 | 0.972  | 0.981 | 0.977                                  | 0.986 | 0.981                                   | 0.990 | 0.986                         | 0.995            | 0.9720                          | 0.9773 | 0.9748                                 | 0.9798 | 0.9773                                  | 0.9823 | 0.9798                        | 0.9848 |
| $1\frac{1}{16}$ -16 | 0.995  | 1.002 | 0.999                                  | 1.005 | 1.002                                   | 1.009 | 1.005                         | 1.013            | 0.9950                          | 0.9991 | 0.9969                                 | 1.0012 | 0.9990                                  | 1.0033 | 1.0011                        | 1.0054 |
| $1\frac{1}{16}$ -18 | 1.002  | 1.009 | 1.005                                  | 1.012 | 1.009                                   | 1.015 | 1.012                         | 1.018            | 1.0020                          | 1.0065 | 1.0044                                 | 1.0085 | 1.0064                                  | 1.0105 | 1.0085                        | 1.0126 |
| $1\frac{1}{8}$ -7   | 0.970  | 0.984 | 0.977                                  | 0.991 | 0.984                                   | 0.998 | 0.991                         | 1.005            | 0.9700                          | 0.9790 | 0.9747                                 | 0.9833 | 0.9789                                  | 0.9875 | 0.9832                        | 0.9918 |
| $1\frac{1}{8}$ -8   | 0.990  | 1.003 | 0.996                                  | 1.009 | 1.003                                   | 1.015 | 1.009                         | 1.021            | 0.9900                          | 0.9972 | 0.9934                                 | 1.0009 | 0.9972                                  | 1.0047 | 1.0010                        | 1.0085 |
| $1\frac{1}{8}$ -12  | 1.035  | 1.044 | 1.040                                  | 1.049 | 1.044                                   | 1.053 | 1.049                         | 1.058            | 1.0350                          | 1.0398 | 1.0373                                 | 1.0423 | 1.0398                                  | 1.0448 | 1.0423                        | 1.0473 |
| $1\frac{1}{8}$ -16  | 1.057  | 1.064 | 1.061                                  | 1.068 | 1.064                                   | 1.071 | 1.068                         | 1.075            | 1.0570                          | 1.0616 | 1.0594                                 | 1.0637 | 1.0615                                  | 1.0658 | 1.0636                        | 1.0679 |
| $1\frac{1}{8}$ -18  | 1.065  | 1.072 | 1.068                                  | 1.075 | 1.072                                   | 1.078 | 1.075                         | 1.081            | 1.0650                          | 1.0690 | 1.0669                                 | 1.0710 | 1.0689                                  | 1.0730 | 1.0710                        | 1.0751 |
| $1\frac{1}{8}$ -20  | 1.071  | 1.077 | 1.074                                  | 1.079 | 1.077                                   | 1.082 | 1.079                         | 1.085            | 1.0710                          | 1.0748 | 1.0727                                 | 1.0767 | 1.0747                                  | 1.0787 | 1.0766                        | 1.0806 |
| $1\frac{1}{8}$ -28  | 1.086  | 1.091 | 1.088                                  | 1.093 | 1.091                                   | 1.095 | 1.093                         | 1.097            | 1.0860                          | 1.0895 | 1.0870                                 | 1.0910 | 1.0886                                  | 1.0926 | 1.0902                        | 1.0942 |
| $1\frac{3}{16}$ -12 | 1.097  | 1.106 | 1.102                                  | 1.111 | 1.106                                   | 1.115 | 1.111                         | 1.120            | 1.0970                          | 1.1023 | 1.0998                                 | 1.1048 | 1.1023                                  | 1.1073 | 1.1048                        | 1.1098 |

**Table 2. (Continued) Recommended Hole Size Limits Before Tapping Unified Threads**

| Thread Size         | Classes 1B and 2B                                    |       |  |       |   |       |                               |                  | Class 3B                        |        |  |        |   |        |                               |        |
|---------------------|--|-------|--|-------|---|-------|-------------------------------|------------------|---------------------------------|--------|--|--------|---|--------|-------------------------------|--------|
|                     | Length of Engagement ( $D =$ Nominal Size of Thread) |       |  |       |   |       |                               |                  |                                 |        |  |        |   |        |                               |        |
|                     | To and Including $\frac{1}{2}D$                      |       | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |       | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |       | Above $1\frac{1}{2}D$ to $3D$ |                  | To and Including $\frac{1}{2}D$ |        | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |        | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |        | Above $1\frac{1}{2}D$ to $3D$ |        |
|                     | Recommended Hole Size Limits                         |       |  |       |   |       |                               |                  |                                 |        |  |        |   |        |                               |        |
| Min <sup>a</sup>    | Max  | Min   | Max                                    | Min   | Max <sup>b</sup>                        | Min   | Max                           | Min <sup>a</sup> | Max                             | Min    | Max                                    | Min    | Max <sup>b</sup>                        | Min    | Max                           |        |
| $1\frac{3}{16}$ -16 | 1.120  | 1.127 | 1.124                                  | 1.131 | 1.127                                   | 1.134 | 1.131                         | 1.138            | 1.1200                          | 1.1241 | 1.1219                                 | 1.1262 | 1.1240                                  | 1.1283 | 1.1261                        | 1.1304 |
| $1\frac{3}{16}$ -18 | 1.127  | 1.134 | 1.130                                  | 1.137 | 1.134                                   | 1.140 | 1.137                         | 1.143            | 1.1270                          | 1.1315 | 1.1294                                 | 1.1335 | 1.1314                                  | 1.1355 | 1.1335                        | 1.1376 |
| $1\frac{1}{4}$ -7   | 1.095  | 1.109 | 1.102                                  | 1.116 | 1.109                                   | 1.123 | 1.116                         | 1.130            | 1.0950                          | 1.1040 | 1.0997                                 | 1.1083 | 1.1039                                  | 1.1125 | 1.1082                        | 1.1168 |
| $1\frac{1}{4}$ -8   | 1.115  | 1.128 | 1.121                                  | 1.134 | 1.128                                   | 1.140 | 1.134                         | 1.146            | 1.1150                          | 1.1222 | 1.1184                                 | 1.1259 | 1.1222                                  | 1.1297 | 1.1260                        | 1.1335 |
| $1\frac{1}{4}$ -12  | 1.160  | 1.169 | 1.165                                  | 1.174 | 1.169                                   | 1.178 | 1.174                         | 1.183            | 1.1600                          | 1.1648 | 1.1623                                 | 1.1673 | 1.1648                                  | 1.1698 | 1.1673                        | 1.1723 |
| $1\frac{1}{4}$ -16  | 1.182  | 1.189 | 1.186                                  | 1.193 | 1.189                                   | 1.196 | 1.193                         | 1.200            | 1.1820                          | 1.1866 | 1.1844                                 | 1.1887 | 1.1865                                  | 1.1908 | 1.1886                        | 1.1929 |
| $1\frac{1}{4}$ -18  | 1.190  | 1.197 | 1.193                                  | 1.200 | 1.197                                   | 1.203 | 1.200                         | 1.206            | 1.1900                          | 1.1940 | 1.1919                                 | 1.1960 | 1.1939                                  | 1.1980 | 1.1960                        | 1.2001 |
| $1\frac{1}{4}$ -20  | 1.196  | 1.202 | 1.199                                  | 1.204 | 1.202                                   | 1.207 | 1.204                         | 1.210            | 1.1960                          | 1.1998 | 1.1977                                 | 1.2017 | 1.1997                                  | 1.2037 | 1.2016                        | 1.2056 |
| $1\frac{3}{16}$ -12 | 1.222  | 1.231 | 1.227                                  | 1.236 | 1.231                                   | 1.240 | 1.236                         | 1.245            | 1.2220                          | 1.2273 | 1.2248                                 | 1.2298 | 1.2273                                  | 1.2323 | 1.2298                        | 1.2348 |
| $1\frac{3}{16}$ -16 | 1.245  | 1.252 | 1.249                                  | 1.256 | 1.252                                   | 1.259 | 1.256                         | 1.263            | 1.2450                          | 1.2491 | 1.2469                                 | 1.2512 | 1.2490                                  | 1.2533 | 1.2511                        | 1.2554 |
| $1\frac{3}{16}$ -18 | 1.252  | 1.259 | 1.256                                  | 1.262 | 1.259                                   | 1.265 | 1.262                         | 1.268            | 1.2520                          | 1.2565 | 1.2544                                 | 1.2585 | 1.2564                                  | 1.2605 | 1.2585                        | 1.2626 |
| $1\frac{3}{8}$ -6   | 1.195  | 1.210 | 1.203                                  | 1.221 | 1.210                                   | 1.225 | 1.221                         | 1.239            | 1.1950                          | 1.2046 | 1.1996                                 | 1.2096 | 1.2046                                  | 1.2146 | 1.2096                        | 1.2196 |
| $1\frac{3}{8}$ -8   | 1.240  | 1.253 | 1.246                                  | 1.259 | 1.253                                   | 1.265 | 1.259                         | 1.271            | 1.2400                          | 1.2472 | 1.2434                                 | 1.2509 | 1.2472                                  | 1.2547 | 1.2510                        | 1.2585 |
| $1\frac{3}{8}$ -12  | 1.285  | 1.294 | 1.290                                  | 1.299 | 1.294                                   | 1.303 | 1.299                         | 1.308            | 1.2850                          | 1.2898 | 1.2873                                 | 1.2923 | 1.2898                                  | 1.2948 | 1.2923                        | 1.2973 |
| $1\frac{3}{8}$ -16  | 1.307  | 1.314 | 1.311                                  | 1.318 | 1.314                                   | 1.321 | 1.318                         | 1.325            | 1.3070                          | 1.3116 | 1.3094                                 | 1.3137 | 1.3115                                  | 1.3158 | 1.3136                        | 1.3179 |
| $1\frac{3}{8}$ -18  | 1.315  | 1.322 | 1.318                                  | 1.325 | 1.322                                   | 1.328 | 1.325                         | 1.331            | 1.3150                          | 1.3190 | 1.3169                                 | 1.3210 | 1.3189                                  | 1.3230 | 1.3210                        | 1.3251 |
| $1\frac{7}{16}$ -12 | 1.347  | 1.354 | 1.350                                  | 1.361 | 1.354                                   | 1.365 | 1.361                         | 1.370            | 1.3470                          | 1.3523 | 1.3498                                 | 1.3548 | 1.3523                                  | 1.3573 | 1.3548                        | 1.3598 |
| $1\frac{7}{16}$ -16 | 1.370  | 1.377 | 1.374                                  | 1.381 | 1.377                                   | 1.384 | 1.381                         | 1.388            | 1.3700                          | 1.3741 | 1.3719                                 | 1.3762 | 1.3740                                  | 1.3783 | 1.3761                        | 1.3804 |
| $1\frac{7}{16}$ -18 | 1.377  | 1.384 | 1.380                                  | 1.387 | 1.384                                   | 1.390 | 1.387                         | 1.393            | 1.3770                          | 1.3815 | 1.3794                                 | 1.3835 | 1.3814                                  | 1.3855 | 1.3835                        | 1.3876 |
| $1\frac{1}{2}$ -6   | 1.320  | 1.335 | 1.328                                  | 1.346 | 1.335                                   | 1.350 | 1.346                         | 1.364            | 1.3200                          | 1.3296 | 1.3246                                 | 1.3346 | 1.3296                                  | 1.3396 | 1.3346                        | 1.3446 |
| $1\frac{1}{2}$ -8   | 1.365  | 1.378 | 1.371                                  | 1.384 | 1.378                                   | 1.390 | 1.384                         | 1.396            | 1.3650                          | 1.3722 | 1.3684                                 | 1.3759 | 1.3722                                  | 1.3797 | 1.3760                        | 1.3835 |
| $1\frac{1}{2}$ -12  | 1.410  | 1.419 | 1.4155                                 | 1.424 | 1.419                                   | 1.428 | 1.424                         | 1.433            | 1.4100                          | 1.4148 | 1.4123                                 | 1.4173 | 1.4148                                  | 1.4198 | 1.4173                        | 1.4223 |
| $1\frac{1}{2}$ -16  | 1.432  | 1.439 | 1.436                                  | 1.443 | 1.439                                   | 1.446 | 1.443                         | 1.450            | 1.4320                          | 1.4366 | 1.4344                                 | 1.4387 | 1.4365                                  | 1.4408 | 1.4386                        | 1.4429 |
| $1\frac{1}{2}$ -18  | 1.440  | 1.446 | 1.443                                  | 1.450 | 1.446                                   | 1.452 | 1.450                         | 1.456            | 1.4400                          | 1.4440 | 1.4419                                 | 1.4460 | 1.4439                                  | 1.4480 | 1.4460                        | 1.4501 |
| $1\frac{1}{2}$ -20  | 1.446  | 1.452 | 1.449                                  | 1.454 | 1.452                                   | 1.457 | 1.454                         | 1.460            | 1.4460                          | 1.4498 | 1.4477                                 | 1.4517 | 1.4497                                  | 1.4537 | 1.4516                        | 1.4556 |
| $1\frac{9}{16}$ -16 | 1.495  | 1.502 | 1.499                                  | 1.506 | 1.502                                   | 1.509 | 1.506                         | 1.513            | 1.4950                          | 1.4991 | 1.4969                                 | 1.5012 | 1.4990                                  | 1.5033 | 1.5011                        | 1.5054 |
| $1\frac{9}{16}$ -18 | 1.502  | 1.509 | 1.505                                  | 1.512 | 1.509                                   | 1.515 | 1.512                         | 1.518            | 1.5020                          | 1.5065 | 1.5044                                 | 1.5085 | 1.5064                                  | 1.5105 | 1.5085                        | 1.5126 |

Table 2. (Continued) Recommended Hole Size Limits Before Tapping Unified Threads

| Thread Size                      | Classes 1B and 2B  |       |  |       |   |       |                               |                  | Class 3B                        |        |  |        |   |        |                               |        |
|----------------------------------|--|-------|--|-------|---|-------|-------------------------------|------------------|---------------------------------|--------|--|--------|---|--------|-------------------------------|--------|
|                                  | Length of Engagement ( $D = \text{Nominal Size of Thread}$ ) |       |  |       |   |       |                               |                  |                                 |        |  |        |   |        |                               |        |
|                                  | To and Including $\frac{1}{3}D$                              |       | Above $\frac{1}{2}D$ to $\frac{2}{3}D$ |       | Above $\frac{2}{3}D$ to $1\frac{1}{2}D$ |       | Above $1\frac{1}{2}D$ to $3D$ |                  | To and Including $\frac{1}{3}D$ |        | Above $\frac{1}{2}D$ to $\frac{2}{3}D$ |        | Above $\frac{2}{3}D$ to $1\frac{1}{2}D$ |        | Above $1\frac{1}{2}D$ to $3D$ |        |
|                                  | Recommended Hole Size Limits                                 |       |  |       |   |       |                               |                  |                                 |        |  |        |   |        |                               |        |
| Min <sup>a</sup>                 | Max  | Min   | Max                                    | Min   | Max <sup>b</sup>                        | Min   | Max                           | Min <sup>a</sup> | Max                             | Min    | Max                                    | Min    | Max <sup>b</sup>                        | Min    | Max                           |        |
| 1 $\frac{1}{8}$ -8               | 1.490  | 1.498 | 1.494                                  | 1.509 | 1.498                                   | 1.515 | 1.509                         | 1.521            | 1.4900                          | 1.4972 | 1.4934                                 | 1.5009 | 1.4972                                  | 1.5047 | 1.5010                        | 1.5085 |
| 1 $\frac{1}{8}$ -12              | 1.535  | 1.544 | 1.540                                  | 1.549 | 1.544                                   | 1.553 | 1.549                         | 1.558            | 1.5350                          | 1.5398 | 1.5373                                 | 1.5423 | 1.5398                                  | 1.5448 | 1.5423                        | 1.5473 |
| 1 $\frac{3}{8}$ -16              | 1.557  | 1.564 | 1.561                                  | 1.568 | 1.564                                   | 1.571 | 1.568                         | 1.575            | 1.5570                          | 1.5616 | 1.5594                                 | 1.5637 | 1.5615                                  | 1.5658 | 1.5636                        | 1.5679 |
| 1 $\frac{3}{8}$ -18              | 1.565  | 1.572 | 1.568                                  | 1.575 | 1.572                                   | 1.578 | 1.575                         | 1.581            | 1.5650                          | 1.5690 | 1.5669                                 | 1.5710 | 1.5689                                  | 1.5730 | 1.5710                        | 1.5751 |
| 1 $\frac{1}{2}$ -16              | 1.620  | 1.627 | 1.624                                  | 1.631 | 1.627                                   | 1.634 | 1.631                         | 1.638            | 1.6200                          | 1.6241 | 1.6219                                 | 1.6262 | 1.6240                                  | 1.6283 | 1.6261                        | 1.6304 |
| 1 $\frac{1}{2}$ -18              | 1.627  | 1.634 | 1.630                                  | 1.637 | 1.634                                   | 1.640 | 1.637                         | 1.643            | 1.6270                          | 1.6315 | 1.6294                                 | 1.6335 | 1.6314                                  | 1.6355 | 1.6335                        | 1.6376 |
| 1 $\frac{3}{4}$ -5               | 1.534  | 1.551 | 1.543                                  | 1.560 | 1.551                                   | 1.568 | 1.560                         | 1.577            | 1.5340                          | 1.5455 | 1.5395                                 | 1.5515 | 1.5455                                  | 1.5575 | 1.5515                        | 1.5635 |
| 1 $\frac{3}{4}$ -8               | 1.615  | 1.628 | 1.621                                  | 1.634 | 1.628                                   | 1.640 | 1.634                         | 1.646            | 1.6150                          | 1.6222 | 1.6184                                 | 1.6259 | 1.6222                                  | 1.6297 | 1.6260                        | 1.6335 |
| 1 $\frac{3}{4}$ -12              | 1.660  | 1.669 | 1.665                                  | 1.674 | 1.669                                   | 1.678 | 1.674                         | 1.683            | 1.6600                          | 1.6648 | 1.6623                                 | 1.6673 | 1.6648                                  | 1.6698 | 1.6673                        | 1.6723 |
| 1 $\frac{3}{4}$ -16              | 1.682  | 1.689 | 1.686                                  | 1.693 | 1.689                                   | 1.696 | 1.693                         | 1.700            | 1.6820                          | 1.6866 | 1.6844                                 | 1.6887 | 1.6865                                  | 1.6908 | 1.6886                        | 1.6929 |
| 1 $\frac{3}{4}$ -20              | 1.696  | 1.702 | 1.699                                  | 1.704 | 1.702                                   | 1.707 | 1.704                         | 1.710            | 1.6960                          | 1.6998 | 1.6977                                 | 1.7017 | 1.6997                                  | 1.7037 | 1.7016                        | 1.7056 |
| 1 $\frac{1}{2}$ -16              | 1.745  | 1.752 | 1.749                                  | 1.756 | 1.752                                   | 1.759 | 1.756                         | 1.763            | 1.7450                          | 1.7491 | 1.7469                                 | 1.7512 | 1.7490                                  | 1.7533 | 1.7511                        | 1.7554 |
| 1 $\frac{1}{2}$ -8               | 1.740  | 1.752 | 1.746                                  | 1.759 | 1.752                                   | 1.765 | 1.759                         | 1.771            | 1.7400                          | 1.7472 | 1.7434                                 | 1.7509 | 1.7472                                  | 1.7547 | 1.7510                        | 1.7585 |
| 1 $\frac{1}{2}$ -12              | 1.785  | 1.794 | 1.790                                  | 1.799 | 1.794                                   | 1.803 | 1.799                         | 1.808            | 1.7850                          | 1.7898 | 1.7873                                 | 1.7923 | 1.7898                                  | 1.7948 | 1.7923                        | 1.7973 |
| 1 $\frac{1}{2}$ -16              | 1.807  | 1.814 | 1.810                                  | 1.818 | 1.814                                   | 1.821 | 1.818                         | 1.825            | 1.8070                          | 1.8116 | 1.8094                                 | 1.8137 | 1.8115                                  | 1.8158 | 1.8136                        | 1.8179 |
| 1 $\frac{1}{2}$ -18              | 1.870  | 1.877 | 1.874                                  | 1.881 | 1.877                                   | 1.884 | 1.881                         | 1.888            | 1.8700                          | 1.8741 | 1.8719                                 | 1.8762 | 1.8740                                  | 1.8783 | 1.8761                        | 1.8804 |
| 2-4 $\frac{1}{2}$                | 1.759  | 1.777 | 1.768                                  | 1.786 | 1.777                                   | 1.795 | 1.786                         | 1.804            | 1.7590                          | 1.7727 | 1.7661                                 | 1.7794 | 1.7728                                  | 1.7861 | 1.7794                        | 1.7927 |
| 2-8                              | 1.865  | 1.878 | 1.871                                  | 1.884 | 1.878                                   | 1.890 | 1.884                         | 1.896            | 1.8650                          | 1.8722 | 1.8684                                 | 1.8759 | 1.8722                                  | 1.8797 | 1.8760                        | 1.8835 |
| 2-12                             | 1.910  | 1.919 | 1.915                                  | 1.924 | 1.919                                   | 1.928 | 1.924                         | 1.933            | 1.9100                          | 1.9148 | 1.9123                                 | 1.9173 | 1.9148                                  | 1.9198 | 1.9173                        | 1.9223 |
| 2-16                             | 1.932  | 1.939 | 1.936                                  | 1.943 | 1.939                                   | 1.946 | 1.943                         | 1.950            | 1.9320                          | 1.9366 | 1.9344                                 | 1.9387 | 1.9365                                  | 1.9408 | 1.9386                        | 1.9429 |
| 2-20                             | 1.946  | 1.952 | 1.949                                  | 1.954 | 1.952                                   | 1.957 | 1.954                         | 1.960            | 1.9460                          | 1.9498 | 1.9477                                 | 1.9517 | 1.9497                                  | 1.9537 | 1.9516                        | 1.9556 |
| 2 $\frac{1}{16}$ -16             | 1.995  | 2.002 | 2.000                                  | 2.006 | 2.002                                   | 2.009 | 2.006                         | 2.012            | 1.9950                          | 1.9991 | 1.9969                                 | 2.0012 | 1.9990                                  | 2.0033 | 2.0011                        | 2.0054 |
| 2 $\frac{1}{8}$ -8               | 1.990  | 2.003 | 1.996                                  | 2.009 | 2.003                                   | 2.015 | 2.009                         | 2.021            | 1.9900                          | 1.9972 | 1.9934                                 | 2.0009 | 1.9972                                  | 2.0047 | 2.0010                        | 2.0085 |
| 2 $\frac{1}{8}$ -12              | 2.035  | 2.044 | 2.040                                  | 2.049 | 2.044                                   | 2.053 | 2.049                         | 2.058            | 2.0350                          | 2.0398 | 2.0373                                 | 2.0423 | 2.0398                                  | 2.0448 | 2.0423                        | 2.0473 |
| 2 $\frac{1}{8}$ -16              | 2.057  | 2.064 | 2.061                                  | 2.068 | 2.064                                   | 2.071 | 2.068                         | 2.075            | 2.0570                          | 2.0616 | 2.0594                                 | 2.0637 | 2.0615                                  | 2.0658 | 2.0636                        | 2.0679 |
| 2 $\frac{1}{16}$ -16             | 2.120  | 2.127 | 2.124                                  | 2.131 | 2.127                                   | 2.134 | 2.131                         | 2.138            | 2.1200                          | 2.1241 | 2.1219                                 | 2.1262 | 2.1240                                  | 2.1283 | 2.1261                        | 2.1304 |
| 2 $\frac{1}{4}$ -4 $\frac{1}{2}$ | 2.009  | 2.027 | 2.018                                  | 2.036 | 2.027                                   | 2.045 | 2.036                         | 2.054            | 2.0090                          | 2.0227 | 2.0161                                 | 2.0294 | 2.0228                                  | 2.0361 | 2.0294                        | 2.0427 |

**Table 2. (Continued) Recommended Hole Size Limits Before Tapping Unified Threads**

| Thread Size        | Classes 1B and 2B  |       |  |       |   |       |                               |                  | Class 3B                        |        |  |        |   |        |                               |        |
|--------------------|--|-------|--|-------|---|-------|-------------------------------|------------------|---------------------------------|--------|--|--------|---|--------|-------------------------------|--------|
|                    | Length of Engagement ( $D = \text{Nominal Size of Thread}$ ) |       |  |       |   |       |                               |                  |                                 |        |  |        |   |        |                               |        |
|                    | To and Including $\frac{1}{2}D$                              |       | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |       | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |       | Above $1\frac{1}{2}D$ to $3D$ |                  | To and Including $\frac{1}{2}D$ |        | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |        | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |        | Above $1\frac{1}{2}D$ to $3D$ |        |
|                    | Recommended Hole Size Limits                                 |       |  |       |   |       |                               |                  |                                 |        |  |        |   |        |                               |        |
| Min <sup>a</sup>   | Max  | Min   | Max                                    | Min   | Max <sup>b</sup>                        | Min   | Max                           | Min <sup>a</sup> | Max                             | Min    | Max                                    | Min    | Max <sup>b</sup>                        | Min    | Max                           |        |
| $\frac{2}{16}$ -8  | 2.115  | 2.128 | 2.121                                  | 2.134 | 2.128                                   | 2.140 | 2.134                         | 2.146            | 2.1150                          | 2.1222 | 2.1184                                 | 2.1259 | 2.1222                                  | 2.1297 | 2.1260                        | 2.1335 |
| $\frac{2}{16}$ -12 | 2.160  | 2.169 | 2.165                                  | 2.174 | 2.169                                   | 2.178 | 2.174                         | 2.182            | 2.1600                          | 2.1648 | 2.1623                                 | 2.1673 | 2.1648                                  | 2.1698 | 2.1673                        | 2.1723 |
| $\frac{2}{16}$ -16 | 2.182  | 2.189 | 2.186                                  | 2.193 | 2.189                                   | 2.196 | 2.193                         | 2.200            | 2.1820                          | 2.1866 | 2.1844                                 | 2.1887 | 2.1865                                  | 2.1908 | 2.1886                        | 2.1929 |
| $\frac{2}{16}$ -20 | 2.196  | 2.202 | 2.199                                  | 2.204 | 2.202                                   | 2.207 | 2.204                         | 2.210            | 2.1960                          | 2.1998 | 2.1977                                 | 2.2017 | 2.1997                                  | 2.2037 | 2.2016                        | 2.2056 |
| $\frac{2}{16}$ -16 | 2.245  | 2.252 | 2.249                                  | 2.256 | 2.252                                   | 2.259 | 2.256                         | 2.263            | 2.2450                          | 2.2491 | 2.2469                                 | 2.2512 | 2.2490                                  | 2.2533 | 2.2511                        | 2.2554 |
| $\frac{2}{16}$ -12 | 2.285  | 2.294 | 2.290                                  | 2.299 | 2.294                                   | 2.303 | 2.299                         | 2.308            | 2.2850                          | 2.2898 | 2.2873                                 | 2.2923 | 2.2898                                  | 2.2948 | 2.2923                        | 2.2973 |
| $\frac{2}{16}$ -8  | 2.307  | 2.314 | 2.311                                  | 2.318 | 2.314                                   | 2.321 | 2.318                         | 2.325            | 2.3070                          | 2.3116 | 2.3094                                 | 2.3137 | 2.3115                                  | 2.3158 | 2.3136                        | 2.3179 |
| $\frac{2}{16}$ -16 | 2.370  | 2.377 | 2.374                                  | 2.381 | 2.377                                   | 2.384 | 2.381                         | 2.388            | 2.3700                          | 2.3741 | 2.3719                                 | 2.3762 | 2.3740                                  | 2.3783 | 2.3761                        | 2.3804 |
| $\frac{2}{16}$ -4  | 2.229  | 2.248 | 2.238                                  | 2.258 | 2.248                                   | 2.267 | 2.258                         | 2.277            | 2.2290                          | 2.2444 | 2.2369                                 | 2.2519 | 2.2444                                  | 2.2594 | 2.2519                        | 2.2669 |
| $\frac{2}{16}$ -8  | 2.365  | 2.378 | 2.371                                  | 2.384 | 2.378                                   | 2.390 | 2.384                         | 2.396            | 2.3650                          | 2.3722 | 2.3684                                 | 2.3759 | 2.3722                                  | 2.3797 | 2.3760                        | 2.3835 |
| $\frac{2}{16}$ -12 | 2.410  | 2.419 | 2.415                                  | 2.424 | 2.419                                   | 2.428 | 2.424                         | 2.433            | 2.4100                          | 2.4148 | 2.4123                                 | 2.4173 | 2.4148                                  | 2.4198 | 2.4173                        | 2.4223 |
| $\frac{2}{16}$ -16 | 2.432  | 2.439 | 2.436                                  | 2.443 | 2.439                                   | 2.446 | 2.443                         | 2.450            | 2.4320                          | 2.4366 | 2.4344                                 | 2.4387 | 2.4365                                  | 2.4408 | 2.4386                        | 2.4429 |
| $\frac{2}{16}$ -20 | 2.446  | 2.452 | 2.449                                  | 2.454 | 2.452                                   | 2.457 | 2.454                         | 2.460            | 2.4460                          | 2.4498 | 2.4478                                 | 2.4517 | 2.4497                                  | 2.4537 | 2.4516                        | 2.4556 |
| $\frac{2}{16}$ -12 | 2.535  | 2.544 | 2.540                                  | 2.549 | 2.544                                   | 2.553 | 2.549                         | 2.558            | 2.5350                          | 2.5398 | 2.5373                                 | 2.5423 | 2.5398                                  | 2.5448 | 2.5423                        | 2.5473 |
| $\frac{2}{16}$ -16 | 2.557  | 2.564 | 2.561                                  | 2.568 | 2.564                                   | 2.571 | 2.568                         | 2.575            | 2.5570                          | 2.5616 | 2.5594                                 | 2.5637 | 2.5615                                  | 2.5658 | 2.5636                        | 2.5679 |
| $\frac{2}{16}$ -4  | 2.479  | 2.498 | 2.489                                  | 2.508 | 2.498                                   | 2.517 | 2.508                         | 2.527            | 2.4790                          | 2.4944 | 2.4869                                 | 2.5019 | 2.4944                                  | 2.5094 | 2.5019                        | 2.5169 |
| $\frac{2}{16}$ -8  | 2.615  | 2.628 | 2.621                                  | 2.634 | 2.628                                   | 2.640 | 2.634                         | 2.644            | 2.6150                          | 2.6222 | 2.6184                                 | 2.6259 | 2.6222                                  | 2.6297 | 2.6260                        | 2.6335 |
| $\frac{2}{16}$ -12 | 2.660  | 2.669 | 2.665                                  | 2.674 | 2.669                                   | 2.678 | 2.674                         | 2.683            | 2.6600                          | 2.6648 | 2.6623                                 | 2.6673 | 2.6648                                  | 2.6698 | 2.6673                        | 2.6723 |
| $\frac{2}{16}$ -16 | 2.682  | 2.689 | 2.686                                  | 2.693 | 2.689                                   | 2.696 | 2.693                         | 2.700            | 2.6820                          | 2.6866 | 2.6844                                 | 2.6887 | 2.6865                                  | 2.6908 | 2.6886                        | 2.6929 |
| $\frac{2}{16}$ -12 | 2.785  | 2.794 | 2.790                                  | 2.809 | 2.794                                   | 2.803 | 2.809                         | 2.808            | 2.7850                          | 2.7898 | 2.7873                                 | 2.7923 | 2.7898                                  | 2.7948 | 2.7923                        | 2.7973 |
| $\frac{2}{16}$ -16 | 2.807  | 2.814 | 2.811                                  | 2.818 | 2.814                                   | 2.821 | 2.818                         | 2.825            | 2.8070                          | 2.8116 | 2.8094                                 | 2.8137 | 2.8115                                  | 2.8158 | 2.8136                        | 2.8179 |
| 3-4                | 2.729  | 2.748 | 2.739                                  | 2.758 | 2.748                                   | 2.767 | 2.758                         | 2.777            | 2.7290                          | 2.7444 | 2.7369                                 | 2.7519 | 2.7444                                  | 2.7594 | 2.7519                        | 2.7669 |
| 3-8                | 2.865  | 2.878 | 2.871                                  | 2.884 | 2.878                                   | 2.890 | 2.884                         | 2.896            | 2.8650                          | 2.8722 | 2.8684                                 | 2.8759 | 2.8722                                  | 2.8797 | 2.8760                        | 2.8835 |
| 3-12               | 2.910  | 2.919 | 2.915                                  | 2.924 | 2.919                                   | 2.928 | 2.924                         | 2.933            | 2.9100                          | 2.9148 | 2.9123                                 | 2.9173 | 2.9148                                  | 2.9198 | 2.9173                        | 2.9223 |
| 3-16               | 2.932  | 2.939 | 2.936                                  | 2.943 | 2.939                                   | 2.946 | 2.943                         | 2.950            | 2.9320                          | 2.9366 | 2.9344                                 | 2.9387 | 2.9365                                  | 2.9408 | 2.9386                        | 2.9429 |
| $\frac{3}{16}$ -12 | 3.035  | 3.044 | 3.040                                  | 3.049 | 3.044                                   | 3.053 | 3.049                         | 3.058            | 3.0350                          | 3.0398 | 3.0373                                 | 3.0423 | 3.0398                                  | 3.0448 | 3.0423                        | 3.0473 |
| $\frac{3}{16}$ -16 | 3.057  | 3.064 | 3.061                                  | 3.068 | 3.064                                   | 3.071 | 3.068                         | 3.075            | 3.0570                          | 3.0616 | 3.0594                                 | 3.0637 | 3.0615                                  | 3.0658 | 3.0636                        | 3.0679 |

Table 2. (Continued) Recommended Hole Size Limits Before Tapping Unified Threads

| Thread Size         | Classes 1B and 2B  |       |  |       |   |                  |                               |       | Class 3B                        |        |  |        |   |                  |                               |        |
|---------------------|--|-------|--|-------|---|------------------|-------------------------------|-------|---------------------------------|--------|--|--------|---|------------------|-------------------------------|--------|
|                     | Length of Engagement ( $D = \text{Nominal Size of Thread}$ ) |       |  |       |   |                  |                               |       |                                 |        |  |        |   |                  |                               |        |
|                     | To and Including $\frac{1}{2}D$                              |       | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |       | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |                  | Above $1\frac{1}{2}D$ to $3D$ |       | To and Including $\frac{1}{2}D$ |        | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |        | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |                  | Above $1\frac{1}{2}D$ to $3D$ |        |
|                     | Recommended Hole Size Limits                                 |       |  |       |   |                  |                               |       |                                 |        |  |        |   |                  |                               |        |
|                     | Min <sup>a</sup>   | Max   | Min                                    | Max   | Min                                     | Max <sup>b</sup> | Min                           | Max   | Min <sup>a</sup>                | Max    | Min                                    | Max    | Min                                     | Max <sup>b</sup> | Min                           | Max    |
| $3\frac{1}{4}-4$    | 2.979  | 2.998 | 2.989                                  | 3.008 | 2.998                                   | 3.017            | 3.008                         | 3.027 | 2.9790                          | 2.9944 | 2.9869                                 | 3.0019 | 2.9944                                  | 3.0094           | 3.0019                        | 3.0169 |
| $3\frac{1}{2}-8$    | 3.115  | 3.128 | 3.121                                  | 3.134 | 3.128                                   | 3.140            | 3.134                         | 3.146 | 3.1150                          | 3.1222 | 3.1184                                 | 3.1259 | 3.1222                                  | 3.1297           | 3.1260                        | 3.1335 |
| $3\frac{1}{2}-12$   | 3.160  | 3.169 | 3.165                                  | 3.174 | 3.169                                   | 3.178            | 3.174                         | 3.183 | 3.1600                          | 3.1648 | 3.1623                                 | 3.1673 | 3.1648                                  | 3.1698           | 3.1673                        | 3.1723 |
| $3\frac{1}{2}-16$   | 3.182  | 3.189 | 3.186                                  | 3.193 | 3.189                                   | 3.196            | 3.193                         | 3.200 | 3.1820                          | 3.1866 | 3.1844                                 | 3.1887 | 3.1865                                  | 3.1908           | 3.1886                        | 3.1929 |
| $3\frac{3}{8}-12$   | 3.285  | 3.294 | 3.290                                  | 3.299 | 3.294                                   | 3.303            | 3.299                         | 3.299 | 3.2850                          | 3.2898 | 3.2873                                 | 3.2923 | 3.2898                                  | 3.2948           | 3.2923                        | 3.2973 |
| $3\frac{3}{8}-16$   | 3.307  | 3.314 | 3.311                                  | 3.318 | 3.314                                   | 3.321            | 3.317                         | 3.325 | 3.3070                          | 3.3116 | 3.3094                                 | 3.3137 | 3.3115                                  | 3.3158           | 3.3136                        | 3.3179 |
| $3\frac{3}{4}-4$    | 3.229  | 3.248 | 3.239                                  | 3.258 | 3.248                                   | 3.267            | 3.258                         | 3.277 | 3.2290                          | 3.2444 | 3.2369                                 | 3.2519 | 3.2444                                  | 3.2594           | 3.2519                        | 3.2669 |
| $3\frac{3}{4}-8$    | 3.365  | 3.378 | 3.371                                  | 3.384 | 3.378                                   | 3.390            | 3.384                         | 3.396 | 3.3650                          | 3.3722 | 3.3684                                 | 3.3759 | 3.3722                                  | 3.3797           | 3.3760                        | 3.3835 |
| $3\frac{3}{4}-12$   | 3.410  | 3.419 | 3.415                                  | 3.424 | 3.419                                   | 3.428            | 3.424                         | 3.433 | 3.4100                          | 3.4148 | 3.4123                                 | 3.4173 | 3.4148                                  | 3.4198           | 3.4173                        | 3.4223 |
| $3\frac{1}{2}-16$   | 3.432  | 3.439 | 3.436                                  | 3.443 | 3.439                                   | 3.446            | 3.443                         | 3.450 | 3.4320                          | 3.4366 | 3.4344                                 | 3.4387 | 3.4365                                  | 3.4408           | 3.4386                        | 3.4429 |
| $3\frac{5}{8}-12$   | 3.535  | 3.544 | 3.544                                  | 3.549 | 3.544                                   | 3.553            | 3.549                         | 3.553 | 3.5350                          | 3.5398 | 3.5373                                 | 3.5423 | 3.5398                                  | 3.5448           | 3.5423                        | 3.5473 |
| $3\frac{5}{8}-16$   | 3.557  | 3.564 | 3.561                                  | 3.568 | 3.567                                   | 3.571            | 3.568                         | 3.575 | 3.5570                          | 3.5616 | 3.5594                                 | 3.5637 | 3.5615                                  | 3.5658           | 3.5636                        | 3.5679 |
| $3\frac{3}{4}-4$    | 3.479  | 3.498 | 3.489                                  | 3.508 | 3.498                                   | 3.517            | 3.508                         | 3.527 | 3.4790                          | 3.4944 | 3.4869                                 | 3.5019 | 3.4944                                  | 3.5094           | 3.5019                        | 3.5169 |
| $3\frac{3}{4}-8$    | 3.615  | 3.628 | 3.615                                  | 3.634 | 3.628                                   | 3.640            | 3.634                         | 3.646 | 3.6150                          | 3.6222 | 3.6184                                 | 3.6259 | 3.6222                                  | 3.6297           | 3.6260                        | 3.6335 |
| $3\frac{3}{4}-12$   | 3.660  | 3.669 | 3.665                                  | 3.674 | 3.669                                   | 3.678            | 3.674                         | 3.683 | 3.6600                          | 3.6648 | 3.6623                                 | 3.6673 | 3.6648                                  | 3.6698           | 3.6673                        | 3.6723 |
| $\frac{3}{4}-16$    | 3.682  | 3.689 | 3.686                                  | 3.693 | 3.689                                   | 3.696            | 3.693                         | 3.700 | 3.6820                          | 3.6866 | 3.6844                                 | 3.6887 | 3.6865                                  | 3.6908           | 3.6886                        | 3.6929 |
| $3\frac{3}{8}-12$   | 3.785  | 3.794 | 3.790                                  | 3.799 | 3.794                                   | 3.803            | 3.799                         | 3.808 | 3.7850                          | 3.7898 | 3.7873                                 | 3.7923 | 3.7898                                  | 3.7948           | 3.7923                        | 3.7973 |
| $3\frac{3}{8}-16$   | 3.807  | 3.814 | 3.811                                  | 3.818 | 3.814                                   | 3.821            | 3.818                         | 3.825 | 3.8070                          | 3.8116 | 3.8094                                 | 3.8137 | 3.8115                                  | 3.8158           | 3.8136                        | 3.8179 |
| 4-4                 | 3.729  | 3.748 | 3.739                                  | 3.758 | 3.748                                   | 3.767            | 3.758                         | 3.777 | 3.7290                          | 3.7444 | 3.7369                                 | 3.7519 | 3.7444                                  | 3.7594           | 3.7519                        | 3.7669 |
| 4-8                 | 3.865  | 3.878 | 3.871                                  | 3.884 | 3.878                                   | 3.890            | 3.884                         | 3.896 | 3.8650                          | 3.8722 | 3.8684                                 | 3.8759 | 3.8722                                  | 3.8797           | 3.8760                        | 3.8835 |
| 4-12                | 3.910  | 3.919 | 3.915                                  | 3.924 | 3.919                                   | 3.928            | 3.924                         | 3.933 | 3.9100                          | 3.9148 | 3.9123                                 | 3.9173 | 3.9148                                  | 3.9198           | 3.9173                        | 3.9223 |
| 4-16                | 3.932  | 3.939 | 3.936                                  | 3.943 | 3.939                                   | 3.946            | 3.943                         | 3.950 | 3.9320                          | 3.9366 | 3.9344                                 | 3.9387 | 3.9365                                  | 3.9408           | 3.9386                        | 3.9429 |
| 4 $\frac{1}{4}$ -4  | 3.979  | 3.998 | 3.989                                  | 4.008 | 3.998                                   | 4.017            | 4.008                         | 4.027 | 3.9790                          | 3.9944 | 3.9869                                 | 4.0019 | 3.9944                                  | 4.0094           | 4.0019                        | 4.0169 |
| 4 $\frac{1}{4}$ -8  | 4.115  | 4.128 | 4.121                                  | 4.134 | 4.128                                   | 4.140            | 4.134                         | 4.146 | 4.1150                          | 4.1222 | 4.1184                                 | 4.1259 | 4.1222                                  | 4.1297           | 4.1260                        | 4.1335 |
| 4 $\frac{1}{4}$ -12 | 4.160  | 4.169 | 4.165                                  | 4.174 | 4.169                                   | 4.178            | 4.174                         | 4.183 | 4.1600                          | 4.1648 | 4.1623                                 | 4.1673 | 4.1648                                  | 4.1698           | 4.1673                        | 4.1723 |
| 4 $\frac{1}{4}$ -16 | 4.182  | 4.189 | 4.186                                  | 4.193 | 4.189                                   | 4.196            | 4.193                         | 4.200 | 4.1820                          | 4.1866 | 4.1844                                 | 4.1887 | 4.1865                                  | 4.1908           | 4.1886                        | 4.1929 |
| 4 $\frac{1}{2}$ -4  | 4.229  | 4.248 | 4.239                                  | 4.258 | 4.248                                   | 4.267            | 4.258                         | 4.277 | 4.2290                          | 4.2444 | 4.2369                                 | 4.2519 | 4.2444                                  | 4.2594           | 4.2519                        | 4.2669 |



**Table 2. (Continued) Recommended Hole Size Limits Before Tapping Unified Threads**

| Thread Size        | Classes 1B and 2B  |       |  |       |   |       |                               |       | Class 3B                        |                  |  |        |   |        |                               |        |  |     |  |
|--------------------|--|-------|--|-------|---|-------|-------------------------------|-------|---------------------------------|------------------|--|--------|---|--------|-------------------------------|--------|--|-----|--|
|                    | Length of Engagement ( $D = \text{Nominal Size of Thread}$ ) |       |  |       |   |       |                               |       |                                 |                  |  |        |   |        |                               |        |  |     |  |
|                    | To and Including $\frac{1}{2}D$                              |       | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |       | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |       | Above $1\frac{1}{2}D$ to $3D$ |       | To and Including $\frac{1}{2}D$ |                  | Above $\frac{1}{2}D$ to $\frac{3}{4}D$ |        | Above $\frac{3}{4}D$ to $1\frac{1}{2}D$ |        | Above $1\frac{1}{2}D$ to $3D$ |        |  |     |  |
|                    | Recommended Hole Size Limits                                 |       |  |       |   |       |                               |       |                                 |                  |  |        |   |        |                               |        |  |     |  |
| Min <sup>a</sup>   |  | Max   |  | Min   |   | Max   |                               | Min   |                                 | Max <sup>b</sup> |  | Min    |   | Max    |                               | Min    |  | Max |  |
| $4\frac{1}{2}$ -8  | 4.365  | 4.378 | 4.371                                  | 4.384 | 4.378                                   | 4.390 | 4.384                         | 4.396 | 4.3650                          | 4.3722           | 4.3684                                 | 4.3759 | 4.3722                                  | 4.3797 | 4.3760                        | 4.3835 |  |     |  |
| $4\frac{1}{2}$ -12 | 4.410  | 4.419 | 4.419                                  | 4.424 | 4.419                                   | 4.428 | 4.424                         | 4.433 | 4.4100                          | 4.4148           | 4.4123                                 | 4.4173 | 4.4148                                  | 4.4198 | 4.4173                        | 4.4223 |  |     |  |
| $4\frac{1}{2}$ -16 | 4.432  | 4.439 | 4.437                                  | 4.444 | 4.439                                   | 4.446 | 4.444                         | 4.455 | 4.4320                          | 4.4366           | 4.4344                                 | 4.4387 | 4.4365                                  | 4.4408 | 4.4386                        | 4.4429 |  |     |  |
| $4\frac{3}{4}$ -8  | 4.615  | 4.628 | 4.621                                  | 4.646 | 4.628                                   | 4.640 | 4.646                         | 4.646 | 4.6150                          | 4.6222           | 4.6184                                 | 4.6259 | 4.6222                                  | 4.6297 | 4.6260                        | 4.6335 |  |     |  |
| $4\frac{3}{4}$ -12 | 4.660  | 4.669 | 4.665                                  | 4.674 | 4.669                                   | 4.678 | 4.674                         | 4.683 | 4.6600                          | 4.6648           | 4.6623                                 | 4.6673 | 4.6648                                  | 4.6698 | 4.6673                        | 4.6723 |  |     |  |
| $4\frac{3}{4}$ -16 | 4.682  | 4.689 | 4.686                                  | 4.693 | 4.689                                   | 4.696 | 4.693                         | 4.700 | 4.6820                          | 4.6866           | 4.6844                                 | 4.6887 | 4.6865                                  | 4.6908 | 4.6886                        | 4.6929 |  |     |  |
| 5-8                | 4.865  | 4.878 | 4.871                                  | 4.884 | 4.878                                   | 4.890 | 4.884                         | 4.896 | 4.8650                          | 4.8722           | 4.8684                                 | 4.8759 | 4.8722                                  | 4.8797 | 4.8760                        | 4.8835 |  |     |  |
| 5-12               | 4.910  | 4.919 | 4.915                                  | 4.924 | 4.919                                   | 4.928 | 4.924                         | 4.933 | 4.9100                          | 4.9148           | 4.9123                                 | 4.9173 | 4.9148                                  | 4.9198 | 4.9173                        | 4.9223 |  |     |  |
| 5-16               | 4.932  | 4.939 | 4.936                                  | 4.943 | 4.939                                   | 4.946 | 4.943                         | 4.950 | 4.9320                          | 4.9366           | 4.9344                                 | 4.9387 | 4.9365                                  | 4.9408 | 4.9386                        | 4.9429 |  |     |  |
| $5\frac{1}{4}$ -8  | 5.115  | 5.128 | 5.121                                  | 5.134 | 5.128                                   | 5.140 | 5.134                         | 5.146 | 5.1150                          | 5.1222           | 5.1184                                 | 5.1259 | 5.1222                                  | 5.1297 | 5.1260                        | 5.1335 |  |     |  |
| $5\frac{1}{4}$ -12 | 5.160  | 5.169 | 5.165                                  | 5.174 | 5.169                                   | 5.178 | 5.174                         | 5.183 | 5.1600                          | 5.1648           | 5.1623                                 | 5.1673 | 5.1648                                  | 5.1698 | 5.1673                        | 5.1723 |  |     |  |
| $5\frac{1}{4}$ -16 | 5.182  | 5.189 | 5.186                                  | 5.193 | 5.189                                   | 5.196 | 5.193                         | 5.200 | 5.1820                          | 5.1866           | 5.1844                                 | 5.1887 | 5.1865                                  | 5.1908 | 5.1886                        | 5.1929 |  |     |  |
| $5\frac{1}{2}$ -8  | 5.365  | 5.378 | 5.371                                  | 5.384 | 5.378                                   | 5.390 | 5.384                         | 5.396 | 5.3650                          | 5.3722           | 5.3684                                 | 5.3759 | 5.3722                                  | 5.3797 | 5.3760                        | 5.3835 |  |     |  |
| $5\frac{1}{2}$ -12 | 5.410  | 5.419 | 5.415                                  | 5.424 | 5.419                                   | 5.428 | 5.424                         | 5.433 | 5.4100                          | 5.4148           | 5.4123                                 | 5.4173 | 5.4148                                  | 5.4198 | 5.4173                        | 5.4223 |  |     |  |
| $5\frac{1}{2}$ -16 | 5.432  | 5.439 | 5.436                                  | 5.442 | 5.439                                   | 5.446 | 5.442                         | 5.450 | 5.4320                          | 5.4366           | 5.4344                                 | 5.4387 | 5.4365                                  | 5.4408 | 5.4386                        | 5.4429 |  |     |  |
| $5\frac{3}{4}$ -8  | 5.615  | 5.628 | 5.621                                  | 5.634 | 5.628                                   | 5.640 | 5.634                         | 5.646 | 5.6150                          | 5.6222           | 5.6184                                 | 5.6259 | 5.6222                                  | 5.6297 | 5.6260                        | 5.6335 |  |     |  |
| $5\frac{3}{4}$ -12 | 5.660  | 5.669 | 5.665                                  | 5.674 | 5.669                                   | 5.678 | 5.674                         | 5.683 | 5.6600                          | 5.6648           | 5.6623                                 | 5.6673 | 5.6648                                  | 5.6698 | 5.6673                        | 5.6723 |  |     |  |
| $5\frac{3}{4}$ -16 | 5.682  | 5.689 | 5.686                                  | 5.693 | 5.689                                   | 5.696 | 5.693                         | 5.700 | 5.6820                          | 5.6866           | 5.6844                                 | 5.6887 | 5.6865                                  | 5.6908 | 5.6886                        | 5.6929 |  |     |  |
| 6-8                | 5.865  | 5.878 | 5.871                                  | 5.896 | 5.878                                   | 5.890 | 5.896                         | 5.896 | 5.8650                          | 5.8722           | 5.8684                                 | 5.8759 | 5.8722                                  | 5.8797 | 5.8760                        | 5.8835 |  |     |  |
| 6-12               | 5.910  | 5.919 | 5.915                                  | 5.924 | 5.919                                   | 5.928 | 5.924                         | 5.933 | 5.9100                          | 5.9148           | 5.9123                                 | 5.9173 | 5.9148                                  | 5.9198 | 5.9173                        | 5.9223 |  |     |  |
| 6-16               | 5.932  | 5.939 | 5.935                                  | 5.943 | 5.939                                   | 5.946 | 5.943                         | 5.950 | 5.9320                          | 5.9366           | 5.9344                                 | 5.9387 | 5.9365                                  | 5.9408 | 5.9386                        | 5.9429 |  |     |  |

<sup>a</sup> This is the minimum minor diameter specified in the thread tables, page 1736.

<sup>b</sup> This is the maximum minor diameter specified in the thread tables, page 1736.

All dimensions are in inches.

For basis of recommended hole size limits see accompanying text.

As an aid in selecting suitable drills, see the listing of American Standard drill sizes in the twist drill section. For amount of expected drill oversize, see page 885.

Table 3. Tap Drill Sizes for Threads of American National Form

| Screw Thread        |            | Commercial Tap Drills <sup>a</sup> |                | Screw Thread                    |            | Commercial Tap Drills <sup>a</sup> |                |
|---------------------|------------|------------------------------------|----------------|---------------------------------|------------|------------------------------------|----------------|
| Outside Diam. Pitch | Root Diam. | Size or Number                     | Decimal Equiv. | Outside Diam. Pitch             | Root Diam. | Size or Number                     | Decimal Equiv. |
| $\frac{1}{16}$ -64  | 0.0422     | $\frac{3}{64}$                     | 0.0469         | 27                              | 0.4519     | $\frac{15}{32}$                    | 0.4687         |
| 72                  | 0.0445     | $\frac{3}{64}$                     | 0.0469         | $\frac{9}{16}$ -12              | 0.4542     | $\frac{31}{64}$                    | 0.4844         |
| $\frac{5}{64}$ -60  | 0.0563     | $\frac{1}{16}$                     | 0.0625         | 18                              | 0.4903     | $\frac{33}{64}$                    | 0.5156         |
| 72                  | 0.0601     | 52                                 | 0.0635         | 27                              | 0.5144     | $\frac{17}{32}$                    | 0.5312         |
| $\frac{3}{32}$ -48  | 0.0667     | 49                                 | 0.0730         | $\frac{5}{8}$ -11               | 0.5069     | $\frac{17}{32}$                    | 0.5312         |
| 50                  | 0.0678     | 49                                 | 0.0730         | 12                              | 0.5168     | $\frac{35}{64}$                    | 0.5469         |
| $\frac{7}{64}$ -48  | 0.0823     | 43                                 | 0.0890         | 18                              | 0.5528     | $\frac{37}{64}$                    | 0.5781         |
| $\frac{1}{8}$ -32   | 0.0844     | $\frac{3}{32}$                     | 0.0937         | 27                              | 0.5769     | $\frac{19}{32}$                    | 0.5937         |
| 40                  | 0.0925     | 38                                 | 0.1015         | $\frac{11}{16}$ -11             | 0.5694     | $\frac{19}{32}$                    | 0.5937         |
| $\frac{9}{64}$ -40  | 0.1081     | 32                                 | 0.1160         | 16                              | 0.6063     | $\frac{5}{8}$                      | 0.6250         |
| $\frac{5}{32}$ -32  | 0.1157     | $\frac{1}{8}$                      | 0.1250         | $\frac{3}{4}$ -10               | 0.6201     | $\frac{21}{32}$                    | 0.6562         |
| 36                  | 0.1202     | 30                                 | 0.1285         | 12                              | 0.6418     | $\frac{43}{64}$                    | 0.6719         |
| $\frac{11}{64}$ -32 | 0.1313     | $\frac{9}{64}$                     | 0.1406         | 16                              | 0.6688     | $\frac{11}{16}$                    | 0.6875         |
| $\frac{3}{16}$ -24  | 0.1334     | 26                                 | 0.1470         | 27                              | 0.7019     | $\frac{23}{32}$                    | 0.7187         |
| 32                  | 0.1469     | 22                                 | 0.1570         | $\frac{13}{16}$ -10             | 0.6826     | $\frac{23}{32}$                    | 0.7187         |
| $\frac{13}{64}$ -24 | 0.1490     | 20                                 | 0.1610         | $\frac{7}{8}$ -9                | 0.7307     | $\frac{49}{64}$                    | 0.7656         |
| $\frac{7}{32}$ -24  | 0.1646     | 16                                 | 0.1770         | 12                              | 0.7668     | $\frac{51}{64}$                    | 0.7969         |
| 32                  | 0.1782     | 12                                 | 0.1890         | 14                              | 0.7822     | $\frac{13}{16}$                    | 0.8125         |
| $\frac{15}{64}$ -24 | 0.1806     | 10                                 | 0.1935         | 18                              | 0.8028     | $\frac{53}{64}$                    | 0.8281         |
| $\frac{1}{4}$ -20   | 0.1850     | 7                                  | 0.2010         | 27                              | 0.8269     | $\frac{27}{32}$                    | 0.8437         |
| 24                  | 0.1959     | 4                                  | 0.2090         | $\frac{15}{16}$ -9              | 0.7932     | $\frac{55}{64}$                    | 0.8281         |
| 27                  | 0.2019     | 3                                  | 0.2130         | 1-8                             | 0.8376     | $\frac{7}{8}$                      | 0.8750         |
| 28                  | 0.2036     | 3                                  | 0.2130         | 12                              | 0.8918     | $\frac{59}{64}$                    | 0.9219         |
| 32                  | 0.2094     | $\frac{7}{32}$                     | 0.2187         | 14                              | 0.9072     | $\frac{15}{16}$                    | 0.9375         |
| $\frac{5}{16}$ -18  | 0.2403     | F                                  | 0.2570         | 27                              | 0.9519     | $\frac{31}{32}$                    | 0.9687         |
| 20                  | 0.2476     | $\frac{17}{64}$                    | 0.2656         | $\frac{13}{8}$ -7               | 0.9394     | $\frac{63}{64}$                    | 0.9844         |
| 24                  | 0.2584     | I                                  | 0.2720         | 12                              | 1.0168     | $\frac{13}{64}$                    | 1.0469         |
| 27                  | 0.2644     | J                                  | 0.2770         | $\frac{13}{4}$ -7               | 1.0644     | $\frac{17}{64}$                    | 1.1094         |
| 32                  | 0.2719     | $\frac{9}{32}$                     | 0.2812         | 12                              | 1.1418     | $\frac{111}{64}$                   | 1.1719         |
| $\frac{3}{8}$ -16   | 0.2938     | $\frac{5}{16}$                     | 0.3125         | $\frac{13}{8}$ -6               | 1.1585     | $\frac{17}{32}$                    | 1.2187         |
| 20                  | 0.3100     | $\frac{21}{64}$                    | 0.3281         | 12                              | 1.2668     | $\frac{119}{64}$                   | 1.2969         |
| 24                  | 0.3209     | Q                                  | 0.3320         | $\frac{13}{2}$ -6               | 1.2835     | $\frac{111}{32}$                   | 1.3437         |
| 27                  | 0.3269     | R                                  | 0.3390         | 12                              | 1.3918     | $\frac{127}{64}$                   | 1.4219         |
| $\frac{7}{16}$ -14  | 0.3447     | U                                  | 0.3680         | $\frac{15}{8}$ -5 $\frac{1}{2}$ | 1.3888     | $\frac{129}{64}$                   | 1.4531         |
| 20                  | 0.3726     | $\frac{25}{64}$                    | 0.3906         | $\frac{13}{4}$ -5               | 1.4902     | $\frac{19}{16}$                    | 1.5625         |
| 24                  | 0.3834     | X                                  | 0.3970         | $\frac{17}{8}$ -5               | 1.6152     | $\frac{111}{16}$                   | 1.6875         |
| 27                  | 0.3894     | Y                                  | 0.4040         | 2-4 $\frac{1}{2}$               | 1.7113     | $\frac{125}{32}$                   | 1.7812         |
| $\frac{1}{2}$ -12   | 0.3918     | $\frac{27}{64}$                    | 0.4219         | $\frac{23}{8}$ -4 $\frac{1}{2}$ | 1.8363     | $\frac{129}{32}$                   | 1.9062         |
| 13                  | 0.4001     | $\frac{27}{64}$                    | 0.4219         | $\frac{23}{4}$ -4 $\frac{1}{2}$ | 1.9613     | $\frac{21}{32}$                    | 2.0312         |
| 20                  | 0.4351     | $\frac{29}{64}$                    | 0.4531         | $\frac{23}{8}$ -4               | 2.0502     | $\frac{21}{8}$                     | 2.1250         |
| 24                  | 0.4459     | $\frac{29}{64}$                    | 0.4531         | $\frac{23}{2}$ -4               | 2.1752     | $\frac{21}{4}$                     | 2.2500         |

<sup>a</sup>These tap drill diameters allow approximately 75 per cent of a full thread to be produced. For small thread sizes in the first column, the use of drills to produce the larger hole sizes shown in Table 2 will reduce defects caused by tap problems and breakage.

**Table 4. Tap Drills and Clearance Drills for Machine Screws with American National Thread Form**

| Size of Screw  |                | No. of Threads per Inch            | Tap Drills                         |                         | Clearance Hole Drills |                |                 |                |
|----------------|----------------|------------------------------------|------------------------------------|-------------------------|-----------------------|----------------|-----------------|----------------|
| No. or Diam.   | Decimal Equiv. |                                    | Drill Size                         | Decimal Equiv.          | Close Fit             |                | Free Fit        |                |
|                |                |                                    |                                    |                         | Drill Size            | Decimal Equiv. | Drill Size      | Decimal Equiv. |
| 0              | .060           | 80                                 | $\frac{3}{64}$                     | .0469                   | 52                    | .0635          | 50              | .0700          |
| 1              | .073           | 64<br>72                           | 53<br>53                           | .0595<br>.0595          | 48                    | .0760          | 46              | .0810          |
| 2              | .086           | 56<br>64                           | 50<br>50                           | .0700<br>.0700          | 43                    | .0890          | 41              | .0960          |
| 3              | .099           | 48<br>56                           | 47<br>45                           | .0785<br>.0820          | 37                    | .1040          | 35              | .1100          |
| 4              | .112           | 36 <sup>a</sup><br>40<br>48        | 44<br>43<br>42                     | .0860<br>.0890<br>.0935 | 32                    | .1160          | 30              | .1285          |
| 5              | .125           | 40<br>44                           | 38<br>37                           | .1015<br>1040           | 30                    | .1285          | 29              | .1360          |
| 6              | .138           | 32<br>40                           | 36<br>33                           | .1065<br>.1130          | 27                    | .1440          | 25              | .1495          |
| 8              | .164           | 32<br>36                           | 29<br>29                           | .1360<br>.1360          | 18                    | .1695          | 16              | .1770          |
| 10             | .190           | 24<br>32                           | 25<br>21                           | .1495<br>1590           | 9                     | .1960          | 7               | .2010          |
| 12             | .216           | 24<br>28                           | 16<br>14                           | .1770<br>.1820          | 2                     | .2210          | 1               | .2280          |
| 14             | .242           | 20 <sup>a</sup><br>24 <sup>a</sup> | 10<br>7                            | .1935<br>.2010          | D                     | .2460          | F               | .2570          |
| $\frac{1}{4}$  | .250           | 20<br>28                           | 7<br>3                             | .2010<br>.2130          | F                     | .2570          | H               | .2660          |
| $\frac{5}{16}$ | .3125          | 18<br>24                           | F<br>I                             | .2570<br>.2720          | P                     | .3230          | Q               | .3320          |
| $\frac{3}{8}$  | .375           | 16<br>24                           | $\frac{5}{16}$<br>Q                | .3125<br>.3320          | W                     | .3860          | X               | .3970          |
| $\frac{7}{16}$ | .4375          | 14<br>20                           | U<br>$\frac{25}{64}$               | .3680<br>.3906          | $\frac{29}{64}$       | .4531          | $\frac{15}{32}$ | .4687          |
| $\frac{1}{2}$  | .500           | 13<br>20                           | $\frac{27}{64}$<br>$\frac{29}{64}$ | .4219<br>4531           | $\frac{33}{64}$       | .5156          | $\frac{17}{32}$ | .5312          |

<sup>a</sup>These screws are not in the American Standard but are from the former A.S.M.E. Standard.

The size of the tap drill hole for any desired percentage of full thread depth can be calculated by the formulas below. In these formulas the Per Cent Full Thread is expressed as a decimal; e.g., 75 per cent is expressed as .75. The tap drill size is the size nearest to the calculated hole size.

For American Unified Thread form:

$$\text{Hole Size} = \text{Basic Major Diameter} - \frac{1.08253 \times \text{Per Cent Full Thread}}{\text{Number of Threads per Inch}}$$

For ISO Metric threads (all dimensions in millimeters):

$$\text{Hole Size} = \text{Basic Major Diameter} - (1.08253 \times \text{Pitch} \times \text{Per Cent Full Thread})$$

The constant 1.08253 in the above equation represents  $5H/8$  where  $H$  is the height of a sharp V-thread (see page 1725). (The pitch is taken to be 1.)

**Factors Influencing Minor Diameter Tolerances of Tapped Holes.**—As stated in the Unified screw thread standard, the principle practical factors that govern minor diameter tolerances of internal threads are tapping difficulties, particularly tap breakage in the small sizes, availability of standard drill sizes in the medium and large sizes, and depth (radial) of engagement. Depth of engagement is related to the stripping strength of the thread assembly, and thus also, to the length of engagement. It also has an influence on the tendency toward disengagement of the threads on one side when assembly is eccentric. The amount of possible eccentricity is one-half of the sum of the pitch diameter allowance and toler-

ances on both mating threads. For a given pitch, or height of thread, this sum increases with the diameter, and accordingly this factor would require a decrease in minor diameter tolerance with increase in diameter. However, such decrease in tolerance would often require the use of special drill sizes; therefore, to facilitate the use of standard drill sizes, for any given pitch the minor diameter tolerance for Unified thread classes 1B and 2B threads of  $\frac{1}{4}$  inch diameter and larger is constant, in accordance with a formula given in the American Standard for Unified Screw Threads.

*Effect of Length of Engagement of Minor Diameter Tolerances:* There may be applications where the lengths of engagement of mating threads is relatively short or the combination of materials used for mating threads is such that the maximum minor diameter tolerance given in the Standard (based on a length of engagement equal to the nominal diameter) may not provide the desired strength of the fastening. Experience has shown that for lengths of engagement less than  $\frac{2}{3}D$  (the minimum thickness of standard nuts) the minor diameter tolerance may be reduced without causing tapping difficulties. In other applications the length of engagement of mating threads may be long because of design considerations or the combination of materials used for mating threads. As the threads engaged increase in number, a shallower depth of engagement may be permitted and still develop stripping strength greater than the external thread breaking strength. Under these conditions the maximum tolerance given in the Standard should be increased to reduce the possibility of tapping difficulties. The following paragraphs indicate how the aforementioned considerations were taken into account in determining the minor diameter limits for various lengths of engagement given in [Table 2](#).

**Recommended Hole Sizes before Tapping.**—Recommended hole size limits before threading to provide for optimum strength of fastenings and tapping conditions are shown in [Table 2](#) for classes 1B, 2B, and 3B. The hole size limit before threading, and the tolerances between them, are derived from the minimum and maximum minor diameters of the internal thread given in the dimensional tables for Unified threads in the screw thread section using the following rules:

- 1) For lengths of engagement in the range to and including  $\frac{1}{3}D$ , where  $D$  equals nominal diameter, the minimum hole size will be equal to the minimum minor diameter of the internal thread and the maximum hole size will be larger by one-half the minor diameter tolerance.
- 2) For the range from  $\frac{1}{3}D$  to  $\frac{2}{3}D$ , the minimum and maximum hole sizes will each be one quarter of the minor diameter tolerance larger than the corresponding limits for the length of engagement to and including  $\frac{1}{3}D$ .
- 3) For the range from  $\frac{2}{3}D$  to  $1\frac{1}{2}D$  the minimum hole size will be larger than the minimum minor diameter of the internal thread by one-half the minor diameter tolerance and the maximum hole size will be equal to the maximum minor diameter.
- 4) For the range from  $1\frac{1}{2}D$  to  $3D$  the minimum and maximum hole sizes will each be one-quarter of the minor diameter tolerance of the internal thread larger than the corresponding limits for the  $\frac{2}{3}D$  to  $1\frac{1}{2}D$  length of engagement.

From the foregoing it will be seen that the difference between limits in each range is the same and equal to one-half of the minor diameter tolerance given in the Unified screw thread dimensional tables. This is a general rule, except that the minimum differences for sizes below  $\frac{1}{4}$  inch are equal to the minor diameter tolerances calculated on the basis of lengths of engagement to and including  $\frac{1}{3}D$ . Also, for lengths of engagement greater than  $\frac{1}{3}D$  and for sizes  $\frac{1}{4}$  inch and larger the values are adjusted so that the difference between limits is never less than 0.004 inch.

For diameter-pitch combinations other than those given in [Table 2](#), the foregoing rules should be applied to the tolerances given in the dimensional tables in the screw thread sec-

tion or the tolerances derived from the formulas given in the Standard to determine the hole size limits.

*Selection of Tap Drills:* In selecting standard drills to produce holes within the limits given in Table 2 it should be recognized that drills have a tendency to cut oversize. The material on page 885 may be used as a guide to the expected amount of oversize.

**Table 5. Unified Miniature Screw Threads—Recommended Hole Size Limits Before Tapping**

| Thread Size     |               | Internal Threads      |               | Lengths of Engagement           |               |   |               |                               |               |
|-----------------|---------------|-----------------------|---------------|---------------------------------|---------------|---|---------------|-------------------------------|---------------|
| Designation     | Pitch<br>mm   | Minor Diameter Limits |               | To and including $\frac{2}{3}D$ |               | Above $\frac{2}{3}D$ to $1\frac{1}{2}D$ |               | Above $1\frac{1}{2}D$ to $3D$ |               |
|                 |               | Min<br>mm             | Max<br>mm     | Recommended Hole Size Limits    |               |   |               |                               |               |
|                 |               |                       |               | Min<br>mm                       | Max<br>mm     | Min<br>mm                               | Max<br>mm     | Min<br>mm                     | Max<br>mm     |
| <b>0.30 UNM</b> | <b>0.080</b>  | <b>0.217</b>          | <b>0.254</b>  | <b>0.226</b>                    | <b>0.240</b>  | <b>0.236</b>                            | <b>0.254</b>  | <b>0.245</b>                  | <b>0.264</b>  |
| 0.35 UNM        | 0.090         | 0.256                 | 0.297         | 0.267                           | 0.282         | 0.277                                   | 0.297         | 0.287                         | 0.307         |
| <b>0.40 UNM</b> | <b>0.100</b>  | <b>0.296</b>          | <b>0.340</b>  | <b>0.307</b>                    | <b>0.324</b>  | <b>0.318</b>                            | <b>0.340</b>  | <b>0.329</b>                  | <b>0.351</b>  |
| 0.45 UNM        | 0.100         | 0.346                 | 0.390         | 0.357                           | 0.374         | 0.368                                   | 0.390         | 0.379                         | 0.401         |
| <b>0.50 UNM</b> | <b>0.125</b>  | <b>0.370</b>          | <b>0.422</b>  | <b>0.383</b>                    | <b>0.402</b>  | <b>0.396</b>                            | <b>0.422</b>  | <b>0.409</b>                  | <b>0.435</b>  |
| 0.55 UNM        | 0.125         | 0.420                 | 0.472         | 0.433                           | 0.452         | 0.446                                   | 0.472         | 0.459                         | 0.485         |
| <b>0.60 UNM</b> | <b>0.150</b>  | <b>0.444</b>          | <b>0.504</b>  | <b>0.459</b>                    | <b>0.482</b>  | <b>0.474</b>                            | <b>0.504</b>  | <b>0.489</b>                  | <b>0.519</b>  |
| 0.70 UNM        | 0.175         | 0.518                 | 0.586         | 0.535                           | 0.560         | 0.552                                   | 0.586         | 0.569                         | 0.603         |
| <b>0.80 UNM</b> | <b>0.200</b>  | <b>0.592</b>          | <b>0.668</b>  | <b>0.611</b>                    | <b>0.640</b>  | <b>0.630</b>                            | <b>0.668</b>  | <b>0.649</b>                  | <b>0.687</b>  |
| 0.90 UNM        | 0.225         | 0.666                 | 0.750         | 0.687                           | 0.718         | 0.708                                   | 0.750         | 0.729                         | 0.771         |
| <b>1.00 UNM</b> | <b>0.250</b>  | <b>0.740</b>          | <b>0.832</b>  | <b>0.763</b>                    | <b>0.798</b>  | <b>0.786</b>                            | <b>0.832</b>  | <b>0.809</b>                  | <b>0.855</b>  |
| 1.10 UNM        | 0.250         | 0.840                 | 0.932         | 0.863                           | 0.898         | 0.886                                   | 0.932         | 0.909                         | 0.955         |
| <b>1.20 UNM</b> | <b>0.250</b>  | <b>0.940</b>          | <b>1.032</b>  | <b>0.963</b>                    | <b>0.998</b>  | <b>0.986</b>                            | <b>1.032</b>  | <b>1.009</b>                  | <b>1.055</b>  |
| 1.40 UNM        | 0.300         | 1.088                 | 1.196         | 1.115                           | 1.156         | 1.142                                   | 1.196         | 1.169                         | 1.223         |
| Designation     | Thds. per in. | inch                  | inch          | inch                            | inch          | inch                                    | inch          | inch                          | inch          |
| <b>0.30 UNM</b> | <b>318</b>    | <b>0.0085</b>         | <b>0.0100</b> | <b>0.0089</b>                   | <b>0.0095</b> | <b>0.0093</b>                           | <b>0.0100</b> | <b>0.0096</b>                 | <b>0.0104</b> |
| 0.35 UNM        | 282           | 0.0101                | 0.0117        | 0.0105                          | 0.0111        | 0.0109                                  | 0.0117        | 0.0113                        | 0.0121        |
| <b>0.40 UNM</b> | <b>254</b>    | <b>0.0117</b>         | <b>0.0134</b> | <b>0.0121</b>                   | <b>0.0127</b> | <b>0.0125</b>                           | <b>0.0134</b> | <b>0.0130</b>                 | <b>0.0138</b> |
| 0.45 UNM        | 254           | 0.0136                | 0.0154        | 0.0141                          | 0.0147        | 0.0145                                  | 0.0154        | 0.0149                        | 0.0158        |
| <b>0.50 UNM</b> | <b>203</b>    | <b>0.0146</b>         | <b>0.0166</b> | <b>0.0150</b>                   | <b>0.0158</b> | <b>0.0156</b>                           | <b>0.0166</b> | <b>0.0161</b>                 | <b>0.0171</b> |
| 0.55 UNM        | 203           | 0.0165                | 0.0186        | 0.0170                          | 0.0178        | 0.0176                                  | 0.0186        | 0.0181                        | 0.0191        |
| <b>0.60 UNM</b> | <b>169</b>    | <b>0.0175</b>         | <b>0.0198</b> | <b>0.0181</b>                   | <b>0.0190</b> | <b>0.0187</b>                           | <b>0.0198</b> | <b>0.0193</b>                 | <b>0.0204</b> |
| 0.70 UNM        | 145           | 0.0204                | 0.0231        | 0.0211                          | 0.0221        | 0.0217                                  | 0.0231        | 0.0224                        | 0.0237        |
| <b>0.80 UNM</b> | <b>127</b>    | <b>0.0233</b>         | <b>0.0263</b> | <b>0.0241</b>                   | <b>0.0252</b> | <b>0.0248</b>                           | <b>0.0263</b> | <b>0.0256</b>                 | <b>0.0270</b> |
| 0.90 UNM        | 113           | 0.0262                | 0.0295        | 0.0270                          | 0.0283        | 0.0279                                  | 0.0295        | 0.0287                        | 0.0304        |
| <b>1.00 UNM</b> | <b>102</b>    | <b>0.0291</b>         | <b>0.0327</b> | <b>0.0300</b>                   | <b>0.0314</b> | <b>0.0309</b>                           | <b>0.0327</b> | <b>0.0319</b>                 | <b>0.0337</b> |
| 1.10 UNM        | 102           | 0.0331                | 0.0367        | 0.0340                          | 0.0354        | 0.0349                                  | 0.0367        | 0.0358                        | 0.0376        |
| <b>1.20 UNM</b> | <b>102</b>    | <b>0.0370</b>         | <b>0.0406</b> | <b>0.0379</b>                   | <b>0.0393</b> | <b>0.0388</b>                           | <b>0.0406</b> | <b>0.0397</b>                 | <b>0.0415</b> |
| 1.40 UNM        | 85            | 0.0428                | 0.0471        | 0.0439                          | 0.0455        | 0.0450                                  | 0.0471        | 0.0460                        | 0.0481        |

As an aid in selecting suitable drills, see the listing of American Standard drill sizes in the twist drill section. Thread sizes in heavy type are preferred sizes.

**Hole Sizes for Tapping Unified Miniature Screw Threads.**—Table 5 indicates the hole size limits recommended for tapping. These limits are derived from the internal thread minor diameter limits given in the American Standard for Unified Miniature Screw Threads ASA B1.10-1958 and are disposed so as to provide the optimum conditions for tapping. The maximum limits are based on providing a functionally adequate fastening for the most common applications, where the material of the externally threaded member is of a strength essentially equal to or greater than that of its mating part. In applications where, because of considerations other than the fastening, the screw is made of an appreciably

weaker material, the use of smaller hole sizes is usually necessary to extend thread engagement to a greater depth on the external thread. Recommended minimum hole sizes are greater than the minimum limits of the minor diameters to allow for the spin-up developed in tapping.

In selecting drills to produce holes within the limits given in [Table 5](#) it should be recognized that drills have a tendency to cut oversize. The material on [page 885](#) may be used as a guide to the expected amount of oversize.

**British Standard Tapping Drill Sizes for Screw and Pipe Threads.**—British Standard BS 1157:1975 (1998) provides recommendations for tapping drill sizes for use with fluted taps for various ISO metric, Unified, British Standard fine, British Association, and British Standard Whitworth screw threads as well as British Standard parallel and taper pipe threads.

**Table 6. British Standard Tapping Drill Sizes for ISO Metric Coarse Pitch Series Threads BS 1157:1975 (1998)**

| Nom. Size and Thread Diam. | Standard Drill Sizes <sup>a</sup> |   |             |   | Nom. Size and Thread Diam. | Standard Drill Sizes <sup>a</sup> |   |             |   |
|----------------------------|-----------------------------------|---|-------------|---|----------------------------|-----------------------------------|---|-------------|---|
|                            | Recommended                       |   | Alternative |   |                            | Recommended                       |   | Alternative |   |
|                            | Size                              | Theoretical Radial Engagement with Ext. Thread (Per Cent) | Size        | Theoretical Radial Engagement with Ext. Thread (Per Cent) |                            | Size                              | Theoretical Radial Engagement with Ext. Thread (Per Cent) | Size        | Theoretical Radial Engagement with Ext. Thread (Per Cent) |
| M 1                        | 0.75                              | 81.5  | 0.78        | 71.7  | M 12                       | 10.20                             | 83.7  | 10.40       | 74.5 <sup>b</sup>   |
| M 1.1                      | 0.85                              | 81.5  | 0.88        | 71.7  | M 14                       | 12.00                             | 81.5  | 12.20       | 73.4 <sup>b</sup>   |
| M 1.2                      | 0.95                              | 81.5  | 0.98        | 71.7  | M 16                       | 14.00                             | 81.5  | 14.25       | 71.3 <sup>c</sup>   |
| M 1.4                      | 1.10                              | 81.5  | 1.15        | 67.9  | M 18                       | 15.50                             | 81.5  | 15.75       | 73.4 <sup>c</sup>   |
| M 1.6                      | 1.25                              | 81.5  | 1.30        | 69.9  | M 20                       | 17.50                             | 81.5  | 17.75       | 73.4 <sup>c</sup>   |
| M 1.8                      | 1.45                              | 81.5  | 1.50        | 69.9  | M 22                       | 19.50                             | 81.5  | 19.75       | 73.4 <sup>c</sup>   |
| M 2                        | 1.60                              | 81.5  | 1.65        | 71.3  | M 24                       | 21.00                             | 81.5  | 21.25       | 74.7 <sup>b</sup>   |
| M 2.2                      | 1.75                              | 81.5  | 1.80        | 72.5  | M 27                       | 24.00                             | 81.5  | 24.25       | 74.7 <sup>b</sup>   |
| M 2.5                      | 2.05                              | 81.5  | 2.10        | 72.5  | M 30                       | 26.50                             | 81.5  | 26.75       | 75.7 <sup>b</sup>   |
| M 3                        | 2.50                              | 81.5  | 2.55        | 73.4  | M 33                       | 29.50                             | 81.5  | 29.75       | 75.7 <sup>b</sup>   |
| M 3.5                      | 2.90                              | 81.5  | 2.95        | 74.7  | M 36                       | 32.00                             | 81.5  | ...         | ...   |
| M 4                        | 3.30                              | 81.5  | 3.40        | 69.9 <sup>b</sup>   | M 39                       | 35.00                             | 81.5  | ...         | ...   |
| M 4.5                      | 3.70                              | 86.8  | 3.80        | 76.1  | M 42                       | 37.50                             | 81.5  | ...         | ...   |
| M 5                        | 4.20                              | 81.5  | 4.30        | 71.3 <sup>b</sup>   | M 45                       | 40.50                             | 81.5  | ...         | ...   |
| M 6                        | 5.00                              | 81.5  | 5.10        | 73.4  | M 48                       | 43.00                             | 81.5  | ...         | ...   |
| M 7                        | 6.00                              | 81.5  | 6.10        | 73.4  | M 52                       | 47.00                             | 81.5  | ...         | ...   |
| M 8                        | 6.80                              | 78.5  | 6.90        | 71.7 <sup>b</sup>   | M 56                       | 50.50                             | 81.5  | ...         | ...   |
| M 9                        | 7.80                              | 78.5  | 7.90        | 71.7 <sup>b</sup>   | M 60                       | 54.50                             | 81.5  | ...         | ...   |
| M 10                       | 8.50                              | 81.5  | 8.60        | 76.1  | M 64                       | 58.00                             | 81.5  | ...         | ...   |
| M 11                       | 9.50                              | 81.5  | 9.60        | 76.1  | M 68                       | 62.00                             | 81.5  | ...         | ...   |

<sup>a</sup> These tapping drill sizes are for fluted taps only.

<sup>b</sup> For tolerance class 6H and 7H threads only.

<sup>c</sup> For tolerance class 7H threads only.

Drill sizes are given in millimeters.

In the accompanying [Table 6](#), recommended and alternative drill sizes are given for producing holes for ISO metric coarse pitch series threads. These coarse pitch threads are suitable for the large majority of general-purpose applications, and the limits and tolerances for internal coarse threads are given in the table starting on [page 1823](#). It should be noted that [Table 6](#) is for fluted taps only since a fluteless tap will require for the same screw thread a different size of twist drill than will a fluted tap. When tapped, holes produced with drills of the recommended sizes provide for a theoretical radial engagement with the external thread of about 81 per cent in most cases. Holes produced with drills of the alternative sizes provide for a theoretical radial engagement with the external thread of about 70 to 75

per cent. In some cases, as indicated in Table 6, the alternative drill sizes are suitable only for medium (6H) or for free (7H) thread tolerance classes.

When relatively soft material is being tapped, there is a tendency for the metal to be squeezed down towards the root of the tap thread, and in such instances, the minor diameter of the tapped hole may become smaller than the diameter of the drill employed. Users may wish to choose different tapping drill sizes to overcome this problem or for special purposes, and reference can be made to the pages mentioned above to obtain the minor diameter limits for internal pitch series threads.

Reference should be made to this standard BS 1157:1975 (1998) for recommended tapping hole sizes for other types of British Standard screw threads and pipe threads.

**Table 7. British Standard Metric Bolt and Screw Clearance Holes BS 4186: 1967**

| Nominal Thread Diameter | Clearance Hole Sizes |                   |                 | Nominal Thread Diameter | Clearance Hole Sizes |                   |                 |
|-------------------------|----------------------|-------------------|-----------------|-------------------------|----------------------|-------------------|-----------------|
|                         | Close Fit Series     | Medium Fit Series | Free Fit Series |                         | Close Fit Series     | Medium Fit Series | Free Fit Series |
| 1.6                     | 1.7                  | 1.8               | 2.0             | 52.0                    | 54.0                 | 56.0              | 62.0            |
| 2.0                     | 2.2                  | 2.4               | 2.6             | 56.0                    | 58.0                 | 62.0              | 66.0            |
| 2.5                     | 2.7                  | 2.9               | 3.1             | 60.0                    | 62.0                 | 66.0              | 70.0            |
| 3.0                     | 3.2                  | 3.4               | 3.6             | 64.0                    | 66.0                 | 70.0              | 74.0            |
| 4.0                     | 4.3                  | 4.5               | 4.8             | 68.0                    | 70.0                 | 74.0              | 78.0            |
| 5.0                     | 5.3                  | 5.5               | 5.8             | 72.0                    | 74.0                 | 78.0              | 82.0            |
| 6.0                     | 6.4                  | 6.6               | 7.0             | 76.0                    | 78.0                 | 82.0              | 86.0            |
| 7.0                     | 7.4                  | 7.6               | 8.0             | 80.0                    | 82.0                 | 86.0              | 91.0            |
| 8.0                     | 8.4                  | 9.0               | 10.0            | 85.0                    | 87.0                 | 91.0              | 96.0            |
| 10.0                    | 10.5                 | 11.0              | 12.0            | 90.0                    | 93.0                 | 96.0              | 101.0           |
| 12.0                    | 13.0                 | 14.0              | 15.0            | 95.0                    | 98.0                 | 101.0             | 107.0           |
| 14.0                    | 15.0                 | 16.0              | 17.0            | 100.0                   | 104.0                | 107.0             | 112.0           |
| 16.0                    | 17.0                 | 18.0              | 19.0            | 105.0                   | 109.0                | 112.0             | 117.0           |
| 18.0                    | 19.0                 | 20.0              | 21.0            | 110.0                   | 114.0                | 117.0             | 122.0           |
| 20.0                    | 21.0                 | 22.0              | 24.0            | 115.0                   | 119.0                | 122.0             | 127.0           |
| 22.0                    | 23.0                 | 24.0              | 26.0            | 120.0                   | 124.0                | 127.0             | 132.0           |
| 24.0                    | 25.0                 | 26.0              | 28.0            | 125.0                   | 129.0                | 132.0             | 137.0           |
| 27.0                    | 28.0                 | 30.0              | 32.0            | 130.0                   | 134.0                | 137.0             | 144.0           |
| 30.0                    | 31.0                 | 33.0              | 35.0            | 140.0                   | 144.0                | 147.0             | 155.0           |
| 33.0                    | 34.0                 | 36.0              | 38.0            | 150.0                   | 155.0                | 158.0             | 165.0           |
| 36.0                    | 37.0                 | 39.0              | 42.0            | ...                     | ...                  | ...               | ...             |
| 39.0                    | 40.0                 | 42.0              | 45.0            | ...                     | ...                  | ...               | ...             |
| 42.0                    | 43.0                 | 45.0              | 48.0            | ...                     | ...                  | ...               | ...             |
| 45.0                    | 46.0                 | 48.0              | 52.0            | ...                     | ...                  | ...               | ...             |
| 48.0                    | 50.0                 | 52.0              | 56.0            | ...                     | ...                  | ...               | ...             |

All dimensions are given in millimeters.

**British Standard Clearance Holes for Metric Bolts and Screws.**—The dimensions of the clearance holes specified in this British Standard BS 4186:1967 have been chosen in such a way as to require the use of the minimum number of drills. The recommendations cover three series of clearance holes, namely close fit (H 12), medium fit (H 13), and free fit (H 14) and are suitable for use with bolts and screws specified in the following metric British Standards: BS 3692, ISO metric precision hexagon bolts, screws, and nuts; BS 4168, Hexagon socket screws and wrench keys; BS 4183, Machine screws and machine screw nuts; and BS 4190, ISO metric black hexagon bolts, screws, and nuts. The sizes are in accordance with those given in ISO Recommendation R273, and the range has been extended up to 150 millimeters diameter in accordance with an addendum to that recommendation. The selection of clearance holes sizes to suit particular design requirements

can of course be dependent upon many variable factors. It is however felt that the medium fit series should suit the majority of general purpose applications. In the Standard, limiting dimensions are given in a table which is included for reference purposes only, for use in instances where it may be desirable to specify tolerances.

To avoid any risk of interference with the radius under the head of bolts and screws, it is necessary to countersink slightly all recommended clearance holes in the close and medium fit series. Dimensional details for the radius under the head of fasteners made according to BS 3692 are given on page 1575; those for fasteners to BS 4168 are given on page 1633; those to BS 4183 are given on pages 1607 through 1611.

**Cold Form Tapping.**—Cold form taps do not have cutting edges or conventional flutes; the threads on the tap form the threads in the hole by displacing the metal in an extrusion or swaging process. The threads thus produced are stronger than conventionally cut threads because the grains in the metal are unbroken and the displaced metal is work hardened. The surface of the thread is burnished and has an excellent finish. Although chip problems are eliminated, cold form tapping does displace the metal surrounding the hole and countersinking or chamfering before tapping is recommended. Cold form tapping is not recommended if the wall thickness of the hole is less than two-thirds of the nominal diameter of the thread. If possible, blind holes should be drilled deep enough to permit a cold form tap having a four thread lead to be used as this will require less torque, produce less burr surrounding the hole, and give a greater tool life.

The operation requires 0 to 50 per cent more torque than conventional tapping, and the cold form tap will pick up its own lead when entering the hole; thus, conventional tapping machines and tapping heads can be used. Another advantage is the better tool life obtained. The best results are obtained by using a good lubricating oil instead of a conventional cutting oil.

The method can be applied only to relatively ductile metals, such as low-carbon steel, leaded steels, austenitic stainless steels, wrought aluminum, low-silicon aluminum die casting alloys, zinc die casting alloys, magnesium, copper, and ductile copper alloys. A higher than normal tapping speed can be used, sometimes by as much as 100 per cent.

Conventional tap drill sizes should not be used for cold form tapping because the metal is displaced to form the thread. The cold formed thread is stronger than the conventionally tapped thread, so the thread height can be reduced to 60 per cent without much loss of strength; however, the use of a 65 per cent thread is strongly recommended. The following formula is used to calculate the theoretical hole size for cold form tapping:

$$\text{Theoretical hole size} = \text{basic tap O.D.} - \frac{0.0068 \times \text{per cent of full thread}}{\text{threads per inch}}$$

The theoretical hole size and the tap drill sizes for American Unified threads are given in Table 8, and Table 9 lists drills for ISO metric threads. Sharp drills should be used to prevent cold working the walls of the hole, especially on metals that are prone to work hardening. Such damage may cause the torque to increase, possibly stopping the machine or breaking the tap. On materials that can be die cast, cold form tapping can be done in cored holes provided the correct core pin size is used. The core pins are slightly tapered, so the theoretical hole size should be at the position on the pin that corresponds to one-half of the required engagement length of the thread in the hole. The core pins should be designed to form a chamfer on the hole to accept the vertical extrusion.



**Table 8. Theoretical and Tap Drill or Core Hole Sizes for Cold Form Tapping Unified Threads**

| Tap Size       | Threads Per Inch | Percentage of Full Thread |                    |             |                  |                    |             |                  |                    |             |
|----------------|------------------|---------------------------|--------------------|-------------|------------------|--------------------|-------------|------------------|--------------------|-------------|
|                |                  | 75                        |                    |             | 65               |                    |             | 55               |                    |             |
|                |                  | Theor. Hole Size          | Nearest Drill Size | Dec. Equiv. | Theor. Hole Size | Nearest Drill Size | Dec. Equiv. | Theor. Hole Size | Nearest Drill Size | Dec. Equiv. |
| 0              | 80               | 0.0536                    | 1.35 mm            | 0.0531      | 0.0545           | ...                | ...         | 0.0554           | 54                 | 0.055       |
|                | 64               | 0.0650                    | 1.65 mm            | 0.0650      | 0.0661           | ...                | ...         | 0.0672           | 51                 | 0.0670      |
| 1              | 72               | 0.0659                    | 1.65 mm            | 0.0650      | 0.0669           | 1.7 mm             | 0.0669      | 0.0679           | 51                 | 0.0670      |
|                | 56               | 0.0769                    | 1.95 mm            | 0.0768      | 0.0781           | $\frac{5}{64}$     | 0.0781      | 0.0794           | 2.0 mm             | 0.0787      |
| 2              | 64               | 0.0780                    | $\frac{5}{64}$     | 0.0781      | 0.0791           | 2.0 mm             | 0.0787      | 0.0802           | ...                | ...         |
|                | 48               | 0.0884                    | 2.25 mm            | 0.0886      | 0.0898           | 43                 | 0.089       | 0.0913           | 2.3 mm             | 0.0906      |
| 3              | 56               | 0.0889                    | 43                 | 0.089       | 0.0911           | 2.3 mm             | 0.0906      | 0.0924           | 2.35 mm            | 0.0925      |
|                | 40               | 0.0993                    | 2.5 mm             | 0.0984      | 0.1010           | 39                 | 0.0995      | 0.1028           | 2.6 mm             | 0.1024      |
| 4              | 48               | 0.0104                    | 38                 | 0.1015      | 0.1028           | 2.6 mm             | 0.1024      | 0.1043           | 37                 | 0.1040      |
|                | 5                | 40                        | 0.1123             | 34          | 0.1110           | 0.1140             | 33          | 0.113            | 0.1158             | 32          |
| 5              | 44               | 0.1134                    | 33                 | 0.113       | 0.1150           | 2.9 mm             | 0.1142      | 0.1166           | 32                 | ...         |
|                | 32               | 0.1221                    | 3.1 mm             | 0.1220      | 0.1243           | ...                | ...         | 0.1264           | 3.2 mm             | 0.1260      |
| 6              | 40               | 0.1253                    | $\frac{1}{8}$      | 0.1250      | 0.1270           | 3.2 mm             | 0.1260      | 0.1288           | 30                 | 0.1285      |
|                | 32               | 0.1481                    | 3.75 mm            | 0.1476      | 0.1503           | 25                 | 0.1495      | 0.1524           | 24                 | 0.1520      |
| 8              | 36               | 0.1498                    | 25                 | 0.1495      | 0.1518           | 24                 | 0.1520      | 0.1537           | 3.9 mm             | 0.1535      |
|                | 24               | 0.1688                    | ...                | ...         | 0.1717           | $\frac{11}{64}$    | 0.1719      | 0.1746           | 17                 | 0.1730      |
| 10             | 32               | 0.1741                    | 17                 | 0.1730      | 0.1763           | ...                | ...         | 0.1784           | 4.5 mm             | 0.1772      |
|                | 24               | 0.1948                    | 10                 | 0.1935      | 0.1977           | 5.0 mm             | 0.1968      | 0.2006           | 5.1 mm             | 0.2008      |
| 12             | 28               | 0.1978                    | 5.0 mm             | 0.1968      | 0.2003           | 8                  | 0.1990      | 0.2028           | ...                | ...         |
|                | 20               | 0.2245                    | 5.7 mm             | 0.2244      | 0.2280           | 1                  | 0.2280      | 0.2315           | ...                | ...         |
| $\frac{1}{4}$  | 28               | 0.2318                    | ...                | ...         | 0.2343           | A                  | 0.2340      | 0.2368           | 6.0 mm             | 0.2362      |
|                | 18               | 0.2842                    | 7.2 mm             | 0.2835      | 0.2879           | 7.3 mm             | 0.2874      | 0.2917           | 7.4 mm             | 0.2913      |
| $\frac{5}{16}$ | 24               | 0.2912                    | 7.4 mm             | 0.2913      | 0.2941           | M                  | 0.2950      | 0.2969           | $\frac{19}{64}$    | 0.2969      |
|                | 16               | 0.3431                    | $\frac{11}{32}$    | 0.3437      | 0.3474           | S                  | 0.3480      | 0.3516           | ...                | ...         |
| $\frac{3}{8}$  | 24               | 0.3537                    | 9.0 mm             | 0.3543      | 0.3566           | ...                | ...         | 0.3594           | $\frac{23}{64}$    | 0.3594      |
|                | 14               | 0.4011                    | ...                | ...         | 0.4059           | $\frac{13}{32}$    | 0.4062      | 0.4108           | ...                | ...         |
| $\frac{7}{16}$ | 20               | 0.4120                    | Z                  | 0.413       | 0.4154           | ...                | ...         | 0.4188           | ...                | ...         |
|                | 13               | 0.4608                    | ...                | ...         | 0.4660           | ...                | ...         | 0.4712           | 12 mm              | 0.4724      |
| $\frac{1}{2}$  | 20               | 0.4745                    | ...                | ...         | 0.4779           | ...                | ...         | 0.4813           | ...                | ...         |
|                | 12               | 0.5200                    | ...                | ...         | 0.5257           | ...                | ...         | 0.5313           | $\frac{17}{32}$    | 0.5312      |
| $\frac{9}{16}$ | 18               | 0.5342                    | 13.5 mm            | 0.5315      | 0.5380           | ...                | ...         | 0.5417           | ...                | ...         |
|                | 11               | 0.5787                    | $\frac{37}{64}$    | 0.5781      | 0.5848           | ...                | ...         | 0.5910           | 15 mm              | 0.5906      |
| $\frac{5}{8}$  | 18               | 0.5976                    | $\frac{19}{32}$    | 0.5937      | 0.6004           | ...                | ...         | 0.6042           | ...                | ...         |
|                | 10               | 0.6990                    | ...                | ...         | 0.7058           | $\frac{45}{64}$    | 0.7031      | 0.7126           | ...                | ...         |
| $\frac{3}{4}$  | 16               | 0.7181                    | $\frac{23}{32}$    | 0.7187      | 0.7224           | ...                | ...         | 0.7266           | ...                | ...         |

**Table 9. Tap Drill or Core Hole Sizes for Cold Form Tapping ISO Metric Threads**

| Nominal Size of Tap | Pitch   | Recommended Tap Drill Size |
|---------------------|---------|----------------------------|
| 1.6 mm              | 0.35 mm | 1.45 mm                    |
| 1.8 mm              | 0.35 mm | 1.65 mm                    |
| 2.0 mm              | 0.40 mm | 1.8 mm                     |
| 2.2 mm.             | 0.45 mm | 2.0 mm                     |
| 2.5 mm              | 0.45 mm | 2.3 mm                     |
| 3.0 mm              | 0.50 mm | 2.8 mm <sup>a</sup>        |
| 3.5 mm              | 0.60 mm | 3.2 mm                     |
| 4.0 mm              | 0.70 mm | 3.7 mm                     |
| 4.5 mm              | 0.75 mm | 4.2 mm <sup>a</sup>        |
| 5.0 mm              | 0.80 mm | 4.6 mm                     |
| 6.0 mm              | 1.00 mm | 5.6 mm <sup>a</sup>        |
| 7.0 mm              | 1.00 mm | 6.5 mm                     |
| 8.0 mm              | 1.25 mm | 7.4 mm                     |
| 10.0 mm             | 1.50 mm | 9.3 mm                     |

<sup>a</sup>These diameters are the nearest stocked drill sizes and not the theoretical hole size, and may not produce 60 to 75 per cent full thread.

The sizes are calculated to provide 60 to 75 per cent of full thread.

**Removing a Broken Tap.**—Broken taps can be removed by electrodischarge machining (EDM), and this method is recommended when available. When an EDM machine is not available, broken taps may be removed by using a tap extractor, which has fingers that enter the flutes of the tap; the tap is backed out of the hole by turning the extractor with a wrench. Sometimes the injection of a small amount of a proprietary solvent into the hole will be helpful. A solvent can be made by diluting about one part nitric acid with five parts water. The action of the proprietary solvent or the diluted nitric acid on the steel loosens the tap so that it can be removed with pliers or with a tap extractor. The hole should be washed out afterwards so that the acid will not continue to work on the part. Another method is to add, by electric arc welding, additional metal to the shank of the broken tap, above the level of the hole. Care must be taken to prevent depositing metal on the threads in the tapped hole. After the shank has been built up, the head of a bolt or a nut is welded to it and then the tap may be backed out.

### Tap Drills for Pipe Taps

| Size of Tap | Drills for Briggs Pipe Taps | Drills for Whitworth Pipe Taps | Size of Tap | Drills for Briggs Pipe Taps | Drills for Whitworth Pipe Taps | Size of Tap | Drills for Briggs Pipe Taps | Drills for Whitworth Pipe Taps |
|-------------|-----------------------------|--------------------------------|-------------|-----------------------------|--------------------------------|-------------|-----------------------------|--------------------------------|
| 1/8         | 11/32                       | 5/16                           | 1 1/4       | 1 1/2                       | 1 15/32                        | 3 1/4       | ...                         | 3 1/2                          |
| 1/4         | 7/16                        | 27/64                          | 1 1/2       | 1 23/32                     | 1 29/32                        | 3 1/2       | 3 3/4                       | 3 3/4                          |
| 3/8         | 19/32                       | 9/16                           | 1 3/4       | ...                         | 1 15/16                        | 3 3/4       | ...                         | 4                              |
| 1/2         | 23/32                       | 11/16                          | 2           | 2 3/16                      | 2 3/32                         | 4           | 4 1/4                       | 4 1/4                          |
| 5/8         | ...                         | 25/32                          | 2 1/4       | ...                         | 2 13/32                        | 4 1/2       | 4 3/4                       | 4 3/4                          |
| 3/4         | 15/16                       | 29/32                          | 2 1/2       | 2 5/8                       | 2 25/32                        | 5           | 5 5/16                      | 5 1/4                          |
| 7/8         | ...                         | 1 1/16                         | 2 3/4       | ...                         | 3 1/32                         | 5 1/2       | ...                         | 5 3/4                          |
| 1           | 1 5/32                      | 1 1/8                          | 3           | 3 1/4                       | 3 9/32                         | 6           | 6 3/8                       | 6 1/4                          |

All dimensions are in inches.

To secure the best results, the hole should be reamed before tapping with a reamer having a taper of 3/4 inch per foot.

**Power for Pipe Taps.**—The power required for driving pipe taps is given in the following table, which includes nominal pipe tap sizes from 2 to 8 inches.

The holes to be tapped were reamed with standard pipe tap reamers before tapping. The horsepower recorded was read off just before the tap was reversed. The table gives the net horsepower, deductions being made for the power required to run the machine without a load. The material tapped was cast iron, except in two instances, where cast steel was tapped. It will be seen that nearly double the power is required for tapping cast steel. The

power varies, of course, with the conditions. More power than that indicated in the table will be required if the cast iron is of a harder quality or if the taps are not properly relieved. The taps used in these experiments were of the inserted-blade type, the blades being made of high-speed steel.

### Power Required for Pipe Taps

| Nominal Tap Size | Rev. per Min. | Net H.P. | Thickness of Metal | Nominal Tap Size | Rev. per Min. | Net H.P. | Thickness of Metal |
|------------------|---------------|----------|--------------------|------------------|---------------|----------|--------------------|
| 2                | 40            | 4.24     | 1 $\frac{1}{8}$    | 3 $\frac{1}{2}$  | 25.6          | 7.20     | 1 $\frac{3}{4}$    |
| 2 $\frac{1}{2}$  | 40            | 5.15     | 1 $\frac{1}{8}$    | 4                | 18            | 6.60     | 2                  |
| 2 $\frac{1}{2}$  | 38.5          | 9.14     | 1 $\frac{1}{8}$    | 5                | 18            | 7.70     | 2                  |
| 3                | 40            | 5.75     | 1 $\frac{1}{8}$    | 6                | 17.8          | 8.80     | 2                  |
| 3                | 38.5          | 9.70     | 1 $\frac{1}{8}$    | 8                | 14            | 7.96     | 2 $\frac{1}{2}$    |

<sup>a</sup>Tapping cast steel; other tests in cast iron.

Tap size and metal thickness are in inches.

**High-Speed CNC Tapping.**—Tapping speed depends on the type of material being cut, the type of cutting tool, the speed and rigidity of the machine, the rigidity of the part-holding fixture, and the proper use of coolants and cutting fluids. When tapping, each revolution of the tool feeds the tap a distance equal to the thread pitch. Both spindle speed and feed per revolution must be accurately controlled so that changes in spindle speed result in a corresponding change in feed rate. If the feed/rev is not right, a stripped thread or broken tap will result. NC/CNC machines equipped with the *synchronous tapping* feature are able to control the tap feed as a function of spindle speed. These machines can use rigid-type tap holders or automatic tapping attachments and are able to control depth very accurately. Older NC machines that are unable to reliably coordinate spindle speed and feed must use a tension-compression type tapping head that permits some variation of the spindle speed while still letting the tap feed at the required rate.

CNC machines capable of synchronous tapping accurately coordinate feed rate and rotational speed so that the tap advances at the correct rate regardless of the spindle speed. A canned tapping cycle (see *Fixed (Canned) Cycles* on page 1287 in the *NUMERICAL CONTROL* section) usually controls the operation, and feed and speed are set by the machine operator or part programmer. Synchronized tapping requires reversing the tapping spindle twice for each hole tapped, once after finishing the cut and again at the end of the cycle. Because the rotating mass is fairly large (motor, spindle, chuck or tap holder, and tap), the acceleration and deceleration of the tap are rather slow and a lot of time is lost by this process. The frequent changes in cutting speed during the cut also accelerate tap wear and reduce tap life.

A self-reversing tapping attachment has a forward drive that rotates in the same direction as the machine spindle, a reverse drive that rotates in the opposite direction, and a neutral position in between the two. When a hole is tapped, the spindle feeds at a slightly slower rate than the tap to keep the forward drive engaged until the tap reaches the bottom of the hole. Through holes are tapped by feeding to the desired depth and then retracting the spindle, which engages the tapping-head reverse drive and backs the tap out of the hole—the spindle does not need to be reversed. For tapping blind holes, the spindle is fed to a depth equal to the thread depth minus the self-feed of the tapping attachment. When the spindle is retracted (without reversing), the tap continues to feed forward a short distance (the tapping head self-feed distance) before the reverse drive engages and reverse drives the tap out of the hole. The depth can be controlled to within about  $\frac{1}{4}$  revolution of the tap. The tapping cycle normally used for the self-reversing tap attachment is a standard boring cycle with feed return and no dwell. A typical programming cycle is illustrated with a G85 block on page 1289. The inward feed is set to about 95 per cent of the normal tapping feed (i.e.,

95 per cent of the pitch per revolution). Because the tap is lightweight, tap reversal is almost instantaneous and tapping speed is very fast compared with synchronous tapping.

Tapping speeds are usually given in surface feet per minute (sfm) or the equivalent feet per minute (fpm or ft/min), so a conversion is necessary to get the spindle speed in revolutions per minute. The tapping speed in rpm depends on the diameter of the tap, and is given by the following formula:

$$\text{rpm} = \frac{\text{sfm} \times 12}{d \times 3.14159} = \frac{\text{sfm} \times 3.82}{d}$$

where  $d$  is the nominal diameter of the tap in inches. As indicated previously, the feed in in/rev is equal to the thread pitch and is independent of the cutting speed. The feed rate in inches per minute is found by dividing the tapping speed in rpm by the number of threads per inch, or by multiplying the speed in rpm by the pitch or feed per revolution:

$$\text{feed rate (in/min)} = \frac{\text{rpm}}{\text{threads per inch}} = \text{rpm} \times \text{thread pitch} = \text{rpm} \times \text{feed/rev}$$

*Example:* If the recommended tapping speed for 1020 steel is given as 45 to 60 sfm, find the required spindle speed and feed rate for tapping a 1/4–20 UNF thread in 1020 steel.

Assuming that the machine being used is in good condition and rigid, and the tap is sharp, use the higher rate of 60 sfm and calculate the required spindle speed and feed rate as follows:

$$\text{speed} = \frac{60 \times 3.82}{0.25} = 916.8 \approx 920 \text{ rpm} \quad \text{feed rate} = \frac{920}{20} = 46 \text{ in/min}$$

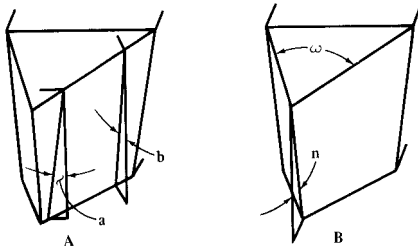
**Coolant for Tapping.**—Proper use of through-the-tap high-pressure coolant/lubricant can result in increased tap life, increased speed and feed, and more accurate threads. In most chip-cutting processes, cutting fluid is used primarily as a coolant, with lubrication being a secondary but important benefit. Tapping, however, requires a cutting fluid with lubricity as the primary property and coolant as a secondary benefit. Consequently, the typical blend of 5 per cent coolant concentrate to 95 per cent water is too low for best results. An increased percentage of concentrate in the blend helps the fluid to cling to the tap, providing better lubrication at the cutting interface. A method of increasing the tap lubrication qualities without changing the concentration of the primary fluid blend is to use a cutting fluid dispenser controlled by an M code different from that used to control the high-pressure flood coolant (for example, use an M08 code in addition to M07). The secondary coolant-delivery system applies a small amount of an edge-type cutting fluid (about a drop at a time) directly onto the tap-cutting surfaces providing the lubrication needed for cutting. The edge-type fluid applied in this way clings to the tap, increasing the lubrication effect and ensuring that the cutting fluid becomes directly involved in the cutting action at the shear zone.

High-pressure coolant fed through the tap is important in many high-volume tapping applications. The coolant is fed directly through the spindle or tool holder to the cutting zone, greatly improving the process of chip evacuation and resulting in better thread quality. High-pressure through-the-tap coolant flushes blind holes before the tap enters and can remove chips from the holes after tapping is finished. The flushing action prevents chip recutting by forcing chips through the flutes and back out of the hole, improving the surface of the thread and increasing tap life. By improving lubrication and reducing heat and friction, the use of high-pressure coolant may result in increased tap life up to five times that of conventional tapping and may permit speed and feed increases that reduce overall cycle time.

**Combined Drilling and Tapping.**—A special tool that drills and taps in one operation can save a lot of time by reducing setup and eliminating a secondary operation in some

applications. A combination drill and tap can be used for through holes if the length of the fluted drill section is greater than the material thickness, but cannot be used for drilling and tapping blind holes because the tip (drill point) must cut completely through the material before the tapping section begins to cut threads. Drilling and tapping depths up to twice the tool diameter are typical. Determine the appropriate speed by starting the tool at the recommended speed for the tap size and material, and adjust the speed higher or lower to suit the application. Feed during tapping is dependent on the thread pitch. NC/CNC programs can use a fast drilling speed and a slower tapping speed to combine both operations into one and minimize cutting time.

**Relief Angles for Single-Point Thread Cutting Tools.**—The surface finish on threads cut with single-point thread cutting tools is influenced by the relief angles on the tools. The leading and trailing cutting edges that form the sides of the thread, and the cutting edge at the nose of the tool must all be provided with an adequate amount of relief. Moreover, it is recommended that the effective relief angle,  $a_e$ , for all of these cutting edges be made equal, although the practice in some shops is to use slightly less relief at the trailing cutting edge. While too much relief may weaken the cutting edge, causing it to chip, an inadequate amount of relief will result in rough threads and in a shortened tool life. Other factors that influence the finish produced on threads include the following: the work material; the cutting speed; the cutting fluid used; the method used to cut the thread; and, the condition of the cutting edge.



Two similar diagrams showing relationships of various relief angles of thread cutting tools

Relief angles on single-point thread cutting tools are often specified on the basis of experience. While this method may give satisfactory results in many instances, better results can usually be obtained by calculating these angles, using the formulas provided further on. When special high helix angle threads are to be cut, the magnitude of the relief angles should always be calculated. These calculations are based on the effective relief angle,  $a_e$ ; this is the angle between the flank of the tool and the sloping sides of the thread, measured in a direction parallel to the axis of the thread. Recommended values of this angle are 8 to 14 degrees for high speed steel tools, and 5 to 10 degrees for cemented carbide tools. The larger values are recommended for cutting threads on soft and gummy materials, and the smaller values are for the harder materials, which inherently take a better surface finish. Harder materials also require more support below the cutting edges, which is provided by using a smaller relief angle. These values are recommended for the relief angle below the cutting edge at the nose without any further modification. The angles below the leading and trailing side cutting edges are modified, using the formulas provided. The angles  $b$  and  $b'$  are the relief angles actually ground on the tool below the leading and trailing side cutting edges respectively; they are measured perpendicular to the side cutting edges. When designing or grinding the thread cutting tool, it is sometimes helpful to know the magnitude of the angle,  $n$ , for which a formula is provided. This angle would occur only in the event that the tool were ground to a sharp point. It is the angle of the edge formed by the intersection of the flank surfaces.

$$\tan \phi = \frac{\text{lead of thread}}{\pi K} \quad \tan \phi' = \frac{\text{lead of thread}}{\pi D}$$

$$a = a_e + \phi$$

$$a' = a_e - \phi'$$

$$\tan b = \tan a \cos \frac{1}{2}\omega$$

$$\tan b' = \tan a' \cos \frac{1}{2}\omega$$

$$\tan n = \frac{\tan a - \tan a'}{2 \tan \frac{1}{2}\omega}$$

where  $\theta$  = helix angle of thread at minor diameter

$\theta'$  = helix angle of thread at major diameter

$K$  = minor diameter of thread

$D$  = major diameter of thread

$a$  = side relief angle parallel to thread axis at leading edge of tool

$a'$  = side relief angle parallel to thread axis at trailing edge of tool

$a_e$  = effective relief angle

$b$  = side relief angle perpendicular to leading edge of tool

$b'$  = side relief angle perpendicular to trailing edge of tool

$\omega$  = included angle of thread cutting tool

$n$  = nose angle resulting from intersection of flank surfaces

*Example:* Calculate the relief angles and the nose angle  $n$  for a single-point thread cutting tool that is to be used to cut a 1-inch diameter, 5-threads-per-inch, double Acme thread. The lead of this thread is  $2 \times 0.200 = 0.400$  inch. The included angle  $\omega$  of this thread is 29 degrees, the minor diameter  $K$  is 0.780 inch, and the effective relief angle  $a_e$  below all cutting edges is to be 10 degrees.

$$\tan \phi = \frac{\text{lead of thread}}{\pi K} = \frac{0.400}{\pi \times 0.780}$$

$$\phi = 9.27^\circ (9^\circ 16')$$

$$\tan \phi' = \frac{\text{lead of thread}}{\pi D} = \frac{0.400}{\pi \times 1.000}$$

$$\phi' = 7.26^\circ (7^\circ 15')$$

$$a = a_e + \phi = 10^\circ + 9.27^\circ = 19.27^\circ$$

$$a' = a_e - \phi' = 10^\circ - 7.26^\circ = 2.74^\circ$$

$$\tan b = \tan a \cos \frac{1}{2}\omega = \tan 19.27 \cos 14.5$$

$$b = 18.70^\circ (18^\circ 42')$$

$$\tan b' = \tan a' \cos \frac{1}{2}\omega = \tan 2.74 \cos 14.5$$

$$b' = 2.65^\circ (2^\circ 39')$$

$$\tan n = \frac{\tan a - \tan a'}{2 \tan \frac{1}{2}\omega} = \frac{\tan 19.27 - \tan 2.74}{2 \tan 14.5}$$

$$n = 30.26^\circ (30^\circ 16')$$

**Lathe Change Gears**

**Change Gears for Thread Cutting.**—To determine the change gears to use for cutting a thread of given pitch, first find what number of threads per inch will be cut when gears of the same size are placed on the lead screw and spindle stud, either by trial or by referring to the index plate; then multiply this number, called the “lathe screw constant,” by some trial number to obtain the number of teeth in the gear for the spindle stud, and multiply the threads per inch to be cut by the *same* trial number to obtain the number of teeth in the gear for the lead screw. Expressing this rule as a formula:

$$\frac{\text{Trial number} \times \text{lathe screw constant}}{\text{Trial number} \times \text{threads per inch to be cut}} = \frac{\text{teeth in gear on spindle stud}}{\text{teeth in gear on lead screw}}$$

For example, suppose the available change gears supplied with the lathe have 24, 28, 32, 36 teeth, etc., the number increasing by 4 up to 100, and that 10 threads per inch are to be cut in a lathe having a lathe screw constant of 6; then, if the screw constant is written as the numerator, the number of threads per inch to be cut as the denominator of a fraction, and both numerator and denominator are multiplied by some trial number, say, 4, it is found that gears having 24 and 40 teeth can be used. Thus:

$$\frac{6}{10} = \frac{6 \times 4}{10 \times 4} = \frac{24}{40}$$

The 24-tooth gear goes on the spindle stud and the 40-tooth gear on the lead screw.

The lathe screw constant is, of course, equal to the number of threads per inch on the lead screw, provided the spindle stud and spindle are geared in the ratio of 1 to 1, which, however, is not always so.

**Compound Gearing.**—To find the change gears used in compound gearing, place the screw constant as the numerator and the number of threads per inch to be cut as the denominator of a fraction; resolve both numerator and denominator into two factors each, and multiply each “pair” of factors by the same number, until values are obtained representing suitable numbers of teeth for the change gears. (One factor in the numerator and one in the denominator make a “pair” of factors.)

*Example:*— $1\frac{3}{4}$  threads per inch are to be cut in a lathe having a screw constant of 8; the available gears have 24, 28, 32, 36, 40 teeth, etc., increasing by 4 up to 100. Following the rule:

$$\frac{8}{1\frac{3}{4}} = \frac{2 \times 4}{1 \times 1\frac{3}{4}} = \frac{(2 \times 36) \times (4 \times 16)}{(1 \times 36) \times (1\frac{3}{4} \times 16)} = \frac{72 \times 64}{36 \times 28}$$

The gears having 72 and 64 teeth are the *driving* gears and those with 36 and 28 teeth are the *driven* gears.

**Fractional Threads.**—Sometimes the lead of a thread is given as a fraction of an inch instead of stating the number of threads per inch. For example, a thread may be required to be cut, having  $\frac{3}{8}$  inch lead. The expression “ $\frac{3}{8}$  inch lead” should first be transformed to “number of threads per inch.” The number of threads per inch (the thread being single) equals:

$$\frac{1}{\frac{3}{8}} = 1 \div \frac{3}{8} = \frac{8}{3} = 2\frac{2}{3}$$

To find the change gears to cut  $2\frac{2}{3}$  threads per inch in a lathe having a screw constant 8 and change gears ranging from 24 to 100 teeth, increasing in increments of 4, proceed as below:

$$\frac{8}{2\frac{2}{3}} = \frac{2 \times 4}{1 \times 2\frac{2}{3}} = \frac{(2 \times 36) \times (4 \times 24)}{(1 \times 36) \times (2\frac{2}{3} \times 24)} = \frac{72 \times 96}{36 \times 64}$$

**Change Gears for Metric Pitches.**—When screws are cut in accordance with the metric system, it is the usual practice to give the lead of the thread in millimeters, instead of the number of threads per unit of measurement. To find the change gears for cutting metric threads, when using a lathe having an inch lead screw, first determine the number of threads per inch corresponding to the given lead in millimeters. Suppose a thread of 3 millimeters lead is to be cut in a lathe having an inch lead screw and a screw constant of 6. As there are 25.4 millimeters per inch, the number of threads per inch will equal  $25.4 \div 3$ . Place the screw constant as the numerator, and the number of threads per inch to be cut as the denominator:

$$\frac{6}{\frac{25.4}{3}} = 6 \div \frac{25.4}{3} = \frac{6 \times 3}{25.4}$$

The numerator and denominator of this fractional expression of the change gear ratio is next multiplied by some trial number to determine the size of the gears. The first whole number by which 25.4 can be multiplied so as to get a whole number as the result is 5. Thus,  $25.4 \times 5 = 127$ . Hence, one gear having 127 teeth is always used when cutting metric threads with an inch lead screw. The other gear required has 90 teeth. Thus:

$$\frac{6 \times 3 \times 5}{25.4 \times 5} = \frac{90}{127}$$

Therefore, the following rule can be used to find the change gears for cutting metric pitches with an inch lead screw:

*Rule:* Place the lathe screw constant multiplied by the lead of the required thread in millimeters multiplied by 5 as the numerator of the fraction and 127 as the denominator. The product of the numbers in the numerator equals the number of teeth for the spindle-stud gear, and 127 is the number of teeth for the lead-screw gear.

If the lathe has a metric pitch lead screw, and a screw having a given number of threads per inch is to be cut, first find the "metric screw constant" of the lathe or the lead of thread in millimeters that would be cut with change gears of equal size on the lead screw and spindle stud; then the method of determining the change gears is simply the reverse of the one already explained for cutting a metric thread with an inch lead screw.

*Rule:* To find the change gears for cutting inch threads with a metric lead screw, place 127 in the numerator and the threads per inch to be cut, multiplied by the metric screw constant multiplied by 5 in the denominator; 127 is the number of teeth on the spindle-stud gear and the product of the numbers in the denominator equals the number of teeth in the lead-screw gear.

**Threads per Inch Obtained with a Given Combination of Gears.**—To determine the number of threads per inch that will be obtained with a given combination of gearing, multiply the lathe screw constant by the number of teeth in the *driven* gear (or by the product of the numbers of teeth in both driven gears of compound gearing), and divide the product thus obtained by the number of teeth in the *driving* gear (or by the product of the two driving gears of a compound train). The quotient equals the number of threads per inch.

**Change Gears for Fractional Ratios.**—When gear ratios cannot be expressed exactly in whole numbers that are within the range of ordinary gearing, the combination of gearing required for the fractional ratio may be determined quite easily, often by the "cancellation method." To illustrate this method, assume that the speeds of two gears are to be in the ratio of 3.423 to 1. The number 3.423 is first changed to  $\frac{3423}{1000}$  to clear it of decimals. Then, in order to secure a fraction that can be reduced, 3423 is changed to 3420;

$$\frac{3420}{1000} = \frac{342}{100} = \frac{3 \times 2 \times 57}{2 \times 50} = \frac{3 \times 57}{1 \times 50}$$



Then, multiplying  $\frac{3}{4}$  by some trial number, say, 24, the following gear combination is obtained:

$$\frac{72}{24} \times \frac{57}{50} = \frac{4104}{1200} = \frac{3.42}{1}$$

As the desired ratio is 3.423 to 1, there is an error of 0.003. When the ratios are comparatively simple, the cancellation method is not difficult and is frequently used; but by the logarithmic method to be described, more accurate results are usually possible.

**Modifying the Quick-Change Gearbox Output.**—On most modern lathes, the gear train connecting the headstock spindle with the lead screw contains a quick-change gearbox. Instead of using different change gears, it is only necessary to position the handles of the gearbox to adjust the speed ratio between the spindle and the lead screw in preparation for cutting a thread. However, a thread sometimes must be cut for which there is no quick-change gearbox setting. It is then necessary to modify the normal, or standard, gear ratio between the spindle and the gearbox by installing modifying change gears to replace the standard gears normally used. Metric and other odd pitch threads can be cut on lathes that have an inch thread lead screw and a quick-change gearbox having only settings for inch threads by using modifying-change gears in the gear train. Likewise, inch threads and other odd pitch threads can be cut on metric lead-screw lathes having a gearbox on which only metric thread settings can be made. Modifying-change gears also can be used for cutting odd pitch threads on lathes having a quick-change gearbox that has both inch and metric thread settings.

The sizes of the modifying-change gears can be calculated by formulas to be given later; they depend on the thread to be cut and on the setting of the quick-change gearbox. Many different sets of gears can be found for each thread to be cut. It is recommended that several calculations be made in order to find the set of gears that is most suitable for installation on the lathe. The modifying-change gear formulas that follow are based on the type of lead screw, i.e., whether the lead screw has inch or metric threads.

*Metric Threads on Inch Lead-Screw Lathes:* A 127-tooth translating gear must be used in the modifying-change gear train in order to be able to cut metric threads on inch lead-screw lathes. The formula for calculating the modifying change gears is:

$$\frac{5 \times \text{gearbox setting in thds/in.} \times \text{pitch in mm to be cut}}{127} = \frac{\text{driving gears}}{\text{driven gears}}$$

The numerator and denominator of this formula are multiplied by equal numbers, called trial numbers, to find the gears. If suitable gears cannot be found with one set, then another set of equal trial numbers is used. (Because these numbers are equal, such as 15/15 or 24/24, they are equal to the number one when thought of as a fraction; their inclusion has the effect of multiplying the formula by one, which does not change its value.) It is necessary to select the gearbox setting in threads per inch that must be used to cut the metric thread when using the gears calculated by the formula. One method is to select a quick-change gearbox setting that is close to the actual number of metric threads in a 1-inch length, called the equivalent threads per inch, which can be calculated by the following formula: Equivalent thds/in. =  $25.4 \div$  pitch in millimeters to be cut.

*Example:* Select the quick-change gearbox setting and calculate the modifying change gears required to set up a lathe having an inch-thread lead screw in order to cut an M12  $\times$  1.75 metric thread.

$$\begin{aligned} \text{Equivalent thds/in.} &= \frac{25.4}{\text{pitch in mm to be cut}} = \frac{25.4}{1.75} = 1.45 \text{ (use 14 thds/in.)} \\ \frac{5 \times \text{gearbox setting in thds/in.} \times \text{pitch in mm to be cut}}{127} &= \frac{5 \times 14 \times 1.75}{127} \\ &= \frac{(24) \times 5 \times 14 \times 1.75}{(24) \times 127} = \frac{(5 \times 14) \times (24 \times 1.75)}{24 \times 127} \\ &= \frac{70 \times 42}{24 \times 127} = \frac{\text{driving gears}}{\text{driven gears}} \end{aligned}$$

*Odd Inch Pitch Threads:* The calculation of the modifying change gears used for cutting odd pitch threads that are specified by their pitch in inches involves the sizes of the standard gears, which can be found by counting their teeth. Standard gears are those used to enable the lathe to cut the thread for which the gearbox setting is made; they are the gears that are normally used. The threads on worms used with worm gears are among the odd pitch threads that can be cut by this method. As before, it is usually advisable to calculate the actual number of threads per inch of the odd pitch thread and to select a gearbox setting that is close to this value. The following formula is used to calculate the modifying-change gears to cut odd inch pitch threads:

$$\begin{aligned} \frac{\text{Standard driving gear} \times \text{pitch to be cut in inches} \times \text{gearbox setting in thds/in.}}{\text{Standard driven gear}} \\ = \frac{\text{driving gears}}{\text{driven gears}} \end{aligned}$$

*Example:* Select the quick-change gearbox setting and calculate the modifying change gears required to cut a thread having a pitch equal to 0.195 inch. The standard driving and driven gears both have 48 teeth. To find equivalent threads per inch:

$$\frac{\text{Thds}}{\text{in.}} = \frac{1}{\text{pitch}} = \frac{1}{0.195} = 5.13 \quad (\text{use 5 thds/in.})$$

$$\begin{aligned} \frac{\text{Standard driving gear} \times \text{pitch to be cut in inches} \times \text{gearbox setting in thds/in.}}{\text{Standard driven gear}} \\ = \frac{48 \times 0.195 \times 5}{48} = \frac{(1000) \times 0.195 \times 5}{(1000)} = \frac{195 \times 5}{500 \times 2} = \frac{39 \times 5}{100 \times 2} = \frac{39 \times 5 \times (8)}{50 \times 2 \times 2 \times (8)} \\ = \frac{39 \times 40}{50 \times 32} = \frac{\text{driving gears}}{\text{driven gears}} \end{aligned}$$

It will be noted that in the second step above, 1000/1000 has been substituted for 48/48. This substitution does not change the ratio. The reason for this substitution is that  $1000 \times 0.195 = 195$ , a whole number. Actually,  $200/200$  might have been substituted because  $200 \times 0.195 = 39$ , also a whole number.

The procedure for calculating the modifying gears using the following formulas is the same as illustrated by the two previous examples.

*Odd Threads per Inch on Inch Lead Screw Lathes:*

$$\frac{\text{Standard driving gear} \times \text{gearbox setting in thds/in.}}{\text{Standard driven gear} \times \text{thds/in. to be cut}} = \frac{\text{driving gears}}{\text{driven gears}}$$

## THREAD CUTTING

*Inch Threads on Metric Lead Screw Lathes:*

$$\frac{127}{5 \times \text{gearbox setting in mm pitch} \times \text{thds/in. to be cut}} = \frac{\text{driving gears}}{\text{driven gears}}$$

*Odd Metric Pitch Threads on Metric Lead Screw Lathes:*

$$\frac{\text{Standard driving gear} \times \text{mm pitch to be cut}}{\text{Standard driven gear} \times \text{gearbox setting in mm pitch}} = \frac{\text{driving gears}}{\text{driven gears}}$$

**Finding Accurate Gear Ratios.**—Tables included in the 23rd and earlier editions of this handbook furnished a series of logarithms of gear ratios as a quick means of finding ratios for all gear combinations having 15 to 120 teeth. The ratios thus determined could be factored into sets of 2, 4, 6, or any other even numbers of gears to provide a desired overall ratio.

Although the method of using logarithms of gear ratios provides results of suitable accuracy for many gear-ratio problems, it does not provide a systematic means of evaluating whether other, more accurate ratios are available. In critical applications, especially in the design of mechanisms using reduction gear trains, it may be desirable to find many or all possible ratios to meet a specified accuracy requirement. The methods best suited to such problems use *Continued Fractions* and *Conjugate Fractions* as explained starting on pages 11 and illustrated in the worked-out example on page 13 for a set of four change gears.

As an example, if an overall reduction of 0.31416 is required, a fraction must be found such that the factors of the numerator and denominator may be used to form a four-gear reduction train in which no gear has more than 120 teeth. By using the method of conjugate fractions discussed on page 12, the ratios listed above, and their factors are found to be successively closer approximations to the required overall gear ratio.

| Ratio      | Numerator Factors     | Denominator               | Error Factors |
|------------|-----------------------|---------------------------|---------------|
| 11/35      | 11                    | 5 × 7                     | +0.00013      |
| 16/51      | 2 × 2 × 2 × 2         | 3 × 17                    | -0.00043      |
| 27/86      | 3 × 3 × 3             | 2 × 43                    | -0.00021      |
| 38/121     | 2 × 19                | 11 × 11                   | -0.00011      |
| 49/156     | 7 × 7                 | 2 × 2 × 3 × 13            | -0.00006      |
| 82/261     | 2 × 41                | 3 × 3 × 29                | +0.00002      |
| 224/713    | 2 × 2 × 2 × 2 × 2 × 7 | 23 × 31                   | +0.000005     |
| 437/1391   | 19 × 23               | 13 × 107                  | +0.000002     |
| 721/2295   | 7 × 103               | 3 × 3 × 3 × 5 × 17        | +0.000001     |
| 1360/4329  | 2 × 2 × 2 × 2395 × 17 | 3 × 3 × 13 × 53           | +0.0000003    |
| 1715/5459  | 5 × 7 × 7 × 7         | 53 × 103                  | +0.0000001    |
| 3927/12500 | 3 × 7 × 11 × 17       | 2 × 2 × 5 × 5 × 5 × 5 × 5 | 0             |

**Lathe Change-gears.**—To calculate the change gears to cut any pitch on a lathe, the “constant” of the machine must be known. For any lathe, the ratio  $C:L = \text{driver}:\text{driven gear}$ , in which  $C = \text{constant of machine}$  and  $L = \text{threads per inch}$ .

For example, to find the change gears required to cut 1.7345 threads per inch on a lathe having a constant of 4, the formula:

$$\frac{C}{L} = \frac{4}{1.7345} = 2.306140$$

may be used. The method of conjugate fractions shown on page 12 will find the ratio,  $113/49 = 2.306122$ , which is closer than any other having suitable factors. This ratio is in error by only  $2.306140 - 2.306122 = 0.000018$ . Therefore, the driver should have 113 teeth and the driven gear 49 teeth.

**Relieving Helical-Fluted Hobs.**—Relieving hobs that have been fluted at right angles to the thread is another example of approximating a required change-gear ratio. The usual method is to change the angle of the helical flutes to agree with previously calculated change-gears. The ratio between the hob and the relieving attachment is expressed in the formula:

$$\frac{N}{(C \times \cos^2 \alpha)} = \frac{\text{driver}}{\text{driven}} \text{ gears}$$

and

$$\tan \alpha = \frac{P}{H_c}$$

in which:  $N$  = number of flutes in hob;  $\alpha$  = helix angle of thread from plane perpendicular to axis;  $C$  = constant of relieving attachment;  $P$  = axial lead of hob; and  $H_c$  = hob pitch circumference, = 3.1416 times pitch diameter.

The constant of the relieving attachment is found on its index plate and is determined by the number of flutes that require equal gears on the change-gear studs. These values will vary with different makes of lathes.

For example, what four change-gears can be used to relieve a helical-fluted worm-gear hob, of 24 diametral pitch, six starts, 13 degrees, 41 minutes helix angle of thread, with eleven helical flutes, assuming a relieving attachment having a constant of 4 is to be used?

$$\frac{N}{(C \times \cos^2 \alpha)} = \frac{11}{(4 \times \cos^2 13^\circ 41')} = \frac{11}{(4 \times 0.944045)} = 2.913136$$

Using the conjugate fractions method discussed on page 12, the following ratios are found to provide factors that are successively closer approximations to the required change-gear ratio 2.913136.

| <i>Numerator/Denominator</i>    | <i>Ratio</i> | <i>Error</i> |
|---------------------------------|--------------|--------------|
| $67 \times 78 / (39 \times 46)$ | 2.913043     | -0.000093    |
| $30 \times 47 / (22 \times 22)$ | 2.913223     | +0.000087    |
| $80 \times 26 / (21 \times 34)$ | 2.913165     | +0.000029    |
| $27 \times 82 / (20 \times 38)$ | 2.913158     | +0.000021    |
| $55 \times 75 / (24 \times 59)$ | 2.913136     | +0.0000004   |
| $74 \times 92 / (57 \times 41)$ | 2.913136     | +0.00000005  |

**THREAD ROLLING**

Screw threads may be formed by rolling either by using some type of thread-rolling machine or by equipping an automatic screw machine or turret lathe with a suitable threading roll. If a thread-rolling machine is used, the unthreaded screw, bolt, or other "blank" is placed (either automatically or by hand) between dies having thread-shaped ridges that sink into the blank, and by displacing the metal, form a thread of the required shape and pitch. The thread-rolling process is applied where bolts, screws, studs, threaded rods, etc., are required in large quantities. Screw threads that are within the range of the rolling process may be produced more rapidly by this method than in any other way. Because of the cold-working action of the dies, the rolled thread is 10 to 20 per cent stronger than a cut or ground thread, and the increase may be much higher for fatigue resistance. Other advantages of the rolling process are that no stock is wasted in forming the thread, and the surface of a rolled thread is harder than that of a cut thread, thus increasing wear resistance.

**Thread-Rolling Machine of Flat-Die Type.**—One type of machine that is used extensively for thread rolling is equipped with a pair of flat or straight dies. One die is stationary and the other has a reciprocating movement when the machine is in use. The ridges on these dies, which form the screw thread, incline at an angle equal to the helix angle of the thread. In making dies for precision thread rolling, the threads may be formed either by milling and grinding after heat treatment, or by grinding "from the solid" after heat treating. A vitrified wheel is used.

In a thread-rolling machine, thread is formed in one passage of the work, which is inserted at one end of the dies, either by hand or automatically, and then rolls between the die faces until it is ejected at the opposite end. The relation between the position of the dies and a screw thread being rolled is such that the top of the thread-shaped ridge of one die, at the point of contact with the screw thread, is directly opposite the bottom of the thread groove in the other die at the point of contact. Some form of mechanism ensures starting the blank at the right time and square with the dies.

**Thread-Rolling Machine of Cylindrical-Die Type.**—With machines of this type, the blank is threaded while being rolled between two or three cylindrical dies (depending upon the type of machine) that are pressed into the blank at a rate of penetration adjusted to the hardness of the material, or wall thickness in threading operations on tubing or hollow parts. The dies have ground, or ground and lapped, threads and a pitch diameter that is a multiple of the pitch diameter of the thread to be rolled. As the dies are much larger in diameter than the work, a multiple thread is required to obtain the same lead angle as that of the work. The thread may be formed in one die revolution or even less, or several revolutions may be required (as in rolling hard materials) to obtain a gradual rate of penetration equivalent to that obtained with flat or straight dies if extended to a length of possibly 15 or 20 feet. Provisions for accurately adjusting or matching the thread rolls to bring them into proper alignment with each other are important features of these machines.

*Two-Roll Type of Machine:* With a two-roll type of machine, the work is rotated between two horizontal power-driven threading rolls and is supported by a hardened rest bar on the lower side. One roll is fed inward by hydraulic pressure to a depth that is governed automatically.

*Three-Roll Type of Machine:* With this machine, the blank to be threaded is held in a "floating position" while being rolled between three cylindrical dies that, through toggle arms, are moved inward at a predetermined rate of penetration until the required pitch diameter is obtained. The die movement is governed by a cam driven through change gears selected to give the required cycle of squeeze, dwell, and release.

**Rate of Production.**—Production rates in thread rolling depend upon the type of machine, the size of both machine and work, and whether the parts to be threaded are inserted by hand or automatically. A reciprocating flat die type of machine, applied to ordinary steels, may thread 30 or 40 parts per minute in diameters ranging from about  $\frac{3}{8}$  to  $1\frac{1}{8}$

inch, and 150 to 175 per minute in machine screw sizes from No. 10 (.190) to No. 6 (.138). In the case of heat-treated alloy steels in the usual hardness range of 26 to 32 Rockwell C, the production may be 30 or 40 per minute or less. With a cylindrical die type of machine, which is designed primarily for precision work and hard metals, 10 to 30 parts per minute are common production rates, the amount depending upon the hardness of material and allowable rate of die penetration per work revolution. These production rates are intended as a general guide only. The diameters of rolled threads usually range from the smallest machine screw sizes up to 1 or 1½ inches, depending upon the type and size of machine.

**Precision Thread Rolling.**—Both flat and cylindrical dies are used in aeronautical and other plants for precision work. With accurate dies and blank diameters held to close limits, it is practicable to produce rolled threads for American Standard Class 3 and Class 4 fits. The blank sizing may be by centerless grinding or by means of a die in conjunction with the heading operations. The blank should be round, and, as a general rule, the diameter tolerance should not exceed ½ to ⅔ the pitch diameter tolerance. The blank diameter should range from the correct size (which is close to the pitch diameter, but should be determined by actual trial), down to the allowable minimum, the tolerance being minus to insure a correct pitch diameter, even though the major diameter may vary slightly. Precision thread rolling has become an important method of threading alloy steel studs and other threaded parts, especially in aeronautical work where precision and high-fatigue resistance are required. Micrometer screws are also an outstanding example of precision thread rolling. This process has also been applied in tap making, although it is the general practice to finish rolled taps by grinding when the Class 3 and Class 4 fits are required.

**Steels for Thread Rolling.**—Steels vary from soft low-carbon types for ordinary screws and bolts, to nickel, nickel-chromium and molybdenum steels for aircraft studs, bolts, etc., or for any work requiring exceptional strength and fatigue resistance. Typical SAE alloy steels are No. 2330, 3135, 3140, 4027, 4042, 4640 and 6160. The hardness of these steels after heat-treatment usually ranges from 26 to 32 Rockwell C, with tensile strengths varying from 130,000 to 150,000 pounds per square inch. While harder materials might be rolled, grinding is more practicable when the hardness exceeds 40 Rockwell C. Thread rolling is applicable not only to a wide range of steels but for non-ferrous materials, especially if there is difficulty in cutting due to "tearing" the threads.

**Diameter of Blank for Thread Rolling.**—The diameter of the screw blank or cylindrical part upon which a thread is to be rolled should be less than the outside screw diameter by an amount that will just compensate for the metal that is displaced and raised above the original surface by the rolling process. The increase in diameter is approximately equal to the depth of one thread. While there are rules and formulas for determining blank diameters, it may be necessary to make slight changes in the calculated size in order to secure a well-formed thread. The blank diameter should be verified by trial, especially when rolling accurate screw threads. Some stock offers greater resistance to displacement than other stock, owing to the greater hardness or tenacity of the metal. The following figures may prove useful in establishing trial sizes. The blank diameters for screws varying from ¼ to ½ are from 0.002 to 0.0025 inch larger than the pitch diameter, and for screws varying from ½ to 1 inch or larger, the blank diameters are from 0.0025 to .003 inch larger than the pitch diameter. Blanks which are slightly less than the pitch diameter are intended for bolts, screws, etc., which are to have a comparatively free fit. Blanks for this class of work may vary from 0.002 to 0.003 inch less than the pitch diameter for screw thread sizes varying from ¼ to ½ inch, and from 0.003 to 0.005 inch less than the pitch diameter for sizes above ½ inch. If the screw threads are smaller than ¼ inch, the blanks are usually from 0.001 to 0.0015 inch less than the pitch diameter for ordinary grades of work.

**Thread Rolling in Automatic Screw Machines.**—Screw threads are sometimes rolled in automatic screw machines and turret lathes when the thread is behind a shoulder so that

it cannot be cut with a die. In such cases, the advantage of rolling the thread is that a second operation is avoided. A circular roll is used for rolling threads in screw machines. The roll may be presented to the work either in a tangential direction or radially, either method producing a satisfactory thread. In the former case, the roll gradually comes into contact with the periphery of the work and completes the thread as it passes across the surface to be threaded. When the roll is held in a radial position, it is simply forced against one side until a complete thread is formed. The method of applying the roll may depend upon the relation between the threading operation and other machining operations. Thread rolling in automatic screw machines is generally applied only to brass and other relatively soft metals, owing to the difficulty of rolling threads in steel. Thread rolls made of chrome-nickel steel containing from 0.15 to 0.20 per cent of carbon have given fairly good results, however, when applied to steel. A 3 per cent nickel steel containing about 0.12 per cent carbon has also proved satisfactory for threading brass.

**Factors Governing the Diameter of Thread Rolling.**—The threading roll used in screw machines may be about the same diameter as the screw thread, but for sizes smaller than, say,  $\frac{3}{4}$  inch, the roll diameter is some multiple of the thread diameter minus a slight amount to obtain a better rolling action. When the diameters of the thread and roll are practically the same, a single-threaded roll is used to form a single thread on the screw. If the diameter of the roll is made double that of the screw, in order to avoid using a small roll, then the roll must have a double thread. If the thread roll is three times the size of the screw thread, a triple thread is used, and so on. These multiple threads are necessary when the roll diameter is some multiple of the work, in order to obtain corresponding helix angles on the roll and work.

**Diameter of Threading Roll.**—The pitch diameter of a threading roll having a single thread is slightly less than the pitch diameter of the screw thread to be rolled, and in the case of multiple-thread rolls, the pitch diameter is not an exact multiple of the screw thread pitch diameter but is also reduced somewhat. The amount of reduction recommended by one screw machine manufacturer is given by the formula shown at the end of this paragraph. A description of the terms used in the formula is given as follows:  $D$  = pitch diameter of threading roll,  $d$  = pitch diameter of screw thread,  $N$  = number of single threads or "starts" on the roll (this number is selected with reference to diameter of roll desired),  $T$  = single depth of thread:

$$D = N\left(d - \frac{T}{2}\right) - T$$

*Example:* Find, by using above formula, the pitch diameter of a double-thread roll for rolling a  $\frac{1}{2}$ -inch American standard screw thread. Pitch diameter  $d = 0.4500$  inch and thread depth  $T = 0.0499$  inch.

$$D = 2\left(0.4500 - \frac{0.0499}{2}\right) - 0.0499 = 0.8001 \text{ inch}$$

**Kind of Thread on Roll and Its Shape.**—The thread (or threads) on the roll should be left hand for rolling a right-hand thread, and *vice versa*. The roll should be wide enough to overlap the part to be threaded, provided there are clearance spaces at the ends, which should be formed if possible. The thread on the roll should be sharp on top for rolling an American (National) standard form of thread, so that less pressure will be required to displace the metal when rolling the thread. The bottom of the thread groove on the roll may also be left sharp or it may have a flat. If the bottom is sharp, the roll is sunk only far enough into the blank to form a thread having a flat top, assuming that the thread is the American form. The number of threads on the roll (whether double, triple, quadruple, etc.) is selected, as a rule, so that the diameter of the thread roll will be somewhere between  $1\frac{1}{4}$  and  $2\frac{1}{4}$  inches. In making a thread roll, the ends are beveled at an angle of 45 degrees, to prevent

the threads on the ends of the roll from chipping. Precautions should be taken in hardening, because, if the sharp edges are burnt, the roll will be useless. Thread rolls are usually lapped after hardening, by holding them on an arbor in the lathe and using emery and oil on a piece of hard wood. To give good results a thread roll should fit closely in the holder. If the roll is made to fit loosely, it will mar the threads.

**Application of Thread Roll.**—The shape of the work and the character of the operations necessary to produce it, govern, to a large extent, the method employed in applying the thread roll. Some of the points to consider are as follows:

- 1) Diameter of the part to be threaded.
- 2) Location of the part to be threaded.
- 3) Length of the part to be threaded.
- 4) Relation that the thread rolling operation bears to the other operations.
- 5) Shape of the part to be threaded, whether straight, tapered or otherwise.
- 6) Method of applying the support.

When the diameter to be rolled is much smaller than the diameter of the shoulder preceding it, a cross-slide knurl-holder should be used. If the part to be threaded is not behind a shoulder, a holder on the swing principle should be used. When the work is long (greater in length than two-and-one-half times its diameter) a swing roll-holder should be employed, carrying a support. When the work can be cut off after the thread is rolled, a cross-slide roll-holder should be used. The method of applying the support to the work also governs to some extent the method of applying the thread roll. When no other tool is working at the same time as the thread roll, and when there is freedom from chips, the roll can be held more rigidly by passing it under instead of over the work. When passing the roll over the work, there is a tendency to raise the cross-slide. Where the part to be threaded is tapered, the roll can best be presented to the work by holding it in a cross-slide roll-holder.

**Speeds and Feeds for Thread Rolling.**—When the thread roll is made from high-carbon steel and used on brass, a surface speed as high as 200 feet per minute can be used. However, better results are obtained by using a lower speed than this. When the roll is held in a holder attached to the cross-slide, and is presented either tangentially or radially to the work, a considerably higher speed can be used than if it is held in a swing tool. This is due to the lack of rigidity in a holder of the swing type. The feeds to be used when a cross-slide roll-holder is used are given in the upper half of the table "Feeds for Thread Rolling;" the lower half of the table gives the feeds for thread rolling with swing tools. These feeds are applicable for rolling threads without a support, when the root diameter of the blank is not less than five times the double depth of the thread. When the root diameter is less than this, a support should be used. A support should also be used when the width of the roll is more than two-and-one-half times the smallest diameter of the piece to be rolled, irrespective of the pitch of the thread. When the smallest diameter of the piece to be rolled is much less than the root diameter of the thread, the smallest diameter should be taken as the deciding factor for the feed to be used.



## Feeds for Thread Rolling

| Root Diam.<br>of Blank | Number of Threads per Inch                          |        |        |        |        |        |        |        |        |        |        |        |        |        |
|------------------------|---|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                        | 72  | 64     | 56     | 48     | 44     | 40     | 36     | 32     | 28     | 24     | 22     | 20     | 18     | 14     |
|                        | Cross-slide Holders — Feed per Revolution in Inches |        |        |        |        |        |        |        |        |        |        |        |        |        |
| $\frac{1}{8}$          | 0.0045  | 0.0040 | 0.0035 | 0.0030 | 0.0025 | 0.0020 | 0.0015 | 0.0010 | .....  | .....  | .....  | .....  | .....  | .....  |
| $\frac{3}{16}$         | 0.0050  | 0.0045 | 0.0040 | 0.0035 | 0.0030 | 0.0025 | 0.0020 | 0.0015 | 0.0005 | .....  | .....  | .....  | .....  | .....  |
| $\frac{1}{4}$          | 0.0055  | 0.0050 | 0.0045 | 0.0040 | 0.0035 | 0.0030 | 0.0025 | 0.0020 | 0.0010 | 0.0005 | 0.0005 | .....  | .....  | .....  |
| $\frac{5}{16}$         | 0.0060  | 0.0055 | 0.0050 | 0.0045 | 0.0040 | 0.0035 | 0.0030 | 0.0025 | 0.0015 | 0.0010 | 0.0010 | 0.0005 | 0.0005 | .....  |
| $\frac{3}{8}$          | 0.0065  | 0.0060 | 0.0055 | 0.0050 | 0.0045 | 0.0040 | 0.0035 | 0.0030 | 0.0020 | 0.0015 | 0.0015 | 0.0010 | 0.0010 | 0.0005 |
| $\frac{7}{16}$         | 0.0070  | 0.0065 | 0.0060 | 0.0055 | 0.0050 | 0.0045 | 0.0040 | 0.0035 | 0.0025 | 0.0020 | 0.0020 | 0.0015 | 0.0015 | 0.0010 |
| $\frac{1}{2}$          | 0.0075  | 0.0070 | 0.0065 | 0.0060 | 0.0055 | 0.0050 | 0.0045 | 0.0040 | 0.0030 | 0.0025 | 0.0025 | 0.0020 | 0.0020 | 0.0015 |
| $\frac{5}{8}$          | 0.0080  | 0.0075 | 0.0070 | 0.0065 | 0.0060 | 0.0055 | 0.0050 | 0.0045 | 0.0035 | 0.0030 | 0.0030 | 0.0025 | 0.0025 | 0.0020 |
| $\frac{3}{4}$          | 0.0085  | 0.0080 | 0.0075 | 0.0070 | 0.0065 | 0.0060 | 0.0055 | 0.0050 | 0.0040 | 0.0035 | 0.0035 | 0.0030 | 0.0030 | 0.0025 |
| $\frac{7}{8}$          | 0.0090  | 0.0085 | 0.0080 | 0.0075 | 0.0070 | 0.0065 | 0.0060 | 0.0055 | 0.0045 | 0.0040 | 0.0040 | 0.0035 | 0.0035 | 0.0030 |
| 1                      | 0.0095  | 0.0090 | 0.0085 | 0.0080 | 0.0075 | 0.0070 | 0.0065 | 0.0060 | 0.0050 | 0.0045 | 0.0045 | 0.0040 | 0.0040 | 0.0035 |
| Root Diam.             | Swing Holders — Feed per Revolution in Inches       |        |        |        |        |        |        |        |        |        |        |        |        |        |
| $\frac{1}{8}$          | 0.0025  | 0.0020 | 0.0015 | 0.0010 | 0.0005 | .....  | .....  | .....  | .....  | .....  | .....  | .....  | .....  | .....  |
| $\frac{3}{16}$         | 0.0028  | 0.0025 | 0.0020 | 0.0015 | 0.0008 | 0.0005 | .....  | .....  | .....  | .....  | .....  | .....  | .....  | .....  |
| $\frac{1}{4}$          | 0.0030  | 0.0030 | 0.0025 | 0.0020 | 0.0010 | 0.0010 | 0.0005 | 0.0005 | 0.0005 | .....  | .....  | .....  | .....  | .....  |
| $\frac{5}{16}$         | 0.0035  | 0.0035 | 0.0030 | 0.0025 | 0.0015 | 0.0015 | 0.0010 | 0.0010 | 0.0010 | 0.0005 | .....  | .....  | .....  | .....  |
| $\frac{3}{8}$          | 0.0040  | 0.0040 | 0.0035 | 0.0030 | 0.0020 | 0.0020 | 0.0015 | 0.0015 | 0.0015 | 0.0010 | 0.0005 | 0.0005 | 0.0005 | .....  |
| $\frac{7}{16}$         | 0.0045  | 0.0045 | 0.0040 | 0.0035 | 0.0030 | 0.0025 | 0.0020 | 0.0020 | 0.0020 | 0.0015 | 0.0010 | 0.0010 | 0.0010 | .....  |
| $\frac{1}{2}$          | 0.0048  | 0.0048 | 0.0045 | 0.0040 | 0.0035 | 0.0030 | 0.0025 | 0.0025 | 0.0025 | 0.0020 | 0.0015 | 0.0015 | 0.0015 | 0.0005 |
| $\frac{5}{8}$          | 0.0050  | 0.0050 | 0.0048 | 0.0043 | 0.0040 | 0.0035 | 0.0030 | 0.0030 | 0.0028 | 0.0025 | 0.0020 | 0.0020 | 0.0018 | 0.0010 |
| $\frac{3}{4}$          | 0.0055  | 0.0052 | 0.0050 | 0.0045 | 0.0043 | 0.0040 | 0.0035 | 0.0035 | 0.0030 | 0.0028 | 0.0025 | 0.0022 | 0.0020 | 0.0013 |
| $\frac{7}{8}$          | 0.0058  | 0.0055 | 0.0052 | 0.0048 | 0.0045 | 0.0043 | 0.0040 | 0.0038 | 0.0032 | 0.0030 | 0.0028 | 0.0025 | 0.0022 | 0.0015 |
| 1                      | 0.0060  | 0.0058 | 0.0054 | 0.0050 | 0.0048 | 0.0047 | 0.0043 | 0.0040 | 0.0035 | 0.0032 | 0.0030 | 0.0028 | 0.0025 | 0.0018 |

## THREAD GRINDING

Thread grinding is employed for precision tool and gage work and also in producing certain classes of threaded parts.

Thread grinding may be utilized 1) because of the accuracy and finish obtained; 2) hardness of material to be threaded; and 3) economy in grinding certain classes of screw threads when using modern machines, wheels, and thread-grinding oils.

In some cases pre-cut threads are finished by grinding; but usually, threads are ground "from the solid," being formed entirely by the grinding process. Examples of work include thread gages and taps of steel and tungsten carbide, hobs, worms, lead-screws, adjusting or traversing screws, alloy steel studs, etc. Grinding is applied to external, internal, straight, and tapering threads, and to various thread forms.

**Accuracy Obtainable by Thread Grinding.**—With single-edge or single-ribbed wheels it is possible to grind threads on gages to a degree of accuracy that requires but very little lapping to produce a so-called "master" thread gage. As far as lead is concerned, some thread grinding machine manufacturers guarantee to hold the lead within 0.0001 inch per inch of thread; and while it is not guaranteed that a higher degree of accuracy for lead is obtainable, it is known that threads have been ground to closer tolerances than this on the lead. Pitch diameter accuracies for either Class 3 or Class 4 fits are obtainable according to the grinding method used; with single-edge wheels, the thread angle can be ground to an accuracy of within two or three minutes in half the angle.

**Wheels for Thread Grinding.**—The wheels used for steel have an aluminous abrasive and, ordinarily, either a resinoid bond or a vitrified bond. The general rule is to use resinoid wheels when extreme tolerances are not required, and it is desirable to form the thread with a minimum number of passes, as in grinding threaded machine parts, such as studs, adjusting screws which are not calibrated, and for some classes of taps. *Resinoid wheels*, as a rule, will hold a fine edge longer than a vitrified wheel but they are more flexible and, consequently, less suitable for accurate work, especially when there is lateral grinding pressure that causes wheel deflection. *Vitrified wheels* are utilized for obtaining extreme accuracy in thread form and lead because they are very rigid and not easily deflected by side pressure in grinding. This rigidity is especially important in grinding pre-cut threads on such work as gages, taps and lead-screws. The progressive lead errors in long lead-screws, for example, might cause an increasing lateral pressure that would deflect a resinoid wheel. Vitrified wheels are also recommended for internal grinding.

*Diamond Wheels:* Diamond wheels set in a rubber or plastic bond are also used for thread grinding, especially for grinding threads in carbide materials and in other hardened alloys. Thread grinding is now being done successfully on a commercial basis on both taps and gages made from carbides. Gear hobs made from carbides have also been tested with successful results. Diamond wheels are dressed by means of silicon-carbide grinding wheels which travel past the diamond-wheel thread form at the angle required for the flanks of the thread to be ground. The action of the dressing wheels is, perhaps, best described as a "scrubbing" of the bond which holds the diamond grits. Obviously, the silicon-carbide wheels do not dress the diamonds, but they loosen the bond until the diamonds not wanted drop out.

**Thread Grinding with Single-Edge Wheel.**—With this type of wheel, the edge is trued to the cross-sectional shape of the thread groove. The wheel, when new, may have a diameter of 18 or 20 inches and, when grinding a thread, the wheel is inclined to align it with the thread groove. On some machines, lead variations are obtained by means of change-gears which transmit motion from the work-driving spindle to the lead-screw. Other machines are so designed that a lead-screw is selected to suit the lead of thread to be ground and transmits motion directly to the work-driving spindle.

**Wheels with Edges for Roughing and Finishing.**—The “three-ribbed” type of wheel has a roughing edge or rib which removes about two-thirds of the metal. This is followed by an intermediate rib which leaves about 0.005 inch for the third or finishing rib. The accuracy obtained with this triple-edge type compares with that of a single-edge wheel, which means that it may be used for the greatest accuracy obtainable in thread grinding.

When the accuracy required makes it necessary, this wheel can be inclined to the helix angle of the thread, the same as is the single-edge wheel.

The three-ribbed wheel is recommended not only for precision work but for grinding threads which are too long for the multi-ribbed wheel referred to later. It is also well adapted to tap grinding, because it is possible to dress a portion of the wheel adjacent to the finish rib for the purpose of grinding the outside diameter of the thread, as indicated in Fig. 1. Furthermore, the wheel can be dressed for grinding or relieving both crests and flanks at the same time.

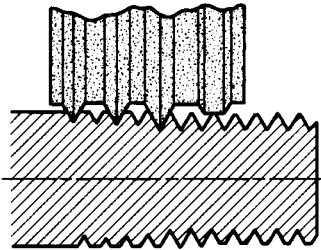


Fig. 1. Wheel with Edges for Roughing and Finishing

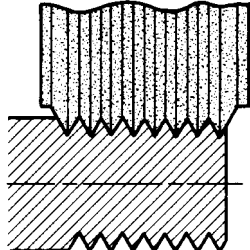


Fig. 2. Multi-ribbed Type of Thread-grinding Wheel

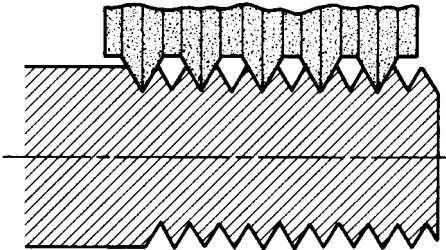


Fig. 3. Alternate-ribbed Wheel for Grinding the Finer Pitches

**Multi-ribbed Wheels.**—This type of wheel is employed when rapid production is more important than extreme accuracy, which means that it is intended primarily for the grinding of duplicate parts in manufacturing. A wheel  $1\frac{1}{4}$  to 2 inches wide has formed upon its face a series of annular thread-shaped ridges (see Fig. 2); hence, if the length of the thread is not greater than the wheel width, a thread may be ground in one work revolution plus about one-half revolution for feeding in and withdrawing the wheel. The principle of operation is the same as that of thread milling with a multiple type cutter. This type of wheel is not inclined to the lead angle. To obtain a Class 3 fit, the lead angle should not exceed 4 degrees.

It is not practicable to use this form of wheel on thread pitches where the root is less than 0.007 inch wide, because of difficulties in wheel dressing. When this method can be applied, it is the fastest means known of producing threads in hardened materials. It is not recommended, however, that thread gages, taps, and work of this character be ground with multi-ribbed wheels. The single-ribbed wheel has a definite field for accurate, small-lot production.

It is necessary, in multi-ribbed grinding, to use more horsepower than is required for single-ribbed wheel grinding. Coarse threads, in particular, may require a wheel motor with two or three times more horsepower than would be necessary for grinding with a single-ribbed wheel.

**Alternate-ribbed Wheel for Fine Pitches.**—The spacing of ribs on this type of wheel (Fig. 3) equals twice the pitch, so that during the first revolution every other thread groove section is being ground; consequently, about two and one-half work revolutions are required for grinding a complete thread, but the better distribution of cooling oil and resulting increase in work speeds makes this wheel very efficient. This alternate-type of wheel is adapted for grinding threads of fine pitch. Since these wheels cannot be tipped to the helix angle of the thread, they are not recommended for anything closer than Class 3 fits. The “three-ribbed” wheels referred to in a previous paragraph are also made in the alternate type for the finer pitches.

**Grinding Threads “from the Solid.”**—The process of forming threads entirely by grinding, or without preliminary cutting, is applied both in the manufacture of certain classes of threaded parts and also in the production of precision tools, such as taps and thread gages. For example, in airplane engine manufacture, certain parts are heat-treated and then the threads are ground “from the solid,” thus eliminating distortion. Minute cracks are sometimes found at the roots of threads that were cut and then hardened, or ground from the solid. Steel threads of coarse pitch that are to be surface hardened, may be rough threaded by cutting, then hardened and finally corrected by grinding. Many ground thread taps are produced by grinding from the solid after heat-treatment. Hardening high-speed steel taps before the thread is formed will make sure there are no narrow or delicate crests to interfere with the application of the high temperature required for uniform hardness and the best steel structure.

**Number of Wheel Passes.**—The number of cuts or passes for grinding from the solid depends upon the type of wheel and accuracy required. In general, threads of 12 or 14 per inch and finer may be ground in one pass of a single-edge wheel unless the “unwrapped” thread length is much greater than normal. Unwrapped length = pitch circumference  $\times$  total number of thread turns, approximately. For example, a thread gage  $1\frac{1}{4}$  inches long with 24 threads per inch would have an unwrapped length equal to  $30 \times$  pitch circumference. (If more convenient, outside circumference may be used instead of pitch circumference.) Assume that there are 6 or 7 feet of unwrapped length on a screw thread having 12 threads per inch. In this case, one pass might be sufficient for a Class 3 fit, whereas two passes might be recommended for a Class 4 fit. When two passes are required, too deep a roughing cut may break down the narrow edge of the wheel. To prevent this, try a roughing cut depth equal to about two-thirds the total thread depth, thus leaving one-third for the finishing cut.

**Wheel and Work Rotation.**—When a screw thread, on the side being ground, is moving *upward* or *against* the grinding wheel rotation, less heat is generated and the grinding operation is more efficient than when wheel and work are moving in the same direction on the grinding side; however, to avoid running a machine idle during its return stroke, many screw threads are ground during both the forward and return traversing movements, by reversing the work rotation at the end of the forward stroke. For this reason, thread grinders generally are equipped so that both forward and return work speeds may be changed; they may also be designed to accelerate the return movement when grinding in one direction only.

**Wheel Speeds.**—Wheel speeds should always be limited to the maximum specified on the wheel by the manufacturer. According to the American National Standard Safety Code, resinoid and vitrified wheels are limited to 12,000 surface feet per minute; however, according to Norton Co., the most efficient speeds are from 9,000 to 10,000 for resinoid wheels and 7,500 to 9,500 for vitrified wheels. Only tested wheels recommended by the wheel manufacturer should be used. After a suitable surface speed has been established, it should be maintained by increasing the rpm of the wheel, as the latter is reduced in diameter by wear.

Since thread grinding wheels work close to the limit of their stock-removing capacity, some adjustment of the wheel or work speed may be required to get the best results. If the wheel speed is too slow for a given job and excessive heat is generated, try an increase in speed, assuming that such increase is within the safety limits. If the wheel is too soft and the edge wears excessively, again an increase in wheel speed will give the effect of a harder wheel and result in better form-retaining qualities.

**Work Speeds.**—The work speed usually ranges from 3 to 10 feet per minute. In grinding with a comparatively heavy feed, and a minimum number of passes, the speed may not exceed  $2\frac{1}{2}$  or 3 feet per minute. If very light feeds are employed, as in grinding hardened high-speed steel, the work speed may be much higher than 3 feet per minute and should be determined by test. If excessive heat is generated by removing stock too rapidly, a work speed reduction is one remedy. If a wheel is working below its normal capacity, an increase in work speed would prevent dulling of the grains and reduce the tendency to heat or "burn" the work. An increase in work speed and reduction in feed may also be employed to prevent burning while grinding hardened steel.

**Truing Grinding Wheels.**—Thread grinding wheels are trued both to maintain the required thread form and also an efficient grinding surface. Thread grinders ordinarily are equipped with precision truing devices which function automatically. One type automatically dresses the wheel and also compensates for the slight amount removed in dressing, thus automatically maintaining size control of the work. While truing the wheel, a small amount of grinding oil should be used to reduce diamond wear. Light truing cuts are advisable, especially in truing resinoid wheels which may be deflected by excessive truing pressure. A master former for controlling the path followed by the truing diamond may require a modified profile to prevent distortion of the thread form, especially when the lead angles are comparatively large. Such modification usually is not required for 60-degree threads when the pitches for a given diameter are standard because then the resulting lead angles are less than  $4\frac{1}{2}$  degrees. In grinding Acme threads or 29-degree worm threads having lead angles greater than 4 or 5 degrees, modified formers may be required to prevent a bulge in the thread profile. The highest point of this bulge is approximately at the pitch line. A bulge of about 0.001 inch may be within allowable limits on some commercial worms but precision worms for gear hobbers, etc., require straight flanks in the axial plane.

*Crushing Method:* Thread grinding wheels are also dressed or formed by the crushing method, which is used in connection with some types of thread grinding machines. When this method is used, the annular ridge or ridges on the wheel are formed by a hardened steel cylindrical dresser or crusher. The crusher has a series of smooth annular ridges which are shaped and spaced like the thread that is to be ground. During the wheel dressing operation, the crusher is positively driven instead of the grinding wheel, and the ridges on the wheel face are formed by the rotating crusher being forced inward.

**Wheel Hardness or Grade.**—Wheel hardness or grade selection is based upon a compromise between efficient cutting and durability of the grinding edge. Grade selection depends on the bond and the character of the work. The following general recommendations are based upon Norton grading.

Vitrified wheels usually range from J to M, and resinoid wheels from R to U. For heat-treated screws or studs and the Unified Standard Thread, try the following. For 8 to 12

threads per inch, grade S resinoid wheel; for 14 to 20 threads per inch, grade T resinoid; for 24 threads per inch and finer, grades T or U resinoid. For high-speed steel taps 4 to 12 threads per inch, grade J vitrified or S resinoid; 14 to 20 threads per inch, grade K vitrified or T resinoid; 24 to 36 threads per inch, grade M vitrified or T resinoid.

**Grain Size.**—A thread grinding wheel usually operates close to its maximum stock-removing capacity, and the narrow edge which forms the root of the thread is the most vulnerable part. In grain selection, the general rule is to use the coarsest grained wheel that will hold its form while grinding a reasonable amount of work. Pitch of thread and quality of finish are two governing factors. Thus, to obtain an exceptionally fine finish, the grain size might be smaller than is needed to retain the edge profile. The usual grain sizes range from 120 to 150. For heat-treated screws and studs with Unified Standard Threads, 100 to 180 is the usual range. For precision screw threads of very fine pitch, the grain size may range from 220 to 320. For high-speed steel taps, the usual range is from 150 to 180 for Unified Standard Threads, and from 80 to 150 for pre-cut Acme threads.

**Thread Grinding by Centerless Method.**—Screw threads may be ground from the solid by the centerless method. A centerless thread grinder is similar in its operating principle to a centerless grinder designed for general work, in that it has a grinding wheel, a regulating or feed wheel (with speed adjustments), and a work-rest. Adjustments are provided to accommodate work of different sizes and for varying the rates of feed. The grinding wheel is a multi-ribbed type, being a series of annular ridges across the face. These ridges conform in pitch and profile with the thread to be ground. The grinding wheel is inclined to suit the helix or lead angle of the thread. In grinding threads on such work as socket type set-screws, the blanks are fed automatically and passed between the grinding and regulating wheels in a continuous stream. To illustrate production possibilities, hardened socket set-screws of  $\frac{1}{4}$  20 size may be ground from the solid at the rate of 60 to 70 per minute and with the wheel operating continuously for 8 hours without redressing. The lead errors of centerless ground screw threads may be limited to 0.0005 inch per inch or even less by reducing the production rate. The pitch diameter tolerances are within 0.0002 to 0.0003 inch of the basic size. The grain size for the wheel is selected with reference to the pitch of the thread, the following sizes being recommended: For 11 to 13 threads per inch, 150; for 16 threads per inch, 180; for 18 to 20 threads per inch, 220; for 24 to 28 threads per inch, 320; for 40 threads per inch, 400.

**THREAD MILLING**

**Single-cutter Method.**—Usually, when a single point cutter is used, the axis of the cutter is inclined an amount equal to the lead angle of the screw thread, in order to locate the cutter in line with the thread groove at the point where the cutting action takes place. Tangent of lead angle = lead of screw thread ÷ pitch circumference of screw.

The helical thread groove is generated by making as many turns around the workpiece diameter as there are pitches in the length of thread to be cut. For example, a 16-pitch thread, 1 inch long, would require 16 turns of the cutter around the work. The single cutter process is especially applicable to the milling of large screw threads of coarse pitch, and either single or multiple threads.

The cutter should revolve as fast as possible without dulling the cutting edges excessively, in order to mill a smooth thread and prevent the unevenness that would result with a slow-moving cutter, on account of the tooth spaces. As the cutter rotates, the part on which a thread is to be milled is also revolved, but at a very slow rate (a few inches per minute), since this rotation of the work is practically a feeding movement. The cutter is ordinarily set to the full depth of the thread groove and finishes a single thread in one passage, although deep threads of coarse pitch may require two or even three cuts. For fine pitches and short threads, the multiple-cutter method (described in the next paragraph) usually is preferable, because it is more rapid. The milling of taper screw threads may be done on a single-cutter type of machine by traversing the cutter laterally as it feeds along in a lengthwise direction, the same as when using a taper attachment on a lathe.

**Multiple-cutter Method.**—The multiple cutter for thread milling is practically a series of single cutters, although formed of one solid piece of steel, at least so far as the cutter proper is concerned. The rows of teeth do not lie in a helical path, like the teeth of a hob or tap, but they are annular or without lead. If the cutter had helical teeth the same as a gear hob, it would have to be geared to revolve in a certain fixed ratio with the screw being milled, but a cutter having annular teeth may rotate at any desired cutting speed, while the screw blank is rotated slowly to provide a suitable rate of feed. (The multiple thread milling cutters used are frequently called "hobs," but the term hob should be applied only to cutters having a helical row of teeth like a gear-cutting hob.)

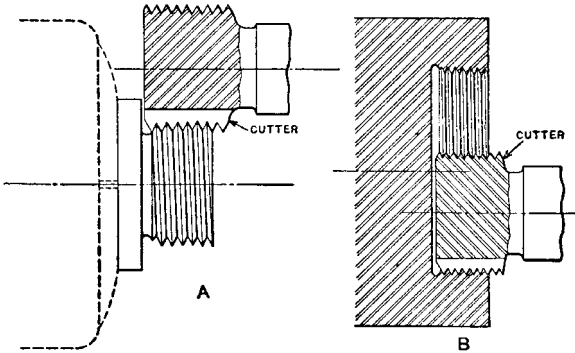
The object in using a multiple cutter instead of a single cutter is to finish a screw thread complete in approximately one revolution of the work, a slight amount of over-travel being allowed to insure milling the thread to the full depth where the end of cut joins the starting point. The cutter which is at least one and one half or two threads or pitches wider than the thread to be milled, is fed in to the full thread depth and then either the cutter or screw blank is moved in a lengthwise direction a distance equal to the lead of the thread during one revolution of the work.

The multiple cutter is used for milling comparatively short threads and coarse, medium or fine pitches. The accompanying illustration shows typical examples of external and internal work for which the multiple-cutter type of thread milling has proved very efficient, although its usefulness is not confined to shoulder work and "blind" holes.

In using multiple cutters either for internal or external thread milling, the axis of the cutter is set parallel with the axis of the work, instead of inclining the cutter to suit the lead angle of the thread, as when using a single cutter. Theoretically, this is not the correct position for a cutter, since each cutting edge is revolving in a plane at right angles to the screw's axis while milling a thread groove of helical form. However, as a general rule, interference between the cutter and the thread, does not result a decided change in the standard thread form.

Usually the deviation is very slight and may be disregarded except when milling threads which incline considerably relative to the axis like a thread of multiple form and large lead angle. Multiple cutters are suitable for external threads having lead angles under  $3\frac{1}{2}$

degrees and for internal threads having lead angles under  $2\frac{1}{2}$  degrees. Threads which have steeper sides or smaller included angles than the American Standard or Whitworth forms have greater limitations on the maximum helix angle and may have to be milled with a single point cutter tilted to the helix angle, assuming that the milling process is preferable to other methods. For instance, in milling an Acme thread which has an included angle between the sides of 29 degrees, there might be considerable interference if a multiple cutter were used, unless the screw thread diameter were large enough in proportion to the pitch to prevent such interference. If an attempt were made to mill a square thread with a multiple cutter, the results would be unsatisfactory owing to the interference.



Examples of External and Internal Thread Milling  
with a Multiple Thread Milling Cutter

Interference between the cutter and work is more pronounced when milling internal threads, because the cutter does not clear itself so well. It is preferable to use as small a cutter as practicable, either for internal or external work, not only to avoid interference, but to reduce the strain on the driving mechanism. Some thread milling cutters, known as "topping cutters," are made for milling the outside diameter of the thread as well as the angular sides and root, but most are made non-tapping.

**Planetary Method.**—The planetary method of thread milling is similar in principle to planetary milling. The part to be threaded is held stationary and the thread milling cutter, while revolving about its own axis, is given a planetary movement around the work in order to mill the thread in one planetary revolution. The machine spindle and the cutter which is held by it is moved longitudinally for thread milling, an amount equal to the thread lead during one planetary revolution. This operation is applicable to both internal and external threads. Other advantages: Thread milling is frequently accompanied by milling operations on other adjoining surfaces, and may be performed with conventional and planetary methods. For example, a machine may be used for milling a screw thread and a concentric cylindrical surface simultaneously. When the milling operation begins, the cutter-spindle feeds the cutter in to the right depth and the planetary movement then begins, thus milling the thread and the cylindrical surface. Thin sharp starting edges are eliminated on threads milled by this method and the thread begins with a smooth gradual approach. One design of machine will mill internal and external threads simultaneously. These threads may be of the same hand or one may be right hand and the other left hand. The threads may also be either of the same pitch or of a different pitch, and either straight or tapered.

**Classes of Work for Thread Milling Machines.**—Thread milling machines are used in preference to lathes or taps and dies for certain threading operations.



There are four general reasons why a thread milling machine may be preferred: 1) Because the pitch of the thread is too coarse for cutting with a die; 2) because the milling process is more efficient than using a single-point tool in a lathe; 3) to secure a smoother and more accurate thread than would be obtained with a tap or die; and 4) because the thread is so located relative to a shoulder or other surface that the milling method is superior, if not the only practicable way.

A thread milling machine having a single cutter is especially adapted for coarse pitches, multiple-threaded screws, or any form or size of thread requiring the removal of a relatively large amount of metal, particularly if the pitch of the thread is large in proportion to the screw diameter, since the torsional strain due to the milling process is relatively small. Thread milling often gives a higher rate of production, and a thread is usually finished by means of a single turn of the multiple thread milling cutter around the thread diameter. The multiple-cutter type of thread milling machine frequently comes into competition with dies and taps, and especially self-opening dies and collapsing taps. The use of a multiple cutter is desirable when a thread must be cut close to a shoulder or to the bottom of a shallow recess, although the usefulness of the multiple cutter is not confined to shoulder work and "blind" holes.

**Maximum Pitches of Die-cut Threads.**—Dies of special design could be constructed for practically any pitch, if the screw blank were strong enough to resist the cutting strains and the size and cost of the die were immaterial; but, as a general rule, when the pitch is coarser than four or five threads per inch, the difficulty of cutting threads with dies increases rapidly, although in a few cases some dies are used successfully on screw threads having two or three threads per inch or less. Much depends upon the design of the die, the finish or smoothness required, and the relation between the pitch of the thread and the diameter of the screw. When the screw diameter is relatively small in proportion to the pitch, there may be considerable distortion due to the twisting strains set up when the thread is being cut. If the number of threads per inch is only one or two less than the standard number for a given diameter, a screw blank ordinarily will be strong enough to permit the use of a die.

**Changing Pitch of Screw Thread Slightly.**—A very slight change in the pitch of a screw thread may be necessary as, for example, when the pitch of a tap is increased a small amount to compensate for shrinkage in hardening. One method of obtaining slight variations in pitch is by means of a taper attachment. This attachment is set at an angle and the work is located at the same angle by adjusting the tailstock center. The result is that the tool follows an angular path relative to the movement of the carriage and, consequently, the pitch of the thread is increased slightly, the amount depending upon the angle to which the work and taper attachment are set. The cosine of this angle, for obtaining a given increase in pitch, equals the standard pitch (which would be obtained with the lathe used in the regular way) divided by the increased pitch necessary to compensate for shrinkage.

*Example:* If the pitch of a  $\frac{3}{4}$ -inch American standard screw is to be increased from 0.100 to 0.1005, the cosine of the angle to which the taper attachment and work should be set is found as follows:

$$\text{Cosine of required angle} = \frac{0.100}{0.1005} = 0.9950$$

which is the cosine of 5 degrees 45 minutes, nearly.

### Change Gears for Helical Milling

**Lead of a Milling Machine.**—If gears with an equal number of teeth are placed on the table feed-screw and the worm-gear stud, then the *lead of the milling machine* is the distance the table will travel while the index spindle makes one complete revolution. This distance is a constant used in figuring the change gears.

The lead of a helix or "spiral" is the distance, measured along the axis of the work, in which the helix makes one full turn around the work. The lead of the milling machine may, therefore, also be expressed as the lead of the helix that will be cut when gears with an equal number of teeth are placed on the feed-screw and the worm-gear stud, and an idler of suitable size is interposed between the gears.

*Rule:* To find the lead of a milling machine, place equal gears on the worm-gear stud and on the feed-screw, and multiply the number of revolutions made by the feed-screw to produce one revolution of the index head spindle, by the lead of the thread on the feed-screw. Expressing the rule given as a formula:

$$\text{lead of milling machine} = \frac{\text{rev. of feed-screw for one revolution of index spindle with equal gears}}{\text{lead of feed-screw}}$$

Assume that it is necessary to make 40 revolutions of the feed-screw to turn the index head spindle one complete revolution, when the gears are equal, and that the lead of the thread on the feed-screw of the milling machine is  $\frac{1}{4}$  inch; then the lead of the machine equals  $40 \times \frac{1}{4}$  inch = 10 inches.

**Change Gears for Helical Milling.**—To find the change gears to be used in the compound train of gears for helical milling, place the lead of the helix to be cut in the numerator and the lead of the milling machine in the denominator of a fraction; divide numerator and denominator into two factors each; and multiply each "pair" of factors by the *same* number until suitable numbers of teeth for the change gears are obtained. (One factor in the numerator and one in the denominator are considered as one "pair" in this calculation.)

*Example:* Assume that the lead of a machine is 10 inches, and that a helix having a 48-inch lead is to be cut. Following the method explained:

$$\frac{48}{10} = \frac{6 \times 8}{2 \times 5} = \frac{(6 \times 12) \times (8 \times 8)}{(2 \times 12) \times (5 \times 8)} = \frac{72 \times 64}{24 \times 40}$$

The gear having 72 teeth is placed on the worm-gear stud and meshes with the 24-tooth gear on the intermediate stud. On the same intermediate stud is then placed the gear having 64 teeth, which is driven by the gear having 40 teeth placed on the feed-screw. This makes the gears having 72 and 64 teeth the driven gears, and the gears having 24 and 40 teeth the driving gears. In general, for compound gearing, the following formula may be used:

$$\frac{\text{lead of helix to be cut}}{\text{lead of machine}} = \frac{\text{product of driven gears}}{\text{product of driving gears}}$$

**Short-lead Milling.**—If the lead to be milled is exceptionally short, the drive may be direct from the table feed-screw to the dividing head spindle to avoid excessive load on feed-screw and change-gears. If the table feed-screw has 4 threads per inch (usual standard), then

$$\text{Change-gear ratio} = \frac{\text{Lead to be milled}}{0.25} = \frac{\text{Driven gears}}{\text{Driving gears}}$$

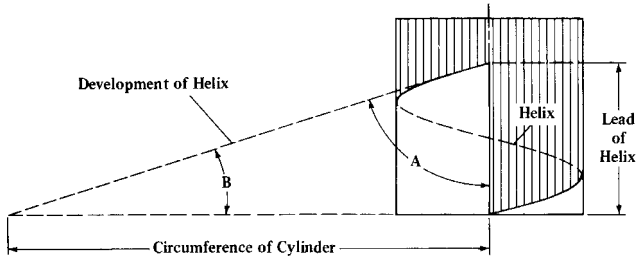
For indexing, the number of teeth on the spindle change-gear should be some multiple of the number of divisions required, to permit indexing by disengaging and turning the gear.

**Helix.**—A helix is a curve generated by a point moving about a cylindrical surface (real or imaginary) at a constant rate in the direction of the cylinder's axis. The curvature of a screw thread is one common example of a helical curve.

*Lead of Helix:* The lead of a helix is the distance that it advances in an axial direction, in one complete turn about the cylindrical surface. To illustrate, the lead of a screw thread

equals the distance that a thread advances in one turn; it also equals the distance that a nut would advance in one turn.

*Development of Helix:* If one turn of a helical curve were unrolled onto a plane surface (as shown by diagram), the helix would become a straight line forming the hypotenuse of a right angle triangle. The length of one side of this triangle would equal the circumference of the cylinder with which the helix coincides, and the length of the other side of the triangle would equal the lead of the helix.



**Helix Angles.**—The triangular development of a helix has one angle  $A$  subtended by the circumference of the cylinder, and another angle  $B$  subtended by the lead of the helix. The term “helix angle” applies to angle  $A$ . For example, the helix angle of a helical gear, according to the general usage of the term, is always angle  $A$ , because this is the angle used in helical gear-designing formulas. Helix angle  $A$  would also be applied in milling the helical teeth of cutters, reamers, etc. Angle  $A$  of a gear or cutter tooth is a measure of its inclination relative to the axis of the gear or cutter.

*Lead Angle:* Angle  $B$  is applied to screw threads and worm threads and is referred to as the lead angle of the screw thread or worm. This angle  $B$  is a measure of the inclination of a screw thread from a plane that is perpendicular to the screw thread axis. Angle  $B$  is called the “lead angle” because it is subtended by the lead of the thread, and to distinguish it from the term “helix angle” as applied to helical gears.

*Finding Helix Angle of Helical Gear:* A helical gear tooth has an infinite number of helix angles, but the angle at the pitch diameter or mid-working depth is the one required in gear designing and gear cutting. This angle  $A$ , relative to the axis of the gear, is found as follows:

$$\tan \text{ helix angle} = \frac{3.1416 \times \text{pitch diameter of gear}}{\text{Lead of gear tooth}}$$

*Finding Lead Angle of Screw Thread:* The lead or helix angle at the pitch diameter of a screw thread usually is required when, for example, a thread milling cutter must be aligned with the thread. This angle measured from a plane perpendicular to the screw thread axis, is found as follows:

$$\tan \text{ lead angle} = \frac{\text{Lead of screw thread}}{3.1416 \times \text{pitch diameter of screw thread}}$$

## Change Gears for Different Leads—0.670 Inch to 2.658 Inches

| Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        |
|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|
|                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |
| 0.670          | 24           | 86                 | 24                  | 100           | 1.711          | 28           | 72                 | 44                  | 100           | 2.182          | 24           | 44                 | 40                  | 100           |
| 0.781          | 24           | 86                 | 28                  | 100           | 1.714          | 24           | 56                 | 40                  | 100           | 2.188          | 24           | 48                 | 28                  | 64            |
| 0.800          | 24           | 72                 | 24                  | 100           | 1.744          | 24           | 64                 | 40                  | 86            | 2.193          | 24           | 56                 | 44                  | 86            |
| 0.893          | 24           | 86                 | 32                  | 100           | 1.745          | 24           | 44                 | 32                  | 100           | 2.200          | 24           | 48                 | 44                  | 100           |
| 0.930          | 24           | 72                 | 24                  | 86            | 1.750          | 28           | 64                 | 40                  | 100           | 2.222          | 24           | 48                 | 32                  | 72            |
| 1.029          | 24           | 56                 | 24                  | 100           | 1.776          | 24           | 44                 | 28                  | 86            | 2.233          | 40           | 86                 | 48                  | 100           |
| 1.042          | 28           | 86                 | 32                  | 100           | 1.778          | 32           | 72                 | 40                  | 100           | 2.238          | 28           | 64                 | 44                  | 86            |
| 1.047          | 24           | 64                 | 24                  | 86            | 1.786          | 24           | 86                 | 64                  | 100           | 2.240          | 28           | 40                 | 32                  | 100           |
| 1.050          | 24           | 64                 | 28                  | 100           | 1.800          | 24           | 64                 | 48                  | 100           | 2.250          | 24           | 40                 | 24                  | 64            |
| 1.067          | 24           | 72                 | 32                  | 100           | 1.809          | 28           | 72                 | 40                  | 86            | 2.274          | 32           | 72                 | 44                  | 86            |
| 1.085          | 24           | 72                 | 28                  | 86            | 1.818          | 24           | 44                 | 24                  | 72            | 2.286          | 32           | 56                 | 40                  | 100           |
| 1.116          | 24           | 86                 | 40                  | 100           | 1.823          | 28           | 86                 | 56                  | 100           | 2.292          | 24           | 64                 | 44                  | 72            |
| 1.196          | 24           | 56                 | 24                  | 86            | 1.860          | 28           | 56                 | 32                  | 86            | 2.326          | 32           | 64                 | 40                  | 86            |
| 1.200          | 24           | 48                 | 24                  | 100           | 1.861          | 24           | 72                 | 48                  | 86            | 2.333          | 28           | 48                 | 40                  | 100           |
| 1.221          | 24           | 64                 | 28                  | 86            | 1.867          | 28           | 48                 | 32                  | 100           | 2.338          | 24           | 44                 | 24                  | 56            |
| 1.228          | 24           | 86                 | 44                  | 100           | 1.875          | 24           | 48                 | 24                  | 64            | 2.344          | 28           | 86                 | 72                  | 100           |
| 1.240          | 24           | 72                 | 32                  | 86            | 1.886          | 24           | 56                 | 44                  | 100           | 2.368          | 28           | 44                 | 32                  | 86            |
| 1.250          | 24           | 64                 | 24                  | 72            | 1.905          | 24           | 56                 | 32                  | 72            | 2.381          | 32           | 86                 | 64                  | 100           |
| 1.302          | 28           | 86                 | 40                  | 100           | 1.919          | 24           | 64                 | 44                  | 86            | 2.386          | 24           | 44                 | 28                  | 64            |
| 1.309          | 24           | 44                 | 24                  | 100           | 1.920          | 24           | 40                 | 32                  | 100           | 2.392          | 24           | 56                 | 48                  | 86            |
| 1.333          | 24           | 72                 | 40                  | 100           | 1.925          | 28           | 64                 | 44                  | 100           | 2.400          | 28           | 56                 | 48                  | 100           |
| 1.340          | 24           | 86                 | 48                  | 100           | 1.944          | 24           | 48                 | 28                  | 72            | 2.424          | 24           | 44                 | 32                  | 72            |
| 1.371          | 24           | 56                 | 32                  | 100           | 1.954          | 24           | 40                 | 28                  | 86            | 2.431          | 28           | 64                 | 40                  | 72            |
| 1.395          | 24           | 48                 | 24                  | 86            | 1.956          | 32           | 72                 | 44                  | 100           | 2.442          | 24           | 32                 | 28                  | 86            |
| 1.400          | 24           | 48                 | 28                  | 100           | 1.990          | 28           | 72                 | 44                  | 86            | 2.445          | 40           | 72                 | 44                  | 100           |
| 1.429          | 24           | 56                 | 24                  | 72            | 1.993          | 24           | 56                 | 40                  | 86            | 2.450          | 28           | 64                 | 56                  | 100           |
| 1.440          | 24           | 40                 | 24                  | 100           | 2.000          | 24           | 40                 | 24                  | 72            | 2.456          | 44           | 86                 | 48                  | 100           |
| 1.458          | 24           | 64                 | 28                  | 72            | 2.009          | 24           | 86                 | 72                  | 100           | 2.481          | 32           | 72                 | 48                  | 86            |
| 1.467          | 24           | 72                 | 44                  | 100           | 2.030          | 24           | 44                 | 32                  | 86            | 2.489          | 32           | 72                 | 56                  | 100           |
| 1.488          | 32           | 86                 | 40                  | 100           | 2.035          | 28           | 64                 | 40                  | 86            | 2.500          | 24           | 48                 | 28                  | 56            |
| 1.500          | 24           | 64                 | 40                  | 100           | 2.036          | 28           | 44                 | 32                  | 100           | 2.514          | 32           | 56                 | 44                  | 100           |
| 1.522          | 24           | 44                 | 24                  | 86            | 2.045          | 24           | 44                 | 24                  | 64            | 2.532          | 28           | 72                 | 56                  | 86            |
| 1.550          | 24           | 72                 | 40                  | 86            | 2.047          | 40           | 86                 | 44                  | 100           | 2.537          | 24           | 44                 | 40                  | 86            |
| 1.563          | 24           | 86                 | 56                  | 100           | 2.057          | 24           | 28                 | 24                  | 100           | 2.546          | 28           | 44                 | 40                  | 100           |
| 1.595          | 24           | 56                 | 32                  | 86            | 2.067          | 32           | 72                 | 40                  | 86            | 2.558          | 32           | 64                 | 44                  | 86            |
| 1.600          | 24           | 48                 | 32                  | 100           | 2.083          | 24           | 64                 | 40                  | 72            | 2.567          | 28           | 48                 | 44                  | 100           |
| 1.607          | 24           | 56                 | 24                  | 64            | 2.084          | 28           | 86                 | 64                  | 100           | 2.571          | 24           | 40                 | 24                  | 56            |
| 1.628          | 24           | 48                 | 28                  | 86            | 2.093          | 24           | 64                 | 48                  | 86            | 2.593          | 28           | 48                 | 32                  | 72            |
| 1.637          | 32           | 86                 | 44                  | 100           | 2.100          | 24           | 64                 | 56                  | 100           | 2.605          | 28           | 40                 | 32                  | 86            |
| 1.650          | 24           | 64                 | 44                  | 100           | 2.121          | 24           | 44                 | 28                  | 72            | 2.618          | 24           | 44                 | 48                  | 100           |
| 1.667          | 24           | 56                 | 28                  | 72            | 2.133          | 24           | 72                 | 64                  | 100           | 2.619          | 24           | 56                 | 44                  | 72            |
| 1.674          | 24           | 40                 | 24                  | 86            | 2.143          | 24           | 56                 | 32                  | 64            | 2.625          | 24           | 40                 | 28                  | 64            |
| 1.680          | 24           | 40                 | 28                  | 100           | 2.171          | 24           | 72                 | 56                  | 86            | 2.640          | 24           | 40                 | 44                  | 100           |
| 1.706          | 24           | 72                 | 44                  | 86            | 2.178          | 28           | 72                 | 56                  | 100           | 2.658          | 32           | 56                 | 40                  | 86            |

## Change Gears for Different Leads—2.667 Inches to 4.040 Inches

| Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        |
|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|
|                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |
| 2.667          | 40           | 72                 | 48                  | 100           | 3.140          | 24           | 86                 | 72                  | 64            | 3.588          | 72           | 56                 | 24                  | 86            |
| 2.674          | 28           | 64                 | 44                  | 72            | 3.143          | 40           | 56                 | 44                  | 100           | 3.600          | 72           | 48                 | 24                  | 100           |
| 2.678          | 24           | 56                 | 40                  | 64            | 3.150          | 28           | 100                | 72                  | 64            | 3.618          | 56           | 72                 | 40                  | 86            |
| 2.679          | 32           | 86                 | 72                  | 100           | 3.175          | 32           | 56                 | 40                  | 72            | 3.636          | 24           | 44                 | 32                  | 48            |
| 2.700          | 24           | 64                 | 72                  | 100           | 3.182          | 28           | 44                 | 32                  | 64            | 3.637          | 48           | 44                 | 24                  | 72            |
| 2.713          | 28           | 48                 | 40                  | 86            | 3.189          | 32           | 56                 | 48                  | 86            | 3.646          | 40           | 48                 | 28                  | 64            |
| 2.727          | 24           | 44                 | 32                  | 64            | 3.190          | 24           | 86                 | 64                  | 56            | 3.655          | 40           | 56                 | 44                  | 86            |
| 2.743          | 24           | 56                 | 64                  | 100           | 3.198          | 40           | 64                 | 44                  | 86            | 3.657          | 64           | 56                 | 32                  | 100           |
| 2.750          | 40           | 64                 | 44                  | 100           | 3.200          | 28           | 100                | 64                  | 56            | 3.663          | 72           | 64                 | 28                  | 86            |
| 2.778          | 32           | 64                 | 40                  | 72            | 3.214          | 24           | 56                 | 48                  | 64            | 3.667          | 40           | 48                 | 44                  | 100           |
| 2.791          | 28           | 56                 | 48                  | 86            | 3.225          | 24           | 100                | 86                  | 64            | 3.673          | 24           | 28                 | 24                  | 56            |
| 2.800          | 24           | 24                 | 28                  | 100           | 3.241          | 28           | 48                 | 40                  | 72            | 3.684          | 44           | 86                 | 72                  | 100           |
| 2.812          | 24           | 32                 | 24                  | 64            | 3.256          | 24           | 24                 | 28                  | 86            | 3.686          | 86           | 56                 | 24                  | 100           |
| 2.828          | 28           | 44                 | 32                  | 72            | 3.267          | 28           | 48                 | 56                  | 100           | 3.704          | 32           | 48                 | 40                  | 72            |
| 2.843          | 40           | 72                 | 44                  | 86            | 3.273          | 24           | 40                 | 24                  | 44            | 3.721          | 24           | 24                 | 32                  | 86            |
| 2.845          | 32           | 72                 | 64                  | 100           | 3.275          | 44           | 86                 | 64                  | 100           | 3.733          | 48           | 72                 | 56                  | 100           |
| 2.849          | 28           | 64                 | 56                  | 86            | 3.281          | 24           | 32                 | 28                  | 64            | 3.750          | 24           | 32                 | 24                  | 48            |
| 2.857          | 24           | 48                 | 32                  | 56            | 3.300          | 44           | 64                 | 48                  | 100           | 3.763          | 86           | 64                 | 28                  | 100           |
| 2.865          | 44           | 86                 | 56                  | 100           | 3.308          | 32           | 72                 | 64                  | 86            | 3.771          | 44           | 56                 | 48                  | 100           |
| 2.867          | 86           | 72                 | 24                  | 100           | 3.333          | 32           | 64                 | 48                  | 72            | 3.772          | 24           | 28                 | 44                  | 100           |
| 2.880          | 24           | 40                 | 48                  | 100           | 3.345          | 28           | 100                | 86                  | 72            | 3.799          | 56           | 48                 | 28                  | 86            |
| 2.894          | 28           | 72                 | 64                  | 86            | 3.349          | 40           | 86                 | 72                  | 100           | 3.809          | 24           | 28                 | 32                  | 72            |
| 2.909          | 32           | 44                 | 40                  | 100           | 3.360          | 56           | 40                 | 24                  | 100           | 3.810          | 64           | 56                 | 24                  | 72            |
| 2.917          | 24           | 64                 | 56                  | 72            | 3.383          | 32           | 44                 | 40                  | 86            | 3.818          | 24           | 40                 | 28                  | 44            |
| 2.924          | 32           | 56                 | 44                  | 86            | 3.403          | 28           | 64                 | 56                  | 72            | 3.819          | 40           | 64                 | 44                  | 72            |
| 2.933          | 44           | 72                 | 48                  | 100           | 3.409          | 24           | 44                 | 40                  | 64            | 3.822          | 86           | 72                 | 32                  | 100           |
| 2.934          | 32           | 48                 | 44                  | 100           | 3.411          | 32           | 48                 | 44                  | 86            | 3.837          | 24           | 32                 | 44                  | 86            |
| 2.946          | 24           | 56                 | 44                  | 64            | 3.422          | 44           | 72                 | 56                  | 100           | 3.840          | 64           | 40                 | 24                  | 100           |
| 2.960          | 28           | 44                 | 40                  | 86            | 3.428          | 24           | 40                 | 32                  | 56            | 3.850          | 44           | 64                 | 56                  | 100           |
| 2.977          | 40           | 86                 | 64                  | 100           | 3.429          | 40           | 28                 | 24                  | 100           | 3.876          | 24           | 72                 | 100                 | 86            |
| 2.984          | 28           | 48                 | 44                  | 86            | 3.438          | 24           | 48                 | 44                  | 64            | 3.889          | 32           | 64                 | 56                  | 72            |
| 3.000          | 24           | 40                 | 28                  | 56            | 3.488          | 40           | 64                 | 48                  | 86            | 3.896          | 24           | 44                 | 40                  | 56            |
| 3.030          | 24           | 44                 | 40                  | 72            | 3.491          | 64           | 44                 | 24                  | 100           | 3.907          | 56           | 40                 | 24                  | 86            |
| 3.044          | 24           | 44                 | 48                  | 86            | 3.492          | 32           | 56                 | 44                  | 72            | 3.911          | 44           | 72                 | 64                  | 100           |
| 3.055          | 28           | 44                 | 48                  | 100           | 3.500          | 40           | 64                 | 56                  | 100           | 3.920          | 28           | 40                 | 56                  | 100           |
| 3.056          | 32           | 64                 | 44                  | 72            | 3.520          | 32           | 40                 | 44                  | 100           | 3.927          | 72           | 44                 | 24                  | 100           |
| 3.070          | 24           | 40                 | 44                  | 86            | 3.535          | 28           | 44                 | 40                  | 72            | 3.929          | 32           | 56                 | 44                  | 64            |
| 3.080          | 28           | 40                 | 44                  | 100           | 3.552          | 56           | 44                 | 24                  | 86            | 3.977          | 28           | 44                 | 40                  | 64            |
| 3.086          | 24           | 56                 | 72                  | 100           | 3.556          | 40           | 72                 | 64                  | 100           | 3.979          | 44           | 72                 | 56                  | 86            |
| 3.101          | 40           | 72                 | 48                  | 86            | 3.564          | 56           | 44                 | 28                  | 100           | 3.987          | 24           | 28                 | 40                  | 86            |
| 3.111          | 28           | 40                 | 32                  | 72            | 3.565          | 28           | 48                 | 44                  | 72            | 4.000          | 24           | 40                 | 32                  | 48            |
| 3.117          | 24           | 44                 | 32                  | 56            | 3.571          | 24           | 48                 | 40                  | 56            | 4.011          | 28           | 48                 | 44                  | 64            |
| 3.125          | 28           | 56                 | 40                  | 64            | 3.572          | 48           | 86                 | 64                  | 100           | 4.019          | 72           | 86                 | 48                  | 100           |
| 3.126          | 48           | 86                 | 56                  | 100           | 3.582          | 44           | 40                 | 28                  | 86            | 4.040          | 32           | 44                 | 40                  | 72            |

## Change Gears for Different Leads—4.059 Inches to 5.568 Inches

| Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        |
|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|
|                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |
| 4.059          | 32           | 44                 | 48                  | 86            | 4.567          | 72           | 44                 | 24                  | 86            | 5.105          | 28           | 48                 | 56                  | 64            |
| 4.060          | 64           | 44                 | 24                  | 86            | 4.572          | 40           | 56                 | 64                  | 100           | 5.116          | 44           | 24                 | 24                  | 86            |
| 4.070          | 28           | 32                 | 40                  | 86            | 4.582          | 72           | 44                 | 28                  | 100           | 5.119          | 86           | 56                 | 24                  | 72            |
| 4.073          | 64           | 44                 | 28                  | 100           | 4.583          | 44           | 64                 | 48                  | 72            | 5.120          | 64           | 40                 | 32                  | 100           |
| 4.074          | 32           | 48                 | 44                  | 72            | 4.584          | 32           | 48                 | 44                  | 64            | 5.133          | 56           | 48                 | 44                  | 100           |
| 4.091          | 24           | 44                 | 48                  | 64            | 4.651          | 40           | 24                 | 24                  | 86            | 5.134          | 44           | 24                 | 28                  | 100           |
| 4.093          | 32           | 40                 | 44                  | 86            | 4.655          | 64           | 44                 | 32                  | 100           | 5.142          | 72           | 56                 | 40                  | 100           |
| 4.114          | 48           | 28                 | 24                  | 100           | 4.667          | 28           | 40                 | 32                  | 48            | 5.143          | 24           | 28                 | 24                  | 40            |
| 4.125          | 24           | 40                 | 44                  | 64            | 4.675          | 24           | 28                 | 24                  | 44            | 5.156          | 44           | 32                 | 24                  | 64            |
| 4.135          | 40           | 72                 | 64                  | 86            | 4.687          | 40           | 32                 | 24                  | 64            | 5.160          | 86           | 40                 | 24                  | 100           |
| 4.144          | 56           | 44                 | 28                  | 86            | 4.688          | 56           | 86                 | 72                  | 100           | 5.168          | 100          | 72                 | 32                  | 86            |
| 4.167          | 28           | 48                 | 40                  | 56            | 4.691          | 86           | 44                 | 24                  | 100           | 5.185          | 28           | 24                 | 32                  | 72            |
| 4.186          | 72           | 64                 | 32                  | 86            | 4.714          | 44           | 40                 | 24                  | 56            | 5.186          | 64           | 48                 | 28                  | 72            |
| 4.200          | 48           | 64                 | 56                  | 100           | 4.736          | 64           | 44                 | 28                  | 86            | 5.195          | 32           | 44                 | 40                  | 56            |
| 4.242          | 28           | 44                 | 32                  | 48            | 4.762          | 40           | 28                 | 24                  | 72            | 5.209          | 100          | 64                 | 24                  | 72            |
| 4.253          | 64           | 56                 | 32                  | 86            | 4.773          | 24           | 32                 | 28                  | 44            | 5.210          | 64           | 40                 | 28                  | 86            |
| 4.264          | 40           | 48                 | 44                  | 86            | 4.778          | 86           | 72                 | 40                  | 100           | 5.226          | 86           | 64                 | 28                  | 72            |
| 4.267          | 64           | 48                 | 32                  | 100           | 4.784          | 72           | 56                 | 32                  | 86            | 5.233          | 72           | 64                 | 40                  | 86            |
| 4.278          | 28           | 40                 | 44                  | 72            | 4.785          | 48           | 28                 | 24                  | 86            | 5.236          | 72           | 44                 | 32                  | 100           |
| 4.286          | 24           | 28                 | 24                  | 48            | 4.800          | 48           | 24                 | 24                  | 100           | 5.238          | 44           | 28                 | 24                  | 72            |
| 4.300          | 86           | 56                 | 28                  | 100           | 4.813          | 44           | 40                 | 28                  | 64            | 5.250          | 24           | 32                 | 28                  | 40            |
| 4.320          | 72           | 40                 | 24                  | 100           | 4.821          | 72           | 56                 | 24                  | 64            | 5.256          | 86           | 72                 | 44                  | 100           |
| 4.341          | 48           | 72                 | 56                  | 86            | 4.849          | 32           | 44                 | 48                  | 72            | 5.280          | 48           | 40                 | 44                  | 100           |
| 4.342          | 64           | 48                 | 28                  | 86            | 4.861          | 40           | 32                 | 28                  | 72            | 5.303          | 28           | 44                 | 40                  | 48            |
| 4.361          | 100          | 64                 | 24                  | 86            | 4.884          | 48           | 64                 | 56                  | 86            | 5.316          | 40           | 28                 | 32                  | 86            |
| 4.363          | 24           | 40                 | 32                  | 44            | 4.889          | 32           | 40                 | 44                  | 72            | 5.328          | 72           | 44                 | 28                  | 86            |
| 4.364          | 40           | 44                 | 48                  | 100           | 4.898          | 24           | 28                 | 32                  | 56            | 5.333          | 40           | 24                 | 32                  | 100           |
| 4.365          | 40           | 56                 | 44                  | 72            | 4.900          | 56           | 32                 | 28                  | 100           | 5.347          | 44           | 64                 | 56                  | 72            |
| 4.375          | 24           | 24                 | 28                  | 64            | 4.911          | 40           | 56                 | 44                  | 64            | 5.348          | 44           | 32                 | 28                  | 72            |
| 4.386          | 24           | 28                 | 44                  | 86            | 4.914          | 86           | 56                 | 32                  | 100           | 5.357          | 40           | 28                 | 24                  | 64            |
| 4.400          | 24           | 24                 | 44                  | 100           | 4.950          | 56           | 44                 | 28                  | 72            | 5.358          | 64           | 86                 | 72                  | 100           |
| 4.444          | 64           | 56                 | 28                  | 72            | 4.961          | 64           | 48                 | 32                  | 86            | 5.375          | 86           | 64                 | 40                  | 100           |
| 4.465          | 64           | 40                 | 24                  | 86            | 4.978          | 56           | 72                 | 64                  | 100           | 5.400          | 72           | 32                 | 24                  | 100           |
| 4.466          | 48           | 40                 | 32                  | 86            | 4.984          | 100          | 56                 | 24                  | 86            | 5.413          | 64           | 44                 | 32                  | 86            |
| 4.477          | 44           | 32                 | 28                  | 86            | 5.000          | 24           | 24                 | 28                  | 56            | 5.426          | 40           | 24                 | 28                  | 86            |
| 4.479          | 86           | 64                 | 24                  | 72            | 5.017          | 86           | 48                 | 28                  | 100           | 5.427          | 40           | 48                 | 56                  | 86            |
| 4.480          | 56           | 40                 | 32                  | 100           | 5.023          | 72           | 40                 | 24                  | 86            | 5.444          | 56           | 40                 | 28                  | 72            |
| 4.500          | 72           | 64                 | 40                  | 100           | 5.029          | 44           | 28                 | 32                  | 100           | 5.455          | 48           | 44                 | 28                  | 56            |
| 4.522          | 100          | 72                 | 28                  | 86            | 5.040          | 72           | 40                 | 28                  | 100           | 5.469          | 40           | 32                 | 28                  | 64            |
| 4.537          | 56           | 48                 | 28                  | 72            | 5.074          | 40           | 44                 | 48                  | 86            | 5.473          | 86           | 44                 | 28                  | 100           |
| 4.545          | 24           | 44                 | 40                  | 48            | 5.080          | 64           | 56                 | 32                  | 72            | 5.486          | 64           | 28                 | 24                  | 100           |
| 4.546          | 28           | 44                 | 40                  | 56            | 5.088          | 100          | 64                 | 28                  | 86            | 5.500          | 44           | 40                 | 24                  | 48            |
| 4.548          | 44           | 72                 | 64                  | 86            | 5.091          | 56           | 44                 | 40                  | 100           | 5.556          | 40           | 24                 | 24                  | 72            |
| 4.558          | 56           | 40                 | 28                  | 86            | 5.093          | 40           | 48                 | 44                  | 72            | 5.568          | 56           | 44                 | 28                  | 64            |

Change Gears for Different Leads—5.581 Inches to 7.500 Inches

| Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        |
|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|
|                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |
| 5.581          | 64           | 32                 | 24                  | 86            | 6.172          | 72           | 28                 | 24                  | 100           | 6.825          | 86           | 56                 | 32                  | 72            |
| 5.582          | 48           | 24                 | 24                  | 86            | 6.202          | 40           | 24                 | 32                  | 86            | 6.857          | 32           | 28                 | 24                  | 40            |
| 5.600          | 56           | 24                 | 24                  | 100           | 6.222          | 64           | 40                 | 28                  | 72            | 6.875          | 44           | 24                 | 24                  | 64            |
| 5.625          | 48           | 32                 | 24                  | 64            | 6.234          | 32           | 28                 | 24                  | 44            | 6.880          | 86           | 40                 | 32                  | 100           |
| 5.657          | 56           | 44                 | 32                  | 72            | 6.250          | 24           | 24                 | 40                  | 64            | 6.944          | 100          | 48                 | 24                  | 72            |
| 5.698          | 56           | 32                 | 28                  | 86            | 6.255          | 86           | 44                 | 32                  | 100           | 6.945          | 100          | 56                 | 28                  | 72            |
| 5.714          | 48           | 28                 | 24                  | 72            | 6.279          | 72           | 64                 | 48                  | 86            | 6.968          | 86           | 48                 | 28                  | 72            |
| 5.730          | 40           | 48                 | 44                  | 64            | 6.286          | 44           | 40                 | 32                  | 56            | 6.977          | 48           | 32                 | 40                  | 86            |
| 5.733          | 86           | 48                 | 32                  | 100           | 6.300          | 72           | 32                 | 28                  | 100           | 6.982          | 64           | 44                 | 48                  | 100           |
| 5.756          | 72           | 64                 | 44                  | 86            | 6.343          | 100          | 44                 | 24                  | 86            | 6.984          | 44           | 28                 | 32                  | 72            |
| 5.759          | 86           | 56                 | 24                  | 64            | 6.350          | 40           | 28                 | 32                  | 72            | 7.000          | 28           | 24                 | 24                  | 40            |
| 5.760          | 72           | 40                 | 32                  | 100           | 6.364          | 56           | 44                 | 24                  | 48            | 7.013          | 72           | 44                 | 24                  | 56            |
| 5.788          | 64           | 72                 | 56                  | 86            | 6.379          | 64           | 28                 | 24                  | 86            | 7.040          | 64           | 40                 | 44                  | 100           |
| 5.814          | 100          | 64                 | 32                  | 86            | 6.396          | 44           | 32                 | 40                  | 86            | 7.071          | 56           | 44                 | 40                  | 72            |
| 5.818          | 64           | 44                 | 40                  | 100           | 6.400          | 64           | 24                 | 24                  | 100           | 7.104          | 56           | 44                 | 48                  | 86            |
| 5.833          | 28           | 24                 | 24                  | 48            | 6.417          | 44           | 40                 | 28                  | 48            | 7.106          | 100          | 72                 | 44                  | 86            |
| 5.847          | 64           | 56                 | 44                  | 86            | 6.429          | 24           | 28                 | 24                  | 32            | 7.111          | 64           | 40                 | 32                  | 72            |
| 5.848          | 44           | 28                 | 32                  | 86            | 6.450          | 86           | 64                 | 48                  | 100           | 7.130          | 44           | 24                 | 28                  | 72            |
| 5.861          | 72           | 40                 | 28                  | 86            | 6.460          | 100          | 72                 | 40                  | 86            | 7.143          | 40           | 28                 | 32                  | 64            |
| 5.867          | 44           | 24                 | 32                  | 100           | 6.465          | 64           | 44                 | 32                  | 72            | 7.159          | 72           | 44                 | 28                  | 64            |
| 5.893          | 44           | 32                 | 24                  | 56            | 6.482          | 56           | 48                 | 40                  | 72            | 7.163          | 56           | 40                 | 44                  | 86            |
| 5.912          | 86           | 64                 | 44                  | 100           | 6.512          | 56           | 24                 | 24                  | 86            | 7.167          | 86           | 40                 | 24                  | 72            |
| 5.920          | 56           | 44                 | 40                  | 86            | 6.515          | 86           | 44                 | 24                  | 72            | 7.176          | 72           | 28                 | 24                  | 86            |
| 5.926          | 64           | 48                 | 32                  | 72            | 6.534          | 56           | 24                 | 28                  | 100           | 7.200          | 72           | 24                 | 24                  | 100           |
| 5.952          | 100          | 56                 | 24                  | 72            | 6.545          | 48           | 40                 | 24                  | 44            | 7.268          | 100          | 64                 | 40                  | 86            |
| 5.954          | 64           | 40                 | 32                  | 86            | 6.548          | 44           | 48                 | 40                  | 56            | 7.272          | 64           | 44                 | 28                  | 56            |
| 5.969          | 44           | 24                 | 28                  | 86            | 6.563          | 56           | 32                 | 24                  | 64            | 7.273          | 32           | 24                 | 24                  | 44            |
| 5.972          | 86           | 48                 | 24                  | 72            | 6.578          | 72           | 56                 | 44                  | 86            | 7.292          | 56           | 48                 | 40                  | 64            |
| 5.980          | 72           | 56                 | 40                  | 86            | 6.600          | 48           | 32                 | 44                  | 100           | 7.310          | 44           | 28                 | 40                  | 86            |
| 6.000          | 48           | 40                 | 28                  | 56            | 6.645          | 100          | 56                 | 32                  | 86            | 7.314          | 64           | 28                 | 32                  | 100           |
| 6.016          | 44           | 32                 | 28                  | 64            | 6.667          | 64           | 48                 | 28                  | 56            | 7.326          | 72           | 32                 | 28                  | 86            |
| 6.020          | 86           | 40                 | 28                  | 100           | 6.689          | 86           | 72                 | 56                  | 100           | 7.330          | 86           | 44                 | 24                  | 64            |
| 6.061          | 40           | 44                 | 32                  | 48            | 6.697          | 100          | 56                 | 24                  | 64            | 7.333          | 44           | 24                 | 40                  | 100           |
| 6.077          | 100          | 64                 | 28                  | 72            | 6.698          | 72           | 40                 | 32                  | 86            | 7.334          | 44           | 40                 | 32                  | 48            |
| 6.089          | 72           | 44                 | 32                  | 86            | 6.719          | 86           | 48                 | 24                  | 64            | 7.347          | 48           | 28                 | 24                  | 56            |
| 6.109          | 56           | 44                 | 48                  | 100           | 6.720          | 56           | 40                 | 48                  | 100           | 7.371          | 86           | 56                 | 48                  | 100           |
| 6.112          | 24           | 24                 | 44                  | 72            | 6.735          | 44           | 28                 | 24                  | 56            | 7.372          | 86           | 28                 | 24                  | 100           |
| 6.122          | 40           | 28                 | 24                  | 56            | 6.750          | 72           | 40                 | 24                  | 64            | 7.400          | 100          | 44                 | 28                  | 86            |
| 6.125          | 56           | 40                 | 28                  | 64            | 6.757          | 86           | 56                 | 44                  | 100           | 7.408          | 40           | 24                 | 32                  | 72            |
| 6.137          | 72           | 44                 | 24                  | 64            | 6.766          | 64           | 44                 | 40                  | 86            | 7.424          | 56           | 44                 | 28                  | 48            |
| 6.140          | 48           | 40                 | 44                  | 86            | 6.784          | 100          | 48                 | 28                  | 86            | 7.442          | 64           | 24                 | 24                  | 86            |
| 6.143          | 86           | 56                 | 40                  | 100           | 6.806          | 56           | 32                 | 28                  | 72            | 7.465          | 86           | 64                 | 40                  | 72            |
| 6.160          | 56           | 40                 | 44                  | 100           | 6.818          | 40           | 32                 | 24                  | 44            | 7.467          | 64           | 24                 | 28                  | 100           |
| 6.171          | 72           | 56                 | 48                  | 100           | 6.822          | 44           | 24                 | 32                  | 86            | 7.500          | 48           | 24                 | 24                  | 64            |

## Change Gears for Different Leads—7.525 Inches to 9.598 Inches

| Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        |
|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|
|                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |
| 7.525          | 86           | 32                 | 28                  | 100           | 8.140          | 56           | 32                 | 40                  | 86            | 8.800          | 48           | 24                 | 44                  | 100           |
| 7.543          | 48           | 28                 | 44                  | 100           | 8.145          | 64           | 44                 | 56                  | 100           | 8.838          | 100          | 44                 | 28                  | 72            |
| 7.576          | 100          | 44                 | 24                  | 72            | 8.148          | 64           | 48                 | 44                  | 72            | 8.839          | 72           | 56                 | 44                  | 64            |
| 7.597          | 56           | 24                 | 28                  | 86            | 8.149          | 44           | 24                 | 32                  | 72            | 8.909          | 56           | 40                 | 28                  | 44            |
| 7.601          | 86           | 44                 | 28                  | 72            | 8.163          | 40           | 28                 | 32                  | 56            | 8.929          | 100          | 48                 | 24                  | 56            |
| 7.611          | 72           | 44                 | 40                  | 86            | 8.167          | 56           | 40                 | 28                  | 48            | 8.930          | 64           | 40                 | 48                  | 86            |
| 7.619          | 64           | 48                 | 32                  | 56            | 8.182          | 48           | 32                 | 24                  | 44            | 8.953          | 56           | 32                 | 44                  | 86            |
| 7.620          | 64           | 28                 | 24                  | 72            | 8.186          | 64           | 40                 | 44                  | 86            | 8.959          | 86           | 48                 | 28                  | 56            |
| 7.636          | 56           | 40                 | 24                  | 44            | 8.212          | 86           | 64                 | 44                  | 72            | 8.960          | 64           | 40                 | 56                  | 100           |
| 7.639          | 44           | 32                 | 40                  | 72            | 8.229          | 72           | 28                 | 32                  | 100           | 8.980          | 44           | 28                 | 32                  | 56            |
| 7.644          | 86           | 72                 | 64                  | 100           | 8.250          | 44           | 32                 | 24                  | 40            | 9.000          | 48           | 32                 | 24                  | 40            |
| 7.657          | 56           | 32                 | 28                  | 64            | 8.306          | 100          | 56                 | 40                  | 86            | 9.044          | 100          | 72                 | 56                  | 86            |
| 7.674          | 72           | 48                 | 44                  | 86            | 8.312          | 64           | 44                 | 32                  | 56            | 9.074          | 56           | 24                 | 28                  | 72            |
| 7.675          | 48           | 32                 | 44                  | 86            | 8.333          | 40           | 24                 | 24                  | 48            | 9.091          | 40           | 24                 | 24                  | 44            |
| 7.679          | 86           | 48                 | 24                  | 56            | 8.334          | 40           | 24                 | 28                  | 56            | 9.115          | 100          | 48                 | 28                  | 64            |
| 7.680          | 64           | 40                 | 48                  | 100           | 8.361          | 86           | 40                 | 28                  | 72            | 9.134          | 72           | 44                 | 48                  | 86            |
| 7.700          | 56           | 32                 | 44                  | 100           | 8.372          | 72           | 24                 | 24                  | 86            | 9.137          | 100          | 56                 | 44                  | 86            |
| 7.714          | 72           | 40                 | 24                  | 56            | 8.377          | 86           | 44                 | 24                  | 56            | 9.143          | 64           | 40                 | 32                  | 56            |
| 7.752          | 100          | 48                 | 32                  | 86            | 8.400          | 72           | 24                 | 28                  | 100           | 9.164          | 72           | 44                 | 56                  | 100           |
| 7.778          | 32           | 24                 | 28                  | 48            | 8.437          | 72           | 32                 | 24                  | 64            | 9.167          | 44           | 24                 | 24                  | 48            |
| 7.792          | 40           | 28                 | 24                  | 44            | 8.457          | 100          | 44                 | 32                  | 86            | 9.210          | 72           | 40                 | 44                  | 86            |
| 7.813          | 100          | 48                 | 24                  | 64            | 8.484          | 32           | 24                 | 28                  | 44            | 9.214          | 86           | 40                 | 24                  | 56            |
| 7.815          | 56           | 40                 | 48                  | 86            | 8.485          | 64           | 44                 | 28                  | 48            | 9.260          | 100          | 48                 | 32                  | 72            |
| 7.818          | 86           | 44                 | 40                  | 100           | 8.485          | 56           | 44                 | 32                  | 48            | 9.302          | 48           | 24                 | 40                  | 86            |
| 7.838          | 86           | 48                 | 28                  | 64            | 8.506          | 64           | 28                 | 32                  | 86            | 9.303          | 56           | 28                 | 40                  | 86            |
| 7.855          | 72           | 44                 | 48                  | 100           | 8.523          | 100          | 44                 | 24                  | 64            | 9.333          | 64           | 40                 | 28                  | 48            |
| 7.857          | 44           | 24                 | 24                  | 56            | 8.527          | 44           | 24                 | 40                  | 86            | 9.334          | 32           | 24                 | 28                  | 40            |
| 7.872          | 44           | 28                 | 32                  | 64            | 8.532          | 86           | 56                 | 40                  | 72            | 9.351          | 48           | 28                 | 24                  | 44            |
| 7.875          | 72           | 40                 | 28                  | 64            | 8.534          | 64           | 24                 | 32                  | 100           | 9.375          | 48           | 32                 | 40                  | 64            |
| 7.883          | 86           | 48                 | 44                  | 100           | 8.552          | 86           | 44                 | 28                  | 64            | 9.382          | 86           | 44                 | 48                  | 100           |
| 7.920          | 72           | 40                 | 44                  | 100           | 8.556          | 56           | 40                 | 44                  | 72            | 9.385          | 86           | 56                 | 44                  | 72            |
| 7.936          | 100          | 56                 | 32                  | 72            | 8.572          | 64           | 32                 | 24                  | 56            | 9.406          | 86           | 40                 | 28                  | 64            |
| 7.954          | 40           | 32                 | 28                  | 44            | 8.572          | 48           | 24                 | 24                  | 56            | 9.428          | 44           | 28                 | 24                  | 40            |
| 7.955          | 56           | 44                 | 40                  | 64            | 8.594          | 44           | 32                 | 40                  | 64            | 9.429          | 48           | 40                 | 44                  | 56            |
| 7.963          | 86           | 48                 | 32                  | 72            | 8.600          | 86           | 24                 | 24                  | 100           | 9.460          | 86           | 40                 | 44                  | 100           |
| 7.974          | 48           | 28                 | 40                  | 86            | 8.640          | 72           | 40                 | 48                  | 100           | 9.472          | 64           | 44                 | 56                  | 86            |
| 7.994          | 100          | 64                 | 44                  | 86            | 8.681          | 100          | 64                 | 40                  | 72            | 9.524          | 40           | 28                 | 32                  | 48            |
| 8.000          | 64           | 32                 | 40                  | 100           | 8.682          | 64           | 24                 | 28                  | 86            | 9.545          | 72           | 44                 | 28                  | 48            |
| 8.021          | 44           | 32                 | 28                  | 48            | 8.687          | 86           | 44                 | 32                  | 72            | 9.546          | 56           | 32                 | 24                  | 44            |
| 8.035          | 72           | 56                 | 40                  | 64            | 8.721          | 100          | 32                 | 24                  | 86            | 9.547          | 56           | 44                 | 48                  | 64            |
| 8.063          | 86           | 40                 | 24                  | 64            | 8.727          | 48           | 40                 | 32                  | 44            | 9.549          | 100          | 64                 | 44                  | 72            |
| 8.081          | 64           | 44                 | 40                  | 72            | 8.730          | 44           | 28                 | 40                  | 72            | 9.556          | 86           | 40                 | 32                  | 72            |
| 8.102          | 100          | 48                 | 28                  | 72            | 8.750          | 28           | 24                 | 24                  | 32            | 9.569          | 72           | 28                 | 32                  | 86            |
| 8.119          | 64           | 44                 | 48                  | 86            | 8.772          | 48           | 28                 | 44                  | 86            | 9.598          | 86           | 56                 | 40                  | 64            |



**Change Gears for Different Leads—9.600 Inches to 12.375 Inches**

| Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        |
|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|
|                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |
| 9.600          | 72           | 24                 | 32                  | 100           | 10.370         | 64           | 24                 | 28                  | 72            | 11.314         | 72           | 28                 | 44                  | 100           |
| 9.625          | 44           | 32                 | 28                  | 40            | 10.371         | 64           | 48                 | 56                  | 72            | 11.363         | 100          | 44                 | 24                  | 48            |
| 9.643          | 72           | 32                 | 24                  | 56            | 10.390         | 40           | 28                 | 32                  | 44            | 11.401         | 86           | 44                 | 28                  | 48            |
| 9.675          | 86           | 64                 | 72                  | 100           | 10.417         | 100          | 32                 | 24                  | 72            | 11.429         | 32           | 24                 | 24                  | 28            |
| 9.690          | 100          | 48                 | 40                  | 86            | 10.419         | 64           | 40                 | 56                  | 86            | 11.454         | 72           | 40                 | 28                  | 44            |
| 9.697          | 64           | 48                 | 32                  | 44            | 10.451         | 86           | 32                 | 28                  | 72            | 11.459         | 44           | 24                 | 40                  | 64            |
| 9.723          | 40           | 24                 | 28                  | 48            | 10.467         | 72           | 32                 | 40                  | 86            | 11.467         | 86           | 24                 | 32                  | 100           |
| 9.741          | 100          | 44                 | 24                  | 56            | 10.473         | 72           | 44                 | 64                  | 100           | 11.512         | 72           | 32                 | 44                  | 86            |
| 9.768          | 72           | 48                 | 56                  | 86            | 10.476         | 44           | 24                 | 32                  | 56            | 11.518         | 86           | 28                 | 24                  | 64            |
| 9.773          | 86           | 44                 | 24                  | 48            | 10.477         | 48           | 28                 | 44                  | 72            | 11.520         | 72           | 40                 | 64                  | 100           |
| 9.778          | 64           | 40                 | 44                  | 72            | 10.500         | 56           | 32                 | 24                  | 40            | 11.574         | 100          | 48                 | 40                  | 72            |
| 9.796          | 64           | 28                 | 24                  | 56            | 10.558         | 86           | 56                 | 44                  | 64            | 11.629         | 100          | 24                 | 24                  | 86            |
| 9.818          | 72           | 40                 | 24                  | 44            | 10.571         | 100          | 44                 | 40                  | 86            | 11.638         | 64           | 40                 | 32                  | 44            |
| 9.822          | 44           | 32                 | 40                  | 56            | 10.606         | 56           | 44                 | 40                  | 48            | 11.667         | 56           | 24                 | 24                  | 48            |
| 9.828          | 86           | 28                 | 32                  | 100           | 10.631         | 64           | 28                 | 40                  | 86            | 11.688         | 72           | 44                 | 40                  | 56            |
| 9.844          | 72           | 32                 | 28                  | 64            | 10.655         | 72           | 44                 | 56                  | 86            | 11.695         | 64           | 28                 | 44                  | 86            |
| 9.900          | 72           | 32                 | 44                  | 100           | 10.659         | 100          | 48                 | 44                  | 86            | 11.719         | 100          | 32                 | 24                  | 64            |
| 9.921          | 100          | 56                 | 40                  | 72            | 10.667         | 64           | 40                 | 48                  | 72            | 11.721         | 72           | 40                 | 56                  | 86            |
| 9.923          | 64           | 24                 | 32                  | 86            | 10.694         | 44           | 24                 | 28                  | 48            | 11.728         | 86           | 40                 | 24                  | 44            |
| 9.943          | 100          | 44                 | 28                  | 64            | 10.713         | 40           | 28                 | 24                  | 32            | 11.733         | 64           | 24                 | 44                  | 100           |
| 9.954          | 86           | 48                 | 40                  | 72            | 10.714         | 48           | 32                 | 40                  | 56            | 11.757         | 86           | 32                 | 28                  | 64            |
| 9.967          | 100          | 56                 | 48                  | 86            | 10.750         | 86           | 40                 | 24                  | 48            | 11.785         | 72           | 48                 | 44                  | 56            |
| 9.968          | 100          | 28                 | 24                  | 86            | 10.800         | 72           | 32                 | 48                  | 100           | 11.786         | 44           | 28                 | 24                  | 32            |
| 10.000         | 56           | 28                 | 24                  | 48            | 10.853         | 56           | 24                 | 40                  | 86            | 11.825         | 86           | 32                 | 44                  | 100           |
| 10.033         | 86           | 24                 | 28                  | 100           | 10.859         | 86           | 44                 | 40                  | 72            | 11.905         | 100          | 28                 | 24                  | 72            |
| 10.046         | 72           | 40                 | 48                  | 86            | 10.909         | 72           | 44                 | 32                  | 48            | 11.938         | 56           | 24                 | 44                  | 86            |
| 10.057         | 64           | 28                 | 44                  | 100           | 10.913         | 100          | 56                 | 44                  | 72            | 11.944         | 86           | 24                 | 24                  | 72            |
| 10.078         | 86           | 32                 | 24                  | 64            | 10.937         | 56           | 32                 | 40                  | 64            | 11.960         | 72           | 28                 | 40                  | 86            |
| 10.080         | 72           | 40                 | 56                  | 100           | 10.945         | 86           | 44                 | 56                  | 100           | 12.000         | 48           | 24                 | 24                  | 40            |
| 10.101         | 100          | 44                 | 32                  | 72            | 10.949         | 86           | 48                 | 44                  | 72            | 12.031         | 56           | 32                 | 44                  | 64            |
| 10.159         | 64           | 28                 | 32                  | 72            | 10.972         | 64           | 28                 | 48                  | 100           | 12.040         | 86           | 40                 | 56                  | 100           |
| 10.175         | 100          | 32                 | 28                  | 86            | 11.000         | 44           | 24                 | 24                  | 40            | 12.121         | 40           | 24                 | 32                  | 44            |
| 10.182         | 64           | 40                 | 28                  | 44            | 11.021         | 72           | 28                 | 24                  | 56            | 12.153         | 100          | 32                 | 28                  | 72            |
| 10.186         | 44           | 24                 | 40                  | 72            | 11.057         | 86           | 56                 | 72                  | 100           | 12.178         | 72           | 44                 | 64                  | 86            |
| 10.209         | 56           | 24                 | 28                  | 64            | 11.111         | 40           | 24                 | 32                  | 48            | 12.216         | 86           | 44                 | 40                  | 64            |
| 10.228         | 72           | 44                 | 40                  | 64            | 11.137         | 56           | 32                 | 28                  | 44            | 12.222         | 44           | 24                 | 32                  | 48            |
| 10.233         | 48           | 24                 | 44                  | 86            | 11.160         | 100          | 56                 | 40                  | 64            | 12.245         | 48           | 28                 | 40                  | 56            |
| 10.238         | 86           | 28                 | 24                  | 72            | 11.163         | 72           | 24                 | 32                  | 86            | 12.250         | 56           | 32                 | 28                  | 40            |
| 10.267         | 56           | 24                 | 44                  | 100           | 11.169         | 86           | 44                 | 32                  | 56            | 12.272         | 72           | 32                 | 24                  | 44            |
| 10.286         | 48           | 28                 | 24                  | 40            | 11.198         | 86           | 48                 | 40                  | 64            | 12.277         | 100          | 56                 | 44                  | 64            |
| 10.312         | 48           | 32                 | 44                  | 64            | 11.200         | 56           | 24                 | 48                  | 100           | 12.286         | 86           | 28                 | 40                  | 100           |
| 10.313         | 72           | 48                 | 44                  | 64            | 11.225         | 44           | 28                 | 40                  | 56            | 12.318         | 86           | 48                 | 44                  | 64            |
| 10.320         | 86           | 40                 | 48                  | 100           | 11.250         | 72           | 24                 | 24                  | 64            | 12.343         | 72           | 28                 | 48                  | 100           |
| 10.336         | 100          | 72                 | 64                  | 86            | 11.313         | 64           | 44                 | 56                  | 72            | 12.375         | 72           | 40                 | 44                  | 64            |

## Change Gears for Different Leads—12.403 Inches to 16.000 Inches

| Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        |
|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|
|                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |
| 12.403         | 64           | 24                 | 40                  | 86            | 13.438         | 86           | 24                 | 24                  | 64            | 14.668         | 44           | 24                 | 32                  | 40            |
| 12.444         | 64           | 40                 | 56                  | 72            | 13.469         | 48           | 28                 | 44                  | 56            | 14.694         | 72           | 28                 | 32                  | 56            |
| 12.468         | 64           | 28                 | 24                  | 44            | 13.500         | 72           | 32                 | 24                  | 40            | 14.743         | 86           | 28                 | 48                  | 100           |
| 12.500         | 40           | 24                 | 24                  | 32            | 13.514         | 86           | 28                 | 44                  | 100           | 14.780         | 86           | 40                 | 44                  | 64            |
| 12.542         | 86           | 40                 | 28                  | 48            | 13.566         | 100          | 24                 | 28                  | 86            | 14.800         | 100          | 44                 | 56                  | 86            |
| 12.508         | 86           | 44                 | 64                  | 100           | 13.611         | 56           | 24                 | 28                  | 48            | 14.815         | 64           | 24                 | 40                  | 72            |
| 12.558         | 72           | 32                 | 48                  | 86            | 13.636         | 48           | 32                 | 40                  | 44            | 14.849         | 56           | 24                 | 28                  | 44            |
| 12.571         | 64           | 40                 | 44                  | 56            | 13.643         | 64           | 24                 | 44                  | 86            | 14.880         | 100          | 48                 | 40                  | 56            |
| 12.572         | 44           | 28                 | 32                  | 40            | 13.650         | 86           | 28                 | 32                  | 72            | 14.884         | 64           | 28                 | 56                  | 86            |
| 12.600         | 72           | 32                 | 56                  | 100           | 13.672         | 100          | 32                 | 28                  | 64            | 14.931         | 86           | 32                 | 40                  | 72            |
| 12.627         | 100          | 44                 | 40                  | 72            | 13.682         | 86           | 40                 | 28                  | 44            | 14.933         | 64           | 24                 | 56                  | 100           |
| 12.686         | 100          | 44                 | 48                  | 86            | 13.713         | 64           | 40                 | 48                  | 56            | 14.950         | 100          | 56                 | 72                  | 86            |
| 12.698         | 64           | 28                 | 40                  | 72            | 13.715         | 64           | 28                 | 24                  | 40            | 15.000         | 48           | 24                 | 24                  | 32            |
| 12.727         | 64           | 32                 | 28                  | 44            | 13.750         | 44           | 24                 | 24                  | 32            | 15.050         | 86           | 32                 | 56                  | 100           |
| 12.728         | 56           | 24                 | 24                  | 44            | 13.760         | 86           | 40                 | 64                  | 100           | 15.150         | 100          | 44                 | 32                  | 48            |
| 12.732         | 100          | 48                 | 44                  | 72            | 13.889         | 100          | 24                 | 24                  | 72            | 15.151         | 100          | 44                 | 48                  | 72            |
| 12.758         | 64           | 28                 | 48                  | 86            | 13.933         | 86           | 48                 | 56                  | 72            | 15.202         | 86           | 44                 | 56                  | 72            |
| 12.791         | 100          | 40                 | 44                  | 86            | 13.935         | 86           | 24                 | 28                  | 72            | 15.238         | 64           | 28                 | 48                  | 72            |
| 12.798         | 86           | 48                 | 40                  | 56            | 13.953         | 72           | 24                 | 40                  | 86            | 15.239         | 64           | 28                 | 32                  | 48            |
| 12.800         | 64           | 28                 | 56                  | 100           | 13.960         | 86           | 44                 | 40                  | 56            | 15.272         | 56           | 40                 | 48                  | 44            |
| 12.834         | 56           | 40                 | 44                  | 48            | 13.968         | 64           | 28                 | 44                  | 72            | 15.278         | 44           | 24                 | 40                  | 48            |
| 12.857         | 72           | 28                 | 32                  | 64            | 14.000         | 56           | 24                 | 24                  | 40            | 15.279         | 100          | 40                 | 44                  | 72            |
| 12.858         | 48           | 28                 | 24                  | 32            | 14.025         | 72           | 44                 | 48                  | 56            | 15.306         | 100          | 28                 | 24                  | 56            |
| 12.900         | 86           | 32                 | 48                  | 100           | 14.026         | 72           | 28                 | 24                  | 44            | 15.349         | 72           | 24                 | 44                  | 86            |
| 12.963         | 56           | 24                 | 40                  | 72            | 14.063         | 72           | 32                 | 40                  | 64            | 15.357         | 86           | 28                 | 24                  | 48            |
| 12.987         | 100          | 44                 | 32                  | 56            | 14.071         | 86           | 44                 | 72                  | 100           | 15.429         | 72           | 40                 | 48                  | 56            |
| 13.020         | 100          | 48                 | 40                  | 64            | 14.078         | 86           | 48                 | 44                  | 56            | 15.469         | 72           | 32                 | 44                  | 64            |
| 13.024         | 56           | 24                 | 48                  | 86            | 14.142         | 72           | 40                 | 44                  | 56            | 15.480         | 86           | 40                 | 72                  | 100           |
| 13.030         | 86           | 44                 | 32                  | 48            | 14.204         | 100          | 44                 | 40                  | 64            | 15.504         | 100          | 48                 | 64                  | 86            |
| 13.062         | 64           | 28                 | 32                  | 56            | 14.260         | 56           | 24                 | 44                  | 72            | 15.556         | 64           | 32                 | 56                  | 72            |
| 13.082         | 100          | 64                 | 72                  | 86            | 14.286         | 40           | 24                 | 24                  | 28            | 15.584         | 48           | 28                 | 40                  | 44            |
| 13.090         | 72           | 40                 | 32                  | 44            | 14.318         | 72           | 32                 | 28                  | 44            | 15.625         | 100          | 24                 | 24                  | 64            |
| 13.096         | 44           | 28                 | 40                  | 48            | 14.319         | 72           | 44                 | 56                  | 64            | 15.636         | 86           | 40                 | 32                  | 44            |
| 13.125         | 72           | 32                 | 28                  | 48            | 14.322         | 100          | 48                 | 44                  | 64            | 15.677         | 86           | 32                 | 28                  | 48            |
| 13.139         | 86           | 40                 | 44                  | 72            | 14.333         | 86           | 40                 | 32                  | 48            | 15.714         | 44           | 24                 | 24                  | 28            |
| 13.157         | 72           | 28                 | 44                  | 86            | 14.352         | 72           | 28                 | 48                  | 86            | 15.750         | 72           | 32                 | 28                  | 40            |
| 13.163         | 86           | 28                 | 24                  | 56            | 14.400         | 72           | 24                 | 48                  | 100           | 15.767         | 86           | 24                 | 44                  | 100           |
| 13.200         | 72           | 24                 | 44                  | 100           | 14.536         | 100          | 32                 | 40                  | 86            | 15.873         | 100          | 56                 | 64                  | 72            |
| 13.258         | 100          | 44                 | 28                  | 48            | 14.545         | 64           | 24                 | 24                  | 44            | 15.874         | 100          | 28                 | 32                  | 72            |
| 13.289         | 100          | 28                 | 32                  | 86            | 14.583         | 56           | 32                 | 40                  | 48            | 15.909         | 100          | 40                 | 28                  | 44            |
| 13.333         | 64           | 24                 | 24                  | 48            | 14.584         | 40           | 24                 | 28                  | 32            | 15.925         | 86           | 48                 | 64                  | 72            |
| 13.393         | 100          | 56                 | 48                  | 64            | 14.651         | 72           | 32                 | 56                  | 86            | 15.926         | 86           | 24                 | 32                  | 72            |
| 13.396         | 72           | 40                 | 64                  | 86            | 14.659         | 86           | 44                 | 48                  | 64            | 15.989         | 100          | 32                 | 44                  | 86            |
| 13.437         | 86           | 32                 | 28                  | 56            | 14.667         | 64           | 40                 | 44                  | 48            | 16.000         | 64           | 24                 | 24                  | 40            |

**Change Gears for Different Leads—16.042 Inches to 21.39 Inches**

| Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        |
|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|
|                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |
| 16.042         | 56           | 24                 | 44                  | 64            | 17.442         | 100          | 32                 | 48                  | 86            | 19.350         | 86           | 32                 | 72                  | 100           |
| 16.043         | 44           | 24                 | 28                  | 32            | 17.454         | 64           | 40                 | 48                  | 44            | 19.380         | 100          | 24                 | 40                  | 86            |
| 16.071         | 72           | 32                 | 40                  | 56            | 17.500         | 56           | 24                 | 24                  | 32            | 19.394         | 64           | 24                 | 32                  | 44            |
| 16.125         | 86           | 32                 | 24                  | 40            | 17.550         | 86           | 28                 | 32                  | 56            | 19.444         | 40           | 24                 | 28                  | 24            |
| 16.204         | 100          | 24                 | 28                  | 72            | 17.677         | 100          | 44                 | 56                  | 72            | 19.480         | 100          | 28                 | 24                  | 44            |
| 16.233         | 100          | 44                 | 40                  | 56            | 17.679         | 72           | 32                 | 44                  | 56            | 19.531         | 100          | 32                 | 40                  | 64            |
| 16.280         | 100          | 40                 | 56                  | 86            | 17.778         | 64           | 24                 | 32                  | 48            | 19.535         | 72           | 24                 | 56                  | 86            |
| 16.288         | 86           | 44                 | 40                  | 48            | 17.858         | 100          | 24                 | 24                  | 56            | 19.545         | 86           | 24                 | 24                  | 44            |
| 16.296         | 64           | 24                 | 44                  | 72            | 17.917         | 86           | 24                 | 32                  | 64            | 19.590         | 64           | 28                 | 48                  | 56            |
| 16.327         | 64           | 28                 | 40                  | 56            | 17.918         | 86           | 24                 | 24                  | 48            | 19.635         | 72           | 40                 | 48                  | 44            |
| 16.333         | 56           | 24                 | 28                  | 40            | 17.959         | 64           | 28                 | 44                  | 56            | 19.642         | 100          | 40                 | 44                  | 56            |
| 16.364         | 72           | 24                 | 24                  | 44            | 18.000         | 72           | 24                 | 24                  | 40            | 19.643         | 44           | 28                 | 40                  | 32            |
| 16.370         | 100          | 48                 | 44                  | 56            | 18.181         | 56           | 28                 | 40                  | 44            | 19.656         | 86           | 28                 | 64                  | 100           |
| 16.423         | 86           | 32                 | 44                  | 72            | 18.182         | 48           | 24                 | 40                  | 44            | 19.687         | 72           | 32                 | 56                  | 64            |
| 16.456         | 72           | 28                 | 64                  | 100           | 18.229         | 100          | 32                 | 28                  | 48            | 19.710         | 86           | 40                 | 44                  | 48            |
| 16.500         | 72           | 40                 | 44                  | 48            | 18.273         | 100          | 28                 | 44                  | 86            | 19.840         | 100          | 28                 | 40                  | 72            |
| 16.612         | 100          | 28                 | 40                  | 86            | 18.285         | 64           | 28                 | 32                  | 40            | 19.886         | 100          | 44                 | 56                  | 64            |
| 16.623         | 64           | 28                 | 32                  | 44            | 18.333         | 56           | 28                 | 44                  | 48            | 19.887         | 100          | 32                 | 28                  | 44            |
| 16.667         | 56           | 28                 | 40                  | 48            | 18.367         | 72           | 28                 | 40                  | 56            | 19.908         | 86           | 24                 | 40                  | 72            |
| 16.722         | 86           | 40                 | 56                  | 72            | 18.428         | 86           | 28                 | 24                  | 40            | 19.934         | 100          | 28                 | 48                  | 86            |
| 16.744         | 72           | 24                 | 48                  | 86            | 18.476         | 86           | 32                 | 44                  | 64            | 20.00          | 72           | 24                 | 32                  | 48            |
| 16.752         | 86           | 44                 | 48                  | 56            | 18.519         | 100          | 24                 | 32                  | 72            | 20.07          | 86           | 24                 | 56                  | 100           |
| 16.753         | 86           | 28                 | 24                  | 44            | 18.605         | 100          | 40                 | 64                  | 86            | 20.09          | 100          | 56                 | 72                  | 64            |
| 16.797         | 86           | 32                 | 40                  | 64            | 18.663         | 100          | 64                 | 86                  | 72            | 20.16          | 86           | 48                 | 72                  | 64            |
| 16.800         | 72           | 24                 | 56                  | 100           | 18.667         | 64           | 24                 | 28                  | 40            | 20.20          | 100          | 44                 | 64                  | 72            |
| 16.875         | 72           | 32                 | 48                  | 64            | 18.700         | 72           | 44                 | 64                  | 56            | 20.35          | 100          | 32                 | 56                  | 86            |
| 16.892         | 86           | 40                 | 44                  | 56            | 18.750         | 100          | 32                 | 24                  | 40            | 20.36          | 64           | 40                 | 56                  | 44            |
| 16.914         | 100          | 44                 | 64                  | 86            | 18.750         | 72           | 32                 | 40                  | 48            | 20.41          | 100          | 28                 | 32                  | 56            |
| 16.969         | 64           | 44                 | 56                  | 48            | 18.770         | 86           | 28                 | 44                  | 72            | 20.42          | 56           | 24                 | 28                  | 32            |
| 16.970         | 64           | 24                 | 28                  | 44            | 18.812         | 86           | 32                 | 28                  | 40            | 20.45          | 72           | 32                 | 40                  | 44            |
| 17.045         | 100          | 32                 | 24                  | 44            | 18.858         | 48           | 28                 | 44                  | 40            | 20.48          | 86           | 48                 | 64                  | 56            |
| 17.046         | 100          | 44                 | 48                  | 64            | 18.939         | 100          | 44                 | 40                  | 48            | 20.57          | 72           | 40                 | 64                  | 56            |
| 17.062         | 86           | 28                 | 40                  | 72            | 19.029         | 100          | 44                 | 72                  | 86            | 20.63          | 72           | 32                 | 44                  | 48            |
| 17.101         | 86           | 44                 | 56                  | 64            | 19.048         | 40           | 24                 | 32                  | 28            | 20.74          | 64           | 24                 | 56                  | 72            |
| 17.102         | 86           | 32                 | 28                  | 44            | 19.090         | 56           | 32                 | 48                  | 44            | 20.78          | 64           | 28                 | 40                  | 44            |
| 17.141         | 64           | 32                 | 48                  | 56            | 19.091         | 72           | 24                 | 28                  | 44            | 20.83          | 100          | 32                 | 48                  | 72            |
| 17.143         | 64           | 28                 | 24                  | 32            | 19.096         | 100          | 32                 | 44                  | 72            | 20.90          | 86           | 32                 | 56                  | 72            |
| 17.144         | 48           | 24                 | 24                  | 28            | 19.111         | 86           | 40                 | 64                  | 72            | 20.93          | 100          | 40                 | 72                  | 86            |
| 17.188         | 100          | 40                 | 44                  | 64            | 19.136         | 72           | 28                 | 64                  | 86            | 20.95          | 64           | 28                 | 44                  | 48            |
| 17.200         | 86           | 32                 | 64                  | 100           | 19.197         | 86           | 32                 | 40                  | 56            | 21.00          | 56           | 32                 | 48                  | 40            |
| 17.275         | 86           | 56                 | 72                  | 64            | 19.200         | 72           | 24                 | 64                  | 100           | 21.12          | 86           | 32                 | 44                  | 56            |
| 17.361         | 100          | 32                 | 40                  | 72            | 19.250         | 56           | 32                 | 44                  | 40            | 21.32          | 100          | 24                 | 44                  | 86            |
| 17.364         | 64           | 24                 | 56                  | 86            | 19.285         | 72           | 32                 | 48                  | 56            | 21.33          | 100          | 56                 | 86                  | 72            |
| 17.373         | 86           | 44                 | 64                  | 72            | 19.286         | 72           | 28                 | 24                  | 32            | 21.39          | 44           | 24                 | 28                  | 24            |

## Change Gears for Different Leads—21.43 Inches to 32.09 Inches

| Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        |
|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|
|                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |
| 21.43          | 100          | 40                 | 48                  | 56            | 24.88          | 100          | 72                 | 86                  | 48            | 28.05          | 72           | 28                 | 48                  | 44            |
| 21.48          | 100          | 32                 | 44                  | 64            | 24.93          | 64           | 28                 | 48                  | 44            | 28.06          | 100          | 28                 | 44                  | 56            |
| 21.50          | 86           | 24                 | 24                  | 40            | 25.00          | 72           | 24                 | 40                  | 48            | 28.13          | 100          | 40                 | 72                  | 64            |
| 21.82          | 72           | 44                 | 64                  | 48            | 25.08          | 86           | 24                 | 28                  | 40            | 28.15          | 86           | 28                 | 44                  | 48            |
| 21.88          | 100          | 40                 | 56                  | 64            | 25.09          | 86           | 40                 | 56                  | 48            | 28.29          | 72           | 28                 | 44                  | 40            |
| 21.90          | 86           | 24                 | 44                  | 72            | 25.13          | 86           | 44                 | 72                  | 56            | 28.41          | 100          | 32                 | 40                  | 44            |
| 21.94          | 86           | 28                 | 40                  | 56            | 25.14          | 64           | 28                 | 44                  | 40            | 28.57          | 100          | 56                 | 64                  | 40            |
| 21.99          | 86           | 44                 | 72                  | 64            | 25.45          | 64           | 44                 | 56                  | 32            | 28.64          | 72           | 44                 | 56                  | 32            |
| 22.00          | 64           | 32                 | 44                  | 40            | 25.46          | 100          | 24                 | 44                  | 72            | 28.65          | 100          | 32                 | 44                  | 48            |
| 22.04          | 72           | 28                 | 48                  | 56            | 25.51          | 100          | 28                 | 40                  | 56            | 28.67          | 86           | 40                 | 64                  | 48            |
| 22.11          | 86           | 28                 | 72                  | 100           | 25.57          | 100          | 64                 | 72                  | 44            | 29.09          | 64           | 24                 | 48                  | 44            |
| 22.22          | 100          | 40                 | 64                  | 72            | 25.60          | 86           | 28                 | 40                  | 48            | 29.17          | 100          | 40                 | 56                  | 48            |
| 22.34          | 86           | 44                 | 64                  | 56            | 25.67          | 56           | 24                 | 44                  | 40            | 29.22          | 100          | 56                 | 72                  | 44            |
| 22.40          | 86           | 32                 | 40                  | 48            | 25.71          | 72           | 24                 | 48                  | 56            | 29.32          | 86           | 48                 | 72                  | 44            |
| 22.50          | 72           | 24                 | 48                  | 64            | 25.72          | 72           | 24                 | 24                  | 28            | 29.34          | 64           | 24                 | 44                  | 40            |
| 22.73          | 100          | 24                 | 24                  | 44            | 25.80          | 86           | 24                 | 72                  | 100           | 29.39          | 72           | 28                 | 64                  | 56            |
| 22.80          | 86           | 48                 | 56                  | 44            | 25.97          | 100          | 44                 | 64                  | 56            | 29.56          | 86           | 32                 | 44                  | 40            |
| 22.86          | 64           | 24                 | 24                  | 28            | 26.04          | 100          | 32                 | 40                  | 48            | 29.76          | 100          | 28                 | 40                  | 48            |
| 22.91          | 72           | 44                 | 56                  | 40            | 26.06          | 86           | 44                 | 64                  | 48            | 29.86          | 100          | 40                 | 86                  | 72            |
| 22.92          | 100          | 40                 | 44                  | 48            | 26.16          | 100          | 32                 | 72                  | 86            | 29.90          | 100          | 28                 | 72                  | 86            |
| 22.93          | 86           | 24                 | 64                  | 100           | 26.18          | 72           | 40                 | 64                  | 44            | 30.00          | 56           | 28                 | 48                  | 32            |
| 23.04          | 86           | 56                 | 72                  | 48            | 26.19          | 44           | 24                 | 40                  | 28            | 30.23          | 86           | 32                 | 72                  | 64            |
| 23.14          | 100          | 24                 | 40                  | 72            | 26.25          | 72           | 32                 | 56                  | 48            | 30.30          | 100          | 48                 | 64                  | 44            |
| 23.26          | 100          | 32                 | 64                  | 86            | 26.33          | 86           | 28                 | 48                  | 56            | 30.48          | 64           | 24                 | 32                  | 28            |
| 23.33          | 64           | 32                 | 56                  | 48            | 26.52          | 100          | 44                 | 56                  | 48            | 30.54          | 100          | 44                 | 86                  | 64            |
| 23.38          | 72           | 28                 | 40                  | 44            | 26.58          | 100          | 28                 | 64                  | 86            | 30.56          | 44           | 24                 | 40                  | 24            |
| 23.44          | 100          | 48                 | 72                  | 64            | 26.67          | 64           | 28                 | 56                  | 48            | 30.61          | 100          | 28                 | 48                  | 56            |
| 23.45          | 86           | 40                 | 48                  | 44            | 26.79          | 100          | 48                 | 72                  | 56            | 30.71          | 86           | 24                 | 48                  | 56            |
| 23.52          | 86           | 32                 | 56                  | 64            | 26.88          | 86           | 28                 | 56                  | 64            | 30.72          | 86           | 24                 | 24                  | 28            |
| 23.57          | 72           | 28                 | 44                  | 48            | 27.00          | 72           | 32                 | 48                  | 40            | 30.86          | 72           | 28                 | 48                  | 40            |
| 23.81          | 100          | 48                 | 64                  | 56            | 27.13          | 100          | 24                 | 56                  | 86            | 31.01          | 100          | 24                 | 64                  | 86            |
| 23.89          | 86           | 32                 | 64                  | 72            | 27.15          | 100          | 44                 | 86                  | 72            | 31.11          | 64           | 24                 | 56                  | 48            |
| 24.00          | 64           | 40                 | 72                  | 48            | 27.22          | 56           | 24                 | 28                  | 24            | 31.25          | 100          | 28                 | 56                  | 64            |
| 24.13          | 86           | 28                 | 44                  | 56            | 27.27          | 100          | 40                 | 48                  | 44            | 31.27          | 86           | 40                 | 64                  | 44            |
| 24.19          | 86           | 40                 | 72                  | 64            | 27.30          | 86           | 28                 | 64                  | 72            | 31.35          | 86           | 32                 | 56                  | 48            |
| 24.24          | 64           | 24                 | 40                  | 44            | 27.34          | 100          | 32                 | 56                  | 64            | 31.36          | 86           | 24                 | 28                  | 32            |
| 24.31          | 100          | 32                 | 56                  | 72            | 27.36          | 86           | 40                 | 56                  | 44            | 31.43          | 64           | 28                 | 44                  | 32            |
| 24.43          | 86           | 32                 | 40                  | 44            | 27.43          | 64           | 28                 | 48                  | 40            | 31.50          | 72           | 32                 | 56                  | 40            |
| 24.44          | 44           | 24                 | 32                  | 24            | 27.50          | 56           | 32                 | 44                  | 28            | 31.75          | 100          | 72                 | 64                  | 28            |
| 24.54          | 72           | 32                 | 48                  | 44            | 27.64          | 86           | 40                 | 72                  | 56            | 31.82          | 100          | 44                 | 56                  | 40            |
| 24.55          | 100          | 32                 | 44                  | 56            | 27.78          | 100          | 32                 | 64                  | 72            | 31.85          | 86           | 24                 | 64                  | 72            |
| 24.57          | 86           | 40                 | 64                  | 56            | 27.87          | 86           | 24                 | 56                  | 72            | 31.99          | 100          | 56                 | 86                  | 48            |
| 24.64          | 86           | 24                 | 44                  | 64            | 27.92          | 86           | 28                 | 40                  | 44            | 32.00          | 64           | 28                 | 56                  | 40            |
| 24.75          | 72           | 32                 | 44                  | 40            | 28.00          | 100          | 64                 | 86                  | 48            | 32.09          | 56           | 24                 | 44                  | 32            |

Change Gears for Different Leads—32.14 Inches to 60.00 Inches

| Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        | Lead in Inches | Driven       | Driver             | Driven              | Driver        |
|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|----------------|--------------|--------------------|---------------------|---------------|
|                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |                | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw |
| 32.14          | 100          | 56                 | 72                  | 40            | 38.20          | 100          | 24                 | 44                  | 48            | 46.07          | 86           | 28                 | 72                  | 48            |
| 32.25          | 86           | 48                 | 72                  | 40            | 38.39          | 100          | 40                 | 86                  | 56            | 46.67          | 64           | 24                 | 56                  | 32            |
| 32.41          | 100          | 24                 | 56                  | 72            | 38.57          | 72           | 28                 | 48                  | 32            | 46.88          | 100          | 32                 | 72                  | 48            |
| 32.47          | 100          | 28                 | 40                  | 44            | 38.89          | 56           | 24                 | 40                  | 24            | 47.15          | 72           | 24                 | 44                  | 28            |
| 32.58          | 86           | 24                 | 40                  | 44            | 38.96          | 100          | 28                 | 48                  | 44            | 47.62          | 100          | 28                 | 64                  | 48            |
| 32.73          | 72           | 32                 | 64                  | 44            | 39.09          | 86           | 32                 | 64                  | 44            | 47.78          | 86           | 24                 | 64                  | 48            |
| 32.74          | 100          | 28                 | 44                  | 48            | 39.29          | 100          | 28                 | 44                  | 40            | 47.99          | 100          | 32                 | 86                  | 56            |
| 32.85          | 86           | 24                 | 44                  | 48            | 39.42          | 86           | 24                 | 44                  | 40            | 48.00          | 72           | 24                 | 64                  | 40            |
| 33.00          | 72           | 24                 | 44                  | 40            | 39.49          | 86           | 28                 | 72                  | 56            | 48.38          | 86           | 32                 | 72                  | 40            |
| 33.33          | 100          | 24                 | 32                  | 40            | 39.77          | 100          | 32                 | 56                  | 44            | 48.61          | 100          | 24                 | 56                  | 48            |
| 33.51          | 86           | 28                 | 48                  | 44            | 40.00          | 72           | 24                 | 64                  | 48            | 48.86          | 100          | 40                 | 86                  | 44            |
| 33.59          | 100          | 64                 | 86                  | 40            | 40.18          | 100          | 32                 | 72                  | 56            | 48.89          | 64           | 24                 | 44                  | 24            |
| 33.79          | 86           | 28                 | 44                  | 40            | 40.31          | 86           | 32                 | 72                  | 48            | 49.11          | 100          | 28                 | 44                  | 32            |
| 33.94          | 64           | 24                 | 56                  | 44            | 40.72          | 100          | 44                 | 86                  | 48            | 49.14          | 86           | 28                 | 64                  | 40            |
| 34.09          | 100          | 48                 | 72                  | 44            | 40.82          | 100          | 28                 | 64                  | 56            | 49.27          | 86           | 24                 | 44                  | 32            |
| 34.20          | 86           | 44                 | 56                  | 32            | 40.91          | 100          | 40                 | 72                  | 44            | 49.77          | 100          | 24                 | 86                  | 72            |
| 34.29          | 72           | 48                 | 64                  | 28            | 40.95          | 86           | 28                 | 64                  | 48            | 50.00          | 100          | 28                 | 56                  | 40            |
| 34.38          | 100          | 32                 | 44                  | 40            | 40.96          | 86           | 24                 | 32                  | 28            | 50.17          | 86           | 24                 | 56                  | 40            |
| 34.55          | 86           | 32                 | 72                  | 56            | 41.14          | 72           | 28                 | 64                  | 40            | 50.26          | 86           | 28                 | 72                  | 44            |
| 34.72          | 100          | 24                 | 40                  | 48            | 41.25          | 72           | 24                 | 44                  | 32            | 51.14          | 100          | 32                 | 72                  | 44            |
| 34.88          | 100          | 24                 | 72                  | 86            | 41.67          | 100          | 32                 | 64                  | 48            | 51.19          | 86           | 24                 | 40                  | 28            |
| 34.90          | 100          | 56                 | 86                  | 44            | 41.81          | 86           | 24                 | 56                  | 48            | 51.43          | 72           | 28                 | 64                  | 32            |
| 35.00          | 72           | 24                 | 56                  | 48            | 41.91          | 64           | 24                 | 44                  | 28            | 51.95          | 100          | 28                 | 64                  | 44            |
| 35.10          | 86           | 28                 | 64                  | 56            | 41.99          | 100          | 32                 | 86                  | 64            | 52.12          | 86           | 24                 | 64                  | 44            |
| 35.16          | 100          | 32                 | 72                  | 64            | 42.00          | 72           | 24                 | 56                  | 40            | 52.50          | 72           | 24                 | 56                  | 32            |
| 35.18          | 86           | 44                 | 72                  | 40            | 42.23          | 86           | 28                 | 44                  | 32            | 53.03          | 100          | 24                 | 56                  | 44            |
| 35.36          | 72           | 32                 | 44                  | 28            | 42.66          | 100          | 28                 | 86                  | 72            | 53.33          | 64           | 24                 | 56                  | 28            |
| 35.56          | 64           | 24                 | 32                  | 24            | 42.78          | 56           | 24                 | 44                  | 24            | 53.57          | 100          | 28                 | 72                  | 48            |
| 35.71          | 100          | 32                 | 64                  | 56            | 42.86          | 100          | 28                 | 48                  | 40            | 53.75          | 86           | 24                 | 48                  | 32            |
| 35.72          | 100          | 24                 | 24                  | 28            | 43.00          | 86           | 32                 | 64                  | 40            | 54.85          | 100          | 28                 | 86                  | 56            |
| 35.83          | 86           | 32                 | 64                  | 48            | 43.64          | 72           | 24                 | 64                  | 44            | 55.00          | 72           | 24                 | 44                  | 24            |
| 36.00          | 72           | 32                 | 64                  | 40            | 43.75          | 100          | 32                 | 56                  | 40            | 55.28          | 86           | 28                 | 72                  | 40            |
| 36.36          | 100          | 44                 | 64                  | 40            | 43.98          | 86           | 32                 | 72                  | 44            | 55.56          | 100          | 24                 | 32                  | 24            |
| 36.46          | 100          | 48                 | 56                  | 32            | 44.44          | 64           | 24                 | 40                  | 24            | 55.99          | 100          | 24                 | 86                  | 64            |
| 36.67          | 48           | 24                 | 44                  | 24            | 44.64          | 100          | 28                 | 40                  | 32            | 56.25          | 100          | 32                 | 72                  | 40            |
| 36.86          | 86           | 28                 | 48                  | 40            | 44.68          | 86           | 28                 | 64                  | 44            | 56.31          | 86           | 24                 | 44                  | 28            |
| 37.04          | 100          | 24                 | 64                  | 72            | 44.79          | 100          | 40                 | 86                  | 48            | 57.14          | 100          | 28                 | 64                  | 40            |
| 37.33          | 100          | 32                 | 86                  | 72            | 45.00          | 72           | 28                 | 56                  | 32            | 57.30          | 100          | 24                 | 44                  | 32            |
| 37.40          | 72           | 28                 | 64                  | 44            | 45.45          | 100          | 32                 | 64                  | 44            | 57.33          | 86           | 24                 | 64                  | 40            |
| 37.50          | 100          | 48                 | 72                  | 40            | 45.46          | 100          | 28                 | 56                  | 44            | 58.33          | 100          | 24                 | 56                  | 40            |
| 37.63          | 86           | 32                 | 56                  | 40            | 45.61          | 86           | 24                 | 56                  | 44            | 58.44          | 100          | 28                 | 72                  | 44            |
| 37.88          | 100          | 24                 | 40                  | 44            | 45.72          | 64           | 24                 | 48                  | 28            | 58.64          | 86           | 24                 | 72                  | 44            |
| 38.10          | 64           | 24                 | 40                  | 28            | 45.84          | 100          | 24                 | 44                  | 40            | 59.53          | 100          | 24                 | 40                  | 28            |
| 38.18          | 72           | 24                 | 56                  | 44            | 45.92          | 100          | 28                 | 72                  | 56            | 60.00          | 72           | 24                 | 64                  | 32            |

## Lead of Helix for Given Helix Angle Relative to Axis, When Diameter = 1

| Deg. | 0'      | 6'       | 12'     | 18'     | 24'     | 30'     | 36'     | 42'     | 48'     | 54'     | 60'     |
|------|---------|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0    | Infin.  | 1800.001 | 899.997 | 599.994 | 449.993 | 359.992 | 299.990 | 257.130 | 224.986 | 199.983 | 179.982 |
| 1    | 179.982 | 163.616  | 149.978 | 138.438 | 128.545 | 119.973 | 112.471 | 105.851 | 99.967  | 94.702  | 89.964  |
| 2    | 89.964  | 85.676   | 81.778  | 78.219  | 74.956  | 71.954  | 69.183  | 66.617  | 64.235  | 62.016  | 59.945  |
| 3    | 59.945  | 58.008   | 56.191  | 54.485  | 52.879  | 51.365  | 49.934  | 48.581  | 47.299  | 46.082  | 44.927  |
| 4    | 44.927  | 43.827   | 42.780  | 41.782  | 40.829  | 39.918  | 39.046  | 38.212  | 37.412  | 36.645  | 35.909  |
| 5    | 35.909  | 35.201   | 34.520  | 33.866  | 33.235  | 32.627  | 32.040  | 31.475  | 30.928  | 30.400  | 29.890  |
| 6    | 29.890  | 29.397   | 28.919  | 28.456  | 28.008  | 27.573  | 27.152  | 26.743  | 26.346  | 25.961  | 25.586  |
| 7    | 25.586  | 25.222   | 24.868  | 24.524  | 24.189  | 23.863  | 23.545  | 23.236  | 22.934  | 22.640  | 22.354  |
| 8    | 22.354  | 22.074   | 21.801  | 21.535  | 21.275  | 21.021  | 20.773  | 20.530  | 20.293  | 20.062  | 19.835  |
| 9    | 19.835  | 19.614   | 19.397  | 19.185  | 18.977  | 18.773  | 18.574  | 18.379  | 18.188  | 18.000  | 17.817  |
| 10   | 17.817  | 17.637   | 17.460  | 17.287  | 17.117  | 16.950  | 16.787  | 16.626  | 16.469  | 16.314  | 16.162  |
| 11   | 16.162  | 16.013   | 15.866  | 15.722  | 15.581  | 15.441  | 15.305  | 15.170  | 15.038  | 14.908  | 14.780  |
| 12   | 14.780  | 14.654   | 14.530  | 14.409  | 14.289  | 14.171  | 14.055  | 13.940  | 13.828  | 13.717  | 13.608  |
| 13   | 13.608  | 13.500   | 13.394  | 13.290  | 13.187  | 13.086  | 12.986  | 12.887  | 12.790  | 12.695  | 12.600  |
| 14   | 12.600  | 12.507   | 12.415  | 12.325  | 12.237  | 12.148  | 12.061  | 11.975  | 11.890  | 11.807  | 11.725  |
| 15   | 11.725  | 11.643   | 11.563  | 11.484  | 11.405  | 11.328  | 11.252  | 11.177  | 11.102  | 11.029  | 10.956  |
| 16   | 10.956  | 10.884   | 10.813  | 10.743  | 10.674  | 10.606  | 10.538  | 10.471  | 10.405  | 10.340  | 10.276  |
| 17   | 10.276  | 10.212   | 10.149  | 10.086  | 10.025  | 9.964   | 9.904   | 9.844   | 9.785   | 9.727   | 9.669   |
| 18   | 9.669   | 9.612    | 9.555   | 9.499   | 9.444   | 9.389   | 9.335   | 9.281   | 9.228   | 9.176   | 9.124   |
| 19   | 9.124   | 9.072    | 9.021   | 8.971   | 8.921   | 8.872   | 8.823   | 8.774   | 8.726   | 8.679   | 8.631   |
| 20   | 8.631   | 8.585    | 8.539   | 8.493   | 8.447   | 8.403   | 8.358   | 8.314   | 8.270   | 8.227   | 8.184   |
| 21   | 8.184   | 8.142    | 8.099   | 8.058   | 8.016   | 7.975   | 7.935   | 7.894   | 7.855   | 7.815   | 7.776   |
| 22   | 7.776   | 7.737    | 7.698   | 7.660   | 7.622   | 7.584   | 7.547   | 7.510   | 7.474   | 7.437   | 7.401   |
| 23   | 7.401   | 7.365    | 7.330   | 7.295   | 7.260   | 7.225   | 7.191   | 7.157   | 7.123   | 7.089   | 7.056   |
| 24   | 7.056   | 7.023    | 6.990   | 6.958   | 6.926   | 6.894   | 6.862   | 6.830   | 6.799   | 6.768   | 6.737   |
| 25   | 6.737   | 6.707    | 6.676   | 6.646   | 6.617   | 6.586   | 6.557   | 6.528   | 6.499   | 6.470   | 6.441   |
| 26   | 6.441   | 6.413    | 6.385   | 6.357   | 6.329   | 6.300   | 6.274   | 6.246   | 6.219   | 6.192   | 6.166   |
| 27   | 6.166   | 6.139    | 6.113   | 6.087   | 6.061   | 6.035   | 6.009   | 5.984   | 5.959   | 5.933   | 5.908   |
| 28   | 5.908   | 5.884    | 5.859   | 5.835   | 5.810   | 5.786   | 5.762   | 5.738   | 5.715   | 5.691   | 5.668   |
| 29   | 5.668   | 5.644    | 5.621   | 5.598   | 5.575   | 5.553   | 5.530   | 5.508   | 5.486   | 5.463   | 5.441   |

## Lead of Helix for Given Helix Angle Relative to Axis, When Diameter = 1(Continued)

| Deg. | 0'    | 6'    | 12'   | 18'   | 24'   | 30'   | 36'   | 42'   | 48'   | 54'   | 60'   |
|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 30   | 5.441 | 5.420 | 5.398 | 5.376 | 5.355 | 5.333 | 5.312 | 5.291 | 5.270 | 5.249 | 5.228 |
| 31   | 5.228 | 5.208 | 5.187 | 5.167 | 5.147 | 5.127 | 5.107 | 5.087 | 5.067 | 5.047 | 5.028 |
| 32   | 5.028 | 5.008 | 4.989 | 4.969 | 4.950 | 4.931 | 4.912 | 4.894 | 4.875 | 4.856 | 4.838 |
| 33   | 4.838 | 4.819 | 4.801 | 4.783 | 4.764 | 4.746 | 4.728 | 4.711 | 4.693 | 4.675 | 4.658 |
| 34   | 4.658 | 4.640 | 4.623 | 4.605 | 4.588 | 4.571 | 4.554 | 4.537 | 4.520 | 4.503 | 4.487 |
| 35   | 4.487 | 4.470 | 4.453 | 4.437 | 4.421 | 4.404 | 4.388 | 4.372 | 4.356 | 4.340 | 4.324 |
| 36   | 4.324 | 4.308 | 4.292 | 4.277 | 4.261 | 4.246 | 4.230 | 4.215 | 4.199 | 4.184 | 4.169 |
| 37   | 4.169 | 4.154 | 4.139 | 4.124 | 4.109 | 4.094 | 4.079 | 4.065 | 4.050 | 4.036 | 4.021 |
| 38   | 4.021 | 4.007 | 3.992 | 3.978 | 3.964 | 3.950 | 3.935 | 3.921 | 3.907 | 3.893 | 3.880 |
| 39   | 3.880 | 3.866 | 3.852 | 3.838 | 3.825 | 3.811 | 3.798 | 3.784 | 3.771 | 3.757 | 3.744 |
| 40   | 3.744 | 3.731 | 3.718 | 3.704 | 3.691 | 3.678 | 3.665 | 3.652 | 3.640 | 3.627 | 3.614 |
| 41   | 3.614 | 3.601 | 3.589 | 3.576 | 3.563 | 3.551 | 3.538 | 3.526 | 3.514 | 3.501 | 3.489 |
| 42   | 3.489 | 3.477 | 3.465 | 3.453 | 3.440 | 3.428 | 3.416 | 3.405 | 3.393 | 3.381 | 3.369 |
| 43   | 3.369 | 3.358 | 3.346 | 3.334 | 3.322 | 3.311 | 3.299 | 3.287 | 3.276 | 3.265 | 3.253 |
| 44   | 3.253 | 3.242 | 3.231 | 3.219 | 3.208 | 3.197 | 3.186 | 3.175 | 3.164 | 3.153 | 3.142 |
| 45   | 3.142 | 3.131 | 3.120 | 3.109 | 3.098 | 3.087 | 3.076 | 3.066 | 3.055 | 3.044 | 3.034 |
| 46   | 3.034 | 3.023 | 3.013 | 3.002 | 2.992 | 2.981 | 2.971 | 2.960 | 2.950 | 2.940 | 2.930 |
| 47   | 2.930 | 2.919 | 2.909 | 2.899 | 2.889 | 2.879 | 2.869 | 2.859 | 2.849 | 2.839 | 2.829 |
| 48   | 2.829 | 2.819 | 2.809 | 2.799 | 2.789 | 2.779 | 2.770 | 2.760 | 2.750 | 2.741 | 2.731 |
| 49   | 2.731 | 2.721 | 2.712 | 2.702 | 2.693 | 2.683 | 2.674 | 2.664 | 2.655 | 2.645 | 2.636 |
| 50   | 2.636 | 2.627 | 2.617 | 2.608 | 2.599 | 2.590 | 2.581 | 2.571 | 2.562 | 2.553 | 2.544 |
| 51   | 2.544 | 2.535 | 2.526 | 2.517 | 2.508 | 2.499 | 2.490 | 2.481 | 2.472 | 2.463 | 2.454 |
| 52   | 2.454 | 2.446 | 2.437 | 2.428 | 2.419 | 2.411 | 2.402 | 2.393 | 2.385 | 2.376 | 2.367 |
| 53   | 2.367 | 2.359 | 2.350 | 2.342 | 2.333 | 2.325 | 2.316 | 2.308 | 2.299 | 2.291 | 2.282 |
| 54   | 2.282 | 2.274 | 2.266 | 2.257 | 2.249 | 2.241 | 2.233 | 2.224 | 2.216 | 2.208 | 2.200 |
| 55   | 2.200 | 2.192 | 2.183 | 2.175 | 2.167 | 2.159 | 2.151 | 2.143 | 2.135 | 2.127 | 2.119 |
| 56   | 2.119 | 2.111 | 2.103 | 2.095 | 2.087 | 2.079 | 2.072 | 2.064 | 2.056 | 2.048 | 2.040 |
| 57   | 2.040 | 2.032 | 2.025 | 2.017 | 2.009 | 2.001 | 1.994 | 1.986 | 1.978 | 1.971 | 1.963 |
| 58   | 1.963 | 1.955 | 1.948 | 1.940 | 1.933 | 1.925 | 1.918 | 1.910 | 1.903 | 1.895 | 1.888 |
| 59   | 1.888 | 1.880 | 1.873 | 1.865 | 1.858 | 1.851 | 1.843 | 1.836 | 1.828 | 1.821 | 1.814 |

Lead of Helix for Given Helix Angle Relative to Axis, When Diameter = 1(Continued)

| Deg. | 0'    | 6'    | 12'   | 18'   | 24'   | 30'   | 36'   | 42'   | 48'   | 54'   | 60'   |
|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 60   | 1.814 | 1.806 | 1.799 | 1.792 | 1.785 | 1.777 | 1.770 | 1.763 | 1.756 | 1.749 | 1.741 |
| 61   | 1.741 | 1.734 | 1.727 | 1.720 | 1.713 | 1.706 | 1.699 | 1.692 | 1.685 | 1.677 | 1.670 |
| 62   | 1.670 | 1.663 | 1.656 | 1.649 | 1.642 | 1.635 | 1.628 | 1.621 | 1.615 | 1.608 | 1.601 |
| 63   | 1.601 | 1.594 | 1.587 | 1.580 | 1.573 | 1.566 | 1.559 | 1.553 | 1.546 | 1.539 | 1.532 |
| 64   | 1.532 | 1.525 | 1.519 | 1.512 | 1.505 | 1.498 | 1.492 | 1.485 | 1.478 | 1.472 | 1.465 |
| 65   | 1.465 | 1.458 | 1.452 | 1.445 | 1.438 | 1.432 | 1.425 | 1.418 | 1.412 | 1.405 | 1.399 |
| 66   | 1.399 | 1.392 | 1.386 | 1.379 | 1.372 | 1.366 | 1.359 | 1.353 | 1.346 | 1.340 | 1.334 |
| 67   | 1.334 | 1.327 | 1.321 | 1.314 | 1.308 | 1.301 | 1.295 | 1.288 | 1.282 | 1.276 | 1.269 |
| 68   | 1.269 | 1.263 | 1.257 | 1.250 | 1.244 | 1.237 | 1.231 | 1.225 | 1.219 | 1.212 | 1.206 |
| 69   | 1.206 | 1.200 | 1.193 | 1.187 | 1.181 | 1.175 | 1.168 | 1.162 | 1.156 | 1.150 | 1.143 |
| 70   | 1.143 | 1.137 | 1.131 | 1.125 | 1.119 | 1.112 | 1.106 | 1.100 | 1.094 | 1.088 | 1.082 |
| 71   | 1.082 | 1.076 | 1.069 | 1.063 | 1.057 | 1.051 | 1.045 | 1.039 | 1.033 | 1.027 | 1.021 |
| 72   | 1.021 | 1.015 | 1.009 | 1.003 | 0.997 | 0.991 | 0.985 | 0.978 | 0.972 | 0.966 | 0.960 |
| 73   | 0.960 | 0.954 | 0.948 | 0.943 | 0.937 | 0.931 | 0.925 | 0.919 | 0.913 | 0.907 | 0.901 |
| 74   | 0.901 | 0.895 | 0.889 | 0.883 | 0.877 | 0.871 | 0.865 | 0.859 | 0.854 | 0.848 | 0.842 |
| 75   | 0.842 | 0.836 | 0.830 | 0.824 | 0.818 | 0.812 | 0.807 | 0.801 | 0.795 | 0.789 | 0.783 |
| 76   | 0.783 | 0.777 | 0.772 | 0.766 | 0.760 | 0.754 | 0.748 | 0.743 | 0.737 | 0.731 | 0.725 |
| 77   | 0.725 | 0.720 | 0.714 | 0.708 | 0.702 | 0.696 | 0.691 | 0.685 | 0.679 | 0.673 | 0.668 |
| 78   | 0.668 | 0.662 | 0.656 | 0.651 | 0.645 | 0.639 | 0.633 | 0.628 | 0.622 | 0.616 | 0.611 |
| 79   | 0.611 | 0.605 | 0.599 | 0.594 | 0.588 | 0.582 | 0.577 | 0.571 | 0.565 | 0.560 | 0.554 |
| 80   | 0.554 | 0.548 | 0.543 | 0.537 | 0.531 | 0.526 | 0.520 | 0.514 | 0.509 | 0.503 | 0.498 |
| 81   | 0.498 | 0.492 | 0.486 | 0.481 | 0.475 | 0.469 | 0.464 | 0.458 | 0.453 | 0.447 | 0.441 |
| 82   | 0.441 | 0.436 | 0.430 | 0.425 | 0.419 | 0.414 | 0.408 | 0.402 | 0.397 | 0.391 | 0.386 |
| 83   | 0.386 | 0.380 | 0.375 | 0.369 | 0.363 | 0.358 | 0.352 | 0.347 | 0.341 | 0.336 | 0.330 |
| 84   | 0.330 | 0.325 | 0.319 | 0.314 | 0.308 | 0.302 | 0.297 | 0.291 | 0.286 | 0.280 | 0.275 |
| 85   | 0.275 | 0.269 | 0.264 | 0.258 | 0.253 | 0.247 | 0.242 | 0.236 | 0.231 | 0.225 | 0.220 |
| 86   | 0.220 | 0.214 | 0.209 | 0.203 | 0.198 | 0.192 | 0.187 | 0.181 | 0.176 | 0.170 | 0.165 |
| 87   | 0.165 | 0.159 | 0.154 | 0.148 | 0.143 | 0.137 | 0.132 | 0.126 | 0.121 | 0.115 | 0.110 |
| 88   | 0.110 | 0.104 | 0.099 | 0.093 | 0.088 | 0.082 | 0.077 | 0.071 | 0.066 | 0.060 | 0.055 |
| 89   | 0.055 | 0.049 | 0.044 | 0.038 | 0.033 | 0.027 | 0.022 | 0.016 | 0.011 | 0.005 | 0.000 |



Leads, Change Gears and Angles for Helical Milling

| Lead of Helix, Inches | Change Gears |                    |                     |               | Diameter of Work, Inches                     |        |        |        |        |        |        |        |        |        |  |  |
|-----------------------|--------------|--------------------|---------------------|---------------|--|--------|--------|--------|--------|--------|--------|--------|--------|--------|--|--|
|                       | Gear on Work | First Gear on Stud | Second Gear on Stud | Gear on Screw | 1/8  | 1/4    | 3/8    | 1/2    | 5/8    | 3/4    | 7/8    | 1      | 1 1/4  | 1 1/2  |  |  |
|                       |              |                    |                     |               | Approximate Angles for Milling Machine Table |        |        |        |        |        |        |        |        |        |  |  |
| 0.67                  | 24           | 86                 | 24                  | 100           | 30 1/4                                       | ...    | ...    | ...    | ...    | ...    | ...    | ...    | ...    | ...    |  |  |
| 0.78                  | 24           | 86                 | 28                  | 100           | 26   | 44 1/2 | ...    | ...    | ...    | ...    | ...    | ...    | ...    | ...    |  |  |
| 0.89                  | 24           | 86                 | 32                  | 100           | 23 1/2                                       | 41     | ...    | ...    | ...    | ...    | ...    | ...    | ...    | ...    |  |  |
| 1.12                  | 24           | 86                 | 40                  | 100           | 19   | 34 1/2 | ...    | ...    | ...    | ...    | ...    | ...    | ...    | ...    |  |  |
| 1.34                  | 24           | 86                 | 48                  | 100           | 16   | 30 1/4 | 41 1/2 | ...    | ...    | ...    | ...    | ...    | ...    | ...    |  |  |
| 1.46                  | 24           | 64                 | 28                  | 72            | 14 3/4                                       | 28     | 38 1/2 | ...    | ...    | ...    | ...    | ...    | ...    | ...    |  |  |
| 1.56                  | 24           | 86                 | 56                  | 100           | 13 1/2                                       | 26 1/2 | 37     | ...    | ...    | ...    | ...    | ...    | ...    | ...    |  |  |
| 1.67                  | 24           | 64                 | 32                  | 72            | 12 3/4                                       | 25     | 34 3/4 | 43 3/4 | ...    | ...    | ...    | ...    | ...    | ...    |  |  |
| 1.94                  | 32           | 64                 | 28                  | 72            | 11 1/4                                       | 21 3/4 | 31     | 39     | 45     | ...    | ...    | ...    | ...    | ...    |  |  |
| 2.08                  | 24           | 64                 | 40                  | 72            | 10 1/4                                       | 20 1/2 | 29 1/2 | 37     | 43 1/4 | ...    | ...    | ...    | ...    | ...    |  |  |
| 2.22                  | 32           | 56                 | 28                  | 72            | 9 3/4  | 19 1/4 | 27 1/2 | 35     | 41 1/4 | ...    | ...    | ...    | ...    | ...    |  |  |
| 2.50                  | 24           | 64                 | 48                  | 72            | 8 3/4  | 17     | 25     | 32     | 38     | 43 1/2 | ...    | ...    | ...    | ...    |  |  |
| 2.78                  | 40           | 56                 | 28                  | 72            | 8  | 15 1/2 | 23     | 29 1/2 | 35 1/4 | 40 1/2 | 44 3/4 | ...    | ...    | ...    |  |  |
| 2.92                  | 24           | 64                 | 56                  | 72            | 7 1/2  | 15     | 21 3/4 | 28 1/4 | 34     | 39     | 43 1/4 | ...    | ...    | ...    |  |  |
| 3.24                  | 40           | 48                 | 28                  | 72            | 6 3/4  | 13 1/4 | 19 3/4 | 25 3/4 | 31 1/4 | 36     | 40 1/2 | 44 1/2 | ...    | ...    |  |  |
| 3.70                  | 40           | 48                 | 32                  | 72            | 6  | 11 3/4 | 17 1/2 | 23     | 28     | 32 1/2 | 36 1/2 | 40 1/2 | ...    | ...    |  |  |
| 3.89                  | 56           | 48                 | 24                  | 72            | 5 1/2  | 11 1/4 | 16 3/4 | 22     | 26 3/4 | 31 1/4 | 35 3/4 | 39     | ...    | ...    |  |  |
| 4.17                  | 40           | 72                 | 48                  | 64            | 5 1/4  | 10 1/2 | 15 3/4 | 20 1/2 | 25 1/4 | 29 1/2 | 33 1/2 | 37     | 43 1/4 | ...    |  |  |
| 4.46                  | 48           | 40                 | 32                  | 86            | 4 3/4  | 9 3/4  | 14 3/4 | 19 1/4 | 23 3/4 | 27 3/4 | 31 1/2 | 35     | 41 1/2 | ...    |  |  |
| 4.86                  | 40           | 64                 | 56                  | 72            | 4 1/2  | 9      | 13 1/2 | 17 3/4 | 22     | 25 3/4 | 29 1/2 | 33     | 39     | 44 1/4 |  |  |
| 5.33                  | 48           | 40                 | 32                  | 72            | 4  | 8 1/4  | 12 1/4 | 16 1/2 | 20 1/4 | 23 3/4 | 27 1/4 | 30 1/2 | 36 1/2 | 41 1/2 |  |  |
| 5.44                  | 56           | 40                 | 28                  | 72            | 4  | 8      | 12     | 16     | 20     | 23 1/2 | 26 3/4 | 30     | 36     | 41     |  |  |
| 6.12                  | 56           | 40                 | 28                  | 64            | 3 1/2  | 7 1/4  | 11     | 14 1/2 | 17 3/4 | 21     | 24 1/4 | 27     | 33     | 37 3/4 |  |  |
| 6.22                  | 56           | 40                 | 32                  | 72            | 3 1/2  | 7      | 10 3/4 | 14 1/4 | 17 1/2 | 20 3/4 | 23 3/4 | 26 3/4 | 32 1/2 | 37 1/4 |  |  |
| 6.48                  | 56           | 48                 | 40                  | 72            | 3 1/4  | 6 3/4  | 10 1/4 | 13 1/2 | 16 3/4 | 20     | 23     | 25 3/4 | 31 1/2 | 36 1/4 |  |  |
| 6.67                  | 64           | 48                 | 28                  | 56            | 3 1/4  | 6 1/2  | 10     | 13 1/4 | 16 1/2 | 19 1/2 | 22 1/2 | 25 1/4 | 30 3/4 | 35 1/4 |  |  |
| 7.29                  | 56           | 48                 | 40                  | 64            | 3  | 6 1/4  | 9 1/4  | 12 1/4 | 15     | 18     | 20 1/2 | 23 1/2 | 28 1/2 | 33     |  |  |
| 7.41                  | 64           | 48                 | 40                  | 72            | 3  | 6      | 9      | 12     | 14 3/4 | 17 1/2 | 20 1/4 | 22 3/4 | 28 1/4 | 32 1/2 |  |  |
| 7.62                  | 64           | 48                 | 32                  | 56            | 2 3/4  | 5 3/4  | 8 3/4  | 11 1/2 | 14 1/2 | 17 1/4 | 19 3/4 | 22 1/4 | 27 1/2 | 32     |  |  |
| 8.33                  | 48           | 32                 | 40                  | 72            | 2 1/2  | 5 1/4  | 8      | 10 1/2 | 13 1/4 | 15 3/4 | 18 1/4 | 20 1/2 | 25 1/2 | 29 1/2 |  |  |
| 8.95                  | 86           | 48                 | 28                  | 56            | 2 1/2  | 5      | 7 1/2  | 10     | 12 1/2 | 15 1/4 | 17 3/4 | 19 1/4 | 24     | 28     |  |  |
| 9.33                  | 56           | 40                 | 48                  | 72            | 2 1/4  | 4 3/4  | 7 1/4  | 9 1/2  | 11 3/4 | 14     | 16 1/4 | 18 1/2 | 23     | 27     |  |  |
| 9.52                  | 64           | 48                 | 40                  | 56            | 2 1/4  | 4 1/2  | 7      | 9 1/4  | 11 1/2 | 13 3/4 | 16     | 18 1/4 | 22     | 26 1/2 |  |  |
| 10.29                 | 72           | 40                 | 32                  | 56            | 2  | 4 1/4  | 6 1/2  | 8 3/4  | 10 3/4 | 12 3/4 | 15     | 17 1/4 | 21     | 24 1/2 |  |  |
| 10.37                 | 64           | 48                 | 56                  | 72            | 2  | 4 1/4  | 6 1/2  | 8 1/2  | 10 1/2 | 12 3/4 | 14 3/4 | 17     | 20 3/4 | 24 1/2 |  |  |
| 10.50                 | 48           | 40                 | 56                  | 64            | 2  | 4 1/4  | 6 1/4  | 8 1/2  | 10 1/2 | 12 1/2 | 14 1/2 | 16 1/4 | 20 1/2 | 24 1/4 |  |  |
| 10.67                 | 64           | 40                 | 48                  | 72            | 2  | 4      | 6 1/4  | 8 1/4  | 10 1/4 | 12 1/4 | 14 1/4 | 16 1/2 | 20 1/4 | 24     |  |  |
| 10.94                 | 56           | 32                 | 40                  | 64            | 2  | 4      | 6      | 8 1/4  | 10 1/4 | 12     | 14     | 16 1/4 | 20     | 23 1/2 |  |  |
| 11.11                 | 64           | 32                 | 40                  | 72            | 2  | 4      | 6      | 8      | 10     | 11 3/4 | 13 3/4 | 16     | 19 3/4 | 23     |  |  |
| 11.66                 | 56           | 32                 | 48                  | 72            | 1 3/4  | 3 3/4  | 5 3/4  | 7 1/2  | 9 1/2  | 11 1/4 | 13 1/4 | 15 1/4 | 18 3/4 | 22     |  |  |
| 12.00                 | 72           | 40                 | 32                  | 48            | 1 3/4  | 3 3/4  | 5 1/2  | 7 1/4  | 9 1/4  | 11     | 12 3/4 | 15     | 18 1/4 | 21 1/2 |  |  |
| 13.12                 | 56           | 32                 | 48                  | 64            | 1 1/2  | 3 1/2  | 5 1/4  | 6 3/4  | 8 1/2  | 10 1/4 | 11 3/4 | 13 1/2 | 16 3/4 | 20     |  |  |
| 13.33                 | 56           | 28                 | 48                  | 72            | 1 1/2  | 3 1/4  | 5      | 6 1/2  | 8 1/4  | 10     | 11 1/2 | 13 1/4 | 16 1/2 | 19 1/2 |  |  |
| 13.71                 | 64           | 40                 | 48                  | 56            | 1 1/2  | 3 3/4  | 4 3/4  | 6 1/2  | 8      | 9 3/4  | 11 1/4 | 13     | 16     | 19     |  |  |
| 15.24                 | 64           | 28                 | 48                  | 72            | 1 1/2  | 3      | 4 1/2  | 5 3/4  | 7 1/4  | 8 3/4  | 10 1/4 | 11 3/4 | 14 1/2 | 17 1/4 |  |  |
| 15.56                 | 64           | 32                 | 56                  | 72            | 1 1/4  | 2 3/4  | 4 1/4  | 5 3/4  | 7 1/4  | 8 1/2  | 10     | 11 1/2 | 14 1/4 | 17     |  |  |
| 15.75                 | 56           | 64                 | 72                  | 40            | 1 1/4  | 2 3/4  | 4 1/4  | 5 1/2  | 7      | 8 1/2  | 9 3/4  | 11 1/4 | 14     | 16 3/4 |  |  |
| 16.87                 | 72           | 32                 | 48                  | 64            | 1 1/4  | 2 1/2  | 4      | 5 1/4  | 6 3/4  | 7 3/4  | 9 1/4  | 10 1/2 | 13 1/4 | 15 3/4 |  |  |
| 17.14                 | 64           | 32                 | 48                  | 56            | 1 1/4  | 2 1/2  | 4      | 5 1/4  | 6 1/2  | 7 3/4  | 9      | 10 1/4 | 13     | 15 1/2 |  |  |
| 18.75                 | 72           | 32                 | 40                  | 48            | 1  | 2 1/4  | 3 1/2  | 4 3/4  | 6      | 7 1/4  | 8 1/4  | 9 1/2  | 12     | 14 1/4 |  |  |
| 19.29                 | 72           | 32                 | 48                  | 56            | 1  | 2 1/4  | 3 1/2  | 4 1/2  | 5 3/4  | 7      | 8      | 9 1/4  | 11 1/2 | 13 3/4 |  |  |
| 19.59                 | 64           | 28                 | 48                  | 56            | 1  | 2 1/4  | 3 1/4  | 4 1/2  | 5 3/4  | 6 3/4  | 8      | 9 1/4  | 11 1/2 | 13 1/2 |  |  |
| 19.69                 | 72           | 32                 | 56                  | 64            | 1  | 2 1/4  | 3 1/4  | 4 1/2  | 5 3/4  | 6 3/4  | 8      | 9      | 11 1/2 | 13 1/2 |  |  |
| 21.43                 | 72           | 24                 | 40                  | 56            | 1  | 2      | 3 1/4  | 4 1/4  | 5 1/4  | 6 1/4  | 7 1/2  | 8 1/2  | 10 1/2 | 12 1/2 |  |  |
| 22.50                 | 72           | 28                 | 56                  | 64            | 1  | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 10     | 12     |  |  |
| 23.33                 | 64           | 32                 | 56                  | 48            | 1  | 2      | 3      | 4      | 5      | 5 3/4  | 6 3/4  | 7 3/4  | 9 3/4  | 11 1/2 |  |  |
| 26.25                 | 72           | 24                 | 56                  | 64            | 1  | 1 3/4  | 2 3/4  | 3 1/2  | 4 1/4  | 5      | 6      | 7      | 8 1/2  | 10 1/4 |  |  |
| 26.67                 | 64           | 28                 | 56                  | 48            | 3/4  | 1 3/4  | 2 3/4  | 3 1/2  | 4 1/4  | 5      | 6      | 6 3/4  | 8 1/2  | 10     |  |  |
| 28.00                 | 64           | 32                 | 56                  | 40            | 3/4  | 1 3/4  | 2 1/2  | 3 1/4  | 4      | 4 3/4  | 5 3/4  | 6 1/2  | 8      | 9 1/2  |  |  |
| 30.86                 | 72           | 28                 | 48                  | 40            | 3/4  | 1 1/2  | 2 1/4  | 3      | 3 3/4  | 4 1/2  | 5      | 5 3/4  | 7 1/4  | 8 3/4  |  |  |

Leads, Change Gears and Angles for Helical Milling

| Lead of Helix, Inches | Change Gears |                    |                     |               | Diameter of Work, Inches                     |     |     |     |     |     |     |     |     |     |
|-----------------------|--------------|--------------------|---------------------|---------------|--|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                       | Gear on Worm | First Gear on Stud | Second Gear on Stud | Gear on Screw | 1¾   | 2   | 2¼  | 2½  | 2¾  | 3   | 3¼  | 3½  | 3¾  | 4   |
|                       |              |                    |                     |               | Approximate Angles for Milling Machine Table |     |     |     |     |     |     |     |     |     |
| 6.12                  | 56           | 40                 | 28                  | 64            | 42   | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 6.22                  | 56           | 40                 | 32                  | 72            | 41½  | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 6.48                  | 56           | 48                 | 40                  | 72            | 40¼  | 44¼ | ... | ... | ... | ... | ... | ... | ... | ... |
| 6.67                  | 64           | 48                 | 28                  | 56            | 39½  | 43½ | ... | ... | ... | ... | ... | ... | ... | ... |
| 7.29                  | 56           | 48                 | 40                  | 64            | 37   | 41  | 44¼ | ... | ... | ... | ... | ... | ... | ... |
| 7.41                  | 64           | 48                 | 40                  | 72            | 36½  | 40¼ | 43¾ | ... | ... | ... | ... | ... | ... | ... |
| 7.62                  | 64           | 48                 | 32                  | 56            | 36   | 39½ | 43  | ... | ... | ... | ... | ... | ... | ... |
| 8.33                  | 48           | 32                 | 40                  | 72            | 33½  | 37  | 40½ | 43½ | ... | ... | ... | ... | ... | ... |
| 8.95                  | 86           | 48                 | 28                  | 56            | 31¾  | 35¼ | 38½ | 41¼ | 44  | ... | ... | ... | ... | ... |
| 9.33                  | 56           | 40                 | 48                  | 72            | 30½  | 34  | 37¼ | 40¼ | 43  | ... | ... | ... | ... | ... |
| 9.52                  | 64           | 48                 | 40                  | 56            | 30   | 33½ | 36½ | 39½ | 42¼ | 45  | ... | ... | ... | ... |
| 10.29                 | 72           | 40                 | 32                  | 56            | 28¼  | 31½ | 34½ | 37½ | 40  | 42½ | 45  | ... | ... | ... |
| 10.37                 | 64           | 48                 | 56                  | 72            | 28   | 31¼ | 34¼ | 37¼ | 39¾ | 42¼ | 44¾ | ... | ... | ... |
| 10.50                 | 48           | 40                 | 56                  | 64            | 27¾  | 31  | 34  | 36¾ | 39½ | 42  | 44¼ | ... | ... | ... |
| 10.67                 | 64           | 40                 | 48                  | 72            | 27¼  | 30½ | 33½ | 36½ | 39  | 41½ | 43¾ | ... | ... | ... |
| 10.94                 | 56           | 32                 | 40                  | 64            | 26¾  | 30  | 33  | 35¾ | 38¼ | 40¾ | 43  | ... | ... | ... |
| 11.11                 | 64           | 32                 | 40                  | 72            | 26½  | 29½ | 32½ | 35¼ | 38  | 40¼ | 42½ | 44¾ | ... | ... |
| 11.66                 | 56           | 32                 | 48                  | 72            | 25¼  | 28½ | 31¼ | 34  | 36½ | 39  | 41¼ | 43½ | ... | ... |
| 12.00                 | 72           | 40                 | 32                  | 48            | 24¾  | 27¾ | 30½ | 33¼ | 35¾ | 38  | 40¼ | 42½ | 44¾ | ... |
| 13.12                 | 56           | 32                 | 48                  | 64            | 22¾  | 25¼ | 28¼ | 31  | 33¼ | 35¾ | 37¾ | 40  | 42  | 43¾ |
| 13.33                 | 56           | 28                 | 48                  | 72            | 22½  | 25½ | 28  | 30½ | 33  | 35¼ | 37½ | 39½ | 41½ | 43¾ |
| 13.71                 | 64           | 40                 | 48                  | 56            | 22   | 24¼ | 27¼ | 30  | 32¼ | 34½ | 36½ | 38¼ | 40¼ | 42½ |
| 15.24                 | 64           | 28                 | 48                  | 72            | 20   | 22½ | 25  | 27¼ | 29½ | 31¾ | 34  | 35¾ | 37¾ | 39½ |
| 15.56                 | 64           | 32                 | 56                  | 72            | 19½  | 22  | 24½ | 27  | 29  | 31¼ | 33¼ | 35¼ | 37  | 39  |
| 15.75                 | 56           | 64                 | 72                  | 40            | 19¼  | 21¾ | 24¼ | 26½ | 28¾ | 31  | 33  | 35  | 36¾ | 38½ |
| 16.87                 | 72           | 32                 | 48                  | 64            | 18¼  | 20½ | 22¾ | 25  | 27  | 29¼ | 31¼ | 33¼ | 35  | 36½ |
| 17.14                 | 64           | 32                 | 48                  | 56            | 17¾  | 20¼ | 22¼ | 24¾ | 26¾ | 29  | 30¾ | 32¾ | 34½ | 36  |
| 18.75                 | 72           | 32                 | 40                  | 48            | 16¼  | 18½ | 20¾ | 22¾ | 25  | 26¾ | 28½ | 30¼ | 32  | 33¾ |
| 19.29                 | 72           | 32                 | 48                  | 56            | 16   | 18¼ | 20¼ | 22¼ | 24  | 26  | 28  | 29¾ | 31½ | 33  |
| 19.59                 | 64           | 28                 | 48                  | 56            | 15¾  | 18  | 20  | 22  | 23¾ | 25¾ | 27½ | 29¼ | 31  | 32¾ |
| 19.69                 | 72           | 32                 | 56                  | 64            | 15¼  | 17¾ | 20  | 21¾ | 23¾ | 25½ | 27½ | 29¼ | 31  | 32½ |
| 21.43                 | 72           | 24                 | 40                  | 56            | 14½  | 16½ | 18½ | 20¼ | 22  | 23¾ | 25½ | 27¼ | 29  | 30¼ |
| 22.50                 | 72           | 28                 | 56                  | 64            | 13¾  | 15¼ | 17½ | 19¼ | 21  | 22½ | 24½ | 26  | 27¾ | 29¼ |
| 23.33                 | 64           | 32                 | 56                  | 48            | 13¼  | 15¼ | 17  | 18¾ | 20¼ | 22  | 23½ | 25¼ | 27  | 28¼ |
| 26.25                 | 72           | 24                 | 56                  | 64            | 12   | 13½ | 15  | 16¾ | 18¼ | 19¾ | 21¼ | 22¾ | 24¼ | 25½ |
| 26.67                 | 64           | 28                 | 56                  | 48            | 11¾  | 13¼ | 14¾ | 16½ | 18  | 19½ | 21  | 22¼ | 23¾ | 25¼ |
| 28.00                 | 64           | 32                 | 56                  | 40            | 11¼  | 12¼ | 14¼ | 15¼ | 17¼ | 18½ | 20  | 21½ | 22¼ | 24  |
| 30.86                 | 72           | 28                 | 48                  | 40            | 10   | 11½ | 13  | 14¼ | 15½ | 17  | 18½ | 19½ | 21  | 22  |
| 31.50                 | 72           | 32                 | 56                  | 40            | 10   | 11¼ | 12¾ | 14  | 15¼ | 16½ | 18  | 19¼ | 20½ | 21¾ |
| 36.00                 | 72           | 32                 | 64                  | 40            | 8¾   | 10  | 11  | 12¼ | 13½ | 14¾ | 16  | 17  | 18¼ | 19¼ |
| 41.14                 | 72           | 28                 | 64                  | 40            | 7¾   | 8¾  | 9¾  | 10¾ | 11¾ | 13  | 14  | 15  | 16  | 17  |
| 45.00                 | 72           | 28                 | 56                  | 32            | 7  | 8   | 9   | 10  | 11  | 11¾ | 12¾ | 13¾ | 14¾ | 15½ |
| 48.00                 | 72           | 24                 | 64                  | 40            | 6½   | 7½  | 8½  | 9¼  | 10¼ | 11¼ | 12  | 13  | 13¾ | 14½ |
| 51.43                 | 72           | 28                 | 64                  | 32            | 6  | 7   | 7¾  | 8¾  | 9½  | 10½ | 11¼ | 12  | 12¾ | 13¾ |
| 60.00                 | 72           | 24                 | 64                  | 32            | 5¼   | 6   | 6¾  | 7½  | 8¼  | 9   | 9½  | 10¼ | 11  | 11¾ |
| 68.57                 | 72           | 24                 | 64                  | 28            | 4¾   | 5¼  | 5¾  | 6½  | 7¼  | 8   | 8½  | 9   | 9¾  | 10¼ |

**Helix Angle for Given Lead and Diameter.**—The table on this and the preceding page gives helix angles (relative to axis) equivalent to a range of leads and diameters. The expression "Diameter of Work" at the top of the table might mean pitch diameter or outside diameter, depending upon the class of work. Assume, for example, that a plain milling cutter 4 inches in diameter is to have helical teeth and a helix angle of about 25 degrees is desired. The table shows that this angle will be obtained approximately by using change-gears that will give a lead of 26.67 inches. As the outside diameter of the cutter is 4 inches,

the helix angle of  $25\frac{1}{4}$  degrees is at the top of the teeth. The angles listed for different diameters are used in setting the table of a milling machine. In milling a right-hand helix (or cutter teeth that turn to the right as seen from the end of the cutter), swivel the right-hand end of the machine table toward the rear, and, inversely, for a left-hand helix, swivel the left-hand end of the table toward the rear. The angles in the table are based upon the following formula:

$$\cot \text{ helix angle relative to axis} = \frac{\text{lead of helix}}{3.1416 \times \text{diameter}}$$

**Lead of Helix for Given Angle.**—The lead of a helix or “spiral” for given angles measured with the axis of the work is given in the table, starting on page 1977, for a diameter of 1. For other diameters, lead equals the value found in the table multiplied by the given diameter. Suppose the angle is 55 degrees, and the diameter 5 inches; what would be the lead? By referring to the table starting on page 1977, it is found that the lead for a diameter of 1 and an angle of 55 degrees 0 minutes equals 2.200. Multiply this value by 5;  $5 \times 2.200 = 11$  inches, which is the required lead. If the lead and diameter are given, and the angle is wanted, divide the given lead by the given diameter, thus obtaining the lead for a diameter equal to 1; then find the angle corresponding to this lead in the table. If the lead and angle are given, and the diameter is wanted, divide the lead by the value in the table for the angle.

**Helix Angle for Given Lead and Pitch Radius.**—To determine the helix angle for a helical gear, knowing the pitch radius and the lead, use the formula:

$$\tan \psi = 2\pi R/L$$

where  $\psi$  = helix angle

$R$  = pitch radius of gear, and

$L$  = lead of tooth

*Example:*

$$R = 3.000, L = 21.000, \tan \psi = (2 \times 3.1416 \times 3.000)/21.000 = 0.89760$$

$$\therefore \psi = 41.911 \text{ degrees}$$

**Helix Angle and Lead, Given Normal DP and Numbers of Teeth.**—When  $N_1$  = number of teeth in pinion,  $N_2$  = number of teeth in gear,  $P_n$  = normal diametral pitch,  $C$  = center distance,  $\psi$  = helix angle,  $L_1$  = lead of pinion, and  $L_2$  = lead of gear, then:

$$\cos \psi = \frac{N_1 + N_2}{2P_n C}, \quad L_1 = \frac{\pi N_1}{P_n \sin \psi}, \quad L_2 = \frac{\pi N_2}{P_n \sin \psi}$$

$$P_n = 6, \quad N_1 = 18, \quad N_2 = 30, \quad C = 4.500$$

$$\cos \psi = \frac{18 + 30}{2 \times 6 \times 4.5} = 0.88889, \therefore \psi = 27.266^\circ, \text{ and } \sin \psi = 0.45812$$

$$L_1 = \frac{3.1416 \times 18}{6 \times 0.45812} = 20.5728, \text{ and } L_2 = \frac{3.1416 \times 30}{6 \times 0.45812} = 34.2880$$

**Lead of Tooth Given Pitch Radius and Helix Angle.**—To determine the lead of the tooth for a helical gear, given the helix angle and the pitch radius, the formula becomes:  
 $L = 2\pi R/\tan \psi$ .

$$\psi = 22.5^\circ, \quad \therefore \tan \psi = 0.41421, \quad R = 2.500.$$

$$L = \frac{2 \times 3.1416 \times 2.500}{0.41421} = 37.9228$$

## SIMPLE, COMPOUND, DIFFERENTIAL, AND BLOCK INDEXING

**Milling Machine Indexing.**—Positioning a workpiece at a precise angle or interval of rotation for a machining operation is called indexing. A dividing head is a milling machine attachment that provides this fine control of rotational positioning through a combination of a crank-operated worm and worm gear, and one or more indexing plates with several circles of evenly spaced holes to measure partial turns of the worm crank. The indexing crank carries a movable indexing pin that can be inserted into and withdrawn from any of the holes in a given circle with an adjustment provided for changing the circle that the indexing pin tracks.

**Hole Circles.**—The Brown & Sharpe dividing head has three standard indexing plates, each with six circles of holes as listed in the table below.

**Numbers of Holes in Brown & Sharpe Standard Indexing Plates**

| Plate Number | Numbers of Holes |    |    |    |    |    |
|--------------|------------------|----|----|----|----|----|
| 1            | 15               | 16 | 17 | 18 | 19 | 20 |
| 2            | 21               | 23 | 27 | 29 | 31 | 33 |
| 3            | 37               | 39 | 41 | 43 | 47 | 49 |

Dividing heads of Cincinnati Milling Machine design have two-sided, standard, and high-number plates with the numbers of holes shown in the following table.

**Numbers of Holes in Cincinnati Milling Machine Standard Indexing Plates**

| Side               | Standard Plate |    |    |    |     |     |     |     |     |     |     |
|--------------------|----------------|----|----|----|-----|-----|-----|-----|-----|-----|-----|
|                    | 1              | 24 | 25 | 28 | 30  | 34  | 37  | 38  | 39  | 41  | 42  |
| 2                  | 46             | 47 | 49 | 51 | 53  | 54  | 57  | 58  | 59  | 62  | 66  |
| High-Number Plates |                |    |    |    |     |     |     |     |     |     |     |
| A                  | 30             | 48 | 69 | 91 | 99  | 117 | 129 | 147 | 171 | 177 | 189 |
| B                  | 36             | 67 | 81 | 97 | 111 | 127 | 141 | 157 | 169 | 183 | 199 |
| C                  | 34             | 46 | 79 | 93 | 109 | 123 | 139 | 153 | 167 | 181 | 197 |
| D                  | 32             | 44 | 77 | 89 | 107 | 121 | 137 | 151 | 163 | 179 | 193 |
| E                  | 26             | 42 | 73 | 87 | 103 | 119 | 133 | 149 | 161 | 175 | 191 |
| F                  | 28             | 38 | 71 | 83 | 101 | 113 | 131 | 143 | 159 | 173 | 187 |

Some dividing heads provide for *Direct Indexing* through the attachment of a special indexing plate directly to the main spindle where a separate indexing pin engages indexing holes in the plate. The worm is disengaged from the worm gear during this quick method of indexing, which is mostly used for common, small-numbered divisions such as six, used in machining hexagonal forms for bolt heads and nuts, for instance.

**Simple Indexing.**—Also called *Plain Indexing* or *Indirect Indexing*, simple indexing is based on the ratio between the worm and the worm gear, which is usually, but not always, 40:1. All the tables in this section are based on a 40:1 gear ratio, except for [Table 8](#) on page 2023 that gives indexing movements for dividing heads utilizing a 60:1 gear ratio.

The number of turns of the indexing crank needed for each indexing movement to produce a specified number of evenly spaced divisions is equal to the number of turns of the crank that produce exactly one full turn of the main spindle, divided by the specified number of divisions required for the workpiece. The accompanying tables in this section provide data for the indexing movements to meet most division requirements, and include the simple indexing movements along with the more complex movements for divisions that are not available through simple indexing. The fractional entries in the tables are deliberately not reduced to lowest terms. Thus, the numerator represents the number of holes to be moved on the circle of holes specified by the denominator.

Setting up for an indexing job includes setting the sector arms to the fractional part of a turn required for each indexing movement to avoid the need to count holes each time. The current location of the indexing pin in the circle of holes to be used is always hole zero when counting the number of holes to be moved. The wormshaft hub carrying the dividing plate may also carry one or two sets of sector arms, each of which can be used to define two arcs of holes. As shown at the right in the drawing of a typical dividing head at the top of the table *Simple and Differential Indexing with Browne & Sharpe Indexing Plates* on page 2011, these sector arms can make up an inner arc, A, and an outer arc, B. The inner arc is used most often, but some indexing movements require the use of the outer arc.

*Example:* With a worm/worm gear ratio of 40:1 making 35 divisions requires each indexing movement to be  $40 \div 35 = 1 \frac{1}{7}$  turns: one full turn of the indexing crank plus one-seventh of a full turn more. A full turn is easily achieved using any circle of holes, but to continue the indexing movement to completion for this example requires a circle in which the number of holes is evenly divisible by 7. The Brown & Sharpe dividing head has a 21-hole circle on plate 2 and a 49-hole circle on plate 3. Either circle could be used because  $3/21$  and  $7/49$  both equal  $1/7$ th. The Cincinnati dividing head standard plate has a 28-hole circle on the first side and a 49-hole circle on the second side and again, either  $4/28$  or  $7/49$  could be used for the fractional part of a turn needed for 35 divisions. In selecting among equivalent indexing solutions, the one with the smallest number of holes in the fractional part of a turn is generally preferred (except that if an indexing plate with an alternate solution is already mounted on the dividing head, the alternate should be used to avoid switching indexing plates).

**Compound Indexing.**—Compound indexing is used to obtain divisions that are not available by simple indexing. Two simple indexing movements are used with different circles of holes on an indexing plate that is not bolted to the dividing head frame so that it is free to rotate on the worm shaft. A second, stationary indexing pin arrangement is clamped or otherwise fixed to the frame of the dividing head to hold the indexing plate in position except during the second portion of the compound indexing movement. If available, a double set of low-profile sector arms would improve the ease and reliability of this method. Sector arms for the innermost circle of an indexing movement should not reach as far as the outermost circle of the movement, and sector arms for the outermost circle should be full length. Positioning the outermost circle sector arms may have to wait until the indexing pin on the innermost circle is withdrawn, and may sometimes coincide with the position of that pin. The indexing pin on the crank is set to track the innermost of the two circles in the compound movement and the stationary indexing pin is set to track the outermost circle. Some divisions are only available using adjacent circles, so the intercircle spacing may become a constraining factor in the design or evaluation of a stationary pin arrangement.

The first part of the indexing movement is performed as in simple indexing by withdrawing the indexing pin on the crank arm from its hole in the indexing plate, rotating the crank to its next position, and reinserting the indexing pin in the new hole. For the second part of the movement, the stationary indexing pin is released from its hole in the indexing plate, and with the crank indexing pin seated in its hole, the crank is used to turn the crank arm and indexing plate together to the next position for reinserting the stationary pin into its new hole.

There are two possibilities for the separate movements in compound indexing: they may both be in the same direction of rotation, referred to as *positive compounding* and indicated in the table by a plus (+) sign between the two indexing movements, or they may be in opposite directions of rotation, referred to as *negative compounding* and indicated in the table by a minus (–) sign between the two indexing movements. In positive compounding, it does not matter whether the rotation is clockwise or counterclockwise, as long as it is the same throughout the job. In negative compounding, there will be one clockwise movement and one counterclockwise movement for each unit of the division. The mathematical difference is in whether the two fractional turns are to be added together or whether one is to

be subtracted from the other. Operationally, this difference is important because of the backlash, or free play, between the worm and the worm gear of the dividing head. In positive compounding, this play is always taken up because the worm is turned continually in the same direction. In negative compounding, however, the direction of each turn is always opposite that of the previous turn, requiring each portion of each division to be started by backing off a few holes to allow the play to be taken up before the movement to the next position begins.

The Tables 1a and 1b, *Simple and Compound Indexing with Brown & Sharpe Plates*, gives indexing movements for all divisions up to and including 250 with plain dividing heads of the Brown & Sharpe design. All the simple indexing movements, and many of the compound indexing movements, are exact for the divisions they provide. There remains a substantial number of divisions for which the indexing movements are approximate. For these divisions, the indexing movements shown come very close to the target number, but the price of getting close is increased length and complexity of the indexing movements. The table shows all divisions that can be obtained through simple indexing and all divisions for which exact compound indexing movements are available. Approximate movements are only used when it is necessary to obtain a division that would otherwise not be available. The approximate indexing movements usually involve multiple revolutions of the workpiece, with successive revolutions filling in spaces left during earlier turns.

**Table 1a. Simple and Compound Indexing with Brown & Sharpe Plates**

| Number of Divisions | Whole Turns | Fractions of a Turn | Number of Divisions | Whole Turns | Fractions of a Turn | Number of Divisions | Whole Turns | Fractions of a Turn |
|---------------------|-------------|---------------------|---------------------|-------------|---------------------|---------------------|-------------|---------------------|
| 2                   | 20          | ...                 | 15                  | 2           | 26/39               | 33                  | 1           | 7/33                |
| 3                   | 13          | 5/15                | 16                  | 2           | 8/16                | 34                  | 1           | 3/17                |
| 3                   | 13          | 7/21                | 17                  | 2           | 6/17                | 35                  | 1           | 3/21                |
| 3                   | 13          | 13/39               | 18                  | 2           | 4/18                | 35                  | 1           | 7/49                |
| 4                   | 10          | ...                 | 18                  | 2           | 6/27                | 36                  | 1           | 2/18                |
| 5                   | 8           | ...                 | 19                  | 2           | 2/19                | 36                  | 1           | 3/27                |
| 6                   | 6           | 10/15               | 20                  | 2           | ...                 | 37                  | 1           | 3/37                |
| 6                   | 6           | 14/21               | 21                  | 1           | 19/21               | 38                  | 1           | 1/19                |
| 6                   | 6           | 26/39               | 22                  | 1           | 27/33               | 39                  | 1           | 1/39                |
| 7                   | 5           | 15/21               | 23                  | 1           | 17/23               | 40                  | 1           | ...                 |
| 8                   | 5           | ...                 | 24                  | 1           | 10/15               | 41                  | ...         | 40/41               |
| 9                   | 4           | 8/18                | 24                  | 1           | 14/21               | 42                  | ...         | 20/21               |
| 9                   | 4           | 12/27               | 24                  | 1           | 26/39               | 43                  | ...         | 40/43               |
| 10                  | 4           | ...                 | 25                  | 1           | 9/15                | 44                  | ...         | 30/33               |
| 11                  | 3           | 21/33               | 26                  | 1           | 21/39               | 45                  | ...         | 16/18               |
| 12                  | 3           | 5/15                | 27                  | 1           | 13/27               | 45                  | ...         | 24/27               |
| 12                  | 3           | 7/21                | 28                  | 1           | 9/21                | 46                  | ...         | 20/23               |
| 12                  | 3           | 13/39               | 29                  | 1           | 11/29               | 47                  | ...         | 40/47               |
| 13                  | 3           | 3/39                | 30                  | 1           | 5/15                | 48                  | ...         | 15/18               |
| 14                  | 2           | 18/21               | 30                  | 1           | 7/21                | 49                  | ...         | 40/49               |
| 14                  | 2           | 42/49               | 30                  | 1           | 13/39               | 50                  | ...         | 12/15               |
| 15                  | 2           | 10/15               | 31                  | 1           | 9/31                |                     |             |                     |
| 15                  | 2           | 14/21               | 32                  | 1           | 4/16                |                     |             |                     |

**Table 1b. Simple and Compound Indexing with Brown & Sharpe Plates**

| Target Divisions | Indexing Movements                     | Workpiece Revolutions | Precise Number of Divisions | Diameter at Which Error = 0.001 | Target Divisions | Indexing Movements   | Workpiece Revolutions | Precise Number of Divisions | Diameter at Which Error = 0.001 |
|------------------|--|-----------------------|-----------------------------|---------------------------------|------------------|--|-----------------------|-----------------------------|---------------------------------|
| 51               | 10/15 + 2/17                           | 1                     | 51.00000                    | Exact                           | 57               | 5/15 + 7/19  | 1                     | 57.00000                    | Exact                           |
| 51 <sup>a</sup>  | 7 <sup>4</sup> / <sub>47</sub> + 37/49 | 11                    | 51.00005                    | 322.55                          | 57 <sup>a</sup>  | 4 <sup>4</sup> / <sub>49</sub> + 3/49                            | 7                     | 56.99991                    | 205.26                          |
| 52               | 30/39                                  | 1                     | 52.00000                    | Exact                           | 58               | 20/29  | 1                     | 58.00000                    | Exact                           |
| 53               | 26/29 + 19/31                          | 2                     | 52.99926                    | 22.89                           | 59               | 18/37 + 9/47   | 1                     | 58.99915                    | 22.14                           |
| 53               | 14/43 + 4 <sup>5</sup> / <sub>47</sub> | 7                     | 52.99991                    | 180.13                          | 59               | 4 <sup>2</sup> / <sub>43</sub> + 1/47                            | 6                     | 59.00012                    | 154.39                          |
| 53 <sup>a</sup>  | 5 <sup>3</sup> / <sub>47</sub> + 43/49 | 9                     | 53.00006                    | 263.90                          | 59 <sup>a</sup>  | 7 <sup>10</sup> / <sub>47</sub> + 12/49                          | 11                    | 58.99971                    | 64.51                           |
| 54               | 20/27                                  | 1                     | 54.00000                    | Exact                           | 59               | 5 <sup>15</sup> / <sub>57</sub> + 3 <sup>2</sup> / <sub>49</sub> | 13                    | 58.99994                    | 300.09                          |
| 55               | 24/33                                  | 1                     | 55.00000                    | Exact                           | 60               | 10/15  | 1                     | 60.00000                    | Exact                           |
| 56               | 15/21                                  | 1                     | 56.00000                    | Exact                           | 60               | 14/21  | 1                     | 60.00000                    | Exact                           |
| 56               | 35/49                                  | 1                     | 56.00000                    | Exact                           | 60               | 26/39  | 1                     | 60.00000                    | Exact                           |

Table 1b. (Continued) Simple and Compound Indexing with Brown &amp; Sharpe Plates

| Target Divisions | Indexing Movements              | Workpiece Revolutions | Precise Number of Divisions | Diameter at Which Error = 0.001 | Target Divisions | Indexing Movements               | Workpiece Revolutions | Precise Number of Divisions | Diameter at Which Error = 0.001 |
|------------------|---------------------------------|-----------------------|-----------------------------|---------------------------------|------------------|----------------------------------|-----------------------|-----------------------------|---------------------------------|
| 61               | $2\frac{3}{43} + 26/47$         | 4                     | 60.99981                    | 102.93                          | 94               | 20/47                            | 1                     | 94.00000                    | Exact                           |
| 61 <sup>a</sup>  | $3\frac{2}{47} + 2/49$          | 6                     | 60.99989                    | 175.94                          | 95               | 8/19                             | 1                     | 95.00000                    | Exact                           |
| 61               | $4\frac{3}{41} + 2/49$          | 8                     | 61.00009                    | 204.64                          | 96 <sup>a</sup>  | $3/18 + 5/20$                    | 1                     | 96.00000                    | Exact                           |
| 62               | 20/31                           | 1                     | 62.00000                    | Exact                           | 97               | $15/41 + 2/43$                   | 1                     | 97.00138                    | 22.45                           |
| 63               | $11/21 + 3/27$                  | 1                     | 63.00000                    | Exact                           | 97               | $1\frac{2}{43} + 4/47$           | 5                     | 97.00024                    | 128.66                          |
| 63 <sup>a</sup>  | $4\frac{19}{59} + 14/33$        | 8                     | 62.99938                    | 32.49                           | 97 <sup>a</sup>  | $3\frac{7}{41} + 43/49$          | 11                    | 96.99989                    | 281.37                          |
| 64               | 10/16                           | 1                     | 64.00000                    | Exact                           | 98               | 20/49                            | 1                     | 98.00000                    | Exact                           |
| 65               | 24/39                           | 1                     | 65.00000                    | Exact                           | 99 <sup>a</sup>  | $6/27 + 6/33$                    | 1                     | 99.00000                    | Exact                           |
| 66               | 20/33                           | 1                     | 66.00000                    | Exact                           | 100              | 6/15                             | 1                     | 100.00000                   | Exact                           |
| 67               | $29/37 + 16/39$                 | 2                     | 66.99942                    | 36.75                           | 101              | $1\frac{3}{43} + 10/47$          | 5                     | 100.99950                   | 64.33                           |
| 67               | $2\frac{2}{41} + 16/49$         | 5                     | 67.00017                    | 127.90                          | 101              | $2\frac{2}{57} + 2/47$           | 7                     | 100.99979                   | 154.99                          |
| 67               | $4\frac{3}{43} + 2\frac{5}{49}$ | 11                    | 67.00007                    | 295.10                          | 101 <sup>a</sup> | $3\frac{3}{43} + 30/49$          | 11                    | 101.00011                   | 295.10                          |
| 68               | 10/17                           | 1                     | 68.00000                    | Exact                           | 102              | $5/15 + 1/17$                    | 1                     | 102.00000                   | Exact                           |
| 69               | $14/21 - 2/23$                  | 1                     | 69.00000                    | Exact                           | 102 <sup>a</sup> | $3\frac{1}{43} + 45/49$          | 11                    | 102.00022                   | 147.55                          |
| 69 <sup>a</sup>  | $19/23 + 11/33$                 | 2                     | 69.00000                    | Exact                           | 103 <sup>a</sup> | $1\frac{3}{43} + 18/49$          | 4                     | 103.00031                   | 107.31                          |
| 70               | 12/21                           | 1                     | 70.00000                    | Exact                           | 103              | $2\frac{2}{57} + 21/41$          | 8                     | 103.00021                   | 154.52                          |
| 70               | 28/49                           | 1                     | 70.00000                    | Exact                           | 103              | $4\frac{3}{57} + 9/49$           | 13                    | 103.00011                   | 300.09                          |
| 71               | $35/37 + 32/43$                 | 3                     | 71.00037                    | 60.77                           | 104              | 15/39                            | 1                     | 104.00000                   | Exact                           |
| 71 <sup>a</sup>  | $2\frac{3}{41} + 27/49$         | 6                     | 70.99985                    | 153.48                          | 105              | 8/21                             | 1                     | 105.00000                   | Exact                           |
| 71               | $4\frac{2}{59} + 2\frac{2}{41}$ | 13                    | 70.99991                    | 264.67                          | 106              | $1\frac{7}{59} + 29/41$          | 5                     | 105.99934                   | 50.90                           |
| 72               | 10/18                           | 1                     | 72.00000                    | Exact                           | 106              | $2\frac{1}{41} + 15/43$          | 7                     | 105.99957                   | 78.57                           |
| 72               | 15/27                           | 1                     | 72.00000                    | Exact                           | 106 <sup>a</sup> | $2\frac{3}{41} + 23/49$          | 9                     | 106.00029                   | 115.11                          |
| 73               | $5/43 + 48/49$                  | 2                     | 73.00130                    | 17.88                           | 107              | $23/43 + 10/47$                  | 2                     | 107.00199                   | 17.15                           |
| 73               | $2\frac{19}{43} + 14/47$        | 5                     | 72.99982                    | 128.66                          | 107 <sup>a</sup> | $1\frac{2}{51} + 31/33$          | 7                     | 107.00037                   | 91.18                           |
| 73               | $2\frac{2}{47} + 3\frac{8}{49}$ | 12                    | 73.00007                    | 351.87                          | 107              | $2\frac{3}{43} + 3/47$           | 8                     | 106.99983                   | 196.28                          |
| 73 <sup>a</sup>  | $5\frac{2}{47} + 48/49$         | 12                    | 73.00007                    | 351.87                          | 107              | $3\frac{3}{59} + 22/43$          | 12                    | 106.99987                   | 256.23                          |
| 74               | 20/37                           | 1                     | 74.00000                    | Exact                           | 108              | 10/27                            | 1                     | 108.00000                   | Exact                           |
| 75               | 8/15                            | 1                     | 75.00000                    | Exact                           | 109              | $1\frac{1}{53} + 2/23$           | 4                     | 108.99859                   | 24.60                           |
| 76               | 10/19                           | 1                     | 76.00000                    | Exact                           | 109              | $1\frac{3}{57} + 26/47$          | 6                     | 108.99974                   | 132.85                          |
| 77 <sup>a</sup>  | $9/21 + 3/33$                   | 1                     | 77.00000                    | Exact                           | 109 <sup>a</sup> | $2\frac{1}{59} + 4/49$           | 7                     | 108.99980                   | 170.32                          |
| 78               | 20/39                           | 1                     | 78.00000                    | Exact                           | 110              | 12/33                            | 1                     | 110.00000                   | Exact                           |
| 79               | $17/37 + 26/47$                 | 2                     | 79.00057                    | 44.28                           | 111              | $1/37 + 13/39$                   | 1                     | 111.00000                   | Exact                           |
| 79 <sup>a</sup>  | $2\frac{2}{43} + 3/49$          | 6                     | 79.00016                    | 160.96                          | 111 <sup>a</sup> | $3\frac{2}{47} + 17/49$          | 11                    | 111.00011                   | 322.55                          |
| 79               | $4\frac{3}{59} + 9/47$          | 10                    | 79.00011                    | 233.38                          | 112 <sup>a</sup> | $3\frac{10}{51} + 20/33$         | 11                    | 111.99801                   | 17.91                           |
| 80               | 8/16                            | 1                     | 80.00000                    | Exact                           | 112              | $33/43 + 2\frac{2}{47}$          | 9                     | 112.00123                   | 28.95                           |
| 81               | $10/43 + 37/49$                 | 2                     | 80.99952                    | 53.65                           | 112              | $14/37 + 4\frac{4}{47}$          | 15                    | 112.00086                   | 41.52                           |
| 81               | $3\frac{2}{47} + 13/49$         | 7                     | 80.99987                    | 205.26                          | 112              | $9\frac{4}{57} + 46/47$          | 29                    | 112.00044                   | 80.26                           |
| 81 <sup>a</sup>  | $4\frac{3}{41} + 40/49$         | 10                    | 80.99990                    | 255.79                          | 113              | $14/37 - 1/41$                   | 1                     | 112.99814                   | 19.32                           |
| 81               | $5\frac{1}{57} + 1\frac{6}{49}$ | 13                    | 81.00009                    | 300.09                          | 113              | $2\frac{3}{41} + 7/47$           | 8                     | 112.99982                   | 196.28                          |
| 82               | 20/41                           | 1                     | 82.00000                    | Exact                           | 113 <sup>a</sup> | $2\frac{3}{49} + 31/49$          | 9                     | 112.99986                   | 263.90                          |
| 83               | $1\frac{1}{59} + 17/31$         | 4                     | 83.00058                    | 45.79                           | 113              | $4\frac{3}{57} + 3/49$           | 13                    | 113.00012                   | 300.09                          |
| 83 <sup>a</sup>  | $2\frac{4}{47} + 44/49$         | 8                     | 83.00034                    | 78.19                           | 114 <sup>a</sup> | $10/15 - 6/19$                   | 1                     | 114.00000                   | Exact                           |
| 83               | $3\frac{1}{57} + 7/31$          | 8                     | 82.99969                    | 85.26                           | 114              | $1\frac{3}{57} + 25/49$          | 7                     | 113.99955                   | 80.79                           |
| 83               | $5\frac{1}{57} + 31/41$         | 12                    | 83.00011                    | 231.78                          | 115              | 8/23                             | 1                     | 115.00000                   | Exact                           |
| 84               | 10/21                           | 1                     | 84.00000                    | Exact                           | 116              | 10/29                            | 1                     | 116.00000                   | Exact                           |
| 85               | 8/17                            | 1                     | 85.00000                    | Exact                           | 117              | $1\frac{6}{41} + 15/47$          | 5                     | 117.00061                   | 61.34                           |
| 86               | 20/43                           | 1                     | 86.00000                    | Exact                           | 117              | $7\frac{1}{47} - 9/49$           | 20                    | 117.00006                   | 586.45                          |
| 87               | $14/21 - 6/29$                  | 1                     | 87.00000                    | Exact                           | 117 <sup>a</sup> | $6\frac{1}{47} + 40/49$          | 20                    | 117.00006                   | 586.45                          |
| 87               | $17/29 + 11/33$                 | 2                     | 87.00000                    | Exact                           | 118 <sup>a</sup> | $1\frac{9}{59} + 24/49$          | 5                     | 117.99938                   | 60.83                           |
| 88               | 15/33                           | 1                     | 88.00000                    | Exact                           | 118              | $30/41 + 2\frac{1}{47}$          | 9                     | 117.99966                   | 110.41                          |
| 89               | $1\frac{2}{57} + 19/41$         | 5                     | 88.99971                    | 96.58                           | 119              | $15/43 + 31/47$                  | 3                     | 118.99902                   | 38.60                           |
| 89               | $2\frac{2}{57} + 5/49$          | 6                     | 88.99980                    | 138.50                          | 119 <sup>a</sup> | $2\frac{1}{53} + 17/33$          | 8                     | 119.00049                   | 77.31                           |
| 89 <sup>a</sup>  | $2\frac{2}{59} + 43/49$         | 8                     | 89.00015                    | 194.65                          | 119              | $3\frac{1}{57} + 25/47$          | 13                    | 118.99987                   | 287.84                          |
| 90               | 8/18                            | 1                     | 90.00000                    | Exact                           | 120              | 5/15                             | 1                     | 120.00000                   | Exact                           |
| 90               | 12/27                           | 1                     | 90.00000                    | Exact                           | 120              | 7/21                             | 1                     | 120.00000                   | Exact                           |
| 91 <sup>a</sup>  | $6/39 + 14/49$                  | 1                     | 91.00000                    | Exact                           | 120              | 13/39                            | 1                     | 120.00000                   | Exact                           |
| 92               | 10/23                           | 1                     | 92.00000                    | Exact                           | 121              | $8/37 + 38/49$                   | 3                     | 121.00111                   | 34.63                           |
| 93               | $7/21 + 3/31$                   | 1                     | 93.00000                    | Exact                           | 121 <sup>a</sup> | $14/47 + 34/49$                  | 3                     | 120.99825                   | 21.99                           |
| 93 <sup>a</sup>  | $3/31 + 11/33$                  | 1                     | 93.00000                    | Exact                           | 121              | $1\frac{1}{43} + 2\frac{10}{47}$ | 10                    | 120.99985                   | 257.32                          |

Table 1b. (Continued) Simple and Compound Indexing with Brown &amp; Sharpe Plates

| Target Divisions | Indexing Movements       | Workpiece Revolutions | Precise Number of Divisions | Diameter at Which Error = 0.001 | Target Divisions | Indexing Movements       | Workpiece Revolutions | Precise Number of Divisions | Diameter at Which Error = 0.001 |
|------------------|--------------------------|-----------------------|-----------------------------|---------------------------------|------------------|--------------------------|-----------------------|-----------------------------|---------------------------------|
| 122              | $1\frac{14}{41} + 14/47$ | 5                     | 122.00063                   | 61.34                           | 147              | 13/39 - 3/49             | 1                     | 147.00000                   | Exact                           |
| 122              | $41/43 + 2\frac{30}{49}$ | 11                    | 122.00026                   | 147.55                          | 147 <sup>a</sup> | 13/39 + 37/49            | 4                     | 147.00000                   | Exact                           |
| 122 <sup>a</sup> | $2\frac{41}{43} + 32/49$ | 11                    | 122.00026                   | 147.55                          | 148              | 10/37                    | 1                     | 148.00000                   | Exact                           |
| 123              | $26/39 - 14/41$          | 1                     | 123.00000                   | Exact                           | 149              | $28/41 + 6/49$           | 3                     | 148.99876                   | 38.37                           |
| 123 <sup>a</sup> | $1\frac{12}{43} + 17/49$ | 5                     | 123.00058                   | 67.07                           | 149              | $1\frac{7}{39} + 7/43$   | 5                     | 149.00044                   | 106.76                          |
| 124              | 10/31                    | 1                     | 124.00000                   | Exact                           | 149 <sup>a</sup> | $2\frac{7}{43} + 41/49$  | 11                    | 149.00032                   | 147.55                          |
| 125              | $41/43 + 16/49$          | 4                     | 124.99815                   | 21.46                           | 149              | $26/37 + 2\frac{27}{47}$ | 13                    | 148.99984                   | 287.84                          |
| 125              | $1\frac{33}{41} + 37/49$ | 8                     | 125.00097                   | 40.93                           | 150              | 4/15                     | 1                     | 150.00000                   | Exact                           |
| 125              | $2\frac{23}{43} + 8/47$  | 7                     | 125.00110                   | 36.03                           | 151              | $5/37 + 31/47$           | 3                     | 150.99855                   | 33.21                           |
| 125              | $3/41 + 3\frac{27}{47}$  | 11                    | 125.00074                   | 53.98                           | 151 <sup>a</sup> | $42/43 + 43/49$          | 7                     | 151.00077                   | 62.60                           |
| 126              | $2/21 + 6/27$            | 1                     | 126.00000                   | Exact                           | 151              | $6/37 + 35/39$           | 4                     | 151.00065                   | 73.49                           |
| 126              | $2\frac{16}{43} + 13/20$ | 11                    | 125.99849                   | 26.61                           | 151              | $2\frac{23}{43} + 20/47$ | 11                    | 151.00017                   | 283.05                          |
| 127              | $2/39 + 42/47$           | 3                     | 126.99769                   | 17.50                           | 152              | 5/19                     | 1                     | 152.00000                   | Exact                           |
| 127              | $2\frac{6}{43} + 2/47$   | 7                     | 127.00052                   | 77.50                           | 153              | $10/18 - 5/17$           | 1                     | 153.00000                   | Exact                           |
| 127 <sup>a</sup> | $2\frac{23}{39} + 12/49$ | 9                     | 127.00018                   | 218.98                          | 153 <sup>a</sup> | $1\frac{47}{47} + 45/49$ | 11                    | 153.00015                   | 322.55                          |
| 128              | 5/16                     | 1                     | 128.00000                   | Exact                           | 154 <sup>a</sup> | $1/21 + 7/33$            | 1                     | 154.00000                   | Exact                           |
| 129              | $13/39 - 1/43$           | 1                     | 129.00000                   | Exact                           | 155              | 8/31                     | 1                     | 155.00000                   | Exact                           |
| 129 <sup>a</sup> | $5\frac{24}{41} + 15/49$ | 19                    | 128.99966                   | 121.50                          | 156              | 10/39                    | 1                     | 156.00000                   | Exact                           |
| 130              | 12/39                    | 1                     | 130.00000                   | Exact                           | 157              | $18/47 - 5/39$           | 1                     | 157.00214                   | 23.34                           |
| 131              | $5/37 + 8/47$            | 1                     | 130.99812                   | 22.14                           | 157              | $22/47 + 27/49$          | 4                     | 157.00043                   | 117.29                          |
| 131 <sup>a</sup> | $2\frac{40}{43} + 21/49$ | 11                    | 130.99901                   | 42.16                           | 157 <sup>a</sup> | $2\frac{23}{43} + 2/33$  | 11                    | 157.00035                   | 143.28                          |
| 131              | $4/37 + 1\frac{18}{43}$  | 5                     | 131.00041                   | 101.29                          | 157              | $22/41 + 2\frac{29}{49}$ | 13                    | 157.00030                   | 166.27                          |
| 131              | $2\frac{27}{43} + 20/47$ | 10                    | 130.99984                   | 257.32                          | 158 <sup>a</sup> | $4\frac{7}{43} + 34/49$  | 19                    | 157.99901                   | 50.97                           |
| 132              | 10/33                    | 1                     | 132.00000                   | Exact                           | 158              | $1\frac{4}{39} + 8/49$   | 5                     | 157.99917                   | 60.83                           |
| 133              | $1/37 + 27/47$           | 2                     | 133.00191                   | 22.14                           | 158              | $1\frac{29}{39} + 23/43$ | 9                     | 158.00052                   | 96.09                           |
| 133              | $12/31 + 17/33$          | 3                     | 133.00108                   | 39.08                           | 159              | $14/37 + 27/43$          | 4                     | 159.00062                   | 81.03                           |
| 133 <sup>a</sup> | $2\frac{23}{39} + 17/33$ | 11                    | 133.00063                   | 67.02                           | 159              | $1\frac{7}{43} + 15/47$  | 7                     | 158.99972                   | 180.13                          |
| 133              | $1\frac{23}{39} + 19/31$ | 8                     | 133.00046                   | 91.57                           | 159 <sup>a</sup> | $2\frac{27}{37} + 16/49$ | 10                    | 159.00022                   | 230.84                          |
| 134              | $4/29 + 25/33$           | 3                     | 134.00233                   | 18.28                           | 160              | 4/16                     | 1                     | 160.00000                   | Exact                           |
| 134              | $1\frac{13}{43} + 37/47$ | 7                     | 133.99953                   | 90.06                           | 161              | $9/23 - 3/21$            | 1                     | 161.00000                   | Exact                           |
| 134 <sup>a</sup> | $3\frac{27}{47} + 15/49$ | 13                    | 134.00022                   | 190.60                          | 161 <sup>a</sup> | $1\frac{10}{39} + 48/49$ | 9                     | 161.00164                   | 31.28                           |
| 135              | 8/27                     | 1                     | 135.00000                   | Exact                           | 162              | $28/47 - 15/43$          | 1                     | 162.00401                   | 12.87                           |
| 136              | 5/17                     | 1                     | 136.00000                   | Exact                           | 162              | $1\frac{30}{39} - 2/49$  | 7                     | 161.99818                   | 28.39                           |
| 137              | $9/37 + 31/49$           | 3                     | 137.00252                   | 17.31                           | 162 <sup>a</sup> | $\frac{30}{39} + 47/49$  | 7                     | 161.99818                   | 28.39                           |
| 137              | $11/41 + 1\frac{30}{49}$ | 7                     | 136.99951                   | 89.53                           | 162              | $2\frac{28}{39} + 25/29$ | 13                    | 161.99907                   | 55.20                           |
| 137              | $17/43 + 2\frac{40}{49}$ | 11                    | 137.00015                   | 295.10                          | 163              | $18/49 - 5/41$           | 1                     | 163.00203                   | 25.58                           |
| 137 <sup>a</sup> | $2\frac{17}{43} + 40/49$ | 11                    | 137.00015                   | 295.10                          | 163              | $19/37 + 22/47$          | 4                     | 162.99941                   | 88.57                           |
| 138              | $7/21 - 1/23$            | 1                     | 138.00000                   | Exact                           | 163 <sup>a</sup> | $2\frac{27}{47} + 25/49$ | 11                    | 162.99959                   | 126.96                          |
| 138 <sup>a</sup> | $18/23 + 22/33$          | 5                     | 138.00000                   | Exact                           | 163              | $2\frac{37}{47} + 26/49$ | 13                    | 162.99986                   | 381.20                          |
| 139              | $23/41 + 13/43$          | 3                     | 139.00131                   | 33.67                           | 164              | 10/41                    | 1                     | 164.00000                   | Exact                           |
| 139              | $1\frac{13}{39} + 9/41$  | 7                     | 139.00031                   | 142.51                          | 165              | 8/33                     | 1                     | 165.00000                   | Exact                           |
| 139              | $3\frac{14}{43} + 6/47$  | 12                    | 138.99986                   | 308.79                          | 166              | $20/29 + 17/33$          | 5                     | 166.00173                   | 30.46                           |
| 139 <sup>a</sup> | $2\frac{25}{43} + 24/49$ | 11                    | 138.99983                   | 253.92                          | 166 <sup>a</sup> | $1\frac{19}{43} + 12/49$ | 7                     | 165.99887                   | 46.95                           |
| 140              | 6/21                     | 1                     | 140.00000                   | Exact                           | 166              | $2\frac{23}{43} + 7/43$  | 11                    | 166.00043                   | 123.46                          |
| 141              | $29/47 - 13/39$          | 1                     | 141.00000                   | Exact                           | 167 <sup>a</sup> | $2\frac{12}{29} + 4/33$  | 9                     | 166.99952                   | 109.66                          |
| 141 <sup>a</sup> | $1\frac{32}{39} + 22/49$ | 8                     | 141.00069                   | 64.88                           | 167              | $23/43 + 9/49$           | 3                     | 167.00132                   | 40.24                           |
| 142              | $23/39 + 12/47$          | 3                     | 142.00129                   | 35.01                           | 167              | $6/37 + 39/49$           | 4                     | 167.00058                   | 92.34                           |
| 142              | $18/41 + 2\frac{31}{47}$ | 11                    | 141.99967                   | 134.94                          | 167              | $2\frac{23}{37} + 20/43$ | 13                    | 167.00040                   | 131.67                          |
| 142 <sup>a</sup> | $4\frac{17}{47} + 10/49$ | 15                    | 141.99979                   | 219.92                          | 168              | 5/21                     | 1                     | 168.00000                   | Exact                           |
| 143 <sup>a</sup> | $36/47 + 31/49$          | 5                     | 142.99907                   | 48.87                           | 169              | $1/41 + 22/49$           | 2                     | 169.00105                   | 51.16                           |
| 143              | $13/37 + 20/41$          | 3                     | 143.00079                   | 57.95                           | 169 <sup>a</sup> | $1\frac{32}{37} + 13/49$ | 9                     | 169.00052                   | 103.88                          |
| 143              | $1\frac{16}{27} + 20/31$ | 8                     | 143.00053                   | 85.26                           | 170              | 4/17                     | 1                     | 170.00000                   | Exact                           |
| 144              | 5/18                     | 1                     | 144.00000                   | Exact                           | 171              | $8/18 - 4/19$            | 1                     | 171.00000                   | Exact                           |
| 145              | 8/29                     | 1                     | 145.00000                   | Exact                           | 171 <sup>a</sup> | $1\frac{20}{47} + 1/49$  | 7                     | 170.99973                   | 205.26                          |
| 146              | $16/41 - 5/43$           | 1                     | 146.00414                   | 11.22                           | 172              | 10/43                    | 1                     | 172.00000                   | Exact                           |
| 146              | $3/37 + 1\frac{41}{49}$  | 7                     | 145.99942                   | 80.79                           | 173              | $27/37 + 8/41$           | 4                     | 173.00071                   | 77.26                           |
| 146 <sup>a</sup> | $1\frac{37}{47} + 41/49$ | 7                     | 145.99942                   | 80.79                           | 173 <sup>a</sup> | $1\frac{7}{43} + 11/49$  | 6                     | 173.00034                   | 160.96                          |
| 146              | $28/37 + 2\frac{31}{41}$ | 13                    | 146.00037                   | 125.55                          |                  |                          |                       |                             |                                 |



Table 1b. (Continued) Simple and Compound Indexing with Brown &amp; Sharpe Plates

| Target Divisions | Indexing Movements                      | Workpiece Revolutions | Precise Number of Divisions | Diameter at Which Error = 0.001 | Target Divisions | Indexing Movements                      | Workpiece Revolutions | Precise Number of Divisions | Diameter at Which Error = 0.001 |
|------------------|---|-----------------------|-----------------------------|---------------------------------|------------------|---|-----------------------|-----------------------------|---------------------------------|
| 174              | 7/21 - 3/29                             | 1                     | 174.00000                   | Exact                           | 199              | 16/41 + 10/47                           | 3                     | 199.00172                   | 36.80                           |
| 174 <sup>a</sup> | 14/29 + 22/33                           | 5                     | 174.00000                   | Exact                           | 199              | 26/37 + 13/43                           | 5                     | 198.99937                   | 101.29                          |
| 175              | 3/37 + 26/43                            | 3                     | 174.99542                   | 12.15                           | 199 <sup>a</sup> | 1 <sup>3</sup> / <sub>41</sub> + 45/49  | 11                    | 199.00045                   | 140.69                          |
| 175 <sup>a</sup> | 1 <sup>1</sup> / <sub>41</sub> + 8/33   | 6                     | 174.99644                   | 15.63                           | 199              | 1 <sup>4</sup> / <sub>43</sub> + 31/47  | 13                    | 199.00019                   | 334.52                          |
| 175              | 1 <sup>1</sup> / <sub>47</sub> + 5/39   | 6                     | 174.99747                   | 22.05                           | 200              | 3/15                                    | 1                     | 200.00000                   | Exact                           |
| 175              | 2 <sup>8</sup> / <sub>41</sub> + 15/47  | 11                    | 175.00103                   | 53.98                           | 201              | 27/37 + 13/49                           | 5                     | 200.99778                   | 28.85                           |
| 176 <sup>a</sup> | 1 <sup>1</sup> / <sub>43</sub> + 13/49  | 7                     | 176.00239                   | 23.47                           | 201              | 1 <sup>3</sup> / <sub>41</sub> + 27/49  | 10                    | 201.00050                   | 127.90                          |
| 176              | 2 <sup>18</sup> / <sub>57</sub> + 22/47 | 13                    | 175.99844                   | 35.98                           | 201 <sup>a</sup> | 2 <sup>18</sup> / <sub>47</sub> + 10/49 | 13                    | 201.00034                   | 190.60                          |
| 177              | 6/37 + 3/47                             | 1                     | 176.99746                   | 22.14                           | 201              | 2 <sup>4</sup> / <sub>41</sub> + 20/43  | 13                    | 200.99978                   | 291.81                          |
| 177              | 1 <sup>17</sup> / <sub>57</sub> + 6/49  | 7                     | 177.00139                   | 40.40                           | 202              | 24/37 + 14/41                           | 5                     | 201.99734                   | 24.14                           |
| 177 <sup>a</sup> | 2 <sup>19</sup> / <sub>57</sub> + 4/49  | 11                    | 177.99913                   | 64.51                           | 202 <sup>a</sup> | 3 <sup>10</sup> / <sub>41</sub> + 6/49  | 17                    | 201.99911                   | 72.47                           |
| 178              | 1 <sup>16</sup> / <sub>59</sub> + 7/43  | 7                     | 177.99848                   | 37.37                           | 202              | 1/43 + 2 <sup>7</sup> / <sub>49</sub>   | 13                    | 201.99853                   | 43.59                           |
| 178 <sup>a</sup> | 3 <sup>26</sup> / <sub>57</sub> + 11/49 | 17                    | 177.99955                   | 124.62                          | 203              | 14/29 - 6/21                            | 1                     | 203.00000                   | Exact                           |
| 178              | 2 <sup>1</sup> / <sub>41</sub> + 32/49  | 13                    | 177.99966                   | 166.27                          | 203 <sup>a</sup> | 1 <sup>2</sup> / <sub>59</sub> + 9/49   | 9                     | 202.99793                   | 31.28                           |
| 179              | 20/37 - 13/41                           | 1                     | 178.99705                   | 19.31                           | 204              | 9/17 - 5/15                             | 1                     | 204.00000                   | Exact                           |
| 179              | 14/39 + 23/43                           | 4                     | 178.99933                   | 85.41                           | 204 <sup>a</sup> | 2 <sup>3</sup> / <sub>41</sub> + 3/49   | 13                    | 203.99922                   | 83.13                           |
| 179 <sup>a</sup> | 1 <sup>3</sup> / <sub>47</sub> + 36/49  | 11                    | 179.00018                   | 322.55                          | 205              | 8/41                                    | 1                     | 205.00000                   | Exact                           |
| 180              | 4/18                                    | 1                     | 180.00000                   | Exact                           | 206              | 1/41 + 24/43                            | 3                     | 205.99805                   | 33.67                           |
| 180              | 6/27                                    | 1                     | 180.00000                   | Exact                           | 206              | 2 <sup>8</sup> / <sub>59</sub> + 15/47  | 13                    | 205.99957                   | 151.70                          |
| 181              | 20/37 + 6/49                            | 3                     | 180.99834                   | 34.63                           | 206 <sup>a</sup> | 2 <sup>3</sup> / <sub>59</sub> + 2/49   | 15                    | 206.00072                   | 91.24                           |
| 181 <sup>a</sup> | 2 <sup>8</sup> / <sub>43</sub> + 12/49  | 11                    | 180.99961                   | 147.55                          | 207              | 5/23 + 15/27                            | 4                     | 207.00000                   | Exact                           |
| 181              | 39/41 + 28/47                           | 7                     | 180.99966                   | 171.75                          | 207 <sup>a</sup> | 2 <sup>8</sup> / <sub>41</sub> + 25/49  | 14                    | 206.99908                   | 71.62                           |
| 181              | 2 <sup>8</sup> / <sub>59</sub> + 21/47  | 12                    | 180.99979                   | 280.06                          | 208              | 8/43 + 38/49                            | 5                     | 207.99605                   | 16.77                           |
| 182 <sup>a</sup> | 3/39 + 7/49                             | 1                     | 182.00000                   | Exact                           | 208 <sup>a</sup> | 1 <sup>9</sup> / <sub>47</sub> + 16/49  | 9                     | 207.99799                   | 32.99                           |
| 183              | 8/29 + 5/31                             | 2                     | 183.00254                   | 22.89                           | 208              | 3 <sup>1</sup> / <sub>43</sub> + 11/49  | 21                    | 208.00094                   | 70.42                           |
| 183              | 1/43 + 40/47                            | 4                     | 182.99943                   | 102.93                          | 209 <sup>a</sup> | 9/41 + 8/49                             | 2                     | 208.99870                   | 51.16                           |
| 183 <sup>a</sup> | 1 <sup>3</sup> / <sub>41</sub> + 8/49   | 8                     | 183.00028                   | 204.64                          | 209              | 1 <sup>3</sup> / <sub>41</sub> + 18/43  | 12                    | 208.99975                   | 269.37                          |
| 184              | 5/23                                    | 1                     | 184.00000                   | Exact                           | 210              | 4/21                                    | 1                     | 210.00000                   | Exact                           |
| 185              | 8/37                                    | 1                     | 185.00000                   | Exact                           | 211 <sup>a</sup> | 1 <sup>2</sup> / <sub>59</sub> + 18/49  | 11                    | 211.00125                   | 53.53                           |
| 186              | 17/31 - 7/21                            | 1                     | 186.00000                   | Exact                           | 211              | 35/37 + 9/47                            | 6                     | 211.00101                   | 66.42                           |
| 186 <sup>a</sup> | 3/31 + 11/33                            | 2                     | 186.00000                   | Exact                           | 211              | 1 <sup>9</sup> / <sub>59</sub> + 17/39  | 9                     | 210.99919                   | 82.68                           |
| 187              | 19/37 + 5/39                            | 3                     | 186.99784                   | 27.56                           | 211              | 1 <sup>3</sup> / <sub>41</sub> + 31/47  | 13                    | 211.00021                   | 318.96                          |
| 187 <sup>a</sup> | 1 <sup>3</sup> / <sub>43</sub> + 14/49  | 8                     | 186.99822                   | 33.51                           | 212              | 34/39 + 22/49                           | 7                     | 211.99683                   | 21.29                           |
| 187              | 21/23 + 10/27                           | 6                     | 187.00125                   | 47.44                           | 212              | 1 <sup>5</sup> / <sub>43</sub> + 47/49  | 11                    | 212.00091                   | 73.77                           |
| 187              | 1 <sup>3</sup> / <sub>43</sub> + 12/47  | 10                    | 186.99977                   | 257.32                          | 212 <sup>a</sup> | 3 <sup>8</sup> / <sub>43</sub> + 6/49   | 17                    | 211.99946                   | 124.62                          |
| 188              | 10/47                                   | 1                     | 188.00000                   | Exact                           | 213 <sup>a</sup> | 1 <sup>18</sup> / <sub>59</sub> + 2/49  | 8                     | 212.99896                   | 64.88                           |
| 189              | 7/27 - 1/21                             | 1                     | 189.00000                   | Exact                           | 213              | 14/37 + 44/47                           | 7                     | 213.00087                   | 77.50                           |
| 189 <sup>a</sup> | 1 <sup>2</sup> / <sub>41</sub> + 34/49  | 11                    | 189.00150                   | 40.20                           | 213              | 2 <sup>3</sup> / <sub>57</sub> + 9/41   | 17                    | 213.00021                   | 328.36                          |
| 190              | 4/19                                    | 1                     | 190.00000                   | Exact                           | 214              | 7/39 + 37/49                            | 5                     | 213.99776                   | 30.41                           |
| 191              | 1/21 + 18/31                            | 3                     | 191.00244                   | 24.87                           | 214 <sup>a</sup> | 2 <sup>7</sup> / <sub>47</sub> + 30/49  | 15                    | 214.00031                   | 219.92                          |
| 191 <sup>a</sup> | 1 <sup>3</sup> / <sub>47</sub> + 14/49  | 10                    | 191.00145                   | 41.89                           | 215              | 8/43                                    | 1                     | 215.00000                   | Exact                           |
| 191              | 34/37 + 5/39                            | 5                     | 190.99934                   | 91.86                           | 216              | 5/27                                    | 1                     | 216.00000                   | Exact                           |
| 191              | 28/39 + 45/47                           | 8                     | 190.99967                   | 186.71                          | 217              | 12/21 - 12/31                           | 1                     | 217.00000                   | Exact                           |
| 192              | 5/15 - 2/16                             | 1                     | 192.00000                   | Exact                           | 217 <sup>a</sup> | 2 <sup>1</sup> / <sub>43</sub> + 16/49  | 13                    | 217.00139                   | 49.82                           |
| 192 <sup>a</sup> | 1 <sup>2</sup> / <sub>41</sub> + 37/49  | 11                    | 191.99826                   | 35.17                           | 218              | 14/39 + 9/47                            | 3                     | 217.99802                   | 35.01                           |
| 193 <sup>a</sup> | 5/37 + 34/49                            | 4                     | 193.00067                   | 92.34                           | 218 <sup>a</sup> | 22/47 + 40/49                           | 7                     | 217.99865                   | 51.31                           |
| 193              | 29/39 + 12/41                           | 5                     | 192.99940                   | 101.80                          | 218              | 19/37 + 1 <sup>3</sup> / <sub>39</sub>  | 13                    | 218.00116                   | 59.71                           |
| 194              | 41/43 + 24/49                           | 7                     | 194.00197                   | 31.30                           | 219              | 24/39 + 14/47                           | 5                     | 218.99642                   | 19.45                           |
| 194 <sup>a</sup> | 1 <sup>2</sup> / <sub>57</sub> + 33/49  | 11                    | 193.99805                   | 31.74                           | 219 <sup>a</sup> | 2 <sup>3</sup> / <sub>43</sub> + 39/49  | 19                    | 218.99891                   | 63.71                           |
| 194              | 1 <sup>17</sup> / <sub>57</sub> + 11/47 | 9                     | 194.00062                   | 99.64                           | 219              | 1 <sup>2</sup> / <sub>57</sub> + 11/49  | 7                     | 218.99914                   | 80.79                           |
| 194              | 2 <sup>8</sup> / <sub>47</sub> + 25/49  | 13                    | 193.99968                   | 190.60                          | 219              | 2 <sup>1</sup> / <sub>41</sub> + 41/49  | 17                    | 218.99968                   | 217.42                          |
| 195              | 8/39                                    | 1                     | 195.00000                   | Exact                           | 220              | 6/33                                    | 1                     | 220.00000                   | Exact                           |
| 196              | 10/49                                   | 1                     | 196.00000                   | Exact                           | 221              | 26/37 + 1/47                            | 4                     | 221.00079                   | 88.57                           |
| 197              | 17/37 - 10/39                           | 1                     | 196.99659                   | 18.37                           | 221 <sup>a</sup> | 5/47 + 48/49                            | 6                     | 220.99960                   | 175.94                          |
| 197              | 19/39 + 5/41                            | 3                     | 197.00205                   | 30.54                           | 221              | 3 <sup>1</sup> / <sub>41</sub> + 25/43  | 21                    | 220.99985                   | 471.39                          |
| 197 <sup>a</sup> | 1 <sup>3</sup> / <sub>43</sub> + 16/49  | 11                    | 196.99958                   | 147.55                          | 222              | 19/37 - 13/39                           | 1                     | 222.00000                   | Exact                           |
| 198 <sup>a</sup> | 3/27 + 3/33                             | 1                     | 198.00000                   | Exact                           | 222 <sup>a</sup> | 1 <sup>5</sup> / <sub>43</sub> + 39/49  | 11                    | 222.00192                   | 36.89                           |

**Table 1b. (Continued) Simple and Compound Indexing with Brown & Sharpe Plates**

| Target Divisions | Indexing Movements                      | Workpiece Revolutions | Precise Number of Divisions | Diameter at Which Error = 0.001 | Target Divisions | Indexing Movements                      | Workpiece Revolutions | Precise Number of Divisions | Diameter at Which Error = 0.001 |
|------------------|---|-----------------------|-----------------------------|---------------------------------|------------------|---|-----------------------|-----------------------------|---------------------------------|
| 223              | 6/37 + 36/49                            | 25                    | 223.00123                   | 57.71                           | 239              | 1/37 + 12/39                            | 2                     | 239.00621                   | 12.25                           |
| 223              | 1 <sup>36</sup> / <sub>37</sub> + 38/47 | 14                    | 222.99977                   | 309.98                          | 239              | 32/39 + 9/49                            | 6                     | 238.99948                   | 145.99                          |
| 223 <sup>a</sup> | 2 <sup>36</sup> / <sub>43</sub> + 13/49 | 16                    | 222.99983                   | 429.23                          | 239 <sup>a</sup> | 1 <sup>36</sup> / <sub>43</sub> + 15/49 | 11                    | 238.99974                   | 295.10                          |
| 223              | 3 <sup>14</sup> / <sub>41</sub> + 15/47 | 20                    | 223.00014                   | 490.71                          | 239              | 2 <sup>36</sup> / <sub>41</sub> + 26/43 | 16                    | 239.00021                   | 359.16                          |
| 224              | 1 <sup>13</sup> / <sub>37</sub> + 11/43 | 9                     | 223.99687                   | 22.79                           | 240              | 3/18                                    | 1                     | 240.00000                   | Exact                           |
| 224              | 2 <sup>16</sup> / <sub>39</sub> + 11/41 | 15                    | 224.00187                   | 38.17                           | 241              | 4/39 + 17/43                            | 3                     | 241.00599                   | 12.81                           |
| 224 <sup>a</sup> | 2 <sup>9</sup> / <sub>23</sub> + 2/33   | 13                    | 223.99546                   | 15.70                           | 241              | 26/41 + 17/47                           | 6                     | 241.00052                   | 147.21                          |
| 224              | 3 <sup>5</sup> / <sub>43</sub> + 13/47  | 19                    | 223.99883                   | 61.11                           | 241 <sup>a</sup> | 1 <sup>4</sup> / <sub>41</sub> + 23/49  | 9                     | 240.99967                   | 230.21                          |
| 225              | 1/15 + 2/18                             | 1                     | 225.00000                   | Exact                           | 241              | 1 <sup>36</sup> / <sub>39</sub> + 35/43 | 15                    | 240.99975                   | 303.86                          |
| 225 <sup>a</sup> | 1/18 + 6/20                             | 2                     | 225.00000                   | Exact                           | 242              | 4/37 + 19/49                            | 3                     | 242.00222                   | 34.63                           |
| 226              | 28/37 + 5/39                            | 5                     | 225.99843                   | 45.93                           | 242              | 1 <sup>36</sup> / <sub>39</sub> + 26/49 | 15                    | 242.00084                   | 91.24                           |
| 226 <sup>a</sup> | 1 <sup>38</sup> / <sub>39</sub> + 16/49 | 13                    | 225.99955                   | 158.16                          | 242 <sup>a</sup> | 1 <sup>36</sup> / <sub>41</sub> + 45/49 | 15                    | 241.99960                   | 191.85                          |
| 227              | 9/39 + 14/47                            | 3                     | 226.99690                   | 23.34                           | 242              | 2 <sup>36</sup> / <sub>39</sub> + 39/43 | 21                    | 241.99966                   | 224.20                          |
| 227              | 1 <sup>11</sup> / <sub>37</sub> + 25/39 | 11                    | 227.00036                   | 202.10                          | 243              | 22/37 + 3/47                            | 4                     | 243.00437                   | 17.71                           |
| 227 <sup>a</sup> | 3 <sup>3</sup> / <sub>43</sub> + 5/49   | 18                    | 226.99985                   | 482.89                          | 243              | 32/41 + 2/47                            | 5                     | 243.00126                   | 61.34                           |
| 228              | 5/15 - 3/19                             | 1                     | 228.00000                   | Exact                           | 243 <sup>a</sup> | 29/41 + 46/49                           | 10                    | 242.99970                   | 255.79                          |
| 229              | 7/39 + 34/49                            | 5                     | 228.99940                   | 121.66                          | 244              | 36/39 + 11/49                           | 7                     | 243.99453                   | 14.19                           |
| 229 <sup>a</sup> | 1 <sup>19</sup> / <sub>41</sub> + 31/49 | 12                    | 229.00024                   | 306.95                          | 244              | 1 <sup>10</sup> / <sub>39</sub> + 8/39  | 9                     | 244.00188                   | 41.34                           |
| 229              | 2 <sup>35</sup> / <sub>41</sub> + 20/43 | 19                    | 229.00017                   | 426.50                          | 244              | 2 <sup>13</sup> / <sub>31</sub> + 10/33 | 17                    | 243.99860                   | 55.36                           |
| 230              | 4/23                                    | 1                     | 230.00000                   | Exact                           | 244 <sup>a</sup> | 1 <sup>38</sup> / <sub>39</sub> + 2/43  | 11                    | 244.00139                   | 55.71                           |
| 231 <sup>a</sup> | 3/21 + 1/33                             | 1                     | 231.00000                   | Exact                           | 245              | 8/49                                    | 1                     | 245.00000                   | Exact                           |
| 232              | 5/29                                    | 1                     | 232.00000                   | Exact                           | 246              | 13/39 - 7/41                            | 1                     | 246.00000                   | Exact                           |
| 233              | 2/37 + 31/49                            | 4                     | 232.99598                   | 18.47                           | 246 <sup>a</sup> | 6/43 + 33/49                            | 5                     | 246.00117                   | 67.07                           |
| 233 <sup>a</sup> | 1 <sup>36</sup> / <sub>47</sub> + 6/49  | 11                    | 233.00069                   | 107.52                          | 247              | 17/37 + 21/41                           | 6                     | 247.00136                   | 57.59                           |
| 233              | 21/37 + 26/41                           | 7                     | 233.00055                   | 135.21                          | 247              | 15/43 + 1 <sup>4</sup> / <sub>49</sub>  | 14                    | 247.00021                   | 375.58                          |
| 233              | 1 <sup>23</sup> / <sub>39</sub> + 41/43 | 15                    | 232.99976                   | 303.86                          | 247 <sup>a</sup> | 1 <sup>15</sup> / <sub>43</sub> + 45/49 | 14                    | 247.00021                   | 375.58                          |
| 234 <sup>a</sup> | 2 <sup>21</sup> / <sub>39</sub> + 6/33  | 17                    | 234.00216                   | 34.52                           | 248              | 5/31                                    | 1                     | 248.00000                   | Exact                           |
| 234              | 8/41 + 31/47                            | 5                     | 234.00121                   | 61.34                           | 249              | 20/37 + 5/49                            | 4                     | 248.99571                   | 18.47                           |
| 234              | 2 <sup>17</sup> / <sub>43</sub> + 24/47 | 17                    | 233.99966                   | 218.72                          | 249              | 10/37 + 1 <sup>4</sup> / <sub>47</sub>  | 14                    | 249.00026                   | 309.98                          |
| 235              | 8/47                                    | 1                     | 235.00000                   | Exact                           | 249              | 4/43 + 2 <sup>7</sup> / <sub>49</sub>   | 19                    | 249.00016                   | 509.72                          |
| 236              | 22/37 + 29/49                           | 7                     | 236.00186                   | 40.40                           | 249 <sup>a</sup> | 2 <sup>36</sup> / <sub>43</sub> + 47/49 | 19                    | 249.00016                   | 509.72                          |
| 236 <sup>a</sup> | 2 <sup>36</sup> / <sub>43</sub> + 9/49  | 17                    | 236.00066                   | 114.02                          | 250              | 1 <sup>8</sup> / <sub>41</sub> + 12/49  | 9                     | 249.99654                   | 23.02                           |
| 237              | 1 <sup>7</sup> / <sub>39</sub> + 7/41   | 8                     | 236.99861                   | 54.29                           | 250 <sup>a</sup> | 1 <sup>17</sup> / <sub>37</sub> + 41/49 | 13                    | 250.00265                   | 30.01                           |
| 237              | 1 <sup>36</sup> / <sub>37</sub> + 6/39  | 11                    | 236.99888                   | 67.37                           | 250              | 2 <sup>36</sup> / <sub>43</sub> + 33/49 | 17                    | 250.00174                   | 45.61                           |
| 237              | 12/47 + 1 <sup>4</sup> / <sub>49</sub>  | 13                    | 236.99980                   | 381.20                          | 250              | 3 <sup>27</sup> / <sub>47</sub> + 48/49 | 27                    | 249.99899                   | 79.17                           |
| 237 <sup>a</sup> | 1 <sup>12</sup> / <sub>47</sub> + 46/49 | 13                    | 236.99980                   | 381.20                          | ...              | ...                                     | ...                   | ...                         | ...                             |
| 238              | 7/37 + 28/43                            | 5                     | 237.99551                   | 16.88                           | ...              | ...                                     | ...                   | ...                         | ...                             |
| 238              | 1/43 + 1 <sup>27</sup> / <sub>47</sub>  | 9                     | 237.99804                   | 38.60                           | ...              | ...                                     | ...                   | ...                         | ...                             |
| 238 <sup>a</sup> | 2 <sup>3</sup> / <sub>31</sub> + 14/33  | 15                    | 237.99922                   | 97.69                           | ...              | ...                                     | ...                   | ...                         | ...                             |
| 238              | 2 <sup>17</sup> / <sub>39</sub> + 4/47  | 15                    | 238.00043                   | 175.04                          | ...              | ...                                     | ...                   | ...                         | ...                             |

<sup>a</sup>Requires only the outer most circle of holes on indexing plate.

The greater spacing between successive machining operations may be used to advantage to spread out and reduce the effects of heat generation on the workpiece. The number of workpiece revolutions required by an approximation is shown in the table in the column to the right of the indexing movements. The table gives two or three choices for each division requiring approximate movements.

Two measures of the closeness of each approximation are provided to aid in the trade-off between complexity and precision. The first measure is the precise number of divisions that a set of indexing movements produces, offering a direct comparison of the degree of approximation. However, the difference between the precise number of divisions and the target number of divisions is angular in nature, so the error introduced by an approximation depends on the size of the circle being divided. The second measure of closeness reflects this characteristic by expressing the degree of approximation as the diameter at which the error is equal to 0.001. This second measure is unitless, so that taking the error as 0.001

inch means that the entries in that column are to be taken as diameters in inches, but the measure works as well with 0.001 centimeter and diameters in centimeters. The measure can also be used to calculate the error of approximation at a given diameter. Divide the given diameter by the value of the measure and multiply the result by 0.001 to determine the amount of error that using an approximation will introduce.

*Example:* A gear is to be cut with 127 teeth at 16 diametral pitch using a Brown & Sharpe plain dividing head. The indexing table gives three approximations for 127 divisions. The pitch diameter of a 16 DP gear with 127 teeth is about 7.9 inches, so the calculated error of approximation for the three choices would be about  $(7.9 \div 17.5) \times 0.001 = 0.00045$  inch,  $(7.9 \div 77.5) \times 0.001 = 0.00010$  inch, and  $(7.9 \div 218.98) \times 0.001 = 0.000036$  inch. Considering the increased potential for operator error with longer indexing movements and such other factors as may be appropriate, assume that the first of the three approximations is selected. Plate 3 is mounted on the worm shaft of the dividing head but not bolted to the frame. A double set of sector arms is installed, if available; otherwise, the single pair of sector arms is installed. The indexing pin on the crank arm is set to track the 39-hole circle. The stationary indexing pin is installed and set to track the 47-hole circle. If only one pair of sector arms is used, it is used for the 42/47 movement and is set for 0-42 holes using the outer arc. Six holes should be showing in the inner arc on the 47-hole circle (the zero-hole, the 42-hole, and four extra holes). The second set of sector arms is set for 0-2 holes on the 39-hole circle using the inner arc (three holes showing). If there is no second pair of sector arms, this is a short enough movement to do freehand without adding much risk of error.

**Angular Indexing.**—The plain dividing head with a 40:1 gear ratio will rotate the main spindle and the workpiece 9 degrees for each full turn of the indexing crank, and therefore 1 degree for movements of 2/18 or 3/27 on Brown & Sharpe dividing heads and 6/54 on heads of Cincinnati design. To find the indexing movement for an angle, divide that angle, in degrees, by 9 to get the number of full turns and the remainder, if any. If the remainder, expressed in minutes, is evenly divisible by 36, 33.75, 30, 27, or 20, then the quotient is the number of holes to be moved on the 15-, 16-, 18-, 20-, or 27-hole circles, respectively, to obtain the fractional turn required (or evenly divisible by 22.5, 21.6, 18, 16.875, 15, 11.25, or 10 for the number of holes to be moved on the 24-, 25-, 30-, 32-, 36-, 48-, or 54-hole circles, respectively, for the standard and high number plates of a Cincinnati dividing head). If none of these divisions is even, it is not possible to index the angle (exactly) by this method.

*Example:* An angle of  $61^{\circ} 48'$  is required. Expressed in degrees, this angle is  $61.8^{\circ}$ , which when divided by 9 equals 6 with a remainder of  $7.8^{\circ}$ , or  $468'$ . Division of 468 by 20, 27, 30, 33.75, and 36 reveals an even division by 36, yielding 13. The indexing movement for  $61^{\circ} 48'$  is six full turns plus 13 holes on the 15-hole circle.

**Tables for Angular Indexing.**—Table 2, headed *Angular Values of One-Hole Moves*, provides the angular movement obtained with a move of one hole in each of the indexing circles available on standard Brown & Sharpe and Cincinnati plates, for a selection of angles that can be approximated with simple indexing.

Table 3, titled *Accurate Angular Indexing*, provides the simple and compound indexing movements to obtain the full range of fractional turns with the standard indexing plates of both the Brown & Sharpe and Cincinnati dividing heads. Compound indexing movements depend on the presence of specific indexing circles on the same indexing plate, so some movements may not be available with plates of different configurations. To use the table to index an angle, first convert the angle to seconds and then divide the number of seconds in the angle by 32,400 (the number of seconds in 9 degrees, which is one full turn of the indexing crank). The whole-number portion of the quotient gives the number of full turns of the indexing crank, and the decimal fraction of the quotient gives the fractional turn required.

**Table 2. Angular Values of One-Hole Moves for B&S and Cincinnati Index Plates**

| Holes in Circle | Angle in Minutes | Holes in Circle | Angle in Minutes | Holes in Circle | Angle in Minutes |
|-----------------|------------------|-----------------|------------------|-----------------|------------------|
| 15              | 36.000           | 53              | 10.189           | 129             | 4.186            |
| 16              | 33.750           | 54              | 10.000           | 131             | 4.122            |
| 17              | 31.765           | 57              | 9.474            | 133             | 4.060            |
| 18              | 30.000           | 58              | 9.310            | 137             | 3.942            |
| 19              | 28.421           | 59              | 9.153            | 139             | 3.885            |
| 20              | 27.000           | 62              | 8.710            | 141             | 3.830            |
| 21              | 25.714           | 66              | 8.182            | 143             | 3.776            |
| 23              | 23.478           | 67              | 8.060            | 147             | 3.673            |
| 24              | 22.500           | 69              | 7.826            | 149             | 3.624            |
| 25              | 21.600           | 71              | 7.606            | 151             | 3.576            |
| 26              | 20.769           | 73              | 7.397            | 153             | 3.529            |
| 27              | 20.000           | 77              | 7.013            | 157             | 3.439            |
| 28              | 19.286           | 79              | 6.835            | 159             | 3.396            |
| 29              | 18.621           | 81              | 6.667            | 161             | 3.354            |
| 30              | 18.000           | 83              | 6.506            | 163             | 3.313            |
| 31              | 17.419           | 87              | 6.207            | 167             | 3.234            |
| 32              | 16.875           | 89              | 6.067            | 169             | 3.195            |
| 33              | 16.364           | 91              | 5.934            | 171             | 3.158            |
| 34              | 15.882           | 93              | 5.806            | 173             | 3.121            |
| 36              | 15.000           | 97              | 5.567            | 175             | 3.086            |
| 37              | 14.595           | 99              | 5.455            | 177             | 3.051            |
| 38              | 14.211           | 101             | 5.347            | 179             | 3.017            |
| 39              | 13.846           | 103             | 5.243            | 181             | 2.983            |
| 41              | 13.171           | 107             | 5.047            | 183             | 2.951            |
| 42              | 12.857           | 109             | 4.954            | 187             | 2.888            |
| 43              | 12.558           | 111             | 4.865            | 189             | 2.857            |
| 44              | 12.273           | 113             | 4.779            | 191             | 2.827            |
| 46              | 11.739           | 117             | 4.615            | 193             | 2.798            |
| 47              | 11.489           | 119             | 4.538            | 197             | 2.741            |
| 48              | 11.250           | 121             | 4.463            | 199             | 2.714            |
| 49              | 11.020           | 123             | 4.390            | ...             | ...              |
| 51              | 10.588           | 127             | 4.252            | ...             | ...              |

Use [Table 3](#) to locate the indexing movement for the decimal fraction nearest to the decimal fraction of the quotient for which there is an entry in the column for the dividing head to be used. If the decimal fraction of the quotient is close to the midpoint between two table entries, calculate the mathematical value of the two indexing movements to more decimal places to make the closeness determination.

*Example:* Movement through an angle of  $31^{\circ} 27' 50''$  is required. Expressed in seconds, this angle  $113270''$ , which, divided by 32,400, equals 3.495987. The indexing movement is three full turns of the crank plus a fractional turn of 0.495987. The nearest [Table 3](#) entry is for 0.4960, which requires a compound indexing movement of 8 holes on the 23-hole circle plus 4 holes on the 27-hole circle in the same direction. Checking the value of these movements shows that  $\frac{8}{23} + \frac{4}{27} = 0.347826 + 0.148148 = 0.495974$ , which, multiplied by 32,400, = 16,069.56, or  $4^{\circ} 27' 49.56''$  from the fractional turn. Adding the  $27^{\circ}$  from three full turns gives a total movement of  $31^{\circ} 27' 49.56''$ .

Table 3. Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.0010         | 12/49 – 10/41                        | 15/51 – 17/58          | 0.0370         | 13/43 – 13/49                        | 6/51 – 5/62            |
| 0.0020         | 24/49 – 20/41                        | 23/51 – 22/49          | 0.0370         | 1/27                                 | 2/54                   |
| 0.0030         | 8/23 – 10/29                         | 7/39 – 6/34            | 0.0377         | ...                                  | 2/53                   |
| 0.0040         | 1/41 – 1/49                          | 4/66 – 3/53            | 0.0380         | 13/41 – 12/43                        | 12/49 – 12/58          |
| 0.0050         | 4/39 – 4/41                          | 3/24 – 3/25            | 0.0390         | 15/29 – 11/23                        | 9/54 – 6/47            |
| 0.0060         | 9/29 – 7/23                          | 18/51 – 17/49          | 0.0392         | ...                                  | 2/51                   |
| 0.0070         | 11/31 – 8/23                         | 5/46 – 6/59            | 0.0400         | 9/41 – 7/39                          | 1/25                   |
| 0.0080         | 2/41 – 2/49                          | 10/49 – 10/51          | 0.0408         | 2/49                                 | 2/49                   |
| 0.0090         | 1/23 – 1/29                          | 8/24 – 12/37           | 0.0410         | 20/41 – 21/47                        | 21/43 – 17/38          |
| 0.0100         | 8/39 – 8/41                          | 6/24 – 6/25            | 0.0417         | ...                                  | 1/24                   |
| 0.0110         | 6/39 – 7/49                          | 11/59 – 10/57          | 0.0420         | 8/47 – 5/39                          | 23/59 – 16/46          |
| 0.0120         | 9/47 – 7/39                          | 15/49 – 15/51          | 0.0426         | 2/47                                 | 2/47                   |
| 0.0130         | 2/33 – 1/21                          | 3/54 – 2/47            | 0.0430         | 7/21 – 9/31                          | 8/59 – 5/54            |
| 0.0140         | 19/47 – 16/41                        | 10/46 – 12/59          | 0.0435         | 1/23                                 | 2/46                   |
| 0.0150         | 8/29 – 6/23                          | 9/24 – 9/25            | 0.0440         | 17/43 – 13/37                        | 17/57 – 15/59          |
| 0.0152         | ...                                  | 1/66                   | 0.0450         | 11/49 – 7/39                         | 3/24 – 2/25            |
| 0.0160         | 18/49 – 13/37                        | 20/49 – 20/51          | 0.0455         | ...                                  | 3/66                   |
| 0.0161         | ...                                  | 1/62                   | 0.0460         | 8/37 – 8/47                          | 19/39 – 15/34          |
| 0.0169         | ...                                  | 1/59                   | 0.0465         | 2/43                                 | 2/43                   |
| 0.0170         | 15/41 – 15/43                        | 9/49 – 11/66           | 0.0470         | 8/49 – 5/43                          | 26/66 – 17/49          |
| 0.0172         | ...                                  | 1/58                   | 0.0476         | 1/21                                 | 2/42                   |
| 0.0175         | ...                                  | 1/57                   | 0.0480         | 11/47 – 8/43                         | 13/51 – 12/58          |
| 0.0180         | 9/39 – 10/47                         | 11/42 – 10/41          | 0.0484         | ...                                  | 3/62                   |
| 0.0185         | ...                                  | 1/54                   | 0.0488         | 2/41                                 | 2/41                   |
| 0.0189         | ...                                  | 1/53                   | 0.0490         | 14/43 – 13/47                        | 8/47 – 8/66            |
| 0.0190         | 7/37 – 8/47                          | 6/49 – 6/58            | 0.0500         | 1/20                                 | 2/24 – 1/30            |
| 0.0196         | ...                                  | 1/51                   | 0.0508         | ...                                  | 3/59                   |
| 0.0200         | 16/39 – 16/41                        | 3/30 – 2/25            | 0.0510         | 2/17 – 1/15                          | 16/54 – 13/53          |
| 0.0204         | 1/49                                 | 1/49                   | 0.0513         | 2/39                                 | 2/39                   |
| 0.0210         | 3/43 – 2/41                          | 15/46 – 18/59          | 0.0517         | ...                                  | 3/58                   |
| 0.0213         | 1/47                                 | 1/47                   | 0.0520         | 19/37 – 18/39                        | 6/46 – 4/51            |
| 0.0217         | ...                                  | 1/46                   | 0.0526         | 1/19                                 | 2/38                   |
| 0.0220         | 12/37 – 13/43                        | 22/59 – 20/57          | 0.0526         | ...                                  | 3/57                   |
| 0.0230         | 4/37 – 4/47                          | 3/47 – 2/49            | 0.0530         | 14/47 – 12/49                        | 1/54 + 2/58            |
| 0.0233         | 1/43                                 | 1/43                   | 0.0540         | 17/47 – 12/39                        | 12/53 – 10/58          |
| 0.0238         | ...                                  | 1/42                   | 0.0541         | 2/37                                 | 2/37                   |
| 0.0240         | 18/47 – 14/39                        | 23/58 – 19/51          | 0.0550         | 4/41 – 2/47                          | 9/24 – 8/25            |
| 0.0244         | 1/41                                 | 1/41                   | 0.0556         | 1/18                                 | 3/54                   |
| 0.0250         | 2/16 – 2/20                          | 2/30 – 1/24            | 0.0560         | 13/49 – 9/43                         | 7/38 – 5/39            |
| 0.0256         | 1/39                                 | 1/39                   | 0.0566         | ...                                  | 3/53                   |
| 0.0260         | 4/33 – 2/21                          | 3/46 – 2/51            | 0.0570         | 13/29 – 9/23                         | 18/49 – 18/58          |
| 0.0263         | ...                                  | 1/38                   | 0.0580         | 19/41 – 15/37                        | 7/53 – 4/54            |
| 0.0270         | 3/23 – 3/29                          | 6/53 – 5/58            | 0.0588         | 1/17                                 | 2/34                   |
| 0.0270         | 1/37                                 | 1/37                   | 0.0588         | ...                                  | 3/51                   |
| 0.0280         | 17/43 – 18/49                        | 20/46 – 24/59          | 0.0590         | 11/41 – 9/43                         | 21/49 – 17/46          |
| 0.0290         | 11/37 – 11/41                        | 4/49 – 3/57            | 0.0600         | 4/39 – 2/47                          | 3/30 – 1/25            |
| 0.0294         | ...                                  | 1/34                   | 0.0606         | 2/33                                 | 4/66                   |
| 0.0300         | 2/39 – 1/47                          | 7/25 – 6/24            | 0.0610         | 7/37 – 5/39                          | 5/51 – 2/54            |
| 0.0303         | 1/33                                 | 2/66                   | 0.0612         | 3/49                                 | 3/49                   |
| 0.0310         | 13/39 – 13/43                        | 13/34 – 13/37          | 0.0620         | 17/43 – 13/39                        | 11/37 – 8/34           |
| 0.0320         | 11/37 – 13/49                        | 8/37 – 7/38            | 0.0625         | 1/16                                 | ...                    |
| 0.0323         | 1/31                                 | 2/62                   | 0.0630         | 2/21 – 1/31                          | 5/59 – 1/46            |
| 0.0330         | 11/49 – 9/47                         | 11/49 – 9/47           | 0.0638         | 3/47                                 | 3/47                   |
| 0.0333         | ...                                  | 1/30                   | 0.0640         | 23/49 – 15/37                        | 10/51 – 7/53           |
| 0.0339         | ...                                  | 2/59                   | 0.0645         | 2/31                                 | 4/62                   |
| 0.0340         | 18/49 – 13/39                        | 18/49 – 17/51          | 0.0650         | 5/43 – 2/39                          | 11/25 – 9/24           |
| 0.0345         | 1/29                                 | 2/58                   | 0.0652         | ...                                  | 3/46                   |
| 0.0350         | 13/41 – 11/39                        | 4/25 – 3/24            | 0.0660         | 22/49 – 18/47                        | 22/49 – 18/47          |
| 0.0351         | ...                                  | 2/57                   | 0.0667         | 1/15                                 | 2/30                   |
| 0.0357         | ...                                  | 1/28                   | 0.0670         | 5/39 – 3/49                          | 19/49 – 17/53          |
| 0.0360         | 18/39 – 20/47                        | 21/41 – 20/42          | 0.0678         | ...                                  | 4/59                   |

Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.0680         | 9/39 - 7/43                          | 23/51 - 18/47          | 0.0980         | ...                                  | 5/51                   |
| 0.0690         | 2/29                                 | 4/58                   | 0.0990         | 1/29 + 2/31                          | 20/47 - 16/49          |
| 0.0690         | 12/37 - 12/47                        | 7/66 - 2/54            | 0.1000         | 2/20                                 | 3/30                   |
| 0.0698         | 3/43                                 | 3/43                   | 0.1010         | 6/27 - 4/33                          | 18/59 - 10/49          |
| 0.0700         | 8/33 - 5/29                          | 8/25 - 6/24            | 0.1017         | ...                                  | 6/59                   |
| 0.0702         | ...                                  | 4/57                   | 0.1020         | 6/47 - 1/39                          | 11/54 - 6/59           |
| 0.0710         | 17/43 - 12/37                        | 11/58 - 7/59           | 0.1020         | 5/49                                 | 5/49                   |
| 0.0714         | ...                                  | 2/28                   | 0.1026         | 4/39                                 | 4/39                   |
| 0.0714         | ...                                  | 3/42                   | 0.1030         | 21/49 - 14/43                        | 18/57 - 10/47          |
| 0.0720         | 7/47 - 3/39                          | 10/49 - 7/53           | 0.1034         | ...                                  | 6/58                   |
| 0.0730         | 9/37 - 8/47                          | 1/47 + 3/58            | 0.1035         | 3/29                                 | ...                    |
| 0.0732         | 3/41                                 | 3/41                   | 0.1040         | 21/41 - 20/49                        | 15/62 - 8/58           |
| 0.0740         | 23/49 - 17/43                        | 19/42 - 14/37          | 0.1050         | 11/41 - 8/49                         | 12/25 - 9/24           |
| 0.0741         | 2/27                                 | 4/54                   | 0.1053         | 2/19                                 | 4/38                   |
| 0.0750         | 2/16 - 1/20                          | 1/24 + 1/30            | 0.1053         | ...                                  | 6/57                   |
| 0.0755         | ...                                  | 4/53                   | 0.1060         | 1/27 + 2/29                          | 2/54 + 4/58            |
| 0.0758         | ...                                  | 5/66                   | 0.1061         | ...                                  | 7/66                   |
| 0.0760         | 17/47 - 14/49                        | 24/49 - 24/58          | 0.1064         | 5/47                                 | 5/47                   |
| 0.0769         | 3/39                                 | 3/39                   | 0.1070         | 10/37 - 8/49                         | 2/51 + 4/59            |
| 0.0770         | ...                                  | 9/46 - 7/59            | 0.1071         | ...                                  | 3/28                   |
| 0.0771         | 6/37 - 4/47                          | ...                    | 0.1080         | 1/23 + 2/31                          | 24/53 - 20/58          |
| 0.0780         | 13/39 - 12/47                        | 9/46 - 6/51            | 0.1081         | 4/37                                 | 4/37                   |
| 0.0784         | ...                                  | 4/51                   | 0.1087         | ...                                  | 5/46                   |
| 0.0789         | ...                                  | 3/38                   | 0.1090         | 8/47 - 3/49                          | 25/58 - 19/59          |
| 0.0790         | 20/37 - 18/39                        | 21/39 - 17/37          | 0.1100         | 2/41 + 3/49                          | 9/25 - 6/24            |
| 0.0800         | 9/37 - 8/49                          | 2/25                   | 0.1110         | 15/49 - 8/41                         | 32/59 - 22/51          |
| 0.0806         | ...                                  | 5/62                   | 0.1111         | 3/27                                 | 6/54                   |
| 0.0810         | 9/23 - 9/29                          | 17/47 - 16/57          | 0.1111         | 2/18                                 | ...                    |
| 0.0811         | 3/37                                 | 3/37                   | 0.1120         | 23/41 - 22/49                        | 23/47 - 20/53          |
| 0.0816         | 4/49                                 | 4/49                   | 0.1129         | ...                                  | 7/62                   |
| 0.0820         | 5/47 - 1/41                          | 4/38 - 1/43            | 0.1130         | 13/41 - 10/49                        | 1/49 + 5/54            |
| 0.0830         | 4/23 - 3/33                          | 8/46 - 6/66            | 0.1132         | ...                                  | 6/53                   |
| 0.0833         | ...                                  | 2/24                   | 0.1140         | 7/43 - 2/41                          | 22/58 - 13/49          |
| 0.0840         | 8/43 - 5/49                          | 8/47 - 5/58            | 0.1150         | 13/31 - 7/23                         | 6/25 - 3/24            |
| 0.0847         | ...                                  | 5/59                   | 0.1160         | 6/29 - 3/33                          | 14/53 - 8/54           |
| 0.0850         | 9/17 - 8/18                          | 3/24 - 1/25            | 0.1163         | 5/43                                 | 5/43                   |
| 0.0851         | 4/47                                 | 4/47                   | 0.1170         | 5/33 - 1/29                          | 5/59 + 2/62            |
| 0.0860         | 13/31 - 7/21                         | 16/59 - 10/54          | 0.1176         | 2/17                                 | 4/34                   |
| 0.0862         | ...                                  | 5/58                   | 0.1176         | ...                                  | 6/51                   |
| 0.0870         | 2/23                                 | 4/46                   | 0.1180         | 6/23 - 3/21                          | 27/59 - 18/53          |
| 0.0870         | 5/33 - 2/31                          | 21/54 - 16/53          | 0.1186         | ...                                  | 7/59                   |
| 0.0877         | ...                                  | 5/57                   | 0.1190         | 10/29 - 7/31                         | 4/47 + 2/59            |
| 0.0880         | 8/37 - 5/39                          | 28/57 - 25/62          | 0.1190         | ...                                  | 5/42                   |
| 0.0882         | ...                                  | 3/34                   | 0.1200         | 8/39 - 4/47                          | 3/25                   |
| 0.0890         | 6/37 - 3/41                          | 22/53 - 15/46          | 0.1207         | ...                                  | 7/58                   |
| 0.0900         | 22/49 - 14/39                        | 6/24 - 4/25            | 0.1210         | 21/43 - 18/49                        | 26/53 - 17/46          |
| 0.0909         | 3/33                                 | 6/66                   | 0.1212         | 4/33                                 | 8/66                   |
| 0.0910         | 23/49 - 14/37                        | 21/51 - 17/53          | 0.1220         | 5/41                                 | 5/41                   |
| 0.0920         | 4/31 - 1/27                          | 4/34 - 1/39            | 0.1220         | 23/47 - 18/49                        | 10/51 - 4/54           |
| 0.0926         | ...                                  | 5/54                   | 0.1224         | 6/49                                 | 6/49                   |
| 0.0930         | 15/29 - 14/33                        | 5/34 - 2/37            | 0.1228         | ...                                  | 7/57                   |
| 0.0930         | 4/43                                 | 4/43                   | 0.1230         | 10/49 - 3/37                         | 1/59 + 7/66            |
| 0.0940         | 23/47 - 17/43                        | 15/49 - 14/66          | 0.1240         | 2/23 + 1/27                          | 18/34 - 15/37          |
| 0.0943         | ...                                  | 5/53                   | 0.1250         | 2/16                                 | 3/24                   |
| 0.0950         | 5/43 - 1/47                          | 9/24 - 7/25            | 0.1260         | 24/47 - 15/39                        | 10/59 - 2/46           |
| 0.0952         | 2/21                                 | 4/42                   | 0.1270         | 22/43 - 15/39                        | 1/46 + 6/57            |
| 0.0960         | 11/39 - 8/43                         | 11/39 - 8/43           | 0.1277         | 6/47                                 | 6/47                   |
| 0.0968         | 3/31                                 | 6/62                   | 0.1280         | 7/37 - 3/49                          | 33/62 - 19/47          |
| 0.0970         | 22/43 - 17/41                        | 12/59 - 5/47           | 0.1282         | 5/39                                 | 5/39                   |
| 0.0976         | 4/41                                 | 4/41                   | 0.1290         | 10/27 - 7/29                         | 24/59 - 15/54          |
| 0.0980         | 7/27 - 5/31                          | 16/47 - 16/66          | 0.1290         | 4/31                                 | 8/62                   |

Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.1296         | ...                                  | 7/54                   | 0.1613         | 5/31                                 | 10/62                  |
| 0.1300         | 10/43 - 4/39                         | 6/24 - 3/25            | 0.1620         | 3/39 + 4/47                          | 25/57 - 13/47          |
| 0.1304         | 3/23                                 | 6/46                   | 0.1622         | 6/37                                 | 6/37                   |
| 0.1310         | 3/43 + 3/49                          | 8/49 - 2/62            | 0.1628         | 7/43                                 | 7/43                   |
| 0.1316         | ...                                  | 5/38                   | 0.1630         | 10/29 - 6/33                         | 22/47 - 18/59          |
| 0.1320         | 11/47 - 5/49                         | 11/47 - 5/49           | 0.1633         | 8/49                                 | 8/49                   |
| 0.1321         | ...                                  | 7/53                   | 0.1640         | 10/47 - 2/41                         | 8/38 - 2/43            |
| 0.1330         | 8/29 - 3/21                          | 2/37 + 3/38            | 0.1650         | 2/47 + 6/49                          | 3/24 + 1/25            |
| 0.1333         | 2/15                                 | 4/30                   | 0.1660         | 8/23 - 6/33                          | 16/46 - 12/66          |
| 0.1340         | 7/17 - 5/18                          | 19/53 - 11/49          | 0.1667         | 3/18                                 | 4/24                   |
| 0.1350         | 10/43 - 4/41                         | 9/24 - 6/25            | 0.1667         | ...                                  | 5/30                   |
| 0.1351         | 5/37                                 | 5/37                   | 0.1667         | ...                                  | 7/42                   |
| 0.1356         | ...                                  | 8/59                   | 0.1667         | ...                                  | 9/54                   |
| 0.1360         | 5/16 - 3/17                          | 11/47 - 5/51           | 0.1667         | ...                                  | 11/66                  |
| 0.1364         | ...                                  | 9/66                   | 0.1670         | 16/39 - 9/37                         | 19/53 - 9/47           |
| 0.1370         | 3/41 + 3/47                          | 10/47 - 5/66           | 0.1680         | 16/43 - 10/49                        | 26/57 - 17/59          |
| 0.1373         | ...                                  | 7/51                   | 0.1690         | 5/39 + 2/49                          | 10/46 - 3/62           |
| 0.1379         | 4/29                                 | 8/58                   | 0.1695         | ...                                  | 10/59                  |
| 0.1380         | 23/47 - 13/37                        | 18/39 - 11/34          | 0.1698         | ...                                  | 9/53                   |
| 0.1390         | 28/49 - 16/37                        | 16/38 - 11/39          | 0.1700         | 6/23 - 3/33                          | 6/24 - 2/25            |
| 0.1395         | 6/43                                 | 6/43                   | 0.1702         | 8/47                                 | 8/47                   |
| 0.1400         | 8/49 - 1/43                          | 1/25 + 3/30            | 0.1707         | 7/41                                 | 7/41                   |
| 0.1404         | ...                                  | 8/57                   | 0.1710         | 15/49 - 5/37                         | 15/47 - 8/54           |
| 0.1410         | 11/47 - 4/43                         | 12/66 - 2/49           | 0.1720         | 1/39 + 6/41                          | 32/59 - 20/54          |
| 0.1420         | 8/49 - 1/47                          | 21/57 - 12/53          | 0.1724         | 5/29                                 | 10/58                  |
| 0.1429         | ...                                  | 4/28                   | 0.1730         | 9/41 - 2/31                          | 9/41 - 2/43            |
| 0.1429         | 3/21                                 | 6/42                   | 0.1739         | 4/23                                 | 8/46                   |
| 0.1429         | 7/49                                 | 7/49                   | 0.1740         | 10/33 - 4/31                         | 21/53 - 12/54          |
| 0.1430         | 10/47 - 3/43                         | 24/51 - 19/58          | 0.1750         | 2/16 + 1/20                          | 1/24 + 4/30            |
| 0.1440         | 19/43 - 14/47                        | 20/49 - 14/53          | 0.1754         | ...                                  | 10/57                  |
| 0.1450         | 9/47 - 2/43                          | 15/24 - 12/25          | 0.1760         | 2/37 + 5/41                          | 2/37 + 5/41            |
| 0.1452         | ...                                  | 9/62                   | 0.1765         | 3/17                                 | 6/34                   |
| 0.1460         | 26/49 - 15/39                        | 2/47 + 6/58            | 0.1765         | ...                                  | 9/51                   |
| 0.1463         | 6/41                                 | 6/41                   | 0.1770         | 5/39 + 2/41                          | 14/49 - 5/46           |
| 0.1470         | 4/21 - 1/23                          | 16/41 - 9/37           | 0.1774         | ...                                  | 11/62                  |
| 0.1471         | ...                                  | 5/34                   | 0.1780         | 23/41 - 18/47                        | 6/49 + 3/54            |
| 0.1480         | 4/19 - 1/16                          | 9/37 - 4/42            | 0.1786         | ...                                  | 5/28                   |
| 0.1481         | 4/27                                 | 8/54                   | 0.1790         | 11/21 - 10/29                        | 19/51 - 12/62          |
| 0.1489         | 7/47                                 | 7/47                   | 0.1795         | 7/39                                 | 7/39                   |
| 0.1490         | 12/31 - 5/21                         | 11/49 - 4/53           | 0.1800         | 11/47 - 2/37                         | 2/25 + 3/30            |
| 0.1500         | 3/20                                 | 7/30 - 2/24            | 0.1810         | 11/37 - 5/43                         | 18/38 - 12/41          |
| 0.1509         | ...                                  | 8/53                   | 0.1818         | 6/33                                 | 12/66                  |
| 0.1510         | 22/47 - 13/41                        | 25/59 - 18/66          | 0.1820         | 9/39 - 2/41                          | 21/46 - 14/51          |
| 0.1515         | 5/33                                 | 10/66                  | 0.1830         | 5/17 - 2/18                          | 33/58 - 22/57          |
| 0.1520         | 11/41 - 5/43                         | 16/62                  | 0.1837         | 9/49                                 | 9/49                   |
| 0.1522         | ...                                  | 7/46                   | 0.1840         | 8/31 - 2/27                          | 19/62 - 6/49           |
| 0.1525         | ...                                  | 9/59                   | 0.1842         | ...                                  | 7/38                   |
| 0.1530         | 10/27 - 5/23                         | 13/54 - 5/57           | 0.1850         | 4/37 + 3/39                          | 14/25 - 9/24           |
| 0.1538         | 6/39                                 | 6/39                   | 0.1852         | 5/27                                 | 10/54                  |
| 0.1540         | 10/37 - 5/43                         | 5/58 + 4/59            | 0.1860         | 1/29 + 5/33                          | 18/47 - 13/66          |
| 0.1550         | 8/37 - 3/49                          | 7/25 - 3/24            | 0.1860         | 8/43                                 | 8/43                   |
| 0.1552         | ...                                  | 9/58                   | 0.1864         | ...                                  | 11/59                  |
| 0.1560         | 4/21 - 1/29                          | 1/49 + 8/59            | 0.1870         | 16/49 - 6/43                         | 24/57 - 11/47          |
| 0.1569         | ...                                  | 8/51                   | 0.1875         | 3/16                                 | ...                    |
| 0.1570         | 15/47 - 6/37                         | 31/59 - 21/57          | 0.1880         | 12/29 - 7/31                         | 30/49 - 28/66          |
| 0.1579         | 3/19                                 | 6/38                   | 0.1887         | ...                                  | 10/53                  |
| 0.1579         | ...                                  | 9/57                   | 0.1890         | 13/29 - 7/27                         | 23/58 - 11/53          |
| 0.1580         | 3/37 + 3/39                          | 3/34 + 3/43            | 0.1892         | 7/37                                 | 7/37                   |
| 0.1590         | 20/43 - 15/49                        | 3/54 + 6/58            | 0.1897         | ...                                  | 11/58                  |
| 0.1600         | 18/37 - 16/49                        | 4/25                   | 0.1900         | 10/43 - 2/47                         | 11/25 - 6/24           |
| 0.1610         | 9/39 - 3/43                          | 9/39 - 3/43            | 0.1905         | 4/21                                 | 8/42                   |

Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.1910         | 17/39 - 12/49                        | 21/57 - 11/62          | 0.2222         | 4/18                                 | ...                    |
| 0.1915         | 9/47                                 | 9/47                   | 0.2222         | 6/27                                 | 12/54                  |
| 0.1920         | 7/41 + 1/47                          | 12/57 - 1/54           | 0.2230         | 15/31 - 6/23                         | 11/46 - 1/62           |
| 0.1930         | ...                                  | 11/57                  | 0.2240         | 5/41 + 5/49                          | 15/38 - 7/41           |
| 0.1930         | 10/19 - 5/15                         | 19/59 - 8/62           | 0.2241         | ...                                  | 13/58                  |
| 0.1935         | 6/31                                 | 12/62                  | 0.2245         | 11/49                                | 11/49                  |
| 0.1940         | 7/41 + 1/43                          | 14/43 - 5/38           | 0.2250         | 2/16 + 2/20                          | 3/24 + 3/30            |
| 0.1950         | 1/23 + 5/33                          | 8/25 - 3/24            | 0.2258         | 7/31                                 | 14/62                  |
| 0.1951         | 8/41                                 | 8/41                   | 0.2260         | 7/39 + 2/43                          | 2/49 + 10/54           |
| 0.1957         | ...                                  | 9/46                   | 0.2264         | ...                                  | 12/53                  |
| 0.1960         | 21/49 - 10/43                        | 34/66 - 15/47          | 0.2270         | 7/27 - 1/31                          | 14/54 - 2/62           |
| 0.1961         | ...                                  | 10/51                  | 0.2273         | ...                                  | 15/66                  |
| 0.1970         | ...                                  | 13/66                  | 0.2280         | 11/39 - 2/37                         | 23/49 - 14/58          |
| 0.1970         | 21/39 - 14/41                        | 11/47 - 2/54           | 0.2281         | ...                                  | 13/57                  |
| 0.1980         | 2/29 + 4/31                          | 17/49 - 7/47           | 0.2290         | 18/39 - 10/43                        | 29/51 - 18/53          |
| 0.1990         | 5/37 + 3/47                          | 27/59 - 15/58          | 0.2300         | 7/37 + 2/49                          | 12/25 - 6/24           |
| 0.2000         | 3/15                                 | 5/25                   | 0.2308         | 9/39                                 | 9/39                   |
| 0.2000         | 4/20                                 | 6/30                   | 0.2310         | 28/49 - 16/47                        | 26/59 - 13/62          |
| 0.2010         | 11/39 - 3/37                         | 8/49 + 2/53            | 0.2320         | 20/41 - 11/43                        | 26/57 - 13/58          |
| 0.2020         | 23/41 - 14/39                        | 23/41 - 14/39          | 0.2326         | 10/43                                | 10/43                  |
| 0.2030         | 2/37 + 7/47                          | 19/62 - 6/58           | 0.2330         | 27/47 - 14/41                        | 25/62 - 8/47           |
| 0.2034         | ...                                  | 12/59                  | 0.2333         | ...                                  | 7/30                   |
| 0.2037         | ...                                  | 11/54                  | 0.2340         | 24/41 - 13/37                        | 2/54 + 13/66           |
| 0.2040         | 12/47 - 2/39                         | 18/51 - 7/47           | 0.2340         | 11/47                                | 11/47                  |
| 0.2041         | 10/49                                | 10/49                  | 0.2350         | 11/27 - 5/29                         | 9/25 - 3/24            |
| 0.2050         | 13/37 - 6/41                         | 3/24 + 2/25            | 0.2353         | 4/17                                 | 8/34                   |
| 0.2051         | 8/39                                 | 8/39                   | 0.2353         | ...                                  | 12/51                  |
| 0.2059         | ...                                  | 7/34                   | 0.2360         | 10/39 - 1/49                         | 29/66 - 12/59          |
| 0.2060         | 15/43 - 7/49                         | 12/53 - 1/49           | 0.2368         | ...                                  | 9/38                   |
| 0.2069         | 6/29                                 | 12/58                  | 0.2370         | 23/37 - 15/39                        | 23/37 - 15/39          |
| 0.2070         | 19/41 - 10/39                        | 19/41 - 10/39          | 0.2373         | ...                                  | 14/59                  |
| 0.2075         | ...                                  | 11/53                  | 0.2380         | 2/43 + 9/47                          | 34/57 - 19/53          |
| 0.2080         | 15/31 - 8/29                         | 13/58 - 1/62           | 0.2381         | 5/21                                 | 10/42                  |
| 0.2083         | ...                                  | 5/24                   | 0.2390         | 24/43 - 15/47                        | 12/62 + 3/66           |
| 0.2090         | 16/33 - 8/29                         | 8/46 + 2/57            | 0.2391         | ...                                  | 11/46                  |
| 0.2093         | 9/43                                 | 9/43                   | 0.2400         | 3/43 + 8/47                          | 6/25                   |
| 0.2097         | ...                                  | 13/62                  | 0.2407         | ...                                  | 13/54                  |
| 0.2100         | 22/37 - 15/39                        | 6/24 - 1/25            | 0.2410         | 19/47 - 8/49                         | 17/47 - 7/58           |
| 0.2105         | 4/19                                 | 8/38                   | 0.2414         | 7/29                                 | 14/58                  |
| 0.2105         | ...                                  | 12/57                  | 0.2419         | ...                                  | 15/62                  |
| 0.2110         | 22/41 - 14/43                        | 22/41 - 14/43          | 0.2420         | 21/37 - 14/43                        | 12/46 - 1/53           |
| 0.2120         | 2/27 - 4/29                          | 4/54 + 8/58            | 0.2424         | 8/33                                 | 16/66                  |
| 0.2121         | 7/33                                 | 14/66                  | 0.2430         | 29/49 - 15/43                        | 4/47 + 9/57            |
| 0.2128         | 10/47                                | 10/47                  | 0.2432         | 9/37                                 | 9/37                   |
| 0.2130         | 23/49 - 10/39                        | 2/30 + 6/41            | 0.2439         | 10/41                                | 10/41                  |
| 0.2140         | 20/37 - 16/49                        | 12/51 - 1/47           | 0.2440         | 13/49 - 1/47                         | 30/53 - 19/59          |
| 0.2143         | ...                                  | 6/28                   | 0.2449         | 12/49                                | 12/49                  |
| 0.2143         | ...                                  | 9/42                   | 0.2450         | 13/37 - 5/47                         | 3/24 + 3/25            |
| 0.2150         | 11/43 - 2/49                         | 9/24 - 4/25            | 0.2453         | ...                                  | 13/53                  |
| 0.2157         | ...                                  | 11/51                  | 0.2456         | ...                                  | 14/57                  |
| 0.2160         | 2/23 + 4/31                          | 25/51 - 17/62          | 0.2460         | 20/49 - 6/37                         | 11/37 - 2/39           |
| 0.2162         | 8/37                                 | 8/37                   | 0.2470         | 10/37 - 1/43                         | 29/49 - 20/58          |
| 0.2170         | 11/41 - 2/39                         | 28/59 - 17/66          | 0.2480         | 4/23 + 2/27                          | 26/49 - 13/46          |
| 0.2174         | 5/23                                 | 10/46                  | 0.2490         | 10/37 - 1/47                         | 17/43 - 6/41           |
| 0.2180         | 3/31 + 4/33                          | 21/59 - 8/58           | 0.2500         | 4/16                                 | 6/24                   |
| 0.2190         | 11/23 - 7/27                         | 3/47 + 9/58            | 0.2500         | 5/20                                 | 7/28                   |
| 0.2195         | 9/41                                 | 9/41                   | 0.2510         | 2/15 + 2/17                          | 34/66 - 14/53          |
| 0.2200         | 4/41 + 6/49                          | 3/25 + 3/30            | 0.2520         | 24/43 - 15/49                        | 22/49 - 13/66          |
| 0.2203         | ...                                  | 13/59                  | 0.2530         | 7/37 + 3/47                          | 11/53 + 3/66           |
| 0.2210         | 18/49 - 6/41                         | 21/47 - 14/62          | 0.2540         | 26/49 - 13/47                        | 2/46 + 12/57           |
| 0.2220         | 25/41 - 19/49                        | 7/51 + 5/59            | 0.2542         | ...                                  | 15/59                  |



Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.2549         | ...                                  | 13/51                  | 0.2857         | ...                                  | 12/42                  |
| 0.2550         | 4/21 + 2/31                          | 9/24 - 3/25            | 0.2857         | ...                                  | 8/28                   |
| 0.2553         | 12/47                                | 12/47                  | 0.2860         | 20/47 - 6/43                         | 20/58 - 3/51           |
| 0.2558         | 11/43                                | 11/43                  | 0.2870         | 7/41 + 5/43                          | 20/42 - 7/37           |
| 0.2560         | 13/33 - 4/29                         | 9/47 + 4/62            | 0.2879         | ...                                  | 19/66                  |
| 0.2564         | 10/39                                | 10/39                  | 0.2880         | 19/43 - 6/39                         | 19/43 - 6/39           |
| 0.2570         | 20/39 - 11/43                        | 8/53 + 7/66            | 0.2881         | ...                                  | 17/59                  |
| 0.2576         | ...                                  | 17/66                  | 0.2890         | 1/21 + 7/29                          | 16/46 - 3/51           |
| 0.2580         | 15/29 - 7/27                         | 24/54 - 11/59          | 0.2895         | ...                                  | 11/38                  |
| 0.2581         | 8/31                                 | 16/62                  | 0.2900         | 23/43 - 12/49                        | 6/24 + 1/25            |
| 0.2586         | ...                                  | 15/58                  | 0.2903         | 9/31                                 | 18/62                  |
| 0.2590         | 24/49 - 9/39                         | 16/42 - 5/41           | 0.2910         | 5/39 + 7/43                          | 7/49 + 8/54            |
| 0.2593         | 7/27                                 | 14/54                  | 0.2917         | ...                                  | 7/24                   |
| 0.2600         | 20/43 - 8/39                         | 4/25 + 3/30            | 0.2920         | 9/39 + 3/49                          | 35/57 - 19/59          |
| 0.2609         | 6/23                                 | 12/46                  | 0.2927         | 12/41                                | 12/41                  |
| 0.2610         | 15/33 - 6/31                         | 5/53 + 9/54            | 0.2930         | 17/39 - 7/49                         | 28/53 - 12/51          |
| 0.2619         | ...                                  | 11/42                  | 0.2931         | ...                                  | 17/58                  |
| 0.2620         | 18/37 - 11/49                        | 16/51 - 3/58           | 0.2940         | 8/21 - 2/23                          | 14/57 + 3/62           |
| 0.2630         | 13/41 - 2/37                         | 13/46 - 1/51           | 0.2941         | 5/17                                 | 10/34                  |
| 0.2632         | 5/19                                 | 10/38                  | 0.2941         | ...                                  | 15/51                  |
| 0.2632         | ...                                  | 15/57                  | 0.2950         | 18/37 - 9/47                         | 9/24 - 2/25            |
| 0.2640         | 22/47 - 10/49                        | 22/47 - 10/49          | 0.2960         | 21/41 - 8/37                         | 29/57 - 10/47          |
| 0.2642         | ...                                  | 14/53                  | 0.2963         | 8/27                                 | 16/54                  |
| 0.2647         | ...                                  | 9/34                   | 0.2970         | 3/29 + 6/31                          | 13/47 + 1/49           |
| 0.2650         | 8/37 + 2/41                          | 15/24 - 9/25           | 0.2973         | 11/37                                | 11/37                  |
| 0.2653         | 13/49                                | 13/49                  | 0.2979         | 14/47                                | 14/47                  |
| 0.2660         | 8/27 - 1/33                          | 28/51 - 15/53          | 0.2980         | 11/21 - 7/31                         | 12/37 - 1/38           |
| 0.2667         | ...                                  | 8/30                   | 0.2982         | ...                                  | 17/57                  |
| 0.2670         | 18/37 - 9/41                         | 19/47 - 7/51           | 0.2990         | 19/43 - 7/49                         | 19/43 - 4/28           |
| 0.2680         | 8/18 - 3/17                          | 27/49 - 15/53          | 0.3000         | 6/20                                 | 9/30                   |
| 0.2683         | 11/41                                | 11/41                  | 0.3010         | 1/41 + 13/47                         | 19/54 - 3/59           |
| 0.2690         | 2/18 + 3/19                          | 6/54 + 9/57            | 0.3019         | ...                                  | 16/53                  |
| 0.2700         | 16/27 - 10/31                        | 13/25 - 6/24           | 0.3020         | 7/29 + 2/33                          | 23/62 - 4/58           |
| 0.2703         | 10/37                                | 10/37                  | 0.3023         | 13/43                                | 13/43                  |
| 0.2710         | 2/43 + 11/49                         | 1/28 + 8/34            | 0.3030         | 15/39 - 4/49                         | 25/57 - 8/59           |
| 0.2712         | ...                                  | 16/59                  | 0.3030         | 10/33                                | 20/66                  |
| 0.2720         | 14/37 - 5/47                         | 17/59 - 1/62           | 0.3040         | 16/31 - 7/33                         | 33/59 - 12/47          |
| 0.2727         | 9/33                                 | 18/66                  | 0.3043         | 7/23                                 | 14/46                  |
| 0.2730         | 1/16 + 4/19                          | 18/34 - 10/39          | 0.3050         | 1/31 + 9/33                          | 15/24 - 8/25           |
| 0.2740         | 6/41 + 6/47                          | 26/59 - 9/54           | 0.3051         | ...                                  | 18/59                  |
| 0.2742         | ...                                  | 17/62                  | 0.3060         | 17/31 - 8/33                         | 33/54 - 18/59          |
| 0.2745         | ...                                  | 14/51                  | 0.3061         | 15/49                                | 15/49                  |
| 0.2750         | 2/16 + 3/20                          | 5/24 + 2/30            | 0.3065         | ...                                  | 19/62                  |
| 0.2759         | 8/29                                 | 16/58                  | 0.3070         | 18/37 - 7/39                         | 1/53 + 17/59           |
| 0.2760         | 12/31 - 3/27                         | 13/43 - 1/38           | 0.3077         | 12/39                                | 12/39                  |
| 0.2766         | 13/47                                | 13/47                  | 0.3080         | 5/41 + 8/43                          | 16/49 - 1/54           |
| 0.2770         | 11/27 - 3/23                         | 18/28 - 15/41          | 0.3090         | 1/43 + 14/49                         | 19/30 - 12/37          |
| 0.2778         | 5/18                                 | 15/54                  | 0.3095         | ...                                  | 13/42                  |
| 0.2780         | 5/23 + 2/33                          | 17/39 - 6/38           | 0.3100         | 16/37 - 6/49                         | 14/25 - 6/24           |
| 0.2790         | 16/29 - 9/33                         | 14/47 - 1/53           | 0.3103         | 9/29                                 | 18/58                  |
| 0.2791         | 12/43                                | 12/43                  | 0.3110         | 3/39 + 11/47                         | 19/46 - 5/49           |
| 0.2800         | 16/49 - 2/43                         | 7/25                   | 0.3120         | 8/21 - 2/29                          | 2/49 + 16/59           |
| 0.2807         | ...                                  | 16/57                  | 0.3125         | 5/16                                 | ...                    |
| 0.2810         | 3/39 + 10/49                         | 17/57 - 1/58           | 0.3130         | 9/37 + 3/43                          | 4/24 + 6/41            |
| 0.2820         | 5/27 + 3/31                          | 24/66 - 4/49           | 0.3137         | ...                                  | 16/51                  |
| 0.2821         | 11/39                                | 11/39                  | 0.3140         | 12/27 - 3/23                         | 14/47 + 1/62           |
| 0.2826         | ...                                  | 13/46                  | 0.3148         | ...                                  | 17/54                  |
| 0.2830         | 14/43 - 2/47                         | 15/53                  | 0.3150         | 26/41 - 15/47                        | 21/24 - 14/25          |
| 0.2840         | 21/47 - 7/43                         | 37/66 - 13/47          | 0.3158         | ...                                  | 12/38                  |
| 0.2850         | 15/43 - 3/47                         | 3/24 + 4/25            | 0.3158         | ...                                  | 18/57                  |
| 0.2857         | 14/49                                | 14/49                  | 0.3160         | 6/37 + 6/39                          | 6/34 + 6/43            |

Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.3170         | 11/18 - 5/17                         | 34/59 - 14/54          | 0.3485         | ...                                  | 23/66                  |
| 0.3171         | 13/41                                | 13/41                  | 0.3488         | 15/43                                | 15/43                  |
| 0.3180         | 22/37 - 13/47                        | 6/54 + 12/58           | 0.3490         | 11/29 - 1/33                         | 2/47 + 19/62           |
| 0.3182         | ...                                  | 21/66                  | 0.3500         | 7/20                                 | 6/24 + 3/30            |
| 0.3190         | 6/27 + 3/31                          | 3/34 + 9/39            | 0.3509         | ...                                  | 20/57                  |
| 0.3191         | 15/47                                | 15/47                  | 0.3510         | 13/27 - 3/23                         | 25/53 - 7/58           |
| 0.3200         | 16/47 - 1/49                         | 8/25                   | 0.3514         | 13/37                                | 13/37                  |
| 0.3208         | ...                                  | 17/53                  | 0.3519         | ...                                  | 19/54                  |
| 0.3210         | 25/49 - 7/37                         | 10/59 + 10/66          | 0.3520         | 4/37 + 10/41                         | 24/62 - 2/57           |
| 0.3214         | ...                                  | 9/28                   | 0.3529         | 6/17                                 | 12/34                  |
| 0.3220         | 18/39 - 6/43                         | 18/39 - 6/43           | 0.3529         | ...                                  | 18/51                  |
| 0.3220         | ...                                  | 19/59                  | 0.3530         | 4/37 + 12/49                         | 31/59 - 10/58          |
| 0.3226         | 10/31                                | 20/62                  | 0.3540         | 14/37 - 1/41                         | 22/59 - 1/53           |
| 0.3230         | 21/41 - 7/37                         | 21/41 - 7/37           | 0.3548         | 11/31                                | 22/62                  |
| 0.3235         | ...                                  | 11/34                  | 0.3550         | 10/43 + 6/49                         | 12/25 - 3/24           |
| 0.3240         | 3/23 + 6/31                          | 21/47 - 7/57           | 0.3559         | ...                                  | 21/59                  |
| 0.3243         | 12/37                                | 12/37                  | 0.3560         | 5/41 + 11/47                         | 12/49 + 6/54           |
| 0.3250         | 2/16 + 4/20                          | 3/24 + 5/25            | 0.3570         | 20/43 - 4/37                         | 20/43 - 4/37           |
| 0.3256         | 14/43                                | 14/43                  | 0.3571         | ...                                  | 10/28                  |
| 0.3260         | 21/49 - 4/39                         | 23/59 - 3/47           | 0.3571         | ...                                  | 15/42                  |
| 0.3261         | ...                                  | 15/46                  | 0.3580         | 14/37 - 1/49                         | 38/62 - 13/51          |
| 0.3265         | 16/49                                | 16/49                  | 0.3585         | ...                                  | 19/53                  |
| 0.3270         | 24/49 - 7/43                         | 17/58 + 2/59           | 0.3590         | 14/39                                | 14/39                  |
| 0.3276         | ...                                  | 19/58                  | 0.3600         | 22/47 - 4/37                         | 9/25                   |
| 0.3280         | 26/41 - 15/49                        | 15/51 + 2/59           | 0.3610         | 9/23 - 1/33                          | 18/46 - 2/66           |
| 0.3290         | 5/21 + 3/33                          | 23/43 - 7/34           | 0.3617         | 17/47                                | 17/47                  |
| 0.3300         | 4/47 + 12/49                         | 6/24 + 2/25            | 0.3620         | 15/27 - 6/31                         | 17/41 - 2/38           |
| 0.3310         | 17/31 - 5/23                         | 23/59 - 3/51           | 0.3621         | ...                                  | 21/58                  |
| 0.3320         | 28/43 - 15/47                        | 30/59 - 9/51           | 0.3630         | 23/49 - 5/47                         | 25/53 - 5/46           |
| 0.3330         | 7/43 + 8/47                          | 36/51 - 22/59          | 0.3636         | 12/33                                | 24/66                  |
| 0.3333         | 5/15                                 | 8/24                   | 0.3640         | 26/47 - 7/37                         | 25/62 - 2/51           |
| 0.3333         | 6/18                                 | 10/30                  | 0.3650         | 28/47 - 9/39                         | 3/24 + 6/25            |
| 0.3333         | 7/21                                 | 13/39                  | 0.3659         | ...                                  | 15/41                  |
| 0.3333         | 9/27                                 | 14/42                  | 0.3660         | 10/17 - 4/18                         | 13/57 + 8/58           |
| 0.3333         | 11/33                                | 17/51                  | 0.3667         | ...                                  | 11/30                  |
| 0.3333         | 13/39                                | 18/54                  | 0.3670         | 5/27 + 6/33                          | 13/49 + 6/59           |
| 0.3333         | ...                                  | 19/57                  | 0.3673         | 18/49                                | 18/49                  |
| 0.3333         | ...                                  | 22/66                  | 0.3680         | 16/31 - 4/27                         | 31/66 - 6/59           |
| 0.3340         | 7/41 + 8/49                          | 29/47 - 15/53          | 0.3684         | 7/19                                 | 14/38                  |
| 0.3350         | 21/37 - 10/43                        | 9/24 - 1/25            | 0.3684         | ...                                  | 21/57                  |
| 0.3360         | 28/41 - 17/49                        | 9/46 + 8/57            | 0.3690         | 30/49 - 9/37                         | 21/62 + 2/66           |
| 0.3370         | 2/39 + 14/49                         | 33/57 - 15/62          | 0.3696         | ...                                  | 17/46                  |
| 0.3380         | 10/23 - 3/31                         | 25/62 - 3/46           | 0.3700         | 30/47 - 11/41                        | 6/24 + 3/25            |
| 0.3387         | ...                                  | 21/62                  | 0.3704         | 10/27                                | 20/54                  |
| 0.3390         | 19/49 - 2/41                         | 20/59                  | 0.3710         | 32/49 - 11/39                        | 23/62                  |
| 0.3396         | ...                                  | 18/53                  | 0.3720         | 2/29 + 10/33                         | 34/57 - 11/49          |
| 0.3400         | 25/49 - 8/47                         | 6/25 + 3/30            | 0.3721         | 16/43                                | 16/43                  |
| 0.3404         | 16/47                                | 16/47                  | 0.3725         | ...                                  | 19/51                  |
| 0.3410         | 12/27 - 3/29                         | 22/46 - 7/51           | 0.3729         | ...                                  | 22/59                  |
| 0.3415         | 14/41                                | 14/41                  | 0.3730         | 30/47 - 13/49                        | 21/49 - 3/54           |
| 0.3420         | 4/21 + 5/33                          | 25/62 - 3/49           | 0.3740         | 32/49 - 12/43                        | 5/46 + 13/49           |
| 0.3421         | ...                                  | 13/38                  | 0.3750         | 6/16                                 | 9/24                   |
| 0.3430         | 13/23 - 6/27                         | 37/57 - 15/49          | 0.3760         | 5/21 + 4/29                          | 11/49 + 10/66          |
| 0.3440         | 2/39 + 12/41                         | 14/54 + 5/59           | 0.3770         | 13/37 + 1/39                         | 20/51 - 1/66           |
| 0.3448         | ...                                  | 20/58                  | 0.3774         | ...                                  | 20/53                  |
| 0.3450         | 2/23 + 8/31                          | 15/24 - 7/25           | 0.3780         | 13/27 - 3/29                         | 31/53 - 12/58          |
| 0.3460         | 18/41 - 4/43                         | 18/41 - 4/43           | 0.3784         | 14/37                                | 14/37                  |
| 0.3469         | 17/49                                | 17/49                  | 0.3788         | ...                                  | 25/66                  |
| 0.3470         | 7/31 + 4/33                          | 7/38 + 7/43            | 0.3790         | 8/37 + 7/43                          | 8/37 + 7/43            |
| 0.3478         | 8/23                                 | 16/46                  | 0.3793         | 11/29                                | 22/58                  |
| 0.3480         | 20/33 - 8/31                         | 31/59 - 11/62          | 0.3800         | 20/43 - 4/47                         | 7/25 + 3/30            |

**Table 3. (Continued) Accurate Angular Indexing**

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.3810         | 8/21                                 | 16/42                  | 0.4120         | 18/41 – 1/37                         | 24/53 – 2/49           |
| 0.3810         | 19/47 – 1/43                         | 8/51 + 13/58           | 0.4130         | 2/39 + 17/47                         | 19/46                  |
| 0.3820         | 25/49 – 5/39                         | 40/62 – 15/57          | 0.4138         | 12/29                                | 24/58                  |
| 0.3824         | ...                                  | 13/34                  | 0.4140         | 19/39 – 3/41                         | 19/39 – 3/41           |
| 0.3830         | 18/47                                | 18/47                  | 0.4146         | 17/41                                | 17/41                  |
| 0.3830         | 27/43 – 12/49                        | 37/58 – 13/51          | 0.4150         | 18/33 – 3/23                         | 9/24 + 1/25            |
| 0.3840         | 27/43 – 10/41                        | 27/43 – 10/41          | 0.4151         | ...                                  | 22/53                  |
| 0.3846         | 15/39                                | 15/39                  | 0.4160         | 21/39 – 6/49                         | 41/62 – 13/53          |
| 0.3850         | 15/37 – 1/49                         | 15/24 – 6/25           | 0.4167         | ...                                  | 10/24                  |
| 0.3860         | 1/37 + 14/39                         | 22/57                  | 0.4170         | 26/37 – 14/49                        | 10/38 + 6/39           |
| 0.3870         | 3/17 + 4/19                          | 16/39 – 1/43           | 0.4180         | 8/21 + 1/27                          | 16/46 + 4/57           |
| 0.3871         | 12/31                                | 24/62                  | 0.4186         | 18/43                                | 18/43                  |
| 0.3878         | 19/49                                | 19/49                  | 0.4190         | 18/39 – 2/47                         | 31/46 – 13/51          |
| 0.3880         | 14/41 + 2/43                         | 18/53 + 3/62           | 0.4194         | 13/31                                | 26/62                  |
| 0.3889         | 7/18                                 | 21/54                  | 0.4200         | 24/49 – 3/43                         | 8/25 + 3/30            |
| 0.3890         | 17/41 – 1/39                         | 24/53 – 3/47           | 0.4210         | 1/39 + 17/43                         | 23/49 – 3/62           |
| 0.3898         | ...                                  | 23/59                  | 0.4211         | 8/19                                 | 16/38                  |
| 0.3900         | 2/23 + 10/33                         | 16/25 – 6/24           | 0.4211         | ...                                  | 24/57                  |
| 0.3902         | 16/41                                | 16/41                  | 0.4220         | 15/29 – 2/21                         | 3/41 + 15/43           |
| 0.3910         | 14/31 – 2/33                         | 29/66 – 3/62           | 0.4230         | 24/43 – 5/37                         | 20/54 + 3/57           |
| 0.3913         | 9/23                                 | 18/46                  | 0.4237         | ...                                  | 25/59                  |
| 0.3920         | 14/33 – 1/31                         | 17/47 + 2/66           | 0.4240         | 4/27 + 8/29                          | 41/62 – 14/59          |
| 0.3922         | ...                                  | 20/51                  | 0.4242         | 14/33                                | 28/66                  |
| 0.3929         | ...                                  | 11/28                  | 0.4250         | 6/16 + 1/20                          | 7/24 + 4/30            |
| 0.3930         | 1/39 + 18/49                         | 28/46 – 11/51          | 0.4255         | 20/47                                | 20/47                  |
| 0.3939         | 13/33                                | 26/66                  | 0.4259         | ...                                  | 23/54                  |
| 0.3940         | 3/39 + 13/41                         | 24/53 – 3/51           | 0.4260         | 27/41 – 10/43                        | 28/57 – 3/46           |
| 0.3947         | ...                                  | 15/38                  | 0.4270         | 27/39 – 13/49                        | 29/59 – 4/62           |
| 0.3950         | 26/37 – 12/39                        | 13/25 – 3/24           | 0.4280         | 12/43 + 7/47                         | 33/57 – 8/53           |
| 0.3953         | 17/43                                | 17/43                  | 0.4286         | 9/21                                 | 12/28                  |
| 0.3960         | 4/29 + 8/31                          | 33/47 – 15/49          | 0.4286         | 21/49                                | 18/42                  |
| 0.3962         | ...                                  | 21/53                  | 0.4286         | ...                                  | 21/49                  |
| 0.3966         | ...                                  | 23/58                  | 0.4290         | 30/47 – 9/43                         | 21/51 + 1/58           |
| 0.3970         | 25/41 – 10/47                        | 7/57 + 17/62           | 0.4300         | 22/43 – 4/49                         | 17/25 – 6/24           |
| 0.3980         | 3/16 + 4/19                          | 28/58 – 5/59           | 0.4310         | 11/39 + 7/47                         | 25/58                  |
| 0.3990         | 7/39 + 9/41                          | 6/37 + 9/38            | 0.4314         | ...                                  | 22/51                  |
| 0.4000         | 6/15                                 | 10/25                  | 0.4320         | 4/23 + 8/31                          | 28/62 – 1/51           |
| 0.4000         | 8/20                                 | 12/30                  | 0.4324         | 16/37                                | 16/37                  |
| 0.4010         | 2/37 + 17/49                         | 27/62 – 2/58           | 0.4330         | 5/37 + 14/47                         | 26/42 – 8/43           |
| 0.4020         | 5/43 + 14/49                         | 16/49 + 4/53           | 0.4333         | ...                                  | 13/30                  |
| 0.4030         | 26/49 – 6/47                         | 30/47 – 12/51          | 0.4340         | 5/31 + 9/33                          | 23/53                  |
| 0.4032         | ...                                  | 25/62                  | 0.4348         | 10/23                                | 20/46                  |
| 0.4035         | ...                                  | 23/57                  | 0.4350         | 21/31 – 8/33                         | 14/25 – 3/24           |
| 0.4040         | 11/39 + 5/41                         | 11/39 + 5/41           | 0.4355         | ...                                  | 27/62                  |
| 0.4043         | 19/47                                | 19/47                  | 0.4359         | ...                                  | 17/39                  |
| 0.4048         | ...                                  | 17/42                  | 0.4360         | 6/31 + 8/33                          | 42/59 – 16/58          |
| 0.4050         | 29/41 – 13/43                        | 3/24 + 7/25            | 0.4370         | 27/39 – 12/47                        | 31/49 – 9/46           |
| 0.4054         | 15/37                                | 15/37                  | 0.4375         | 7/16                                 | ...                    |
| 0.4060         | 21/47 – 2/49                         | 17/58 + 7/62           | 0.4380         | 13/27 – 1/23                         | 24/57 + 1/59           |
| 0.4068         | ...                                  | 24/59                  | 0.4386         | ...                                  | 25/57                  |
| 0.4070         | 9/19 – 1/15                          | 7/47 + 16/62           | 0.4390         | 18/43 + 1/49                         | 34/59 – 7/51           |
| 0.4074         | 11/27                                | 22/54                  | 0.4390         | 18/41                                | 18/41                  |
| 0.4080         | 16/37 – 1/41                         | 2/54 + 23/62           | 0.4394         | ...                                  | 29/66                  |
| 0.4082         | 20/49                                | 20/49                  | 0.4400         | 8/41 + 12/49                         | 11/25                  |
| 0.4090         | 15/39 + 1/41                         | 15/39 + 1/41           | 0.4407         | ...                                  | 26/59                  |
| 0.4091         | ...                                  | 27/66                  | 0.4410         | 10/37 + 7/41                         | 10/37 + 7/41           |
| 0.4100         | 1/37 + 18/47                         | 6/24 + 4/25            | 0.4412         | ...                                  | 15/34                  |
| 0.4103         | 16/39                                | 16/39                  | 0.4419         | 19/43                                | 19/43                  |
| 0.4110         | 9/41 + 9/47                          | 7/34 + 8/39            | 0.4420         | 18/33 – 3/29                         | 34/62 – 5/47           |
| 0.4118         | 7/17                                 | 14/34                  | 0.4430         | 4/39 + 16/47                         | 20/51 + 3/59           |
| 0.4118         | ...                                  | 21/51                  | 0.4440         | 9/41 + 11/49                         | 14/51 + 10/59          |

Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.4444         | 12/27                                | 24/54                  | 0.4737         | ...                                  | 27/57                  |
| 0.4444         | 8/18                                 | ...                    | 0.4740         | 9/37 + 9/39                          | 9/34 + 9/43            |
| 0.4450         | 7/37 + 11/43                         | 3/24 + 8/25            | 0.4746         | ...                                  | 28/59                  |
| 0.4460         | 11/23 - 1/31                         | 22/46 - 2/62           | 0.4750         | 6/16 + 2/20                          | 9/24 + 3/30            |
| 0.4468         | 21/47                                | 21/47                  | 0.4760         | 4/43 + 18/47                         | 15/53 + 11/57          |
| 0.4470         | 6/21 + 5/31                          | 14/49 + 10/62          | 0.4762         | 10/21                                | 20/42                  |
| 0.4474         | ...                                  | 17/38                  | 0.4770         | 26/43 - 6/47                         | 30/47 - 10/62          |
| 0.4480         | 10/41 + 10/49                        | 27/41 - 8/38           | 0.4780         | 12/31 + 3/33                         | 24/62 + 6/66           |
| 0.4483         | 13/29                                | 26/58                  | 0.4783         | 11/23                                | 22/46                  |
| 0.4490         | 22/49                                | 22/49                  | 0.4790         | 22/39 - 4/47                         | 10/53 + 18/62          |
| 0.4490         | 20/39 - 3/47                         | 14/57 + 12/59          | 0.4800         | 16/39 + 3/43                         | 12/25                  |
| 0.4500         | 9/20                                 | 6/24 + 6/30            | 0.4810         | 14/41 + 6/43                         | 22/58 + 6/59           |
| 0.4510         | ...                                  | 23/51                  | 0.4815         | 13/27                                | 26/54                  |
| 0.4510         | 5/15 + 2/17                          | 42/62 - 12/53          | 0.4820         | 33/49 - 9/47                         | 19/46 + 4/58           |
| 0.4516         | 14/31                                | 28/62                  | 0.4828         | 14/29                                | 28/58                  |
| 0.4520         | 14/39 + 4/43                         | 4/49 + 20/54           | 0.4830         | 27/39 - 9/43                         | 27/39 - 9/43           |
| 0.4524         | ...                                  | 19/42                  | 0.4839         | 15/31                                | 30/62                  |
| 0.4528         | ...                                  | 24/53                  | 0.4840         | 5/37 + 15/43                         | 24/46 - 2/53           |
| 0.4530         | 3/23 + 10/31                         | 16/59 + 12/66          | 0.4848         | 16/33                                | 32/66                  |
| 0.4540         | 14/27 - 2/31                         | 1/54 + 27/62           | 0.4850         | 24/47 - 1/39                         | 3/24 + 9/25            |
| 0.4545         | 15/33                                | 30/66                  | 0.4860         | 13/43 + 9/49                         | 43/62 - 11/53          |
| 0.4550         | 25/47 - 3/39                         | 9/24 + 2/25            | 0.4865         | 18/37                                | 18/37                  |
| 0.4560         | 9/37 + 10/47                         | 17/62 + 12/66          | 0.4870         | 15/37 + 4/49                         | 26/43 - 4/34           |
| 0.4561         | ...                                  | 26/57                  | 0.4872         | 19/39                                | 19/39                  |
| 0.4565         | ...                                  | 21/46                  | 0.4878         | 20/41                                | 20/41                  |
| 0.4570         | 4/37 + 15/43                         | 27/39 - 8/34           | 0.4880         | 8/29 + 7/33                          | 5/46 + 22/58           |
| 0.4576         | ...                                  | 27/59                  | 0.4884         | 21/43                                | 21/43                  |
| 0.4580         | 27/49 - 4/43                         | 20/53 + 5/62           | 0.4890         | 28/43 - 6/37                         | 19/47 + 5/59           |
| 0.4583         | ...                                  | 11/24                  | 0.4894         | 23/47                                | 23/47                  |
| 0.4590         | 35/49 - 12/47                        | 18/51 + 7/66           | 0.4898         | 24/49                                | 24/49                  |
| 0.4595         | 17/37                                | 17/37                  | 0.4900         | 13/21 - 4/31                         | 6/24 + 6/25            |
| 0.4600         | 16/41 + 3/43                         | 9/25 + 3/30            | 0.4902         | ...                                  | 25/51                  |
| 0.4610         | 13/39 + 6/47                         | 22/34 - 8/43           | 0.4906         | ...                                  | 26/53                  |
| 0.4615         | 18/39                                | 18/39                  | 0.4910         | 15/39 + 5/47                         | 21/46 + 2/58           |
| 0.4620         | 15/47 + 7/49                         | 36/62 - 7/59           | 0.4912         | ...                                  | 28/57                  |
| 0.4630         | ...                                  | 25/54                  | 0.4915         | ...                                  | 29/59                  |
| 0.4630         | ...                                  | 10/46 + 14/57          | 0.4920         | 25/37 - 9/49                         | 17/46 + 6/49           |
| 0.4631         | 9/21 + 1/29                          | ...                    | 0.4930         | 8/41 + 14/47                         | 21/53 + 6/62           |
| 0.4634         | 19/41                                | 19/41                  | 0.4940         | 33/49 - 7/39                         | 14/46 + 11/58          |
| 0.4640         | 21/43 - 1/41                         | 32/58 - 5/57           | 0.4950         | 5/29 + 10/31                         | 9/24 + 3/25            |
| 0.4643         | ...                                  | 13/28                  | 0.4960         | 8/23 + 4/27                          | 20/53 + 7/59           |
| 0.4650         | 21/37 - 4/39                         | 15/24 - 4/25           | 0.4970         | 33/47 - 8/39                         | 7/46 + 20/58           |
| 0.4651         | 20/43                                | 20/43                  | 0.4980         | 20/37 - 2/47                         | 29/41 - 9/43           |
| 0.4655         | ...                                  | 27/58                  | 0.4990         | 26/41 - 5/37                         | 26/41 - 5/37           |
| 0.4660         | 13/41 + 7/47                         | 31/47 - 12/62          | 0.5000         | 8/16                                 | 12/24                  |
| 0.4667         | 7/15                                 | 14/30                  | 0.5000         | 9/18                                 | 14/28                  |
| 0.4670         | 19/37 - 2/43                         | 25/34 - 11/41          | 0.5000         | 10/20                                | 15/30                  |
| 0.4677         | ...                                  | 29/62                  | 0.5000         | ...                                  | 17/34                  |
| 0.4680         | 11/27 + 2/33                         | 3/49 + 24/59           | 0.5000         | ...                                  | 19/38                  |
| 0.4681         | 22/47                                | 22/47                  | 0.5000         | ...                                  | 21/42                  |
| 0.4690         | 8/23 + 4/33                          | 35/49 - 13/53          | 0.5000         | ...                                  | 23/46                  |
| 0.4694         | 23/49                                | 23/49                  | 0.5000         | ...                                  | 27/54                  |
| 0.4697         | ...                                  | 31/66                  | 0.5000         | ...                                  | 29/58                  |
| 0.4700         | 19/29 - 5/27                         | 18/25 - 6/24           | 0.5000         | ...                                  | 31/62                  |
| 0.4706         | 8/17                                 | 16/34                  | 0.5000         | ...                                  | 33/66                  |
| 0.4706         | ...                                  | 24/51                  | 0.5010         | 5/37 + 15/41                         | 37/51 - 11/49          |
| 0.4710         | 12/39 + 8/49                         | 12/47 + 11/51          | 0.5020         | 17/37 + 2/47                         | 25/53 + 2/66           |
| 0.4717         | ...                                  | 25/53                  | 0.5030         | 8/39 + 14/47                         | 16/49 + 9/51           |
| 0.4720         | 20/39 - 2/49                         | 31/53 - 7/62           | 0.5040         | 5/43 + 19/49                         | 37/66 - 3/53           |
| 0.4730         | 6/39 + 15/47                         | 29/59 - 1/54           | 0.5050         | 21/31 - 5/29                         | 15/24 - 3/25           |
| 0.4737         | 9/19                                 | 18/38                  | 0.5060         | 7/39 + 16/49                         | 22/53 + 6/66           |

Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.5070         | 33/47 - 8/41                         | 28/46 - 6/59           | 0.5370         | ...                                  | 29/54                  |
| 0.5080         | 12/37 + 9/49                         | 41/66 - 6/53           | 0.5370         | ...                                  | 6/51 + 26/62           |
| 0.5085         | ...                                  | 30/59                  | 0.5371         | 17/41 + 6/49                         | ...                    |
| 0.5088         | ...                                  | 29/57                  | 0.5380         | 4/18 + 6/19                          | 12/49 + 17/58          |
| 0.5090         | 24/39 - 5/47                         | 27/51 - 1/49           | 0.5385         | 21/39                                | 21/39                  |
| 0.5094         | ...                                  | 27/53                  | 0.5390         | 26/39 - 6/47                         | 34/51 - 6/47           |
| 0.5098         | ...                                  | 26/51                  | 0.5400         | 25/41 - 3/43                         | 6/25 + 9/30            |
| 0.5100         | 8/21 + 4/31                          | 18/24 - 6/25           | 0.5405         | 20/37                                | 20/37                  |
| 0.5102         | 25/49                                | 25/49                  | 0.5410         | 12/47 + 14/49                        | 2/38 + 21/43           |
| 0.5106         | 24/47                                | 24/47                  | 0.5417         | ...                                  | 13/24                  |
| 0.5110         | 6/37 + 15/43                         | 26/49 - 1/51           | 0.5420         | 4/43 + 22/49                         | 7/46 + 23/59           |
| 0.5116         | 22/43                                | 22/43                  | 0.5424         | ...                                  | 32/59                  |
| 0.5120         | 21/29 - 7/33                         | 45/66 - 9/53           | 0.5430         | 33/43 - 11/49                        | 22/54 + 8/59           |
| 0.5122         | 21/41                                | 21/41                  | 0.5435         | ...                                  | 25/46                  |
| 0.5128         | 20/39                                | 20/39                  | 0.5439         | ...                                  | 31/57                  |
| 0.5130         | 22/37 - 4/49                         | 30/54 - 2/47           | 0.5440         | 4/37 + 17/39                         | 4/37 + 17/39           |
| 0.5135         | 19/37                                | 19/37                  | 0.5450         | 3/39 + 22/47                         | 15/24 - 2/25           |
| 0.5140         | 30/43 - 9/49                         | 33/46 - 12/59          | 0.5455         | 18/33                                | 36/66                  |
| 0.5150         | 1/39 + 23/47                         | 16/25 - 3/24           | 0.5460         | 13/27 + 2/31                         | 2/34 + 19/39           |
| 0.5152         | 17/33                                | 34/66                  | 0.5470         | 21/31 - 3/23                         | 32/49 - 7/66           |
| 0.5160         | 28/43 - 5/37                         | 37/59 - 6/54           | 0.5472         | ...                                  | 29/53                  |
| 0.5161         | 16/31                                | 32/62                  | 0.5476         | ...                                  | 23/42                  |
| 0.5170         | 13/39 + 9/49                         | 9/49 + 17/51           | 0.5480         | 12/41 + 12/47                        | 25/39 - 4/43           |
| 0.5172         | 15/29                                | 30/58                  | 0.5484         | 17/31                                | 34/62                  |
| 0.5180         | 9/47 + 16/49                         | 31/41 - 10/42          | 0.5490         | 10/15 - 2/17                         | 8/47 + 25/66           |
| 0.5185         | 14/27                                | 28/54                  | 0.5490         | ...                                  | 28/51                  |
| 0.5190         | 27/41 - 6/43                         | 6/49 + 23/58           | 0.5500         | 11/20                                | 6/24 + 9/30            |
| 0.5200         | 3/41 + 21/47                         | 13/25                  | 0.5510         | 19/39 + 3/47                         | 31/53 - 2/59           |
| 0.5210         | 17/39 + 4/47                         | 41/59 - 8/46           | 0.5510         | ...                                  | 27/49                  |
| 0.5217         | 12/23                                | 24/46                  | 0.5517         | 16/29                                | 32/58                  |
| 0.5220         | 19/31 - 3/33                         | 14/47 + 13/58          | 0.5520         | 31/41 - 10/49                        | 29/46 - 4/51           |
| 0.5230         | 17/43 + 6/47                         | 14/49 + 14/59          | 0.5526         | ...                                  | 21/38                  |
| 0.5238         | 11/21                                | 22/42                  | 0.5530         | 15/21 - 5/31                         | 28/54 + 2/58           |
| 0.5240         | 29/47 - 4/43                         | 32/51 - 6/58           | 0.5532         | 26/47                                | 26/47                  |
| 0.5250         | 6/16 + 3/20                          | 7/24 + 7/30            | 0.5540         | 12/23 + 1/31                         | 12/53 + 19/58          |
| 0.5254         | ...                                  | 31/59                  | 0.5550         | 1/41 + 26/49                         | 17/25 - 3/24           |
| 0.5260         | 28/37 - 9/39                         | 26/46 - 2/51           | 0.5556         | 10/18                                | 30/54                  |
| 0.5263         | 10/19                                | 20/38                  | 0.5556         | 15/27                                | ...                    |
| 0.5263         | ...                                  | 30/57                  | 0.5560         | 32/41 - 11/49                        | 35/47 - 10/53          |
| 0.5270         | 32/47 - 6/39                         | 6/53 + 24/58           | 0.5570         | 22/41 + 1/49                         | 18/49 + 11/58          |
| 0.5280         | 19/39 + 2/49                         | 35/59 - 3/46           | 0.5580         | 3/29 + 15/33                         | 7/53 + 23/54           |
| 0.5283         | ...                                  | 28/53                  | 0.5581         | 24/43                                | 24/43                  |
| 0.5290         | 18/37 + 2/47                         | 30/53 - 2/54           | 0.5588         | ...                                  | 19/34                  |
| 0.5294         | 9/17                                 | 18/34                  | 0.5590         | 27/37 - 7/41                         | 43/59 - 9/53           |
| 0.5294         | ...                                  | 27/51                  | 0.5593         | ...                                  | 33/59                  |
| 0.5300         | 5/27 + 10/29                         | 6/24 + 7/25            | 0.5600         | 37/49 - 8/41                         | 14/25                  |
| 0.5303         | ...                                  | 35/66                  | 0.5606         | ...                                  | 37/66                  |
| 0.5306         | 26/49                                | 26/49                  | 0.5610         | 23/41                                | 23/41                  |
| 0.5310         | 15/23 - 4/33                         | 24/37 - 4/34           | 0.5610         | 4/23 + 12/31                         | 5/51 + 25/54           |
| 0.5319         | 25/47                                | 25/47                  | 0.5614         | ...                                  | 32/57                  |
| 0.5320         | 7/27 + 9/33                          | 5/51 + 23/53           | 0.5620         | 1/23 + 14/27                         | 9/34 + 11/37           |
| 0.5323         | ...                                  | 33/62                  | 0.5625         | 9/16                                 | ...                    |
| 0.5330         | 18/37 + 2/43                         | 16/46 + 10/54          | 0.5630         | 12/39 + 12/47                        | 22/46 + 5/59           |
| 0.5333         | 8/15                                 | 16/30                  | 0.5640         | 25/33 - 6/31                         | 41/49 - 18/66          |
| 0.5340         | 28/41 - 7/47                         | 37/51 - 9/47           | 0.5641         | 22/39                                | 22/39                  |
| 0.5345         | ...                                  | 31/58                  | 0.5645         | ...                                  | 35/62                  |
| 0.5349         | 23/43                                | 23/43                  | 0.5650         | 10/31 + 8/33                         | 3/24 + 11/25           |
| 0.5350         | 16/37 + 4/39                         | 9/24 + 4/25            | 0.5652         | 13/23                                | 26/46                  |
| 0.5357         | ...                                  | 15/28                  | 0.5660         | 4/39 + 19/41                         | 9/46 + 20/54           |
| 0.5360         | 1/41 + 22/43                         | 5/49 + 23/53           | 0.5660         | ...                                  | 30/53                  |
| 0.5366         | 22/41                                | 22/41                  | 0.5667         | ...                                  | 17/30                  |

Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.5670         | 33/47 – 5/37                         | 25/47 + 2/57           | 0.5970         | 6/47 + 23/49                         | 13/58 + 22/59          |
| 0.5676         | 21/37                                | 21/37                  | 0.5980         | 35/49 – 5/43                         | 16/47 + 17/66          |
| 0.5680         | 23/31 – 4/23                         | 21/47 + 8/66           | 0.5990         | 17/37 + 6/43                         | 23/49 + 7/54           |
| 0.5686         | ...                                  | 29/51                  | 0.6000         | 9/15                                 | 15/25                  |
| 0.5690         | ...                                  | 33/58                  | 0.6000         | 12/20                                | 18/30                  |
| 0.5690         | 28/39 – 7/47                         | 42/59 – 7/49           | 0.6010         | 32/41 – 7/39                         | 32/41 – 7/39           |
| 0.5700         | 21/43 + 4/49                         | 6/24 + 8/25            | 0.6020         | 13/16 – 4/19                         | 20/47 + 9/51           |
| 0.5710         | 9/43 + 17/47                         | 39/57 – 6/53           | 0.6030         | 16/41 + 10/47                        | 24/49 + 6/53           |
| 0.5714         | 12/21                                | 16/28                  | 0.6034         | ...                                  | 35/58                  |
| 0.5714         | 28/49                                | 24/42                  | 0.6038         | ...                                  | 32/53                  |
| 0.5714         | ...                                  | 28/49                  | 0.6040         | 23/31 – 4/29                         | 21/58 + 15/62          |
| 0.5720         | 31/43 – 7/47                         | 40/58 – 6/51           | 0.6047         | ...                                  | 26/43                  |
| 0.5730         | 12/39 + 13/49                        | 23/57 + 10/59          | 0.6050         | 11/37 + 12/39                        | 3/24 + 12/25           |
| 0.5740         | 14/41 + 10/43                        | 23/37 – 2/42           | 0.6053         | ...                                  | 23/38                  |
| 0.5741         | ...                                  | 31/54                  | 0.6060         | 28/41 – 3/39                         | 29/54 + 4/58           |
| 0.5745         | 27/47                                | 27/47                  | 0.6061         | 20/33                                | 40/66                  |
| 0.5750         | 3/15 + 6/16                          | 9/24 + 6/30            | 0.6070         | 31/49 – 1/39                         | 23/47 + 6/51           |
| 0.5758         | 19/33                                | 38/66                  | 0.6071         | ...                                  | 17/28                  |
| 0.5760         | 21/29 – 4/27                         | 24/49 + 5/58           | 0.6078         | ...                                  | 31/51                  |
| 0.5763         | ...                                  | 34/59                  | 0.6080         | 1/31 + 19/33                         | 24/53 + 9/58           |
| 0.5770         | 5/37 + 19/43                         | 32/46 – 7/59           | 0.6087         | 14/23                                | 28/46                  |
| 0.5780         | 2/21 + 14/29                         | 25/49 + 4/59           | 0.6090         | 17/31 + 2/33                         | 40/59 – 4/58           |
| 0.5789         | 11/19                                | 22/38                  | 0.6098         | 25/41                                | 25/41                  |
| 0.5789         | ...                                  | 33/57                  | 0.6100         | 23/33 – 2/23                         | 6/24 + 9/25            |
| 0.5790         | 26/43 – 1/39                         | 38/62 – 2/59           | 0.6102         | ...                                  | 36/59                  |
| 0.5800         | 3/43 + 25/49                         | 12/25 + 3/30           | 0.6110         | 1/39 + 24/41                         | 5/28 + 16/37           |
| 0.5806         | 18/31                                | 36/62                  | 0.6111         | ...                                  | 33/54                  |
| 0.5810         | 21/39 + 2/47                         | 18/53 + 14/58          | 0.6120         | 27/41 – 2/43                         | 29/39 – 5/38           |
| 0.5814         | 25/43                                | 25/43                  | 0.6122         | 30/49                                | 30/49                  |
| 0.5820         | 6/21 + 8/27                          | 23/38 – 1/43           | 0.6129         | 19/31                                | 38/62                  |
| 0.5830         | 11/37 + 14/49                        | 8/46 + 27/66           | 0.6130         | 15/19 – 3/17                         | 1/49 + 32/54           |
| 0.5833         | ...                                  | 14/24                  | 0.6140         | 25/39 – 1/37                         | 36/49 – 7/58           |
| 0.5840         | 18/39 + 6/49                         | 13/57 + 21/59          | 0.6140         | ...                                  | 35/57                  |
| 0.5849         | ...                                  | 31/53                  | 0.6150         | 22/37 + 1/49                         | 9/24 + 6/25            |
| 0.5850         | 3/23 + 15/33                         | 15/24 – 1/25           | 0.6154         | 24/39                                | 24/39                  |
| 0.5854         | 24/41                                | 24/41                  | 0.6160         | 10/41 + 16/43                        | 14/53 + 19/54          |
| 0.5860         | 20/39 + 3/41                         | 17/54 + 16/59          | 0.6170         | 12/37 + 12/41                        | 5/59 + 33/62           |
| 0.5862         | 17/29                                | 34/58                  | 0.6170         | 29/47                                | 29/47                  |
| 0.5870         | ...                                  | 27/46                  | 0.6176         | ...                                  | 21/34                  |
| 0.5870         | 30/47 – 2/39                         | 37/53 – 6/54           | 0.6180         | 5/39 + 24/49                         | 3/53 + 32/57           |
| 0.5880         | 1/37 + 23/41                         | 28/57 + 6/62           | 0.6190         | 1/43 + 28/47                         | 17/53 + 17/57          |
| 0.5882         | 10/17                                | 20/34                  | 0.6190         | 13/21                                | 26/42                  |
| 0.5882         | ...                                  | 30/51                  | 0.6200         | 23/43 + 4/47                         | 8/25 + 9/30            |
| 0.5890         | 32/41 – 9/47                         | 8/46 + 22/53           | 0.6207         | ...                                  | 36/58                  |
| 0.5897         | 23/39                                | 23/39                  | 0.6210         | 29/37 – 7/43                         | 6/46 + 26/53           |
| 0.5900         | 29/47 – 1/37                         | 18/24 – 4/25           | 0.6212         | ...                                  | 41/66                  |
| 0.5909         | ...                                  | 39/66                  | 0.6216         | 23/37                                | 23/37                  |
| 0.5910         | 24/39 – 1/41                         | 40/59 – 4/46           | 0.6220         | 14/27 + 3/29                         | 15/53 + 20/59          |
| 0.5918         | 29/49                                | 29/49                  | 0.6226         | ...                                  | 33/53                  |
| 0.5920         | 21/37 + 1/41                         | 21/34 – 1/39           | 0.6230         | 24/37 – 1/39                         | 24/37 – 1/39           |
| 0.5926         | 16/27                                | 32/54                  | 0.6240         | 5/29 + 14/31                         | 4/49 + 32/59           |
| 0.5930         | 1/15 + 10/19                         | 22/34 – 2/37           | 0.6250         | 10/16                                | 15/24                  |
| 0.5932         | ...                                  | 35/59                  | 0.6260         | 12/43 + 17/49                        | 21/46 + 10/59          |
| 0.5940         | 6/29 + 12/31                         | 15/49 + 19/66          | 0.6270         | 17/47 + 13/49                        | 24/46 + 6/57           |
| 0.5946         | 22/37                                | 22/37                  | 0.6271         | ...                                  | 37/59                  |
| 0.5950         | 12/41 + 13/43                        | 18/25 – 3/24           | 0.6275         | ...                                  | 32/51                  |
| 0.5952         | ...                                  | 25/42                  | 0.6279         | 27/43                                | 27/43                  |
| 0.5957         | 28/47                                | 28/47                  | 0.6280         | 23/33 – 2/29                         | 28/47 + 2/62           |
| 0.5960         | 28/39 – 5/41                         | 15/51 + 16/53          | 0.6290         | 11/39 + 17/49                        | 12/54 + 24/59          |
| 0.5965         | ...                                  | 34/57                  | 0.6290         | ...                                  | 39/62                  |
| 0.5968         | ...                                  | 37/62                  | 0.6296         | 17/27                                | 34/54                  |

Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.6300         | 11/41 + 17/47                        | 18/24 - 3/25           | 0.6610         | ...                                  | 39/59                  |
| 0.6304         | ...                                  | 29/46                  | 0.6613         | ...                                  | 41/62                  |
| 0.6310         | 9/37 + 19/49                         | 8/49 + 29/62           | 0.6620         | 13/23 + 3/31                         | 36/53 - 1/58           |
| 0.6316         | 12/19                                | 24/38                  | 0.6630         | 35/49 - 2/39                         | 11/39 + 16/42          |
| 0.6316         | ...                                  | 36/57                  | 0.6640         | 13/41 + 17/49                        | 33/51 + 1/59           |
| 0.6320         | 12/37 + 12/39                        | 12/34 + 12/43          | 0.6650         | 16/37 + 10/43                        | 15/24 + 1/25           |
| 0.6327         | 31/49                                | 31/49                  | 0.6660         | 34/41 - 8/49                         | 21/51 + 15/59          |
| 0.6330         | 13/27 + 5/33                         | 14/51 + 19/53          | 0.6667         | 10/15                                | 16/24                  |
| 0.6333         | ...                                  | 19/30                  | 0.6667         | 12/18                                | 20/30                  |
| 0.6340         | 7/17 + 4/18                          | 25/37 - 1/24           | 0.6667         | 14/21                                | 26/39                  |
| 0.6341         | 26/41                                | 26/41                  | 0.6667         | 18/27                                | 28/42                  |
| 0.6350         | 9/39 + 19/47                         | 19/25 - 3/24           | 0.6667         | 22/33                                | 34/51                  |
| 0.6360         | 7/37 + 21/47                         | 12/54 + 24/58          | 0.6667         | 26/39                                | 36/54                  |
| 0.6364         | 21/33                                | 42/66                  | 0.6667         | ...                                  | 38/57                  |
| 0.6370         | 5/47 + 26/49                         | 10/47 + 28/66          | 0.6667         | ...                                  | 44/66                  |
| 0.6379         | ...                                  | 37/58                  | 0.6670         | 24/41 + 4/49                         | 5/51 + 33/58           |
| 0.6380         | 12/27 + 6/31                         | 6/34 + 18/39           | 0.6680         | 14/41 + 16/49                        | 11/47 + 23/53          |
| 0.6383         | 30/47                                | 30/47                  | 0.6690         | 5/23 + 14/31                         | 10/46 + 28/62          |
| 0.6390         | 14/23 + 1/33                         | 28/39 - 3/38           | 0.6700         | 37/49 - 4/47                         | 18/24 - 2/25           |
| 0.6400         | 4/37 + 25/47                         | 16/25                  | 0.6710         | 9/21 + 8/33                          | 15/47 + 19/54          |
| 0.6410         | ...                                  | 45/66 - 2/49           | 0.6720         | 15/41 + 15/49                        | 7/54 + 32/59           |
| 0.6410         | 25/39                                | 25/39                  | 0.6724         | ...                                  | 39/58                  |
| 0.6415         | ...                                  | 34/53                  | 0.6730         | 7/43 + 25/49                         | 42/57 - 3/47           |
| 0.6420         | 23/37 + 1/49                         | 20/59 + 20/66          | 0.6735         | 33/49                                | 33/49                  |
| 0.6429         | ...                                  | 18/28                  | 0.6739         | ...                                  | 31/46                  |
| 0.6429         | ...                                  | 27/42                  | 0.6740         | 4/39 + 28/49                         | 21/53 + 15/54          |
| 0.6430         | 41/37 - 20/43                        | 24/51 + 10/58          | 0.6744         | 29/43                                | 29/43                  |
| 0.6440         | 31/43 - 3/39                         | 31/43 - 3/39           | 0.6750         | 10/16 + 1/20                         | 9/24 + 9/30            |
| 0.6441         | ...                                  | 38/59                  | 0.6757         | 25/37                                | 25/37                  |
| 0.6450         | 33/43 - 6/49                         | 3/24 + 13/25           | 0.6760         | 20/23 - 6/31                         | 43/62 - 1/57           |
| 0.6452         | 20/31                                | 40/62                  | 0.6765         | ...                                  | 23/34                  |
| 0.6460         | 23/37 + 1/41                         | 2/47 + 35/58           | 0.6770         | 7/37 + 20/41                         | 26/53 + 11/59          |
| 0.6470         | 8/39 + 19/43                         | 24/47 + 9/66           | 0.6774         | 21/31                                | 42/62                  |
| 0.6471         | 11/17                                | 22/34                  | 0.6780         | ...                                  | 40/59                  |
| 0.6471         | ...                                  | 33/51                  | 0.6780         | 21/39 + 6/43                         | 6/49 + 30/54           |
| 0.6480         | 31/41 - 4/37                         | 43/57 - 5/47           | 0.6786         | ...                                  | 19/28                  |
| 0.6481         | ...                                  | 35/54                  | 0.6790         | 7/37 + 24/49                         | 19/51 + 19/62          |
| 0.6486         | 24/37                                | 24/37                  | 0.6792         | ...                                  | 36/53                  |
| 0.6490         | 3/23 + 14/27                         | 8/30 + 13/34           | 0.6800         | 31/47 + 1/49                         | 17/25                  |
| 0.6491         | ...                                  | 37/57                  | 0.6809         | 32/47                                | 32/47                  |
| 0.6500         | 13/20                                | 6/24 + 12/30           | 0.6810         | 21/27 - 3/31                         | 29/41 - 1/38           |
| 0.6510         | 18/29 + 1/33                         | 25/59 + 15/66          | 0.6818         | ...                                  | 45/66                  |
| 0.6512         | ...                                  | 28/43                  | 0.6820         | 15/37 + 13/47                        | 37/51 - 2/46           |
| 0.6515         | ...                                  | 43/66                  | 0.6829         | 28/41                                | 28/41                  |
| 0.6520         | 8/31 + 13/33                         | 46/59 - 6/47           | 0.6830         | 5/17 + 7/18                          | 35/57 + 4/58           |
| 0.6522         | 15/23                                | 30/46                  | 0.6840         | 31/37 - 6/39                         | 13/47 + 22/54          |
| 0.6530         | 24/31 - 4/33                         | 22/54 + 14/57          | 0.6842         | 13/19                                | 26/38                  |
| 0.6531         | 32/49                                | 32/49                  | 0.6842         | ...                                  | 39/57                  |
| 0.6540         | 23/41 + 4/43                         | 34/58 + 4/59           | 0.6850         | 15/41 + 15/47                        | 3/24 + 14/25           |
| 0.6550         | 23/31 - 2/23                         | 9/24 + 7/25            | 0.6852         | ...                                  | 37/54                  |
| 0.6552         | 19/29                                | 38/58                  | 0.6860         | 3/23 + 15/27                         | 19/49 + 17/57          |
| 0.6560         | 29/41 - 2/39                         | 23/24 - 13/43          | 0.6863         | ...                                  | 35/51                  |
| 0.6570         | 10/23 + 6/27                         | 20/46 + 12/54          | 0.6870         | 28/37 - 3/43                         | 36/51 - 1/53           |
| 0.6579         | ...                                  | 25/38                  | 0.6875         | 11/16                                | ...                    |
| 0.6580         | 10/21 + 6/33                         | 20/34 + 3/43           | 0.6880         | 13/21 + 2/29                         | 30/49 + 5/66           |
| 0.6585         | 27/41                                | 27/41                  | 0.6890         | 36/47 - 3/39                         | 42/53 - 6/58           |
| 0.6590         | 15/27 + 3/29                         | 3/54 + 35/58           | 0.6897         | 20/29                                | 40/58                  |
| 0.6596         | 31/47                                | 31/47                  | 0.6900         | 21/37 + 6/49                         | 6/24 + 11/25           |
| 0.6600         | 8/47 + 24/49                         | 9/25 + 9/30            | 0.6905         | ...                                  | 29/42                  |
| 0.6604         | ...                                  | 35/53                  | 0.6910         | 35/49 - 1/43                         | 21/57 + 20/62          |
| 0.6610         | 2/41 + 30/49                         | 34/57 + 4/62           | 0.6920         | 35/43 - 5/41                         | 35/43 - 5/41           |

Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.6923         | 27/39                                | 27/39                  | 0.7234         | ...                                  | 34/47                  |
| 0.6930         | 19/37 + 7/39                         | 19/37 + 7/39           | 0.7240         | 3/27 + 19/31                         | 34/41 - 4/38           |
| 0.6935         | ...                                  | 43/62                  | 0.7241         | 21/29                                | 42/58                  |
| 0.6939         | 34/49                                | 34/49                  | 0.7250         | 2/16 + 12/20                         | 7/24 + 13/30           |
| 0.6940         | 10/23 + 7/27                         | 14/38 + 14/43          | 0.7255         | ...                                  | 37/51                  |
| 0.6949         | ...                                  | 41/59                  | 0.7258         | ...                                  | 45/62                  |
| 0.6950         | 24/33 - 1/31                         | 9/24 + 8/25            | 0.7260         | 34/41 - 6/47                         | 2/49 + 37/54           |
| 0.6957         | 16/23                                | 32/46                  | 0.7270         | 15/19 - 1/16                         | 14/54 + 29/62          |
| 0.6960         | 15/31 + 7/33                         | 32/47 + 1/66           | 0.7273         | 24/33                                | 48/66                  |
| 0.6970         | ...                                  | 46/66                  | 0.7280         | 23/37 + 5/47                         | 23/49 + 15/58          |
| 0.6970         | 24/39 + 4/49                         | 24/51 + 12/53          | 0.7288         | ...                                  | 43/59                  |
| 0.6977         | 30/43                                | 30/43                  | 0.7290         | 38/49 - 2/43                         | 12/47 + 27/57          |
| 0.6980         | 22/29 - 2/33                         | 4/47 + 38/62           | 0.7297         | 27/37                                | 27/37                  |
| 0.6981         | ...                                  | 37/53                  | 0.7300         | 11/27 + 10/31                        | 6/24 + 12/25           |
| 0.6990         | 34/47 - 1/41                         | 14/58 + 27/59          | 0.7310         | 15/37 + 14/43                        | 26/59 + 18/62          |
| 0.7000         | 14/20                                | 21/30                  | 0.7317         | 30/41                                | 30/41                  |
| 0.7010         | 24/43 + 7/49                         | 28/47 + 6/57           | 0.7320         | 20/37 + 9/47                         | 26/57 + 16/58          |
| 0.7018         | ...                                  | 40/57                  | 0.7330         | 19/37 + 9/41                         | 39/47 - 6/62           |
| 0.7020         | 10/21 + 7/31                         | 7/37 + 20/39           | 0.7333         | 11/15                                | 22/30                  |
| 0.7021         | 33/47                                | 33/47                  | 0.7340         | 6/21 + 13/29                         | 26/49 + 12/59          |
| 0.7027         | 26/37                                | 26/37                  | 0.7347         | 36/49                                | 36/49                  |
| 0.7030         | 25/31 - 3/29                         | 23/58 + 19/62          | 0.7350         | 29/37 - 2/41                         | 9/24 + 9/25            |
| 0.7037         | 19/27                                | 38/54                  | 0.7353         | ...                                  | 25/34                  |
| 0.7040         | 8/37 + 20/41                         | 47/59 - 5/54           | 0.7358         | ...                                  | 39/53                  |
| 0.7050         | 19/37 + 9/47                         | 15/24 + 2/25           | 0.7360         | 25/47 + 10/49                        | 47/59 - 4/66           |
| 0.7059         | 12/17                                | 24/34                  | 0.7368         | 14/19                                | 28/38                  |
| 0.7059         | ...                                  | 36/51                  | 0.7368         | ...                                  | 42/57                  |
| 0.7060         | 18/37 + 9/41                         | 38/58 + 3/59           | 0.7370         | 2/37 + 28/41                         | 13/49 + 25/53          |
| 0.7069         | ...                                  | 41/58                  | 0.7380         | 19/37 + 11/49                        | 31/47 + 4/51           |
| 0.7070         | 6/39 + 26/47                         | 7/30 + 18/38           | 0.7381         | ...                                  | 31/42                  |
| 0.7073         | 29/41                                | 29/41                  | 0.7390         | 6/31 + 18/33                         | 12/62 + 36/66          |
| 0.7080         | 30/39 - 3/49                         | 13/58 + 30/62          | 0.7391         | 17/23                                | 34/46                  |
| 0.7083         | ...                                  | 17/24                  | 0.7400         | 8/39 + 23/43                         | 6/25 + 15/30           |
| 0.7090         | 34/39 - 7/43                         | 31/46 + 2/57           | 0.7407         | 20/27                                | 40/54                  |
| 0.7097         | 22/31                                | 44/62                  | 0.7410         | 9/39 + 25/49                         | 49/57 - 7/59           |
| 0.7100         | 20/43 + 12/49                        | 18/24 - 1/25           | 0.7414         | ...                                  | 43/58                  |
| 0.7105         | ...                                  | 27/38                  | 0.7419         | 23/31                                | 46/62                  |
| 0.7110         | 22/29 - 1/21                         | 33/39 - 5/37           | 0.7420         | 17/39 + 15/49                        | 28/51 + 11/57          |
| 0.7119         | ...                                  | 42/59                  | 0.7424         | ...                                  | 49/66                  |
| 0.7120         | 6/39 + 24/43                         | 31/54 + 8/58           | 0.7430         | 19/39 + 11/43                        | 1/53 + 42/58           |
| 0.7121         | ...                                  | 47/66                  | 0.7436         | ...                                  | 29/39                  |
| 0.7130         | 27/43 + 4/47                         | 17/30 + 6/41           | 0.7440         | 4/29 + 20/33                         | 27/49 + 11/57          |
| 0.7140         | 6/43 + 27/47                         | 45/57 - 4/53           | 0.7442         | 32/43                                | 32/43                  |
| 0.7143         | 15/21                                | 20/28                  | 0.7447         | 35/47                                | 35/47                  |
| 0.7143         | 35/49                                | 30/42                  | 0.7450         | 17/21 - 2/31                         | 15/24 + 3/25           |
| 0.7143         | ...                                  | 35/49                  | 0.7451         | ...                                  | 38/51                  |
| 0.7150         | 28/43 + 3/47                         | 21/25 - 3/24           | 0.7458         | ...                                  | 44/59                  |
| 0.7160         | 2/47 + 33/49                         | 25/51 + 14/62          | 0.7460         | 13/47 + 23/49                        | 2/59 + 47/66           |
| 0.7170         | ...                                  | 38/53                  | 0.7470         | 23/41 + 8/43                         | 29/49 + 9/58           |
| 0.7170         | 29/43 + 2/47                         | 28/59 + 16/66          | 0.7480         | 19/43 + 15/49                        | 10/53 + 33/59          |
| 0.7174         | ...                                  | 33/46                  | 0.7490         | 13/15 - 2/17                         | 36/47 - 1/59           |
| 0.7179         | 28/39                                | 28/39                  | 0.7500         | 12/16                                | 18/24                  |
| 0.7180         | 22/27 - 3/31                         | 21/58 + 21/59          | 0.7500         | 15/20                                | 21/28                  |
| 0.7190         | 39/49 - 3/39                         | 12/57 + 30/59          | 0.7510         | 11/23 + 9/33                         | 39/53 + 1/66           |
| 0.7193         | ...                                  | 41/57                  | 0.7520         | 19/23 - 2/27                         | 39/57 + 4/59           |
| 0.7200         | 2/43 + 33/49                         | 18/25                  | 0.7530         | 23/39 + 8/49                         | 11/53 + 36/66          |
| 0.7209         | 31/43                                | 31/43                  | 0.7540         | 6/37 + 29/49                         | 25/46 + 12/57          |
| 0.7210         | 13/29 + 9/33                         | 21/47 + 17/62          | 0.7544         | ...                                  | 43/57                  |
| 0.7220         | 18/23 - 2/33                         | 13/46 + 29/66          | 0.7547         | ...                                  | 40/53                  |
| 0.7222         | 13/18                                | 39/54                  | 0.7550         | 24/37 + 5/47                         | 21/24 - 3/25           |
| 0.7230         | 6/29 + 16/31                         | 11/46 + 30/62          | 0.7551         | 37/49                                | 37/49                  |



Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.7560         | 1/47 + 36/49                         | 9/47 + 35/62           | 0.7860         | 17/37 + 16/49                        | 49/58 - 3/51           |
| 0.7561         | 31/41                                | 31/41                  | 0.7870         | 10/39 + 26/49                        | 30/37 - 1/42           |
| 0.7568         | 28/37                                | 28/37                  | 0.7872         | 37/47                                | 37/47                  |
| 0.7570         | 15/43 + 20/49                        | 8/53 + 40/66           | 0.7879         | 26/33                                | 52/66                  |
| 0.7576         | 25/33                                | 50/66                  | 0.7880         | 6/39 + 26/41                         | 45/51 - 5/53           |
| 0.7580         | 16/37 + 14/43                        | 48/59 - 3/54           | 0.7890         | 19/41 + 14/43                        | 37/49 + 2/59           |
| 0.7581         | ...                                  | 47/62                  | 0.7895         | ...                                  | 30/38                  |
| 0.7586         | 22/29                                | 44/58                  | 0.7895         | ...                                  | 45/57                  |
| 0.7590         | 28/47 + 8/49                         | 36/41 - 5/42           | 0.7900         | 15/37 + 15/39                        | 18/24 + 1/25           |
| 0.7593         | ...                                  | 41/54                  | 0.7903         | ...                                  | 49/62                  |
| 0.7600         | 39/47 - 3/43                         | 19/25                  | 0.7907         | 34/43                                | 34/43                  |
| 0.7609         | ...                                  | 35/46                  | 0.7910         | 8/29 + 17/33                         | 7/49 + 35/54           |
| 0.7610         | 19/43 + 15/47                        | 34/51 + 5/53           | 0.7917         | ...                                  | 19/24                  |
| 0.7619         | 16/21                                | 32/42                  | 0.7920         | 8/29 + 16/31                         | 4/47 + 41/58           |
| 0.7620         | 38/47 - 2/43                         | 16/51 + 26/58          | 0.7925         | ...                                  | 42/53                  |
| 0.7627         | ...                                  | 45/59                  | 0.7930         | 10/39 + 22/41                        | 7/47 + 38/59           |
| 0.7630         | 14/37 + 15/39                        | 36/46 - 1/51           | 0.7931         | 23/29                                | 46/58                  |
| 0.7632         | ...                                  | 29/38                  | 0.7940         | 28/43 + 7/49                         | 14/57 + 34/62          |
| 0.7640         | 29/39 + 1/49                         | 27/57 + 18/62          | 0.7941         | ...                                  | 27/34                  |
| 0.7647         | 13/17                                | 26/34                  | 0.7949         | 31/39                                | 31/39                  |
| 0.7647         | ...                                  | 39/51                  | 0.7950         | 24/37 + 6/41                         | 21/24 - 2/25           |
| 0.7650         | 16/27 + 5/29                         | 3/24 + 16/25           | 0.7959         | 39/49                                | 39/49                  |
| 0.7660         | 36/47                                | 36/47                  | 0.7960         | 2/39 + 35/47                         | 18/37 + 13/42          |
| 0.7660         | 13/37 + 17/41                        | 4/37 + 25/38           | 0.7963         | ...                                  | 43/54                  |
| 0.7667         | ...                                  | 23/30                  | 0.7966         | ...                                  | 47/59                  |
| 0.7670         | 14/41 + 20/47                        | 31/38 - 2/41           | 0.7970         | 40/47 - 2/37                         | 13/53 + 32/58          |
| 0.7674         | 33/43                                | 33/43                  | 0.7980         | 14/39 + 18/41                        | 33/51 + 8/53           |
| 0.7680         | 21/41 + 11/43                        | 21/41 + 11/43          | 0.7990         | 3/37 + 28/39                         | 10/28 + 19/43          |
| 0.7690         | 16/47 + 21/49                        | 15/54 + 28/57          | 0.8000         | 12/15                                | 20/25                  |
| 0.7692         | 30/39                                | 30/39                  | 0.8000         | 16/20                                | 24/30                  |
| 0.7700         | 14/23 + 5/31                         | 6/24 + 13/25           | 0.8010         | 32/37 - 3/47                         | 10/47 + 30/51          |
| 0.7710         | 21/39 + 10/43                        | 48/59 - 2/47           | 0.8020         | 27/31 - 2/29                         | 54/62 - 4/58           |
| 0.7719         | ...                                  | 44/57                  | 0.8030         | 18/39 + 14/41                        | 18/39 + 14/41          |
| 0.7720         | 2/37 + 28/39                         | 2/37 + 28/39           | 0.8030         | ...                                  | 53/66                  |
| 0.7727         | ...                                  | 51/66                  | 0.8039         | ...                                  | 41/51                  |
| 0.7730         | 20/27 + 1/31                         | 1/34 + 29/39           | 0.8040         | 10/43 + 28/49                        | 32/49 + 8/53           |
| 0.7736         | ...                                  | 41/53                  | 0.8043         | ...                                  | 37/46                  |
| 0.7740         | 32/39 - 2/43                         | 32/39 - 2/43           | 0.8049         | 33/41                                | 33/41                  |
| 0.7742         | 24/31                                | 48/62                  | 0.8050         | 22/23 - 5/33                         | 3/24 + 17/25           |
| 0.7750         | 6/16 + 8/20                          | 9/24 + 12/30           | 0.8060         | 34/41 - 1/43                         | 13/47 + 27/51          |
| 0.7755         | 38/49                                | 38/49                  | 0.8065         | 25/31                                | 50/62                  |
| 0.7759         | ...                                  | 45/58                  | 0.8070         | 5/15 + 9/19                          | 15/58 + 34/62          |
| 0.7760         | 36/41 - 5/49                         | 5/51 + 40/59           | 0.8070         | ...                                  | 46/57                  |
| 0.7770         | 6/23 + 16/31                         | 47/59 - 1/51           | 0.8080         | 19/21 - 3/31                         | 22/39 + 10/41          |
| 0.7778         | 14/18                                | 42/54                  | 0.8085         | 38/47                                | 38/47                  |
| 0.7778         | 21/27                                | ...                    | 0.8090         | 22/39 + 12/49                        | 28/53 + 16/57          |
| 0.7780         | 16/41 + 19/49                        | 41/47 - 5/53           | 0.8095         | ...                                  | 34/42                  |
| 0.7790         | 6/41 + 31/49                         | 49/57 - 5/62           | 0.8100         | 33/43 + 2/47                         | 6/24 + 14/25           |
| 0.7797         | ...                                  | 46/59                  | 0.8103         | ...                                  | 47/58                  |
| 0.7800         | 28/37 + 1/43                         | 17/25 + 3/30           | 0.8108         | 30/37                                | 30/37                  |
| 0.7805         | 32/41                                | 32/41                  | 0.8110         | 7/27 + 16/29                         | 34/53 + 10/59          |
| 0.7810         | 12/23 + 7/27                         | 17/57 + 28/58          | 0.8113         | ...                                  | 43/53                  |
| 0.7820         | 28/31 - 4/33                         | 45/49 - 9/66           | 0.8120         | 17/29 + 7/31                         | 34/58 + 14/62          |
| 0.7826         | 18/23                                | 36/46                  | 0.8125         | 13/16                                | ...                    |
| 0.7830         | 13/31 + 12/33                        | 23/46 + 15/53          | 0.8130         | 6/43 + 33/49                         | 16/24 + 6/41           |
| 0.7838         | 29/37                                | 29/37                  | 0.8136         | ...                                  | 48/59                  |
| 0.7840         | 21/23 - 4/31                         | 34/47 + 4/66           | 0.8140         | 35/43                                | 35/43                  |
| 0.7843         | ...                                  | 40/51                  | 0.8140         | 28/33 - 1/29                         | 14/47 + 32/62          |
| 0.7850         | 32/43 + 2/49                         | 15/24 + 4/25           | 0.8148         | 22/27                                | 44/54                  |
| 0.7857         | ...                                  | 22/28                  | 0.8150         | 22/47 + 17/49                        | 9/24 + 11/25           |
| 0.7857         | ...                                  | 33/42                  | 0.8158         | ...                                  | 31/38                  |

Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.8160         | 5/37 + 32/47                         | 23/34 + 6/43           | 0.8478         | ...                                  | 39/46                  |
| 0.8163         | 40/49                                | 40/49                  | 0.8480         | 30/41 + 5/43                         | 31/59 + 20/62          |
| 0.8170         | 12/17 + 2/18                         | 13/54 + 34/59          | 0.8485         | 28/33                                | 56/66                  |
| 0.8180         | 30/39 + 2/41                         | 33/54 + 12/58          | 0.8490         | 13/41 + 25/47                        | 2/47 + 50/62           |
| 0.8182         | 27/33                                | 54/66                  | 0.8491         | ...                                  | 45/53                  |
| 0.8190         | 26/37 + 5/43                         | 20/34 + 9/39           | 0.8500         | 17/20                                | 18/24 + 3/30           |
| 0.8200         | 28/39 + 5/49                         | 8/25 + 15/30           | 0.8510         | 5/21 + 19/31                         | 22/37 + 10/39          |
| 0.8205         | 32/39                                | 32/39                  | 0.8511         | 40/47                                | 40/47                  |
| 0.8210         | 10/21 + 10/29                        | 10/59 + 43/66          | 0.8519         | 23/27                                | 46/54                  |
| 0.8214         | ...                                  | 23/28                  | 0.8520         | 1/16 + 15/19                         | 55/62 - 2/57           |
| 0.8220         | 18/41 + 18/47                        | 11/57 + 39/62          | 0.8529         | ...                                  | 29/34                  |
| 0.8226         | ...                                  | 51/62                  | 0.8530         | 17/21 + 1/23                         | 19/58 + 31/59          |
| 0.8230         | 34/39 - 2/41                         | 4/49 + 43/58           | 0.8537         | 35/41                                | 35/41                  |
| 0.8235         | 14/17                                | 28/34                  | 0.8540         | 15/39 + 23/49                        | 54/62 - 1/59           |
| 0.8235         | ...                                  | 42/51                  | 0.8548         | ...                                  | 53/62                  |
| 0.8240         | 15/37 + 18/43                        | 19/53 + 27/58          | 0.8550         | 19/37 + 14/41                        | 9/24 + 12/25           |
| 0.8246         | ...                                  | 47/57                  | 0.8560         | 24/43 + 14/47                        | 37/53 + 9/57           |
| 0.8250         | 6/16 + 9/20                          | 7/24 + 16/30           | 0.8570         | 3/43 + 37/47                         | 51/57 - 2/53           |
| 0.8260         | 4/31 + 23/33                         | 39/62 + 13/66          | 0.8571         | 18/21                                | 24/28                  |
| 0.8261         | 19/23                                | 38/46                  | 0.8571         | 42/49                                | 36/42                  |
| 0.8270         | 32/41 + 2/43                         | 46/58 + 2/59           | 0.8571         | ...                                  | 42/49                  |
| 0.8276         | 24/29                                | 48/58                  | 0.8580         | 25/43 + 13/47                        | 38/51 + 7/62           |
| 0.8280         | 35/41 - 1/39                         | 35/41 - 1/39           | 0.8590         | 11/27 + 14/31                        | 22/54 + 28/62          |
| 0.8290         | 5/37 + 34/49                         | 10/34 + 23/43          | 0.8596         | ...                                  | 49/57                  |
| 0.8293         | 34/41                                | 34/41                  | 0.8600         | 1/43 + 41/49                         | 9/25 + 15/30           |
| 0.8298         | 39/47                                | 39/47                  | 0.8605         | 37/43                                | 37/43                  |
| 0.8300         | 17/23 + 3/33                         | 18/24 + 2/25           | 0.8610         | 16/37 + 21/49                        | 18/46 + 31/66          |
| 0.8302         | ...                                  | 44/53                  | 0.8620         | 13/37 + 24/47                        | 17/38 + 17/41          |
| 0.8305         | ...                                  | 49/59                  | 0.8621         | 25/29                                | 50/58                  |
| 0.8310         | 34/39 - 2/49                         | 39/49 + 2/57           | 0.8627         | ...                                  | 44/51                  |
| 0.8320         | 27/43 + 10/49                        | 27/53 + 20/62          | 0.8630         | 38/41 - 3/47                         | 18/46 + 25/53          |
| 0.8330         | 9/37 + 23/39                         | 42/47 - 4/66           | 0.8636         | ...                                  | 57/66                  |
| 0.8333         | 15/18                                | 20/24                  | 0.8640         | 11/16 + 3/17                         | 56/62 - 2/51           |
| 0.8333         | ...                                  | 25/30                  | 0.8644         | ...                                  | 51/59                  |
| 0.8333         | ...                                  | 35/42                  | 0.8649         | 32/37                                | 32/37                  |
| 0.8333         | ...                                  | 45/54                  | 0.8650         | 4/41 + 33/43                         | 15/24 + 6/25           |
| 0.8333         | ...                                  | 55/66                  | 0.8660         | 10/17 + 5/18                         | 13/57 + 37/58          |
| 0.8340         | 15/23 + 6/33                         | 20/38 + 12/39          | 0.8667         | 13/15                                | 26/30                  |
| 0.8350         | 43/49 - 2/47                         | 21/24 - 1/25           | 0.8670         | 3/21 + 21/29                         | 28/54 + 23/66          |
| 0.8360         | 2/41 + 37/47                         | 32/46 + 8/57           | 0.8679         | ...                                  | 46/53                  |
| 0.8367         | 41/49                                | 41/49                  | 0.8680         | 36/47 + 5/49                         | 53/59 - 2/66           |
| 0.8370         | 19/29 + 6/33                         | 33/57 + 16/62          | 0.8684         | ...                                  | 33/38                  |
| 0.8372         | ...                                  | 36/43                  | 0.8690         | 40/43 - 3/49                         | 39/47 + 2/51           |
| 0.8378         | ...                                  | 31/37                  | 0.8696         | 20/23                                | 40/46                  |
| 0.8380         | 7/39 + 27/41                         | 20/46 + 25/62          | 0.8700         | 4/39 + 33/43                         | 18/24 + 3/25           |
| 0.8387         | 26/31                                | 52/62                  | 0.8704         | ...                                  | 47/54                  |
| 0.8390         | 30/39 + 3/43                         | 3/49 + 42/54           | 0.8710         | 27/31                                | 54/62                  |
| 0.8400         | 19/37 + 16/49                        | 21/25                  | 0.8710         | 17/27 + 7/29                         | 31/51 + 15/57          |
| 0.8410         | 23/43 + 15/49                        | 44/51 - 1/46           | 0.8718         | 34/39                                | 34/39                  |
| 0.8420         | 34/37 - 3/39                         | 46/49 - 6/62           | 0.8720         | 30/37 + 3/49                         | 26/58 + 25/59          |
| 0.8421         | 16/19                                | 32/38                  | 0.8723         | 41/47                                | 41/47                  |
| 0.8421         | ...                                  | 48/57                  | 0.8730         | 15/39 + 21/43                        | 21/49 + 24/54          |
| 0.8430         | 6/37 + 32/47                         | 9/47 + 43/66           | 0.8740         | 15/39 + 23/47                        | 5/53 + 46/59           |
| 0.8431         | ...                                  | 43/51                  | 0.8750         | 14/16                                | 21/24                  |
| 0.8440         | 17/21 + 1/29                         | 41/54 + 5/59           | 0.8760         | 21/23 - 1/27                         | 48/57 + 2/59           |
| 0.8448         | ...                                  | 49/58                  | 0.8770         | 3/37 + 39/49                         | 37/51 + 10/66          |
| 0.8450         | 29/37 + 3/49                         | 3/24 + 18/25           | 0.8772         | ...                                  | 50/57                  |
| 0.8460         | 27/37 + 5/43                         | 22/54 + 25/57          | 0.8776         | 43/49                                | 43/49                  |
| 0.8462         | 33/39                                | 33/39                  | 0.8780         | 24/47 + 18/49                        | 31/53 + 17/58          |
| 0.8470         | 5/23 + 17/27                         | 26/38 + 7/43           | 0.8780         | 36/41                                | 36/41                  |
| 0.8475         | ...                                  | 50/59                  | 0.8788         | ...                                  | 58/66                  |

Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.8790         | 22/43 + 18/49                        | 52/58 - 1/57           | 0.9110         | 31/37 + 3/41                         | 31/37 + 3/41           |
| 0.8793         | ...                                  | 51/58                  | 0.9118         | ...                                  | 31/34                  |
| 0.8800         | 31/39 + 4/47                         | 22/25                  | 0.9120         | 26/37 + 9/43                         | 52/43 - 11/37          |
| 0.8810         | ...                                  | 37/42                  | 0.9123         | ...                                  | 52/57                  |
| 0.8810         | 19/29 + 7/31                         | 8/51 + 42/58           | 0.9130         | 2/31 + 28/33                         | 35/62 + 23/66          |
| 0.8814         | ...                                  | 52/59                  | 0.9130         | 21/23                                | 42/46                  |
| 0.8820         | 20/37 + 14/41                        | 42/57 + 9/62           | 0.9138         | ...                                  | 53/58                  |
| 0.8824         | 15/17                                | 30/34                  | 0.9140         | 7/21 + 18/31                         | 42/47 + 1/49           |
| 0.8824         | ...                                  | 45/51                  | 0.9149         | 43/47                                | 43/47                  |
| 0.8830         | 27/41 + 11/49                        | 7/51 + 44/59           | 0.9150         | 8/17 + 8/18                          | 21/24 + 1/25           |
| 0.8837         | 38/43                                | 38/43                  | 0.9153         | ...                                  | 54/59                  |
| 0.8840         | 23/29 + 3/33                         | 37/47 + 6/62           | 0.9160         | 35/43 + 5/49                         | 40/53 + 10/62          |
| 0.8850         | 7/23 + 18/31                         | 3/24 + 19/25           | 0.9167         | ...                                  | 22/24                  |
| 0.8860         | 38/41 - 2/49                         | 38/59 + 15/62          | 0.9170         | 19/23 + 3/33                         | 29/38 + 6/39           |
| 0.8868         | ...                                  | 47/53                  | 0.9180         | 1/41 + 42/47                         | 39/46 + 4/57           |
| 0.8870         | 28/41 + 10/49                        | 34/51 + 13/59          | 0.9184         | 45/49                                | 45/49                  |
| 0.8871         | ...                                  | 55/62                  | 0.9189         | 34/37                                | 34/37                  |
| 0.8880         | 18/41 + 22/49                        | 28/51 + 20/59          | 0.9190         | 14/23 + 9/29                         | 8/46 + 38/51           |
| 0.8889         | 16/18                                | 48/54                  | 0.9194         | ...                                  | 57/62                  |
| 0.8889         | 24/27                                | ...                    | 0.9200         | 28/37 + 8/49                         | 23/25                  |
| 0.8890         | 8/41 + 34/49                         | 53/57 - 2/49           | 0.9210         | 17/37 + 18/39                        | 23/49 + 28/62          |
| 0.8900         | 39/41 - 3/49                         | 6/24 + 16/25           | 0.9211         | ...                                  | 35/38                  |
| 0.8910         | 29/41 + 9/49                         | 52/57 - 1/47           | 0.9216         | ...                                  | 47/51                  |
| 0.8913         | ...                                  | 41/46                  | 0.9220         | 26/39 + 12/47                        | 10/34 + 27/43          |
| 0.8919         | 33/37                                | 33/37                  | 0.9229         | 31/37 + 4/47                         | ...                    |
| 0.8920         | 19/41 + 21/49                        | 17/47 + 35/66          | 0.9230         | ...                                  | 29/54 + 22/57          |
| 0.8929         | ...                                  | 25/28                  | 0.9231         | 36/39                                | 36/39                  |
| 0.8930         | 27/37 + 8/49                         | 5/46 + 40/51           | 0.9240         | 15/41 + 24/43                        | 45/59 + 10/62          |
| 0.8936         | 42/47                                | 42/47                  | 0.9242         | ...                                  | 61/66                  |
| 0.8939         | ...                                  | 59/66                  | 0.9245         | ...                                  | 49/53                  |
| 0.8940         | 27/29 - 1/27                         | 28/49 + 20/62          | 0.9250         | 14/16 + 1/20                         | 7/24 + 19/30           |
| 0.8947         | 17/19                                | 34/38                  | 0.9259         | 25/27                                | 50/54                  |
| 0.8947         | ...                                  | 51/57                  | 0.9260         | 17/43 + 26/49                        | 2/51 + 47/53           |
| 0.8950         | 30/41 + 8/49                         | 9/24 + 13/25           | 0.9268         | 38/41                                | 38/41                  |
| 0.8960         | 20/41 + 20/49                        | 8/47 + 45/62           | 0.9270         | 28/37 + 8/47                         | 29/59 + 27/62          |
| 0.8966         | 26/29                                | 52/58                  | 0.9280         | 3/39 + 40/47                         | 47/57 + 6/58           |
| 0.8970         | 14/43 + 28/49                        | 7/57 + 48/62           | 0.9286         | ...                                  | 26/28                  |
| 0.8974         | 35/39                                | 35/39                  | 0.9286         | ...                                  | 39/42                  |
| 0.8980         | 44/49                                | 44/49                  | 0.9290         | 12/37 + 26/43                        | 16/53 + 37/59          |
| 0.8980         | 1/39 + 41/47                         | 28/57 + 24/59          | 0.9298         | ...                                  | 53/57                  |
| 0.8983         | ...                                  | 53/59                  | 0.9300         | 5/29 + 25/33                         | 6/24 + 17/25           |
| 0.8990         | 8/39 + 34/49                         | 42/51 + 4/53           | 0.9302         | 40/43                                | 40/43                  |
| 0.9000         | 18/20                                | 27/30                  | 0.9310         | 25/37 + 12/47                        | 7/30 + 30/43           |
| 0.9010         | 28/29 - 2/31                         | 27/58 + 27/62          | 0.9310         | 27/29                                | 54/58                  |
| 0.9020         | 20/27 + 5/31                         | 46/51                  | 0.9320         | 30/39 + 7/43                         | 59/62 + 1/51           |
| 0.9020         | ...                                  | 29/53 + 22/62          | 0.9322         | ...                                  | 55/59                  |
| 0.9024         | 37/41                                | 37/41                  | 0.9330         | 34/39 + 3/49                         | 5/42 + 35/43           |
| 0.9030         | 17/41 + 21/43                        | 17/41 + 21/43          | 0.9333         | 14/15                                | 28/30                  |
| 0.9032         | 28/31                                | 56/62                  | 0.9340         | 1/37 + 39/43                         | 56/59 - 1/66           |
| 0.9040         | 17/41 + 23/47                        | 7/53 + 44/57           | 0.9348         | ...                                  | 43/46                  |
| 0.9048         | 19/21                                | 38/42                  | 0.9350         | 2/39 + 38/43                         | 9/24 + 14/25           |
| 0.9050         | 38/43 + 1/47                         | 15/24 + 7/25           | 0.9355         | 29/31                                | 58/62                  |
| 0.9057         | ...                                  | 48/53                  | 0.9360         | 15/37 + 26/49                        | 13/58 + 42/59          |
| 0.9060         | 17/43 + 24/47                        | 17/58 + 38/62          | 0.9362         | 44/47                                | 44/47                  |
| 0.9070         | 39/43                                | 39/43                  | 0.9370         | 19/21 + 1/31                         | 29/53 + 23/59          |
| 0.9070         | 14/29 + 14/33                        | 7/47 + 47/62           | 0.9375         | 15/16                                | ...                    |
| 0.9074         | ...                                  | 49/54                  | 0.9380         | 13/39 + 26/43                        | 21/46 + 26/54          |
| 0.9080         | 1/27 + 27/31                         | 29/54 + 23/62          | 0.9388         | 46/49                                | 46/49                  |
| 0.9090         | 14/37 + 26/49                        | 8/53 + 47/62           | 0.9390         | 30/37 + 5/39                         | 30/37 + 5/39           |
| 0.9091         | 30/33                                | 60/66                  | 0.9394         | 31/33                                | 62/66                  |
| 0.9100         | 14/39 + 27/49                        | 18/24 + 4/25           | 0.9400         | 35/39 + 2/47                         | 16/25 + 9/30           |

Table 3. (Continued) Accurate Angular Indexing

| Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond | Part of a Turn | B&S, Becker, Hendey, K&T, & Rockford | Cincinnati and LeBlond |
|----------------|--------------------------------------|------------------------|----------------|--------------------------------------|------------------------|
| 0.9410         | 30/41 + 9/43                         | 25/47 + 27/66          | 0.9670         | 9/47 + 38/49                         | 8/34 + 30/41           |
| 0.9412         | 16/17                                | 32/34                  | 0.9677         | 30/31                                | 60/62                  |
| 0.9412         | ...                                  | 48/51                  | 0.9680         | 26/37 + 13/49                        | 2/46 + 49/53           |
| 0.9420         | 15/37 + 22/41                        | 42/47 + 3/62           | 0.9690         | 26/39 + 13/43                        | 5/51 + 54/62           |
| 0.9430         | 9/23 + 16/29                         | 12/49 + 37/53          | 0.9697         | 32/33                                | 64/66                  |
| 0.9434         | ...                                  | 50/53                  | 0.9700         | 12/23 + 13/29                        | 6/24 + 18/25           |
| 0.9440         | 9/43 + 36/49                         | 26/46 + 25/66          | 0.9706         | ...                                  | 33/34                  |
| 0.9444         | 17/18                                | 51/54                  | 0.9710         | 26/37 + 11/41                        | 14/46 + 34/51          |
| 0.9450         | 37/41 + 2/47                         | 15/24 + 8/25           | 0.9720         | 26/43 + 18/49                        | 31/53 + 24/62          |
| 0.9459         | 35/37                                | 35/37                  | 0.9730         | 36/37                                | 36/37                  |
| 0.9460         | 12/39 + 30/47                        | 22/46 + 29/62          | 0.9730         | 20/23 + 3/29                         | 26/54 + 29/59          |
| 0.9470         | 33/47 + 12/49                        | 14/49 + 41/62          | 0.9737         | ...                                  | 37/38                  |
| 0.9474         | 18/19                                | 36/38                  | 0.9740         | 16/21 + 7/33                         | 26/34 + 9/43           |
| 0.9474         | ...                                  | 54/57                  | 0.9744         | 38/39                                | 38/39                  |
| 0.9480         | 18/37 + 18/39                        | 11/38 + 27/41          | 0.9750         | 10/16 + 7/20                         | 13/24 + 13/30          |
| 0.9483         | ...                                  | 55/58                  | 0.9756         | 40/41                                | 40/41                  |
| 0.9487         | 37/39                                | 37/39                  | 0.9760         | 14/39 + 29/47                        | 10/49 + 44/57          |
| 0.9490         | 1/15 + 15/17                         | 13/47 + 39/58          | 0.9762         | ...                                  | 41/42                  |
| 0.9492         | ...                                  | 56/59                  | 0.9767         | 42/43                                | 42/43                  |
| 0.9500         | 19/20                                | 6/24 + 21/30           | 0.9770         | 33/37 + 4/47                         | 30/47 + 21/62          |
| 0.9510         | 29/43 + 13/47                        | 41/53 + 11/62          | 0.9780         | 25/37 + 13/43                        | 25/37 + 13/43          |
| 0.9512         | 39/41                                | 39/41                  | 0.9783         | ...                                  | 45/46                  |
| 0.9516         | ...                                  | 59/62                  | 0.9787         | 46/47                                | 46/47                  |
| 0.9520         | 8/43 + 36/47                         | 30/53 + 22/57          | 0.9790         | 13/23 + 12/29                        | 10/53 + 49/62          |
| 0.9524         | 20/21                                | 40/42                  | 0.9796         | 48/49                                | 48/49                  |
| 0.9530         | 5/43 + 41/49                         | 16/59 + 45/66          | 0.9800         | 23/39 + 16/41                        | 17/25 + 9/30           |
| 0.9535         | 41/43                                | 41/43                  | 0.9804         | ...                                  | 50/51                  |
| 0.9540         | 29/37 + 8/47                         | 28/54 + 27/62          | 0.9810         | 22/43 + 23/49                        | 51/58 + 6/59           |
| 0.9545         | ...                                  | 63/66                  | 0.9811         | ...                                  | 52/53                  |
| 0.9550         | 7/39 + 38/49                         | 21/24 + 2/25           | 0.9815         | ...                                  | 53/54                  |
| 0.9560         | 13/37 + 26/43                        | 13/37 + 26/43          | 0.9820         | 30/39 + 10/47                        | 19/46 + 33/58          |
| 0.9565         | 22/23                                | 44/46                  | 0.9825         | ...                                  | 56/57                  |
| 0.9570         | 14/21 + 9/31                         | 21/47 + 25/49          | 0.9828         | ...                                  | 57/58                  |
| 0.9574         | 45/47                                | 45/47                  | 0.9830         | 26/41 + 15/43                        | 45/57 + 12/62          |
| 0.9580         | 5/39 + 39/47                         | 20/53 + 36/62          | 0.9831         | ...                                  | 58/59                  |
| 0.9583         | ...                                  | 23/24                  | 0.9839         | ...                                  | 61/62                  |
| 0.9590         | 21/41 + 21/47                        | 18/51 + 40/66          | 0.9840         | 13/37 + 31/49                        | 1/46 + 51/53           |
| 0.9592         | 47/49                                | 47/49                  | 0.9848         | ...                                  | 65/66                  |
| 0.9600         | 7/39 + 32/41                         | 24/25                  | 0.9850         | 6/23 + 21/29                         | 15/24 + 9/25           |
| 0.9608         | ...                                  | 49/51                  | 0.9860         | 16/23 + 9/31                         | 42/53 + 12/62          |
| 0.9610         | 11/23 + 14/29                        | 5/34 + 35/43           | 0.9870         | 15/21 + 9/33                         | 13/34 + 26/43          |
| 0.9620         | 28/41 + 12/43                        | 52/59 + 5/62           | 0.9880         | 7/39 + 38/47                         | 5/46 + 51/58           |
| 0.9623         | ...                                  | 51/53                  | 0.9890         | 33/39 + 7/49                         | 20/39 + 20/42          |
| 0.9630         | 26/27                                | 52/54                  | 0.9900         | 10/29 + 20/31                        | 18/24 + 6/25           |
| 0.9630         | 30/43 + 13/49                        | 1/51 + 50/53           | 0.9910         | 22/23 + 1/29                         | 21/46 + 31/58          |
| 0.9640         | 21/39 + 20/47                        | 52/57 + 3/58           | 0.9920         | 39/41 + 2/49                         | 40/53 + 14/59          |
| 0.9643         | ...                                  | 27/28                  | 0.9930         | 8/23 + 20/31                         | 21/53 + 37/62          |
| 0.9649         | ...                                  | 55/57                  | 0.9940         | 7/23 + 20/29                         | 14/46 + 40/58          |
| 0.9650         | 11/39 + 28/41                        | 3/24 + 21/25           | 0.9950         | 35/39 + 4/41                         | 21/24 + 3/25           |
| 0.9655         | 28/29                                | 56/58                  | 0.9960         | 40/41 + 1/49                         | 43/46 + 3/49           |
| 0.9660         | 13/39 + 31/49                        | 15/39 + 25/43          | 0.9970         | 15/23 + 10/29                        | 30/46 + 20/58          |
| 0.9661         | ...                                  | 57/59                  | 0.9980         | 20/41 + 25/49                        | 12/51 + 45/59          |
| 0.9667         | ...                                  | 29/30                  | 0.9990         | 10/41 + 37/49                        | 6/51 + 52/59           |

**Approximate Indexing for Small Angles.**—To find *approximate* indexing movements for small angles, such as the remainder from the method discussed in *Angular Indexing* starting on page 1990, on a dividing head with a 40:1 worm-gear ratio, divide 540 by the number of minutes in the angle, and then divide the number of holes in each of the available indexing circles by this quotient. The result that is closest to a whole number is the best approximation of the angle for a simple indexing movement and is the number of holes to

be moved in the corresponding circle of holes. If the angle is greater than 9 degrees, the whole number will be greater than the number of holes in the circle, indicating that one or more full turns of the crank are required. Dividing by the number of holes in the indicated circle of holes will reduce the required indexing movement to the number of full turns, and the remainder will be the number of holes to be moved for the fractional turn. If the angle is less than about 11 minutes, it cannot be indexed by simple indexing with standard B & S plates (the corresponding angle for standard plates on a Cincinnati head is about 8 minutes, and for Cincinnati high number plates, 2.7 minutes. See [Tables 5, 6a, and 6b](#) for indexing movements with Cincinnati standard and high number plates).

*Example:* An angle of  $7^{\circ} 25'$  is to be indexed. Expressed in minutes, it is 445' and 540 divided by 445 equals 1.213483. The indexing circles available on standard B & S plates are 15, 16, 17, 18, 19, 20, 21, 23, 27, 29, 31, 33, 37, 39, 41, 43, 47, and 49. Each of these numbers is divided by 1.213483 and the closest to a whole number is found to be  $17 \div 1.213483 = 14.00926$ . The best approximation for a simple indexing movement to obtain  $7^{\circ} 25'$  is 14 holes on the 17-hole circle.

**Differential Indexing.**—This method is the same, in principle, as compound indexing (see *Compound Indexing* on page 1984), but differs from the latter in that the index plate is rotated by suitable gearing that connects it to the spiral-head spindle. This rotation or differential motion of the index plate takes place when the crank is turned, the plate moving either in the same direction as the crank or opposite to it, as may be required. The result is that the *actual* movement of the crank, at every indexing, is either greater or less than its movement with relation to the index plate. The differential method makes it possible to obtain almost any division by using only one circle of holes for that division and turning the index crank in one direction, as with plain indexing.

The gears to use for turning the index plate the required amount (when gears are required) are shown by [Tables 4a and 4b](#), *Simple and Differential Indexing with Browne & Sharpe Indexing Plates*, which shows what divisions can be obtained by plain indexing, and when it is necessary to use gears and the differential system. For example, if 50 divisions are required, the 20-hole index circle is used and the crank is moved 16 holes, but no gears are required. For 51 divisions, a 24-tooth gear is placed on the wormshaft and a 48-tooth gear on the spindle. These two gears are connected by two idler gears having 24 and 44 teeth, respectively.

To illustrate the principle of differential indexing, suppose a dividing head is to be geared for 271 divisions. [Table 4b](#) calls for a gear on the wormshaft having 56 teeth, a spindle gear with 72 teeth, and a 24-tooth idler to rotate the index plate in the same direction as the crank. The sector arms should be set to give the crank a movement of 3 holes in the 21-hole circle. If the spindle and the index plate were not connected through gearing, 280 divisions would be obtained by successively moving the crank 3 holes in the 21-hole circle, but the gears cause the index plate to turn in the same direction as the crank at such a rate that, when 271 indexings have been made, the work is turned one complete revolution. Therefore, we have 271 divisions instead of 280, the number being reduced because the total movement of the crank, for each indexing, is equal to the movement relative to the index plate, *plus* the movement of the plate itself when, as here, the crank and plate rotate in the same direction.

If they were rotated in opposite directions, the crank would have a total movement equal to the amount it turned relative to the plate, *minus* the plate's movement. Sometimes it is necessary to use compound gearing to move the index plate the required amount for each turn of the crank. The differential method cannot be used in connection with helical or spiral milling because the spiral head is then geared to the leadscrew of the machine.

**Finding Ratio of Gearing for Differential Indexing.**—To find the ratio of gearing for differential indexing, first select some approximate number *A* of divisions either greater or less than the required number *N*. For example, if the required number *N* is 67, the approxi-

mate number  $A$  might be 70. Then, if 40 turns of the index crank are required for 1 revolution of the spindle, the gearing ratio  $R = (A - N) \times 40/A$ . If the approximate number  $A$  is less than  $N$ , the formula is the same as above except that  $A - N$  is replaced by  $N - A$ .

*Example:* Find the gearing ratio and indexing movement for 67 divisions.

$$\text{If } A = 70, \text{ gearing ratio} = (70 - 67) \times \frac{40}{70} = \frac{12}{7} = \frac{\text{gear on spindle (driver)}}{\text{gear on worm (driven)}}$$

The fraction  $12/7$  is raised to obtain a numerator and a denominator to match gears that are available. For example,  $12/7 = 48/28$ .

Various combinations of gearing and index circles are possible for a given number of divisions. The index numbers and gear combinations in the accompanying [Tables 4a](#) and [4b](#) apply to a given series of index circles and gear-tooth numbers. The approximate number  $A$  on which any combination is based may be determined by dividing 40 by the fraction representing the indexing movement. For example, the approximate number used for 109 divisions equals  $40 \div 6/16$ , or  $40 \times 16/6 = 106\frac{2}{3}$ . If this approximate number is inserted in the preceding formula, it will be found that the gear ratio is  $7/8$ , as shown in the table.

*Second Method of Determining Gear Ratio:* In illustrating a somewhat different method of obtaining the gear ratio, 67 divisions will again be used. If 70 is selected as the approximate number, then  $40/70 = 4/7$  or  $12/21$  turn of the index crank will be required. If the crank is indexed four-sevenths of a turn, sixty-seven times, it will make  $4/7 \times 67 = 38\frac{2}{7}$  revolutions. This number is  $1\frac{5}{7}$  turns less than the 40 required for one revolution of the work (indicating that the gearing should be arranged to rotate the index plate in the same direction as the index crank to increase the indexing movement). Hence the gear ratio  $1\frac{5}{7} = 12/7$ .

**To Find the Indexing Movement.**—The indexing movement is represented by the fraction  $40/A$ . For example, if 70 is the approximate number  $A$  used in calculating the gear ratio for 67 divisions, then, to find the required movement of the index crank, reduce  $40/70$  to any fraction of equal value and having as denominator any number equal to the number of holes available in an index circle.

$$\text{To illustrate, } \frac{40}{70} = \frac{4}{7} = \frac{12}{21} = \frac{\text{number of holes indexed}}{\text{number of holes in index circle}}$$

**Use of Idler Gears.**—In differential indexing, idler gears are used to rotate the index plate in the same direction as the index crank, thus *increasing* the resulting indexing movement, or to rotate the index plate in the opposite direction, thus *reducing* the resulting indexing movement.

*Example 1:* If the approximate number  $A$  is *greater* than the required number of divisions  $N$ , simple gearing will require one idler, and compound gearing, no idler. Index plate and crank rotate in the same direction.

*Example 2:* If the approximate number  $A$  is *less* than the required number of divisions  $N$ , simple gearing requires two idlers, and compound gearing, one idler. Index plate and crank rotate in opposite directions.

**When Compound Gearing Is Required.**—It is sometimes necessary, as shown in the table, to use a train of four gears to obtain the required ratio with the gear-tooth numbers that are available.

*Example:* Find the gear combination and indexing movement for 99 divisions, assuming that an approximate number  $A$  of 100 is used.

$$\text{Ratio} = (100 - 99) \times \frac{40}{100} = \frac{4}{10} = \frac{4 \times 1}{5 \times 2} = \frac{32}{40} \times \frac{28}{56}$$

The final numbers here represent available gear sizes. The gears having 32 and 28 teeth are the drivers (gear on spindle and first gear on stud), and gears having 40 and 56 teeth are

driven (second gear on stud and gear on wormshaft). The indexing movement is represented by the fraction  $\frac{40}{100}$ , which is reduced to  $\frac{2}{25}$ , the 20-hole index circle being used here.

*Example:* Determine the gear combination to use for indexing 53 divisions. If 56 is used as an approximate number (possibly after one or more trial solutions to find an approximate number and resulting gear ratio coinciding with available gears):

$$\text{Gearing ratio} = (56 - 53) \times \frac{40}{56} = \frac{15}{7} = \frac{3 \times 5}{1 \times 7} = \frac{72 \times 40}{24 \times 56}$$

The tooth numbers above the line here represent *gear on spindle and first gear on stud*. The tooth numbers below the line represent *second gear on stud and gear on wormshaft*.

$$\text{Indexing movement} = \frac{40}{56} = \frac{5}{7} = \frac{5 \times 7}{7 \times 7} = \frac{35 \text{ holes}}{49\text{-hole circle}}$$

**To Check the Number of Divisions Obtained with a Given Gear Ratio and Index Movement.**—Invert the fraction representing the indexing movement. Let  $C$  = this inverted fraction and  $R$  = gearing ratio.

*Example 1:* If simple gearing with one idler, or compound gearing with no idler, is used: number of divisions  $N = 40C - RC$ .

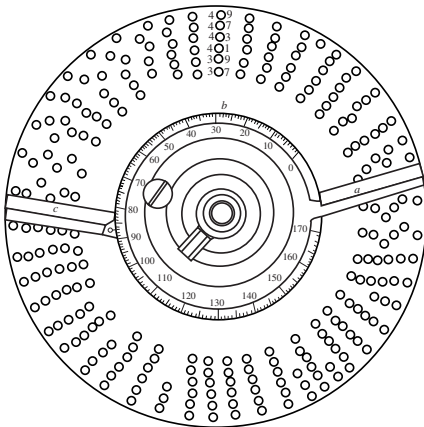
For instance, if the gear ratio is  $\frac{12}{7}$ , there is simple gearing and one idler, and the indexing movement is  $\frac{12}{21}$ , making the inverted fraction  $C$ ,  $\frac{21}{12}$ ; find the number of divisions  $N$ .

$$N = \left(40 \times \frac{21}{12}\right) - \left(\frac{12}{7} \times \frac{21}{12}\right) = 70 - \frac{21}{7} = 67$$

*Example 2:* If simple gearing with two idlers, or compound gearing with one idler, is used: number of divisions  $N = 40C + RC$ .

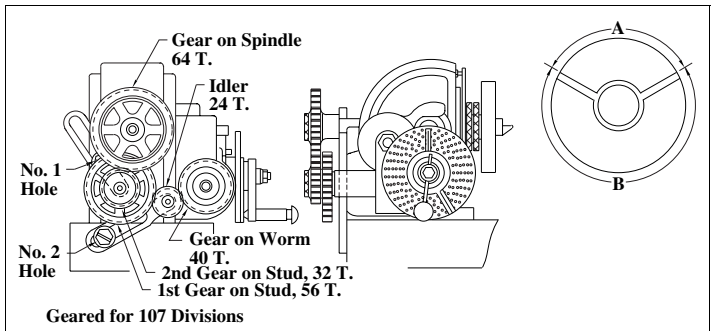
For instance, if the gear ratio is  $\frac{7}{8}$ , two idlers are used with simple gearing, and the indexing movement is 6 holes in the 16-hole circle, then number of divisions:

$$N = \left(40 \times \frac{16}{6}\right) + \left(\frac{7}{8} \times \frac{16}{6}\right) = 109$$



Sector Graduations

**Table 4a. Simple and Differential Indexing with Browne & Sharpe Indexing Plates**



| No. of Div. | Index Circle | No. of Turns of Crank | Graduation on Sector | No. of Div. | Index Circle | No. of Turns of Crank | Graduation on Sector | Gear on Worm  | No. 1 Hole         |                     | Gear on Spindle | Idlers     |            |
|-------------|--------------|-----------------------|----------------------|-------------|--------------|-----------------------|----------------------|---|--------------------|---------------------|-----------------|------------|------------|
|             |              |                       |                      |             |              |                       |                      |   | First Gear on Stud | Second Gear on Stud |                 | No. 1 Hole | No. 2 Hole |
| 2           | Any          | 20                    | ...                  | 33          | 33           | 1 7/33                | 41                   | <p><i>Note:</i> The data in columns labeled Graduation on Sector refer to a graduated dial that accompanies the sector arms on some dividing heads, page 2010. The graduated sector ring eliminates the requirement of counting holes and thereby lessens the possibility of error. Graduations in table indicate setting for sector arms when index crank moves through arc A, except figures marked *, when crank moves through arc B.</p> <p><b>Differential Indexing</b><br/>                     Certain divisions such as 51, 53, 57, etc., require the use of differential indexing. In differential indexing, change gears are used to transmit motion from the main spindle of the dividing head to the index plate, which turns (either in the same direction as the index plate or in the opposite direction) whatever amount is required to obtain the correct indexing movement.</p> <p>The numbers in the columns below represent numbers of teeth for the change gears necessary to give the divisions required. Where no numbers are shown simple indexing, which does not require change gears, is used.</p> |                    |                     |                 |            |            |
| 3           | 39           | 13 13/39              | 65                   | 34          | 17           | 1 3/17                | 33                   |   |                    |                     |                 |            |            |
| 4           | Any          | 10                    | ...                  | 35          | 49           | 1 7/49                | 26                   |   |                    |                     |                 |            |            |
| 5           | Any          | 8                     | ...                  | 36          | 27           | 1 3/27                | 21                   |   |                    |                     |                 |            |            |
| 6           | 39           | 6 2/39                | 132                  | 37          | 37           | 1 3/37                | 15                   |   |                    |                     |                 |            |            |
| 7           | 49           | 5 5/49                | 140                  | 38          | 19           | 1 1/19                | 9                    |   |                    |                     |                 |            |            |
| 8           | Any          | 5                     | ...                  | 39          | 39           | 1 1/39                | 3                    |   |                    |                     |                 |            |            |
| 9           | 27           | 4 1/27                | 88                   | 40          | Any          | 1                     | ...                  |   |                    |                     |                 |            |            |
| 10          | Any          | 4                     | ...                  | 41          | 41           | 40/41                 | 3*                   |   |                    |                     |                 |            |            |
| 11          | 33           | 3 21/33               | 126                  | 42          | 21           | 20/21                 | 9*                   |   |                    |                     |                 |            |            |
| 12          | 39           | 3 13/39               | 65                   | 43          | 43           | 40/43                 | 12*                  |   |                    |                     |                 |            |            |
| 13          | 39           | 3 3/39                | 14                   | 44          | 33           | 30/33                 | 17*                  |   |                    |                     |                 |            |            |
| 14          | 49           | 2 4/49                | 169                  | 45          | 27           | 24/27                 | 21*                  |   |                    |                     |                 |            |            |
| 15          | 39           | 2 2/39                | 132                  | 46          | 23           | 20/23                 | 172                  |   |                    |                     |                 |            |            |
| 16          | 20           | 2 10/20               | 98                   | 47          | 47           | 40/47                 | 168                  |   |                    |                     |                 |            |            |
| 17          | 17           | 2 9/17                | 69                   | 48          | 18           | 15/18                 | 165                  |   |                    |                     |                 |            |            |
| 18          | 27           | 2 6/27                | 43                   | 49          | 49           | 40/49                 | 161                  |   |                    |                     |                 |            |            |
| 19          | 19           | 2 19/19               | 19                   | 50          | 20           | 16/20                 | 158                  |   |                    |                     |                 |            |            |
| 20          | Any          | 2                     | ...                  | 51          | 17           | 14/17                 | 33*                  |   |                    |                     |                 |            |            |
| 21          | 21           | 1 19/21               | 18*                  | 52          | 39           | 30/39                 | 152                  |   |                    |                     |                 |            |            |
| 22          | 33           | 1 27/33               | 161                  | 53          | 49           | 35/49                 | 140                  |   |                    |                     |                 |            |            |
| 23          | 23           | 1 17/23               | 147                  | 54          | 27           | 20/27                 | 147                  |   |                    |                     |                 |            |            |
| 24          | 39           | 1 30/39               | 132                  | 55          | 33           | 24/33                 | 144                  |   |                    |                     |                 |            |            |
| 25          | 20           | 1 12/20               | 118                  | 56          | 49           | 35/49                 | 140                  |   |                    |                     |                 |            |            |
| 26          | 39           | 1 29/39               | 106                  | 57          | 21           | 15/21                 | 142                  |   |                    |                     |                 |            |            |
| 27          | 27           | 1 13/27               | 95                   | 58          | 29           | 20/29                 | 136                  |   |                    |                     |                 |            |            |
| 28          | 49           | 1 21/49               | 83                   | 59          | 39           | 26/39                 | 132                  |   |                    |                     |                 |            |            |
| 29          | 29           | 1 11/29               | 75                   | 60          | 39           | 26/39                 | 132                  |   |                    |                     |                 |            |            |
| 30          | 39           | 1 13/39               | 65                   | 61          | 39           | 26/39                 | 132                  |   |                    |                     |                 |            |            |
| 31          | 31           | 1 9/31                | 56                   | 62          | 31           | 20/31                 | 127                  |   |                    |                     |                 |            |            |
| 32          | 20           | 1 3/20                | 48                   | 63          | 39           | 26/39                 | 132                  |   |                    |                     |                 |            |            |
|             |              |                       |                      |             |              |                       |                      | <b>Differential Gears</b>   |                    |                     |                 |            |            |
|             |              |                       |                      |             |              |                       |                      | 24  | ...                | ...                 | 48              | 24         | 44         |
|             |              |                       |                      |             |              |                       |                      | ...   | ...                | ...                 | ...             | ...        | ...        |
|             |              |                       |                      |             |              |                       |                      | 56  | 40                 | 24                  | 72              | ...        | ...        |
|             |              |                       |                      |             |              |                       |                      | ...   | ...                | ...                 | ...             | ...        | ...        |
|             |              |                       |                      |             |              |                       |                      | ...   | ...                | ...                 | ...             | ...        | ...        |
|             |              |                       |                      |             |              |                       |                      | 56  | ...                | ...                 | 40              | 24         | 44         |
|             |              |                       |                      |             |              |                       |                      | ...   | ...                | ...                 | ...             | ...        | ...        |
|             |              |                       |                      |             |              |                       |                      | 48  | ...                | ...                 | 32              | 44         | ...        |
|             |              |                       |                      |             |              |                       |                      | ...   | ...                | ...                 | ...             | ...        | ...        |
|             |              |                       |                      |             |              |                       |                      | 48  | ...                | ...                 | 32              | 24         | 44         |
|             |              |                       |                      |             |              |                       |                      | ...   | ...                | ...                 | ...             | ...        | ...        |
|             |              |                       |                      |             |              |                       |                      | 24  | ...                | ...                 | 48              | 24         | 44         |



**Table 4b. Simple and Differential Indexing  
Browne & Sharpe Indexing Plates**

| No. of Divisions | Index Circle | No. of Turns of Crank | Graduation on Sector <sup>a</sup> | Gear on Worm | No. 1 Hole         |                     | Gear on Spindle | Idlers     |                         |
|------------------|--------------|-----------------------|-----------------------------------|--------------|--------------------|---------------------|-----------------|------------|-------------------------|
|                  |              |                       |                                   |              | First Gear on Stud | Second Gear on Stud |                 | No. 1 Hole | No. 2 Hole <sup>b</sup> |
|                  |              |                       |                                   |              |                    |                     |                 |            |                         |
| 64               | 16           | 10/16                 | 123                               | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 65               | 39           | 24/39                 | 121                               | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 66               | 33           | 20/33                 | 120                               | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 67               | 21           | 12/21                 | 113                               | 28           | ...                | ...                 | 48              | 44         | ...                     |
| 68               | 17           | 10/17                 | 116                               | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 69               | 20           | 12/20                 | 118                               | 40           | ...                | ...                 | 56              | 24         | 44                      |
| 70               | 49           | 28/49                 | 112                               | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 71               | 18           | 10/18                 | 109                               | 72           | ...                | ...                 | 40              | 24         | ...                     |
| 72               | 27           | 15/27                 | 110                               | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 73               | 21           | 12/21                 | 113                               | 28           | ...                | ...                 | 48              | 24         | 44                      |
| 74               | 37           | 20/37                 | 107                               | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 75               | 15           | 8/15                  | 105                               | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 76               | 19           | 10/19                 | 103                               | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 77               | 20           | 10/20                 | 98                                | 32           | ...                | ...                 | 48              | 44         | ...                     |
| 78               | 39           | 20/39                 | 101                               | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 79               | 20           | 10/20                 | 98                                | 48           | ...                | ...                 | 24              | 44         | ...                     |
| 80               | 20           | 10/20                 | 98                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 81               | 20           | 10/20                 | 98                                | 48           | ...                | ...                 | 24              | 24         | 44                      |
| 82               | 41           | 20/41                 | 96                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 83               | 20           | 10/20                 | 98                                | 32           | ...                | ...                 | 48              | 24         | 44                      |
| 84               | 21           | 10/21                 | 94                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 85               | 17           | 8/17                  | 92                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 86               | 43           | 20/48                 | 91                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 87               | 15           | 7/15                  | 92                                | 40           | ...                | ...                 | 24              | 24         | 44                      |
| 88               | 33           | 15/33                 | 89                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 89               | 18           | 8/18                  | 87                                | 72           | ...                | ...                 | 32              | 44         | ...                     |
| 90               | 27           | 12/27                 | 88                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 91               | 39           | 18/39                 | 91                                | 24           | ...                | ...                 | 48              | 24         | 44                      |
| 92               | 23           | 10/23                 | 86                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 93               | 18           | 8/18                  | 87                                | 24           | ...                | ...                 | 32              | 24         | 44                      |
| 94               | 47           | 20/47                 | 83                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 95               | 19           | 8/19                  | 82                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 96               | 21           | 9/21                  | 85                                | 28           | ...                | ...                 | 32              | 24         | 44                      |
| 97               | 20           | 8/20                  | 78                                | 40           | ...                | ...                 | 48              | 44         | ...                     |
| 98               | 49           | 20/49                 | 79                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 99               | 20           | 8/20                  | 78                                | 56           | 28                 | 40                  | 32              | ...        | ...                     |
| 100              | 20           | 8/20                  | 78                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 101              | 20           | 8/20                  | 78                                | 72           | 24                 | 40                  | 48              | ...        | 24                      |
| 102              | 20           | 8/20                  | 78                                | 40           | ...                | ...                 | 32              | 24         | 44                      |
| 103              | 20           | 8/20                  | 78                                | 40           | ...                | ...                 | 48              | 24         | 44                      |
| 104              | 39           | 15/39                 | 75                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 105              | 21           | 8/21                  | 75                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 106              | 43           | 16/43                 | 73                                | 86           | 24                 | 24                  | 48              | ...        | ...                     |
| 107              | 20           | 8/20                  | 78                                | 40           | 56                 | 32                  | 64              | ...        | 24                      |
| 108              | 27           | 10/27                 | 73                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 109              | 16           | 6/16                  | 73                                | 32           | ...                | ...                 | 28              | 24         | 44                      |
| 110              | 33           | 12/33                 | 71                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 111              | 39           | 13/39                 | 65                                | 24           | ...                | ...                 | 72              | 32         | ...                     |
| 112              | 39           | 13/39                 | 65                                | 24           | ...                | ...                 | 64              | 44         | ...                     |
| 113              | 39           | 13/39                 | 65                                | 24           | ...                | ...                 | 56              | 44         | ...                     |
| 114              | 39           | 13/39                 | 65                                | 24           | ...                | ...                 | 48              | 44         | ...                     |
| 115              | 23           | 8/23                  | 68                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 116              | 29           | 10/29                 | 68                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 117              | 39           | 13/39                 | 65                                | 24           | ...                | ...                 | 24              | 56         | ...                     |
| 118              | 39           | 13/39                 | 65                                | 48           | ...                | ...                 | 32              | 44         | ...                     |
| 119              | 39           | 13/39                 | 65                                | 72           | ...                | ...                 | 24              | 44         | ...                     |
| 120              | 39           | 13/39                 | 65                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 121              | 39           | 13/39                 | 65                                | 72           | ...                | ...                 | 24              | 24         | 44                      |
| 122              | 39           | 13/39                 | 65                                | 48           | ...                | ...                 | 32              | 24         | 44                      |
| 123              | 39           | 13/39                 | 65                                | 24           | ...                | ...                 | 24              | 24         | 44                      |
| 124              | 31           | 10/31                 | 63                                | ...          | ...                | ...                 | ...             | ...        | ...                     |

**Table 4b. (Continued) Simple and Differential Indexing  
Browne & Sharpe Indexing Plates**

| No. of Divisions | Index Circle | No. of Turns of Crank | Graduation on Sector <sup>a</sup> | Gear on Worm | No. 1 Hole         |                     | Gear on Spindle | Idlers     |                         |
|------------------|--------------|-----------------------|-----------------------------------|--------------|--------------------|---------------------|-----------------|------------|-------------------------|
|                  |              |                       |                                   |              | First Gear on Stud | Second Gear on Stud |                 | No. 1 Hole | No. 2 Hole <sup>b</sup> |
|                  |              |                       |                                   |              |                    |                     |                 |            |                         |
| 126              | 39           | 13/39                 | 65                                | 24           | ...                | ...                 | 48              | 24         | 44                      |
| 127              | 39           | 13/39                 | 65                                | 24           | ...                | ...                 | 56              | 24         | 44                      |
| 128              | 16           | 5/16                  | 61                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 129              | 39           | 13/39                 | 65                                | 24           | ...                | ...                 | 72              | 24         | 44                      |
| 130              | 39           | 12/39                 | 60                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 131              | 20           | 6/20                  | 58                                | 40           | ...                | ...                 | 28              | 44         | ...                     |
| 132              | 33           | 10/33                 | 59                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 133              | 21           | 6/21                  | 56                                | 24           | ...                | ...                 | 48              | 44         | ...                     |
| 134              | 21           | 6/21                  | 56                                | 28           | ...                | ...                 | 48              | 44         | ...                     |
| 135              | 27           | 8/27                  | 58                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 136              | 17           | 5/17                  | 57                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 137              | 21           | 6/21                  | 56                                | 28           | ...                | ...                 | 24              | 56         | ...                     |
| 138              | 21           | 6/21                  | 56                                | 56           | ...                | ...                 | 32              | 44         | ...                     |
| 139              | 21           | 6/21                  | 56                                | 56           | 32                 | 48                  | 24              | ...        | ...                     |
| 140              | 49           | 14/49                 | 55                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 141              | 18           | 5/18                  | 54                                | 48           | ...                | ...                 | 40              | 44         | ...                     |
| 142              | 21           | 6/21                  | 56                                | 56           | ...                | ...                 | 32              | 24         | 44                      |
| 143              | 21           | 6/21                  | 56                                | 28           | ...                | ...                 | 24              | 24         | 44                      |
| 144              | 18           | 5/18                  | 54                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 145              | 29           | 8/29                  | 54                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 146              | 21           | 6/21                  | 56                                | 28           | ...                | ...                 | 48              | 24         | 44                      |
| 147              | 21           | 6/21                  | 56                                | 24           | ...                | ...                 | 48              | 24         | 44                      |
| 148              | 37           | 10/37                 | 53                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 149              | 21           | 6/21                  | 56                                | 28           | ...                | ...                 | 72              | 24         | 44                      |
| 150              | 15           | 4/15                  | 52                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 151              | 20           | 5/20                  | 48                                | 32           | ...                | ...                 | 72              | 44         | ...                     |
| 152              | 19           | 5/19                  | 51                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 153              | 20           | 5/20                  | 48                                | 32           | ...                | ...                 | 56              | 44         | ...                     |
| 154              | 20           | 5/20                  | 48                                | 32           | ...                | ...                 | 48              | 44         | ...                     |
| 155              | 31           | 8/31                  | 50                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 156              | 39           | 10/39                 | 50                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 157              | 20           | 5/20                  | 48                                | 32           | ...                | ...                 | 24              | 56         | ...                     |
| 158              | 20           | 5/20                  | 48                                | 48           | ...                | ...                 | 24              | 44         | ...                     |
| 159              | 20           | 5/20                  | 48                                | 64           | 32                 | 56                  | 28              | ...        | ...                     |
| 160              | 20           | 5/20                  | 48                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 161              | 20           | 5/20                  | 48                                | 64           | 32                 | 56                  | 28              | ...        | 24                      |
| 162              | 20           | 5/20                  | 48                                | 48           | ...                | ...                 | 24              | 24         | 44                      |
| 163              | 20           | 5/20                  | 48                                | 32           | ...                | ...                 | 24              | 24         | 44                      |
| 164              | 41           | 10/41                 | 47                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 165              | 33           | 8/33                  | 47                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 166              | 20           | 5/20                  | 48                                | 32           | ...                | ...                 | 48              | 24         | 44                      |
| 167              | 20           | 5/20                  | 48                                | 32           | ...                | ...                 | 56              | 24         | 44                      |
| 168              | 21           | 5/21                  | 47                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 169              | 20           | 5/20                  | 48                                | 32           | ...                | ...                 | 72              | 24         | 44                      |
| 170              | 17           | 4/17                  | 45                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 171              | 21           | 5/21                  | 47                                | 56           | ...                | ...                 | 40              | 24         | 44                      |
| 172              | 43           | 10/43                 | 44                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 173              | 18           | 4/18                  | 43                                | 72           | 56                 | 32                  | 64              | ...        | ...                     |
| 174              | 18           | 4/18                  | 43                                | 24           | ...                | ...                 | 32              | 56         | ...                     |
| 175              | 18           | 4/18                  | 43                                | 72           | 40                 | 32                  | 64              | ...        | ...                     |
| 176              | 18           | 4/18                  | 43                                | 72           | 24                 | 24                  | 64              | ...        | ...                     |
| 177              | 18           | 4/18                  | 43                                | 72           | ...                | ...                 | 48              | 24         | ...                     |
| 178              | 18           | 4/18                  | 43                                | 72           | ...                | ...                 | 32              | 44         | ...                     |
| 179              | 18           | 4/18                  | 43                                | 72           | 24                 | 48                  | 32              | ...        | ...                     |
| 180              | 18           | 4/18                  | 43                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 181              | 18           | 4/18                  | 43                                | 72           | 24                 | 48                  | 32              | ...        | 24                      |
| 182              | 18           | 4/18                  | 43                                | 72           | ...                | ...                 | 32              | 24         | 44                      |
| 183              | 18           | 4/18                  | 43                                | 48           | ...                | ...                 | 32              | 24         | 44                      |
| 184              | 23           | 5/23                  | 42                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 185              | 37           | 8/37                  | 42                                | ...          | ...                | ...                 | ...             | ...        | ...                     |

**Table 4b. (Continued) Simple and Differential Indexing  
Browne & Sharpe Indexing Plates**

| No. of Divisions | Index Circle | No. of Turns of Crank | Graduation on Sector <sup>a</sup> | Gear on Worm | No. 1 Hole         |                     | Gear on Spindle | Idlers     |                         |
|------------------|--------------|-----------------------|-----------------------------------|--------------|--------------------|---------------------|-----------------|------------|-------------------------|
|                  |              |                       |                                   |              | First Gear on Stud | Second Gear on Stud |                 | No. 1 Hole | No. 2 Hole <sup>b</sup> |
| 186              | 18           | 4/18                  | 43                                | 48           | ...                | ...                 | 64              | 24         | 44                      |
| 187              | 18           | 4/18                  | 43                                | 72           | 48                 | 24                  | 56              | ...        | 24                      |
| 188              | 47           | 10/47                 | 40                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 189              | 18           | 4/18                  | 43                                | 32           | ...                | ...                 | 64              | 24         | 44                      |
| 190              | 19           | 4/19                  | 40                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 191              | 20           | 4/20                  | 38                                | 40           | ...                | ...                 | 72              | 24         | ...                     |
| 192              | 20           | 4/20                  | 38                                | 40           | ...                | ...                 | 64              | 44         | ...                     |
| 193              | 20           | 4/20                  | 38                                | 40           | ...                | ...                 | 56              | 44         | ...                     |
| 194              | 20           | 4/20                  | 38                                | 40           | ...                | ...                 | 48              | 44         | ...                     |
| 195              | 39           | 8/39                  | 39                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 196              | 49           | 10/49                 | 38                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 197              | 20           | 4/20                  | 38                                | 40           | ...                | ...                 | 24              | 56         | ...                     |
| 198              | 20           | 4/20                  | 38                                | 56           | 28                 | 40                  | 32              | ...        | ...                     |
| 199              | 20           | 4/20                  | 38                                | 100          | 40                 | 64                  | 32              | ...        | ...                     |
| 200              | 20           | 4/20                  | 38                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 201              | 20           | 4/20                  | 38                                | 72           | 24                 | 40                  | 24              | ...        | 24                      |
| 202              | 20           | 4/20                  | 38                                | 72           | 24                 | 40                  | 48              | ...        | 24                      |
| 203              | 20           | 4/20                  | 38                                | 40           | ...                | ...                 | 24              | 24         | 44                      |
| 204              | 20           | 4/20                  | 38                                | 40           | ...                | ...                 | 32              | 24         | 44                      |
| 204              | 20           | 4/20                  | 38                                | 40           | ...                | ...                 | 32              | 24         | 44                      |
| 205              | 41           | 8/41                  | 37                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 206              | 20           | 4/20                  | 38                                | 40           | ...                | ...                 | 48              | 24         | 44                      |
| 207              | 20           | 4/20                  | 38                                | 40           | ...                | ...                 | 56              | 24         | 44                      |
| 208              | 20           | 4/20                  | 38                                | 40           | ...                | ...                 | 64              | 24         | 44                      |
| 209              | 20           | 4/20                  | 38                                | 40           | ...                | ...                 | 72              | 24         | 44                      |
| 210              | 21           | 4/21                  | 37                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 211              | 16           | 3/16                  | 36                                | 64           | ...                | ...                 | 28              | 44         | ...                     |
| 212              | 43           | 8/43                  | 35                                | 86           | 24                 | 24                  | 48              | ...        | ...                     |
| 213              | 27           | 5/27                  | 36                                | 72           | ...                | ...                 | 40              | 44         | ...                     |
| 214              | 20           | 4/20                  | 38                                | 40           | 56                 | 32                  | 64              | ...        | 24                      |
| 215              | 43           | 8/43                  | 35                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 216              | 27           | 5/27                  | 36                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 217              | 21           | 4/21                  | 37                                | 48           | ...                | ...                 | 64              | 24         | 44                      |
| 218              | 16           | 3/16                  | 36                                | 64           | ...                | ...                 | 56              | 24         | 44                      |
| 219              | 21           | 4/21                  | 37                                | 28           | ...                | ...                 | 48              | 24         | 44                      |
| 220              | 33           | 6/33                  | 35                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 221              | 17           | 3/17                  | 33                                | 24           | ...                | ...                 | 24              | 56         | ...                     |
| 222              | 18           | 3/18                  | 32                                | 24           | ...                | ...                 | 72              | 44         | ...                     |
| 223              | 43           | 8/43                  | 35                                | 86           | 8                  | 24                  | 64              | ...        | 24                      |
| 224              | 18           | 3/18                  | 32                                | 24           | ...                | ...                 | 64              | 44         | ...                     |
| 225              | 27           | 5/27                  | 36                                | 24           | ...                | ...                 | 40              | 24         | 44                      |
| 226              | 18           | 3/18                  | 32                                | 24           | ...                | ...                 | 56              | 44         | ...                     |
| 227              | 49           | 8/49                  | 30                                | 56           | 64                 | 28                  | 72              | ...        | ...                     |
| 228              | 18           | 3/18                  | 32                                | 24           | ...                | ...                 | 48              | 44         | ...                     |
| 229              | 18           | 3/18                  | 32                                | 24           | ...                | ...                 | 44              | 48         | ...                     |
| 230              | 23           | 4/23                  | 34                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 231              | 18           | 3/18                  | 32                                | 32           | ...                | ...                 | 48              | 44         | ...                     |
| 232              | 29           | 5/29                  | 33                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 233              | 18           | 3/18                  | 32                                | 48           | ...                | ...                 | 56              | 44         | ...                     |
| 234              | 18           | 3/18                  | 32                                | 24           | ...                | ...                 | 24              | 56         | ...                     |
| 235              | 47           | 8/47                  | 32                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 236              | 18           | 3/18                  | 32                                | 48           | ...                | ...                 | 32              | 44         | ...                     |
| 237              | 18           | 3/18                  | 32                                | 48           | ...                | ...                 | 24              | 44         | ...                     |
| 238              | 18           | 3/18                  | 32                                | 72           | ...                | ...                 | 24              | 44         | ...                     |
| 239              | 18           | 3/18                  | 32                                | 72           | 24                 | 64                  | 32              | ...        | ...                     |
| 240              | 18           | 3/18                  | 32                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 241              | 18           | 3/18                  | 32                                | 72           | 24                 | 64                  | 32              | ...        | 24                      |
| 242              | 18           | 3/18                  | 32                                | 72           | ...                | ...                 | 24              | 24         | 44                      |
| 243              | 18           | 3/18                  | 32                                | 64           | ...                | ...                 | 32              | 24         | 44                      |
| 244              | 18           | 3/18                  | 32                                | 48           | ...                | ...                 | 32              | 24         | 44                      |
| 245              | 49           | 8/49                  | 30                                | ...          | ...                | ...                 | ...             | ...        | ...                     |

**Table 4b. (Continued) Simple and Differential Indexing  
Browne & Sharpe Indexing Plates**

| No. of Divisions | Index Circle | No. of Turns of Crank | Graduation on Sector <sup>a</sup> | Gear on Worm | No. 1 Hole         |                     | Gear on Spindle | Idlers     |                         |
|------------------|--------------|-----------------------|-----------------------------------|--------------|--------------------|---------------------|-----------------|------------|-------------------------|
|                  |              |                       |                                   |              | First Gear on Stud | Second Gear on Stud |                 | No. 1 Hole | No. 2 Hole <sup>b</sup> |
| 246              | 18           | 3/18                  | 32                                | 24           | ...                | ...                 | 24              | 24         | 44                      |
| 247              | 18           | 3/18                  | 32                                | 48           | ...                | ...                 | 56              | 24         | 44                      |
| 248              | 31           | 5/31                  | 31                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 249              | 18           | 3/18                  | 32                                | 32           | ...                | ...                 | 48              | 24         | 44                      |
| 250              | 18           | 3/18                  | 32                                | 24           | ...                | ...                 | 40              | 24         | 44                      |
| 251              | 18           | 3/18                  | 32                                | 48           | 44                 | 32                  | 64              | ...        | 24                      |
| 252              | 18           | 3/18                  | 32                                | 24           | ...                | ...                 | 48              | 24         | 44                      |
| 253              | 33           | 5/33                  | 29                                | 24           | ...                | ...                 | 40              | 56         | ...                     |
| 254              | 18           | 3/18                  | 32                                | 24           | ...                | ...                 | 56              | 24         | 44                      |
| 255              | 18           | 3/18                  | 32                                | 48           | 40                 | 24                  | 72              | ...        | 24                      |
| 256              | 18           | 3/18                  | 32                                | 24           | ...                | ...                 | 64              | 24         | 44                      |
| 257              | 49           | 8/49                  | 30                                | 56           | 48                 | 28                  | 64              | ...        | 24                      |
| 258              | 43           | 7/43                  | 31                                | 32           | ...                | ...                 | 64              | 24         | 44                      |
| 259              | 21           | 3/21                  | 28                                | 24           | ...                | ...                 | 72              | 44         | ...                     |
| 260              | 39           | 6/39                  | 29                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 261              | 29           | 4/29                  | 26                                | 48           | 64                 | 24                  | 72              | ...        | ...                     |
| 262              | 20           | 3/20                  | 28                                | 40           | ...                | ...                 | 28              | 44         | ...                     |
| 263              | 49           | 8/49                  | 30                                | 56           | 64                 | 28                  | 72              | ...        | 24                      |
| 264              | 33           | 5/33                  | 29                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 265              | 21           | 3/21                  | 28                                | 56           | 40                 | 24                  | 72              | ...        | ...                     |
| 266              | 21           | 3/21                  | 28                                | 32           | ...                | ...                 | 64              | 44         | ...                     |
| 267              | 27           | 4/27                  | 28                                | 72           | ...                | ...                 | 32              | 44         | ...                     |
| 268              | 21           | 3/21                  | 28                                | 28           | ...                | ...                 | 48              | 44         | ...                     |
| 269              | 20           | 3/20                  | 28                                | 64           | 32                 | 40                  | 28              | ...        | 24                      |
| 270              | 27           | 4/27                  | 28                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 271              | 21           | 3/21                  | 28                                | 56           | 24                 | 24                  | 72              | ...        | ...                     |
| 272              | 21           | 3/21                  | 28                                | 56           | ...                | ...                 | 64              | 24         | ...                     |
| 273              | 21           | 3/21                  | 28                                | 24           | ...                | ...                 | 24              | 56         | ...                     |
| 274              | 21           | 3/21                  | 28                                | 56           | ...                | ...                 | 48              | 44         | ...                     |
| 275              | 21           | 3/21                  | 28                                | 56           | ...                | ...                 | 40              | 44         | ...                     |
| 276              | 21           | 3/21                  | 28                                | 56           | ...                | ...                 | 32              | 44         | ...                     |
| 277              | 21           | 3/21                  | 28                                | 56           | ...                | ...                 | 24              | 44         | ...                     |
| 278              | 21           | 3/21                  | 28                                | 56           | 32                 | 48                  | 24              | ...        | ...                     |
| 279              | 27           | 4/27                  | 28                                | 24           | ...                | ...                 | 32              | 24         | 44                      |
| 280              | 49           | 7/49                  | 26                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 281              | 21           | 3/21                  | 28                                | 72           | 24                 | 56                  | 24              | ...        | 24                      |
| 282              | 43           | 6/43                  | 26                                | 86           | 24                 | 24                  | 56              | ...        | ...                     |
| 283              | 21           | 3/21                  | 28                                | 56           | ...                | ...                 | 24              | 24         | 44                      |
| 284              | 21           | 3/21                  | 28                                | 56           | ...                | ...                 | 32              | 24         | 44                      |
| 285              | 21           | 3/21                  | 28                                | 56           | ...                | ...                 | 40              | 24         | 44                      |
| 286              | 21           | 3/21                  | 28                                | 56           | ...                | ...                 | 48              | 24         | 44                      |
| 287              | 21           | 3/21                  | 28                                | 24           | ...                | ...                 | 24              | 24         | 44                      |
| 288              | 21           | 3/21                  | 28                                | 28           | ...                | ...                 | 32              | 24         | 44                      |
| 289              | 21           | 3/21                  | 28                                | 56           | 24                 | 24                  | 72              | ...        | 24                      |
| 290              | 29           | 4/29                  | 26                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 291              | 15           | 2/15                  | 25                                | 40           | ...                | ...                 | 48              | 44         | ...                     |
| 292              | 21           | 3/21                  | 28                                | 28           | ...                | ...                 | 48              | 24         | 44                      |
| 293              | 15           | 2/15                  | 25                                | 48           | 32                 | 40                  | 56              | ...        | ...                     |
| 294              | 21           | 3/21                  | 28                                | 24           | ...                | ...                 | 48              | 24         | 44                      |
| 295              | 15           | 2/15                  | 25                                | 48           | ...                | ...                 | 32              | 44         | ...                     |
| 296              | 37           | 5/37                  | 26                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 297              | 33           | 4/33                  | 23                                | 28           | 48                 | 24                  | 56              | ...        | ...                     |
| 298              | 21           | 3/21                  | 28                                | 28           | ...                | ...                 | 72              | 24         | 44                      |
| 299              | 23           | 3/23                  | 25                                | 24           | ...                | ...                 | 24              | 56         | ...                     |
| 300              | 15           | 2/15                  | 25                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 301              | 43           | 6/43                  | 26                                | 24           | ...                | ...                 | 48              | 24         | 44                      |
| 302              | 16           | 2/16                  | 24                                | 32           | ...                | ...                 | 72              | 24         | ...                     |
| 303              | 15           | 2/15                  | 25                                | 72           | 24                 | 40                  | 48              | ...        | 24                      |
| 304              | 16           | 2/16                  | 24                                | 24           | ...                | ...                 | 48              | 44         | ...                     |
| 305              | 15           | 2/15                  | 25                                | 48           | ...                | ...                 | 32              | 24         | 44                      |
| 306              | 15           | 2/15                  | 25                                | 40           | ...                | ...                 | 32              | 24         | 44                      |

**Table 4b. (Continued) Simple and Differential Indexing  
Browne & Sharpe Indexing Plates**

| No. of Divisions | Index Circle | No. of Turns of Crank | Graduation on Sector <sup>a</sup> | Gear on Worm | No. 1 Hole         |                     | Gear on Spindle | Idlers     |                         |
|------------------|--------------|-----------------------|-----------------------------------|--------------|--------------------|---------------------|-----------------|------------|-------------------------|
|                  |              |                       |                                   |              | First Gear on Stud | Second Gear on Stud |                 | No. 1 Hole | No. 2 Hole <sup>b</sup> |
| 307              | 15           | 2/15                  | 25                                | 72           | 48                 | 40                  | 56              | ...        | 24                      |
| 308              | 16           | 2/16                  | 24                                | 32           | ...                | ...                 | 48              | 44         | ...                     |
| 309              | 15           | 2/15                  | 25                                | 40           | ...                | ...                 | 48              | 24         | 44                      |
| 310              | 31           | 4/31                  | 24                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 311              | 16           | 2/16                  | 24                                | 64           | 24                 | 24                  | 72              | ...        | ...                     |
| 312              | 39           | 5/39                  | 24                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 313              | 16           | 2/16                  | 24                                | 32           | ...                | ...                 | 28              | 56         | ...                     |
| 314              | 16           | 2/16                  | 24                                | 32           | ...                | ...                 | 24              | 56         | ...                     |
| 315              | 16           | 2/16                  | 24                                | 64           | ...                | ...                 | 40              | 24         | ...                     |
| 316              | 16           | 2/16                  | 24                                | 64           | ...                | ...                 | 32              | 44         | ...                     |
| 317              | 16           | 2/16                  | 24                                | 64           | ...                | ...                 | 24              | 44         | ...                     |
| 318              | 16           | 2/16                  | 24                                | 56           | 28                 | 48                  | 24              | ...        | ...                     |
| 319              | 29           | 4/29                  | 26                                | 48           | 64                 | 24                  | 72              | ...        | 24                      |
| 320              | 16           | 2/16                  | 24                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 321              | 16           | 2/16                  | 24                                | 72           | 24                 | 64                  | 24              | ...        | 24                      |
| 322              | 23           | 3/23                  | 25                                | 32           | ...                | ...                 | 64              | 24         | 44                      |
| 323              | 16           | 2/16                  | 24                                | 64           | ...                | ...                 | 24              | 24         | 44                      |
| 324              | 16           | 2/16                  | 24                                | 64           | ...                | ...                 | 32              | 24         | 44                      |
| 325              | 16           | 2/16                  | 24                                | 64           | ...                | ...                 | 40              | 24         | 44                      |
| 326              | 16           | 2/16                  | 24                                | 32           | ...                | ...                 | 24              | 24         | 44                      |
| 327              | 16           | 2/16                  | 24                                | 32           | ...                | ...                 | 28              | 24         | 44                      |
| 328              | 41           | 5/41                  | 23                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 329              | 16           | 2/16                  | 24                                | 64           | 24                 | 24                  | 72              | ...        | 24                      |
| 330              | 33           | 4/33                  | 23                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 331              | 16           | 2/16                  | 24                                | 64           | 44                 | 24                  | 48              | ...        | 24                      |
| 332              | 16           | 2/16                  | 24                                | 32           | ...                | ...                 | 48              | 24         | 44                      |
| 333              | 18           | 2/18                  | 21                                | 24           | ...                | ...                 | 72              | 44         | ...                     |
| 334              | 16           | 2/16                  | 24                                | 32           | ...                | ...                 | 56              | 24         | 44                      |
| 335              | 33           | 4/33                  | 23                                | 72           | 48                 | 44                  | 40              | ...        | 24                      |
| 336              | 16           | 2/16                  | 24                                | 32           | ...                | ...                 | 64              | 24         | 44                      |
| 337              | 43           | 5/43                  | 21                                | 86           | 40                 | 32                  | 56              | ...        | ...                     |
| 338              | 16           | 2/16                  | 24                                | 32           | ...                | ...                 | 72              | 24         | 44                      |
| 339              | 18           | 2/18                  | 21                                | 24           | ...                | ...                 | 56              | 44         | ...                     |
| 340              | 17           | 2/17                  | 22                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 341              | 43           | 5/43                  | 21                                | 86           | 24                 | 32                  | 40              | ...        | ...                     |
| 342              | 18           | 2/18                  | 21                                | 32           | ...                | ...                 | 64              | 44         | ...                     |
| 343              | 15           | 2/15                  | 25                                | 40           | 64                 | 24                  | 86              | ...        | 24                      |
| 344              | 43           | 5/43                  | 21                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 345              | 18           | 2/18                  | 21                                | 24           | ...                | ...                 | 40              | 56         | ...                     |
| 346              | 18           | 2/18                  | 21                                | 72           | 56                 | 32                  | 64              | ...        | ...                     |
| 347              | 43           | 5/43                  | 21                                | 86           | 24                 | 32                  | 40              | ...        | 24                      |
| 348              | 18           | 2/18                  | 21                                | 24           | ...                | ...                 | 32              | 56         | ...                     |
| 349              | 18           | 2/18                  | 21                                | 72           | 44                 | 24                  | 48              | ...        | ...                     |
| 350              | 18           | 2/18                  | 21                                | 72           | 40                 | 32                  | 64              | ...        | ...                     |
| 351              | 18           | 2/18                  | 21                                | 24           | ...                | ...                 | 24              | 56         | ...                     |
| 352              | 18           | 2/18                  | 21                                | 72           | 24                 | 24                  | 64              | ...        | ...                     |
| 353              | 18           | 2/18                  | 21                                | 72           | 24                 | 24                  | 56              | ...        | ...                     |
| 354              | 18           | 2/18                  | 21                                | 72           | ...                | ...                 | 48              | 24         | ...                     |
| 355              | 18           | 2/18                  | 21                                | 72           | ...                | ...                 | 40              | 24         | ...                     |
| 356              | 18           | 2/18                  | 21                                | 72           | ...                | ...                 | 32              | 24         | ...                     |
| 357              | 18           | 2/18                  | 21                                | 72           | ...                | ...                 | 24              | 44         | ...                     |
| 358              | 18           | 2/18                  | 21                                | 72           | 32                 | 48                  | 24              | ...        | ...                     |
| 359              | 43           | 5/43                  | 21                                | 86           | 48                 | 32                  | 100             | ...        | 24                      |
| 360              | 18           | 2/18                  | 21                                | ...          | ...                | ...                 | ...             | ...        | ...                     |
| 361              | 19           | 2/19                  | 19                                | 32           | ...                | ...                 | 64              | 44         | ...                     |
| 362              | 18           | 2/18                  | 21                                | 72           | 28                 | 56                  | 32              | ...        | 24                      |
| 363              | 18           | 2/18                  | 21                                | 72           | ...                | ...                 | 24              | 24         | 44                      |
| 364              | 18           | 2/18                  | 21                                | 72           | ...                | ...                 | 32              | 24         | 44                      |

<sup>a</sup> See Note on page 2011.<sup>b</sup> On B & S numbers 1, 1½, and 2 machines, number 2 hole is in the machine table. On numbers 3 and 4 machines, number 2 hole is in the head.

**Table 5. Indexing Movements for Standard Index Plate Cincinnati Milling Machine**

The standard index plate indexes all numbers up to and including 60; all even numbers and those divisible by 5 up to 120; and all divisions listed below up to 400. This plate is drilled on both sides, and has holes as follows:

First side: 24, 25, 28, 30, 34, 37, 38, 39, 41, 42, 43.

Second side: 46, 47, 49, 51, 53, 54, 57, 58, 59, 62, 66.

| No. of Divisions | Index Plate Circle | No. of Turns | No. of Holes | No. of Divisions | Index Plate Circle | No. of Holes | No. of Divisions | Index Plate Circle | No. of Holes | No. of Divisions | Index Plate Circle | No. of Holes |
|------------------|--------------------|--------------|--------------|------------------|--------------------|--------------|------------------|--------------------|--------------|------------------|--------------------|--------------|
| 2                | Any                | 20           | ...          | 44               | 66                 | 60           | 104              | 39                 | 15           | 205              | 41                 | 8            |
| 3                | 24                 | 13           | 8            | 45               | 54                 | 48           | 105              | 42                 | 16           | 210              | 42                 | 8            |
| 4                | Any                | 10           | ...          | 46               | 46                 | 40           | 106              | 53                 | 20           | 212              | 53                 | 10           |
| 5                | Any                | 8            | ...          | 47               | 47                 | 40           | 108              | 54                 | 20           | 215              | 43                 | 8            |
| 6                | 24                 | 6            | 16           | 48               | 24                 | 20           | 110              | 66                 | 24           | 216              | 54                 | 10           |
| 7                | 28                 | 5            | 20           | 49               | 49                 | 40           | 112              | 28                 | 10           | 220              | 66                 | 12           |
| 8                | Any                | 5            | ...          | 50               | 25                 | 20           | 114              | 57                 | 20           | 224              | 28                 | 5            |
| 9                | 54                 | 4            | 24           | 51               | 51                 | 40           | 115              | 46                 | 16           | 228              | 57                 | 10           |
| 10               | Any                | 4            | ...          | 52               | 39                 | 30           | 116              | 58                 | 20           | 230              | 46                 | 8            |
| 11               | 66                 | 3            | 42           | 53               | 53                 | 40           | 118              | 59                 | 20           | 232              | 58                 | 10           |
| 12               | 24                 | 3            | 8            | 54               | 54                 | 40           | 120              | 66                 | 22           | 235              | 47                 | 8            |
| 13               | 39                 | 3            | 3            | 55               | 66                 | 48           | 124              | 62                 | 20           | 236              | 59                 | 10           |
| 14               | 49                 | 2            | 42           | 56               | 28                 | 20           | 125              | 25                 | 8            | 240              | 66                 | 11           |
| 15               | 24                 | 2            | 16           | 57               | 57                 | 40           | 130              | 39                 | 12           | 245              | 49                 | 8            |
| 16               | 24                 | 2            | 12           | 58               | 58                 | 40           | 132              | 66                 | 20           | 248              | 62                 | 10           |
| 17               | 34                 | 2            | 12           | 59               | 59                 | 40           | 135              | 54                 | 16           | 250              | 25                 | 4            |
| 18               | 54                 | 2            | 12           | 60               | 42                 | 28           | 136              | 34                 | 10           | 255              | 51                 | 8            |
| 19               | 38                 | 2            | 4            | 62               | 62                 | 40           | 140              | 28                 | 8            | 260              | 39                 | 6            |
| 20               | Any                | 2            | ...          | 64               | 24                 | 15           | 144              | 54                 | 15           | 264              | 66                 | 10           |
| 21               | 42                 | 1            | 38           | 65               | 39                 | 24           | 145              | 58                 | 16           | 270              | 54                 | 8            |
| 22               | 66                 | 1            | 54           | 66               | 66                 | 40           | 148              | 37                 | 10           | 272              | 34                 | 5            |
| 23               | 46                 | 1            | 34           | 68               | 34                 | 20           | 150              | 30                 | 8            | 280              | 28                 | 4            |
| 24               | 24                 | 1            | 16           | 70               | 28                 | 16           | 152              | 38                 | 10           | 290              | 58                 | 8            |
| 25               | 25                 | 1            | 15           | 72               | 54                 | 30           | 155              | 62                 | 16           | 296              | 37                 | 5            |
| 26               | 39                 | 1            | 21           | 74               | 37                 | 20           | 156              | 39                 | 10           | 300              | 30                 | 4            |
| 27               | 54                 | 1            | 26           | 75               | 30                 | 16           | 160              | 28                 | 7            | 304              | 38                 | 5            |
| 28               | 42                 | 1            | 18           | 76               | 38                 | 20           | 164              | 41                 | 10           | 310              | 62                 | 8            |
| 29               | 58                 | 1            | 22           | 78               | 39                 | 20           | 165              | 66                 | 16           | 312              | 39                 | 5            |
| 30               | 24                 | 1            | 8            | 80               | 34                 | 17           | 168              | 42                 | 10           | 320              | 24                 | 3            |
| 31               | 62                 | 1            | 18           | 82               | 41                 | 20           | 170              | 34                 | 8            | 328              | 41                 | 5            |
| 32               | 28                 | 1            | 7            | 84               | 42                 | 20           | 172              | 43                 | 10           | 330              | 66                 | 8            |
| 33               | 66                 | 1            | 14           | 85               | 34                 | 16           | 176              | 66                 | 15           | 336              | 42                 | 5            |
| 34               | 34                 | 1            | 6            | 86               | 43                 | 20           | 180              | 54                 | 12           | 340              | 34                 | 4            |
| 35               | 28                 | 1            | 4            | 88               | 66                 | 30           | 184              | 46                 | 10           | 344              | 43                 | 5            |
| 36               | 54                 | 1            | 6            | 90               | 54                 | 24           | 185              | 37                 | 8            | 360              | 54                 | 6            |
| 37               | 37                 | 1            | 3            | 92               | 46                 | 20           | 188              | 47                 | 10           | 368              | 46                 | 5            |
| 38               | 38                 | 1            | 2            | 94               | 47                 | 20           | 190              | 38                 | 8            | 370              | 37                 | 4            |
| 39               | 39                 | 1            | 1            | 95               | 38                 | 16           | 192              | 24                 | 5            | 376              | 47                 | 5            |
| 40               | Any                | 1            | ...          | 96               | 24                 | 10           | 195              | 39                 | 8            | 380              | 38                 | 4            |
| 41               | 41                 | ...          | 40           | 98               | 49                 | 20           | 196              | 49                 | 10           | 390              | 39                 | 4            |
| 42               | 42                 | ...          | 40           | 100              | 25                 | 10           | 200              | 30                 | 6            | 392              | 49                 | 5            |
| 43               | 43                 | ...          | 40           | 102              | 51                 | 20           | 204              | 51                 | 10           | 400              | 30                 | 3            |

**Table 6a. Indexing Movements for High Numbers  
Cincinnati Milling Machine**

| This set of 3 index plates indexes all numbers up to and including 200; all even numbers and those divisible by 5 up to and including 400. The plates are drilled on each side, making six sides <i>A, B, C, D, E</i> and <i>F</i> .                           |          |        |       |       |                  |          |        |       |       |                  |          |        |       |       |
|--|----------|--------|-------|-------|------------------|----------|--------|-------|-------|------------------|----------|--------|-------|-------|
| <i>Example:</i> —It is required to index 35 divisions. The preferred side is <i>F</i> , since this requires the least number of holes; but should one of plates <i>D, A</i> or <i>E</i> be in place, either can be used, thus avoiding the changing of plates. |          |        |       |       |                  |          |        |       |       |                  |          |        |       |       |
| No. of Divisions   | Side     | Circle | Turns | Holes | No. of Divisions | Side     | Circle | Turns | Holes | No. of Divisions | Side     | Circle | Turns | Holes |
| 2  | Any      | Any    | 20    | ....  | 15               | <i>C</i> | 93     | 2     | 62    | 28               | <i>D</i> | 77     | 1     | 33    |
| 3  | <i>A</i> | 30     | 13    | 10    | 15               | <i>F</i> | 159    | 2     | 106   | 28               | <i>A</i> | 91     | 1     | 39    |
| 3  | <i>B</i> | 36     | 13    | 12    | 16               | <i>E</i> | 26     | 2     | 13    | 29               | <i>E</i> | 87     | 1     | 33    |
| 3  | <i>E</i> | 42     | 13    | 14    | 16               | <i>F</i> | 28     | 2     | 14    | 30               | <i>A</i> | 30     | 1     | 10    |
| 3  | <i>C</i> | 93     | 13    | 31    | 16               | <i>A</i> | 30     | 2     | 15    | 30               | <i>B</i> | 36     | 1     | 12    |
| 3  | <i>F</i> | 159    | 13    | 53    | 16               | <i>D</i> | 32     | 2     | 16    | 30               | <i>E</i> | 42     | 1     | 14    |
| 4  | Any      | Any    | 10    | ....  | 16               | <i>C</i> | 34     | 2     | 17    | 30               | <i>C</i> | 93     | 1     | 31    |
| 5  | Any      | Any    | 8     | ....  | 16               | <i>B</i> | 36     | 2     | 18    | 30               | <i>F</i> | 159    | 1     | 53    |
| 6  | <i>A</i> | 30     | 6     | 20    | 17               | <i>C</i> | 34     | 2     | 12    | 31               | <i>C</i> | 93     | 1     | 27    |
| 6  | <i>B</i> | 36     | 6     | 24    | 17               | <i>E</i> | 119    | 2     | 42    | 32               | <i>F</i> | 28     | 1     | 7     |
| 6  | <i>E</i> | 42     | 6     | 28    | 17               | <i>C</i> | 153    | 2     | 54    | 32               | <i>D</i> | 32     | 1     | 8     |
| 6  | <i>C</i> | 93     | 6     | 62    | 17               | <i>F</i> | 187    | 2     | 66    | 32               | <i>B</i> | 36     | 1     | 9     |
| 6  | <i>F</i> | 159    | 6     | 106   | 18               | <i>B</i> | 36     | 2     | 8     | 32               | <i>A</i> | 48     | 1     | 12    |
| 7  | <i>F</i> | 28     | 5     | 20    | 18               | <i>A</i> | 99     | 2     | 22    | 33               | <i>A</i> | 99     | 1     | 21    |
| 7  | <i>E</i> | 42     | 5     | 30    | 18               | <i>C</i> | 153    | 2     | 34    | 34               | <i>C</i> | 34     | 1     | 6     |
| 7  | <i>D</i> | 77     | 5     | 55    | 19               | <i>F</i> | 38     | 2     | 4     | 34               | <i>E</i> | 119    | 1     | 21    |
| 7  | <i>A</i> | 91     | 5     | 65    | 19               | <i>E</i> | 133    | 2     | 14    | 34               | <i>F</i> | 187    | 1     | 33    |
| 8  | Any      | Any    | 5     | ....  | 19               | <i>A</i> | 171    | 2     | 18    | 35               | <i>F</i> | 28     | 1     | 4     |
| 9  | <i>B</i> | 36     | 4     | 16    | 20               | Any      | Any    | 2     | ....  | 35               | <i>D</i> | 77     | 1     | 11    |
| 9  | <i>A</i> | 99     | 4     | 44    | 21               | <i>E</i> | 42     | 1     | 38    | 35               | <i>A</i> | 91     | 1     | 13    |
| 9  | <i>C</i> | 153    | 4     | 68    | 21               | <i>A</i> | 147    | 1     | 133   | 35               | <i>E</i> | 119    | 1     | 17    |
| 10   | Any      | Any    | 4     | ....  | 22               | <i>D</i> | 44     | 1     | 36    | 36               | <i>B</i> | 36     | 1     | 4     |
| 11   | <i>D</i> | 44     | 3     | 28    | 22               | <i>A</i> | 99     | 1     | 81    | 36               | <i>A</i> | 99     | 1     | 11    |
| 11   | <i>A</i> | 99     | 3     | 63    | 22               | <i>F</i> | 143    | 1     | 117   | 36               | <i>C</i> | 153    | 1     | 17    |
| 11   | <i>F</i> | 143    | 3     | 91    | 23               | <i>C</i> | 46     | 1     | 34    | 37               | <i>B</i> | 111    | 1     | 9     |
| 12   | <i>A</i> | 30     | 3     | 10    | 23               | <i>A</i> | 69     | 1     | 51    | 38               | <i>F</i> | 38     | 1     | 2     |
| 12   | <i>B</i> | 36     | 3     | 12    | 23               | <i>E</i> | 161    | 1     | 119   | 38               | <i>E</i> | 133    | 1     | 7     |
| 12   | <i>E</i> | 42     | 3     | 14    | 24               | <i>A</i> | 30     | 1     | 20    | 38               | <i>A</i> | 171    | 1     | 9     |
| 12   | <i>C</i> | 93     | 3     | 31    | 24               | <i>B</i> | 36     | 1     | 24    | 39               | <i>A</i> | 117    | 1     | 3     |
| 12   | <i>F</i> | 159    | 3     | 53    | 24               | <i>E</i> | 42     | 1     | 28    | 40               | Any      | Any    | 1     | ....  |
| 13   | <i>E</i> | 26     | 3     | 2     | 24               | <i>C</i> | 93     | 1     | 62    | 41               | <i>C</i> | 123    | ....  | 120   |
| 13   | <i>A</i> | 91     | 3     | 7     | 24               | <i>F</i> | 159    | 1     | 106   | 42               | <i>E</i> | 42     | ....  | 40    |
| 13   | <i>F</i> | 143    | 3     | 11    | 25               | <i>A</i> | 30     | 1     | 18    | 42               | <i>A</i> | 147    | ....  | 140   |
| 13   | <i>B</i> | 169    | 3     | 13    | 25               | <i>E</i> | 175    | 1     | 105   | 43               | <i>A</i> | 129    | ....  | 120   |
| 14   | <i>F</i> | 28     | 2     | 24    | 26               | <i>F</i> | 26     | 1     | 14    | 44               | <i>D</i> | 44     | ....  | 40    |
| 14   | <i>E</i> | 42     | 2     | 36    | 26               | <i>A</i> | 91     | 1     | 49    | 44               | <i>A</i> | 99     | ....  | 90    |
| 14   | <i>D</i> | 77     | 2     | 66    | 26               | <i>B</i> | 169    | 1     | 91    | 44               | <i>F</i> | 143    | ....  | 130   |
| 14   | <i>A</i> | 91     | 2     | 78    | 27               | <i>B</i> | 81     | 1     | 39    | 45               | <i>B</i> | 36     | ....  | 32    |
| 15   | <i>A</i> | 30     | 2     | 20    | 27               | <i>A</i> | 189    | 1     | 91    | 45               | <i>A</i> | 99     | ....  | 88    |
| 15   | <i>B</i> | 36     | 2     | 24    | 28               | <i>F</i> | 28     | 1     | 12    | 45               | <i>C</i> | 153    | ....  | 136   |
| 15   | <i>E</i> | 42     | 2     | 28    | 28               | <i>E</i> | 42     | 1     | 18    | 46               | <i>C</i> | 46     | ....  | 40    |

**Table 6b. Indexing Movements for High Numbers  
Cincinnati Milling Machine**

| No. of Division | Side | Circle | Holes | No. of Divisions | Side | Circle | Holes | No. of Division | Side | Circle | Holes |
|-----------------|------|--------|-------|------------------|------|--------|-------|-----------------|------|--------|-------|
| 46              | A    | 69     | 60    | 70               | E    | 119    | 68    | 96              | B    | 36     | 15    |
| 46              | E    | 161    | 140   | 71               | F    | 71     | 40    | 96              | A    | 48     | 20    |
| 47              | B    | 141    | 120   | 72               | B    | 36     | 20    | 97              | B    | 97     | 40    |
| 48              | A    | 30     | 25    | 72               | A    | 117    | 65    | 98              | A    | 147    | 60    |
| 48              | B    | 36     | 30    | 72               | C    | 153    | 85    | 99              | A    | 99     | 40    |
| 49              | A    | 147    | 120   | 73               | E    | 73     | 40    | 100             | A    | 30     | 12    |
| 50              | A    | 30     | 24    | 74               | B    | 111    | 60    | 100             | E    | 175    | 70    |
| 50              | E    | 175    | 140   | 75               | A    | 30     | 16    | 101             | F    | 101    | 40    |
| 51              | C    | 153    | 120   | 76               | F    | 38     | 20    | 102             | C    | 153    | 60    |
| 52              | E    | 26     | 20    | 76               | E    | 133    | 70    | 103             | E    | 103    | 40    |
| 52              | A    | 91     | 70    | 76               | A    | 171    | 90    | 104             | E    | 26     | 10    |
| 52              | F    | 143    | 110   | 77               | D    | 77     | 40    | 104             | A    | 91     | 35    |
| 52              | B    | 169    | 130   | 78               | A    | 117    | 60    | 104             | F    | 143    | 55    |
| 53              | F    | 159    | 120   | 79               | C    | 79     | 40    | 104             | B    | 169    | 65    |
| 54              | B    | 81     | 60    | 80               | E    | 26     | 13    | 105             | E    | 42     | 16    |
| 54              | A    | 189    | 140   | 80               | F    | 28     | 14    | 105             | A    | 147    | 56    |
| 55              | D    | 44     | 32    | 80               | A    | 30     | 15    | 106             | F    | 159    | 60    |
| 55              | F    | 143    | 104   | 80               | D    | 32     | 16    | 107             | D    | 107    | 40    |
| 56              | F    | 28     | 20    | 80               | C    | 34     | 17    | 108             | B    | 81     | 30    |
| 56              | E    | 42     | 30    | 80               | B    | 36     | 18    | 108             | A    | 189    | 70    |
| 56              | D    | 77     | 55    | 80               | E    | 42     | 21    | 109             | C    | 109    | 40    |
| 56              | A    | 91     | 65    | 81               | B    | 81     | 40    | 110             | D    | 44     | 16    |
| 57              | A    | 171    | 120   | 82               | C    | 123    | 60    | 110             | A    | 99     | 36    |
| 58              | E    | 87     | 60    | 83               | F    | 83     | 40    | 110             | F    | 143    | 52    |
| 59              | A    | 177    | 120   | 84               | E    | 42     | 20    | 111             | B    | 111    | 40    |
| 60              | A    | 30     | 20    | 84               | A    | 147    | 70    | 112             | F    | 28     | 10    |
| 60              | B    | 36     | 24    | 85               | C    | 34     | 16    | 112             | E    | 42     | 15    |
| 60              | E    | 42     | 28    | 85               | E    | 119    | 56    | 113             | F    | 113    | 40    |
| 60              | F    | 159    | 106   | 85               | F    | 187    | 88    | 114             | A    | 171    | 60    |
| 61              | B    | 183    | 120   | 86               | A    | 129    | 60    | 115             | C    | 46     | 16    |
| 62              | C    | 93     | 60    | 87               | E    | 87     | 40    | 115             | A    | 69     | 24    |
| 63              | A    | 189    | 120   | 88               | D    | 44     | 20    | 115             | E    | 161    | 56    |
| 64              | D    | 32     | 20    | 88               | A    | 99     | 45    | 116             | E    | 87     | 30    |
| 64              | A    | 48     | 30    | 88               | F    | 143    | 65    | 117             | A    | 117    | 40    |
| 65              | E    | 26     | 16    | 89               | D    | 89     | 40    | 118             | A    | 177    | 60    |
| 65              | A    | 91     | 56    | 90               | B    | 36     | 16    | 119             | E    | 119    | 40    |
| 65              | F    | 143    | 88    | 90               | A    | 99     | 44    | 120             | A    | 30     | 10    |
| 65              | B    | 169    | 104   | 90               | C    | 153    | 68    | 120             | B    | 36     | 12    |
| 66              | A    | 99     | 60    | 91               | A    | 91     | 40    | 120             | E    | 42     | 14    |
| 67              | B    | 67     | 40    | 92               | C    | 46     | 20    | 120             | C    | 93     | 31    |
| 68              | C    | 34     | 20    | 92               | A    | 69     | 30    | 120             | F    | 159    | 53    |
| 68              | E    | 119    | 70    | 92               | E    | 161    | 70    | 121             | D    | 121    | 40    |
| 68              | F    | 187    | 110   | 93               | C    | 93     | 40    | 122             | B    | 183    | 60    |
| 69              | A    | 69     | 40    | 94               | B    | 141    | 60    | 123             | C    | 123    | 40    |
| 70              | F    | 28     | 16    | 95               | F    | 38     | 16    | 124             | C    | 93     | 30    |
| 70              | D    | 42     | 24    | 95               | E    | 133    | 56    | 125             | E    | 175    | 56    |
| 70              | A    | 91     | 52    | 95               | A    | 171    | 72    | 126             | A    | 189    | 60    |
| 127             | B    | 127    | 40    | 160              | A    | 48     | 12    | 198             | A    | 99     | 20    |
| 128             | D    | 32     | 10    | 161              | E    | 161    | 40    | 199             | B    | 199    | 40    |
| 128             | A    | 48     | 15    | 162              | B    | 81     | 20    | 200             | A    | 30     | 6     |
| 129             | A    | 129    | 40    | 163              | D    | 163    | 40    | 200             | E    | 175    | 35    |
| 130             | E    | 26     | 8     | 164              | C    | 123    | 30    | 202             | F    | 101    | 20    |
| 130             | A    | 91     | 28    | 165              | A    | 99     | 24    | 204             | C    | 153    | 30    |
| 130             | F    | 143    | 44    | 166              | F    | 83     | 20    | 205             | C    | 123    | 24    |
| 130             | B    | 169    | 52    | 167              | C    | 167    | 40    | 206             | E    | 103    | 20    |
| 131             | F    | 131    | 40    | 168              | E    | 42     | 10    | 208             | E    | 26     | 5     |
| 132             | A    | 99     | 30    | 168              | A    | 147    | 35    | 210             | E    | 42     | 8     |
| 133             | E    | 133    | 40    | 169              | B    | 169    | 40    | 210             | A    | 147    | 28    |
| 134             | B    | 67     | 20    | 170              | C    | 34     | 8     | 212             | F    | 159    | 30    |
| 135             | B    | 81     | 24    | 170              | E    | 119    | 28    | 214             | D    | 107    | 20    |
| 135             | A    | 189    | 56    | 170              | F    | 187    | 44    | 215             | A    | 129    | 24    |
| 136             | C    | 34     | 10    | 171              | A    | 171    | 40    | 216             | B    | 81     | 15    |
| 136             | E    | 119    | 35    | 172              | A    | 129    | 30    | 216             | A    | 189    | 35    |



**Table 6b. (Continued) Indexing Movements for High Numbers  
Cincinnati Milling Machine**

| No. of Division | Side | Circle | Holes | No. of Divisions | Side | Circle | Holes | No. of Division | Side | Circle | Holes |
|-----------------|------|--------|-------|------------------|------|--------|-------|-----------------|------|--------|-------|
| 137             | D    | 137    | 40    | 173              | F    | 173    | 40    | 218             | C    | 109    | 20    |
| 138             | A    | 69     | 20    | 174              | E    | 87     | 20    | 220             | D    | 44     | 8     |
| 139             | C    | 139    | 40    | 175              | E    | 175    | 40    | 220             | A    | 99     | 18    |
| 140             | F    | 28     | 8     | 176              | D    | 44     | 10    | 220             | F    | 143    | 26    |
| 140             | E    | 42     | 12    | 177              | A    | 177    | 40    | 222             | B    | 111    | 20    |
| 140             | D    | 77     | 22    | 178              | D    | 89     | 20    | 224             | F    | 28     | 5     |
| 140             | A    | 91     | 26    | 179              | D    | 179    | 40    | 226             | F    | 113    | 20    |
| 141             | B    | 141    | 40    | 180              | B    | 36     | 8     | 228             | A    | 171    | 30    |
| 142             | F    | 71     | 20    | 180              | A    | 99     | 22    | 230             | C    | 46     | 8     |
| 143             | F    | 143    | 40    | 180              | C    | 153    | 34    | 230             | A    | 69     | 12    |
| 144             | B    | 36     | 10    | 181              | C    | 181    | 40    | 230             | E    | 161    | 28    |
| 145             | E    | 87     | 24    | 182              | A    | 91     | 20    | 232             | E    | 87     | 15    |
| 146             | E    | 73     | 20    | 183              | B    | 183    | 40    | 234             | A    | 117    | 20    |
| 147             | A    | 147    | 40    | 184              | C    | 46     | 10    | 235             | B    | 141    | 24    |
| 148             | B    | 111    | 30    | 184              | A    | 69     | 15    | 236             | A    | 177    | 30    |
| 149             | E    | 149    | 40    | 184              | E    | 161    | 35    | 238             | E    | 119    | 20    |
| 150             | A    | 30     | 8     | 185              | B    | 111    | 24    | 240             | A    | 30     | 5     |
| 151             | D    | 151    | 40    | 186              | C    | 93     | 20    | 240             | B    | 36     | 6     |
| 152             | F    | 38     | 10    | 187              | F    | 187    | 40    | 240             | E    | 42     | 7     |
| 152             | E    | 133    | 35    | 188              | B    | 141    | 30    | 240             | A    | 48     | 8     |
| 152             | A    | 171    | 45    | 189              | A    | 189    | 40    | 242             | D    | 121    | 20    |
| 153             | C    | 153    | 40    | 190              | F    | 38     | 8     | 244             | B    | 183    | 30    |
| 154             | D    | 77     | 20    | 190              | E    | 133    | 28    | 245             | A    | 147    | 24    |
| 155             | C    | 93     | 24    | 190              | A    | 171    | 36    | 246             | C    | 123    | 20    |
| 156             | A    | 117    | 30    | 191              | E    | 191    | 40    | 248             | C    | 93     | 15    |
| 157             | B    | 157    | 40    | 192              | A    | 48     | 10    | 250             | E    | 175    | 28    |
| 158             | C    | 79     | 20    | 193              | D    | 193    | 40    | 252             | A    | 189    | 30    |
| 159             | F    | 159    | 40    | 194              | B    | 97     | 20    | 254             | B    | 127    | 20    |
| 160             | F    | 28     | 7     | 195              | A    | 117    | 24    | 255             | C    | 153    | 24    |
| 160             | D    | 32     | 8     | 196              | A    | 147    | 30    | 256             | D    | 32     | 5     |
| 160             | B    | 36     | 9     | 197              | C    | 197    | 40    | 258             | A    | 129    | 20    |
| 260             | E    | 26     | 4     | 304              | F    | 38     | 5     | 354             | A    | 177    | 20    |
| 260             | A    | 91     | 14    | 305              | B    | 183    | 24    | 355             | F    | 71     | 8     |
| 260             | F    | 143    | 22    | 306              | C    | 153    | 20    | 356             | D    | 89     | 10    |
| 260             | B    | 169    | 26    | 308              | D    | 77     | 10    | 358             | D    | 179    | 20    |
| 262             | F    | 131    | 20    | 310              | C    | 93     | 12    | 360             | B    | 36     | 4     |
| 264             | A    | 99     | 15    | 312              | A    | 117    | 15    | 360             | A    | 99     | 11    |
| 265             | F    | 159    | 24    | 314              | B    | 157    | 20    | 360             | C    | 153    | 17    |
| 266             | E    | 133    | 20    | 315              | A    | 189    | 24    | 362             | C    | 181    | 20    |
| 268             | B    | 67     | 10    | 316              | C    | 79     | 10    | 364             | A    | 91     | 10    |
| 270             | B    | 81     | 12    | 318              | F    | 159    | 20    | 365             | E    | 73     | 8     |
| 270             | A    | 189    | 28    | 320              | D    | 32     | 4     | 366             | B    | 183    | 20    |
| 272             | C    | 34     | 5     | 320              | A    | 48     | 6     | 368             | C    | 46     | 5     |
| 274             | D    | 137    | 20    | 322              | E    | 161    | 20    | 370             | B    | 111    | 12    |
| 276             | A    | 69     | 10    | 324              | B    | 81     | 10    | 372             | C    | 93     | 10    |
| 278             | C    | 139    | 20    | 326              | D    | 163    | 20    | 374             | F    | 187    | 20    |
| 280             | F    | 28     | 4     | 328              | C    | 123    | 15    | 376             | B    | 141    | 15    |
| 280             | E    | 42     | 6     | 330              | A    | 99     | 12    | 378             | A    | 189    | 20    |
| 280             | D    | 77     | 11    | 332              | F    | 83     | 10    | 380             | F    | 38     | 4     |
| 280             | A    | 91     | 13    | 334              | C    | 167    | 20    | 380             | E    | 133    | 14    |
| 282             | B    | 141    | 20    | 335              | B    | 67     | 8     | 380             | A    | 171    | 18    |
| 284             | F    | 71     | 10    | 336              | E    | 42     | 5     | 382             | E    | 191    | 20    |
| 285             | A    | 171    | 24    | 338              | B    | 169    | 20    | 384             | A    | 48     | 5     |
| 286             | F    | 143    | 20    | 340              | C    | 34     | 4     | 385             | D    | 77     | 8     |
| 288             | B    | 36     | 5     | 340              | E    | 119    | 14    | 386             | D    | 193    | 20    |
| 290             | E    | 87     | 12    | 340              | F    | 187    | 22    | 388             | B    | 97     | 10    |
| 292             | E    | 73     | 10    | 342              | A    | 171    | 20    | 390             | A    | 117    | 12    |
| 294             | A    | 147    | 20    | 344              | A    | 129    | 15    | 392             | A    | 147    | 15    |
| 295             | A    | 177    | 24    | 345              | A    | 69     | 8     | 394             | C    | 197    | 20    |
| 296             | B    | 111    | 15    | 346              | F    | 173    | 20    | 395             | C    | 79     | 8     |
| 298             | E    | 149    | 20    | 348              | E    | 87     | 10    | 396             | A    | 99     | 10    |
| 300             | A    | 30     | 4     | 350              | E    | 175    | 20    | 398             | B    | 199    | 20    |
| 302             | D    | 151    | 20    | 352              | D    | 44     | 5     | 400             | A    | 30     | 3     |

**Indexing Tables.**—Indexing tables are usually circular, with a flat, T-slotted table, 12 to 24 in. in diameter, to which workpieces can be clamped. The flat table surface may be horizontal, universal, or angularly adjustable. The table can be turned continuously through 360° about an axis normal to the surface. Rotation is through a worm drive with a graduated scale, and a means of angular readout is provided. Indexed locations to 0.25° with accuracy of ±0.1 second can be obtained from mechanical means, or greater accuracy from an autocollimator or sine-angle attachment built into the base, or under numerical control. Provision is made for locking the table at any angular position while a machining operation is being performed.

Power for rotation of the table during machining can be transmitted, as with a dividing head, for cutting a continuous, spiral scroll, for instance. The indexing table is usually more rigid and can be used with larger workpieces than the dividing head.

**Block or Multiple Indexing for Gear Cutting.**—With the block system of indexing, numbers of teeth are indexed at one time, instead of cutting the teeth consecutively, and the gear is revolved several times before all the teeth are finished. For example, when cutting a gear having 25 teeth, the indexing mechanism is geared to index four teeth at once (see Table 7) and the first time around, six widely separated tooth spaces are cut. The second time around, the cutter is one tooth behind the spaces originally milled. On the third indexing, the cutter has dropped back another tooth, and the gear in question is thus finished by indexing it through four cycles.

The various combinations of change gears to use for block or multiple indexing are given in the accompanying Table 7. The advantage claimed for block indexing is that the heat generated by the cutter (especially when cutting cast iron gears of coarse pitch) is distributed more evenly about the rim and is dissipated to a greater extent, thus avoiding distortion due to local heating and permitting higher speeds and feeds to be used.

Table 7 gives values for use with Brown & Sharpe automatic gear cutting machines, but the gears for any other machine equipped with a similar indexing mechanism can be calculated easily. Assume, for example, that a gear cutter requires the following change gears for indexing a certain number of teeth: driving gears having 20 and 30 teeth, respectively, and driven gears having 50 and 60 teeth.

Then if it is desired to cut, for instance, every fifth tooth, multiply the fractions 20/60 and 30/50 by 5. Then  $20/60 \times 30/50 \times 5/1 = 1/1$ . In this instance, the blank could be divided so that every fifth space was cut, by using gears of equal size. The number of teeth in the gear and the number of teeth indexed in each block must not have a common factor.

**Table 7. Block or Multiple Indexing for Gear Cutting**

| Number of Teeth to be Cut | Number Indexed at Once | 1st Driver | 1st Follower | 2nd Driver | 2nd Follower | Turns of Locking Disk | Number of Teeth to be Cut | Number Indexed at Once | 1st Driver | 1st Follower | 2nd Driver | 2nd Follower | Turns of Locking Disk |
|---------------------------|------------------------|------------|--------------|------------|--------------|-----------------------|---------------------------|------------------------|------------|--------------|------------|--------------|-----------------------|
| 25                        | 4                      | 100        | 50           | 72         | 30           | 4                     | 36                        | 5                      | 100        | 48           | 80         | 40           | 4                     |
| 26                        | 3                      | 100        | 50           | 90         | 52           | 4                     | 37                        | 5                      | 100        | 30           | 90         | 74           | 4                     |
| 27                        | 2                      | 100        | 50           | 60         | 54           | 4                     | 38                        | 5                      | 100        | 30           | 90         | 76           | 4                     |
| 28                        | 3                      | 100        | 50           | 90         | 56           | 4                     | 39                        | 5                      | 100        | 30           | 90         | 78           | 4                     |
| 29                        | 3                      | 100        | 50           | 90         | 58           | 4                     | 40                        | 3                      | 100        | 50           | 90         | 80           | 4                     |
| 30                        | 7                      | 100        | 30           | 84         | 40           | 4                     | 41                        | 5                      | 100        | 30           | 90         | 82           | 4                     |
| 31                        | 3                      | 100        | 50           | 90         | 62           | 4                     | 42                        | 5                      | 100        | 30           | 90         | 84           | 4                     |
| 32                        | 3                      | 100        | 50           | 90         | 64           | 4                     | 43                        | 5                      | 100        | 30           | 90         | 86           | 4                     |
| 33                        | 4                      | 100        | 50           | 80         | 44           | 4                     | 44                        | 5                      | 100        | 30           | 90         | 88           | 4                     |
| 34                        | 3                      | 100        | 50           | 90         | 68           | 4                     | 45                        | 7                      | 100        | 50           | 70         | 30           | 4                     |
| 35                        | 4                      | 100        | 50           | 96         | 56           | 4                     | 46                        | 5                      | 100        | 30           | 90         | 92           | 4                     |

**Table 7. (Continued) Block or Multiple Indexing for Gear Cutting**

| Number of Teeth to be Cut | Number Indexed at Once | 1st Driver | 1st Follower | 2nd Driver | 2nd Follower | Turns of Locking Disk | Number of Teeth to be Cut | Number Indexed at Once | 1st Driver | 1st Follower | 2nd Driver | 2nd Follower | Turns of Locking Disk |
|---------------------------|------------------------|------------|--------------|------------|--------------|-----------------------|---------------------------|------------------------|------------|--------------|------------|--------------|-----------------------|
| 47                        | 5                      | 100        | 30           | 90         | 94           | 4                     | 119                       | 3                      | 100        | 70           | 72         | 68           | 2                     |
| 48                        | 5                      | 100        | 30           | 90         | 96           | 4                     | 120                       | 7                      | 100        | 50           | 70         | 40           | 2                     |
| 49                        | 5                      | 100        | 30           | 90         | 98           | 4                     | 121                       | 4                      | 60         | 66           | 96         | 44           | 2                     |
| 50                        | 7                      | 100        | 50           | 84         | 40           | 4                     | 123                       | 7                      | 100        | 30           | 84         | 82           | 2                     |
| 51                        | 4                      | 100        | 30           | 96         | 68           | 2                     | 124                       | 5                      | 100        | 60           | 90         | 62           | 2                     |
| 52                        | 5                      | 100        | 30           | 90         | 52           | 2                     | 125                       | 7                      | 100        | 50           | 84         | 50           | 2                     |
| 54                        | 5                      | 100        | 30           | 90         | 54           | 2                     | 126                       | 5                      | 100        | 50           | 50         | 42           | 2                     |
| 55                        | 4                      | 100        | 50           | 96         | 44           | 2                     | 128                       | 5                      | 100        | 60           | 90         | 64           | 2                     |
| 56                        | 5                      | 100        | 30           | 90         | 56           | 2                     | 129                       | 7                      | 100        | 30           | 84         | 86           | 2                     |
| 57                        | 4                      | 100        | 30           | 96         | 76           | 2                     | 130                       | 7                      | 100        | 50           | 84         | 52           | 2                     |
| 58                        | 5                      | 100        | 30           | 90         | 58           | 2                     | 132                       | 5                      | 100        | 88           | 80         | 40           | 2                     |
| 60                        | 7                      | 100        | 30           | 84         | 40           | 2                     | 133                       | 4                      | 100        | 70           | 96         | 76           | 2                     |
| 62                        | 5                      | 100        | 30           | 90         | 62           | 2                     | 134                       | 5                      | 100        | 60           | 90         | 67           | 2                     |
| 63                        | 5                      | 100        | 30           | 80         | 56           | 2                     | 135                       | 7                      | 100        | 50           | 84         | 54           | 2                     |
| 64                        | 5                      | 100        | 30           | 90         | 64           | 2                     | 136                       | 5                      | 100        | 60           | 90         | 68           | 2                     |
| 65                        | 4                      | 100        | 50           | 96         | 52           | 2                     | 138                       | 5                      | 100        | 92           | 80         | 40           | 2                     |
| 66                        | 5                      | 100        | 44           | 80         | 40           | 2                     | 140                       | 3                      | 50         | 50           | 90         | 70           | 2                     |
| 67                        | 5                      | 100        | 30           | 90         | 67           | 2                     | 141                       | 5                      | 100        | 94           | 80         | 40           | 2                     |
| 68                        | 5                      | 100        | 30           | 90         | 68           | 2                     | 143                       | 6                      | 90         | 66           | 96         | 52           | 2                     |
| 69                        | 5                      | 100        | 46           | 80         | 40           | 2                     | 144                       | 5                      | 100        | 60           | 90         | 72           | 2                     |
| 70                        | 3                      | 100        | 50           | 90         | 70           | 2                     | 145                       | 6                      | 100        | 50           | 72         | 58           | 2                     |
| 72                        | 5                      | 100        | 30           | 90         | 72           | 2                     | 147                       | 5                      | 100        | 98           | 80         | 40           | 2                     |
| 74                        | 5                      | 100        | 30           | 90         | 74           | 2                     | 148                       | 5                      | 100        | 60           | 90         | 74           | 2                     |
| 75                        | 7                      | 100        | 30           | 84         | 50           | 2                     | 150                       | 7                      | 100        | 60           | 84         | 50           | 2                     |
| 76                        | 5                      | 100        | 30           | 90         | 76           | 2                     | 152                       | 5                      | 100        | 60           | 90         | 76           | 2                     |
| 77                        | 4                      | 100        | 70           | 96         | 44           | 2                     | 153                       | 5                      | 100        | 68           | 80         | 60           | 2                     |
| 78                        | 5                      | 100        | 30           | 90         | 78           | 2                     | 154                       | 5                      | 100        | 56           | 72         | 66           | 2                     |
| 80                        | 3                      | 100        | 50           | 90         | 80           | 2                     | 155                       | 6                      | 100        | 50           | 72         | 62           | 2                     |
| 81                        | 7                      | 100        | 30           | 84         | 52           | 2                     | 156                       | 5                      | 100        | 60           | 90         | 78           | 2                     |
| 82                        | 5                      | 100        | 30           | 90         | 82           | 2                     | 160                       | 7                      | 100        | 50           | 84         | 64           | 2                     |
| 84                        | 5                      | 100        | 30           | 90         | 84           | 2                     | 161                       | 5                      | 100        | 70           | 60         | 46           | 2                     |
| 85                        | 4                      | 100        | 50           | 96         | 68           | 2                     | 162                       | 7                      | 100        | 60           | 84         | 52           | 2                     |
| 86                        | 5                      | 100        | 30           | 90         | 86           | 2                     | 164                       | 5                      | 100        | 60           | 90         | 82           | 2                     |
| 87                        | 7                      | 100        | 30           | 84         | 58           | 2                     | 165                       | 7                      | 100        | 50           | 84         | 66           | 2                     |
| 88                        | 5                      | 100        | 30           | 90         | 88           | 2                     | 168                       | 5                      | 100        | 60           | 90         | 84           | 2                     |
| 90                        | 7                      | 100        | 30           | 70         | 50           | 2                     | 169                       | 6                      | 96         | 52           | 90         | 78           | 2                     |
| 91                        | 3                      | 100        | 70           | 72         | 52           | 2                     | 170                       | 7                      | 100        | 50           | 84         | 68           | 2                     |
| 92                        | 5                      | 100        | 30           | 90         | 92           | 2                     | 171                       | 5                      | 70         | 42           | 80         | 76           | 2                     |
| 93                        | 7                      | 100        | 30           | 84         | 62           | 2                     | 172                       | 5                      | 100        | 60           | 90         | 86           | 2                     |
| 94                        | 5                      | 100        | 30           | 90         | 94           | 2                     | 174                       | 7                      | 100        | 60           | 84         | 58           | 2                     |
| 95                        | 4                      | 100        | 50           | 96         | 76           | 2                     | 175                       | 8                      | 100        | 50           | 96         | 70           | 2                     |
| 96                        | 5                      | 100        | 30           | 90         | 96           | 2                     | 176                       | 5                      | 100        | 60           | 90         | 88           | 2                     |
| 98                        | 5                      | 100        | 30           | 90         | 98           | 2                     | 180                       | 7                      | 100        | 60           | 70         | 50           | 2                     |
| 99                        | 10                     | 100        | 30           | 80         | 44           | 2                     | 182                       | 9                      | 90         | 56           | 96         | 52           | 2                     |
| 100                       | 7                      | 100        | 50           | 84         | 40           | 2                     | 184                       | 5                      | 100        | 60           | 90         | 92           | 2                     |
| 102                       | 5                      | 100        | 30           | 60         | 68           | 2                     | 185                       | 6                      | 100        | 50           | 72         | 74           | 2                     |
| 104                       | 5                      | 100        | 60           | 90         | 52           | 2                     | 186                       | 7                      | 100        | 60           | 84         | 62           | 2                     |
| 105                       | 4                      | 100        | 70           | 96         | 60           | 2                     | 187                       | 5                      | 100        | 44           | 48         | 68           | 2                     |
| 108                       | 7                      | 100        | 30           | 70         | 60           | 2                     | 188                       | 5                      | 100        | 60           | 90         | 94           | 2                     |
| 110                       | 7                      | 100        | 50           | 84         | 44           | 2                     | 189                       | 5                      | 100        | 60           | 80         | 84           | 2                     |
| 111                       | 5                      | 100        | 74           | 80         | 40           | 2                     | 190                       | 7                      | 100        | 50           | 84         | 76           | 2                     |
| 112                       | 5                      | 100        | 60           | 90         | 56           | 2                     | 192                       | 5                      | 100        | 60           | 90         | 96           | 2                     |
| 114                       | 7                      | 100        | 30           | 84         | 76           | 2                     | 195                       | 7                      | 100        | 50           | 84         | 78           | 2                     |
| 115                       | 8                      | 100        | 50           | 96         | 46           | 2                     | 196                       | 5                      | 100        | 60           | 90         | 98           | 2                     |
| 116                       | 5                      | 100        | 60           | 90         | 58           | 2                     | 198                       | 7                      | 100        | 50           | 70         | 66           | 2                     |
| 117                       | 8                      | 100        | 30           | 96         | 78           | 2                     | 200                       | 7                      | 60         | 60           | 84         | 40           | 2                     |

**Table 8. Indexing Movements for 60-Tooth Worm-Wheel Dividing Head**

| Divisions | Index Circle | No. of Turns | No. of Holes | Divisions | Index Circle | No. of Turns | No. of Holes | Divisions | Index Circle | No. of Holes | Divisions | Index Circle | No. of Holes |
|-----------|--------------|--------------|--------------|-----------|--------------|--------------|--------------|-----------|--------------|--------------|-----------|--------------|--------------|
| 2         | Any          | 30           | ..           | 50        | 60           | 1            | 12           | 98        | 49           | 30           | 146       | 73           | 30           |
| 3         | Any          | 20           | ..           | 51        | 17           | 1            | 3            | 99        | 33           | 20           | 147       | 49           | 20           |
| 4         | Any          | 15           | ..           | 52        | 26           | 1            | 4            | 100       | 60           | 36           | 148       | 37           | 15           |
| 5         | Any          | 12           | ..           | 53        | 53           | 1            | 7            | 101       | 101          | 60           | 149       | 149          | 60           |
| 6         | Any          | 10           | ..           | 54        | 27           | 1            | 3            | 102       | 17           | 10           | 150       | 60           | 24           |
| 7         | 21           | 8            | 12           | 55        | 33           | 1            | 3            | 103       | 103          | 60           | 151       | 151          | 60           |
| 8         | 26           | 7            | 13           | 56        | 28           | 1            | 2            | 104       | 26           | 15           | 152       | 76           | 30           |
| 9         | 21           | 6            | 14           | 57        | 19           | 1            | 1            | 105       | 21           | 12           | 153       | 51           | 20           |
| 10        | Any          | 6            | ..           | 58        | 29           | 1            | 1            | 106       | 53           | 30           | 154       | 77           | 30           |
| 11        | 33           | 5            | 15           | 59        | 59           | 1            | 1            | 107       | 107          | 60           | 155       | 31           | 12           |
| 12        | Any          | 5            | ..           | 60        | Any          | 1            | ..           | 108       | 27           | 15           | 156       | 26           | 10           |
| 13        | 26           | 4            | 16           | 61        | 61           | ..           | 60           | 109       | 109          | 60           | 157       | 157          | 60           |
| 14        | 21           | 4            | 6            | 62        | 31           | ..           | 30           | 110       | 33           | 18           | 158       | 79           | 30           |
| 15        | Any          | 4            | ..           | 63        | 21           | ..           | 20           | 111       | 37           | 20           | 159       | 53           | 20           |
| 16        | 28           | 3            | 21           | 64        | 32           | ..           | 30           | 112       | 28           | 15           | 160       | 32           | 12           |
| 17        | 17           | 3            | 9            | 65        | 26           | ..           | 24           | 113       | 113          | 60           | 161       | 161          | 60           |
| 18        | 21           | 3            | 7            | 66        | 33           | ..           | 30           | 114       | 19           | 10           | 162       | 27           | 10           |
| 19        | 19           | 3            | 3            | 67        | 67           | ..           | 60           | 115       | 23           | 12           | 163       | 163          | 60           |
| 20        | Any          | 3            | ..           | 68        | 17           | ..           | 15           | 116       | 29           | 15           | 164       | 41           | 15           |
| 21        | 21           | 2            | 18           | 69        | 23           | ..           | 20           | 117       | 39           | 20           | 165       | 33           | 12           |
| 22        | 33           | 2            | 24           | 70        | 21           | ..           | 18           | 118       | 59           | 30           | 166       | 83           | 30           |
| 23        | 23           | 2            | 14           | 71        | 71           | ..           | 60           | 119       | 119          | 60           | 167       | 167          | 60           |
| 24        | 26           | 2            | 13           | 72        | 60           | ..           | 50           | 120       | 26           | 13           | 168       | 28           | 10           |
| 25        | 60           | 2            | 24           | 73        | 73           | ..           | 60           | 121       | 121          | 60           | 169       | 169          | 60           |
| 26        | 26           | 2            | 8            | 74        | 37           | ..           | 30           | 122       | 61           | 30           | 170       | 17           | 6            |
| 27        | 27           | 2            | 6            | 75        | 60           | ..           | 48           | 123       | 41           | 20           | 171       | 57           | 20           |
| 28        | 21           | 2            | 3            | 76        | 19           | ..           | 15           | 124       | 31           | 15           | 172       | 43           | 15           |
| 29        | 29           | 2            | 2            | 77        | 77           | ..           | 60           | 125       | 100          | 48           | 173       | 173          | 60           |
| 30        | Any          | 2            | ..           | 78        | 26           | ..           | 20           | 126       | 21           | 10           | 174       | 29           | 10           |
| 31        | 31           | 1            | 29           | 79        | 79           | ..           | 60           | 127       | 127          | 60           | 175       | 35           | 12           |
| 32        | 32           | 1            | 28           | 80        | 28           | ..           | 21           | 128       | 32           | 15           | 176       | 44           | 15           |
| 33        | 33           | 1            | 27           | 81        | 27           | ..           | 20           | 129       | 43           | 20           | 177       | 59           | 20           |
| 34        | 17           | 1            | 13           | 82        | 41           | ..           | 30           | 130       | 26           | 12           | 178       | 89           | 30           |
| 35        | 21           | 1            | 15           | 83        | 83           | ..           | 60           | 131       | 131          | 60           | 179       | 179          | 60           |
| 36        | 21           | 1            | 14           | 84        | 21           | ..           | 15           | 132       | 33           | 15           | 180       | 21           | 7            |
| 37        | 37           | 1            | 23           | 85        | 17           | ..           | 12           | 133       | 133          | 60           | 181       | 181          | 60           |
| 38        | 19           | 1            | 11           | 86        | 43           | ..           | 30           | 134       | 67           | 30           | 182       | 91           | 30           |
| 39        | 26           | 1            | 14           | 87        | 29           | ..           | 20           | 135       | 27           | 12           | 183       | 61           | 20           |
| 40        | 26           | 1            | 13           | 88        | 44           | ..           | 30           | 136       | 68           | 30           | 184       | 46           | 15           |
| 41        | 41           | 1            | 19           | 89        | 89           | ..           | 60           | 137       | 137          | 60           | 185       | 37           | 12           |
| 42        | 21           | 1            | 9            | 90        | 21           | ..           | 14           | 138       | 23           | 10           | 186       | 31           | 10           |
| 43        | 43           | 1            | 17           | 91        | 91           | ..           | 60           | 139       | 139          | 60           | 187       | 187          | 60           |
| 44        | 33           | 1            | 12           | 92        | 23           | ..           | 15           | 140       | 21           | 9            | 188       | 47           | 15           |
| 45        | 21           | 1            | 7            | 93        | 31           | ..           | 20           | 141       | 47           | 20           | 189       | 63           | 20           |
| 46        | 23           | 1            | 7            | 94        | 47           | ..           | 30           | 142       | 71           | 30           | 190       | 19           | 6            |
| 47        | 47           | 1            | 13           | 95        | 19           | ..           | 12           | 143       | 143          | 60           | 191       | 191          | 60           |
| 48        | 28           | 1            | 7            | 96        | 32           | ..           | 20           | 144       | 60           | 25           | 192       | 32           | 10           |
| 49        | 49           | 1            | 11           | 97        | 97           | ..           | 60           | 145       | 29           | 12           | 193       | 193          | 60           |

**Linear Indexing for Rack Cutting.**—When racks are cut on a milling machine, two general methods of linear indexing are used. One is by using the graduated dial on the feed-screw and the other is by using an indexing attachment. The accompanying Table 9 shows the indexing movements when the first method is employed. This table applies to milling machines having feed-screws with the usual lead of  $\frac{1}{4}$  inch and 250 dial graduations each equivalent to 0.001 inch of table movement.

$$\text{Actual rotation of feed-screw} = \frac{\text{Linear pitch of rack}}{\text{Lead of feed-screw}}$$

Multiply *decimal* part of turn (obtained by above formula) by 250, to obtain dial reading for fractional part of indexing movement, assuming that dial has 250 graduations.

**Table 9. Linear Indexing Movements for Cutting Rack Teeth on a Milling Machine**

| Pitch of Rack Teeth |                    | Indexing, Movement |                             | Pitch of Rack Teeth |                    | Indexing, Movement |                             |
|---------------------|--------------------|--------------------|-----------------------------|---------------------|--------------------|--------------------|-----------------------------|
| Diametral Pitch     | Linear or Circular | No. of Whole Turns | No. of 0.001 Inch Divisions | Diametral Pitch     | Linear or Circular | No. of Whole Turns | No. of 0.001 Inch Divisions |
| 2                   | 1.5708             | 6                  | 70.8                        | 12                  | 0.2618             | 1                  | 11.8                        |
| 2 $\frac{1}{4}$     | 1.3963             | 5                  | 146.3                       | 13                  | 0.2417             | 0                  | 241.7                       |
| 2 $\frac{1}{2}$     | 1.2566             | 5                  | 6.6                         | 14                  | 0.2244             | 0                  | 224.4                       |
| 2 $\frac{3}{4}$     | 1.1424             | 4                  | 142.4                       | 15                  | 0.2094             | 0                  | 208.4                       |
| 3                   | 1.0472             | 4                  | 47.2                        | 16                  | 0.1963             | 0                  | 196.3                       |
| 3 $\frac{1}{2}$     | 0.8976             | 3                  | 147.6                       | 17                  | 0.1848             | 0                  | 184.8                       |
| 4                   | 0.7854             | 3                  | 35.4                        | 18                  | 0.1745             | 0                  | 174.8                       |
| 5                   | 0.6283             | 2                  | 128.3                       | 19                  | 0.1653             | 0                  | 165.3                       |
| 6                   | 0.5263             | 2                  | 23.6                        | 20                  | 0.1571             | 0                  | 157.1                       |
| 7                   | 0.4488             | 1                  | 198.8                       | 22                  | 0.1428             | 0                  | 142.8                       |
| 8                   | 0.3927             | 1                  | 142.7                       | 24                  | 0.1309             | 0                  | 130.9                       |
| 9                   | 0.3491             | 1                  | 99.1                        | 26                  | 0.1208             | 0                  | 120.8                       |
| 10                  | 0.3142             | 1                  | 64.2                        | 28                  | 0.1122             | 0                  | 112.2                       |
| 11                  | 0.2856             | 1                  | 35.6                        | 30                  | 0.1047             | 0                  | 104.7                       |

These movements are for table feed-screws having the usual lead of  $\frac{1}{4}$  inch

*Note:* The linear pitch of the rack equals the circular pitch of gear or pinion which is to mesh with the rack. The table gives both standard diametral pitches and their equivalent linear or circular pitches.

*Example:* Find indexing movement for cutting rack to mesh with a pinion of 10 diametral pitch.

Indexing movement equals 1 whole turn of feed-screw plus 64.2 thousandths or divisions on feed-screw dial. The feed-screw may be turned this fractional amount by setting dial back to its zero position for each indexing (without backward movement of feed-screw), or, if preferred, 64.2 (in this example) may be added to each successive dial position as shown below.

Dial reading for second position =  $64.2 \times 2 = 128.4$  (complete movement = 1 turn  $\times$  64.2 additional divisions by turning feed-screw until dial reading is 128.4).

Third dial position =  $64.2 \times 3 = 192.6$  (complete movement = 1 turn + 64.2 additional divisions by turning until dial reading is 192.6).

Fourth position =  $64.2 \times 4 - 250 = 6.8$  (1 turn + 64.2 additional divisions by turning feed-screw until dial reading is 6.8 divisions past the zero mark); or, to simplify operation, set dial back to zero for fourth indexing (without moving feed-screw) and then repeat settings for the three previous indexings or whatever number can be made before making a complete turn of the dial.

**Counter Milling.**—Changing the direction of a linear milling operation by a specific angle requires a linear offset before changing the angle of cut. This compensates for the radius of the milling cutters, as illustrated in Figs. 1a and 1b.

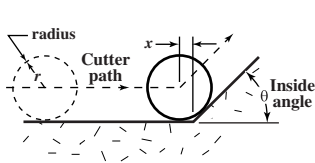


Fig. 1a. Inside Milling

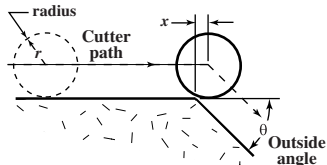


Fig. 1b. Outside Milling

For inside cuts the offset is subtracted from the point at which the cutting direction changes (Fig. 1a), and for outside cuts the offset is added to the point at which the cutting direction changes (Fig. 1b). The formula for the offset is

$$x = rM$$

where  $x$  = offset distance;  $r$  = radius of the milling cutter; and,  $M$  = the multiplication factor ( $M = \tan \frac{\theta}{2}$ ). The value of  $M$  for certain angles can be found in Table 10.

Table 10. Offset Multiplication Factors

| Deg° | $M$     | Deg° | $M$     | Deg° | $M$     | Deg° | $M$     | Deg° | $M$     |
|------|---------|------|---------|------|---------|------|---------|------|---------|
| 1°   | 0.00873 | 19°  | 0.16734 | 37°  | 0.33460 | 55°  | 0.52057 | 73°  | 0.73996 |
| 2°   | 0.01746 | 20°  | 0.17633 | 38°  | 0.34433 | 56°  | 0.53171 | 74°  | 0.75355 |
| 3°   | 0.02619 | 21°  | 0.18534 | 39°  | 0.35412 | 57°  | 0.54296 | 75°  | 0.76733 |
| 4°   | 0.03492 | 22°  | 0.19438 | 40°  | 0.36397 | 58°  | 0.55431 | 76°  | 0.78129 |
| 5°   | 0.04366 | 23°  | 0.20345 | 41°  | 0.37388 | 59°  | 0.56577 | 77°  | 0.79544 |
| 6°   | 0.05241 | 24°  | 0.21256 | 42°  | 0.38386 | 60°  | 0.57735 | 78°  | 0.80978 |
| 7°   | 0.06116 | 25°  | 0.22169 | 43°  | 0.39391 | 61°  | 0.58905 | 79°  | 0.82434 |
| 8°   | 0.06993 | 26°  | 0.23087 | 44°  | 0.40403 | 62°  | 0.60086 | 80°  | 0.83910 |
| 9°   | 0.07870 | 27°  | 0.24008 | 45°  | 0.41421 | 63°  | 0.61280 | 81°  | 0.85408 |
| 10°  | 0.08749 | 28°  | 0.24933 | 46°  | 0.42447 | 64°  | 0.62487 | 82°  | 0.86929 |
| 11°  | 0.09629 | 29°  | 0.25862 | 47°  | 0.43481 | 65°  | 0.63707 | 83°  | 0.88473 |
| 12°  | 0.10510 | 30°  | 0.26795 | 48°  | 0.44523 | 66°  | 0.64941 | 84°  | 0.90040 |
| 13°  | 0.11394 | 31°  | 0.27732 | 49°  | 0.45573 | 67°  | 0.66189 | 85°  | 0.91633 |
| 14°  | 0.12278 | 32°  | 0.28675 | 50°  | 0.46631 | 68°  | 0.67451 | 86°  | 0.93252 |
| 15°  | 0.13165 | 33°  | 0.29621 | 51°  | 0.47698 | 69°  | 0.68728 | 87°  | 0.94896 |
| 16°  | 0.14054 | 34°  | 0.30573 | 52°  | 0.48773 | 70°  | 0.70021 | 88°  | 0.96569 |
| 17°  | 0.14945 | 35°  | 0.31530 | 53°  | 0.49858 | 71°  | 0.71329 | 89°  | 0.98270 |
| 18°  | 0.15838 | 36°  | 0.32492 | 54°  | 0.50953 | 72°  | 0.72654 | 90°  | 1.00000 |

Multiply factor  $M$  by the tool radius  $r$  to determine the offset dimension

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## GEARS AND GEARING

*External spur gears* are cylindrical gears with straight teeth cut parallel to the axes. Gears transmit drive between parallel shafts. Tooth loads produce no axial thrust. Excellent at moderate speeds but tend to be noisy at high speeds. Shafts rotate in opposite directions.

*Internal spur gears* provide compact drive arrangements for transmitting motion between parallel shafts rotating in the same direction.

*Helical gears* are cylindrical gears with teeth cut at an angle to the axes. Provides drive between shafts rotating in opposite directions, with superior load carrying capacity and quietness than spur gears. Tooth loads produce axial thrust.

*Crossed helical gears* are helical gears that mesh together on non-parallel axes.

*Straight bevel gears* have teeth that are radial toward the apex and are of conical form. Designed to operate on intersecting axes, bevel gears are used to connect two shafts on intersecting axes. The angle between the shafts equals the angle between the two axes of the meshing teeth. End thrust developed under load tends to separate the gears.

*Spiral bevel gears* have curved oblique teeth that contact each other smoothly and gradually from one end of a tooth to the other. Meshing is similar to that of straight bevel gears but is smoother and quieter in use. Left hand spiral teeth incline away from the axis in an anti-clockwise direction looking on small end of pinion or face of gear, right-hand teeth incline away from axis in clockwise direction. The hand of spiral of the pinion is always opposite to that of the gear and is used to identify the hand of the gear pair. Used to connect two shafts on intersecting axes as with straight bevel gears. The spiral angle does not affect the smoothness and quietness of operation or the efficiency but does affect the direction of the thrust loads created. A left-hand spiral pinion driving clockwise when viewed from the large end of the pinion creates an axial thrust that tends to move the pinion out of mesh.

*Zero bevel gears* have curved teeth lying in the same general direction as straight bevel teeth but should be considered to be spiral bevel gears with zero spiral angle.

*Hypoid bevel gears* are a cross between spiral bevel gears and worm gears. The axes of hypoid bevel gears are non-intersecting and non-parallel. The distance between the axes is called the offset. The offset permits higher ratios of reduction than is practicable with other bevel gears. Hypoid bevel gears have curved oblique teeth on which contact begins gradually and continues smoothly from one end of the tooth to the other.

*Worm gears* are used to transmit motion between shafts at right angles, that do not lie in a common plane and sometimes to connect shafts at other angles. Worm gears have line tooth contact and are used for power transmission, but the higher the ratio the lower the efficiency.

**Definitions of Gear Terms.**—The following terms are commonly applied to the various classes of gears:

*Active face width* is the dimension of the tooth face width that makes contact with a mating gear.

*Addendum* is the radial or perpendicular distance between the pitch circle and the top of the tooth.

*Arc of action* is the arc of the pitch circle through which a tooth travels from the first point of contact with the mating tooth to the point where contact ceases.

*Arc of approach* is the arc of the pitch circle through which a tooth travels from the first point of contact with the mating tooth to the pitch point.

*Arc of recession* is the arc of the pitch circle through which a tooth travels from its contact with a mating tooth at the pitch point until contact ceases.

*Axial pitch* is the distance parallel to the axis between corresponding sides of adjacent teeth.

*Axial plane* is the plane that contains the two axes in a pair of gears. In a single gear the axial plane is any plane containing the axis and any given point.

*Axial thickness* is the distance parallel to the axis between two pitch line elements of the same tooth.

*Backlash* is the shortest distance between the non-driving surfaces of adjacent teeth when the working flanks are in contact.

*Base circle* is the circle from which the involute tooth curve is generated or developed.

*Base helix angle* is the angle at the base cylinder of an involute gear that the tooth makes with the gear axis.

*Base pitch* is the circular pitch taken on the circumference of the base circles, or the distance along the line of action between two successive and corresponding involute tooth profiles. The *normal base pitch* is the base pitch in the normal plane and the *axial base pitch* is the base pitch in the axial plane.

*Base tooth thickness* is the distance on the base circle in the plane of rotation between involutes of the same pitch.

*Bottom land* is the surface of the gear between the flanks of adjacent teeth.

*Center distance* is the shortest distance between the non-intersecting axes of mating gears, or between the parallel axes of spur gears and parallel helical gears, or the crossed axes of crossed helical gears or worm gears.

*Central plane* is the plane perpendicular to the gear axis in a worm gear, which contains the common perpendicular of the gear and the worm axes. In the usual arrangement with the axes at right angles, it contains the worm axis.

*Chordal addendum* is the radial distance from the circular thickness chord to the top of the tooth, or the height from the top of the tooth to the chord subtending the circular thickness arc.

*Chordal thickness* is the length of the chord subtended by the circular thickness arc. The dimension obtained when a gear tooth caliper is used to measure the tooth thickness at the pitch circle.

*Circular pitch* is the distance on the circumference of the pitch circle, in the plane of rotation, between corresponding points of adjacent teeth. The length of the arc of the pitch circle between the centers or other corresponding points of adjacent teeth.

*Circular thickness* is the thickness of the tooth on the pitch circle in the plane of rotation, or the length of arc between the two sides of a gear tooth measured on the pitch circle.

*Clearance* is the radial distance between the top of a tooth and the bottom of a mating tooth space, or the amount by which the dedendum in a given gear exceeds the addendum of its mating gear.

*Contact diameter* is the smallest diameter on a gear tooth with which the mating gear makes contact.

*Contact ratio* is the ratio of the arc of action in the plane of rotation to the circular pitch, and is sometimes thought of as the average number of teeth in contact. This ratio is obtained most directly as the ratio of the length of action to the base pitch.

*Contact ratio – face* is the ratio of the face advance to the circular pitch in helical gears.

*Contact ratio – total* is the ratio of the sum of the arc of action and the face advance to the circular pitch.

*Contact stress* is the maximum compressive stress within the contact area between mating gear tooth profiles. Also called the Hertz stress.

*Cycloid* is the curve formed by the path of a point on a circle as it rolls along a straight line. When such a circle rolls along the outside of another circle the curve is called an *epicycloid*, and when it rolls along the inside of another circle it is called a *hypocycloid*. These curves are used in defining the former American Standard composite Tooth Form.

*Dedendum* is the radial or perpendicular distance between the pitch circle and the bottom of the tooth space.

*Diametral pitch* is the ratio of the number of teeth to the number of inches in the pitch diameter in the plane of rotation, or the number of gear teeth to each inch of pitch diameter. Normal diametral pitch is the diametral pitch as calculated in the normal plane, or the diametral pitch divided by the cosine of the helix angle.

*Efficiency* is the torque ratio of a gear set divided by its gear ratio.

*Equivalent pitch radius* is the radius of curvature of the pitch surface at the pitch point in a plane normal to the pitch line element.

*Face advance* is the distance on the pitch circle that a gear tooth travels from the time pitch point contact is made at one end of the tooth until pitch point contact is made at the other end.

*Fillet radius* is the radius of the concave portion of the tooth profile where it joins the bottom of the tooth space.

*Fillet stress* is the maximum tensile stress in the gear tooth fillet.

*Flank of tooth* is the surface between the pitch circle and the bottom land, including the gear tooth fillet.

*Gear ratio* is the ratio between the numbers of teeth in mating gears.

*Helical overlap* is the effective face width of a helical gear divided by the gear axial pitch.

*Helix angle* is the angle that a helical gear tooth makes with the gear axis at the pitch circle, unless specified otherwise.

*Hertz stress*, see *Contact stress*.

*Highest point of single tooth contact (HPSTC)* is the largest diameter on a spur gear at which a single tooth is in contact with the mating gear.

*Interference* is the contact between mating teeth at some point other than along the line of action.

*Internal diameter* is the diameter of a circle that coincides with the tops of the teeth of an internal gear.

*Internal gear* is a gear with teeth on the inner cylindrical surface.

*Involute* is the curve generally used as the profile of gear teeth. The curve is the path of a point on a straight line as it rolls along a convex base curve, usually a circle.

*Land* The top land is the top surface of a gear tooth and the *bottom land* is the surface of the gear between the fillets of adjacent teeth.

*Lead* is the axial advance of the helix in one complete turn, or the distance along its own axis on one revolution if the gear were free to move axially.

*Length of action* is the distance on an involute line of action through which the point of contact moves during the action of the tooth profile.

*Line of action* is the portion of the common tangent to the base cylinders along which contact between mating involute teeth occurs.

*Lowest point of single tooth contact (LPSTC)* is the smallest diameter on a spur gear at which a single tooth is in contact with its mating gear. Gear set contact stress is determined with a load placed on the pinion at this point.

*Module* is the ratio of the pitch diameter to the number of teeth, normally the ratio of pitch diameter in mm to the number of teeth. Module in the inch system is the ratio of the pitch diameter in inches to the number of teeth.

*Normal plane* is a plane normal to the tooth surfaces at a point of contact and perpendicular to the pitch plane.

*Number of teeth* is the number of teeth contained in a gear.

*Outside diameter* is the diameter of the circle that contains the tops of the teeth of external gears.

*Pitch* is the distance between similar, equally-spaced tooth surfaces in a given direction along a given curve or line.

*Pitch circle* is the circle through the pitch point having its center at the gear axis.

*Pitch diameter* is the diameter of the pitch circle. The operating pitch diameter is the pitch diameter at which the gear operates.

*Pitch plane* is the plane parallel to the axial plane and tangent to the pitch surfaces in any pair of gears. In a single gear, the pitch plane may be any plane tangent to the pitch surfaces.

*Pitch point* is the intersection between the axes of the line of centers and the line of action.

*Plane of rotation* is any plane perpendicular to a gear axis.

**Pressure angle** is the angle between a tooth profile and a radial line at its pitch point. In involute teeth, the pressure angle is often described as the angle between the line of action and the line tangent to the pitch circle. *Standard pressure angles* are established in connection with standard tooth proportions. A given pair of involute profiles will transmit smooth motion at the same velocity ratio when the center distance is changed. Changes in center distance in gear design and gear manufacturing operations may cause changes in pitch diameter, pitch and pressure angle in the same gears under different conditions. Unless otherwise specified, the pressure angle is the *standard pressure angle at the standard pitch diameter*. The *operating pressure angle* is determined by the center distance at which a pair of gears operate. In oblique teeth such as helical and spiral designs, the pressure angle is specified in the transverse, normal or axial planes.

**Principle reference planes** are pitch plane, axial plane and transverse plane, all intersecting at a point and mutually perpendicular.

**Rack:** A rack is a gear with teeth spaced along a straight line, suitable for straight line motion. A basic rack is a rack that is adopted as the basis of a system of interchangeable gears. Standard gear tooth dimensions are often illustrated on an outline of a basic rack.

**Roll angle** is the angle subtended at the center of a base circle from the origin of an involute to the point of tangency of a point on a straight line from any point on the same involute. The radian measure of this angle is the tangent of the pressure angle of the point on the involute.

**Root diameter** is the diameter of the circle that contains the roots or bottoms of the tooth spaces.

**Tangent plane** is a plane tangent to the tooth surfaces at a point or line of contact.

**Tip relief** is an arbitrary modification of a tooth profile where a small amount of material is removed from the involute face of the tooth surface near the tip of the gear tooth.

**Tooth face** is the surface between the pitch line element and the tooth tip.

**Tooth surface** is the total tooth area including the flank of the tooth and the tooth face.

**Total face width** is the dimensional width of a gear blank and may exceed the effective face width as with a double-helical gear where the total face width includes any distance separating the right-hand and left-hand helical gear teeth.

**Transverse plane** is a plane that is perpendicular to the axial plane and to the pitch plane. In gears with parallel axes, the transverse plane and the plane of rotation coincide.

**Trochoid** is the curve formed by the path of a point on the extension of a radius of a circle as it rolls along a curve or line. A trochoid is also the curve formed by the path of a point on a perpendicular to a straight line as the straight line rolls along the convex side of a base curve. By the first definition, a trochoid is derived from the *cycloid*, by the second definition it is derived from the *involute*.

**True involute form diameter** is the smallest diameter on the tooth at which the point of tangency of the involute tooth profile exists. Usually this position is the point of tangency of the involute tooth profile and the fillet curve, and is often referred to as the TIF diameter.

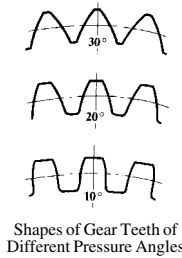
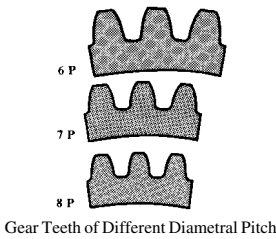
**Undercut** is a condition in generated gear teeth when any part of the fillet curve lies inside a line drawn at a tangent to the working profile at its lowest point. Undercut may be introduced deliberately to facilitate shaving operations, as in pre-shaving.

**Whole depth** is the total depth of a tooth space, equal to the addendum plus the dedendum and equal to the working depth plus clearance.

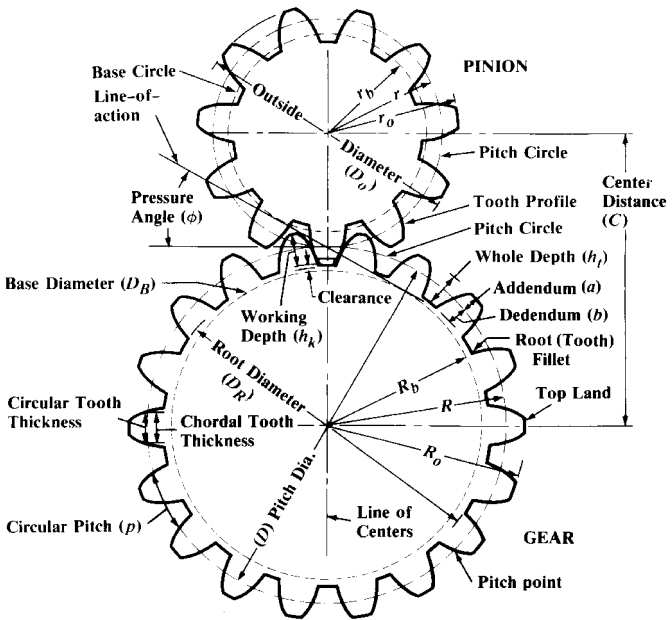
**Working depth** is the depth of engagement of two gears, or the sum of their addendums. The standard working distance is the depth to which a tooth extends into the tooth space of a mating gear when the center distance is standard.

Definitions of gear terms are given in AGMA Standards 112.05, 115.01, and 116.01 entitled "Terms, Definitions, Symbols and Abbreviations," "Reference Information—Basic Gear Geometry," and "Glossary—Terms Used in Gearing," respectively; obtainable from American Gear Manufacturers Assn., 500 Montgomery St., St., Alexandria, VA 22314.

Comparative Sizes and Shape of Gear Teeth



Nomenclature of Gear Teeth



Terms Used in Gear Geometry from Table 1 on page 2035

**Properties of the Involute Curve.**—The involute curve is used almost exclusively for gear-tooth profiles, because of the following important properties.

1) The form or shape of an involute curve depends upon the diameter of the base circle from which it is derived. (If a taut line were unwound from the circumference of a circle—the *base circle* of the involute—the end of that line or any point on the unwound portion, would describe an involute curve.)

2) If a gear tooth of involute curvature acts against the involute tooth of a mating gear while rotating at a uniform rate, the angular motion of the driven gear will also be uniform, even though the center-to-center distance is varied.

3) The relative rate of motion between driving and driven gears having involute tooth curves is established by the diameters of their base circles.

4) Contact between intermeshing involute teeth on a driving and driven gear is along a straight line that is tangent to the two base circles of these gears. This is the *line of action*.

5) The point where the line of action intersects the common center-line of the mating involute gears, establishes the radii of the pitch circles of these gears; hence true pitch circle diameters are affected by a change in the center distance. (Pitch diameters obtained by dividing the number of teeth by the diametral pitch apply when the center distance equals the total number of teeth on both gears divided by twice the diametral pitch.)

6) The pitch diameters of mating involute gears are directly proportional to the diameters of their respective base circles; thus, if the base circle of one mating gear is three times as large as the other, the pitch circle diameters will be in the same ratio.

7) The angle between the line of action and a line perpendicular to the common center-line of mating gears, is the *pressure angle*; hence the pressure angle is affected by any change in the center distance.

8) When an involute curve acts against a straight line (as in the case of an involute pinion acting against straight-sided rack teeth), the straight line is tangent to the involute and perpendicular to its line of action.

9) The pressure angle, in the case of an involute pinion acting against straight-sided rack teeth, is the angle between the line of action and the line of the rack's motion. If the involute pinion rotates at a uniform rate, movement of the rack will also be uniform.

*Nomenclature:*

$\phi$  = Pressure Angle

$a$  = Addendum     $a_G$  = Addendum of Gear     $a_p$  = Addendum of Pinion

$b$  = Dedendum

$c$  = Clearance

$C$  = Center Distance

$D$  = Pitch Diameter     $D_G$  = Pitch Diameter of Gear     $D_p$  = Pitch Diameter of Pinion

$D_B$  = Base Circle Diameter     $D_O$  = Outside Diameter     $D_R$  = Root Diameter

$F$  = Face Width

$h_k$  = Working Depth of Tooth     $h_t$  = Whole Depth of Tooth

$m_G$  = Gear Ratio

$N$  = Number of Teeth     $N_G$  = Number of Teeth in Gear     $N_p$  = Number of Teeth in Pinion

$p$  = Circular Pitch     $P$  = Diametral Pitch

**Diametral and Circular Pitch Systems.**—Gear tooth system standards are established by specifying the tooth proportions of the basic rack. The diametral pitch system is applied to most of the gearing produced in the United States. If gear teeth are larger than about one diametral pitch, it is common practice to use the circular pitch system. The circular pitch system is also applied to cast gearing and it is commonly used in connection with the design and manufacture of worm gearing.

**Pitch Diameters Obtained with Diametral Pitch System.**—The diametral pitch system is arranged to provide a series of standard tooth sizes, the principle being similar to the standardization of screw thread pitches. Inasmuch as there must be a whole number of teeth on each gear, the increase in pitch diameter per tooth varies according to the pitch. For example, the pitch diameter of a gear having, say, 20 teeth of 4 diametral pitch, will be 5 inches; 21 teeth,  $5\frac{1}{4}$  inches; and so on, the increase in diameter for each additional tooth being equal to  $\frac{1}{4}$  inch for 4 diametral pitch. Similarly, for 2 diametral pitch the variations for successive numbers of teeth would equal  $\frac{1}{2}$  inch, and for 10 diametral pitch the varia-

tions would equal  $\frac{1}{10}$  inch, etc. Where a given center distance must be maintained and no standard diametral pitch can be used, gears should be designed with reference to the gear set center distance procedure discussed in *Gears for Given Center Distance and Ratio* starting on page 2043.

**Table 1. Formulas for Dimensions of Standard Spur Gears**

| To Find              | Formula                              | To Find   | Formula                              |
|----------------------|--------------------------------------|---|--------------------------------------|
| Base Circle Diameter | $D_B = D \cos \phi$ (1)              | Number of Teeth                                 | $N = P \times D$ (6a)                |
| Circular Pitch       | $p = \frac{3.1416D}{N}$ (2a)         |   | $N = \frac{3.1416D}{p}$ (6b)         |
|                      | $p = \frac{3.1416}{P}$ (2b)          | Outside Diameter (Full-depth Teeth)             | $D_O = \frac{N+2}{P}$ (7a)           |
| Center Distance      | $C = \frac{N_P(m_G+1)}{2P}$ (3a)     |   | $D_O = \frac{(N+2)p}{3.1416}$ (7b)   |
|                      | $C = \frac{D_P+D_G}{2}$ (3b)         | Outside Diameter (American Standard Stub Teeth) | $D_O = \frac{N+1.6}{P}$ (8a)         |
|                      | $C = \frac{N_G+N_P}{2P}$ (3c)        |   | $D_O = \frac{(N+1.6)p}{3.1416}$ (8b) |
|                      | $C = \frac{(N_G+N_P)p}{6.2832}$ (3d) | Outside Diameter                                | $D_O = D + 2a$ (9)                   |
| Diametral Pitch      | $P = \frac{3.1416}{p}$ (4a)          | Pitch Diameter                                  | $D = \frac{N}{P}$ (10a)              |
|                      | $P = \frac{N}{D}$ (4b)               |   | $D = \frac{Np}{3.1416}$ (10b)        |
|                      | $P = \frac{N_P(m_G+1)}{2C}$ (4c)     | Root Diameter <sup>a</sup>                      | $D_R = D - 2b$ (11)                  |
| Gear Ratio           | $m_G = \frac{N_G}{N_P}$ (5)          | Whole Depth                                     | $a + b$ (12)                         |
|                      |                                      | Working Depth                                   | $a_G + a_P$ (13)                     |

<sup>a</sup> See also formulas in Tables 2 and 4 on pages 2035 and 2039.

**Table 2. Formulas for Tooth Parts, 20- and 25-degree Involute Full-depth Teeth ANSI Coarse Pitch Spur Gear Tooth Forms ANSI B6.1-1968 (R1974)**

| To Find   | Diametral Pitch, $P$ , Known | Circular Pitch, $p$ , Known |
|---|------------------------------|-----------------------------|
| Addendum  | $a = 1.000 \div P$           | $a = 0.3183 \times p$       |
| Dedendum (Preferred)<br>(Shaved or Ground Teeth) <sup>a</sup> | $b = 1.250 \div P$           | $b = 0.3979 \times p$       |
|   | $b = 1.350 \div P$           | $b = 0.4297 \times p$       |
| Working Depth   | $h_k = 2.000 \div P$         | $h_k = 0.6366 \times p$     |
| Whole Depth (Preferred)<br>(Shaved or Ground Teeth)           | $h_t = 2.250 \div P$         | $h_t = 0.7162 \times p$     |
|   | $h_t = 2.350 \div P$         | $h_t = 0.7480 \times p$     |
| Clearance (Preferred) <sup>b</sup>                            | $c = 0.250 \div P$           | $c = 0.0796 \times p$       |



**Table 2. (Continued) Formulas for Tooth Parts, 20- and 25-degree Involute Full-depth Teeth ANSI Coarse Pitch Spur Gear Tooth Forms ANSI B6.1-1968 (R1974)**

| To Find                           | Diametral Pitch,<br>$P$ , Known | Circular Pitch,<br>$p$ , Known   |
|-----------------------------------|---------------------------------|----------------------------------|
| (Shaved or Ground Teeth)          | $c = 0.350 \div P$              | $c = 0.1114 \times p$            |
| Fillet Radius (Rack) <sup>c</sup> | $r_f = 0.300 \div P$            | $r_f = 0.0955 \times p$          |
| Pitch Diameter                    | $D = N \div P$                  | $D = 0.3183 \times N_p$          |
| Outside Diameter                  | $D_O = (N + 2) \div P$          | $D_O = 0.3183 \times (N + 2)p$   |
| Root Diameter (Preferred)         | $D_R = (N - 2.5) \div P$        | $D_R = 0.3183 \times (N - 2.5)p$ |
| (Shaved or Ground Teeth)          | $D_R = (N - 2.7) \div P$        | $D_R = 0.3183 \times (N - 2.7)p$ |
| Circular Thickness—Basic          | $t = 1.5708 \div P$             | $t = p \div 2$                   |

<sup>a</sup> When gears are preshaved cut on a gear shaper the dedendum will usually need to be increased to  $1.40/P$  to allow for the higher fillet trochoid produced by the shaper cutter. This is of particular importance on gears of few teeth or if the gear blank configuration requires the use of a small diameter shaper cutter, in which case the dedendum may need to be increased to as much as  $1.45/P$ . This should be avoided on highly loaded gears where the consequently reduced  $J$  factor will increase gear tooth stress excessively.

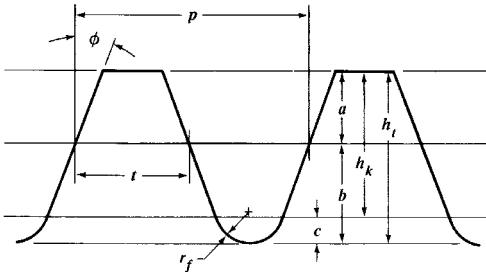
<sup>b</sup> A minimum clearance of  $0.157/P$  may be used for the basic 20-degree and 25-degree pressure angle rack in the case of shallow root sections and use of existing hobs or cutters. However, whenever less than standard clearance is used, the location of the TIF diameter should be determined by the method shown in *True Involute Form Diameter* starting on page 2061. The TIF diameter must be less than the Contact Diameter determined by the method shown on page 2059.

<sup>c</sup> The fillet radius of the basic rack should not exceed  $0.235/P$  for a 20-degree pressure angle rack or  $0.270/P$  for a 25-degree pressure angle rack for a clearance of  $0.157/P$ . The basic rack fillet radius must be reduced for teeth with a 25-degree pressure angle having a clearance in excess of  $0.250/P$ .

**American National Standard Coarse Pitch Spur Gear Tooth Forms.**—The American National Standard (ANSI B6.1-1968, R1974) provides tooth proportion information on two involute spur gear forms. These two forms are identical except that one has a pressure angle of 20 degrees and a minimum allowable tooth number of 18 while the other has a pressure angle of 25 degrees and a minimum allowable tooth number of 12. (For pinions with fewer teeth, see tooth proportions for long addendum pinions and their mating short addendum gears in Tables 7 through 9d starting on page 2050.) A gear tooth standard is established by specifying the tooth proportions of the basic rack. Gears made to this standard will thus be conjugate with the specified rack and with each other. The basic rack forms for the 20-degree and 25-degree standard are shown on the following page; basic formulas for these proportions as a function of the gear diametral pitch and also of the circular pitch are given in Table 2. Tooth parts data are given in Table 3.

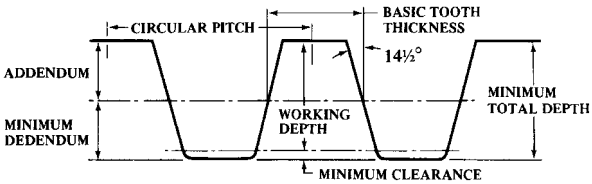
In recent years the established standard of almost universal use is the ANSI 20-degree standard spur gear form. It provides a gear with good strength and without fillet undercut in pinions of as few as eighteen teeth. Some more recent applications have required a tooth form of even greater strength and fewer teeth than eighteen. This requirement has stimulated the establishment of the ANSI 25-degree standard. This 25-degree form will give greater tooth strength than the 20-degree standard, will provide pinions of as few as twelve teeth without fillet undercut and will provide a lower contact compressive stress for greater gear set surface durability.

**American National Standard and Former American Standard Gear Tooth Forms**  
 ANSI B6.1-1968, (R1974) and ASA B6.1-1932

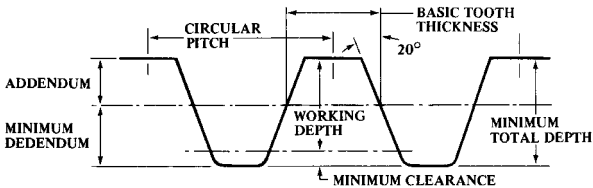


- |                 |                       |  |
|-----------------|-----------------------|--|
| $a$ = addendum  | $h_k$ = working depth | $r_f$ = fillet radius of basic rack    |
| $b$ = dedendum  | $h_t$ = whole depth   | $t$ = circular tooth thickness — basic |
| $c$ = clearance | $p$ = circular pitch  | $\phi$ = pressure angle                |

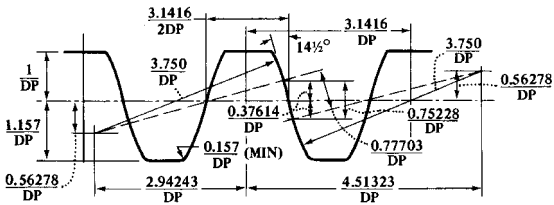
Basic Rack of the 20-Degree and 25-Degree Full-Depth Involute Systems



Basic Rack of the 14½-Degree Full-Depth Involute System



Basic Rack of the 20-Degree Stub Involute System



Approximation of Basic Rack for the 14½-Degree Composite System

**Table 3. Gear Tooth Parts for American National Standard Coarse Pitch 20- and 25-Degree Pressure Angle Gears**

| Dia. Pitch | Circ. Pitch | Stand. Addend. <sup>a</sup> | Stand. Dedend. | Spec. Dedend. <sup>b</sup> | Min. Dedend. | Stand. F. Rad. | Min. F. Rad. |
|------------|-------------|-----------------------------|----------------|----------------------------|--------------|----------------|--------------|
| $P$        | $p$         | $a$                         | $b$            | $b$                        | $b$          | $r_f$          | $r_f$        |
| 0.3142     | 10.         | 3.1831                      | 3.9789         | 4.2972                     | 3.6828       | 0.9549         | 0.4997       |
| 0.3307     | 9.5         | 3.0239                      | 3.7799         | 4.0823                     | 3.4987       | 0.9072         | 0.4748       |
| 0.3491     | 9.          | 2.8648                      | 3.5810         | 3.8675                     | 3.3146       | 0.8594         | 0.4498       |
| 0.3696     | 8.5         | 2.7056                      | 3.3820         | 3.6526                     | 3.1304       | 0.8117         | 0.4248       |
| 0.3927     | 8.          | 2.5465                      | 3.1831         | 3.4377                     | 2.9463       | 0.7639         | 0.3998       |
| 0.4189     | 7.5         | 2.3873                      | 2.9842         | 3.2229                     | 2.7621       | 0.7162         | 0.3748       |
| 0.4488     | 7.          | 2.2282                      | 2.7852         | 3.0080                     | 2.5780       | 0.6685         | 0.3498       |
| 0.4833     | 6.5         | 2.0690                      | 2.5863         | 2.7932                     | 2.3938       | 0.6207         | 0.3248       |
| 0.5236     | 6.          | 1.9099                      | 2.3873         | 2.5783                     | 2.2097       | 0.5730         | 0.2998       |
| 0.5712     | 5.5         | 1.7507                      | 2.1884         | 2.3635                     | 2.0256       | 0.5252         | 0.2749       |
| 0.6283     | 5.          | 1.5915                      | 1.9894         | 2.1486                     | 1.8414       | 0.4775         | 0.2499       |
| 0.6981     | 4.5         | 1.4324                      | 1.7905         | 1.9337                     | 1.6573       | 0.4297         | 0.2249       |
| 0.7854     | 4.          | 1.2732                      | 1.5915         | 1.7189                     | 1.4731       | 0.3820         | 0.1999       |
| 0.8976     | 3.5         | 1.1141                      | 1.3926         | 1.5040                     | 1.2890       | 0.3342         | 0.1749       |
| 1.         | 3.1416      | 1.0000                      | 1.2500         | 1.3500                     | 1.1570       | 0.3000         | 0.1570       |
| 1.25       | 2.5133      | 0.8000                      | 1.0000         | 1.0000                     | 0.9256       | 0.2400         | 0.1256       |
| 1.5        | 2.0944      | 0.6667                      | 0.8333         | 0.9000                     | 0.7713       | 0.2000         | 0.1047       |
| 1.75       | 1.7952      | 0.5714                      | 0.7143         | 0.7714                     | 0.6611       | 0.1714         | 0.0897       |
| 2.         | 1.5708      | 0.5000                      | 0.6250         | 0.6750                     | 0.5785       | 0.1500         | 0.0785       |
| 2.25       | 1.3963      | 0.4444                      | 0.5556         | 0.6000                     | 0.5142       | 0.1333         | 0.0698       |
| 2.5        | 1.2566      | 0.4000                      | 0.5000         | 0.5400                     | 0.4628       | 0.1200         | 0.0628       |
| 2.75       | 1.1424      | 0.3636                      | 0.4545         | 0.4909                     | 0.4207       | 0.1091         | 0.0571       |
| 3.         | 1.0472      | 0.3333                      | 0.4167         | 0.4500                     | 0.3857       | 0.1000         | 0.0523       |
| 3.25       | 0.9666      | 0.3077                      | 0.3846         | 0.4154                     | 0.3560       | 0.0923         | 0.0483       |
| 3.5        | 0.8976      | 0.2857                      | 0.3571         | 0.3857                     | 0.3306       | 0.0857         | 0.0449       |
| 3.75       | 0.8378      | 0.2667                      | 0.3333         | 0.3600                     | 0.3085       | 0.0800         | 0.0419       |
| 4.         | 0.7854      | 0.2500                      | 0.3125         | 0.3375                     | 0.2893       | 0.0750         | 0.0392       |
| 4.5        | 0.6981      | 0.2222                      | 0.2778         | 0.3000                     | 0.2571       | 0.0667         | 0.0349       |
| 5.         | 0.6283      | 0.2000                      | 0.2500         | 0.2700                     | 0.2314       | 0.0600         | 0.0314       |
| 5.5        | 0.5712      | 0.1818                      | 0.2273         | 0.2455                     | 0.2104       | 0.0545         | 0.0285       |
| 6.         | 0.5236      | 0.1667                      | 0.2083         | 0.2250                     | 0.1928       | 0.0500         | 0.0262       |
| 6.5        | 0.4833      | 0.1538                      | 0.1923         | 0.2077                     | 0.1780       | 0.0462         | 0.0242       |
| 7.         | 0.4488      | 0.1429                      | 0.1786         | 0.1929                     | 0.1653       | 0.0429         | 0.0224       |
| 7.5        | 0.4189      | 0.1333                      | 0.1667         | 0.1800                     | 0.1543       | 0.0400         | 0.0209       |
| 8.         | 0.3927      | 0.1250                      | 0.1563         | 0.1687                     | 0.1446       | 0.0375         | 0.0196       |
| 8.5        | 0.3696      | 0.1176                      | 0.1471         | 0.1588                     | 0.1361       | 0.0353         | 0.0185       |
| 9.         | 0.3491      | 0.1111                      | 0.1389         | 0.1500                     | 0.1286       | 0.0333         | 0.0174       |
| 9.5        | 0.3307      | 0.1053                      | 0.1316         | 0.1421                     | 0.1218       | 0.0316         | 0.0165       |
| 10.        | 0.3142      | 0.1000                      | 0.1250         | 0.1350                     | 0.1157       | 0.0300         | 0.0157       |
| 11.        | 0.2856      | 0.0909                      | 0.1136         | 0.1227                     | 0.1052       | 0.0273         | 0.0143       |
| 12.        | 0.2618      | 0.0833                      | 0.1042         | 0.1125                     | 0.0964       | 0.0250         | 0.0131       |
| 13.        | 0.2417      | 0.0769                      | 0.0962         | 0.1038                     | 0.0890       | 0.0231         | 0.0121       |
| 14.        | 0.2244      | 0.0714                      | 0.0893         | 0.0964                     | 0.0826       | 0.0214         | 0.0112       |
| 15.        | 0.2094      | 0.0667                      | 0.0833         | 0.0900                     | 0.0771       | 0.0200         | 0.0105       |
| 16.        | 0.1963      | 0.0625                      | 0.0781         | 0.0844                     | 0.0723       | 0.0188         | 0.0098       |
| 17.        | 0.1848      | 0.0588                      | 0.0735         | 0.0794                     | 0.0681       | 0.0176         | 0.0092       |
| 18.        | 0.1745      | 0.0556                      | 0.0694         | 0.0750                     | 0.0643       | 0.0167         | 0.0087       |
| 19.        | 0.1653      | 0.0526                      | 0.0658         | 0.0711                     | 0.0609       | 0.0158         | 0.0083       |
| 20.        | 0.1571      | 0.0500                      | 0.0625         | 0.0675                     | 0.0579       | 0.0150         | 0.0079       |

<sup>a</sup> When using equal addendums on pinion and gear the minimum number of teeth on the pinion is 18 and the minimum total number of teeth in the pair is 36 for 20-degree full depth involute tooth form and 12 and 24, respectively, for 25-degree full depth tooth form.

<sup>b</sup> The dedendum in this column is used when the gear tooth is shaved. It allows for the higher fillet cut by a protuberance hob.

The working depth is equal to twice the addendum.

The whole depth is equal to the addendum plus the dedendum.

**Table 4. Tooth Proportions for Fine-Pitch Involute Spur and Helical Gears of 14½°, 20-, and 25-Degree Pressure Angle ANSI B6.7-1977**

| Item   | Spur  | Helical  |
|--|---|--|
| Addendum, $a$  | $\frac{1.000}{P}$   | $\frac{1.000}{P_n}$  |
| Dedendum, $b$  | $\frac{1.200}{P} + 0.002$ (min.)                              | $\frac{1.200}{P_n} + 0.002$ (min.)   |
| Working Depth, $h_k$   | $\frac{2.000}{P}$   | $\frac{2.000}{P_n}$  |
| Whole Depth, $h_t$   | $\frac{2.200}{P} + 0.002$ (min.)                              | $\frac{2.200}{P_n} + 0.002$ (min.)   |
| Clearance, $c$<br>(Standard)   | $\frac{0.200}{P} + 0.002$ (min.)                              | $\frac{0.200}{P_n} + 0.002$ (min.)   |
| (Shaved or Ground Teeth)   | $\frac{0.350}{P} + 0.002$ (min.)                              | $\frac{0.350}{P_n} + 0.002$ (min.)   |
| Tooth Thickness, $t$<br>At Pitch Diameter  | $t = \frac{1.5708}{P}$  | $t_n = \frac{1.5708}{P_n}$   |
| Circular Pitch, $p$  | $p = \frac{\pi D}{N}$ or $\frac{\pi d}{n}$ or $\frac{\pi}{P}$ | $p_n = \frac{\pi}{P_n}$  |
| Pitch Diameter<br>Pinion, $d$  | $\frac{n}{P}$   | $\frac{n}{P_n \cos \psi}$  |
| Gear, $D$  | $\frac{N}{P}$   | $\frac{N}{P_n \cos \psi}$  |
| Outside Diameter<br>Pinion, $d_o$  | $\frac{n+2}{P}$   | $\frac{1}{P_n} \left( \frac{n}{\cos \psi} + 2 \right)$                             |
| Gear, $D_o$  | $\frac{N+2}{P}$   | $\frac{1}{P_n} \left( \frac{N}{\cos \psi} + 2 \right)$                             |
| Center Distance, $C$   | $\frac{N+n}{2P}$  | $\frac{N+n}{2P_n \cos \psi}$   |
| All dimensions are in inches.<br>$P$ = Transverse Diametral Pitch<br>$P_n$ = Normal Diametral Pitch<br>$t_n$ = Normal Tooth Thickness at Pitch Diameter<br>$p_n$ = Normal Circular Pitch |   | $\psi$ = Helix Angle<br>$n$ = Number of pinion teeth<br>$N$ = Number of gear teeth |

**American National Standard Tooth Proportions for Fine-Pitch Involute Spur and Helical Gears.**—The proportions of spur gears in this Standard (ANSI B6.7-1977) follow closely ANSI B6.1-1968, R1974, “Tooth Proportions for Coarse-Pitch Involute Spur Gears.” The main difference between fine-pitch and coarse-pitch gears is the greater clearance specified for fine-pitch gears. The increased clearance provides for any foreign material that may tend to accumulate at the bottoms of the teeth and also the relatively larger fillet radius resulting from proportionately greater wear on the tips of fine-pitch cutting tools.

**Pressure Angle:** The standard pressure angle for fine-pitch gears is 20 degrees and is recommended for most applications. For helical gears this pressure angle applies in the *normal* plane. In certain cases, notably sintered or molded gears, or in gearing where greatest strength and wear resistance are desired, a 25-degree pressure angle may be required.

However, pressure angles greater than 20 degrees tend to require use of generating tools having very narrow point widths, and higher pressure angles require closer control of center distance when backlash requirements are critical.

In those cases where consideration of angular position or backlash is critical and both pinion and gear contain relatively large numbers of teeth, a  $14\frac{1}{2}$ -degree pressure angle may be desirable. In general, pressure angles less than 20 degrees require greater amounts of tooth modification to avoid undercutting problems and are limited to larger total numbers of teeth in pinion and gear when operating at a standard center distance. Information Sheet B in the Standard provides tooth proportions for both  $14\frac{1}{2}$ - and 25-degree pressure angle fine-pitch gears. [Table 4](#) provides tooth proportions for fine-pitch spur and helical gears with  $14\frac{1}{2}$ -, 20-, and 25-degree pressure angles, and [Table 5](#) provides tooth parts.

*Diametral Pitches:* Diametral pitches preferred are: 20, 24, 32, 40, 48, 64, 72, 80, 96, and 120.

**Table 5. American National Standard Fine Pitch Standard Gear Tooth Parts— $14\frac{1}{2}$ -, 20-, and 25-Degree Pressure Angles**

| Diametral Pitch | Circular Pitch | Circular Thickness | Standard Addend. | Standard Dedend. | Special Dedend. <sup>a</sup> |
|-----------------|----------------|--------------------|------------------|------------------|------------------------------|
| <i>P</i>        | <i>p</i>       | <i>t</i>           | <i>a</i>         | <i>b</i>         | <i>b</i>                     |
| 20              | 0.1571         | 0.0785             | 0.0500           | 0.0620           | 0.0695                       |
| 24              | 0.1309         | 0.0654             | 0.0417           | 0.0520           | 0.0582                       |
| 32              | 0.0982         | 0.0491             | 0.0313           | 0.0395           | 0.0442                       |
| 40              | 0.0785         | 0.0393             | 0.0250           | 0.0320           | 0.0358                       |
| 48              | 0.0654         | 0.0327             | 0.0208           | 0.0270           | 0.0301                       |
| 64              | 0.0491         | 0.0245             | 0.0156           | 0.0208           | 0.0231                       |
| 72              | 0.0436         | 0.0218             | 0.0139           | 0.0187           | 0.0208                       |
| 80              | 0.0393         | 0.0196             | 0.0125           | 0.0170           | 0.0189                       |
| 96              | 0.0327         | 0.0164             | 0.0104           | 0.0145           | 0.0161                       |
| 120             | 0.0262         | 0.0131             | 0.0083           | 0.0120           | 0.0132                       |

<sup>a</sup>Based upon clearance for shaved or ground teeth.

The working depth is equal to twice the addendum. The whole depth is equal to the addendum plus the dedendum. For minimum number of teeth see page [2058](#).

**Other American Spur Gear Standards.**—An appended information sheet in the American National Standard ANSI B6.1-1968, R1974 provides tooth proportion information for three spur gear forms with the notice that they are “not recommended for new designs.” These forms are therefore considered to be obsolescent but the information is given on their proportions because they have been used widely in the past. These forms are the  $14\frac{1}{2}$ -degree full depth form, the 20-degree stub involute form and the  $14\frac{1}{2}$ -degree composite form which were covered in the former American Standard (ASA B6.1-1932). The basic rack for the  $14\frac{1}{2}$ -degree full depth form is shown on page [2036](#); basic formulas for these proportions are given in [Table 6](#).

**Table 6. Formulas for Tooth Parts—Former American Standard Spur Gear Tooth Forms ASA B6.1-1932**

| To Find                              | Diametral Pitch, $P$<br>Known | Circular Pitch, $p$<br>Known |
|--------------------------------------|-------------------------------|------------------------------|
| 14½-Degree Involute Full-depth Teeth |                               |                              |
| Addendum                             | $a = 1.000 \div P$            | $a = 0.3183 \times p$        |
| Minimum Dedendum                     | $b = 1.157 \div P$            | $b = 0.3683 \times p$        |
| Working Depth                        | $h_k = 2.000 \div P$          | $h_k = 0.6366 \times p$      |
| Minimum Whole Depth                  | $h_t = 2.157 \div P$          | $h_t = 0.6866 \times p$      |
| Basic Tooth Thickness on Pitch Line  | $t = 1.5708 \div P$           | $t = 0.500 \times p$         |
| Minimum Clearance                    | $c = 0.157 \div P$            | $c = 0.050 \times p$         |
| 20-Degree Involute Stub Teeth        |                               |                              |
| Addendum                             | $a = 0.800 \div P$            | $a = 0.2546 \times p$        |
| Minimum Dedendum                     | $b = 1.000 \div P$            | $b = 0.3183 \times p$        |
| Working Depth                        | $h_k = 1.600 \div P$          | $h_k = 0.5092 \times p$      |
| Minimum Whole Depth                  | $h_t = 1.800 \div P$          | $h_t = 0.5729 \times p$      |
| Basic Tooth Thickness on Pitch Line  | $t = 1.5708 \div P$           | $t = 0.500 \times p$         |
| Minimum Clearance                    | $c = 0.200 \div P$            | $c = 0.0637 \times p$        |

Note: Radius of fillet equals  $1\frac{1}{3} \times$  clearance for 14½-degree full-depth teeth and  $1\frac{1}{2} \times$  clearance for 20-degree full-depth teeth.

Note: A suitable working tolerance should be considered in connection with all minimum recommendations.

**Fellows Stub Tooth.**—The system of stub gear teeth introduced by the Fellows Gear Shaper Co. is based upon the use of two diametral pitches. One diametral pitch, say, 8, is used as the basis for obtaining the dimensions for the addendum and dedendum, while another diametral pitch, say, 6, is used for obtaining the dimensions of the thickness of the tooth, the number of teeth, and the pitch diameter. Teeth made according to this system are designated as  $\frac{6}{8}$  pitch,  $\frac{12}{14}$  pitch, etc., the numerator in this fraction indicating the pitch determining the thickness of the tooth and the number of teeth, and the denominator, the pitch determining the depth of the tooth. The clearance is made greater than in the ordinary gear-tooth system and equals  $0.25 \div$  denominator of the diametral pitch. The pressure angle is 20 degrees.

This type of stub gear tooth is now used infrequently. For information as to the tooth part dimensions see 18th and earlier editions of Machinery's Handbook.

**Basic Gear Dimensions.**—The basic dimensions for all involute spur gears may be obtained using the formulas shown in Table 1. This table is used in conjunction with Table 3 to obtain dimensions for coarse pitch gears and Table 5 to obtain dimensions for fine pitch standard spur gears. To obtain the dimensions of gears that are specified at a standard circular pitch, the equivalent diametral pitch is first calculated by using the formula in Table 1. If the required number of teeth in the pinion ( $N_p$ ) is less than the minimum specified in either Table 3 or Table 5, whichever is applicable, the gears must be proportioned by the long and short addendum method shown on page 2052.

**Formulas for Outside and Root Diameters of Spur Gears that are  
Finish-hobbed, Shaped, or Pre-shaved**

| Notation   |                                     |
|--|-------------------------------------|
| $D$ = Pitch Diameter   | $a$ = Standard Addendum             |
| $D_O$ = Outside Diameter   | $b$ = Standard Minimum Dedendum     |
| $D_R$ = Root Diameter  | $b_s$ = Standard Dedendum           |
| $P$ = Diametral Pitch  | $b_{ps}$ = Dedendum for Pre-shaving |
| 14½, 20-, And 25-degree Involute Full-depth Teeth (19P and coarser) <sup>a</sup> |                                     |
| $D_O = D + 2a = \frac{N}{P} + \left(2 \times \frac{1}{P}\right)$                 |                                     |
| $D_R = D - 2b = \frac{N}{P} - \left(2 \times \frac{1.157}{P}\right)$             | (Hobbed) <sup>b</sup>               |
| $D_R = D - 2b_s = \frac{N}{P} - \left(2 \times \frac{1.25}{P}\right)$            | (Shaped) <sup>c</sup>               |
| $D_R = D - 2b_{ps} = \frac{N}{P} - \left(2 \times \frac{1.35}{P}\right)$         | (Pre-shaved) <sup>d</sup>           |
| $D_R = D - 2b_{ps} = \frac{N}{P} - \left(2 \times \frac{1.40}{P}\right)$         | (Pre-shaved) <sup>e</sup>           |
| 20-degree Involute Fine-pitch Full-depth Teeth (20P and finer)                   |                                     |
| $D_O = D + 2a = \frac{N}{P} + \left(2 \times \frac{1}{P}\right)$                 |                                     |
| $D_R = D - 2b = \frac{N}{P} - 2\left(\frac{1.2}{P} + 0.002\right)$               | (Hobbed or Shaped) <sup>f</sup>     |
| $D_R = D - 2b_{ps} = \frac{N}{P} - 2\left(\frac{1.35}{P} + 0.002\right)$         | (Pre-shaved) <sup>g</sup>           |
| 20-degree Involute Stub Teeth <sup>a</sup>                                       |                                     |
| $D_O = D + 2a = \frac{N}{P} + \left(2 \times \frac{0.8}{P}\right)$               |                                     |
| $D_R = D - 2b = \frac{N}{P} - \left(2 \times \frac{1}{P}\right)$                 | (Hobbed)                            |
| $D_R = D - 2b_{ps} = \frac{N}{P} - \left(2 \times \frac{1.35}{P}\right)$         | (Pre-shaved)                        |

<sup>a</sup> 14½-degree full-depth and 20-degree stub teeth are not recommended for new designs.

<sup>b</sup> According to ANSI B6.1-1968 a minimum clearance of  $0.157/P$  may be used for the basic 20-degree and 25-degree pressure angle rack in the case of shallow root sections and the use of existing hobs and cutters.

<sup>c</sup> According to ANSI B6.1-1968 the preferred clearance is  $0.250/P$ .

<sup>d</sup> According to ANSI B6.1-1968 the clearance for teeth which are shaved or ground is  $0.350/P$ .

<sup>e</sup> When gears are preshave cut on a gear shaper the dedendum will usually need to be increased to  $1.40/P$  to allow for the higher fillet trochoid produced by the shaper cutter; this is of particular importance on gears of few teeth or if the gear blank configuration requires the use of a small diameter shaper cutter, in which case the dedendum may need to be increased to as much as  $1.45/P$ . This should be avoided on highly loaded gears where the consequently reduced  $J$  factor will increase gear tooth stress excessively.

<sup>f</sup> According to ANSI B6.7-1967 the standard clearance is  $0.200/P + 0.002$  (min.).

<sup>g</sup> According to ANSI B6.7-1967 the clearance for shaved or ground teeth is  $0.350/P + 0.002$  (min.).

**Gears for Given Center Distance and Ratio.**—When it is necessary to use a pair of gears of given ratio at a specified center distance  $C_1$ , it may be found that no gears of standard diametral pitch will satisfy the center distance requirement. Gears of standard diametral pitch  $P$  may need to be redesigned to operate at other than their standard pitch diameter  $D$  and standard pressure angle  $\phi$ . The diametral pitch  $P_1$  at which these gears will operate is

$$P_1 = \frac{N_P + N_G}{2C_1} \quad (1)$$

where  $N_p$  = number of teeth in pinion

$N_G$  = number of teeth in gear

and their operating pressure angle  $\phi_1$  is

$$\phi_1 = \arccos\left(\frac{P_1}{P} \cos \phi\right) \quad (2)$$

Thus although the pair of gears are cut to a diametral pitch  $P$  and a pressure angle  $\phi$ , they operate as standard gears of diametral pitch  $P_1$  and pressure angle  $\phi_1$ . The pitch  $P$  and pressure angle  $\phi$  should be chosen so that  $\phi_1$  lies between about 18 and 25 degrees.

The operating pitch diameters of the pinion  $D_{p1}$  and of the gear  $D_{G1}$  are

$$D_{P1} = \frac{N_P}{P_1} \quad (3a) \quad \text{and} \quad D_{G1} = \frac{N_G}{P_1} \quad (3b)$$

The base diameters of the pinion  $D_{PB1}$  and of the gear  $D_{GB1}$  are

$$D_{PB1} = D_{P1} \cos \phi_1 \quad (4a) \quad \text{and} \quad D_{GB1} = D_{G1} \cos \phi_1 \quad (4b)$$

The basic tooth thickness,  $t_1$ , at the operating pitch diameter for both pinion and gear is

$$t_1 = \frac{1.5708}{P_1} \quad (5)$$

The root diameters of the pinion  $D_{PR1}$  and gear  $D_{GR1}$  and the corresponding outside diameters  $D_{PO1}$  and  $D_{GO1}$  are not standard because each gear is to be cut with a cutter that is not standard for the operating pitch diameters  $D_{P1}$  and  $D_{G1}$ .

The root diameters are

$$D_{PR1} = \frac{N_P}{P} - 2b_{P1} \quad (6a) \quad \text{and} \quad D_{GR1} = \frac{N_G}{P} - 2b_{G1} \quad (6b)$$

where

$$b_{P1} = b_c - \left( \frac{t_{P2} - 1.5708/P}{2 \tan \phi} \right) \quad (7a)$$

and

$$b_{G1} = b_c - \frac{t_{G2} - 1.5708/P}{2 \tan \phi} \quad (7b)$$

where  $b_c$  is the hob or cutter addendum for the pinion and gear.

The tooth thicknesses of the pinion  $t_{P2}$  and the gear  $t_{G2}$  are

$$t_{P2} = \frac{N_P}{P} \left( \frac{1.5708}{N_P} + \text{inv } \phi_1 - \text{inv } \phi \right) \quad (8a)$$




## SPUR GEARING

$$t_{G2} = \frac{N_G}{P} \left( \frac{1.5708}{N_G} + \text{inv } \phi_1 - \text{inv } \phi \right) \quad (8b)$$

The outside diameter of the pinion  $D_{PO}$  and the gear  $D_{GO}$  are

$$D_{PO} = 2 \times C_1 - D_{GR1} - 2(b_c - 1/P) \quad (9a)$$

and 
$$D_{GO} = 2 \times C_1 - D_{PR1} - 2(b_c - 1/P) \quad (9b)$$

 *Example:* Design gears of 8 diametral pitch, 20-degree pressure angle, and 28 and 88 teeth to operate at 7.50-inch center distance. The gears are to be cut with a hob of 0.169-inch addendum.

$$P_1 = \frac{28 + 88}{2 \times 7.50} = 7.7333 \quad (1)$$

$$\phi_1 = \arccos\left(\frac{7.7333}{8} \times 0.93969\right) = 24.719^\circ \quad (2)$$

$$D_{P1} = \frac{28}{7.7333} = 3.6207 \text{ in.} \quad (3a)$$

and 
$$D_{G1} = \frac{88}{7.7333} = 11.3794 \text{ in.} \quad (3b)$$

$$D_{PB1} = 3.6207 \times 0.90837 = 3.2889 \text{ in.} \quad (4a)$$

and 
$$D_{GB1} = 11.3794 \times 0.90837 = 10.3367 \text{ in.} \quad (4b)$$

$$t_1 = \frac{1.5708}{7.7333} = 0.20312 \text{ in.} \quad (5)$$

$$D_{PR1} = \frac{28}{8} - 2 \times 0.1016 = 3.2968 \text{ in.} \quad (6a)$$

and 
$$D_{GR1} = \frac{88}{8} - 2 \times (-0.0428) = 11.0856 \text{ in.} \quad (6b)$$

$$b_{P1} = 0.169 - \left( \frac{0.2454 - 1.5708/8}{2 \times 0.36397} \right) = 0.1016 \text{ in.} \quad (7a)$$

$$b_{G1} = 0.169 - \left( \frac{0.3505 - 1.5708/8}{2 \times 0.36397} \right) = -0.0428 \text{ in.} \quad (7b)$$

$$t_{P2} = \frac{28}{8} \left( \frac{1.5708}{28} + 0.028922 - 0.014904 \right) = 0.2454 \text{ in.} \quad (8a)$$

$$t_{G2} = \frac{88}{8} \left( \frac{1.5708}{88} + 0.028922 - 0.014904 \right) - 0.3505 \text{ in.} \quad (8b)$$

$$D_{PO1} = 2 \times 7.50 - 11.0856 - 2(0.169 - 1/8) = 3.8264 \text{ in.} \quad (9a)$$

$$D_{GO1} = 2 \times 7.50 - 3.2968 - 2(0.169 - 1/8) = 11.6152 \text{ in.} \quad (9b)$$

**Tooth Thickness Allowance for Shaving.**—Proper stock allowance is important for good results in shaving operations. If too much stock is left for shaving, the life of the shaving tool is reduced and, in addition, shaving time is increased. The following figures represent the amount of stock to be left on the teeth for removal by shaving under average conditions: For diametral pitches of 2 to 4, a thickness of 0.003 to 0.004 inch (one-half on each side of the tooth); for 5 to 6 diametral pitch, 0.0025 to 0.0035 inch; for 7 to 10 diametral pitch, 0.002 to 0.003 inch; for 11 to 14 diametral pitch, 0.0015 to 0.0020 inch; for 16 to 18 diametral pitch, 0.001 to 0.002 inch; for 20 to 48 diametral pitch, 0.0005 to 0.0015 inch; and for 52 to 72 diametral pitch, 0.0003 to 0.0007 inch.

The thickness of the gear teeth may be measured in several ways to determine the amount of stock left on the sides of the teeth to be removed by shaving. If it is necessary to measure the tooth thickness during the preshaping operation while the gear is in the gear shaper or hobbing machine, a gear tooth caliper or pins would be employed. Caliper methods of measuring gear teeth are explained in detail on page 2051 for measurements over single teeth, and on page 2140 for measurements over two or more teeth.

When the preshaped gear can be removed from the machine for checking, the center distance method may be employed. In this method, the preshaped gear is meshed without backlash with a gear of standard tooth thickness and the increase in center distance over standard is noted. The amount of total tooth thickness over standard on the preshaped gear can then be determined by the formula:  $t_2 = 2 \tan \phi \times d$ , where  $t_2$  = amount that the total thickness of the tooth exceeds the standard thickness,  $\phi$  = pressure angle, and  $d$  = amount that the center distance between the two gears exceeds the standard center distance.

**Circular Pitch for Given Center Distance and Ratio.**—When it is necessary to use a pair of gears of given ratio at a specified center distance, it may be found that no gears of standard diametral pitch will satisfy the center distance requirement. Hence, circular pitch gears may be selected. To find the required circular pitch  $p$ , when the center distance  $C$  and total number of teeth  $N$  in both gears are known, use the following formula:

$$p = \frac{C \times 6.2832}{N}$$

*Example:* A pair of gears having a ratio of 3 is to be used at a center distance of 10.230 inches. If one gear has 60 teeth and the other 20, what must be their circular pitch?

$$p = \frac{10.230 \times 6.2832}{60 + 20} = 0.8035 \text{ inch}$$

**Circular Thickness of Tooth when Outside Diameter is Standard.**—For a full-depth or stub tooth gear of standard outside diameter, the tooth thickness on the pitch circle (circular thickness or arc thickness) is found by the following formula:

$$t = \frac{1.5708}{P}$$

where  $t$  = circular thickness and  $P$  = diametral pitch. In Fellows stub tooth gears the diametral pitch used is the numerator of the pitch fraction (for example, 6 if the pitch is 6/8).

*Example 1:* Find the tooth thickness on the pitch circle of a 14½-degree full-depth tooth of 12 diametral pitch.

$$t = \frac{1.5708}{12} = 0.1309 \text{ inch}$$

*Example 2:* Find the tooth thickness on the tooth circle of a 20-degree full-depth involute tooth having a diametral pitch of 5.

$$t = \frac{1.5708}{5} = 0.31416, \text{ say } 0.3142 \text{ inch}$$

The tooth thickness on the pitch circle can be determined very accurately by means of measurement over wires which are located in tooth spaces that are diametrically opposite or as nearly diametrically opposite as possible. Where measurement over wires is not feasible, the circular or arc tooth thickness can be used in determining the chordal thickness which is the dimension measured with a gear tooth caliper.

**Circular Thickness of Tooth when Outside Diameter has been Enlarged.**—When the outside diameter of a small pinion is not standard but is enlarged to avoid undercut and to improve tooth action, the teeth are located farther out radially relative to the standard pitch diameter and consequently the circular tooth thickness at the standard pitch diameter is increased. To find this increased arc thickness the following formula is used, where  $t$  = tooth thickness;  $e$  = amount outside diameter is increased over standard;  $\phi$  = pressure angle; and  $p$  = circular pitch at the standard pitch diameter.

$$t = \frac{p}{2} + e \tan \phi$$

*Example:* The outside diameter of a pinion having 10 teeth of 5 diametral pitch and a pressure angle of  $14\frac{1}{2}$  degrees is to be increased by 0.2746 inch. The circular pitch equivalent to 5 diametral pitch is 0.6283 inch. Find the arc tooth thickness at the standard pitch diameter.

$$t = \frac{0.6283}{2} + (0.2746 \times \tan 14\frac{1}{2}^\circ)$$

$$t = 0.3142 + (0.2746 \times 0.25862) = 0.3852 \text{ inch}$$

**Circular Thickness of Tooth when Outside Diameter has been Reduced.**—If the outside diameter of a gear is reduced, as is frequently done to maintain the standard center distance when the outside diameter of the mating pinion is increased, the circular thickness of the gear teeth at the standard pitch diameter will be reduced. This decreased circular thickness can be found by the following formula where  $t$  = circular thickness at the standard pitch diameter;  $e$  = amount outside diameter is reduced under standard;  $\phi$  = pressure angle; and  $p$  = circular pitch.

$$t = \frac{p}{2} - e \tan \phi$$

*Example:* The outside diameter of a gear having a pressure angle of  $14\frac{1}{2}$  degrees is to be reduced by 0.2746 inch or an amount equal to the increase in diameter of its mating pinion. The circular pitch is 0.6283 inch. Determine the circular tooth thickness at the standard pitch diameter.

$$t = \frac{0.6283}{2} - (0.2746 \times \tan 14\frac{1}{2}^\circ)$$

$$t = 0.3142 - (0.2746 \times 0.25862) = 0.2432 \text{ inch}$$

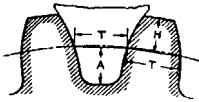
**Chordal Thickness of Tooth when Outside Diameter is Standard.**—To find the chordal or straight line thickness of a gear tooth the following formula can be used where  $t_c$  = chordal thickness;  $D$  = pitch diameter; and  $N$  = number of teeth.

$$t_c = D \sin\left(\frac{90^\circ}{N}\right)$$

*Example:* A pinion has 15 teeth of 3 diametral pitch; the pitch diameter is equal to  $15 \div 3$  or 5 inches. Find the chordal thickness at the standard pitch diameter.

$$t_c = 5 \sin\left(\frac{90^\circ}{15}\right) = 5 \sin 6^\circ = 5 \times 0.10453 = 0.5226 \text{ inch}$$

### Chordal Thicknesses and Chordal Addenda of Milled, Full-depth Gear Teeth and of Gear Milling Cutters



$T$  = chordal thickness of gear tooth and cutter tooth at pitch line;  
 $H$  = chordal addendum for full-depth gear tooth;  
 $A$  = chordal addendum of cutter =  $(2.157 \div \text{diametral pitch}) - H$   
 $= (0.6866 \times \text{circular pitch}) - H$ .

| Diametral Pitch | Dimension | Number of Gear Cutter, and Corresponding Number of Teeth |                   |                   |                   |                   |                   |                   |                   |
|-----------------|-----------|--|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
|                 |           | No. 1<br>135 Teeth                                       | No. 2<br>55 Teeth | No. 3<br>35 Teeth | No. 4<br>26 Teeth | No. 5<br>21 Teeth | No. 6<br>17 Teeth | No. 7<br>14 Teeth | No. 8<br>12 Teeth |
| 1               | T         | 1.5707   | 1.5706            | 1.5702            | 1.5698            | 1.5694            | 1.5686            | 1.5675            | 1.5663            |
|                 | H         | 1.0047   | 1.0112            | 1.0176            | 1.0237            | 1.0294            | 1.0362            | 1.0440            | 1.0514            |
| 1½              | T         | 1.0471   | 1.0470            | 1.0468            | 1.0465            | 1.0462            | 1.0457            | 1.0450            | 1.0442            |
|                 | H         | 0.6698   | 0.6741            | 0.6784            | 0.6824            | 0.6862            | 0.6908            | 0.6960            | 0.7009            |
| 2               | T         | 0.7853   | 0.7853            | 0.7851            | 0.7849            | 0.7847            | 0.7843            | 0.7837            | 0.7831            |
|                 | H         | 0.5023   | 0.5056            | 0.5088            | 0.5118            | 0.5147            | 0.5181            | 0.5220            | 0.5257            |
| 2½              | T         | 0.6283   | 0.6282            | 0.6281            | 0.6279            | 0.6277            | 0.6274            | 0.6270            | 0.6265            |
|                 | H         | 0.4018   | 0.4044            | 0.4070            | 0.4094            | 0.4117            | 0.4144            | 0.4176            | 0.4205            |
| 3               | T         | 0.5235   | 0.5235            | 0.5234            | 0.5232            | 0.5231            | 0.5228            | 0.5225            | 0.5221            |
|                 | H         | 0.3349   | 0.3370            | 0.3392            | 0.3412            | 0.3431            | 0.3454            | 0.3480            | 0.3504            |
| 3½              | T         | 0.4487   | 0.4487            | 0.4486            | 0.4485            | 0.4484            | 0.4481            | 0.4478            | 0.4475            |
|                 | H         | 0.2870   | 0.2889            | 0.2907            | 0.2919            | 0.2935            | 0.2954            | 0.2977            | 0.3004            |
| 4               | T         | 0.3926   | 0.3926            | 0.3926            | 0.3924            | 0.3923            | 0.3921            | 0.3919            | 0.3915            |
|                 | H         | 0.2511   | 0.2528            | 0.2544            | 0.2559            | 0.2573            | 0.2590            | 0.2610            | 0.2628            |
| 5               | T         | 0.3141   | 0.3141            | 0.3140            | 0.3139            | 0.3138            | 0.3137            | 0.3135            | 0.3132            |
|                 | H         | 0.2009   | 0.2022            | 0.2035            | 0.2047            | 0.2058            | 0.2072            | 0.2088            | 0.2102            |
| 6               | T         | 0.2618   | 0.2617            | 0.2617            | 0.2616            | 0.2615            | 0.2614            | 0.2612            | 0.2610            |
|                 | H         | 0.1674   | 0.1685            | 0.1696            | 0.1706            | 0.1715            | 0.1727            | 0.1740            | 0.1752            |
| 7               | T         | 0.2244   | 0.2243            | 0.2243            | 0.2242            | 0.2242            | 0.2240            | 0.2239            | 0.2237            |
|                 | H         | 0.1435   | 0.1444            | 0.1453            | 0.1462            | 0.1470            | 0.1480            | 0.1491            | 0.1502            |
| 8               | T         | 0.1963   | 0.1963            | 0.1962            | 0.1962            | 0.1961            | 0.1960            | 0.1959            | 0.1958            |
|                 | H         | 0.1255   | 0.1264            | 0.1272            | 0.1279            | 0.1286            | 0.1295            | 0.1305            | 0.1314            |
| 9               | T         | 0.1745   | 0.1745            | 0.1744            | 0.1744            | 0.1743            | 0.1743            | 0.1741            | 0.1740            |
|                 | H         | 0.1116   | 0.1123            | 0.1130            | 0.1137            | 0.1143            | 0.1151            | 0.1160            | 0.1168            |
| 10              | T         | 0.1570   | 0.1570            | 0.1570            | 0.1569            | 0.1569            | 0.1568            | 0.1567            | 0.1566            |
|                 | H         | 0.1004   | 0.1011            | 0.1017            | 0.1023            | 0.1029            | 0.1036            | 0.1044            | 0.1051            |
| 11              | T         | 0.1428   | 0.1428            | 0.1427            | 0.1427            | 0.1426            | 0.1426            | 0.1425            | 0.1424            |
|                 | H         | 0.0913   | 0.0919            | 0.0925            | 0.0930            | 0.0935            | 0.0942            | 0.0949            | 0.0955            |
| 12              | T         | 0.1309   | 0.1309            | 0.1308            | 0.1308            | 0.1308            | 0.1307            | 0.1306            | 0.1305            |
|                 | H         | 0.0837   | 0.0842            | 0.0848            | 0.0853            | 0.0857            | 0.0863            | 0.0870            | 0.0876            |
| 14              | T         | 0.1122   | 0.1122            | 0.1121            | 0.1121            | 0.1121            | 0.1120            | 0.1119            | 0.1118            |
|                 | H         | 0.0717   | 0.0722            | 0.0726            | 0.0731            | 0.0735            | 0.0740            | 0.0745            | 0.0751            |
| 16              | T         | 0.0981   | 0.0981            | 0.0981            | 0.0981            | 0.0980            | 0.0980            | 0.0979            | 0.0979            |
|                 | H         | 0.0628   | 0.0632            | 0.0636            | 0.0639            | 0.0643            | 0.0647            | 0.0652            | 0.0657            |
| 18              | T         | 0.0872   | 0.0872            | 0.0872            | 0.0872            | 0.0872            | 0.0871            | 0.0870            | 0.0870            |
|                 | H         | 0.0558   | 0.0561            | 0.0565            | 0.0568            | 0.0571            | 0.0575            | 0.0580            | 0.0584            |
| 20              | T         | 0.0785   | 0.0785            | 0.0785            | 0.0785            | 0.0784            | 0.0784            | 0.0783            | 0.0783            |
|                 | H         | 0.0502   | 0.0505            | 0.0508            | 0.0511            | 0.0514            | 0.0518            | 0.0522            | 0.0525            |

### Chordal Thicknesses and Chordal Addenda of Milled, Full-depth Gear Teeth and of Gear Milling Cutters

| Circular Pitch | Dimension | Number of Gear Cutter, and Corresponding Number of Teeth |                   |                   |                   |                   |                   |                   |                   |
|----------------|-----------|--|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
|                |           | No. 1<br>135 Teeth                                       | No. 2<br>55 Teeth | No. 3<br>35 Teeth | No. 4<br>26 Teeth | No. 5<br>21 Teeth | No. 6<br>17 Teeth | No. 7<br>14 Teeth | No. 8<br>12 Teeth |
| 1/4            | T         | 0.1250   | 0.1250            | 0.1249            | 0.1249            | 0.1249            | 0.1248            | 0.1247            | 0.1246            |
|                | H         | 0.0799   | 0.0804            | 0.0809            | 0.0814            | 0.0819            | 0.0824            | 0.0830            | 0.0836            |
| 5/16           | T         | 0.1562   | 0.1562            | 0.1562            | 0.1561            | 0.1561            | 0.1560            | 0.1559            | 0.1558            |
|                | H         | 0.0999   | 0.1006            | 0.1012            | 0.1018            | 0.1023            | 0.1030            | 0.1038            | 0.1045            |
| 3/8            | T         | 0.1875   | 0.1875            | 0.1874            | 0.1873            | 0.1873            | 0.1872            | 0.1871            | 0.1870            |
|                | H         | 0.1199   | 0.1207            | 0.1214            | 0.1221            | 0.1228            | 0.1236            | 0.1245            | 0.1254            |
| 7/16           | T         | 0.2187   | 0.2187            | 0.2186            | 0.2186            | 0.2185            | 0.2184            | 0.2183            | 0.2181            |
|                | H         | 0.1399   | 0.1408            | 0.1416            | 0.1425            | 0.1433            | 0.1443            | 0.1453            | 0.1464            |
| 1/2            | T         | 0.2500   | 0.2500            | 0.2499            | 0.2498            | 0.2498            | 0.2496            | 0.2495            | 0.2493            |
|                | H         | 0.1599   | 0.1609            | 0.1619            | 0.1629            | 0.1638            | 0.1649            | 0.1661            | 0.1673            |
| 9/16           | T         | 0.2812   | 0.2812            | 0.2811            | 0.2810            | 0.2810            | 0.2808            | 0.2806            | 0.2804            |
|                | H         | 0.1799   | 0.1810            | 0.1821            | 0.1832            | 0.1842            | 0.1855            | 0.1868            | 0.1882            |
| 5/8            | T         | 0.3125   | 0.3125            | 0.3123            | 0.3123            | 0.3122            | 0.3120            | 0.3118            | 0.3116            |
|                | H         | 0.1998   | 0.2012            | 0.2023            | 0.2036            | 0.2047            | 0.2061            | 0.2076            | 0.2091            |
| 11/16          | T         | 0.3437   | 0.3437            | 0.3436            | 0.3435            | 0.3434            | 0.3432            | 0.3430            | 0.3427            |
|                | H         | 0.2198   | 0.2213            | 0.2226            | 0.2239            | 0.2252            | 0.2267            | 0.2283            | 0.2300            |
| 3/4            | T         | 0.3750   | 0.3750            | 0.3748            | 0.3747            | 0.3747            | 0.3744            | 0.3742            | 0.3740            |
|                | H         | 0.2398   | 0.2414            | 0.2428            | 0.2443            | 0.2457            | 0.2473            | 0.2491            | 0.2509            |
| 13/16          | T         | 0.4062   | 0.4062            | 0.4060            | 0.4059            | 0.4059            | 0.4056            | 0.4054            | 0.4050            |
|                | H         | 0.2598   | 0.2615            | 0.2631            | 0.2647            | 0.2661            | 0.2679            | 0.2699            | 0.2718            |
| 7/8            | T         | 0.4375   | 0.4375            | 0.4373            | 0.4372            | 0.4371            | 0.4368            | 0.4366            | 0.4362            |
|                | H         | 0.2798   | 0.2816            | 0.2833            | 0.2850            | 0.2866            | 0.2885            | 0.2906            | 0.2927            |
| 15/16          | T         | 0.4687   | 0.4687            | 0.4685            | 0.4684            | 0.4683            | 0.4680            | 0.4678            | 0.4674            |
|                | H         | 0.2998   | 0.3018            | 0.3035            | 0.3054            | 0.3071            | 0.3092            | 0.3114            | 0.3137            |
| 1              | T         | 0.5000   | 0.5000            | 0.4998            | 0.4997            | 0.4996            | 0.4993            | 0.4990            | 0.4986            |
|                | H         | 0.3198   | 0.3219            | 0.3238            | 0.3258            | 0.3276            | 0.3298            | 0.3322            | 0.3346            |
| 1 1/8          | T         | 0.5625   | 0.5625            | 0.5623            | 0.5621            | 0.5620            | 0.5617            | 0.5613            | 0.5610            |
|                | H         | 0.3597   | 0.3621            | 0.3642            | 0.3665            | 0.3685            | 0.3710            | 0.3737            | 0.3764            |
| 1 1/4          | T         | 0.6250   | 0.6250            | 0.6247            | 0.6246            | 0.6245            | 0.6241            | 0.6237            | 0.6232            |
|                | H         | 0.3997   | 0.4023            | 0.4047            | 0.4072            | 0.4095            | 0.4122            | 0.4152            | 0.4182            |
| 1 3/8          | T         | 0.6875   | 0.6875            | 0.6872            | 0.6870            | 0.6869            | 0.6865            | 0.6861            | 0.6856            |
|                | H         | 0.4397   | 0.4426            | 0.4452            | 0.4479            | 0.4504            | 0.4534            | 0.4567            | 0.4600            |
| 1 1/2          | T         | 0.7500   | 0.7500            | 0.7497            | 0.7495            | 0.7494            | 0.7489            | 0.7485            | 0.7480            |
|                | H         | 0.4797   | 0.4828            | 0.4857            | 0.4887            | 0.4914            | 0.4947            | 0.4983            | 0.5019            |
| 1 3/4          | T         | 0.8750   | 0.8750            | 0.8746            | 0.8744            | 0.8743            | 0.8737            | 0.8732            | 0.8726            |
|                | H         | 0.5596   | 0.5633            | 0.5666            | 0.5701            | 0.5733            | 0.5771            | 0.5813            | 0.5855            |
| 2              | T         | 1.0000   | 1.0000            | 0.9996            | 0.9994            | 0.9992            | 0.9986            | 0.9980            | 0.9972            |
|                | H         | 0.6396   | 0.6438            | 0.6476            | 0.6516            | 0.6552            | 0.6596            | 0.6644            | 0.6692            |
| 2 1/4          | T         | 1.1250   | 1.1250            | 1.1246            | 1.1242            | 1.1240            | 1.1234            | 1.1226            | 1.1220            |
|                | H         | 0.7195   | 0.7242            | 0.7285            | 0.7330            | 0.7371            | 0.7420            | 0.7474            | 0.7528            |
| 2 1/2          | T         | 1.2500   | 1.2500            | 1.2494            | 1.2492            | 1.2490            | 1.2482            | 1.2474            | 1.2464            |
|                | H         | 0.7995   | 0.8047            | 0.8095            | 0.8145            | 0.8190            | 0.8245            | 0.8305            | 0.8365            |
| 3              | T         | 1.5000   | 1.5000            | 1.4994            | 1.4990            | 1.4990            | 1.4978            | 1.4970            | 1.4960            |
|                | H         | 0.9594   | 0.9657            | 0.9714            | 0.9774            | 0.9828            | 0.9894            | 0.9966            | 1.0038            |

**Chordal Thickness of Tooth when Outside Diameter is Special.**—When the outside diameter is larger or smaller than standard the chordal thickness at the standard pitch diameter is found by the following formula where  $t_c$  = chordal thickness at the standard pitch diameter  $D$ ;  $t$  = circular thickness at the standard pitch diameter of the enlarged pinion or reduced gear being measured.

$$t_c = t - \frac{t^3}{6 \times D^2}$$

*Example 1:* The outside diameter of a pinion having 10 teeth of 5 diametral pitch has been enlarged by 0.2746 inch. This enlargement has increased the circular tooth thickness at the standard pitch diameter (as determined by the formula previously given) to 0.3852 inch. Find the equivalent chordal thickness.

$$t_c = 0.3852 - \frac{0.3852^3}{6 \times 2^2} = 0.3852 - 0.0024 = 0.3828 \text{ inch}$$

(The error introduced by rounding the circular thickness to three significant figures before cubing it only affects the fifth decimal place in the result.)

*Example 2:* A gear having 30 teeth is to mesh with the pinion in [Example 1](#) and is reduced so that the circular tooth thickness at the standard pitch diameter is 0.2432 inch. Find the equivalent chordal thickness.

$$t_c = 0.2432 - \frac{0.2432^3}{6 \times 6^2} = 0.2432 - 0.00007 = 0.2431 \text{ inch}$$

**Chordal Addendum.**—In measuring the chordal thickness, the vertical scale of a gear tooth caliper is set to the chordal or “corrected” addendum to locate the caliper jaws at the pitch line (see *Method of setting a gear tooth caliper* on page 2052). The simplified formula which follows may be used in determining the chordal addendum either when the addendum is standard for full-depth or stub teeth or when the addendum is either longer or shorter than standard as in case of an enlarged pinion or a gear which is to mesh with an enlarged pinion and has a reduced addendum to maintain the standard center distance. If  $a_c$  = chordal addendum;  $a$  = addendum; and  $t$  = circular thickness of tooth at pitch diameter  $D$ ; then,

$$a_c = a + \frac{t^2}{4D}$$

*Example 1:* The outside diameter of an 8 diametral pitch 14-tooth pinion with 20-degree full-depth teeth is to be increased by using an enlarged addendum of  $1.234 \div 8 = 0.1542$  inch (see [Table 7](#) on page 2050). The basic tooth thickness of the enlarged pinion is  $1.741 \div 8 = 0.2176$  inch. What is the chordal addendum?

$$\text{Chordal addendum} = 0.1542 + \frac{0.2176^2}{4 \times (14 \div 8)} = 0.1610 \text{ inch}$$

*Example 2:* The outside diameter of a 14½-degree pinion having 12 teeth of 2 diametral pitch is to be enlarged 0.624 inch to avoid undercut (see [Table 8](#) on page 2050), thus increasing the addendum from 0.5000 to 0.8120 inch and the arc thickness at the pitch line from 0.7854 to 0.9467 inch. Then,

$$\text{Chordal addendum of pinion} = 0.8120 + \frac{0.9467^2}{4 \times (12 \div 2)} = 0.8493 \text{ inch}$$

**Table 7. Addendums and Tooth Thicknesses for Coarse-Pitch Long-Addendum Pinions and their Mating Short-Addendum Gears—20- and 25-degree Pressure Angles ANSI B6.1-1968 (R1974)**

| Number of Teeth in Pinion   | Addendum |       | Basic Tooth Thickness |       | Number of Teeth in Gear |
|---|----------|-------|-----------------------|-------|-------------------------|
|   | Pinion   | Gear  | Pinion                | Gear  |                         |
| $N_p$   | $a_p$    | $a_G$ | $t_p$                 | $t_G$ | $N_G$ (min)             |
| 20-Degree Involute Full Depth Tooth Form (Less than 20 Diametral Pitch) |          |       |                       |       |                         |
| 10  | 1.468    | .532  | 1.912                 | 1.230 | 25                      |
| 11  | 1.409    | .591  | 1.868                 | 1.273 | 24                      |
| 12  | 1.351    | .649  | 1.826                 | 1.315 | 23                      |
| 13  | 1.292    | .708  | 1.783                 | 1.358 | 22                      |
| 14  | 1.234    | .766  | 1.741                 | 1.400 | 21                      |
| 15  | 1.175    | .825  | 1.698                 | 1.443 | 20                      |
| 16  | 1.117    | .883  | 1.656                 | 1.486 | 19                      |
| 17  | 1.058    | .942  | 1.613                 | 1.529 | 18                      |
| 25-Degree Involute Full Depth Tooth Form (Less than 20 Diametral Pitch) |          |       |                       |       |                         |
| 10  | 1.184    | .816  | 1.742                 | 1.399 | 15                      |
| 11  | 1.095    | .905  | 1.659                 | 1.482 | 14                      |

All values are for 1 diametral pitch. For any other sizes of teeth all linear dimensions should be divided by the diametral pitch. Basic tooth thicknesses do not include an allowance for backlash.

**Table 8. Enlarged Pinion and Reduced Gear Dimensions to Avoid Interference Coarse Pitch 14½-degree Involute Full Depth Teeth**

| Number of Pinion Teeth | Changes in Pinion and Gear Diameters | Circular Tooth Thickness |             | Min. No. of Teeth in Mating Gear |                          |
|------------------------|--------------------------------------|--------------------------|-------------|----------------------------------|--------------------------|
|                        |                                      | Pinion                   | Mating Gear | To Avoid Undercut                | For Full Involute Action |
| 10                     | 1.3731                               | 1.9259                   | 1.2157      | 54                               | 27                       |
| 11                     | 1.3104                               | 1.9097                   | 1.2319      | 53                               | 27                       |
| 12                     | 1.2477                               | 1.8935                   | 1.2481      | 52                               | 28                       |
| 13                     | 1.1850                               | 1.8773                   | 1.2643      | 51                               | 28                       |
| 14                     | 1.1223                               | 1.8611                   | 1.2805      | 50                               | 28                       |
| 15                     | 1.0597                               | 1.8449                   | 1.2967      | 49                               | 28                       |
| 16                     | 0.9970                               | 1.8286                   | 1.3130      | 48                               | 28                       |
| 17                     | 0.9343                               | 1.8124                   | 1.3292      | 47                               | 28                       |
| 18                     | 0.8716                               | 1.7962                   | 1.3454      | 46                               | 28                       |
| 19                     | 0.8089                               | 1.7800                   | 1.3616      | 45                               | 28                       |
| 20                     | 0.7462                               | 1.7638                   | 1.3778      | 44                               | 28                       |
| 21                     | 0.6835                               | 1.7476                   | 1.3940      | 43                               | 28                       |
| 22                     | 0.6208                               | 1.7314                   | 1.4102      | 42                               | 27                       |
| 23                     | 0.5581                               | 1.7151                   | 1.4265      | 41                               | 27                       |
| 24                     | 0.4954                               | 1.6989                   | 1.4427      | 40                               | 27                       |
| 25                     | 0.4328                               | 1.6827                   | 1.4589      | 39                               | 26                       |
| 26                     | 0.3701                               | 1.6665                   | 1.4751      | 38                               | 26                       |
| 27                     | 0.3074                               | 1.6503                   | 1.4913      | 37                               | 26                       |
| 28                     | 0.2447                               | 1.6341                   | 1.5075      | 36                               | 25                       |
| 29                     | 0.1820                               | 1.6179                   | 1.5237      | 35                               | 25                       |
| 30                     | 0.1193                               | 1.6017                   | 1.5399      | 34                               | 24                       |
| 31                     | 0.0566                               | 1.5854                   | 1.5562      | 33                               | 24                       |

All dimensions are given in inches and are for 1 diametral pitch. For other pitches divide tabular values by desired diametral pitch.

Add to the standard outside diameter of the pinion the amount given in the second column of the table divided by the desired diametral pitch, and (to maintain standard center distance) subtract the same amount from the outside diameter of the mating gear. Long addendum pinions will mesh with standard gears, but the center distance will be greater than standard.

*Example 3:* The outside diameter of the mating gear for the pinion in [Example 3](#) is to be reduced 0.624 inch. The gear has 60 teeth and the addendum is reduced from 0.5000 to 0.1881 inch (to maintain the standard center distance), thus reducing the arc thickness to 0.6240 inch. Then,

$$\text{Chordal addendum of gear} = 0.1881 + \frac{0.6240^2}{4 \times (60 \div 2)} = 0.1913 \text{ inch}$$

When a gear addendum is reduced as much as the mating pinion addendum is enlarged, the minimum number of gear teeth required to prevent undercutting depends upon the enlargement of the mating pinion. To illustrate, if a 14½-degree pinion with 13 teeth is enlarged 1.185 inches, then the reduced mating gear should have a minimum of 51 teeth to avoid undercut (see [Table 8](#) on page 2050).

**Tables for Chordal Thicknesses and Chordal Addenda of Milled, Full-depth Teeth.**—Two convenient tables for checking gears with milled, full-depth teeth are given on pages 2047 and 2048. The first shows chordal thicknesses and chordal addenda for the lowest number of teeth cut by gear cutters Nos. 1 through 8, and for the commonly used diametral pitches. The second gives similar data for commonly used circular pitches. In each case the data shown are accurate for the number of gear teeth indicated, but are approximate for other numbers of teeth within the range of the cutter under which they appear in the table. For the higher diametral pitches and lower circular pitches, the error introduced by using the data for any tooth number within the range of the cutter under which it appears is comparatively small. The chordal thicknesses and chordal addenda for gear cutters Nos. 1 through 8 of the more commonly used diametral and circular pitches can be obtained from the table and formulas on pages 2047 and 2048.

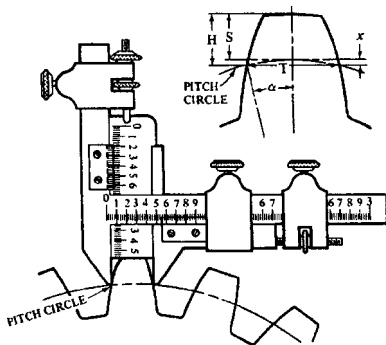
**Caliper Measurement of Gear Tooth.**—In cutting gear teeth, the general practice is to adjust the cutter or hob until it grazes the outside diameter of the blank; the cutter is then sunk to the total depth of the tooth space plus whatever slight additional amount may be required to provide the necessary play or backlash between the teeth. (For recommendations concerning backlash and excess depth of cut required, see *Backlash* starting on page 2067.) If the outside diameter of the gear blank is correct, the tooth thickness should also be correct after the cutter has been sunk to the depth required for a given pitch and backlash. However, it is advisable to check the tooth thickness by measuring it, and the vernier gear-tooth caliper (see following illustration) is commonly used in measuring the thickness.

The vertical scale of this caliper is set so that when it rests upon the top of the tooth as shown, the lower ends of the caliper jaws will be at the height of the pitch circle; the horizontal scale then shows the chordal thickness of the tooth at this point. If the gear is being cut on a milling machine or with the type of gear-cutting machine employing a formed milling cutter, the tooth thickness is checked by first taking a trial cut for a short distance at one side of the blank; then the gear blank is indexed for the next space and another cut is taken far enough to mill the full outline of the tooth. The tooth thickness is then measured.

Before the gear-tooth caliper can be used, it is necessary to determine the correct chordal thickness and also the chordal addendum (or “corrected addendum” as it is sometimes called). The vertical scale is set to the chordal addendum, thus locating the ends of the jaws at the height of the pitch circle. The rules or formulas to use in determining the chordal thickness and chordal addendum will depend upon the outside diameter of the gear; for example, if the outside diameter of a small pinion is enlarged to avoid undercut and improve the tooth action, this must be taken into account in figuring the chordal thickness and chordal addendum as shown by the accompanying rules. The detail of a gear tooth included with the gear-tooth caliper illustration, represents the chordal thickness  $T$ , the addendum  $S$ , and the chordal addendum  $H$ . For the caliper measurements over two or more teeth see *Checking Spur Gear Size by Chordal Measurement Over Two or More Teeth* starting on page 2140.



## SPUR GEARING



Method of setting a gear tooth caliper

**Selection of Involute Gear Milling Cutter for a Given Diametral Pitch and Number of Teeth.**—When gear teeth are cut by using formed milling cutters, the cutter must be selected to suit both the pitch and the number of teeth, because the shapes of the tooth spaces vary according to the number of teeth. For instance, the tooth spaces of a small pinion are not of the same shape as the spaces of a large gear of equal pitch. Theoretically, there should be a different formed cutter for every tooth number, but such refinement is unnecessary in practice. The involute formed cutters commonly used are made in series of eight cutters for each diametral pitch (see *Series of Involute, Finishing Gear Milling Cutters for Each Pitch*). The shape of each cutter in this series is correct for a certain number of teeth only, but it can be used for other numbers within the limits given. For instance, a No. 6 cutter may be used for gears having from 17 to 20 teeth, but the tooth outline is correct only for 17 teeth or the lowest number in the range, which is also true of the other cutters listed. When this cutter is used for a gear having, say, 19 teeth, too much material is removed from the upper surfaces of the teeth, although the gear meets ordinary requirements. When greater accuracy of tooth shape is desired to ensure smoother or quieter operation, an intermediate series of cutters having half-numbers may be used provided the number of gear teeth is between the number listed for the regular cutters (see *Series of Involute, Finishing Gear Milling Cutters for Each Pitch*).

Involute gear milling cutters are designed to cut a composite tooth form, the center portion being a true involute while the top and bottom portions are cycloidal. This composite form is necessary to prevent tooth interference when milled mating gears are meshed with each other. Because of their composite form, milled gears will not mate satisfactorily enough for high grade work with those of generated, full-involute form. Composite form hobs are available, however, which will produce generated gears that mesh with those cut by gear milling cutters.

*Metric Module Gear Cutters:* The accompanying table for selecting the cutter number to be used to cut a given number of teeth may be used also to select metric module gear cutters except that the numbers are designated in reverse order. For example, cutter No. 1, in the metric module system, is used for 12–13 teeth, cutter No. 2 for 14–16 teeth, etc.

**Increasing Pinion Diameter to Avoid Undercut or Interference.**—On coarse-pitch pinions with small numbers of teeth (10 to 17 for 20-degree and 10 and 11 for 25-degree pressure angle involute tooth forms) undercutting of the tooth profile or fillet interference with the tip of the mating gear can be avoided by making certain changes from the standard tooth proportions that are specified in [Table 3](#) on page 2038. These changes consist essen-

**Circular Pitch in Gears—Pitch Diameters, Outside Diameters, and Root Diameters**

For any particular circular pitch and number of teeth, use the table as shown in the example to find the pitch diameter, outside diameter, and root diameter. *Example:* Pitch diameter for 57 teeth of 6-inch circular pitch = 10 × pitch diameter given under factor for 5 teeth plus pitch diameter given under factor for 7 teeth. (10 × 9.5493) + 13.3690 = 108.862 inches.

Outside diameter of gear equals pitch diameter plus outside diameter factor from next-to-last column in table = 108.862 + 3.8197 = 112.682 inches.

Root diameter of gear equals pitch diameter minus root diameter factor from last column in table = 108.862 – 4.4194 = 104.443 inches.

| Circular Pitch<br>in<br>Inches | Factor for Number of Teeth                                 |        |        |        |        |         |         |         |         | Outside Dia.<br>Factor | Root<br>Diameter<br>Factor |
|--------------------------------|--|--------|--------|--------|--------|---------|---------|---------|---------|------------------------|----------------------------|
|                                | 1  | 2      | 3      | 4      | 5      | 6       | 7       | 8       | 9       |                        |                            |
|                                | Pitch Diameter Corresponding to Factor for Number of Teeth |        |        |        |        |         |         |         |         |                        |                            |
| 6                              | 1.9099   | 3.8197 | 5.7296 | 7.6394 | 9.5493 | 11.4591 | 13.3690 | 15.2788 | 17.1887 | 3.8197                 | 4.4194                     |
| 5½                             | 1.7507   | 3.5014 | 5.2521 | 7.0028 | 8.7535 | 10.5042 | 12.2549 | 14.0056 | 15.7563 | 3.5014                 | 4.0511                     |
| 5                              | 1.5915   | 3.1831 | 4.7746 | 6.3662 | 7.9577 | 9.5493  | 11.1408 | 12.7324 | 14.3239 | 3.1831                 | 3.6828                     |
| 4½                             | 1.4324   | 2.8648 | 4.2972 | 5.7296 | 7.1620 | 8.5943  | 10.0267 | 11.4591 | 12.8915 | 2.8648                 | 3.3146                     |
| 4                              | 1.2732   | 2.5465 | 3.8197 | 5.0929 | 6.3662 | 7.6394  | 8.9127  | 10.1859 | 11.4591 | 2.5465                 | 2.9463                     |
| 3½                             | 1.1141   | 2.2282 | 3.3422 | 4.4563 | 5.5704 | 6.6845  | 7.7986  | 8.9127  | 10.0267 | 2.2282                 | 2.5780                     |
| 3                              | 0.9549   | 1.9099 | 2.8648 | 3.8197 | 4.7746 | 5.7296  | 6.6845  | 7.6394  | 8.5943  | 1.9099                 | 2.2097                     |
| 2½                             | 0.7958   | 1.5915 | 2.3873 | 3.1831 | 3.9789 | 4.7746  | 5.5704  | 6.3662  | 7.1620  | 1.5915                 | 1.8414                     |
| 2                              | 0.6366   | 1.2732 | 1.9099 | 2.5465 | 3.1831 | 3.8197  | 4.4563  | 5.0929  | 5.7296  | 1.2732                 | 1.4731                     |
| 1⅞                             | 0.5968   | 1.1937 | 1.7905 | 2.3873 | 2.9841 | 3.5810  | 4.1778  | 4.7746  | 5.3715  | 1.1937                 | 1.3811                     |
| 1¾                             | 0.5570   | 1.1141 | 1.6711 | 2.2282 | 2.7852 | 3.3422  | 3.8993  | 4.4563  | 5.0134  | 1.1141                 | 1.2890                     |
| 1⅝                             | 0.5173   | 1.0345 | 1.5518 | 2.0690 | 2.5863 | 3.1035  | 3.6208  | 4.1380  | 4.6553  | 1.0345                 | 1.1969                     |
| 1½                             | 0.4775   | 0.9549 | 1.4324 | 1.9099 | 2.3873 | 2.8648  | 3.3422  | 3.8197  | 4.2972  | 0.9549                 | 1.1049                     |
| 1⅜                             | 0.4576   | 0.9151 | 1.3727 | 1.8303 | 2.2878 | 2.7454  | 3.2030  | 3.6606  | 4.1181  | 0.9151                 | 1.0588                     |
| 1⅓                             | 0.4377   | 0.8754 | 1.3130 | 1.7507 | 2.1884 | 2.6261  | 3.0637  | 3.5014  | 3.9391  | 0.8754                 | 1.0128                     |
| 1⅔                             | 0.4178   | 0.8356 | 1.2533 | 1.6711 | 2.0889 | 2.5067  | 2.9245  | 3.3422  | 3.7600  | 0.8356                 | 0.9667                     |
| 1¼                             | 0.3979   | 0.7958 | 1.1937 | 1.5915 | 1.9894 | 2.3873  | 2.7852  | 3.1831  | 3.5810  | 0.7958                 | 0.9207                     |
| 1⅓                             | 0.3780   | 0.7560 | 1.1340 | 1.5120 | 1.8900 | 2.2680  | 2.6459  | 3.0239  | 3.4019  | 0.7560                 | 0.8747                     |
| 1⅝                             | 0.3581   | 0.7162 | 1.0743 | 1.4324 | 1.7905 | 2.1486  | 2.5067  | 2.8648  | 3.2229  | 0.7162                 | 0.8286                     |
| 1⅞                             | 0.3382   | 0.6764 | 1.0146 | 1.3528 | 1.6910 | 2.0292  | 2.3674  | 2.7056  | 3.0438  | 0.6764                 | 0.7826                     |
| 1                              | 0.3183   | 0.6366 | 0.9549 | 1.2732 | 1.5915 | 1.9099  | 2.2282  | 2.5465  | 2.8648  | 0.6366                 | 0.7366                     |
| 15/16                          | 0.2984   | 0.5968 | 0.8952 | 1.1937 | 1.4921 | 1.7905  | 2.0889  | 2.3873  | 2.6857  | 0.5968                 | 0.6905                     |
| 7/8                            | 0.2785   | 0.5570 | 0.8356 | 1.1141 | 1.3926 | 1.6711  | 1.9496  | 2.2282  | 2.5067  | 0.5570                 | 0.6445                     |
| 13/16                          | 0.2586   | 0.5173 | 0.7759 | 1.0345 | 1.2931 | 1.5518  | 1.8104  | 2.0690  | 2.3276  | 0.5173                 | 0.5985                     |
| 3/4                            | 0.2387   | 0.4775 | 0.7162 | 0.9549 | 1.1937 | 1.4324  | 1.6711  | 1.9099  | 2.1486  | 0.4775                 | 0.5524                     |
| 11/16                          | 0.2188   | 0.4377 | 0.6565 | 0.8754 | 1.0942 | 1.3130  | 1.5319  | 1.7507  | 1.9695  | 0.4377                 | 0.5064                     |
| 2/5                            | 0.2122   | 0.4244 | 0.6366 | 0.8488 | 1.0610 | 1.2732  | 1.4854  | 1.6977  | 1.9099  | 0.4244                 | 0.4910                     |
| 3/8                            | 0.1989   | 0.3979 | 0.5968 | 0.7958 | 0.9947 | 1.1937  | 1.3926  | 1.5915  | 1.7905  | 0.3979                 | 0.4604                     |
| 9/16                           | 0.1790   | 0.3581 | 0.5371 | 0.7162 | 0.8952 | 1.0743  | 1.2533  | 1.4324  | 1.6114  | 0.3581                 | 0.4143                     |
| 1/2                            | 0.1592   | 0.3183 | 0.4775 | 0.6366 | 0.7958 | 0.9549  | 1.1141  | 1.2732  | 1.4324  | 0.3183                 | 0.3683                     |
| 7/16                           | 0.1393   | 0.2785 | 0.4178 | 0.5570 | 0.6963 | 0.8356  | 0.9748  | 1.1141  | 1.2533  | 0.2785                 | 0.3222                     |
| 3/8                            | 0.1194   | 0.2387 | 0.3581 | 0.4775 | 0.5968 | 0.7162  | 0.8356  | 0.9549  | 1.0743  | 0.2387                 | 0.2762                     |
| 1/3                            | 0.1061   | 0.2122 | 0.3183 | 0.4244 | 0.5305 | 0.6366  | 0.7427  | 0.8488  | 0.9549  | 0.2122                 | 0.2455                     |
| 5/16                           | 0.0995   | 0.1989 | 0.2984 | 0.3979 | 0.4974 | 0.5968  | 0.6963  | 0.7958  | 0.8952  | 0.1989                 | 0.2302                     |
| 1/4                            | 0.0796   | 0.1592 | 0.2387 | 0.3183 | 0.3979 | 0.4775  | 0.5570  | 0.6366  | 0.7162  | 0.1592                 | 0.1841                     |
| 3/16                           | 0.0597   | 0.1194 | 0.1790 | 0.2387 | 0.2984 | 0.3581  | 0.4178  | 0.4775  | 0.5371  | 0.1194                 | 0.1381                     |
| 1/8                            | 0.0398   | 0.0796 | 0.1194 | 0.1592 | 0.1989 | 0.2387  | 0.2785  | 0.3183  | 0.3581  | 0.0796                 | 0.0921                     |
| 1/16                           | 0.0199   | 0.0398 | 0.0597 | 0.0796 | 0.0995 | 0.1194  | 0.1393  | 0.1592  | 0.1790  | 0.0398                 | 0.0460                     |

tially in increasing the addendum and hence the outside diameter of the pinion and decreasing the addendum and hence the outside diameter of the mating gear. These changes in outside diameters of pinion and gear do not change the velocity ratio or the procedures in cutting the teeth on a hobbing machine or generating type of shaper or planer.

Data in Table 7 on page 2050 are taken from ANSI Standard B6.1-1968, reaffirmed 1974, and show for 20-degree and 25-degree full-depth standard tooth forms, respectively, the addendums and tooth thicknesses for long addendum pinions and their mating short

addendum gears when the number of teeth in the pinion is as given. Similar data for former standard 14½-degree full-depth teeth (20 diametral pitch and coarser) are given in [Table 8](#) on page 2050.

*Example:* A 14-tooth, 20-degree pressure angle pinion of 6 diametral pitch is to be enlarged. What will be the outside diameters of the pinion and a 60-tooth mating gear? If the mating gear is to have the minimum number of teeth to avoid undercut, what will be its outside diameter?

$$D_o(\text{ pinion}) = \frac{N_P}{P} + 2a = \frac{14}{6} + 2\left(\frac{1.234}{6}\right) = 2.745 \text{ inches}$$

$$D_o(\text{ gear}) = \frac{N_G}{P} + 2a = \frac{60}{6} + 2\left(\frac{0.766}{6}\right) = 10.255 \text{ inches}$$

For a mating gear with minimum number of teeth to avoid undercut:

$$D_o(\text{ gear}) = \frac{N_G}{P} + 2a = \frac{21}{6} + 2\left(\frac{0.766}{6}\right) = 3.755 \text{ inches}$$

### Series of Involute, Finishing Gear Milling Cutters for Each Pitch

| Number of Cutter | Will cut Gears from | Number of Cutter | Will cut Gears from |
|------------------|---------------------|------------------|---------------------|
| 1                | 135 teeth to a rack | 5                | 21 to 25 teeth      |
| 2                | 55 to 134 teeth     | 6                | 17 to 20 teeth      |
| 3                | 35 to 54 teeth      | 7                | 14 to 16 teeth      |
| 4                | 26 to 34 teeth      | 8                | 12 to 13 teeth      |

The regular cutters listed above are used ordinarily.

The cutters listed below (an intermediate series having half numbers) may be used when greater accuracy of tooth shape is essential in cases where the number of teeth is between the numbers for which the regular cutters are intended.

| Number of Cutter | Will cut Gears from | Number of Cutter | Will cut Gears from |
|------------------|---------------------|------------------|---------------------|
| 1½               | 80 to 134 teeth     | 5½               | 19 to 20 teeth      |
| 2½               | 42 to 54 teeth      | 6½               | 15 to 16 teeth      |
| 3½               | 30 to 34 teeth      | 7½               | 13 teeth            |
| 4½               | 23 to 25 teeth      | ...              | ...                 |

Roughing cutters are made with No. 1 form only. Dimensions of roughing and finishing cutters are given on page 816. Dimensions of cutters for bevel gears are given on page 817.

*Enlarged Fine-Pitch Pinions:* American Standard ANSI B6.7–1977, Information Sheet A provides a different system for 20-degree pressure angle pinion enlargement than is used for coarse-pitch gears. Pinions with 11 through 23 teeth (9 through 14 teeth for 25-degree pressure angle) are enlarged so that a standard tooth thickness rack with addendum  $1.05/P$  will start contact 5° of roll above the base circle radius. The use of  $1.05/P$  for the addendum allows for center distance variation and eccentricity of the mating gear outside diameter; the 5° roll angle avoids the fabrication of the involute in the troublesome area near the base circle.

Pinions with less than 11 teeth (9 teeth for 25-degree pressure angle) are enlarged to the extent that the highest point of undercut coincides with the start of contact with the standard rack described previously. The height of undercut considered is that produced by a sharp-cornered 120 pitch hob. Pinions with less than 13 teeth (11 teeth for 25-degree pressure angle) are truncated to provide a top land of  $0.275/P$ . Data for enlarged pinions may be found in [Tables 9a, 9b, 9c, and 9d](#).

**Table 9a. Increase in Dedendum,  $\Delta$  for 20-, and 25-Degree Pressure Angle Fine-Pitch Enlarged Pinions and Reduced Gears ANSI B6.7-1977**

| Diametral Pitch, $P$ | $\Delta$ | Diametral Pitch, $P$ | $\Delta$ | Diametral Pitch, $P$ | $\Delta$ | Diametral Pitch, $P$ | $\Delta$ | Diametral Pitch, $P$ | $\Delta$ |
|----------------------|----------|----------------------|----------|----------------------|----------|----------------------|----------|----------------------|----------|
| 20                   | 0.0000   | 32                   | 0.0007   | 48                   | 0.0012   | 72                   | 0.0015   | 96                   | 0.0016   |
| 24                   | 0.0004   | 40                   | 0.0010   | 64                   | 0.0015   | 80                   | 0.0015   | 120                  | 0.0017   |

$\Delta$  = increase in standard dedendum to provide increased clearance. See footnote to Table 9d.

**Table 9b. Dimensions Required when Using Enlarged, Fine-pitch, 14½-Degree Pressure Angle Pinions ANSI B6.7-1977, Information Sheet B**

| Enlarged Pinion  |                  |   | Standard Center-distance System<br>(Long and Short Addendum) |   |                                      |                                       | Enlarged Center-distance System        |  |  |
|------------------|------------------|---|--|---|--------------------------------------|---------------------------------------|--|--|--|
|                  |                  |   | Reduced Mating Gear  |   |                                      | Contact Ratio, $n$<br>Mating with $N$ | Enlarged Pinion Mating with St'd. Gear | Two Equal Enlarged Mating Pinions <sup>a</sup> | Contact Ratio of Two Equal Enlarged Mating Pinions |
| No. of Teeth $n$ | Outside Diameter | Cir. Tooth Thickness at Standard Pitch Dia. | Decrease in Standard Outside Dia. <sup>b</sup>               | Cir. Tooth Thickness at Standard Pitch Dia. | Recommended Minimum No. of Teeth $N$ |                                       |  |  |  |
| 10               | 13.3731          | 1.9259                                      | 1.3731   | 1.2157                                      | 54                                   | 1.831                                 | 0.6866                                 | 1.3732   | 1.053  |
| 11               | 14.3104          | 1.9097                                      | 1.3104   | 1.2319                                      | 53                                   | 1.847                                 | 0.6552                                 | 1.3104   | 1.088  |
| 12               | 15.2477          | 1.8935                                      | 1.2477   | 1.2481                                      | 52                                   | 1.860                                 | 0.6239                                 | 1.2477   | 1.121  |
| 13               | 16.1850          | 1.8773                                      | 1.1850   | 1.2643                                      | 51                                   | 1.873                                 | 0.5925                                 | 1.1850   | 1.154  |
| 14               | 17.1223          | 1.8611                                      | 1.1223   | 1.2805                                      | 50                                   | 1.885                                 | 0.5612                                 | 1.2223   | 1.186  |
| 15               | 18.0597          | 1.8448                                      | 1.0597   | 1.2967                                      | 49                                   | 1.896                                 | 0.5299                                 | 1.0597   | 1.217  |
| 16               | 18.9970          | 1.8286                                      | 0.9970   | 1.3130                                      | 48                                   | 1.906                                 | 0.4985                                 | 0.9970   | 1.248  |
| 17               | 19.9343          | 1.8124                                      | 0.9343   | 1.3292                                      | 47                                   | 1.914                                 | 0.4672                                 | 0.9343   | 1.278  |
| 18               | 20.8716          | 1.7962                                      | 0.8716   | 1.3454                                      | 46                                   | 1.922                                 | 0.4358                                 | 0.8716   | 1.307  |
| 19               | 21.8089          | 1.7800                                      | 0.8089   | 1.3616                                      | 45                                   | 1.929                                 | 0.4045                                 | 0.8089   | 1.336  |
| 20               | 22.7462          | 1.7638                                      | 0.7462   | 1.3778                                      | 44                                   | 1.936                                 | 0.3731                                 | 0.7462   | 1.364  |
| 21               | 23.6835          | 1.7476                                      | 0.6835   | 1.3940                                      | 43                                   | 1.942                                 | 0.3418                                 | 0.6835   | 1.392  |
| 22               | 24.6208          | 1.7314                                      | 0.6208   | 1.4102                                      | 42                                   | 1.948                                 | 0.3104                                 | 0.6208   | 1.419  |
| 23               | 25.5581          | 1.7151                                      | 0.5581   | 1.4265                                      | 41                                   | 1.952                                 | 0.2791                                 | 0.5581   | 1.446  |
| 24               | 26.4954          | 1.6989                                      | 0.4954   | 1.4427                                      | 40                                   | 1.956                                 | 0.2477                                 | 0.4954   | 1.472  |
| 25               | 27.4328          | 1.6827                                      | 0.4328   | 1.4589                                      | 39                                   | 1.960                                 | 0.2164                                 | 0.4328   | 1.498  |
| 26               | 28.3701          | 1.6665                                      | 0.3701   | 1.4751                                      | 38                                   | 1.963                                 | 0.1851                                 | 0.3701   | 1.524  |
| 27               | 29.3074          | 1.6503                                      | 0.3074   | 1.4913                                      | 37                                   | 1.965                                 | 0.1537                                 | 0.3074   | 1.549  |
| 28               | 30.2447          | 1.6341                                      | 0.2448   | 1.5075                                      | 36                                   | 1.967                                 | 0.1224                                 | 0.2448   | 1.573  |
| 29               | 31.1820          | 1.6179                                      | 0.1820   | 1.5237                                      | 35                                   | 1.969                                 | 0.0910                                 | 0.1820   | 1.598  |
| 30               | 32.1193          | 1.6017                                      | 0.1193   | 1.5399                                      | 34                                   | 1.970                                 | 0.0597                                 | 0.1193   | 1.622  |
| 31               | 33.0566          | 1.5854                                      | 0.0566   | 1.5562                                      | 33                                   | 1.971                                 | 0.0283                                 | 0.0566   | 1.646  |

<sup>a</sup> If enlarged mating pinions are of unequal size, the center distance is increased by an amount equal to one-half the sum of their increase over standard outside diameters. Data in this column are not given in the standard.

<sup>b</sup> To maintain standard center distance when using an enlarged pinion, the mating gear diameter must be decreased by the amount of the pinion enlargement.

All dimensions are given in inches and are for 1 diametral pitch. For other pitches divide tabulated dimensions by the diametral pitch.

**Table 9c. Tooth Proportions Recommended for Enlarging Fine-Pitch Pinions of 20-Degree Pressure Angle—  
20 Diametral Pitch and Finer ANSI B6.7-1977**

| Enlarged Pinion Dimensions                      |   |                                   |  |  | Enlarged C.D. System<br>Pinion Mating with<br>Standard Gear |  | Standard Center Distance<br>(Long and Short Addendums)<br>Reduced Gear Dimensions |  |  |   |  |
|---|---|-----------------------------------|--|--|---|--|---|--|--|---|--|
| Number<br>of<br>Teeth, <sup>a</sup><br><i>n</i> | Outside<br>Diameter,<br><i>D<sub>oP</sub></i> | Addendum,<br><i>a<sub>P</sub></i> | Basic<br>Tooth<br>Thickness,<br><i>t<sub>P</sub></i> | Dedendum<br>Based on<br>20 Pitch, <sup>b</sup><br><i>b<sub>P</sub></i> | Contact<br>Ratio<br>Two Equal<br>Pinions                    | Contact<br>Ratio<br>with a<br>24-Tooth<br>Gear | Addendum, <i>a<sub>G</sub></i>  | Basic<br>Tooth<br>Thickness,<br><i>t<sub>G</sub></i> | Dedendum<br>Based on<br>20 Pitch, <sup>b</sup><br><i>b<sub>G</sub></i> | Recommended<br>Minimum No.<br>of Teeth,<br><i>N</i> | Contact<br>Ratio<br><i>n</i> Mating<br>with <i>N</i> |
| 7   | 10.0102                                       | 1.5051                            | 2.14114  | 0.4565   | 0.697   | 1.003  | 0.2165  | 1.00045  | 2.0235   | 42  | 1.079  |
| 8   | 11.0250                                       | 1.5125                            | 2.09854  | 0.5150   | 0.792   | 1.075  | 0.2750  | 1.04305  | 1.9650   | 40  | 1.162  |
| 9   | 12.0305                                       | 1.5152                            | 2.05594  | 0.5735   | 0.893   | 1.152  | 0.3335  | 1.08565  | 1.9065   | 39  | 1.251  |
| 10  | 13.0279                                       | 1.5140                            | 2.01355  | 0.6321   | 0.982   | 1.211  | 0.3921  | 1.12824  | 1.8479   | 38  | 1.312  |
| 11  | 14.0304                                       | 1.5152                            | 1.97937  | 0.6787   | 1.068   | 1.268  | 0.4387  | 1.16222  | 1.8013   | 37  | 1.371  |
| 12  | 15.0296                                       | 1.5148                            | 1.94703  | 0.7232   | 1.151   | 1.322  | 0.4832  | 1.19456  | 1.7568   | 36  | 1.427  |
| 13  | 15.9448                                       | 1.4724                            | 1.91469  | 0.7676   | 1.193   | 1.353  | 0.5276  | 1.22690  | 1.7124   | 35  | 1.457  |
| 14  | 16.8560                                       | 1.4280                            | 1.88235  | 0.8120   | 1.232   | 1.381  | 0.5720  | 1.25924  | 1.6680   | 34  | 1.483  |
| 15  | 17.7671                                       | 1.3836                            | 1.85001  | 0.8564   | 1.270   | 1.408  | 0.6164  | 1.29158  | 1.6236   | 33  | 1.507  |
| 16  | 18.6782                                       | 1.3391                            | 1.81766  | 0.9009   | 1.323   | 1.434  | 0.6609  | 1.32393  | 1.5791   | 32  | 1.528  |
| 17  | 19.5894                                       | 1.2947                            | 1.78532  | 0.9453   | 1.347   | 1.458  | 0.7053  | 1.35627  | 1.5347   | 31  | 1.546  |
| 18  | 20.5006                                       | 1.2503                            | 1.75298  | 0.9897   | 1.385   | 1.482  | 0.7497  | 1.38861  | 1.4903   | 30  | 1.561  |
| 19  | 21.4116                                       | 1.2058                            | 1.72064  | 1.0342   | 1.423   | 1.505  | 0.7942  | 1.42095  | 1.4458   | 29  | 1.574  |
| 20  | 22.3228                                       | 1.1614                            | 1.68839  | 1.0786   | 1.461   | 1.527  | 0.8386  | 1.45320  | 1.4014   | 28  | 1.584  |
| 21  | 23.2340                                       | 1.1170                            | 1.65595  | 1.1230   | 1.498   | 1.548  | 0.8830  | 1.48564  | 1.3570   | 27  | 1.592  |
| 22  | 24.1450                                       | 1.0725                            | 1.62361  | 1.1675   | 1.536   | 1.568  | 0.9275  | 1.51798  | 1.3125   | 26  | 1.598  |
| 23  | 25.0561                                       | 1.0281                            | 1.59127  | 1.2119   | 1.574   | 1.588  | 0.9719  | 1.55032  | 1.2681   | 25  | 1.601  |
| 24  | 26.0000                                       | 1.0000                            | 1.57080  | 1.2400   | 1.602   | 1.602  | 1.0000  | 1.57080  | 1.2400   | 24  | 1.602  |

<sup>a</sup>Caution should be exercised in the use of pinions above the horizontal lines. They should be checked for suitability, particularly in the areas of contact ratio (less than 1.2 is not recommended), center distance, clearance, and tooth strength.

<sup>b</sup>The actual dedendum is calculated by dividing the values in this column by the desired diametral pitch and then adding to the result an amount  $\Delta$  found in Table 9a. As an example, a 20-degree pressure angle 7-tooth pinion meshing with a 42-tooth gear would have, for 24 diametral pitch, a dedendum of  $0.4565 \div 24 + 0.0004 = 0.0194$ . The 42-tooth gear would have a dedendum of  $2.0235 \div 24 + 0.004 = 0.0847$  inch.

All dimensions are given in inches.

**Table 9d. Tooth Proportions Recommended for Enlarging Fine-Pitch Pinions of 25-Degree Pressure Angle—  
20 Diametral Pitch and Finer ANSI B6.7-1977, Information Sheet B**

| Enlarged Pinion Dimensions                      |   |                                   |  |   | Enlarged C.D. System<br>Pinion Mating with<br>Standard Gear |  | Standard Center Distance<br>(Long and Short Addendums)<br>Reduced Gear Dimensions |  |  |   |  |
|---|---|-----------------------------------|--|---|---|--|---|--|--|---|--|
| Number<br>of<br>Teeth, <sup>a</sup><br><i>n</i> | Outside<br>Diameter,<br><i>D<sub>oP</sub></i> | Addendum,<br><i>a<sub>P</sub></i> | Basic<br>Tooth<br>Thickness,<br><i>t<sub>P</sub></i> | Dedendum<br>Based on 20<br>Pitch,<br>Dedendum<br>Based on<br>20 Pitch, <sup>b</sup><br><i>b<sub>P</sub></i> | Contact<br>Ratio<br>Two Equal<br>Pinions                    | Contact<br>Ratio<br>with a<br>15-Tooth<br>Gear | Addendum, <i>a<sub>G</sub></i>  | Basic<br>Tooth<br>Thickness,<br><i>t<sub>G</sub></i> | Dedendum<br>Based on<br>20 Pitch, <sup>b</sup><br><i>b<sub>G</sub></i> | Recommended<br>Minimum No.<br>of Teeth,<br><i>N</i> | Contact<br>Ratio<br><i>n</i> Mating<br>with <i>N</i> |
| 6   | 8.7645  | 1.3822                            | 2.18362  | 0.5829  | 0.696   | 0.954  | 0.3429  | 0.95797  | 1.8971   | 24  | 1.030  |
| 7   | 9.7253  | 1.3626                            | 2.10029  | 0.6722  | 0.800   | 1.026  | 0.4322  | 1.04130  | 1.8078   | 23  | 1.108  |
| 8   | 10.6735                                       | 1.3368                            | 2.01701  | 0.7616  | 0.904   | 1.094  | 0.5216  | 1.12459  | 1.7184   | 22  | 1.177  |
| 9   | 11.6203                                       | 1.3102                            | 1.94110  | 0.8427  | 1.003   | 1.156  | 0.6029  | 1.20048  | 1.6371   | 20  | 1.234  |
| 10  | 12.5691                                       | 1.2846                            | 1.87345  | 0.9155  | 1.095   | 1.211  | 0.6755  | 1.26814  | 1.5645   | 19  | 1.282  |
| 11  | 13.5039                                       | 1.2520                            | 1.80579  | 0.9880  | 1.183   | 1.261  | 0.7480  | 1.33581  | 1.4920   | 18  | 1.322  |
| 12  | 14.3588                                       | 1.1794                            | 1.73813  | 1.0606  | 1.231   | 1.290  | 0.8206  | 1.40346  | 1.4194   | 17  | 1.337  |
| 13  | 15.2138                                       | 1.1069                            | 1.67047  | 1.1331  | 1.279   | 1.317  | 0.8931  | 1.47112  | 1.3469   | 16  | 1.347  |
| 14  | 16.0686                                       | 1.0343                            | 1.60281  | 1.2057  | 1.328   | 1.343  | 0.9657  | 1.53878  | 1.2743   | 15  | 1.352  |
| 15  | 17.0000                                       | 1.0000                            | 1.57030  | 1.2400  | 1.358   | 1.358  | 1.0000  | 1.57080  | 1.2400   | 15  | 1.358  |

<sup>a</sup> Caution should be exercised in the use of pinions above the horizontal lines. They should be checked for suitability, particularly in the areas of contact ratio (less than 1.2 is not recommended), center distance, clearance, and tooth strength.

<sup>b</sup> The actual dedendum is calculated by dividing the values in this column by the desired diametral pitch and then adding to the result an amount  $\Delta$  found in Table 9a. As an example, a 20-degree pressure angle 7-tooth pinion meshing with a 42-tooth gear would have, for 24 diametral pitch, a dedendum of  $0.4565 \div 24 + 0.0004 = 0.0194$ . The 42-tooth gear would have a dedendum of  $2.0235 \div 24 + 0.0004 = 0.0847$  inch.

All dimensions are given in inches.

All values are for 1 diametral pitch. For any other sizes of teeth, all linear dimensions should be divided by the diametral pitch.

*Note:* The tables in the ANSI B6.7-1977 standard also specify Form Diameter, Roll Angle to Form Diameter, and Top Land. These are not shown here. The top land is in no case less than  $0.275/P$ . The form diameters and the roll angles to form diameter shown in the Standard are the values which should be met with a standard hob when generating the tooth thicknesses shown in the tables. These form diameters provides more than enough length of involute profile for any mating gear smaller than a rack. However, since these form diameters are based on gear tooth generation using standard hobs, they should impose little or no hardship on manufacture except in cases of the most critical quality levels. In such cases, form diameter specifications and master gear design should be based upon actual mating conditions.

**Minimum Number of Teeth to Avoid Undercutting by Hob.**—The data in the above tables give tooth proportions for low numbers of teeth to avoid interference between the gear tooth tip and the pinion tooth flank. Consideration must also be given to possible undercutting of the pinion tooth flank by the hob used to cut the pinion. The minimum number of teeth  $N_{\min}$  of standard proportion that may be cut without undercut is:

$N_{\min} = 2P \csc^2 \phi [a_H - r_t (1 - \sin \phi)]$  where:  $a_H$  = cutter addendum;  $r_t$  = radius at cutter tip or corners;  $\phi$  = cutter pressure angle; and  $P$  = diametral pitch.

**Gear to Mesh with Enlarged Pinion.**—Data in the fifth column of [Table 8](#) show minimum number of teeth in a mating gear which can be cut with hob or rack type cutter without undercut, when outside diameter of gear has been reduced an amount equal to the pinion enlargement to retain the standard center distance. To calculate  $N$  for the gear, insert addendum  $a$  of enlarged mating pinion in the formula  $N = 2a \times \csc^2 \phi$ .

*Example:* A gear is to mesh with a 24-tooth pinion of 1 diametral pitch which has been enlarged 0.4954 inch, as shown by the table. The pressure angle is  $14\frac{1}{2}$  degrees. Find minimum number of teeth  $N$  for reduced gear.

$$\text{Pinion addendum} = 1 + (0.4954 \div 2) = 1.2477$$

$$\text{Hence, } N = 2 \times 1.2477 \times 15.95 = 39.8 \text{ (use 40)}$$

In the case of fine pitch gears with reduced outside diameters, the recommended minimum numbers of teeth given in [Tables 9b](#), [9c](#), and [9d](#), are somewhat more than the minimum numbers required to prevent undercutting and are based upon studies made by the *American Gear Manufacturers Association*.

**Standard Center-distance System for Enlarged Pinions.**—In this system, sometimes referred to as “long and short addendums,” the center distance is made standard for the numbers of teeth in pinion and gear. The outside diameter of the gear is decreased by the same amount that the outside of the pinion is enlarged.

The advantages of this system are: 1) No change in center distance or ratio is required; 2) The operating pressure angle remains standard; and 3) A slightly greater contact ratio is obtained than when the center distance is increased.

The disadvantages are 1) The gears as well as the pinion must be changed from standard dimensions; 2) Pinions having fewer than the minimum number of teeth to avoid undercut cannot be satisfactorily meshed together; and 3) In most cases where gear trains include idler gears, the standard center-distance system cannot be used.

**Enlarged Center-distance System for Enlarged Pinions.**—If an enlarged pinion is meshed with another enlarged pinion or with a gear of standard outside diameter, the center distance must be increased. For fine-pitch gears, it is usually satisfactory to increase the center distance by an amount equal to one-half of the enlargements (see eighth column of [Table 9b](#)). This is an approximation as theoretically there is a slight increase in backlash.

The advantages of this system are: 1) Only the pinions need be changed from the standard dimensions; 2) Pinions having fewer than 18 teeth may engage other pinions in this range; 3) The pinion tooth, which is the weaker member, is made stronger by the enlargement; and 4) The tooth contact stress, which controls gear durability, is lowered by being moved away from the pinion base circle.

The disadvantages are: 1) Center distances must be enlarged over the standard; 2) The operating pressure angle increases slightly with different combinations of pinions and gears, which is usually not important; and 3) The contact ratio is slightly smaller than that obtained with the standard center-distance system.

This consideration is of minor importance as in the worst case the loss is approximately only 6 per cent.

*Enlarged Pinions Meshing without Backlash:* When two enlarged pinions are to mesh without backlash, their center distance will be greater than the standard and less than that

for the enlarged center-distance system. This center distance may be calculated by the formulas given in the following section.

**Center Distance at Which Modified Mating Spur Gears Will Mesh with No Backlash.**—When the tooth thickness of one or both of a pair of mating spur gears has been increased or decreased from the standard value ( $\pi \div 2P$ ), the center distance at which they will mesh tightly (without backlash) may be calculated from the following formulas:

$$\text{inv } \phi_1 = \text{inv } \phi + \frac{P(t+T) - \pi}{n+N}$$

$$C = \frac{n+N}{2P}$$

$$C_1 = \frac{\cos \phi}{\cos \phi_1} \times C$$

In these formulas,  $P$  = diametral pitch;  $n$  = number of teeth in pinion;  $N$  = number of teeth in gear;  $t$  and  $T$  are the actual tooth thicknesses of the pinion and gear, respectively, on their standard pitch circles;  $\text{inv } \phi$  = involute function of standard pressure angle of gears;  $C$  = standard center distance for the gears;  $C_1$  = center distance at which the gears mesh without backlash; and  $\text{inv } \phi_1$  = involute function of operating pressure angle when gears are meshed tightly at center distance  $C_1$ .

*Example:* Calculate the center distance for no backlash when an enlarged 10-tooth pinion of 100 diametral pitch and 20-degree pressure angle is meshed with a standard 30-tooth gear, the circular tooth thickness of the pinion and gear, respectively, being 0.01873 and 0.015708 inch.

$$\text{inv } \phi_1 = \text{inv } 20^\circ + \frac{100(0.01873 + 0.015708) - \pi}{(10 + 30)}$$

From the table of involute functions,  $\text{inv } 20$ -degrees = 0.014904. Therefore,

$$\text{inv } \phi_1 = 0.014904 + \frac{0.34438 - 0.31416}{4} = 0.022459$$

$$\phi_1 = 22^\circ 49' \text{ from page 99}$$

$$C = \frac{n+N}{2P} = \frac{10+30}{2 \times 100} = 0.2000 \text{ inch}$$

$$C_1 = \frac{\cos 20^\circ}{\cos 22^\circ 49'} \times 0.2000 = \frac{0.93969}{0.92175} \times 0.2000 = 0.2039 \text{ inch}$$

**Contact Diameter.**—For two meshing gears it is important to know the contact diameter of each. A first gear with number of teeth,  $n$ , and outside diameter,  $d_0$ , meshes at a standard center distance with a second gear with number of teeth,  $N$ , and outside diameter,  $D_0$ ; both gears have a diametral pitch,  $P$ , and pressure angle,  $\phi$ ,  $a$ ,  $A$ ,  $b$ , and  $B$  are unnamed angles used only in the calculations. The contact diameter,  $d_c$ , is found by a three-step calculation that can be done by hand using a trigonometric table and a logarithmic table or a desk calculator. Slide rule calculation is not recommended because it is not accurate enough to give good results. The three-step formulas to find the contact diameter,  $d_c$ , of the first gear are:

$$\cos A = \frac{N \cos \phi}{D_0 \times P} \quad (1)$$

$$\tan b = \tan \phi - \frac{N}{n} (\tan A - \tan \phi) \quad (2)$$



## SPUR GEARING

$$d_c = \frac{n \cos \phi}{P \cos b} \quad (3)$$

Similarly the three-step formulas to find the contact diameter,  $D_c$ , of the second gear are:

$$\cos a = \frac{n \cos \phi}{d_o \times P} \quad (4)$$

$$\tan B = \tan \phi - \frac{n}{N}(\tan a - \tan \phi) \quad (5)$$

$$D_c = \frac{N \cos \phi}{P \cos B} \quad (6)$$

**Contact Ratio.**—The contact ratio of a pair of mating spur gears must be well over 1.0 to assure a smooth transfer of load from one pair of teeth to the next pair as the two gears rotate under load. Because of a reduction in contact ratio due to such factors as tooth deflection, tooth spacing errors, tooth tip breakage, and outside diameter and center distance tolerances, the contact ratio of gears for power transmission as a general rule should not be less than about 1.4. A contact ratio of as low as 1.15 may be used in extreme cases, provided the tolerance effects mentioned above are accounted for in the calculation. The formula for determining the contact ratio,  $m_f$ , using the nomenclature in the previous section is:

$$m_f = \frac{N}{6.28318}(\tan A - \tan B) \quad (7a)$$

or

$$m_f = \frac{N}{6.28318}(\tan a - \tan b) \quad (7b)$$

or

$$m_f = \frac{\sqrt{R_0^2 - R_B^2} + \sqrt{r_0^2 - r_B^2} - C \sin \theta}{P \cos \theta} \quad (7c)$$

where  $R_0$  = outside radius of first gear;  $R_B$  = base radius of first gear;  $r_0$  = outside radius of second gear;  $r_B$  = base radius of second gear;  $C$  = center distance;  $I$  = pressure angle; and,  $p$  = circular pitch.

Both formulas [Equations \(7a\)](#) and [Equations \(7b\)](#) should give the same answer. It is good practice to use both formulas as a check on the previous calculations.

**Lowest Point of Single Tooth Contact.**—This diameter on the pinion (sometimes referred to as LPSTQ) is used to find the maximum contact compressive stress (sometimes called the Hertz Stress) of a pair of mating spur gears. The two-step formulas for determining this pinion diameter,  $d_L$ , using the same nomenclature as in the previous sections with  $c$  and  $C$  as unnamed angles used only in the calculations are:

$$\tan c = \tan a - \frac{6.28318}{n} \quad (8)$$

$$d_L = \frac{n \cos \phi}{P \cos c} \quad (9)$$

In some cases it is necessary to have a plot of the compressive stress over the whole cycle of contact; in this case the LPSTC for the gear is required also. The similar two-step formulas for this gear diameter are:

$$\tan C = \tan A - \frac{6.28318}{N} \quad (10)$$

$$D_L = \frac{N \cos \phi}{P \cos C} \quad (11)$$

**Maximum Hob Tip Radius.**—The standard gear tooth proportions given by the formulas in Table 2 on page 2035 provide a specified size for the rack fillet radius in the general form of (a constant)  $\times$  (pitch). For any given standard this constant may vary up to a maximum which it is geometrically impossible to exceed; this maximum constant,  $r_c$  (max), is found by the formula:

$$r_c \text{ (max)} = \frac{0.785398 \cos \phi - b \sin \phi}{1 - \sin \phi} \quad (12)$$

where  $b$  is the similar constant in the specified formula for the gear dedendum. The hob tip radius of any standard hob to finish cut any standard gear may vary from zero up to this limiting value.

**Undercut Limit for Hobbled Involute Gears.**—It is well to avoid designing and specifying gears that will have a hobbled trochoidal fillet that undercuts the involute gear tooth profile. This should be avoided because it may cause the involute profile to be cut away up to a point above the required contact diameter with the mating gear so that involute action is lost and the contact ratio reduced to a level that may be too low for proper conjugate action. An undercut fillet will also weaken the beam strength and thus raise the fillet tensile stress of the gear tooth. To assure that the hobbled gear tooth will not have an undercut fillet, the following formula must be satisfied:

$$\frac{b - r_c}{\sin \phi} + r_c \leq 0.5n \sin \phi \quad (13)$$

where  $b$  is the dedendum constant;  $r_c$  is the hob or rack tip radius constant;  $n$  is the number of teeth in the gear; and  $\phi$  is the gear and hob pressure angle. If the gear is not standard or the hob does not roll at the gear pitch diameter, this formula can not be applied and the determination of the expected existence of undercut becomes a considerably more complicated procedure.

**Highest Point of Single Tooth Contact.**—This diameter is used to place the maximum operating load for the determination of the gear tooth fillet stress. The two-step formulas for determining this diameter,  $d_H$ , of the pinion using the same nomenclature as in the previous sections with  $d$  and  $D$  as unnamed angles used only in the calculations are:

$$\tan d = \tan b + \frac{6.28318}{n} \quad (14)$$

$$d_H = \frac{n \cos \phi}{P \cos d} \quad (15)$$

Similarly for the gear:

$$\tan D = \tan B + \frac{6.28318}{N} \quad (16)$$

$$D_H = \frac{N \cos \phi}{P \cos D} \quad (17)$$

**True Involute Form Diameter.**—The point on the gear tooth at which the fillet and the involute profile are tangent to each other should be determined to assure that it lies at a smaller diameter than the required contact diameter with the mating gear. If the TIF diameter is larger than the contact diameter, then fillet interference will occur with severe damage to the gear tooth profile and rough action of the gear set. This two-step calculation is

made by using the following two formulas with  $e$  and  $E$  as unnamed angles used only in the calculations:

$$\tan e = \tan \phi - \frac{4}{n} \left( \frac{b - r_c}{\sin 2\phi} + \frac{r_c}{2 \cos \phi} \right) \quad (18)$$

$$d_{TIF} = \frac{n \cos \phi}{P \cos e} \quad (19)$$

As in the previous sections,  $\phi$  is the pressure angle of the gear;  $n$  is the number of teeth in the pinion;  $b$  is the dedendum constant,  $r_c$  is the rack or hob tip radius constant,  $P$  is the gear diametral pitch and  $d_{TIF}$  is the true involute form diameter.

Similarly, for the mating gear:

$$\tan E = \tan \phi - \frac{4}{N} \left( \frac{b - r_c}{\sin 2\phi} + \frac{r_c}{2 \cos \phi} \right) \quad (20)$$

$$D_{TIF} = \frac{N \cos \phi}{P \cos E} \quad (21)$$

where  $N$  is number of teeth in this mating gear and  $D_{TIF}$  is the true involute form diameter.

**Profile Checker Settings.**—The actual tooth profile tolerance will need to be determined on high performance gears that operate either at high unit loads or at high pitch-line velocity. This is done on an involute checker, a machine which requires two settings, the gear base radius and the roll angle in degrees to significant points on the involute. From the smallest diameter outward these significant points are: TIF, Contact Diameter, LPSTC, Pitch Diameter, HPSTC, and Outside Diameter.

The base radius is:

$$R_b = \frac{N \cos \phi}{2P} \quad (22)$$

The roll angle, in degrees, at any point is equal to the tangent of the pressure angle at that point multiplied by 57.2958. The following table shows the tangents to be used at each significant diameter.

| Significant Point on Tooth Profile | Pinion      | Gear        | For Computation            |
|------------------------------------|-------------|-------------|----------------------------|
| TIF                                | $\tan e$    | $\tan E$    | (See Formulas (18) & (20)) |
| Contact Dia.                       | $\tan b$    | $\tan B$    | (See Formulas (2) & (5))   |
| LPSTC                              | $\tan c$    | $\tan C$    | (See Formulas (8) & (10))  |
| Pitch Dia.                         | $\tan \phi$ | $\tan \phi$ | ( $\phi$ = Pressure angle) |
| HPSTC                              | $\tan d$    | $\tan D$    | (See Formulas (14) & (16)) |
| Outside Dia.                       | $\tan a$    | $\tan A$    | (See Formulas (4) & (1))   |

*Example:* Find the significant diameters, contact ratio and hob tip radius for a 10-diametral pitch, 23-tooth, 20-degree pressure angle pinion of 2.5-inch outside diameter if it is to mesh with a 31-tooth gear of 3.3-inch outside diameter.

Thus:  $n = 23$   
 $d_O = 2.5$   
 $P = 10$   
 $N = 31$   
 $D_O = 3.3$   
 $\phi = 20^\circ$

1) Pinion contact diameter,  $d_c$ 

$$\cos A = \frac{31 \times 0.93969}{3.3 \times 10} \quad (1)$$

$$= 0.88274 \quad A = 28^\circ 1' 30''$$

$$\tan b = 0.36397 - \frac{31}{23}(0.53227 - 0.36397) \quad (2)$$

$$= 0.13713 \quad b = 7^\circ 48' 26''$$

$$d_c = \frac{23 \times 0.93969}{10 \times 0.99073} \quad (3)$$

$$= 2.1815 \text{ inches}$$

2) Gear contact diameter,  $D_c$ 

$$\cos a = \frac{23 \times 0.93963}{2.5 \times 10} \quad (4)$$

$$= 0.86452 \quad a = 30^\circ 10' 20''$$

$$\tan B = 0.36397 - \frac{23}{31}(0.58136 - 0.36937) \quad (5)$$

$$= 0.20267 \quad B = 11^\circ 27' 26''$$

$$D_c = \frac{31 \times 0.93969}{10 \times 0.98000} \quad (6)$$

$$= 2.9725 \text{ inches}$$

3) Contact ratio,  $m_f$ 

$$m_f = \frac{31}{6.28318}(0.53227 - 0.20267) \quad (7a)$$

$$= 1.626$$

$$m_f = \frac{23}{6.28318}(0.58136 - 0.13713) \quad (7b)$$

$$= 1.626$$

4) Pinion LPSTC,  $d_L$ 

$$\tan c = 0.58136 - \frac{6.28318}{23} \quad (8)$$

$$= 0.30818 \quad c = 17^\circ 7' 41''$$

$$d_L = \frac{23 \times 0.93969}{10 \times 0.95565} \quad (9)$$

$$= 2.2616 \text{ inches}$$

5) Gear LPSTC,  $D_L$ 

$$\tan C = 0.53227 - \frac{6.28318}{31} \quad (10)$$

$$= 0.32959 \quad C = 18^\circ 14' 30''$$

$$D_L = \frac{31 \times 0.93969}{10 \times 0.94974} \quad (11)$$

$$= 3.0672 \text{ inches}$$

6) Maximum permissible hob tip radius,  $r_c$  (max). The dedendum factor is 1.25.

$$r_c \text{ (max)} = \frac{0.785398 \times 0.93969 - 1.25 \times 0.34202}{1 - 0.34202} \quad (12)$$

$$= 0.4719 \text{ inch}$$

7) If the hob tip radius  $r_c$  is 0.30, determine if the pinion involute is undercut.

$$\frac{1.25 - 0.30}{0.34202} + 0.30 \leq 0.5 \times 23 \times 0.34202 \quad (13)$$

$$3.0776 < 3.9332$$

8) therefore there is no involute undercut.

9) Pinion HPSTC,  $D_H$

$$\tan d = 0.13713 + \frac{6.28318}{23} \quad (14)$$

$$= 0.41031 \quad d = 22^\circ 18' 32''$$

$$d_H = \frac{23 \times 0.93969}{10 \times 0.92515} \quad (15)$$

$$= 2.3362 \text{ inches}$$

10) Gear HPSTC,  $D_H$

$$\tan D = 0.20267 + \frac{6.28318}{31} \quad (16)$$

$$= 0.40535 \quad D = 22^\circ 3' 55''$$

$$D_H = \frac{31 \times 0.93969}{10 \times 0.92676} \quad (17)$$

$$= 3.1433 \text{ inches}$$

11) Pinion TIF diameter,  $d_{TIF}$

$$\tan e = 0.36397 - \frac{4}{23} \left( \frac{1.25 - 0.30}{0.64279} + \frac{0.30}{2 \times 0.93969} \right) \quad (18)$$

$$= 0.07917 \quad e = 4^\circ 31' 36''$$

$$d_{TIF} = \frac{23 \times 0.93969}{10 \times 0.99688} \quad (19)$$

$$= 2.1681 \text{ inches}$$

12) Gear TIF diameter,  $D_{TIF}$

$$\tan E = 0.36397 - \frac{4}{31} \left( \frac{1.25 - 0.30}{0.64279} + \frac{0.30}{2 \times 0.93969} \right) \quad (20)$$

$$= 0.15267 \quad E = 8^\circ 40' 50''$$

$$D_{TIF} = \frac{31 \times 0.93969}{10 \times 0.98855} = 2.9468 \text{ inches} \quad (21)$$

**Gear Blanks for Fine-pitch Gears.**—The accuracy to which gears can be produced is considerably affected by the design of the gear blank and the accuracy to which the various surfaces of the blank are machined. The following recommendations should not be regarded as inflexible rules, but rather as minimum average requirements for gear-blank quality compatible with the expected quality class of the finished gear.

*Design of Gear Blanks:* The accuracy to which gears can be produced is affected by the design of the blank, so the following points of design should be noted: 1) Gears designed with a hole should have the hole large enough that the blank can be adequately supported during machining of the teeth and yet not so large as to cause distortion; 2) Face widths should be wide enough, in proportion to outside diameters, to avoid springing and to permit obtaining flatness in important surfaces; 3) Short bore lengths should be avoided wherever possible. It is feasible, however, to machine relatively thin blanks in stacks, provided the surfaces are flat and parallel to each other; 4) Where gear blanks with hubs are to be designed, attention should be given to the wall sections of the hubs. Too thin a section will not permit proper clamping of the blank during machining operations and may also affect proper mounting of the gear; and 5) Where pinions or gears integral with their shafts are to be designed, deflection of the shaft can be minimized by having the shaft length and shaft diameter well proportioned to the gear or pinion diameter. The foregoing general principles may also be useful when applied to blanks for coarser pitch gears.

**Specifying Spur and Helical Gear Data on Drawings.**—The data that may be shown on drawings of spur and helical gears falls into three groups: The first group consists of data basic to the design of the gear; the second group consists of data used in manufacturing and inspection; and the third group consists of engineering reference data. The accompanying table may be used as a checklist for the various data which may be placed on gear drawings and the sequence in which they should appear.

*Explanation of Terms Used in Gear Specifications:* 1) Number of teeth is the number of teeth in 360 deg of gear circumference. In a sector gear, both the actual number of teeth in the sector and the theoretical number of teeth in 360 deg should be given.

2) Diametral pitch is the ratio of the number of teeth in the gear to the number of inches in the standard pitch diameter. It is used in this standard as a nominal specification of tooth size.

a) Normal diametral pitch is the diametral pitch in the normal plane.

b) Transverse diametral pitch is the diametral pitch in the transverse plane.

c) Module is the ratio of the number of teeth in the gear to the number of mm in the standard pitch diameter.

d) Normal module is the module measured in the normal plane.

e) Transverse module is the module measured in the transverse plane.

3) Pressure angle is the angle between the gear tooth profile and a radial line at the pitch point. It is used in this standard to specify the pressure angle of the basic rack used in defining the gear tooth profile.

a) Normal pressure angle is the pressure angle in the normal plane.

b) Transverse pressure angle is the pressure angle in the transverse plane.

4) Helix angle is the angle between the pitch helix and an element of the pitch cylinder, unless otherwise specified.

a) Hand of helix is the direction in which the teeth twist as they recede from an observer along the axis. A right hand helix twists clockwise and a left hand helix twists counterclockwise.

5) Standard pitch diameter is the diameter of the pitch circle. It equals the number of teeth divided by the transverse diametral pitch.

6) Tooth form may be specified as standard addendum, long addendum, short addendum, modified involute or special. If a modified involute or special tooth form is required, a detailed view should be shown on the drawing. If a special tooth form is specified, roll angles must be supplied (see page 2062).

7) Addendum is the radial distance between the standard pitch circle and the outside circle. The actual value depends on the specification of outside diameter.

8) Whole depth is the total radial depth of the tooth space. The actual value is dependent on the specification of outside diameter and root diameter.

9) Maximum calculated circular thickness on the standard pitch circle is the tooth thickness which will provide the desired minimum backlash when the gear is assembled in mesh with its mate on minimum center distance. Control may best be exerted by testing in tight mesh with a master which integrates all errors in the several teeth in mesh through the arc of action as explained on page 2073. This value is independent of the effect of runout.

a) Maximum calculated *normal* circular thickness is the circular tooth thickness in the normal plane which satisfies requirements explained in (9).

10) Gear testing radius is the distance from its axis of rotation to the standard pitch line of a standard master when in intimate contact under recommended pressure on a variable-center-distance running gage. Maximum testing radius should be calculated to provide the maximum circular tooth thickness specified in (9) when checked as explained on page 2073. This value is affected by the runout of the gear. Tolerance on testing radius must be equal to or greater than the total composite error permitted by the quality class specified in (11).

11) Quality class is specified for convenience when talking or writing about the accuracy of the gear.

12) Maximum total composite error, and 13) Maximum tooth-to-tooth composite error. Actual tolerance values (12 and 13) permitted by the quality class (11) are specified in inches to provide machine operator or inspector with tolerances required to inspect the gear.

14) Testing pressure recommendations are given on page 2073. Incorrect testing pressure will result in incorrect measurement of testing radius.

15) Master specifications by tool or code number may be required to call for the use of a special master gear when tooth thickness deviates excessively from standard.

16) Measurement over two 0.xxxx diameter pins may be specified to assist the manufacturing department in determining size at machine for setup only.

17) Outside diameter is usually shown on the drawing of the gear together with other blank dimensions so that it will not be necessary for machine operators to search gear tooth data for this dimension. Since outside diameter is also frequently used in the manufacture and inspection of the teeth, it may be included in the data block with other tooth specifications if preferred. To permit use of topping hobs for cutting gears on which the tooth thickness has been modified from standard, the outside diameter should be related to the specified gear testing radius (10).

18) Maximum root diameter is specified to assure adequate clearance for the outside diameter of the mating gear. This dimension is usually considered acceptable if the gear is checked with a master and meets specifications (10) through (13).

19) Active profile diameter of a gear is the smallest diameter at which the mating gear tooth profile can make contact. Because of difficulties involved in checking, this specification is not recommended for gears finer than 48 pitch.

20) Surface roughness on active profile surfaces may be specified in microinches to be checked by instrument up to about 32 pitch, or by visual comparison in the finer pitch ranges. It is difficult to determine accurately the surface roughness of fine pitch gears. For many commercial applications surface roughness may be considered acceptable on gears which meet the maximum tooth-to-tooth-error specification (13).

21) Mating gear part number may be shown as a convenient reference. If the gear is used in several applications, all mating gears may be listed but usual practice is to record this information in a reference file.

22) Number of teeth in mating gear, and 23) Minimum operating center distance. This information is often specified to eliminate the necessity of getting prints of the mating gear and assemblies for checking the design specifications, interference, backlash, determination of master gear specification, and acceptance or rejection of gears made out of tolerance.

## Data for Spur and Helical Gear Drawings

| Type of Data                 | Min. Spur Gear Data | Min. Helical Gear-Data | Add'l Optional Data | Item Number <sup>a</sup>                                  | Data <sup>a</sup>                                      |
|------------------------------|---------------------|------------------------|---------------------|---|--|
| Basic Specifications         | ●                   | ●                      |                     | 1   | Number of teeth  |
|                              | ●                   |                        |                     | 2   | Diametral pitch or module                              |
|                              |                     | ●                      |                     | 2a  | Normal diametral pitch or module                       |
|                              |                     |                        | ●                   | 2b  | Transverse diametral pitch or module                   |
|                              | ●                   |                        |                     | 3   | Pressure angle   |
|                              |                     | ●                      |                     | 3a  | Normal pressure angle                                  |
|                              |                     |                        | ●                   | 3b  | Transverse pressure angle                              |
|                              |                     | ●                      |                     | 4   | Helix angle  |
|                              |                     | ●                      |                     | 4a  | Hand of helix  |
|                              | ●                   | ●                      |                     | 5   | Standard pitch diameter                                |
|                              | ●                   | ●                      |                     | 6   | Tooth form   |
|                              |                     |                        | ●                   | 7   | Addendum   |
|                              |                     |                        | ●                   | 8   | Whole depth  |
| ●                            |                     |                        | 9                   | Max. calc. circular thickness on std. pitch circle        |  |
|                              | ●                   |                        | 9a                  | Max. calc. normal circular thickness on std. pitch circle |  |
| Manufacturing and Inspection |                     |                        | ●                   | 10  | Roll angles  |
|                              | ●                   | ●                      |                     | 11  | A.G.M.A. quality class                                 |
|                              | ●                   | ●                      |                     | 12  | Max. total composite error                             |
|                              | ●                   | ●                      |                     | 13  | Max. tooth-to-tooth composite error                    |
|                              |                     |                        | ●                   | 14  | Testing pressure (Ounces)                              |
|                              | ●                   | ●                      |                     | 15  | Master specification                                   |
|                              |                     |                        | ●                   | 16  | Meas. over two .0005 dia. pins (For setup only)        |
|                              | ●                   | ●                      |                     | 17  | Outside diameter (Preferably shown on drawing of gear) |
|                              |                     |                        | ●                   | 18  | Max. root diameter                                     |
|                              |                     |                        | ●                   | 19  | Active profile diameter                                |
| Engineering Reference        |                     |                        | ●                   | 20  | Surface roughness of active profile                    |
|                              |                     |                        | ●                   | 21  | Mating gear part number                                |
|                              |                     |                        | ●                   | 22  | Number of teeth in mating gear                         |
|                              |                     |                        | ●                   | 23  | Minimum operating center distance                      |

<sup>a</sup> An item-by-item explanation of the terms used in this table is given beginning on page 2065.

### Backlash

In general, backlash in gears is play between mating teeth. For purposes of measurement and calculation, backlash is defined as the amount by which a tooth space exceeds the thickness of an engaging tooth. It does not include the effect of center-distance changes of the mountings and variations in bearings. When not otherwise specified, numerical values of backlash are understood to be given on the pitch circles. The general purpose of backlash is to prevent gears from jamming together and making contact on both sides of their teeth simultaneously. Lack of backlash may cause noise, overloading, overheating of the gears and bearings, and even seizing and failure.

Excessive backlash is objectionable, particularly if the drive is frequently reversing, or if there is an overrunning load as in cam drives. On the other hand, specification of an unnecessarily small amount of backlash allowance will increase the cost of gears, because errors in runout, pitch, profile, and mounting must be held correspondingly smaller. Backlash does not affect involute action and usually is not detrimental to proper gear action.

**Determining Proper Amount of Backlash.**—In specifying proper backlash and tolerances for a pair of gears, the most important factor is probably the maximum permissible amount of runout in both gear and pinion (or worm). Next are the allowable errors in profile, pitch, tooth thickness, and helix angle. Backlash between a pair of gears will vary as successive teeth make contact because of the effect of composite tooth errors, particularly runout, and errors in the gear center distances and bearings.

Other important considerations are speed and space for lubricant film. Slow-moving gears, in general, require the least backlash. Fast-moving fine-pitch gears are usually lubri-



cated with relatively light oil, but if there is insufficient clearance for an oil film, and particularly if oil trapped at the root of the teeth cannot escape, heat and excessive tooth loading will occur.

Heat is a factor because gears may operate warmer, and, therefore, expand more, than the housings. The heat may result from oil churning or from frictional losses between the teeth, at bearings or oil seals, or from external causes. Moreover, for the same temperature rise, the material of the gears—for example, bronze and aluminum—may expand more than the material of the housings, usually steel or cast iron.

The higher the helix angle or spiral angle, the more transverse backlash is required for a given normal backlash. The transverse backlash is equal to the normal backlash divided by the cosine of the helix angle.

In designs employing normal pressure angles higher than 20 degrees, special consideration must be given to backlash, because more backlash is required on the pitch circles to obtain a given amount of backlash in a direction normal to the tooth profiles.

Errors in boring the gear housings, both in center distance and alignment, are of extreme importance in determining allowance to obtain the backlash desired. The same is true in the mounting of the gears, which is affected by the type and adjustment of bearings, and similar factors. Other influences in backlash specification are heat treatment subsequent to cutting the teeth, lapping operations, need for recutting, and reduction of tooth thickness through normal wear.

Minimum backlash is necessary for timing, indexing, gun-sighting, and certain instrument gear trains. If the operating speed is very low and the necessary precautions are taken in the manufacture of such gear trains, the backlash may be held to extremely small limits. However, the specification of "zero backlash," so commonly stipulated for gears of this nature, usually involves special and expensive techniques, and is difficult to obtain.

**Table 1. AGMA Recommended Backlash Range for Coarse-Pitch Spur, Helical, and Herringbone Gearing**

| Center Distance (Inches) | Normal Diametral Pitches                    |           |           |           |           |
|--------------------------|---|-----------|-----------|-----------|-----------|
|                          | 0.5–1.99                                    | 2–3.49    | 3.5–5.99  | 6–9.99    | 10–19.99  |
|                          | Backlash, Normal Plane, Inches <sup>a</sup> |           |           |           |           |
| Up to 5                  | ...   | ...       | ...       | ...       | .005–.015 |
| Over 5 to 10             | ...   | ...       | ...       | .010–.020 | .010–.020 |
| Over 10 to 20            | ...   | ...       | .020–.030 | .015–.025 | .010–.020 |
| Over 20 to 30            | ...   | .030–.040 | .025–.030 | .020–.030 | ...       |
| Over 30 to 40            | .040–.060                                   | .035–.045 | .030–.040 | .025–.035 | ...       |
| Over 40 to 50            | .050–.070                                   | .040–.055 | .035–.050 | .030–.040 | ...       |
| Over 50 to 80            | .060–.080                                   | .045–.065 | .040–.060 | ...       | ...       |
| Over 80 to 100           | .070–.095                                   | .050–.080 | ...       | ...       | ...       |
| Over 100 to 120          | .080–.110                                   | ...       | ...       | ...       | ...       |

<sup>a</sup> Suggested backlash, on nominal centers, measured after rotating to the point of closest engagement. For helical and herringbone gears, divide above values by the cosine of the helix angle to obtain the transverse backlash.

The above backlash tolerances contain allowance for gear expansion due to differential in the operating temperature of the gearing and their supporting structure. The values may be used where the operating temperatures are up to 70 deg F higher than the ambient temperature.

For most gearing applications the recommended backlash ranges will provide proper running clearance between engaging teeth of mating gears. Deviation below the minimum or above the maximum values shown, which do not affect operational use of the gearing, should not be cause for rejection.

Definite backlash tolerances on coarse-pitch gearing are to be considered binding on the gear manufacturer only when agreed upon in writing.

Some applications may require less backlash than shown in the above table. In such cases the amount and tolerance should be by agreement between manufacturer and purchaser.

**Recommended Backlash:** In the following tables American Gear Manufacturers Association recommendations for backlash ranges for various kinds of gears are given.\* For purposes of measurement and calculation, backlash is defined as the amount by which a tooth space exceeds the thickness of an engaging tooth. When not otherwise specified, numerical values of backlash are understood to be measured at the tightest point of mesh on the pitch circle in a direction normal to the tooth surface when the gears are mounted in their specified position.

**Coarse-Pitch Gears:** Table 1 gives the recommended backlash range for coarse-pitch spur, helical and herringbone gearing. Because backlash for helical and herringbone gears is more conveniently measured in the normal plane, Table 1 has been prepared to show backlash in the normal plane for coarse-pitch helical and herringbone gearing and in the transverse plane for spur gears. To obtain backlash in the transverse plane for helical and herringbone gears, divide the normal plane backlash in Table 1 by the cosine of the helix angle.

**Table 2. AGMA Recommended Backlash Range for Bevel and Hypoid Gears**

| Diametral Pitch | Normal Backlash, Inch        |                             | Diametral Pitch | Normal Backlash, Inch        |                             |
|-----------------|------------------------------|-----------------------------|-----------------|------------------------------|-----------------------------|
|                 | Quality Numbers 7 through 13 | Quality Numbers 3 through 6 |                 | Quality Numbers 7 through 13 | Quality Numbers 3 through 6 |
| 1.00 to 1.25    | 0.020–0.030                  | 0.045–0.065                 | 5.00 to 6.00    | 0.005–0.007                  | 0.006–0.013                 |
| 1.25 to 1.50    | 0.018–0.026                  | 0.035–0.055                 | 6.00 to 8.00    | 0.004–0.006                  | 0.005–0.010                 |
| 1.50 to 1.75    | 0.016–0.022                  | 0.025–0.045                 | 8.00 to 10.00   | 0.003–0.005                  | 0.004–0.008                 |
| 1.75 to 2.00    | 0.014–0.018                  | 0.020–0.040                 | 10.00 to 16.00  | 0.002–0.004                  | 0.003–0.005                 |
| 2.00 to 2.50    | 0.012–0.016                  | 0.020–0.030                 | 16.00 to 20.00  | 0.001–0.003                  | 0.002–0.004                 |
| 2.50 to 3.00    | 0.010–0.013                  | 0.015–0.025                 | 20 to 50        | 0.000–0.002                  | 0.000–0.002                 |
| 3.00 to 3.50    | 0.008–0.011                  | 0.012–0.022                 | 50 to 80        | 0.000–0.001                  | 0.000–0.001                 |
| 3.50 to 4.00    | 0.007–0.009                  | 0.010–0.020                 | 80 and finer    | 0.000–0.0007                 | 0.000–0.0007                |
| 4.00 to 5.00    | 0.006–0.008                  | 0.008–0.016                 | ...             | ...                          | ...                         |

Measured at tightest point of mesh

The backlash tolerances given in this table contain allowances for gear expansion due to a differential in the operating temperature of the gearing and their supporting structure. The values may be used where the operating temperature is up to 70 degrees F. higher than the ambient temperature. These backlash values will provide proper running clearances for most gear applications.

The following important factors must be considered in establishing backlash tolerances:

- a) Center distance tolerance; b) Parallelism of gear axes; c) Side runout or wobble;
- d) Tooth thickness tolerance; e) Pitch line runout tolerance; f) Profile tolerance; g) Pitch tolerance; h) Lead tolerance; i) Types of bearings and subsequent wear; j) Deflection under load; k) Gear tooth wear; l) Pitch line velocity; m) Lubrication requirements; and
- n) Thermal expansion of gears and housing.

A tight mesh may result in objectionable gear sound, increased power losses, overheating, rupture of the lubricant film, overloaded bearings and premature gear failure. However, it is recognized that there are some gearing applications where a tight mesh (zero backlash) may be required.

Specifying unnecessarily close backlash tolerances will increase the cost of the gearing. It is obvious from the above summary that the desired amount of backlash is difficult to evaluate. It is, therefore, recommended that when a designer, user or purchaser includes a reference to backlash in a gearing specification and drawing, consultation be arranged with the manufacturer.

\* Extracted from Gear Classification Manual, AGMA 390.03 with permission of the publisher, the American Gear Manufacturers Association, 1500 King St., Alexandria, VA 22314.

*Bevel and Hypoid Gears:* Table 2 gives similar backlash range values for bevel and hypoid gears. These are values based upon average conditions for general purpose gearing, but may require modification to meet specific needs.

Backlash on bevel and hypoid gears can be controlled to some extent by axial adjustment of the gears during assembly. However, due to the fact that actual adjustment of a bevel or hypoid gear in its mounting will alter the amount of backlash, it is imperative that the amount of backlash cut into the gears during manufacture is not excessive. Bevel and hypoid gears must always be capable of operation without interference when adjusted for zero backlash. This requirement is imposed by the fact that a failure of the axial thrust bearing might permit the gears to operate under this condition. Therefore, bevel and hypoid gears should never be designed to operate with normal backlash in excess of  $0.080/P$  where  $P$  is diametral pitch.

*Fine-Pitch Gears:* Table 3 gives similar backlash range values for fine-pitch spur, helical and herringbone gearing.

**Providing Backlash.**—In order to obtain the amount of backlash desired, it is necessary to decrease tooth thicknesses. However, because of manufacturing and assembling inaccuracies not only in the gears but also in other parts, the allowances made on tooth thickness almost always must exceed the desired amount of backlash. Since the amounts of these allowances depend on the closeness of control exercised on all manufacturing operations, no general recommendations for them can be given.

It is customary to make half the allowance for backlash on the tooth thickness of each gear of a pair, although there are exceptions. For example, on pinions having very low numbers of teeth it is desirable to provide all the allowance on the mating gear, so as not to weaken the pinion teeth. In worm gearing, ordinary practice is to provide all of the allowance on the worm which is usually made of a material stronger than that of the worm gear.

In some instances the backlash allowance is provided in the cutter, and the cutter is then operated at the standard tooth depth. In still other cases, backlash is obtained by setting the distance between two tools for cutting the two sides of the teeth, as in straight bevel gears, or by taking side cuts, or by changing the center distance between the gears in their mountings. In spur and helical gearing, backlash allowance is usually obtained by sinking the cutter deeper into the blank than the standard depth. The accompanying table gives the excess depth of cut for various pressure angles.

**Excess Depth of Cut  $E$  to Provide Backlash Allowance**

| Distribution of Backlash  | Pressure Angle $\phi$ , Degrees |                 |           |           |           |
|---|---------------------------------|-----------------|-----------|-----------|-----------|
|   | $14\frac{1}{2}$                 | $17\frac{1}{2}$ | 20        | 25        | 30        |
| Excess Depth of Cut $E$ to Obtain Circular Backlash $B^a$                             |                                 |                 |           |           |           |
| All on One Gear   | $1.93B$                         | $1.59B$         | $1.37B$   | $1.07B$   | $0.87B$   |
| One-half on Each Gear   | $0.97B$                         | $0.79B$         | $0.69B$   | $0.54B$   | $0.43B$   |
| Excess Depth of Cut $E$ to Obtain Backlash $B_b$ Normal to Tooth Profile <sup>b</sup> |                                 |                 |           |           |           |
| All on One Gear   | $2.00B_b$                       | $1.66B_b$       | $1.46B_b$ | $1.18B_b$ | $1.99B_b$ |
| One-half on Each Gear   | $1.00B_b$                       | $0.83B_b$       | $0.73B_b$ | $0.59B_b$ | $0.50B_b$ |

<sup>a</sup> Circular backlash is the amount by which the width of a tooth space is greater than the thickness of the engaging tooth on the pitch circles. As described in pages 2067 and 2071 this is what is meant by backlash unless otherwise specified.

<sup>b</sup> Backlash measured normal to the tooth profile by inserting a feeler gage between meshing teeth; to convert to circular backlash,  $B = B_b \div \cos \phi$ .

**Control of Backlash Allowances in Production.**—Measurement of the tooth thickness of gears is perhaps the simplest way of controlling backlash allowances in production.

There are several ways in which this may be done including: 1) chordal thickness measurements as described on page 2049; 2) caliper measurements over two or more teeth as described on page 2140; and 3) measurements over wires.

In this last method, first the theoretical measurement over wires when the backlash allowance is zero is determined by the method described on page 2125; then the amount this measurement must be reduced to obtain a desired backlash allowance is taken from the table on page 2139.

It should be understood, as explained in the section *Measurement of Backlash* that merely making tooth thickness allowances will not guarantee the amount of backlash in the ready-to-run assembly of two or more gears. Manufacturing limitations will introduce such gear errors as runout, pitch error, profile error, and lead error, and gear-housing errors in both center distance and alignment. All of these make the backlash of the assembled gears different from that indicated by tooth thickness measurements on the individual gears.

**Measurement of Backlash.**—Backlash is commonly measured by holding one gear of a pair stationary and rocking the other back and forth. The movement is registered by a dial indicator having its pointer or finger in a plane of rotation at or near the pitch diameter and in a direction parallel to a tangent to the pitch circle of the moving gear. If the direction of measurement is normal to the teeth, or other than as specified above, it is recommended that readings be converted to the plane of rotation and in a tangent direction at or near the pitch diameter, for purposes of standardization and comparison.

In spur gears, parallel helical gears, and bevel gears, it is immaterial whether the pinion or gear is held stationary for the test. In crossed helical and hypoid gears, readings may vary according to which member is stationary; hence, it is customary to hold the pinion stationary and measure on the gear.

In some instances, backlash is measured by thickness gages or feelers. A similar method utilizes a soft lead wire inserted between the teeth as they pass through mesh. In both methods, it is likewise recommended that readings be converted to the plane of rotation and in a tangent direction at or near the pitch diameter, taking into account the normal pressure angle, and the helix angle or spiral angle of the teeth.

Sometimes backlash in parallel helical or herringbone gears is checked by holding the gear stationary, and moving the pinion axially back and forth, readings being taken on the face or shaft of the pinion, and converted to the plane of rotation by calculation. Another method consists of meshing a pair of gears tightly together on centers and observing the variation from the specified center distance. Such readings should also be converted to the plane of rotation and in a tangent direction at or near the pitch diameter for the reasons previously given.

Measurements of backlash may vary in the same pair of gears, depending on accuracy of manufacturing and assembling. Incorrect tooth profiles will cause a change of backlash at different phases of the tooth action. Eccentricity may cause a substantial difference between maximum and minimum backlash at different positions around the gears. In stating amounts of backlash, it should always be remembered that merely making allowances on tooth thickness does not guarantee the minimum amount of backlash that will exist in assembled gears.

*Fine-Pitch Gears:* The measurement of backlash of fine-pitch gears, when assembled, cannot be made in the same manner and by the same techniques employed for gears of coarser pitches. In the very fine pitches, it is virtually impossible to use indicating devices for measuring backlash. Sometimes a toolmaker's microscope is used for this purpose to good advantage on very small mechanisms.

Another means of measuring backlash in fine-pitch gears is to attach a beam to one of the shafts and measure the angular displacement in inches when one member is held stationary. The ratio of the length of the beam to the nominal pitch radius of the gear or pinion to which the beam is attached gives the approximate ratio of indicator reading to circular backlash. Because of the limited means of measuring backlash between a pair of fine-pitch gears, gear centers and tooth thickness of the gears when cut must be held to very close lim-

its. Tooth thickness of fine-pitch spur and helical gears can best be checked on a variable-center-distance fixture using a master gear. When checked in this manner, tooth thickness change =  $2 \times$  center distance change  $\times$  tangent of transverse pressure angle, approximately.

**Control of Backlash in Assemblies.**—Provision is often made for adjusting one gear relative to the other, thereby affording complete control over backlash at initial assembly and throughout the life of the gears. Such practice is most common in bevel gearing. It is fairly common in spur and helical gearing when the application permits slight changes between shaft centers. It is practical in worm gearing only for single thread worms with low lead angles. Otherwise faulty contact results.

Another method of controlling backlash quite common in bevel gears and less common in spur and helical gears is to match the high and low spots of the runout gears of one to one ratio and mark the engaging teeth at the point where the runout of one gear cancels the runout of the mating gear.

**Table 3. AGMA Backlash Allowance and Tolerance for Fine-Pitch Spur, Helical and Herringbone Gearing**

| Backlash Designation | Normal Diametral Pitch Range | Tooth Thinning to Obtain Backlash <sup>a</sup> |                           | Resulting Approximate Backlash (per Mesh) Normal Plane <sup>b</sup> Inch |
|----------------------|------------------------------|--|---------------------------|--|
|                      |                              | Allowance, per Gear, Inch                      | Tolerance, per Gear, Inch |  |
| A                    | 20 thru 45                   | .002   | 0 to .002                 | .004 to .008   |
|                      | 46 thru 70                   | .0015  | 0 to .002                 | .003 to .007   |
|                      | 71 thru 90                   | .001   | 0 to .00175               | .002 to .0055  |
|                      | 91 thru 200                  | .00075   | 0 to .00075               | .0015 to .003  |
| B                    | 20 thru 60                   | .001   | 0 to .001                 | .002 to .004   |
|                      | 61 thru 120                  | .00075   | 0 to .00075               | .0015 to .003  |
|                      | 121 thru 200                 | .0005  | 0 to .0005                | .001 to .002   |
| C                    | 20 thru 60                   | .0005  | 0 to .0005                | .001 to .002   |
|                      | 61 thru 120                  | .00035   | 0 to .0004                | .0007 to .0015   |
|                      | 121 thru 200                 | .0002  | 0 to .0003                | .0004 to .001  |
| D                    | 20 thru 60                   | .00025   | 0 to .00025               | .0005 to .001  |
|                      | 61 thru 120                  | .0002  | 0 to .0002                | .0004 to .0008   |
|                      | 121 thru 200                 | .0001  | 0 to .0001                | .0002 to .0004   |
| E                    | 20 thru 60                   |  | 0 to .00025               | 0 to .0005   |
|                      | 61 thru 120                  | Zero <sup>c</sup>                              | 0 to .0002                | 0 to .0004   |
|                      | 121 thru 200                 |  | 0 to .0001                | 0 to .0002   |

<sup>a</sup> These dimensions are shown primarily for the benefit of the gear manufacturer and represent the amount that the thickness of teeth should be reduced in the pinion and gear below the standard calculated value, to provide for backlash in the mesh. In some cases, particularly with pinions involving small numbers of teeth, it may be desirable to provide for total backlash by thinning the teeth in the gear member only by twice the allowance value shown in column (3). In this case both members will have the tolerance shown in column (4). In some cases, particularly in meshes with a small number of teeth, backlash may be achieved by an increase in basic center at distance. In such cases, neither member is reduced by the allowance shown in column (3).

<sup>b</sup> These dimensions indicate the approximate backlash that will occur in a mesh in which each of the mating pairs of gears have the teeth thinned by the amount referred to in Note 1, and are meshed on theoretical centers.

<sup>c</sup> Backlash in gear sets can also be achieved by increasing the center distance above nominal and using the teeth at standard tooth thickness. Class E backlash designation infers gear sets operating under these conditions.

*Backlash* in gears is the play between mating tooth surfaces. For purposes of measurement and calculation, backlash is defined as the amount by which a tooth space exceeds the thickness of an engaging tooth. When not otherwise specified, numerical values of backlash are understood to be measured at the tightest point of mesh on the pitch circle in a direction normal to the tooth surface when the gears are mounted in their specified position.

*Allowance* is the basic amount that a tooth is thinned from basic calculated circular tooth thickness to obtain the required backlash class.

*Tolerance* is the total permissible variation in the circular thickness of the teeth.

**Angular Backlash in Gears.**—When the backlash on the pitch circles of a meshing pair of gears is known, the angular backlash or angular play corresponding to this backlash may be computed from the following formulas.

$$\theta_D = \frac{6875B}{D} \text{ minutes} \quad \theta_d = \frac{6875B}{d} \text{ minutes}$$

In these formulas,  $B$  = backlash between gears, in inches;  $D$  = pitch diameter of larger gear, in inches;  $d$  = pitch diameter of smaller gear, in inches;  $\theta_D$  = angular backlash or angular movement of larger gear in minutes when smaller gear is held fixed and larger gear rocked back and forth; and  $\theta_d$  = angular backlash or angular movement of smaller gear, in minutes, when the larger gear is held fixed and the smaller gear rocked back and forth.

**Inspection of Gears.**—Perhaps the most widely used method of determining relative accuracy in a gear is to rotate the gear through at least one complete revolution in intimate contact with a master gear of known accuracy. The gear to be tested and the master gear are mounted on a variable-center-distance fixture and the resulting radial displacements or changes in center distance during rotation of the gear are measured by a suitable device. Except for the effect of backlash, this so-called “composite check” approximates the action of the gear under operating conditions and gives the combined effect of the following errors: runout; pitch error; tooth-thickness variation; profile error; and lateral runout (sometimes called wobble).

*Tooth-to-Tooth Composite Error*, illustrated below, is the error that shows up as flicker on the indicator of a variable-center-distance fixture as the gear being tested is rotated from tooth to tooth in intimate contact with the master gear. Such flicker shows the combined or composite effect of circular pitch error, tooth-thickness variation, and profile error.

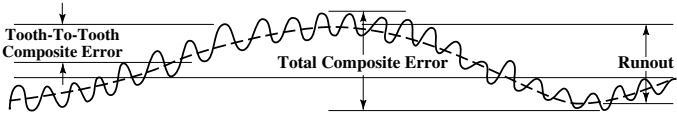


Diagram Showing Nature of Composite Errors

*Total Composite Error*, shown above, is made up of runout, wobble, and the tooth-to-tooth composite error; it is the total center-distance displacement read on the indicating device of the testing fixture, as shown in the accompanying diagram.

**Pressure for Composite Checking of Fine-Pitch Gears.**—In using a variable-center-distance fixture, excessive pressure on fine-pitch gears of narrow face width will result in incorrect readings due to deflection of the teeth. Based on tests, the following checking pressures are recommended for gears of 0.100-inch face width: 20 to 29 diametral pitch, 28 ounces; 30 to 39 pitch, 24 ounces; 40 to 49 pitch, 20 ounces; 50 to 59 pitch, 16 ounces; 60 to 79 pitch, 12 ounces; 80 to 99 pitch, 8 ounces, 100 to 149 pitch, 4 ounces; and 150 and finer pitches, 2 ounces, minimum. These recommended checking pressures are based on the use of antifriction mountings for the movable head of the checking fixture and include the pressure of the indicating device. For face widths less than 0.100 inch, the recommended pressures should be reduced proportionately; for larger widths, no increase is necessary although the force may be increased safely in the proper proportion.

### Internal Gearing

**Internal Spur Gears.**—An internal gear may be proportioned like a standard spur gear turned “outside in” or with addendum and dedendum in reverse positions; however, to avoid interference or improve the tooth form and action, the internal diameter of the gear should be increased and the outside diameter of the mating pinion is also made larger than the size based upon standard or conventional tooth proportions. The extent of these enlargements will be illustrated by means of examples given following table, *Rules for Internal Gears—20-degree Full-Depth Teeth*. The 20-degree involute full-depth tooth form is recommended for internal gears; the 20-degree stub tooth and the 14½-degree full-depth tooth are also used.

**Methods of Cutting Internal Gears.**—Internal spur gears are cut by methods similar in principle to those employed for external spur gears.

They may be cut by one of the following methods: 1) By a generating process, as when using a Fellows gear shaper; 2) by using a formed cutter and milling the teeth; 3) by planing, using a machine of the template or form-copying type (especially applicable to gears of large pitch); and 4) by using a formed tool that reproduces its shape and is given a planing action either on a slotting or a planing type of machine.

Internal gears frequently have a web at one side that limits the amount of clearance space at the ends of the teeth. Such gears may be cut readily on a gear shaper. The most practical method of cutting very large internal gears is on a planer of the form-copying type. A regular spur gear planer is equipped with a special tool holder for locating the tool in the position required for cutting internal teeth.

**Formed Cutters for Internal Gears.**—When formed cutters are used, a special cutter usually is desirable, because the tooth spaces of an internal gear are not the same shape as the tooth spaces of external gearing having the same pitch and number of teeth. This difference is because an internal gear is a spur gear “turned outside in.” According to one rule, the standard No. 1 cutter for external gearing may be used for internal gears of 4 diametral pitch and finer, when there are 60 or more teeth. This No. 1 cutter, as applied to external gearing, is intended for all gears having from 135 teeth to a rack. The finer the pitch and the larger the number of teeth, the better the results obtained with a No. 1 cutter. The standard No. 1 cutter is considered satisfactory for jobbing work, and usually when the number of gears to be cut does not warrant obtaining a special cutter, although the use of the No. 1 cutter is not practicable when the number of teeth in the pinion is large in proportion to the number of teeth in the internal gear.

**Arc Thickness of Internal Gear Tooth.**—*Rule:* If internal diameter of an internal gear is enlarged as determined by Rules 1 and 2 for Internal Diameters (see *Rules for Internal Gears—20-degree Full-Depth Teeth*), the arc tooth thickness at the pitch circle equals 1.3888 divided by the diametral pitch, assuming a pressure angle of 20 degrees.

**Arc Thickness of Pinion Tooth.**—*Rule:* If the pinion for an internal gear is larger than conventional size (see Outside Diameter of Pinion for Internal Gear, under *Rules for Internal Gears—20-degree Full-Depth Teeth*), then the arc tooth thickness on the pitch circle equals 1.7528 divided by the diametral pitch, assuming a pressure angle of 20 degrees.

*Note:* For chordal thickness and chordal addendum, see rules and formulas for spur gears.

**Relative Sizes of Internal Gear and Pinion.**—If a pinion is too large or too near the size of its mating internal gear, serious interference or modification of the tooth shape may occur.

*Rule:* For internal gears having a 20-degree pressure angle and full-depth teeth, the difference between the numbers of teeth in gear and pinion should not be less than 12. For teeth of stub form, the smallest difference should be 7 or 8 teeth. For a pressure angle of 14½ degrees, the difference in tooth numbers should not be less than 15.

## Rules for Internal Gears—20-degree Full-Depth Teeth

| To Find  | Rule   |
|--|--|
| Pitch Diameter                                     | <i>Rule:</i> To find the pitch diameter of an internal gear, divide the number of internal gear teeth by the diametral pitch. The pitch diameter of the mating pinion also equals the number of pinion teeth divided by the diametral pitch, the same as for external spur gears.  |
| Internal Diameter (Enlarged to Avoid Interference) | <p><i>Rule 1:</i> For internal gears to mesh with pinions having 16 teeth or more, subtract 1.2 from the number of teeth and divide the remainder by the diametral pitch.</p> <p><i>Example:</i> An internal gear has 72 teeth of 6 diametral pitch and the mating pinion has 18 teeth; then</p> $\text{Internal diameter} = \frac{72 - 1.2}{6} = 11.8 \text{ inches}$ <p><i>Rule 2:</i> If circular pitch is used, subtract 1.2 from the number of internal gear teeth, multiply the remainder by the circular pitch, and divide the product by 3.1416.</p>   |
| Internal Diameter (Based upon Spur Gear Reversed)  | <p><i>Rule:</i> If the internal gear is to be designed to conform to a spur gear turned outside in, subtract 2 from the number of teeth and divide the remainder by the diametral pitch to find the internal diameter.</p> <p><i>Example:</i> (Same as Example above.)</p> $\text{Internal diameter} = \frac{72 - 2}{6} = 11.666 \text{ inches}$   |
| Outside Diameter of Pinion for Internal Gear       | <p><i>Note:</i> If the internal gearing is to be proportioned like standard spur gearing, use the rule or formula previously given for spur gears in determining the outside diameter. The rule and formula following apply to a pinion that is enlarged and intended to mesh with an internal gear enlarged as determined by the preceding Rules 1 and 2 above.</p> <p><i>Rule:</i> For pinions having 16 teeth or more, add 2.5 to the number of pinion teeth and divide by the diametral pitch.</p> <p><i>Example 1:</i> A pinion for driving an internal gear is to have 18 teeth (full depth) of 6 diametral pitch; then</p> $\text{Outside diameter} = \frac{18 + 2.5}{6} = 3.416 \text{ inches}$ <p>By using the rule for external spur gears, the outside diameter = 3.333 inches.</p> |
| Center Distance                                    | <i>Rule:</i> Subtract the number of pinion teeth from the number of internal gear teeth and divide the remainder by two times the diametral pitch.   |
| Tooth Thickness                                    | See paragraphs, <i>Arc Thickness of Internal Gear Tooth</i> and <i>Effect of Diameter of Cutting on Profile and Pressure Angle of Worms</i> , on previous page.  |



**British Standard for Spur and Helical Gears**

**British Standard For Spur And Helical Gears.**—BS 436: Part 1: 1967: Spur and Helical Gears, Basic Rack Form, Pitches and Accuracy for Diametral Pitch Series, now has sections concerned with basic requirements for general tooth form, standard pitches, accuracy and accuracy testing procedures, and the showing of this information on engineering drawings to make sure that the gear manufacturer receives the required data. The latest form of the standard complies with ISO agreements. The standard pitches are in accordance with ISO R54, and the basic rack form and its modifications are in accordance with the ISO R53 “Basic Rack of Cylindrical Gears for General Engineering and for Heavy Engineering Standard”.

Five grades of gear accuracy in previous versions are replaced by grades 3 to 12 of the draft ISO Standard. Grades 1 and 2 cover master gears that are not dealt with here. BS 436: Part 1: 1967 is a companion to the following British Standards:

BS 235 “Gears for Traction”

BS 545 “Bevel Gears (Machine Cut)”

BS 721 “Worm Gearing”

BS 821 “Iron Castings for Gears and Gear Blanks (Ordinary, Medium and High Grade)”

BS 978 “Fine Pitch Gears” Part 1, “Involute, Spur and Helical Gears”; Part 2, “Cycloidal Gears” (with addendum 1, PD 3376: “Double Circular Arc Type Gears.”; Part 3, “Bevel Gears”

BS 1807 “Gears for Turbines and Similar Drives” Part 1, “Accuracy” Part 2, “Tooth Form and Pitches”

BS 2519 “Glossary of Terms for Toothed Gearing”

BS 3027 “Dimensions for Worm Gear Units”

BS 3696 “Master Gears”

Part 1 of BS 436 applies to external and internal involute spur and helical gears on parallel shafts and having normal diametral pitch of 20 or coarser. The basic rack and tooth form are specified, also first and second preference standard pitches and fundamental tolerances that determine the grades of gear accuracy, and requirements for terminology and notation.

These requirements include: center distance  $a$ ; reference circle diameter  $d$ , for pinion  $d_1$  and wheel  $d_2$ ; tip diameter  $d_a$  for pinion  $d_{a1}$  and wheel  $d_{a2}$ ; center distance modification coefficient  $\gamma$ ; face width  $b$  for pinion  $b_1$  and wheel  $b_2$ ; addendum modification coefficient  $x$ ; for pinion  $x_1$  and wheel  $x_2$ ; length of arc  $l$ ; diametral pitch  $P$ ; normal diametral pitch  $p_n$ ; transverse pitch  $p_t$ ; number of teeth  $z$ , for pinion  $z_1$  and wheel  $z_2$ ; helix angle at reference cylinder  $\beta$ ; pressure angle at reference cylinder  $\alpha$ ; normal pressure angle at reference cylinder  $\alpha_n$ ; transverse pressure angle at reference cylinder  $\alpha_t$ ; and transverse pressure angle, working,  $\alpha_{tw}$ .

The basic rack tooth profile has a pressure angle of  $20^\circ$ . The Standard permits the total tooth depth to be varied within 2.25 to 2.40, so that the root clearance can be increased within the limits of 0.25 to 0.040 to allow for variations in manufacturing processes; and the root radius can be varied within the limits of 0.25 to 0.39. Tip relief can be varied within the limits shown at the right in the illustration.

*Standard normal diametral pitches  $P_n$* , BS 436 Part 1:1967, are in accordance with ISO R54. The preferred series, rather than the second choice, should be used where possible.

Preferred normal diametral pitches for spur and helical gears (second choices in parentheses) are: 20 (18), 16 (14), 12 (11), 10 (9), 8 (7), 6 (5.5), 5 (4.5), 4 (3.5), 3 (2.75), 2.5 (2.25), 2 (1.75), 1.5, 1.25, and 1.

*Information to be Given on Drawings:* British Standard BS 308, “Engineering Drawing Practice”, specifies data to be included on drawings of spur and helical gears. For all gears the data should include: number of teeth, normal diametral pitch, basic rack tooth form, axial pitch, tooth profile modifications, blank diameter, reference circle diameter, and helix angle at reference cylinder ( $0^\circ$  for straight spur gears), tooth thickness at reference

cylinder, grade of gear, drawing number of mating gear, working center distance, and backlash.

For single helical gears, the above data should be supplemented with hand and lead of the tooth helix; and for double helical gears, with the hand in relation to a specific part of the face width and the lead of tooth helix.

Inspection instructions should be included, care being taken to avoid conflicting requirements for accuracy of individual elements, and single- and dual-flank testing. Supplementary data covering specific design, manufacturing and inspection requirements or limitations may be needed, together with other dimensions and tolerances, material, heat treatment, hardness, case depth, surface texture, protective finishes, and drawing scale.

**Addendum Modification to Involute Spur and Helical Gears.**—The British Standards Institute guide PD 6457:1970 contains certain design recommendations aimed at making it possible to use standard cutting tools for some sizes of gears. Essentially, the guide covers addendum modification and includes formulas for both English and metric units.

*Addendum Modification* is an enlargement or reduction of gear tooth dimensions that results from displacement of the reference plane of the generating rack from its normal position. The displacement is represented by the coefficient  $X$ ,  $X_1$ , or  $X_2$ , where  $X$  is the equivalent dimension for gears of unit module or diametral pitch. The addendum modification establishes a datum tooth thickness at the reference circle of the gear but does not necessarily establish the height of either the reference addendum or the working addendum. In any pair of gears, the datum tooth thicknesses are those that always give zero backlash at the meshing center distance. Normal practice requires allowances for backlash for all unmodified gears.

Taking full advantage of the adaptability of the involute system allows various tooth design features to be obtained. Addendum modification has the following applications: avoiding undercut tooth profiles; achieving optimum tooth proportions and control of the proportion of receding to approaching contact; adapting a gear pair to a predetermined center distance without recourse to non-standard pitches; and permitting use of a range of working pressure angles using standard geometry tools.

**BS 436, Part 3:1986 "Spur and Helical Gears".**—This part provides methods for calculating contact and root bending stresses for metal involute gears, and is somewhat similar to the ANSI/AGMA Standard for calculating stresses in pairs of involute spur or helical gears. Stress factors covered in the British Standard include the following:

*Tangential Force* is the nominal force for contact and bending stresses.

*Zone Factor* accounts for the influence of tooth flank curvature at the pitch point on Hertzian stress.

*Contact Ratio Factor* takes account of the load-sharing influence of the transverse contact ratio and the overlap ratio on the specific loading.

*Elasticity Factor* takes into account the influence of the modulus of elasticity of the material and of Poisson's ratio on the Hertzian stress.

*Basic Endurance Limit* for contact makes allowance for the surface hardness.

*Material Quality* covers the quality of the material used.

*Lubricant Influence, Roughness, and Speed* The lubricant viscosity, surface roughness and pitch line speed affect the lubricant film thickness, which in turn, affects the Hertzian stresses.

*Work Hardening Factor* accounts for the increase in surface durability due to the meshing action.

*Size Factor* covers the possible influences of size on the material quality and its response to manufacturing processes.

*Life Factor* accounts for the increase in permissible stresses when the number of stress cycles is less than the endurance life.

*Application Factor* allows for load fluctuations from the mean load or loads in the load histogram caused by sources external to the gearing.

*Dynamic Factor* allows for load fluctuations arising from contact conditions at the gear mesh.

*Load Distribution* accounts for the increase in local load due to maldistribution of load across the face of the gear tooth caused by deflections, alignment tolerances and helix modifications.

*Minimum Demanded and Actual Safety Factor* The minimum demanded safety factor is agreed between the supplier and the purchaser. The actual safety factor is calculated.

*Geometry Factors* allow for the influence of the tooth form, the effect of the fillet and the helix angle on the nominal bending stress for the application of load at the highest point of single pair tooth contact.

*Sensitivity Factor* allows for the sensitivity of the gear material to the presence of notches such as the root fillet.

*Surface Condition Factor* accounts for reduction of the endurance limit due to flaws in the material and the surface roughness of the tooth root fillets.

**ISO TC/600.**—The ISO TC/600 Standard is similar to BS 436, Part 3:1986, but is far more comprehensive. For general gear design, the ISO Standard provides a complicated method of arriving at a conclusion similar to that reached by the less complex British Standard. Factors additional to the above that are included in the ISO Standard include the following

*Application Factor* account for dynamic overloads from sources external to the gearing.

*Dynamic Factor* allows for internally generated dynamic loads caused by vibrations of the pinion and wheel against each other.

*Load Distribution* makes allowance for the effects of non-uniform distribution of load across the face width, depending on the mesh alignment error of the loaded gear pair and the mesh stiffness.

*Transverse Load Distribution Factor* takes into account the effect of the load distribution on gear tooth contact stresses.

*Gear Tooth Stiffness Constants* are defined as the load needed to deform one or several meshing gear teeth having 1 mm face width, by an amount of  $1\ \mu\text{m}$  (0.00004 in).

*Allowable Contact Stress* is the permissible Hertzian pressure on the gear tooth face.

*Minimum demanded and Calculated Safety Factors* The minimum demanded safety factor is agreed between the supplier and the customer. The calculated safety factor is the actual safety factor of the gear pair.

*Zone Factor* accounts for the influence on the Hertzian pressure of the tooth flank curvature at the pitch point.

*Elasticity Factor* takes account of the influence of the material properties such as the modulus of elasticity and Poisson's ratio.

*Contact Ratio Factor* accounts for the influence of the transverse contact ratio and the overlap ratio on the specific surface load of the gears.

*Helix Angle Factor* makes allowance for influence of helix angle on surface durability.

*Endurance Limit* is the limit of repeated Hertzian stresses that can be permanently endured by a given material

*Life Factor* takes account of a higher permissible Hertzian stress if only limited durability is demanded.

*Lubrication Film Factor* The film of lubricant between the tooth flanks influences the surface load capacity. Factors include the oil viscosity, pitch line velocity and roughness of the tooth flanks.

*Work Hardening Factor* takes account of the increase in surface durability due to meshing a steel wheel with a hardened pinion having smooth tooth surfaces.

*Coefficient of Friction* The mean value of the local coefficient of friction depends on the lubricant, surface roughness, the lay of surface irregularities, material properties of the tooth flanks, and the force and size of tangential velocities.

*Bulk Temperature Thermal Flash Factor* is dependent on moduli of elasticity and thermal contact coefficients of pinion and wheel materials and geometry of the line of action.

*Welding Factor* Accounts for different tooth materials and heat treatments.

*Geometrical Factor* is defined as a function of the gear ratio and the dimensionless parameter on the line of action.

*Integral Temperature Criterion* The integral temperature of the gears depends on the lubricant viscosity and tendency toward cuffing and scoring of the gear materials.

Examination of the above factors shows the similarity in the approach of the British and the ISO Standards to that of the ANSI/AGMA Standards. Slight variations in the methods used to calculate the factors will result in different allowable stress figures. Experimental work using some of the stressing formulas has shown wide variations and designers must continue to rely on experience to arrive at satisfactory results.

### Standards Nomenclature

All standards are referenced and identified throughout this book by an alphanumeric prefix which designates the organization that administered the development work on the standard, and followed by a standards number.

All standards are reviewed by the relevant committees at regular time intervals, as specified by the overseeing standards organization, to determine whether the standard should be confirmed (reissued without changes other than correction of typographical errors), updated, or removed from service.

The following is for example use only. ANSI B18.8.2-1984, R1994 is a standard for Taper, Dowel, Straight, Grooved, and Spring Pins. ANSI refers to the American National Standards Institute that is responsible for overseeing the development or approval of the standard, and B18.8.2 is the number of the standard. The first date, 1984, indicates the year in which the standard was issued, and the sequence R1994 indicates that this standard was reviewed and reaffirmed in that 1994. The current designation of the standard, ANSI/ASME B18.8.2-1995, indicates that it was revised in 1995; it is ANSI approved; and, ASME (American Society of Mechanical Engineers) was the standards body responsible for development of the standard. This standard is sometimes also designated ASME B18.8.2-1995.

ISO (International Organization for Standardization) standards use a slightly different format, for example, ISO 5127-1:1983. The entire ISO reference number consists of a prefix ISO, a serial number, and the year of publication.

Aside from content, ISO standards differ from American National standards in that they often smaller focused documents, which in turn reference other standards or other parts of the same standard. Unlike the numbering scheme used by ANSI, ISO standards related to a particular topic often do not carry sequential numbers nor are they in consecutive series.

British Standards Institute standards use the following format: BS 1361: 1971 (1986). The first part is the organization prefix BS, followed by the reference number and the date of issue. The number in parenthesis is the date that the standard was most recently reconfirmed. British Standards may also be designated *withdrawn* (no longer to be used) and *obsolescent* (going out of use, but may be used for servicing older equipment).

| Organization   | Web Address     | Organization                                    | Web Address  |
|--|-----------------|---|--------------|
| ISO (International Organization for Standardization) | www.iso.ch      | JIS (Japanese Industrial Standards)             | www.jisc.org |
| IEC (International Electrotechnical Commission)      | www.iec.ch      | ASME (American Society of Mechanical Engineers) | www.asme.org |
| ANSI (American National Standards Institute)         | www.ansi.org    | SAE (Society of Automotive Engineers)           | www.sae.org  |
| BSI (British Standards Institute)                    | www.bsi-inc.org | SME (Society of Manufacturing Engineers)        | www.sme.org  |

**HYPOID AND BEVEL GEARING****Hypoid Gears**

Hypoid gears are offset and in effect, are spiral gears whose axes do not intersect but are staggered by an amount decided by the application. Due to the offset, contact between the teeth of the two gears does not occur along a surface line of the cones as it does with spiral bevels having intersecting axes, but along a curve in space inclined to the surface line. The basic solids of the hypoid gear members are not cones, as in spiral bevels, but are hyperboloids of revolution which cannot be projected into the common plane of ordinary flat gears, thus the name hypoid. The visualization of hypoid gears is based on an imaginary flat gear which is a substitute for the theoretically correct helical surface. If certain rules are observed during the calculations to fix the gear dimensions, the errors that result from the use of an imaginary flat gear as an approximation are negligible.

The staggered axes result in meshing conditions that are beneficial to the strength and running properties of the gear teeth. A uniform sliding action takes place between the teeth, not only in the direction of the tooth profile but also longitudinally, producing ideal conditions for movement of lubricants. With spiral gears, great differences in sliding motion arise over various portions of the tooth surface, creating vibration and noise. Hypoid gears are almost free from the problems of differences in these sliding motions and the teeth also have larger curvature radii in the direction of the profile. Surface pressures are thus reduced so that there is less wear and quieter operation.

The teeth of hypoid gears are 1.5 to 2 times stronger than those of spiral bevel gears of the same dimensions, made from the same material. Certain limits must be imposed on the dimensions of hypoid gear teeth so that their proportions can be calculated in the same way as they are for spiral bevel gears. The offset must not be larger than 1/7th of the ring gear outer diameter, and the tooth ratio must not be much less than 4 to 1. Within these limits, the tooth proportions can be calculated in the same way as for spiral bevel gears and the radius of lengthwise curvature can be assumed in such a way that the normal module is a maximum at the center of the tooth face width to produce stabilized tooth bearings.

If the offset is larger or the ratio is smaller than specified above, a tooth form must be selected that is better adapted to the modified meshing conditions. In particular, the curvature of the tooth length curve must be determined with other points in view. The limits are only guidelines since it is impossible to account for all other factors involved, including the pitch line speed of the gears, lubrication, loads, design of shafts and bearings, and the general conditions of operation.

Of the three different designs of hypoid bevel gears now available, the most widely used, especially in the automobile industry, is the Gleason system. Two other hypoid gear systems have been introduced by Oerlikon (Swiss) and Klingelberg (German). All three methods use the involute gear form, but they have teeth with differing curvatures, produced by the cutting method. Teeth in the Gleason system are arc shaped and their depth tapers. Both the European systems are designed to combine rolling with the sideways motion of the teeth and use a constant tooth depth. Oerlikon uses an epicycloidal tooth form and Klingelberg uses a true involute form.

With their circular arcuate tooth face curves, Gleason hypoid gears are produced with multi-bladed face milling cutters. The gear blank is rolled relative to the rotating cutter to make one inter-tooth groove, then the cutter is withdrawn and returned to its starting position while the blank is indexed into the position for cutting the next tooth. Both roughing and finishing cutters are kept parallel to the tooth root lines, which are at an angle to the gear pitch line. Depending on this angularity, plus the spiral angle, a correction factor must be calculated for both the leading and trailing faces of the gear tooth.

In operation, the convex faces of the teeth on one gear always bear on the concave faces of the teeth on the mating gear. For correct meshing between the pinion and gear wheel, the

spiral angles should not vary over the full face width. The tooth form generated is a logarithmic spiral and, as a compromise, the cutter radius is made equal to the mean radius of a corresponding logarithmic spiral.

The involute tooth face curves of the Klingelnberg system gears have constant-pitch teeth cut by (usually) a single-start taper hob. The machine is set up to rotate both the cutter and the gear blank at the correct relative speeds. The surface of the hob is set tangential to a circle radius, which is the gear base circle, from which all the parallel involute curves are struck. To keep the hob size within reasonable dimensions, the cone must lie a minimum distance within the teeth and this requirement governs the size of the module.

Both the module and the tooth depth are constant over the full face width and the spiral angle varies. The cutting speed variations, especially with regard to crown wheels, over the cone surface of the hob, make it difficult to produce a uniform surface finish on the teeth, so a finishing cut is usually made with a truncated hob which is tilted to produce the required amount of crowning automatically, for correct tooth marking and finishing. The dependence of the module, spiral angle and other features on the base circle radius, and the need for suitable hob proportions restrict the gear dimensions and the system cannot be used for gears with a low or zero angle. However, gears can be cut with a large root radius giving teeth of high strength. The favorable geometry of the tooth form gives quieter running and tolerance of inaccuracies in assembly.

Teeth of gears made by the Oerlikon system have elongated epicycloidal form, produced with a face-type rotating cutter. Both the cutter and the gear blank rotate continuously, with no indexing. The cutter head has separate groups of cutters for roughing, outside cutting and inside cutting so that tooth roots and flanks are cut simultaneously, but the feed is divided into two stages. As stresses are released during cutting, there is some distortion of the blank and this distortion will usually be worse for a hollow crown wheel than for a solid pinion.

All the heavy cuts are taken during the first stages of machining with the Oerlikon system and the second stage is used to finish the tooth profile accurately, so distortion effects are minimized. As with the Klingelnberg process, the Oerlikon system produces a variation in spiral angle and module over the width of the face, but unlike the Klingelnberg method, the tooth length curve is cycloidal. It is claimed that, under load, the tilting force in an Oerlikon gear set acts at a point 0.4 times the distance from the small diameter end of the gear and not in the mid-tooth position as in other gear systems, so that the radius is obviously smaller and the tilting moment is reduced, resulting in lower loading of the bearings.

Gears cut by the Oerlikon system have tooth markings of different shape than gears cut by other systems, showing that more of the face width of the Oerlikon tooth is involved in the load-bearing pattern. Thus, the surface loading is spread over a greater area and becomes lighter at the points of contact.

### Bevel Gearing

**Types of Bevel Gears.**—Bevel gears are conical gears, that is, gears in the shape of cones, and are used to connect shafts having intersecting axes. Hypoid gears are similar in general form to bevel gears, but operate on axes that are offset. With few exceptions, most bevel gears may be classified as being either of the straight-tooth type or of the curved-tooth type. The latter type includes spiral bevels, Zerol bevels, and hypoid gears. The following is a brief description of the distinguishing characteristics of the different types of bevel gears.

*Straight Bevel Gears:* The teeth of this most commonly used type of bevel gear are straight but their sides are tapered so that they would intersect the axis at a common point called the pitch cone apex if extended inward. The face cone elements of most straight bevel gears, however, are now made parallel to the root cone elements of the mating gear to obtain uniform clearance along the length of the teeth. The face cone elements of such

gears, therefore, would intersect the axis at a point inside the pitch cone. Straight bevel gears are the easiest to calculate and are economical to produce.

Straight bevel gear teeth may be generated for full-length contact or for localized contact. The latter are slightly convex in a lengthwise direction so that some adjustment of the gears during assembly is possible and small displacements due to load deflections can occur without undesirable load concentration on the ends of the teeth. This slight lengthwise rounding of the tooth sides need not be computed in the design but is taken care of automatically in the cutting operation on the newer types of bevel gear generators.

*Zerol Bevel Gears:* The teeth of Zerol bevel gears are curved but lie in the same general direction as the teeth of straight bevel gears. They may be thought of as spiral bevel gears of zero spiral angle and are manufactured on the same machines as spiral bevel gears. The face cone elements of Zerol bevel gears do not pass through the pitch cone apex but instead are approximately parallel to the root cone elements of the mating gear to provide uniform tooth clearance. The root cone elements also do not pass through the pitch cone apex because of the manner in which these gears are cut. Zerol bevel gears are used in place of straight bevel gears when generating equipment of the spiral type but not the straight type is available, and may be used when hardened bevel gears of high accuracy (produced by grinding) are required.

*Spiral Bevel Gears:* Spiral bevel gears have curved oblique teeth on which contact begins gradually and continues smoothly from end to end. They mesh with a rolling contact similar to straight bevel gears. As a result of their overlapping tooth action, however, spiral bevel gears will transmit motion more smoothly than straight bevel or Zerol bevel gears, reducing noise and vibration that become especially noticeable at high speeds.

One of the advantages associated with spiral bevel gears is the complete control of the localized tooth contact. By making a slight change in the radii of curvature of the mating tooth surfaces, the amount of surface over which tooth contact takes place can be changed to suit the specific requirements of each job. Localized tooth contact promotes smooth, quiet running spiral bevel gears, and permits some mounting deflections without concentrating the load dangerously near either end of the tooth. Permissible deflections established by experience are given under the heading *Mountings for Bevel Gears*.

Because their tooth surfaces can be ground, spiral bevel gears have a definite advantage in applications requiring hardened gears of high accuracy. The bottoms of the tooth spaces and the tooth profiles may be ground simultaneously, resulting in a smooth blending of the tooth profile, the tooth fillet, and the bottom of the tooth space. This feature is important from a strength standpoint because it eliminates cutter marks and other surface interruptions that frequently result in stress concentrations.

*Hypoid Gears:* In general appearance, hypoid gears resemble spiral bevel gears, except that the axis of the pinion is offset relative to the gear axis. If there is sufficient offset, the shafts may pass one another thus permitting the use of a compact straddle mounting on the gear and pinion. Whereas a spiral bevel pinion has equal pressure angles and symmetrical profile curvatures on both sides of the teeth, a hypoid pinion properly conjugate to a mating gear having equal pressure angles on both sides of the teeth must have nonsymmetrical profile curvatures for proper tooth action. In addition, to obtain equal arcs of motion for both sides of the teeth, it is necessary to use unequal pressure angles on hypoid pinions. Hypoid gears are usually designed so that the pinion has a larger spiral angle than the gear. The advantage of such a design is that the pinion diameter is increased and is stronger than a corresponding spiral bevel pinion. This diameter increment permits the use of comparatively high ratios without the pinion becoming too small to allow a bore or shank of adequate size. The sliding action along the lengthwise direction of their teeth in hypoid gears is a function of the difference in the spiral angles on the gear and pinion. This sliding effect makes such gears even smoother running than spiral bevel gears. Grinding of hypoid gears can be accomplished on the same machines used for grinding spiral bevel and Zerol bevel gears.

**Applications of Bevel and Hypoid Gears.**—Bevel and hypoid gears may be used to transmit power between shafts at practically any angle and speed. The particular type of gearing best suited for a specific job, however, depends on the mountings and the operating conditions.

*Straight and Zerol Bevel Gears:* For peripheral speeds up to 1000 feet per minute, where maximum smoothness and quietness are not the primary consideration, straight and Zerol bevel gears are recommended. For such applications, plain bearings may be used for radial and axial loads, although the use of antifriction bearings is always preferable. Plain bearings permit a more compact and less expensive design, which is one reason why straight and Zerol bevel gears are much used in differentials. This type of bevel gearing is the simplest to calculate and set up for cutting, and is ideal for small lots where fixed charges must be kept to a minimum.

Zerol bevel gears are recommended in place of straight bevel gears where hardened gears of high accuracy are required, because Zerol gears may be ground; and when only spiral-type equipment is available for cutting bevel gears.

*Spiral Bevel and Hypoid Gears:* Spiral bevel and hypoid gears are recommended for applications where peripheral speeds exceed 1000 feet per minute or 1000 revolutions per minute. In many instances, they may be used to advantage at lower speeds, particularly where extreme smoothness and quietness are desired. For peripheral speeds above 8000 feet per minute, ground gears should be used.

For large reduction ratios the use of spiral and hypoid gears will reduce the overall size of the installation because the continuous pitch line contact of these gears makes it practical to obtain smooth performance with a smaller number of teeth in the pinion than is possible with straight or Zerol bevel gears.

Hypoid gears are recommended for industrial applications: when maximum smoothness of operation is desired; for high reduction ratios where compactness of design, smoothness of operation, and maximum pinion strength are important; and for nonintersecting shafts.

Bevel and hypoid gears may be used for both speed-reducing and speed-increasing drives. In speed-increasing drives, however, the ratio should be kept as low as possible and the pinion mounted on antifriction bearings; otherwise bearing friction will cause the drive to lock.

**Notes on the Design of Bevel Gear Blanks.**—The quality of any finished gear is dependent, to a large degree, on the design and accuracy of the gear blank. A number of factors that affect manufacturing economy as well as performance must be considered.

A gear blank should be designed to avoid localized stresses and serious deflections within itself. Sufficient thickness of metal should be provided under the roots of gear teeth to give them proper support. As a general rule, the amount of metal under the root should equal the whole depth of the tooth; this metal depth should be maintained under the small ends of the teeth as well as under the middle. On webless-type ring gears, the minimum stock between the root line and the bottom of tap drill holes should be one-third the tooth depth. For heavily loaded gears, a preliminary analysis of the direction and magnitude of the forces is helpful in the design of both the gear and its mounting. Rigidity is also necessary for proper chucking when cutting the teeth. For this reason, bores, hubs, and other locating surfaces must be in proper proportion to the diameter and pitch of the gear. Small bores, thin webs, or any condition that necessitates excessive overhang in cutting should be avoided.

Other factors to be considered are the ease of machining and, in gears that are to be hardened, proper design to ensure the best hardening conditions. It is desirable to provide a locating surface of generous size on the backs of gears. This surface should be machined or ground square with the bore and is used both for locating the gear axially in assembly and for holding it when the teeth are cut. The front clamping surface must, of course, be flat and parallel to the back surface. In connection with cutting the teeth on Zerol bevel, spiral



bevel, and hypoid gears, clearance must be provided for face-mill type cutters; front and rear hubs should not intersect the extended root line of the gear or they will interfere with the path of the cutter. In addition, there must be enough room in the front of the gear for the clamp nut that holds the gear on the arbor, or in the chuck, while cutting the teeth. The same considerations must be given to straight bevel gears that are to be generated using a circular-type cutter instead of reciprocating tools.

**Mountings for Bevel Gears.**—Rigid mountings should be provided for bevel gears to keep the displacements of the gears under operating loads within recommended limits. To align gears properly, care should be taken to ensure accurately machined mountings, properly fitted keys, and couplings that run true and square.

As a result of deflection tests on gears and their mountings, and having observed these same units in service, the *Gleason Works* recommends that the following allowable deflections be used for gears from 6 to 15 inches in diameter: neither the pinion nor the gear should lift or depress more than 0.003 inch at the center of the face width; the pinion should not yield axially more than 0.003 inch in either direction; and the gear should not yield axially more than 0.003 inch in either direction on 1 to 1 ratio gears (miter gears), or near miters, or more than 0.010 inch away from the pinion on higher ratios.

When deflections exceed these limits, additional problems are involved in obtaining satisfactory gears. It becomes necessary to narrow and shorten the tooth contacts to suit the more flexible mounting. These changes decrease the bearing area, raise the unit tooth pressure, and reduce the number of teeth in contact, resulting in increased noise and the danger of surface failure as well as tooth breakage.

Spiral bevel and hypoid gears in general should be mounted on antifriction bearings in an oil-tight case. Designs for a given set of conditions may use plain bearings for radial and thrust loads, maintaining gears in satisfactory alignment is usually more easily accomplished with ball or roller bearings.

*Bearing Spacing and Shaft Stiffness:* Bearing spacing and shaft stiffness are extremely important if gear deflections are to be minimized. For both straddle mounted and overhung mounted gears the spread between bearings should never be less than 70 per cent of the pitch diameter of the gear. On overhung mounted gears the spread should be at least  $2\frac{1}{2}$  times the overhang and, in addition, the shaft diameter should be equal to or preferably greater than the overhang to provide sufficient shaft stiffness. When two spiral bevel or hypoid gears are mounted on the same shaft, the axial thrust should be taken at one place only and near the gear where the greater thrust is developed. Provision should be made for adjusting both the gear and pinion axially in assembly. Details on how this may be accomplished are given in the *Gleason Works* booklet, "Assembling Bevel Gears."

**Cutting Bevel Gear Teeth.**—A correctly formed bevel gear tooth has the same sectional shape throughout its length, but on a uniformly diminishing scale from the large to the small end. The only way to obtain this correct form is by using a generating type of bevel gear cutting machine. This accounts, in part, for the extensive use of generating type gear cutting equipment in the production of bevel gears.

Bevel gears too large to be cut by generating equipment (100 inches or over in diameter) may be produced by a form-copying type of gear planer. With this method, a template or former is used to mechanically guide a single cutting tool in the proper path to cut the profile of the teeth. Since the tooth profile produced by this method is dependent on the contour of the template used, it is possible to produce tooth profiles to suit a variety of requirements.

Although generating methods are to be preferred, there are still some cases where straight bevel gears are produced by milling. Milled gears cannot be produced with the accuracy of generated gears and generally are not suitable for use in high-speed applications or where angular motion must be transmitted with a high degree of accuracy. Milled gears are used chiefly as replacement gears in certain applications, and gears which are

subsequently to be finished on generating type equipment are sometimes roughed out by milling. Formulas and methods used for the cutting of bevel gears are given in the latter part of this section.

In producing gears by generating methods, the tooth curvature is generated from a straight-sided cutter or tool having an angle equal to the required pressure angle. This tool represents the side of a crown gear tooth. The teeth of a true involute crown gear, however, have sides which are very slightly curved. If the curvature of the cutting tool conforms to that of the involute crown gear, an involute form of bevel gear tooth will be obtained. The use of a straight-sided tool is more practical and results in a very slight change of tooth shape to what is known as the "octoid" form. Both the octoid and involute forms of bevel gear tooth give theoretically correct action.

Bevel gear teeth, like those for spur gears, differ as to pressure angle and tooth proportions. The whole depth and the addendum at the large end of the tooth may be the same as for a spur gear of equal pitch. Most bevel gears, however, both of the straight tooth and spiral-bevel types, have lengthened pinion addendums and shortened gear addendums as in the case of some spur gears, the amount of departure from equal addendums varying with the ratio of gearing. Long addendums on the pinion are used principally to avoid undercut and to increase tooth strength. In addition, where long and short addendums are used, the tooth thickness of the gear is decreased and that of the pinion increased to provide a better balance of strength. See the Gleason Works System for straight and spiral bevel gears and also the British Standard.

**Nomenclature for Bevel Gears.**—The accompanying diagram, [Fig. 1a](#), *Bevel Gear Nomenclature*, illustrates various angles and dimensions referred to in describing bevel gears. In connection with the face angles shown in the diagram, it should be noted that the face cones are made parallel to the root cones of the mating gears to provide uniform clearance along the length of the teeth. See also [Fig. 1b](#), page 2087.

**American Standard for Bevel Gears.**—American Standard ANSI/AGMA 2005-B88, Design Manual for Bevel Gears, replaces AGMA Standards 202.03, 208.03, 209.04, and 330.01, and provides standards for design of straight, zerol, and spiral bevel gears and hypoid gears with information on fabrication, inspection, and mounting. The information covers preliminary design, drawing formats, materials, rating, strength, inspection, lubrication, mountings, and assembly. Blanks for standard taper, uniform depth, duplex taper, and tilted root designs are included so that the material applies to users of Gleason, Klingenberg, and Oerlikon gear cutting machines.

**Formulas for Dimensions of Milled Bevel Gears.**—As explained earlier, most bevel gears are produced by generating methods. Even so, there are applications for which it may be desired to cut a pair of mating bevel gears by using rotary formed milling cutters. Examples of such applications include replacement gears for certain types of equipment and gears for use in experimental developments.

The tooth proportions of milled bevel gears differ in some respects from those of generated gears, the principal difference being that for milled bevel gears the tooth thicknesses of pinion and gear are made equal, and the addendum and dedendum of the pinion are respectively the same as those of the gear. The rules and formulas in the accompanying table may be used to calculate the dimensions of milled bevel gears with shafts at a right angle, an acute angle, and an obtuse angle.

In the accompanying diagrams, [Figs. 1a](#) and [1b](#), and list of notations, the various terms and symbols applied to milled bevel gears are as indicated.

- $N$  = number of teeth
- $P$  = diametral pitch
- $p$  = circular pitch
- $\alpha$  = pitch cone angle and edge angle
- $\Sigma$  = angle between shafts

## BEVEL GEARING

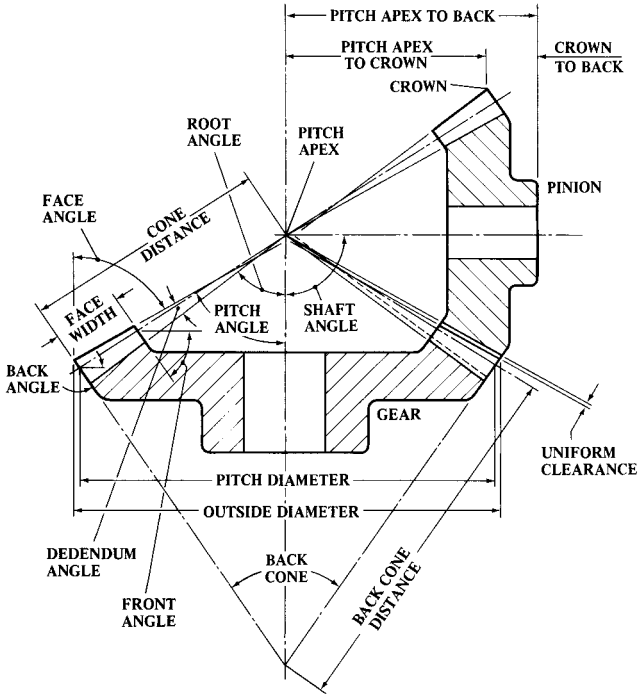


Fig. 1a. Bevel Gear Nomenclature

- $D$  = pitch diameter  
 $S$  = addendum  
 $S+A$  = dedendum ( $A$  = clearance)  
 $W$  = whole depth of tooth  
 $T$  = thickness of tooth at pitch line  
 $C$  = pitch cone radius  
 $F$  = width of face  
 $s$  = addendum at small end of tooth  
 $t$  = thickness of tooth at pitch line at small end  
 $\theta$  = addendum angle  
 $\phi$  = dedendum angle  
 $\gamma$  = face angle = pitch cone angle + addendum angle  
 $\delta$  = angle of compound rest  
 $\zeta$  = cutting angle  
 $K$  = angular addendum  
 $O$  = outside diameter  
 $J$  = vertex distance

$j$  = vertex distance at small end

$N'$  = number of teeth for which to select cutter

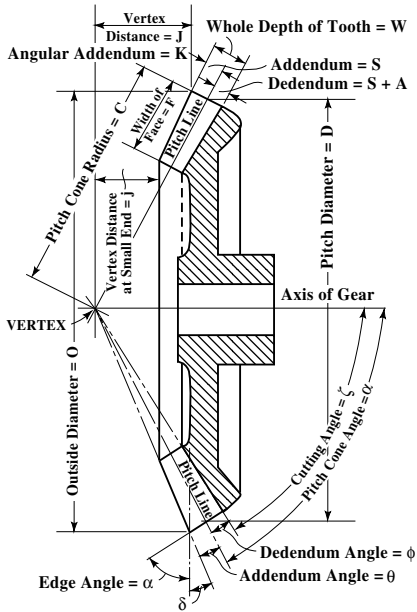


Fig. 1b. Bevel Gear Nomenclature

The formulas for milled bevel gears should be modified to make the clearance at the bottom of the teeth uniform instead of tapering toward the vertex. If this recommendation is followed, then the cutting angle (root angle) should be determined by subtracting the *addendum* angle from the pitch cone angle instead of subtracting the *dedendum* angle as in the formula given in the table.

#### Rules and Formulas for Calculating Dimensions of Milled Bevel Gears

| To Find                    | Rule   | Formula  |
|----------------------------|--|--|
| Pitch Cone Angle of Pinion | Divide the sine of the shaft angle by the sum of the cosine of the shaft angle and the quotient obtained by dividing the number of teeth in the gear by the number of teeth in the pinion; this gives the tangent. <i>Note:</i> For shaft angles greater than $90^\circ$ the cosine is negative. | $\tan \alpha_p = \frac{\sin \Sigma}{\frac{N_G}{N_P} + \cos \Sigma}$ For $90^\circ$ shaft angle,<br>$\tan \alpha_p = \frac{N_P}{N_G}$ |
| Pitch Cone Angle of Gear   | Subtract the pitch cone angle of the pinion from the shaft angle.  | $\alpha_G = \Sigma - \alpha_p$   |
| Pitch Diameter             | Divide the number of teeth by the diametral pitch.   | $D = N \div P$   |

**Rules and Formulas for Calculating Dimensions of Milled Bevel Gears (Continued)**

| To Find                                       | Rule   | Formula                                |
|---|--|--|
| Addendum                                      | Divide 1 by the diametral pitch.   | $S = 1 \div P$                         |
| Dedendum                                      | Divide 1.157 by the diametral pitch.   | $S + A = 1.157 \div P$                 |
| Whole Depth of Tooth                          | Divide 2.157 by the diametral pitch.   | $W = 2.157 \div P$                     |
| Thickness of Tooth at Pitch Line              | Divide 1.571 by the diametral pitch.   | $T = 1.571 \div P$                     |
| Pitch Cone Radius                             | Divide the pitch diameter by twice the sine of the pitch cone angle.   | $C = \frac{D}{2 \times \sin \alpha}$   |
| Addendum of Small End of Tooth                | Subtract the width of face from the pitch cone radius, divide the remainder by the pitch cone radius and multiply by the addendum.                             | $s = S \times \frac{C-F}{C}$           |
| Thickness of Tooth at Pitch Line at Small End | Subtract the width of face from the pitch cone radius, divide the remainder by the pitch cone radius and multiply by the thickness of the tooth at pitch line. | $t = T \times \frac{C-F}{C}$           |
| Addendum Angle                                | Divide the addendum by the pitch cone radius to get the tangent.   | $\tan \theta = \frac{S}{C}$            |
| Dedendum Angle                                | Divide the dedendum by the pitch cone radius to get the tangent.   | $\tan \phi = \frac{S+A}{C}$            |
| Face Width (Max.)                             | Divide the pitch cone radius by 3 or divide 8 by the diametral pitch, whichever gives the smaller value.   | $F = \frac{C}{3}$ or $F = \frac{8}{P}$ |
| Circular Pitch                                | Divide 3.1416 by the diametral pitch.  | $\rho = 3.1416 \div P$                 |
| Face Angle                                    | Add the addendum angle to the pitch cone angle   | $\gamma = \alpha + \theta$             |
| Compound Rest Angle for Turning Blank         | Subtract both the pitch cone angle and the addendum angle from 90 degrees.   | $\delta = 90^\circ - \alpha - \theta$  |
| Cutting Angle                                 | Subtract the dedendum angle from the pitch cone angle.   | $\zeta = \alpha - \phi$                |
| Angular Addendum                              | Multiply the addendum by the cosine of the pitch cone angle.   | $K = S \times \cos \alpha$             |
| Outside Diameter                              | Add twice the angular addendum to the pitch diameter.  | $O = D + 2K$                           |
| Vertex or Apex Distance                       | Multiply one-half the outside diameter by the cotangent of the face angle.   | $J = \frac{O}{2} \times \cot \gamma$   |
| Vertex Distance at Small End of Tooth         | Subtract the width of face from the pitch cone radius; divide the remainder by the pitch cone radius and multiply by the apex distance.                        | $j = J \times \frac{C-F}{C}$           |
| Number of Teeth for which to Select Cutter    | Divide the number of teeth by the cosine of the pitch cone angle.  | $N' = \frac{N}{\cos \alpha}$           |

These dimensions are the same for both gear and pinion.

**Numbers of Formed Cutters Used to Mill Teeth in Mating Bevel Gear and Pinion with Shafts at Right Angles**

|                         |    | Number of Teeth in Pinion |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |  |
|-------------------------|----|---------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--|
|                         |    | 12                        | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  | 21  | 22  | 23  | 24  | 25  | 26  | 27  | 28  |  |
| Number of Teeth in Gear | 12 | 7-7                       | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |  |
|                         | 13 | 6-7                       | 6-6 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |  |
|                         | 14 | 5-7                       | 6-6 | 6-6 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |  |
|                         | 15 | 5-7                       | 5-6 | 5-6 | 5-5 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |  |
|                         | 16 | 4-7                       | 5-7 | 5-6 | 5-6 | 5-5 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |  |
|                         | 17 | 4-7                       | 4-7 | 4-6 | 5-6 | 5-5 | 5-5 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |  |
|                         | 18 | 4-7                       | 4-7 | 4-6 | 4-6 | 4-5 | 4-5 | 5-5 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |  |
|                         | 19 | 3-7                       | 4-7 | 4-6 | 4-6 | 4-6 | 4-5 | 4-5 | 4-4 | ... | ... | ... | ... | ... | ... | ... | ... | ... |  |
|                         | 20 | 3-7                       | 3-7 | 4-6 | 4-6 | 4-6 | 4-5 | 4-5 | 4-4 | 4-4 | ... | ... | ... | ... | ... | ... | ... | ... |  |
|                         | 21 | 3-8                       | 3-7 | 3-7 | 3-6 | 4-6 | 4-5 | 4-5 | 4-5 | 4-4 | 4-4 | ... | ... | ... | ... | ... | ... | ... |  |
|                         | 22 | 3-8                       | 3-7 | 3-7 | 3-6 | 3-6 | 3-5 | 4-5 | 4-5 | 4-4 | 4-4 | 4-4 | ... | ... | ... | ... | ... | ... |  |
|                         | 23 | 3-8                       | 3-7 | 3-7 | 3-6 | 3-6 | 3-5 | 3-5 | 3-5 | 3-4 | 4-4 | 4-4 | 4-4 | ... | ... | ... | ... | ... |  |
|                         | 24 | 3-8                       | 3-7 | 3-7 | 3-6 | 3-6 | 3-5 | 3-5 | 3-5 | 3-4 | 3-4 | 3-4 | 4-4 | 4-4 | 4-4 | ... | ... | ... |  |
|                         | 25 | 2-8                       | 2-7 | 3-7 | 3-6 | 3-6 | 3-6 | 3-5 | 3-5 | 3-5 | 3-4 | 3-4 | 3-4 | 4-4 | 3-3 | ... | ... | ... |  |
|                         | 26 | 2-8                       | 2-7 | 3-7 | 3-6 | 3-6 | 3-6 | 3-5 | 3-5 | 3-5 | 3-4 | 3-4 | 3-4 | 3-4 | 3-4 | 3-3 | 3-3 | ... |  |
|                         | 27 | 2-8                       | 2-7 | 2-7 | 2-6 | 3-6 | 3-6 | 3-5 | 3-5 | 3-5 | 3-4 | 3-4 | 3-4 | 3-4 | 3-4 | 3-4 | 3-3 | 3-3 |  |
|                         | 28 | 2-8                       | 2-7 | 2-7 | 2-6 | 2-6 | 3-6 | 3-5 | 3-5 | 3-5 | 3-4 | 3-4 | 3-4 | 3-4 | 3-4 | 3-4 | 3-3 | 3-3 |  |
|                         | 29 | 2-8                       | 2-7 | 2-7 | 2-7 | 2-6 | 2-6 | 3-5 | 3-5 | 3-5 | 3-4 | 3-4 | 3-4 | 3-4 | 3-4 | 3-4 | 3-3 | 3-3 |  |
|                         | 30 | 2-8                       | 2-7 | 2-7 | 2-7 | 2-6 | 2-6 | 2-5 | 2-5 | 3-5 | 3-5 | 3-4 | 3-4 | 3-4 | 3-4 | 3-4 | 3-3 | 3-3 |  |
|                         | 31 | 2-8                       | 2-7 | 2-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 3-4 | 3-4 | 3-4 | 3-4 | 3-4 | 3-3 | 3-3 |  |
|                         | 32 | 2-8                       | 2-7 | 2-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 3-4 | 3-4 | 3-4 | 3-3 | 3-3 |  |
|                         | 33 | 2-8                       | 2-8 | 2-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 3-4 | 3-4 | 3-4 | 3-3 |  |
|                         | 34 | 2-8                       | 2-8 | 2-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 | 3-4 | 3-3 |  |
|                         | 35 | 2-8                       | 2-8 | 2-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 | 2-3 |  |
|                         | 36 | 2-8                       | 2-8 | 2-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 | 2-3 |  |
|                         | 37 | 2-8                       | 2-8 | 2-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 | 2-3 |  |
|                         | 38 | 2-8                       | 2-8 | 2-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 39 | 2-8                       | 2-8 | 2-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 40 | 1-8                       | 2-8 | 2-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 41 | 1-8                       | 1-8 | 2-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 42 | 1-8                       | 1-8 | 2-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 43 | 1-8                       | 1-8 | 1-7 | 2-7 | 2-6 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 44 | 1-8                       | 1-8 | 1-7 | 1-7 | 2-6 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 45 | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 46 | 1-8                       | 1-8 | 1-7 | 1-7 | 1-7 | 2-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 47 | 1-8                       | 1-8 | 1-7 | 1-7 | 1-7 | 1-6 | 2-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 48 | 1-8                       | 1-8 | 1-7 | 1-7 | 1-7 | 1-6 | 1-6 | 2-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 49 | 1-8                       | 1-8 | 1-7 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 50 | 1-8                       | 1-8 | 1-7 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 2-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 51 | 1-8                       | 1-8 | 1-7 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-5 | 2-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 52 | 1-8                       | 1-8 | 1-7 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 2-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 53 | 1-8                       | 1-8 | 1-7 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 2-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 54 | 1-8                       | 1-8 | 1-7 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 2-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |
|                         | 55 | 1-8                       | 1-8 | 1-7 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 2-4 | 2-4 | 2-4 | 2-4 |  |

BEVEL GEARING

Numbers of Formed Cutters Used to Mill Teeth in Mating Bevel Gear and Pinion with Shafts at Right Angles (Continued)

|     | Number of Teeth in Pinion |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |  |
|-----|---------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--|
|     | 12                        | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  | 21  | 22  | 23  | 24  | 25  | 26  | 27  | 28  |  |
| 56  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 2-4 | 2-4 | 2-4 |  |
| 57  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 2-4 | 2-4 |  |
| 58  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 | 2-4 |  |
| 59  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 60  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 61  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 62  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 63  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 64  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 65  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 66  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 67  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 68  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 69  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 70  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 71  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 72  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 73  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 74  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 75  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 76  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 77  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 78  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 79  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 80  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 81  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 82  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 83  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 84  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 85  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 86  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 87  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 88  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 89  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 90  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 91  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 92  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 93  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 94  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 95  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 96  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 97  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 98  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 99  | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |
| 100 | 1-8                       | 1-8 | 1-7 | 1-7 | 1-6 | 1-6 | 1-6 | 1-6 | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 | 1-4 | 1-4 | 1-4 | 1-4 |  |

Number of cutter for gear given first, followed by number for pinion. See text, page 2091

**Selecting Formed Cutters for Milling Bevel Gears.**—For milling  $14\frac{1}{2}$ -degree pressure angle bevel gears, the standard cutter series furnished by manufacturers of formed milling cutters is commonly used. There are 8 cutters in the series for each diametral pitch to cover the full range from a 12-tooth pinion to a crown gear. The difference between formed cutters used for milling spur gears and those used for bevel gears is that bevel gear cutters are thinner because they must pass through the narrow tooth space at the small end of the bevel gear; otherwise the shape of the cutter and hence, the cutter number, are the same.

To select the proper number of cutter to be used when a bevel gear is to be milled, it is necessary, first, to compute what is called the "Number of Teeth,  $N'$  for which to Select Cutter." This number of teeth can then be used to select the proper number of bevel gear cutter from the spur gear milling cutter table on page 2054. The value of  $N'$  may be computed using the last formula in the table on page 2087.

*Example 1:* What numbers of cutters are required for a pair of bevel gears of 4 diametral pitch and 70 degree shaft angle if the gear has 50 teeth and the pinion 20 teeth?

The pitch cone angle of the pinion is determined by using the first formula in the table on page 2087:

$$\tan \alpha_P = \frac{\sin \Sigma}{\frac{N_G}{N_P} + \cos \Sigma} = \frac{\sin 70^\circ}{\frac{50}{20} + \cos 70^\circ} = 0.33064; \alpha_P = 18^\circ 18'$$

The pitch cone angle of the gear is determined from the second formula in the table on page 2087:

$$\alpha_G = \Sigma - \alpha_P = 70^\circ - 18^\circ 18' = 51^\circ 42'$$

The numbers of teeth  $N'$  for which to select the cutters for the gear and pinion may now be determined from the last formula in the table on page 2087:

$$N' \text{ for the pinion} = \frac{N_P}{\cos \alpha_P} = \frac{20}{\cos 18^\circ 18'} = 21.1 \approx 21 \text{ teeth}$$

$$N' \text{ for the gear} = \frac{N_G}{\cos \alpha_G} = \frac{50}{\cos 51^\circ 42'} = 80.7 \approx 81 \text{ teeth}$$

From the table on page 2054 the numbers of the cutters for pinion and gear are found to be, respectively, 5 and 2.

*Example 2:* Required the cutters for a pair of bevel gears where the gear has 24 teeth and the pinion 12 teeth. The shaft angle is 90 degrees. As in the first example, the formulas given in the table on page 2087 will be used.

$$\tan \alpha_P = N_P \div N_G = 12 \div 24 = 0.5000 \text{ and } \alpha_P = 26^\circ 34'$$

$$\alpha_G = \Sigma - \alpha_P = 90^\circ - 26^\circ 34' = 63^\circ 26'$$

$$N' \text{ for pinion} = 12 \div \cos 26^\circ 34' = 13.4 \approx 13 \text{ teeth}$$

$$N' \text{ for gear} = 24 \div \cos 63^\circ 26' = 53.6 \approx 54 \text{ teeth}$$

And from the table on page 2054 the cutters for pinion and gear are found to be, respectively, 8 and 3.

**Use of Table for Selecting Formed Cutters for Milling Bevel Gears.**—The table beginning on page 2089 gives the numbers of cutters to use for milling various numbers of teeth in the gear and pinion. The table applies only to bevel gears with axes at right angles. Thus, in *Example 2* given above, the numbers of the cutters could have been obtained directly by entering the table with the actual numbers of teeth in the gear, 24, and the pinion, 12.



**Offset of Cutter for Milling Bevel Gears.**—When milling bevel gears with a rotary formed cutter, it is necessary to take two cuts through each tooth space with the gear blank slightly off center, first on one side and then on the other, to obtain a tooth of approximately the correct form. The gear blank is also rotated proportionately to obtain the proper tooth thickness at the large and small ends. The amount that the gear blank or cutter should be offset from the central position can be determined quite accurately by the use of the table *Factors for Obtaining Offset for Milling Bevel Gears* in conjunction with the following rule: Find the factor in the table corresponding to the number of cutter used and to the ratio of the pitch cone radius to the face width; then divide this factor by the diametral pitch and subtract the result from half the thickness of the cutter at the pitch line.

**Factors for Obtaining Offset for Milling Bevel Gears**

| No. of Cutter | Ratio of Pitch Cone Radius to Width of Face $\left(\frac{C}{F}\right)$ |                          |                          |                          |               |                          |                          |                          |               |                          |               |               |               |
|---------------|--|--------------------------|--------------------------|--------------------------|---------------|--------------------------|--------------------------|--------------------------|---------------|--------------------------|---------------|---------------|---------------|
|               | $\frac{3}{1}$  | $\frac{3\frac{1}{4}}{1}$ | $\frac{3\frac{1}{2}}{1}$ | $\frac{3\frac{3}{4}}{1}$ | $\frac{4}{1}$ | $\frac{4\frac{1}{4}}{1}$ | $\frac{4\frac{1}{2}}{1}$ | $\frac{4\frac{3}{4}}{1}$ | $\frac{5}{1}$ | $\frac{5\frac{1}{2}}{1}$ | $\frac{6}{1}$ | $\frac{7}{1}$ | $\frac{8}{1}$ |
| 1             | 0.254  | 0.254                    | 0.255                    | 0.256                    | 0.257         | 0.257                    | 0.257                    | 0.258                    | 0.258         | 0.259                    | 0.260         | 0.262         | 0.264         |
| 2             | 0.266  | 0.268                    | 0.271                    | 0.272                    | 0.273         | 0.274                    | 0.274                    | 0.275                    | 0.277         | 0.279                    | 0.280         | 0.283         | 0.284         |
| 3             | 0.266  | 0.268                    | 0.271                    | 0.273                    | 0.275         | 0.278                    | 0.280                    | 0.282                    | 0.283         | 0.286                    | 0.287         | 0.290         | 0.292         |
| 4             | 0.275  | 0.280                    | 0.285                    | 0.287                    | 0.291         | 0.293                    | 0.296                    | 0.298                    | 0.298         | 0.302                    | 0.305         | 0.308         | 0.311         |
| 5             | 0.280  | 0.285                    | 0.290                    | 0.293                    | 0.295         | 0.296                    | 0.298                    | 0.300                    | 0.302         | 0.307                    | 0.309         | 0.313         | 0.315         |
| 6             | 0.311  | 0.318                    | 0.323                    | 0.328                    | 0.330         | 0.334                    | 0.337                    | 0.340                    | 0.343         | 0.348                    | 0.352         | 0.356         | 0.362         |
| 7             | 0.289  | 0.298                    | 0.308                    | 0.316                    | 0.324         | 0.329                    | 0.334                    | 0.338                    | 0.343         | 0.350                    | 0.360         | 0.370         | 0.376         |
| 8             | 0.275  | 0.286                    | 0.296                    | 0.309                    | 0.319         | 0.331                    | 0.338                    | 0.344                    | 0.352         | 0.361                    | 0.368         | 0.380         | 0.386         |

Note.—For obtaining offset by above table, use formula:

$$\text{Offset} = \frac{T}{2} - \frac{\text{factor from table}}{P}$$

$P$  = diametral pitch of gear to be cut

$T$  = thickness of cutter used, measured at pitch line

To illustrate, what would be the amount of offset for a bevel gear having 24 teeth, 6 diametral pitch, 30-degree pitch cone angle and  $1\frac{1}{4}$ -inch face or tooth length? In order to obtain a factor from the table, the ratio of the pitch cone radius to the face width must be determined. The pitch cone radius equals the pitch diameter divided by twice the sine of the pitch cone angle =  $4 \div (2 \times 0.5) = 4$  inches. As the face width is 1.25, the ratio is  $4 \div 1.25$  or about  $3\frac{1}{4}$  to 1. The factor in the table for this ratio is 0.280 with a No. 4 cutter, which would be the cutter number for this particular gear. The thickness of the cutter at the pitch line is measured by using a vernier gear tooth caliper. The depth  $S + A$  (see Fig. 2;  $S$  = addendum;  $A$  = clearance) at which to take the measurement equals 1.157 divided by the diametral pitch; thus,  $1.157 \div 6 = 0.1928$  inch. The cutter thickness at this depth will vary with different cutters and even with the same cutter as it is ground away, because formed bevel gear cutters are commonly provided with side relief. Assuming that the thickness is 0.1745 inch, and substituting the values in the formula given, we have:

$$\text{Offset} = \frac{0.1745}{2} - \frac{0.280}{6} = 0.0406 \text{ inch}$$

**Adjusting the Gear Blank for Milling.**—After the offset is determined, the blank is adjusted laterally by this amount, and the tooth spaces are milled around the blank. After having milled one side of each tooth to the proper dimensions, the blank is set over in the opposite direction the same amount from a position central with the cutter, and is rotated to line up the cutter with a tooth space at the small end. A trial cut is then taken, which will leave the tooth being milled a little too thick, provided the cutter is thin enough—as it should be—to pass through the small end of the tooth space of the finished gear. This trial tooth is made the proper thickness by rotating the blank toward the cutter. To test the amount of offset, measure the tooth thickness (with a vernier caliper) at the large and small ends. The caliper should be set so that the addendum at the small end is in proper proportion to the addendum at the large end; that is, in the ratio,  $(C - F)/C$  (see Fig. 2).

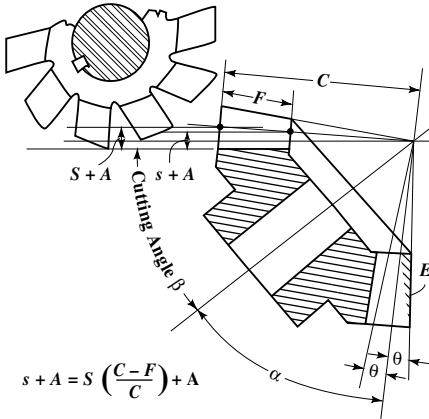


Fig. 2.

In taking these measurements, if the thicknesses at both ends (which should be in the same ratio) are too great, rotate the tooth toward the cutter and take trial cuts until the proper thickness at either the large or small end is obtained. If the large end of the tooth is the right thickness and the small end too thick, the blank was offset too much; inversely, if the small end is correct and the large end too thick, the blank was not set enough off center, and, either way, its position should be changed accordingly. The formula and table previously referred to will enable a properly turned blank to be set accurately enough for general work. The dividing head should be set to the cutting angle  $\beta$  (see Fig. 2), which is found by subtracting the addendum angle  $\theta$  from the pitch cone angle  $\alpha$ . After a bevel gear is cut by the method described, the sides of the teeth at the small end should be filed as indicated by the shade lines at *E*; that is, by filing off a triangular area from the point of the tooth at the large end to the point at the small end, thence down to the pitch line and back diagonally to a point at the large end.

## Typical Steels Used for Bevel Gear Applications

| Carburizing Steels                       |  |  |  |                       |  |
|--|--|--|--|-----------------------|--|
| SAE<br>or<br>AISI<br>No.                 | Type of Steel                            | Purchase Specifications  |  |                       | Remarks  |
|  |  | Preliminary<br>Heat Treatment  | Brinell<br>Hard-<br>ness<br>Number       | ASTM<br>Grain<br>Size |  |
| 1024                                     | Manganese                                | Normalize  |  |                       | Low Alloy — oil quench limited to thin sections  |
| 2512                                     | Nickel Alloy                             | Normalize —<br>Anneal  | 163–228                                  | 5–8                   | Aircraft quality   |
| 3310<br>3312X                            | Nickel-Chromium                          | Normalize, then<br>heat to 1450°F,<br>cool in furnace.<br>Reheat to 1170°F<br>— cool in air                        | 163–228                                  | 5–8                   | Used for maximum resistance to wear and fatigue  |
| 4028                                     | Molybdenum                               | Normalize  | 163–217                                  |                       | Low Alloy  |
| 4615<br>4620                             | Nickel-Molybdenum                        | Normalize —<br>1700°F–1750°F   | 163–217                                  | 5–8                   | Good machining qualities. Well adapted to direct quench — gives tough core with minimum distortion   |
| 4815<br>4820                             | Nickel-Molybdenum                        | Normalize  | 163–241                                  | 5–8                   | For aircraft and heavily loaded service  |
| 5120                                     | Chromium                                 | Normalize  | 163–217                                  | 5–8                   |  |
| 8615<br>8620<br>8715<br>8720             | Chromium-Nickel-Molybdenum               | Normalize —<br>cool at hammer  | 163–217                                  | 5–8                   | Used as an alternate for 4620  |
| Oil Hardening and Flame Hardening Steels |  |  |  |                       |  |
| 1141                                     | Sulfurized free-cutting carbon steel     | Normalize<br>Heat-treated  | 179–228<br>255–269                       | 5 or<br>Coarser       | Free-cutting steel used for unhardened gears, oil-treated gears, and for gears to be surface hardened where stresses are low                                       |
| 4140<br>4640                             | Chromium-Molybdenum<br>Nickel-Molybdenum | For oil hardening,<br>Normalize —<br>Anneal<br>For surface hardening,<br>Normalize,<br>reheat, quench,<br>and draw | 179–212<br>235–269<br>269–302<br>302–341 |                       | Used for heat-treated, oil-hardened, and surface-hardened gears. Machine qualities of 4640 are superior to 4140, and it is the preferred steel for flame hardening |
| 6145                                     | Chromium-Vanadium                        | Normalize—<br>reheat, quench,<br>and draw  | 235–269<br>269–302<br>302–341            |                       | Fair machining qualities. Used for surface hardened gears when 4640 is not available   |
| 8640<br>8739                             | Chromium-Nickel-Molybdenum               | Same as for 4640   |  |                       | Used as an alternate for 4640  |
| Nitriding Steels                         |  |  |  |                       |  |
| Nitralloy<br>H & G                       | Special Alloy                            | Anneal   | 163–192                                  |                       | Normal hardness range for cutting is 20–28 Rockwell C  |

Other steels with qualities equivalent to those listed in the table may also be used.

**Circular Thickness, Chordal Thickness, and Chordal Addendum of Milled Bevel Gear Teeth.**—In the formulas that follow,  $T$  = circular tooth thickness on pitch circle at large end of tooth;  $t$  = circular thickness at small end;  $T_c$  and  $t_c$  = chordal thickness at large and small ends, respectively;  $S_c$  and  $s_c$  = chordal addendum at large and small ends, respectively;  $D$  = pitch diameter at large end; and  $C, F, P, S, s,$  and  $\alpha$  are as defined on page 2085.

$$T = \frac{1.5708}{P} \quad T_c = T - \frac{T^3}{6D^2} \quad S_c = S + \frac{T^2 \cos \alpha}{4D}$$

$$t = \frac{T(C-F)}{C} \quad t_c = t - \frac{t^3}{6(D-2F \sin \alpha)^2} \quad s_c = s + \frac{t^2 \cos \alpha}{4(D-2F \sin \alpha)}$$

### Worm Gearing

**Worm Gearing.**—Worm gearing may be divided into two general classes, fine-pitch worm gearing, and coarse-pitch worm gearing. Fine-pitch worm gearing is segregated from coarse-pitch worm gearing for the following reasons:

- 1) Fine-pitch worms and wormgears are used largely to transmit motion rather than power. Tooth strength except at the coarser end of the fine-pitch range is seldom an important factor; durability and accuracy, as they affect the transmission of uniform angular motion, are of greater importance.
- 2) Housing constructions and lubricating methods are, in general, quite different for fine-pitch worm gearing.
- 3) Because fine-pitch worms and wormgears are so small, profile deviations and tooth bearings cannot be measured with the same accuracy as can those of coarse pitches.
- 4) Equipment generally available for cutting fine-pitch wormgears has restrictions which limit the diameter, the lead range, the degree of accuracy attainable, and the kind of tooth bearing obtainable.
- 5) Special consideration must be given to top lands in fine-pitch hardened worms and wormgear-cutting tools.
- 6) Interchangeability and high production are important factors in fine-pitch worm gearing; individual matching of the worm to the gear, as often practiced with coarse-pitch precision worms, is impractical in the case of fine-pitch worm drives.

**American Standard Design for Fine-pitch Worm Gearing (ANSI B6.9-1977).**—This standard is intended as a design procedure for fine-pitch worms and wormgears having axes at right angles. It covers cylindrical worms with helical threads, and wormgears hobbled for fully conjugate tooth surfaces. It does not cover helical gears used as wormgears.

**Hobs:** The hob for producing the gear is a duplicate of the mating worm with regard to tooth profile, number of threads, and lead. The hob differs from the worm principally in that the outside diameter of the hob is larger to allow for resharpening and to provide bottom clearance in the wormgear.

**Pitches:** Eight standard axial pitches have been established to provide adequate coverage of the pitch range normally required: 0.030, 0.040, 0.050, 0.065, 0.080, 0.100, 0.130, and 0.160 inch.

Axial pitch is used as a basis for this design standard because: 1) Axial pitch establishes lead which is a basic dimension in the production and inspection of worms; 2) the axial pitch of the worm is equal to the circular pitch of the gear in the central plane; and 3) only one set of change gears or one master lead cam is required for a given lead, regardless of lead angle, on commonly-used worm-producing equipment.

**Table 1. Formulas for Proportions of American Standard Fine-pitch Worms and Wormgears ANSI B6.9-1977**

|   |  |
|---|--|
| <p style="text-align: center;">LETTER SYMBOLS</p> <p><math>P</math> = Circular pitch of wormgear<br/> <math>P</math> = axial pitch of the worm, <math>P_x</math>, in the central plane<br/> <math>P_x</math> = Axial pitch of worm<br/> <math>P_n</math> = Normal circular pitch of worm and wormgear = <math>P_x</math><br/> <math>\cos \lambda = P \cos \psi</math><br/> <math>\lambda</math> = Lead angle of worm<br/> <math>\psi</math> = Helix angle of wormgear<br/> <math>n</math> = Number of threads in worm<br/> <math>N</math> = Number of teeth in wormgear<br/> <math>N = nm_G</math><br/> <math>m_G</math> = Ratio of gearing = <math>N \div n</math></p> |  |
|---|--|

| Item   | Formula                         | Item   | Formula  |
|--|---------------------------------|--|--|
| <b>WORM DIMENSIONS</b>                                       |                                 | <b>WORMGEAR DIMENSIONS<sup>a</sup></b>         |  |
| Lead   | $l = nP_x$                      | Pitch Diameter                                 | $D = NP \div \pi = N P_x \div \pi$                           |
| Pitch Diameter   | $d = l \div (\pi \tan \lambda)$ | Outside Diameter                               | $D_o = 2C - d + 2a$  |
| Outside Diameter   | $d_o = d + 2a$                  | Face Width                                     | $F_{Gmin} = 1.125 \times \sqrt{(d_o + 2c)^2 - (d_o - 4a)^2}$ |
| Safe Minimum Length of Threaded Portion of Worm <sup>b</sup> | $F_W = \sqrt{D_o^2 - D^2}$      |  |  |
| <b>DIMENSIONS FOR BOTH WORM AND WORMGEAR</b>                 |                                 |  |  |
| Addendum   | $a = 0.3183P_n$                 | Tooth thickness                                | $t_n = 0.5P_n$   |
| Whole Depth  | $h_t = 0.7003P_n + 0.002$       | Approximate normal pressure angle <sup>c</sup> | $\phi_n = 20$ degrees  |
| Working Depth  | $h_k = 0.6366P_n$               | Center distance                                | $C = 0.5(d + D)$   |
| Clearance  | $c = h_t - h_k$                 |  |  |

<sup>a</sup> Current practice for fine-pitch worm gearing does not require the use of throated blanks. This results in the much simpler blank shown in the diagram which is quite similar to that for a spur or helical gear. The slight loss in contact resulting from the use of non-throated blanks has little effect on the load-carrying capacity of fine-pitch worm gears. It is sometimes desirable to use topping hobs for producing wormgears in which the size relation between the outside and pitch diameters must be closely controlled. In such cases the blank is made slightly larger than  $D_o$  by an amount (usually from 0.010 to 0.020) depending on the pitch. Topped wormgears will appear to have a small throat which is the result of the hobbing operation. For all intents and purposes, the throating is negligible and a blank so made is not to be considered as being a throated blank.

<sup>b</sup> This formula allows a sufficient length for fine-pitch worms.

<sup>c</sup> As stated in the text on page 2097, the actual pressure angle will be slightly greater due to the manufacturing process.

All dimensions in inches unless otherwise indicated.

**Lead Angles:** Fifteen standard lead angles have been established to provide adequate coverage: 0.5, 1, 1.5, 2, 3, 4, 5, 7, 9, 11, 14, 17, 21, 25, and 30 degrees.

This series of lead angles has been standardized to: 1) Minimize tooling; 2) permit obtaining geometric similarity between worms of different axial pitch by keeping the same lead angle; and 3) take into account the production distribution found in fine-pitch worm gearing applications.

For example, most fine-pitch worms have either one or two threads. This requires smaller increments at the low end of the lead angle series. For the less frequently used thread num-

bers, proportionately greater increments at the high end of the lead angle series are sufficient.

**Pressure Angle of Worm:** A pressure angle of 20 degrees has been selected as standard for cutters and grinding wheels used to produce worms within the scope of this Standard because it avoids objectionable undercutting regardless of lead angle.

Although the pressure angle of the cutter or grinding wheel used to produce the worm is 20 degrees, the normal pressure angle produced in the worm will actually be slightly greater, and will vary with the worm diameter, lead angle, and diameter of cutter or grinding wheel. A method for calculating the pressure angle change is given under the heading *Effect of Production Method on Worm Profile and Pressure Angle*.

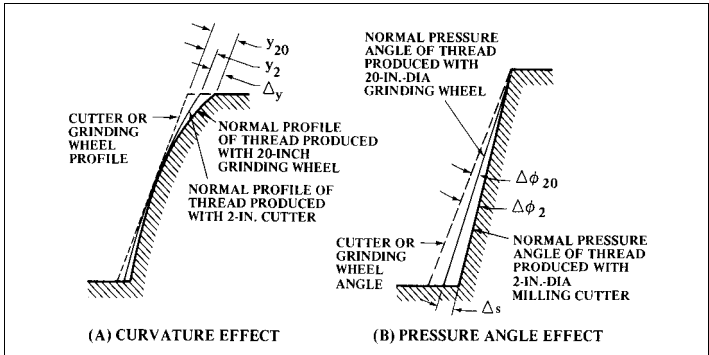
**Pitch Diameter Range of Worms:** The minimum recommended worm pitch diameter is 0.250 inch and the maximum is 2.000 inches.

**Tooth Form of Worm and Wormgear:** The shape of the worm thread in the normal plane is defined as that which is produced by a symmetrical double-conical cutter or grinding wheel having straight elements and an included angle of 40 degrees.

Because worms and wormgears are closely related to their method of manufacture, it is impossible to specify clearly the tooth form of the wormgear without referring to the mating worm. For this reason, worm specifications should include the method of manufacture and the diameter of cutter or grinding wheel used. Similarly, for determining the shape of the generating tool, information about the method of producing the worm threads must be given to the manufacturer if the tools are to be designed correctly.

The worm profile will be a curve that departs from a straight line by varying amounts, depending on the worm diameter, lead angle, and the cutter or grinding wheel diameter. A method for calculating this deviation is given in the Standard. The tooth form of the wormgear is understood to be made fully conjugate to the mating worm thread.

#### Effect of Diameter of Cutting on Profile and Pressure Angle of Worms



**Effect of Production Method on Worm Profile and Pressure Angle.**—In worm gearing, tooth bearing is usually used as the means of judging tooth profile accuracy since direct profile measurements on fine-pitch worms or wormgears is not practical. According to AGMA 370.01, Design Manual for Fine-Pitch Gearing, a minimum of 50 per cent initial area of contact is suitable for most fine-pitch worm gearing, although in some cases, such as when the load fluctuates widely, a more restricted initial area of contact may be desirable.

Except where single-pointed lathe tools, end mills, or cutters of special shape are used in the manufacture of worms, the pressure angle and profile produced by the cutter are differ-

ent from those of the cutter itself. The amounts of these differences depend on several factors, namely, diameter and lead angle of the worm, thickness and depth of the worm thread, and diameter of the cutter or grinding wheel. The accompanying diagram shows the curvature and pressure angle effects produced in the worm by cutters and grinding wheels, and how the amount of variation in worm profile and pressure angle is influenced by the diameter of the cutting tool used.

**Materials for Worm Gearing.**—Worm gearing, especially for power transmission, should have steel worms and phosphor bronze wormgears. This combination is used extensively. The worms should be hardened and ground to obtain accuracy and a smooth finish.

The phosphor bronze wormgears should contain from 10 to 12 per cent of tin. The S.A.E. phosphor gear bronze (No. 65) contains 88–90% copper, 10–12% tin, 0.50% lead, 0.50% zinc (but with a maximum total lead, zinc and nickel content of 1.0 per cent), phosphorous 0.10–0.30%, aluminum 0.005%. The S.A.E. nickel phosphor gear bronze (No. 65 + Ni) contains 87% copper, 11% tin, 2% nickel and 0.2% phosphorous.

**Single-thread Worms.**—The ratio of the worm speed to the wormgear speed may range from 1.5 or even less up to 100 or more. Worm gearing having high ratios are not very efficient as transmitters of power; nevertheless high as well as low ratios often are required. Since the ratio equals the number of wormgear teeth divided by the number of threads or “starts” on the worm, single-thread worms are used to obtain a high ratio. As a general rule, a ratio of 50 is about the maximum recommended for a single worm and wormgear combination, although ratios up to 100 or higher are possible. When a high ratio is required, it may be preferable to use, in combination, two sets of worm gearing of the multi-thread type in preference to one set of the single-thread type in order to obtain the same total reduction and a higher combined efficiency.

Single-thread worms are comparatively inefficient because of the effect of the low lead angle; consequently, single-thread worms are not used when the primary purpose is to transmit power as efficiently as possible but they may be employed either when a large speed reduction with one set of gearing is necessary, or possibly as a means of adjustment, especially if “mechanical advantage” or self-locking are important factors.

**Multi-thread Worms.**—When worm gearing is designed primarily for transmitting power efficiently, the lead angle of the worm should be as high as is consistent with other requirements and preferably between, say, 25 or 30 and 45 degrees. This means that the worm must be multi-threaded. To obtain a given ratio, some number of wormgear teeth divided by some number of worm threads must equal the ratio. Thus, if the ratio is 6, combinations such as the following might be used:

$$\frac{24}{4}, \frac{30}{5}, \frac{36}{6}, \frac{42}{7}$$

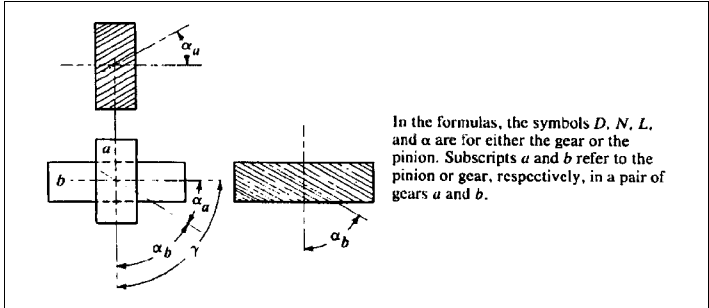
The numerators represent the number of wormgear teeth and the denominators, the number of worm threads or “starts.” The number of wormgear teeth may not be an exact multiple of the number of threads on a multi-thread worm in order to obtain a “hunting tooth” action.

*Number of Threads or “Starts” on Worm:* The number of threads on the worm ordinarily varies from one to six or eight, depending upon the ratio of the gearing. As the ratio is increased, the number of worm threads is reduced, as a general rule. In some cases, however, the higher of two ratios may also have a larger number of threads. For example, a ratio of  $6\frac{1}{5}$  would have 5 threads whereas a ratio of  $6\frac{3}{6}$  would have 6 threads. Whenever the ratio is fractional, the number of threads on the worm equals the denominator of the fractional part of the ratio.

## HELICAL GEARING

**Basic Rules and Formulas for Helical Gear Calculations.**—The rules and formulas in the following table and elsewhere in this article are basic to helical gear calculations. The notation used in the formulas is:  $P_n$  = normal diametral pitch of cutter;  $D$  = pitch diameter;  $N$  = number of teeth;  $\alpha$  = helix angle;  $\gamma$  = center angle or angle between shafts;  $C$  = center distance;  $N'$  = number of teeth for which to select a formed cutter for milled teeth;  $L$  = lead of tooth helix;  $S$  = addendum;  $W$  = whole depth;  $T_n$  = normal tooth thickness at pitch line; and  $O$  = outside diameter.

## Rules and Formulas for Helical Gear Calculations

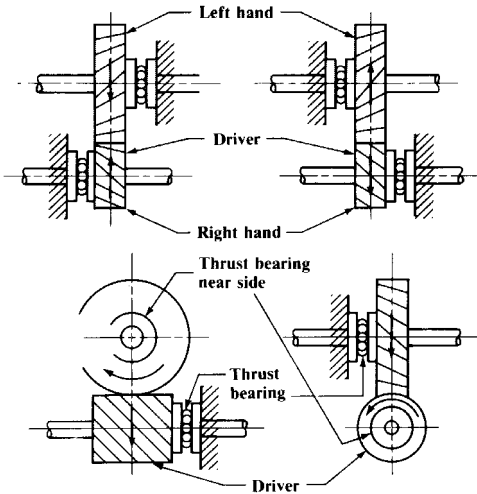


| No. | To Find                              | Rule   | Formula                         |
|-----|--------------------------------------|--|---------------------------------|
| 1   | Pitch Diameter                       | Divide the number of teeth by the product of the normal diametral pitch and the cosine of the helix angle. | $D = \frac{N}{P_n \cos \alpha}$ |
| 2   | Center Distance                      | Add together the two pitch diameters and divide by 2.  | $C = \frac{D_a + D_b}{2}$       |
| 3   | Lead of Tooth Helix                  | Multiply the pitch diameter by 3.1416 by the cotangent of the helix angle.                                 | $L = \pi D \cot \alpha$         |
| 4   | Addendum                             | Divide 1 by the normal diametral pitch.  | $S = \frac{1}{P_n}$             |
| 5   | Whole Depth of tooth                 | Divide 2.157 by the normal diametral pitch.  | $W = \frac{2.157}{P_n}$         |
| 6   | Normal Tooth Thickness at Pitch Line | Divide 1.5708 by the normal diametral pitch.   | $T_n = \frac{1.5708}{P_n}$      |
| 7   | Outside Diameter                     | Add twice the addendum to the pitch diameter.  | $O = D + 2S$                    |

**Determining Direction of Thrust.**—The first step in helical gear design is to determine the desired direction of the thrust. When the direction of the thrust has been determined and the relative positions of the driver and driven gears are known, then the direction of helix (right- or left-hand) may be found from the accompanying thrust diagrams, *Directions of Rotation and Resulting Thrust for Parallel Shaft and 90 Degree Shaft Angle Helical Gears*. The diagrams show the directions of rotation and the resulting thrust for parallel-



shaft and 90-degree shaft angle helical gears. The thrust bearings are located so as to take the thrust caused by the tooth loads. The direction of the thrust depends on the direction of the helix, the relative positions of driver and driven gears, and the direction of rotation. The thrust may be changed to the opposite direction by changing any one of the three conditions, namely, by changing the hand of the helix, by reversing the direction of rotation, or by exchanging of driver and driven gear positions.

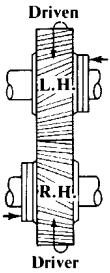


Directions of Rotation and Resulting Thrust for Parallel Shaft and 90 Degree Shaft Angle Helical Gears

**Determining Helix Angles.**—The following rules should be observed for helical gears with shafts at any given angle. If each helix angle is less than the shaft angle, then the sum of the helix angles of the two gears will equal the angle between the shafts, and the helix angle is of the same hand for both gears; if the helix angle of one of the gears is larger than the shaft angle, then the difference between the helix angles of the two gears will be equal to the shaft angle, and the gears will be of opposite hand.

**Pitch of Cutter to be Used.**—The thickness of the cutter at the pitchline for cutting helical gears should equal one-half the *normal* circular pitch. The normal pitch varies with the helix angle, hence, the helix angle must be considered when selecting a cutter. The cutter should be of the same pitch as the *normal* diametral pitch of the gear. This normal pitch is found by dividing the transverse diametral pitch of the gear by the cosine of the helix angle. To illustrate, if the pitch diameter of a helical gear is 6.718 and there are 38 teeth having a helix angle of 45 degrees, the transverse diametral pitch equals 38 divided by 6.718 = 5.656; then the normal diametral pitch equals 5.656 divided by 0.707 = 8. A cutter, then, of 8 diametral pitch is the one to use for this particular gear.

Helical gears should preferably be cut on a generating-type gear cutting machine such as a hobber or shaper. Milling machines are used in some shops when hobbors or shapers are not available or when single, replacement gears are being made. In such instances, the pitch of the formed cutter used in milling a helical gear must not only conform to the normal diametral pitch of the gear, but the cutter number must also be determined. See *Selecting Cutter for Milling Helical Gears* starting on page 2108.

**1. Shafts Parallel, Center Distance Approximate.**—Given or assumed:

- 1) Position of gear having right- or left-hand helix, depending upon rotation and direction in which thrust is to be received
- 2)  $C_a$  = approximate center distance
- 3)  $P_n$  = normal diametral pitch
- 4)  $N$  = number of teeth in large gear
- 5)  $n$  = number of teeth in small gear
- 6)  $\alpha$  = angle of helix

To find:

$$1) D = \text{pitch diameter of large gear} = \frac{N}{P_n \cos \alpha}$$

$$2) d = \text{pitch diameter of small gear} = \frac{n}{P_n \cos \alpha}$$

$$3) O = \text{outside diameter of large gear} = D + \frac{2}{P_n}$$

$$4) o = \text{outside diameter of small gear} = d + \frac{2}{P_n}$$

$$5) T = \text{number of teeth marked on formed milling cutter (large gear)} = \frac{N}{\cos^3 \alpha}$$

$$6) t = \text{number of teeth marked on formed milling cutter (small gear)} = \frac{n}{\cos^3 \alpha}$$

$$7) L = \text{lead of helix on large gear} = \pi D \cot \alpha$$

$$8) l = \text{lead of helix on small gear} = \pi d \cot \alpha$$

$$9) C = \text{center distance (if not right, vary } \alpha) = \frac{1}{2}(D + d)$$

*Example:* Given or assumed: 1) See illustration; 2)  $C_a = 17$  inches; 3)  $P_n = 2$ ; 4)  $N = 48$ ; 5)  $n = 20$ ; and 6)  $\alpha = 20$ .

To find:

$$1) D = \frac{N}{P_n \cos \alpha} = \frac{48}{2 \times 0.9397} = 25.541 \text{ inches}$$

$$2) d = \frac{n}{P_n \cos \alpha} = \frac{20}{2 \times 0.9397} = 10.642 \text{ inches}$$

$$3) O = \frac{2}{P_n} = 25.541 + \frac{2}{2} = 26.541 \text{ inches}$$

$$4) o = d + \frac{2}{P_n} = 10.642 + \frac{2}{2} = 11.642 \text{ inches}$$

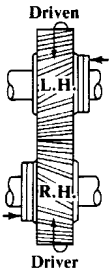
$$5) T = \frac{N}{\cos^3 \alpha} = \frac{48}{(0.9397)^3} = 57.8, \text{ say } 58 \text{ teeth}$$

$$6) t = \frac{n}{\cos^3 \alpha} = \frac{20}{(0.9397)^3} = 24.1, \text{ say } 24 \text{ teeth}$$

$$7) L = \pi D \cot \alpha = 3.1416 \times 25.541 \times 2.747 = 220.42 \text{ inches}$$

$$8) l = \pi d \cot \alpha = 3.1416 \times 10.642 \times 2.747 = 91.84 \text{ inches}$$

$$9) C = \frac{1}{2}(D + d) = \frac{1}{2}(25.541 + 10.642) = 18.091 \text{ inches}$$

**2. Shafts Parallel, Center Distance Exact.**—Given or assumed:

1) Position of gear having right- or left-hand helix, depending upon rotation and direction in which thrust is to be received

2)  $C$  = exact center distance

3)  $P_n$  = normal diametral pitch (pitch of cutter)

4)  $N$  = number of teeth in large gear

5)  $n$  = number of teeth in small gear

To find:

$$1) \cos \alpha = \frac{N + n}{2P_n C}$$

$$2) D = \text{pitch diameter of large gear} = \frac{N}{P_n \cos \alpha}$$

$$3) d = \text{pitch diameter of small gear} = \frac{n}{P_n \cos \alpha}$$

$$4) O = \text{outside diameter of large gear} = D + \frac{2}{P_n}$$

$$5) o = \text{outside diameter of small gear} = d + \frac{2}{P_n}$$

$$6) T = \text{number of teeth marked on formed milling cutter (large gear)} = \frac{N}{\cos^3 \alpha}$$

$$7) t = \text{number of teeth marked on formed milling cutter (small gear)} = \frac{n}{\cos^3 \alpha}$$

$$8) L = \text{lead of helix (large gear)} = \pi D \cot \alpha$$

$$9) l = \text{lead of helix (small gear)} = \pi d \cot \alpha$$

*Example:* Given or assumed: 1) See illustration; 2)  $C = 18.75$  inches; 3)  $P_n = 4$ ; 4)  $N = 96$ ; and 5)  $n = 48$ .

$$1) \cos \alpha = \frac{N + n}{2P_n C} = \frac{96 + 48}{2 \times 4 \times 18.75} = 0.96, \text{ or } \alpha = 16^\circ 16'$$

$$2) D = \frac{N}{P_n \cos \alpha} = \frac{96}{4 \times 0.96} = 25 \text{ inches}$$

$$3) d = \frac{n}{P_n \cos \alpha} = \frac{48}{4 \times 0.96} = 12.5 \text{ inches}$$

$$4) O = D + \frac{2}{P_n} = 25 + \frac{2}{4} = 25.5 \text{ inches}$$

$$5) o = d + \frac{2}{P_n} = 12.5 + \frac{2}{4} = 13 \text{ inches}$$

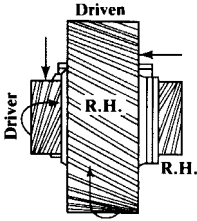
$$6) T = \frac{N}{\cos^3 \alpha} = \frac{96}{(0.96)^3} = 108 \text{ teeth}$$

$$7) t = \frac{n}{\cos^3 \alpha} = \frac{48}{(0.96)^3} = 54 \text{ teeth}$$

$$8) L = \pi D \cot \alpha = 3.1416 \times 25 \times 3.427 = 269.15 \text{ inches}$$

$$9) l = \pi d \cot \alpha = 3.1416 \times 12.5 \times 3.427 = 134.57 \text{ inches}$$

**3. Shafts at Right Angles, Center Distance Approx.**—Sum of helix angles of gear and pinion must equal 90 degrees.



Given or assumed:

- 1) Position of gear having right- or left-hand helix, depending on rotation and direction in which thrust is to be received
- 2)  $C_a$  = approximate center distance
- 3)  $P_n$  = normal diametral pitch (pitch of cutter)
- 4)  $R$  = ratio of gear to pinion size

$$5) n = \text{number of teeth in pinion} = \frac{1.41 C_a P_n}{R + 1} \text{ for 45 degrees;}$$

$$\text{and } \frac{2 C_a P_n \cos \alpha \cos \beta}{R \cos \beta + \cos \alpha} \text{ for any angle}$$

$$6) N = \text{number of teeth in gear} = nR$$

$$7) \alpha = \text{angle of helix of gear}$$

$$8) \beta = \text{angle of helix of pinion}$$

To find:

a) When helix angles are 45 degrees,

$$1) D = \text{pitch diameter of gear} = \frac{N}{0.70711 P_n}$$

$$2) d = \text{pitch diameter of pinion} = \frac{n}{0.70711 P_n}$$

$$3) O = \text{outside diameter of gear} = D + \frac{2}{P_n}$$

$$4) o = \text{outside diameter of pinion} = d + \frac{2}{P_n}$$

$$5) T = \text{number of formed cutter (gear)} = \frac{N}{0.353}$$

$$6) t = \text{number of formed cutter (pinion)} = \frac{n}{0.353}$$

$$7) L = \text{lead of helix of gear} = \pi D$$

$$8) l = \text{lead of helix of pinion} = \pi d$$

$$9) C = \text{center distance (exact)} = \frac{D + d}{2}$$

b) When helix angles are other than 45 degrees

$$1) D = \frac{N}{P_n \cos \alpha} \quad 2) d = \frac{n}{P_n \cos \beta} \quad 3) T = \frac{N}{\cos^3 \alpha}$$

$$4) t = \frac{n}{\cos^3 \beta} \quad 5) L = \pi D \cot \alpha \quad 6) l = \pi d \cot \beta$$

*Example:* Given or assumed: 1) See illustration; 2)  $C_a = 3.2$  inches; 3)  $P_n = 10$ ; and 4)  $R = 1.5$ .

$$5) n = \frac{1.41 C_a P_n}{R + 1} = \frac{1.41 \times 3.2 \times 10}{1.5 + 1} = \text{say 18 teeth.}$$

6)  $N = nR = 18 \times 1.5 = 27$  teeth; 7)  $\alpha = 45$  degrees; and 8)  $\beta = 45$  degrees.

To find:

$$1) D = \frac{N}{0.70711 P_n} = \frac{27}{0.70711 \times 10} = 3.818 \text{ inches}$$

$$2) d = \frac{n}{0.70711 P_n} = \frac{18}{0.70711 \times 10} = 2.545 \text{ inches}$$

$$3) O = D + \frac{2}{P_n} = 3.818 + \frac{2}{10} = 4.018 \text{ inches}$$

$$4) o = d + \frac{2}{P_n} = 2.545 + \frac{2}{10} = 2.745 \text{ inches}$$

$$5) T = \frac{N}{0.353} = \frac{27}{0.353} = 76.5, \text{ say } 76 \text{ teeth}$$

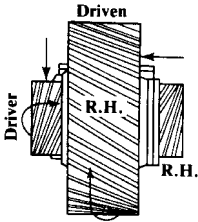
$$6) t = \frac{n}{0.353} = \frac{18}{0.353} = 51 \text{ teeth}$$

$$7) L = \pi D = 3.1416 \times 3.818 = 12 \text{ inches}$$

$$8) l = \pi d = 3.1416 \times 2.545 = 8 \text{ inches}$$

$$9) C = \frac{D + d}{2} = \frac{3.818 + 2.545}{2} = 3.182 \text{ inches}$$

**4A. Shafts at Right Angles, Center Distance Exact.**—Gears have same direction of helix. Sum of the helix angles will equal 90 degrees.



Given or assumed:

- 1) Position of gear having right- or left-hand helix depending on rotation and direction in which thrust is to be received
- 2)  $P_n$  = normal diametral pitch (pitch of cutter)
- 3)  $R$  = ratio of number of teeth in large gear to number of teeth in small gear
- 4)  $\alpha_a$  = approximate helix angle of large gear
- 5)  $C$  = exact center distance

To find:

$$1) n = \text{number of teeth in small gear nearest} = 2 CP_n \sin \alpha_a \div 1 + R \tan \alpha_a$$

$$2) N = \text{number of teeth in large gear} = Rn$$

$$3) \alpha = \text{exact helix angle of large gear, found by trial from } R \sec \alpha + \operatorname{cosec} \alpha = 2 CP_n \div n$$

$$4) \beta = \text{exact helix angle of small gear} = 90^\circ - \alpha$$

$$5) D = \text{pitch diameter of large gear} = \frac{N}{P_n \cos \alpha}$$

$$6) d = \text{pitch diameter of small gear} = \frac{n}{P_n \cos \beta}$$

$$7) O = \text{outside diameter of large gear} = D + \frac{2}{P_n}$$

$$8) o = \text{outside diameter of small gear} = d + \frac{2}{P_n}$$

9)  $N'$  and  $n'$  = numbers of teeth marked on cuttters for large and small gears (see page 2108)

$$10) L = \text{lead of helix on large gear} = \pi D \cot \alpha$$

$$11) l = \text{lead of helix on small gear} = \pi d \cot \beta$$

*Example:* Given or assumed: 1) See illustration; 2)  $P_n = 8$ ; 3)  $R = 3$ ; 4)  $\alpha_a = 45$  degrees; and 5)  $C = 10$  in.

To find:

$$1) n = \frac{2CP_n \sin \alpha_a}{1 + R \tan \alpha_a} = \frac{2 \times 10 \times 8 \times 0.70711}{1 + 3} = 28.25, \text{ say } 28 \text{ teeth}$$

$$2) N = Rn = 3 \times 28 = 84 \text{ teeth}$$

$$3) R \sec \alpha + \operatorname{cosec} \alpha = \frac{2CP_n}{n} = \frac{2 \times 10 \times 8}{28} = 5.714, \text{ or } \alpha = 46^\circ 6'$$

$$4) \beta = 90^\circ - \alpha = 90^\circ - 46^\circ 6' = 43^\circ 54'$$

$$5) D = \frac{N}{P_n \cos \alpha} = \frac{84}{8 \times 0.6934} = 15.143 \text{ inches}$$

$$6) d = \frac{n}{P_n \cos \beta} = \frac{28}{8 \times 0.72055} = 4.857 \text{ inches}$$

$$7) O = D + \frac{2}{P_n} = 15.143 + 0.25 = 15.393 \text{ inches}$$

$$8) o = d + \frac{2}{P_n} = 4.857 + 0.25 = 5.107 \text{ inches}$$

$$9) N' = 275; n' = 94 \text{ (see page 2108)}$$

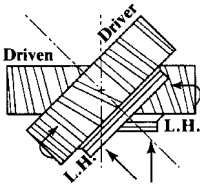
$$10) L = \pi D \cot \alpha = 3.1416 \times 15.143 \times 0.96232 = 45.78 \text{ inches}$$

$$11) l = \pi d \cot \beta = 3.1416 \times 4.857 \times 1.0392 = 15.857 \text{ inches}$$

#### 4B. Shafts at Right Angles, Any Ratio, Helix Angle for Minimum Center Distance.—

Diagram similar to 4A. Gears have same direction of helix. The sum of the helix angles will equal 90 degrees.

For any given ratio of gearing  $R$  there is a helix angle  $\alpha$  for the larger gear and a helix angle  $\beta = 90^\circ - \alpha$  for the smaller gear that will make the center distance  $C$  a minimum. Helix angle  $\alpha$  is found from the formula  $\cot \alpha = R^{1/3}$ . As an example, using the data found in Case 4A, helix angles  $\alpha$  and  $\beta$  for minimum center distance would be:  $\cot \alpha = R^{1/3} = 1.4422$ ;  $\alpha = 34^\circ 44'$  and  $\beta = 90^\circ - 34^\circ 44' = 55^\circ 16'$ . Using these helix angles,  $D = 12.777$ ;  $d = 6.143$ ; and  $C = 9.460$  from the formulas for  $D$  and  $d$  given under Case 4A.

**5. Shafts at Any Angle, Center Distance Approx.—**

The sum of the helix angles of the two gears equals the shaft angle, and the gears are of the same hand, if each angle is less than the shaft angle. The difference between the helix angles equals the shaft angle, and the gears are of opposite hand, if either angle is greater than the shaft angle.

Given or assumed:

- 1) Hand of helix, depending on rotation and direction in which thrust is to be received
- 2)  $C_a$  = center distance
- 3)  $P_n$  = normal diametral pitch (pitch of cutter)

$$4) R = \text{ratio of gear to pinion} = \frac{N}{n}$$

5)  $\alpha$  = angle of helix, gear

6)  $\beta$  = angle of helix, pinion

$$7) n = \text{number of teeth in pinion nearest } \frac{2C_a P_n \cos \alpha \cos \beta}{R \cos \beta + \cos \alpha} \text{ for any angle}$$

$$\text{and } \frac{2C_a P_n \cos \alpha}{R + 1} \text{ when both angles are equal}$$

8)  $N$  = number of teeth in gear =  $Rn$

To find:

$$1) D = \text{pitch diameter of gear} = \frac{N}{P_n \cos \alpha}$$

$$2) d = \text{pitch diameter of pinion} = \frac{n}{P_n \cos \beta}$$

$$3) O = \text{outside diameter of gear} = D + \frac{2}{P_n}$$

$$4) o = \text{outside diameter of pinion} = d + \frac{2}{P_n}$$

$$5) T = \text{number of teeth marked on cutter for gear} = \frac{N}{\cos^3 \alpha}$$

$$6) t = \text{number of teeth marked on cutter for pinion} = \frac{n}{\cos^3 \beta}$$

7)  $L$  = lead of helix on gear =  $\pi D \cot \alpha$

8)  $l$  = lead of helix on pinion =  $\pi d \cot \beta$

$$9) C = \text{actual center distance} = \frac{D + d}{2}$$

*Example:* Given or assumed (angle of shafts, 60 degrees):

1) See illustration 2)  $C_a$  = 12 inches 3)  $P_n$  = 8

4)  $R$  = 4 5)  $\alpha$  = 30 degrees 6)  $\beta$  = 30 degrees

$$7) n = \frac{2C_a P_n \cos \alpha}{R + 1} = \frac{2 \times 12 \times 8 \times 0.86603}{4 + 1} = 33 \text{ teeth}$$

$$8) N = 4 \times 33 = 132 \text{ teeth}$$

To find:

$$1) D = \frac{N}{P_n \cos \alpha} = \frac{132}{8 \times 0.86603} = 19.052 \text{ inches}$$

$$2) d = \frac{n}{P_n \cos \beta} = \frac{33}{8 \times 0.86603} = 4.763 \text{ inches}$$

$$3) O = D + \frac{2}{P_n} = 19.052 + \frac{2}{8} = 19.302 \text{ inches}$$

$$4) o = d + \frac{2}{P_n} = 4.763 + \frac{2}{8} = 5.013 \text{ inches}$$

$$5) T = \frac{N}{\cos^3 \alpha} = \frac{132}{0.65} = 203 \text{ teeth}$$

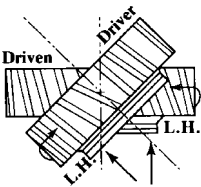
$$6) t = \frac{n}{\cos^3 \beta} = \frac{33}{0.65} = 51 \text{ teeth}$$

$$7) L = \pi D \cot \alpha = \pi \times 19.052 \times 1.732 = 103.66 \text{ inches}$$

$$8) l = \pi d \cot \beta = \pi \times 4.763 \times 1.732 = 25.92 \text{ inches}$$

$$9) C = \frac{D + d}{2} = \frac{19.052 + 4.763}{2} = 11.9075 \text{ inches}$$

**6. Shafts at Any Angle, Center Distance Exact.**—The sum of the helix angles of



the two gears equals the shaft angle, and the gears are of the same hand, if each angle is less than the shaft angle. The difference between the helix angles equals the shaft angle, and the gears are of opposite hand, if either angle is greater than the shaft angle.

Given or assumed:

- 1) Hand of helix, depending on rotation and direction in which thrust is to be received
- 2)  $C$  = center distance
- 3)  $P_n$  = normal diametral pitch (pitch of cutter)

4)  $\alpha_a$  = approximate helix angle of gear

5)  $\beta_a$  = approximate helix angle of pinion

6)  $R$  = ratio of gear to pinion size =  $\frac{N}{n}$

7)  $n$  = number of pinion teeth nearest  $\frac{2CP_n \cos \alpha_a \cos \beta_a}{R \cos \beta_a + \cos \alpha_a}$

8)  $N$  = number of gear teeth =  $Rn$

To find:

1)  $\alpha$  and  $\beta$ , exact helix angles, found by trial from  $R \sec \alpha + \sec \beta = \frac{2CP_n}{n}$



$$2) D = \text{pitch diameter of gear} = \frac{N}{P_n \cos \alpha}$$

$$3) d = \text{pitch diameter of pinion} = \frac{n}{P_n \cos \beta}$$

$$4) O = \text{outside diameter of gear} = D + \frac{2}{P_n}$$

$$5) o = \text{outside diameter of pinion} = d + \frac{2}{P_n}$$

6)  $N'$  = number of teeth marked on formed cutter for gear (see below)

7)  $n'$  = number of teeth marked on formed cutter for pinion (see below)

8)  $L$  = lead of helix on gear =  $\pi D \cot \alpha$

9)  $l$  = lead of helix on pinion =  $\pi d \cot \beta$

**Selecting Cutter for Milling Helical Gears.**—The proper milling cutter to use for spur gears depends on the pitch of the teeth and also upon the number of teeth as explained on page 2052 but a cutter for milling helical gears is not selected with reference to the actual number of teeth in the gear, as in spur gearing, but rather with reference to a calculated number  $N'$  that takes into account the effect on the tooth profile of lead angle, normal diametral pitch, and cutter diameter.

In the helical gearing examples starting on page 2101 the number of teeth  $N'$  on which to base the selection of the cutter has been determined using the approximate formula  $N' = N \div \cos^3 \alpha$  or  $N' = N \sec^3 \alpha$ , where  $N$  = the actual number of teeth in the helical gear and  $\alpha$  = the helix angle. However, the use of this formula may, where a combination of high helix angle and low tooth number is involved, result in the selection of a higher number of cutter than should actually be used for greatest accuracy. This condition is most likely to occur when the aforementioned formula is used to calculate  $N'$  for gears of high helix angle and low number of teeth.

To avoid the possibility of error in choice of cutter number, the following formula, which gives theoretically correct results for all combinations of helix angle and tooth numbers, is to be preferred:

$$N' = N \sec^3 \alpha + P_n D_c \tan^2 \alpha \quad (1)$$

where:  $N'$  = number of teeth on which to base selection of cutter number from table on page 2054;  $N$  = actual number of teeth in helical gear;  $\alpha$  = helix angle;  $P_n$  = normal diametral pitch of gear and cutter; and  $D_c$  = pitch diameter of cutter.

To simplify calculations, Formula (1) may be written as follows:

$$N' = NK + QK' \quad (2)$$

In this formula,  $K$ ,  $K'$  and  $Q$  are constants obtained from the tables on page 2109.

*Example:* Helix angle = 30 degrees; number of teeth in helical gear = 15; and normal diametral pitch = 20. From the tables on page 2109  $K$ ,  $K'$ , and  $Q$  are, respectively, 1.540, 0.333, and 37.80.

$$\begin{aligned} N' &= (15 \times 1.540) + (37.80 \times 0.333) = 23.10 + 12.60 \\ &= 35.70, \text{ say, } 36 \end{aligned}$$

Hence, from page 2054 select a number 3 cutter. Had the approximate formula been used, then a number 5 cutter would have been selected on the basis of  $N' = 23$ .

## Factors for Selecting Cutters for Milling Helical Gears

| Helix Angle, $\alpha$ | $K$   | $K'$  | Helix Angle, $\alpha$ | $K$   | $K'$  | Helix Angle, $\alpha$ | $K$   | $K'$  | Helix Angle, $\alpha$ | $K$    | $K'$  |
|-----------------------|-------|-------|-----------------------|-------|-------|-----------------------|-------|-------|-----------------------|--------|-------|
| 0                     | 1.000 | 0     | 16                    | 1.127 | 0.082 | 32                    | 1.640 | 0.390 | 48                    | 3.336  | 1.233 |
| 1                     | 1.001 | 0     | 17                    | 1.145 | 0.093 | 33                    | 1.695 | 0.422 | 49                    | 3.540  | 1.323 |
| 2                     | 1.002 | 0.001 | 18                    | 1.163 | 0.106 | 34                    | 1.755 | 0.455 | 50                    | 3.767  | 1.420 |
| 3                     | 1.004 | 0.003 | 19                    | 1.182 | 0.119 | 35                    | 1.819 | 0.490 | 51                    | 4.012  | 1.525 |
| 4                     | 1.007 | 0.005 | 20                    | 1.204 | 0.132 | 36                    | 1.889 | 0.528 | 52                    | 4.284  | 1.638 |
| 5                     | 1.011 | 0.008 | 21                    | 1.228 | 0.147 | 37                    | 1.963 | 0.568 | 53                    | 4.586  | 1.761 |
| 6                     | 1.016 | 0.011 | 22                    | 1.254 | 0.163 | 38                    | 2.044 | 0.610 | 54                    | 4.925  | 1.894 |
| 7                     | 1.022 | 0.015 | 23                    | 1.282 | 0.180 | 39                    | 2.130 | 0.656 | 55                    | 5.295  | 2.039 |
| 8                     | 1.030 | 0.020 | 24                    | 1.312 | 0.198 | 40                    | 2.225 | 0.704 | 56                    | 5.710  | 2.198 |
| 9                     | 1.038 | 0.025 | 25                    | 1.344 | 0.217 | 41                    | 2.326 | 0.756 | 57                    | 6.190  | 2.371 |
| 10                    | 1.047 | 0.031 | 26                    | 1.377 | 0.238 | 42                    | 2.436 | 0.811 | 58                    | 6.720  | 2.561 |
| 11                    | 1.057 | 0.038 | 27                    | 1.414 | 0.260 | 43                    | 2.557 | 0.870 | 59                    | 7.321  | 2.770 |
| 12                    | 1.068 | 0.045 | 28                    | 1.454 | 0.283 | 44                    | 2.687 | 0.933 | 60                    | 8.000  | 3.000 |
| 13                    | 1.080 | 0.053 | 29                    | 1.495 | 0.307 | 45                    | 2.828 | 1     | 61                    | 8.780  | 3.254 |
| 14                    | 1.094 | 0.062 | 30                    | 1.540 | 0.333 | 46                    | 2.983 | 1.072 | 62                    | 9.658  | 3.537 |
| 15                    | 1.110 | 0.072 | 31                    | 1.588 | 0.361 | 47                    | 3.152 | 1.150 | 63                    | 10.687 | 3.852 |

$$K = 1 \div \cos^3 \alpha = \sec^3 \alpha; K' = \tan^2 \alpha$$

## Outside and Pitch Diameters of Standard Involute-form Milling Cutters

| Normal Diametral Pitch, $P_n$ | Outside Dia., $D_o$ | Pitch Dia., $D_c$ | $Q = P_n D_c$ | Normal Diametral Pitch, $P_n$ | Outside Dia., $D_o$ | Pitch Dia., $D_c$ | $Q = P_n D_c$ | Normal Diametral Pitch, $P_n$ | Outside Dia., $D_o$ | Pitch Dia., $D_c$ | $Q = P_n D_c$ |
|-------------------------------|---------------------|-------------------|---------------|-------------------------------|---------------------|-------------------|---------------|-------------------------------|---------------------|-------------------|---------------|
| 1                             | 8.500               | 6.18              | 6.18          | 6                             | 3.125               | 2.76              | 16.56         | 20                            | 2.000               | 1.89              | 37.80         |
| 1¼                            | 7.750               | 5.70              | 7.12          | 7                             | 2.875               | 2.54              | 17.78         | 24                            | 1.750               | 1.65              | 39.60         |
| 1½                            | 7.000               | 5.46              | 8.19          | 8                             | 2.875               | 2.61              | 20.88         | 28                            | 1.750               | 1.67              | 46.76         |
| 1¾                            | 6.500               | 5.04              | 8.82          | 9                             | 2.750               | 2.50              | 22.50         | 32                            | 1.750               | 1.68              | 53.76         |
| 2                             | 5.750               | 4.60              | 9.20          | 10                            | 2.375               | 2.14              | 21.40         | 36                            | 1.750               | 1.69              | 60.84         |
| 2½                            | 5.750               | 4.83              | 12.08         | 12                            | 2.250               | 2.06              | 24.72         | 40                            | 1.750               | 1.70              | 68.00         |
| 3                             | 4.750               | 3.98              | 11.94         | 14                            | 2.125               | 1.96              | 27.44         | 48                            | 1.750               | 1.70              | 81.60         |
| 4                             | 4.250               | 3.67              | 14.68         | 16                            | 2.125               | 1.98              | 31.68         | ..                            | ...                 | ...               | ...           |
| 5                             | 3.750               | 3.29              | 16.45         | 18                            | 2.000               | 1.87              | 33.66         | ..                            | ...                 | ...               | ...           |

Pitch diameters shown in the table are computed from the formula:  $D_c = D_o - 2(1.57 \div P_n)$ . This same formula may be used to compute the pitch diameter of a non-standard outside diameter cutter when the normal diametral pitch  $P_n$  and the outside diameter  $D_o$  are known.

**Milling the Helical Teeth.**—The teeth of a helical gear are proportioned from the normal pitch and not the circular pitch. The whole depth of the tooth can be found by dividing 2.157 by the normal diametral pitch of the gear, which corresponds to the pitch of the cut-

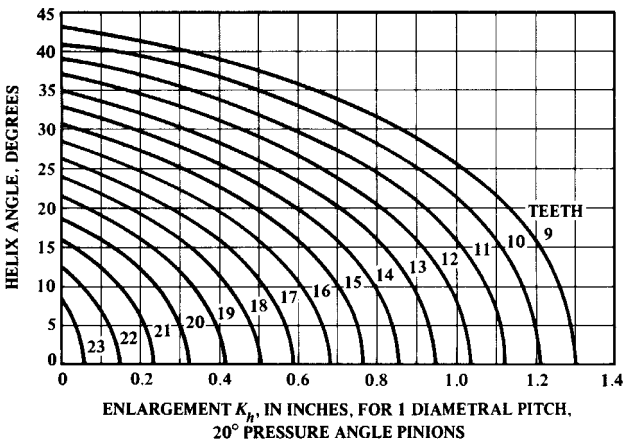
ter. The thickness of the tooth at the pitch line equals 1.571 divided by the normal diametral pitch. After a tooth space has been milled, the cutter should be prevented from dragging through it when being returned for another cut. This can be done by lowering the blank slightly, or by stopping the machine and turning the cutter to such a position that the teeth will not touch the work. If the gear has teeth coarser than 10 or 12 diametral pitch, it is well to take a roughing and a finishing cut. When pressing a helical gear blank on the arbor, it should be remembered that it is more likely to slip when being milled than a spur gear, because the pressure of the cut, being at an angle, tends to rotate the blank on the arbor.

*Angular Position of Table:* When cutting a helical gear on a milling machine, the table is set to the helix angle of the gear. If the lead of the helical gear is known, but not the helix angle, the helix angle is determined by multiplying the pitch diameter of the gear by 3.1416 and dividing this product by the lead; the result is the tangent of the lead angle which may be obtained from trigonometric tables or a calculator.

**American National Standard Fine-Pitch Teeth For Helical Gears.**—This Standard, ANSI B6.7-1977, provides a 20-degree tooth form for both spur and helical gears of 20 diametral pitch and finer. Formulas for tooth parts are given on page 2039.

*Enlargement of Helical Pinions, 20-Degree Normal Pressure Angle:* Formula (4) and the accompanying graph are based on the use of hobs having sharp corners at their top lands. Pinions cut by shaper cutters may not require as much modification as indicated by (4) or the graph. The number 2.1 appearing in (4) results from the use of a standard tooth thickness rack having an addendum of  $1.05/P_n$  which will start contact at a roll angle 5 degrees above the base radius. The roll angle of 5 degrees is also reflected in Formula (4).

To avoid undercutting of the teeth and to provide more favorable contact conditions near the base of the tooth, it is recommended that helical pinions with less than 24 teeth be enlarged in accordance with the following graph and formulas. As with enlarged spur pinions, when an enlarged helical pinion is used it is necessary either to reduce the diameter of the mating gear or to increase the center distance. In the formulas that follow,  $\phi_n$  = normal pressure angle;  $\phi_t$  = transverse pressure angle;  $\psi$  = helix angle of pinion;  $P_n$  = normal diametral pitch;  $P_t$  = transverse diametral pitch;  $d$  = pitch diameter of pinion;  $d_o$  = outside diameter of enlarged pinion,  $K_h$  = enlargement for full depth pinions of 1 normal diametral pitch; and  $n$  = number of teeth in pinion.



To eliminate the need for making the calculations indicated in [Formulas \(3\) and \(4\)](#), the accompanying graph may be used to obtain the value of  $K_h$  directly for full-depth pinions of 20-degree normal pressure angle.

$$P_t = P_n \cos \psi \quad (1)$$

$$d = n \div P_t \quad (2)$$

$$\tan \psi_t = \tan \phi_n \div \cos \psi \quad (3)$$

$$K_h = 2.1 - \frac{n}{\cos \psi} (\sin \phi_t - \cos \phi_t \tan 5^\circ) \sin \phi_t \quad (4)$$

$$d_o = d + \frac{2 + K_h}{P_n} \quad (5)$$

*Example:* Find the outside diameter of a helical pinion having 12 teeth, 32 normal diametral pitch, 20-degree pressure angle, and 18-degree helix angle.

$$P_t = P_n \cos \psi = 32 \cos 18^\circ = 32 \times 0.95106 = 30.4339$$

$$d = n \div P_t = 12 \div 30.4339 = 0.3943 \text{ inch}$$

$$K_h = 0.851 \text{ (from graph)}$$

$$d_o = 0.3943 + \frac{2 + 0.851}{32} = 0.4834$$

**Center Distance at Which Modified Mating Helical Gears Will Mesh with no Backlash.**—If the helical pinion in the previous example on page 2111 had been made to standard dimensions, that is, not enlarged, and was in tight mesh with a standard 24-tooth mating gear, the center distance for tight mesh could be calculated from the formula on page 2039:

$$C = \frac{n + N}{2P_n \cos \psi} = \frac{12 + 24}{2 \times 32 \times \cos 18^\circ} = 0.5914 \text{ inch} \quad (1)$$

However, if the pinion is enlarged as in the example and meshed with the same standard 24-tooth gear, then the center distance for tight mesh will be increased. To calculate the new center distance, the following formulas and calculations are required:

First, calculate the transverse pressure angle  $\phi_t$  using [Formula \(2\)](#):

$$\tan \phi_t = \tan \phi_n \div \cos \psi = \tan 20^\circ \div \cos 18^\circ = 0.38270 \quad (2)$$

and from a calculator the angle  $\phi_t$  is found to be  $20^\circ 56' 30''$ . In the table on page 104,  $\text{inv } \phi_t$  is found to be 0.017196, and the cosine from a calculator as 0.93394.

Using [Formula \(3\)](#), calculate the pressure angle  $\phi$  at which the gears are in tight mesh:

$$\text{inv } \phi = \text{inv } \phi_t + \frac{(t_{nP} + t_{nG}) - \pi}{n + N} \quad (3)$$

In this formula, the value for  $t_{nP}$  for 1 diametral pitch is that found in [Table 9c](#) on page 2056, for a 12-tooth pinion, in the fourth column: 1.94703. The value of  $t_{nG}$  for 1 diametral pitch for a standard gear is always 1.5708.

$$\text{inv } \phi = 0.017196 + \frac{(1.94703 + 1.5708) - \pi}{12 + 24} = 0.027647$$

From the table on page 105, or a calculator, 0.027647 is the involute of  $24^\circ 22' 7''$  and the cosine corresponding to this angle is 0.91091.

Finally, using [Formula \(4\)](#), the center distance for tight mesh,  $C'$  is found:

$$C' = \frac{C \cos \phi_t}{\cos \phi} = \frac{0.5914 \times 0.93394}{0.91091} = 0.606 \text{ inch} \quad (4)$$

**Change-gears for Helical Gear Hobbing.**—If a gear-hobbing machine is not equipped with a differential, there is a fixed relation between the index and feed gears and it is necessary to compensate for even slight errors in the index gear ratio, to avoid excessive lead errors. This may be done readily (as shown by the example to follow) by modifying the ratio of the feed gears slightly, thus offsetting the index gear error and making very accurate leads possible.

*Machine Without Differential:* The formulas which follow may be applied in computing the index gear ratio.

$R$  = index-gear ratio

$L$  = lead of gear, inches

$F$  = feed per gear revolution, inch

$K$  = machine constant

$T$  = number of threads on hob

$N$  = number of teeth on gear

$P_n$  = normal diametral pitch

$P_{nc}$  = normal circular pitch

$A$  = helix angle, relative to axis

$M$  = feed gear constant

$$R = \frac{L \div F}{(L \div F) \pm 1} \times \frac{KT}{N} = \frac{L}{L \pm F} \times \frac{KT}{N} = \frac{\text{Driving gear sizes}}{\text{Driven gear sizes}} \quad (1)$$

Use minus (–) sign in [Formulas \(1\) and \(2\)](#) when gear and hob are the same “hand” and plus (+) sign when they are of opposite hand; when *climb* hobbing is to be used, reverse this rule.

$$R = \frac{KT}{N \pm \frac{P_n \times \sin A \times F}{\pi}} = \frac{KT}{N \pm \frac{\sin A \times F}{P_{nc}}} \quad (2)$$

$$\text{Ratio of feed gears} = \frac{F}{M} \quad F = \frac{L(NR - KT)}{NR} \quad (3)$$

$$L = \frac{FNR}{(NR - KT)} = \text{lead obtained with available index and feed gears} \quad (4)$$

*Note:* If gear and hob are of opposite hand, then in [Formulas \(3\) and \(4\)](#) change  $(NR - KT)$  to  $(KT - NR)$ . This change is also made if gear and hob are of same hand but *climb* hobbing is used.

*Example:* A right-hand helical gear with 48 teeth of 10 normal diametral pitch, has a lead of 44.0894 inches. The feed is to be 0.035 inch, with whatever slight adjustment may be necessary to compensate for the error in available index gears.  $K = 30$  and  $M = 0.075$ . A single-thread right-hand hob is to be used.

$$R = \frac{44.0894}{44.0894 - 0.035} \times \frac{30 \times 1}{48} = 0.62549654$$

Using the method of *Conjugate Fractions* beginning on page [12](#), several suitable ratios close to 0.62549654 were found. One of these,  $(34 \times 53)/(43 \times 67) = 0.625477264839$  will be used as the index ratio. Other usable ratios and their decimal values were found to be as follows:

$$\frac{32 \times 38}{27 \times 72} = 0.6255144 \quad \frac{27 \times 42}{42 \times 37} = 0.62548263$$

$$\frac{44 \times 29}{34 \times 60} = 0.6254902 \quad \frac{26 \times 97}{96 \times 42} = 0.62549603$$

$$\frac{20 \times 41}{23 \times 57} = 0.62547674$$

Index ratio error =  $0.62549654 - 0.62547726 = 0.00001928$ .

Now use [Formula \(3\)](#) to find slight change required in rate of feed. This change compensates sufficiently for the error in available index gears.

*Change in Feed Rate:* Insert in [Formula \(3\)](#) obtainable index ratio.

$$F = \frac{44.0894 \times (48 \times 0.62547726 - 30)}{48 \times 0.62547726} = 0.0336417$$

$$\text{Modified feed gear ratio} = \frac{F}{M} = \frac{0.0336417}{0.075} = 0.448556$$

$$\text{Log } 0.448556 = \bar{1}.651817 \quad \text{log of reciprocal} = 0.348183$$

To find close approximation to modified feed gear ratio, proceed as in finding suitable gears for index ratio, thus obtaining  $\frac{106}{71} \times \frac{112}{75}$ . Inverting, modified feed gear ratio =

$$\frac{71}{106} \times \frac{75}{112} = 0.448534.$$

Modified feed  $F$  = obtainable modified feed ratio  $\times M = 0.448534 \times 0.075 = 0.03364$  inch. If the feed rate is not modified, even a small error in the index gear ratio may result in an excessive lead error.

*Checking Accuracy of Lead:* The modified feed and obtainable index ratio are inserted in [Formula \(4\)](#). Desired lead = 44.0894 inches. Lead obtained = 44.087196 inches; hence the computed error =  $44.0894 - 44.087196 = 0.002204$  inch or about 0.00005 inch per inch of lead.

*Machine with Differential:* If a machine is equipped with a differential, the *lead gears* are computed in order to obtain the required helix angle and lead. The instructions of the hobbing machine manufacturer should be followed in computing the lead gears, because the ratio formula is affected by the location of the differential gears. If these gears are *ahead* of the index gears, the lead gear ratio is not affected by a change in the number of teeth to be cut (see [Formula \(5\)](#)); hence, the same lead gears are used when, for example, a gear and pinion are cut on the same machine. In the formulas which follow, the notation is the same as previously given, with these exceptions:  $R_d$  = lead gear ratio for machine with differential;  $P_a$  = axial or linear pitch of helical gear = distance from center of one tooth to center of next tooth measured parallel to gear axis = total lead  $L \div$  number of teeth  $N$ .

$$R_d = \frac{P_a \times T}{K} = \frac{L \times T}{N \times K} = \frac{\pi \times \text{cosec } A \times T}{P_n \times K} = \frac{\text{Driven gear sizes}}{\text{Driving gear sizes}} \quad (5)$$

The number of hob threads  $T$  is included in the formula because double-thread hobs are used sometimes, especially for roughing in order to reduce the hobbing time. Lead gears having a ratio sufficiently close to the required ratio may be determined by using the table of gear ratio logarithms as previously described in connection with the non-differential type of machine. When using a machine equipped with a differential, the effect of a lead-gear ratio error upon the lead of the gear is small in comparison with the effect of an index gear error when using a non-differential type of machine. The lead obtained with a given or

obtainable lead gear ratio may be determined by the following formula:  $L = (R_d NK) \div T$ . In this formula,  $R_d$  represents the ratio obtained with available gears. If the given lead is 44.0894 inches, as in the preceding example, then the desired ratio as obtained with **Formula (5)** would be 0.9185292 if  $K = 1$ . Assume that the lead gears selected by using logs of ratios have a ratio of 0.9184704; then this ratio error of 0.0000588 would result in a computed lead error of only 0.000065 inch per inch.

**Formula (5)**, as mentioned, applies to machines having the differential located *ahead* of the index gears. If the differential is located after the index gears, it is necessary to change lead gears whenever the index gears are changed for hobbing a different number of teeth, as indicated by the following formula which gives the lead gear ratio. In this formula,  $D =$  pitch diameter.

$$R_d = \frac{L \times T}{K} = \frac{D \times \pi \times T}{K \times \tan A} = \frac{\text{Driven gear sizes}}{\text{Driving gear sizes}} \quad (6)$$

**General Remarks on Helical Gear Hobbing.**—In cutting teeth having large angles, it is desirable to have the direction of helix of the hob the same as the direction of helix of the gear, or in other words, the gear and the hob of the same “hand.” Then the direction of the cut will come against the movement of the blank. At ordinary angles, however, one hob will cut both right- and left-hand gears. In setting up the hobbing machine for helical gears, care should be taken to see that the vertical feed does not trip until the machine has been stopped or the hob has fed down past the finished gear.

### Herringbone Gears

Double helical or herringbone gears are commonly used in parallel-shaft transmissions, especially when a smooth, continuous action (due to the gradual overlapping engagement of the teeth) is essential, as in high-speed drives where the pitch-line velocity may range from about 1000 to 3000 feet per minute in commercial gearing and up to 12,000 feet per minute or higher in more specialized installations. These relatively high speeds are encountered in marine reduction gears, in certain speed-reducing and speed-increasing units, and in various other transmissions, particularly in connection with steam turbine and electric motor drives.

**General Classes of Helical Gear Problems.**—There are two general classes of problems. In one, the problem is to design gears capable of transmitting a given amount of power at a given speed, safely and without excessive wear; hence, the required proportions must be determined. In the second, the proportions and speed are known and the power-transmitting capacity is required. The first is the more difficult and common problem.

**Causes of Herringbone Gear Failures.**—Where failure occurs in a herringbone gear transmission, it is rarely due to tooth breakage but usually to excessive wear or sub-surface failures, such as pitting and spalling; hence, it is common practice to base the design of such gears upon durability, or upon tooth pressures which are within the allowable limits for wear. In this connection, it seems to have been well established by tests of both spur gears and herringbone gears, that there is a critical surface pressure value for teeth having given physical properties and coefficient of friction. According to these tests, pressures above the critical value result in rapid wear and a short gear life, whereas when pressures are below the critical, wear is negligible. The yield point or endurance limit of the material marks the critical loading point, and in practical designing a reasonable factor of safety would, of course, be applied.

### Elliptic Gears

Gears of this type provide simple means of obtaining a quick-return motion but they present a rather cumbersome manufacturing problem and, as a general rule, it is preferable

to obtain quick-return motions by some other type of mechanism. When elliptic gears are used, the two gears that mesh with each other must be equal in size, and each gear must revolve about one of the foci of the ellipse forming the pitch line, as indicated by the diagram, in Fig. 1a. By the use of elliptic gears so mounted, it is possible to obtain a variable motion of the driven shaft, because the gear on the driving shaft, while revolving one half of a revolution, will engage with only a small portion of the circumference of the driven gear, while during the other half of its revolution, the driving gear will engage with a great deal more than one-half of the total number of teeth in the driven gear; hence, the cutting stroke of a machine tool, for example, may be made to have a slow motion, while the return stroke is at a rapid rate. The ellipse has two points, each of which is called a *focus*, located as indicated at *A* and *B*. The sum of the distance between the foci and the elliptic curve is constant at all points and is equal to the longer or major axis of the ellipse. On account of this peculiarity of the ellipse, two equal ellipses can be made to mesh with each other during a complete revolution about their axes, if one is mounted on a shaft at its focus *A* and the other at its focus *B*.

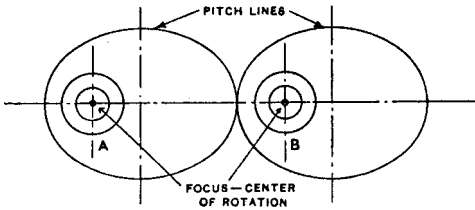


Fig. 1a. General Arrangement of Elliptic Gears.

### Planetary Gearing

Planetary or epicyclic gearing provides means of obtaining a compact design of transmission, with driving and driven shafts in line, and a large speed reduction when required. Typical arrangements of planetary gearing are shown by the following diagrams which are accompanied by speed ratio formulas. When planetary gears are arranged as shown by Figs. 5, 6, 9 and 12, the speed of the follower relative to the driver is increased, whereas Figs. 7, 8, 10, and 11 illustrate speed-reducing mechanisms.

**Direction of Rotation.**—In using the following formulas, if the final result is preceded by a minus sign (negative), this indicates that the driver and follower will rotate in opposite directions; otherwise, both will rotate in the same direction.

**Compound Drive.**—The formulas accompanying Figs. 19 through 22 are for obtaining the speed ratios when there are *two* driving members rotating at different speeds. For example, in Fig. 19, the central shaft with its attached link is one driver. The internal gear  $z$ , instead of being fixed, is also rotated. In Fig. 22, if  $z = 24$ ,  $B = 60$  and  $S = 3\frac{1}{2}$ , with both drivers rotating in the same direction, then  $F = 0$ , thus indicating, in this case, the point where a larger value of  $S$  will reverse follower rotation.

**Planetary Bevel Gears.**—Two forms of planetary gears of the bevel type are shown in Figs. 23 and 24. The planet gear in Fig. 23 rotates about a fixed bevel gear at the center of which is the driven shaft. Fig. 24 illustrates the Humpage reduction gear. This is sometimes referred to as cone-pulley back-gearing because of its use within the cone pulleys of certain types of machine tools.



**Ratios of Planetary or Epicyclic Gearing**

$D$  = rotation of *driver* per revolution of follower or driven member  
 $F$  = rotation of *follower* or driven member per revolution of driver. (In Figs. 1 through 4,  $F$  = rotation of planet type follower about its axis.)  
 $A$  = size of driving gear (use either number of teeth or pitch diameter). Note: When follower derives its motion both from  $A$  and from a secondary driving member,  $A$  = size of *initial* driving gear, and formula gives speed relationship between  $A$  and follower.  
 $B$  = size of *driven* gear or *follower* (use either pitch diameter or number of teeth)  
 $C$  = size of *fixed* gear (use either pitch diameter or number of teeth)  
 $x$  = size of *planet gear* as shown by diagram (use either pitch diameter or number of teeth)  
 $y$  = size of *planet gear* as shown by diagram (use either pitch diameter or number of teeth)  
 $z$  = size of secondary or *auxiliary driving gear*, when follower derives its motion from two driving members  
 $S$  = rotation of *secondary driver*, per revolution of *initial driver*.  $S$  is negative when secondary and initial drivers rotate in opposite directions. (Formulas in which  $S$  is used, give speed relationship between follower and the initial driver.)  
 Note: In all cases, if  $D$  is known,  $F = 1 \div D$ , or, if  $F$  is known,  $D = 1 \div F$ .

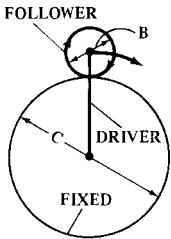


Fig. 1.

$$F = 1 + \frac{C}{B}$$

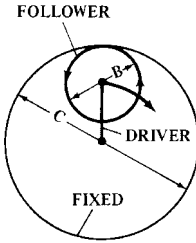


Fig. 2.

$$F = 1 - \frac{C}{B}$$

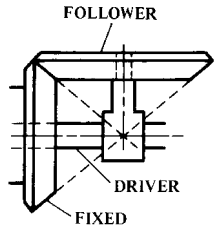


Fig. 3.

$$F = \frac{C}{B}$$

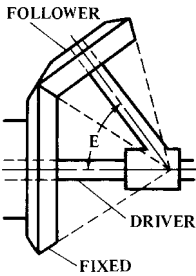


Fig. 4.

$$F = \cos E + \frac{C}{B}$$

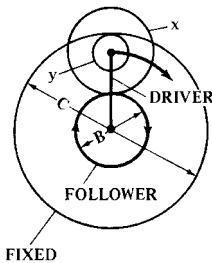


Fig. 5.

$$F = 1 + \frac{x \times C}{y \times B}$$

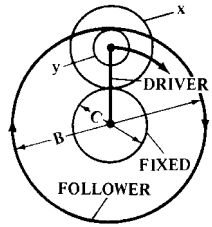
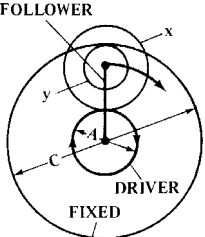
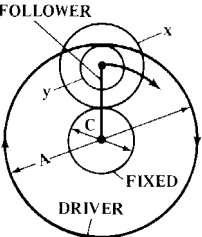
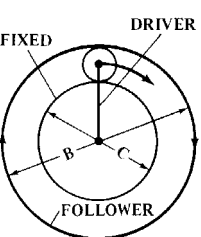
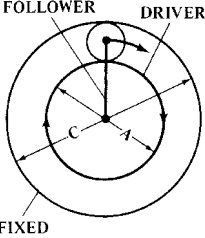
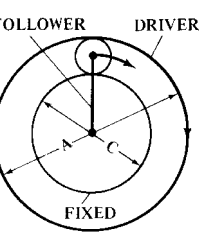
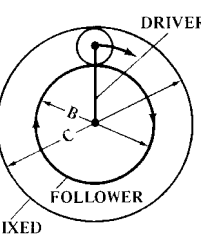
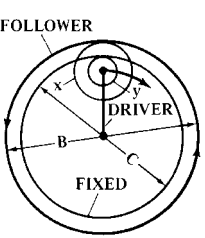
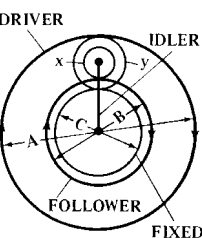
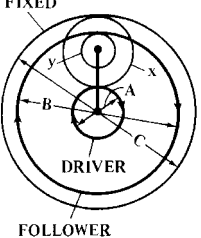


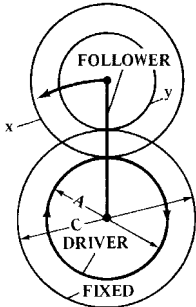
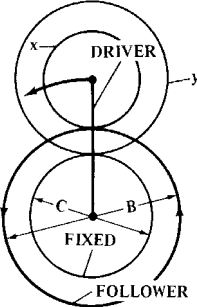
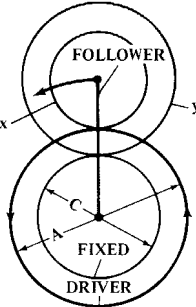
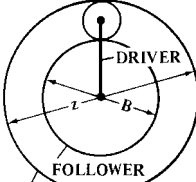
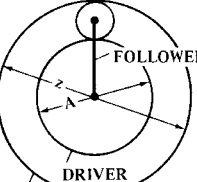
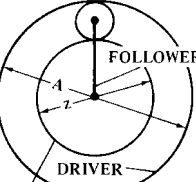
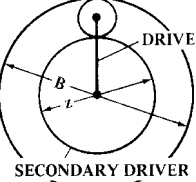
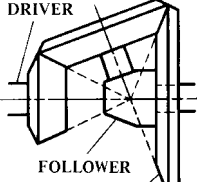
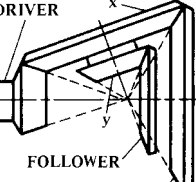
Fig. 6.

$$F = 1 + \frac{y \times C}{x \times B}$$

## Ratios of Planetary or Epicyclic Gearing (Continued)

|   |  |  |
|---|--|--|
|  <p>Fig. 7.</p> $D = 1 + \frac{x \times C}{y \times A}$                   |  <p>Fig. 8.</p> $D = 1 + \frac{y \times C}{x \times A}$   |  <p>Fig. 9.</p> $F = 1 + \frac{C}{B}$   |
|  <p>Fig. 10.</p> $D = 1 + \frac{C}{A}$                                    |  <p>Fig. 11.</p> $D = 1 + \frac{C}{A}$  |  <p>Fig. 12.</p> $F = 1 + \frac{C}{B}$  |
|  <p>Fig. 13.</p> $F = 1 - \left( \frac{C \times x}{y \times B} \right)$ |  <p>Fig. 14.</p> $D = \frac{1 + \frac{C}{A}}{1 - \left( \frac{C \times x}{y \times B} \right)}$ |  <p>Fig. 15.</p> $D = \frac{1 + \frac{C}{A}}{1 - \left( \frac{C \times y}{x \times B} \right)}$ |

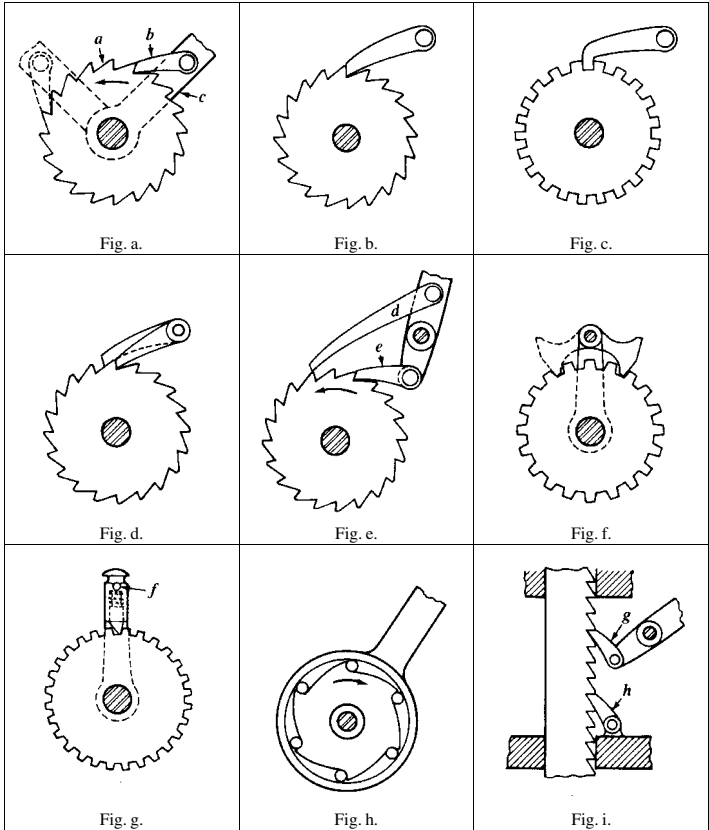
Ratios of Planetary or Epicyclic Gearing (Continued)

|   |  |  |
|---|--|--|
|  <p>Fig. 16.</p> $D = 1 - \left( \frac{C \times x}{y \times A} \right)$ |  <p>Fig. 17.</p> $F = 1 - \left( \frac{C \times x}{y \times B} \right)$ |  <p>Fig. 18.</p> $D = 1 - \left( \frac{C \times x}{y \times A} \right)$                           |
|  <p>Fig. 19.</p> $F = 1 + \frac{z \times (1 - S)}{B}$                   |  <p>Fig. 20.</p> $D = \frac{A + z}{A + (S \times z)}$                   |  <p>Fig. 21.</p> $D = \frac{A + z}{A + (S \times z)}$   |
|  <p>Fig. 22.</p> $F = 1 + \frac{z \times (1 - S)}{B}$                 |  <p>Fig. 23.</p> $D = 1 + \frac{C}{A}$                                |  <p>Fig. 24.</p> $D = \frac{1 + \frac{C}{A}}{1 - \left( \frac{C \times y}{x \times B} \right)}$ |

## Ratchet Gearing

Ratchet gearing may be used to transmit intermittent motion, or its only function may be to prevent the ratchet wheel from rotating backward. Ratchet gearing of this latter form is commonly used in connection with hoisting mechanisms of various kinds, to prevent the hoisting drum or shaft from rotating in a reverse direction under the action of the load.

## Types of Ratchet Gearing



Ratchet gearing in its simplest form consists of a toothed ratchet wheel *a* (see Fig. a), and a pawl or detent *b*, and it may be used to transmit intermittent motion or to prevent relative motion between two parts except in one direction. The pawl *b* is pivoted to lever *c* which, when given an oscillating movement, imparts an intermittent rotary movement to ratchet wheel *a*. Fig. b illustrates another application of the ordinary ratchet and pawl mechanism. In this instance, the pawl is pivoted to a stationary member and its only function is to prevent the ratchet wheel from rotating backward. With the stationary design, illustrated at

Fig. c, the pawl prevents the ratchet wheel from rotating in either direction, so long as it is in engagement with the wheel.

The principle of *multiple-pawl ratchet gearing* is illustrated at Fig. d, which shows the use of two pawls. One of these pawls is longer than the other, by an amount equal to one-half the pitch of the ratchet-wheel teeth, so that the practical effect is that of reducing the pitch one-half. By placing a number of driving pawls side by side and proportioning their lengths according to the pitch of the teeth, a very fine feed can be obtained with a ratchet wheel of comparatively coarse pitch.

This method of obtaining a fine feed from relatively coarse-pitch ratchets may be preferable to the use of single ratchets of fine pitch which, although providing the feed required, may have considerably weaker teeth.

The type of ratchet gearing shown at Fig. e is sometimes employed to impart a rotary movement to the ratchet wheel for both the forward and backward motions of the lever to which the two pawls are attached.

A simple form of *reversing ratchet* is illustrated at Fig. f. The teeth of the wheel are so shaped that either side may be used for driving by simply changing the position of the double-ended pawl, as indicated by the full and dotted lines.

Another form of reversible ratchet gearing for shapers is illustrated at Fig. g. The pawl, in this case, instead of being a pivoted latch, is in the form of a plunger which is free to move in the direction of its axis, but is normally held into engagement with the ratchet wheel by a small spring. When the pawl is lifted and turned one-half revolution, the driving face then engages the opposite sides of the teeth and the ratchet wheel is given an intermittent rotary motion in the opposite direction.

The *frictional type* of ratchet gearing differs from the designs previously referred to, in that there is no positive engagement between the driving and driven members of the ratchet mechanism, the motion being transmitted by frictional resistance. One type of frictional ratchet gearing is illustrated at Fig. h. Rollers or balls are placed between the ratchet wheel and an outer ring which, when turned in one direction, causes the rollers or balls to wedge between the wheel and ring as they move up the inclined edges of the teeth.

Fig. i illustrates one method of utilizing ratchet gearing for moving the driven member in a straight line, as in the case of a lifting jack. The pawl g is pivoted to the operating lever of the jack and does the lifting, whereas the pawl h holds the load while the lifting pawl g is being returned preparatory to another lifting movement.

**Shape of Ratchet Wheel Teeth.**—When designing ratchet gearing, it is important to so shape the teeth that the pawl will remain in engagement when a load is applied. The faces of the teeth which engage the end of the pawl should be in such relation with the center of the pawl pivot that a line perpendicular to the face of the engaging tooth will pass somewhere between the center of the ratchet wheel and the center of the pivot about which the pawl swings. This is true if the pawl *pushes* the ratchet wheel, or if the ratchet wheel *pushes* the pawl. However, if the pawl *pulls* the ratchet wheel or if the ratchet wheel *pulls* the pawl, the perpendicular from the face of the ratchet teeth should fall outside the pawl pivot center. Ratchet teeth may be either cut by a milling cutter having the correct angle, or hobbled in a gear-hobbing machine by the use of a special hob.

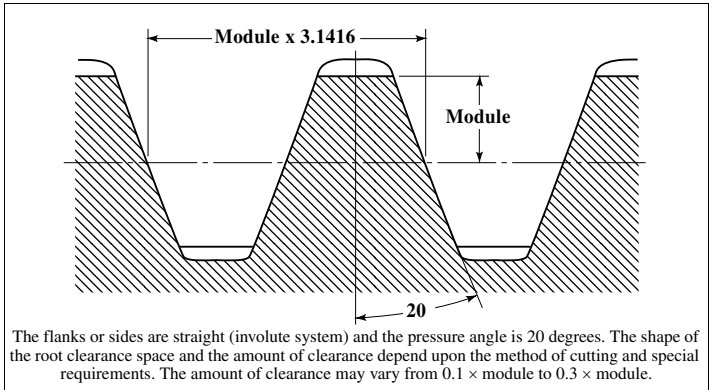
**Pitch of Ratchet Wheel Teeth.**—The pitch of ratchet wheels used for holding suspended loads may be calculated by the following formula, in which  $P$  = circular pitch, in inches, measured at the outside circumference;  $M$  = turning moment acting upon the ratchet wheel shaft, in inch-pounds;  $L$  = length of tooth face, in inches (thickness of ratchet gear);  $S$  = safe stress (for steel, 2500 pounds per square inch when subjected to shock, and 4000 pounds per square inch when not subjected to shock);  $N$  = number of teeth in ratchet wheel;  $F$  = a factor the value of which is 50 for ratchet gears with 12 teeth or less, 35 for gears having from 12 to 20 teeth, and 20 for gears having over 20 teeth:

$$P = \frac{\sqrt{FM}}{LSN}$$

This formula has been used in the calculation of ratchet gears for crane design.

**Gear Design Based upon Module System.**—The *module* of a gear is equal to the pitch diameter divided by the number of teeth, whereas *diametral pitch* is equal to the number of teeth divided by the pitch diameter. The module system (see accompanying table and diagram) is in general use in countries that have adopted the metric system; hence, the term module is usually understood to mean the pitch diameter *in millimeters* divided by the number of teeth. The module system, however, may also be based on inch measurements and then it is known as the English module to avoid confusion with the metric module. Module is an actual dimension, whereas diametral pitch is only a ratio. Thus, if the pitch diameter of a gear is 50 millimeters and the number of teeth 25, the module is 2, which means that there are 2 millimeters of pitch diameter for each tooth. The table *Tooth Dimensions Based Upon Module System* shows the relation among module, diametral pitch, and circular pitch.

#### German Standard Tooth Form for Spur and Bevel Gears DIN 867



| To Find                       | Module Known                      | Circular Pitch Known                       |
|-------------------------------|-----------------------------------|--|
| Addendum                      | Equals module                     | $0.31823 \times \text{Circular pitch}$     |
| Dedendum                      | $1.157 \times \text{module}^*$    | $0.3683 \times \text{Circular pitch}^*$    |
|                               | $1.167 \times \text{module}^{**}$ | $0.3714 \times \text{Circular pitch}^{**}$ |
| Working Depth                 | $2 \times \text{module}$          | $0.6366 \times \text{Circular pitch}$      |
| Total Depth                   | $2.157 \times \text{module}^*$    | $0.6866 \times \text{Circular pitch}^*$    |
|                               | $2.167 \times \text{module}^{**}$ | $0.6898 \times \text{Circular pitch}^{**}$ |
| Tooth Thickness on Pitch Line | $1.5708 \times \text{module}$     | $0.5 \times \text{Circular pitch}$         |

Formulas for dedendum and total depth, marked (\*) are used when clearance equals  $0.157 \times \text{module}$ . Formulas marked (\*\*) are used when clearance equals one-sixth module. It is common practice among American cutter manufacturers to make the clearance of metric or module cutters equal to  $0.157 \times \text{module}$ .

## MODULE SYSTEM GEARING

## Tooth Dimensions Based Upon Module System

| Module,<br><i>DIN</i><br>Standard<br>Series | Equivalent<br>Diametral<br>Pitch | Circular Pitch |        | Addendum,<br>Millimeters | Dedendum,<br>Millimeters <sup>a</sup> | Whole<br>Depth, <sup>a</sup><br>Millimeters | Whole<br>Depth, <sup>b</sup><br>Millimeters |
|---|----------------------------------|----------------|--------|--------------------------|---------------------------------------|---|---|
|   |                                  | Millimeters    | Inches |                          |                                       |   |   |
| 0.3   | 84.667                           | 0.943          | 0.0371 | 0.30                     | 0.35                                  | 0.650                                       | 0.647                                       |
| 0.4   | 63.500                           | 1.257          | 0.0495 | 0.40                     | 0.467                                 | 0.867                                       | 0.863                                       |
| 0.5   | 50.800                           | 1.571          | 0.0618 | 0.50                     | 0.583                                 | 1.083                                       | 1.079                                       |
| 0.6   | 42.333                           | 1.885          | 0.0742 | 0.60                     | 0.700                                 | 1.300                                       | 1.294                                       |
| 0.7   | 36.286                           | 2.199          | 0.0865 | 0.70                     | 0.817                                 | 1.517                                       | 1.510                                       |
| 0.8   | 31.750                           | 2.513          | 0.0989 | 0.80                     | 0.933                                 | 1.733                                       | 1.726                                       |
| 0.9   | 28.222                           | 2.827          | 0.1113 | 0.90                     | 1.050                                 | 1.950                                       | 1.941                                       |
| 1   | 25.400                           | 3.142          | 0.1237 | 1.00                     | 1.167                                 | 2.167                                       | 2.157                                       |
| 1.25  | 20.320                           | 3.927          | 0.1546 | 1.25                     | 1.458                                 | 2.708                                       | 2.697                                       |
| 1.5   | 16.933                           | 4.712          | 0.1855 | 1.50                     | 1.750                                 | 3.250                                       | 3.236                                       |
| 1.75  | 14.514                           | 5.498          | 0.2164 | 1.75                     | 2.042                                 | 3.792                                       | 3.774                                       |
| 2   | 12.700                           | 6.283          | 0.2474 | 2.00                     | 2.333                                 | 4.333                                       | 4.314                                       |
| 2.25  | 11.289                           | 7.069          | 0.2783 | 2.25                     | 2.625                                 | 4.875                                       | 4.853                                       |
| 2.5   | 10.160                           | 7.854          | 0.3092 | 2.50                     | 2.917                                 | 5.417                                       | 5.392                                       |
| 2.75  | 9.236                            | 8.639          | 0.3401 | 2.75                     | 3.208                                 | 5.958                                       | 5.932                                       |
| 3   | 8.466                            | 9.425          | 0.3711 | 3.00                     | 3.500                                 | 6.500                                       | 6.471                                       |
| 3.25  | 7.815                            | 10.210         | 0.4020 | 3.25                     | 3.791                                 | 7.041                                       | 7.010                                       |
| 3.5   | 7.257                            | 10.996         | 0.4329 | 3.50                     | 4.083                                 | 7.583                                       | 7.550                                       |
| 3.75  | 6.773                            | 11.781         | 0.4638 | 3.75                     | 4.375                                 | 8.125                                       | 8.089                                       |
| 4   | 6.350                            | 12.566         | 0.4947 | 4.00                     | 4.666                                 | 8.666                                       | 8.628                                       |
| 4.5   | 5.644                            | 14.137         | 0.5566 | 4.50                     | 5.25                                  | 9.750                                       | 9.707                                       |
| 5   | 5.080                            | 15.708         | 0.6184 | 5.00                     | 5.833                                 | 10.833                                      | 10.785                                      |
| 5.5   | 4.618                            | 17.279         | 0.6803 | 5.50                     | 6.416                                 | 11.916                                      | 11.864                                      |
| 6   | 4.233                            | 18.850         | 0.7421 | 6.00                     | 7.000                                 | 13.000                                      | 12.942                                      |
| 6.5   | 3.908                            | 20.420         | 0.8035 | 6.50                     | 7.583                                 | 14.083                                      | 14.021                                      |
| 7   | 3.628                            | 21.991         | 0.8658 | 7.                       | 8.166                                 | 15.166                                      | 15.099                                      |
| 8   | 3.175                            | 25.132         | 0.9895 | 8.                       | 9.333                                 | 17.333                                      | 17.256                                      |
| 9   | 2.822                            | 28.274         | 1.1132 | 9.                       | 10.499                                | 19.499                                      | 19.413                                      |
| 10  | 2.540                            | 31.416         | 1.2368 | 10.                      | 11.666                                | 21.666                                      | 21.571                                      |
| 11  | 2.309                            | 34.558         | 1.3606 | 11.                      | 12.833                                | 23.833                                      | 23.728                                      |
| 12  | 2.117                            | 37.699         | 1.4843 | 12.                      | 14.000                                | 26.000                                      | 25.884                                      |
| 13  | 1.954                            | 40.841         | 1.6079 | 13.                      | 15.166                                | 28.166                                      | 28.041                                      |
| 14  | 1.814                            | 43.982         | 1.7317 | 14.                      | 16.332                                | 30.332                                      | 30.198                                      |
| 15  | 1.693                            | 47.124         | 1.8541 | 15.                      | 17.499                                | 32.499                                      | 32.355                                      |
| 16  | 1.587                            | 50.266         | 1.9790 | 16.                      | 18.666                                | 34.666                                      | 34.512                                      |
| 18  | 1.411                            | 56.549         | 2.2263 | 18.                      | 21.000                                | 39.000                                      | 38.826                                      |
| 20  | 1.270                            | 62.832         | 2.4737 | 20.                      | 23.332                                | 43.332                                      | 43.142                                      |
| 22  | 1.155                            | 69.115         | 2.7210 | 22.                      | 25.665                                | 47.665                                      | 47.454                                      |
| 24  | 1.058                            | 75.398         | 2.9685 | 24.                      | 28.000                                | 52.000                                      | 51.768                                      |
| 27  | 0.941                            | 84.823         | 3.339  | 27.                      | 31.498                                | 58.498                                      | 58.239                                      |
| 30  | 0.847                            | 94.248         | 3.711  | 30.                      | 35.000                                | 65.000                                      | 64.713                                      |
| 33  | 0.770                            | 103.673        | 4.082  | 33.                      | 38.498                                | 71.498                                      | 71.181                                      |
| 36  | 0.706                            | 113.097        | 4.453  | 36.                      | 41.998                                | 77.998                                      | 77.652                                      |
| 39  | 0.651                            | 122.522        | 4.824  | 39.                      | 45.497                                | 84.497                                      | 84.123                                      |
| 42  | 0.605                            | 131.947        | 5.195  | 42.                      | 48.997                                | 90.997                                      | 90.594                                      |
| 45  | 0.564                            | 141.372        | 5.566  | 45.                      | 52.497                                | 97.497                                      | 97.065                                      |
| 50  | 0.508                            | 157.080        | 6.184  | 50.                      | 58.330                                | 108.330                                     | 107.855                                     |
| 55  | 0.462                            | 172.788        | 6.803  | 55.                      | 64.163                                | 119.163                                     | 118.635                                     |
| 60  | 0.423                            | 188.496        | 7.421  | 60.                      | 69.996                                | 129.996                                     | 129.426                                     |
| 65  | 0.391                            | 204.204        | 8.040  | 65.                      | 75.829                                | 140.829                                     | 140.205                                     |
| 70  | 0.363                            | 219.911        | 8.658  | 70.                      | 81.662                                | 151.662                                     | 150.997                                     |
| 75  | 0.339                            | 235.619        | 9.276  | 75.                      | 87.495                                | 162.495                                     | 161.775                                     |

<sup>a</sup> Dedendum and total depth when clearance =  $0.1666 \times$  module, or one-sixth module.

<sup>b</sup> Total depth equivalent to American standard full-depth teeth. (Clearance =  $0.157 \times$  module.)

## Rules for Module System of Gearing

| To Find                                     | Rule  |
|---|---|
| Metric Module                               | <p><i>Rule 1:</i> To find the metric module, divide the pitch diameter in millimeters by the number of teeth.</p> <p><i>Example 1:</i> The pitch diameter of a gear is 200 millimeters and the number of teeth, 40; then</p> $\text{Module} = \frac{200}{40} = 5$ <p><i>Rule 2:</i> Multiply circular pitch in millimeters by 0.3183.</p> <p><i>Example 2:</i> (Same as Example 1. Circular pitch of this gear equals 15.708 millimeters.)</p> $\text{Module} = 15.708 \times 0.3183 = 5$ <p><i>Rule 3:</i> Divide outside diameter in millimeters by the number of teeth plus 2.</p> |
| English Module                              | <p><i>Note:</i> The module system is usually applied when gear dimensions are expressed in millimeters, but module may also be based on inch measurements.</p> <p><i>Rule:</i> To find the English module, divide pitch diameter in inches by the number of teeth.</p> <p><i>Example:</i> A gear has 48 teeth and a pitch diameter of 12 inches.</p> $\text{Module} = \frac{12}{48} = \frac{1}{4} \text{ module or 4 diametral pitch}$  |
| Metric Module Equivalent to Diametral Pitch | <p><i>Rule:</i> To find the metric module equivalent to a given diametral pitch, divide 25.4 by the diametral pitch.</p> <p><i>Example:</i> Determine metric module equivalent to 10 diametral pitch.</p> $\text{Equivalent module} = \frac{25.4}{10} = 2.54$ <p><i>Note:</i> The nearest standard module is 2.5.</p>   |
| Diametral Pitch Equivalent to Metric Module | <p><i>Rule:</i> To find the diametral pitch equivalent to a given module, divide 25.4 by the module. (25.4 = number of millimeters per inch.)</p> <p><i>Example:</i> The module is 12; determine equivalent diametral pitch.</p> $\text{Equivalent diametral pitch} = \frac{25.4}{12} = 2.117$ <p><i>Note:</i> A diametral pitch of 2 is the nearest <i>standard</i> equivalent.</p>  |
| Pitch Diameter                              | <p><i>Rule:</i> Multiply number of teeth by module.</p> <p><i>Example:</i> The metric module is 8 and the gear has 40 teeth; then</p> $D = 40 \times 8 = 320 \text{ millimeters} = 12.598 \text{ inches}$   |
| Outside Diameter                            | <p><i>Rule:</i> Add 2 to the number of teeth and multiply sum by the module.</p> <p><i>Example:</i> A gear has 40 teeth and module is 6. Find outside or blank diameter.</p> $\text{Outside diameter} = (40 + 2) \times 6 = 252 \text{ millimeters}$  |

For tooth dimensions, see table *Tooth Dimensions Based Upon Module System*; also formulas in *German Standard Tooth Form for Spur and Bevel Gears DIN 867*.



**Equivalent Diametral Pitches, Circular Pitches, and Metric Modules  
Commonly Used Pitches and Modules in Bold Type**

| Diametral Pitch                  | Circular Pitch, Inches           | Module Millimeters | Diametral Pitch                  | Circular Pitch, Inches           | Module Millimeters               | Diametral Pitch | Circular Pitch, Inches | Module Millimeters               |
|----------------------------------|----------------------------------|--------------------|----------------------------------|----------------------------------|----------------------------------|-----------------|------------------------|----------------------------------|
| $\frac{1}{2}$                    | 6.2832                           | 50.8000            | 2.2848                           | $1\frac{3}{8}$                   | 11.1170                          | 10.0531         | $\frac{5}{16}$         | 2.5266                           |
| 0.5080                           | 6.1842                           | <b>50</b>          | 2.3091                           | 1.3605                           | <b>11</b>                        | 10.1600         | 0.3092                 | <b>2<math>\frac{1}{2}</math></b> |
| 0.5236                           | <b>6</b>                         | 48.5104            | <b>2<math>\frac{1}{2}</math></b> | 1.2566                           | 10.1600                          | <b>11</b>       | 0.2856                 | 2.3091                           |
| 0.5644                           | 5.5658                           | <b>45</b>          | 2.5133                           | <b>1<math>\frac{1}{4}</math></b> | 10.1063                          | <b>12</b>       | 0.2618                 | 2.1167                           |
| 0.5712                           | <b>5<math>\frac{1}{2}</math></b> | 44.4679            | 2.5400                           | 1.2368                           | <b>10</b>                        | 12.5664         | $\frac{1}{4}$          | 2.0213                           |
| 0.6283                           | <b>5</b>                         | 40.4253            | <b>2<math>\frac{3}{4}</math></b> | 1.1424                           | 9.2364                           | 12.7000         | 0.2474                 | <b>2</b>                         |
| 0.6350                           | 4.9474                           | <b>40</b>          | 2.7925                           | <b>1<math>\frac{1}{8}</math></b> | 9.0957                           | <b>13</b>       | 0.2417                 | 1.9538                           |
| 0.6981                           | <b>4<math>\frac{1}{2}</math></b> | 36.3828            | 2.8222                           | 1.1132                           | <b>9</b>                         | <b>14</b>       | 0.2244                 | 1.8143                           |
| 0.7257                           | 4.3290                           | <b>35</b>          | <b>3</b>                         | 1.0472                           | 8.4667                           | <b>15</b>       | 0.2094                 | 1.6933                           |
| $\frac{3}{4}$                    | 4.1888                           | 33.8667            | 3.1416                           | <b>1</b>                         | 8.0851                           | <b>16</b>       | 0.1963                 | 1.5875                           |
| 0.7854                           | <b>4</b>                         | 32.3403            | 3.1750                           | 0.9895                           | <b>8</b>                         | 16.7552         | $\frac{3}{16}$         | 1.5160                           |
| 0.8378                           | <b>3<math>\frac{3}{4}</math></b> | 30.3190            | 3.3510                           | $\frac{15}{16}$                  | 7.5797                           | 16.9333         | 0.1855                 | <b>1<math>\frac{1}{2}</math></b> |
| 0.8467                           | 3.7105                           | <b>30</b>          | <b>3<math>\frac{1}{2}</math></b> | 0.8976                           | 7.2571                           | <b>17</b>       | 0.1848                 | 1.4941                           |
| 0.8976                           | <b>3<math>\frac{1}{2}</math></b> | 28.2977            | 3.5904                           | $\frac{7}{8}$                    | 7.0744                           | <b>18</b>       | 0.1745                 | 1.4111                           |
| 0.9666                           | <b>3<math>\frac{1}{4}</math></b> | 26.2765            | 3.6286                           | 0.8658                           | <b>7</b>                         | <b>19</b>       | 0.1653                 | 1.3368                           |
| <b>1</b>                         | 3.1416                           | 25.4000            | 3.8666                           | $\frac{13}{16}$                  | 6.5691                           | <b>20</b>       | 0.1571                 | 1.2700                           |
| 1.0160                           | 3.0921                           | <b>25</b>          | 3.9078                           | 0.8040                           | <b>6<math>\frac{1}{2}</math></b> | <b>22</b>       | 0.1428                 | 1.1545                           |
| 1.0472                           | <b>3</b>                         | 24.2552            | <b>4</b>                         | 0.7854                           | 6.3500                           | <b>24</b>       | 0.1309                 | 1.0583                           |
| 1.1424                           | <b>2<math>\frac{3}{4}</math></b> | 22.2339            | 4.1888                           | $\frac{3}{4}$                    | 6.0638                           | <b>25</b>       | 0.1257                 | 1.0160                           |
| <b>1<math>\frac{1}{4}</math></b> | 2.5133                           | 20.3200            | 4.2333                           | 0.7421                           | <b>6</b>                         | 25.1328         | $\frac{1}{8}$          | 1.0106                           |
| 1.2566                           | <b>2<math>\frac{1}{2}</math></b> | 20.2127            | 4.5696                           | $\frac{11}{16}$                  | 5.5585                           | 25.4000         | 0.1237                 | <b>1</b>                         |
| 1.2700                           | 2.4737                           | <b>20</b>          | 4.6182                           | 0.6803                           | 5 $\frac{1}{2}$                  | <b>26</b>       | 0.1208                 | 0.9769                           |
| 1.3963                           | <b>2<math>\frac{1}{4}</math></b> | 18.1914            | <b>5</b>                         | 0.6283                           | 5.0800                           | <b>28</b>       | 0.1122                 | 0.9071                           |
| 1.4111                           | 2.2263                           | <b>18</b>          | 5.0265                           | $\frac{5}{8}$                    | 5.0532                           | <b>30</b>       | 0.1047                 | 0.8467                           |
| <b>1<math>\frac{1}{2}</math></b> | 2.0944                           | 16.9333            | 5.0800                           | 0.6184                           | <b>5</b>                         | <b>32</b>       | 0.0982                 | 0.7937                           |
| 1.5708                           | <b>2</b>                         | 16.1701            | 5.5851                           | $\frac{9}{16}$                   | 4.5478                           | <b>34</b>       | 0.0924                 | 0.7470                           |
| 1.5875                           | 1.9790                           | <b>16</b>          | 5.6443                           | 0.5566                           | <b>4<math>\frac{1}{2}</math></b> | <b>36</b>       | 0.0873                 | 0.7056                           |
| 1.6755                           | <b>1<math>\frac{7}{8}</math></b> | 15.1595            | <b>6</b>                         | 0.5236                           | 4.2333                           | <b>38</b>       | 0.0827                 | 0.6684                           |
| 1.6933                           | 1.8553                           | <b>15</b>          | 6.2832                           | $\frac{1}{2}$                    | 4.0425                           | <b>40</b>       | 0.0785                 | 0.6350                           |
| <b>1<math>\frac{3}{4}</math></b> | 1.7952                           | 14.5143            | 6.3500                           | 0.4947                           | <b>4</b>                         | <b>42</b>       | 0.0748                 | 0.6048                           |
| 1.7952                           | <b>1<math>\frac{3}{4}</math></b> | 14.1489            | <b>7</b>                         | 0.4488                           | 3.6286                           | <b>44</b>       | 0.0714                 | 0.5773                           |
| 1.8143                           | 1.7316                           | <b>14</b>          | 7.1808                           | $\frac{7}{16}$                   | 3.5372                           | <b>46</b>       | 0.0683                 | 0.5522                           |
| 1.9333                           | <b>1<math>\frac{5}{8}</math></b> | 13.1382            | 7.2571                           | 0.4329                           | <b>3<math>\frac{1}{2}</math></b> | <b>48</b>       | 0.0654                 | 0.5292                           |
| 1.9538                           | 1.6079                           | <b>13</b>          | <b>8</b>                         | 0.3927                           | 3.1750                           | <b>50</b>       | 0.0628                 | 0.5080                           |
| <b>2</b>                         | 1.5708                           | 12.7000            | 8.3776                           | $\frac{3}{8}$                    | 3.0319                           | 50.2656         | $\frac{1}{16}$         | 0.5053                           |
| 2.0944                           | <b>1<math>\frac{1}{2}</math></b> | 12.1276            | 8.4667                           | 0.3711                           | <b>3</b>                         | 50.8000         | 0.0618                 | $\frac{1}{2}$                    |
| 2.1167                           | 1.4842                           | <b>12</b>          | <b>9</b>                         | 0.3491                           | 2.8222                           | <b>56</b>       | 0.0561                 | 0.4536                           |
| <b>2<math>\frac{1}{4}</math></b> | 1.3963                           | 11.2889            | <b>10</b>                        | 0.3142                           | 2.5400                           | <b>60</b>       | 0.0524                 | 0.4233                           |

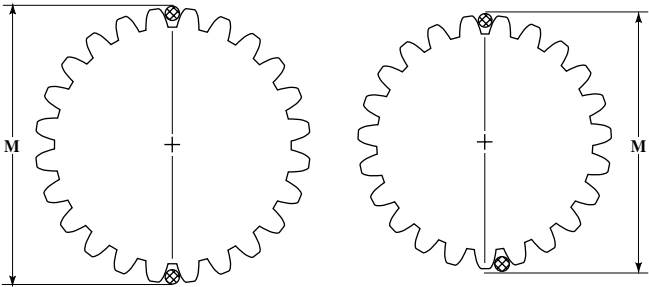
The module of a gear is the pitch diameter divided by the number of teeth. The module may be expressed in any units; but when no units are stated, it is understood to be in millimeters. The metric module, therefore, equals the pitch diameter in millimeters divided by the number of teeth. To find the metric module equivalent to a given diametral pitch, divide 25.4 by the diametral pitch. To find the diametral pitch equivalent to a given module, divide 25.4 by the module. (25.4 = number of millimeters per inch.)

## CHECKING GEAR SIZES

## Checking Gear Size by Measurement Over Wires or Pins

The wire or pin method of checking gear sizes is accurate, easily applied, and especially useful in shops with limited inspection equipment. Two cylindrical wires or pins of predetermined diameter are placed in diametrically opposite tooth spaces (see diagram). If the gear has an odd number of teeth, the wires are located as nearly opposite as possible, as shown by the diagram at the right. The overall measurement  $M$  is checked by using any sufficiently accurate method of measurement. The value of measurement  $M$  when the pitch diameter is correct can be determined easily and quickly by means of the calculated values in the accompanying tables.

**Measurements for Checking External Spur Gears when Wire Diameter Equals 1.728 Divided by Diametral Pitch.**—Tables 1 and 2 give measurements  $M$ , in inches, for checking the pitch diameters of external spur gears of 1 diametral pitch. For any other diametral pitch, divide the measurement given in the table by whatever diametral pitch is required. The result shows what measurement  $M$  should be when the pitch diameter is correct and there is no allowance for backlash. The procedure for obtaining a given amount of backlash will be explained later. Tables 1 through 4 inclusive are based on wire sizes conforming to the Van Keuren standard. For external spur gears, the wire size equals 1.728 divided by the diametral pitch. The wire diameters for various diametral pitches will be found in the left-hand section of Table 5.



**Even Number of Teeth:** Table 1 is for even numbers of teeth. To illustrate the use of the table, assume that a spur gear has 32 teeth of 4 diametral pitch and a pressure angle of 20 degrees. Table 1 shows that the measurement for 1 diametral pitch is 34.4130; hence, for 4 diametral pitch, the measurement equals  $34.4130 \div 4 = 8.6032$  inches. This dimension is the measurement over the wires when the pitch diameter is correct, provided there is no allowance for backlash. The wire diameter here equals  $1.728 \div 4 = 0.432$  inch (Table 5).

Measurement for even numbers of teeth above 170 and not in Table 1 may be determined as shown by the following example: Assume that number of teeth = 240 and pressure angle =  $14\frac{1}{2}$  degrees; then, for 1 diametral pitch, figure at left of decimal point = given No. of teeth + 2 =  $240 + 2 = 242$ . Figure at right of decimal point lies between decimal values given in table for 200 teeth and 300 teeth and is obtained by interpolation. Thus,  $240 - 200 = 40$  (change to 0.40);  $0.5395 - 0.5321 = 0.0074 =$  difference between decimal values for 300 and 200 teeth; hence, decimal required =  $0.5321 + (0.40 \times 0.0074) = 0.53506$ . Total dimension =  $242.53506$  divided by the diametral pitch required.

**Odd Number of Teeth:** Table 2 is for odd numbers of teeth. Measurement for odd numbers above 171 and not in Table 2 may be determined as shown by the following example: Assume that number of teeth = 335 and pressure angle = 20 degrees; then, for 1 diametral

CHECKING GEAR SIZES

pitch, figure at left of decimal point = given No. of teeth + 2 = 335 + 2 = 337. Figure at right of decimal point lies between decimal values given in table for 301 and 401 teeth. Thus, 335 - 301 = 34 (change to 0.34); 0.4565 - 0.4538 = 0.0027; hence, decimal required = 0.4538 + (0.34 × 0.0027) = 0.4547. Total dimension = 337.4547.

**Table 1. Checking External Spur Gear Sizes by Measurement Over Wires**

| EVEN NUMBERS OF TEETH  |                |         |         |         |         |
|--|----------------|---------|---------|---------|---------|
| Dimensions in table are for 1 diametral pitch and Van Keuren standard wire sizes. For any other diametral pitch, divide dimension in table by given pitch. |                |         |         |         |         |
| Wire or pin diameter = $\frac{1.728}{\text{Diametral Pitch}}$  |                |         |         |         |         |
| No. of Teeth   | Pressure Angle |         |         |         |         |
|  | 14½°           | 17½°    | 20°     | 25°     | 30°     |
| 6  | 8.2846         | 8.2927  | 8.3032  | 8.3340  | 8.3759  |
| 8  | 10.3160        | 10.3196 | 10.3271 | 10.3533 | 10.3919 |
| 10   | 12.3399        | 12.3396 | 12.3445 | 12.3667 | 12.4028 |
| 12   | 14.3590        | 14.3552 | 14.3578 | 14.3768 | 14.4108 |
| 14   | 16.3746        | 16.3677 | 16.3683 | 16.3846 | 16.4169 |
| 16   | 18.3877        | 18.3780 | 18.3768 | 18.3908 | 18.4217 |
| 18   | 20.3989        | 20.3866 | 20.3840 | 20.3959 | 20.4256 |
| 20   | 22.4087        | 22.3940 | 22.3900 | 22.4002 | 22.4288 |
| 22   | 24.4172        | 24.4004 | 24.3952 | 24.4038 | 24.4315 |
| 24   | 26.4247        | 26.4060 | 26.3997 | 26.4069 | 26.4339 |
| 26   | 28.4314        | 28.4110 | 28.4036 | 28.4096 | 28.4358 |
| 28   | 30.4374        | 30.4154 | 30.4071 | 30.4120 | 30.4376 |
| 30   | 32.4429        | 32.4193 | 32.4102 | 32.4141 | 32.4391 |
| 32   | 34.4478        | 34.4228 | 34.4130 | 34.4159 | 34.4405 |
| 34   | 36.4523        | 36.4260 | 36.4155 | 36.4176 | 36.4417 |
| 36   | 38.4565        | 38.4290 | 38.4178 | 38.4191 | 38.4428 |
| 38   | 40.4603        | 40.4317 | 40.4198 | 40.4205 | 40.4438 |
| 40   | 42.4638        | 42.4341 | 42.4217 | 42.4217 | 42.4447 |
| 42   | 44.4671        | 44.4364 | 44.4234 | 44.4228 | 44.4455 |
| 44   | 46.4701        | 46.4385 | 46.4250 | 46.4239 | 46.4463 |
| 46   | 48.4729        | 48.4404 | 48.4265 | 48.4248 | 48.4470 |
| 48   | 50.4756        | 50.4422 | 50.4279 | 50.4257 | 50.4476 |
| 50   | 52.4781        | 52.4439 | 52.4292 | 52.4265 | 52.4482 |
| 52   | 54.4804        | 54.4454 | 54.4304 | 54.4273 | 54.4487 |
| 54   | 56.4826        | 56.4469 | 56.4315 | 56.4280 | 56.4492 |
| 56   | 58.4847        | 58.4483 | 58.4325 | 58.4287 | 58.4497 |
| 58   | 60.4866        | 60.4496 | 60.4335 | 60.4293 | 60.4501 |
| 60   | 62.4884        | 62.4509 | 62.4344 | 62.4299 | 62.4506 |
| 62   | 64.4902        | 64.4520 | 64.4352 | 64.4304 | 64.4510 |
| 64   | 66.4918        | 66.4531 | 66.4361 | 66.4309 | 66.4513 |
| 66   | 68.4933        | 68.4542 | 68.4369 | 68.4314 | 68.4517 |
| 68   | 70.4948        | 70.4552 | 70.4376 | 70.4319 | 70.4520 |
| 70   | 72.4963        | 72.4561 | 72.4383 | 72.4323 | 72.4523 |
| 72   | 74.4977        | 74.4570 | 74.4390 | 74.4327 | 74.4526 |
| 74   | 76.4990        | 76.4578 | 76.4396 | 76.4331 | 76.4529 |
| 76   | 78.5002        | 78.4586 | 78.4402 | 78.4335 | 78.4532 |
| 78   | 80.5014        | 80.4594 | 80.4408 | 80.4339 | 80.4534 |
| 80   | 82.5026        | 82.4601 | 82.4413 | 82.4342 | 82.4536 |
| 82   | 84.5037        | 84.4608 | 84.4418 | 84.4345 | 84.4538 |
| 84   | 86.5047        | 86.4615 | 86.4423 | 86.4348 | 86.4540 |
| 86   | 88.5057        | 88.4621 | 88.4428 | 88.4351 | 88.4542 |
| 88   | 90.5067        | 90.4627 | 90.4433 | 90.4354 | 90.4544 |

**Table 1. (Continued) Checking External Spur Gear Sizes  
by Measurement Over Wires**

| EVEN NUMBERS OF TEETH  |                |          |          |          |          |
|--|----------------|----------|----------|----------|----------|
| Dimensions in table are for 1 diametral pitch and Van Keuren standard wire sizes. For any other diametral pitch, divide dimension in table by given pitch. |                |          |          |          |          |
| Wire or pin diameter = $\frac{1.728}{\text{Diametral Pitch}}$  |                |          |          |          |          |
| No. of Teeth   | Pressure Angle |          |          |          |          |
|  | 14½°           | 17½°     | 20°      | 25°      | 30°      |
| 90   | 92.5076        | 92.4633  | 92.4437  | 92.4357  | 92.4546  |
| 92   | 94.5085        | 94.4639  | 94.4441  | 94.4359  | 94.4548  |
| 94   | 96.5094        | 96.4644  | 96.4445  | 96.4362  | 96.4550  |
| 96   | 98.5102        | 98.4649  | 98.4449  | 98.4364  | 98.4552  |
| 98   | 100.5110       | 100.4655 | 100.4453 | 100.4367 | 100.4554 |
| 100  | 102.5118       | 102.4660 | 102.4456 | 102.4369 | 102.4555 |
| 102  | 104.5125       | 104.4665 | 104.4460 | 104.4370 | 104.4557 |
| 104  | 106.5132       | 106.4669 | 106.4463 | 106.4372 | 106.4558 |
| 106  | 108.5139       | 108.4673 | 108.4466 | 108.4374 | 108.4560 |
| 108  | 110.5146       | 110.4678 | 110.4469 | 110.4376 | 110.4561 |
| 110  | 112.5152       | 112.4682 | 112.4472 | 112.4378 | 112.4562 |
| 112  | 114.5159       | 114.4686 | 114.4475 | 114.4380 | 114.4563 |
| 114  | 116.5165       | 116.4690 | 116.4478 | 116.4382 | 116.4564 |
| 116  | 118.5171       | 118.4693 | 118.4481 | 118.4384 | 118.4565 |
| 118  | 120.5177       | 120.4697 | 120.4484 | 120.4385 | 120.4566 |
| 120  | 122.5182       | 122.4701 | 122.4486 | 122.4387 | 122.4567 |
| 122  | 124.5188       | 124.4704 | 124.4489 | 124.4388 | 124.4568 |
| 124  | 126.5193       | 126.4708 | 126.4491 | 126.4390 | 126.4569 |
| 126  | 128.5198       | 128.4711 | 128.4493 | 128.4391 | 128.4570 |
| 128  | 130.5203       | 130.4714 | 130.4496 | 130.4393 | 130.4571 |
| 130  | 132.5208       | 132.4717 | 132.4498 | 132.4394 | 132.4572 |
| 132  | 134.5213       | 134.4720 | 134.4500 | 134.4395 | 134.4573 |
| 134  | 136.5217       | 136.4723 | 136.4502 | 136.4397 | 136.4574 |
| 136  | 138.5221       | 138.4725 | 138.4504 | 138.4398 | 138.4575 |
| 138  | 140.5226       | 140.4728 | 140.4506 | 140.4399 | 140.4576 |
| 140  | 142.5230       | 142.4730 | 142.4508 | 142.4400 | 142.4577 |
| 142  | 144.5234       | 144.4733 | 144.4510 | 144.4401 | 144.4578 |
| 144  | 146.5238       | 146.4736 | 146.4512 | 146.4402 | 146.4578 |
| 146  | 148.5242       | 148.4738 | 148.4513 | 148.4403 | 148.4579 |
| 148  | 150.5246       | 150.4740 | 150.4515 | 150.4404 | 150.4580 |
| 150  | 152.5250       | 152.4742 | 152.4516 | 152.4405 | 152.4580 |
| 152  | 154.5254       | 154.4745 | 154.4518 | 154.4406 | 154.4581 |
| 154  | 156.5257       | 156.4747 | 156.4520 | 156.4407 | 156.4581 |
| 156  | 158.5261       | 158.4749 | 158.4521 | 158.4408 | 158.4582 |
| 158  | 160.5264       | 160.4751 | 160.4523 | 160.4409 | 160.4582 |
| 160  | 162.5267       | 162.4753 | 162.4524 | 162.4410 | 162.4583 |
| 162  | 164.5270       | 164.4755 | 164.4526 | 164.4411 | 164.4584 |
| 164  | 166.5273       | 166.4757 | 166.4527 | 166.4411 | 166.4584 |
| 166  | 168.5276       | 168.4759 | 168.4528 | 168.4412 | 168.4585 |
| 168  | 170.5279       | 170.4760 | 170.4529 | 170.4413 | 170.4585 |
| 170  | 172.5282       | 172.4761 | 172.4531 | 172.4414 | 172.4586 |
| 180  | 182.5297       | 182.4771 | 182.4537 | 182.4418 | 182.4589 |
| 190  | 192.5310       | 192.4780 | 192.4542 | 192.4421 | 192.4591 |
| 200  | 202.5321       | 202.4786 | 202.4548 | 202.4424 | 202.4593 |
| 300  | 302.5395       | 302.4831 | 302.4579 | 302.4443 | 302.4606 |
| 400  | 402.5434       | 402.4854 | 402.4596 | 402.4453 | 402.4613 |
| 500  | 502.5458       | 502.4868 | 502.4606 | 502.4458 | 502.4619 |

## CHECKING GEAR SIZES

**Table 2. Checking External Spur Gear Sizes  
by Measurement Over Wires**

| <b>ODD NUMBERS OF TEETH</b>  |                |         |         |         |         |
|--|----------------|---------|---------|---------|---------|
| Dimensions in table are for 1 diametral pitch and Van Keuren standard wire sizes. For any other diametral pitch, divide dimension in table by given pitch. |                |         |         |         |         |
| Wire or pin diameter = $\frac{1.728}{\text{Diametral Pitch}}$  |                |         |         |         |         |
| No. of Teeth   | Pressure Angle |         |         |         |         |
|  | 14½°           | 17½°    | 20°     | 25°     | 30°     |
| 7  | 9.1116         | 9.1172  | 9.1260  | 9.1536  | 9.1928  |
| 9  | 11.1829        | 11.1844 | 11.1905 | 11.2142 | 11.2509 |
| 11   | 13.2317        | 13.2296 | 13.2332 | 13.2536 | 13.2882 |
| 13   | 15.2677        | 15.2617 | 15.2639 | 15.2814 | 15.3142 |
| 15   | 17.2957        | 17.2873 | 17.2871 | 17.3021 | 17.3329 |
| 17   | 19.3182        | 19.3072 | 19.3053 | 19.3181 | 19.3482 |
| 19   | 21.3368        | 21.3233 | 21.3200 | 21.3310 | 21.3600 |
| 21   | 23.3524        | 23.3368 | 23.3321 | 23.3415 | 23.3696 |
| 23   | 25.3658        | 25.3481 | 25.3423 | 25.3502 | 25.3775 |
| 25   | 27.3774        | 27.3579 | 27.3511 | 27.3576 | 27.3842 |
| 27   | 29.3876        | 29.3664 | 29.3586 | 29.3640 | 29.3899 |
| 29   | 31.3966        | 31.3738 | 31.3652 | 31.3695 | 31.3948 |
| 31   | 33.4047        | 33.3804 | 33.3710 | 33.3743 | 33.3991 |
| 33   | 35.4119        | 35.3863 | 35.3761 | 35.3786 | 35.4029 |
| 35   | 37.4185        | 37.3916 | 37.3807 | 37.3824 | 37.4063 |
| 37   | 39.4245        | 39.3964 | 39.3849 | 39.3858 | 39.4094 |
| 39   | 41.4299        | 41.4007 | 41.3886 | 41.3889 | 41.4120 |
| 41   | 43.4348        | 43.4047 | 43.3920 | 43.3917 | 43.4145 |
| 43   | 45.4394        | 45.4083 | 45.3951 | 45.3942 | 45.4168 |
| 45   | 47.4437        | 47.4116 | 47.3980 | 47.3965 | 47.4188 |
| 47   | 49.4477        | 49.4147 | 49.4007 | 49.3986 | 49.4206 |
| 49   | 51.4514        | 51.4175 | 51.4031 | 51.4006 | 51.4223 |
| 51   | 53.4547        | 53.4202 | 53.4053 | 53.4024 | 53.4239 |
| 53   | 55.4579        | 55.4227 | 55.4074 | 55.4041 | 55.4254 |
| 55   | 57.4609        | 57.4249 | 57.4093 | 57.4056 | 57.4267 |
| 57   | 59.4637        | 59.4271 | 59.4111 | 59.4071 | 59.4280 |
| 59   | 61.4664        | 61.4291 | 61.4128 | 61.4084 | 61.4292 |
| 61   | 63.4689        | 63.4310 | 63.4144 | 63.4097 | 63.4303 |
| 63   | 65.4712        | 65.4328 | 65.4159 | 65.4109 | 65.4313 |
| 65   | 67.4734        | 67.4344 | 67.4173 | 67.4120 | 67.4323 |
| 67   | 69.4755        | 69.4360 | 69.4186 | 69.4130 | 69.4332 |
| 69   | 71.4775        | 71.4375 | 71.4198 | 71.4140 | 71.4341 |
| 71   | 73.4795        | 73.4389 | 73.4210 | 73.4150 | 73.4349 |
| 73   | 75.4813        | 75.4403 | 75.4221 | 75.4159 | 75.4357 |
| 75   | 77.4830        | 77.4416 | 77.4232 | 77.4167 | 77.4364 |
| 77   | 79.4847        | 79.4428 | 79.4242 | 79.4175 | 79.4371 |
| 79   | 81.4863        | 81.4440 | 81.4252 | 81.4183 | 81.4378 |
| 81   | 83.4877        | 83.4451 | 83.4262 | 83.4190 | 83.4384 |
| 83   | 85.4892        | 85.4462 | 85.4271 | 85.4196 | 85.4390 |
| 85   | 87.4906        | 87.4472 | 87.4279 | 87.4203 | 87.4395 |
| 87   | 89.4919        | 89.4481 | 89.4287 | 89.4209 | 89.4400 |
| 89   | 91.4932        | 91.4490 | 91.4295 | 91.4215 | 91.4405 |
| 91   | 93.4944        | 93.4499 | 93.4303 | 93.4221 | 93.4410 |
| 93   | 95.4956        | 95.4508 | 95.4310 | 95.4227 | 95.4415 |

**Table 2. (Continued) Checking External Spur Gear Sizes by Measurement Over Wires**

| ODD NUMBERS OF TEETH   |                |          |          |          |          |
|--|----------------|----------|----------|----------|----------|
| Dimensions in table are for 1 diametral pitch and Van Keuren standard wire sizes. For any other diametral pitch, divide dimension in table by given pitch. |                |          |          |          |          |
| Wire or pin diameter = $\frac{1.728}{\text{Diametral Pitch}}$  |                |          |          |          |          |
| No. of Teeth   | Pressure Angle |          |          |          |          |
|  | 14½°           | 17½°     | 20°      | 25°      | 30°      |
| 95   | 97.4967        | 97.4516  | 97.4317  | 97.4232  | 97.4420  |
| 97   | 99.4978        | 99.4524  | 99.4323  | 99.4237  | 99.4424  |
| 99   | 101.4988       | 101.4532 | 101.4329 | 101.4242 | 101.4428 |
| 101  | 103.4998       | 103.4540 | 103.4335 | 103.4247 | 103.4432 |
| 103  | 105.5008       | 105.4546 | 105.4341 | 105.4252 | 105.4436 |
| 105  | 107.5017       | 107.4553 | 107.4346 | 107.4256 | 107.4440 |
| 107  | 109.5026       | 109.4559 | 109.4352 | 109.4260 | 109.4443 |
| 109  | 111.5035       | 111.4566 | 111.4357 | 111.4264 | 111.4447 |
| 111  | 113.5044       | 113.4572 | 113.4362 | 113.4268 | 113.4450 |
| 113  | 115.5052       | 115.4578 | 115.4367 | 115.4272 | 115.4453 |
| 115  | 117.5060       | 117.4584 | 117.4372 | 117.4275 | 117.4456 |
| 117  | 119.5068       | 119.4589 | 119.4376 | 119.4279 | 119.4459 |
| 119  | 121.5075       | 121.4594 | 121.4380 | 121.4282 | 121.4462 |
| 121  | 123.5082       | 123.4599 | 123.4384 | 123.4285 | 123.4465 |
| 123  | 125.5089       | 125.4604 | 125.4388 | 125.4288 | 125.4468 |
| 125  | 127.5096       | 127.4609 | 127.4392 | 127.4291 | 127.4471 |
| 127  | 129.5103       | 129.4614 | 129.4396 | 129.4294 | 129.4473 |
| 129  | 131.5109       | 131.4619 | 131.4400 | 131.4297 | 131.4476 |
| 131  | 133.5115       | 133.4623 | 133.4404 | 133.4300 | 133.4478 |
| 133  | 135.5121       | 135.4628 | 135.4408 | 135.4302 | 135.4480 |
| 135  | 137.5127       | 137.4632 | 137.4411 | 137.4305 | 137.4483 |
| 137  | 139.5133       | 139.4636 | 139.4414 | 139.4307 | 139.4485 |
| 139  | 141.5139       | 141.4640 | 141.4418 | 141.4310 | 141.4487 |
| 141  | 143.5144       | 143.4644 | 143.4421 | 143.4312 | 143.4489 |
| 143  | 145.5149       | 145.4648 | 145.4424 | 145.4315 | 145.4491 |
| 145  | 147.5154       | 147.4651 | 147.4427 | 147.4317 | 147.4493 |
| 147  | 149.5159       | 149.4655 | 149.4430 | 149.4319 | 149.4495 |
| 149  | 151.5164       | 151.4658 | 151.4433 | 151.4321 | 151.4497 |
| 151  | 153.5169       | 153.4661 | 153.4435 | 153.4323 | 153.4498 |
| 153  | 155.5174       | 155.4665 | 155.4438 | 155.4325 | 155.4500 |
| 155  | 157.5179       | 157.4668 | 157.4440 | 157.4327 | 157.4502 |
| 157  | 159.5183       | 159.4671 | 159.4443 | 159.4329 | 159.4504 |
| 159  | 161.5188       | 161.4674 | 161.4445 | 161.4331 | 161.4505 |
| 161  | 163.5192       | 163.4677 | 163.4448 | 163.4333 | 163.4507 |
| 163  | 165.5196       | 165.4680 | 165.4450 | 165.4335 | 165.4508 |
| 165  | 167.5200       | 167.4683 | 167.4453 | 167.4337 | 167.4510 |
| 167  | 169.5204       | 169.4686 | 169.4455 | 169.4338 | 169.4511 |
| 169  | 171.5208       | 171.4688 | 171.4457 | 171.4340 | 171.4513 |
| 171  | 173.5212       | 173.4691 | 173.4459 | 173.4342 | 173.4514 |
| 181  | 183.5230       | 183.4704 | 183.4469 | 183.4350 | 183.4520 |
| 191  | 193.5246       | 193.4715 | 193.4478 | 193.4357 | 193.4526 |
| 201  | 203.5260       | 203.4725 | 203.4487 | 203.4363 | 203.4532 |
| 301  | 303.5355       | 303.4790 | 303.4538 | 303.4402 | 303.4565 |
| 401  | 403.5404       | 403.4823 | 403.4565 | 403.4422 | 403.4582 |
| 501  | 503.5433       | 503.4843 | 503.4581 | 503.4434 | 503.4592 |

## CHECKING GEAR SIZES

**Table 3. Checking Internal Spur Gear Sizes  
by Measurement Between Wires**

| EVEN NUMBERS OF TEETH  |                |         |         |         |         |
|--|----------------|---------|---------|---------|---------|
| Dimensions in table are for 1 diametral pitch and Van Keuren standard wire sizes. For any other diametral pitch, divide dimension in table by given pitch. |                |         |         |         |         |
| Wire or pin diameter = $\frac{1.44}{\text{Diametral Pitch}}$   |                |         |         |         |         |
| No. of Teeth   | Pressure Angle |         |         |         |         |
|  | 14½°           | 17½°    | 20°     | 25°     | 30°     |
| 10   | 8.8337         | 8.7383  | 8.6617  | 8.5209  | 8.3966  |
| 12   | 10.8394        | 10.7404 | 10.6623 | 10.5210 | 10.3973 |
| 14   | 12.8438        | 12.7419 | 12.6627 | 12.5210 | 12.3978 |
| 16   | 14.8474        | 14.7431 | 14.6630 | 14.5210 | 14.3982 |
| 18   | 16.8504        | 16.7441 | 16.6633 | 16.5210 | 16.3985 |
| 20   | 18.8529        | 18.7449 | 18.6635 | 18.5211 | 18.3987 |
| 22   | 20.8550        | 20.7456 | 20.6636 | 20.5211 | 20.3989 |
| 24   | 22.8569        | 22.7462 | 22.6638 | 22.5211 | 22.3991 |
| 26   | 24.8585        | 24.7467 | 24.6639 | 24.5211 | 24.3992 |
| 28   | 26.8599        | 26.7471 | 26.6640 | 26.5211 | 26.3993 |
| 30   | 28.8612        | 28.7475 | 28.6641 | 28.5211 | 28.3994 |
| 32   | 30.8623        | 30.7478 | 30.6642 | 30.5211 | 30.3995 |
| 34   | 32.8633        | 32.7481 | 32.6642 | 32.5211 | 32.3995 |
| 36   | 34.8642        | 34.7483 | 34.6643 | 34.5212 | 34.3996 |
| 38   | 36.8650        | 36.7486 | 36.6642 | 36.5212 | 36.3996 |
| 40   | 38.8658        | 38.7488 | 38.6644 | 38.5212 | 38.3997 |
| 42   | 40.8665        | 40.7490 | 40.6644 | 40.5212 | 40.3997 |
| 44   | 42.8672        | 42.7492 | 42.6645 | 42.5212 | 42.3998 |
| 46   | 44.8678        | 44.7493 | 44.6645 | 44.5212 | 44.3998 |
| 48   | 46.8683        | 46.7495 | 46.6646 | 46.5212 | 46.3999 |
| 50   | 48.8688        | 48.7496 | 48.6646 | 48.5212 | 48.3999 |
| 52   | 50.8692        | 50.7497 | 50.6646 | 50.5212 | 50.3999 |
| 54   | 52.8697        | 52.7499 | 52.6647 | 52.5212 | 52.4000 |
| 56   | 54.8701        | 54.7500 | 54.6647 | 54.5212 | 54.4000 |
| 58   | 56.8705        | 56.7501 | 56.6648 | 56.5212 | 56.4001 |
| 60   | 58.8709        | 58.7502 | 58.6648 | 58.5212 | 58.4001 |
| 62   | 60.8712        | 60.7503 | 60.6648 | 60.5212 | 60.4001 |
| 64   | 62.8715        | 62.7504 | 62.6648 | 62.5212 | 62.4001 |
| 66   | 64.8718        | 64.7505 | 64.6649 | 64.5212 | 64.4001 |
| 68   | 66.8721        | 66.7505 | 66.6649 | 66.5212 | 66.4001 |
| 70   | 68.8724        | 68.7506 | 68.6649 | 68.5212 | 68.4001 |
| 72   | 70.8727        | 70.7507 | 70.6649 | 70.5212 | 70.4002 |
| 74   | 72.8729        | 72.7507 | 72.6649 | 72.5212 | 72.4002 |
| 76   | 74.8731        | 74.7508 | 74.6649 | 74.5212 | 74.4002 |
| 78   | 76.8734        | 76.7509 | 76.6649 | 76.5212 | 76.4002 |
| 80   | 78.8736        | 78.7509 | 78.6649 | 78.5212 | 78.4002 |
| 82   | 80.8738        | 80.7510 | 80.6649 | 80.5212 | 80.4002 |
| 84   | 82.8740        | 82.7510 | 82.6649 | 82.5212 | 82.4002 |
| 86   | 84.8742        | 84.7511 | 84.6650 | 84.5212 | 84.4002 |
| 88   | 86.8743        | 86.7511 | 86.6650 | 86.5212 | 86.4003 |
| 90   | 88.8745        | 88.7512 | 88.6650 | 88.5212 | 88.4003 |
| 92   | 90.8747        | 90.7512 | 90.6650 | 90.5212 | 90.4003 |
| 94   | 92.8749        | 92.7513 | 92.6650 | 92.5212 | 92.4003 |

**Table 3. (Continued) Checking Internal Spur Gear Sizes by Measurement Between Wires**

| EVEN NUMBERS OF TEETH  |                |          |          |          |          |
|--|----------------|----------|----------|----------|----------|
| Dimensions in table are for 1 diametral pitch and Van Keuren standard wire sizes. For any other diametral pitch, divide dimension in table by given pitch. |                |          |          |          |          |
| Wire or pin diameter = $\frac{1.44}{\text{Diametral Pitch}}$   |                |          |          |          |          |
| No. of Teeth   | Pressure Angle |          |          |          |          |
|  | 14½°           | 17½°     | 20°      | 25°      | 30°      |
| 96   | 94.8750        | 94.7513  | 94.6650  | 94.5212  | 94.4003  |
| 98   | 96.8752        | 96.7513  | 96.6650  | 96.5212  | 96.4003  |
| 100  | 98.8753        | 98.7514  | 98.6650  | 98.5212  | 98.4003  |
| 102  | 100.8754       | 100.7514 | 100.6650 | 100.5212 | 100.4003 |
| 104  | 102.8756       | 102.7514 | 102.6650 | 102.5212 | 102.4003 |
| 106  | 104.8757       | 104.7515 | 104.6650 | 104.5212 | 104.4003 |
| 108  | 106.8758       | 106.7515 | 106.6650 | 106.5212 | 106.4003 |
| 110  | 108.8759       | 108.7515 | 108.6651 | 108.5212 | 108.4004 |
| 112  | 110.8760       | 110.7516 | 110.6651 | 110.5212 | 110.4004 |
| 114  | 112.8761       | 112.7516 | 112.6651 | 112.5212 | 112.4004 |
| 116  | 114.8762       | 114.7516 | 114.6651 | 114.5212 | 114.4004 |
| 118  | 116.8763       | 116.7516 | 116.6651 | 116.5212 | 116.4004 |
| 120  | 118.8764       | 118.7517 | 118.6651 | 118.5212 | 118.4004 |
| 122  | 120.8765       | 120.7517 | 120.6651 | 120.5212 | 120.4004 |
| 124  | 122.8766       | 122.7517 | 122.6651 | 122.5212 | 122.4004 |
| 126  | 124.8767       | 124.7517 | 124.6651 | 124.5212 | 124.4004 |
| 128  | 126.8768       | 126.7518 | 126.6651 | 126.5212 | 126.4004 |
| 130  | 128.8769       | 128.7518 | 128.6652 | 128.5212 | 128.4004 |
| 132  | 130.8769       | 130.7518 | 130.6652 | 130.5212 | 130.4004 |
| 134  | 132.8770       | 132.7518 | 132.6652 | 132.5212 | 132.4004 |
| 136  | 134.8771       | 134.7519 | 134.6652 | 134.5212 | 134.4004 |
| 138  | 136.8772       | 136.7519 | 136.6652 | 136.5212 | 136.4004 |
| 140  | 138.8773       | 138.7519 | 138.6652 | 138.5212 | 138.4004 |
| 142  | 140.8773       | 140.7519 | 140.6652 | 140.5212 | 140.4004 |
| 144  | 142.8774       | 142.7519 | 142.6652 | 142.5212 | 142.4004 |
| 146  | 144.8774       | 144.7520 | 144.6652 | 144.5212 | 144.4004 |
| 148  | 146.8775       | 146.7520 | 146.6652 | 146.5212 | 146.4004 |
| 150  | 148.8775       | 148.7520 | 148.6652 | 148.5212 | 148.4005 |
| 152  | 150.8776       | 150.7520 | 150.6652 | 150.5212 | 150.4005 |
| 154  | 152.8776       | 152.7520 | 152.6652 | 152.5212 | 152.4005 |
| 156  | 154.8777       | 154.7520 | 154.6652 | 154.5212 | 154.4005 |
| 158  | 156.8778       | 156.7520 | 156.6652 | 156.5212 | 156.4005 |
| 160  | 158.8778       | 158.7520 | 158.6652 | 158.5212 | 158.4005 |
| 162  | 160.8779       | 160.7520 | 160.6652 | 160.5212 | 160.4005 |
| 164  | 162.8779       | 162.7521 | 162.6652 | 162.5212 | 162.4005 |
| 166  | 164.8780       | 164.7521 | 164.6652 | 164.5212 | 164.4005 |
| 168  | 166.8780       | 166.7521 | 166.6652 | 166.5212 | 166.4005 |
| 170  | 168.8781       | 168.7521 | 168.6652 | 168.5212 | 168.4005 |
| 180  | 178.8783       | 178.7522 | 178.6652 | 178.5212 | 178.4005 |
| 190  | 188.8785       | 188.7522 | 188.6652 | 188.5212 | 188.4005 |
| 200  | 198.8788       | 198.7523 | 198.6652 | 198.5212 | 198.4005 |
| 300  | 298.8795       | 298.7525 | 298.6654 | 298.5212 | 298.4005 |
| 400  | 398.8803       | 398.7527 | 398.6654 | 398.5212 | 398.4006 |
| 500  | 498.8810       | 498.7528 | 498.6654 | 498.5212 | 498.4006 |



## CHECKING GEAR SIZES

**Table 4. Checking Internal Spur Gear Sizes by Measurement Between Wires**

| ODD NUMBERS OF TEETH  |                |          |          |          |          |
|---|----------------|----------|----------|----------|----------|
| Dimensions in table are for 1 diametral pitch and Van Keuren standard wire sizes. For any other diametral pitch, divide dimensions in table by given pitch. |                |          |          |          |          |
| Wire or pin diameter = $\frac{1.44}{\text{Diametral Pitch}}$  |                |          |          |          |          |
| No. of Teeth  | Pressure Angle |          |          |          |          |
|   | 14½°           | 17½°     | 20°      | 25°      | 30°      |
| 7   | 5.6393         | 5.5537   | 5.4823   | 5.3462   | 5.2232   |
| 9   | 7.6894         | 7.5976   | 7.5230   | 7.3847   | 7.2618   |
| 11  | 9.7219         | 9.6256   | 9.5490   | 9.4094   | 9.2867   |
| 13  | 11.7449        | 11.6451  | 11.5669  | 11.4265  | 11.3040  |
| 15  | 13.7620        | 13.6594  | 13.5801  | 13.4391  | 13.3167  |
| 17  | 15.7752        | 15.6703  | 15.5902  | 15.4487  | 15.3265  |
| 19  | 17.7858        | 17.6790  | 17.5981  | 17.4563  | 17.3343  |
| 21  | 19.7945        | 19.6860  | 19.6045  | 19.4625  | 19.3405  |
| 23  | 21.8017        | 21.6918  | 21.6099  | 21.4676  | 21.3457  |
| 25  | 23.8078        | 23.6967  | 23.6143  | 23.4719  | 23.3501  |
| 27  | 25.8130        | 25.7009  | 25.6181  | 25.4755  | 25.3538  |
| 29  | 27.8176        | 27.7045  | 27.6214  | 27.4787  | 27.3571  |
| 31  | 29.8216        | 29.7076  | 29.6242  | 29.4814  | 29.3599  |
| 33  | 31.8251        | 31.7104  | 31.6267  | 31.4838  | 31.3623  |
| 35  | 33.8282        | 33.7128  | 33.6289  | 33.4860  | 33.3645  |
| 37  | 35.8311        | 35.7150  | 35.6310  | 35.4879  | 35.3665  |
| 39  | 37.8336        | 37.7169  | 37.6327  | 37.4896  | 37.3682  |
| 41  | 39.8359        | 39.7187  | 39.6343  | 39.4911  | 39.3698  |
| 43  | 41.8380        | 41.7203  | 41.6357  | 41.4925  | 41.3712  |
| 45  | 43.8399        | 43.7217  | 43.6371  | 43.4938  | 43.3725  |
| 47  | 45.8416        | 45.7231  | 45.6383  | 45.4950  | 45.3737  |
| 49  | 47.8432        | 47.7243  | 47.6394  | 47.4960  | 47.3748  |
| 51  | 49.8447        | 49.7254  | 49.6404  | 49.4970  | 49.3758  |
| 53  | 51.8461        | 51.7265  | 51.6414  | 51.4979  | 51.3768  |
| 55  | 53.8474        | 53.7274  | 53.6422  | 53.4988  | 53.3776  |
| 57  | 55.8486        | 55.7283  | 55.6431  | 55.4996  | 55.3784  |
| 59  | 57.8497        | 57.7292  | 57.6438  | 57.5003  | 57.3792  |
| 61  | 59.8508        | 59.7300  | 59.6445  | 59.5010  | 59.3799  |
| 63  | 61.8517        | 61.7307  | 61.6452  | 61.5016  | 61.3806  |
| 65  | 63.8526        | 63.7314  | 63.6458  | 63.5022  | 63.3812  |
| 67  | 65.8535        | 65.7320  | 65.6464  | 65.5028  | 65.3818  |
| 69  | 67.8543        | 67.7327  | 67.6469  | 67.5033  | 67.3823  |
| 71  | 69.8551        | 69.7332  | 69.6475  | 69.5038  | 69.3828  |
| 73  | 71.8558        | 71.7338  | 71.6480  | 71.5043  | 71.3833  |
| 75  | 73.8565        | 73.7343  | 73.6484  | 73.5048  | 73.3838  |
| 77  | 75.8572        | 75.7348  | 75.6489  | 75.5052  | 75.3842  |
| 79  | 77.8579        | 77.7352  | 77.6493  | 77.5056  | 77.3846  |
| 81  | 79.8584        | 79.7357  | 79.6497  | 79.5060  | 79.3850  |
| 83  | 81.8590        | 81.7361  | 81.6501  | 81.5064  | 81.3854  |
| 85  | 83.8595        | 83.7365  | 83.6505  | 83.5067  | 83.3858  |
| 87  | 85.8600        | 85.7369  | 85.6508  | 85.5071  | 85.3861  |
| 89  | 87.8605        | 87.7373  | 87.6511  | 87.5074  | 87.3864  |
| 91  | 89.8610        | 89.7376  | 89.6514  | 89.5077  | 89.3867  |
| 93  | 91.8614        | 91.7379  | 91.6517  | 91.5080  | 91.3870  |
| 95  | 93.8619        | 93.7383  | 93.6520  | 93.5082  | 93.3873  |
| 97  | 95.8623        | 95.7386  | 95.6523  | 95.5085  | 95.3876  |
| 99  | 97.8627        | 97.7389  | 97.6526  | 97.5088  | 97.3879  |
| 101   | 99.8631        | 99.7391  | 99.6528  | 99.5090  | 99.3881  |
| 103   | 101.8635       | 101.7394 | 101.6531 | 101.5093 | 101.3883 |
| 105   | 103.8638       | 103.7397 | 103.6533 | 103.5095 | 103.3886 |
| 107   | 105.8642       | 105.7399 | 105.6535 | 105.5097 | 105.3888 |
| 109   | 107.8645       | 107.7402 | 107.6537 | 107.5099 | 107.3890 |
| 111   | 109.8648       | 109.7404 | 109.6539 | 109.5101 | 109.3893 |

**Table 4. (Continued) Checking Internal Spur Gear Sizes by Measurement Between Wires**

| ODD NUMBERS OF TEETH  |                |          |          |          |          |
|---|----------------|----------|----------|----------|----------|
| Dimensions in table are for 1 diametral pitch and Van Keuren standard wire sizes. For any other diametral pitch, divide dimensions in table by given pitch. |                |          |          |          |          |
| Wire or pin diameter = $\frac{1.44}{\text{Diametral Pitch}}$  |                |          |          |          |          |
| No. of Teeth  | Pressure Angle |          |          |          |          |
|   | 14½°           | 17½°     | 20°      | 25°      | 30°      |
| 113   | 111.8651       | 111.7406 | 111.6541 | 111.5103 | 111.3895 |
| 115   | 113.8654       | 113.7409 | 113.6543 | 113.5105 | 113.3897 |
| 117   | 115.8657       | 115.7411 | 115.6545 | 115.5107 | 115.3899 |
| 119   | 117.8660       | 117.7413 | 117.6547 | 117.5109 | 117.3900 |
| 121   | 119.8662       | 119.7415 | 119.6548 | 119.5110 | 119.3902 |
| 123   | 121.8663       | 121.7417 | 121.6550 | 121.5112 | 121.3904 |
| 125   | 123.8668       | 123.7418 | 123.6552 | 123.5114 | 123.3905 |
| 127   | 125.8670       | 125.7420 | 125.6554 | 125.5115 | 125.3907 |
| 129   | 127.8672       | 127.7422 | 127.6556 | 127.5117 | 127.3908 |
| 131   | 129.8675       | 129.7424 | 129.6557 | 129.5118 | 129.3910 |
| 133   | 131.8677       | 131.7425 | 131.6559 | 131.5120 | 131.3911 |
| 135   | 133.8679       | 133.7427 | 133.6560 | 133.5121 | 133.3913 |
| 137   | 135.8681       | 135.7428 | 135.6561 | 135.5123 | 135.3914 |
| 139   | 137.8683       | 137.7430 | 137.6563 | 137.5124 | 137.3916 |
| 141   | 139.8685       | 139.7431 | 139.6564 | 139.5125 | 139.3917 |
| 143   | 141.8687       | 141.7433 | 141.6565 | 141.5126 | 141.3918 |
| 145   | 143.8689       | 143.7434 | 143.6566 | 143.5127 | 143.3919 |
| 147   | 145.8691       | 145.7436 | 145.6568 | 145.5128 | 145.3920 |
| 149   | 147.8693       | 147.7437 | 147.6569 | 147.5130 | 147.3922 |
| 151   | 149.8694       | 149.7438 | 149.6570 | 149.5131 | 149.3923 |
| 153   | 151.8696       | 151.7439 | 151.6571 | 151.5132 | 151.3924 |
| 155   | 153.8698       | 153.7441 | 153.6572 | 153.5133 | 153.3925 |
| 157   | 155.8699       | 155.7442 | 155.6573 | 155.5134 | 155.3926 |
| 159   | 157.8701       | 157.7443 | 157.6574 | 157.5135 | 157.3927 |
| 161   | 159.8702       | 159.7444 | 159.6575 | 159.5136 | 159.3928 |
| 163   | 161.8704       | 161.7445 | 161.6576 | 161.5137 | 161.3929 |
| 165   | 163.8705       | 163.7446 | 163.6577 | 163.5138 | 163.3930 |
| 167   | 165.8707       | 165.7447 | 165.6578 | 165.5139 | 165.3931 |
| 169   | 167.8708       | 167.7448 | 167.6579 | 167.5139 | 167.3932 |
| 171   | 169.8710       | 169.7449 | 169.6580 | 169.5140 | 169.3933 |
| 181   | 179.8717       | 179.7453 | 179.6584 | 179.5144 | 179.3937 |
| 191   | 189.8721       | 189.7458 | 189.6588 | 189.5148 | 189.3940 |
| 201   | 199.8727       | 199.7461 | 199.6591 | 199.5151 | 199.3944 |
| 301   | 299.8759       | 299.7485 | 299.6612 | 299.5171 | 299.3965 |
| 401   | 399.8776       | 399.7496 | 399.6623 | 399.5182 | 399.3975 |
| 501   | 499.8786       | 499.7504 | 499.6629 | 499.5188 | 499.3981 |

**Table 5. Van Keuren Wire Diameters for Gears**

| External Gears Wire Dia. = 1.728 ÷ D.P. |         |      |         | Internal Gears Wire Dia. = 1.44 ÷ D.P. |         |      |         |
|---|---------|------|---------|--|---------|------|---------|
| D.P.                                    | Dia.    | D.P. | Dia.    | D.P.                                   | Dia.    | D.P. | Dia.    |
| 2                                       | 0.86400 | 16   | 0.10800 | 2                                      | 0.72000 | 16   | 0.09000 |
| 2½                                      | 0.69120 | 18   | 0.09600 | 2½                                     | 0.57600 | 18   | 0.08000 |
| 3                                       | 0.57600 | 20   | 0.08640 | 3                                      | 0.48000 | 20   | 0.07200 |
| 4                                       | 0.43200 | 22   | 0.07855 | 4                                      | 0.36000 | 22   | 0.06545 |
| 5                                       | 0.34560 | 24   | 0.07200 | 5                                      | 0.28800 | 24   | 0.06000 |
| 6                                       | 0.28800 | 28   | 0.06171 | 6                                      | 0.24000 | 28   | 0.05143 |
| 7                                       | 0.24686 | 32   | 0.05400 | 7                                      | 0.20571 | 32   | 0.04500 |
| 8                                       | 0.21600 | 36   | 0.04800 | 8                                      | 0.18000 | 36   | 0.04000 |
| 9                                       | 0.19200 | 40   | 0.04320 | 9                                      | 0.16000 | 40   | 0.03600 |
| 10                                      | 0.17280 | 48   | 0.03600 | 10                                     | 0.14400 | 48   | 0.03000 |
| 11                                      | 0.15709 | 64   | 0.02700 | 11                                     | 0.13091 | 64   | 0.02250 |
| 12                                      | 0.14400 | 72   | 0.02400 | 12                                     | 0.12000 | 72   | 0.02000 |
| 14                                      | 0.12343 | 80   | 0.02160 | 14                                     | 0.10286 | 80   | 0.01800 |

**Measurements for Checking Internal Gears when Wire Diameter Equals 1.44 Divided by Diametral Pitch.**—Tables 3 and 4 give measurements between wires for checking internal gears of 1 diametral pitch. For any other diametral pitch, divide the measurement given in the table by the diametral pitch required. These measurements are based upon the Van Keuren standard wire size, which, for internal spur gears, equals 1.44 divided by the diametral pitch (see Table 5).

*Even Number of Teeth:* For an even number of teeth above 170 and not in Table 3, proceed as shown by the following example: Assume that the number of teeth = 380 and pressure angle is  $14\frac{1}{2}$  degrees; then, for 1 diametral pitch, figure at left of decimal point = given number of teeth  $- 2 = 380 - 2 = 378$ . Figure at right of decimal point lies between decimal values given in table for 300 and 400 teeth and is obtained by interpolation. Thus,  $380 - 300 = 80$  (change to 0.80);  $0.8803 - 0.8795 = 0.0008$ ; hence, decimal required =  $0.8795 + (0.80 \times 0.0008) 0.88014$ . Total dimension = 378.88014.

*Odd Number of Teeth:* Table 4 is for internal gears having odd numbers of teeth. For tooth numbers above 171 and not in the table, proceed as shown by the following example: Assume that number of teeth = 337 and pressure angle is  $14\frac{1}{2}$  degrees; then, for 1 diametral pitch, figure at left of decimal point = given No. of teeth  $- 2 = 337 - 2 = 335$ . Figure at right of decimal point lies between decimal values given in table for 301 and 401 teeth and is obtained by interpolation. Thus,  $337 - 301 = 36$  (change to 0.36);  $0.8776 - 0.8759 = 0.0017$ ; hence, decimal required =  $0.8759 + (0.36 \times 0.0017) = 0.8765$ . Total dimension = 335.8765.

**Measurements for Checking External Spur Gears when Wire Diameter Equals 1.68 Divided by Diametral Pitch.**—Tables 7 and 8 give measurements  $M$ , in inches, for checking the pitch diameters of external spur gears of 1 diametral pitch. For any other diametral pitch, divide the measurement given in the table by whatever diametral pitch is required. The result shows what measurement  $M$  should be when the pitch diameter is correct and there is no allowance for backlash. The procedure for checking for a given amount of backlash when the diameter of the measuring wires equals 1.68 divided by the diametral pitch is explained under a subsequent heading. Tables 7 and 8 are based upon wire sizes equal to 1.68 divided by the diametral pitch. The corresponding wire diameters for various diametral pitches are given in Table 6.

**Table 6. Wire Diameters for Spur and Helical Gears Based upon 1.68 Constant**

| Diametral or Normal Diametral Pitch | Wire Diameter | Diametral or Normal Diametral Pitch | Wire Diameter | Diametral or Normal Diametral Pitch | Wire Diameter | Diametral or Normal Diametral Pitch | Wire Diameter |
|-------------------------------------|---------------|-------------------------------------|---------------|-------------------------------------|---------------|-------------------------------------|---------------|
| 2                                   | 0.840         | 8                                   | 0.210         | 18                                  | 0.09333       | 40                                  | 0.042         |
| $2\frac{1}{2}$                      | 0.672         | 9                                   | 0.18666       | 20                                  | 0.084         | 48                                  | 0.035         |
| 3                                   | 0.560         | 10                                  | 0.168         | 22                                  | 0.07636       | 64                                  | 0.02625       |
| 4                                   | 0.420         | 11                                  | 0.15273       | 24                                  | 0.070         | 72                                  | 0.02333       |
| 5                                   | 0.336         | 12                                  | 0.140         | 28                                  | 0.060         | 80                                  | 0.021         |
| 6                                   | 0.280         | 14                                  | 0.120         | 32                                  | 0.0525        | ...                                 | ...           |
| 7                                   | 0.240         | 16                                  | 0.105         | 36                                  | 0.04667       | ...                                 | ...           |

Pin diameter =  $1.68 \div$  diametral pitch for spur gears and  $1.68 \div$  normal diametral pitch for helical gears.

To find measurement  $M$  of an external spur gear using wire sizes equal to 1.68 inches divided by the diametral pitch, the same method is followed in using Tables 7 and 8 as that outlined for Tables 1 and 2.

**Table 7. Checking External Spur Gear Sizes by Measurement Over Wires**

| EVEN NUMBERS OF TEETH   |                |          |          |          |          |
|---|----------------|----------|----------|----------|----------|
| Dimensions in table are for 1 diametral pitch and 1.68-inch series wire sizes (a Van Keuren standard). For any other diametral pitch, divide dimension in table by given pitch. |                |          |          |          |          |
| Wire or pin diameter = $\frac{1.68}{\text{Diametral Pitch}}$  |                |          |          |          |          |
| No. of Teeth  | Pressure Angle |          |          |          |          |
|   | 14½°           | 17½°     | 20°      | 25°      | 30°      |
| 6   | 8.1298         | 8.1442   | 8.1600   | 8.2003   | 8.2504   |
| 8   | 10.1535        | 10.1647  | 10.1783  | 10.2155  | 10.2633  |
| 10  | 12.1712        | 12.1796  | 12.1914  | 12.2260  | 12.2722  |
| 12  | 14.1851        | 14.1910  | 14.2013  | 14.2338  | 14.2785  |
| 14  | 16.1964        | 16.2001  | 16.2091  | 16.2397  | 16.2833  |
| 16  | 18.2058        | 18.2076  | 18.2154  | 18.2445  | 18.2871  |
| 18  | 20.2137        | 20.2138  | 20.2205  | 20.2483  | 20.2902  |
| 20  | 22.2205        | 22.2190  | 22.2249  | 22.2515  | 22.2927  |
| 22  | 24.2265        | 24.2235  | 24.2286  | 24.2542  | 24.2949  |
| 24  | 26.2317        | 26.2275  | 26.2318  | 26.2566  | 26.2967  |
| 26  | 28.2363        | 28.2309  | 28.2346  | 28.2586  | 28.2982  |
| 28  | 30.2404        | 30.2339  | 30.2371  | 30.2603  | 30.2996  |
| 30  | 32.2441        | 32.2367  | 32.2392  | 32.2619  | 32.3008  |
| 32  | 34.2475        | 34.2391  | 34.2412  | 34.2632  | 34.3017  |
| 34  | 36.2505        | 36.2413  | 36.2430  | 36.2644  | 36.3026  |
| 36  | 38.2533        | 38.2433  | 38.2445  | 38.2655  | 38.3035  |
| 38  | 40.2558        | 40.2451  | 40.2460  | 40.2666  | 40.3044  |
| 40  | 42.2582        | 42.2468  | 42.2473  | 42.2675  | 42.3051  |
| 42  | 44.2604        | 44.2483  | 44.2485  | 44.2683  | 44.3057  |
| 44  | 46.2624        | 46.2497  | 46.2496  | 46.2690  | 46.3063  |
| 46  | 48.2642        | 48.2510  | 48.2506  | 48.2697  | 48.3068  |
| 48  | 50.2660        | 50.2522  | 50.2516  | 50.2704  | 50.3073  |
| 50  | 52.2676        | 52.2534  | 52.2525  | 52.2710  | 52.3078  |
| 52  | 54.2691        | 54.2545  | 54.2533  | 54.2716  | 54.3082  |
| 54  | 56.2705        | 56.2555  | 56.2541  | 56.2721  | 56.3086  |
| 56  | 58.2719        | 58.2564  | 58.2548  | 58.2726  | 58.3089  |
| 58  | 60.2731        | 60.2572  | 60.2555  | 60.2730  | 60.3093  |
| 60  | 62.2743        | 62.2580  | 62.2561  | 62.2735  | 62.3096  |
| 62  | 64.2755        | 64.2587  | 64.2567  | 64.2739  | 64.3099  |
| 64  | 66.2765        | 66.2594  | 66.2572  | 66.2742  | 66.3102  |
| 66  | 68.2775        | 68.2601  | 68.2577  | 68.2746  | 68.3104  |
| 68  | 70.2785        | 70.2608  | 70.2582  | 70.2749  | 70.3107  |
| 70  | 72.2794        | 72.2615  | 72.2587  | 72.2752  | 72.3109  |
| 72  | 74.2803        | 74.2620  | 74.2591  | 74.2755  | 74.3111  |
| 74  | 76.2811        | 76.2625  | 76.2596  | 76.2758  | 76.3113  |
| 76  | 78.2819        | 78.2631  | 78.2600  | 78.2761  | 78.3115  |
| 78  | 80.2827        | 80.2636  | 80.2604  | 80.2763  | 80.3117  |
| 80  | 82.2834        | 82.2641  | 82.2607  | 82.2766  | 82.3119  |
| 82  | 84.2841        | 84.2646  | 84.2611  | 84.2768  | 84.3121  |
| 84  | 86.2847        | 86.2650  | 86.2614  | 86.2771  | 86.3123  |
| 86  | 88.2854        | 88.2655  | 88.2617  | 88.2773  | 88.3124  |
| 88  | 90.2860        | 90.2659  | 90.2620  | 90.2775  | 90.3126  |
| 90  | 92.2866        | 92.2662  | 92.2624  | 92.2777  | 92.3127  |
| 92  | 94.2872        | 94.2666  | 94.2626  | 94.2779  | 94.3129  |
| 94  | 96.2877        | 96.2670  | 96.2629  | 96.2780  | 96.3130  |
| 96  | 98.2882        | 98.2673  | 98.2632  | 98.2782  | 98.3131  |
| 98  | 100.2887       | 100.2677 | 100.2635 | 100.2784 | 100.3132 |
| 100   | 102.2892       | 102.2680 | 102.2638 | 102.2785 | 102.3134 |
| 102   | 104.2897       | 104.2683 | 104.2640 | 104.2787 | 104.3135 |

**Table 7. (Continued) Checking External Spur Gear Sizes by Measurement Over Wires**

| EVEN NUMBERS OF TEETH   |                |          |          |          |          |
|---|----------------|----------|----------|----------|----------|
| Dimensions in table are for 1 diametral pitch and 1.68-inch series wire sizes (a Van Keuren standard). For any other diametral pitch, divide dimension in table by given pitch. |                |          |          |          |          |
| Wire or pin diameter = $\frac{1.68}{\text{Diametral Pitch}}$  |                |          |          |          |          |
| No. of Teeth  | Pressure Angle |          |          |          |          |
|   | 14½°           | 17½°     | 20°      | 25°      | 30°      |
| 104   | 106.2901       | 106.2685 | 106.2642 | 106.2788 | 106.3136 |
| 106   | 108.2905       | 108.2688 | 108.2644 | 108.2789 | 108.3137 |
| 108   | 110.2910       | 110.2691 | 110.2645 | 110.2791 | 110.3138 |
| 110   | 112.2914       | 112.2694 | 112.2647 | 112.2792 | 112.3139 |
| 112   | 114.2918       | 114.2696 | 114.2649 | 114.2793 | 114.3140 |
| 114   | 116.2921       | 116.2699 | 116.2651 | 116.2794 | 116.3141 |
| 116   | 118.2925       | 118.2701 | 118.2653 | 118.2795 | 118.3142 |
| 118   | 120.2929       | 120.2703 | 120.2655 | 120.2797 | 120.3142 |
| 120   | 122.2932       | 122.2706 | 122.2656 | 122.2798 | 122.3143 |
| 122   | 124.2936       | 124.2708 | 124.2658 | 124.2799 | 124.3144 |
| 124   | 126.2939       | 126.2710 | 126.2660 | 126.2800 | 126.3145 |
| 126   | 128.2941       | 128.2712 | 128.2661 | 128.2801 | 128.3146 |
| 128   | 130.2945       | 130.2714 | 130.2663 | 130.2802 | 130.3146 |
| 130   | 132.2948       | 132.2716 | 132.2664 | 132.2803 | 132.3147 |
| 132   | 134.2951       | 134.2718 | 134.2666 | 134.2804 | 134.3147 |
| 134   | 136.2954       | 136.2720 | 136.2667 | 136.2805 | 136.3148 |
| 136   | 138.2957       | 138.2722 | 138.2669 | 138.2806 | 138.3149 |
| 138   | 140.2960       | 140.2724 | 140.2670 | 140.2807 | 140.3149 |
| 140   | 142.2962       | 142.2725 | 142.2671 | 142.2808 | 142.3150 |
| 142   | 144.2965       | 144.2727 | 144.2672 | 144.2808 | 144.3151 |
| 144   | 146.2967       | 146.2729 | 146.2674 | 146.2809 | 146.3151 |
| 146   | 148.2970       | 148.2730 | 148.2675 | 148.2810 | 148.3152 |
| 148   | 150.2972       | 150.2732 | 150.2676 | 150.2811 | 150.3152 |
| 150   | 152.2974       | 152.2733 | 152.2677 | 152.2812 | 152.3153 |
| 152   | 154.2977       | 154.2735 | 154.2678 | 154.2812 | 154.3153 |
| 154   | 156.2979       | 156.2736 | 156.2679 | 156.2813 | 156.3154 |
| 156   | 158.2981       | 158.2737 | 158.2680 | 158.2813 | 158.3155 |
| 158   | 160.2983       | 160.2739 | 160.2681 | 160.2814 | 160.3155 |
| 160   | 162.2985       | 162.2740 | 162.2682 | 162.2815 | 162.3155 |
| 162   | 164.2987       | 164.2741 | 164.2683 | 164.2815 | 164.3156 |
| 164   | 166.2989       | 166.2742 | 166.2684 | 166.2816 | 166.3156 |
| 166   | 168.2990       | 168.2744 | 168.2685 | 168.2816 | 168.3157 |
| 168   | 170.2992       | 170.2745 | 170.2686 | 170.2817 | 170.3157 |
| 170   | 172.2994       | 172.2746 | 172.2687 | 172.2818 | 172.3158 |
| 180   | 182.3003       | 182.2752 | 182.2691 | 182.2820 | 182.3160 |
| 190   | 192.3011       | 192.2757 | 192.2694 | 192.2823 | 192.3161 |
| 200   | 202.3018       | 202.2761 | 202.2698 | 202.2825 | 202.3163 |
| 300   | 302.3063       | 302.2790 | 302.2719 | 302.2839 | 302.3173 |
| 400   | 402.3087       | 402.2804 | 402.2730 | 402.2845 | 402.3178 |
| 500   | 502.3101       | 502.2813 | 502.2736 | 502.2850 | 502.3181 |

*Allowance for Backlash:* Tables 1, 2, 7, and 8 give measurements over wires when the pitch diameters are correct and there is no allowance for backlash or play between meshing teeth. Backlash is obtained by cutting the teeth somewhat deeper than standard, thus reducing the thickness. Usually, the teeth of both mating gears are reduced in thickness an amount equal to one-half of the total backlash desired. However, if the pinion is small, it is common practice to reduce the gear teeth the full amount of backlash and the pinion is made to standard size. The changes in measurements  $M$  over wires, for obtaining backlash in external spur gears, are listed in Table 9.

**Table 8. Checking External Spur Gear Sizes by Measurement Over Wires**

| ODD NUMBERS OF TEETH  |                |         |         |         |         |
|---|----------------|---------|---------|---------|---------|
| Dimensions in table are for 1 diametral pitch and 1.68-inch series wire sizes (a Van Keuren standard). For any other diametral pitch, divide dimension in table by given pitch. |                |         |         |         |         |
| Wire or pin diameter = $\frac{1.68}{\text{Diametral Pitch}}$  |                |         |         |         |         |
| No. of Teeth  | Pressure Angle |         |         |         |         |
|   | 14½°           | 17 ½°   | 20°     | 25°     | 30°     |
| 5   | 6.8485         | 6.8639  | 6.8800  | 6.9202  | 6.9691  |
| 7   | 8.9555         | 8.9679  | 8.9822  | 9.0199  | 9.0675  |
| 9   | 11.0189        | 11.0285 | 11.0410 | 11.0762 | 11.1224 |
| 11  | 13.0615        | 13.0686 | 13.0795 | 13.1126 | 13.1575 |
| 13  | 15.0925        | 15.0973 | 15.1068 | 15.1381 | 15.1819 |
| 15  | 17.1163        | 17.1190 | 17.1273 | 17.1570 | 17.1998 |
| 17  | 19.1351        | 19.1360 | 19.1432 | 19.1716 | 19.2136 |
| 19  | 21.1505        | 21.1498 | 21.1561 | 21.1832 | 21.2245 |
| 21  | 23.1634        | 23.1611 | 23.1665 | 23.1926 | 23.2334 |
| 23  | 25.1743        | 25.1707 | 25.1754 | 25.2005 | 25.2408 |
| 25  | 27.1836        | 27.1788 | 27.1828 | 27.2071 | 27.2469 |
| 27  | 29.1918        | 29.1859 | 29.1892 | 29.2128 | 29.2522 |
| 29  | 31.1990        | 31.1920 | 31.1948 | 31.2177 | 31.2568 |
| 31  | 33.2053        | 33.1974 | 33.1997 | 33.2220 | 33.2607 |
| 33  | 35.2110        | 35.2021 | 35.2041 | 35.2258 | 35.2642 |
| 35  | 37.2161        | 37.2065 | 37.2079 | 37.2292 | 37.2674 |
| 37  | 39.2208        | 39.2104 | 39.2115 | 39.2323 | 39.2702 |
| 39  | 41.2249        | 41.2138 | 41.2147 | 41.2349 | 41.2726 |
| 41  | 43.2287        | 43.2170 | 43.2174 | 43.2374 | 43.2749 |
| 43  | 45.2323        | 45.2199 | 45.2200 | 45.2396 | 45.2769 |
| 45  | 47.2355        | 47.2226 | 47.2224 | 47.2417 | 47.2788 |
| 47  | 49.2385        | 49.2251 | 49.2246 | 49.2435 | 49.2805 |
| 49  | 51.2413        | 51.2273 | 51.2266 | 51.2452 | 51.2820 |
| 51  | 53.2439        | 53.2294 | 53.2284 | 53.2468 | 53.2835 |
| 53  | 55.2463        | 55.2313 | 55.2302 | 55.2483 | 55.2848 |
| 55  | 57.2485        | 57.2331 | 57.2318 | 57.2497 | 57.2861 |
| 57  | 59.2506        | 59.2348 | 59.2333 | 59.2509 | 59.2872 |
| 59  | 61.2526        | 61.2363 | 61.2347 | 61.2521 | 61.2883 |
| 61  | 63.2545        | 63.2378 | 63.2360 | 63.2532 | 63.2893 |
| 63  | 65.2562        | 65.2392 | 65.2372 | 65.2543 | 65.2902 |
| 65  | 67.2579        | 67.2406 | 67.2383 | 67.2553 | 67.2911 |
| 67  | 69.2594        | 69.2419 | 69.2394 | 69.2562 | 69.2920 |
| 69  | 71.2609        | 71.2431 | 71.2405 | 71.2571 | 71.2928 |
| 71  | 73.2623        | 73.2442 | 73.2414 | 73.2579 | 73.2935 |
| 73  | 75.2636        | 75.2452 | 75.2423 | 75.2586 | 75.2942 |
| 75  | 77.2649        | 77.2462 | 77.2432 | 77.2594 | 77.2949 |
| 77  | 79.2661        | 79.2472 | 79.2440 | 79.2601 | 79.2955 |
| 79  | 81.2673        | 81.2481 | 81.2448 | 81.2607 | 81.2961 |
| 81  | 83.2684        | 83.2490 | 83.2456 | 83.2614 | 83.2967 |
| 83  | 85.2694        | 85.2498 | 85.2463 | 85.2620 | 85.2972 |
| 85  | 87.2704        | 87.2506 | 87.2470 | 87.2625 | 87.2977 |
| 87  | 89.2714        | 89.2514 | 89.2476 | 89.2631 | 89.2982 |
| 89  | 91.2723        | 91.2521 | 91.2482 | 91.2636 | 91.2987 |
| 91  | 93.2732        | 93.2528 | 93.2489 | 93.2641 | 93.2991 |
| 93  | 95.2741        | 95.2534 | 95.2494 | 95.2646 | 95.2996 |

## CHECKING GEAR SIZES

**Table 8. (Continued) Checking External Spur Gear Sizes  
by Measurement Over Wires**

| ODD NUMBERS OF TEETH  |                |          |          |          |          |
|---|----------------|----------|----------|----------|----------|
| Dimensions in table are for 1 diametral pitch and 1.68-inch series wire sizes (a Van Keuren standard). For any other diametral pitch, divide dimension in table by given pitch. |                |          |          |          |          |
| Wire or pin diameter = $\frac{1.68}{\text{Diametral Pitch}}$  |                |          |          |          |          |
| No. of Teeth  | Pressure Angle |          |          |          |          |
|   | 14½°           | 17 ½°    | 20°      | 25°      | 30°      |
| 95  | 97.2749        | 97.2541  | 97.2500  | 97.2650  | 97.3000  |
| 97  | 99.2757        | 99.2547  | 99.2506  | 99.2655  | 99.3004  |
| 99  | 101.2764       | 101.2553 | 101.2511 | 101.2659 | 101.3008 |
| 101   | 103.2771       | 103.2558 | 103.2516 | 103.2663 | 103.3011 |
| 103   | 105.2778       | 105.2563 | 105.2520 | 105.2667 | 105.3015 |
| 105   | 107.2785       | 107.2568 | 107.2525 | 107.2671 | 107.3018 |
| 107   | 109.2791       | 109.2573 | 109.2529 | 109.2674 | 109.3021 |
| 109   | 111.2798       | 111.2578 | 111.2533 | 111.2678 | 111.3024 |
| 111   | 113.2804       | 113.2583 | 113.2537 | 113.2681 | 113.3027 |
| 113   | 115.2809       | 115.2588 | 115.2541 | 115.2684 | 115.3030 |
| 115   | 117.2815       | 117.2592 | 117.2544 | 117.2687 | 117.3033 |
| 117   | 119.2821       | 119.2596 | 119.2548 | 119.2690 | 119.3036 |
| 119   | 121.2826       | 121.2601 | 121.2552 | 121.2693 | 121.3038 |
| 121   | 123.2831       | 123.2605 | 123.2555 | 123.2696 | 123.3041 |
| 123   | 125.2836       | 125.2608 | 125.2558 | 125.2699 | 125.3043 |
| 125   | 127.2841       | 127.2612 | 127.2562 | 127.2702 | 127.3046 |
| 127   | 129.2846       | 129.2615 | 129.2565 | 129.2704 | 129.3048 |
| 129   | 131.2851       | 131.2619 | 131.2568 | 131.2707 | 131.3050 |
| 131   | 133.2855       | 133.2622 | 133.2571 | 133.2709 | 133.3053 |
| 133   | 135.2859       | 135.2626 | 135.2574 | 135.2712 | 135.3055 |
| 135   | 137.2863       | 137.2629 | 137.2577 | 137.2714 | 137.3057 |
| 137   | 139.2867       | 139.3632 | 139.2579 | 139.2716 | 139.3059 |
| 139   | 141.2871       | 141.2635 | 141.2582 | 141.2718 | 141.3060 |
| 141   | 143.2875       | 143.2638 | 143.2584 | 143.2720 | 143.3062 |
| 143   | 145.2879       | 145.2641 | 145.2587 | 145.2722 | 145.3064 |
| 145   | 147.2883       | 147.2644 | 147.2589 | 147.2724 | 147.3066 |
| 147   | 149.2887       | 149.2647 | 149.2591 | 149.2726 | 149.3068 |
| 149   | 151.2890       | 151.2649 | 151.2594 | 151.2728 | 151.3069 |
| 151   | 153.2893       | 153.2652 | 153.2596 | 153.2730 | 153.3071 |
| 153   | 155.2897       | 155.2654 | 155.2598 | 155.2732 | 155.3073 |
| 155   | 157.2900       | 157.2657 | 157.2600 | 157.2733 | 157.3074 |
| 157   | 159.2903       | 159.2659 | 159.2602 | 159.2735 | 159.3076 |
| 159   | 161.2906       | 161.2661 | 161.2604 | 161.2736 | 161.3077 |
| 161   | 163.2909       | 163.2663 | 163.2606 | 163.2738 | 163.3078 |
| 163   | 165.2912       | 165.2665 | 165.2608 | 165.2740 | 165.3080 |
| 165   | 167.2915       | 167.2668 | 167.2610 | 167.2741 | 167.3081 |
| 167   | 169.2917       | 169.2670 | 169.2611 | 169.2743 | 169.3083 |
| 169   | 171.2920       | 171.2672 | 171.2613 | 171.2744 | 171.3084 |
| 171   | 173.2922       | 173.2674 | 173.2615 | 173.2746 | 173.3085 |
| 181   | 183.2936       | 183.2684 | 183.2623 | 183.2752 | 183.3091 |
| 191   | 193.2947       | 193.2692 | 193.2630 | 193.2758 | 193.3097 |
| 201   | 203.2957       | 203.2700 | 203.2636 | 203.2764 | 203.3101 |
| 301   | 303.3022       | 303.2749 | 303.2678 | 303.2798 | 303.3132 |
| 401   | 403.3056       | 403.2774 | 403.2699 | 403.2815 | 403.3147 |
| 501   | 503.3076       | 503.2789 | 503.2711 | 503.2825 | 503.3156 |

**Table 9. Backlash Allowances for External and Internal Spur Gears**

| No. of Teeth | 14½°  |       | 17½°  |       | 20°   |       | 25°   |       | 30°   |       |
|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|              | Ext.  | Int.  | Ext.  | Int.  | Ext.  | Int.  | Ext.  | Int.  | Ext.  | Int.  |
| 5            | .0019 | .0024 | .0018 | .0024 | .0017 | .0023 | .0015 | .0021 | .0013 | .0019 |
| 10           | .0024 | .0029 | .0022 | .0027 | .0020 | .0026 | .0017 | .0022 | .0015 | .0018 |
| 20           | .0028 | .0032 | .0025 | .0029 | .0023 | .0027 | .0019 | .0022 | .0016 | .0018 |
| 30           | .0030 | .0034 | .0026 | .0030 | .0024 | .0027 | .0020 | .0022 | .0016 | .0018 |
| 40           | .0031 | .0035 | .0027 | .0030 | .0025 | .0027 | .0020 | .0022 | .0017 | .0018 |
| 50           | .0032 | .0036 | .0028 | .0031 | .0025 | .0027 | .0020 | .0022 | .0017 | .0018 |
| 100          | .0035 | .0037 | .0030 | .0031 | .0026 | .0027 | .0021 | .0022 | .0017 | .0017 |
| 200          | .0036 | .0038 | .0031 | .0031 | .0027 | .0027 | .0021 | .0022 | .0017 | .0017 |

*External Gears:* For each 0.001 inch reduction in pitch-line tooth thickness, *reduce* measurement over wires obtained from Tables 1, 2, 7, or 8 by the amount shown below.

*Internal Gears:* For each 0.001 inch reduction in pitch-line tooth thickness, *increase* measurement between wires obtained from Tables 3 or 4 by the amounts shown below.

Backlash on pitch line equals double tooth thickness reduction when teeth of *both* mating gears are reduced. If teeth of *one* gear only are reduced, backlash on pitch line equals amount of reduction.

*Example:* For a 30-tooth, 10-diametral pitch, 20-degree pressure angle, external gear the measurement over wires from Table 1 is  $32.4102 \div 10$ . For a backlash of 0.002 this measurement must be reduced by  $2 \times 0.0024$  to 3.2362 or (3.2410 - 0.0048).

**Measurements for Checking Helical Gears using Wires or Balls.**—Helical gears may be checked for size by using one wire, or ball; two wires, or balls; and three wires, depending on the case at hand. Three wires may be used for measurement of either even or odd tooth numbers provided that the face width and helix angle of the gear permit the arrangement of two wires in adjacent tooth spaces on one side of the gear and a third wire on the opposite side. The wires should be held between flat, parallel plates. The measurement between these plates, and perpendicular to the gear axis, will be the same for both even and odd numbers of teeth because the axial displacement of the wires with the odd numbers of teeth does not affect the perpendicular measurement between the plates. The calculation of measurements over three wires is the same as described for measurements over two wires for even numbers of teeth.

*Measurements over One Wire or One Ball for Even or Odd Numbers of Teeth:* This measurement is calculated by the method for measurement over two wires for even numbers of teeth and the result divided by two to obtain the measurement from over the wire or ball to the center of the gear mounted on an arbor.

*Measurement over Two Wires or Two Balls for Even Numbers of Teeth:* The measurement over two wires (or two balls kept in the same plane by holding them against a surface parallel to the face of the gear) is calculated as follows: First, calculate the pitch diameter of the helical gear from the formula  $D = \text{Number of teeth} \div \text{the product of the normal diametral pitch and the cosine of the helix angle}$ ,  $D = N \div (P_n \times \cos \psi)$ . Next, calculate the number of teeth,  $N_e$ , there would be in a spur gear for it to have the same tooth curvature as the helical gear has in the normal plane:  $N_e = N / \cos^3 \psi$ . Next, refer to Table 7 for spur gears with even tooth numbers and find, by interpolation, the *decimal* value of the constant for this number of teeth under the given *normal* pressure angle. Finally, add 2 to this decimal value and divide the sum by the normal diametral pitch  $P_n$ . The result of this calculation, added to the pitch diameter  $D$ , is the measurement over two wires or balls.

*Example:* A helical gear has 32 teeth of 6 normal diametral pitch, 20 degree pressure angle, and 23 degree helix angle. Determine the measurement over two wires,  $M$ , without allowance for backlash.

$D = 32 \div 6 \times \cos 23^\circ = 5.7939$ ;  $N_e = 32 \div \cos^3 23^\circ = 41.027$ ; and in Table 7, fourth column, the decimal part of the measurement for 40 teeth is .2473 and that for 42 teeth is .2485. The



decimal part for 41.027 teeth is, by interpolation,  $\frac{(41.027 - 40)}{(42 - 40)} \times (.2485 - .2473) + .2473 = 0.2479$ ;  $(0.2479 + 2) \div 6 = 0.3747$ ; and  $M = 0.3747 + 5.7939 = 6.1686$ .

This measurement over wires or balls is based upon the use of  $1.68/P_n$  wires or balls. If measurements over  $1.728/P_n$  diameter wires or balls are preferred, use Table 1 to find the decimal part described above instead of Table 7.

**Measurement over Two Wires or Two Balls for Odd Numbers of Teeth:** The procedure is similar to that for two wire or two ball measurement for even tooth numbers except that a correction is made in the final  $M$  value to account for the wires or balls not being diametrically opposite by one-half tooth interval. In addition, care must be taken to ensure that the balls or wires are kept in a plane of the gear's rotation as described previously.

**Example:** A helical gear has 13 teeth of 8 normal diametral pitch,  $14\frac{1}{2}$  degree pressure angle, and 45 degree helix angle. Determine measurement  $M$  without allowance for backlash based upon the use of  $1.728/P_n$  balls or wires.

As before,  $D = 13/8 \times \cos 45^\circ = 2.2981$ ;  $N_e = 13/\cos^3 45^\circ = 36.770$ ; and in the second column of Table 1 the decimal part of the measurement for 36 teeth is .4565 and that for 38 teeth is .4603. The decimal part for 36.770 teeth is, by interpolation,  $\frac{(36.770 - 36)}{(38 - 36)} \times (.4603 - .4565) + .4565 = 0.4580$ ;  $(0.4580 + 2)/8 = 0.3073$ ; and  $M = 0.3073 + 2.2981 = 2.6054$ . This measurement is correct for three-wire measurements but, for two balls or wires held in the plane of rotation of the gear,  $M$  must be corrected as follows:

$$\begin{aligned} M \text{ corrected} &= (M - \text{Ball Diam.}) \times \cos(90^\circ/N) + \text{Ball Diam.} \\ &= (2.6054 - 1.728/8) \times \cos(90^\circ/13) + 1.728/8 = 2.5880 \end{aligned}$$

### Checking Spur Gear Size by Chordal Measurement Over Two or More Teeth.—

Another method of checking gear sizes, that is generally available, is illustrated by the diagram accompanying Table 10. A vernier caliper is used to measure the distance  $M$  over two or more teeth. The diagram illustrates the measurement over two teeth (or with one intervening tooth space), but three or more teeth might be included, depending upon the pitch. The jaws of the caliper are merely held in contact with the sides or profiles of the teeth and perpendicular to the axis of the gear. Measurement  $M$  for involute teeth of the correct size is determined as follows

**General Formula for Checking External and Internal Spur Gears by Measurement Over Wires:** The following formulas may be used for pressure angles or wire sizes not covered by the tables. In these formulas,  $M$  = measurement over wires for external gears or measurement between wires for internal gears;  $D$  = pitch diameter;  $T$  = arc tooth thickness on pitch circle;  $W$  = wire diameter;  $N$  = number of gear teeth;  $A$  = pressure angle of gear;  $a$  = angle, the cosine of which is required in Formulas (2) and (3).

First determine the involute function of angle  $a$  ( $\text{inv } a$ ); then the corresponding angle  $a$  is found by referring to the tables of involute functions beginning on page 104,

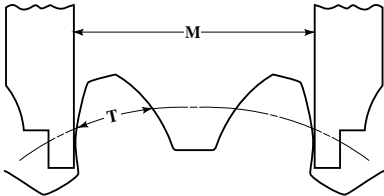
$$\text{inv } a = \text{inv } A \pm \frac{T}{D} \pm \frac{W}{D \cos A} \mp \frac{\pi}{N} \quad (1)$$

$$\text{For even numbers of teeth, } M = \frac{D \cos A}{\cos a} \pm W \quad (2)$$

$$\text{For odd numbers of teeth, } M = \left( \frac{D \cos A}{\cos a} \right) \left( \cos \frac{90^\circ}{N} \right) \pm W \quad (3)$$

**Note:** In Formulas (1), (2), and (3), use the upper sign for external and the lower sign for internal gears wherever a  $\pm$  or  $\mp$  appears in the formulas.

**Table 10. Chordal Measurements over Spur Gear Teeth of 1 Diametral Pitch**

| <p>Find value of <math>M</math> under pressure angle and opposite number of teeth; divide <math>M</math> by diametral pitch of gear to be measured and then subtract one-half total backlash to obtain a measurement <math>M</math> equivalent to given pitch and backlash. The number of teeth to gage or measure over is shown by Table 11.</p>  |                          |                      |                          |                      |                          |                      |                          |
|---|--------------------------|----------------------|--------------------------|----------------------|--------------------------|----------------------|--------------------------|
| Number of Gear Teeth  | $M$ in Inches for 1 D.P. | Number of Gear Teeth | $M$ in Inches for 1 D.P. | Number of Gear Teeth | $M$ in Inches for 1 D.P. | Number of Gear Teeth | $M$ in Inches for 1 D.P. |
| Pressure Angle, 14½ Degrees   |                          |                      |                          |                      |                          |                      |                          |
| 12  | 4.6267                   | 37                   | 7.8024                   | 62                   | 14.0197                  | 87                   | 20.2370                  |
| 13  | 4.6321                   | 38                   | 10.8493                  | 63                   | 17.0666                  | 88                   | 23.2838                  |
| 14  | 4.6374                   | 39                   | 10.8547                  | 64                   | 17.0720                  | 89                   | 23.2892                  |
| 15  | 4.6428                   | 40                   | 10.8601                  | 65                   | 17.0773                  | 90                   | 23.2946                  |
| 16  | 4.6482                   | 41                   | 10.8654                  | 66                   | 17.0827                  | 91                   | 23.2999                  |
| 17  | 4.6536                   | 42                   | 10.8708                  | 67                   | 17.0881                  | 92                   | 23.3053                  |
| 18  | 4.6589                   | 43                   | 10.8762                  | 68                   | 17.0934                  | 93                   | 23.3107                  |
| 19  | 7.7058                   | 44                   | 10.8815                  | 69                   | 17.0988                  | 94                   | 23.3160                  |
| 20  | 7.7112                   | 45                   | 10.8869                  | 70                   | 17.1042                  | 95                   | 23.3214                  |
| 21  | 7.7166                   | 46                   | 10.8923                  | 71                   | 17.1095                  | 96                   | 23.3268                  |
| 22  | 7.7219                   | 47                   | 10.8976                  | 72                   | 17.1149                  | 97                   | 23.3322                  |
| 23  | 7.7273                   | 48                   | 10.9030                  | 73                   | 17.1203                  | 98                   | 23.3375                  |
| 24  | 7.7326                   | 49                   | 10.9084                  | 74                   | 17.1256                  | 99                   | 23.3429                  |
| 25  | 7.7380                   | 50                   | 10.9137                  | 75                   | 17.1310                  | 100                  | 23.3483                  |
| 26  | 7.7434                   | 51                   | 13.9606                  | 76                   | 20.1779                  | 101                  | 26.3952                  |
| 27  | 7.7488                   | 52                   | 13.9660                  | 77                   | 20.1833                  | 102                  | 26.4005                  |
| 28  | 7.7541                   | 53                   | 13.9714                  | 78                   | 20.1886                  | 103                  | 26.4059                  |
| 29  | 7.7595                   | 54                   | 13.9767                  | 79                   | 20.1940                  | 104                  | 26.4113                  |
| 30  | 7.7649                   | 55                   | 13.9821                  | 80                   | 20.1994                  | 105                  | 26.4166                  |
| 31  | 7.7702                   | 56                   | 13.9875                  | 81                   | 20.2047                  | 106                  | 26.4220                  |
| 32  | 7.7756                   | 57                   | 13.9929                  | 82                   | 20.2101                  | 107                  | 26.4274                  |
| 33  | 7.7810                   | 58                   | 13.9982                  | 83                   | 20.2155                  | 108                  | 26.4327                  |
| 34  | 7.7863                   | 59                   | 14.0036                  | 84                   | 20.2208                  | 109                  | 26.4381                  |
| 35  | 7.7917                   | 60                   | 14.0090                  | 85                   | 20.2262                  | 110                  | 26.4435                  |
| 36  | 7.7971                   | 61                   | 14.0143                  | 86                   | 20.2316                  | ...                  | ...                      |
| Pressure Angle, 20 Degrees  |                          |                      |                          |                      |                          |                      |                          |
| 12  | 4.5963                   | 30                   | 10.7526                  | 48                   | 16.9090                  | 66                   | 23.0653                  |
| 13  | 4.6103                   | 31                   | 10.7666                  | 49                   | 16.9230                  | 67                   | 23.0793                  |
| 14  | 4.6243                   | 32                   | 10.7806                  | 50                   | 16.9370                  | 68                   | 23.0933                  |
| 15  | 4.6383                   | 33                   | 10.7946                  | 51                   | 16.9510                  | 69                   | 23.1073                  |
| 16  | 4.6523                   | 34                   | 10.8086                  | 52                   | 16.9650                  | 70                   | 23.1214                  |
| 17  | 4.6663                   | 35                   | 10.8226                  | 53                   | 16.9790                  | 71                   | 23.1354                  |
| 18  | 4.6803                   | 36                   | 10.8366                  | 54                   | 16.9930                  | 72                   | 23.1494                  |
| 19  | 7.6464                   | 37                   | 13.8028                  | 55                   | 19.9591                  | 73                   | 26.1155                  |
| 20  | 7.6604                   | 38                   | 13.8168                  | 56                   | 19.9731                  | 74                   | 26.1295                  |
| 21  | 7.6744                   | 39                   | 13.8307                  | 57                   | 19.9872                  | 75                   | 26.1435                  |
| 22  | 7.6884                   | 40                   | 13.8447                  | 58                   | 20.0012                  | 76                   | 26.1575                  |
| 23  | 7.7024                   | 41                   | 13.8587                  | 59                   | 20.0152                  | 77                   | 26.1715                  |
| 24  | 7.7165                   | 42                   | 13.8727                  | 60                   | 20.0292                  | 78                   | 26.1855                  |
| 25  | 7.7305                   | 43                   | 13.8867                  | 61                   | 20.0432                  | 79                   | 26.1995                  |
| 26  | 7.7445                   | 44                   | 13.9007                  | 62                   | 20.0572                  | 80                   | 26.2135                  |
| 27  | 7.7585                   | 45                   | 13.9147                  | 63                   | 20.0712                  | 81                   | 26.2275                  |
| 28  | 10.7246                  | 46                   | 16.8810                  | 64                   | 23.0373                  | ...                  | ...                      |
| 29  | 10.7386                  | 47                   | 16.8950                  | 65                   | 23.0513                  | ...                  | ...                      |

*Table for Determining the Chordal Dimension:* Table 10 gives the chordal dimensions for one diametral pitch when measuring over the number of teeth indicated in Table 11. To obtain any chordal dimension, it is simply necessary to divide chord  $M$  in the table (opposite the given number of teeth) by the diametral pitch of the gear to be measured and then subtract from the quotient one-half the total backlash between the mating pair of gears. In cases where a small pinion is used with a large gear and all of the backlash is to be obtained by reducing the gear teeth, the total amount of backlash is subtracted from the chordal dimension of the gear and nothing from the chordal dimension of the pinion. The application of the tables will be illustrated by an example.

**Table 11. Number of Teeth Included in Chordal Measurement**

| Tooth Range for 14½° Pressure Angle | Tooth Range for 20° Pressure Angle | Number of Teeth to Gage Over | Tooth Range for 14½° Pressure Angle | Tooth Range for 20° Pressure Angle | Number of Teeth to Gage Over |
|-------------------------------------|------------------------------------|------------------------------|-------------------------------------|------------------------------------|------------------------------|
| 12 to 18                            | 12 to 18                           | 2                            | 63 to 75                            | 46 to 54                           | 6                            |
| 19 to 37                            | 19 to 27                           | 3                            | 76 to 87                            | 55 to 63                           | 7                            |
| 38 to 50                            | 28 to 36                           | 4                            | 88 to 100                           | 64 to 72                           | 8                            |
| 51 to 62                            | 37 to 45                           | 5                            | 101 to 110                          | 73 to 81                           | 9                            |

This table shows the number of teeth to be included between the jaws of the vernier caliper in measuring dimension  $M$  as explained in connection with Table 10.

*Example:* Determine the chordal dimension for checking the size of a gear having 30 teeth of 5 diametral pitch and a pressure angle of 20 degrees. A total backlash of 0.008 inch is to be obtained by reducing equally the teeth of both mating gears.

Table 10 shows that chordal distance for 30 teeth of one diametral pitch and a pressure angle of 20 degrees is 10.7526 inches; one-half of the backlash equals 0.004 inch; hence,

$$\text{Chordal dimension} = \frac{10.7526}{5} - 0.004 = 2.1465 \text{ inches}$$

Table 11 shows that this is the chordal dimension when the vernier caliper spans four teeth, this being the number of teeth to gage over whenever gears of 20-degree pressure angle have any number of teeth from 28 to 36, inclusive.

If it is considered necessary to leave enough stock on the gear teeth for a shaving or finishing cut, this allowance is simply added to the chordal dimension of the finished teeth to obtain the required measurement over the teeth for the roughing operation. It may be advisable to place this chordal dimension for rough machining on the detail drawing.

**Formula for Chordal Dimension  $M$ .**—The required measurement  $M$  over spur gear teeth may be obtained by the following formula in which  $R$  = pitch radius of gear,  $A$  = pressure angle,  $T$  = tooth thickness along pitch circle,  $N$  = number of gear teeth,  $S$  = number of tooth spaces between caliper jaws,  $F$  = a factor depending on the pressure angle = 0.01109 for 14½°; = 0.01973 for 17½°; = 0.0298 for 20°; = 0.04303 for 22½°; = 0.05995 for 25°. This factor  $F$  equals twice the involute function of the pressure angle.

$$M = R \times \cos A \times \left( \frac{T}{R} + \frac{6.2832 \times S}{N} + F \right)$$

*Example:* A spur gear has 30 teeth of 6 diametral pitch and a pressure angle of 14½ degrees. Determine measurement  $M$  over three teeth, there being two intervening tooth spaces.

The pitch radius = 2½ inches, the arc tooth thickness equivalent to 6 diametral pitch is 0.2618 inch (if no allowance is made for backlash) and factor  $F$  for 14½ degrees = 0.01109 inch.

$$M = 2.5 \times 0.96815 \times \left( \frac{0.2618}{2.5} + \frac{6.2832 \times 2}{30} + 0.01109 \right) = 1.2941 \text{ inches}$$

**Checking Enlarged Pinions by Measuring Over Pins or Wires.**—When the teeth of small spur gears or pinions would be undercut if generated by an unmodified straight-sided rack cutter or hob, it is common practice to make the outside diameter larger than standard. The amount of increase in outside diameter varies with the pressure angle and number of teeth, as shown by Table 7 on page 2050. The teeth are always cut to standard depth on a generating type of machine such as a gear hobber or gear shaper; and because the number of teeth and pitch are not changed, the pitch diameter also remains unchanged. The tooth thickness on the pitch circle, however, is increased and wire sizes suitable for standard gears are not large enough to extend above the tops of these enlarged gears or pinions; hence, the Van Keuren wire size recommended for these enlarged pinions equals  $1.92 \div$  diametral pitch. Table 12 gives measurements over wires of this size, for checking full-depth involute gears of 1 diametral pitch. For any other pitch, merely divide the measurement given in the table by the diametral pitch. Table 12 applies to pinions that have been enlarged by the same amounts as given in tables 7 and 8, starting on page 2050. These enlarged pinions will mesh with standard gears; but if the standard center distance is to be maintained, reduce the gear diameter below the standard size by as much as the pinion diameter is increased.

**Table 12. Checking Enlarged Spur Pinions by Measurement Over Wires**

| Measurements over wires are given in table for 1 diametral pitch. For any other diametral pitch, divide measurement in table by given pitch. Wire size equals $1.92 \div$ diametral pitch. |                                    |                                   |                        |  |                                    |                                   |                        |
|--|------------------------------------|-----------------------------------|------------------------|--|------------------------------------|-----------------------------------|------------------------|
| Number of Teeth  | Outside or Major Diameter (Note 1) | Circular Tooth Thickness (Note 2) | Measurement Over Wires | Number of Teeth  | Outside or Major Diameter (Note 1) | Circular Tooth Thickness (Note 2) | Measurement Over Wires |
| 14½-degree full-depth involute teeth:  |                                    |                                   |                        | 20-degree full-depth involute teeth:   |                                    |                                   |                        |
| 10   | 13.3731                            | 1.9259                            | 13.6186                | 10   | 12.936                             | 1.912                             | 13.5039                |
| 11   | 14.3104                            | 1.9097                            | 14.4966                | 11   | 13.818                             | 1.868                             | 14.3299                |
| 12   | 15.2477                            | 1.8935                            | 15.6290                | 12   | 14.702                             | 1.826                             | 15.4086                |
| 13   | 16.1850                            | 1.8773                            | 16.5211                | 13   | 15.584                             | 1.783                             | 16.2473                |
| 14   | 17.1223                            | 1.8611                            | 17.6244                | 14   | 16.468                             | 1.741                             | 17.2933                |
| 15   | 18.0597                            | 1.8449                            | 18.5260                | 15   | 17.350                             | 1.698                             | 18.1383                |
| 16   | 18.9970                            | 1.8286                            | 19.6075                | 16   | 18.234                             | 1.656                             | 19.1596                |
| 17   | 19.9343                            | 1.8124                            | 20.5156                | 17   | 19.116                             | 1.613                             | 20.0080                |
| 18   | 20.8716                            | 1.7962                            | 21.5806                | <p>Note 1: These enlargements, which are to improve the tooth form and avoid undercut, conform to those given in Tables 7 and 8, starting on page 2050 where data will be found on the minimum number of teeth in the mating gear.</p> <p>Note 2: The circular or arc thickness is at the standard pitch diameter. The corresponding chordal thickness may be found as follows: Multiply arc thickness by 90 and then divide product by <math>3.1416 \times</math> pitch radius; find sine of angle thus obtained and multiply it by pitch diameter.</p> |                                    |                                   |                        |
| 19   | 21.8089                            | 1.7800                            | 22.4934                |  |                                    |                                   |                        |
| 20   | 22.7462                            | 1.7638                            | 23.5451                |  |                                    |                                   |                        |
| 21   | 23.6835                            | 1.7476                            | 24.4611                |  |                                    |                                   |                        |
| 22   | 24.6208                            | 1.7314                            | 25.5018                |  |                                    |                                   |                        |
| 23   | 25.5581                            | 1.7151                            | 26.4201                |  |                                    |                                   |                        |
| 24   | 26.4954                            | 1.6989                            | 27.4515                |  |                                    |                                   |                        |
| 25   | 27.4328                            | 1.6827                            | 28.3718                |  |                                    |                                   |                        |
| 26   | 28.3701                            | 1.6665                            | 29.3952                |  |                                    |                                   |                        |
| 27   | 29.3074                            | 1.6503                            | 30.3168                |  |                                    |                                   |                        |
| 28   | 30.2447                            | 1.6341                            | 31.3333                |  |                                    |                                   |                        |
| 29   | 31.1820                            | 1.6179                            | 32.2558                |  |                                    |                                   |                        |
| 30   | 32.1193                            | 1.6017                            | 33.2661                |  |                                    |                                   |                        |
| 31   | 33.0566                            | 1.5854                            | 34.1889                |  |                                    |                                   |                        |

**GEAR MATERIALS**

**Classification of Gear Steels.**—Gear steels may be divided into two general classes — the plain carbon and the alloy steels. Alloy steels are used to some extent in the industrial field, but heat-treated plain carbon steels are far more common. The use of untreated alloy steels for gears is seldom, if ever, justified, and then, only when heat-treating facilities are lacking. The points to be considered in determining whether to use heat-treated plain carbon steels or heat-treated alloy steels are: Does the service condition or design require the superior characteristics of the alloy steels, or, if alloy steels are not required, will the advantages to be derived offset the additional cost? For most applications, plain carbon steels, heat-treated to obtain the best of their qualities for the service intended, are satisfactory and quite economical. The advantages obtained from using heat-treated alloy steels in place of heat-treated plain carbon steels are as follows:

- 1) Increased surface hardness and depth of hardness penetration for the same carbon content and quench.
- 2) Ability to obtain the same surface hardness with a less drastic quench and, in the case of some of the alloys, a lower quenching temperature, thus giving less distortion.
- 3) Increased toughness, as indicated by the higher values of yield point, elongation, and reduction of area.
- 4) Finer grain size, with the resulting higher impact toughness and increased wear resistance.
- 5) In the case of some of the alloys, better machining qualities or the possibility of machining at higher hardnesses.

**Use of Casehardening Steels.**—Each of the two general classes of gear steels may be further subdivided as follows: 1) Casehardening steels; 2) full-hardening steels; and 3) steels that are heat-treated and drawn to a hardness that will permit machining.

The first two — casehardening and full-hardening steels — are interchangeable for some kinds of service, and the choice is often a matter of personal opinion. Casehardening steels with their extremely hard, fine-grained (when properly treated) case and comparatively soft and ductile core are generally used when resistance to wear is desired. Casehardening alloy steels have a fairly tough core, but not as tough as that of the full-hardening steels. In order to realize the greatest benefits from the core properties, casehardened steels should be double-quenched. This is particularly true of the alloy steels, because the benefits derived from their use seldom justify the additional expense, unless the core is refined and toughened by a second quench. The penalty that must be paid for the additional refinement is increased distortion, which may be excessive if the shape or design does not lend itself to the casehardening process.

**Use of “Thru-Hardening” Steels.**—Thru-hardening steels are used when great strength, high endurance limit, toughness, and resistance to shock are required. These qualities are governed by the kind of steel and treatment used. Fairly high surface hardnesses are obtainable in this group, though not so high as those of the casehardening steels. For that reason, the resistance to wear is not so great as might be obtained, but when wear resistance combined with great strength and toughness is required, this type of steel is superior to the others. Thru-hardening steels become distorted to some extent when hardened, the amount depending upon the steel and quenching medium used. For that reason, thru-hardening steels are not suitable for high-speed gearing where noise is a factor, or for gearing where accuracy is of paramount importance, except, of course, in cases where grinding of the teeth is practicable. The medium and high-carbon percentages require an oil quench, but a water quench may be necessary for the lower carbon contents, in order to obtain the highest physical properties and hardness. The distortion, however, will be greater with the water quench.

**Heat-Treatment that Permits Machining.**—When the grinding of gear teeth is not practicable and a high degree of accuracy is required, hardened steels may be drawn or tem-

pered to a hardness that will permit the cutting of the teeth. This treatment gives a highly refined structure, great toughness, and, in spite of the low hardness, excellent wearing qualities. The lower strength is somewhat compensated for by the elimination of the increment loads due to the impacts which are caused by inaccuracies. When steels that have a low degree of hardness penetration from surface to core are treated in this manner, the design cannot be based on the physical properties corresponding to the hardness at the surface. Since the physical properties are determined by the hardness, the drop in hardness from surface to core will give lower physical properties at the root of the tooth, where the stress is greatest. The quenching medium may be either oil, water, or brine, depending on the steel used and hardness penetration desired. The amount of distortion, of course, is immaterial, because the machining is done after heat-treating.

**Making Pinion Harder than Gear to Equalize Wear.**—Beneficial results from a wear standpoint are obtained by making the pinion harder than the gear. The pinion, having a lesser number of teeth than the gear, naturally does more work per tooth, and the differential in hardness between the pinion and the gear (the amount being dependent on the ratio) serves to equalize the rate of wear. The harder pinion teeth correct the errors in the gear teeth to some extent by the initial wear and then seem to burnish the teeth of the gear and increase its ability to withstand wear by the greater hardness due to the cold-working of the surface. In applications where the gear ratio is high and there are no severe shock loads, a casehardened pinion running with an oil-treated gear, treated to a Brinell hardness at which the teeth may be cut after treating, is an excellent combination. The pinion, being relatively small, is distorted but little, and distortion in the gear is circumvented by cutting the teeth after treatment.

**Forged and Rolled Carbon Steels for Gears.**—These compositions cover steel for gears in three groups, according to heat treatment, as follows:

- a) case-hardened gears
- b) unhardened gears, not heat treated after machining
- c) hardened and tempered gears

Forged and rolled carbon gear steels are purchased on the basis of the requirements as to chemical composition specified in [Table 1](#). Class N steel will normally be ordered in ten point carbon ranges within these limits. Requirements as to physical properties have been omitted, but when they are called for the requirements as to carbon shall be omitted. The steels may be made by either or both the open hearth and electric furnace processes.

**Table 1. Compositions of Forged and Rolled Carbon Steels for Gears**

| Heat Treatment          | Class | Carbon    | Manganese | Phosphorus | Sulfur    |
|-------------------------|-------|-----------|-----------|------------|-----------|
| Case-hardened           | C     | 0.15–0.25 | 0.40–0.70 | 0.045 max  | 0.055 max |
| Untreated               | N     | 0.25–0.50 | 0.50–0.80 | 0.045 max  | 0.055 max |
| Hardened (or untreated) | H     | 0.40–0.50 | 0.40–0.70 | 0.045 max  | 0.055 max |

**Forged and Rolled Alloy Steels for Gears.**—These compositions cover alloy steel for gears, in two classes according to heat treatment, as follows:

- a) casehardened gears
- b) hardened and tempered gears

Forged and rolled alloy gear steels are purchased on the basis of the requirements as to chemical composition specified in [Table 2](#). Requirements as to physical properties have been omitted. The steel shall be made by either or both the open hearth and electric furnace process.

**Table 2. Compositions of Forged and Rolled Alloy Steels for Gears**

| Steel Specification   | Chemical Composition <sup>a</sup> |           |           |           |           |           |
|-----------------------|-----------------------------------|-----------|-----------|-----------|-----------|-----------|
|                       | C                                 | Mn        | Si        | Ni        | Cr        | Mo        |
| AISI 4130             | 0.28–0.30                         | 0.40–0.60 | 0.20–0.35 | ...       | 0.80–1.1  | 0.15–0.25 |
| AISI 4140             | 0.38–0.43                         | 0.75–1.0  | 0.20–0.35 | ...       | 0.80–1.1  | 0.15–0.25 |
| AISI 4340             | 0.38–0.43                         | 0.60–0.80 | 0.20–0.35 | 1.65–2.0  | 0.70–0.90 | 0.20–0.30 |
| AISI 4615             | 0.13–0.18                         | 0.45–0.65 | 0.20–0.35 | 1.65–2.0  | ...       | 0.20–0.30 |
| AISI 4620             | 0.17–0.22                         | 0.45–0.65 | 0.20–0.35 | 1.65–2.0  | ...       | 0.20–0.30 |
| AISI 8615             | 0.13–0.18                         | 0.70–0.90 | 0.20–0.35 | 0.40–0.70 | 0.40–0.60 | 0.15–0.25 |
| AISI 8620             | 0.18–0.23                         | 0.70–0.90 | 0.20–0.35 | 0.40–0.70 | 0.40–0.60 | 0.15–0.25 |
| AISI 9310             | 0.08–0.13                         | 0.45–0.65 | 0.20–0.35 | 3.0–3.5   | 1.0–1.4   | 0.08–0.15 |
| Nitralloy             |                                   |           |           |           |           |           |
| Type N <sup>b</sup>   | 0.20–0.27                         | 0.40–0.70 | 0.20–0.40 | 3.2–3.8   | 1.0–1.3   | 0.20–0.30 |
| 135 Mod. <sup>b</sup> | 0.38–0.45                         | 0.40–0.70 | 0.20–0.40 | ...       | 1.4–1.8   | 0.30–0.45 |

<sup>a</sup> C = carbon; Mn = manganese; Si = silicon; Ni = nickel; Cr = chromium, and Mo = molybdenum.

<sup>b</sup> Both Nitralloy alloys contain aluminum 0.85–1.2%

**Steel Castings for Gears.**—It is recommended that steel castings for cut gears be purchased on the basis of chemical analysis and that only two types of analysis be used, one for case-hardened gears and the other for both untreated gears and those which are to be hardened and tempered. The steel is to be made by the open hearth, crucible, or electric furnace processes. The converter process is not recognized. Sufficient risers must be provided to secure soundness and freedom from undue segregation. Risers should not be broken off the unannealed castings by force. Where risers are cut off with a torch, the cut should be at least one-half inch above the surface of the castings, and the remaining metal removed by chipping, grinding, or other noninjurious method.

Steel for use in gears should conform to the requirements for chemical composition indicated in Table 3. All steel castings for gears must be thoroughly normalized or annealed, using such temperature and time as will entirely eliminate the characteristic structure of unannealed castings.

**Table 3. Compositions of Cast Steels for Gears**

| Steel Specification | Chemical Composition <sup>a</sup> |           |           |                    |
|---------------------|-----------------------------------|-----------|-----------|--------------------|
|                     | C                                 | Mn        | Si        |                    |
| SAE-0022            | 0.12–0.22                         | 0.50–0.90 | 0.60 Max. | May be carburized  |
| SAE-0050            | 0.40–0.50                         | 0.50–0.90 | 0.80 Max. | Hardenable 210–250 |

<sup>a</sup> C = carbon; Mn = manganese; and Si = silicon.

**Effect of Alloying Metals on Gear Steels.**—The effect of the various alloying elements on steel are here summarized to assist in deciding on the particular kind of alloy steel to use for specific purposes. The characteristics outlined apply only to heat-treated steels. When the effect of the addition of an alloying element is stated, it is understood that reference is made to alloy steels of a given carbon content, compared with a plain carbon steel of the same carbon content.

**Nickel:** The addition of nickel tends to increase the hardness and strength, with but little sacrifice of ductility. The hardness penetration is somewhat greater than that of plain carbon steels. Use of nickel as an alloying element lowers the critical points and produces less distortion, due to the lower quenching temperature. The nickel steels of the case-hardening group carburize more slowly, but the grain growth is less.

**Chromium:** Chromium increases the hardness and strength over that obtained by the use of nickel, though the loss of ductility is greater. Chromium refines the grain and imparts a

greater depth of hardness. Chromium steels have a high degree of wear resistance and are easier machined in spite of the fine grain.

*Manganese:* When present in sufficient amounts to warrant the use of the term alloy, the addition of manganese is very effective. It gives greater strength than nickel and a higher degree of toughness than chromium. Owing to its susceptibility to cold-working, it is likely to flow under severe unit pressures. Up to the present time, it has never been used to any great extent for heat-treated gears, but is now receiving an increasing amount of attention.

*Vanadium:* Vanadium has a similar effect to that of manganese—increasing the hardness, strength, and toughness. The loss of ductility is somewhat more than that due to manganese, but the hardness penetration is greater than for any of the other alloying elements. Owing to the extremely fine-grained structure, the impact strength is high; but vanadium tends to make machining difficult.

*Molybdenum:* Molybdenum has the property of increasing the strength without affecting the ductility. For the same hardness, steels containing molybdenum are more ductile than any other alloy steels, and having nearly the same strength, are tougher; in spite of the increased toughness, the presence of molybdenum does not make machining more difficult. In fact, such steels can be machined at a higher hardness than any of the other alloy steels. The impact strength is nearly as great as that of the vanadium steels.

*Chrome-Nickel Steels:* The combination of the two alloying elements chromium and nickel adds the beneficial qualities of both. The high degree of ductility present in nickel steels is complemented by the high strength, finer grain size, deep hardening, and wear-resistant properties imparted by the addition of chromium. The increased toughness makes these steels more difficult to machine than the plain carbon steels, and they are more difficult to heat treat. The distortion increases with the amount of chromium and nickel.

*Chrome-Vanadium Steels:* Chrome-vanadium steels have practically the same tensile properties as the chrome-nickel steels, but the hardening power, impact strength, and wear resistance are increased by the finer grain size. They are difficult to machine and become distorted more easily than the other alloy steels.

*Chrome-Molybdenum Steels:* This group has the same qualities as the straight molybdenum steels, but the hardening depth and wear resistance are increased by the addition of chromium. This steel is very easily heat treated and machined.

*Nickel-Molybdenum Steels:* Nickel-molybdenum steels have qualities similar to chrome-molybdenum steel. The toughness is said to be greater, but the steel is somewhat more difficult to machine.

**Sintered Materials.**—For high production of low and moderately loaded gears, significant production cost savings may be effected by the use of a sintered metal powder. With this material, the gear is formed in a die under high pressure and then sintered in a furnace. The primary cost saving comes from the great reduction in labor cost of machining the gear teeth and other gear blank surfaces. The volume of production must be high enough to amortize the cost of the die and the gear blank must be of such a configuration that it may be formed and readily ejected from the die.

**Bronze and Brass Gear Castings.**—These specifications cover nonferrous metals for spur, bevel, and worm gears, bushings and flanges for composition gears. This material shall be purchased on the basis of chemical composition. The alloys may be made by any approved method.

*Spur and Bevel Gears:* For spur and bevel gears, hard cast bronze is recommended (ASTM B-10-18; SAE No. 62; and the well-known 88-10-2 mixture) with the following limits as to composition: Copper, 86 to 89; tin, 9 to 11; zinc, 1 to 3; lead (max), 0.20; iron (max), 0.06 per cent. Good castings made from this bronze should have the following minimum physical characteristics: Ultimate strength, 30,000 pounds per square inch; yield point, 15,000 pounds per square inch; elongation in 2 inches, 14 per cent.



## Steels for Industrial Gearing

| Material Specification                     | Hardness |          | Typical Heat Treatment, Characteristics, and Uses   |
|--|----------|----------|---|
|  | Case Rc  | Core Bhn |   |
| Case-Hardening Steels                      |          |          |   |
| AISI 1020<br>AISI 1116                     | 55–60    | 160–230  | Carburize, harden, temper at 350°F.<br>For gears that must be wear-resistant. Normalized material is easily machined. Core is ductile but has little strength.  |
| AISI 4130<br>AISI 4140                     | 50–55    | 270–370  | Harden, temper at 900°F, Nitride.<br>For parts requiring greater wear resistance than that of through-hardened steels but cannot tolerate the distortion of carburizing. Case is shallow, core is tough.  |
| AISI 4615<br>AISI 4620                     | } 55–60  | 170–260  | Carburize, harden, temper at 350°F.<br>For gears requiring high fatigue resistance and strength. The 86xx series has better machinability.<br>The 20 point steels are used for coarser teeth.   |
| AISI 8615<br>AISI 8620                     |          | 200–300  |   |
| AISI 9310                                  | 58–63    | 250–350  | Carburize, harden, temper at 300°F.<br>Primarily for aerospace gears that are highly loaded and operate at high pitch line velocity and for other gears requiring high reliability under extreme operating conditions. This material is not used at high temperatures.<br><br>Harden, temper at 1200°F, Nitride.      |
| Nitralloy N<br>and Type 135<br>Mod. (15-N) | 90–94    | 300–370  | For gears requiring high strength and wear resistance that cannot tolerate the distortion of the carburizing process or that operate at high temperatures.<br>Gear teeth are usually finished before nitriding. Care must be exercised in running nitrided gears together to avoid crazing of case-hardened surfaces. |
| Through-Hardening Steels                   |          |          |   |
| AISI 1045<br>AISI 1140                     | 24–40    | ...      | Harden and temper to required hardness. Oil quench for lower hardness and water quench for higher hardness.<br>For gears of medium and large size requiring moderate strength and wear resistance. Gears that must have consistent, solid sections to withstand quenching.  |
| AISI 4140<br>AISI 4340                     | 24–40    | ...      | Harden (oil quench), temper to required hardness.<br>For gears requiring high strength and wear resistance, and high shock loading resistance. Use 41xx series for moderate sections and 43xx series for heavy sections. Gears must have consistent, solid sections to withstand quenching.                           |

*Worm Gears:* For bronze worm gears, two alternative analyses of phosphor bronze are recommended, SAE No. 65 and No. 63.

SAE No. 65 (called phosphor gear bronze) has the following composition: Copper, 88 to 90; tin, 10 to 12; phosphorus, 0.1 to 0.3; lead, zinc, and impurities (max) 0.5 per cent.

Good castings made of this alloy should have the following minimum physical characteristics: Ultimate strength, 35,000 pounds per square inch; yield point, 20,000 pounds per square inch; elongation in 2 inches, 10 per cent.

The composition of SAE No. 63 (called leaded gun metal) follows: copper, 86 to 89; tin, 9 to 11; lead, 1 to 2.5; phosphorus (max), 0.25; zinc and impurities (max), 0.50 per cent.

Good castings made of this alloy should have the following minimum physical characteristics: Ultimate strength, 30,000 pounds per square inch; yield point, 12,000 pounds per square inch; elongation in 2 inches, 10 per cent.

These alloys, especially No. 65, are adapted to chilling for hardness and refinement of grain. No. 65 is to be preferred for use with worms of great hardness and fine accuracy. No. 63 is to be preferred for use with unhardened worms.

*Gear Bushings:* For bronze bushings for gears, SAE No. 64 is recommended of the following analysis: copper, 78.5 to 81.5; tin, 9 to 11; lead, 9 to 11; phosphorus, 0.05 to 0.25; zinc (max), 0.75; other impurities (max), 0.25 per cent. Good castings of this alloy should have the following minimum physical characteristics: Ultimate strength, 25,000 pounds per square inch; yield point, 12,000 pounds per square inch; elongation in 2 inches, 8 per cent.

*Flanges for Composition Pinions:* For brass flanges for composition pinions ASTM B-30-32T, and SAE No. 40 are recommended. This is a good cast red brass of sufficient strength and hardness to take its share of load and wear when the design is such that the flanges mesh with the mating gear. The composition is as follows: copper, 83 to 86; tin, 4.5 to 5.5; lead, 4.5 to 5.5; zinc, 4.5 to 5.5; iron (max) 0.35; antimony (max), 0.25 per cent; aluminum, none. Good castings made from this alloy should have the following minimum physical characteristics: ultimate strength, 27,000 pounds per square inch; yield point, 12,000 pounds per square inch; elongation in 2 inches, 16 per cent.

**Materials for Worm Gearing.**—The Hamilton Gear & Machine Co. conducted an extensive series of tests on a variety of materials that might be used for worm gears, to ascertain which material is the most suitable. According to these tests chill-cast nickel-phosphor-bronze ranks first in resistance to wear and deformation. This bronze is composed of approximately 87.5 per cent copper, 11 per cent tin, 1.5 per cent nickel, with from 0.1 to 0.2 per cent phosphorus. The worms used in these tests were made from SAE-2315, 3½ per cent nickel steel, case-hardened, ground, and polished. The Shore scleroscope hardness of the worms was between 80 and 90. This nickel alloy steel was adopted after numerous tests of a variety of steels, because it provided the necessary strength, together with the degree of hardness required.

The material that showed up second best in these tests was a No. 65 SAE bronze. Navy bronze (88-10-2) containing 2 per cent zinc, with no phosphorus, and not chilled, performed satisfactorily at speeds of 600 revolutions per minute, but was not sufficiently strong at lower speeds. Red brass (85-5-5) proved slightly better at from 1500 to 1800 revolutions per minute, but would bend at lower speeds, before it would show actual wear.

**Non-metallic Gearing.**—Non-metallic or composition gearing is used primarily where quietness of operation at high speed is the first consideration. Non-metallic materials are also applied very generally to timing gears and numerous other classes of gearing. Rawhide was used originally for non-metallic gears, but other materials have been introduced that have important advantages. These later materials are sold by different firms under various trade names, such as Micarta, Textolite, Formica, Dilecto, Spauldite, Phenolite, Fibroc, Fabroil, Synthane, Celoron, etc. Most of these gear materials consist of layers of canvas or other material that is impregnated with plastics and forced together under hydraulic pressure, which, in conjunction with the application of heat, forms a dense rigid mass.

Although phenol resin gears in general are resilient, they are self-supporting and require no side plates or shrouds unless subjected to a heavy starting torque. The phenol resinoid element protects these gears from vermin and rodents.

The non-metallic gear materials referred to are generally assumed to have the power-transmitting capacity of cast iron. Although the tensile strength may be considerably less than that of cast iron, the resiliency of these materials enables them to withstand impact and

abrasion to a degree that might result in excessive wear of cast-iron teeth. Thus, composition gearing of impregnated canvas has often proved to be more durable than cast iron.

**Application of Non-metallic Gears.**—The most effective field of use for these non-metallic materials is for high-speed duty. At low speeds, when the starting torque may be high, or when the load may fluctuate widely, or when high shock loads may be encountered, these non-metallic materials do not always prove satisfactory. In general, non-metallic materials should not be used for pitch-line velocities below 600 feet per minute.

**Tooth Form:** The best tooth form for non-metallic materials is the 20-degree stub-tooth system. When only a single pair of gears is involved and the center distance can be varied, the best results will be obtained by making the non-metallic driving pinion of all-addendum form, and the driven metal gear with standard tooth proportions. Such a drive will carry from 50 to 75 per cent greater loads than one of standard tooth proportions.

**Material for Mating Gear:** For durability under load, the use of hardened steel (over 400 Brinell) for the mating metal gear appears to give the best results. A good second choice for the material of the mating member is cast iron. The use of brass, bronze, or soft steel (under 400 Brinell) as a material for the mating member of phenolic laminated gears leads to excessive abrasive wear.

**Power-Transmitting Capacity of Non-metallic Gears.**—The characteristics of gears made of phenolic laminated materials are so different from those of metal gears that they should be considered in a class by themselves. Because of the low modulus of elasticity, most of the effects of small errors in tooth form and spacing are absorbed at the tooth surfaces by the elastic deformation, and have but little effect on the strength of the gears.

If  $S$  = safe working stress for a given velocity

$S_s$  = allowable static stress

$V$  = pitch-line velocity in feet per minute

then, according to the recommended practice of the American Gear Manufacturers' Association,

$$S = S_s \times \left( \frac{150}{200 + V} + 0.25 \right)$$

The value of  $S_s$  for phenolic laminated materials is given as 6000 pounds per square inch. The accompanying table gives the safe working stresses  $S$  for different pitch-line velocities. When the value of  $S$  is known, the horsepower capacity is determined by substituting the value of  $S$  for  $S_s$  in the appropriate equations in the section on power-transmitting capacity of plastics gears starting on page 625.

**Safe Working Stresses for Non-metallic Gears**

| Pitch-Line Velocity, Feet per Minute, $V$ | Safe Working Stresses | Pitch-Line Velocity, Feet per Minute, $V$ | Safe Working Stresses | Pitch-Line Velocity, Feet per Minute, $V$ | Safe Working Stresses |
|---|-----------------------|---|-----------------------|---|-----------------------|
| 600                                       | 2625                  | 1800                                      | 1950                  | 4000                                      | 1714                  |
| 700                                       | 2500                  | 2000                                      | 1909                  | 4500                                      | 1691                  |
| 800                                       | 2400                  | 2200                                      | 1875                  | 5000                                      | 1673                  |
| 900                                       | 2318                  | 2400                                      | 1846                  | 5500                                      | 1653                  |
| 1000                                      | 2250                  | 2600                                      | 1821                  | 6000                                      | 1645                  |
| 1200                                      | 2143                  | 2800                                      | 1800                  | 6500                                      | 1634                  |
| 1400                                      | 2063                  | 3000                                      | 1781                  | 7000                                      | 1622                  |
| 1600                                      | 2000                  | 3500                                      | 1743                  | 7500                                      | 1617                  |

The tensile strength of the phenolic laminated materials used for gears is slightly less than that of cast iron. These materials are far softer than any metal, and the modulus of elasticity is about one-thirtieth that of steel. In other words, if the tooth load on a steel gear that causes a deformation of 0.001 inch were applied to the tooth of a similar gear made of phenolic laminated material, the tooth of the non-metallic gear would be deformed about  $\frac{1}{32}$  inch. Under these conditions, several things will happen. With all gears, regardless of the theoretical duration of contact, one tooth only will carry the load until the load is sufficient to deform the tooth the amount of the error that may be present. On metal gears, when the tooth has been deformed the amount of the error, the stresses set up in the materials may approach or exceed the elastic limit of the material. Hence, for standard tooth forms and those generated from standard basic racks, it is dangerous to calculate their strength as very much greater than that which can safely be carried on a single tooth. On gears made of phenolic laminated materials, on the other hand, the teeth will be deformed the amount of this normal error without setting up any appreciable stresses in the material, so that the load is actually supported by several teeth.

All materials have their own peculiar and distinct characteristics, so that under certain specific conditions, each material has a field of its own where it is superior to any other. Such fields may overlap to some extent, and only in such overlapping fields are different materials directly competitive. For example, steel is more or less ductile, has a high tensile strength, and a high modulus of elasticity. Cast iron, on the other hand, is not ductile, has a low tensile strength, but a high compressive strength, and a low modulus of elasticity. Hence, when stiffness and high tensile strength are essential, steel is far superior to cast iron. On the other hand, when these two characteristics are unimportant, but high compressive strength and a moderate amount of elasticity are essential, cast iron is superior to steel.

**Preferred Pitch for Non-metallic Gears.**—The pitch of the gear or pinion should bear a reasonable relation either to the horsepower or speed or to the applied torque, as shown by the accompanying table. The upper half of this table is based upon horsepower transmitted at a given pitch-line velocity. The lower half gives the torque in pounds-feet or the torque at a 1-foot radius. This torque  $T$  for any given horsepower and speed can be obtained from the following formula:

$$T = \frac{5252 \times \text{hp}}{\text{rpm}}$$

**Bore Sizes for Non-metallic Gears.**—For plain phenolic laminated pinions, that is, pinions without metal end plates, a drive fit of 0.001 inch per inch of shaft diameter should be used. For shafts above 2.5 inches in diameter, the fit should be constant at 0.0025 to 0.003 inch. When metal reinforcing end plates are used, the drive fit should conform to the same standards as used for metal.

The root diameter of a pinion of phenolic laminated type should be such that the minimum distance from the edge of the keyway to the root diameter will be at least equal to the depth of tooth.

**Keyway Stresses for Non-metallic Gears.**—The keyway stress should not exceed 3000 pounds per square inch on a plain phenolic laminated gear or pinion. The keyway stress is calculated by the formula

$$S = \frac{33,000 \times \text{hp}}{V \times A}$$

where  $S$  = unit stress in pounds per square inch

$hp$  = horsepower transmitted

$V$  = peripheral speed of shaft in feet per minute; and

$A$  = square inch area of keyway in pinion (length  $\times$  height)

## Preferred Pitches for Non-metallic Gears

| Diametral Pitch for Given Horsepower and Pitch Line Velocities |  |   |   |
|--|--|---|---|
| Horsepower Transmitted   | Pitch Line Velocity up to 1000 Feet per Minute | Pitch Line Velocity from 1000 to 2000 Feet per Minute | Pitch Line Velocity over 2000 Feet per Minute |
| ¼-1  | 8-10   | 10-12   | 12-16   |
| 1-2  | 7-8  | 8-10  | 10-12   |
| 2-3  | 6-7  | 7-8   | 8-10  |
| 3-7½   | 5-6  | 6-7   | 7-8   |
| 7½-10  | 4-5  | 5-6   | 6-7   |
| 10-15  | 3-4  | 4-5   | 5-6   |
| 15-25  | 2½-3   | 3-4   | 4-5   |
| 25-60  | 2-2½   | 2½-3  | 3-4   |
| 60-100   | 1¾-2   | 2-2½  | 2½-3  |
| 100-150  | 1½-1¾  | 1¾-2  | 2-2½  |

| Torque in Pounds-feet for Given Diametral Pitch |                       |         |                 |                       |         |
|---|-----------------------|---------|-----------------|-----------------------|---------|
| Diametral Pitch                                 | Torque in Pounds-feet |         | Diametral Pitch | Torque in Pounds-feet |         |
|   | Minimum               | Maximum |                 | Minimum               | Maximum |
| 16  | 1                     | 2       | 4               | 50                    | 100     |
| 12  | 2                     | 4       | 3               | 100                   | 200     |
| 10  | 4                     | 8       | 2½              | 200                   | 450     |
| 8   | 8                     | 15      | 2               | 450                   | 900     |
| 6   | 15                    | 30      | 1½              | 900                   | 1800    |
| 5   | 30                    | 50      | 1               | 1800                  | 3500    |

These preferred pitches are applicable both to rawhide and the phenolic laminated types of materials.

If the keyway stress formula is expressed in terms of shaft radius  $r$  and revolutions per minute, it will read

$$S = \frac{63,000 \times \text{hp}}{\text{rpm} \times r \times A}$$

When the design is such that the keyway stresses exceed 3000 pounds, metal reinforcing end plates may be used. Such end plates should not extend beyond the root diameter of the teeth. The distance from the outer edge of the retaining bolt to the root diameter of the teeth shall not be less than a full tooth depth. The use of drive keys should be avoided, but if required, metal end plates should be used on the pinion to take the wedging action of the key.

For phenolic laminated pinions, the face of the mating gear should be the same or slightly greater than the pinion face.

**Invention of Gear Teeth.**—The invention of gear teeth represents a gradual evolution from gearing of primitive form. The earliest evidence we have of an investigation of the problem of *uniform motion* from toothed gearing and the successful solution of that problem dates from the time of Olaf Roemer, the celebrated Danish astronomer, who, in the year 1674, proposed the epicycloidal form to obtain uniform motion. Evidently Robert Willis, professor at the University of Cambridge, was the first to make a practical application of the epicycloidal curve so as to provide for an interchangeable series of gears. Willis gives credit to Camus for conceiving the idea of interchangeable gears, but claims for himself its first application. The involute tooth was suggested as a theory by early scientists and mathematicians, but it remained for Willis to present it in a practical form. Perhaps the

earliest conception of the application of this form of teeth to gears was by Philippe de Lahire, a Frenchman, who considered it, in theory, equally suitable with the epicycloidal for tooth outlines. This was about 1695 and not long after Roemer had first demonstrated the epicycloidal form. The applicability of the involute had been further elucidated by Leonard Euler, a Swiss mathematician, born at Basel, 1707, who is credited by Willis with being the first to suggest it. Willis devised the Willis odontograph for laying out involute teeth.

A pressure angle of  $14\frac{1}{2}$  degrees was selected for three different reasons. First, because the sine of  $14\frac{1}{2}$  degrees is nearly  $\frac{1}{4}$ , making it convenient in calculation; second, because this angle coincided closely with the pressure angle resulting from the usual construction of epicycloidal gear teeth; third, because the angle of the straight-sided involute rack is the same as the 29-degree worm thread.

**Calculating Replacement-Gear Dimensions from Simple Measurements.**—The following Tables 1a, 1b, and 1c, provide formulas with which to calculate the dimensions needed to produce replacement spur, bevel, and helical gears when only the number of teeth, the outside diameter, and the tooth depth of the gear to be replaced are known.

For helical gears, exact helix angles can be obtained by the following procedure.

- 1) Using a common protractor, measure the approximate helix angle  $A$  at the approximate pitch line.
- 2) Place sample or its mating gear on the arbor of a gear hobbing machine.
- 3) Calculate the index and lead gears differentially for the angle obtained by the measurements, and set up the machine as though a gear is to be cut.
- 4) Attach a dial indicator on an adjustable arm to the vertical swivel head, with the indicator plunger in a plane perpendicular to the gear axis and in contact with the tooth face. Contact may be anywhere between the top and the root of the tooth.
- 5) With the power shut off, engage the starting lever and traverse the indicator plunger axially by means of the handwheel.
- 6) If angle  $A$  is correct, the indicator plunger will not move as it traverses the face width of the gear. If it does move from 0, note the amount. Divide the amount of movement by the width of the gear to obtain the tangent of the angle by which to correct angle  $A$ , plus or minus, depending on the direction of indicator movement.

**Table 1a. Formulas for Calculating Spur Gear Dimensions**

| Tooth Form and Pressure Angle                                | Diametral Pitch $P$   | Pitch Diameter $D$ | Circular Pitch $P_c$ | Outside Diameter $O$            | Addendum $J$    | Dedendum $K$       | Whole Tooth Depth $W$ | Clearance $K - J$  | Tooth Thickness on Pitch Circle |
|--|-----------------------|--------------------|----------------------|---------------------------------|-----------------|--------------------|-----------------------|--------------------|---------------------------------|
| American Standard $14\frac{1}{2}$ - and 20-degree full depth | $\frac{N + 2}{O}$     | $\frac{N}{P}$      | $\frac{3.1416}{P}$   | $\frac{N + 2}{P}$               | $\frac{1}{P}$   | $\frac{1.157}{P}$  | $\frac{2.157}{P}$     | $\frac{0.157}{P}$  | $\frac{1.5708}{P}$              |
| American Standard 20-degree stub                             | $\frac{N + 1.6}{O}$   | $\frac{N}{P}$      | $\frac{3.1416}{P}$   | $\frac{N + 1.6}{P}$             | $\frac{0.8}{P}$ | $\frac{1}{P}$      | $\frac{1.8}{P}$       | $\frac{0.2}{P}$    | $\frac{1.5708}{P}$              |
| Fellows 20-degree stub                                       | See Note <sup>a</sup> | $\frac{N}{P_N}$    | $\frac{3.1416}{P_N}$ | $\frac{N}{P_N} + \frac{2}{P_D}$ | $\frac{1}{P_D}$ | $\frac{1.25}{P_D}$ | $\frac{2.25}{P_D}$    | $\frac{0.25}{P_D}$ | $\frac{1.5708}{P_N}$            |

<sup>a</sup> In the Fellows stub-tooth system,  $P_N$  = diametral pitch in numerator of stub-tooth designation and is used to determine circular pitch and number of teeth, and  $P_D$  = diametral pitch in the denominator of stub-tooth designation and is used to determine tooth depth.

$N$  = number of teeth.

**Table 1b. Formulas for Calculating Dimensions of Milled Bevel Gears — 90 degree Shafts<sup>a</sup>**

| Tooth Form and Pressure Angle                   | Tangent of Pitch Cone Angle of Gear, $\tan A$ | Tangent of Pitch Cone Angle of Pinion, $\tan a$ | Diametral Pitch <sup>b</sup> of Both Gear and Pinion, $P$          | Outside Diameter of Gear, $O$ , or Pinion, $o$   | Pitch-Cone Radius <sup>b</sup> or Cone Distance, $E$ | Tangent of Addendum Angle <sup>b</sup>   | Tangent of Dedendum Angle <sup>b</sup>   | Cosine of Pitch-Cone Angle <sup>c</sup> of Gear, $\cos A$ |
|---|---|---|--|--|--|--|--|---|
| American Standard 14½° and 20-degree full depth | $\frac{N_G}{N_P}$                             | $\frac{N_P}{N_G}$                               | $\frac{N_G + 2 \cos A}{O}$<br>or<br>$\frac{N_P + 2 \cos a}{o}$     | $\frac{N_G + 2 \cos A}{P}$<br>or<br>$\frac{N_P + 2 \cos a}{P}$                             | $\frac{D}{2 \sin A}$<br>or<br>$\frac{d}{2 \sin a}$   | $\frac{2 \sin A}{N_a}$<br>or<br>$\frac{2 \sin a}{N_p}$                             | $\frac{2.314 \sin A}{N_G}$<br>or<br>$\frac{2.314 \sin a}{N_P}$                         | $\frac{(P \times O) - N_G}{2}$                            |
| American Standard 20-degree stub                | $\frac{N_G}{N_P}$                             | $\frac{N_P}{N_G}$                               | $\frac{N_G + 1.6 \cos A}{O}$<br>or<br>$\frac{N_P + 1.6 \cos a}{o}$ | $\frac{N_G + 1.6 \cos A}{P}$<br>or<br>$\frac{N_P + 1.6 \cos a}{P}$                         | $\frac{D}{2 \sin A}$<br>or<br>$\frac{d}{2 \sin a}$   | $\frac{1.6 \sin A}{N_G}$<br>or<br>$\frac{1.6 \sin a}{N_P}$                         | $\frac{2 \sin A}{N_G}$<br>or<br>$\frac{2 \sin a}{N_P}$                                 | $\frac{(P \times O) - N_G}{1.6}$                          |
| Fellows 20-degree stub                          | $\frac{N_G}{N_P}$                             | $\frac{N_P}{N_G}$                               | ...  | $\frac{N_G}{P_N} + \frac{2 \cos A}{P_D}$<br>or<br>$\frac{N_P}{P_N} + \frac{2 \cos a}{P_D}$ | $\frac{D}{2 \sin A}$<br>or<br>$\frac{d}{2 \sin a}$   | $\frac{2P_N \sin A}{N_G \times P_D}$<br>or<br>$\frac{2P_N \sin a}{N_P \times P_D}$ | $\frac{2.5P_N \sin A}{N_G \times P_D}$<br>or<br>$\frac{2.5P_N \sin a}{N_P \times P_D}$ | $\frac{P_D[(O \times P_N) - N_G]}{2P_N}$                  |

<sup>a</sup>These formulas do not apply to Gleason System Gearing.

<sup>b</sup>These values are the same for both gear and pinion.

<sup>c</sup>The same formulas apply to the pinion, substituting  $N_P$  for  $N_G$  and  $o$  for  $O$ .

$N_G$  = number of teeth in gear;  $N_P$  = number of teeth in pinion;  $O$  = outside diameter of gear;  $o$  = outside diameter of pinion;  $D$  = pitch diameter of gear =  $N_G \div P$ ;  $d$  = pitch diameter of pinion =  $N_P \div P$ ;  $P_c$  = circular pitch;  $J$  = addendum;  $K$  = dedendum;  $W$  = whole depth.

See footnote in Table 1a for meaning of  $P_N$  and  $P_D$ . The tooth thickness on the pitch circle is found by means of the formulas in the last column under spur gears.

Table 1c. Formulas for Calculating Dimensions of Helical Gears

| Tooth Form and Pressure Angle                   | Normal Diametral Pitch $P_N$   | Diametral Pitch $P$                              | Outside Diameter of Blank $O$   | Pitch Diameter $D$                            | Cosine of Helix Angle $A$                                | Addendum  | Dedendum  | Whole Depth   |
|---|--|--|---|---|--|---|---|---|
| American Standard 14½° and 20-degree full depth | $\frac{N + 2 \cos A}{O \times \cos A}$<br>or<br>$\frac{P}{\cos A}$   | $P_N \cos A$<br>or<br>$\frac{N + 2 \cos A}{O}$   | $\frac{N + 2 \cos A}{P_N \cos A}$<br>or<br>$\frac{N + 2 \cos A}{P}$     | $\frac{N}{P_N \cos A}$<br>or<br>$\frac{N}{P}$ | $\frac{P}{P_N}$<br>or<br>$\frac{N}{O \times P_N - 2}$    | $\frac{1}{P_N}$<br>or<br>$\frac{\cos A}{P}$       | $\frac{1.157}{P_N}$<br>or<br>$\frac{1.157 \cos A}{P}$ | $\frac{2.157}{P_N}$<br>or<br>$\frac{2.157 \cos A}{P}$ |
| American Standard 20-degree stub                | $\frac{N + 1.6 \cos A}{O \times \cos A}$<br>or<br>$\frac{P}{\cos A}$ | $P_N \cos A$<br>or<br>$\frac{N + 1.6 \cos A}{O}$ | $\frac{N + 1.6 \cos A}{P_N \cos A}$<br>or<br>$\frac{N + 1.6 \cos A}{P}$ | $\frac{N}{P_N \cos A}$<br>or<br>$\frac{N}{P}$ | $\frac{P}{P_N}$<br>or<br>$\frac{N}{O \times P_N - 1.6}$  | $\frac{0.8}{P_N}$<br>or<br>$\frac{0.8 \cos A}{P}$ | $\frac{1}{P_N}$<br>or<br>$\frac{\cos A}{P}$           | $\frac{1.8}{P_N}$<br>or<br>$\frac{1.8 \cos A}{P}$     |
| Fellows 20-degree stub                          | ...  | ...  | $\frac{N}{(P_N)_N \cos A} + \frac{2}{(P_N)_D}$                          | $\frac{N}{(P_N)_N \cos A}$                    | $\frac{N}{(P_N)_N \left( O - \frac{2}{(P_N)_D} \right)}$ | $\frac{1}{(P_N)_D}$                               | $\frac{1.25}{(P_N)_D}$                                | $\frac{2.25}{(P_N)_D}$                                |

$P_N$  = normal diametral pitch = normal diametral pitch of cutter or hob used to cut teeth

$P$  = diametral pitch

$O$  = outside diameter of blank

$D$  = pitch diameter

$A$  = helix angle

$N$  = number of teeth

$(P_N)_N$  = normal diametral pitch in numerator of stub-tooth designation, which determines thickness of tooth and number of teeth

$(P_N)_D$  = normal diametral pitch in denominator of stub-tooth designation, which determines the addendum, dedendum, and whole depth



**SPLINES AND SERRATIONS**

A splined shaft is one having a series of parallel keys formed integrally with the shaft and mating with corresponding grooves cut in a hub or fitting; this arrangement is in contrast to a shaft having a series of keys or feathers fitted into slots cut into the shaft. The latter construction weakens the shaft to a considerable degree because of the slots cut into it and consequently, reduces its torque-transmitting capacity.

Splined shafts are most generally used in three types of applications: 1) for coupling shafts when relatively heavy torques are to be transmitted without slippage; 2) for transmitting power to slidably-mounted or permanently-fixed gears, pulleys, and other rotating members; and 3) for attaching parts that may require removal for indexing or change in angular position.

Splines having straight-sided teeth have been used in many applications (see SAE Parallel Side Splines for Soft Broached Holes in Fittings); however, the use of splines with teeth of involute profile has steadily increased since 1) involute spline couplings have greater torque-transmitting capacity than any other type; 2) they can be produced by the same techniques and equipment as is used to cut gears; and 3) they have a self-centering action under load even when there is backlash between mating members.

**Involute Splines**

**American National Standard Involute Splines\*.**—These splines or multiple keys are similar in form to internal and external involute gears. The general practice is to form the external splines either by hobbing, rolling, or on a gear shaper, and internal splines either by broaching or on a gear shaper. The internal spline is held to basic dimensions and the external spline is varied to control the fit. Involute splines have maximum strength at the base, can be accurately spaced and are self-centering, thus equalizing the bearing and stresses, and they can be measured and fitted accurately.

In American National Standard ANSI B92.1-1970 (R 1993), many features of the 1960 standard are retained; plus the addition of three tolerance classes, for a total of four. The term “involute serration,” formerly applied to involute splines with 45-degree pressure angle, has been deleted and the standard now includes involute splines with 30-, 37.5-, and 45-degree pressure angles. Tables for these splines have been rearranged accordingly. The term “serration” will no longer apply to splines covered by this Standard.

The Standard has only one fit class for all side fit splines; the former Class 2 fit. Class 1 fit has been deleted because of its infrequent use. The major diameter of the flat root side fit spline has been changed and a tolerance applied to include the range of the 1950 and the 1960 standards. The interchangeability limitations with splines made to previous standards are given later in the section entitled “Interchangeability.”

There have been no tolerance nor fit changes to the major diameter fit section.

The Standard recognizes the fact that proper assembly between mating splines is dependent only on the spline being within effective specifications from the tip of the tooth to the form diameter. Therefore, on side fit splines, the internal spline major diameter now is shown as a maximum dimension and the external spline minor diameter is shown as a minimum dimension. The minimum internal major diameter and the maximum external minor diameter must clear the specified form diameter and thus do not need any additional control.

The spline specification tables now include a greater number of tolerance level selections. These tolerance classes were added for greater selection to suit end product needs. The selections differ only in the tolerance as applied to space width and tooth thickness.

\* See American National Standard ANSI B92.2M-1980 (R 1989), Metric Module Involute Splines; also see page 2176.

The tolerance class used in ASA B5.15-1960 is the basis and is now designated as tolerance Class 5. The new tolerance classes are based on the following formulas:

$$\text{Tolerance Class 4} = \text{Tolerance Class 5} \times 0.71$$

$$\text{Tolerance Class 6} = \text{Tolerance Class 5} \times 1.40$$

$$\text{Tolerance Class 7} = \text{Tolerance Class 5} \times 2.00$$

All dimensions listed in this standard are for the finished part. Therefore, any compensation that must be made for operations that take place during processing, such as heat treatment, must be taken into account when selecting the tolerance level for manufacturing.

The standard has the same internal minimum effective space width and external maximum effective tooth thickness for all tolerance classes and has two types of fit. For tooth side fits, the minimum effective space width and the maximum effective tooth thickness are of equal value. This basic concept makes it possible to have interchangeable assembly between mating splines where they are made to this standard regardless of the tolerance class of the individual members. A tolerance class "mix" of mating members is thus allowed, which often is an advantage where one member is considerably less difficult to produce than its mate, and the "average" tolerance applied to the two units is such that it satisfies the design need. For instance, assigning a Class 5 tolerance to one member and Class 7 to its mate will provide an assembly tolerance in the Class 6 range. The maximum effective tooth thickness is less than the minimum effective space width for major diameter fits to allow for eccentricity variations.

In the event the fit as provided in this standard does not satisfy a particular design need and a specific amount of effective clearance or press fit is desired, the change should be made only to the external spline by a reduction or an increase in effective tooth thickness and a like change in actual tooth thickness. The minimum effective space width, in this standard, is always basic. The basic minimum effective space width should always be retained when special designs are derived from the concept of this standard.

**Terms Applied to Involute Splines.**—The following definitions of involute spline terms, here listed in alphabetical order, are given in the American National Standard. Some of these terms are illustrated in the diagram in [Table 6](#).

*Active Spline Length ( $L_a$ )* is the length of spline that contacts the mating spline. On sliding splines, it exceeds the length of engagement.

*Actual Space Width ( $s$ )* is the circular width on the pitch circle of any single space considering an infinitely thin increment of axial spline length.

*Actual Tooth Thickness ( $t$ )* is the circular thickness on the pitch circle of any single tooth considering an infinitely thin increment of axial spline length.

*Alignment Variation* is the variation of the effective spline axis with respect to the reference axis (see [Fig. 1c](#)).

*Base Circle* is the circle from which involute spline tooth profiles are constructed.

*Base Diameter ( $D_b$ )* is the diameter of the base circle.

*Basic Space Width* is the basic space width for 30-degree pressure angle splines; half the circular pitch. The basic space width for 37.5- and 45-degree pressure angle splines, however, is greater than half the circular pitch. The teeth are proportioned so that the external tooth, at its base, has about the same thickness as the internal tooth at the form diameter. This proportioning results in greater minor diameters than those of comparable involute splines of 30-degree pressure angle.

*Circular Pitch ( $p$ )* is the distance along the pitch circle between corresponding points of adjacent spline teeth.

*Depth of Engagement* is the radial distance from the minor circle of the internal spline to the major circle of the external spline, minus corner clearance and/or chamfer depth.

*Diametral Pitch ( $P$ )* is the number of spline teeth per inch of pitch diameter. The diametral pitch determines the circular pitch and the basic space width or tooth thickness. In conjunction with the number of teeth, it also determines the pitch diameter. (See also Pitch.)

*Effective Clearance ( $c_v$ )* is the effective space width of the internal spline minus the effective tooth thickness of the mating external spline.

*Effective Space Width ( $S_v$ )* of an internal spline is equal to the circular tooth thickness on the pitch circle of an imaginary perfect external spline that would fit the internal spline without looseness or interference considering engagement of the entire axial length of the spline. The minimum effective space width of the internal spline is always basic, as shown in Table 3. Fit variations may be obtained by adjusting the tooth thickness of the external spline.

### Three types of involute spline variations

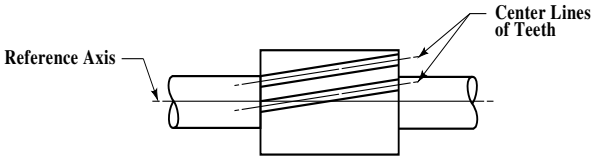


Fig. 1a. Lead Variation

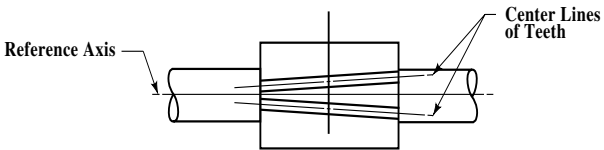


Fig. 1b. Parallelism Variation

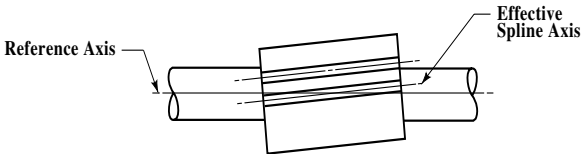


Fig. 1c. Alignment Variation

*Effective Tooth Thickness ( $t_v$ )* of an external spline is equal to the circular space width on the pitch circle of an imaginary perfect internal spline that would fit the external spline without looseness or interference, considering engagement of the entire axial length of the spline.

*Effective Variation* is the accumulated effect of the spline variations on the fit with the mating part.

*External Spline* is a spline formed on the outer surface of a cylinder.

*Fillet* is the concave portion of the tooth profile that joins the sides to the bottom of the space.

*Fillet Root Splines* are those in which a single fillet in the general form of an arc joins the sides of adjacent teeth.

*Flat Root Splines* are those in which fillets join the arcs of major or minor circles to the tooth sides.

*Form Circle* is the circle which defines the deepest points of involute form control of the tooth profile. This circle along with the tooth tip circle (or start of chamfer circle) determines the limits of tooth profile requiring control. It is located near the major circle on the internal spline and near the minor circle on the external spline.

*Form Clearance* ( $c_f$ ) is the radial depth of involute profile beyond the depth of engagement with the mating part. It allows for looseness between mating splines and for eccentricities between the minor circle (internal), the major circle (external), and their respective pitch circles.

*Form Diameter* ( $D_{Fe}$ ,  $D_{Fi}$ ) the diameter of the form circle.

*Internal Spline* is a spline formed on the inner surface of a cylinder.

*Involute Spline* is one having teeth with involute profiles.

*Lead Variation* is the variation of the direction of the spline tooth from its intended direction parallel to the reference axis, also including parallelism and alignment variations (see Fig. 1a). *Note:* Straight (nonhelical) splines have an infinite lead.

*Length of Engagement* ( $L_q$ ) is the axial length of contact between mating splines.

*Machining Tolerance* ( $m$ ) is the permissible variation in actual space width or actual tooth thickness.

*Major Circle* is the circle formed by the outermost surface of the spline. It is the outside circle (tooth tip circle) of the external spline or the root circle of the internal spline.

*Major Diameter* ( $D_o$ ,  $D_{ri}$ ) is the diameter of the major circle.

*Minor Circle* is the circle formed by the innermost surface of the spline. It is the root circle of the external spline or the inside circle (tooth tip circle) of the internal spline.

*Minor Diameter* ( $D_{re}$ ,  $D_i$ ) is the diameter of the minor circle.

*Nominal Clearance* is the actual space width of an internal spline minus the actual tooth thickness of the mating external spline. It does not define the fit between mating members, because of the effect of variations.

*Out of Roundness* is the variation of the spline from a true circular configuration.

*Parallelism Variation* is the variation of parallelism of a single spline tooth with respect to any other single spline tooth (see Fig. 1b).

*Pitch* ( $PIP_s$ ) is a combination number of a one-to-two ratio indicating the spline proportions; the upper or first number is the diametral pitch, the lower or second number is the stub pitch and denotes, as that fractional part of an inch, the basic radial length of engagement, both above and below the pitch circle.

*Pitch Circle* is the reference circle from which all transverse spline tooth dimensions are constructed.

*Pitch Diameter* ( $D$ ) is the diameter of the pitch circle.

*Pitch Point* is the intersection of the spline tooth profile with the pitch circle.

*Pressure Angle* ( $\phi$ ) is the angle between a line tangent to an involute and a radial line through the point of tangency. Unless otherwise specified, it is the standard pressure angle.

*Profile Variation* is any variation from the specified tooth profile normal to the flank.

*Spline* is a machine element consisting of integral keys (spline teeth) or keyways (spaces) equally spaced around a circle or portion thereof.

*Standard (Main) Pressure Angle* ( $\phi_D$ ) is the pressure angle at the specified pitch diameter.

*Stub Pitch* ( $P_s$ ) is a number used to denote the radial distance from the pitch circle to the major circle of the external spline and from the pitch circle to the minor circle of the internal spline. The stub pitch for splines in this standard is twice the diametral pitch.

*Total Index Variation* is the greatest difference in any two teeth (adjacent or otherwise) between the actual and the perfect spacing of the tooth profiles.

*Total Tolerance* ( $m + \lambda$ ) is the machining tolerance plus the variation allowance.

*Variation Allowance* ( $\lambda$ ) is the permissible effective variation.

**Tooth Proportions.**—There are 17 pitches: 2.5/5, 3/6, 4/8, 5/10, 6/12, 8/16, 10/20, 12/24, 16/32, 20/40, 24/48, 32/64, 40/80, 48/96, 64/128, 80/160, and 128/256. The numerator in this fractional designation is known as the diametral pitch and controls the pitch diameter; the denominator, which is always double the numerator, is known as the stub pitch and controls the tooth depth. For convenience in calculation, only the numerator is used in the formulas given and is designated as  $P$ . Diametral pitch, as in gears, means the number of teeth per inch of pitch diameter.

Table 1 shows the symbols and Table 2 the formulas for basic tooth dimensions of involute spline teeth of various pitches. Basic dimensions are given in Table 3.

**Table 1. American National Standard Involute Spline Symbols**  
ANSI B92.1-1970, R1993

|          |   |             |   |
|----------|---|-------------|---|
| $c_v$    | effective clearance                           | $M_i$       | measurement between pins, internal spline               |
| $c_F$    | form clearance                                | $N$         | number of teeth   |
| $D$      | pitch diameter                                | $P$         | diametral pitch   |
| $D_b$    | base diameter                                 | $P_s$       | stub pitch  |
| $D_{ci}$ | pin contact diameter, internal spline         | $p$         | circular pitch  |
| $D_{ce}$ | pin contact diameter, external spline         | $r_f$       | fillet radius   |
| $D_{Fe}$ | form diameter, external spline                | $s$         | actual space width, circular                            |
| $D_{Fi}$ | form diameter, internal spline                | $s_v$       | effective space width, circular                         |
| $D_i$    | minor diameter, internal spline               | $s_c$       | allowable compressive stress, psi                       |
| $D_o$    | major diameter, external spline               | $s_s$       | allowable shear stress, psi                             |
| $D_{re}$ | minor diameter, external spline (root)        | $t$         | actual tooth thickness, circular                        |
| $D_{ri}$ | major diameter, internal spline (root)        | $t_v$       | effective tooth thickness, circular                     |
| $d_e$    | diameter of measuring pin for external spline | $\lambda$   | variation allowance                                     |
| $d_i$    | diameter of measuring pin for internal spline | $\epsilon$  | involute roll angle                                     |
| $K_e$    | change factor for external spline             | $\phi$      | pressure angle  |
| $K_i$    | change factor for internal spline             | $\phi_D$    | standard pressure angle                                 |
| $L$      | spline length                                 | $\phi_{ci}$ | pressure angle at pin contact diameter, internal spline |
| $L_a$    | active spline length                          | $\phi_{ce}$ | pressure angle at pin contact diameter, external spline |
| $L_g$    | length of engagement                          | $\phi_i$    | pressure angle at pin center, internal spline           |
| $m$      | machining tolerance                           | $\phi_e$    | pressure angle at pin center, external spline           |
| $M_e$    | measurement over pins, external spline        | $\phi_F$    | pressure angle at form diameter                         |

**Table 2. Formulas for Involute Spline Basic Dimensions** *ANSI B92.1-1970, R1993*

| Term                          | Symbol                 | 30 deg $\phi_D$                             |                             |                      | 37.5 deg $\phi_D$    | 45 deg $\phi_D$       |
|-------------------------------|------------------------|---|-----------------------------|----------------------|----------------------|-----------------------|
|                               |                        | Flat Root Side Fit                          | Flat Root Major Dia Fit     | Fillet Root Side Fit | Fillet Root Side Fit | Fillet Root Side Fit  |
|                               |                        | 2.5/5 – 32/64 Pitch                         | 3/6 – 16/32 Pitch           | 2.5/5 – 48/96 Pitch  | 2.5/5 – 48/96 Pitch  | 10/20 – 128/256 Pitch |
| Stub Pitch                    | $P_s$                  | $2P$  | $2P$                        | $2P$                 | $2P$                 | $2P$                  |
| Pitch Diameter                | $D$                    | $N/P$                                       | $N/P$                       | $N/P$                | $N/P$                | $N/P$                 |
| Base Diameter                 | $D_b$                  | $D \cos \phi_D$                             | $D \cos \phi_D$             | $D \cos \phi_D$      | $D \cos \phi_D$      | $D \cos \phi_D$       |
| Circular Pitch                | $p$                    | $\pi/P$                                     | $\pi/P$                     | $\pi/P$              | $\pi/P$              | $\pi/P$               |
| Minimum Effective Space Width | $s_v$                  | $\pi/(2P)$                                  | $\pi/(2P)$                  | $\pi/(2P)$           | $(0.5\pi + 0.1)/P$   | $(0.5\pi + 0.2)/P$    |
| Major Diameter, Internal      | $D_{ri}$               | $(N + 1.35)/P$                              | $(N + 1)/P$                 | $(N + 1.8)/P$        | $(N + 1.6)/P$        | $(N + 1.4)/P$         |
| Major Diameter, External      | $D_o$                  | $(N + 1)/P$                                 | $(N + 1)/P$                 | $(N + 1)/P$          | $(N + 1)/P$          | $(N + 1)/P$           |
| Minor Diameter, Internal      | $D_i$                  | $(N - 1)/P$                                 | $(N - 1)/P$                 | $(N - 1)/P$          | $(N - 0.8)/P$        | $(N - 0.6)/P$         |
| Minor Dia. Ext.               | 2.5/5 thru 12/24 pitch | $D_{re}$                                    | $(N - 1.35)/P$              | $(N - 1.8)/P$        | $(N - 1.3)/P$        | ...                   |
|                               | 16/32 pitch and finer  |   |                             | $(N - 2)/P$          |                      |                       |
|                               | 10/20 pitch and finer  |   |                             | ...                  |                      |                       |
| Form Diameter, Internal       | $D_{Fi}$               | $(N + 1)/P + 2cF$                           | $(N + 0.8)/P - 0.004 + 2cF$ | $(N + 1)/P + 2cF$    | $(N + 1)/P + 2cF$    | $(N + 1)/P + 2cF$     |
| Form Diameter, External       | $D_{Fe}$               | $(N - 1)/P - 2cF$                           | $(N - 1)/P - 2cF$           | $(N - 1)/P - 2cF$    | $(N - 0.8)/P - 2cF$  | $(N - 0.6)/P - 2cF$   |
| Form Clearance (Radial)       | $c_F$                  | 0.001 $D$ , with max of 0.010, min of 0.002 |                             |                      |                      |                       |

$$\pi = 3.1415927$$

Note: All spline specification table dimensions in the standard are derived from these basic formulas by application of tolerances.

**Table 3. Basic Dimensions for Involute Splines** *ANSI B92.1-1970, R1993*

| Pitch,<br>$P/P_s$ | Circular<br>Pitch,<br>$p$ | Min Effective Space Width<br>(BASIC),<br>$S_v$ min |                 |               | Pitch,<br>$P/P_s$ | Circular<br>Pitch,<br>$p$ | Min Effective Space Width<br>(BASIC),<br>$S_v$ min |                 |               |
|-------------------|---------------------------|--|-----------------|---------------|-------------------|---------------------------|--|-----------------|---------------|
|                   |                           | 30 deg $\phi$                                      | 37.5 deg $\phi$ | 45 deg $\phi$ |                   |                           | 30 deg $\phi$                                      | 37.5 deg $\phi$ | 45 deg $\phi$ |
| 2.5/5             | 1.2566                    | 0.6283   | 0.6683          | ...           | 20/40             | 0.1571                    | 0.0785   | 0.0835          | 0.0885        |
| 3/6               | 1.0472                    | 0.5236   | 0.5569          | ...           | 24/48             | 0.1309                    | 0.0654   | 0.0696          | 0.0738        |
| 4/8               | 0.7854                    | 0.3927   | 0.4177          | ...           | 32/64             | 0.0982                    | 0.0491   | 0.0522          | 0.0553        |
| 5/10              | 0.6283                    | 0.3142   | 0.3342          | ...           | 40/80             | 0.0785                    | 0.0393   | 0.0418          | 0.0443        |
| 6/12              | 0.5236                    | 0.2618   | 0.2785          | ...           | 48/96             | 0.0654                    | 0.0327   | 0.0348          | 0.0369        |
| 8/16              | 0.3927                    | 0.1963   | 0.2088          | ...           | 64/128            | 0.0491                    | ...  | ...             | 0.0277        |
| 10/20             | 0.3142                    | 0.1571   | 0.1671          | 0.1771        | 80/160            | 0.0393                    | ...  | ...             | 0.0221        |
| 12/24             | 0.2618                    | 0.1309   | 0.1392          | 0.1476        | 128/256           | 0.0246                    | ...  | ...             | 0.0138        |
| 16/32             | 0.1963                    | 0.0982   | 0.1044          | 0.1107        | ...               | ...                       | ...  | ...             | ...           |

**Tooth Numbers.**—The American National Standard covers involute splines having tooth numbers ranging from 6 to 60 with a 30- or 37.5-degree pressure angle and from 6 to 100 with a 45-degree pressure angle. In selecting the number of teeth for a given spline application, it is well to keep in mind that there are no advantages to be gained by using odd numbers of teeth and that the diameters of splines with odd tooth numbers, particularly internal splines, are troublesome to measure with pins since no two tooth spaces are diametrically opposite each other.

**Types and Classes of Involute Spline Fits.**—Two types of fits are covered by the American National Standard for involute splines, the side fit, and the major diameter fit. Dimensional data for flat root side fit, flat root major diameter fit, and fillet root side fit splines are tabulated in this standard for 30-degree pressure angle splines; but for only the fillet root side fit for 37.5- and 45-degree pressure angle splines.

*Side Fit:* In the side fit, the mating members contact only on the sides of the teeth; major and minor diameters are clearance dimensions. The tooth sides act as drivers and centralize the mating splines.

*Major Diameter Fit:* Mating parts for this fit contact at the major diameter for centralizing. The sides of the teeth act as drivers. The minor diameters are clearance dimensions.

The major diameter fit provides a minimum effective clearance that will allow for contact and location at the major diameter with a minimum amount of location or centralizing effect by the sides of the teeth. The major diameter fit has only one space width and tooth thickness tolerance which is the same as side fit Class 5.

A fillet root may be specified for an external spline, even though it is otherwise designed to the flat root side fit or major diameter fit standard. An internal spline with a fillet root can be used only for the side fit.

**Classes of Tolerances.**—This standard includes four classes of tolerances on space width and tooth thickness. This has been done to provide a range of tolerances for selection to suit a design need. The classes are variations of the former single tolerance which is now Class 5 and are based on the formulas shown in the footnote of Table 4. All tolerance classes have the same minimum effective space width and maximum effective tooth thickness limits so that a mix of classes between mating parts is possible.

**Table 4. Maximum Tolerances for Space Width and Tooth Thickness of Tolerance Class 5 Splines ANSI B92.1-1970, R1993**  
(Values shown in ten thousandths; 20 = 0.0020)

| No. of Teeth   | Pitch, $P/P_s$                 |              |               |                 |                 |                  |                   |          |    |    |    |    |
|----------------|--------------------------------|--------------|---------------|-----------------|-----------------|------------------|-------------------|----------|----|----|----|----|
|                | 2.5/5 and 3/6                  | 4/8 and 5/10 | 6/12 and 8/16 | 10/20 and 12/24 | 16/32 and 20/40 | 24/48 thru 48/96 | 64/128 and 80/160 | 128/256  |    |    |    |    |
| <i>N</i>       | Machining Tolerance, <i>m</i>  |              |               |                 |                 |                  |                   |          |    |    |    |    |
| 10             | 15.8                           | 14.5         | 12.5          | 12.0            | 11.7            | 11.7             | 9.6               | 9.5      |    |    |    |    |
| 20             | 17.6                           | 16.0         | 14.0          | 13.0            | 12.4            | 12.4             | 10.2              | 10.0     |    |    |    |    |
| 30             | 18.4                           | 17.5         | 15.5          | 14.0            | 13.1            | 13.1             | 10.8              | 10.5     |    |    |    |    |
| 40             | 21.8                           | 19.0         | 17.0          | 15.0            | 13.8            | 13.8             | 11.4              | —        |    |    |    |    |
| 50             | 23.0                           | 20.5         | 18.5          | 16.0            | 14.5            | 14.5             | —                 | —        |    |    |    |    |
| 60             | 24.8                           | 22.0         | 20.0          | 17.0            | 15.2            | 15.2             | —                 | —        |    |    |    |    |
| 70             | —                              | —            | —             | 18.0            | 15.9            | 15.9             | —                 | —        |    |    |    |    |
| 80             | —                              | —            | —             | 19.0            | 16.6            | 16.6             | —                 | —        |    |    |    |    |
| 90             | —                              | —            | —             | 20.0            | 17.3            | 17.3             | —                 | —        |    |    |    |    |
| 100            | —                              | —            | —             | 21.0            | 18.0            | 18.0             | —                 | —        |    |    |    |    |
| <i>N</i>       | Variation Allowance, $\lambda$ |              |               |                 |                 |                  |                   |          |    |    |    |    |
| 10             | 23.5                           | 20.3         | 17.0          | 15.7            | 14.2            | 12.2             | 11.0              | 9.8      |    |    |    |    |
| 20             | 27.0                           | 22.6         | 19.0          | 17.4            | 15.4            | 13.4             | 12.0              | 10.6     |    |    |    |    |
| 30             | 30.5                           | 24.9         | 21.0          | 19.1            | 16.6            | 14.6             | 13.0              | 11.4     |    |    |    |    |
| 40             | 34.0                           | 27.2         | 23.0          | 21.6            | 17.8            | 15.8             | 14.0              | —        |    |    |    |    |
| 50             | 37.5                           | 29.5         | 25.0          | 22.5            | 19.0            | 17.0             | —                 | —        |    |    |    |    |
| 60             | 41.0                           | 31.8         | 27.0          | 24.2            | 20.2            | 18.2             | —                 | —        |    |    |    |    |
| 70             | —                              | —            | —             | 25.9            | 21.4            | 19.4             | —                 | —        |    |    |    |    |
| 80             | —                              | —            | —             | 27.6            | 22.6            | 20.6             | —                 | —        |    |    |    |    |
| 90             | —                              | —            | —             | 29.3            | 23.8            | 21.8             | —                 | —        |    |    |    |    |
| 100            | —                              | —            | —             | 31.0            | 25.0            | 23.0             | —                 | —        |    |    |    |    |
| <i>N</i>       | Total Index Variation          |              |               |                 |                 |                  |                   |          |    |    |    |    |
| 10             | 20                             | 17           | 15            | 15              | 14              | 12               | 11                | 10       |    |    |    |    |
| 20             | 24                             | 20           | 18            | 17              | 15              | 13               | 12                | 11       |    |    |    |    |
| 30             | 28                             | 22           | 20            | 19              | 16              | 15               | 14                | 13       |    |    |    |    |
| 40             | 32                             | 25           | 22            | 20              | 18              | 16               | 15                | —        |    |    |    |    |
| 50             | 36                             | 27           | 25            | 22              | 19              | 17               | —                 | —        |    |    |    |    |
| 60             | 40                             | 30           | 27            | 24              | 20              | 18               | —                 | —        |    |    |    |    |
| 70             | —                              | —            | —             | 26              | 21              | 20               | —                 | —        |    |    |    |    |
| 80             | —                              | —            | —             | 28              | 22              | 21               | —                 | —        |    |    |    |    |
| 90             | —                              | —            | —             | 29              | 24              | 23               | —                 | —        |    |    |    |    |
| 100            | —                              | —            | —             | 31              | 25              | 24               | —                 | —        |    |    |    |    |
| <i>N</i>       | Profile Variation              |              |               |                 |                 |                  |                   |          |    |    |    |    |
| All            | +7<br>-10                      | +6<br>-8     | +5<br>-7      | +4<br>-6        | +3<br>-5        | +2<br>-4         | +2<br>-4          | +2<br>-4 |    |    |    |    |
| Lead Variation |                                |              |               |                 |                 |                  |                   |          |    |    |    |    |
| $L_g$ , in.    | 0.3                            | 0.5          | 1             | 2               | 3               | 4                | 5                 | 6        | 7  | 8  | 9  | 10 |
| Variation      | 2                              | 3            | 4             | 5               | 6               | 7                | 8                 | 9        | 10 | 11 | 12 | 13 |

For other tolerance classes: Class 4 =  $0.71 \times$  Tabulated value

Class 5 = As tabulated in table

Class 6 =  $1.40 \times$  Tabulated value

Class 7 =  $2.00 \times$  Tabulated value



**Fillets and Chamfers.**—Spline teeth may have either a flat root or a rounded fillet root.

*Flat Root Splines:* are suitable for most applications. The fillet that joins the sides to the bottom of the tooth space, if generated, has a varying radius of curvature. Specification of this fillet is usually not required. It is controlled by the form diameter, which is the diameter at the deepest point of the desired true involute form (sometimes designated as TIF).

When flat root splines are used for heavily loaded couplings that are not suitable for fillet root spline application, it may be desirable to minimize the stress concentration in the flat root type by specifying an approximate radius for the fillet.

Because internal splines are stronger than external splines due to their broad bases and high pressure angles at the major diameter, broaches for flat root internal splines are normally made with the involute profile extending to the major diameter.

*Fillet Root Splines:* are recommended for heavy loads because the larger fillets provided reduce the stress concentrations. The curvature along any generated fillet varies and cannot be specified by a radius of any given value.

External splines may be produced by generating with a pinion-type shaper cutter or with a hob, or by cutting with no generating motion using a tool formed to the contour of a tooth space. External splines are also made by cold forming and are usually of the fillet root design. Internal splines are usually produced by broaching, by form cutting, or by generating with a shaper cutter. Even when full-tip radius tools are used, each of these cutting methods produces a fillet contour with individual characteristics. Generated spline fillets are curves related to the prolate epicycloid for external splines and the prolate hypocycloid for internal splines. These fillets have a minimum radius of curvature at the point where the fillet is tangent to the external spline minor diameter circle or the internal spline major diameter circle and a rapidly increasing radius of curvature up to the point where the fillet comes tangent to the involute profile.

*Chamfers and Corner Clearance:* In major diameter fits, it is always necessary to provide corner clearance at the major diameter of the spline coupling. This clearance is usually effected by providing a chamfer on the top corners of the external member. This method may not be possible or feasible because of the following:

- If the external member is roll formed by plastic deformation, a chamfer cannot be provided by the process.
- A semitopping cutter may not be available.
- When cutting external splines with small numbers of teeth, a semitopping cutter may reduce the width of the top land to a prohibitive point.

In such conditions, the corner clearance can be provided on the internal spline, as shown in Fig. 2.

When this option is used, the form diameter may fall in the protuberance area.

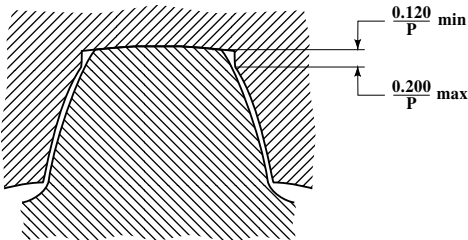


Fig. 2. Internal corner clearance.

**Spline Variations.**—The maximum allowable variations for involute splines are listed in Table 4.

*Profile Variation:* The reference profile, from which variations occur, passes through the point used to determine the actual space width or tooth thickness. This is either the pitch point or the contact point of the standard measuring pins.

Profile variation is positive in the direction of the space and negative in the direction of the tooth. Profile variations may occur at any point on the profile for establishing effective fits and are shown in Table 4.

*Lead Variations:* The lead tolerance for the total spline length applies also to any portion thereof unless otherwise specified.

*Out of Roundness:* This condition may appear merely as a result of index and profile variations given in Table 4 and requires no further allowance. However, heat treatment and deflection of thin sections may cause out of roundness, which increases index and profile variations. Tolerances for such conditions depend on many variables and are therefore not tabulated. Additional tooth and/or space width tolerance must allow for such conditions.

*Eccentricity:* Eccentricity of major and minor diameters in relation to the effective diameter of side fit splines should not cause contact beyond the form diameters of the mating splines, even under conditions of maximum effective clearance. This standard does not establish specific tolerances.

Eccentricity of major diameters in relation to the effective diameters of major diameter fit splines should be absorbed within the maximum material limits established by the tolerances on major diameter and effective space width or effective tooth thickness.

If the alignment of mating splines is affected by eccentricity of locating surfaces relative to each other and/or the splines, it may be necessary to decrease the effective and actual tooth thickness of the external splines in order to maintain the desired fit condition. This standard does not include allowances for eccentric location.

**Effect of Spline Variations.**—Spline variations can be classified as index variations, profile variations, or lead variations.

*Index Variations:* These variations cause the clearance to vary from one set of mating tooth sides to another. Because the fit depends on the areas with minimum clearance, index variations reduce the effective clearance.

*Profile Variations:* Positive profile variations affect the fit by reducing effective clearance. Negative profile variations do not affect the fit but reduce the contact area.

*Lead Variations:* These variations will cause clearance variations and therefore reduce the effective clearance.

*Variation Allowance:* The effect of individual spline variations on the fit (effective variation) is less than their total, because areas of more than minimum clearance can be altered without changing the fit. The variation allowance is 60 percent of the sum of twice the positive profile variation, the total index variation and the lead variation for the length of engagement. The variation allowances in Table 4 are based on a lead variation for an assumed length of engagement equal to one-half the pitch diameter. Adjustment may be required for a greater length of engagement.

**Effective and Actual Dimensions.**—Although each space of an internal spline may have the same width as each tooth of a perfect mating external spline, the two may not fit because of variations of index and profile in the internal spline. To allow the perfect external spline to fit in any position, all spaces of the internal spline must then be widened by the amount of interference. The resulting width of these tooth spaces is the *actual* space width of the internal spline. The *effective* space width is the tooth thickness of the perfect mating external spline. The same reasoning applied to an external spline that has variations of index and profile when mated with a perfect internal spline leads to the concept of effective

tooth thickness, which exceeds the actual tooth thickness by the amount of the effective variation.

The effective space width of the internal spline minus the effective tooth thickness of the external spline is the effective clearance and defines the fit of the mating parts. (This statement is strictly true only if high points of mating parts come into contact.) Positive effective clearance represents looseness or backlash. Negative effective clearance represents tightness or interference.

**Space Width and Tooth Thickness Limits.**—The variation of actual space width and actual tooth thickness within the machining tolerance causes corresponding variations of effective dimensions, so that there are four limit dimensions for each component part.

These variations are shown diagrammatically in Table 5.

**Table 5. Specification Guide for Space Width and Tooth Thickness**  
ANSI B92.1-1970, R1993

| Dimension                          | Dimension of Variations, Clearances, and Tolerances on Part |        | Dimensioning Method |              |          |
|------------------------------------|---|--------|---------------------|--------------|----------|
|                                    | Effective   | Actual | Standard            | Alternatives |          |
|                                    |   |        |                     | A            | B        |
| Space Width of Internal Spline     |   |        | Required            | Required     | Ref.     |
|                                    |   |        | Ref.                | Ref.         | Ref.     |
| (Basic)                            | $\pi$   |        | Ref.                | Required     | Required |
| Tooth Thickness of External Spline |   |        | Required            | Required     | Required |
|                                    |   |        | Ref.                | Required     | Required |
|                                    |   |        | Ref.                | Ref.         | Ref.     |
|                                    |   |        | Required            | Required     | Ref.     |

The minimum effective space width is always basic. The maximum effective tooth thickness is the same as the minimum effective space width except for the major diameter fit. The major diameter fit maximum effective tooth thickness is less than the minimum effective space width by an amount that allows for eccentricity between the effective spline and the major diameter. The permissible variation of the effective clearance is divided between the internal and external splines to arrive at the maximum effective space width and the minimum effective tooth thickness. Limits for the actual space width and actual tooth thickness are constructed from suitable variation allowances.

**Use of Effective and Actual Dimensions.**—Each of the four dimensions for space width and tooth thickness shown in Table 5 has a definite function.

*Minimum Effective Space Width and Maximum Effective Tooth Thickness:* These dimensions control the minimum effective clearance, and must always be specified.

*Minimum Actual Space Width and Maximum Actual Tooth Thickness:* These dimensions cannot be used for acceptance or rejection of parts. If the actual space width is less than the minimum without causing the effective space width to be undersized, or if the actual tooth thickness is more than the maximum without causing the effective tooth thickness to be oversized, the effective variation is less than anticipated; such parts are desirable and not defective. The specification of these dimensions as processing reference dimensions is optional. They are also used to analyze undersize effective space width or oversize effective tooth thickness conditions to determine whether or not these conditions are caused by excessive effective variation.

**Maximum Actual Space Width and Minimum Actual Tooth Thickness:** These dimensions control machining tolerance and limit the effective variation. The spread between these dimensions, reduced by the effective variation of the internal and external spline, is the maximum effective clearance. Where the effective variation obtained in machining is appreciably less than the variation allowance, these dimensions must be adjusted in order to maintain the desired fit.

**Maximum Effective Space Width and Minimum Effective Tooth Thickness:** These dimensions define the maximum effective clearance but they do not limit the effective variation. They may be used, in addition to the maximum actual space width and minimum actual tooth thickness, to prevent the increase of maximum effective clearance due to reduction of effective variations. The notation "inspection optional" may be added where maximum effective clearance is an assembly requirement, but does not need absolute control. It will indicate, without necessarily adding inspection time and equipment, that the actual space width of the internal spline must be held below the maximum, or the actual tooth thickness of the external spline above the minimum, if machining methods result in less than the allowable variations. Where effective variation needs no control or is controlled by laboratory inspection, these limits may be substituted for maximum actual space width and minimum actual tooth thickness.

**Combinations of Involute Spline Types.**—Flat root side fit internal splines may be used with fillet root external splines where the larger radius is desired on the external spline for control of stress concentrations. This combination of fits may also be permitted as a design option by specifying for the minimum root diameter of the external, the value of the minimum root diameter of the fillet root external spline and noting this as "optional root."

A design option may also be permitted to provide either flat root internal or fillet root internal by specifying for the maximum major diameter, the value of the maximum major diameter of the fillet root internal spline and noting this as "optional root."

**Interchangeability.**—Splines made to this standard may interchange with splines made to older standards. Exceptions are listed below.

**External Splines:** These external splines will mate with older internal splines as follows:

| Year              | Major Dia. Fit | Flat Root Side Fit  | Fillet Root Side Fit |
|-------------------|----------------|---------------------|----------------------|
| 1946              | Yes            | No (A) <sup>a</sup> | No (A)               |
| 1950 <sup>b</sup> | Yes (B)        | Yes (B)             | Yes (C)              |
| 1950 <sup>c</sup> | Yes (B)        | No (A)              | Yes (C)              |
| 1957 SAE          | Yes            | No (A)              | Yes (C)              |
| 1960              | Yes            | No (A)              | Yes (C)              |

<sup>a</sup> For exceptions A, B, C, see the paragraph on *Exceptions* that follows.

<sup>b</sup> Full dedendum.

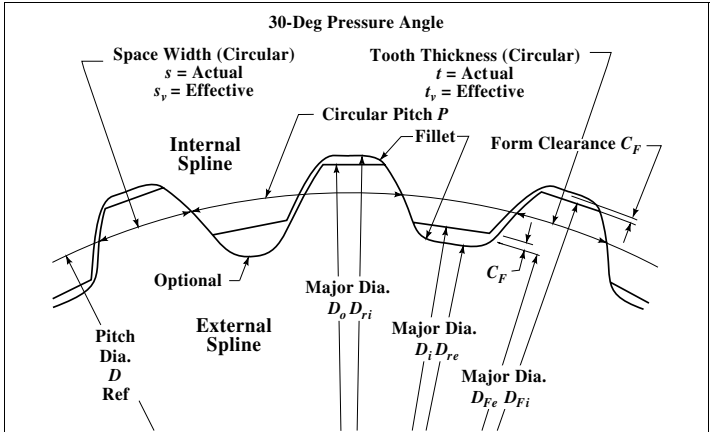
<sup>c</sup> Short dedendum.

**Internal Splines:** These will mate with older external splines as follows:

| Year     | Major Dia. Fit      | Flat Root Side Fit | Fillet Root Side Fit |
|----------|---------------------|--------------------|----------------------|
| 1946     | No (D) <sup>a</sup> | No (E)             | No (D)               |
| 1950     | Yes (F)             | Yes                | Yes (C)              |
| 1957 SAE | Yes (G)             | Yes                | Yes                  |
| 1960     | Yes (G)             | Yes                | Yes                  |

<sup>a</sup> For exceptions C, D, E, F, G, see the paragraph on *Exceptions* that follows.

**Table 6. Spline Terms, Symbols, and Drawing Data, 30-Degree Pressure Angle, Flat Root Side Fit ANSI B92.1-1970, R1993**



The fit shown is used in restricted areas (as with tubular parts with wall thickness too small to permit use of fillet roots, and to allow hobbing closer to shoulders, etc.) and for economy (when hobbing, shaping, etc., and using shorter broaches for the internal member).

Press fits are not tabulated because their design depends on the degree of tightness desired and must allow for such factors as the shape of the blank, wall thickness, material, hardness, thermal expansion, etc. Close tolerances or selective size grouping may be required to limit fit variations.

**Drawing Data**

| Internal Involute Spline Data                       |              | External Involute Spline Data                       |              |
|---|--------------|---|--------------|
| Flat Root Side Fit                                  |              | Flat Root Side Fit                                  |              |
| Number of Teeth                                     | xx           | Number of Teeth                                     | xx           |
| Pitch   | xx/xx        | Pitch   | xx/xx        |
| Pressure Angle                                      | 30°          | Pressure Angle                                      | 30°          |
| Base Diameter                                       | x.xxxxxx Ref | Base Diameter                                       | x.xxxxxx Ref |
| Pitch Diameter                                      | x.xxxxxx Ref | Pitch Diameter                                      | x.xxxxxx Ref |
| Major Diameter                                      | x.xxx max    | Major Diameter                                      | x.xxx/x.xxx  |
| Form Diameter                                       | x.xxx        | Form Diameter                                       | x.xxx        |
| Minor Diameter                                      | x.xxx/x.xxx  | Minor Diameter                                      | x.xxx min    |
| Circular Space Width                                |              | Circular Tooth Thickness                            |              |
| Max Actual  | x.xxxx       | Max Effective                                       | x.xxxx       |
| Min Effective                                       | x.xxxx       | Min Actual  | x.xxxx       |
| The following information may be added as required: |              | The following information may be added as required: |              |
| Max Measurement Between Pins                        | x.xxx Ref    | Min Measurement Over Pins                           | x.xxxx Ref   |
| Pin Diameter  | x.xxxx       | Pin Diameter  | x.xxxx       |

The above drawing data are required for the spline specifications. The standard system is shown; for alternate systems, see Table 5. Number of x's indicates number of decimal places normally used.

*Exceptions:*

a) The external major diameter, unless chamfered or reduced, may interfere with the internal form diameter on flat root side fit splines. Internal splines made to the 1957 and 1960 standards had the same dimensions as shown for the major diameter fit splines in this standard.

b) For 15 teeth or less, the minor diameter of the internal spline, unless chamfered, will interfere with the form diameter of the external spline.

c) For 9 teeth or less, the minor diameter of the internal spline, unless chamfered, will interfere with form diameter of the external spline.

d) The internal minor diameter, unless chamfered, will interfere with the external form diameter.

e) The internal minor diameter, unless chamfered, will interfere with the external form diameter.

f) For 10 teeth or less, the minimum chamfer on the major diameter of the external spline may not clear the internal form diameter.

g) Depending upon the pitch of the spline, the minimum chamfer on the major diameter may not clear the internal form diameter.

**Drawing Data.**—It is important that uniform specifications be used to show complete information on detail drawings of splines. Much misunderstanding will be avoided by following the suggested arrangement of dimensions and data as given in [Table 6](#). The number of x's indicates the number of decimal places normally used. With this tabulated type of spline specifications, it is usually not necessary to show a graphic illustration of the spline teeth.

**Spline Data and Reference Dimensions.**—Spline data are used for engineering and manufacturing purposes. Pitch and pressure angle are not subject to individual inspection.

As used in this standard, *reference* is an added notation or modifier to a dimension, specification, or note when that dimension, specification, or note is:

- 1) Repeated for drawing clarification.
- 2) Needed to define a nonfeature datum or basis from which a form or feature is generated.
- 3) Needed to define a nonfeature dimension from which other specifications or dimensions are developed.
- 4) Needed to define a nonfeature dimension at which toleranced sizes of a feature are specified.
- 5) Needed to define a nonfeature dimension from which control tolerances or sizes are developed or added as useful information.

Any dimension, specification, or note that is noted "REF" should not be used as a criterion for part acceptance or rejection.

**Estimating Key and Spline Sizes and Lengths.**—[Fig. 3](#) may be used to estimate the size of American Standard involute splines required to transmit a given torque. It also may be used to find the outside diameter of shafts used with single keys. After the size of the shaft is found, the proportions of the key can be determined from [Table 1](#) on page [2363](#).

Curve A is for flexible splines with teeth hardened to Rockwell C 55–65. For these splines, lengths are generally made equal to or somewhat greater than the pitch diameter for diameters below 1¼ inches; on larger diameters, the length is generally one-third to two-thirds the pitch diameter. Curve A also applies for a single key used as a fixed coupling, the length of the key being one to one and one-quarter times the shaft diameter. The stress in the shaft, neglecting stress concentration at the keyway, is about 7500 pounds per square inch. See also *Effect of Keyways on Shaft Strength* starting on page [305](#).

Curve B represents high-capacity single keys used as fixed couplings for stresses of 9500 pounds per square inch, neglecting stress concentration. Key-length is one to one and one-quarter times shaft diameter and both shaft and key are of moderately hard heat-treated

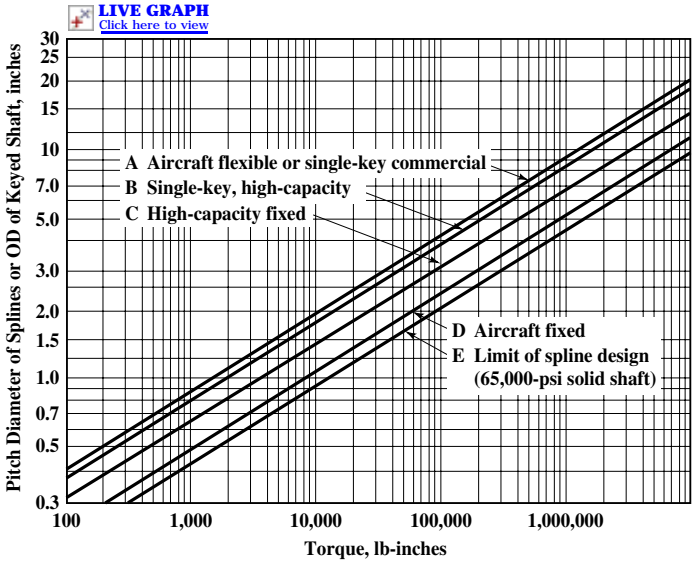


Fig. 3. Chart for Estimating Involute Spline Size Based on Diameter-Torque Relationships

steel. This type of connection is commonly used to key commercial flexible couplings to motor or generator shafts.

Curve C is for multiple-key fixed splines with lengths of three-quarters to one and one-quarter times pitch diameter and shaft hardness of 200–300 BHN.

Curve D is for high-capacity splines with lengths one-half to one times the pitch diameter. Hardnesses up to Rockwell C 58 are common and in aircraft applications the shaft is generally hollow to reduce weight.

Curve E represents a solid shaft with 65,000 pounds per square inch shear stress. For hollow shafts with inside diameter equal to three-quarters of the outside diameter the shear stress would be 95,000 pounds per square inch.

*Length of Splines:* Fixed splines with lengths of one-third the pitch diameter will have the same shear strength as the shaft, assuming uniform loading of the teeth; however, errors in spacing of teeth result in only half the teeth being fully loaded. Therefore, for balanced strength of teeth and shaft the length should be two-thirds the pitch diameter. If weight is not important, however, this may be increased to equal the pitch diameter. In the case of flexible splines, long lengths do not contribute to load carrying capacity when there is misalignment to be accommodated. Maximum effective length for flexible splines may be approximated from Fig. 4.

**Formulas for Torque Capacity of Involute Splines.**—The formulas for torque capacity of 30-degree involute splines given in the following paragraphs are derived largely from an article “When Splines Need Stress Control” by D. W. Dudley, *Product Engineering*, Dec. 23, 1957.

In the formulas that follow the symbols used are as defined on page 2160 with the following additions:  $D_i$  = inside diameter of hollow shaft, inches;  $K_a$  = application factor from Table 7;  $K_m$  = load distribution factor from Table 8;  $K_f$  = fatigue life factor from Table 9;  $K_w$

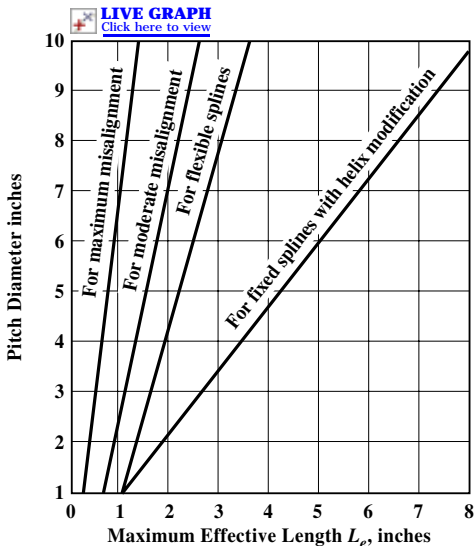


Fig. 4. Maximum Effective Length for Fixed and Flexible Splines

= wear life factor from Table 10;  $L_e$  = maximum effective length from Fig. 4, to be used in stress formulas even though the actual length may be greater;  $T$  = transmitted torque, pound-inches. For fixed splines without helix modification, the effective length  $L_e$  should never exceed  $5000 D^{3.5} \div T$ .

Table 7. Spline Application Factors,  $K_a$ 

| Power Source                               | Type of Load                |   |   |  |
|--|-----------------------------|---|---|--|
|  | Uniform<br>(Generator, Fan) | Light Shock<br>(Oscillating<br>Pumps, etc.) | Intermittent<br>Shock<br>(Actuating<br>Pumps, etc.) | Heavy<br>Shock<br>(Punches,<br>Shears, etc.) |
|  | Application Factor, $K_a$   |   |   |  |
| Uniform (Turbine, Motor)                   | 1.0                         | 1.2   | 1.5   | 1.8  |
| Light Shock (Hydraulic Motor)              | 1.2                         | 1.3   | 1.8   | 2.1  |
| Medium Shock (Internal Combustion, Engine) | 2.0                         | 2.2   | 2.4   | 2.8  |

Table 8. Load Distribution Factors,  $K_m$ , for Misalignment of Flexible Splines

| Misalignment,<br>inches per inch | Load Distribution Factor, $K_m^a$ |                  |                  |                  |
|----------------------------------|-----------------------------------|------------------|------------------|------------------|
|                                  | $\frac{1}{2}$ -in. Face Width     | 1-in. Face Width | 2-in. Face Width | 4-in. Face Width |
| 0.001                            | 1                                 | 1                | 1                | $1 \frac{1}{2}$  |
| 0.002                            | 1                                 | 1                | $1 \frac{1}{2}$  | 2                |
| 0.004                            | 1                                 | $1 \frac{1}{2}$  | 2                | $2 \frac{1}{2}$  |
| 0.008                            | $1 \frac{1}{2}$                   | 2                | $2 \frac{1}{2}$  | 3                |

<sup>a</sup> For fixed splines,  $K_m = 1$ .

For fixed splines,  $K_m = 1$ .



**Table 9. Fatigue-Life Factors,  $K_f$ , for Splines**

| No. of Torque Cycles <sup>a</sup> | Fatigue-Life Factor, $K_f$ |                |
|-----------------------------------|----------------------------|----------------|
|                                   | Unidirectional             | Fully-reversed |
| 1,000                             | 1.8                        | 1.8            |
| 10,000                            | 1.0                        | 1.0            |
| 100,000                           | 0.5                        | 0.4            |
| 1,000,000                         | 0.4                        | 0.3            |
| 10,000,000                        | 0.3                        | 0.2            |

<sup>a</sup> A torque cycle consists of one start and one stop, not the number of revolutions.

**Table 10. Wear Life Factors,  $K_w$ , for Flexible Splines**

| Number of Revolutions of Spline | Life Factor, $K_w$ | Number of Revolutions of Spline | Life Factor, $K_w$ |
|---------------------------------|--------------------|---------------------------------|--------------------|
| 10,000                          | 4.0                | 100,000,000                     | 1.0                |
| 100,000                         | 2.8                | 1,000,000,000                   | 0.7                |
| 1,000,000                       | 2.0                | 10,000,000,000                  | 0.5                |
| 10,000,000                      | 1.4                | ...                             | ...                |

Wear life factors, unlike fatigue life factors given in Table 9, are based on the total number of revolutions of the spline, since each revolution of a flexible spline results in a complete cycle of rocking motion which contributes to spline wear.

*Definitions:* A *fixed* spline is one which is either shrink fitted or loosely fitted but piloted with rings at each end to prevent rocking of the spline which results in small axial movements that cause wear. A *flexible* spline permits some rocking motion such as occurs when the shafts are not perfectly aligned. This flexing or rocking motion causes axial movement and consequently wear of the teeth. Straight-toothed flexible splines can accommodate only small angular misalignments (less than 1 deg.) before wear becomes a serious problem. For greater amounts of misalignment (up to about 5 deg.), crowned splines are preferable to reduce wear and end-loading of the teeth.

*Shear Stress Under Roots of External Teeth:* For a transmitted torque  $T$ , the torsional shear stress induced in the shaft under the root diameter of an external spline is:

$$S_s = \frac{16TK_a}{\pi D_{re}^3 K_f} \quad \text{for a solid shaft} \quad (1)$$

$$S_s = \frac{16TD_{re}K_a}{\pi(D_{re}^4 - D_h^4)K_f} \quad \text{for a hollow shaft} \quad (2)$$

The computed stress should not exceed the values in Table 11.

**Table 11. Allowable Shear, Compressive, and Tensile Stresses for Splines**

| Material                                  | Hardness |            | Max. Allowable Stress |                         |         |                     |
|---|----------|------------|-----------------------|-------------------------|---------|---------------------|
|   |          |            | Shear Stress, psi     | Compressive Stress, psi |         | Tensile Stress, psi |
|   | Brinell  | Rockwell C |                       | Straight                | Crowned |                     |
| Steel                                     | 160–200  | —          | 20,000                | 1,500                   | 6,000   | 22,000              |
|   | 230–260  | —          | 30,000                | 2,000                   | 8,000   | 32,000              |
|   | 302–351  | 33–38      | 40,000                | 3,000                   | 12,000  | 45,000              |
| Surface-hardened Steel                    | —        | 48–53      | 40,000                | 4,000                   | 16,000  | 45,000              |
| Case-hardened Steel                       | —        | 58–63      | 50,000                | 5,000                   | 20,000  | 55,000              |
| Through-hardened Steel (Aircraft Quality) | —        | 42–46      | 45,000                | —                       | —       | 50,000              |

*Shear Stress at the Pitch Diameter of Teeth:* The shear stress at the pitch line of the teeth for a transmitted torque  $T$  is:

$$S_s = \frac{4TK_aK_m}{DNL_e t K_f} \quad (3)$$

The factor of 4 in (3) assumes that only half the teeth will carry the load because of spacing errors. For poor manufacturing accuracies, change the factor to 6.

The computed stress should not exceed the values in [Table 11](#).

*Compressive Stresses on Sides of Spline Teeth:* Allowable compressive stresses on splines are very much lower than for gear teeth since non-uniform load distribution and misalignment result in unequal load sharing and end loading of the teeth.

$$\text{For flexible splines, } S_c = \frac{2TK_mK_a}{DNL_e h K_w} \quad (4)$$

$$\text{For fixed splines, } S_c = \frac{2TK_mK_a}{9DNL_e h K_f} \quad (5)$$

In these formulas,  $h$  is the depth of engagement of the teeth, which for flat root splines is  $0.9/P$  and for fillet root splines is  $1/P$ , approximately.

The stresses computed from [Formulas \(4\)](#) and [\(5\)](#) should not exceed the values in [Table 11](#).

*Bursting Stresses on Splines:* Internal splines may burst due to three kinds of tensile stress: 1) tensile stress due to the radial component of the transmitted load; 2) centrifugal tensile stress; and 3) tensile stress due to the tangential force at the pitch line causing bending of the teeth.

$$\text{Radial load tensile stress, } S_1 = \frac{T \tan \phi}{\pi D t_w L} \quad (6)$$

where  $t_w$  = wall thickness of internal spline = outside diameter of spline sleeve minus spline major diameter, all divided by 2.  $L$  = full length of spline.

$$\text{Centrifugal tensile stress, } S_2 = \frac{1.656 \times (\text{rpm})^2 (D_{oi}^2 + 0.212 D_{ri}^2)}{1,000,000} \quad (7)$$

where  $D_{oi}$  = outside diameter of spline sleeve.

$$\text{Beam loading tensile stress, } S_3 = \frac{4T}{D^2 L_e Y} \quad (8)$$

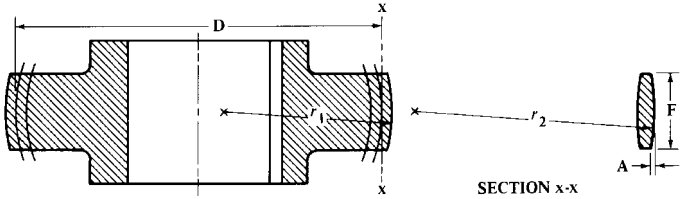
In [Equation \(8\)](#),  $Y$  is the Lewis form factor obtained from a tooth layout. For internal splines of 30-deg. pressure angle a value of  $Y = 1.5$  is a satisfactory estimate. The factor 4 in (8) assumes that only half the teeth are carrying the load.

The total tensile stress tending to burst the rim of the external member is:

$S_t = [K_a K_m (S_1 + S_3) + S_2] / K_f$ ; and should be less than those in [Table 11](#).

**Crowned Splines for Large Misalignments.**—As mentioned on page [2172](#), crowned splines can accommodate misalignments of up to about 5 degrees. Crowned splines have considerably less capacity than straight splines of the same size if both are operating with precise alignment. However, when large misalignments exist, the crowned spline has greater capacity.

American Standard tooth forms may be used for crowned external members so that they may be mated with straight internal members of Standard form.



The accompanying diagram of a crowned spline shows the radius of the crown  $r_1$ ; the radius of curvature of the crowned tooth,  $r_2$ ; the pitch diameter of the spline,  $D$ ; the face width,  $F$ ; and the relief or crown height  $A$  at the ends of the teeth. The crown height  $A$  should always be made somewhat greater than one-half the face width multiplied by the tangent of the misalignment angle. For a crown height  $A$ , the approximate radius of curvature  $r_2$  is  $F^2 \div 8A$ , and  $r_1 = r_2 \tan \phi$ , where  $\phi$  is the pressure angle of the spline.

For a torque  $T$ , the compressive stress on the teeth is:

$$S_c = 2290 \sqrt{2T \div D N h r_2};$$

and should be less than the value in [Table 11](#).

**Fretting Damage to Splines and Other Machine Elements.**—Fretting is wear that occurs when cyclic loading, such as vibration, causes two surfaces in intimate contact to undergo small oscillatory motions with respect to each other. During fretting, high points or asperities of the mating surfaces adhere to each other and small particles are pulled out, leaving minute, shallow pits and a powdery debris. In steel parts exposed to air, the metallic debris oxidizes rapidly and forms a red, rustlike powder or sludge; hence, the coined designation “fretting corrosion.”

Fretting is mechanical in origin and has been observed in most materials, including those that do not oxidize, such as gold, platinum, and nonmetallics; hence, the corrosion accompanying fretting of steel parts is a secondary factor.

Fretting can occur in the operation of machinery subject to motion or vibration or both. It can destroy close fits; the debris may clog moving parts; and fatigue failure may be accelerated because stress levels to initiate fatigue in fretted parts are much lower than for undamaged material. Sites for fretting damage include interference fits; splined, bolted, keyed, pinned, and riveted joints; between wires in wire rope; flexible shafts and tubes; between leaves in leaf springs; friction clamps; small amplitude-of-oscillation bearings; and electrical contacts.

Vibration or cyclic loadings are the main causes of fretting. If these factors cannot be eliminated, greater clamping force may reduce movement but, if not effective, may actually worsen the damage. Lubrication may delay the onset of damage; hard plating or surface hardening methods may be effective, not by reducing fretting, but by increasing the fatigue strength of the material. Plating soft materials having inherent lubricity onto contacting surfaces is effective until the plating wears through.

**Involute Spline Inspection Methods.**—Spline gages are used for routine inspection of production parts.

Analytical inspection, which is the measurement of individual dimensions and variations, may be required:

- To supplement inspection by gages, for example, where NOT GO composite gages are used in place of NOT GO sector gages and variations must be controlled.
- To evaluate parts rejected by gages.
- For prototype parts or short runs where spline gages are not used.

d) To supplement inspection by gages where each individual variation must be restrained from assuming too great a portion of the tolerance between the minimum material actual and the maximum material effective dimensions.

**Inspection with Gages.**—A variety of gages is used in the inspection of involute splines.

*Types of Gages:* A composite spline gage has a full complement of teeth. A sector spline gage has two diametrically opposite groups of teeth. A sector plug gage with only two teeth per sector is also known as a “paddle gage.” A sector ring gage with only two teeth per sector is also known as a “snap ring gage.” A progressive gage is a gage consisting of two or more adjacent sections with different inspection functions. Progressive GO gages are physical combinations of GO gage members that check consecutively first one feature or one group of features, then their relationship to other features. GO and NOT GO gages may also be combined physically to form a progressive gage.

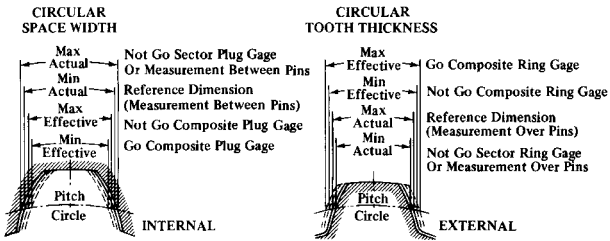


Fig. 5. Space width and tooth-thickness inspection.

*GO and NOT GO Gages:* GO gages are used to inspect maximum material conditions (maximum external, minimum internal dimensions). They may be used to inspect an individual dimension or the relationship between two or more functional dimensions. They control the minimum looseness or maximum interference.

NOT GO gages are used to inspect minimum material conditions (minimum external, maximum internal dimensions), thereby controlling the maximum looseness or minimum interference. Unless otherwise agreed upon, a product is acceptable only if the NOT GO gage does not enter or go on the part. A NOT GO gage can be used to inspect only one dimension. An attempt at simultaneous NOT GO inspection of more than one dimension could result in failure of such a gage to enter or go on (acceptance of part), even though all but one of the dimensions were outside product limits. In the event all dimensions are outside the limits, their relationship could be such as to allow acceptance.

*Effective and Actual Dimensions:* The effective space width and tooth thickness are inspected by means of an accurate mating member in the form of a composite spline gage.

The actual space width and tooth thickness are inspected with sector plug and ring gages, or by measurements with pins.

**Measurements with Pins.**—The actual space width of internal splines, and the actual tooth thickness of external splines, may be measured with pins. These measurements do not determine the fit between mating parts, but may be used as part of the analytic inspection of splines to evaluate the effective space width or effective tooth thickness by approximation.

*Formulas for 2-Pin Measurement Between Pins:* For measurement *between* pins of internal splines using the symbols given on page 2160:

1) Find involute of pressure angle at pin center:

$$\text{inv } \phi_i = \frac{s}{D} + \text{inv } \phi_d - \frac{d_i}{D_b}$$

2) Find the value of  $\phi_i$  in degrees, in the involute function tables beginning on page 104. Find  $\sec \phi_i = 1/\cosine \phi_i$  in the trig tables, pages 100 through 102, using interpolation to obtain higher accuracy.

3) Compute measurement,  $M_i$ , between pins:

For even numbers of teeth:  $M_i = D_b \sec \phi_i - d_i$

For odd numbers of teeth:  $M_i = (D_b \cos 90^\circ/N) \sec \phi_i - d_i$

where:  $d_i = 1.7280/P$  for  $30^\circ$  and  $37.5^\circ$  standard pressure angle ( $\phi_D$ ) splines

$d_i = 1.9200/P$  for  $45^\circ$  pressure angle splines

*Example:* Find the measurement between pins for *maximum* actual space width of an internal spline of  $30^\circ$  pressure angle, tolerance class 4,  $\frac{3}{6}$  diametral pitch, and 20 teeth.

The maximum actual space width to be substituted for  $s$  in Step 1 above is obtained as follows: In Table 5, page 2166, the maximum actual space width is the sum of the minimum effective space width (second column) and  $\lambda + m$  (third column). The minimum effective space width  $s_v$  from Table 2, page 2161, is  $\pi/2P = \pi/(2 \times 3)$ . The values of  $\lambda$  and  $m$  from Table 4, page 2163, are, for a class 4 fit,  $\frac{3}{6}$  diametral pitch, 20-tooth spline:  $\lambda = 0.0027 \times 0.71 = 0.00192$ ; and  $m = 0.00176 \times 0.71 = 0.00125$ , so that  $s = 0.52360 + 0.00192 + 0.00125 = 0.52677$ .

Other values required for Step 1 are:

$$D = N \div P = 20 \div 3 = 6.66666$$

$$\text{inv } \phi_D = \text{inv } 30^\circ = 0.053751 \text{ from a calculator}$$

$$d_i = 1.7280/3 = 0.57600$$

$$D_b = D \cos \phi_D = 6.66666 \times 0.86603 = 5.77353$$

The computation is made as follows:

$$1) \text{inv } \phi_i = 0.52677/6.66666 + 0.053751 - 0.57600/5.77353 = 0.03300$$

$$2) \text{ From a calculator, } \phi_i = 25^\circ 46.18' \text{ and } \sec \phi_i = 1.11044$$

$$3) M_i = 5.77353 \times 1.11044 - 0.57600 = 5.8352 \text{ inches}$$

*Formulas for 2-Pin Measurement Over Pins:* For measurement *over* pins of external splines:

1) Find involute of pressure angle at pin center:

$$\text{inv } \phi_e = \frac{t}{D} + \text{inv } \phi_D + \frac{d_e}{D_b} - \frac{\pi}{N}$$

2) Find the value of  $\phi_e$  and  $\sec \phi_e$  from the involute function tables beginning on page 104.

3) Compute measurement,  $M_e$ , over pins:

For even numbers of teeth:  $M_e = D_b \sec \phi_e + d_e$

For odd numbers of teeth:  $M_e = (D_b \cos 90^\circ/N) \sec \phi_e + d_e$

where  $d_e = 1.9200/P$  for all external splines

**American National Standard Metric Module Splines.**—ANSI B92.2M-1980 (R1989) is the American National Standards Institute version of the International Standards Organization involute spline standard. It is not a "soft metric" conversion of any previous, inch-based, standard,\* and splines made to this hard metric version are not intended for use with components made to the B92.1 or other, previous standards. The ISO 4156 Standard from

\* A "soft" conversion is one in which dimensions in inches, when multiplied by 25.4 will, after being appropriately rounded off, provide equivalent dimensions in millimeters. In a "hard" system the tools of production, such as hobs, do not bear a usable relation to the tools in another system; i.e., a 10 diametral pitch hob calculates to be equal to a 2.54 module hob in the metric module system, a hob that does not exist in the metric standard.

which this one is derived is the result of a cooperative effort between the ANSI B92 committee and other members of the ISO/TC 14-2 involute spline committee.

Many of the features of the previous standard, ANSI B92.1-1970 (R1993), have been retained such as: 30-, 37.5-, and 45-degree pressure angles; flat root and fillet root side fits; the four tolerance classes 4, 5, 6, and 7; tables for a single class of fit; and the effective fit concept.

Among the major differences are: use of modules of from 0.25 through 10 mm in place of diametral pitch; dimensions in millimeters instead of inches; the "basic rack"; removal of the major diameter fit; and use of ISO symbols in place of those used previously. Also, provision is made for calculating three defined clearance fits.

The Standard recognizes that proper assembly between mating splines is dependent only on the spline being within effective specifications from the tip of the tooth to the form diameter. Therefore, the internal spline major diameter is shown as a maximum dimension and the external spline minor diameter is shown as a minimum dimension. The minimum internal major diameter and the maximum external minor diameter must clear the specified form diameter and thus require no additional control. All dimensions are for the finished part; any compensation that must be made for operations that take place during processing, such as heat treatment, must be considered when selecting the tolerance level for manufacturing.

The Standard provides the same internal minimum effective space width and external maximum effective tooth thickness for all tolerance classes. This basic concept makes possible interchangeable assembly between mating splines regardless of the tolerance class of the individual members, and permits a tolerance class "mix" of mating members. This arrangement is often an advantage when one member is considerably less difficult to produce than its mate, and the "average" tolerance applied to the two units is such that it satisfies the design need. For example, by specifying Class 5 tolerance for one member and Class 7 for its mate, an assembly tolerance in the Class 6 range is provided.

If a fit given in this Standard does not satisfy a particular design need, and a specific clearance or press fit is desired, the change shall be made only to the external spline by a reduction of, or an increase in, the effective tooth thickness and a like change in the actual tooth thickness. The minimum effective space width is always basic and this basic width should always be retained when special designs are derived from the concept of this Standard.

*Spline Terms and Definitions:* The spline terms and definitions given for American National Standard ANSI B92.1-1970 (R1993) described in the preceding section, may be used in regard to ANSI B92.2M-1980 (R1989). The 1980 Standard utilizes ISO symbols in place of those used in the 1970 Standard; these differences are shown in [Table 12](#).

*Dimensions and Tolerances:* Dimensions and tolerances of splines made to the 1980 Standard may be calculated using the formulas given in [Table 13](#). These formulas are for metric module splines in the range of from 0.25 to 10 mm metric module of side-fit design and having pressure angles of 30-, 37.5-, and 45-degrees. The standard modules in the system are: 0.25; 0.5; 0.75; 1; 1.25; 1.5; 1.75; 2; 2.5; 3; 4; 5; 6; 8; and 10. The range of from 0.5 to 10 module applies to all splines except 45-degree fillet root splines; for these, the range of from 0.25 to 2.5 module applies.

*Fit Classes:* Four classes of side fit splines are provided: spline fit class H/h having a minimum effective clearance,  $c_v = es = 0$ ; classes H/f, H/e, and H/d having tooth thickness modifications,  $es$ , of  $f$ ,  $e$ , and  $d$ , respectively, to provide progressively greater effective clearance  $c_v$ . The tooth thickness modifications  $h$ ,  $f$ ,  $e$ , and  $d$  in [Table 14](#) are fundamental deviations selected from ISO R286, "ISO System of Limits and Fits." They are applied to the external spline by shifting the tooth thickness total tolerance below the basic tooth thickness by the amount of the tooth thickness modification to provide a prescribed minimum effective clearance  $c_v$ .

**Table 12. Comparison of Symbols Used in ANSI B92.2M-1980 (R1989) and Those in ANSI B92.1-1970, R1993**

| Symbol       |           | Meaning of Symbol                                    | Symbol               |                   | Meaning of Symbol  |
|--------------|-----------|--|----------------------|-------------------|--|
| B92.2M       | B92.1     |  | B92.2M               | B92.1             |  |
| $c$          | ...       | theoretical clearance                                | $m$                  | ...               | module   |
| $c_v$        | ...       | effective clearance                                  | ...                  | $P$               | diametral pitch  |
| $c_F$        | $c_F$     | form clearance                                       | ...                  | $P_s$             | stub pitch = $2P$  |
| $D$          | $D$       | pitch diameter                                       | $P_b$                | ...               | base pitch   |
| $DB$         | $D_b$     | base diameter  | $p$                  | $p$               | circular pitch   |
| $d_{ce}$     | $D_{ce}$  | pin contact diameter, external spline                | $\pi$                | $\pi$             | 3.141592654  |
| $d_{ci}$     | $D_{ci}$  | pin contact diameter, internal spline                | $rfe$                | $r_f$             | fillet rad., ext. spline   |
| $DEE$        | $D_o$     | major diam., ext. spline                             | $rfi$                | $r_f$             | fillet rad., int. spline   |
| $DEI$        | $D_{fi}$  | major diam., int. spline                             | $E_{bsc}$            | $s_v \text{ min}$ | basic circular space width   |
| $DFE$        | $D_{Fe}$  | form diam., ext. spline                              | $E_{max}$            | $s$               | max. actual circular space width   |
| $DFI$        | $D_{fi}$  | form diam., int. spline                              | $E_{min}$            | $s$               | min. actual circular space width   |
| $DIE$        | $D_{re}$  | minor diam., ext. spline                             | $EV$                 | $s_v$             | effective circular space width   |
| $DII$        | $D_i$     | minor diam., int. spline                             | $S_{bsc}$            | $t_v \text{ max}$ | basic circular tooth thickness   |
| $DRE$        | $d_e$     | pin diam., ext. spline                               | $S_{max}$            | $t$               | max. actual circular tooth thick.  |
| $DRI$        | $d_i$     | pin diam., int. spline                               | $S_{min}$            | $t$               | min. actual circular tooth thick.  |
| $h_s$        | ...       | see Figs. 6a, 6b, 6c, and 6d                         | $SV$                 | $t_v$             | effective circular tooth thick.  |
| $\lambda$    | $\lambda$ | effective variation                                  | $\alpha$             | $\phi$            | pressure angle   |
| INV $\alpha$ | ...       | involute $\alpha = \tan \alpha - \text{arc } \alpha$ | $\alpha_D$           | $\phi_D$          | standard pressure angle  |
| $KE$         | $K_e$     | change factor, ext. spline                           | $\alpha_{ci}$        | $\phi_{ci}$       | press. angle at pin contact diameter, internal spline  |
| $KI$         | $K_i$     | change factor, int. spline                           | $\alpha_{ce}$        | $\phi_{ce}$       | press. angle at pin contact diameter, external spline  |
| $g$          | $L$       | spline length  | $\alpha_i$           | $\phi_i$          | press. angle at pin center, internal spline  |
| $g_w$        | ...       | active spline length                                 | $\alpha_e$           | $\phi_e$          | press. angle at pin center, external spline  |
| $g\gamma$    | ...       | length of engagement                                 | $\alpha_{Fe}$        | $\phi_F$          | press. angle at form diameter, external spline   |
| $T$          | $m$       | machining tolerance                                  | $\alpha_{Fi}$        | $\phi_F$          | press. angle at form diameter, internal spline   |
| $MRE$        | $M_e$     | meas. over 2 pins, ext. spline                       | $es$                 | ...               | ext. spline cir. tooth thick. modification for required fit class = $c_v \text{ min}$ (Table 14) |
| $MRI$        | $M_i$     | meas. bet. 2 pins, int. spline                       | $h, f, e,$<br>or $d$ | ...               | tooth thick, size modifiers (called fundamental deviation in ISO R286), Table 14                 |
| $Z$          | $N$       | number of teeth                                      | $H$                  | ...               | space width size modifier (called fundamental deviation in ISO R286), Table 14                   |

**Table 13. Formulas for Dimensions and Tolerances for All Fit Classes—  
Metric Module Involute Splines**

| Term  | Symbol          | Formula   |   |   |   |
|---|-----------------|---|---|---|---|
|   |                 | 30-Degree Flat Root<br>0.5 to 10 module   | 30-Degree Fillet Root<br>0.5 to 10 module | 37.5-Degree Fillet Root<br>0.5 to 10 module | 45-Degree Fillet Root<br>0.25 to 2.5 module |
| Pitch Diameter  | $D$             | $mZ$  |   |   |   |
| Base Diameter   | $DB$            | $mZ \cos \alpha_D$  |   |   |   |
| Circular Pitch  | $p$             | $\pi m$   |   |   |   |
| Base Pitch  | $p_b$           | $\pi m \cos \alpha_D$   |   |   |   |
| Tooth Thick Mod   | $es$            | According to selected fit class, H/h, H/f, H/e, or H/d (see Table 14)   |   |   |   |
| Min Maj. Diam. Int  | $DEI$ min       | $m(Z + 1.5)$  | $m(Z + 1.8)$                              | $m(Z + 1.4)$                                | $m(Z + 1.2)$                                |
| Max Maj Diam. Int.  | $DEI$ max       | $DEI$ min + $(T + \lambda)/\tan \alpha_D$ (see Footnote <sup>a</sup> )  |   |   |   |
| Form Diam, Int.   | $DFI$           | $m(Z + 1) + 2c_F$   | $m(Z + 1) + 2c_F$                         | $m(Z + 0.9) + 2c_F$                         | $m(Z + 0.8) + 2c_F$                         |
| Min Minor Diam, Int   | $DII$ min       | $DFE + 2c_F$ (see Footnote <sup>b</sup> )   |   |   |   |
| Max Minor Diam, Int   | $DII$ max       | $DII$ min + $(0.2m^{0.667} - 0.01m^{-0.5})$ (see Footnote <sup>c</sup> )  |   |   |   |
| Cir Space Width,<br>Basic   | $E_{bsc}$       | $0.5\pi m$  |   |   |   |
| Min Effective   | $EV$ min        | $0.5\pi m$  |   |   |   |
| Max Actual  | $E$ max         | $EV$ min + $(T + \lambda)$ for classes 4, 5, 6, and 7 (see Table 15 for $T + \lambda$ )                               |   |   |   |
| Min Actual  | $E$ min         | $EV$ min + $\lambda$ (see text on page 2180 for $\lambda$ )   |   |   |   |
| Max Effective   | $EV$ max        | $E$ max - $\lambda$ (see text on page 2180 for $\lambda$ )  |   |   |   |
| Max Major Diam,<br>Ext <sup>d</sup>   | $DEE$ max       | $m(Z + 1) - es/\tan \alpha_D$   | $m(Z + 1) - es/\tan \alpha_D$             | $m(Z + 0.9) - es/\tan \alpha_D$             | $m(Z + 0.8) - es/\tan \alpha_D$             |
| Min Major Diam.<br>Ext  | $DEE$ min       | $DEE$ max - $(0.2m^{0.667} - 0.01m^{-0.5})c$  |   |   |   |
| Form Diam, External   | $DFE$           | $2 \times \sqrt{(0.5DB)^2 + \left[0.5D \sin \alpha_D - \frac{h_s + ((0.5es)/\tan \alpha_D)}{\sin \alpha_D}\right]^2}$ |   |   |   |
| Max Minor Diam,<br>Ext <sup>d</sup>   | $DIE$ max       | $m(Z - 1.5) - es/\tan \alpha_D$   | $m(Z - 1.8) - es/\tan \alpha_D$           | $m(Z - 1.4) - es/\tan \alpha_D$             | $m(Z - 1.2) - es/\tan \alpha_D$             |
| Min Minor Diam,<br>Ext  | $DIE$ min       | $DIE$ max - $(T + \lambda)/\tan \alpha_D$ (see Footnote <sup>a</sup> )  |   |   |   |
| Cir Tooth Thick,<br>Basic   | $S_{bsc}$       | $0.5\pi m$  |   |   |   |
| Max Effective   | $SV$ max        | $S_{bsc} - es$  |   |   |   |
| Min Actual  | $S$ min         | $SV$ max - $(T + \lambda)$ for classes 4, 5, 6, and 7 (see Table 15 for $T + \lambda$ )                               |   |   |   |
| Max Actual  | $S$ max         | $SV$ max - $\lambda$ (see text on page 2180 for $\lambda$ )   |   |   |   |
| Min Effective   | $SV$ min        | $S$ min + $\lambda$ (see text on page 2180 for $\lambda$ )  |   |   |   |
| Total Tolerance on<br>Circular Space<br>Width or Tooth<br>Thickness               | $(T + \lambda)$ | See formulas in Table 15  |   |   |   |
| Machining Toler-<br>ance on Circular<br>Space Width or<br>Tooth Thickness         | $T$             | $T = (T + \lambda)$ from Table 15 - $\lambda$ from text on page 2180.   |   |   |   |
| Effective Variation<br>Allowed on Circu-<br>lar Space Width or<br>Tooth Thickness | $\lambda$       | See text on page 2180.  |   |   |   |
| Form Clearance  | $c_F$           | 0.1m  |   |   |   |
| Rack Dimension  | $h_s$           | 0.6m(see Fig. 6a)   | 0.6m(see Fig. 6b)                         | 0.55m(see Fig. 6c)                          | 0.5m(see Fig. 6d)                           |

<sup>a</sup> Use  $(T + \lambda)$  for class 7 from Table 15

<sup>b</sup> For all types of fit, always use the  $DFE$  value corresponding to the H/h fit.



<sup>c</sup> Values of  $(0.2m^{0.667} - 0.01m^{-0.5})$  are as follows: for 10 module, 0.93; for 8 module, 0.80; for 6 module, 0.66; for 5 module, 0.58; for 4 module, 0.50; for 3 module, 0.41; for 2.5 module, 0.36; for 2 module, 0.31; for 1.75 module, 0.28; for 1.5 module, 0.25; for 1.25 module, 0.22; for 1 module, 0.19; for 0.75 module, 0.15; for 0.5 module, 0.11; and for 0.25 module, 0.06.

<sup>d</sup> See Table 17 for values of  $es/\tan \alpha_D$ .

**Table 14. Tooth Thickness Modification,  $es$ , for Selected Spline Fit Classes**

| Pitch Diameter in mm, $D$ | External Splines <sup>a</sup>  |              |       |   | Pitch Diameter in mm, $D$ | External Splines <sup>a</sup>  |              |              |   |
|---------------------------|--|--------------|-------|---|---------------------------|--|--------------|--------------|---|
|                           | Selected Fit Class   |              |       |   |                           | Selected Fit Class   |              |              |   |
|                           | d  | e            | f     | h |                           | d  | e            | f            | h |
|                           | Tooth Thickness Modification (Reduction) Relative to Basic Tooth Thickness at Pitch Diameter, $es$ , in mm |              |       |   |                           | Tooth Thickness Modification (Reduction) Relative to Basic Tooth Thickness at Pitch Diameter, $es$ , in mm |              |              |   |
| ≤ 3                       | 0.020  | 0.014        | 0.006 | 0 | > 120 to 180              | 0.145  | 0.085        | 0.043        | 0 |
| > 3 to 6                  | 0.030  | 0.020        | 0.010 | 0 | > 180 to 250              | 0.170  | 0.100        | 0.050        | 0 |
| > 6 to 10                 | <b>0.040</b>   | 0.025        | 0.013 | 0 | > 250 to 315              | 0.190  | 0.110        | 0.056        | 0 |
| > 10 to 18                | 0.050  | 0.032        | 0.016 | 0 | > 315 to 400              | 0.210  | <b>0.125</b> | <b>0.062</b> | 0 |
| > 18 to 30                | 0.065  | 0.040        | 0.020 | 0 | > 400 to 500              | 0.230  | 0.135        | <b>0.068</b> | 0 |
| > 30 to 50                | 0.080  | 0.050        | 0.025 | 0 | > 500 to 630              | 0.260  | 0.145        | <b>0.076</b> | 0 |
| > 50 to 80                | 0.100  | 0.060        | 0.030 | 0 | > 630 to 800              | 0.290  | 0.160        | <b>0.080</b> | 0 |
| > 80 to 120               | 0.120  | <b>0.072</b> | 0.036 | 0 | > 800 to 1000             | 0.320  | <b>0.170</b> | <b>0.086</b> | 0 |

<sup>a</sup> Internal splines are fit class H and have space width modification from basic space width equal to zero; thus, an H/h fit class has effective clearance  $c_v = 0$ .

*Note:* The values listed in this table are taken from ISO R286 and have been computed on the basis of the geometrical mean of the size ranges shown. Values in **boldface** type do not comply with any documented rule for rounding but are those used by ISO R286; they are used in this table to comply with established international practice.

*Basic Rack Profiles:* The basic rack profile for the standard pressure angle splines are shown in Figs. 6a, 6b, 6c, and 6d. The dimensions shown are for maximum material condition and for fit class H/h.

**Spline Machining Tolerances and Variations.**—The total tolerance ( $T + \lambda$ ), Table 15, is the sum of Effective Variation,  $\lambda$ , and a Machining Tolerance,  $T$ .

**Table 15. Space Width and Tooth Thickness Total Tolerance,  $(T + \lambda)$ , in Millimeters**

| Spline Tolerance Class | Formula for Total Tolerance, $(T + \lambda)$ | Spline Tolerance Class | Formula for Total Tolerance, $(T + \lambda)$ | In these formulas, $i^*$ and $i^{**}$ are tolerance units based upon pitch diameter and tooth thickness, respectively:<br><br>$i^* = 0.001(0.45^3\sqrt{D} + 0.001D)$ for $D \leq 500$ mm<br>$= 0.001(0.004D + 2.1)$ for $D > 500$ mm<br><br>$i^{**} = 0.001(0.45^3\sqrt{S_{\text{bsc}}} + 0.001S_{\text{bsc}})$ |
|------------------------|--|------------------------|--|---|
| 4                      | $10i^* + 40i^{**}$                           | 6                      | $25i^* + 100i^{**}$                          |   |
| 5                      | $16i^* + 64i^{**}$                           | 7                      | $40i^* + 160i^{**}$                          |   |

*Effective Variation:* The effective variation,  $\lambda$ , is the combined effect that total index variation, positive profile variation, and tooth alignment variation has on the effective fit of mating involute splines. The effect of the individual variations is less than the sum of the allowable variations because areas of more than minimum clearance can have profile, tooth alignment, or index variations without changing the fit. It is also unlikely that these variations would occur in their maximum amounts simultaneously on the same spline. For this reason, total index variation, total profile variation, and tooth alignment variation are used to calculate the combined effect by the following formula:

$$\lambda = 0.6 \sqrt{(F_p)^2 + (f_f)^2 + (F_\beta)^2} \text{ millimeters}$$

The above variation is based upon a length of engagement equal to one-half the pitch diameter of the spline; adjustment of  $\lambda$  may be required for a greater length of engagement. Formulas for values of  $F_p$ ,  $f_f$ , and  $F_\beta$  used in the above formula are given in Table 16.

**Table 16. Formulas for  $F_p, f_f,$  and  $F_\beta$  used to calculate  $\lambda$**

| Spline Tolerance Class | Total Index Variation, in mm, $F_p$ | Total Profile Variation, in mm, $f_f$ | Total Lead Variation, in mm, $F_\beta$ |
|------------------------|-------------------------------------|---------------------------------------|--|
| 4                      | $0.001(2.5\sqrt{mZ\pi/2} + 6.3)$    | $0.001 [1.6m(1 + 0.0125Z) + 10]$      | $0.001(0.8\sqrt{g} + 4)$               |
| 5                      | $0.001(3.55\sqrt{mZ\pi/2} + 9)$     | $0.001 [2.5m(1 + 0.0125Z) + 16]$      | $0.001(1.0\sqrt{g} + 5)$               |
| 6                      | $0.001(5\sqrt{mZ\pi/2} + 12.5)$     | $0.001 [4m(1 + 0.0125Z) + 25]$        | $0.001(1.25\sqrt{g} + 6.3)$            |
| 7                      | $0.001(7.1\sqrt{mZ\pi/2} + 18)$     | $0.001 [6.3m(1 + 0.0125Z) + 40]$      | $0.001(2\sqrt{g} + 10)$                |

$g$  = length of spline in millimeters.

**Table 17. Reduction,  $es/\tan \alpha_D,$  of External Spline Major and Minor Diameters Required for Selected Fit Classes**

| Pitch Diameter $D$ in mm          | Standard Pressure Angle, in Degrees |       |       |       |       |       |       |       |       |     |
|-----------------------------------|-------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-----|
|                                   | 30                                  | 37.5  | 45    | 30    | 37.5  | 45    | 30    | 37.5  | 45    | All |
|                                   | Classes of Fit                      |       |       |       |       |       |       |       |       |     |
|                                   | d                                   |       |       | e     |       |       | f     |       |       | h   |
| $es/\tan \alpha_D$ in millimeters |                                     |       |       |       |       |       |       |       |       |     |
| $\leq 3$                          | 0.035                               | 0.026 | 0.020 | 0.024 | 0.018 | 0.014 | 0.010 | 0.008 | 0.006 | 0   |
| $> 3$ to 6                        | 0.052                               | 0.039 | 0.030 | 0.035 | 0.026 | 0.020 | 0.017 | 0.013 | 0.010 | 0   |
| $> 6$ to 10                       | 0.069                               | 0.052 | 0.040 | 0.043 | 0.033 | 0.025 | 0.023 | 0.017 | 0.013 | 0   |
| $> 10$ to 18                      | 0.087                               | 0.065 | 0.050 | 0.055 | 0.042 | 0.032 | 0.028 | 0.021 | 0.016 | 0   |
| $> 18$ to 30                      | 0.113                               | 0.085 | 0.065 | 0.069 | 0.052 | 0.040 | 0.035 | 0.026 | 0.020 | 0   |
| $> 30$ to 50                      | 0.139                               | 0.104 | 0.080 | 0.087 | 0.065 | 0.050 | 0.043 | 0.033 | 0.025 | 0   |
| $> 50$ to 80                      | 0.173                               | 0.130 | 0.100 | 0.104 | 0.078 | 0.060 | 0.052 | 0.039 | 0.030 | 0   |
| $> 80$ to 120                     | 0.208                               | 0.156 | 0.120 | 0.125 | 0.094 | 0.072 | 0.062 | 0.047 | 0.036 | 0   |
| $> 120$ to 180                    | 0.251                               | 0.189 | 0.145 | 0.147 | 0.111 | 0.085 | 0.074 | 0.056 | 0.043 | 0   |
| $> 180$ to 250                    | 0.294                               | 0.222 | 0.170 | 0.173 | 0.130 | 0.100 | 0.087 | 0.065 | 0.050 | 0   |
| $> 250$ to 315                    | 0.329                               | 0.248 | 0.190 | 0.191 | 0.143 | 0.110 | 0.097 | 0.073 | 0.056 | 0   |
| $> 315$ to 400                    | 0.364                               | 0.274 | 0.210 | 0.217 | 0.163 | 0.125 | 0.107 | 0.081 | 0.062 | 0   |
| $> 400$ to 500                    | 0.398                               | 0.300 | 0.230 | 0.234 | 0.176 | 0.135 | 0.118 | 0.089 | 0.068 | 0   |
| $> 500$ to 630                    | 0.450                               | 0.339 | 0.260 | 0.251 | 0.189 | 0.145 | 0.132 | 0.099 | 0.076 | 0   |
| $> 630$ to 800                    | 0.502                               | 0.378 | 0.290 | 0.277 | 0.209 | 0.160 | 0.139 | 0.104 | 0.080 | 0   |
| $> 800$ to 1000                   | 0.554                               | 0.417 | 0.320 | 0.294 | 0.222 | 0.170 | 0.149 | 0.112 | 0.086 | 0   |

These values are used with the applicable formulas in Table 13.

**Machining Tolerance:** A value for machining tolerance may be obtained by subtracting the effective variation,  $\lambda$ , from the total tolerance ( $T + \lambda$ ). Design requirements or specific processes used in spline manufacture may require a different amount of machining tolerance in relation to the total tolerance.

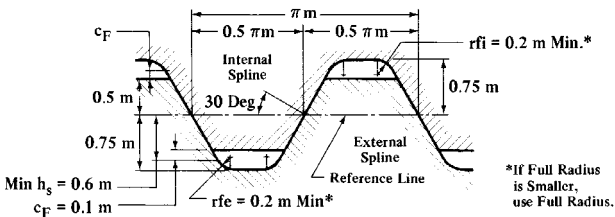


Fig. 6a. Profile of Basic Rack for 30° Flat Root Spline

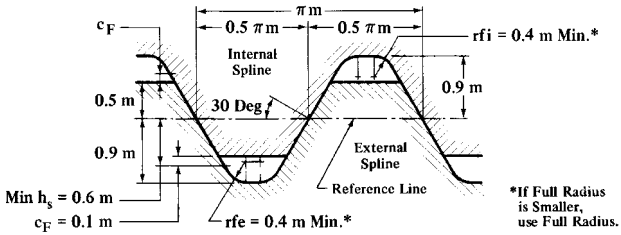


Fig. 6b. Profile of Basic Rack for 30° Fillet Root Spline

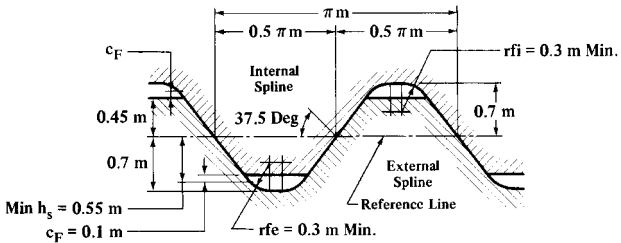


Fig. 6c. Profile of Basic Rack for 37.5° Fillet Root Spline

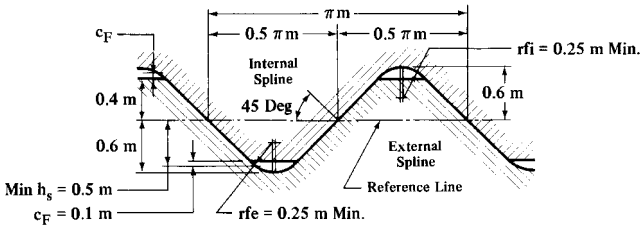


Fig. 6d. Profile of Basic Rack for 45° Fillet Root Spline

**British Standard Straight Splines.**—British Standard BS 2059:1953, “Straight-sided Splines and Serrations”, was introduced because of the widespread development and use of splines and because of the increasing use of involute splines it was necessary to provide a separate standard for straight-sided splines. BS 2059 was prepared on the hole basis, the hole being the constant member, and provide for different fits to be obtained by varying the size of the splined or serrated shaft. Part 1 of the standard deals with 6 splines only, irrespective of the shaft diameter, with two depths termed shallow and deep. The splines are bottom fitting with top clearance.

The standard contains three different grades of fit, based on the principle of variations in the diameter of the shaft at the root of the splines, in conjunction with variations in the widths of the splines themselves. Fit 1 represents the condition of closest fit and is designed for minimum backlash. Fit 2 has a positive allowance and is designed for ease of assembly, and Fit 3 has a larger positive allowance for applications that can accept such clearances.

all these splines allow for clearance on the sides of the splines (the widths), but in Fit 1, the minor diameters of the hole and the shaft may be of identical size.

Assembly of a splined shaft and hole requires consideration of the designed profile of each member, and this consideration should concentrate on the maximum diameter of the shafts and the widths of external splines, in association with the minimum diameter of the hole and the widths of the internal splineways. In other words, both internal and external splines are in the maximum metal condition. The accuracy of spacing of the splines will affect the quality of the resultant fit. If angular positioning is inaccurate, or the splines are not parallel with the axis, there will be interference between the hole and the shaft.

Part 2 of the Standard deals with straight-sided 90° serrations having nominal diameters from 0.25 to 6.0 inches. Provision is again made for three grades of fits, the basic constant being the serrated hole size. Variations in the fits of these serrations is obtained by varying the sizes of the serrations on the shaft, and the fits are related to flank bearing, the depth of engagement being constant for each size and allowing positive clearance at crest and root.

Fit 1 is an interference fit intended for permanent or semi-permanent assemblies. Heating to expand the internally-serrated member is needed for assembly. Fit 2 is a transition fit intended for assemblies that require accurate location of the serrated members, but must allow disassembly. In maximum metal conditions, heating of the outside member may be needed for assembly. Fit 3 is a clearance or sliding fit, intended for general applications.

Maximum and minimum dimensions for the various features are shown in the Standard for each class of fit. Maximum metal conditions presupposes that there are no errors of form such as spacing, alignment, or roundness of hole or shaft. Any compensation needed for such errors may require reduction of a shaft diameter or enlargement of a serrated bore, but the measured effective size must fall within the specified limits.

British Standard BS 3550:1963, "Involute Splines", is complementary to BS 2059, and the basic dimensions of all the sizes of splines are the same as those in the ANSI/ASME B5.15-1960, for major diameter fit and side fit. The British Standard uses the same terms and symbols and provides data and guidance for design of straight involute splines of 30° pressure angle, with tables of limiting dimensions. The standard also deals with manufacturing errors and their effect on the fit between mating spline elements. The range of splines covered is:

Side fit, flat root, 2.5/5.0 to 32/64 pitch, 6 to 60 splines.

Major diameter, flat root, 3.0/6.0 to 16/32 pitch, 6 to 60 splines.

Side fit, fillet root, 2.5/5.0 to 48/96 pitch, 6 to 60 splines.

British Standard BS 6186, Part 1:1981, "Involute Splines, Metric Module, Side Fit" is identical with sections 1 and 2 of ISO 4156 and with ANSI B92.2M-1980 (R1989) "Straight Cylindrical Involute Splines, Metric Module, Side Fit – Generalities, Dimensions and Inspection".

**S.A.E. Standard Spline Fittings.**—The S.A.E. spline fittings (Tables 18 through 21 inclusive) have become an established standard for many applications in the agricultural, automotive, machine tool, and other industries. The dimensions given, in inches, apply only to soft broached holes. Dimensions are illustrated in Figs. 7a, 7b, and 7c. The tolerances given may be readily maintained by usual broaching methods. The tolerances selected for the large and small diameters may depend upon whether the fit between the mating part, as finally made, is on the large or the small diameter. The other diameter, which is designed for clearance, may have a larger manufactured tolerance. If the final fit between the parts is on the sides of the spline only, larger tolerances are permissible for both the large and small diameters. The spline should not be more than 0.006 inch per foot out of parallel with respect to the shaft axis. No allowance is made for corner radii to obtain clearance. Radii at the corners of the spline should not exceed 0.015 inch.

STRAIGHT-SIDED SPLINES

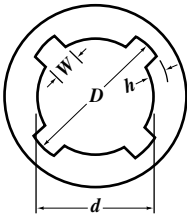


Fig. 7a. 4-Spline Fitting

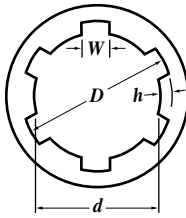


Fig. 7b. 6-Spline Fitting

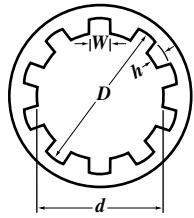


Fig. 7c. 10-Spline Fitting

Table 18. S.A.E. Standard 4-Spline Fittings

| Nom. Diam. | For All Fits |       |       |       | 4A—Permanent Fit |       |       |       | T <sup>a</sup> | 4B—To Slide—No Load |       |       |       | T <sup>a</sup> |
|------------|--------------|-------|-------|-------|------------------|-------|-------|-------|----------------|---------------------|-------|-------|-------|----------------|
|            | D            |       | W     |       | d                |       | h     |       |                | d                   |       | h     |       |                |
|            | Min.         | Max.  | Min.  | Max.  | Min.             | Max.  | Min.  | Max.  |                | Min.                | Max.  | Min.  | Max.  |                |
| 3/4        | 0.749        | 0.750 | 0.179 | 0.181 | 0.636            | 0.637 | 0.055 | 0.056 | 78             | 0.561               | 0.562 | 0.093 | 0.094 | 123            |
| 7/8        | 0.874        | 0.875 | 0.209 | 0.211 | 0.743            | 0.744 | 0.065 | 0.066 | 107            | 0.655               | 0.656 | 0.108 | 0.109 | 167            |
| 1          | 0.999        | 1.000 | 0.239 | 0.241 | 0.849            | 0.850 | 0.074 | 0.075 | 139            | 0.749               | 0.750 | 0.124 | 0.125 | 219            |
| 1 1/8      | 1.124        | 1.125 | 0.269 | 0.271 | 0.955            | 0.956 | 0.083 | 0.084 | 175            | 0.843               | 0.844 | 0.140 | 0.141 | 277            |
| 1 1/4      | 1.249        | 1.250 | 0.299 | 0.301 | 1.061            | 1.062 | 0.093 | 0.094 | 217            | 0.936               | 0.937 | 0.155 | 0.156 | 341            |
| 1 3/8      | 1.374        | 1.375 | 0.329 | 0.331 | 1.168            | 1.169 | 0.102 | 0.103 | 262            | 1.030               | 1.031 | 0.171 | 0.172 | 414            |
| 1 1/2      | 1.499        | 1.500 | 0.359 | 0.361 | 1.274            | 1.275 | 0.111 | 0.112 | 311            | 1.124               | 1.125 | 0.186 | 0.187 | 491            |
| 1 5/8      | 1.624        | 1.625 | 0.389 | 0.391 | 1.380            | 1.381 | 0.121 | 0.122 | 367            | 1.218               | 1.219 | 0.202 | 0.203 | 577            |
| 1 3/4      | 1.749        | 1.750 | 0.420 | 0.422 | 1.486            | 1.487 | 0.130 | 0.131 | 424            | 1.311               | 1.312 | 0.218 | 0.219 | 670            |
| 2          | 1.998        | 2.000 | 0.479 | 0.482 | 1.698            | 1.700 | 0.148 | 0.150 | 555            | 1.498               | 1.500 | 0.248 | 0.250 | 875            |
| 2 1/4      | 2.248        | 2.250 | 0.539 | 0.542 | 1.910            | 1.912 | 0.167 | 0.169 | 703            | 1.685               | 1.687 | 0.279 | 0.281 | 1106           |
| 2 1/2      | 2.498        | 2.500 | 0.599 | 0.602 | 2.123            | 2.125 | 0.185 | 0.187 | 865            | 1.873               | 1.875 | 0.310 | 0.312 | 1365           |
| 3          | 2.998        | 3.000 | 0.720 | 0.723 | 2.548            | 2.550 | 0.223 | 0.225 | 1249           | 2.248               | 2.250 | 0.373 | 0.375 | 1969           |

<sup>a</sup> See note at end of Table 21.

Table 19. S.A.E. Standard 6-Spline Fittings

| Nom. Diam. | For All Fits |       |       |       | 6A—Permanent Fit |       |                | 6B—To Slide—No Load |       |                | 6C—To Slide Under Load |       |                |
|------------|--------------|-------|-------|-------|------------------|-------|----------------|---------------------|-------|----------------|------------------------|-------|----------------|
|            | D            |       | W     |       | d                |       | T <sup>a</sup> | d                   |       | T <sup>a</sup> | d                      |       | T <sup>a</sup> |
|            | Min.         | Max.  | Min.  | Max.  | Min.             | Max.  |                | Min.                | Max.  |                | Min.                   | Max.  |                |
| 3/4        | 0.749        | 0.750 | 0.186 | 0.188 | 0.674            | 0.675 | 80             | 0.637               | 0.638 | 117            | 0.599                  | 0.600 | 152            |
| 7/8        | 0.874        | 0.875 | 0.217 | 0.219 | 0.787            | 0.788 | 109            | 0.743               | 0.744 | 159            | 0.699                  | 0.700 | 207            |
| 1          | 0.999        | 1.000 | 0.248 | 0.250 | 0.899            | 0.900 | 143            | 0.849               | 0.850 | 208            | 0.799                  | 0.800 | 270            |
| 1 1/8      | 1.124        | 1.125 | 0.279 | 0.281 | 1.012            | 1.013 | 180            | 0.955               | 0.956 | 263            | 0.899                  | 0.900 | 342            |
| 1 1/4      | 1.249        | 1.250 | 0.311 | 0.313 | 1.124            | 1.125 | 223            | 1.062               | 1.063 | 325            | 0.999                  | 1.000 | 421            |
| 1 3/8      | 1.374        | 1.375 | 0.342 | 0.344 | 1.237            | 1.238 | 269            | 1.168               | 1.169 | 393            | 1.099                  | 1.100 | 510            |
| 1 1/2      | 1.499        | 1.500 | 0.373 | 0.375 | 1.349            | 1.350 | 321            | 1.274               | 1.275 | 468            | 1.199                  | 1.200 | 608            |
| 1 5/8      | 1.624        | 1.625 | 0.404 | 0.406 | 1.462            | 1.463 | 376            | 1.380               | 1.381 | 550            | 1.299                  | 1.300 | 713            |
| 1 3/4      | 1.749        | 1.750 | 0.436 | 0.438 | 1.574            | 1.575 | 436            | 1.487               | 1.488 | 637            | 1.399                  | 1.400 | 827            |
| 2          | 1.998        | 2.000 | 0.497 | 0.500 | 1.798            | 1.800 | 570            | 1.698               | 1.700 | 833            | 1.598                  | 1.600 | 1080           |
| 2 1/4      | 2.248        | 2.250 | 0.560 | 0.563 | 2.023            | 2.025 | 721            | 1.911               | 1.913 | 1052           | 1.798                  | 1.800 | 1367           |
| 2 1/2      | 2.498        | 2.500 | 0.622 | 0.625 | 2.248            | 2.250 | 891            | 2.123               | 2.125 | 1300           | 1.998                  | 2.000 | 1688           |
| 3          | 2.998        | 3.000 | 0.747 | 0.750 | 2.698            | 2.700 | 1283           | 2.548               | 2.550 | 1873           | 2.398                  | 2.400 | 2430           |

<sup>a</sup> See note at end of Table 21.

**Table 20. S.A.E. Standard 10-Spline Fittings**

| Nom. Diam. | For All Fits |       |       |       | 10A—Permanent Fit |       |                | 10B—To Slide, No Load |       |                | 10C—To Slide Under Load |       |                |
|------------|--------------|-------|-------|-------|-------------------|-------|----------------|-----------------------|-------|----------------|-------------------------|-------|----------------|
|            | D            |       | W     |       | d                 |       | T <sup>a</sup> | d                     |       | T <sup>a</sup> | d                       |       | T <sup>a</sup> |
|            | Min.         | Max.  | Min.  | Max.  | Min.              | Max.  |                | Min.                  | Max.  |                | Min.                    | Max.  |                |
| 3/4        | 0.749        | 0.750 | 0.115 | 0.117 | 0.682             | 0.683 | 120            | 0.644                 | 0.645 | 183            | 0.607                   | 0.608 | 241            |
| 7/8        | 0.874        | 0.875 | 0.135 | 0.137 | 0.795             | 0.796 | 165            | 0.752                 | 0.753 | 248            | 0.708                   | 0.709 | 329            |
| 1          | 0.999        | 1.000 | 0.154 | 0.156 | 0.909             | 0.910 | 215            | 0.859                 | 0.860 | 326            | 0.809                   | 0.810 | 430            |
| 1 1/8      | 1.124        | 1.125 | 0.174 | 0.176 | 1.023             | 1.024 | 271            | 0.967                 | 0.968 | 412            | 0.910                   | 0.911 | 545            |
| 1 1/4      | 1.249        | 1.250 | 0.193 | 0.195 | 1.137             | 1.138 | 336            | 1.074                 | 1.075 | 508            | 1.012                   | 1.013 | 672            |
| 1 3/8      | 1.374        | 1.375 | 0.213 | 0.215 | 1.250             | 1.251 | 406            | 1.182                 | 1.183 | 614            | 1.113                   | 1.114 | 813            |
| 1 1/2      | 1.499        | 1.500 | 0.232 | 0.234 | 1.364             | 1.365 | 483            | 1.289                 | 1.290 | 732            | 1.214                   | 1.215 | 967            |
| 1 5/8      | 1.624        | 1.625 | 0.252 | 0.254 | 1.478             | 1.479 | 566            | 1.397                 | 1.398 | 860            | 1.315                   | 1.316 | 1135           |
| 1 3/4      | 1.749        | 1.750 | 0.271 | 0.273 | 1.592             | 1.593 | 658            | 1.504                 | 1.505 | 997            | 1.417                   | 1.418 | 1316           |
| 2          | 1.998        | 2.000 | 0.309 | 0.312 | 1.818             | 1.820 | 860            | 1.718                 | 1.720 | 1302           | 1.618                   | 1.620 | 1720           |
| 2 1/4      | 2.248        | 2.250 | 0.348 | 0.351 | 2.046             | 2.048 | 1088           | 1.933                 | 1.935 | 1647           | 1.821                   | 1.823 | 2176           |
| 2 1/2      | 2.498        | 2.500 | 0.387 | 0.390 | 2.273             | 2.275 | 1343           | 2.148                 | 2.150 | 2034           | 2.023                   | 2.025 | 2688           |
| 3          | 2.998        | 3.000 | 0.465 | 0.468 | 2.728             | 2.730 | 1934           | 2.578                 | 2.580 | 2929           | 2.428                   | 2.430 | 3869           |
| 3 1/2      | 3.497        | 3.500 | 0.543 | 0.546 | 3.182             | 3.185 | 2632           | 3.007                 | 3.010 | 3987           | 2.832                   | 2.835 | 5266           |
| 4          | 3.997        | 4.000 | 0.621 | 0.624 | 3.637             | 3.640 | 3438           | 3.437                 | 3.440 | 5208           | 3.237                   | 3.240 | 6878           |
| 4 1/2      | 4.497        | 4.500 | 0.699 | 0.702 | 4.092             | 4.095 | 4351           | 3.867                 | 3.870 | 6591           | 3.642                   | 3.645 | 8705           |
| 5          | 4.997        | 5.000 | 0.777 | 0.780 | 4.547             | 4.550 | 5371           | 4.297                 | 4.300 | 8137           | 4.047                   | 4.050 | 10746          |
| 5 1/2      | 5.497        | 5.500 | 0.855 | 0.858 | 5.002             | 5.005 | 6500           | 4.727                 | 4.730 | 9846           | 4.452                   | 4.455 | 13003          |
| 6          | 5.997        | 6.000 | 0.933 | 0.936 | 5.457             | 5.460 | 7735           | 5.157                 | 5.160 | 11718          | 4.857                   | 4.860 | 15475          |

<sup>a</sup> See note at end of Table 21.

**Table 21. S.A.E. Standard 16-Spline Fittings**

| Nom. Diam. | For All Fits |       |       |       | 16A—Permanent Fit |       |                | 16B—To Slide—No Load |       |                | 16C—To Slide Under Load |       |                |
|------------|--------------|-------|-------|-------|-------------------|-------|----------------|----------------------|-------|----------------|-------------------------|-------|----------------|
|            | D            |       | W     |       | d                 |       | T <sup>a</sup> | d                    |       | T <sup>a</sup> | d                       |       | T <sup>a</sup> |
|            | Min.         | Max.  | Min.  | Max.  | Min.              | Max.  |                | Min.                 | Max.  |                | Min.                    | Max.  |                |
| 2          | 1.997        | 2.000 | 0.193 | 0.196 | 1.817             | 1.820 | 1375           | 1.717                | 1.720 | 2083           | 1.617                   | 1.620 | 2751           |
| 2 1/2      | 2.497        | 2.500 | 0.242 | 0.245 | 2.273             | 2.275 | 2149           | 2.147                | 2.150 | 3255           | 2.022                   | 2.025 | 4299           |
| 3          | 2.997        | 3.000 | 0.291 | 0.294 | 2.727             | 2.730 | 3094           | 2.577                | 2.580 | 4687           | 2.427                   | 2.430 | 6190           |
| 3 1/2      | 3.497        | 3.500 | 0.340 | 0.343 | 3.182             | 3.185 | 4212           | 3.007                | 3.010 | 6378           | 2.832                   | 2.835 | 8426           |
| 4          | 3.997        | 4.000 | 0.389 | 0.392 | 3.637             | 3.640 | 5501           | 3.437                | 3.440 | 8333           | 3.237                   | 3.240 | 11005          |
| 4 1/2      | 4.497        | 4.500 | 0.438 | 0.441 | 4.092             | 4.095 | 6962           | 3.867                | 3.870 | 10546          | 3.642                   | 3.645 | 13928          |
| 5          | 4.997        | 5.000 | 0.487 | 0.490 | 4.547             | 4.550 | 8595           | 4.297                | 4.300 | 13020          | 4.047                   | 4.050 | 17195          |
| 5 1/2      | 5.497        | 5.500 | 0.536 | 0.539 | 5.002             | 5.005 | 10395          | 4.727                | 4.730 | 15754          | 4.452                   | 4.455 | 20806          |
| 6          | 5.997        | 6.000 | 0.585 | 0.588 | 5.457             | 5.460 | 12377          | 5.157                | 5.160 | 18749          | 4.857                   | 4.860 | 24760          |

<sup>a</sup> *Torque Capacity of Spline Fittings:* The torque capacities of the different spline fittings are given in the columns headed "T." The torque capacity, per inch of bearing length at 1000 pounds pressure per square inch on the sides of the spline, may be determined by the following formula, in which *T* = torque capacity in inch-pounds per inch of length, *N* = number of splines, *R* = mean radius or radial distance from center of hole to center of spline, *h* = depth of spline:  $T = 1000NRh$

**Table 22. Formulas for Determining Dimensions of S.A.E. Standard Splines**

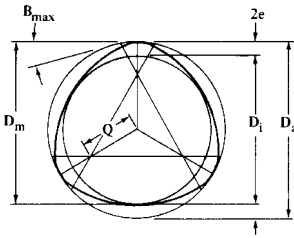
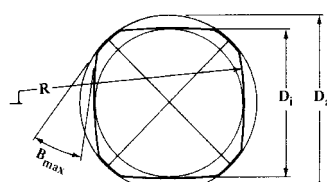
| No. of Splines | W<br>For All Fits   | A<br>Permanent Fit |          | B<br>To Slide Without Load |          | C<br>To Slide Under Load |          |
|----------------|---------------------|--------------------|----------|----------------------------|----------|--------------------------|----------|
|                |                     | <i>h</i>           | <i>d</i> | <i>h</i>                   | <i>d</i> | <i>h</i>                 | <i>d</i> |
| Four           | 0.241D <sup>a</sup> | 0.075D             | 0.850D   | 0.125D                     | 0.750D   | ...                      | ...      |
| Six            | 0.250D              | 0.050D             | 0.900D   | 0.075D                     | 0.850D   | 0.100D                   | 0.800D   |
| Ten            | 0.156D              | 0.045D             | 0.910D   | 0.070D                     | 0.860D   | 0.095D                   | 0.810D   |
| Sixteen        | 0.098D              | 0.045D             | 0.910D   | 0.070D                     | 0.860D   | 0.095D                   | 0.810D   |

<sup>a</sup>Four splines for fits *A* and *B* only.

The formulas in the table above give the maximum dimensions for *W*, *h*, and *d*, as listed in Tables 18 through 21 inclusive.

**Polygon-Type Shaft Connections.**— Involute-form and straight-sided splines are used for both fixed and sliding connections between machine members such as shafts and gears. Polygon-type connections, so called because they resemble regular polygons but with curved sides, may be used similarly. German DIN Standards 32711 and 32712 include data for three- and four-sided metric polygon connections. Data for 11 of the sizes shown in those Standards, but converted to inch dimensions by Stoffel Polygon Systems, are given in the accompanying table.

### Dimensions of Three- and Four-Sided Polygon-type Shaft Connections

| DRAWING FOR 3-SIDED DESIGNS   |                |              |                             |                              | DRAWING FOR 4-SIDED DESIGNS   |                |              |                             |                              |
|---|----------------|--------------|-----------------------------|------------------------------|---|----------------|--------------|-----------------------------|------------------------------|
|  |                |              |                             |                              |  |                |              |                             |                              |
| Three-Sided Designs   |                |              |                             |                              | Four-Sided Designs  |                |              |                             |                              |
| Nominal Sizes   |                |              | Design Data                 |                              | Nominal Sizes   |                |              | Design Data                 |                              |
| $D_A$<br>(in.)  | $D_1$<br>(in.) | $e$<br>(in.) | Area<br>(in. <sup>2</sup> ) | $Z_P$<br>(in. <sup>3</sup> ) | $D_A$<br>(in.)  | $D_1$<br>(in.) | $e$<br>(in.) | Area<br>(in. <sup>2</sup> ) | $Z_P$<br>(in. <sup>3</sup> ) |
| 0.530   | 0.470          | 0.015        | 0.194                       | 0.020                        | 0.500   | 0.415          | 0.075        | 0.155                       | 0.014                        |
| 0.665   | 0.585          | 0.020        | 0.302                       | 0.039                        | 0.625   | 0.525          | 0.075        | 0.250                       | 0.028                        |
| 0.800   | 0.700          | 0.025        | 0.434                       | 0.067                        | 0.750   | 0.625          | 0.125        | 0.350                       | 0.048                        |
| 0.930   | 0.820          | 0.027        | 0.594                       | 0.108                        | 0.875   | 0.725          | 0.150        | 0.470                       | 0.075                        |
| 1.080   | 0.920          | 0.040        | 0.765                       | 0.153                        | 1.000   | 0.850          | 0.150        | 0.650                       | 0.12                         |
| 1.205   | 1.045          | 0.040        | 0.977                       | 0.224                        | 1.125   | 0.950          | 0.200        | 0.810                       | 0.17                         |
| 1.330   | 1.170          | 0.040        | 1.208                       | 0.314                        | 1.250   | 1.040          | 0.200        | 0.980                       | 0.22                         |
| 1.485   | 1.265          | 0.055        | 1.450                       | 0.397                        | 1.375   | 1.135          | 0.225        | 1.17                        | 0.29                         |
| 1.610   | 1.390          | 0.055        | 1.732                       | 0.527                        | 1.500   | 1.260          | 0.225        | 1.43                        | 0.39                         |
| 1.870   | 1.630          | 0.060        | 2.378                       | 0.850                        | 1.750   | 1.480          | 0.250        | 1.94                        | 0.64                         |
| 2.140   | 1.860          | 0.070        | 3.090                       | 1.260                        | 2.000   | 1.700          | 0.250        | 2.60                        | 0.92                         |

Dimensions *Q* and *R* shown on the diagrams are approximate and used only for drafting purposes:  $Q \approx 7.5e$ ;  $R \approx D_1/2 + 16e$ .

Dimension  $D_M = D_1 + 2e$ . Pressure angle  $B_{max}$  is approximately  $344e/D_M$  degrees for three sides, and  $299e/D_M$  degrees for four sides.

Tolerances: ISO H7 tolerances apply to bore dimensions. For shafts, g6 tolerances apply for sliding fits; k7 tolerances for tight fits.

**Choosing Between Three- and Four-Sided Designs:** Three-sided designs are best for applications in which no relative movement between mating components is allowed while torque is transmitted. If a hub is to slide on a shaft while under torque, four-sided designs, which have larger pressure angles  $B_{max}$  than those of three-sided designs, are better suited to sliding even though the axial force needed to move the sliding member is approximately 50 percent greater than for comparable involute spline connections.

*Strength of Polygon Connections:* In the formulas that follow,

$H_w$  = hub width, inches  $H_t$  = hub wall thickness, inches

$M_b$  = bending moment, lb-inch

$M_t$  = torque, lb-inch

$Z$  = section modulus, bending, in.<sup>3</sup>

=0.098 $D_M^4/D_A$  for three sides =0.15 $D_f^3$  for four sides

$Z_p$  = polar section modulus, torsion, in.<sup>3</sup>

=0.196 $D_M^4/D_A$  for three sides =0.196 $D_f^3$  for four sides

$D_A$  and  $D_M$ . See table footnotes.

$S_b$  = bending stress, allowable, lb/in.<sup>2</sup>

$S_s$  = shearing stress, allowable, lb/in.<sup>2</sup>

$S_t$  = tensile stress, allowable, lb/in.<sup>2</sup>

For shafts,  $M_t$  (maximum) =  $S_s Z_p$ ;

$M_b$  (maximum) =  $S_b Z$

For bores,

$$H_t(\text{minimum}) = K \sqrt{\frac{M_t}{S_t H_w}}$$

in which  $K = 1.44$  for three sides except that if  $D_M$  is greater than 1.375 inches, then  $K = 1.2$ ;  $K = 0.7$  for four sides.

Failure may occur in the hub of a polygon connection if the hoop stresses in the hub exceed the allowable tensile stress for the material used. The radial force tending to expand the rim and cause tensile stresses is calculated from

$$\text{Radial Force, lb} = \frac{2M_t}{D_f n \tan(B_{max} + 11.3)}$$

This radial force acting at  $n$  points may be used to calculate the tensile stress in the hub wall using formulas from strength of materials.

*Manufacturing:* Polygon shaft profiles may be produced using conventional machining processes such as hobbing, shaping, contour milling, copy turning, and numerically controlled milling and grinding. Bores are produced using broaches, spark erosion, gear shapers with generating cutters of appropriate form, and, in some instances, internal grinders of special design. Regardless of the production methods used, points on both of the mating profiles may be calculated from the following equations:

$$X = (D_f/2 + e) \cos \alpha - e \cos n \alpha \cos \alpha - n e \sin n \alpha \sin \alpha$$

$$Y = (D_f/2 + e) \sin \alpha - e \cos n \alpha \sin \alpha + n e \sin n \alpha \cos \alpha$$

In these equations,  $\alpha$  is the angle of rotation of the workpiece from any selected reference position;  $n$  is the number of polygon sides, either 3 or 4;  $D_f$  is the diameter of the inscribed circle shown on the diagram in the table; and  $e$  is the dimension shown on the diagram in the table and which may be used as a setting on special polygon grinding machines. The value of  $e$  determines the shape of the profile. A value of 0, for example, results in a circular shaft having a diameter of  $D_f$ . The values of  $e$  in the table were selected arbitrarily to provide suitable proportions for the sizes shown.



## CAMS AND CAM DESIGN

**Classes of Cams.**—Cams may, in general, be divided into two classes: uniform motion cams and accelerated motion cams. The uniform motion cam moves the follower at the same rate of speed from the beginning to the end of the stroke; but as the movement is started from zero to the full speed of the uniform motion and stops in the same abrupt way, there is a distinct shock at the beginning and end of the stroke, if the movement is at all rapid. In machinery working at a high rate of speed, therefore, it is important that cams are so constructed that sudden shocks are avoided when starting the motion or when reversing the direction of motion of the follower.

The uniformly accelerated motion cam is suitable for moderate speeds, but it has the disadvantage of sudden changes in acceleration at the beginning, middle and end of the stroke. A cycloidal motion curve cam produces no abrupt changes in acceleration and is often used in high-speed machinery because it results in low noise, vibration and wear. The cycloidal motion displacement curve is so called because it can be generated from a cycloid which is the locus of a point of a circle rolling on a straight line.\*

**Cam Follower Systems.**—The three most used cam and follower systems are radial and offset translating roller follower, Figs. 1a and 1b; and the swinging roller follower, Fig. 1c. When the cam rotates, it imparts a translating motion to the roller followers in Figs. 1a and 1b and a swinging motion to the roller follower in Fig. 1c. The motion of the follower is, of course, dependent on the shape of the cam; and the following section on displacement diagrams explains how a favorable motion is obtained so that the cam can rotate at high speed without shock.

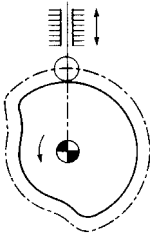


Fig. 1a. Radial Translating Roller Follower

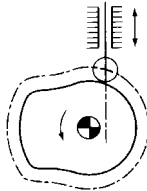


Fig. 1b. Offset Translating Roller Follower

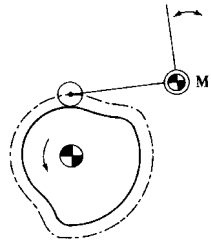


Fig. 1c. Swinging Roller Follower

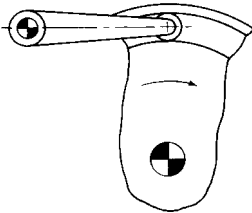


Fig. 2a. Closed-Track Cam

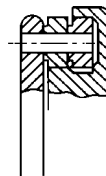


Fig. 2b. Closed-Track Cam With Two Rollers

The arrangements in Figs. 1a, 1b, and 1c show open-track cams. In Figs. 2a and 2b the roller is forced to move in a closed track. Open-track cams build smaller than closed-track

\* Jensen, P. W., *Cam Design and Manufacture*, Industrial Press Inc.

cams but, in general, springs are necessary to keep the roller in contact with the cam at all times. Closed-track cams do not require a spring and have the advantage of positive drive throughout the rise and return cycle. The positive drive is sometimes required as in the case where a broken spring would cause serious damage to a machine.

**Displacement Diagrams.**—Design of a cam begins with the displacement diagram. A simple displacement diagram is shown in Fig. 3. One cycle means one whole revolution of the cam; i.e., one cycle represents  $360^\circ$ . The horizontal distances  $T_1, T_2, T_3, T_4$  are expressed in units of time (seconds); or radians or degrees. The vertical distance,  $h$ , represents the maximum “rise” or stroke of the follower.

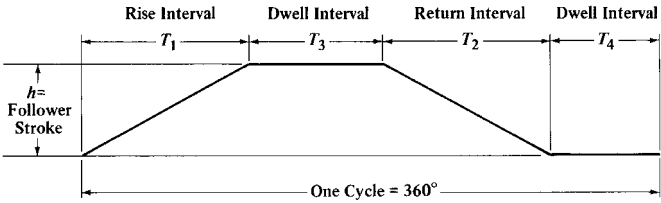


Fig. 3. A Simple Displacement Diagram

The displacement diagram of Fig. 3 is not a very favorable one because the motion from rest (the horizontal lines) to constant velocity takes place instantaneously and this means that accelerations become infinitely large at these transition points.

*Types of Cam Displacement Curves:* A variety of cam curves are available for moving the follower. In the following sections only the rise portions of the total time-displacement diagram are studied. The return portions can be analyzed in a similar manner. Complex cams are frequently employed which may involve a number of rise-dwell-return intervals in which the rise and return aspects are quite different. To analyze the action of a cam it is necessary to study its time-displacement and associated velocity and acceleration curves. The latter are based on the first and second time-derivatives of the equation describing the time-displacement curve:

$$y = \text{displacement} = f(t) \quad \text{or} \quad y = f(\phi)$$

$$v = \frac{dy}{dt} = \text{velocity} = \omega \frac{dy}{d\phi}$$

$$a = \frac{d^2y}{dt^2} = \text{acceleration} = \omega^2 \frac{d^2y}{d\phi^2}$$

*Meaning of Symbols and Equivalent Relations:*  $y$  = displacement of follower, inch

$h$  = maximum displacement of follower, inch

$t$  = time for cam to rotate through angle  $\phi$ , sec,  $= \phi/\omega$ , sec

$T$  = time for cam to rotate through angle  $\beta$ , sec,  $= \beta/\omega$ , or  $\beta/6N$ , sec

$\phi$  = cam angle rotation for follower displacement  $y$ , degrees

$\beta$  = cam angle rotation for total rise  $h$ , degrees

$v$  = velocity of follower, in./sec

$a$  = follower acceleration, in./sec<sup>2</sup>

$$t/T = \phi/\beta$$

$N$  = cam speed, rpm

$\omega$  = angular velocity of cam, degrees/sec  $= \beta/T = \phi/t = d\phi/dt = 6N$

$\omega_R$  = angular velocity of cam, radians/sec  $= \pi\omega/180$

$W$  = effective weight, lbs

- $g$  = gravitational constant = 386 in./sec<sup>2</sup>
- $f(t)$  = means a function of  $t$
- $f(\phi)$  = means a function of  $\phi$
- $R_{min}$  = minimum radius to the cam pitch curve, inch
- $R_{max}$  = maximum radius to the cam pitch curve, inch
- $r_f$  = radius of cam follower roller, inch
- $\rho$  = radius of curvature of cam pitch curve (path of center of roller follower), inch
- $R_c$  = radius of curvature of actual cam surface, in., =  $\rho - r_f$  for convex surface;  
=  $\rho + r_f$  for concave surface.

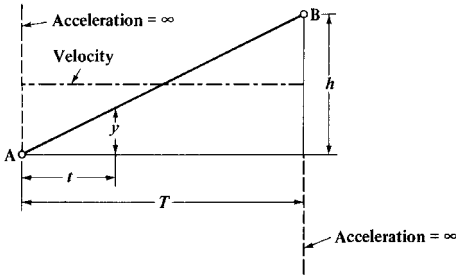


Fig. 4. Cam Displacement, Velocity, and Acceleration Curves for Constant Velocity Motion  
Four displacement curves are of the greatest utility in cam design.

1. Constant-Velocity Motion: (Fig. 4)

$$y = \frac{h t}{T} \quad \text{or} \quad y = \frac{h \phi}{\beta} \quad (1a)$$

$$v = \frac{dy}{dt} = \frac{h}{T} \quad \text{or} \quad v = \frac{h \omega}{\beta} \quad (1b)$$

$$a = \frac{d^2 y}{dt^2} = 0^* \quad (1c)$$

}  $0 < t < T$

\* Except at  $t = 0$  and  $t = T$  where the acceleration is theoretically infinite.

This motion and its disadvantages were mentioned previously. While in the unaltered form shown it is rarely used except in very crude devices, nevertheless, the advantage of uniform velocity is an important one and by modifying the start and finish of the follower stroke this form of cam motion can be utilized. Such modification is explained in the section Displacement Diagram Synthesis.

2. Parabolic Motion: (Fig. 5)

For  $0 \leq t \leq T/2$  and  $0 \leq \phi \leq \beta/2$

For  $T/2 \leq t \leq T$  and  $\beta/2 \leq \phi \leq \beta$

$$y = 2h(t/T)^2 = 2h(\phi/\beta)^2 \quad (2a)$$

$$y = h[1 - 2(1 - t/T)^2] = h[1 - 2(1 - \phi/\beta)^2] \quad (2d)$$

$$v = 4ht/T^2 = 4h\omega\phi/\beta^2 \quad (2b)$$

$$v = 4h/T(1 - t/T) = (4h\omega/\beta)(1 - \phi/\beta) \quad (2e)$$

$$a = 4h/T^2 = 4h(\omega/\beta)^2 \quad (2c)$$

$$a = -4h/T^2 = -4h(\omega/\beta)^2 \quad (2f)$$

Examination of the above formulas shows that the velocity is zero when  $t = 0$  and  $y = 0$ ; and when  $t = T$  and  $y = h$ .

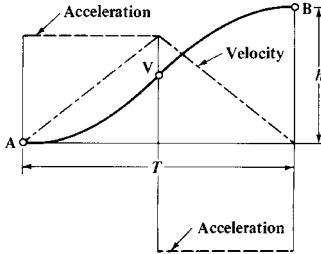


Fig. 5. Cam Displacement, Velocity, and Acceleration Curves for Parabolic Motion

The most important advantage of this curve is that for a given angle of rotation and rise it produces the smallest possible acceleration. However, because of the sudden changes in acceleration at the beginning, middle, and end of the stroke, shocks are produced. If the follower system were perfectly rigid with no backlash or flexibility, this would be of little significance. But such systems are mechanically impossible to build and a certain amount of impact is caused at each of these changeover points.

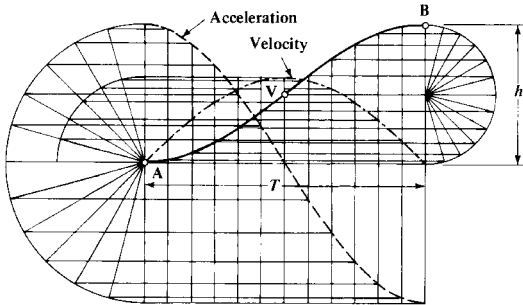


Fig. 6. Cam Displacement, Velocity, and Acceleration Curves for Simple Harmonic Motion

### 3. Simple Harmonic Motion: (Fig. 6)

$$y = \frac{h}{2} \left[ 1 - \cos\left(\frac{180^\circ t}{T}\right) \right] \quad \text{or} \quad y = \frac{h}{2} \left[ 1 - \cos\left(\frac{180^\circ \phi}{\beta}\right) \right] \quad (3a)$$

$$v = \frac{h}{2} \cdot \frac{\pi}{T} \sin\left(\frac{180^\circ t}{T}\right) \quad \text{or} \quad v = \frac{h}{2} \cdot \frac{\pi \omega}{\beta} \sin\left(\frac{180^\circ \phi}{\beta}\right) \quad (3b) \quad \left. \begin{array}{l} \\ \end{array} \right\} 0 \leq t \leq T$$

$$a = \frac{h}{2} \cdot \frac{\pi^2}{T^2} \cos\left(\frac{180^\circ t}{T}\right) \quad \text{or} \quad a = \frac{h}{2} \cdot \left(\frac{\pi \omega}{\beta}\right)^2 \cos\left(\frac{180^\circ \phi}{\beta}\right) \quad (3c)$$

Smoothness in velocity and acceleration during the stroke is the advantage inherent in this curve. However, the instantaneous changes in acceleration at the beginning and end of the stroke tend to cause vibration, noise, and wear. As can be seen from Fig. 6, the maximum acceleration values occur at the ends of the stroke. Thus, if inertia loads are to be overcome by the follower, the resulting forces cause stresses in the members. These forces are in many cases much larger than the externally applied loads.

## 4. Cycloidal Motion: (Fig. 7)

$$y = h \left[ \frac{t}{T} - \frac{1}{2\pi} \sin \left( \frac{360^\circ t}{T} \right) \right] \quad \text{or} \quad y = h \left[ \frac{\phi}{\beta} - \frac{1}{2\pi} \sin \left( \frac{360^\circ \phi}{\beta} \right) \right] \quad (4a)$$

$$v = \frac{h}{T} \left[ 1 - \cos \left( \frac{360^\circ t}{T} \right) \right] \quad \text{or} \quad v = \frac{h\omega}{\beta} \left[ 1 - \cos \left( \frac{360^\circ \phi}{\beta} \right) \right] \quad (4b) \quad \left. \vphantom{\frac{h}{T}} \right\} 0 \leq t \leq T$$

$$a = \frac{2\pi h}{T^2} \sin \left( \frac{360^\circ t}{T} \right) \quad \text{or} \quad a = \frac{2\pi h\omega^2}{\beta^2} \sin \left( \frac{360^\circ \phi}{\beta} \right) \quad (4c)$$

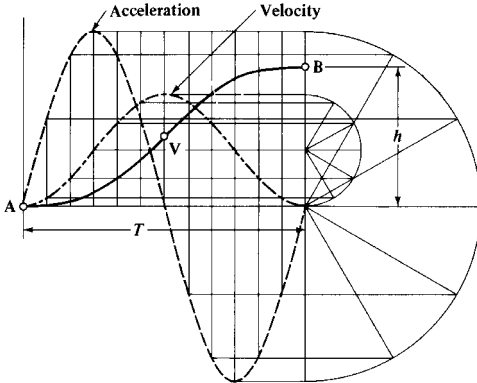


Fig. 7. Cam Displacement, Velocity, and Acceleration Curves for Cycloidal Motion

This time-displacement curve has excellent acceleration characteristics; there are no abrupt changes in its associated acceleration curve. The maximum value of the acceleration of the follower for a given rise and time is somewhat higher than that of the simple harmonic motion curve. In spite of this, the cycloidal curve is used often as a basis for designing cams for high-speed machinery because it results in low levels of noise, vibration, and wear.

**Displacement Diagram Synthesis.**—The straight-line graph shown in Fig. 3 has the important advantage of uniform velocity. This is so desirable that many cams based on this graph are used. To avoid impact at the beginning and end of the stroke, a modification is introduced at these points. There are many different types of modifications possible, ranging from a simple circular arc to much more complicated curves. One of the better curves used for this purpose is the parabolic curve given by Equation (2a). As seen from the derived time graphs, this curve causes the follower to begin a stroke with zero velocity but having a finite and constant acceleration. We must accept the necessity of acceleration, but effort should be made to hold it to a minimum.

**Matching of Constant Velocity and Parabolic Motion Curves:** By matching a parabolic cam curve to the beginning and end of a straight-line cam displacement diagram it is possible to reduce the acceleration from infinity to a finite constant value to avoid impact loads. As illustrated in Fig. 8, it can be shown that for any parabola the vertex of which is at  $O$ , the tangent to the curve at the point  $P$  intersects the line  $OQ$  at its midpoint. This means that the tangent at  $P$  represents the velocity of the follower at time  $X_0$  as shown in Fig. 8. Since the tangent also represents the velocity of the follower over the constant velocity portion of the stroke, the transition from rest to the maximum velocity is accomplished with smoothness.

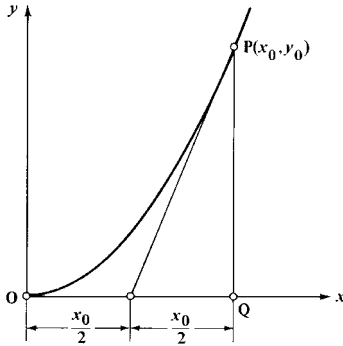


Fig. 8. The Tangent at  $P$  Bisects  $OQ$ , When Curve is a Parabola

*Example:* A cam follower is to rise  $\frac{1}{4}$  in. with constant acceleration;  $1\frac{1}{4}$  in. with constant velocity, over an angle of 50 degrees; and then  $\frac{1}{2}$  in. with constant deceleration.

In Fig. 9 the three rise distances are laid out,  $y_1 = \frac{1}{4}$  in.,  $y_2 = 1\frac{1}{4}$  in.,  $y_3 = \frac{1}{2}$  in., and horizontals drawn. Next, an arbitrary horizontal distance  $\phi_2$  proportional to 50 degrees is measured off and points  $A$  and  $B$  are located. The line  $AB$  is extended to  $M_1$  and  $M_2$ . By remembering that a tangent to a parabola, Fig. 8, will cut the abscissa axis at point  $(X_0/2, 0)$  where  $X_0$  is the abscissa of the point of tangency, the two values  $\phi_1 = 20^\circ$  and  $\phi_3 = 40^\circ$  will be found. Analytically,

$$\frac{M_1E}{\phi_2} = \frac{y_1}{y_2} \quad \frac{\frac{1}{2}\phi_1}{50^\circ} = \frac{0.25}{1.25} \quad \therefore \phi_1 = 20^\circ$$

$$\frac{FM_2}{\phi_2} = \frac{y_3}{y_2} \quad \frac{\frac{1}{2}\phi_3}{50^\circ} = \frac{0.50}{1.25} \quad \therefore \phi_3 = 40^\circ$$

In Fig. 9, the portions of the parabola have been drawn in; the details of this operation are as follows:

Assume that accuracy to the nearest thousandth of one inch is desired, and it is decided to plot values for every 5 degrees of cam rotation.

The formula for the acceleration portion of the parabolic curve is:

$$y = \frac{2h}{T^2}t^2 = 2h\left(\frac{\phi}{\beta}\right)^2 \quad (5)$$

Two different parabolas are involved in this example; one for accelerating the follower during a cam rotation of 20 degrees, the other for decelerating it in 40 degrees, these two being tangent, to opposite ends of the same line  $AB$ .

In Fig. 9 only the first half of a complete acceleration-deceleration parabolic curve is used to blend with the left end of the straight line  $AB$ . Therefore, in using the Formula (5) substitute  $2y_1$  for  $h$  and  $2\phi_1$  for  $\beta$  so that

$$y = \frac{2h\phi^2}{\beta^2} = \frac{(2)(2y_1)}{(2\phi_1)^2} \phi^2$$

For the right end of the straight line  $AB$ , the calculations are similar but, in using [Formula \(5\)](#), calculated  $y$  values are *subtracted* from the *total rise* of the cam ( $y_1 + y_2 + y_3$ ) to obtain the follower displacement.

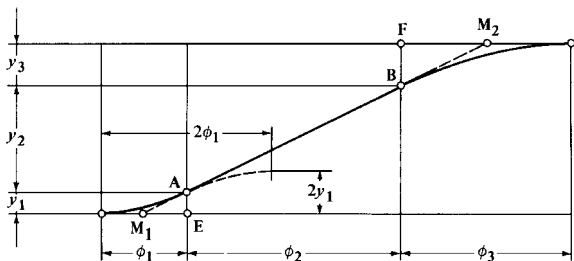


Fig. 9. Matching a Parabola at Each End of Straight Line Displacement Curve  $AB$  to Provide More Acceptable Acceleration and Deceleration

[Table 1](#) shows the computations and resulting values for the cam displacement diagram described. The calculations are shown in detail so that if equations are programmed for a digital computer, the results can be verified easily. Obviously, the intermediate points are not needed to draw the straight line, but when the cam profile is later to be drawn or cut, these values will be needed since they are to be measured on radial lines.

The matching procedure when using cycloidal motion is exactly the same as for parabolic motion, because parabolic and cycloidal motion have the same maximum velocity for equal rise (or return) and lift angle (or return angle).

**Cam Profile Determination.**—In the cam constructions that follow an artificial device called an *inversion* is used. This represents a mental concept which is very helpful in performing the graphical work. The construction of a cam profile requires the drawing of many positions of the cam with the follower in each case in its related location. However, instead of revolving the cam, it is assumed that the follower rotates around the *fixed* cam. It requires the drawing of many follower positions, but since this is done more or less diagrammatically, it is relatively simple.

As part of the inversion process, the direction of rotation is important. In order to preserve the correct sequence of events, the artificial rotation of the follower must be the reverse of the cam's prescribed rotation. Thus, in [Fig. 10](#) the cam rotation is counterclockwise, whereas the artificial rotation of the follower is clockwise.

**Radial Translating Roller Follower:** The time-displacement diagram for a cam with a radial translating roller follower is shown in [Fig. 10\(a\)](#). This diagram is read from left to right as follows: For 100 degrees of cam shaft rotation the follower rises  $h$  inches ( $AB$ ), dwells in its upper position for 20 degrees ( $BC$ ), returns over 180 degrees ( $CD$ ), and finally dwells in its lowest position for 60 degrees ( $DE$ ). Then the entire cycle is repeated.

[Fig. 10\(b\)](#) shows the cam construction layout with the cam pitch curve as a dot and dash line. To locate a point on this curve, take a point on the displacement curve, as  $6'$  at the 60-degree position, and project this horizontally to point  $6''$  on the 0-degree position of the cam construction diagram. Using the center of cam rotation, an arc is struck from point  $6''$  to intercept the 60-degree position radial line which gives point  $6'''$  on the cam pitch curve. It will be seen that the smaller circle in the cam construction layout has a radius  $R_{\min}$  equal

to the smallest distance from the center of cam rotation to the pitch curve and, similarly, the larger circle has a radius  $R_{\max}$  equal to the largest distance to the pitch curve. Thus, the difference in radii of these two circles is equal to the maximum rise  $h$  of the follower.

The cam pitch curve is also the actual profile or working surface when a knife-edged follower is used. To get the profile or working surface for a cam with a roller follower, a series of arcs with centers on the pitch curve and radii equal to the radius of the roller are drawn and the inner envelope drawn tangent to these arcs is the cam working surface or profile shown as a solid line in Fig. 10(b).

**Table 1. Development of Modified Constant Velocity Cam with Parabolic Matching**

| Rise Angle          | $\phi$<br>Degrees | Computation                       | Follower Displacement<br>$y$ | Explanation   |
|---------------------|-------------------|-----------------------------------|------------------------------|---|
| $\phi_1 = 20^\circ$ | 0                 | 0                                 | 0                            | $\beta = 40^\circ h = 0.500$<br>$y = \frac{(2)(0.500)}{(40)^2} \phi^2$<br>$= 0.000625 \phi^2$   |
|                     | 5                 | $0.000625 \times 5^2$             | 0.016                        |   |
|                     | 10                | $0.000625 \times 10^2$            | 0.063                        |   |
|                     | 15                | $0.000625 \times 15^2$            | 0.141                        |   |
|                     | 20                | $0.000625 \times 20^2$            | 0.250                        |   |
| $\phi_2 = 50^\circ$ | 25                |                                   | 0.375                        | 1.250 in. divided into<br>10 uniform divisions  |
|                     | 30                |                                   | 0.500                        |   |
|                     | 35                |                                   | 0.625                        |   |
|                     | 40                |                                   | 0.750                        |   |
|                     | 45                |                                   | 0.875                        |   |
|                     | 50                |                                   | 1.000                        |   |
|                     | 55                |                                   | 1.125                        |   |
|                     | 60                |                                   | 1.250                        |   |
|                     | 65                |                                   | 1.375                        |   |
|                     | 70                |                                   | 1.500                        |   |
| $\phi_3 = 40^\circ$ | 75                | $2.000 - (0.0003125 \times 35^2)$ | 1.617                        | $\beta = 80^\circ h = 1.000$<br>$y = 2 - \frac{(2)(1.000)}{(80)^2} (110^\circ - \phi)^2$<br>$= 2 - 0.0003125 (110^\circ - \phi)^2$<br>See footnote <sup>a</sup> |
|                     | 80                | $2.000 - (0.0003125 \times 30^2)$ | 1.617                        |   |
|                     | 85                | $2.000 - (0.0003125 \times 25^2)$ | 1.805                        |   |
|                     | 90                | $2.000 - (0.0003125 \times 20^2)$ | 1.875                        |   |
|                     | 95                | $2.000 - (0.0003125 \times 15^2)$ | 1.930                        |   |
|                     | 100               | $2.000 - (0.0003125 \times 10^2)$ | 1.969                        |   |
|                     | 105               | $2.000 - (0.0003125 \times 5^2)$  | 1.992                        |   |
|                     | 110               | $2.000 - (0.0003125 \times 0^2)$  | 2.000                        |   |

<sup>a</sup> Since the deceleration portion of a parabolic cam is the same shape as the acceleration portion, but inverted, Formula (5) may be used to calculate the  $y$  values by substituting  $2y_3$  for  $h$  and for  $\beta$  and the result subtracted from the total rise ( $y_1 + y_2 + y_3$ ) to obtain the follower displacement.



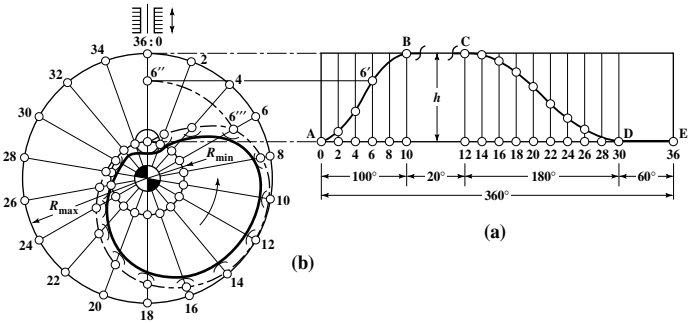


Fig. 10. (a) Time-Displacement Diagram for Cam to be Laid Out; (b) Construction of Contour of Cam With Radial Translating Roller Follower

**Offset Translating Roller Follower:** Given the time-displacement diagram Fig. 11(a) and an offset follower. The construction of the cam in this case is very similar to the foregoing case and is shown in Fig. 11(b). In this construction it will be noted that the angular position lines are not drawn radially from the cam shaft center but tangent to a circle having a radius equal to the amount of offset of the center line of the cam follower from the center of the cam shaft. For counterclockwise rotation of the cam, points 6', 6'', and 6''' are located in succession as indicated.

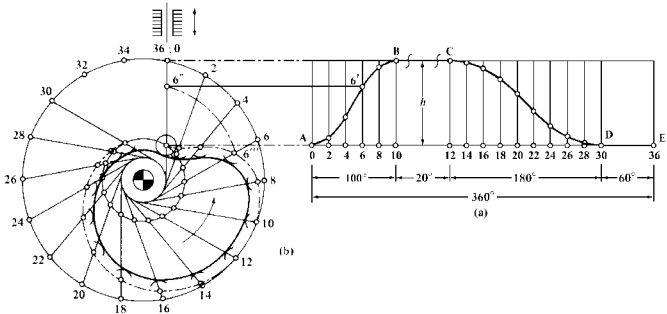


Fig. 11. (a) Time-Displacement Diagram for Cam to be Laid Out; (b) Construction of Contour of Cam With Offset Translating Roller Follower

**Swinging Roller Follower:** Given the time-displacement diagram Fig. 12(a) and the length of the swinging follower arm  $L_f$ , it is required that the displacement of the follower center along the circular arc that it describes be equal to the corresponding displacements in the time-displacement diagram. If  $\phi_0$  is known, the displacement  $h$  of Fig. 12(a) would be found from the formula  $h = \pi\phi_0 L_f / 180^\circ$ ; otherwise the maximum rise  $h$  of the follower is stepped off on the arc drawn with  $M$  as a center and starting at a point on the  $R_{\min}$  circle. Point  $M$  is the actual position of the pivot center of the swinging follower with respect to the cam shaft center. It is again required that the rotation of the cam be counterclockwise and therefore  $M$  is considered to have been rotated clockwise around the cam shaft center, whereby the points 2, 4, 6, etc., are obtained as shown in Fig. 12(b). Around each of the pivot points, 2, 4, 6, etc., circular arcs whose radii equal  $L_f$  are drawn between the  $R_{\min}$  and

$R_{\max}$  circles giving the points 2', 4', 6', etc. The  $R_{\min}$  circle with center at the cam shaft center is drawn through the lowest position of the center of the roller follower and the  $R_{\max}$  circle through the highest position as shown. The different points on the pitch curve are now located. Point 6''', for instance, is found by stepping off the  $y_6$  ordinate of the displacement diagram on arc 6' starting at the  $R_{\min}$  circle.

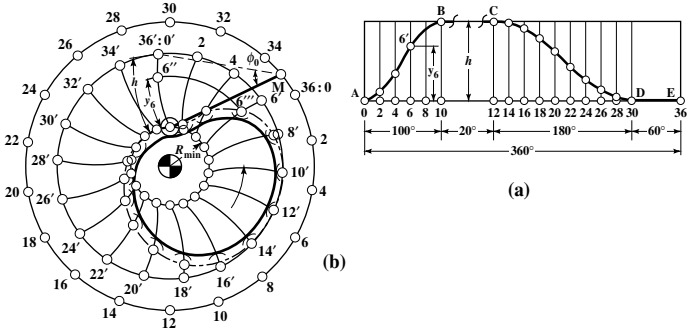


Fig. 12. (a) Time-Displacement Diagram for Cam to be Laid Out; (b) Construction of Contour of Cam With Swinging Roller Follower

**Pressure Angle and Radius of Curvature.**—The pressure angle at any point on the profile of a cam may be defined as the angle between the direction where the follower wants to go at that point and where the cam wants to push it. It is the angle between the tangent to the path of follower motion and the line perpendicular to the tangent of the cam profile at the point of cam-roller contact.

The size of the pressure angle is important because:

- 1) Increasing the pressure angle increases the side thrust and this increases the forces exerted on cam and follower.
- 2) Reducing the pressure angle increases the cam size and often this is not desirable because:
  - a) The size of the cam determines, to a certain extent, the size of the machine.
  - b) Larger cams require more precise cutting points in manufacturing and, therefore, an increase in cost.
  - c) Larger cams have higher circumferential speed and small deviations from the theoretical path of the follower cause additional acceleration, the size of which increases with the square of the cam size.
  - d) Larger cams mean more revolving weight and in high-speed machines this leads to increased vibrations in the machine.
  - e) The inertia of a large cam may interfere with quick starting and stopping.

The maximum pressure angle  $\alpha_m$  should, in general, be kept at or below 30 degrees for translating-type followers and at or below 45 degrees for swinging-type followers. These values are on the conservative side and in many cases may be increased considerably, but beyond these limits trouble could develop and an analysis is necessary.

In the following, graphical methods are described by which a cam mechanism can be designed with translating or swinging roller followers having specified maximum pressure angles for rise and return. These methods are applicable to any kind of time-displacement diagram.

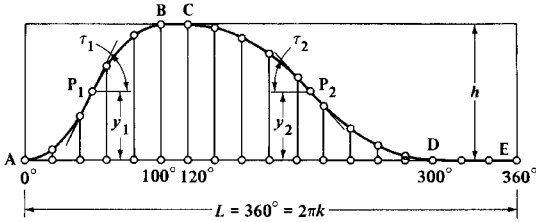


Fig. 13. Displacement Diagram

**Determination of Cam Size for a Radial or an Offset Translating Follower.**—Fig. 13 shows a time-displacement diagram. The maximum displacement is preferably made to scale, but the length of the abscissa,  $L$ , can be chosen arbitrarily. The distance  $L$  from 0 to 360 degrees is measured and is set equal to  $2\pi k$  from which

$$k = \frac{L}{2\pi}$$

$k$  is calculated and laid out as length  $E$  to  $M$  in Fig. 14.

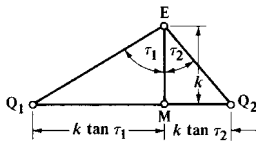
In Fig. 13 the two points  $P_1$  and  $P_2$  having the maximum angles of slope,  $\tau_1$ , and  $\tau_2$ , are located by inspection. In this example  $y_1$  and  $y_2$  are of equal length.

Angles  $\tau_1$  and  $\tau_2$  are laid out as shown in Fig. 14, and the points of intersection with a perpendicular to  $EM$  at  $M$  determine  $Q_1$  and  $Q_2$ . The measured distances

$$MQ_1 = k \tan \tau_1 \quad \text{and} \quad MQ_2 = k \tan \tau_2$$

are laid out in Fig. 15, which is constructed as follows:

Draw a vertical line  $R_u R_o$  of length  $h$  equal to the stroke of the roller follower,  $R_u$  being the lowest position and  $R_o$  the highest position of the center of the roller follower. From  $R_u$  lay out  $R_u R_{y_1} = y_1$  and  $R_u R_{y_2} = y_2$ ; these are equal lengths in this example. Next, if the rotation of the cam is counterclockwise, lay out  $k \tan \tau_1$ , to the left,  $k \tan \tau_2$  to the right from points  $R_{y_1}$  and  $R_{y_2}$ , respectively,  $R_{y_1}$  and  $R_{y_2}$  being the same point in this case.

Fig. 14. Construction to Find  $k \tan \tau_1$  and  $k \tan \tau_2$ 

The specified maximum pressure angle  $\alpha_1$  is laid out at  $E_1$  as shown, and a ray (line)  $E_1 F_1$  is determined. Any point on this ray chosen as the cam shaft center will proportion the cam so that the pressure angle at a point on the cam profile corresponding to point  $P_1$ , of the displacement diagram will be exactly  $\alpha_1$ .

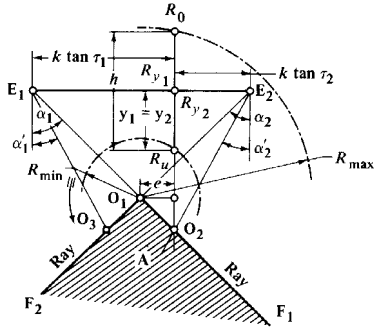


Fig. 15. Finding Proportions of Cam; Offset Translating Follower

The angle  $\alpha_2$  is laid out at  $E_2$  as shown, and another ray  $E_2F_2$  is determined. Similarly, any point on this ray chosen as the cam shaft center will proportion the cam so that the pressure angle at a point on the cam profile corresponding to point  $P_2$  of the displacement diagram will be exactly  $\alpha_2$ .

Any point chosen within the cross-hatched area A as the cam center will yield a cam whose pressure angles at points corresponding to  $P_1$  and  $P_2$  will not exceed the specified values  $\alpha_1$  and  $\alpha_2$  respectively. If  $O_1$  is chosen as the cam shaft center, the pressure angles on the cam profile corresponding to points  $P_1$  and  $P_2$  are exactly  $\alpha_1$  and  $\alpha_2$ , respectively. Selection of point  $O_1$  also yields the smallest possible cam for the given requirements and requires an offset follower in which  $e$  is the offset distance.

If  $O_2$  is chosen as the cam shaft center, a radial translating follower is obtained (zero offset). In that case, the pressure angle  $\alpha_1$  for the rise is unchanged, whereas the pressure angle for the return is changed from  $\alpha_2$  to  $\alpha'_2$ . That is, the pressure angle on the return stroke is reduced at the point  $P_2$ . If point  $O_3$  had been selected, then  $\alpha_2$  would remain unchanged but  $\alpha_1$  would be decreased and the offset,  $e$ , increased.

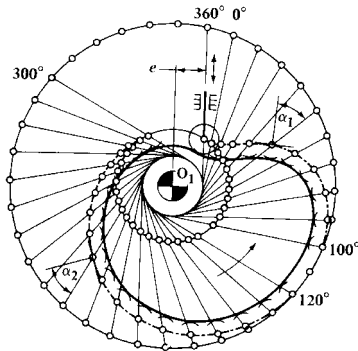


Fig. 16. Construction of Cam Contour; Offset Translating Follower

Fig. 16 shows the shape of the cam when  $O_1$  from Fig. 15 is chosen as the cam shaft center, and it is seen that the pressure angle at a point on the cam profile corresponding to point  $P_1$  is  $\alpha_1$  and at a point corresponding to point  $P_2$  is  $\alpha_2$ .

In the foregoing, a cam mechanism has been so proportioned that the pressure angles  $\alpha_1$  and  $\alpha_2$  at points on the cam corresponding to points  $P_1$  and  $P_2$  were obtained. Even though  $P_1$  and  $P_2$  are the points of greatest slope on the displacement diagram, the pressure angles produced at some other points on the actual cam may be slightly greater.

However, if the pressure angles  $\alpha_1$  and  $\alpha_2$  are not to be exceeded at any point — i.e., they are to be maximum pressure angles — then  $P_1$  and  $P_2$  must be selected to be at the locations where these maximum pressure angles occur. If these locations are not known, then the graphical procedure described must be repeated, letting  $P_1$  take various positions on the curve for rise ( $AB$ ) and  $P_2$  various positions on the return curve ( $CD$ ) and then setting  $R_{\min}$  equal to the largest of the values determined from the various positions.

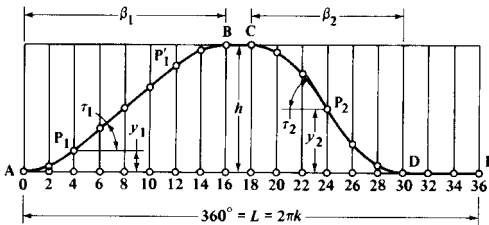


Fig. 17. Displacement Diagram

**Determination of Cam Size for Swinging Roller Follower.**—The proportioning of a cam with swinging roller follower having specific pressure angles at selected points follows the same procedure as that for a translating follower.

*Example:* Given the diagram for the roller displacement along its circular arc, Fig. 17 with  $h = 1.95$  in., the periods of rise and fall, respectively,  $\beta_1 = 160^\circ$  and  $\beta_2 = 120^\circ$ , the length of the swinging follower arm  $L_f = 3.52$  in., rotation of the cam away from pivot point  $M$ , and pressure angles  $\alpha_1 = \alpha_2 = 45^\circ$  (corresponding to the points  $P_1$  and  $P_2$  in the displacement diagram). Find the cam proportions.

*Solution:* Distances  $k \tan \tau_1$  and  $k \tan \tau_2$  are determined as in the previous example, Fig. 14. In Fig. 18,  $R_{y_1}$  is determined by making the distance  $R_u R_{y_1} = y_1$  along the arc  $R_u R_o$  and  $R_{y_2}$  by making  $R_u R_{y_2} = y_2$ . The arc  $R_u R_o = h$  and  $R_u$  indicates the lowest position of the center of the swinging roller follower and  $R_o$  the highest position.

Because the cam (i.e., the surface of the cam as it passes under the follower roller) rotates away from pivot point  $M$ ,  $k \tan \tau_1$  is laid out away from  $M$ , that is, from  $R_{y_1}$  to  $E_1$  and  $k \tan \tau_2$  is laid out toward  $M$  from  $R_{y_2}$  to  $E_2$ . Angle  $\alpha_1$  at  $E_1$  determines one ray and  $\alpha_2$  at  $E_2$  another ray, which together subtend an area  $A$  having the property that if the cam shaft center is chosen inside this area, the pressure angles at the points of the cam corresponding to  $P_1$  and  $P_2$  in the displacement diagram will not exceed the given values  $\alpha_1$  and  $\alpha_2$ , respectively. If the cam shaft center is chosen on the ray drawn from  $E_1$  at an angle  $\alpha_1 = 45^\circ$ , the pressure angle  $\alpha_1$  on the cam profile corresponding to point  $P_1$  will be exactly  $45^\circ$ , and if chosen on the ray from  $E_2$ , the pressure angle  $\alpha_2$  corresponding to  $P_2$  will be exactly  $45^\circ$ . If another point,  $O_2$  for example, is chosen as the cam shaft center, the pressure angle corresponding to  $P_1$  will be  $\alpha'_1$  and that corresponding to  $P_2$  will be  $\alpha_2$ .

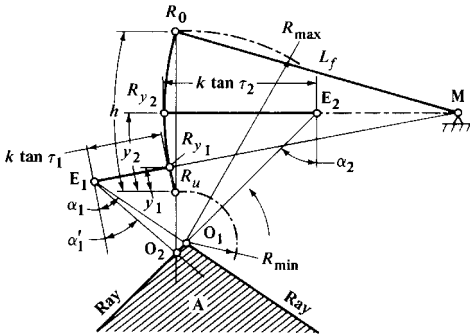


Fig. 18. Finding Proportions of Cam; Swinging Roller Follower (CCW Rotation)

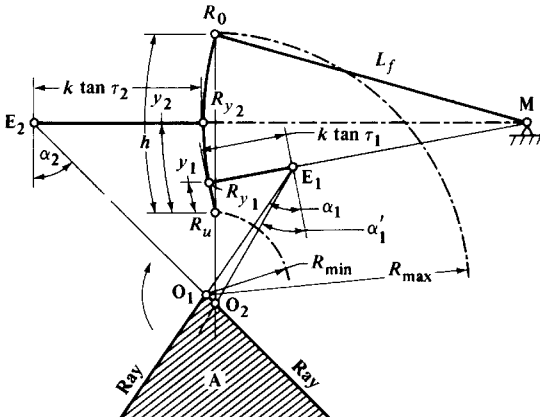


Fig. 19. Finding Proportions of Cam; Swinging Roller Follower (CW Rotation)

Fig. 19 shows the construction for rotation toward pivot point  $M$  (clockwise rotation of the cam in this case). The layout of the cam curve is made in a manner similar to that shown previously in Fig. 12.

In this example, the cam mechanism was so proportioned that the pressure angles at certain points (corresponding to  $P_1$  and  $P_2$ ) do not exceed certain specified values (namely  $\alpha_1$  and  $\alpha_2$ ).

To make sure that the pressure angle at *no point* along the cam profile exceeds the specified value, the previous procedure should be repeated for a series of points along the profile.

**Formulas for Calculating Pressure Angles.**—The graphical methods described previously are useful because they permit layout and measurement of pressure angles and radii of curvature of *any* cam profile. For cams of complicated profiles, and especially if the pro-

file cannot be represented by a simple formula, the graphical method may be the only practical solution. However, for some of the standard cam profiles utilizing *radial* translating roller followers, the following formulas may be used to determine key cam dimensions before laying out the cam. These formulas enable the designer to specify the maximum pressure angle (usually  $30^\circ$  or less) and, using the specified value, to calculate the minimum cam size that will satisfy the requirement.

The following symbols are in addition to those starting on page 2189.

$\alpha_{max}$  = specified maximum pressure angle, degrees

$R_{\alpha_{max}}$  = radius from cam center to point on pitch curve where  $\alpha_{max}$  is located, inches

$\phi_p$  = rise angle, in degrees, corresponding to  $\alpha_{max}$  and  $R_{\alpha_{max}}$

$\alpha$  = pressure angle at any selected point, degrees

$R_\alpha$  = radius from cam center to pitch curve at  $\alpha$ , inches

$\phi$  = rise angle, in degrees, corresponding to  $\alpha$  and  $R_\alpha$

For Uniform Velocity Motion:  $\alpha = \arctan \left[ \frac{180^\circ h}{\pi \beta R_\alpha} \right]$  at radius  $R_\alpha$  to the pitch curve (6a)

$\alpha_{max} = \arctan \left[ \frac{180^\circ h}{\pi \beta R_{min}} \right]$  at radius  $R_{min}$  of the pitch curve ( $\phi=0^\circ$ ). (6b)

If  $\alpha_{max}$  is specified, then the minimum radius to the lowest point on the pitch curve,  $R_{min}$ , is:

$R_{min} = \frac{180^\circ h}{\pi \beta \tan \alpha_{max}}$  which corresponds to  $\phi=0^\circ$ . (6c)

For Parabolic Motion:  $\alpha = \arctan \left[ \frac{720^\circ h \phi}{\pi \beta^2 R_\alpha} \right]$  at radius  $R_\alpha$  to the pitch curve at angle  $\phi$ ,

where  $0 \leq \phi \leq \beta/2$  (7a)

$\alpha = \arctan \left[ \frac{720^\circ h (1 - \phi/\beta)}{\pi \beta R_\alpha} \right]$  at radius  $R_\alpha$  to the pitch curve at angle  $\phi$ , where  $\beta/2 \leq \phi \leq \beta$ .

$\alpha = \arctan \left[ \frac{360^\circ h}{\pi \beta R_\alpha} \right]$  which occurs at  $\phi=\beta/2$  and  $R_\alpha=R_{min}+h/2$  (7b)

If  $\alpha_{max}$  is specified, then the minimum radius to the lowest point of the pitch curve is:

$R_{min} = \left[ \frac{360^\circ h}{\pi \beta \tan \alpha_{max}} - \frac{h}{2} \right]$  which corresponds to  $\phi=0^\circ$ . (7c)

For Simple Harmonic Motion:  $\alpha = \arctan \left[ \frac{90^\circ h}{\beta R_\alpha} \sin \left( \frac{180^\circ \phi}{\beta} \right) \right]$  at radius  $R_\alpha$  to the pitch curve at angle  $\phi$  (8a)

$\phi_p = \left( \frac{\beta}{180^\circ} \right) \left[ \arccot \left( \frac{\beta}{180^\circ} \tan \alpha_{max} \right) \right]$  = value of  $\phi$  where specified pressure angle  $\alpha_{max}$  occurs (8b)

$R_{\alpha_{max}} = \frac{h [\sin (180^\circ \phi_p / \beta)]^2}{2 \cos (180^\circ \phi_p / \beta)}$  at point where  $\alpha=\alpha_{max}$  and  $\phi=\phi_{max}$  (8c)

$$R_{\min} = R_{\alpha \max} - \frac{h}{2} \left[ 1 - \cos \left( \frac{180^\circ \phi_p}{\beta} \right) \right] \quad (8d)$$

For Cycloidal Motion:  $\alpha = \arctan \left[ \frac{180^\circ}{\pi \beta R_{\alpha}} \left[ 1 - \cos \left( \frac{360^\circ \phi}{\beta} \right) \right] \right]$  at radius  $R_{\alpha}$  to the pitch curve at angle  $\phi$  (9a)

$$\phi_p = \frac{\beta}{180^\circ} \left[ \operatorname{arccot} \left( \frac{\beta \tan \alpha_{\max}}{360^\circ} \right) \right] \quad \phi_p = \text{value of } \phi \text{ where specified pressure angle } \alpha_{\max} \text{ occurs} \quad (9b)$$

$$R_{\alpha \max} = \frac{h}{2\pi} \frac{[1 - \cos(360^\circ \phi_p / \beta)]^2}{\sin(360^\circ \phi_p / \beta)} \quad \text{at point where } \alpha = \alpha_{\max} \text{ and } \phi = \phi_p \quad (9c)$$

$$R_{\min} = R_{\alpha \max} - h \left[ \frac{\phi_p}{\beta} - \frac{1}{2\pi} \sin \left( \frac{360^\circ \phi_p}{\beta} \right) \right] \quad (9d)$$

**Radius of Curvature.**—The minimum radius of curvature of a cam should be kept as large as possible (1) to prevent undercutting of the convex portion of the cam and (2) to prevent too high surface stresses. Figs. 20(a), (b) and (c) illustrate how undercutting occurs.

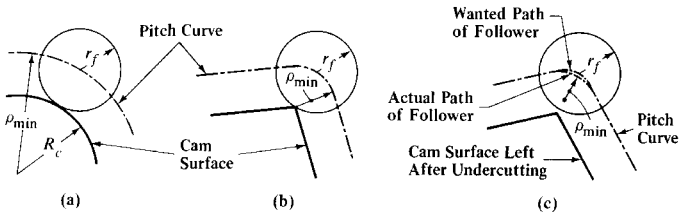


Fig. 20. (a) No Undercutting. (b) Sharp Corner on Cam. (c) Undercutting

In Fig. 20(a) the radius of curvature of the path of the follower is  $\rho_{\min}$  and the cam will at that point have a radius of curvature  $R_c = \rho_{\min} - r_f$ .

In Fig. 20(b)  $\rho_{\min} = r_f$  and  $R_c = 0$ . Therefore, the actual cam will have a sharp corner which in most cases will result in too high surface stresses.

In Fig. 20(c) is shown the case where  $\rho_{\min} < r_f$ . This case is not possible because undercutting will occur and the actual motion of the roller follower will deviate from the desired one as shown.

Undercutting cannot occur at the *concave* portion of the cam profile (working surface), but caution should be exerted in not making the radius of curvature equal to the radius of the roller follower. This condition would occur if there is a cusp on the displacement diagram which, of course, should always be avoided. To enable milling or grinding of *concave* portions of a cam profile, the radius of curvature of concave portions of the cam,  $R_c = \rho_{\min} + r_f$  must be larger than the radius of the cutter to be used.

The radius of curvature is used in calculating surface stresses (see following section), and may be determined by measurement on the cam layout or, in the case of radial translating followers, may be calculated using the formulas that follow. Although these formulas are exact for radial followers, they may be used for offset and swinging followers to obtain an approximation.



Based upon polar coordinates, the radius of curvature is:

$$\rho = \frac{\left[ r^2 + \left( \frac{dr}{d\phi} \right)^2 \right]^{3/2}}{r^2 + 2 \left( \frac{dr}{d\phi} \right)^2 - r \left( \frac{d^2r}{d\phi^2} \right)} \quad (10)$$

\*Positive values (+) indicate convex curve; negative values (-), concave.

In Equation (10),  $r = (R_{\min} + y)$ , where  $R_{\min}$  is the smallest radius to the pitch curve (see Fig. 12) and  $y$  is the displacement of the follower from its lowest position given in terms of  $\phi$ , the angle of cam rotation. The following formulas for  $r$ ,  $dr/d\phi$ , and  $d^2r/d\phi^2$  may be substituted into Equation (10) to calculate the radius of curvature at any point of the cam pitch curve; however, to determine the possibility of undercutting of the convex portion of the cam, it is the minimum radius of curvature on the convex portion,  $\rho_{\min}$ , that is needed. The minimum radius of curvature occurs, generally, at the point of maximum *negative* acceleration.

*Parabolic motion:*

$$r = R_{\min} + h - 2h \left( 1 - \frac{\phi}{\beta} \right)^2 \quad (11a)$$

$$\frac{dr}{d\phi} = \frac{720^\circ h}{\pi \beta} \left( 1 - \frac{\phi}{\beta} \right) \quad (11b) \quad \left. \vphantom{\frac{dr}{d\phi}} \right\} \frac{\beta}{2} \leq \phi \leq \beta$$

$$\frac{d^2r}{d\phi^2} = \frac{-4(180^\circ)^2 h}{\pi^2 \beta^2} \quad (11c)$$

These equations are for the deceleration portion of the curve as explained in the footnote to Table 1.

The minimum radius of curvature can occur at either  $\phi = \beta/2$  or at  $\phi = \beta$ , depending on the magnitudes of  $h$ ,  $R_{\min}$ , and  $\beta$ . Therefore, to determine which is the case, make two calculations using Formula (10), one for  $\phi = \beta/2$ , and the other for  $\phi = \beta$ .

*Simple harmonic motion:*

$$r = R_{\min} + \frac{h}{2} \left[ 1 - \cos \left( \frac{180^\circ \phi}{\beta} \right) \right] \quad (12a)$$

$$\frac{dr}{d\phi} = \frac{180^\circ h}{2\beta} \sin \left( \frac{180^\circ \phi}{\beta} \right) \quad (12b) \quad \left. \vphantom{\frac{dr}{d\phi}} \right\} 0 \leq \phi \leq \beta$$

$$\frac{d^2r}{d\phi^2} = \frac{(180^\circ)^2 h}{2\beta^2} \cos \left( \frac{180^\circ \phi}{\beta} \right) \quad (12c)$$

The minimum radius of curvature can occur at either  $\phi = \beta/2$  or at  $\phi = \beta$ , depending on the magnitudes of  $h$ ,  $R_{\min}$ , and  $\beta$ . Therefore, to determine which is the case, make two calculations using Formula (10), one for  $\phi = \beta/2$ , and the other for  $\phi = \beta$ .

*Cycloidal motion:*

$$r = R_{\min} + h \left[ \frac{\phi}{\beta} - \frac{1}{2\pi} \sin \left( \frac{360^\circ \phi}{\beta} \right) \right] \quad (13a)$$

$$\frac{dr}{d\phi} = \frac{180^\circ h}{\pi \beta} \left[ 1 - \cos \left( \frac{360^\circ \phi}{\beta} \right) \right] \quad (13b) \quad \left. \vphantom{\frac{dr}{d\phi}} \right\} 0 \leq \phi \leq \beta$$

$$\frac{d^2r}{d\phi^2} = \frac{2(180^\circ)^2 h}{\pi\beta^2} \sin\left(\frac{360^\circ\phi}{\beta}\right) \quad (13c)$$

$$\rho_{\min} = \frac{[(R_{\min} + 0.91h)^2 + (180^\circ h/\pi\beta)^2]^{3/2}}{(R_{\min} + 0.91h)^2 + 2(180^\circ h/\pi\beta)^2 + (R_{\min} + 0.91h)[2(180^\circ)^2 h/\pi\beta^2]} \quad (13d)$$

( $\rho_{\min}$  occurs near  $\phi = 0.75\beta$ .)

*Example:* Given  $h = 1$  in.,  $R_{\min} = 2.9$  in., and  $\beta = 60^\circ$ . Find  $\rho_{\min}$  for parabolic motion, simple harmonic motion, and cycloidal motion.

*Solution:*  $\rho_{\min} = 2.02$  in. for parabolic motion, from Equation (10)

$\rho_{\min} = 1.8$  in. for simple harmonic motion, from Equation (10)

$\rho_{\min} = 1.6$  in. for cycloidal motion, from Equation (13d)

The value of  $\rho_{\min}$  on any cam may also be obtained by measurement on the layout of the cam using a compass.

**Cam Forces, Contact Stresses, and Materials.**—After a cam and follower configuration has been determined, the forces acting on the cam may be calculated or otherwise determined. Next, the stresses at the cam surface are calculated and suitable materials to withstand the stress are selected. If the calculated maximum stress is too great, it will be necessary to change the cam design.

Such changes may include: 1) increasing the cam size to decrease pressure angle and increase the radius of curvature; 2) changing to an offset or swinging follower to reduce the pressure angle; 3) reducing the cam rotation speed to reduce inertia forces; 4) increasing the cam rise angle,  $\beta$ , during which the rise,  $h$ , occurs; 5) increasing the thickness of the cam, provided that deflections of the follower are small enough to maintain uniform loading across the width of the cam; and 6) using a more suitable cam curve or modifying the cam curve at critical points.

Although parabolic motion seems to be the best with respect to minimizing the calculated maximum acceleration and, therefore, also the maximum acceleration forces, nevertheless, in the case of high speed cams, cycloidal motion yields the lower maximum acceleration forces. Thus, it can be shown that owing to the sudden change in acceleration (called *jerk* or *pulse*) in the case of parabolic motion, the actual forces acting on the cam are doubled and sometimes even tripled at high speed, whereas with cycloidal motion, owing to the gradually changing acceleration, the actual dynamic forces are only slightly higher than the theoretical. Therefore, the calculated force due to acceleration should be multiplied by at least a factor of 2 for parabolic and 1.05 for cycloidal motion to provide an allowance for the load-increasing effects of elasticity and backlash.

The main factors influencing cam forces are: 1) displacement and cam speed (forces due to acceleration); 2) dynamic forces due to backlash and flexibility; 3) linkage dimensions which affect weight and weight distribution; 4) pressure angle and friction forces; and 5) spring forces.

The main factors influencing stresses in cams are: 1) radius of curvature for cam and roller; and 2) materials.

*Acceleration Forces:* The formula for the force acting on a translating body given an acceleration  $a$  is:

$$R = \frac{Wa}{g} = \frac{Wa}{386} \quad (14)$$

In this formula,  $g = 386$  inches/second squared,  $a =$  acceleration of  $W$  in inches/second squared;  $R =$  resultant of all the external forces (except friction) acting on the weight  $W$ . For cam analysis purposes,  $W$ , in pounds, consists of the weight of the follower, a portion of the

weight of the return spring ( $\frac{1}{3}$ ), and the weight of the members of the external mechanism against which the follower pushes, for example, the weight of a piston:

$$W = W_f + \frac{1}{3}W_s + W_e \tag{15}$$

where  $W$  = equivalent single weight;  $W_f$  = follower weight;  $W_s$  = spring weight; and  $W_e$  = external weight, all in pounds.

*Spring Forces:* The return spring,  $K_s$ , shown in Fig. 21a must be strong enough to hold the follower against the cam at all times. At high cam speeds the main force attempting to separate the follower from the cam surface is the acceleration force  $R$  at the point of maximum negative acceleration. Thus, at that point the spring must exert a force  $F_s$ ,

$$F_s = R - W_f - F_e - F_f \tag{16}$$

where  $F_e$  = external force resisting motion of follower, and  $F_f$  = friction force from follower guide bushings and other sources.

When the follower is at its lowest position ( $R_{min}$  in Fig. 21a), it is usual practice to have the spring provide some estimated preload to account for "set" that takes place in a spring after repeated use and to prevent roller sliding at the start of movement.

The required spring constant,  $K_s$ , in pounds per inch of spring deflection is:

$$K_s = \frac{F_s - \text{preload}}{y_a} \tag{17}$$

where  $y_a$  = rise of cam from  $R_{min}$  to height at which maximum negative acceleration takes place.

The force,  $F_y$ , that the spring exerts at any height  $y$  above  $R_{min}$  is:

$$F_y = yK_s + \text{preload} \tag{18}$$

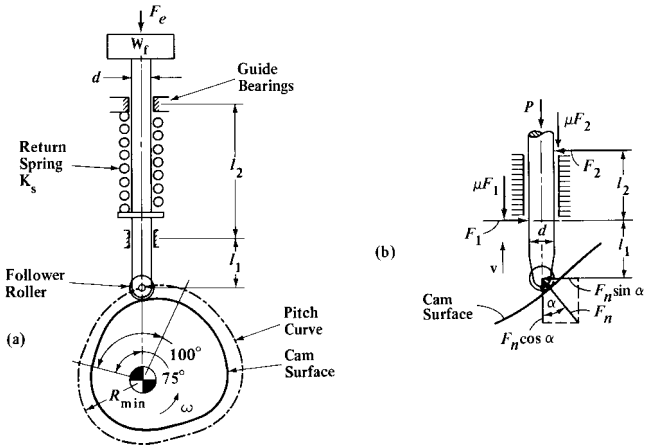


Fig. 21. (a) Radial Translating Follower and Cam System (b) Force Acting on a Translating Follower

*Pressure Angle and Friction Forces:* As shown in Fig. 21b, the pressure angle of the cam causes a sideways component  $F_n \sin \alpha$  which produces friction forces  $\mu F_1$  and  $\mu F_2$  in the guide bushing. If the follower rod is too flexible, bending of the follower will increase

these friction forces. The effect of the friction forces and the pressure angle are taken into account in the formula,

$$F_n = \frac{P}{\cos \alpha - \frac{\mu \sin \alpha}{l_2} (2l_1 + l_2 - \mu d)} \quad (19a)$$

where  $\mu$  = coefficient of friction in bushing;  $l_1$ ,  $l_2$ , and  $d$  are as shown in Fig. 21; and  $P$  = the sum of all the forces acting down against the upward motion of the follower (acceleration force + spring force + follower weight + external force)

$$P = \frac{W \times a}{386} + (yK_s + \text{preload}) + W_f + F_e \quad (19b)$$

**Cam Torque:** The follower pressing against the cam causes resisting torques during the rise period and assisting torques during the return period. The maximum value of the resisting torque determines the cam drive requirements. Instantaneous torque values may be calculated from

$$T_o = \frac{30vF_n \cos \alpha}{\pi N} = (R_{\min} + y)F_n \sin \alpha \quad (20)$$

in which  $T_o$  = instantaneous torque in pound-inches.

**Example of Force Analysis:** A radial translating follower system is shown in Fig. 21a. The follower is moved with cycloidal motion over a distance of 1 in. and an angle of lift  $\beta = 100^\circ$ . Cam speed  $N = 900$  rpm. The weight of the follower mass,  $W_f$  is 2 pounds. Both the spring weight  $W_s$  and the external weight  $W_e$  are negligible. The follower stem diameter is 0.75 in.,  $l_1 = 1.5$  in.,  $l_2 = 4$  in., coefficient of friction  $\mu = 0.05$ , external force  $F_e = 10$  lbs, and the pressure angle is not to exceed  $30^\circ$ .

(a) What is the smallest radius  $R_{\min}$  to the pitch curve?

From Formula (9b) the rise angle  $\phi_p$  to where the maximum pressure angle  $\alpha_{\max}$  exists is:

$$\begin{aligned} \phi_p &= \frac{\beta}{180^\circ} \left[ \operatorname{arccot} \left( \frac{\beta \tan \alpha_{\max}}{360^\circ} \right) \right] = \frac{100^\circ}{180^\circ} \left[ \operatorname{arccot} \left( \frac{100^\circ \times \tan 30^\circ}{360^\circ} \right) \right] \\ &= 44.94^\circ = 45^\circ \end{aligned}$$

From Formula (9c) the radius,  $R_{\alpha_{\max}}$ , at which the angle of rise is  $\phi_p$  is:

$$R_{\alpha_{\max}} = \frac{h}{2\pi} \frac{[1 - \cos(360^\circ \phi_p / \beta)]^2}{\sin(360^\circ \phi_p / \beta)} = \frac{1}{2\pi} \frac{[1 - \cos[(360^\circ \times 45^\circ) / 100^\circ]]^2}{\sin[(360^\circ \times 45^\circ) / 100^\circ]} = 1.96 \text{ in.}$$

From Formula (9d),  $R_{\min}$  is given by

$$\begin{aligned} R_{\min} &= R_{\alpha_{\max}} - h \left[ \frac{\phi_p}{\beta} - \frac{1}{2\pi} \sin \left( \frac{360^\circ \phi_p}{\beta} \right) \right] \\ &= 1.96 - 1 \times \left[ \frac{45^\circ}{100^\circ} - \frac{1}{2\pi} \sin \left( \frac{360^\circ \times 45^\circ}{100^\circ} \right) \right] = 1.560 \text{ in.} \end{aligned}$$

The same results could have been obtained graphically. If this  $R_{\min}$  is too small, i.e., if the cam bore and hub require a larger cam, then  $R_{\min}$  can be increased, in which case the maximum pressure angle will be less than  $30^\circ$ .

(b) If the return spring  $K_s$  is specified to provide a preload of 36 lbs when the follower is at  $R_{\min}$ , what is the spring constant required to hold the follower on the cam throughout the cycle?

The follower tends to leave the cam at the point of maximum *negative* acceleration. Fig. 7 shows this to be at  $\phi = \frac{3}{4}\beta = 75^\circ$ .

From Formula (4c),

$$a = \frac{2\pi h \omega^2}{\beta^2} \sin\left(\frac{360^\circ \phi}{\beta}\right) = \frac{2\pi \times 1 \times (6 \times 900)^2}{(100^\circ)^2} \sin\left(\frac{360^\circ \times 75^\circ}{100^\circ}\right) = -18,300 \text{ in./sec}^2$$

From Formulas (14) and (15),

$$R = \frac{Wa}{386} = \frac{(W_f + \frac{1}{3}W_s + W_e)a}{386} = \frac{(2 + 0 + 0)(-18,300)}{386} = 95 \text{ lbs (upward)}$$

Using Formula (16) to determine the spring force  $F_s$  to hold the follower on the cam,

$$F_s = R - W_f - F_e - F_f$$

as stated on page 2205, the value of  $R$  in the above formula should be multiplied by 1.05 for cycloidal motion to provide a factor of safety for dynamic pulses. Thus,

$$F_s = 1.05R - W_f - F_e - F_f = 1.05 \times 95 - 2 - 10 - 0 = 88 \text{ lbs (downward)}$$

The spring constant from Formula (17) is:

$$K_s = \frac{F_s - \text{preload}}{y_a} = \frac{88 - 36}{y_a}$$

and, from Formula (4a)  $y_a$  is:

$$y_a = h \left[ \frac{\phi}{\beta} - \frac{1}{2\pi} \sin\left(\frac{360^\circ \phi}{\beta}\right) \right] = 1 \times \left[ \frac{75^\circ}{100^\circ} - \frac{1}{2\pi} \sin\left(\frac{360^\circ \times 75^\circ}{100^\circ}\right) \right] = 0.909 \text{ in.}$$

so that  $K_s = (88 - 36)/0.909 = 57 \text{ lb/in.}$

(c) At the point where the pressure angle  $\alpha_{\max}$  is  $30^\circ$  ( $\phi = 45^\circ$ ) the rise of the follower is  $1.96 - 1.56 = 0.40 \text{ in.}$  What is the normal force,  $F_n$ , on the cam? From Formulas (19a) and (19b)

$$F_n = \frac{Wa/386 + yK_s + \text{preload} + W_f + F_e}{\cos \alpha - \frac{\mu \sin \alpha}{l_2} (2l_1 + l_2 - \mu d)}$$

using  $\phi = 45^\circ$ ,  $h = 1 \text{ in.}$ ,  $\beta = 100^\circ$ , and  $\omega = 6 \times 900 \text{ in}$  in Formula (4c) gives  $a = 5660 \text{ in./sec}^2$ . So that, with  $W = 2 \text{ lbs}$ ,  $y = 0.4$ ,  $K_s = 57$ , preload = 36 lbs,  $W_f = 2 \text{ lbs}$ ,  $F_e = 10 \text{ lbs}$ ,  $\alpha = 30^\circ$ ,  $\mu = 0.05$ ,  $l_1 = 1.5$ ,  $l_2 = 4$ , and  $d = 0.75$ ,

$$F_n = \frac{(2 \times 5660)/386 + 0.4 \times 57 + 36 + 2}{\cos 30^\circ - \frac{0.05 \times \sin 30^\circ}{4} (2 \times 1.5 + 4 - 0.05 \times 0.75)} = 110 \text{ lbs}$$

*Note:* If the coefficient of friction had been assumed to be 0, then  $F_n = 104$ ; on the other hand, if the follower is too flexible, so that sidewise bending occurs causing jamming in the bushing, the coefficient of friction may increase to, say, 0.5, in which case the calculated  $F_n = 200 \text{ lbs.}$

(d) Assuming that in the manufacture of this cam that an error or "bump" resulting from a chattermark or as a result of poor blending occurred, and that this "bump" rose to a height of 0.001 in. in a  $1^\circ$  rise of the cam in the vicinity of  $\phi = 45^\circ$ . What effect would this bump have on the acceleration force  $R$ ?

One formula that may be used to calculate the change in acceleration caused by such a cam error is:

$$\Delta a = \pm 2e \left( \frac{6N}{\Delta\phi} \right)^2 \quad (21)$$

where  $\Delta a$  = change in acceleration,

$e$  = error in inches,

$\Delta\phi$  = width of error in degrees. The plus (+) sign is used for a "bump" and the minus (-) sign for a dent or hollow in the surface

For  $e = 0.001$ ,  $\Delta\phi = 1^\circ$ , and  $N = 900$  rpm,

$$\Delta a = +2 \times 0.001 \left( \frac{6 \times 900}{1^\circ} \right)^2 = 58,320 \text{ in./sec}^2$$

which is 10 times the acceleration calculated for a perfect cam and would cause sufficient force  $F_n$  to damage the cam surface. On high speed cams, therefore, accuracy is of considerable importance.

(e) What is the cam torque at  $\phi = 45^\circ$ ?

From Formula (20),

$$\begin{aligned} T_o &= (R_{\min} + y) F_n \sin \alpha \\ &= (1.56 + 0.4) \times 110 \times \sin 30^\circ = 108 \text{ in.-lbs} \end{aligned}$$

(f) What is the radius of curvature at  $\phi = 45^\circ$ ?

From Formula (10),

$$\begin{aligned} \rho &= \frac{\left[ r^2 + \left( \frac{dr}{d\phi} \right)^2 \right]^{3/2}}{r^2 + 2 \left( \frac{dr}{d\phi} \right)^2 - r \left( \frac{d^2r}{d\phi^2} \right)} \\ r &= R_{\min} + y = 1.56 + 0.4 = 1.96 \end{aligned}$$

From Formula (13b),

$$\begin{aligned} \frac{dr}{d\phi} &= \frac{180^\circ h}{\pi \beta} \left[ 1 - \cos \left( \frac{360^\circ \phi}{\beta} \right) \right] = \frac{180^\circ \times 1}{\pi \times 100^\circ} \left[ 1 - \cos \left( \frac{360^\circ \times 45^\circ}{100^\circ} \right) \right] \\ &= 1.12 \end{aligned}$$

From Formula (13c),

$$\begin{aligned} \frac{d^2r}{d\phi^2} &= \frac{2(180^\circ)^2 h}{\pi \beta^2} \sin \left( \frac{360^\circ \phi}{\beta} \right) = \frac{2 \times (180^\circ)^2 \times 1}{\pi \times (100^\circ)^2} \sin \left( \frac{360^\circ \times 45^\circ}{100^\circ} \right) \\ &= 0.64 \\ \rho &= \frac{[(1.96)^2 + (1.12)^2]^{3/2}}{(1.96)^2 + 2(1.12)^2 - 1.96 \times 0.64} = 2.26 \text{ in.} \end{aligned}$$

**Calculation of Contact Stresses.**—When a roller follower is loaded against a cam, the compressive stress developed at the surface of contact may be calculated from

$$S_c = 2290 \sqrt{\frac{F_n}{b} \left( \frac{1}{r_f} \pm \frac{1}{R_c} \right)} \quad (22)$$

for a steel roller against a steel cam. For a steel roller on a cast iron cam, use 1850 instead of 2290 in Equation (22).

$S_c$  = maximum calculated compressive stress, psi

$F_n$  = normal load, lb

$b$  = width of cam, inch

$R_c$  = radius of curvature of cam surface, inch

$r_f$  = radius of roller follower, inch

The plus sign in (21) is used in calculating the maximum compressive stress when the roller is in contact with the convex portion of the cam profile and the minus sign is used when the roller is in contact with the concave portion. When the roller is in contact with the straight (flat) portion of the cam profile,  $R_c = \infty$  and  $1/R_c = 0$ . In practice, the greatest compressive stress is most apt to occur when the roller is in contact with that part of the cam profile which is convex and has the smallest radius of curvature.

*Example:* Given the previous cam example, the radius of the roller  $r_f = 0.25$  in., the convex radius of the cam  $R_c = (2.26 - 0.25)$  in., the width of contact  $b = 0.3$  in., and the normal load  $F_n = 110$  lbs. Find the maximum surface compressive stress. From (21),

$$S_c = 2290 \sqrt{\frac{110}{0.3} \left( \frac{1}{0.25} + \frac{1}{2.01} \right)} = 93,000 \text{ psi}$$

This calculated stress should be less than the allowable stress for the material selected from Table 2.

*Cam Materials:* In considering materials for cams it is difficult to select any single material as being the best for every application. Often the choice is based on custom or the machinability of the material rather than its strength. However, the failure of a cam or roller is commonly due to fatigue, so that an important factor to be considered is the limiting wear load, which depends on the surface endurance limits of the materials used and the relative hardnesses of the mating surfaces.

**Table 2. Cam Materials**

| Cam Materials for Use with Roller of Hardened Steel                                | Maximum Allowable Compressive Stress, psi |
|--|---|
| Gray-iron casting, ASTM A 48-48, Class 20, 160–190 Bhn, phosphate-coated           | 58,000                                    |
| Gray-iron casting, ASTM A 339-51T, Grade 20, 140–160 Bhn                           | 51,000                                    |
| Nodular-iron casting, ASTM A 339-51T, Grade 80-60-03, 207–241 Bhn                  | 72,000                                    |
| Gray-iron casting, ASTM A 48–48, Class 30, 200–220 Bhn                             | 65,000                                    |
| Gray-iron casting, ASTM A 48–48, Class 35, 225–225 Bhn                             | 78,000                                    |
| Gray-iron casting, ASTM A 48-48, Class 30, heat treated (Austempered), 225–300 Bhn | 90,000                                    |
| SAE 1020 steel, 130–150 Bhn  | 82,000                                    |
| SAE 4150 steel, heat treated to 270–300 Bhn, phosphate coated                      | 20,000                                    |
| SAE 4150 steel, heat treated to 270–300 Bhn  | 188,000                                   |
| SAE 1020 steel, carburized to 0.045 in. depth of case, 50–58 Rc                    | 226,000                                   |
| SAE 1340 steel, induction hardened to 45–55 Rc                                     | 198,000                                   |
| SAE 4340 steel, induction hardened to 50–55 Rc                                     | 226,000                                   |

Based on United Shoe Machinery Corp. data by Guy J. Talbourdet.

In Table 2 are given maximum permissible compressive stresses (surface endurance limits) for various cam materials when in contact with a roller of hardened steel. The stress values shown are based on 100,000,000 cycles or repetitions of stress for pure rolling. Where the repetitions of stress are considerably greater than 100,000,000, where there is appreciable misalignment, or where there is sliding, more conservative stress figures must be used.

**Layout of Cylinder Cams.**—In Fig. 22 is shown the development of a uniformly accelerated motion cam curve laid out on the surface of a cylindrical cam. This development is necessary for finding the projection on the cylindrical surface, as shown at *KL*. To construct the developed curve, first divide the base circle of the cylinder into, say, twelve equal parts. Set off these parts along line *ag*. Only one-half of the layout has been shown, as the other half is constructed in the same manner, except that the curve is here falling instead of rising. Divide line *aH* into the same number of divisions as the half circle, the divisions being in the proportion 1 : 3 : 5 : 5 : 3 : 1. Draw horizontal lines from these division points and vertical lines from *a, b, c, etc.* The intersections between the two sets of lines are points on the developed cam curve. These points are transferred to the cylindrical surface at the left by projection in the usual manner.

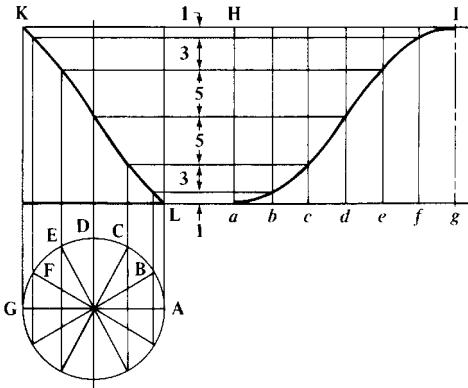


Fig. 22. Development of Cylindrical Cam

**Shape of Rolls for Cylinder Cams.**—The rolls for cylindrical cams working in a groove in the cam should be conical rather than cylindrical in shape, in order that they may rotate freely and without excessive friction. Fig. 23(a) shows a straight roll and groove, the action of which is faulty because of the varying surface speed at the top and bottom of the groove. Fig. 23(b) shows a roll with curved surface. For heavy work, however, the small bearing area is quickly worn down and the roll presses a groove into the side of the cam as well, thus destroying the accuracy of the movement and creating backlash. Fig. 23(c) shows the conical shape which permits a true rolling action in the groove. The amount of taper depends on the angle of spiral of the cam groove. As this angle, as a rule, is not constant for the whole movement, the roll and groove should be designed to meet the requirements on that section of the cam where the heaviest duty is performed. Frequently the cam groove is of a nearly even spiral angle for a considerable length. The method for determining the angle of the roll and groove to work correctly during the important part of the cycle is as follows:

In Fig. 23(d), *b* is the circumferential distance on the surface of the cam that includes the section of the groove for which correct rolling action is required. The throw of the cam for this circumferential movement is *a*. Line *OU* is the development of the movement of the



cam roll during the given part of the cycle, and  $c$  is the movement corresponding to  $b$ , but on a circle the diameter of which is equal to that of the cam at the bottom of the groove. With the same throw  $a$  as before, the line  $OV$  will be the development of the cam at the bottom of the groove.  $OU$  then is the length of the helix traveled by the top of the roll, while  $OV$  is the travel at the bottom of the groove. If, then, the top width and bottom width of the groove be made proportional to  $OU$  and  $OV$ , the groove will be properly proportioned.

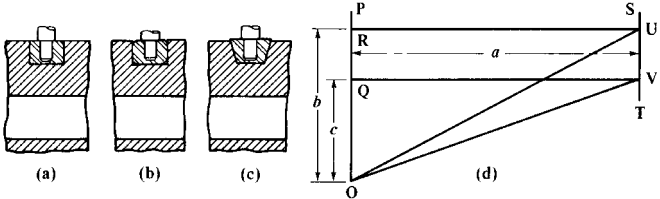


Fig. 23. Shape of Rolls for Cylinder Cams

**Cam Milling.**—Plate cams having a constant rise, such as are used on automatic screw machines, can be cut in a universal milling machine, with the spiral head set at an angle  $\alpha$ , as shown by the illustration.

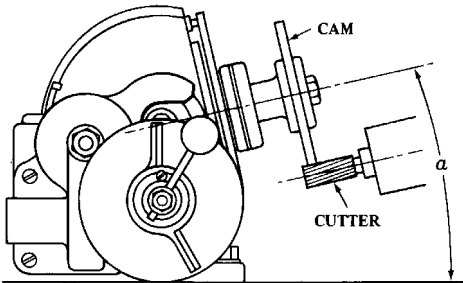


Fig. 24.

When the spiral head is set vertical, the “lead” of the cam (or its rise for one complete revolution) is the same as the lead for which the machine is geared; but when the spiral head and cutter are inclined, any lead or rise of the cam can be obtained, provided it is less than the lead for which the machine is geared, that is, less than the forward feed of the table for one turn of the spiral-head spindle. The cam lead, then, can be varied within certain limits by simply changing the inclination  $\alpha$  of the spiral head and cutter. The following formula is for determining this angle of inclination, for a given rise of cam and with the machine geared for a lead,  $L$ , selected from the tables beginning on page 1967,

$$\sin \alpha = \frac{360^\circ \times r}{\phi \times L}$$

where  $\alpha$  = angle to which index head and milling attachment are set from horizontal as shown in the accompanying diagram

$r$  = rise of cam in given part of circumference

$L$  = spiral lead for which milling machine is geared

$\phi$  = angle in which rise is required, expressed in degrees

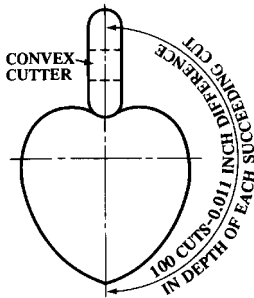
For example, suppose a cam is to be milled having a rise of 0.125 inch in 300 degrees and that the machine is geared for the smallest possible lead, or 0.670 inch; then:

$$\sin \alpha = \frac{360^\circ \times 0.125}{300^\circ \times 0.670} = 0.2239$$

which is the sine of  $12^\circ 56'$ . Therefore, to secure a rise of 0.125 inch with the machine geared for 0.670 inch lead, the spiral head is elevated to an angle of  $12^\circ 56'$  and the vertical milling attachment is also swiveled around to locate the cutter in line with the spiral-head spindle, so that the edge of the finished cam will be parallel to its axis of rotation. In the example given, the lead used was 0.670. A larger lead, say 0.930, could have been selected from the table on page 1967. In that case,  $\alpha = 9^\circ 17'$ .

When there are several lobes on a cam, having different leads, the machine can be geared for a lead somewhat in excess of the greatest lead on the cam, and then all the lobes can be milled without changing the spiral head gearing, by simply varying the angle of the spiral head and cutter to suit the different cam leads. Whenever possible, it is advisable to mill on the under side of the cam, as there is less interference from chips; moreover, it is easier to see any lines that may be laid out on the cam face. To set the cam for a new cut, it is first turned back by operating the handle of the table feed screw, after which the index crank is disengaged from the plate and turned the required amount.

**Simple Method for Cutting Uniform Motion Cams.**—Some cams are laid out with dividers, machined and filed to the line; but for a cam that must advance a certain number of thousandths per revolution of spindle this method is not accurate. Cams are easily and accurately cut in the following manner.



Let it be required to make the heart cam shown in the illustration. The throw of this cam is 1.1 inch. Now, by setting the index on the milling machine to cut 200 teeth and also dividing 1.1 inch by 100, we find that we have 0.011 inch to recede from or advance towards the cam center for each cut across the cam. Placing the cam securely on an arbor, and the latter between the centers of the milling machine, and using a convex cutter set the proper distance from the center of the arbor, make the first cut across the cam. Then, by lowering the milling machine knee 0.011 inch and turning the index pin the proper number of holes on the index plate, take the next cut and so on.

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## PLAIN BEARINGS

## Introduction

On the following pages are given data and procedures for designing full-film or hydrodynamically lubricated bearings of the journal and thrust types. However, before proceeding to these design methods, it is thought useful to first review those bearing aspects concerning the types of bearings available; lubricants and lubrication methods; hardness and surface finish; machining methods; seals; retainers; and typical length-to-diameter ratios for various applications.

The following paragraphs preceding the design sections provide guidance in these matters and suggest modifications in allowable loads when other than full-film operating conditions exist in a bearing.

**Classes of Plain Bearings.**—Bearings that provide sliding contact between mating surfaces fall into three general classes: *radial bearings* that support rotating shafts or journals; *thrust bearings* that support axial loads on rotating members; and *guide or slipper bearings* that guide moving parts in a straight line. Radial sliding bearings, more commonly called sleeve bearings, may be of several types, the most usual being the plain full journal bearing, which has 360-degree contact with its mating journal, and the partial journal bearing, which has less than 180-degree contact. This latter type is used when the load direction is constant and has the advantages of simplicity, ease of lubrication, and reduced frictional loss.

The relative motions between the parts of plain bearings may take place: 1) as pure sliding without the benefit of a liquid or gaseous lubricating medium between the moving surfaces such as with the dry operation of nylon or Teflon; 2) with hydrodynamic lubrication in which a wedge or film buildup of lubricating medium is produced, with either whole or partial separation of the bearing surfaces; 3) with hydrostatic lubrication in which a lubricating medium is introduced under pressure between the mating surfaces causing a force opposite to the applied load and a lifting or separation of these surfaces; and 4) with a hybrid form or combination of hydrodynamic and hydrostatic lubrication.

Listed below are some of the advantages and disadvantages of sliding contact (plain) bearings as compared with rolling contact (antifriction) bearings.

*Advantages:* 1) require less space; 2) are quieter in operation; 3) are lower in cost, particularly in high-volume production; 4) have greater rigidity; and 5) their life is generally not limited by fatigue.

*Disadvantages:* 1) have higher frictional properties resulting in higher power consumption; 2) are more susceptible to damage from foreign material in lubrication system; 3) have more stringent lubrication requirements; and 4) are more susceptible to damage from interrupted lubrication supply.

**Types of Journal Bearings.**—Many types of journal bearing configurations have been developed; some of these are shown in Fig. 1.

*Circumferential-groove bearings*, Fig. 1(a), have an oil groove extending circumferentially around the bearing. The oil is maintained under pressure in the groove. The groove divides the bearing into two shorter bearings that tend to run at a slightly greater eccentricity. However, the advantage in terms of stability is slight, and this design is most commonly used in reciprocating-load main and connecting-rod bearings because of the uniformity of oil distribution.

Short cylindrical bearings are a better solution than the circumferential-groove bearing for high-speed, low-load service. Often the bearing can be shortened enough to increase the unit loading to a substantial value, causing the shaft to ride at a position of substantial eccentricity in the bearing. Experience has shown that instability rarely results when the shaft eccentricity is greater than 0.6. Very short bearings are not often used for this type of

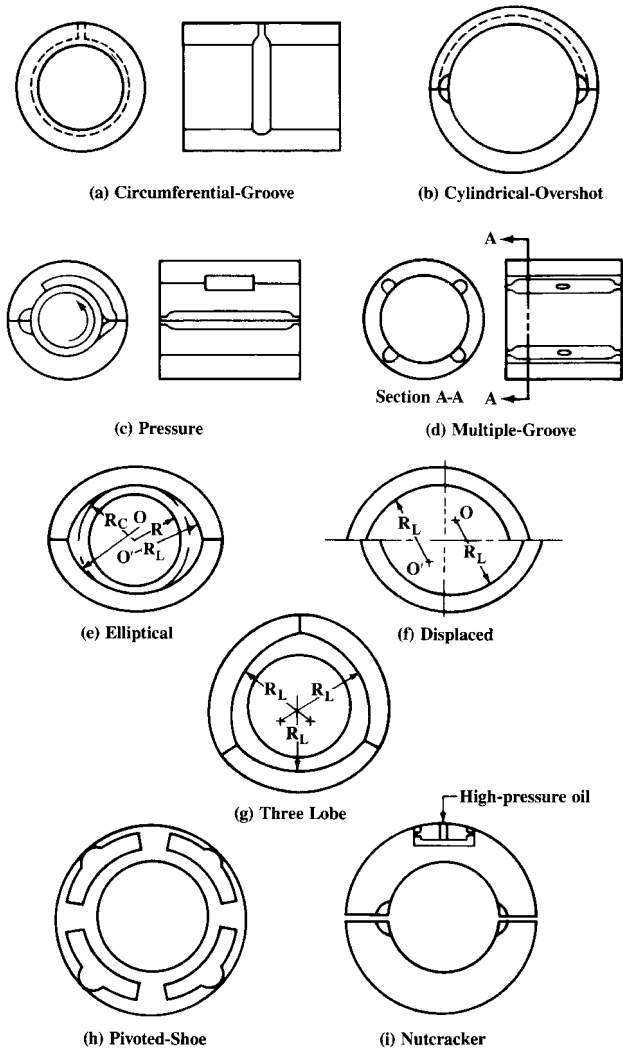


Fig. 1. Typical shapes of several types of pressure-fed bearings.

application, because they do not provide a high temporary rotating-load capacity in the event some unbalance should be created in the rotor during service.



*Cylindrical-overshot bearings*, Fig. 1(b), are used where surface speeds of 10,000 fpm or more exist, and where additional oil flow is desired to maintain a reasonable bearing temperature. This bearing has a wide circumferential groove extending from one axial oil groove to the other over the upper half of the bearing. Oil is usually admitted to the trailing-edge oil groove. An inlet orifice is used to control the oil flow. Cooler operation results from the elimination of shearing action over a large section of the upper half of the bearing and, to a great extent, from the additional flow of cool oil over the top half of the bearing.

*Pressure bearings*, Fig. 1(c), employ a groove over the top half of the bearing. The groove terminates at a sharp dam about 45 degrees beyond the vertical in the direction of shaft rotation. Oil is pumped into this groove by shear action from the rotation of the shaft and is then stopped by the dam. In high-speed operation, this situation creates a high oil pressure over the upper half of the bearing. The pressure created in the oil groove and surrounding upper half of the bearing increases the load on the lower half of the bearing. This self-generated load increases the shaft eccentricity. If the eccentricity is increased to 0.6 or greater, stable operation under high-speed, low-load conditions can result. The central oil groove can be extended around the lower half of the bearing, further increasing the effective loading. This design has one primary disadvantage: Dirt in the oil will tend to abrade the sharp edge of the dam and impair ability to create high pressures.

*Multiple-groove bearings*, Fig. 1(d), are sometimes used to provide increased oil flow. The interruptions in the oil film also appear to give this bearing some merit as a stable design.

*Elliptical bearings*, Fig. 1(e), are not truly elliptical, but are formed from two sections of a cylinder. This two-piece bearing has a large clearance in the direction of the split and a smaller clearance in the load direction at right angles to the split. At light loads, the shaft runs eccentric to both halves of the bearing, and hence, the elliptical bearing has a higher oil flow than the corresponding cylindrical bearing. Thus, the elliptical bearing will run cooler and will be more stable than a cylindrical bearing.

*Elliptical-overshot bearings* (not shown) are elliptical bearings in which the upper half is relieved by a wide oil groove connecting the axial oil grooves. They are analogous to cylindrical-overshot bearings.

*Displaced elliptical bearings*, Fig. 1(f), shift the centers of the two bearing arcs in both a horizontal and a vertical direction. This design has greater stiffness than a cylindrical bearing, in both horizontal and vertical directions, with substantially higher oil flow. It has not been extensively used, but offers the prospect of high stability and cool operation.

*Three-lobe bearings*, Fig. 1(g), are made up in cross section of three circular arcs. They are most effective as anti-whip bearings when the centers of curvature of each of the three lobes lie well outside the clearance circle that the shaft center can describe within the bearing. Three axial oil-feed grooves are used. It is a more difficult design to manufacture, because it is almost necessary to make it in three parts instead of two. The bore is machined with shims between each of the three parts. The shims are removed after machining is completed.

*Pivoted-shoe bearings*, Fig. 1(h), are one of the most stable bearings. The bearing surface is divided into three or more segments, each of which is pivoted at the center. In operation, each shoe tilts to form a wedge-shaped oil film, thus creating a force tending to push the shaft toward the center of the bearing. For single-direction rotation, the shoes are sometimes pivoted near one end and forced toward the shaft by springs.

*Nutcracker bearings*, Fig. 1(i), consist of two cylindrical half-bearings. The upper half-bearing is free to move in a vertical direction and is forced toward the shaft by a hydraulic cylinder. External oil pressure may be used to create load on the upper half of the bearing through the hydraulic cylinder. Or the high-pressure oil may be obtained from the lower half of the bearing by tapping a hole into the high-pressure oil film, thus creating a self-loading bearing. Either type can increase bearing eccentricity to the point where stable operation can be achieved.

**Hydrostatic Bearings.**—Hydrostatic bearings are used when operating conditions require full film lubrication that cannot be developed hydrodynamically. The hydrostatically lubricated bearing, either thrust or radial, is supplied with lubricant under pressure from an external source. Some advantages of the hydrostatic bearing over bearings of other types are: low friction; high load capacity; high reliability; high stiffness; and long life.

Hydrostatic bearings are used successfully in many applications including machine tools, rolling mills, and other heavily loaded slow-moving machinery. However, specialized techniques, including a thorough understanding of hydraulic components external to the bearing package is required. The designer is cautioned against use of this type of bearing without a full knowledge of all aspects of the problem. Determination of the operating performance of hydrostatic bearings is a specialized area of the lubrication field and is described in specialized reference books.

**Guide Bearings.**—This type of bearing is generally used as a positioning device or as a guide to linear motion such as in machine tools. Fig. 2 shows several examples of guide-way bearing designs. It is normal for this type of bearing to operate in the boundary lubrication region with either dry, dry film such as molybdenum disulfide ( $\text{MoS}_2$ ) or tetrafluorethylene (TFE), grease, oil, or gaseous lubrication. Hydrostatic lubrication is often used to improve performance, reduce wear, and increase stability. This type of design uses pumps to supply air or gas under pressure to pockets designed to produce a bearing film and maintain complete separation of the sliding surfaces.

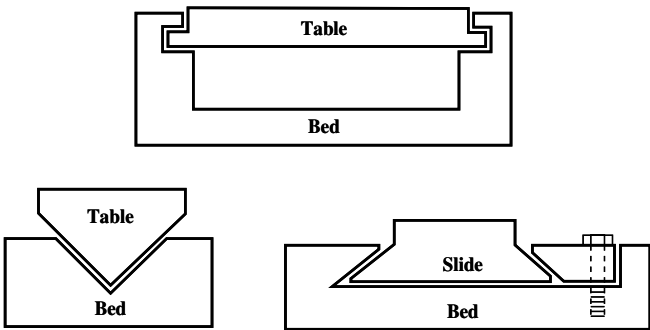


Fig. 2. Types of Guide Bearings

**Design.**—The design of a sliding bearing is generally accomplished in one of two ways: 1) a bearing operating under similar conditions is used as a model or basis from which the new bearing is designed; and 2) in the absence of any previous experience with similar bearings in similar environments, certain assumptions concerning operating conditions and requirements are made and a tentative design prepared based on general design parameters or rules of thumb. Detailed lubrication analysis is then performed to establish design and operating details and requirements.

**Modes of Bearing Operation.**—The load-carrying ability of a sliding bearing depends upon the kind of fluid film that is formed between its moving surfaces. The formation of this film is dependent, in part, on the design of the bearing and, in part, on the speed of rotation. The bearing has three modes or regions of operation designated as *full-film*, *mixed-film*, and *boundary* lubrication with effects on bearing friction, as shown in Fig. 3.

In terms of physical bearing operation these three modes may be further described as follows:

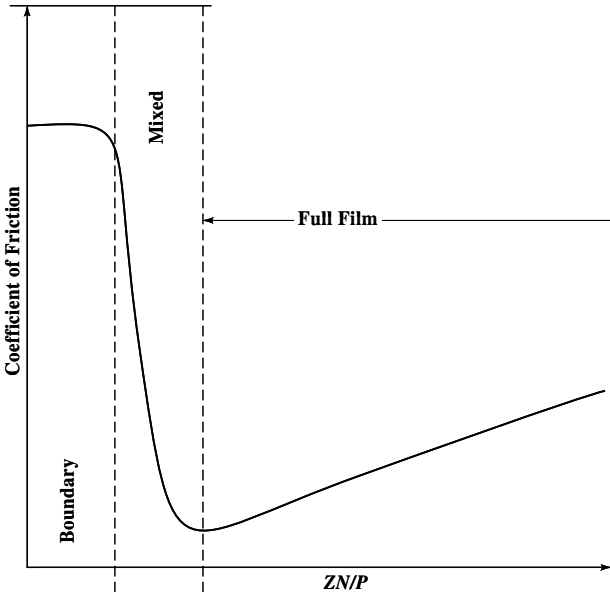


Fig. 3. Three modes of bearing operation.

1) Full-film, or hydrodynamic, lubrication produces a complete physical separation of the sliding surfaces resulting in low friction and long wear-free service life.

To promote full-film lubrication in hydrodynamic operation, the following parameters should be satisfied: a) Lubricant selected has the correct viscosity for the proposed operation; b) proper lubricant flow rates are maintained; c) proper design methods and considerations have been utilized; and d) surface velocity in excess of 25 feet per minute is maintained.

When full-film lubrication is achieved, a coefficient of friction between 0.001 and 0.005 can be expected.

2) Mixed-film lubrication is a mode of operation between the full-film and boundary modes. With this mode, there is a partial separation of the sliding surfaces by the lubricant film; however, as in boundary lubrication, limitations on surface speed and wear will result. With this type of lubrication, a surface velocity in excess of 10 feet per minute is required with resulting coefficients of friction of 0.02 to 0.08.

3) Boundary lubrication takes place when the sliding surfaces are rubbing together with only an extremely thin film of lubricant present. This type of operation is acceptable only in applications with oscillating or slow rotary motion. In complete boundary lubrication, the oscillatory or rotary motion is usually less than 10 feet per minute with resulting coefficients of friction of 0.08 to 0.14. These bearings are usually grease lubricated or periodically oil lubricated.

In starting up and accelerating to its operating point, a journal bearing passes through all three modes of operation. At rest, the journal and bearing are in contact, and thus when starting, the operation is in the boundary lubrication region. As the shaft begins to rotate

more rapidly and the hydrodynamic film starts to build up, bearing operation enters the region of mixed-film lubrication. When design speeds and loads are reached, the hydrodynamic action in a properly designed bearing will promote full-film lubrication.

**Methods of Retaining Bearings.**—Several methods are available to ensure that a bearing remains in place within a housing. Which method to use depends upon the particular application but requires first that the unit lends itself to convenient assembly and disassembly; additionally, the bearing wall should be of uniform thickness to avoid introduction of weak points in the construction that may lead to elastic or thermal distortion.

*Press or Shrink Fit:* One common and satisfactory technique for retaining the bearing is to press or shrink the bearing in the housing with an interference fit. This method permits the use of bearings having uniform wall thickness over the entire bearing length.

Standard bushings with finished inside and outside diameters are available in sizes up to approximately 5 inches inside diameter. Stock bushings are commonly provided 0.002 to 0.003 inch over nominal on outside diameter sizes of 3 inches or less. For diameters greater than 3 inches, outside diameters are 0.003 to 0.005 inch over nominal. Because these tolerances are built into standard bushings, the amount of press fit is controlled by the housing-bore size.

As a result of a press or shrink fit, the bore of the bearing material “closes in” by some amount. In general, this diameter decrease is approximately 70 to 100 per cent of the amount of the interference fit. Any attempt to accurately predict the amount of reduction, in an effort to avoid final clearance machining, should be avoided.

Shrink fits may be accomplished by chilling the bearing in a mixture of dry ice and alcohol, or in liquid air. These methods are easier than heating the housing and are preferred. Dry ice in alcohol has a temperature of  $-110$  degrees F and liquid air boils at  $-310$  degrees F.

When a bearing is pressed into the housing, the driving force should be uniformly applied to the end of the bearing to avoid upsetting or peening of the bearing. Of equal importance, the mating surfaces must be clean, smoothly finished, and free of machining imperfections.

*Keying Methods:* A variety of methods can be used to fix the position of the bearing with respect to its housing by “keying” the two together. Possible keying methods are shown in Figs. 4a through 4f including: a) set screws; b) Woodruff keys; c) bolted bearing flanges; d) threaded bearings; e) dowel pins; and f) housing caps.

Factors to be considered when selecting one of these methods are as follows:

- 1) Maintaining uniform wall thickness of the bearing material, if possible, especially in the load-carrying region of the bearing.
- 2) Providing as much contact area as possible between bearing and housing. Mating surfaces should be clean, smooth, and free from imperfections to facilitate heat transfer.
- 3) Preventing any local deformation of the bearing that might result from the keying method. Machining after keying is recommended.
- 4) Considering the possibility of bearing distortion resulting from the effect of temperature changes on the particular keying method.

**Methods of Sealing.**—In applications where lubricants or process fluids are utilized in operation, provision must be made normally to prevent leakage to other areas. This provision is made by the use of static and dynamic type sealing devices. In general, three terms are used to describe the devices used for sealing:

*Seal:* A means of preventing migration of fluids, gases, or particles across a joint or opening in a container.

*Packing:* A dynamic seal, used where some form of relative motion occurs between rigid members of an assembly.

*Gaskets:* A static seal, used where there is no relative motion between joined parts.

## Methods of Bearing Retention

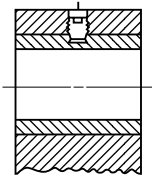


Fig. 4a. Set Screws

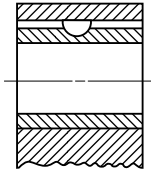
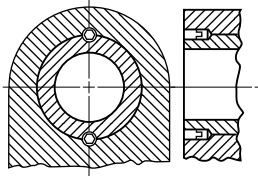


Fig. 4b. Woodruff Key

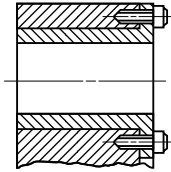


Fig. 4c. Bolts through Flange

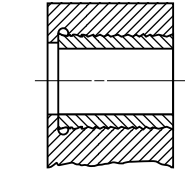


Fig. 4d. Bearing Screwed into Housing

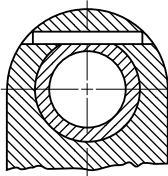


Fig. 4e. Dowel Pin

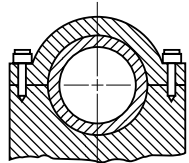


Fig. 4f. Housing Cap

Two major functions must be achieved by all sealing applications: prevent escape of fluid; and prevent migration of foreign matter from the outside.

The first determination in selecting the proper seal is whether the application is static or dynamic. To meet the requirements of a static application there must be no relative motion between the joining parts or between the seal and the mating part. If there is any relative motion, the application must be considered dynamic, and the seal selected accordingly.

Dynamic sealing requires control of fluids leaking between parts with relative motion. Two primary methods are used to this end: positive contact or rubbing seals; and controlled clearance noncontact seals.

*Positive Contact or Rubbing Seals:* These seals are used where positive containment of liquids or gases is required, or where the seal area is continuously flooded. If properly selected and applied, contact seals can provide zero leakage for most fluids. However, because they are sensitive to temperature, pressure, and speed, improper application can result in early failure. These seals are applicable to rotating and reciprocating shafts. In many assemblies, positive-contact seals are available as off-the-shelf items. In other instances, they are custom-designed to the special demands of a particular application. Custom design is offered by many seal manufacturers and, for extreme cases, probably offers the best solution to the sealing problem.

*Controlled Clearance Noncontact Seals:* Representative of the controlled-clearance seals, which includes all seals in which there is no rubbing contact between the rotating and

stationary members, are throttling bushings and labyrinths. Both types operate by fluid-throttling action in narrow annular or radial passages.

Clearance seals are frictionless and very insensitive to temperature and speed. They are chiefly effective as devices for limiting leakage rather than stopping it completely. Although they are employed as primary seals in many applications, the clearance seal also finds use as auxiliary protection in contact-seal applications. These seals are usually designed into the equipment by the designer himself, and they can take on many different forms.

Advantages of this seal are that friction is kept to an absolute minimum and there is no wear or distortion during the life of the equipment. However, there are two significant disadvantages: The seal has limited use when leakage rates are critical; and it becomes quite costly as the configuration becomes elaborate.

*Static Seals:* Static seals such as gaskets, "O" rings, and molded packings cover very broad ranges of both design and materials.

Some of the typical types are as follows: 1) Molded packings: a) lip type, and b) squeeze-molded; 2) simple compression packings; 3) diaphragm seals; 4) nonmetallic gaskets; 5) "O" rings; and 6) metallic gaskets and "O" rings.

Data on "O" rings are found starting on page 2502.

Detailed design information for specific products should be obtained directly from manufacturers.

**Hardness and Surface Finish.**—Even in well-lubricated full-film sleeve bearings, momentary contact between journal and bearing may occur under such conditions as starting, stopping, or overloading. In mixed-film and boundary-film lubricated sleeve bearings, continuous metal-to-metal contact occurs. Hence, to allow for any necessary wearing-in, the journal is usually made harder than the bearing material. This arrangement allows the effects of scoring or wearing to take place on the bearing, which is more easily replaced, rather than on the more expensive shaft. As a general rule, recommended Brinell (Bhn) hardness of the journal is at least 100 points harder than the bearing material.

The softer cast bronzes used for bearings are those with high lead content and very little tin. Such bronzes give adequate service in boundary- and mixed-film applications where full advantage is taken of their excellent "bearing" characteristics.

High-tin, low-lead content cast bronzes are the harder bronzes and these have high ultimate load-carrying capacity; higher journal hardnesses are required with these bearing bronzes. Aluminum bronze, for example, requires a journal hardness in the range of 550 to 600 Bhn.

In general, harder bearing materials require better alignment and more reliable lubrication to minimize local heat generation if and when the journal touches the shaft. Also, abrasives that find their way into the bearing are a problem for the harder bearing materials and greater care should be taken to exclude them.

*Surface Finish:* Whether bearing operation is complete boundary, mixed film, or fluid film, surface finishes of the journal and bearing must receive careful attention. In applications where operation is hydrodynamic or full-film, peak surface variations should be less than the expected minimum film thickness; otherwise, peaks on the journal surface will contact peaks on the bearing surface, with resulting high friction and temperature rise. Ranges of surface roughness obtained by various finishing methods are: boring, broaching, and reaming, 32 to 64 microinches, rms; grinding, 16 to 64 microinches, rms; and fine grinding, 4 to 16 microinches, rms.

In general, the better surface finishes are required for full-film bearings operating at high eccentricity ratios because full-film lubrication must be maintained with small clearances, and metal-to-metal contact must be avoided. Also, the harder the material, the better the surface finish required. For boundary- and mixed-film applications, surface finish requirements may be somewhat relaxed because bearing wear-in will in time smooth the surfaces.

Fig. 5 is a general guide to the ranges required for bearing and journal surface finishes. Selecting a particular surface finish in each range can be simplified by observing the general rule that smoother finishes are required for the harder materials, for high loads, and for high speeds.

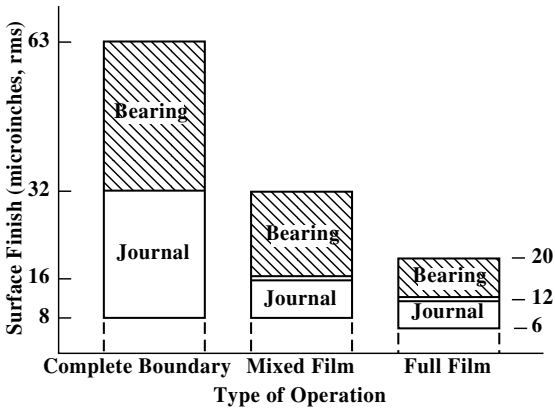


Fig. 5. Recommended ranges of surface finish for the three types of sleeve bearing operations.

**Machining Bores.**—The methods most commonly used in finishing journal bearing bores are boring, broaching, reaming, and burnishing.

Broaching is a rapid finishing method providing good size and alignment control when adequate piloting is possible. Soft babbitt materials are particularly compatible with the broaching method. A third finishing method, reaming, facilitates good size and alignment control when piloting is utilized. Reaming can be accomplished both manually or by machine, the machine method being preferred. Burnishing is a fast sizing operation that gives good alignment control, but does not give as good size control as the cutting methods. It is not recommended for soft materials such as babbitt. Burnishing has an ironing effect that gives added seating of the bushing outside diameter in the housing bore; consequently, it is often used for this purpose, especially on a  $\frac{1}{32}$ -inch wall bushing, even if a further sizing operation is to be used subsequently.

Boring of journal bearings provides the best concentricity, alignment, and size control and is the finishing method of choice when close tolerances and clearances are desirable.

**Methods of Lubrication.**—There are numerous ways to supply lubricant to bearings. The more common of these are described in the following.

*Pressure lubrication*, in which an abundance of oil is fed to the bearing from a central groove, single or multiple holes, or axial grooves, is effective and efficient. The moving oil assists in flushing dirt from the bearing and helps keep the bearing cool. In fact, it removes heat faster than other lubricating methods and, therefore, permits thinner oil films and unimpaired load capacities. The oil-supply pressure needed for bushings carrying the basic load is directly proportional to the shaft speed, but for most installations, 50 psi will be adequate.

*Splash fed* applies to a variety of intermittently lubricated bushings. It includes everything from bearings spattered with oil from the action of other moving parts to bearings regularly dipped in oil. Like oil bath lubrication, splash feeding is practical when the housing can be made oiltight and when the moving parts do not churn the oil. The fluctuating

nature of the load and the intermittent oil supply in splash fed applications requires the designer to use experience and judgment when determining the probable load capacity of bearings lubricated in this way.

*Oil bath lubrication*, in which the bushing is submerged in oil, is the most reliable of all methods except pressure lubrication. It is practical if the housing can be made oil tight, and if the shaft speed is not so great as to cause excessive churning of the oil.

*Oil ring lubrication*, in which oil is supplied to the bearing by a ring in contact with the shaft, will, within reasonable limits, bring enough oil to the bearing to maintain hydrodynamic lubrication. If the shaft speed is too low, little oil will follow the ring to the bearing; and, if the speed is too high, the ring speed will not keep pace with the shaft. Also, a ring revolving at high speed will lose oil by centrifugal force. For best results, the peripheral speed of the shaft should be between 200 and 2000 feet per minute. Safe load to achieve hydrodynamic lubrication should be one-half of that for pressure fed bearings. Unless the load is light, hydrodynamic lubrication is doubtful. The safe load, then, to achieve hydrodynamic lubrication, should be one-quarter of that of pressure fed bearings.

*Wick or waste pack lubrication* delivers oil to a bushing by the capillary action of a wick or waste pack; the amount delivered is proportional to the size of the wick or pack.

*Lubricants:* The value of an oil as a lubricant depends mainly on its film-forming capacity, that is, its capability to maintain a film of oil between the bearing surfaces. The film-forming capacity depends to a large extent on the viscosity of the oil, but this should not be understood to mean that oil of the highest viscosity is always the most suitable lubricant. For practical reasons, an oil of the lowest viscosity that will retain an unbroken oil film between the bearing surfaces is the most suitable for purposes of lubrication. A higher viscosity than that necessary to maintain the oil film results in a waste of power due to the expenditure of energy necessary to overcome the internal friction of the oil itself.

Fig. 6 provides representative values of viscosity in centipoises for SAE mineral oils. Table 55a on page 2586 is provided as a means of converting viscosities of other units to centipoises.

Grease packed in a cavity surrounding the bushing is less adequate than an oil system, but it has the advantage of being more or less permanent. Although hydrodynamic lubrication is possible under certain very favorable circumstances, boundary lubrication is the usual state.

**Lubricant Selection.**—In selecting lubricants for journal bearing operation, several factors must be considered: 1) type of operation (full, mixed, or boundary film) anticipated; 2) surface speed; and 3) bearing loading.

Fig. 7 combines these factors and facilitates general selection of the proper lubricant viscosity range.

As an example of using these curves, consider a lightly loaded bearing operating at 2000 rpm. At the bottom of the figure, locate 2000 rpm and move vertically to intersect the light-load full-film lubrication curve, which indicates an SAE 5 oil.

As a general rule-of-thumb, heavier oils are recommended for high loads and lighter oils for high speeds.

In addition, other than using conventional lubrication oils, journal bearings may be lubricated with greases or solid lubricants. Some of the reasons for use of these lubricants are to:

- 1) Lengthen the period between relubrication;
- 2) Avoid contaminating surrounding equipment or material with "leaking" lubricating oil;
- 3) Provide effective lubrication under extreme temperature ranges;
- 4) Provide effective lubrication in the presence of contaminating atmospheres; and
- 5) Prevent intimate metal-to-metal contact under conditions of high unit pressure which might destroy boundary lubricating films.



## BEARING LUBRICANTS

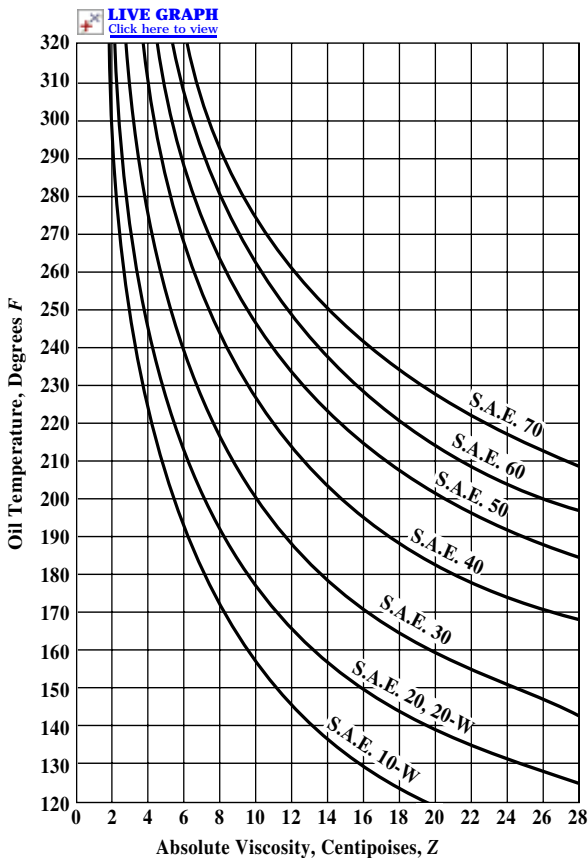


Fig. 6. Viscosity vs. Temperature—SAE oils.

**Greases:** Where full-film lubrication is not possible or is impractical for slow-speed fairly high-load applications, greases are widely used as bearing lubricants. Although full-film lubrication with grease is possible, it is not normally considered since an elaborate pumping system is required to continuously supply a prescribed amount of grease to the bearing. Bearings supplied with grease are usually lubricated periodically. Grease lubrication, therefore, implies that the bearing will operate under conditions of complete boundary lubrication and should be designed accordingly.

Lubricating greases are essentially a combination of a mineral lubricating oil and a thickening agent, which is usually a metallic soap. When suitably mixed, they make excellent bearing lubricants. There are many different types of greases which, in general, may be classified according to the soap base used. Information on commonly used greases is shown in Table 3.

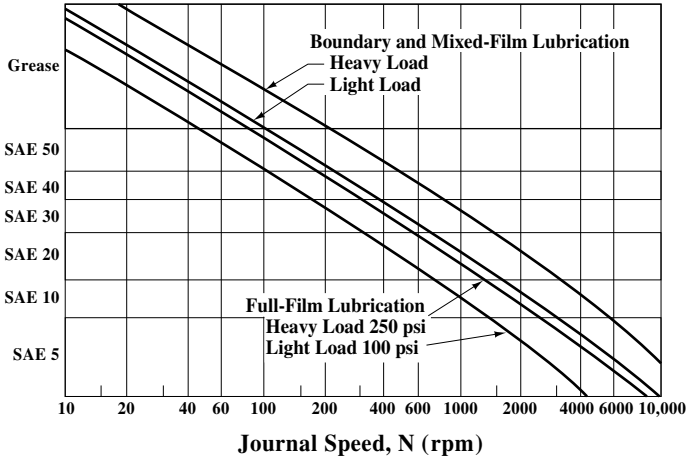


Fig. 7. Lubricant Selection Guide

Table 3. Commonly Used Greases and Solid Lubricants

| Type                 | Operating Temperature, Degrees F | Load     | Comments             |
|----------------------|----------------------------------|----------|----------------------|
| Greases              |                                  |          |                      |
| Calcium or lime soap | 160                              | Moderate | ...                  |
| Sodium soap          | 300                              | Wide     | For wide speed range |
| Aluminum soap        | 180                              | Moderate | ...                  |
| Lithium soap         | 300                              | Moderate | Good low temperature |
| Barium soap          | 350                              | Wide     | ...                  |
| Solid Lubricants     |                                  |          |                      |
| Graphite             | 1000                             | Wide     | ...                  |
| Molybdenum disulfide | -100 to 750                      | Wide     | ...                  |

Synthetic greases are composed of normal types of soaps but use synthetic hydrocarbons instead of normal mineral oils. They are available in a range of consistencies in both water-soluble and insoluble types. Synthetic greases can accommodate a wide range of variation in operating temperature; however, recommendations on special-purpose greases should be obtained from the lubricant manufacturer.

Application of grease is accomplished by one of several techniques depending upon grease consistency. These classifications are shown in Table 4 along with typical methods of application. Grooves for grease are generally greater in width, up to 1.5 times, than for oil.

Coefficients of friction for grease-lubricated bearings range from 0.08 to 0.16, depending upon consistency of the grease, frequency of lubrication, and type of grease. An average value of 0.12 may be used for design purposes.

*Solid Lubricants:* The need for effective high-temperature lubricants led to the development of several solid lubricants. Essentially, solid lubricants may be described as low-shear-strength solid materials. Their function within a bronze bearing is to act as an inter-

**Table 4. NLGI Consistency Numbers**

| NLGI <sup>a</sup><br>Consistency No. | Consistency<br>of Grease | Typical<br>Method of Application            |
|--------------------------------------|--------------------------|---|
| 0                                    | Semifluid                | Brush or gun                                |
| 1                                    | Very soft                | Pin-type cup or gun                         |
| 2                                    | Soft                     | Pressure gun or centralized pressure system |
| 3                                    | Light cup grease         | Pressure gun or centralized pressure system |
| 4                                    | Medium cup grease        | Pressure gun or centralized pressure system |
| 5                                    | Heavy cup grease         | Pressure gun or hand                        |
| 6                                    | Block grease             | Hand, cut to fit                            |

<sup>a</sup>NLGI is National Lubricating Grease Institute

mediary material between sliding surfaces. Since these solids have very low shear strength, they shear more readily than the bearing material and thereby allow relative motion. So long as solid lubricant remains between the moving surfaces, effective lubrication is provided and friction and wear are reduced to acceptable levels.

Solid lubricants provide the most effective boundary films in terms of reduced friction, wear, and transfer of metal from one sliding component to the other. However, there is a significant deterioration in these desirable properties as the operating temperature of the boundary film approaches the melting point of the solid film. At this temperature the friction may increase by a factor of 5 to 10 and the rate of metal transfer may increase by as much as 1000. What occurs is that the molecules of the lubricant lose their orientation to the surface that exists when the lubricant is solid. As the temperature further increases, additional deterioration sets in with the friction increasing by some additional small amount but the transfer of metal accelerates by an additional factor of 20 or more. The final effect of too high temperature is the same as metal-to-metal contact without benefit of lubricant. These changes, which are due to the physical state of the lubricant, are reversed when cooling takes place.

The effects just described also partially explain why fatty acid lubricants are superior to paraffin base lubricants. The fatty acid lubricants react chemically with the metallic surfaces to form a metallic soap that has a higher melting point than the lubricant itself, the result being that the breakdown temperature of the film, now in the form of a metallic soap is raised so that it acts more like a solid film lubricant than a fluid film lubricant.

### Journal or Sleeve Bearings

Although this type of bearing may take many shapes and forms, there are always three basic components: journal or shaft, bushing or bearing, and lubricant. Fig. 1 shows these components with the nomenclature generally used to describe a journal bearing:  $W$  = applied load,  $N$  = revolution,  $e$  = eccentricity of journal center to bearing center,  $\theta$  = attitude angle, which is the angle between the applied load and the point of minimum film thickness,  $d$  = diameter of the shaft,  $c_d$  = bearing clearance,  $d + c_d$  = diameter of the bearing and  $h_o$  = minimum film thickness.

**Grooving and Oil Feeding.**—Grooving in a journal bearing has two purposes:

- 1) to establish and maintain an efficient film of lubricant between the bearing moving surfaces and
- 2) to provide adequate bearing cooling

The obvious and only practical location for introducing lubricant to the bearing is in a region of low pressure. A typical pressure profile of a bearing is shown by Fig. 2. The arrow  $W$  shows the applied load. Typical grooving configurations used for journal bearings are shown in Figs. 3a through 3e.

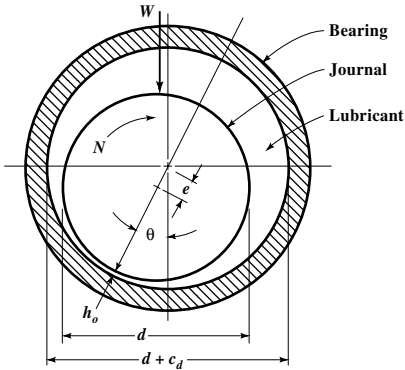


Fig. 1. Basic components of a journal bearing.

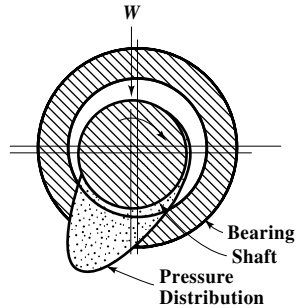


Fig. 2. Typical pressure profile of journal bearing.

### Types of Journal Bearing Oil Grooving

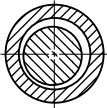


Fig. 3a. Single inlet hole

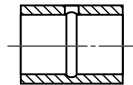


Fig. 3b. Circular groove

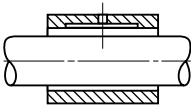


Fig. 3c. Straight axial groove

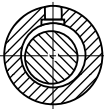


Fig. 3d. Straight axial groove with feeder groove

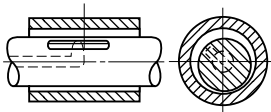
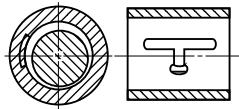


Fig. 3e. Straight axial groove in shaft

**Heat Radiating Capacity.**—In a self-contained lubrication system for a journal bearing, the heat generated by bearing friction must be removed to prevent continued temperature rise to an unsatisfactory level. The heat-radiating capacity  $H_R$  of the bearing in foot-pounds per minute may be calculated from the formula  $H_R = Ld Ct_R$  in which  $C$  is a constant determined by O. Lasche, and  $t_R$  is temperature rise in degrees Fahrenheit.

Values for the product  $Ct_R$  may be found from the curves in Fig. 4 for various values of bearing temperature rise  $t_R$  and for three operating conditions. In this equation,  $L$  = total length of the bearing in inches and  $d$  = bearing diameter in inches.

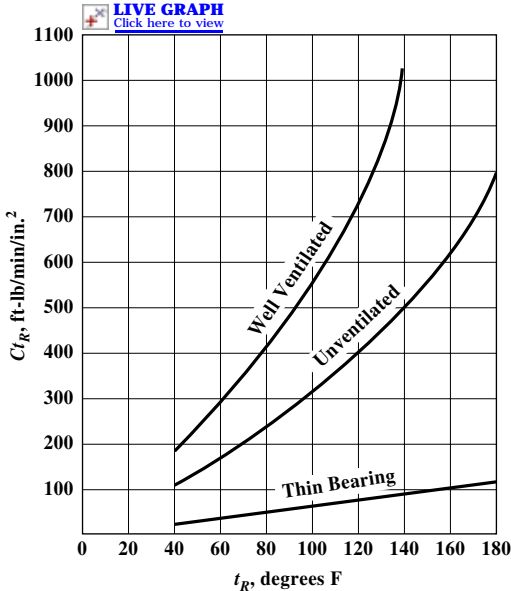


Fig. 4. Heat-radiating capacity factor,  $C_{tR}$ , vs. bearing temperature rise,  $t_R$ —journal bearings.

**Journal Bearing Design Notation.**—The symbols used in the following step-by-step procedure for lubrication analysis and design of a plain sleeve or journal bearing are as follows:

- $c$  = specific heat of lubricant, Btu/lb/degree F
- $c_d$  = diametral clearance, inches
- $C_n$  = bearing capacity number
- $d$  = journal diameter, inches
- $e$  = eccentricity, inches
- $h_o$  = minimum film thickness, inch
- $K$  = constants
- $l$  = bearing length as defined in Fig. 5, inches
- $L$  = actual length of bearing, inches
- $m$  = clearance modulus
- $N$  = rpm
- $p_b$  = unit load, psi
- $p_s$  = oil supply pressure, psi
- $P_f$  = friction horsepower
- $P'$  = bearing pressure parameter
- $q$  = flow factor
- $Q_1$  = hydrodynamic flow, gpm
- $Q_2$  = pressure flow, gpm
- $Q$  = total flow, gpm
- $Q_{new}$  = new total flow, gpm
- $Q_R$  = total flow required, gpm

- $r$  = journal radius, inches  
 $\Delta t$  = actual temperature rise of oil in bearing, °F  
 $\Delta t_a$  = assumed temperature rise of oil in bearing, °F  
 $\Delta t_{new}$  = new assumed temperature rise of oil in bearing, °F  
 $t_b$  = bearing operating temperature, °F  
 $t_{in}$  = oil inlet temperature, °F  
 $T_f$  = friction torque, inch-pounds/inch  
 $T'$  = torque parameter  
 $W$  = load, pounds  
 $X$  = factor  
 $Z$  = viscosity, centipoises  
 $\epsilon$  = eccentricity ratio — ratio of eccentricity to radial clearance  
 $\alpha$  = oil density, lbs/inch<sup>3</sup>

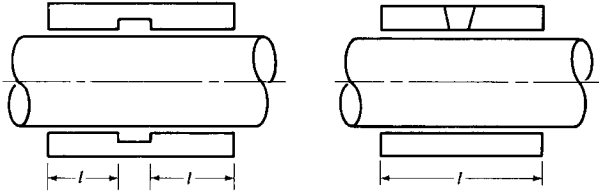


Fig. 5. Length,  $l$ , of bearing for circular groove type (left) and single inlet hole type (right).

**Journal Bearing Lubrication Analysis.**—The following procedure leads to a complete lubrication analysis which forms the basis for the bearing design.

1) *Diameter of bearing  $d$* : This is usually determined by considering strength and/or deflection requirements for the shaft using principles of strength of materials.

2) *Length of bearing  $L$* : This is determined by an assumed  $l/d$  ratio in which  $l$  may or may not be equal to the overall length,  $L$  (See Step 6). Bearing pressure and the possibility of edge loading due to shaft deflection and misalignment are factors to be considered. In general, shaft misalignment resulting from location tolerances and/or shaft deflections should be maintained below 0.0003 inch per inch of length.

3) *Bearing pressure  $p_b$* : The unit load in pound per square inch is calculated from the formula:

$$p_b = \frac{W}{Kld}$$

where  $K = 1$  for single oil hole

$K = 2$  for central groove

$W$  = load, pounds

$l$  = bearing length as defined in Fig. 5, inches

$d$  = journal diameter, inches

Typical unit loads in service are shown in Table 5. These pressures can be used as a safe guide in selection. However, if space limitations impose a higher limit of loading, the complete lubrication analysis and evaluation of material properties will determine acceptability.

**Table 5. Allowable Sleeve Bearing Pressures for Various Classes of Bearings**

| Types of Bearing or Kind of Service           | Pressure <sup>a</sup><br>psi | Types of Bearing or Kind of Service | Pressure <sup>a</sup><br>psi |
|---|------------------------------|-------------------------------------|------------------------------|
| Electric Motor & Generator Bearings (General) | 100–200                      | Diesel Engine Rod                   | 1000–2000                    |
| Turbine & Reduction Gears                     | 100–250                      | Wrist Pins                          | 1800–2000                    |
| Heavy Line Shafting                           | 100–150                      | Automotive, Main Bearings           | 500–700                      |
| Locomotive Axles                              | 300–350                      | Automotive, Rod Bearings            | 1500–2500                    |
| Light Line Shafting                           | 15–35                        | Centrifugal Pumps                   | 80–100                       |
| Diesel Engine, Main                           | 800–1500                     | Aircraft Rod Bearings               | 700–3000                     |

<sup>a</sup>These pressures in pounds per square inch of area equal to length times diameter are intended as a general guide only. The allowable unit pressure depends upon operating conditions, especially in regard to lubrication, design of bearings, workmanship, velocity, and nature of load.

4) *Diametral clearance  $c_d$* : This is selected on a trial basis from Fig. 6 which shows suggested diametral clearance ranges for various shaft sizes and for two speed ranges. These are *hot* or *operating* clearances so that thermal expansion of journal and bearing to these temperatures must be taken into consideration in establishing machining dimensions. The optimum operating clearance should be determined on the basis of a complete lubrication analysis (See paragraph following Step (23)).

5) *Clearance modulus  $m$* : This is calculated from the formula:  $m = \frac{c_d}{d}$

6) *Length to diameter ratio  $l/d$* : This is usually between 1 and 2; however, with the modern trend toward higher speeds and more compact units, lower ratios down to 0.3 are used. In shorter bearings there is a consequent reduction in load carrying capacity due to excessive end or side leakage of lubricant. In longer bearings there may be a tendency towards edge loading. Length  $l$  for a single oil feed hole is taken as the total length of the bearing as shown in Fig. 5. For a central oil groove length,  $l$  is taken as one-half the total length.

Typical  $l/d$  ratio's use for various types of applications are given in Table 6.

7) *Assumed operating temperature  $t_b$* : A temperature rise of the lubricant as it passes through the bearing is assumed and the consequent operating temperature in degrees F is calculated from the formula:

$$t_b = t_{in} + \Delta t_a$$

where  $t_{in}$  = inlet temperature of oil in °F

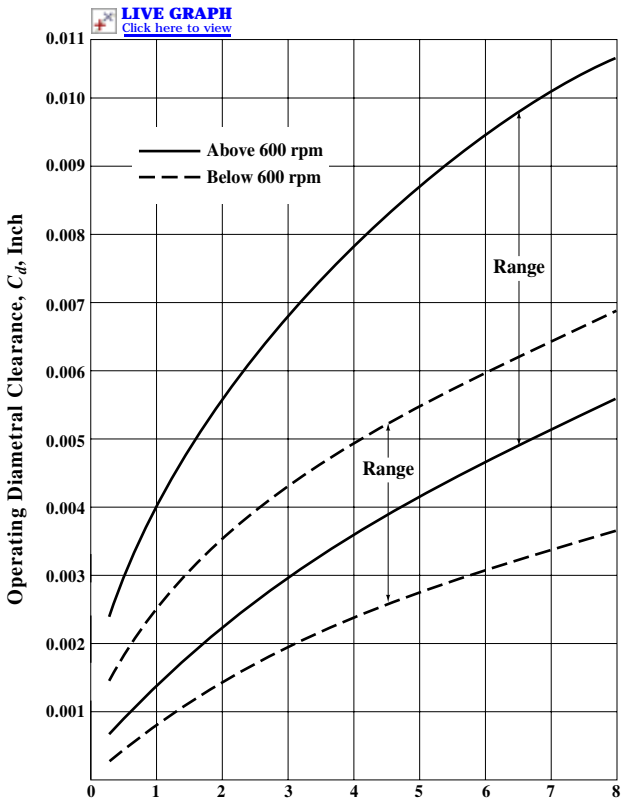
$\Delta t_a$  = assumed temperature rise of oil in bearing in °F. An initial assumption of 20°F is usually made.

8) *Viscosity of lubricant  $Z$* : The viscosity in centipoises at the assumed bearing operating temperature is found from the curve in Fig. 6 which shows the viscosity of SAE grade oils versus temperature.

9) *Bearing pressure parameter  $P'$* : This value is required to find the eccentricity ratio and is calculated from the formula:

$$P' = \frac{6.9(1000m)^2 p_b}{ZN}$$

where  $N$  = rpm



| Type of Service   | $l/d$      | Type of Service               | $l/d$      |
|---|------------|-------------------------------|------------|
| Gasoline and diesel engine<br>main bearings and crankpins | 0.3 to 1.0 | Light shafting                | 2.5 to 3.5 |
| Generators and motors                                     | 1.2 to 2.5 | Heavy shafting                | 2.0 to 3.0 |
| Turbogenerators   | 0.8 to 1.5 | Steam engine<br>Main bearings | 1.5 to 2.5 |
| Machine tools   | 2.0 to 3.0 | Crank and wrist pins          | 1.0 to 1.3 |

10) *Eccentricity ratio*  $\epsilon$ : Using  $P'$  and  $l/d$ , the value of  $1/(1 - \epsilon)$  is determined from Fig. 7 and from this,  $\epsilon$  can be determined.

11) *Torque parameter*  $T'$ : This value is obtained from Fig. 8 or Fig. 9 using  $1/(1 - \epsilon)$  and  $l/d$ .



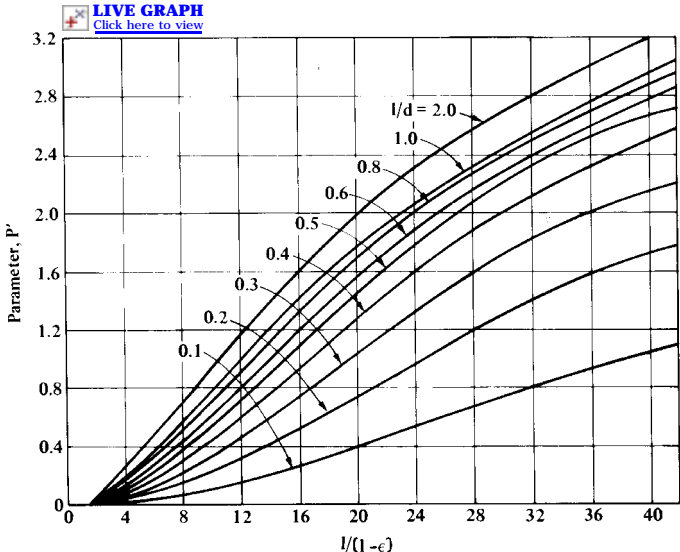


Fig. 7. Bearing parameter,  $P'$ , vs. eccentricity ratio,  $l/(1-\epsilon)$ —journal bearings.

12) *Friction torque*  $T$ : This value is calculated from the formula:

$$T = \frac{T' r^2 Z N}{6900(1000m)}$$

where  $r$  = journal radius, inches

13) *Friction horsepower*  $P_f$ : This value is calculated from the formula:

$$P_f = \frac{K T N l}{63,000}$$

where  $K = 1$  for single oil hole, 2 for central groove.

14) *Factor*  $X$ : This factor is used in the calculation of the lubricant flow and can either be obtained from [Table 7](#) or calculated from the formula:

$$X = 0.1837/\alpha c$$

where  $\alpha$  = oil density in pounds per cubic inch

$c$  = specific heat of lubricant in Btu/lb/°F

15) *Total flow of lubricant required*  $Q_R$ : This is calculated from the formula:

$$Q_R = \frac{X(P_f)}{\Delta t_a}$$

16) *Bearing capacity number*  $C_n$ : This value is needed to obtain the flow factor and is calculated from the formula:

$$C_n = \left(\frac{l}{d}\right)^2 / 60P'$$

17) *Flow factor*  $q$ : This value is obtained from the curve in [Fig. 10](#).

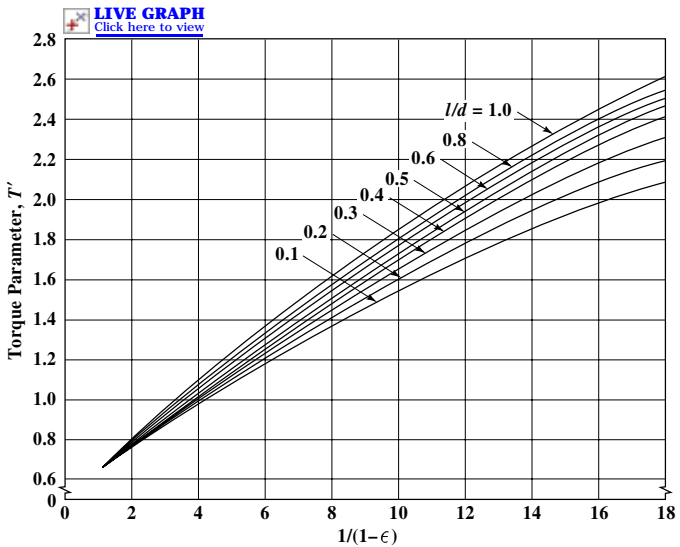


Fig. 8. Torque parameter,  $T'$ , vs. eccentricity ratio,  $1/(1-\epsilon)$  — journal bearings.

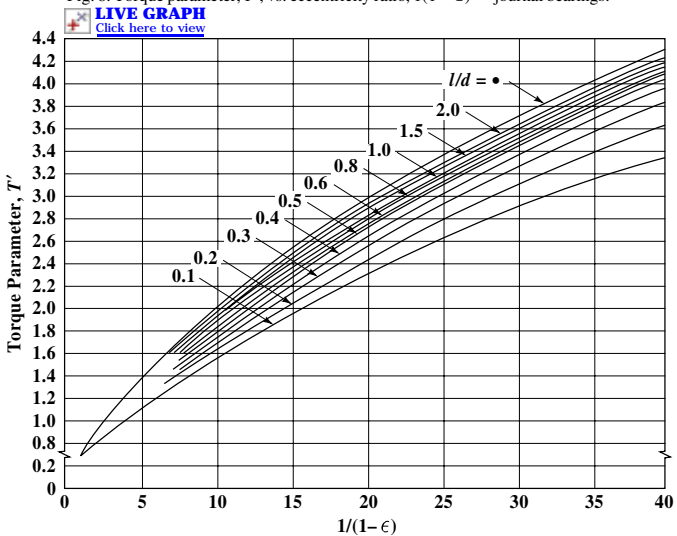
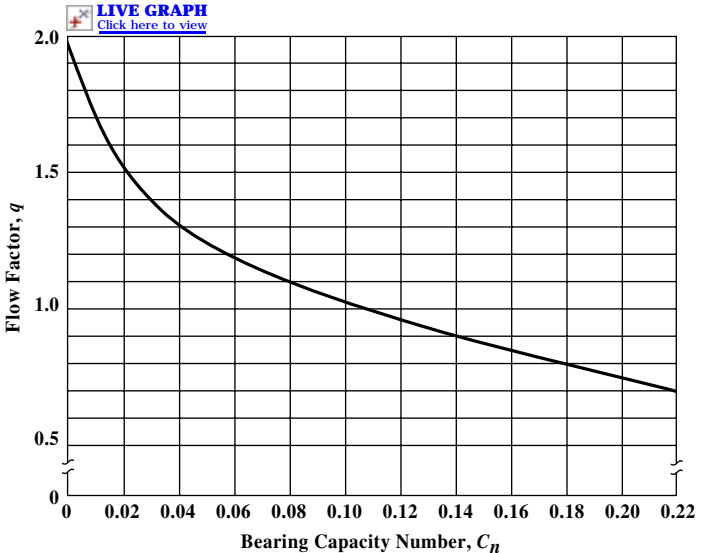


Fig. 9. Torque parameter,  $T'$ , vs. eccentricity ratio,  $1/(1-\epsilon)$  — journal bearings.

**Table 7. X Factor vs. Temperature of Mineral Oils**

| Temperature | X Factor |
|-------------|----------|
| 100         | 12.9     |
| 150         | 12.4     |
| 200         | 12.1     |
| 250         | 11.8     |
| 300         | 11.5     |

Fig. 10. Flow factor,  $q$ , vs. bearing capacity number,  $C_n$ —journal bearings.

18) *Hydrodynamic flow of lubricant  $Q_1$* : This flow in gallons per minute is calculated from the formula:

$$Q_1 = \frac{Nlc_dqd}{294}$$

19) *Pressure flow of lubricant  $Q_2$* : This flow in gallons per minute is calculated from the formula:

$$Q_2 = \frac{Kp_s c_d^3 d(1 + 1.5\epsilon^2)}{Zl}$$

where  $K = 1.64 \times 10^5$  for single oil hole

$K = 2.35 \times 10^5$  for central groove

$p_s$  = oil supply pressure

20) *Total flow of lubricant  $Q$* : This value is obtained by adding the hydrodynamic flow and the pressure flow.

$$Q = Q_1 + Q_2$$

21) *Bearing temperature rise  $\Delta t$* : This temperature rise in degrees F is obtained from the formula:

$$\Delta t = \frac{X(P_f)}{Q}$$

22) *Comparison of actual and assumed temperature rises*: At this point if  $\Delta t_a$  and  $\Delta t$  differ by more than 5 degrees F, Steps 7 through 22 are repeated using a  $\Delta t_{new}$  halfway between the former  $\Delta t_a$  and  $\Delta t$ .

23) *Minimum film thickness  $h_o$* : When Step 22 has been satisfied, the minimum film thickness in inches is calculated from the formula:  $h_o = \frac{1}{2}C_d(1 - \epsilon)$ .

A new diametral clearance  $c_d$  is now assumed and Steps 5 through 23 are repeated. When this repetition has been done for a sufficient number of values for  $c_d$ , the full lubrication study is plotted as shown in Fig. 11. From this chart a working range of diametral clearance can be determined that optimizes film thickness, differential temperature, friction horsepower and oil flow.

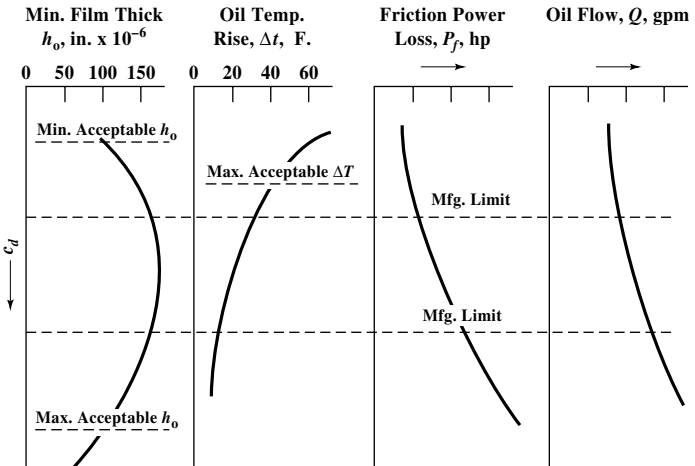


Fig. 11. Example of lubrication analysis curves for journal bearing.

**Use of Lubrication Analysis.**—Once the lubrication analysis has been completed and plotted as shown in Fig. 11, the following steps lead to the optimum bearing design, taking into consideration both basic operating requirements and requirements peculiar to the application.

1) Examine the curve (Fig. 11) for minimum film thickness and determine the acceptable range of diametral clearance,  $c_d$ , based on

- a) a minimum of  $200 \times 10^{-6}$  inches for small bearings under 1 inch diameter
- b) a minimum of  $500 \times 10^{-6}$  inches for bearings from 1 to 4 inches diameter
- c) a minimum of  $750 \times 10^{-6}$  inches for larger bearings.

More conservative designs would increase these requirements

2) Determine the minimum acceptable  $c_d$  based on a maximum  $\Delta t$  of 40°F from the oil temperature rise curve (Fig. 11).

3) If there are no requirements for maintaining low friction horsepower and oil flow, the possible limits of diametral clearance are now defined.

4) The required manufacturing tolerances can now be placed within this band to optimize  $h_o$  as shown by Fig. 11.

5) If oil flow and power loss are a consideration, the manufacturing tolerances may then be shifted, within the range permitted by the requirements for  $h_o$  and  $\Delta t$ .

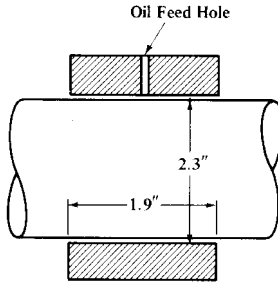


Fig. 12. Full journal bearing example design.

*Example:* A full journal bearing, Fig. 12, 2.3 inches in diameter and 1.9 inches long is to carry a load of 6000 pounds at 4800 rpm, using SAE 30 oil supplied at 200°F through a single oil hole at 30 psi. Determine the operating characteristics of this bearing as a function of diametral clearance.

1) *Diameter of bearing*, given as 2.3 inches.

2) *Length of bearing*, given as 1.9 inches.

3) *Bearing pressure:*

$$p_b = \frac{6000}{1 \times 1.9 \times 2.3} = 1372 \text{ lbs. per sq. in.}$$

4) *Diametral clearance:* Assume  $c_d$  is equal to 0.003 inch from Fig. 6 on page 2235 for first calculation.

5) *Clearance modulus:*  $m = \frac{0.003}{2.3} = 0.0013$  inch

6) *Length-to-diameter ratio:*

$$\frac{l}{d} = \frac{1.9}{2.3} = 0.83$$

7) *Assumed operating temperature:* If the temperature rise  $\Delta t_a$  is assumed to be 20°F,

$$t_b = 200 + 20 = 220^\circ\text{F}$$

8) *Viscosity of lubricant:* From Fig. 6 on page 2228,  $Z = 7.7$  centipoises

9) *Bearing-pressure parameter:*

$$P' = \frac{6.9 \times 1.3^2 \times 1372}{7.7 \times 4800} = 0.43$$

10) *Eccentricity ratio:* From Fig. 7,  $\frac{1}{1 - \epsilon} = 6.8$  and  $\epsilon = 0.85$

11) *Torque parameter:* From Fig. 8,  $T' = 1.46$

12) *Friction torque:*

$$T_f = \frac{1.46 \times 1.15^2 \times 7.7 \times 4800}{6900 \times 1.3} = 7.96 \text{ inch-pounds per inch}$$

13) Friction horsepower:

$$P_f = \frac{1 \times 7.96 \times 4800 \times 1.9}{63,000} = 1.15 \text{ horsepower}$$

14) Factor X: From Table 7,  $X = 12$ , approximately

15) Total flow of lubricant required:

$$Q_R = \frac{12 \times 1.15}{20} = 0.69 \text{ gallon per minute}$$

16) Bearing-capacity number:

$$C_n = \frac{0.83^2}{60 \times 0.43} = 0.027$$

17) Flow factor: From Fig. 10,  $q = 1.43$

18) Actual hydrodynamic flow of lubricant:

$$Q_1 = \frac{4800 \times 1.9 \times 0.003 \times 1.43 \times 2.3}{294} = 0.306 \text{ gallon per minute}$$

19) Actual pressure flow of lubricant:

$$Q_2 = \frac{1.64 \times 10^5 \times 30 \times 0.003^3 \times 2.3 \times (1 + 1.5 \times 0.85^2)}{7.7 \times 1.9} = 0.044 \text{ gallon per min}$$

20) Actual total flow of lubricant:

$$Q = 0.306 + 0.044 = 0.350 \text{ gallon per minute}$$

21) Actual bearing-temperature rise:

$$\Delta t = \frac{12 \times 1.15}{0.350} = 39.4^\circ\text{F}$$

22) Comparison of actual and assumed temperature rises: Because  $\Delta t_a$  and  $\Delta t$  differ by more than  $5^\circ\text{F}$ , a new  $\Delta t_a$ , midway between these two, of  $30^\circ\text{F}$  is assumed and Steps 7 through 22 are repeated.

7a) Assumed operating temperature:

$$t_b = 200 + 30 = 230^\circ\text{F}$$

8a) Viscosity of lubricant: From Fig. 6,  $Z = 6.8$  centipoises

9a) Bearing-pressure parameter:

$$P' = \frac{6.9 \times 1.3^2 \times 1372}{6.8 \times 4800} = 0.49$$

10a) Eccentricity ratio: From Fig. 7,

$$\frac{1}{1 - \epsilon} = 7.4$$

and  $\epsilon = 0.86$

11a) Torque parameter: From Fig. 8,  $T' = 1.53$

12a) Friction torque:

$$T_f = \frac{1.53 \times 1.15^2 \times 6.8 \times 4800}{6900 \times 1.3} = 7.36 \text{ inch-pounds per inch}$$

13a) Friction horsepower:

$$P_f = \frac{1 \times 7.36 \times 4800 \times 1.9}{63,000} = 1.07 \text{ horsepower}$$

14a) Factor X: From Table 7,  $X = 11.9$  approximately

15a) Total flow of lubricant required:

$$Q_R = \frac{11.9 \times 1.07}{30} = 0.42 \text{ gallon per minute}$$

16a) *Bearing-capacity number:*

$$C_n = \frac{0.83^2}{60 \times 0.49} = 0.023$$

17a) *Flow factor:* From Fig. 10,  $q = 1.48$

18a) *Actual hydrodynamic flow of lubricant:*

$$Q_1 = \frac{4800 \times 1.9 \times 0.003 \times 1.48 \times 2.3}{294} = 0.317 \text{ gallon per minute}$$

19a) *Pressure flow:*

$$Q_2 = \frac{1.64 \times 10^5 \times 30 \times 0.003^3 \times 2.3 \times (1 + 1.5 \times 0.86^2)}{6.8 \times 1.9} = 0.050 \text{ gallon per minute}$$

20a) *Actual flow of lubricant:*

$$Q_{\text{new}} = 0.317 + 0.050 = 0.367 \text{ gallon per minute}$$

21a) *Actual bearing-temperature rise:*

$$\Delta t = \frac{11.9 \times 1.06}{0.367} = 34.4^\circ\text{F}$$

22a) *Comparison of actual and assumed temperature rises:* Now  $\Delta t$  and  $\Delta t_a$  are within 5 degrees F.

23) *Minimum film thickness:*

$$h_o = \frac{0.003}{2}(1 - 0.86) = 0.00021 \text{ inch}$$

This analysis may now be repeated for other values of  $c_d$  determined from Fig. 6 and a complete lubrication analysis performed and plotted as shown in Fig. 11. An operating range for  $c_d$  can then be determined to optimize minimum clearance, friction horsepower loss, lubricant flow, and temperature rise.

### Thrust Bearings

As the name implies, thrust bearings are used either to absorb axial shaft loads or to position shafts axially. Brief descriptions of the normal designs for these bearings follow with approximate design methods for each. The generally accepted load ranges for these types of bearings are given in Table 1 and the schematic configurations are shown in Fig. 1.

*The parallel or flat plate thrust bearing* is probably the most frequently used type. It is the simplest and lowest in cost of those considered; however, it is also the least capable of absorbing load, as can be seen from Table 1. It is most generally used as a positioning device where loads are either light or occasional.

*The step bearing*, like the parallel plate, is also a relatively simple design. This type of bearing will accept the normal range of thrust loads and lends itself to low-cost, high-volume production. However, this type of bearing becomes sensitive to alignment as its size increases.

*The tapered land thrust bearing*, as shown in Table 1, is capable of high load capacity. Where the step bearing is generally used for small sizes, the tapered land type can be used in larger sizes. However, it is more costly to manufacture and does require good alignment as size is increased.

*The tilting pad or Kingsbury thrust bearing* (as it is commonly referred to) is also capable of high thrust capacity. Because of its construction it is more costly, but it has the inherent advantage of being able to absorb significant amounts of misalignment.

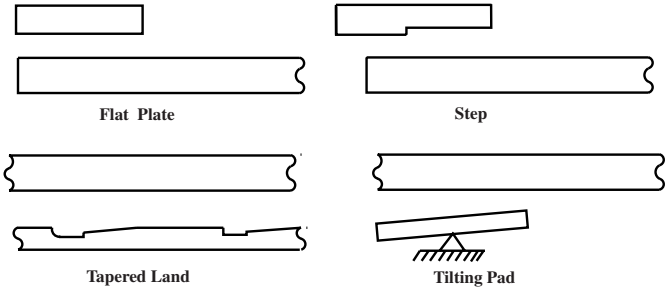


Fig. 1. Types of thrust bearings.

**Table 1. Thrust Bearing Loads\***

| Type             | Normal Unit Loads,<br>Lb per Sq. In. | Maximum Unit Loads,<br>Lb per Sq. In. |
|------------------|--------------------------------------|---------------------------------------|
| Parallel surface | <75                                  | <150                                  |
| Step             | 200                                  | 500                                   |
| Tapered land     | 200                                  | 500                                   |
| Tilting pad      | 200                                  | 500                                   |

**Thrust Bearing Design Notation.**—The symbols used in the design procedures that follow for flat plate, step, tapered land, and tilting pad thrust bearings are as follows:

$a$  = radial width of pad, inches

$b$  = circumferential length of pad at pitch line, inches

$b_2$  = pad step length

$B$  = circumference of pitch circle, inches

$c$  = specific heat of oil, Btu/gal/°F

$D$  = diameter, inches

$e$  = depth of step, inch

$f$  = coefficient of friction

$g$  = depth of 45° chamfer, inches

$h$  = film thickness, inch

$i$  = number of pads

$J$  = power loss coefficient

$K$  = film thickness factor

$K_g$  = fraction of circumference occupied by the pads; usually, 0.8

$l$  = length of chamfer, inches

$M$  = horsepower per square inch

$N$  = revolutions per minute

$O$  = operating number

$p$  = bearing unit load, psi

$p_s$  = oil-supply pressure, psi

$P_f$  = friction horsepower

$Q$  = total flow, gpm

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- $Q_c$  = required flow per chamfer, gpm  
 $Q_c^o$  = uncorrected required flow per chamfer, gpm  
 $Q_F$  = film flow, gpm  
 $s$  = oil-groove width  
 $\Delta t$  = temperature rise, °F  
 $U$  = velocity, feet per minute  
 $V$  = effective width-to-length ratio for one pad  
 $W$  = applied load, pounds  
 $Y_G$  = oil-flow factor  
 $Y_L$  = leakage factor  
 $Y_S$  = shape factor  
 $Z$  = viscosity, centipoises  
 $\alpha$  = dimensionless film-thickness factor  
 $\delta$  = taper  
 $\xi$  = kinetic energy correction factor

*Note:* In the following, subscript 1 denotes inside diameter and subscript 2 denotes outside diameter. Subscript  $i$  denotes inlet and subscript  $o$  denotes outlet.

**Flat Plate Thrust Bearing Design.**—The following steps define the performance of a flat plate thrust bearing, one section of which is shown in Fig. 2. Although each bearing section is wedge shaped, as shown below right, for the purposes of design calculation, it is considered to be a rectangle with a length  $b$  equal to the circumferential length along the pitch line of the section being considered, and a width  $a$  equal to the difference in the external and internal radii.

*General Parameters:* a) From Table 1, the maximum unit load is between 75 and 100 pounds per square inch; and b) The outside diameter is usually between 1.5 and 2.5 times the inside diameter.

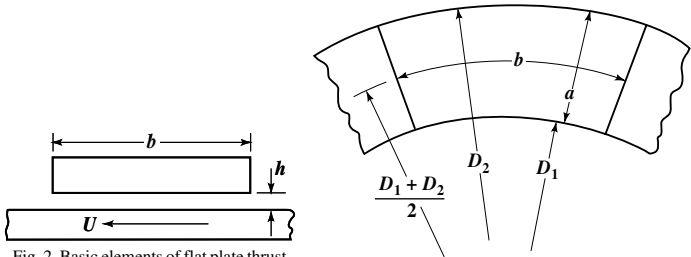


Fig. 2. Basic elements of flat plate thrust bearing.\*

Basic elements of flat plate thrust bearing.\*

- 1) *Inside diameter,  $D_1$ .* Determined by shaft size and clearance.
- 2) *Outside diameter,  $D_2$ .* Calculated by the formula

$$D_2 = \left( \frac{4W}{\pi K_g p} + D_1^2 \right)^{1/2}$$

where  $W$  = applied load, pounds

$K_g$  = fraction of circumference occupied by pads; usually, 0.8

$p$  = bearing unit load, psi

- 3) *Radial pad width,  $a$ .* Equal to one-half the difference between the inside and outside diameters.

$$a = \frac{D_2 - D_1}{2}$$

4) *Pitch line circumference, B.* Found from the pitch diameter.

$$B = \pi(D_2 - a)$$

5) *Number of pads, i.* Assume an oil groove width,  $s$ . If the length of pad is assumed to be optimum, i.e., equal to its width,

$$i_{\text{app}} = \frac{B}{a + s}$$

Take  $i$  as nearest even number.

6) *Length of pad, b.* If number of pads and oil groove width are known,

$$b = \frac{B - (i \times s)}{i}$$

7) *Actual unit load, p.* Calculated in pounds per square inch based on pad dimensions.

$$p = \frac{W}{iab}$$

8) *Pitch line velocity, U.* Found in feet per minute from

$$U = \frac{BN}{12}$$

where  $N = \text{rpm}$

9) *Friction power loss,  $P_f$ .* Friction power loss is difficult to calculate for this type of bearing because there is no theoretical method of determining the operating film thickness. However, a good approximation can be made using Fig. 3. From this curve, the value of  $M$ , horsepower loss per square inch of bearing surface, can be obtained. The total power loss,  $P_f$ , is then calculated from

$$P_f = iabM$$

10) *Oil flow required, Q.* May be estimated in gallons per minute for a given temperature rise from

$$Q = \frac{42.4P_f}{c\Delta t}$$

where  $c = \text{specific heat of oil in Btu/gal/}^\circ\text{F}$

$\Delta t = \text{temperature rise of the oil in } ^\circ\text{F}$

Note: A  $\Delta t$  of  $50^\circ\text{F}$  is an acceptable maximum.

Because there is no theoretical method of predicting the minimum film thickness in this type of bearing, only an approximation, based on experience, of the film flow can be made. For this reason and based on practical experience, it is desirable to have a minimum of one-half of the desired oil flow pass through the chamfer.

11) *Film flow,  $Q_F$ .* Calculated in gallons per minute from

$$Q_F = \frac{(1.5)(10^5)iVh^3p_s}{Z_2}$$

where  $V = \text{effective width-to-length ratio for one pad, } a/b$

$Z_2 = \text{oil viscosity at outlet temperature}$

$h = \text{film thickness}$

Note: Because  $h$  cannot be calculated, use  $h = 0.002$  inch.

12) *Required flow per chamfer,  $Q_c$ .* Readily found from the formula

## THRUST BEARINGS

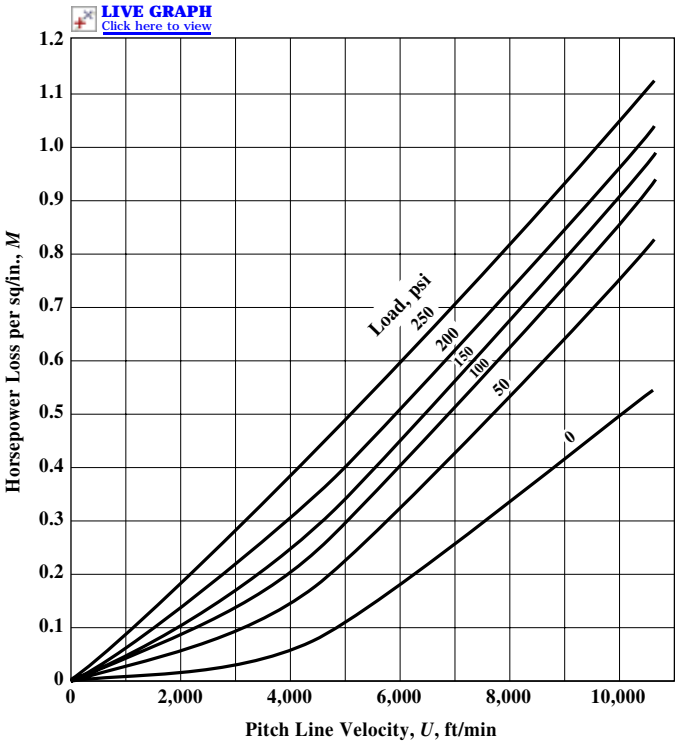


Fig. 3. Friction power loss,  $M$ , vs. peripheral speed,  $U$  — thrust bearings.<sup>a</sup>

<sup>a</sup> See footnote on page 2243.

$$Q_c = \frac{Q}{i}$$

13) *Kinetic energy correction factor*,  $\xi$ . Found by assuming a chamfer length  $l$  and entering Fig. 4 with a value  $Z_2 l$  and  $Q_c$ .

14) *Uncorrected required flow per chamfer*,  $Q_c^0$ . Found from the formula

$$Q_c^0 = \frac{Q_c}{\xi}$$

15) *Depth of chamfer*,  $g$ . Found from the formula

$$g = \sqrt[4]{\frac{Q_c^0 / Z_2}{4.74 \times 10^4 p_s}}$$

*Example:* Design a flat plate thrust bearing to carry 900 pounds load at 4000 rpm using an SAE 10 oil with a specific heat of 3.5 Btu/gal/°F at 120°F and 30-psi inlet conditions. The

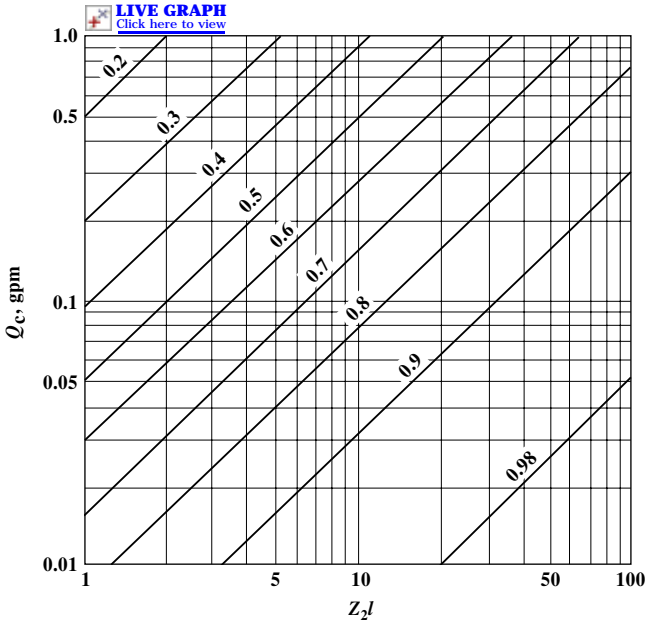


Fig. 4. Kinetic energy correction factor,  $\xi$ —thrust bearings.<sup>a</sup>

<sup>a</sup> See footnote on page 2243.

shaft is  $2\frac{3}{4}$  inches in diameter and the temperature rise is not to exceed 40°F. Fig. 5 shows the final design of this bearing.

1) *Inside diameter.* Assumed to be 3 inches to clear shaft.

2) *Outside diameter.* Assuming a unit bearing load of 75 pounds per square inch from Table 1,

$$D_2 = \sqrt{\frac{4 \times 900}{\pi \times 0.8 \times 75} + 3^2} = 5.30 \text{ inches}$$

Use  $5\frac{1}{2}$  inches.

3) *Radial pad width.*

$$a = \frac{5.5 - 3}{2} = 1.25 \text{ inches}$$

4) *Pitch-line circumference.*

$$B = \pi \times 4.25 = 13.35 \text{ inches}$$

5) *Number of pads.* Assume an oil groove width of  $\frac{3}{16}$  inch. If length of pad is assumed to be equal to width of pad, then

$$i_{\text{app}} = \frac{13.3}{1.25 + 0.1875} = 9+$$

If the number of pads,  $i$ , is taken as 10, then

## THRUST BEARINGS

$$6) \text{ Length of pad. } b = \frac{13.35 - (10 \times 0.1875)}{10} = 1.14 \text{ inches}$$

7) *Actual unit load.*

$$p = \frac{900}{10 \times 1.25 \times 1.14} = 63 \text{ psi}$$

8) *Pitch-line velocity.*

$$U = \frac{13.35 \times 4000}{12} = 4,430 \text{ ft per min.}$$

9) *Friction power loss.* From Fig. 3,  $M = 0.19$

$$P_f = 10 \times 1.25 \times 1.14 \times 0.19 = 2.7 \text{ horsepower}$$

10) *Oil flow required.*

$$Q = \frac{42.4 \times 2.7}{3.5 \times 40} = 0.82 \text{ gallon per minute}$$

(Assuming a temperature rise of 40°F—the maximum allowable according to the given condition—then the assumed operating temperature will be 120°F + 40°F = 160°F and the oil viscosity  $Z_2$  is found from Fig. 6 to be 9.6 centipoises.)

11) *Film flow.*

$$Q_F = \frac{1.5 \times 10^5 \times 10 \times 1 \times 0.002^3 \times 30}{9.6} = 0.038 \text{ gpm}$$

Because 0.038 gpm is a very small part of the required flow of 0.82 gpm, the bulk of the flow must be carried through the chamfers.

12) *Required flow per chamfer.* Assume that all the oil flow is to be carried through the chamfers.

$$Q_c = \frac{0.82}{10} = 0.082 \text{ gpm}$$

13) *Kinetic energy correction factor.* If  $l$ , the length of chamfer is made  $\frac{1}{8}$  inch, then  $Z_2 l = 9.6 \times \frac{1}{8} = 1.2$ . Entering Fig. 4 with this value and  $Q_c = 0.082$ ,

$$\xi = 0.44$$

14) *Uncorrected required oil flow per chamfer.*

$$Q_c^0 = \frac{0.082}{0.44} = 0.186 \text{ gpm}$$

15) *Depth of chamfer.*

$$g = 4 \sqrt[4]{\frac{0.186 \times 0.125 \times 9.6}{4.74 \times 10^4 \times 30}}$$

$$g = 0.02 \text{ inch}$$

A schematic drawing of this bearing is shown in Fig. 5.

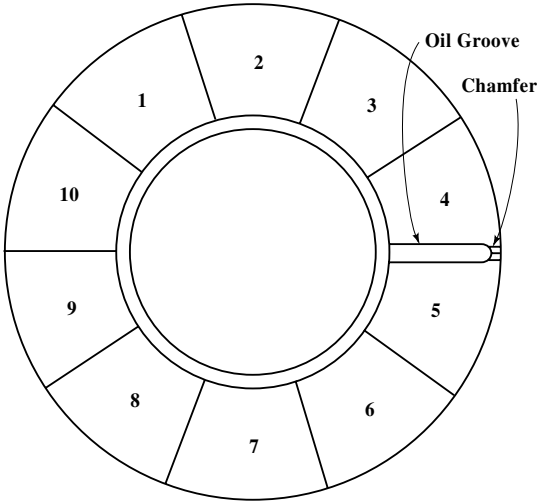


Fig. 5. Flat plate thrust bearing example design.\*

**Step Thrust Bearing Design.**—The following steps define the performance of a step thrust bearing, one section of which is shown in Fig. 6.

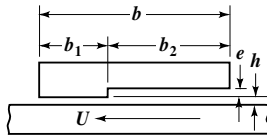


Fig. 6. Basic elements of step thrust bearing.\*

Although each bearing section is wedge shaped, as shown at the right in Fig. 6, for the purposes of design calculation it is considered to be a rectangle with a length  $b$  equal to the circumferential length along the pitch line of the section being considered, and a width  $a$  equal to the difference in the external and internal radii.

*General Parameters:* For optimum proportions,  $a = b$ ,  $b_2 = 1.2b_1$ , and  $e = 0.7h$ .

1) *Internal diameter,  $D_1$ .* An internal diameter is assumed that is sufficient to clear the shaft.

2) *External diameter,  $D_2$ .* A unit bearing pressure is assumed from Table 1 and the external diameter is then found from the formula

$$D_2 = \sqrt{\frac{4W}{\pi K_g p} + D_1^2}$$

3) *Radial pad width,  $a$ .* Equal to the difference between the external and internal radii.

$$a = \frac{D_2 - D_1}{2}$$

\* See footnote on page 2243.

4) *Pitch-line circumference, B.* Found from the formula

$$B = \frac{\pi(D_1 + D_2)}{2}$$

5) *Number of pads, i.* Assume an oil groove width,  $s$  (0.062 inch may be taken as a minimum), and find the approximate number of pads, assuming the pad length is equal to  $a$ . Note that if a chamfer is found necessary to increase the oil flow (see Step 13), the oil groove width should be greater than the chamfer width.

$$i_{\text{app}} = \frac{B}{a + s}$$

Then  $i$  is taken as the nearest even number.

6) *Length of pad, b.* Readily determined from the number of pads and groove width.

$$b = \frac{B}{i} - s$$

7) *Pitch-line velocity, U.* Found in feet per minute from the formula  $U = \frac{BN}{12}$

8) *Film thickness, h.* Found in inches from the formula

$$h = \sqrt[4]{\frac{2.09 \times 10^{-9} i a^3 U Z}{W}}$$

9) *Depth of step, e.* According to the general parameter

$$e = 0.7h$$

10) *Friction power loss, P<sub>f</sub>.* Found from the formula

$$P_f = \frac{7.35 \times 10^{-13} i a^2 U^2 Z}{h}$$

11) *Pad step length, b<sub>2</sub>.* This distance, on the pitch line, from the leading edge of the pad to the step in inches is determined by the general parameters

$$b_2 = \frac{1.2b}{2.2}$$

12) *Hydrodynamic oil flow, Q.* Found in gallons per minute from the formula

$$Q = 6.65 \times 10^{-4} i a h U$$

13) *Temperature rise, Δt.* Found in degrees F from the formula

$$\Delta t = \frac{42.4 P_f}{c Q}$$

If the flow is insufficient, as indicated by too high a temperature rise, chamfers can be added to provide adequate flow as in Steps 12–15 of the flat plate thrust bearing design.

*Example:* Design a step thrust bearing for positioning a  $\frac{7}{8}$ -inch diameter shaft operating with a 25-pound thrust load and a speed of 5,000 rpm. The lubricating oil has a viscosity of 25 centipoises at the operating temperature of 160 deg. F and has a specific heat of 3.4 Btu per gal. per deg. F.

1) *Internal diameter.* Assumed to be 1 inch to clear the shaft.

2) *External diameter.* Because the example is a positioning bearing with low total load, unit load will be negligible and the external diameter is not established by using the formula given in Step 2 of the procedure, but a convenient size is taken to give the desired overall bearing proportions.

$$D_2 = 3 \text{ inches}$$

3) *Radial pad width.*

$$a = \frac{3-1}{2} = 1 \text{ inch}$$

4) *Pitch-line circumference.*

$$B = \frac{\pi(3+1)}{2} = 6.28 \text{ inches}$$

5) *Number of pads.* Assuming a minimum groove width of 0.062 inch,

$$i_{\text{app}} = \frac{6.28}{1+0.062} = 5.9$$

Take  $i = 6$ .

6) *Length of pad.*

$$b = \frac{6.28}{6} - 0.062 = 0.985$$

7) *Pitch-line velocity.*

$$U = \frac{6.28 \times 5,000}{12} = 2,620 \text{ fpm}$$

8) *Film thickness.*

$$h = \sqrt{\frac{2.09 \times 10^{-9} \times 6 \times 1^3 \times 2,620 \times 25}{25}} = 0.0057 \text{ inch}$$

9) *Depth of step.*

$$e = 0.7 \times 0.0057 = 0.004 \text{ inch}$$

10) *Power loss.*

$$P_f = \frac{7.35 \times 10^{-13} \times 6 \times 1^2 \times 2,620^2 \times 25}{0.0057} = 0.133 \text{ hp}$$

11) *Pad step length.*

$$b_2 = \frac{1.2 \times 0.985}{2.2} = 0.537 \text{ inch}$$

12) *Total hydrodynamic oil flow.*

$$Q = 6.65 \times 10^{-4} \times 6 \times 1 \times 0.0057 \times 2,620 = 0.060 \text{ gpm}$$

13) *Temperature rise.*

$$\Delta t = \frac{42.4 \times 0.133}{3.4 \times 0.060} = 28^\circ \text{ F}$$

**Tapered Land Thrust Bearing Design.**—The following steps define the performance of a tapered land thrust bearing, one section of which is shown in Fig. 7. Although each bearing section is wedge shaped, as shown in Fig. 7, right, for the purposes of design calculation, it is considered to be a rectangle with a length  $b$  equal to the circumferential length along the pitch line of the section being considered and a width  $a$  equal to the difference in the external and internal radii.

*General Parameters:* Usually, the taper extends to only 80 per cent of the pad length with the remainder being flat, thus:  $b_2 = 0.8b$  and  $b_1 = 0.2b$ .



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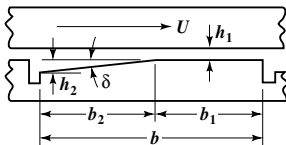


Fig. 7. Basic elements of tapered land thrust bearing.\*

- 1) *Inside diameter,  $D_1$* . Determined by shaft size and clearance.
- 2) *Outside diameter,  $D_2$* . Calculated by the formula

$$D_2 = \left( \frac{4W}{\pi K_g P_a} + D_1^2 \right)^{1/2}$$

where  $K_g = 0.8$  or  $0.9$  and  $W =$  applied load, pounds

$P_a =$  assumed unit load from Table 1, page 2243

- 3) *Radial pad width,  $a$* . Equal to one-half the difference between the inside and outside diameters.

$$a = \frac{D_2 - D_1}{2}$$

- 4) *Pitch-line circumference,  $B$* . Found from the mean diameter:

$$B = \frac{\pi(D_1 + D_2)}{2}$$

- 5) *Number of pads,  $i$* . Assume an oil groove width,  $s$ , and find the approximate number of pads, assuming the pad length is equal to  $a$ .

$$i_{\text{app}} = \frac{B}{a + s}$$

Then  $i$  is taken as the nearest even number.

- 6) *Length of pad,  $b$* . Readily determined because the number of pads and groove width are known.

$$b = \frac{B - is}{i}$$

- 7) *Taper values,  $\delta_1$  and  $\delta_2$* . Can be taken from Table 2.

- 8) *Actual bearing unit load,  $p$* . Calculated in pounds per square inch from the formula

$$p = \frac{W}{iab}$$

- 9) *Pitch-line velocity,  $U$* . Found in feet per minute at the pitch circle from the formula

$$U = \frac{BN}{12}$$

where  $N =$  rpm

- 10) *Oil leakage factor,  $Y_L$* . Found either from Fig. 8 which shows curves for  $Y_L$  as functions of the pad width  $a$  and length of land  $b$  or from the formula

$$Y_L = \frac{b}{1 + (\pi^2 b^2 / 12 a^2)}$$

- 11) *Film thickness factor,  $K$* . Calculated using the formula

$$K = \frac{5.75 \times 10^6 p}{UY_L Z}$$

\* See footnote on page 2243.

12) *Minimum film thickness,  $h$ .* Using the value of  $K$  just determined and the selected taper values  $\delta_1$  and  $\delta_2$ ,  $h$  is found from Fig. 9. In general,  $h$  should be 0.001 inch for small bearings and 0.002 inch for larger and high-speed bearings.

13) *Friction power loss,  $P_f$ .* Using the film thickness  $h$ , the coefficient  $J$  can be obtained from Fig. 10. The friction loss in horsepower is then calculated from the formula

$$P_f = 8.79 \times 10^{-13} iabJU^2Z$$

14) *Required oil flow,  $Q$ .* May be estimated in gallons per minute for a given temperature rise  $\Delta_t$  from the formula

$$Q = \frac{42.4P_f}{c\Delta t}$$

where  $c$  = specific heat of the oil in Btu/gal/°F

Note: A  $\Delta t$  of 50°F is an acceptable maximum.

15) *Shape factor,  $Y_s$ .* Needed to compute the actual oil flow and calculated from

$$Y_s = \frac{8ab}{D_2^2 - D_1^2}$$

16) *Oil flow factor,  $Y_G$ .* Found from Fig. 11 using  $Y_s$  and  $D_1/D_2$ .

17) *Actual oil film flow,  $Q_F$ .* The amount of oil in gallons per minute that the bearing film will pass is calculated from the formula

$$Q_F = \frac{8.9 \times 10^{-4} i \delta_2 D_2^3 N Y_G Y_s^2}{D_2 - D_1}$$

18) If the flow is insufficient, the tapers can be increased or chamfers calculated to provide adequate flow, as in Steps 12–15 of the flat plate thrust bearing design procedure.

*Example:* Design a tapered land thrust bearing for 70,000 pounds at 3600 rpm. The shaft diameter is 6.5 inches. The oil inlet temperature is 110°F at 20 psi.

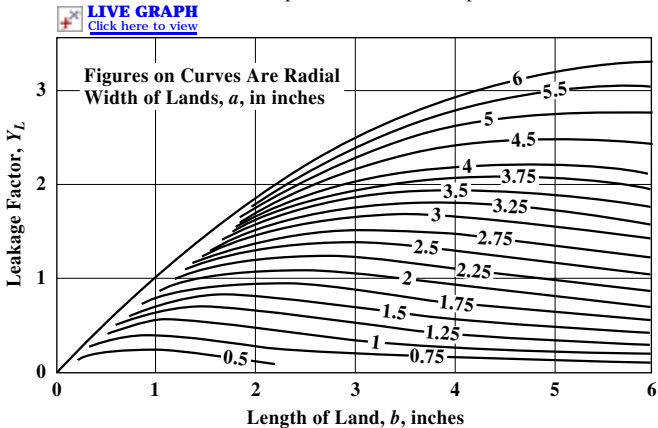


Fig. 8. Leakage factor,  $Y_L$ , vs. pad dimensions  $a$  and  $b$ —tapered land thrust bearings.\*

\* See footnote on page 2243.

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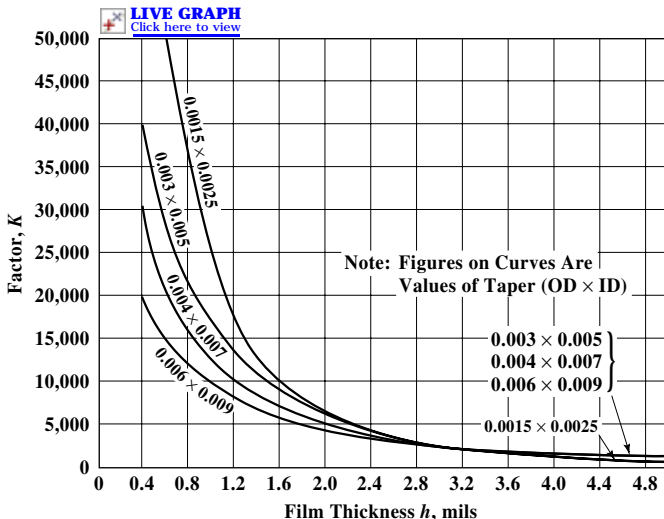


Fig. 9. Thickness,  $h$ , vs. factor  $K$ —tapered land thrust bearings.\*

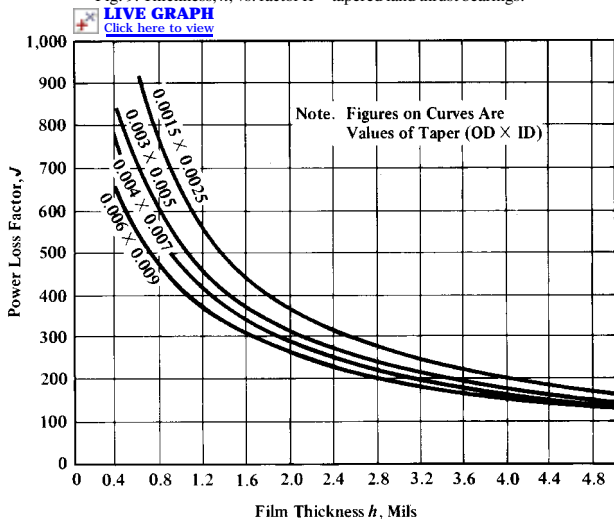


Fig. 10. Power-loss coefficient,  $J$ , vs. film thickness,  $h$ —tapered land thrust bearings.\*

A maximum temperature rise of 50°F is acceptable and results in a viscosity of 18 centipoises. Use values of  $K_g = 0.9$  and  $c = 3.5$  Btu/gal/°F.

\* See footnote on page 2243.

1) *Internal diameter.* Assume  $D_1 = 7$  inches to clear shaft.

2) *External diameter.* Assume a unit bearing load  $p_a$  of 400 pounds per square inch from Table 1, then

$$D_2 = \sqrt{\frac{4 \times 70,000}{3.14 \times 0.9 \times 400}} + 7^2 = 17.2 \text{ inches}$$

Round off to 17 inches.

3) *Radial pad width.*

$$a = \frac{17 - 7}{2} = 5 \text{ inches}$$

4) *Pitch-line circumference.*

$$B = \frac{3.14(17 + 7)}{2} = 37.7 \text{ inches}$$

5) *Number of pads.* Assume groove width of 0.5 inch, then

$$i_{\text{app}} = \frac{37.7}{5 + 0.5} = 6.85$$

Take  $i = 6$ .

6) *Length of pad.*

$$b = \frac{37.7 - 6 \times 0.5}{6} = 5.78 \text{ inches}$$

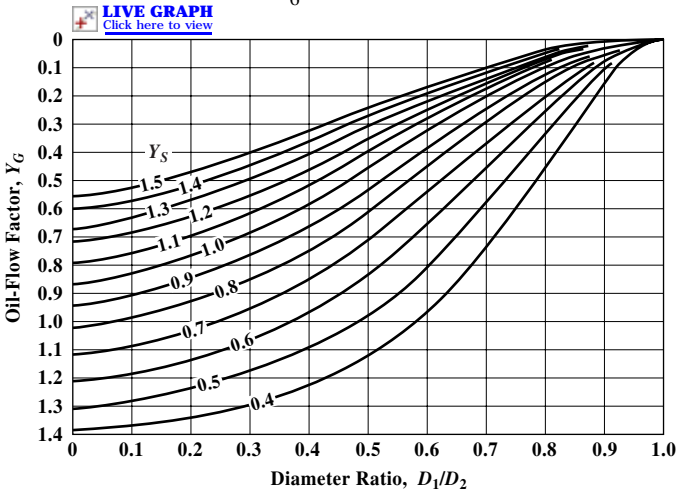


Fig. 11. Oil-flow factor,  $Y_G$ , vs. diameter ratio  $D_1/D_2$ —tapered land bearings.\*

7) *Taper values.* Interpolate in Table 2 to obtain

$$\delta_1 = 0.008 \text{ inch} \quad \text{and} \quad \delta_2 = 0.005 \text{ inch}$$

8) *Actual bearing unit load.*

$$p = \frac{70,000}{6 \times 5 \times 5.78} = 404 \text{ psi}$$

\* See footnote on page 2243.

9) *Pitch-line velocity.*

$$U = \frac{37.7 \times 3600}{12} = 11,300 \text{ ft per min}$$

10) *Oil leakage factor.*

$$\text{From Fig. 8, } Y_L = 2.75$$

11) *Film-thickness factor.*

$$K = \frac{5.75 \times 10^6 \times 404}{11,300 \times 2.75 \times 18} = 4150$$

12) *Minimum film thickness.*

$$\text{From Fig. 9, } h = 2.2 \text{ mils}$$

13) *Friction power loss.* From Fig. 10,  $J = 260$ , then

$$P_f = 8.79 \times 10^{-13} \times 6 \times 5 \times 5.78 \times 260 \times 11,300^2 \times 18 = 91 \text{ hp}$$

14) *Required oil flow.*

$$Q = \frac{42.4 \times 91}{3.5 \times 50} = 22.0 \text{ gpm}$$

See footnote on page 2243.

15) *Shape factor.*

$$Y_S = \frac{8 \times 5 \times 5.78}{17^2 - 7^2} = 0.963$$

16) *Oil-flow factor.*

$$\text{From Fig. 11, } Y_G = 0.61$$

where  $D_1/D_2 = 0.41$

17) *Actual oil film flow.*

$$Q_F = \frac{8.9 \times 10^{-4} \times 6 \times 0.005 \times 17^3 \times 3600 \times 0.61 \times 0.963^2}{17 - 7} = 26.7 \text{ gpm}$$

Because calculated film flow exceeds required oil flow, chamfers are not necessary. However, if film flow were less than required, suitable chamfers would be needed.

**Table 2. Taper Values for Tapered Land Thrust Bearings**

| Pad Dimensions, Inches           | Taper, Inch                    |                                |
|----------------------------------|--------------------------------|--------------------------------|
|                                  | $\delta_1 = h_2 - h_1$ (at ID) | $\delta_2 = h_2 - h_1$ (at OD) |
| $\frac{1}{2} \times \frac{1}{2}$ | 0.0025                         | 0.0015                         |
| $1 \times 1$                     | 0.005                          | 0.003                          |
| $3 \times 3$                     | 0.007                          | 0.004                          |
| $7 \times 7$                     | 0.009                          | 0.006                          |

**Tilting Pad Thrust Bearing Design.**—The following steps define the performance of a tilting pad thrust bearing, one section of which is shown in Fig. 12. Although each bearing section is wedge shaped, as shown at the right below, for the purposes of design calculation, it is considered to be a rectangle with a length  $b$  equal to the circumferential length along the pitch line of the section being considered and a width  $a$  equal to the difference in the external and internal radii, as shown at left in Fig. 12. The location of the pivot shown in Fig. 12 is optimum. If shaft rotation in both directions is required, however, the pivot must be at the midpoint, which results in little or no detrimental effect on the performance.

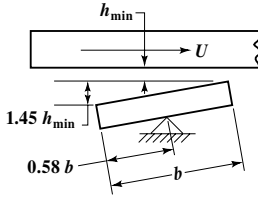


Fig. 12. Basic elements of tilting pad thrust bearing.\*

- 1) *Inside diameter,  $D_1$* . Determined by shaft size and clearance.
- 2) *Outside diameter,  $D_2$* . Calculated from the formula

$$D_2 = \left( \frac{4W}{\pi K_g p} + D_1^2 \right)^{1/2}$$

where  $W$  = applied load, pounds

$$K_g = 0.8$$

$p$  = unit load from Table 1

- 3) *Radial pad width,  $a$* . Equal to one-half the difference between the inside and outside diameters:

$$a = \frac{D_2 - D_1}{2}$$

- 4) *Pitch-line circumference,  $B$* . Found from the mean diameter:

$$B = \pi \left( \frac{D_1 + D_2}{2} \right)$$

- 5) *Number of pads,  $i$* . The number of pads may be estimated from the formula

$$i = \frac{BK_g}{a}$$

Select the nearest even number.

- 6) *Length of pad,  $b$* . Found from the formula

$$b \cong \frac{BK_g}{i}$$

- 7) *Pitch-line velocity,  $U$* . Calculated in feet per minute from the formula

$$U = \frac{BN}{12}$$

- 8) *Bearing unit load,  $p$* . Calculated from the formula

$$p = \frac{W}{iab}$$

- 9) *Operating number,  $O$* . Calculated from the formula

$$O = \frac{1.45 \times 10^{-7} Z_2 U}{5pb}$$

10) where  $Z_2$  = viscosity of oil at outlet temperature (inlet temperature plus assumed temperature rise through the bearing).

\* See footnote on page 2243.

11) *Minimum film thickness,  $h_{\min}$* . By using the operating number, the value of  $\alpha$  = dimensionless film thickness is found from Fig. 13. Then the actual minimum film thickness is calculated from the formula:

$$h_{\min} = \alpha b$$

In general, this value should be 0.001 inch for small bearings and 0.002 inch for larger and high-speed bearings.

12) *Coefficient of friction,  $f$* . Found from Fig. 14.

13) *Friction power loss,  $P_f$* . This horsepower loss now is calculated by the formula

$$P_f = \frac{fWU}{33,000}$$

14) *Actual oil flow,  $Q$* . This flow over the pad in gallons per minute is calculated from the formula

$$Q = 0.0591 \alpha i a b U$$

15) *Temperature rise,  $\Delta t$* . Found from the formula

$$\Delta t = 0.0217 \frac{f p}{\alpha c}$$

where  $c$  = specific heat of oil in Btu/gal/°F

If the flow is insufficient, as indicated by too high a temperature rise, chamfers can be added to provide adequate flow, as in Steps 12–15 of the flat plate thrust bearing design.

*Example:* Design a tilting pad thrust bearing for 70,000 pounds thrust at 3600 rpm. The shaft diameter is 6.5 inches and a maximum OD of 15 inches is available. The oil inlet temperature is 110°F and the supply pressure is 20 pounds per square inch. A maximum temperature rise of 50°F is acceptable and results in a viscosity of 18 centipoises. Use a value of 3.5 Btu/gal/°F for  $c$ .

1) *Inside diameter*. Assume  $D_1 = 7$  inches to clear shaft.

2) *Outside diameter*. Given maximum  $D_2 = 15$  inches.

3) *Radial pad width*.

$$a = \frac{15 - 7}{2} = 4 \text{ inches}$$

4) *Pitch-line circumference*.

$$B = \pi \left( \frac{7 + 15}{2} \right) = 34.6 \text{ inches}$$

5) *Number of pads*.

$$i = \frac{34.6 \times 0.8}{4} = 6.9$$

Select 6 pads:  $i = 6$ .

6) *Length of pad*.

$$b = \frac{34.6 \times 0.8}{6} = 4.61 \text{ inches}$$

Make  $b = 4.75$  inches.

7) *Pitch-line velocity*.

$$U = \frac{34.6 \times 3600}{12} = 10,400 \text{ ft/min}$$

8) *Bearing unit load*.

$$p = \frac{70,000}{6 \times 4 \times 4.75} = 614 \text{ psi}$$

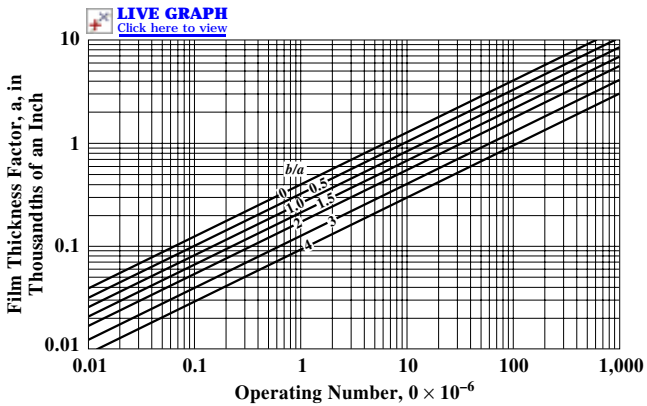


Fig. 13. Dimensionless minimum film thickness,  $\alpha$ , vs. operating number,  $O$ —tilting pad thrust bearings.\*

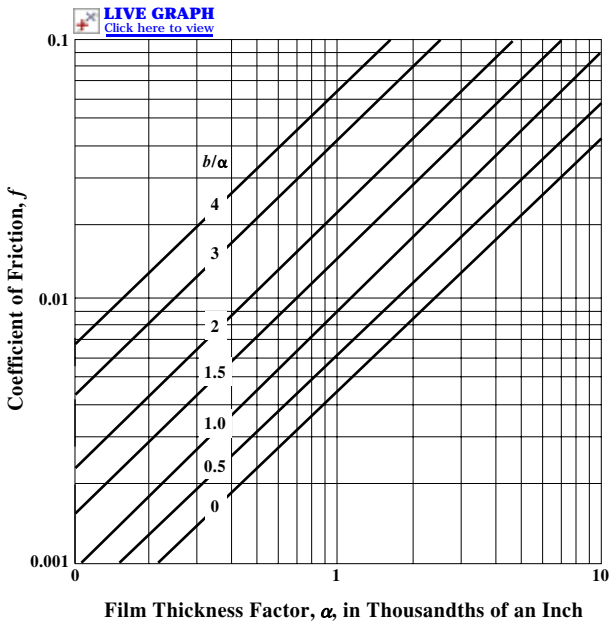


Fig. 14. Coefficient of friction  $f$  vs. dimensionless film thickness  $\alpha$  for tilting pad thrust bearings with optimum pivot location.\*

\* See footnote on page 2243.



9) *Operating number.*

$$O = \frac{1.45 \times 10^{-7} \times 18 \times 10,400}{5 \times 614 \times 4.75} = 1.86 \times 10^{-6}$$

10) *Minimum film thickness.* From Fig. 13,  $\alpha = 0.30 \times 10^{-3}$ .

$$h_{\min} = 0.00030 \times 4.75 = 0.0014 \text{ inch}$$

11) *Coefficient of friction.* From Fig. 14,  $f = 0.0036$ .

12) *Friction power loss.*

$$P_f = \frac{0.0036 \times 70,000 \times 10,400}{33,000} = 79.4 \text{ hp}$$

13) *Oil flow.*

$$Q = 0.0591 \times 6 \times 0.30 \times 10^{-3} \times 4 \times 4.75 \times 10,400 = 21.02 \text{ gpm}$$

14) *Temperature rise.*

$$\Delta t = \frac{0.0217 \times 0.0036 \times 614}{0.30 \times 10^{-3} \times 3.5} = 45.7^\circ \text{F}$$

Because this temperature is less than the 50°F, which is considered as the acceptable maximum, the design is satisfactory.

### Plain Bearing Materials

Materials used for sliding bearings cover a wide range of metals and nonmetals. To make the optimum selection requires a complete analysis of the specific application. The important general categories are: Babbitts, alkali-hardened lead, cadmium alloys, copper lead, aluminum bronze, silver, sintered metals, plastics, wood, rubber, and carbon graphite.

**Properties of Bearing Materials.**—For a material to be used as a plain bearing, it must possess certain physical and chemical properties that permit it to operate properly. If a material does not possess all of these characteristics to some degree, it will not function long as a bearing. It should be noted, however, that few, if any, materials are outstanding in all these characteristics. Therefore, the selection of the optimum bearing material for a given application is at best a compromise to secure the most desirable combination of properties required for that particular usage.

The seven properties generally acknowledged to be the most significant are: 1) Fatigue resistance; 2) Embeddability; 3) Compatibility; 4) Conformability; 5) Thermal conductivity; 6) Corrosion resistance; and 7) Load capacity.

These properties are described as follows:

1) *Fatigue resistance* is the ability of the bearing lining material to withstand repeated applications of stress and strain without cracking, flaking, or being destroyed by some other means.

2) *Embeddability* is the ability of the bearing lining material to absorb or embed within itself any of the larger of the small dirt particles present in a lubrication system. Poor embeddability permits particles circulating around the bearing to score both the bearing surface and the journal or shaft. Good embeddability will permit these particles to be trapped and forced into the bearing surface and out of the way where they can do no harm.

3) *Compatibility or antiscoring tendencies* permit the shaft and bearing to “get along” with each other. It is the ability to resist galling or seizing under conditions of metal-to-metal contact such as at startup. This characteristic is most truly a bearing property, because contact between the bearing and shaft in good designs occurs only at startup.

4) *Conformability* is defined as malleability or as the ability of the bearing material to creep or flow slightly under load, as in the initial stages of running, to permit the shaft and bearing contours to conform with each other or to compensate for nonuniform loading caused by misalignment.

**Table 3. Bearing and Bushing Alloys—Composition, Forms, Characteristics, and Applications SAE General Information**

| SAE No. and Alloy Grouping |     | Nominal Composition, Per cent          | Form of Use (1), Characteristics (2), and Applications (3)   |
|----------------------------|-----|--|--|
| Sn-Base Alloys             | 11  | Sn, 87.5; Sb, 6.75; Cu, 5.75           | (1) Cast on steel, bronze, or brass backs, or directly in the bearing housing. (2) Soft, corrosion-resistant with moderate fatigue resistance. (3) Main and connecting-rod bearings; motor bushings. Operates with either hard or soft journal.  |
|                            | 12  | Sn, 89; Sb, 7.5; Cu, 3.5               |  |
| Pb-Base Alloys             | 13  | Pb, 84; Sb, 10; Sn, 6                  | (1) SAE 13 and 14 are cast on steel, bronze, or brass, or in the bearing housing; SAE 15 is cast on steel; and SAE 16 is cast into and on a porous sintered matrix, usually copper-nickel bonded to steel. (2) Soft, moderately fatigue-resistant, corrosion-resistant. (3) Main and connecting-rod bearings. Operates with hard or soft journal with good finish.   |
|                            | 14  | Pb, 75; Sb, 15; Sn, 10                 |  |
|                            | 15  | Pb, 83; Sb, 15; Sn, 14; As, 1          |  |
| Pb-Sn Overlays             | 16  | Pb, 92; Sb, 3.5; Sn, 4.5               | (1) Electrodeposited as a thin layer on copper-lead or silver bearings faces. (2) Soft, corrosion-resistant. Bearings so coated run satisfactorily on soft shafts throughout the life of the coating. (3) Heavy-duty, high-speed main and connecting-rod bearings.   |
|                            | 19  | Pb, 90; Sn, 10                         |  |
| Cu-Pb Alloys               | 190 | Pb, 93; Sn, 7                          | (1) Cast or sintered on steel back with the exception of SAE 481, which is cast on steel back only. (2) Moderately hard. Somewhat subject to oil corrosion. Some oils minimize this; protection with overlay may be desirable. Fatigue resistance good to fairly good. Listed in order of decreasing hardness and fatigue resistance. (3) Main and connecting-rod bearings. The higher lead alloys can be used unplated against a soft shaft, although an overlay is helpful. The lower lead alloys may be used against a hard shaft, or with an overlay against a soft one. |
|                            | 49  | Cu, 76; Pb, 24                         |  |
|                            | 48  | Cu, 70; Pb, 30                         |  |
|                            | 480 | Cu, 65; Pb, 35                         |  |
| Cu-Pb-Sn-Alloys            | 481 | Cu, 60; Pb, 40                         | (1) Steel-backed and lined with a structure combining sintered copper alloy matrix with corrosion-resistant lead alloy. (2) Moderately hard. Corrosion resistance improved over copper-leads of equal lead content without tin. Fatigue resistance fairly good. Listed in order of decreasing hardness and fatigue resistance. (3) Main and connecting-rod bearings. Generally used without overlay. SAE 484 and 485 may be used with hard or soft shaft, and a hardened or cast shaft is recommended for SAE 482.   |
|                            | 482 | Cu, 67; Pb, 28; Sn, 5                  |  |
|                            | 484 | Cu, 55; Pb, 42; Sn, 3                  |  |
| Al-Base Alloys             | 485 | Cu, 46; Pb, 51; Sn, 3                  | (1) SAE 770 cast in permanent molds; work-hardened to improve physical properties. SAE 780 and 782 usually bonded to steel back but is procurable in strip form without steel backing. SAE 781 usually bonded to steel back but can be produced as castings or wrought strip without steel back. (2) Hard, extremely fatigue-resistant, resistant to oil corrosion. (3) Main and connecting-rod bearings. Generally used with suitable overlay. SAE 781 and 782 also used for bushings and thrust bearings with or without overlay.  |
|                            | 770 | Al, 91.75; Sn, 6.25; Cu, 1; Ni, 1      |  |
|                            | 780 | Al, 91; Sn, 6; Si, 1.5; Cu, 1; Ni, 0.5 |  |
|                            | 781 | Al, 95; Si, 4; Cd, 1                   |  |
| Other Cu-Base Alloys       | 782 | Al, 95; Cu, 1; Ni, 1; Cd, 3            | (1) Wrought solid bronze, (2) Hard, strong, good fatigue resistance, (3) Intermediate-load oscillating motion such as tie-rods and brake shafts.   |
|                            | 795 | Cu, 90; Zn, 9.5; Sn, 0.5               |  |
|                            | 791 | Cu, 88; Zn, 4; Sn, 4; Pb, 4            |  |
|                            | 793 | Cu, 84; Pb, 8; Sn, 4; Zn, 4            |  |
| Other Cu-Base Alloys       | 798 | Cu, 84; Pb, 8; Sn, 4; Zn, 4            | (1) SAE 791, wrought solid bronze; SAE 793, cast on steel back; SAE 798, sintered on steel back. (2) General-purpose bearing material, good shock and load capacity. Resistant to high temperatures. Hard shaft desirable. Less score-resistant than higher lead alloys. (3) Medium to high loads. Transmission bushings and thrust washers. SAE 791 also used for piston pin and 793 and 798 for chassis bushings.  |
|                            | 792 | Cu, 80; Sn, 10; Pb, 10                 |  |
|                            | 797 | Cu, 80; Sn, 10; Pb, 10                 |  |
|                            | 794 | Cu, 73.5; Pb, 23; Sn, 3.5              |  |
| Other Cu-Base Alloys       | 799 | Cu, 73.5; Pb, 23; Sn, 3.5              | (1) SAE 794, cast on steel back; SAE 799, sintered on steel back. (2) Higher lead content gives improved surface action for higher speeds but results in somewhat less corrosion resistance. (3) Intermediate load application for both oscillating and rotating shafts, that is, rocker-arm bushings, transmissions, and farm implements.   |
|                            | 799 | Cu, 73.5; Pb, 23; Sn, 3.5              |  |

5) *High thermal conductivity* is required to absorb and carry away the heat generated in the bearing. This conductivity is most important, not in removing frictional heat generated in the oil film, but in preventing seizures due to hot spots caused by local asperity breakthroughs or foreign particles.

6) *Corrosion resistance* is required to resist attack by organic acids that are sometimes formed in oils at operating conditions.

7) *Load capacity or strength* is the ability of the material to withstand the hydrodynamic pressures exerted upon it during operation.

**Babbitt or White Metal Alloys.**—Many different bearing metal compositions are referred to as babbitt metals. The exact composition of the original babbitt metal is not known; however, the ingredients were probably tin, copper, and antimony in approximately the following percentages: 89.3, 3.6, and 7.1. Tin and lead-base babbitts are probably the best known of all bearing materials. With their excellent embeddability and compatibility characteristics under boundary lubrication, babbitt bearings are used in a wide range of applications including household appliances, automobile and diesel engines, railroad cars, electric motors, generators, steam and gas turbines, and industrial and marine gear units.

**Table 4. White Metal Bearing Alloys—Composition and Properties**  
*ASTM B23-83, reapproved 1988*

| ASTM Alloy <sup>a</sup> Number | Nominal Composition, Per Cent |      |      |      | Compressive Yield Point, <sup>b</sup> psi |        | Ultimate Compressive Strength, <sup>c</sup> psi |        | Brinell Hardness <sup>d</sup> |        | Melting Point °F | Proper Pouring Temperature, °F |
|--------------------------------|-------------------------------|------|------|------|---|--------|---|--------|-------------------------------|--------|------------------|--------------------------------|
|                                | Sn                            | Sb   | Pb   | Cu   | 68 °F                                     | 212 °F | 68 °F   | 212 °F | 68 °F                         | 212 °F |                  |                                |
| 1                              | 91.0                          | 4.5  | ...  | 4.5  | 4400                                      | 2650   | 12,850  | 6950   | 17.0                          | 8.0    | 433              | 825                            |
| 2                              | 89.0                          | 7.5  | ...  | 3.5  | 6100                                      | 3000   | 14,900  | 8700   | 24.5                          | 12.0   | 466              | 795                            |
| 3                              | 83.33                         | 8.33 | ...  | 8.33 | 6600                                      | 3150   | 17,600  | 9900   | 27.0                          | 14.5   | 464              | 915                            |
| 4                              | 75.0                          | 12.0 | 10.0 | 3.0  | 5550                                      | 2150   | 16,150  | 6900   | 24.5                          | 12.0   | 363              | 710                            |
| 5                              | 65.0                          | 15.0 | 18.0 | 2.0  | 5050                                      | 2150   | 15,050  | 6750   | 22.5                          | 10.0   | 358              | 690                            |
| 6                              | 20.0                          | 15.0 | 63.5 | 1.5  | 3800                                      | 2050   | 14,550  | 8050   | 21.0                          | 10.5   | 358              | 655                            |
| 7 <sup>e</sup>                 | 10.0                          | 15.0 | bal. | ...  | 3550                                      | 1600   | 15,650  | 6150   | 22.5                          | 10.5   | 464              | 640                            |
| 8 <sup>e</sup>                 | 5.0                           | 15.0 | bal. | ...  | 3400                                      | 1750   | 15,600  | 6150   | 20.0                          | 9.5    | 459              | 645                            |
| 10                             | 2.0                           | 15.0 | 83.0 | ...  | 3350                                      | 1850   | 15,450  | 5750   | 17.5                          | 9.0    | 468              | 630                            |
| 11                             | ...                           | 15.0 | 85.0 | ...  | 3050                                      | 1400   | 12,800  | 5100   | 15.0                          | 7.0    | 471              | 630                            |
| 12                             | ...                           | 10.0 | 90.0 | ...  | 2800                                      | 1250   | 12,900  | 5100   | 14.5                          | 6.5    | 473              | 625                            |
| 15 <sup>f</sup>                | 1.0                           | 16.0 | bal. | 0.5  | ...                                       | ...    | ...   | ...    | 21.0                          | 13.0   | 479              | 662                            |
| 16                             | 10.0                          | 12.5 | 77.0 | 0.5  | ...                                       | ...    | ...   | ...    | 27.5                          | 13.6   | 471              | 620                            |
| 19                             | 5.0                           | 9.0  | 86.0 | ...  | ...                                       | ...    | 15,600  | 6100   | 17.7                          | 8.0    | 462              | 620                            |

<sup>a</sup> Data for ASTM alloys 1, 2, 3, 7, 8, and 15 appear in the Appendix of ASTM B23-83; the data for alloys 4, 5, 6, 10, 11, 12, 16, and 19 are given in ASTM B23-49. All values are for reference purposes only.

<sup>b</sup> The values for yield point were taken from stress-strain curves at the deformation of 0.125 per cent reduction of gage.

<sup>c</sup> The ultimate strength values were taken as the unit load necessary to produce a deformation of 25 per cent of the length of the specimen.

<sup>d</sup> These values are the average Brinell number of three impressions on each alloy using a 10-mm ball and a 500-kg load applied for 30 seconds.

<sup>e</sup> Also nominal arsenic, 0.45 per cent.

<sup>f</sup> Also nominal arsenic, 1 per cent.

The compression test specimens were cylinders 1.5 inches in length and 0.5 inch in diameter, machined from chill castings 2 inches in length and 0.75 inch in diameter. The Brinell tests were made on the bottom face of parallel machined specimens cast in a 2-inch diameter by 0.625-inch deep steel mold at room temperature.

Both the Society of Automotive Engineers and American Society for Testing and Materials have classified white metal bearing alloys. [Tables 3 and 4](#) give compositions and properties or characteristics for the two classifications.

In small bushings for fractional-horsepower motors and in automotive engine bearings, the babbitt is generally used as a thin coating over a flat steel strip. After forming oil distribution grooves and drilling required holes, the strip is cut to size, then rolled and shaped into the finished bearing. These bearings are available for shaft diameters from 0.5 to 5 inches. Strip bearings are turned out by the millions yearly in highly automated factories and offer an excellent combination of low cost with good bearing properties.

For larger bearings in heavy-duty equipment, a thicker babbitt is cast on a rigid backing of steel or cast iron. Chemical and electrolytic cleaning of the bearing shell, thorough rinsing, tinning, and then centrifugal casting of the babbitt are desirable for sound bonding of the babbitt to the bearing shell. After machining, the babbitt layer is usually  $\frac{1}{2}$  to  $\frac{1}{4}$  inch thick.

Compared to other bearing materials, babbitts generally have lower load-carrying capacity and fatigue strength, are a little higher in cost, and require a more complicated design. Also, their strength decreases rapidly with increasing temperature. These shortcomings can be avoided by using an intermediate layer of high-strength, fatigue-resistant material that is placed between a steel backing and a thin babbitt surface layer. Such composite bearings frequently eliminate any need for using alternate materials having poorer bearing characteristics.

Tin babbitt is composed of 80 to 90 per cent tin to which is added about 3 to 8 per cent copper and 4 to 14 per cent antimony. An increase in copper or antimony produces increased hardness and tensile strength with decreased ductility. However, if the percentages of these alloys are increased above those shown in [Table 4](#), the resulting alloy will have decreased fatigue resistance. These alloys have very little tendency to cause wear to their journals because of their ability to embed dirt. They resist the corrosive effects of acids, are not prone to oil-film failure, and are easily bonded and cast. Two drawbacks are encountered from use of these alloys because they have low fatigue resistance and their hardness and strength drop appreciably at low temperatures.

Lead babbitt compositions generally range from 10 to 15 per cent antimony and up to 10 per cent tin in combination with the lead. Like tin-base babbitts, these alloys have little tendency to cause wear to their journals, embed dirt well, resist the corrosive effects of acids, are not prone to oil-film failure and are easily bonded and cast. Their chief disadvantages when compared with tin-base alloys are a rather lower strength and a susceptibility to corrosion.

**Cadmium Base.**—Cadmium alloy bearings have a greater resistance to fatigue than babbitt bearings, but their use is very limited due to their poor corrosion resistance. These alloys contain 1 to 15 per cent nickel, or 0.4 to 0.75 per cent copper, and 0.5 to 2.0 per cent silver. Their prime attribute is their high-temperature capability. The load-carrying capacity and relative basic bearing properties are shown in [Table 5](#).

**Copper-Lead.**—Copper-lead bearings are a binary mixture of copper and lead containing from 20 to 40 per cent lead. Lead is practically insoluble in copper, so a cast microstructure consists of lead pockets in a copper matrix. A steel backing is commonly used with this material and high volume is achieved either by continuous casting or by powder metallurgy techniques. This material is very often used with an overplate such as lead-tin and lead-tin-copper to increase basic bearing properties. [Table 5](#) provides comparisons of material properties.

The combination of good fatigue strength, high-load capacity, and high-temperature performance has resulted in extensive use of this material for heavy-duty main and connecting-rod bearings as well as moderate-load and speed applications in turbines and electric motors.

**Table 5. Properties of Bearing Alloys and Bearing Characteristics Ratings**

| Material           | Recommended Shaft Hardness, Brinell | Load-Carrying Capacity, psi | Maximum Operating Temp., °F | Compatibility <sup>a</sup> | Conformability and Embeddability <sup>a</sup> | Corrosion Resistance <sup>a</sup> | Fatigue Strength <sup>a</sup> |
|--------------------|-------------------------------------|-----------------------------|-----------------------------|----------------------------|---|-----------------------------------|-------------------------------|
| Tin-Base Babbitt   | 150 or less                         | 800 – 1500                  | 300                         | 1                          | 1   | 1                                 | 5                             |
| Lead-Base Babbitt  | 150 or less                         | 800 – 1200                  | 300                         | 1                          | 1   | 3                                 | 5                             |
| Cadmium Base       | 200 – 250                           | 1200 – 2000                 | 500                         | 1                          | 2   | 5                                 | 4                             |
| Copper-Lead        | 300                                 | 1500 – 2500                 | 350                         | 2                          | 2   | 5                                 | 3                             |
| Tin-Bronze         | 300 – 400                           | 4000+                       | 500+                        | 3                          | 5   | 2                                 | 1                             |
| Lead-Bronze        | 300                                 | 3000 – 4500                 | 450 – 500                   | 3                          | 4   | 4                                 | 2                             |
| Aluminum           | 300                                 | 4000+                       | 225 – 300                   | 5                          | 3   | 1                                 | 2                             |
| Silver-Overplate   | 300                                 | 4000+                       | 500                         | 2                          | 3   | 1                                 | 1                             |
| Trimetal-Overplate | 230 or less                         | 2000 – 4000+                | 225 – 300                   | 1                          | 2   | 2                                 | 3                             |

<sup>a</sup>Note: 1 is best; 5 is worst.

**Leaded Bronze and Tin-Bronze.**—Leaded and tin-bronzes contain up to 25 per cent lead or approximately 10 per cent tin, respectively. Cast leaded bronze bearings offer good compatibility, excellent casting, and easy machining characteristics, low cost, good structural properties and high-load capacity, usefulness as a single material that requires neither a separate overlay nor a steel backing. Bronzes are available in standard bar stock, sand or permanent molds, investment, centrifugal or continuous casting. Leaded bronzes have better compatibility than tin-bronzes because the spheroids of lead smear over the bearing surface under conditions of inadequate lubrication. These alloys are generally a first choice at intermediate loads and speeds. Table 5 provides comparisons of basic bearing properties of these materials.

**Aluminum.**—Aluminum bearings are either cast solid aluminum, aluminum with a steel backing, or aluminum with a suitable overlay. The aluminum is usually alloyed with small amounts of tin, silicon, cadmium, nickel, or copper, as shown in Table 3. An aluminum bearing alloy with 20 to 30 per cent tin alloy and up to 3 per cent copper has shown promise as a substitute for bronzes in some industrial applications.

These bearings are best suited for operation with hard journals. Owing to the high thermal expansion of the metal (resulting in diametral contraction when it is confined as a bearing in a rigid housing), large clearances are required, which tend to make the bearing noisy, especially on starting. Overlays of lead-tin, lead, or lead-tin-copper may be applied to aluminum bearings to facilitate their use with soft shafts.

Aluminum alloys are available with properties specifically designed for bearing applications, such as high load-carrying capacity, fatigue strength, and thermal conductivity, in addition to excellent corrosion resistance and low cost.

**Silver.**—Silver bearings were developed for and have an excellent record in heavy-duty applications such as aircraft master rod and diesel engine main bearings. Silver has a higher fatigue rating than any of the other bearing materials; the steel backing used with this material may show evidence of fatigue before the silver. The advent of overlays, or more commonly called overplates, made it possible for silver to be used as a bearing material. Silver by itself does not possess any of the desirable bearing qualities except high fatigue resistance and high thermal conductivity. The overlays such as lead, lead-tin, or lead-indium improve the embeddability and antiscoring properties of silver. The relative basic properties of this material, when used as an overplate, are shown in Table 5.

**Cast Iron.**—Cast iron is an inexpensive bearing material capable of operation at light loads and low speeds, i.e., up to 130 ft/min and 150 lb/in.<sup>2</sup> These bearings must be well

lubricated and have a rather large clearance so as to avoid scoring from particles torn from the cast iron that ride between bearing and journal. A journal hardness of between 150 and 250 Brinell has been found to be best when using cast-iron bearings.

**Porous Metals.**—Porous metal self-lubricating bearings are usually made by sintering metals such as plain or leaded bronze, iron, and stainless steel. The sintering produces a spongelike structure capable of absorbing fairly large quantities of oil, usually 10–35 per cent of the total volume. These bearings are used where lubrication supply is difficult, inadequate, or infrequent. This type of bearing should be flooded from time to time to resaturate the material. Another use of these porous materials is to meter a small quantity of oil to the bearings such as in drip feed systems. The general design operating characteristics of this class of materials are shown in [Table 6](#).

**Table 6. Application Limits — Sintered Metal and Nonmetallic Bearings**

| Bearing Material      | Load Capacity (psi) | Maximum Temperature (°F) | Surface Speed, $V_{max}$ (max. fpm) | PV Limit $P = \text{psi load}$<br>$V = \text{surface ft/min}$ |
|-----------------------|---------------------|--------------------------|-------------------------------------|---|
| Acetal                | 1000                | 180                      | 1000                                | 3000  |
| Graphite (dry)        | 600                 | 750                      | 2500                                | 15,000  |
| Graphite (lubricated) | 600                 | 750                      | 2500                                | 150,000   |
| Nylon, Polycarbonate  | 1000                | 200                      | 1000                                | 3000  |
| Nylon composite       | ...                 | 400                      | ...                                 | 16,000  |
| Phenolics             | 6000                | 200                      | 2500                                | 15,000  |
| Porous bronze         | 4500                | 160                      | 1500                                | 50,000  |
| Porous iron           | 8000                | 160                      | 800                                 | 50,000  |
| Porous metals         | 4000–8000           | 150                      | 1500                                | 50,000  |
| Virgin Teflon (TFE)   | 500                 | 500                      | 50                                  | 1000  |
| Reinforced Teflon     | 2500                | 500                      | 1000                                | 10,000–15,000   |
| TFE fabric            | 60,000              | 500                      | 150                                 | 25,000  |
| Rubber                | 50                  | 150                      | 4000                                | 15,000  |
| Maple & Lignum Vitae  | 2000                | 150                      | 2000                                | 15,000  |

[Tables 7](#), [8](#), and [9](#) give the chemical compositions, permissible loads, interference fits, and running clearances of bronze-base and iron-base metal-powder sintered bearings that are specified in the ASTM specifications for oil-impregnated metal-powder sintered bearings (B438-83a and B439-83).

**Plastics Bearings.**—Plastics are finding increased use as bearing materials because of their resistance to corrosion, quiet operation, ability to be molded into many configurations, and their excellent compatibility, which minimizes or eliminates the need for lubrication. Many plastics are capable of operating as bearings, especially phenolic, tetrafluoroethylene (TFE), and polyamide (nylon) resins. The general application limits for these materials are shown in [Table 6](#).

*Laminated Phenolics:* These composite materials consist of cotton fabric, asbestos, or other fillers bonded with phenolic resin. They have excellent compatibility with various fluids as well as strength and shock resistance. However, precautions must be taken to maintain adequate bearing cooling because the thermal conductivity of these materials is low.

*Nylon:* This material has the widest use for small, lightly loaded applications. It has low frictional properties and requires no lubrication.

*Teflon:* This material, with its exceptional low coefficient of friction, self-lubricating characteristics, resistance to attack by almost any chemicals, and its wide temperature

range, is one of the most interesting of the plastics for bearing use. High cost combined with low load capacity cause Teflon to be selected mostly in modified form, where other less expensive materials have proved inadequate for design requirements.

Bearings made of laminated phenolics, nylon, or Teflon are all unaffected by acids and alkalis except if highly concentrated and therefore can be used with lubricants containing dilute acids or alkalis. Water is used to lubricate most phenolic laminate bearings but oil, grease, and emulsions of grease and water are also used. Water and oil are used as lubricants for nylon and Teflon bearings. Almost all types of plastic bearings absorb water and oil to some extent. In some the dimensional change caused by the absorption may be as much as three per cent in one direction. This means that bearings have to be treated before use so that proper clearances will be kept. This may be done by boiling in water, for water lubricated bearings. Boiling in water makes bearings swell the maximum amount. Clearances for phenolic bearings are kept at about 0.001 inch per inch of diameter on treated bearings. Partially lubricated or dry nylon bearings are given a clearance of 0.004 to 0.006 inches for a one-inch diameter bearing.

*Rubber:* Rubber bearings give excellent performance on propeller shafts and rudders of ships, hydraulic turbines, pumps, sand and gravel washers, dredges and other industrial equipment that handle water or slurries. The resilience of rubber helps to isolate vibration and provide quiet operation, allows running with relatively large clearances and helps to compensate for misalignment. In these bearings a fluted rubber structure is supported by a metal shell. The flutes or scallops in the rubber form a series of grooves through which lubricant or, as generally used, water and foreign material such as sand may pass through the bearing.

**Wood.**—Bearings made from such woods as lignum vitae, rock maple, or oak offer self-lubricating properties, low cost, and clean operation. However, they have frequently been displaced in recent years by various plastics, rubber and sintered-metal bearings. General applications are shown in [Table 6](#).

**Carbon-Graphite.**—Bearings of molded and machined carbon-graphite are used where regular maintenance and lubrication cannot be given. They are dimensionally stable over a wide range of temperatures, may be lubricated if desired, and are not affected by chemicals. These bearings may be used up to temperatures of 700 to 750 degrees F. in air or 1200 degrees F. in a non-oxidizing atmosphere, and generally are operated at a maximum load of 20 pounds per square inch. In some instances a metal or metal alloy is added to the carbon-graphite composition to improve such properties as compressive strength and density. The temperature limitation depends upon the melting point of the metal or alloy and the maximum load is generally 350 pounds per square inch when used with no lubrication or 600 pounds per square inch when used with lubrication.

Normal running clearances for both types of carbon-graphite bearings used with steel shafts and operating at a temperature of less than 200 degrees F. are as follows: 0.001 inch for bearings of 0.187 to 0.500-inch inside diameter, 0.002 inch for bearings of 0.501 to 1.000-inch inside diameter, 0.003 inch for bearings of 1.001 to 1.250-inch inside diameter, 0.004 inch for bearings of 1.251 to 1.500-inch diameter, and 0.005 inch for bearings of 1.501 to 2.000-inch inside diameter. Speeds depend upon too many variables to list specifically so it can only be stated here that high loads require a low number of rpm and low loads permit a high number of rpm. Smooth journals are necessary in these bearings as rough ones tend to abrade the bearings quickly. Cast iron and hard chromium-plate steel shafts of 400 Brinell and over, and phosphor-bronze shafts over 135 Brinell are recommended.

**Table 7. Copper- and Iron-Base Sintered Bearings (Oil Impregnated) —**  
*ASTM B438-83a (R1989), B439-83 (R1989), and Appendices*

| Chemical Requirements          |                        |           |           |           |                    |           |                      |                      |
|--------------------------------|------------------------|-----------|-----------|-----------|--------------------|-----------|----------------------|----------------------|
| Alloying Elements <sup>a</sup> | Percentage Composition |           |           |           |                    |           |                      |                      |
|                                | Copper-Base Bearings   |           |           |           | Iron-Base Bearings |           |                      |                      |
|                                | Grade 1                |           | Grade 2   |           | Grades             |           |                      |                      |
|                                | Class A                | Class B   | Class A   | Class B   | 1                  | 2         | 3                    | 4                    |
| Cu                             | 87.5–99.5              | 87.5–90.5 | 87.5–90.5 | 87.5–90.5 | ...                | ...       | 7.0–11.0             | 18.0–22.0            |
| Sn                             | 9.5–10.5               | 9.5–10.5  | 9.5–10.5  | 9.5–10.5  | ...                | ...       | ...                  | ...                  |
| Graphite                       | 0.1 max.               | 1.75 max. | 0.1 max.  | 1.75 max. | ...                | ...       | ...                  | ...                  |
| Pb                             | ...                    | ...       | 2.0–4.0   | 2.0–4.0   | ...                | ...       | ...                  | ...                  |
| Fe                             | 1.0 max.               | 1.0 max.  | 1.0 max.  | 1.0 max.  | 96.25 min.         | 95.9 min. | Balance <sup>b</sup> | Balance <sup>b</sup> |
| Comb. C <sup>c</sup>           | ...                    | ...       | ...       | ...       | 0.25 max.          | 0.25–0.60 | ...                  | ...                  |
| Si, max.                       | ...                    | ...       | ...       | ...       | 0.3                | 0.3       | ...                  | ...                  |
| Al, max.                       | ...                    | ...       | ...       | ...       | 0.2                | 0.2       | ...                  | ...                  |
| Others                         | 0.5 max.               | 0.5 max.  | 1.0 max.  | 1.0 max.  | 3.0 max.           | 3.0 max.  | 3.0 max.             | 3.0 max.             |

<sup>a</sup> Abbreviations used for the alloying elements are as follows: Cu, copper; Fe, iron; Sn, tin; Pb, lead; Zn, zinc; Ni, nickel; Sb, antimony; Si, silicon; Al, aluminum; and C, carbon.

<sup>b</sup> Total of iron plus copper shall be 97 per cent, minimum.

<sup>c</sup> Combined carbon (on basis of iron only) may be a metallographic estimate of the carbon in the iron.

| Permissible Loads     |                |        |             |                       |              |              |
|-----------------------|----------------|--------|-------------|-----------------------|--------------|--------------|
| Copper-Base Bearings  |                |        |             | Iron-Base Bearings    |              |              |
| Shaft Velocity, fpm   | Grades 1 & 2   |        |             | Shaft Velocity, fpm   | Grades 1 & 2 | Grades 3 & 4 |
|                       | Type 1         | Type 2 | Types 3 & 4 |                       |              |              |
|                       | Max. Load, psi |        |             |                       |              |              |
| Slow and intermittent | 3200           | 4000   | 4000        | Slow and intermittent | 3600         | 8000         |
| 25                    | 2000           | 2000   | 2000        | 25                    | 1800         | 3000         |
| 50 to 100             | 500            | 500    | 550         | 50 to 100             | 450          | 700          |
| Over 100 to 150       | 365            | 325    | 365         | Over 100 to 150       | 300          | 400          |
| Over 150 to 200       | 280            | 250    | 280         | Over 150 to 200       | 225          | 300          |
| Over 200              |                | a      | a           | a                     | Over 200     | a            |

<sup>a</sup> For shaft velocities over 200 fpm, the permissible loads may be calculated as follows:  $P = 50,000/V$ ; where  $P$  = safe load, psi of projected area; and  $V$  = shaft velocity, fpm. With a shaft velocity of less than 50 fpm and a permissible load greater than 1,000 psi, an extreme pressure lubricant should be used; with heat dissipation and removal techniques, higher  $PV$  ratings can be obtained.

| Clearances            |        |       |                                 |                |             |                |
|-----------------------|--------|-------|---------------------------------|----------------|-------------|----------------|
| Press-Fit Clearances  |        |       | Running Clearances <sup>a</sup> |                |             |                |
| Copper- and Iron-Base |        |       | Copper-Base                     |                | Iron-Base   |                |
| Bearing OD            | Min.   | Max.  | Shaft Size                      | Min. Clearance | Shaft Size  | Min. Clearance |
| Up to 0.760           | 0.001  | 0.003 | Up to 0.250                     | 0.0003         | Up to 0.760 | 0.0005         |
| 0.761–1.510           | 0.0015 | 0.004 | 0.250–0.760                     | 0.0005         | 0.761–1.510 | 0.001          |
| 1.511–2.510           | 0.002  | 0.005 | 0.760–1.510                     | 0.0010         | 1.511–2.510 | 0.0015         |
| 2.511–3.010           | 0.002  | 0.006 | 1.510–2.510                     | 0.0015         | Over 2.510  | 0.002          |
| Over 3.010            | 0.002  | 0.007 | Over 2.510                      | 0.0020         |             |                |

<sup>a</sup> Only minimum recommended clearances are listed. It is assumed that ground steel shafting will be used and that all bearings will be oil-impregnated.



**Table 8. Copper- and Iron-Base Sintered Bearings (Oil Impregnated) —**  
*ASTM B438-83a (R1989), B439-83 (R1989), and Appendices*

| Commercial Dimensional Tolerances <sup>ab</sup> |                           |                  |                         |                            |                           |                  |                         |
|---|---------------------------|------------------|-------------------------|----------------------------|---------------------------|------------------|-------------------------|
| Diameter Tolerance                              |                           | Length Tolerance |                         | Diameter Tolerance         |                           | Length Tolerance |                         |
| Copper Base                                     |                           |                  |                         | Iron Base                  |                           |                  |                         |
| Inside or Outside Diameter                      | Total Diameter Tolerances | Length           | Total Length Tolerances | Inside or Outside Diameter | Total Diameter Tolerances | Length           | Total Length Tolerances |
| Up to 1   | 0.001                     | Up to 1.5        | 0.01                    | Up to 0.760                | -0.001                    | Up to 1.495      | 0.01                    |
| 1 to 1.5  | 0.0015                    | 1.5 to 3         | 0.01                    | 0.761-1.510                | -0.0015                   | 1.496-1.990      | 0.02                    |
| 1.5 to 2  | 0.002                     | 3 to 4.5         | 0.02                    | 1.511-2.510                | -0.002                    | 1.991-2.990      | 0.02                    |
| 2 to 2.5  | 0.0025                    | ...              | ...                     | 2.511-3.010                | -0.003                    | 2.991-4.985      | 0.03                    |
| 2.5 to 3  | 0.003                     | ...              | ...                     | 3.011-4.010                | -0.005                    | ...              | ...                     |
| ...   | ...                       | ...              | ...                     | 4.011-5.010                | -0.005                    | ...              | ...                     |
| ...   | ...                       | ...              | ...                     | 5.011-6.010                | -0.006                    | ...              | ...                     |

| Concentricity Tolerance <sup>a,b,c</sup> |                     |                         |                  |        |                         |
|--|---------------------|-------------------------|------------------|--------|-------------------------|
| Iron Base                                |                     |                         | Copper Base      |        |                         |
| Outside Diameter                         | Max. Wall Thickness | Concentricity Tolerance | Outside Diameter | Length | Concentricity Tolerance |
| Up to 1.510                              | Up to 0.355         | 0.003                   | Up to 1          | 0 to 1 | 0.00                    |
|  |                     |                         |                  | 1 to 2 | 0.004                   |
| 1.511 to 2.010                           | Up to 0.505         | 0.004                   | Up to 1          | 2 to 3 | 0.005                   |
|  |                     |                         |                  | 0 to 1 | 0.004                   |
| 2.011 to 4.010                           | Up to 1.010         | 0.005                   | 1 to 2           | 1 to 2 | 0.005                   |
|  |                     |                         |                  | 2 to 3 | 0.006                   |
| 4.011 to 5.010                           | Up to 1.510         | 0.006                   | 2 to 3           | 0 to 1 | 0.005                   |
|  |                     |                         |                  | 1 to 2 | 0.006                   |
| 5.011 to 6.010                           | Up to 2.010         | 0.007                   | 2 to 3           | 0.007  | 0.007                   |

<sup>a</sup> For copper-base bearings with 4-to-1 maximum-length-diameter ratio and a 24-to-1 maximum-length-to-wall-thickness ratio; bearings with greater ratios are not covered here.

<sup>b</sup> For iron-base bearings with a 3-to-1 maximum-length-to-inside diameter ratio and a 20-to-1 maximum-length-to-wall-thickness ratio; bearings with greater ratios are not covered here.

<sup>c</sup> Total indicator reading.

**Table 9. Copper- and Iron-Base Sintered Bearings (Oil Impregnated) —**  
*ASTM B438-83a (R1989), B439-83 (R1989), and Appendices*

| Diameter Range | Flange and Thrust Bearings, Diameter, and Thickness Tolerances <sup>a</sup> |         |                            |         | Parallellism <sup>a</sup> on Faces, max. |         |           |         |
|----------------|---|---------|----------------------------|---------|--|---------|-----------|---------|
|                | Flange Diameter Tolerance   |         | Flange Thickness Tolerance |         | Copper Base                              |         | Iron Base |         |
|                | Standard  | Special | Standard                   | Special | Standard                                 | Special | Standard  | Special |
| 0 to 1½        | ±0.005  | ±0.0025 | ±0.005                     | ±0.0025 | 0.003                                    | 0.002   | 0.005     | 0.003   |
| Over 1½ to 3   | ±0.010  | ±0.005  | ±0.010                     | ±0.007  | 0.004                                    | 0.003   | 0.007     | 0.005   |
| Over 3 to 6    | ±0.025  | ±0.010  | ±0.015                     | ±0.010  | 0.005                                    | 0.004   | 0.010     | 0.007   |

<sup>a</sup> Standard and special tolerances are specified for diameters, thicknesses, and parallellism. Special tolerances should not be specified unless required because they require additional or secondary operations and, therefore, are costlier. Thrust bearings (¼ inch thickness, max.) have a standard thickness tolerance of ±0.005 inch and a special thickness tolerance of ±0.0025 inch for all diameters.

All dimensions in inches except where otherwise noted.

## BALL, ROLLER, AND NEEDLE BEARINGS

### Rolling Contact Bearings

Rolling contact bearings substitute a rolling element, ball or roller, for a hydrodynamic or hydrostatic fluid film to carry an impressed load without wear and with reduced friction. Because of their greatly reduced starting friction, when compared to the conventional journal bearing, they have acquired the common designation of "anti-friction" bearings. Although normally made with hardened rolling elements and races, and usually utilizing a separator to space the rolling elements and reduce friction, many variations are in use throughout the mechanical and electrical industries. The most common anti-friction bearing application is that of the deep-groove ball bearing with ribbon-type separator and sealed-grease lubrication used to support a shaft with radial and thrust loads in rotating equipment. This shielded or sealed bearing has become a standard and commonplace item ordered from a supplier's catalogue in much the same manner as nuts and bolts. Because of the simple design approach and the elimination of a separate lubrication system or device, this bearing is found in as many installations as the wick-fed or impregnated porous plain bushing.

Currently, a number of manufacturers produce a complete range of ball and roller bearings in a fully interchangeable series with standard dimensions, tolerances and fits as specified in Anti-Friction Bearing Manufacturers Association (AFBMA) Standards. Except for deep-groove ball bearings, performance standards are not so well defined and sizing and selection must be done in close conformance with the specific manufacturer's catalogue requirements. In general, desired functional features should be carefully gone over with the vendor's representatives.















Rolling contact bearings are made to high standards of accuracy and with close metallurgical control. Balls and rollers are normally held to diametral tolerances of .0001 inch or less within one bearing and are often used as "gage" blocks in routine toolroom operations. This accuracy is essential to the performance and durability of rolling-contact bearings and in limiting runout, providing proper radial and axial clearances, and ensuring smoothness of operation.

Because of their low friction, both starting and running, rolling-contact bearings are utilized to reduce the complexity of many systems that normally function with journal bearings. Aside from this advantage and that of precise radial and axial location of rotating elements, however, they also are desirable because of their reduced lubrication requirements and their ability to function during brief interruptions in normal lubrication.

In applying rolling-contact bearings it is well to appreciate that their life is limited by the fatigue life of the material from which they are made and is modified by the lubricant used. In rolling-contact fatigue, precise relationships among life, load, and design characteristics are not predictable, but a statistical function described as the "probability of survival" is used to relate them according to equations recommended by the AFBMA. Deviations from these formulas result when certain extremes in applications such as speed, deflection, temperature, lubrication, and internal geometry must be dealt with.

**Types of Anti-friction Bearings.**—The general types are usually determined by the shape of the rolling element, but many variations have been developed that apply conventional elements in unique ways. Thus it is well to know that special bearings can be procured with races adapted to specific applications, although this is not practical for other than high volume configurations or where the requirements cannot be met in a more economical manner. "Special" races are appreciably more expensive. Quite often, in such situations, races are made to incorporate other functions of the mechanism, or are "submerged" in the surrounding structure, with the rolling elements supported by a shaft or housing that has been hardened and finished in a suitable manner. Typical anti-friction bearing types are shown in [Tables 1a](#) through [1g](#).

**Table 1a. Types of Rolling Element Bearings and Their Symbols**

| BALL BEARINGS, SINGLE ROW, RADIAL CONTACT                               |  |  |        |  |  |
|---|--|--|--------|--|--|
| Symbol  | Description  |  | Symbol | Description  |  |
| BC  | Non-filling slot assembly  |   | BH     | Non-separable counter-bore assembly  |   |
| BL  | Filling slot assembly  |   | BM     | Separable assembly   |   |
| BALL BEARINGS, SINGLE ROW, ANGULAR CONTACT <sup>a</sup>                 |  |  |        |  |  |
| Symbol  | Description  |  | Symbol | Description  |  |
| BN  | Non-separable<br>Nominal contact angle:<br>from above 10° to and<br>including 22°        |   | BAS    | Separable inner ring<br>Nominal contact angle:<br>from above 22° to and<br>including 32° |   |
| BNS   | Separable outer ring<br>Nominal contact angle:<br>from above 10° to and<br>including 22° |   | BT     | Non-separable<br>Nominal contact angle:<br>from above 32° to and<br>including 45°        |   |
| BNT   | Separable inner ring<br>Nominal contact angle:<br>from above 10° to and<br>including 22° |   | BY     | Two-piece outer ring   |   |
| BA  | Non-separable<br>Nominal contact angle:<br>from above 22° to and<br>including 32°        |   | BZ     | Two-piece inner ring   |   |
| BALL BEARINGS, SINGLE ROW, RADIAL CONTACT,<br>SPHERICAL OUTSIDE SURFACE |  |  |        |  |  |
| Symbol  | Description  |  | Symbol | Description  |  |
| BCA   | Non-filling slot assembly  |  | BLA    | Filling slot assembly  |  |







<sup>a</sup> A line through the ball contact points forms an acute angle with a perpendicular to the bearing axis.

**Types of Ball Bearings.**—Most types of ball bearings originate from three basic designs: the single-row radial, the single-row angular contact, and the double-row angular contact.

*Single-row Radial, Non-filling Slot:* This is probably the most widely used ball bearing and is employed in many modified forms. It is also known as the “Conrad” type or “Deep-groove” type. It is a symmetrical unit capable of taking combined radial and thrust loads in which the thrust component is relatively high, but is not intended for pure thrust loads, however. Because this type is not self-aligning, accurate alignment between shaft and housing bore is required.

*Single-row Radial, Filling Slot:* This type is designed primarily to carry radial loads. Bearings of this type are assembled with as many balls as can be introduced by eccentric displacement of the rings, as in the non-filling slot type, and then several more balls are inserted through the loading slot, aided by a slight spreading of the rings and heat expansion of the outer ring, if necessary. This type of bearing will take a certain degree of thrust when in combination with a radial load but is not recommended where thrust loads exceed 60 per cent of the radial load.

**Table 1b. Types of Rolling Element Bearings and Their Symbols**

| BALL BEARINGS, DOUBLE ROW, RADIAL CONTACT               |  |   |   |  |
|---|--|---|---|--|
| Symbol  | Description  |   | Symbol  | Description  |
| BF  | Filling slot assembly  |  | BHA   | Non-separable two-piece outer ring   |
| BK  | Non-filling slot assembly  |  |   |  |
| BALL BEARINGS, DOUBLE ROW, ANGULAR CONTACT <sup>a</sup> |  |   |   |  |
| Symbol  | Description  |   | Symbol  | Description  |
| BD  | Filling slot assembly<br>Vertex of contact angles inside bearing     |  | BG  | Non-filling slot assembly<br>Vertex of contact angles outside bearing            |
| BE  | Filling slot assembly<br>Vertex of contact angles outside bearing    |  | BAA   | Non-separable<br>Vertex of contact angles inside bearing<br>Two-piece outer ring |
| BJ  | Non-filling slot assembly<br>Vertex of contact angles inside bearing |  | BVV   | Separable<br>Vertex of contact angles outside bearing<br>Two-piece inner ring    |
| BALL BEARINGS, DOUBLE ROW, SELF-ALIGNING <sup>a</sup>   |  |   |   |  |
|   | Symbol   | Description   |   |  |
|   | BS   | Raceway of outer ring spherical   |  |  |

<sup>a</sup> A line through the ball contact points forms an acute angle with a perpendicular to the bearing axis.















**Single-row Angular-contact:** This type is designed for combined radial and thrust loads where the thrust component may be large and axial deflection must be confined within very close limits. A high shoulder on one side of the outer ring is provided to take the thrust, while the shoulder on the other side is only high enough to make the bearing non-separable. Except where used for a pure thrust load in one direction, this type is applied either in pairs (duplex) or one at each end of the shaft, opposed.

**Double-row Bearings:** These are, in effect, two single-row angular-contact bearings built as a unit with the internal fit between balls and raceway fixed at the time of bearing assembly. This fit is therefore not dependent upon mounting methods for internal rigidity. These bearings usually have a known amount of internal preload built in for maximum resistance to deflection under combined loads with thrust from either direction. Thus, with balls and races under compression before an external load is applied, due to this internal preload, the bearings are very effective for radial loads where bearing deflection must be minimized.

**Other Types:** Modifications of these basic types provide arrangements for self-sealing, location by snap ring, shielding, etc., but the fundamentals of mounting are not changed. A special type is the *self-aligning* ball bearing which can be used to compensate for an appreciable degree of misalignment between shaft and housing due to shaft deflections, mount-

ing inaccuracies, or other causes commonly encountered. With a single row of balls, alignment is provided by a spherical outer surface on the outer ring; with a double row of balls, alignment is provided by a spherical raceway on the outer ring. Bearings in the wide series have a considerable amount of thrust capacity.

**Table 1c. Types of Rolling Element Bearings and Their Symbols**

| CYLINDRICAL ROLLER BEARING, SINGLE ROW,<br>NON-LOCATING TYPE            |  |   |        |   |   |
|---|--|---|--------|---|---|
| Symbol  | Description  |   | Symbol | Description   |   |
| RU  | Inner ring without ribs<br>Double-ribbed outer ring<br>Inner ring separable                              |    | RNS    | Double-ribbed inner ring<br>Outer ring without ribs<br>Outer ring separable<br>Spherical outside surface                                  |    |
| RUP   | Inner ring without ribs<br>Double-ribbed outer ring<br>with one loose rib<br>Both rings separable        |    | RAB    | Inner ring without ribs<br>Single-ribbed outer ring<br>Both rings separable   |    |
| RUA   | Inner ring without ribs<br>Double-ribbed outer ring<br>Inner ring separable<br>Spherical outside surface |    | RM     | Inner ring without ribs<br>Rollers located by cage,<br>end-rings or internal snap<br>rings recesses in outer<br>ring Inner ring separable |    |
| RN  | Double-ribbed inner ring<br>Outer ring without ribs<br>Outer ring separable                              |    | RNU    | Inner ring without ribs<br>Outer ring without ribs<br>Both rings separable  |    |
| CYLINDRICAL ROLLER BEARINGS, SINGLE ROW,<br>ONE-DIRECTION-LOCATING TYPE |  |   |        |   |   |
| Symbol  | Description  |   | Symbol | Description   |   |
| RR  | Single-ribbed inner-ring<br>Outer ring with two<br>internal snap rings<br>Inner ring separable           |    | RF     | Double-ribbed inner ring<br>Single-ribbed outer ring<br>Outer ring separable  |    |
| RJ  | Single-ribbed inner ring<br>Double-ribbed outer ring<br>Inner ring separable                             |   | RS     | Single-ribbed inner ring<br>Outer ring with one rib and<br>one internal snap ring<br>Inner ring separable                                 |   |
| RJP   | Single-ribbed inner ring<br>Double-ribbed outer ring<br>with one loose rib<br>Both rings separable       |  | RAA    | Single-ribbed inner ring<br>Single-ribbed outer ring<br>Both rings separable  |  |








**Types of Roller Bearings.**—Types of roller bearings are distinguished by the design of rollers and raceways to handle axial, combined axial and thrust, or thrust loads.

**Cylindrical Roller:** These bearings have solid or helically wound hollow cylindrical rollers. The free ring may have a restraining flange to provide some restraint to endwise movement in one direction or may be without a flange so that the bearing rings may be displaced axially with respect to each other. Either rolls or roller path on the races may be slightly crowned to prevent edge loading under slight shaft misalignment. Low friction makes this type suitable for relatively high speeds.

**Barrel Roller:** These bearings have rollers that are barrel-shaped and symmetrical. They are furnished in both single- and double-row mountings. As with cylindrical roller bearings, the single-row mounting type has a low thrust capacity, but angular mounting of rolls in the double-row type permits its use for combined axial and thrust loads.

**Spherical Roller:** These bearings are usually furnished in a double-row, self-aligning mounting. Both rows of rollers have a common spherical outer raceway. The rollers are

**Table 1d. Types of Rolling Element Bearings and Their Symbols**

| CYLINDRICAL ROLLER BEARINGS, SINGLE ROW,<br>TWO-DIRECTION-LOCATING TYPE |   |   |  |  |   |
|---|---|---|--|--|---|
| Symbol  | Description   |   | Symbol   | Description  |   |
| RK  | Double-ribbed inner ring<br>Outer ring with two<br>internal snap rings<br>Non-separable                         |  | RY   | Double-ribbed inner ring<br>Outer ring with one rib and<br>one internal snap ring<br>Non-separable |  |
| RC  | Double-ribbed inner ring<br>Double-ribbed outer ring<br>Non-separable   |  | RCS  | Double-ribbed inner ring<br>Double-ribbed outer ring<br>Non-separable<br>Spherical outside surface |  |
| RG  | Inner ring, with one rib and<br>one snap ring<br>Double-ribbed outer ring<br>Non-separable                      |  |  |  |   |
| RP  | Double-ribbed inner ring<br>Double-ribbed outer ring<br>with one loose rib<br>Outer ring separable              |  | RT   | Double-ribbed inner<br>ring with one loose rib<br>Double-ribbed outer ring<br>Inner ring separable |  |
| CYLINDRICAL ROLLER BEARINGS   |   |   |  |  |   |
| Double Row Non-Locating Type  |   | Double Row Two-Direction-Locating Type  |  |  |   |
| Symbol  | Description   | Symbol  | Description  |  |   |
| RA  | Inner ring without ribs<br>Three integral ribs on<br>outer ring<br>Inner ring separable                         | RB  | Three integral ribs<br>on inner ring<br>Outer ring without ribs,<br>with two internal<br>snap rings<br>Non-separable |  |   |
| RD  | Three integral ribs on<br>inner ring<br>Outer ring without ribs<br>Outer ring separable                         | Multi-Row Non-Locating Type   |  |  |   |
|   |   | Symbol  | Description  |  |   |
| RE  | Inner ring without ribs<br>Outer rings without ribs,<br>with two internal<br>snap rings<br>Inner ring separable | RV  | Inner ring without ribs<br>Double-ribbed outer ring<br>(loose ribs)<br>Both rings separable                          |  |   |

barrel-shaped with one end smaller than the other to provide a small thrust to keep the rollers in contact with the center guide flange. This type of roller bearing has a high radial and thrust load carrying capacity with the ability to maintain this capacity under some degree of misalignment of shaft and bearing housing.












**Tapered Roller:** In this type, straight tapered rollers are held in accurate alignment by means of a guide flange on the inner ring. The basic characteristic of these bearings is that the apexes of the tapered working surfaces of both rollers and races, if extended, would coincide on the bearing axis. These bearings are separable. They have a high radial and thrust carrying capacity.

**Types of Ball and Roller Thrust Bearings.**—Are designed to take thrust loads alone or in combination with radial loads.

**One-direction Ball Thrust:** These bearings consist of a shaft ring and a flat or spherical housing ring with a single row of balls between. They are capable of carrying pure thrust loads in one direction only. They cannot carry any radial load.

**Two-direction Ball Thrust:** These bearings consist of a shaft ring with a ball groove in either side, two sets of balls, and two housing rings so arranged that thrust loads in either direction can be supported. No radial loads can be carried.

**Table 1e. Types of Rolling Element Bearings and Their Symbols**

| SELF-ALIGNING ROLLER BEARINGS, DOUBLE ROW   |   |   |  |             |
|---|---|---|--|-------------|
| Symbol  | Description   |   | Symbol Description   |             |
| SD  | Three integral ribs on inner ring<br>Raceway of outer ring spherical                                    |    | SL<br>Raceway of outer ring spherical<br>Rollers guided by the cage<br>Two integral ribs on inner ring   |             |
| SE  | Raceway of outer ring spherical<br>Rollers guided by separate center guide ring in outer ring           |    | SELF-ALIGNING ROLLER BEARINGS SINGLE ROW   |             |
|   |   |   | Symbol   | Description |
| SW  | Raceway of inner ring spherical   |    | SR<br>Inner ring with ribs<br>Raceway of outer ring spherical<br>Radial contact                          |             |
| SC  | Raceway of outer ring spherical<br>Rollers guided by separate axially floating guide ring on inner ring |    | SA<br>Raceway of outer ring spherical<br>Angular contact   |             |
|   |   |   | SB<br>Raceway of inner ring spherical<br>Angular contact   |             |
| THRUST BALL BEARINGS  |   |   |  |             |
| Symbol  | Description   |   | Symbol Description   |             |
| TA<br>TB <sup>a</sup>   | Single direction, grooved raceways, flat seats  |    | TDA<br>Double direction, washers with grooved raceways, flat seats                                       |             |
| TBF <sup>a</sup>  | Single direction, flat washers, flat seats  |    |  |             |
|    |   |   |  |             |
| THRUST ROLLER BEARINGS  |   |   |  |             |
| Symbol  | Description   |   | Symbol Description   |             |
| TS  | Single direction, aligning flat seats, spherical rollers  |  | TPC <sup>a</sup><br>Single direction, flat seats, flat races, outside band, cylindrical rollers          |             |
| TP  | Single direction, flat seats, cylindrical rollers   |  | TR <sup>a</sup><br>Single direction, flat races, aligning seat with aligning washer, cylindrical rollers |             |
|  |   |   |                       |             |

<sup>a</sup> Inch dimensioned only.









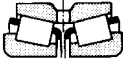

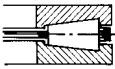
**Spherical Roller Thrust:** This type is similar in design to the radial spherical roller bearing except that it has a much larger contact angle. The rollers are barrel shaped with one end smaller than the other. This type of bearing has a very high thrust load carrying capacity and can also carry radial loads.

**Tapered Roller Thrust:** In this type the rollers are tapered and several different arrangements of housing and shaft are used.

**Roller Thrust:** In this type the rollers are straight and several different arrangements of housing and shaft are used.

**Types of Needle Bearings.**—Needle bearings are characterized by their relatively small size rollers, usually not above  $\frac{1}{4}$  inch in diameter, and a relatively high ratio of length to diameter, usually ranging from about 3 to 1 and 10 to 1. Another feature that is characteris-

**Table 1f. Types of Rolling Element Bearings and Their Symbols**

| TAPERED ROLLER BEARINGS — INCH   |  |                 |  |
|----------------------------------|--|-----------------|--|
| Symbol                           | Description  | Symbol          | Description  |
| TS                               | Single row    | TDI             | Two row, double-cone single cups                              |
| TDO                              | Two row, double-cup single-cone adjustable    | TNA             | Two row, double-cup single cone nonadjustable                 |
| TQD, TQI                         | Four row, cup adjusted    |                 |   |
| TAPERED ROLLER BEARINGS — METRIC |  |                 |  |
| Symbol                           | Description  | Symbol          | Description  |
| TS                               | Single row, straight bore   | TSF             | Single row, straight bore, flanged cup                        |
| TDO                              | Double row, straight bore, two single cones, one double cup with lubrication hole and groove  | 2TS             | Double row, straight bore, two single cones, two single cups  |
| THRUST TAPERED ROLLER BEARINGS   |  |                 |  |
|                                  | Symbol   | Description     |  |
|                                  | TT   | Thrust bearings |    |

tic of several types of needle bearings is the absence of a cage or separator for retaining the individual rollers. Needle bearings may be divided into three classes: loose-roller, outer race and retained roller, and non-separable units.










**Loose-roller:** This type of bearing has no integral races or retaining members, the needles being located directly between the shaft and the outer bearing bore. Usually both shaft and outer bore bearing surfaces are hardened and retaining members that have smooth unbroken surfaces are provided to prevent endwise movement. Compactness and high radial load capacity are features of this type.

**Outer Race and Retained Roller:** There are two types of outer race and retained roller bearings. In the *Drawn Shell* type, the needle rollers are enclosed by a hardened shell that acts as a retaining member and as a hardened outer race. The needles roll directly on the shaft, the bearing surface of which should be hardened. The capacity for given roller length and shaft diameter is about two-thirds that of the loose roller type. It is mounted in the housing with a press fit.

In the *Machined Race* type, the outer race consists of a heavy machined member. Various modifications of this type provide heavy ends or faces for end location of the needle rollers, or open end construction with end washers for roller retention, or a cage that maintains alignment of the rollers and is itself held in place by retaining rings. An auxiliary outer member with spherical seat that holds the outer race may be provided for self-alignment.



**Table 1g. Types of Rolling Element Bearings and Their Symbols**

| NEEDLE ROLLER BEARINGS, DRAWN CUP |   |   |  |  |   |
|-----------------------------------|---|---|--|--|---|
| Symbol <sup>a</sup>               | Description   |   | Symbol <sup>a</sup>  | Description  |   |
| NIB<br>NB                         | Needle roller bearing, full complement, drawn cup, without inner ring                                 |  | NIYM<br>NYM  | Needle roller bearing, full complement, rollers retained by lubricant, drawn cup, closed end, without inner ring |  |
| NIBM<br>NBM                       | Needle roller bearing, full complement, drawn cup, closed end, without inner ring                     |  | NIH<br>NH  | Needle roller bearing, with cage, drawn cup, without inner ring  |  |
| NIY<br>NY                         | Needle roller bearing, full complement, rollers retained by lubricant, drawn cup, without inner ring  |  | NIHM<br>NHM  | Needle roller bearing, with cage, drawn cup, closed end, without inner ring                                      |  |
| NEEDLE ROLLER BEARINGS            |   |   | NEEDLE ROLLER AND CAGE ASSEMBLIES  |  |   |
| Symbol <sup>a</sup>               | Description   |   | Symbol <sup>a</sup>  | Description  |   |
| NIA<br>NA                         | Needle roller bearing, with cage, machined ring lubrication hole and groove in OD, without inner ring |  | NIM<br>NM  | Needle roller and cage assembly  |  |
| NEEDLE ROLLER BEARING INNER RINGS |   |   | Machined Ring Needle Roller Bearings Type NIA may be used with inch dimensioned inner rings, Type NIR, and Type NA may be used with metric dimensional inner rings, Type NR. |  |   |
| Symbol <sup>a</sup>               | Description   |   |  |  |   |
| NIR<br>NR                         | Needle roller bearing inner ring, lubrication hole and groove in bore                                 |  |  |  |   |

<sup>a</sup> Symbols with I, as NIB, are inch-dimensioned, and those without the I, as NB, are metric dimensioned.

This type is applicable where split housings occur or where a press fit of the bearing into the housing is not possible.

**Non-separable:** This type consists of a non-separable unit of outer race, rollers and inner race. These bearings are used where high static or oscillating motion loads are expected as in certain aircraft components and where both outer and inner races are necessary.

**Special or Unconventional Types.**—Rolling contact bearings have been developed for many highly specialized applications. They may be constructed of non-corrosive materials, non-magnetic materials, plastics, ceramics, and even wood. Although the materials are chosen to adapt more conventional configurations to difficult applications or environments, even greater ingenuity has been applied in utilizing rolling contact for solving particular problems. Thus, linear or recirculating bearings are available to provide low friction, accurate location, and simplified lubrication features to such applications as machine ways, axial motion devices, jack-screws, steering linkages, collets, and chucks. This type of bearing utilizes the “full-complement” style of loading the rolling elements between “races” or ways without a cage and with each element advancing by the action of “races” in the loaded areas and by contact with the adjacent element in the unloaded areas. The “races” may not be cylindrical or bodies of revolution but plane surfaces, with suitable interruptions to free the rolling elements so that they can follow a return trough or slot back to the entry-point at the start of the “race” contact area. Combinations of radial and thrust bearings are available for the user with special requirements.

**Plastics Bearings.**—A more recent development has been the use of Acetal resin rollers and balls in applications where abrasive, corrosive and difficult-to-lubricate conditions exist. Although these bearings do not have the load carrying capacity nor the low friction factor of their hard steel counterparts, they do offer freedom from indentation, wear, and corrosion, while at the same time providing significant weight savings.

Of additional value are: 1) their resistance to indentation from shock loads or oscillation; and 2) their self-lubricating properties.

Usually these bearings are not available from stock, but must be designed and produced in accordance with the data made available by the plastics processor.

**Pillow Block and Flanged Housing Bearings.**—Of great interest to the shop man and particularly adaptable to “line-shafting” applications are a series of ball and roller bearings supplied with their own housings, adapters, and seals. Often called pre-mounted bearings, they come with a wide variety of flange mountings permitting location on faces parallel to or perpendicular to the shaft axis.

Inner races can be mounted directly on ground shafts, or can be adapter-mounted to “drill-rod” or to commercial shafting. For installations sensitive to imbalance and vibration, the use of accurately ground shaft seats is recommended.

Most pillow block designs incorporate self-aligning types of bearings so they do not require the precision mountings utilized with more normal bearing installations.

**Conventional Bearing Materials.**—Most rolling contact bearings are made with all load carrying members of full hard steel, either through- or case-hardened. For greater reliability this material is controlled and selected for cleanliness and alloying practices in conformity with rigid specifications in order to reduce anomalies and inclusions that could limit the useful fatigue life. Magnaflux inspection is employed to ensure that elements are free from both material defects and cracks. Likewise, a light etch is employed between rough and finish grinding to allow detection of burns due to heavy stock removal and associated decarburization in finished pieces.

**Cage Materials.**—Standard bearings are normally made with cages of free-machining brass or low carbon sulfurized steel. In high-speed applications or where lubrication may be intermittent or marginal, special materials may be employed. Iron-silicon-bronze, laminated phenolics, silver-plating, over-lays, solid-film baked-on coatings, carbon-graphite inserts, and, in extreme cases, sintered or even impregnated materials are used in separators.

Commercial bearings usually rely on stamped steel with or without a phosphate treatment; some low cost varieties are found with snap-in plastic or metallic cages.

So long as lubrication is adequate and speeds are both reasonable and steady, the materials and design of the cage are of secondary importance when compared with those of the rolling elements and their contacts with the races. In spite of this tolerance, a good portion of all rolling bearing failures encountered can be traced to cage failures resulting from inadequate lubrication. It can never be overemphasized that *no bearing can be designed to run continuously without lubrication!*

**Standard Method of Bearing Designation.**—The Anti-Friction Bearing Manufacturers Association has adopted a standard identification code that provides a specific designation for each different ball, roller, and needle bearing. Thus, for any given bearing, a uniform designation is provided for manufacturer and user alike, so that the confusion of different company designations can be avoided.

In this identification code there is a “basic number” for each bearing that consists of three elements: a one- to four-digit number to indicate the size of the bore in numbers of millimeters (metric series); a two- or three-letter symbol to indicate the type of bearing; and a two-digit number to identify the dimension series to which the bearing belongs.

In addition to this “basic number” other numbers and letters are added to designate type of tolerance, cage, lubrication, fit up, ring modification, addition of shields, seals, mounting accessories, etc. Thus, a complete designating symbol might be *50BC02JPXE0A10*, for example. The basic number is *50BC02* and the remainder is the supplementary number. For a radial bearing, this latter consists of up to four letters to indicate modification of design, one or two digits to indicate internal fit and tolerances, a letter to indicate lubricants and preservatives, and up to three digits to indicate special requirements.

For a thrust bearing the supplementary number would consist of two letters to indicate modifications of design, one digit to indicate tolerances, one letter to indicate lubricants and preservatives, and up to three digits to indicate special requirements.

For a needle bearing the supplementary number would consist of up to three letters indicating cage material or integral seal information or whether the outer ring has a crowned outside surface and one letter to indicate lubricants or preservatives.

*Dimension Series:* Annular ball, cylindrical roller, and self-aligning roller bearings are made in a series of different outside diameters for every given bore diameter and in a series of different widths for every given outside diameter. Thus, each of these bearings belongs to a dimension series that is designated by a two-digit number such as 08, 23, 93, etc. The first digit (8, 0, 1, 2, 3, 4, 5, 6 and 9) indicates the *width series* and the second digit (7, 8, 9, 0, 1, 2, 3, and 4) the *diameter series* to which the bearing belongs. Similar types of identification codes are used for ball and roller thrust bearings and needle roller bearings.

### Bearing Tolerances

**Ball and Roller Bearings.**—In order to provide standards of precision for proper application of ball or roller bearings in all types of equipment, five classes of tolerances have been established by the Anti-Friction Bearing Manufacturers Association for ball bearings, three for cylindrical roller bearings and one for spherical roller bearings. These tolerances are given in [Tables 2, 3, 4, 5, and 6](#). They are designated as ABEC-1, ABEC-3, ABEC-5, ABEC-7 and ABEC-9 for ball bearings, the ABEC-9 being the most precise, RBEC-1, RBEC-3, and RBEC-5 for roller bearings. In general, bearings to specifications closer than ABEC-1 or RBEC-1 are required because of the need for very precise fits on shaft or housing, to reduce eccentricity or runout of shaft or supported part, or to permit operation at very high speeds. All five classes include tolerances for bore, outside diameter, ring width, and radial runouts of inner and outer rings. ABEC-5, ABEC-7 and ABEC-9 provide added tolerances for parallelism of sides, side runout and groove parallelism with sides.

**Thrust Bearings.**—Anti-Friction Bearing Manufacturers Association and American National Standard tolerance limits for metric single direction thrust ball and roller bearings are given in [Table 8](#). Tolerance limits for single direction thrust ball bearings, inch dimensioned are given in [Table 7](#), and for cylindrical thrust roller bearings, inch dimensioned in [Table 9](#).

Only one class of tolerance limits is established for metric thrust bearings.

**Radial Needle Roller Bearings.**—Tolerance limits for needle roller bearings, drawn cup, without inner ring, inch types NIB, NIBM, NIY, NIYM, NIH, and NIHM are given in [Table 10](#) and for metric types NB, NBM, NY, NYM, NH and NHM in [Table 11](#). Standard tolerance limits for needle roller bearings, with cage, machined ring, without inner ring, inch type NIA are given in [Table 12](#) and for needle roller bearings inner rings, inch type NIR in [Table 13](#).

**Table 2. ABEC-1 and RBEC-1 Tolerance Limits for Metric Ball and Roller Bearings ANSI/ABMA 20-1987**

| Basic Inner Ring Bore Diameter, $d$ |       | $V_{dp}$ <sup>a</sup> max |     |       | $\Delta_{dmp}$ <sup>b</sup> |     | $K_{ia}$ <sup>c</sup> |
|-------------------------------------|-------|---------------------------|-----|-------|-----------------------------|-----|-----------------------|
| mm                                  |       | Diameter Series           |     |       |                             |     |                       |
| Over                                | Incl. | 7,8,9                     | 0,1 | 2,3,4 | High                        | Low | max                   |
| 2.5                                 | 10    | 10                        | 8   | 6     | 0                           | -8  | 10                    |
| 10                                  | 18    | 10                        | 8   | 6     | 0                           | -8  | 10                    |
| 18                                  | 30    | 13                        | 10  | 8     | 0                           | -10 | 13                    |
| 30                                  | 50    | 15                        | 12  | 9     | 0                           | -12 | 15                    |
| 50                                  | 80    | 19                        | 19  | 11    | 0                           | -15 | 20                    |
| 80                                  | 120   | 25                        | 25  | 15    | 0                           | -20 | 25                    |
| 120                                 | 180   | 31                        | 31  | 19    | 0                           | -25 | 30                    |
| 180                                 | 250   | 38                        | 38  | 23    | 0                           | -30 | 40                    |
| 250                                 | 315   | 44                        | 44  | 26    | 0                           | -35 | 50                    |
| 315                                 | 400   | 50                        | 50  | 30    | 0                           | -40 | 60                    |

<sup>a</sup> Bore diameter variation in a single radial plane.

<sup>b</sup> Single plane mean bore diameter deviation from basic. (For a basically tapered bore,  $\Delta_{dmp}$  refers only to the theoretical small end of the bore.)

<sup>c</sup> Radial runout of assembled bearing inner ring.

| Basic Outer Ring Outside Outside Diameter, $D$ |       | $V_{Dp}$ <sup>a</sup> max |     |                              |       | $\Delta_{Dmp}$ <sup>b</sup> |     | $K_{ea}$ <sup>c</sup> |
|--|-------|---------------------------|-----|------------------------------|-------|-----------------------------|-----|-----------------------|
| mm   |       | Open Bearings             |     | Capped Bearings <sup>d</sup> |       |                             |     |                       |
| Over   | Incl. | 7,8,9                     | 0,1 | 2,3,4                        | 2,3,4 | High                        | Low | max                   |
| 6  | 18    | 10                        | 8   | 6                            | 10    | 0                           | -8  | 15                    |
| 18   | 30    | 12                        | 9   | 7                            | 12    | 0                           | -9  | 15                    |
| 30   | 50    | 14                        | 11  | 8                            | 16    | 0                           | -11 | 20                    |
| 50   | 80    | 16                        | 13  | 10                           | 20    | 0                           | -13 | 25                    |
| 80   | 120   | 19                        | 19  | 11                           | 26    | 0                           | -15 | 35                    |
| 120  | 150   | 23                        | 23  | 14                           | 30    | 0                           | -18 | 40                    |
| 150  | 180   | 31                        | 31  | 19                           | 38    | 0                           | -25 | 45                    |
| 180  | 250   | 38                        | 38  | 23                           | ...   | 0                           | -30 | 50                    |
| 250  | 315   | 44                        | 44  | 26                           | ...   | 0                           | -35 | 60                    |
| 315  | 400   | 50                        | 50  | 30                           | ...   | 0                           | -40 | 70                    |

<sup>a</sup> Outside diameter variation in a single radial plane. Applies before mounting and after removal of internal or external snap ring.

<sup>b</sup> Single plane mean outside diameter deviation from basic.

<sup>c</sup> Radial runout of assembled bearing outer ring.

<sup>d</sup> No values have been established for diameters series 7, 8, 9, 0, and 1.

| Width Tolerances |       |                            |        |                       |      |       |                            |        |                       |
|------------------|-------|----------------------------|--------|-----------------------|------|-------|----------------------------|--------|-----------------------|
| $d$              |       | $\Delta_{Bs}$ <sup>a</sup> |        |                       | $d$  |       | $\Delta_{Bs}$ <sup>a</sup> |        |                       |
| mm               |       | All                        | Normal | Modified <sup>b</sup> | mm   |       | All                        | Normal | Modified <sup>b</sup> |
| Over             | Incl. | High                       | Low    |                       | Over | Incl. | High                       | Low    |                       |
| 2.5              | 10    | 0                          | -120   | -250                  | 80   | 120   | 0                          | -200   | -380                  |
| 10               | 18    | 0                          | -120   | -250                  | 120  | 180   | 0                          | -250   | -500                  |
| 18               | 30    | 0                          | -120   | -250                  | 180  | 250   | 0                          | -300   | -500                  |
| 30               | 50    | 0                          | -120   | -250                  | 250  | 315   | 0                          | -350   | -500                  |
| 50               | 80    | 0                          | -150   | -380                  | 315  | 400   | 0                          | -400   | -630                  |

<sup>a</sup> Single inner ring width deviation from basic.  $\Delta_{Cs}$  (single outer ring width deviation from basic) is identical to  $\Delta_{Bs}$  of inner ring of same bearing.

<sup>b</sup> Refers to the rings of single bearings made for paired or stack mounting.

All units are micrometers, unless otherwise indicated. For sizes beyond range of this table, see Standard. This table does not cover tapered roller bearings.

**Table 3. ABEC-3 AND RBEC-3 Tolerance Limits for Metric Ball and Roller Bearings ANSI/ABMA 20-1987**

| Basic Inner Ring Bore Diameter, $d$ |       | $V_{dp}$ <sup>a</sup> max |      |         | $\Delta_{dmp}$ <sup>b</sup> |     | $K_{ia}$ <sup>c</sup> |
|-------------------------------------|-------|---------------------------|------|---------|-----------------------------|-----|-----------------------|
| mm                                  |       | Diameter Series           |      |         |                             |     |                       |
| Over                                | Incl. | 7, 8, 9                   | 0, 1 | 2, 3, 4 | High                        | Low | max                   |
| 2.5                                 | 10    | 9                         | 7    | 5       | 0                           | -7  | 6                     |
| 10                                  | 18    | 9                         | 7    | 5       | 0                           | -7  | 7                     |
| 18                                  | 30    | 10                        | 8    | 6       | 0                           | -8  | 8                     |
| 30                                  | 50    | 13                        | 10   | 8       | 0                           | -10 | 10                    |
| 50                                  | 80    | 15                        | 15   | 9       | 0                           | -12 | 10                    |
| 80                                  | 120   | 19                        | 19   | 11      | 0                           | -15 | 13                    |
| 120                                 | 180   | 23                        | 23   | 14      | 0                           | -18 | 18                    |
| 180                                 | 250   | 28                        | 28   | 17      | 0                           | -22 | 20                    |
| 250                                 | 315   | 31                        | 31   | 19      | 0                           | -25 | 25                    |
| 315                                 | 400   | 38                        | 38   | 23      | 0                           | -30 | 30                    |

<sup>a</sup> Bore diameter variation in a single radial plane.

<sup>b</sup> Single plane mean bore diameter deviation from basic. (For a basically tapered bore,  $\Delta_{dmp}$  refers only to the theoretical small end of the bore.)

<sup>c</sup> Radial runout of assembled bearing inner ring.

| Basic Outer Ring Outside Outsider Diameter, $D$ |       | $V_{Dp}$ <sup>a</sup> max |     |                              |       | $\Delta_{Dmp}$ <sup>b</sup> |     | $K_{ea}$ <sup>c</sup> |
|---|-------|---------------------------|-----|------------------------------|-------|-----------------------------|-----|-----------------------|
| mm  |       | Open Bearings             |     | Capped Bearings <sup>d</sup> |       |                             |     |                       |
| Over  | Incl. | 7,8,9                     | 0,1 | 2,3,4                        | 2,3,4 | High                        | Low | max                   |
| 6   | 18    | 9                         | 7   | 5                            | 9     | 0                           | -7  | 8                     |
| 18  | 30    | 10                        | 8   | 6                            | 10    | 0                           | -8  | 9                     |
| 30  | 50    | 11                        | 9   | 7                            | 13    | 0                           | -9  | 10                    |
| 50  | 80    | 14                        | 11  | 8                            | 16    | 0                           | -11 | 13                    |
| 80  | 120   | 16                        | 16  | 10                           | 20    | 0                           | -13 | 18                    |
| 120   | 150   | 19                        | 19  | 11                           | 25    | 0                           | -15 | 20                    |
| 150   | 180   | 23                        | 23  | 14                           | 30    | 0                           | -18 | 23                    |
| 180   | 250   | 25                        | 25  | 15                           | ...   | 0                           | -20 | 25                    |
| 250   | 315   | 31                        | 31  | 19                           | ...   | 0                           | -25 | 30                    |
| 315   | 400   | 35                        | 35  | 21                           | ...   | 0                           | -28 | 35                    |

<sup>a</sup> Outside diameter variation in a single radial plane. Applies before mounting and after removal of internal or external snap ring.

<sup>b</sup> Single plane mean outside diameter deviation from basic.

<sup>c</sup> Radial runout of assembled bearing outer ring.

<sup>d</sup> No values have been established for diameter series 7, 8, 9, 0, and 1.

| Width Tolerances |       |                            |        |                       |      |       |                            |        |                       |
|------------------|-------|----------------------------|--------|-----------------------|------|-------|----------------------------|--------|-----------------------|
| $d$              |       | $\Delta_{Bs}$ <sup>a</sup> |        |                       | $d$  |       | $\Delta_{Bs}$ <sup>a</sup> |        |                       |
| mm               |       | All                        | Normal | Modified <sup>b</sup> | mm   |       | All                        | Normal | Modified <sup>b</sup> |
| Over             | Incl. | High                       | Low    |                       | Over | Incl. | High                       | Low    |                       |
| 2.5              | 10    | 0                          | -120   | -250                  | 80   | 120   | 0                          | -200   | -380                  |
| 10               | 18    | 0                          | -120   | -250                  | 120  | 180   | 0                          | -250   | -500                  |
| 18               | 30    | 0                          | -120   | -250                  | 180  | 250   | 0                          | -300   | -500                  |
| 30               | 50    | 0                          | -120   | -250                  | 250  | 315   | 0                          | -350   | -500                  |
| 50               | 80    | 0                          | -150   | -380                  | 315  | 400   | 0                          | -400   | -630                  |

<sup>a</sup> Single inner ring width deviation from basic.  $\Delta_{Cs}$  (single outer ring width deviation from basic) is identical to  $\Delta_{Bs}$  of inner ring of same bearing.

<sup>b</sup> Refers to the rings of single bearings made for paired or stack mounting.

All units are micrometers, unless otherwise indicated. For sizes beyond range of this table, see Standard. This table does not cover tapered roller bearings.

**Table 4. ABEC-5 and RBEC-5 Tolerance Limits for Metric Ball and Roller Bearings ANSI/ABMA 20-1987**

| INNER RING                               |       |  |               |                             |     |                              |   |  |                            |        |                       |     |
|--|-------|--|---------------|-----------------------------|-----|------------------------------|---|--|----------------------------|--------|-----------------------|-----|
| Inner Ring Bore<br>Basic Dia., $d$<br>mm |       | $V_{dp}$ <sup>a</sup> max<br>Diameter Series |               | $\Delta_{dmp}$ <sup>b</sup> |     | Radial<br>Runout<br>$K_{ia}$ | Ref. Face<br>Runout<br>with Bore<br>$S_d$ | Axial<br>Runout<br>$S_{ia}$ <sup>c</sup> | Width                      |        |                       |     |
|  |       |  |               |                             |     |                              |   |  | $\Delta_{Bs}$ <sup>d</sup> |        | $V_{Bs}$ <sup>e</sup> |     |
| Over                                     | Incl. | 7, 8, 9                                      | 0, 1, 2, 3, 4 | High                        | Low | max                          | max                                       | max                                      | All                        | Normal | Modified <sup>f</sup> | max |
| 2.5                                      | 10    | 5  | 4             | 0                           | -5  | 4                            | 7   | 7  | 0                          | -40    | -250                  | 5   |
| 10                                       | 18    | 5  | 4             | 0                           | -5  | 4                            | 7   | 7  | 0                          | -80    | -250                  | 5   |
| 18                                       | 30    | 6  | 5             | 0                           | -6  | 4                            | 8   | 8  | 0                          | -120   | -250                  | 5   |
| 30                                       | 50    | 8  | 6             | 0                           | -8  | 5                            | 8   | 8  | 0                          | -120   | -250                  | 5   |
| 50                                       | 80    | 9  | 7             | 0                           | -9  | 5                            | 8   | 8  | 0                          | -150   | -250                  | 6   |
| 80                                       | 120   | 10   | 8             | 0                           | -10 | 6                            | 9   | 9  | 0                          | -200   | -380                  | 7   |
| 120                                      | 180   | 13   | 10            | 0                           | -13 | 8                            | 10  | 10                                       | 0                          | -250   | -380                  | 8   |
| 180                                      | 250   | 15   | 12            | 0                           | -15 | 10                           | 11  | 13                                       | 0                          | -300   | -500                  | 10  |

<sup>a</sup> Bore ( $V_{dp}$ ) and outside diameter ( $V_{Dp}$ ) variation in a single radial plane.

<sup>b</sup> Single plane mean bore ( $\Delta_{dmp}$ ) and outside diameter ( $\Delta_{Dmp}$ ) deviation from basic. (For a basically tapered bore,  $\Delta_{dmp}$  refers only to the theoretical small end of the bore.)

<sup>c</sup> Axial runout of assembled bearing with inner ring  $S_{ia}$ . Applies to groove-type ball bearings only.

<sup>d</sup> Single bore ( $\Delta_{Bs}$ ) and outer ring ( $\Delta_{Cs}$ ) width variation.

<sup>e</sup> Inner ( $V_{Bs}$ ) and outer ( $V_{Cs}$ ) ring width deviation from basic.

<sup>f</sup> Applies to the rings of single bearings made for paired or stack mounting.

| OUTER RING                                  |       |  |               |                             |     |                              |  |  |                            |     |                       |
|---|-------|--|---------------|-----------------------------|-----|------------------------------|--|--|----------------------------|-----|-----------------------|
| Basic Outer Ring<br>Outside Dia., $D$<br>mm |       | $V_{Dp}$ <sup>a</sup> max<br>Diameter Series |               | $\Delta_{Dmp}$ <sup>b</sup> |     | Radial<br>Runout<br>$K_{ea}$ | Outside<br>Cylindrical<br>Surface Runout<br>$S_D$ <sup>b</sup> | Axial<br>Runout<br>$S_{ea}$ <sup>c</sup> | Width                      |     |                       |
|   |       |  |               |                             |     |                              |  |  | $\Delta_{Cs}$ <sup>d</sup> |     | $V_{Cs}$ <sup>e</sup> |
| Over  | Incl. | 7, 8, 9                                      | 0, 1, 2, 3, 4 | High                        | Low | max                          | max  | max                                      | High                       | Low | max                   |
| 6   | 18    | 5  | 4             | 0                           | -5  | 5                            | 8  | 8  |                            |     | 5                     |
| 18  | 30    | 6  | 5             | 0                           | -6  | 6                            | 8  | 8  |                            |     | 5                     |
| 30  | 50    | 7  | 5             | 0                           | -7  | 7                            | 8  | 8  |                            |     | 5                     |
| 50  | 80    | 9  | 7             | 0                           | -9  | 8                            | 8  | 10                                       |                            |     | 6                     |
| 80  | 120   | 10   | 8             | 0                           | -10 | 10                           | 9  | 11                                       |                            |     | 8                     |
| 120   | 150   | 11   | 8             | 0                           | -11 | 11                           | 10   | 13                                       |                            |     | 8                     |
| 150   | 180   | 13   | 10            | 0                           | -13 | 13                           | 10   | 14                                       |                            |     | 8                     |
| 180   | 250   | 15   | 11            | 0                           | -15 | 15                           | 11   | 15                                       |                            |     | 10                    |

<sup>a</sup> No values have been established for capped bearings.

<sup>b</sup> Outside cylindrical surface runout with outer ring reference face  $S_D$ .

<sup>c</sup> Axial runout of assembled bearing with outer ring  $S_{ea}$ .

All units are micrometers, unless otherwise indicated. For sizes beyond range of this table, see Standard. This table does not cover instrument bearings and tapered roller bearings.

**Table 5. ABEC-7 Tolerance Limits for Metric Ball and Roller Bearings ANSI/ABMA 20-1987**

| INNER RING                             |       |   |               |                             |     |                            |     |                        |                                  |                                    |       |        |                       |                           |
|--|-------|---|---------------|-----------------------------|-----|----------------------------|-----|------------------------|----------------------------------|------------------------------------|-------|--------|-----------------------|---------------------------|
| Inner Ring Bore Basic Diameter, $d$ mm |       | $V_{dp}$ <sup>a</sup> max Diameter Series |               | $\Delta_{dmp}$ <sup>b</sup> |     | $\Delta_{ds}$ <sup>c</sup> |     | Radial Runout $K_{ia}$ | Ref. Face Runout with Bore $S_d$ | Axial Runout $S_{ia}$ <sup>d</sup> | Width |        |                       |                           |
| Over                                   | Incl. | 7, 8, 9                                   | 0, 1, 2, 3, 4 | High                        | Low | High                       | Low | max                    | max                              | max                                | All   | Normal | Modified <sup>g</sup> | $V_{Bs}$ <sup>f</sup> max |
| 2.5                                    | 10    | 4   | 3             | 0                           | -4  | 0                          | -4  | 2.5                    | 3                                | 3                                  | 0     | -40    | -250                  | 2.5                       |
| 10                                     | 18    | 4   | 3             | 0                           | -4  | 0                          | -4  | 2.5                    | 3                                | 3                                  | 0     | -80    | -250                  | 2.5                       |
| 18                                     | 30    | 5   | 4             | 0                           | -5  | 0                          | -5  | 3                      | 4                                | 4                                  | 0     | -120   | -250                  | 2.5                       |
| 30                                     | 50    | 6   | 5             | 0                           | -6  | 0                          | -6  | 4                      | 4                                | 4                                  | 0     | -120   | -250                  | 3                         |
| 50                                     | 80    | 7   | 5             | 0                           | -7  | 0                          | -7  | 4                      | 5                                | 5                                  | 0     | -150   | -250                  | 4                         |
| 80                                     | 120   | 8   | 6             | 0                           | -8  | 0                          | -8  | 5                      | 5                                | 5                                  | 0     | -200   | -380                  | 4                         |
| 120                                    | 180   | 10  | 8             | 0                           | -10 | 0                          | -10 | 6                      | 6                                | 7                                  | 0     | -250   | -380                  | 5                         |
| 180                                    | 250   | 12  | 9             | 0                           | -12 | 0                          | -12 | 8                      | 7                                | 8                                  | 0     | -300   | -500                  | 6                         |

<sup>a</sup> Bore ( $V_{dp}$ ) and outside diameter ( $V_{Dp}$ ) variation in a single radial plane.

<sup>b</sup> Single plane mean bore ( $\Delta_{dmp}$ ) and outside diameter ( $\Delta_{Dmp}$ ) deviation from basic. (For a basically tapered bore,  $\Delta_{dmp}$  refers only to the theoretical small end of the bore.)

<sup>c</sup> Single bore ( $\Delta_{ds}$ ) and outside diameter ( $\Delta_{Ds}$ ) deviations from basic. These deviations apply to diameter series 0, 1, 2, 3, and 4 only.

<sup>d</sup> Axial run out of assembled bearing with inner ring  $S_{ia}$ . Applies to groove-type ball bearings only.

<sup>e</sup> Single bore ( $\Delta_{Bs}$ ) and outer ring ( $\Delta_{Cs}$ ) width deviation from basic.

<sup>f</sup> Inner ( $V_{Bs}$ ) and outer ( $V_{Cs}$ ) ring width variation.

<sup>g</sup> Applies to the rings of single bearings made for paired or stack mounting.

| OUTER RING                            |       |   |               |                             |     |                            |     |                        |                                   |                                    |       |     |     |
|---------------------------------------|-------|---|---------------|-----------------------------|-----|----------------------------|-----|------------------------|-----------------------------------|------------------------------------|-------|-----|-----|
| Basic Outer Ring Outside Dia., $D$ mm |       | $V_{Dp}$ <sup>a</sup> max Diameter Series |               | $\Delta_{Dmp}$ <sup>b</sup> |     | $\Delta_{Ds}$ <sup>c</sup> |     | Radial Runout $K_{ea}$ | Surface Runout $S_D$ <sup>d</sup> | Axial Runout $S_{ea}$ <sup>e</sup> | Width |     |     |
| Over                                  | Incl. | 7, 8, 9                                   | 0, 1, 2, 3, 4 | High                        | Low | High                       | Low | max                    | max                               | max                                | High  | Low | max |
| 6                                     | 18    | 4   | 3             | 0                           | -4  | 0                          | -4  | 3                      | 4                                 | 5                                  |       |     | 2.5 |
| 18                                    | 30    | 5   | 4             | 0                           | -5  | 0                          | -5  | 4                      | 4                                 | 5                                  |       |     | 2.5 |
| 30                                    | 50    | 6   | 5             | 0                           | -6  | 0                          | -6  | 5                      | 4                                 | 5                                  |       |     | 2.5 |
| 50                                    | 80    | 7   | 5             | 0                           | -7  | 0                          | -7  | 5                      | 4                                 | 5                                  |       |     | 3   |
| 80                                    | 120   | 8   | 6             | 0                           | -8  | 0                          | -8  | 6                      | 5                                 | 6                                  |       |     | 4   |
| 120                                   | 150   | 9   | 7             | 0                           | -9  | 0                          | -9  | 7                      | 5                                 | 7                                  |       |     | 5   |
| 150                                   | 180   | 10  | 8             | 0                           | -10 | 0                          | -10 | 8                      | 5                                 | 8                                  |       |     | 5   |
| 180                                   | 250   | 11  | 8             | 0                           | -11 | 0                          | -11 | 19                     | 7                                 | 10                                 |       |     | 7   |

<sup>a</sup> No values have been established for capped bearings.

<sup>b</sup> Single plane mean bore ( $\Delta_{dmp}$ ) and outside diameter ( $\Delta_{Dmp}$ ) deviation from basic. (For a basically tapered bore,  $\Delta_{dmp}$  refers only to the theoretical small end of the bore.)

<sup>c</sup> Single bore ( $\Delta_{ds}$ ) and outside diameter ( $\Delta_{Ds}$ ) deviations from basic. These deviations apply to diameter series 0, 1, 2, 3, and 4 only.

<sup>d</sup> Outside cylindrical surface runout outer ring reference face  $S_D$

<sup>e</sup> Axial run out of assembled bearing with outer ring  $S_{ea}$ . Applies to groove-type ball bearings only.

<sup>f</sup> Single bore ( $\Delta_{Bs}$ ) and outer ring ( $\Delta_{Cs}$ ) width deviation from basic.

<sup>g</sup> Inner ( $V_{Bs}$ ) and outer ( $V_{Cs}$ ) ring width variation.

All units are micrometers, unless otherwise indicated. For sizes beyond range of this table, see Standard. This table does not cover instrument bearings.

**Table 6. ABEC-9 Tolerance Limits for Metric Ball and Roller Bearing ANSI/ABMA 20-1987**

| INNER RING                              |       |                           |                             |      |                            |      |                        |                                  |  |                            |      |                       |
|---|-------|---------------------------|-----------------------------|------|----------------------------|------|------------------------|----------------------------------|--|----------------------------|------|-----------------------|
| Inner Ring Bore Basic Dia., <i>d</i> mm |       | $V_{dp}$ <sup>a</sup> max | $\Delta_{Dmp}$ <sup>b</sup> |      | $\Delta_{Ds}$ <sup>c</sup> |      | Radial Runout $K_{ia}$ | Ref. Face Runout with Bore $S_d$ | Axial Runout of Assembled Bearing with Inner Ring $S_{ia}^d$ | Width                      |      |                       |
|   |       |                           |                             |      |                            |      |                        |                                  |  | $\Delta_{Bs}$ <sup>e</sup> |      | $V_{Bs}$ <sup>f</sup> |
| Over                                    | Incl. | max                       | High                        | Low  | High                       | Low  | max                    | max                              | max  | High                       | Low  |                       |
| 2.5                                     | 10    | 2.5                       | 0                           | -2.5 | 0                          | -2.5 | 1.5                    | 1.5                              | 1.5  | 0                          | -40  | 1.5                   |
| 10                                      | 18    | 2.5                       | 0                           | -2.5 | 0                          | -2.5 | 1.5                    | 1.5                              | 1.5  | 0                          | -80  | 1.5                   |
| 18                                      | 30    | 2.5                       | 0                           | -2.5 | 0                          | -2.5 | 2.5                    | 1.5                              | 2.5  | 0                          | -120 | 1.5                   |
| 30                                      | 50    | 2.5                       | 0                           | -2.5 | 0                          | -2.5 | 2.5                    | 1.5                              | 2.5  | 0                          | -120 | 1.5                   |
| 50                                      | 80    | 4                         | 0                           | -4   | 0                          | -4   | 2.5                    | 1.5                              | 2.5  | 0                          | -150 | 1.5                   |
| 50                                      | 80    | 4                         | 0                           | -4   | 0                          | -4   | 2.5                    | 1.5                              | 2.5  | 0                          | -150 | 1.5                   |
| 80                                      | 120   | 5                         | 0                           | -5   | 0                          | -5   | 2.5                    | 2.5                              | 2.5  | 0                          | -200 | 2.5                   |
| 120                                     | 150   | 7                         | 0                           | -7   | 0                          | -7   | 2.5                    | 2.5                              | 2.5  | 0                          | -250 | 2.5                   |
| 150                                     | 180   | 7                         | 0                           | -7   | 0                          | -7   | 5                      | 4                                | 5  | 0                          | -300 | 4                     |
| 180                                     | 250   | 8                         | 0                           | -8   | 0                          | -8   | 5                      | 5                                | 5  | 0                          | -350 | 5                     |

- <sup>a</sup> Bore ( $V_{dp}$ ) and outside diameter ( $V_{Dp}$ ) variation in a single radial plane.
- <sup>b</sup> Single plane mean bore ( $\Delta_{Dmp}$ ) and outside diameter ( $\Delta_{Dmp}$ ) deviation from basic. (For a basically tapered bore,  $\Delta_{Dmp}$  refers to the theoretical small end of the bore.)
- <sup>c</sup> Single bore diameter ( $\Delta_{Ds}$ ) and outside diameter ( $\Delta_{Ds}$ ) deviation from basic.
- <sup>d</sup> Applies to groove-type ball bearings only.
- <sup>e</sup> Single bore ( $\Delta_{Bs}$ ) and outer ring ( $\Delta_{Cs}$ ) width variation from basic.
- <sup>f</sup> Inner ( $V_{Bs}$ ) and outer ( $V_{Cs}$ ) ring width variation.

| OUTER RING                          |       |                       |                             |      |                            |      |                        |  |  |  |     |                       |
|-------------------------------------|-------|-----------------------|-----------------------------|------|----------------------------|------|------------------------|--|--|--|-----|-----------------------|
| Basic Outside Diameter, <i>D</i> mm |       | $V_{Dp}$ <sup>a</sup> | $\Delta_{Dmp}$ <sup>b</sup> |      | $\Delta_{Ds}$ <sup>c</sup> |      | Radial Runout $K_{ea}$ | Outside Cylindrical Surface Runout with Outer Ring $S_D$ | Axial Runout of Assembled Bearing with Outer Ring $S_{ea}$ | Width  |     |                       |
|                                     |       |                       |                             |      |                            |      |                        |  |  | $\Delta_{Cs}$ <sup>e</sup>                               |     | $V_{Cs}$ <sup>f</sup> |
| Over                                | Incl. | max                   | High                        | Low  | High                       | Low  | max                    | max  | max  | High   | Low |                       |
| 6                                   | 18    | 2.5                   | 0                           | -2.5 | 0                          | -2.5 | 1.5                    | 1.5  | 1.5  | Identical to $\Delta_{Bs}$ of inner ring of same bearing |     | 1.5                   |
| 18                                  | 30    | 4                     | 0                           | -4   | 0                          | -4   | 2.5                    | 1.5  | 2.5  |  |     | 1.5                   |
| 30                                  | 50    | 4                     | 0                           | -4   | 0                          | -4   | 2.5                    | 1.5  | 2.5  |  |     | 1.5                   |
| 50                                  | 80    | 4                     | 0                           | -4   | 0                          | -4   | 4                      | 1.5  | 4  |  |     | 1.5                   |
| 80                                  | 120   | 5                     | 0                           | -5   | 0                          | -5   | 5                      | 2.5  | 5  |  |     | 1.5                   |
| 120                                 | 150   | 5                     | 0                           | -5   | 0                          | -5   | 5                      | 2.5  | 5  |  |     | 1.5                   |
| 150                                 | 180   | 7                     | 0                           | -7   | 0                          | -7   | 5                      | 2.5  | 5  |  |     | 2.5                   |
| 180                                 | 250   | 8                     | 0                           | -8   | 0                          | -8   | 7                      | 4  | 7  |  |     | 4                     |
| 250                                 | 315   | 8                     | 0                           | -8   | 0                          | -8   | 7                      | 5  | 7  |  |     | 5                     |

- <sup>a</sup> No values have been established for capped bearings.
- All units are micrometers, unless otherwise indicated. For sizes beyond range of this table, see Standard. This table does not cover instrument bearings.

**Table 7. Tolerance Limits for Single Direction Ball Thrust Bearings—Inch Design ANSI/ABMA 24.2-1998**

| Bore Diameter <sup>a</sup> <i>d</i> , Inches |         | Single Plane Mean Bore Dia. Variation, <i>d</i> , Inch |     | Outside Diameter <i>D</i> , Inches |         | Single Plane Mean O.D. Variation, <i>D</i> , Inch |        |
|--|---------|--|-----|------------------------------------|---------|---|--------|
| Over   | Incl.   | High   | Low | Over                               | Incl.   | High  | Low    |
| 0  | 6.7500  | +0.005   | 0   | 0                                  | 5.3125  | +0  | -0.002 |
| 6.7500                                       | 20.0000 | +0.010   | 0   | 5.3125                             | 17.3750 | +0  | -0.003 |
| ...  | ...     | ...  | ... | 17.3750                            | 39.3701 | +0  | -0.004 |

- <sup>a</sup> Bore tolerance limits: For bore diameters 0 to 1.8125 inches, inclusive, +0.005, -0.005; over 1.8125 to 12.000 inches, inclusive, +0.010, -0.010; over 12.000 to 20.000, inclusive, +0.0150, -0.0150.



**Table 8. AFBMA and American National Standard Tolerance Limits for Metric Single Direction Thrust Ball (Type TA) and Roller Type (Type TS) Bearings ANSI/ABMA 24.1-1989**

| Bore Dia. of Shaft Washer, <i>d</i> |            | $\Delta d_{mp}^a$ |            | $S_r, S_c^b$ | $\Delta T_r Min^c$ |         |         | Outside Dia. of Housing Washer, <i>D</i> |            | $\Delta D_{mp}^a$ |            |
|-------------------------------------|------------|-------------------|------------|--------------|--------------------|---------|---------|--|------------|-------------------|------------|
| mm                                  |            | High              | Low        | Max          | Max                | Type TA | Type TS | Over                                     | Incl.      | High              | Low        |
| 18                                  | 30         | 0                 | -10        | 10           | 20                 | -250    | ...     | 10                                       | 18         | 0                 | -11        |
| <b>30</b>                           | <b>50</b>  | <b>0</b>          | <b>-12</b> | 10           | <b>20</b>          | -250    | -300    | 18                                       | 30         | 0                 | -13        |
| <b>50</b>                           | <b>80</b>  | <b>0</b>          | <b>-15</b> | 10           | <b>20</b>          | -300    | -400    | 30                                       | 50         | 0                 | -16        |
| <b>80</b>                           | <b>120</b> | <b>0</b>          | <b>-20</b> | 15           | <b>25</b>          | -300    | -400    | <b>50</b>                                | <b>80</b>  | <b>0</b>          | <b>-19</b> |
| <b>120</b>                          | <b>180</b> | <b>0</b>          | <b>-25</b> | 15           | <b>25</b>          | -400    | -500    | <b>80</b>                                | <b>120</b> | <b>0</b>          | <b>-22</b> |
| <b>180</b>                          | <b>250</b> | <b>0</b>          | <b>-30</b> | 20           | <b>30</b>          | -400    | -500    | <b>120</b>                               | <b>180</b> | <b>0</b>          | <b>-25</b> |
| <b>250</b>                          | <b>315</b> | <b>0</b>          | <b>-35</b> | 25           | <b>40</b>          | -400    | -700    | <b>180</b>                               | <b>250</b> | <b>0</b>          | <b>-30</b> |
| <b>315</b>                          | <b>400</b> | <b>0</b>          | <b>-40</b> | 30           | <b>40</b>          | -500    | -700    | <b>250</b>                               | <b>315</b> | <b>0</b>          | <b>-35</b> |
| <b>400</b>                          | <b>500</b> | <b>0</b>          | <b>-45</b> | 30           | <b>50</b>          | -500    | -900    | <b>315</b>                               | <b>400</b> | <b>0</b>          | <b>-40</b> |
| <b>500</b>                          | <b>630</b> | <b>0</b>          | <b>-50</b> | 35           | <b>60</b>          | -600    | -1200   | <b>400</b>                               | <b>500</b> | <b>0</b>          | <b>-45</b> |

<sup>a</sup> Single plane mean bore diameter deviation of central shaft washer ( $\Delta d_{mp}$ ) and outside diameter ( $\Delta D_{mp}$ ) variation.

<sup>b</sup> Raceway parallelism with the face, housing-mounted ( $S_r$ ) and boremounted ( $S_c$ ) race or washer.

<sup>c</sup> Deviation of the actual bearing height.

All dimensions in micrometers, unless otherwise indicated. Tolerances are for normal tolerance class only. For sizes beyond the range of this table and for other tolerance class values, see Standard. All entries apply to type TA bearings; boldface entries also apply to type TS bearings.

**Table 9. Tolerance Limits for Cylindrical Roller Thrust Bearings—Inch Design ANSI/ABMA 24.2-1998**

| Basic Bore Dia., <i>d</i>  |        | $\Delta d_{mp}^a$ |        | $\Delta T_r^b$ |        | Basic Outside dia., <i>D</i> |        | $\Delta D_{mp}^c$ |        |
|----------------------------|--------|-------------------|--------|----------------|--------|------------------------------|--------|-------------------|--------|
| Over                       | Incl.  | Low               | High   | High           | Low    | Over                         | Incl.  | High              | Low    |
| EXTRA LIGHT SERIES—TYPE TP |        |                   |        |                |        |                              |        |                   |        |
| 0                          | 0.9375 | +0.040            | +0.060 | +0.050         | -0.050 | 0                            | 4.7188 | +0                | -0.030 |
| 0.9375                     | 1.9375 | +0.050            | +0.070 | +0.050         | -0.050 | 4.7188                       | 5.2188 | +0                | -0.030 |
| 1.9375                     | 3.0000 | +0.060            | +0.080 | +0.050         | -0.050 | ...                          | ...    | ...               | ...    |
| 3.0000                     | 3.5000 | +0.080            | +0.100 | -0.100         | -0.100 | ...                          | ...    | ...               | ...    |

<sup>a</sup> Single plane mean bore diameter deviation.

<sup>b</sup> Deviation of the actual bearing height, single direction bearing.

<sup>c</sup> Single plane mean outside diameter deviation.

| Basic Bore Diameter, <i>d</i> |         | $\Delta d_{mp}^a$ |        | Basic Outside Diameter, <i>D</i> |         | Outside Dia., <i>D</i> Tolerance Limits |        | Basic Bore Diameter, <i>d</i> |         | $\Delta T_r$ |       |
|-------------------------------|---------|-------------------|--------|----------------------------------|---------|---|--------|-------------------------------|---------|--------------|-------|
| Over                          | Incl.   | High              | Low    | Over                             | Incl.   | High                                    | Low    | Over                          | Incl.   | High         | Low   |
| LIGHT SERIES—TYPE TP          |         |                   |        |                                  |         |   |        |                               |         |              |       |
| 0                             | 1.1870  | +0                | -0.005 | 0                                | 2.8750  | +0.005                                  | -0     | 0                             | 2.0000  | +0           | -0.06 |
| 1.1870                        | 1.3750  | +0                | -0.006 | 2.8750                           | 3.3750  | +0.007                                  | -0     | 2.0000                        | 3.0000  | +0           | -0.08 |
| 1.3750                        | 1.5620  | +0                | -0.007 | 3.3750                           | 3.7500  | +0.009                                  | -0     | 3.0000                        | 6.0000  | +0           | -0.10 |
| 1.5620                        | 1.7500  | +0                | -0.008 | 3.7500                           | 4.1250  | +0.011                                  | -0     | 6.0000                        | 10.0000 | +0           | -0.15 |
| 1.7500                        | 1.9370  | +0                | -0.009 | 4.1250                           | 4.7180  | +0.013                                  | -0     | 10.0000                       | 18.0000 | +0           | -0.20 |
| 1.9370                        | 2.1250  | +0                | -0.010 | 4.7180                           | 5.2180  | +0.015                                  | -0     | 18.0000                       | 30.0000 | +0           | -0.25 |
| 2.1250                        | 2.5000  | +0                | -0.011 | ...                              | ...     | ...                                     | ...    | ...                           | ...     | ...          | ...   |
| 2.2500                        | 3.0000  | +0                | -0.012 | ...                              | ...     | ...                                     | ...    | ...                           | ...     | ...          | ...   |
| 3.0000                        | 3.5000  | +0                | -0.013 | ...                              | ...     | ...                                     | ...    | ...                           | ...     | ...          | ...   |
| HEAVY SERIES—TYPE TP          |         |                   |        |                                  |         |   |        |                               |         |              |       |
| 2.0000                        | 3.0000  | +0                | -0.010 | 5.0000                           | 10.0000 | +0.015                                  | -0     | 0                             | 2.000   | +0           | -0.06 |
| 3.0000                        | 3.5000  | +0                | -0.012 | 10.0000                          | 18.0000 | +0.020                                  | -0     | 2.000                         | 3.000   | +0           | -0.08 |
| 3.5000                        | 9.0000  | +0                | -0.015 | 18.0000                          | 26.0000 | +0.025                                  | -0     | 3.000                         | 6.000   | +0           | -0.10 |
| 9.0000                        | 12.0000 | +0                | -0.018 | 26.0000                          | 34.0000 | +0.030                                  | -0     | 6.000                         | 10.000  | +0           | -0.15 |
| 12.0000                       | 18.0000 | +0                | -0.020 | 34.0000                          | 44.0000 | +0.040                                  | -0     | 10.000                        | 18.000  | +0           | -0.20 |
| 18.0000                       | 22.0000 | +0                | -0.025 | ...                              | ...     | ...                                     | ...    | 18.000                        | 30.000  | +0           | -0.25 |
| 22.0000                       | 30.0000 | +0                | -0.03  | ...                              | ...     | ...                                     | ...    | ...                           | ...     | ...          | ...   |
| TYPE TPC                      |         |                   |        |                                  |         |   |        |                               |         |              |       |
| 0                             | 2.0156  | +0.010            | -0     | 2.5000                           | 4.0000  | +0.005                                  | -0.005 | 0                             | 2.0156  | +0           | -0.08 |
| 2.0156                        | 3.0156  | +0.010            | -0.020 | 4.0000                           | 6.0000  | +0.006                                  | -0.006 | 2.0156                        | 3.0156  | +0           | -0.10 |
| 3.0156                        | 6.0156  | +0.015            | -0.020 | 6.0000                           | 10.0000 | +0.010                                  | -0.010 | 3.0156                        | 6.0156  | +0           | -0.15 |
| 6.0156                        | 10.1560 | +0.015            | -0.050 | 10.0000                          | 18.0000 | +0.012                                  | -0.012 | 6.0156                        | 10.1560 | +0           | -0.20 |

All dimensions are in inches. For Type TR bearings, see Standard.

**Table 10. AFBMA and American National Standard Tolerance Limits for Needle Roller Bearings, Drawn Cup, Without Inner Ring — Inch Types NIB, NIBM, NIY, NIYM, NIH, and NIHM ANSI/ABMA 18.2-1982 (R1993)**

| Ring Gage Bore Diameter <sup>a</sup>            |        |                            | Basic Bore Diameter under Needle Rollers, $F_w$ | Allowable Deviation from $F_w$ <sup>a</sup> |         | Allowable Deviation from Width, $B$ |      |         |
|---|--------|----------------------------|---|---|---------|-------------------------------------|------|---------|
| Basic Outside Diameter, $D$<br>Inch             |        | Deviation from $D$<br>Inch |   | Inch  |         | Inch                                |      |         |
| Over  | Incl.  |                            |   | Over  | Incl.   | Low                                 | High | High    |
| 0.1875  | 0.9375 | +0.0005                    | 0.1875  | 0.6875                                      | +0.0015 | +0.0024                             | +0   | -0.0100 |
| 0.9375  | 4.0000 | -0.0005                    | 0.6875  | 1.2500                                      | +0.0005 | +0.0014                             | +0   | -0.0100 |
| For fitting and mounting practice see Table 19. |        |                            | 1.2500  | 1.3750                                      | +0.0005 | +0.0015                             | +0   | -0.0100 |
|   |        |                            | 1.3750  | 1.6250                                      | +0.0005 | +0.0016                             | +0   | -0.0100 |
|   |        |                            | 1.6250  | 1.8750                                      | +0.0005 | +0.0017                             | +0   | -0.0100 |
|   |        |                            | 1.8750  | 2.0000                                      | +0.0006 | +0.0018                             | +0   | -0.0100 |
|   |        |                            | 2.0000  | 2.5000                                      | +0.0006 | +0.0020                             | +0   | -0.0100 |
|   |        |                            | 2.5000  | 3.5000                                      | +0.0010 | +0.0024                             | +0   | -0.0100 |

<sup>a</sup> The bore diameter under needle rollers can be measured only when bearing is pressed into a ring gage, which rounds and sizes the bearing.

**Table 11. AFBMA and American National Standard Tolerance Limits for Needle Roller Bearings, Drawn Cup, Without Inner Ring — Metric Types NB, NBM, NY, NYM, NH, and NHM ANSI/ABMA 18.1-1982 (R1994)**

| Ring Gage Bore Diameter <sup>a</sup> |       |                                   | Basic Bore Diameter under Needle Rollers, $F_w$ | Allowable Deviation from $F_w$ <sup>a</sup> |       | Allowable Deviation from Width, $B$ |      |      |
|--------------------------------------|-------|-----------------------------------|---|---|-------|-------------------------------------|------|------|
| Basic Outside Diameter, $D$<br>mm    |       | Deviation from $D$<br>Micrometers |   | mm  |       | Micrometers                         |      |      |
| Over                                 | Incl. |                                   |   | Over  | Incl. | Low                                 | High | High |
| 6                                    | 10    | -16                               | 3   | 6   | +10   | +28                                 | +0   | -250 |
| 10                                   | 18    | -20                               | 6   | 10  | +13   | +31                                 | +0   | -250 |
| 30                                   | 50    | -28                               | 18  | 30  | +20   | +41                                 | +0   | -250 |
| 50                                   | 80    | -33                               | 30  | 50  | +25   | +50                                 | +0   | -250 |
| ...                                  | ...   | ...                               | 50  | 70  | +30   | +60                                 | +0   | -250 |

<sup>a</sup> The bore diameter under needle rollers can be measured only when bearing is pressed into a ring gage, which rounds and sizes the bearing.

For fitting and mounting practice, see Table 19.

**Table 12. AFBMA and American National Standard Tolerance Limits for Needle Roller Bearings, With Cage, Machined Ring, Without Inner Ring — Inch Type NIA ANSI/ABMA 18.2-1982 (R1993)**

| Basic Outside Diameter, $D$ |         | Allowable Deviation From $D$ of Single Mean Diameter, $D_{mp}$ |         | Basic Bore Diameter under Needle Rollers, $F_w$ |        | Allowable Deviation from $F_w$ |         | Allowable Deviation from Width, $B$ |         |
|-----------------------------|---------|--|---------|---|--------|--------------------------------|---------|-------------------------------------|---------|
| Inch                        |         | Inch   |         | Inch  |        | Inch                           |         | Inch                                |         |
| Over                        | Incl.   | High   | Low     | Over  | Incl.  | Low                            | High    | High                                | Low     |
| 0.7500                      | 2.0000  | +0   | -0.0005 | 0.3150  | 0.7087 | +0.0008                        | +0.0017 | +0                                  | -0.0050 |
| 2.0000                      | 3.2500  | +0   | -0.0006 | 0.7087  | 1.1811 | +0.0009                        | +0.0018 | +0                                  | -0.0050 |
| 3.2500                      | 4.7500  | +0   | -0.0008 | 1.1811  | 1.6535 | +0.0010                        | +0.0019 | +0                                  | -0.0050 |
| 4.7500                      | 7.2500  | +0   | -0.0010 | 1.6535  | 1.9685 | +0.0010                        | +0.0020 | +0                                  | -0.0050 |
|                             |         |  |         | 1.9685  | 2.7559 | +0.0011                        | +0.0021 | +0                                  | -0.0050 |
| 7.2500                      | 10.2500 | +0   | -0.0012 | 2.7559  | 3.1496 | +0.0011                        | +0.0023 | +0                                  | -0.0050 |
| 10.2500                     | 11.1250 | +0   | -0.0014 | 3.1496  | 4.0157 | +0.0012                        | +0.0024 | +0                                  | -0.0050 |
| ...                         | ...     | ...  | ...     | 4.0157  | 4.7244 | +0.0012                        | +0.0026 | +0                                  | -0.0050 |
| ...                         | ...     | ...  | ...     | 4.7244  | 6.2992 | +0.0013                        | +0.0027 | +0                                  | -0.0050 |
| ...                         | ...     | ...  | ...     | 6.2992  | 7.0866 | +0.0013                        | +0.0029 | +0                                  | -0.0050 |
| ...                         | ...     | ...  | ...     | 7.0866  | 7.8740 | +0.0014                        | +0.0030 | +0                                  | -0.0050 |
| ...                         | ...     | ...  | ...     | 7.8740  | 9.2520 | +0.0014                        | +0.0032 | +0                                  | -0.0050 |

For fitting and mounting practice, see Table 20.

**Table 13. AFBMA and American National Standard Tolerance Limits for Needle Roller Bearing Inner Rings—Inch Type NIR ANSI/ABMA 18.2-1982 (R1993)**

| Basic Outside Diameter, $F$ |        | Allowable Deviation From $F$ of Single Mean Diameter, $F_{mp}$ |         | Basic Bore Diameter $d$ |        | Allowable Deviation from $d$ of Single Mean Diameter, $d_{mp}$ |         | Allowable Deviation from Width, $B$ |         |
|-----------------------------|--------|--|---------|-------------------------|--------|--|---------|-------------------------------------|---------|
| Inch                        |        | Inch   |         | Inch                    |        | Inch   |         | Inch                                |         |
| Over                        | Incl.  | High   | Low     | Over                    | Incl.  | High   | Low     | High                                | Low     |
| 0.3937                      | 0.7087 | -0.0005  | -0.0009 | 0.3125                  | 0.7500 | +0   | -0.0004 | +0.0100                             | +0.0050 |
| 0.7087                      | 1.0236 | -0.0007  | -0.0012 | 0.7500                  | 2.0000 | +0   | -0.0005 | +0.0100                             | +0.0050 |
| 1.0236                      | 1.1811 | -0.0009  | -0.0014 | 2.0000                  | 3.2500 | +0   | -0.0006 | +0.0100                             | +0.0050 |
| 1.1811                      | 1.3780 | -0.0009  | -0.0015 | 3.2500                  | 4.2500 | +0   | -0.0008 | +0.0100                             | +0.0050 |
| 1.3780                      | 1.9685 | -0.0010  | -0.0016 | 4.2500                  | 4.7500 | +0   | -0.0008 | +0.0150                             | +0.0100 |
| 1.9685                      | 3.1496 | -0.0011  | -0.0018 | 4.7500                  | 7.0000 | +0   | -0.0010 | +0.0150                             | +0.0100 |
| 3.1496                      | 3.9370 | -0.0013  | -0.0022 | 7.0000                  | 8.0000 | +0   | -0.0012 | +0.0150                             | +0.0100 |
| 3.9370                      | 4.7244 | -0.0015  | -0.0024 | ...                     | ...    | ...  | ...     | ...                                 | ...     |
| 4.7244                      | 5.5118 | -0.0015  | -0.0025 | ...                     | ...    | ...  | ...     | ...                                 | ...     |
| 5.5118                      | 7.0866 | -0.0017  | -0.0027 | ...                     | ...    | ...  | ...     | ...                                 | ...     |
| 7.0866                      | 8.2677 | -0.0019  | -0.0031 | ...                     | ...    | ...  | ...     | ...                                 | ...     |
| 8.2677                      | 9.2520 | -0.0020  | -0.0032 | ...                     | ...    | ...  | ...     | ...                                 | ...     |

For fitting and mounting practice, see [Table 21](#).

**Metric Radial Ball and Roller Bearing Shaft and Housing Fits.**—To select the proper fits, it is necessary to consider the type and extent of the load, bearing type, and certain other design and performance requirements.

The required shaft and housing fits are indicated in [Tables 14](#) and [15](#). The terms “Light,” “Normal,” and “Heavy” loads refer to radial loads that are generally within the following limits, with some overlap ( $C$  being the Basic Load Rating computed in accordance with AFBMA-ANSI Standards):

| Bearing Type       | Radial Load    |                          |              |
|--------------------|----------------|--------------------------|--------------|
|                    | Light          | Normal                   | Heavy        |
| Ball               | Up to $0.075C$ | From $0.075C$ to $0.15C$ | Over $0.15C$ |
| Cylindrical Roller | Up to $0.075C$ | From $0.075C$ to $0.2C$  | Over $0.15C$ |
| Spherical Roller   | Up to $0.075C$ | From $0.070C$ to $0.25C$ | Over $0.15C$ |

**Shaft Fits:** [Table 14](#) indicates the initial approach to shaft fit selection. Note that for most normal applications where the shaft rotates and the radial load direction is constant, an interference fit should be used. Also, the heavier the load, the greater is the required interference. For stationary shaft conditions and constant radial load direction, the inner ring may be moderately loose on the shaft.

For pure thrust (axial) loading, heavy interference fits are not necessary; only a moderately loose to tight fit is needed.

The upper part of [Table 16](#) shows how the shaft diameters for various ANSI shaft limit classifications deviate from the basic bore diameters.

[Table 17](#) gives metric values for the shaft diameter and housing bore tolerance limits given in [Table 16](#).

The lower parts of [Tables 16](#) and [17](#) show how housing bores for various ANSI hole limit classifications deviate from the basic shaft outside diameters.

**Table 14. Selection of Shaft Tolerance Classifications for Metric Radial Ball and Roller Bearings of ABEC-1 and RBEC-1 Tolerance Classes ANSI/ABMA 7-1995**

| Operating Conditions   |              |  | Ball Bearings          |               | Cylindrical Roller Bearings  |               | Spherical Roller Bearings |                 | Tolerance Symbol <sup>a</sup> |
|--|--------------|--|------------------------|---------------|------------------------------|---------------|---------------------------|-----------------|-------------------------------|
|  |              |  | mm                     | Inch          | mm                           | Inch          | mm                        | Inch            |                               |
| Inner ring stationary in relation to the direction of the load.                                      | All loads    | Inner ring has to be easily displaceable           | All diameters          | All diameters | All diameters                | All diameters | All diameters             | All diameters   | g6                            |
|  |              | Inner ring does not have to be easily displaceable | All diameters          | All diameters | All diameters                | All diameters | All diameters             | All diameters   | h6                            |
| Direction of load indeterminate or the inner ring rotating in relation to the direction of the load. | Radial load: |  | Nominal Shaft Diameter |               |                              |               |                           |                 |                               |
|  | LIGHT        | ≤18  | ≤0.71                  | ≤40           | ≤1.57                        | ≤40           | ≤1.57                     | h5              |                               |
|  |              | >18  | >0.71                  | (40)–140      | (1.57)–5.51                  | (40)–100      | (1.57)–3.94               | j6 <sup>b</sup> |                               |
|  |              |  |                        | (140)–320     | (5.51)–12.6                  | (100)–320     | (3.94)–12.6               | k6 <sup>b</sup> |                               |
|  | NORMAL       |  |                        | (320)–500     | (126)–19.7                   | (320)–500     | (126)–19.7                | m6 <sup>b</sup> |                               |
|  |              |  | >500                   | >19.7         | >500                         | >19.7         | n6                        |                 |                               |
|  |              |  |                        |               |                              |               | p6                        |                 |                               |
| HEAVY  | ≤18          | ≤0.71  | ≤40                    | ≤1.57         | ≤40                          | ≤1.57         | j5                        |                 |                               |
|  | >18          | >0.71  | (40)–100               | (1.57)–3.94   | (40)–65                      | (1.57)–2.56   | k5                        |                 |                               |
|  |              |  | (100)–140              | (3.94)–5.51   | (65)–100                     | (2.56)–3.94   | m5                        |                 |                               |
|  |              | (140)–320  | (5.51)–12.6            | (100)–140     | (3.94)–5.51                  | n6            |                           |                 |                               |
|  |              | (320)–500  | (12.6)–19.7            | (140)–280     | (5.51)–11.0                  | p6            |                           |                 |                               |
|  |              | >500   | >19.7                  | (280)–500     | (11.0)–19.7                  | r6            |                           |                 |                               |
|  |              |  |                        | >500          | >19.7                        | >19.7         | r7                        |                 |                               |
|  |              | (18)–100   | (0.71)–3.94            | ≤40           | ≤1.57                        | ≤40           | ≤1.57                     | k5              |                               |
|  |              | >100   | >3.94                  | (40)–65       | (1.57)–2.56                  | (40)–65       | (1.57)–2.56               | m5              |                               |
|  |              |  |                        | (65)–140      | (2.56)–5.51                  | (65)–100      | (2.56)–3.94               | m6 <sup>b</sup> |                               |
|  |              |  |                        | (140)–200     | (5.51)–7.87                  | (100)–140     | (3.94)–5.51               | n6 <sup>b</sup> |                               |
|  |              |  |                        | (200)–500     | (7.87)–19.7                  | (140)–200     | (5.51)–7.87               | p6 <sup>b</sup> |                               |
|  |              |  |                        | >500          | >19.7                        | >200          | >7.87                     | r6 <sup>b</sup> |                               |
|  |              |  |                        |               |                              |               |                           | r7 <sup>b</sup> |                               |
| Pure Thrust Load   |              |  | All diam.              | All diam.     | Consult Bearing Manufacturer |               |                           |                 | j6                            |

<sup>a</sup> For solid steel shafts. For hollow or nonferrous shafts, tighter fits may be needed.

<sup>b</sup> When greater accuracy is required, use j5, k5, and m5 instead of j6, k6, and m6, respectively.

Numerical values are given in [Tables 16](#) and [17](#).

**Table 15. Selection of Housing Tolerance Classifications for Metric Radial Ball and Roller Bearings of ABEC-1 and RBEC-1 Tolerance Classes**

| Design and Operating Conditions                     |   |  |                               | Tolerance Classification <sup>a</sup> |
|---|---|--|-------------------------------|---------------------------------------|
| Rotational Conditions                               | Loading                                 | Outer Ring Axial Displacement Limitations      | Other Conditions              |                                       |
| Outer ring stationary in relation to load direction | Light<br>Normal<br>and<br>Heavy         | Outer ring must be easily axially displaceable | Heat input through shaft      | G7                                    |
|   |   |  | Housing split axially         | H7 <sup>b</sup>                       |
|   | Shock with temporary complete unloading | Transitional Range <sup>c</sup>                | Housing not split axially     | split housing not recommended         |
| J6 <sup>b</sup>                                     |   |  |                               |                                       |
| Load direction is indeterminate                     | Light and normal                        | Transitional Range <sup>c</sup>                | split housing not recommended | K6 <sup>b</sup>                       |
|   | Normal and Heavy                        |  |                               | M6 <sup>b</sup>                       |
|   | Heavy Shock                             |  |                               | N6 <sup>b</sup>                       |
| Outer ring rotating in relation to load direction   | Light                                   | Outer ring need not be axially displaceable    | Thin wall housing not split   | M6 <sup>b</sup>                       |
|   | Normal and Heavy                        |  |                               | N6 <sup>b</sup>                       |
|   | Heavy                                   | P6 <sup>b</sup>                                |                               |                                       |

<sup>a</sup>For cast iron or steel housings. For housings of nonferrous alloys tighter fits may be needed.

<sup>b</sup>Where wider tolerances are permissible, use tolerance classifications P7, N7, M7, K7, J7, and H7, in place of P6, N6, M6, K6, J6, and H6, respectively.

<sup>c</sup>The tolerance zones are such that the outer ring may be either tight or loose in the housing.

**Table 16. AFBMA and American National Standard Shaft Diameter and Housing Bore Tolerance Limits ANSI/ABMA 7-1995**

| Allowable Deviations of Shaft Diameter from Basic Bore Diameter, Inch           |        |      |       |                  |             |             |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |
|---|--------|------|-------|------------------|-------------|-------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Inches  |        | mm   |       | g6               | h6          | h5          | j5               | j6               | k5               | k6               | m5               | m6               | n6               | p6               | r6               | r7               |
| Over  | Incl.  | Over | Incl. |                  |             |             |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |
| Base Bore Diameter  |        |      |       |                  |             |             |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |
| 0.2362  | 0.3937 | 6    | 10    | -0.002<br>-0.006 | 0<br>-0.004 | 0<br>-0.002 | +0.002<br>-0.001 | +0.003<br>-0.001 | +0.003<br>0      |                  | +0.005<br>+0.002 |                  |                  |                  |                  |                  |
| 0.3937  | 0.7087 | 10   | 18    | -0.002<br>-0.007 | 0<br>-0.004 | 0<br>-0.003 | +0.002<br>-0.001 | +0.003<br>-0.001 | +0.004<br>0      |                  | +0.006<br>+0.003 |                  |                  |                  |                  |                  |
| 0.7087  | 1.1811 | 18   | 30    | -0.003<br>-0.008 | 0<br>-0.005 |             | +0.002<br>-0.002 | +0.004<br>-0.002 | +0.004<br>+0.001 |                  | +0.007<br>+0.003 |                  |                  |                  |                  |                  |
| 1.1811  | 1.9685 | 30   | 50    | -0.004<br>-0.010 | 0<br>-0.006 |             | +0.002<br>-0.002 | +0.004<br>-0.002 | +0.005<br>+0.001 | +0.007<br>+0.001 | +0.008<br>+0.004 | +0.010<br>+0.004 |                  |                  |                  |                  |
| 1.9685  | 3.1496 | 50   | 80    | -0.004<br>-0.011 | 0<br>-0.007 |             | +0.002<br>-0.003 | +0.005<br>-0.003 | +0.006<br>+0.001 | +0.008<br>+0.001 | +0.009<br>+0.004 | +0.012<br>+0.004 | +0.018<br>+0.009 |                  |                  |                  |
| 3.1496  | 4.7244 | 80   | 120   | -0.005<br>-0.013 | 0<br>-0.009 |             | +0.002<br>-0.004 | +0.005<br>-0.004 | +0.007<br>+0.001 | +0.010<br>+0.001 | +0.011<br>+0.005 | +0.014<br>+0.005 | +0.019<br>+0.010 | +0.023<br>+0.015 |                  |                  |
| Allowable Deviations of Housing Bore from Basic Outside Diameter of Shaft, Inch |        |      |       |                  |             |             |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |
| Basic Outside Diameter  |        |      |       | G7               | H7          | H6          | J7               | J6               | K6               | K7               | M6               | M7               | N6               | N7               | P6               | P7               |
| 0.7087  | 1.1811 | 18   | 30    | +0.003<br>+0.011 | 0<br>+0.008 | 0<br>+0.005 | -0.004<br>+0.005 | -0.002<br>+0.003 | -0.004<br>+0.001 | -0.006<br>+0.002 | -0.007<br>+0.002 | -0.008<br>0      | -0.009<br>-0.004 | -0.011<br>-0.003 | -0.012<br>-0.007 | -0.014<br>-0.006 |
| 1.1811  | 1.9685 | 30   | 50    | +0.004<br>+0.013 | 0<br>+0.010 | 0<br>+0.006 | -0.004<br>+0.006 | -0.002<br>+0.004 | -0.005<br>+0.001 | -0.007<br>+0.003 | -0.008<br>-0.002 | -0.010<br>0      | -0.011<br>-0.005 | -0.013<br>-0.003 | -0.015<br>-0.008 | -0.017<br>-0.007 |
| 1.9685  | 3.1496 | 50   | 80    | +0.004<br>+0.016 | 0<br>+0.012 | 0<br>+0.007 | -0.005<br>+0.007 | -0.002<br>+0.005 | -0.006<br>+0.002 | -0.008<br>+0.004 | -0.009<br>-0.002 | -0.012<br>0      | -0.013<br>-0.006 | -0.015<br>-0.004 | -0.018<br>-0.010 | -0.020<br>-0.008 |
| 3.1496  | 4.7244 | 80   | 120   | +0.005<br>+0.019 | 0<br>+0.014 | 0<br>+0.009 | -0.005<br>+0.009 | -0.002<br>+0.006 | -0.007<br>+0.002 | -0.010<br>+0.004 | -0.011<br>-0.002 | -0.014<br>0      | -0.015<br>-0.006 | -0.018<br>-0.004 | -0.020<br>-0.012 | -0.023<br>-0.009 |
| 4.7244  | 7.0866 | 120  | 180   | +0.006<br>+0.021 | 0<br>+0.016 | 0<br>+0.010 | -0.006<br>+0.010 | -0.003<br>+0.007 | -0.008<br>+0.002 | -0.011<br>+0.005 | -0.013<br>-0.003 | -0.016<br>0      | -0.018<br>-0.008 | -0.020<br>-0.005 | -0.024<br>-0.014 | -0.027<br>-0.011 |
| 7.0866  | 9.8425 | 180  | 250   | +0.006<br>+0.024 | 0<br>+0.018 | 0<br>+0.011 | -0.006<br>+0.012 | -0.003<br>+0.009 | -0.009<br>+0.002 | -0.013<br>+0.005 | -0.015<br>-0.003 | -0.018<br>0      | -0.020<br>-0.009 | -0.024<br>-0.006 | -0.028<br>-0.016 | -0.031<br>-0.013 |

Based on ANSI B4.1-1967 (R1994) Preferred Limits and Fits for Cylindrical Parts. Symbols g6, h6, etc., are shaft and G7, H7, etc., hole limits designations. For larger diameters and metric values see AFBMA Standard 7.

**Table 17. AFBMA and American National Standard Shaft Diameter and Housing Bore Tolerance Limits ANSI/ABMA 7-1995**

| Allowable Deviations of Shaft Diameter from Basic Bore Diameter, mm           |        |      |       |                |            |            |                |                |                |                |                |                |                |                |                |                |
|---|--------|------|-------|----------------|------------|------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Inches  |        | mm   |       | g6             | h6         | h5         | j5             | j6             | k5             | k6             | m5             | m6             | n6             | p6             | r6             | r7             |
| Over  | Incl.  | Over | Incl. |                |            |            |                |                |                |                |                |                |                |                |                |                |
| Base Bore Diameter  |        |      |       |                |            |            |                |                |                |                |                |                |                |                |                |                |
| 0.2362  | 0.3937 | 6    | 10    | -0.05<br>-0.14 | 0<br>-0.09 | 0<br>-0.06 | +0.04<br>-0.02 | +0.07<br>-0.02 | +0.07<br>-0.01 |                | +0.12<br>+0.06 |                |                |                |                |                |
| 0.3937  | 0.7087 | 10   | 18    | -0.06<br>-0.17 | 0<br>-0.11 | 0<br>-0.08 | +0.05<br>-0.03 | +0.08<br>-0.03 | +0.09<br>+0.01 |                | +0.15<br>+0.07 |                |                |                |                |                |
| 0.7087  | 1.1811 | 18   | 30    | -0.07<br>-0.20 | 0<br>-0.13 |            | +0.05<br>-0.04 | +0.09<br>-0.04 | +0.11<br>+0.02 |                | +0.17<br>+0.08 |                |                |                |                |                |
| 1.1811  | 1.9685 | 30   | 50    | -0.09<br>-0.25 | 0<br>-0.16 |            | +0.06<br>-0.05 | +0.11<br>-0.05 | +0.13<br>+0.02 | +0.18<br>+0.02 | +0.20<br>+0.09 | +0.25<br>+0.09 |                |                |                |                |
| 1.9685  | 3.1496 | 50   | 80    | -0.10<br>-0.29 | 0<br>-0.19 |            | +0.06<br>-0.07 | +0.12<br>-0.07 | +0.15<br>+0.02 | +0.21<br>+0.02 | +0.24<br>+0.11 | +0.30<br>+0.11 | +0.39<br>+0.20 |                |                |                |
| 3.1496  | 4.7244 | 80   | 120   | -0.12<br>-0.34 | 0<br>-0.22 |            | +0.06<br>-0.09 | +0.13<br>-0.09 | +0.18<br>+0.03 | +0.25<br>+0.03 | +0.28<br>+0.13 | +0.35<br>+0.13 | +0.45<br>+0.23 | +0.59<br>+0.37 |                |                |
| Allowable Deviations of Housing Bore from Basic Outside Diameter of Shaft, mm |        |      |       |                |            |            |                |                |                |                |                |                |                |                |                |                |
| Basic Outside Diameter  |        |      |       | G7             | H7         | H6         | J7             | J6             | K6             | K7             | M6             | M7             | N6             | N7             | P6             | P7             |
| .7086   | 1.1811 | 18   | 30    | +0.07<br>+0.28 | 0<br>+0.21 | 0<br>+0.13 | -0.09<br>+0.12 | -0.05<br>+0.08 | -0.11<br>+0.02 | -0.15<br>+0.06 | -0.17<br>-0.04 | -0.21<br>0     | -0.24<br>-0.11 | -0.28<br>-0.07 | -0.31<br>-0.18 | -0.35<br>-0.14 |
| 1.1811  | 1.9685 | 30   | 50    | +0.09<br>+0.34 | 0<br>+0.25 | 0<br>+0.16 | -0.11<br>+0.14 | -0.06<br>+0.10 | -0.13<br>+0.03 | -0.18<br>+0.07 | -0.20<br>-0.04 | -0.25<br>0     | -0.28<br>-0.12 | -0.33<br>-0.08 | -0.37<br>-0.21 | -0.42<br>-0.17 |
| 1.9685  | 3.1496 | 50   | 80    | +0.10<br>+0.40 | 0<br>+0.30 | 0<br>+0.19 | -0.12<br>+0.18 | -0.06<br>+0.13 | -0.15<br>+0.04 | -0.21<br>+0.09 | -0.24<br>-0.05 | -0.30<br>0     | -0.33<br>-0.14 | -0.39<br>-0.09 | -0.45<br>-0.26 | -0.51<br>-0.21 |
| 3.1496  | 4.7244 | 80   | 120   | +0.12<br>+0.47 | 0<br>+0.35 | 0<br>+0.22 | -0.13<br>+0.22 | -0.06<br>+0.16 | -0.18<br>+0.04 | -0.25<br>+0.10 | -0.28<br>-0.06 | -0.35<br>0     | -0.38<br>-0.16 | -0.45<br>-0.10 | -0.52<br>-0.30 | -0.59<br>-0.24 |
| 4.7244  | 7.0866 | 120  | 180   | +0.14<br>+0.54 | 0<br>+0.40 | 0<br>+0.25 | -0.12<br>+0.26 | -0.07<br>+0.18 | -0.21<br>+0.04 | -0.28<br>+0.12 | -0.33<br>-0.08 | -0.40<br>0     | -0.45<br>-0.20 | -0.52<br>-0.12 | -0.61<br>-0.36 | -0.68<br>-0.28 |
| 7.0866  | 9.8425 | 180  | 250   | +0.15<br>+0.61 | 0<br>+0.46 | 0<br>+0.29 | -0.16<br>+0.30 | -0.07<br>+0.22 | -0.24<br>+0.05 | -0.33<br>+0.13 | -0.37<br>-0.08 | -0.46<br>0     | -0.51<br>-0.22 | -0.60<br>-0.14 | -0.70<br>-0.41 | -0.79<br>-0.33 |

Based on ANSI B4.1-1967 (R1994) Preferred Limits and Fits for Cylindrical Parts. Symbols g6, h6, etc., are shaft and G7, H7, etc., hole limits designations. For larger diameters and metric values see AFBMA Standard 7.

**Design and Installation Considerations.**—Interference fitting will reduce bearing radial internal clearance, so it is recommended that prospective users consult bearing manufacturers to make certain that the required bearings are correctly specified to satisfy all mounting, environmental and other operating conditions and requirements. This check is particularly necessary where heat sources in associated parts may further diminish bearing clearances in operation.

Standard values of radial internal clearances of radial bearings are listed in AFBMA-ANSI Standard 20.

**Allowance for Axial Displacement.**—Consideration should be given to axial displacement of bearing components owing to thermal expansion or contraction of associated parts. Displacement may be accommodated either by the internal construction of the bearing or by allowing one of the bearing rings to be axially displace-able. For unusual applications consult bearing manufacturers.

**Needle Roller Bearing Fitting and Mounting Practice.**—The tolerance limits required for shaft and housing seat diameters for needle roller bearings with inner and outer rings as well as limits for raceway diameters where inner or outer rings or both are omitted and rollers operate directly upon these surfaces are given in Tables 18 through 21, inclusive. Unusual design and operating conditions may require a departure from these practices. In such cases, bearing manufacturers should be consulted.

*Needle Roller Bearings, Drawn Cup:* These bearings without inner ring, Types NIB, NB, NIBM, NBM, NIY, NY, NIYM, NYM, NIH, NH, NIHM, NHM, and Inner Rings, Type NIR depend on the housings into which they are pressed for their size and shape. Therefore, the housings must not only have the proper bore dimensions but also must have sufficient strength. Tables 18 and 19, show the bore tolerance limits for rigid housings such as those made from cast iron or steel of heavy radial section equal to or greater than the ring gage section given in AFBMA Standard 4, 1984. The bearing manufacturers should be consulted for recommendations if the housings must be of lower strength materials such as aluminum or even of steel of thin radial section. The shape of the housing bores should be such that when the mean bore diameter of a housing is measured in each of several radial planes, the maximum difference between these mean diameters should not exceed 0.0005 inch (0.013 mm) or one-half the housing bore tolerance limit, if smaller. Also, the radial deviation from circular form should not exceed 0.00025 inch (0.006 mm). The housing bore surface finish should not exceed 125 micro-inches (3.2 micrometers) arithmetical average.

**Table 18. AFBMA and American National Standard Tolerance Limits for Shaft Raceway and Housing Bore Diameters—Needle Roller Bearings, Drawn Cup, Without Inner Ring, Inch Types NIB, NIBM, NIY, NIYM, NIH, and NIHM ANSI/ABMA 18.2-1982 (R1993)**

| Basic Bore Diameter under Needle Rollers,<br>$F_w$ |        | Shaft Raceway Diameter <sup>a</sup><br>Allowable Deviation<br>from $F_w$ |         | Basic Outside Diameter,<br>$D$ |        | Housing Bore Diameter <sup>a</sup> Allowable Deviation<br>from $D$ |         |
|--|--------|--|---------|--------------------------------|--------|--|---------|
| Inch   |        | Inch   |         | Inch                           |        | Inch   |         |
| Over   | Incl.  | High   | Low     | Over                           | Incl.  | Low  | High    |
| OUTER RING STATIONARY RELATIVE TO LOAD             |        |  |         |                                |        |  |         |
| 0.1875   | 1.8750 | +0   | -0.0005 | 0.3750                         | 4.0000 | -0.0005  | +0.0005 |
| 1.8750   | 3.5000 | +0   | -0.0006 | ...                            | ...    | ...  | ...     |
| OUTER RING ROTATING RELATIVE TO LOAD               |        |  |         |                                |        |  |         |
| 0.1875   | 1.8750 | -0.0005  | -0.0010 | 0.3750                         | 4.0000 | -0.0010  | +0      |
| 1.8750   | 3.5000 | -0.0005  | -0.0011 | ...                            | ...    | ...  | ...     |

<sup>a</sup> See text for additional requirements.

For bearing tolerances, see Table 10.



**Table 19. AFBMA and American National Standard Tolerance Limits for Shaft Raceway and Housing Bore Diameters—Needle Roller Bearings, Drawn Cup, Without Inner Ring, Metric Types NB, NBM, NY, NYM, NH, and NHM  
ANSI/ABMA 18.1-1982 (R1994)**

| Basic Bore Diameter Under Needle Rollers, $F_w$ |       |        |        | Shaft Raceway Diameter <sup>a</sup> Allowable Deviation from $F_w$ |         | Basic Outside Diameter, $D$ |       |        |        | Housing Bore Diameter <sup>a</sup> Allowable Deviation from $D$ |         |
|---|-------|--------|--------|--|---------|-----------------------------|-------|--------|--------|---|---------|
| OUTER RING STATIONARY RELATIVE TO LOAD          |       |        |        |  |         |                             |       |        |        |   |         |
| mm  |       | Inch   |        | ANSI h6, Inch  |         | mm                          |       | Inch   |        | ANSI N7, Inch   |         |
| Over  | Incl. | Over   | Incl.  | High   | Low     | Over                        | Incl. | Over   | Incl.  | Low   | High    |
| 3   | 6     | 0.1181 | 0.2362 | +0   | -0.0003 | 6                           | 10    | 0.2362 | 0.3937 | -0.0007   | -0.0002 |
| 6   | 10    | 0.2362 | 0.3937 | +0   | -0.0004 | 10                          | 18    | 0.3937 | 0.7087 | -0.0009   | -0.0002 |
| 10  | 18    | 0.3937 | 0.7087 | +0   | -0.0004 | 18                          | 30    | 0.7087 | 1.1811 | -0.0011   | -0.0003 |
| 18  | 30    | 0.7087 | 1.1811 | +0   | -0.0005 | 30                          | 50    | 1.1811 | 1.9685 | -0.0013   | -0.0003 |
| 30  | 50    | 1.1811 | 1.9685 | +0   | -0.0006 | 50                          | 80    | 1.9685 | 3.1496 | -0.0015   | -0.0004 |
| 50  | 80    | 1.9685 | 3.1496 | +0   | -0.0007 | ...                         | ...   | ...    | ...    | ...   | ...     |
| OUTER RING ROTATING RELATIVE TO LOAD            |       |        |        |  |         |                             |       |        |        |   |         |
| mm  |       | Inch   |        | ANSI f6, Inch  |         | mm                          |       | Inch   |        | ANSI R7, Inch   |         |
| Over  | Incl. | Over   | Incl.  | High   | Low     | Over                        | Incl. | Over   | Incl.  | Low   | High    |
| 3   | 6     | 0.1181 | 0.2362 | -0.0004  | -0.0007 | 6                           | 10    | 0.2362 | 0.3937 | -0.0011   | -0.0005 |
| 6   | 10    | 0.2362 | 0.3937 | -0.0005  | -0.0009 | 10                          | 18    | 0.3937 | 0.7087 | -0.0013   | -0.0006 |
| 10  | 18    | 0.3937 | 0.7087 | -0.0006  | -0.0011 | 18                          | 30    | 0.7087 | 1.1811 | -0.0016   | -0.0008 |
| 18  | 30    | 0.7087 | 1.1811 | -0.0008  | -0.0013 | 30                          | 50    | 1.1811 | 1.9685 | -0.0020   | -0.0010 |
| 30  | 50    | 1.1811 | 1.9685 | -0.0010  | -0.0016 | 50                          | 65    | 1.9685 | 2.5591 | -0.0024   | -0.0012 |
| 50  | 80    | 1.9685 | 3.1496 | -0.0012  | -0.0019 | 65                          | 80    | 2.5591 | 3.1496 | -0.0024   | -0.0013 |

For bearing tolerances, see Table 11.

**Table 20. AFBMA and American National Standard Tolerance Limits for Shaft Raceway and Housing Bore Diameters—Needle Roller Bearings, With Cage, Machined Ring, Without Inner Ring, Inch Type NIA  
ANSI/ABMA 18.2-1982 (R1993)**

| Basic Bore Diameter under Needle Rollers, $F_w$ |        | Shaft Raceway Diameter <sup>a</sup> Allowable Deviation from $F_w$ |         | Basic Outside Diameter, $D$ |         | Housing Bore Diameter <sup>a</sup> Allowable Deviation from $D$ |         |
|---|--------|--|---------|-----------------------------|---------|---|---------|
| OUTER RING STATIONARY RELATIVE TO LOAD          |        |  |         |                             |         |   |         |
| Inch  |        | ANSI h6, Inch  |         | Inch                        |         | ANSI H7, Inch   |         |
| Over  | Incl.  | High   | Low     | Over                        | Incl.   | Low   | High    |
| 0.2362  | 0.3937 | +0   | -0.0004 | 0.3937                      | 0.7087  | +0  | +0.0007 |
| 0.3937  | 0.7087 | +0   | -0.0004 | 0.7087                      | 1.1811  | +0  | +0.0008 |
| 0.7087  | 1.1811 | +0   | -0.0005 | 1.1811                      | 1.9685  | +0  | +0.0010 |
| 1.1811  | 1.9685 | +0   | -0.0006 | 1.9685                      | 3.1496  | +0  | +0.0012 |
| 1.9685  | 3.1496 | +0   | -0.0007 | 3.1496                      | 4.7244  | +0  | +0.0014 |
| 3.1496  | 4.7244 | +0   | -0.0009 | 4.7244                      | 7.0866  | +0  | +0.0016 |
| 4.7244  | 7.0866 | +0   | -0.0010 | 7.0866                      | 9.8425  | +0  | +0.0018 |
| 7.0866  | 9.8425 | +0   | -0.0011 | 9.8425                      | 12.4016 | +0  | +0.0020 |
| OUTER RING ROTATING RELATIVE TO LOAD            |        |  |         |                             |         |   |         |
| Inch  |        | ANSI f6, Inch  |         | Inch                        |         | ANSI N7, Inch   |         |
| Over  | Incl.  | High   | Low     | Over                        | Incl.   | Low   | High    |
| 0.2362  | 0.3937 | -0.0005  | -0.0009 | 0.3937                      | 0.7087  | -0.0009   | -0.0002 |
| 0.3937  | 0.7087 | -0.0006  | -0.0011 | 0.7087                      | 1.1811  | -0.0011   | -0.0003 |
| 0.7087  | 1.1811 | -0.0008  | -0.0013 | 1.1811                      | 1.9685  | -0.0013   | -0.0003 |
| 1.1811  | 1.9685 | -0.0010  | -0.0016 | 1.9685                      | 3.1496  | -0.0015   | -0.0004 |
| 1.9685  | 3.1496 | -0.0012  | -0.0019 | 3.1496                      | 4.7244  | -0.0018   | -0.0004 |
| 3.1496  | 4.7244 | -0.0014  | -0.0023 | 4.7244                      | 7.0866  | -0.0020   | -0.0005 |
| 4.7244  | 7.0866 | -0.0016  | -0.0027 | 7.0866                      | 9.8425  | -0.0024   | -0.0006 |
| 7.0866  | 9.8425 | -0.0020  | -0.0031 | 9.8425                      | 11.2205 | -0.0026   | -0.0006 |

<sup>a</sup> See text for additional requirements.

For bearing tolerances, see Table 12.

**Table 21. AFBMA and American National Standard Tolerance Limits for Shaft Diameters—Needle Roller Bearing Inner Rings, Inch Type NIR (Used with Bearing Type NIA) ANSI/ABMA 18.2-1982 (R1993)**

| Basic Bore,<br><i>d</i> |        | Shaft Diameter <sup>a</sup>  |         |  |         |
|-------------------------|--------|--|---------|--|---------|
|                         |        | Shaft Rotating Relative to Load,<br>Outer Ring Stationary<br>Relative to Load<br>Allowable Deviation from <i>d</i> |         | Shaft Stationary Relative<br>to Load, Outer Ring<br>Rotating Relative to Load<br>Allowable Deviation from <i>d</i> |         |
| Inch                    |        | ANSI m5, Inch  |         | ANSI g6, Inch  |         |
| Over                    | Incl.  | High   | Low     | High   | Low     |
| 0.2362                  | 0.3937 | +0.0005  | +0.0002 | -0.0002  | -0.0006 |
| 0.3937                  | 0.7087 | +0.0006  | +0.0003 | -0.0002  | -0.0007 |
| 0.7087                  | 1.1811 | +0.0007  | +0.0003 | -0.0003  | -0.0008 |
| 1.1811                  | 1.9685 | +0.0008  | +0.0004 | -0.0004  | -0.0010 |
| 1.9685                  | 3.1496 | +0.0009  | +0.0004 | -0.0004  | -0.0011 |
| 3.1496                  | 4.7244 | +0.0011  | +0.0005 | -0.0005  | -0.0013 |
| 4.7244                  | 7.0866 | +0.0013  | +0.0006 | -0.0006  | -0.0015 |
| 7.0866                  | 9.8425 | +0.0015  | +0.0007 | -0.0006  | -0.0017 |

<sup>a</sup> See text for additional requirements.

For inner ring tolerance limits, see [Table 13](#).

Most needle roller bearings do not use inner rings, but operate directly on the surfaces of shafts. When shafts are used as inner raceways, they should be made of bearing quality steel hardened to Rockwell C 58 minimum. [Tables 15](#) and [19](#) show the shaft raceway tolerance limits and [Table 21](#) shows the shaft seat tolerance limits when inner rings are used. However, whether the shaft surfaces are used as inner raceways or as seats for inner rings, the mean outside diameter of the shaft surface in each of several radial planes should be determined. The difference between these mean diameters should not exceed 0.0003 inch (0.008 mm) or one-half the diameter tolerance limit, if smaller. The radial deviation from circular form should not exceed 0.0001 inch (0.0025 mm), for diameters up to and including 1 in. (25.4 mm). Above one inch the allowable deviation is 0.0001 times the shaft diameter. The surface finish should not exceed 16 micro-inches (0.4 micrometer) arithmetical average. The housing bore and shaft diameter tolerance limits depend upon whether the load rotates relative to the shaft or the housing.

*Needle Roller Bearing With Cage, Machined Ring, Without Inner Ring:* The following covers needle roller bearings Type NIA and inner rings Type NIR. The shape of the housing bores should be such that when the mean bore diameter of a housing is measured in each of several radial planes, the maximum difference between these mean diameters does not exceed 0.0005 inch (0.013 mm) or one-half the housing bore tolerance limit, if smaller. Also, the radial deviation from circular form should not exceed 0.00025 inch (0.006 mm). The housing bore surface finish should not exceed 125 micro-inches (3.2 micrometers) arithmetical average. [Table 21](#) shows the housing bore tolerance limits.

When shafts are used as inner raceways their requirements are the same as those given above for Needle Roller Bearings, Drawn Cup. [Table 20](#) shows the shaft raceway tolerance limits and [Table 21](#) shows the shaft seat tolerance limits when inner rings are used.

*Needle Roller and Cage Assemblies, Types NIM and NM:* For information concerning boundary dimensions, tolerance limits, and fitting and mounting practice, reference should be made to ANSI/ABMA 18.1-1982 (R1994) and ANSI/ABMA 18.2-1982 (R1993).

### Bearing Mounting Practice

Because of their inherent design and material rigidity, rolling contact bearings must be mounted with careful control of their alignment and runout. Medium-speed or slower (400,000  $DN$  values or less where  $D$  is the bearing bore in millimeters and  $N$  is the bearing speed in revolutions per minute), and medium to light load ( $C/P$  values of 7 or greater where  $C$  is the bearing specific dynamic capacity in pounds and  $P$  is the average bearing load in pounds) applications can endure misalignments equivalent to those acceptable for high-capacity, precision journal bearings utilizing hard bearing materials such as silver, copper-lead, or aluminum. In no case, however, should the maximum shaft deflection exceed .001 inch per inch for well-crowned roller bearings, and .003 inch per inch for deep-groove ball-bearings. Except for self-aligning ball-bearings and spherical or barrel roller bearings, all other types require shaft alignments with deflections no greater than .0002 inch per inch. With preloaded ball bearings, this same limit is recommended as a maximum. Close-clearance tapered bearings or thrust bearings of most types require the same shaft alignment also.

Of major importance for all bearings requiring good reliability, is the location of the races on the shaft and in the housing.

Assembly methods must insure: 1) that the faces are square, before the cavity is closed; 2) that the cover face is square to the shoulder and pulled in evenly; and 3) that it will be located by a face parallel to it when finally seated against the housing.

These requirements are shown in the accompanying [Table 22](#). In applications not controlled by automatic tooling with closely controlled fixtures and bolt torquing mechanisms, races should be checked for squareness by sweeping with a dial indicator mounted as shown below. For commercial applications with moderate life and reliability requirements, outer race runouts should be held to .0005 inch per inch of radius and inner race runout to .0004 inch per inch of radius. In preloaded and precision applications, these tolerances must be cut in half. In regard to the question of alignment, it must be recognized that rolling-contact bearings, being made of fully-hardened steel, do not wear in as may certain journal bearings when carefully applied and initially operated. Likewise, rolling contact bearings absorb relatively little deflection when loaded to  $C/P$  values of 6 or less. At such stress levels the rolling element-race deformation is generally not over .0002 inch. Consequently, proper mounting and control of shaft deflections are imperative for reliable bearing performance. Aside from inadequate lubrication, these factors are the most frequent causes of premature bearing failures.

**Mountings for Precision and Quiet-running Applications.**—In applications of rolling-element bearings where vibration or smoothness of operation is critical, special precautions must be taken to eliminate those conditions which can serve to initiate radial and axial motions. These exciting forces can result in shaft excursions which are in resonance with shaft or housing components over a range of frequencies from well below shaft speed to as much as 100 times above it. The more sensitive the configuration, the greater is the need for precision bearings and mountings to be used.

Precision bearings are normally made to much closer tolerances than standard and therefore benefit from better finishing techniques. Special inspection operations are required, however, to provide races and rolling elements with smoothness and runouts compatible with the needs of the application. Similarly, shafts and housings must be carefully controlled.

Among the important elements to be controlled are shaft, race, and housing roundness; squareness of faces, diameters, shoulders, and rolling paths. Though not readily appreciated, grinding chatter, lobular and compensating out-of-roundness, waviness, and flats of less than .0005 inch deviation from the average or mean diameter can cause significant roughness. To detect these and insure the selection of good pieces, three-point electronic indicator inspection must be made. For ultra-precise or quiet applications, pieces are often

checked on a "Talyrod" or a similar continuous recording instrument capable of measuring to within a few millionths of an inch. Though this may seem extreme, it has been found that shaft deformities will be reflected through inner races shrunk onto them. Similarly, tight-fit outer races pick up significant deviations in housings. In many instrument and in missile guidance applications, such deviations and deformities may have to be limited to less than .00002 inch.

In most of these precision applications, bearings are used with rolling elements controlled to less than 5 millionths of an inch deviation from roundness and within the same range for diameter.

Special attention is required both in housing design and in assembly of the bearing to shaft and housing. Housing response to axial excursions forced by bearing wobble (which in itself is a result of out-of-square mounting) has been found to be a major source of small electric and other rotating equipment noise and howl. Stiffer, more massive housings and careful alignment of bearing races can make significant improvements in applications where noise or vibration has been found to be objectionable.

**Table 22. Commercial Application Alignment Tolerances**

| Feature  | Location | Tolerance   |
|--|----------|---|
| <b>Housing Face Runout</b>                         | 1        | Square to shaft center within .0004 inch/inch of radius full indicator reading.   |
| <b>Outer Race Face Runout</b>                      | 2        | Square to shaft center within .0004 inch/inch of radius full indicator reading and complementary to the housing runout (not opposed). |
| <b>Inner Race Face Runout</b>                      | 3        | Square to shaft center within .0003 inch/inch of radius full indicator reading.   |
| <b>Cover and Closure Mounting Face Parallelism</b> | 4 and 5  | Parallel within .001.   |
| <b>Housing Mounting Face Parallelism</b>           | 6        | Parallel within .001  |

**Squareness and Alignment.**—In addition to the limits for roundness and wall variation of the races and their supports, squareness of end faces and shoulders must be closely controlled. Tolerances of .0001 inch full indicator reading per inch of diameter are normally required for end faces and shoulders, with appropriately selected limits for fillet eccentricities. The latter must also fall within specified limits for radii tolerances to prevent interference and the resulting cocking of the race. Reference should be made to the bearing dimension tables which list corner radii for typical bearings. Shoulders must also be of a sufficient height to insure proper support for the races, since they are of hardened steel and are less capable of absorbing shock loads and abuse. The general subject of squareness and alignment is of primary importance to the life of rolling element bearings.

The following recommendations for shaft and housing design are given by the New Departure Division of General Motors Corporation.\*

“As a rule, there is little trouble experienced with inaccuracies in shafts. Bearings seats and locating shoulders are turned and ground to size with the shaft held on centers and, with ordinary care, there is small chance for serious out-of-roundness or taper. Shaft shoulders should present sufficient surface in contact with the bearing face to assure positive and accurate location.

“Where an undercut must be made for wheel runout in grinding a bearing seat, care should be exercised that no sharp corners are left, for it is at such points that fatigue is most likely to result in shaft breakage. It is best to undercut as little as possible and to have the undercut end in a fillet instead of a sharp corner.

“Where clamping nuts are to be used, it is important to cut the threads as true and square as possible in order to insure even pressure at all points on the bearing inner ring faces when the nuts are set up tight. It is also important not to cut threads so far into the bearing seat as to leave part of the inner ring unsupported or carried on the threads. Excessive deflection is usually the result of improperly designed or undersized machine parts. With a weak shaft, it is possible to seriously affect bearing operation through misalignment due to shaft deflection. Where shafts are comparatively long, the diameter between bearings must be great enough to properly resist bending. In general, the use of more than two bearings on a single shaft should be avoided, owing to the difficulty of securing accurate alignment. With bearings mounted close to each other, this can result in extremely heavy bearing loads.

“Design is as important as careful machining in construction of accurate bearing housings. There should be plenty of metal in the wall sections and large, thin areas should be avoided as much as possible, since they are likely to permit deflection of the boring tool when the housing is being finish-machined.

“Wherever possible, it is best to design a housing so that the radial load placed on the bearing is transmitted as directly as possible to the wall or rib supporting the housing. Diaphragm walls connecting an offset housing to the main wall or side of a machine are apt to deflect unless made thick and well braced.

“When two bearings are to be mounted opposed, but in separate housings, the housings should be so reinforced with fins or webs as to prevent deflection due to the axial load under which the bearings are opposed.

“Where housings are deep and considerable overhang of the boring tool is required, there is a tendency to produce out-of-roundness and taper, unless the tool is very rigid and light finishing cuts are taken. In a too roughly bored housing there is a possibility for the ridges of metal to peen down under load, thus eventually resulting in too loose a fit for the bearing outer ring.”

**Soft Metal and Resilient Housings.**—In applications relying on bearing housings made of soft materials (aluminum, magnesium, light sheet metal, etc.) or those which lose their fit because of differential thermal expansion, outer race mounting must be approached in a cautious manner. Of first importance is the determination of the possible consequences of race loosening and turning. In conjunction with this, the type of loading must be considered for it may serve to magnify the effect of race loosening. It must be remembered that generally, balancing processes do not insure zero unbalance at operating speeds, but rather an “acceptable” maximum. This force exerted by the rotating element on the outer race can initiate a precession which will aggravate the race loosening problem by causing further attrition through wear, pounding, and abrasion. Since this force is generally of an order greater than the friction forces in effect between the outer race, housing, and closures (retaining nuts also), no foolproof method can be recommended for securing outer races in housings which deform significantly under load or after appreciable service wear. Though

\*New Departure Handbook. Vol. II—1951.

many such “fixes” are offered, the only sure solution is to press the race into a housing of sufficient stiffness with the heaviest fit consistent with the installed and operating clearances. In many cases, inserts, or liners of cast iron or steel are provided to maintain the desired fit and increase useful life of both bearing and housing.

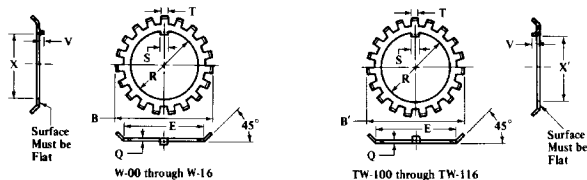
**Quiet or Vibration-free Mountings.**—In seeming contradiction is the approach to bearing mountings in which all shaft or rotating element excursions must be isolated from the frame, housing, or supporting structure. Here bearing outer races are often supported on elastomeric or metallic springs. Fundamentally, this is an isolation problem and must be approached with caution to insure solution of the primary bearing objective — location and restraint of the rotating body, as well as the reduction or elimination of the dynamic problem. Again, the danger of skidding rolling elements must be considered and reference to the resident engineers or sales engineers of the numerous bearing companies is recommended, as this problem generally develops requirements for special, or non-catalog-type bearings.

**General Mounting Precautions.**—Since the last operations involving the bearing application — mounting and closing — have such important effects on bearing performance, durability, and reliability, it must be cautioned that more bearings are abused or “killed” in this early stage of their life than wear out or “die” under conditions for which they were designed. Hammer and chisel “mechanics” invariably handle bearings as though no blow could be too hard, no dirt too abrasive, and no misalignment of any consequence. Proper tools, fixtures, and techniques are a must for rolling bearing application, and it is the responsibility of the design engineer to provide for this in his design, advisory notes, mounting instructions, and service manuals. Nicks, dents, scores, scratches, corrosion staining, and dirt must be avoided if reliability, long life, and smooth running are to be expected of rolling bearings. All manufacturers have pertinent service instructions available for the bearing user. These should be followed for best performance. In a later section, methods for inspecting bearings and descriptions of most common bearing deficiencies will be given.

**Seating Fits for Bearings.**—Anti-Friction Bearing Manufacturers Association (AFBMA) standard shaft and housing bearing seat tolerances are given in [Tables 13 through 18](#), inclusive.

**Clamping and Retaining Methods.**—Various methods of clamping bearings to prevent axial movement on the shaft are employed, one of the most common being a nut screwed on the end of the shaft and held in place by a tongued lock washer (see [Table 23](#)). The shaft thread for the clamping nut (see [Table 24](#)) should be cut in accurate relation to bearing seats and shoulders if bearing stresses are to be avoided. The threads used are of American National Form, Class 3; special diameters and data for these are given in [Tables 25 and 26](#). Where somewhat closer than average accuracy is required, the washers and locknut faces may be obtained ground for closer alignment with the threads. For a high degree of accuracy the shaft threads are ground and a more precise clamping means is employed. Where a bearing inner ring is to be clamped, it is important to provide a sufficiently high shoulder on the shaft to locate the bearing positively and accurately. If the difference between bearing bore and maximum shaft diameter gives a low shoulder which would enter the corner of the radius of the bearing, a shoulder ring that extends above the shoulder and well into the shaft corner is employed. A shoulder ring with snap wire fitting into a groove in the shaft is sometimes used where no locating shaft shoulder is present. A snap ring fitting into a groove is frequently employed to prevent endwise movement of the bearing away from the locating shoulder where tight clamping is not required. Such a retaining ring should not be used where a slot in the shaft surface might lead to fatigue failure. Snap rings are also used to locate the outer bearing ring in the housing. Dimensions of snap rings used for this latter purpose are given in AFBMA and ANSI standards.

**Table 23. AFBMA Standard Lockwashers (Series W-00) for Ball Bearings and Cylindrical and Spherical Roller Bearings and (Series TW-100) for Tapered Roller Bearings. Inch Design.**



| Type W No. | Q    | Type TW No. | Q    | No. | Tangs |      | Key     |      |       |       |       |       | Bore R |       | Diameter |      | Dia. Over Tangs. |       |
|------------|------|-------------|------|-----|-------|------|---------|------|-------|-------|-------|-------|--------|-------|----------|------|------------------|-------|
|            |      |             |      |     | T     | V    | Width S |      | X     |       | X'    |       | Min.   | Max.  | E        | Tol. | Max.             |       |
|            |      |             |      |     |       |      | Min.    | Max. | Min.  | Max.  | Min.  | Max.  |        |       |          |      | B                | B'    |
| W-00       | .032 | TW-100      | .032 | 9   | .120  | .031 | .110    | .120 | .334  | .359  | .334  | .359  | .406   | 0.421 | 0.625    | +015 | 0.875            | 0.891 |
| W-01       | .032 | TW-101      | .032 | 9   | .120  | .031 | .110    | .120 | .412  | .437  | .412  | .437  | .484   | .499  | 0.719    | +015 | 1.016            | 1.031 |
| W-02       | .032 | TW-102      | .048 | 11  | .120  | .031 | .110    | .120 | .529  | .554  | .513  | .538  | .601   | .616  | 0.813    | +015 | 1.156            | 1.156 |
| W-03       | .032 | TW-103      | .048 | 11  | .120  | .031 | .110    | .120 | .607  | .632  | .591  | .616  | .679   | .694  | 0.938    | +015 | 1.328            | 1.344 |
| W-04       | .032 | TW-104      | .048 | 11  | .166  | .031 | .156    | .176 | .729  | .754  | .713  | .738  | .801   | .816  | 1.125    | +015 | 1.531            | 1.563 |
| W-05       | .040 | TW-105      | .052 | 13  | .166  | .047 | .156    | .176 | .909  | .939  | .897  | .927  | .989   | 1.009 | 1.281    | +015 | 1.719            | 1.703 |
| W-06       | .040 | TW-106      | .052 | 13  | .166  | .047 | .156    | .176 | 1.093 | 1.128 | 1.081 | 1.116 | 1.193  | 1.213 | 1.500    | +015 | 1.922            | 1.953 |
|            |      | TW-065      | .052 | 15  | .166  | ...  | .156    | .176 | ...   | ...   | 1.221 | 1.256 | 1.333  | 1.353 | 1.813    | +015 | ...              | 2.234 |
| W-07       | .040 | TW-107      | .052 | 15  | .166  | .047 | .156    | .176 | 1.296 | 1.331 | 1.284 | 1.319 | 1.396  | 1.416 | 1.813    | +015 | 2.250            | 2.250 |
| W-08       | .048 | TW-108      | .062 | 15  | .234  | .047 | .250    | .290 | 1.475 | 1.510 | 1.461 | 1.496 | 1.583  | 1.603 | 2.000    | +030 | 2.469            | 2.484 |
| W-09       | .048 | TW-109      | .062 | 17  | .234  | .062 | .250    | .290 | 1.684 | 1.724 | 1.670 | 1.710 | 1.792  | 1.817 | 2.281    | +030 | 2.734            | 2.719 |
| W-10       | .048 | TW-110      | .062 | 17  | .234  | .062 | .250    | .290 | 1.884 | 1.924 | 1.870 | 1.910 | 1.992  | 2.017 | 2.438    | +030 | 2.922            | 2.922 |
| W-11       | .053 | TW-111      | .062 | 17  | .234  | .062 | .250    | .290 | 2.069 | 2.109 | 2.060 | 2.100 | 2.182  | 2.207 | 2.656    | +030 | 3.109            | 3.094 |
| W-12       | .053 | TW-112      | .072 | 17  | .234  | .062 | .250    | .290 | 2.267 | 2.307 | 2.248 | 2.288 | 2.400  | 2.425 | 2.844    | +030 | 3.344            | 3.328 |
| W-13       | .053 | TW-113      | .072 | 19  | .234  | .062 | .250    | .290 | 2.455 | 2.495 | 2.436 | 2.476 | 2.588  | 2.613 | 3.063    | +030 | 3.578            | 3.563 |
| W-14       | .053 | TW-114      | .072 | 19  | .234  | .094 | .250    | .290 | 2.658 | 2.698 | 2.639 | 2.679 | 2.791  | 2.816 | 3.313    | +030 | 3.828            | 3.813 |
| W-15       | .062 | TW-115      | .085 | 19  | .328  | .094 | .250    | .290 | 2.831 | 2.876 | 2.808 | 2.853 | 2.973  | 3.003 | 3.563    | +030 | 4.109            | 4.047 |
| W-16       | .062 | TW-116      | .085 | 19  | .328  | .094 | .313    | .353 | 3.035 | 3.080 | 3.012 | 3.057 | 3.177  | 3.207 | 3.844    | +030 | 4.375            | 4.391 |

<sup>a</sup> *Tolerances:* On width,  $T$ ,  $-.010$  inch for Types W-00 to W-03 and TW-100 to TW-103;  $-.020$  inch for W-04 to W-07 and TW-104 to TW-107;  $-.030$  inch for all others shown. On Projection  $V$ ,  $+.031$  inch for all sizes up through W-13 and TW-113;  $+.062$  inch for all others shown.

All dimensions in inches. For dimensions in millimeters, multiply inch values by 25.4 and round result to two decimal places.

Data for sizes larger than shown are given in ANSI/AFBMA Standard 8.2-1991.

**Table 24. AFBMA Standard Locknuts (Series N-00) for Ball Bearings and Cylindrical and Spherical Roller Bearings and (Series TN-00) for Tapered Roller Bearings. Inch Design.**

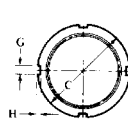
Runout and parallelism of faces measured on a tight fitting threaded arbor.

N-00 to N-06 = .002 Max.  
N-07 to AN-15 = .004 Max.

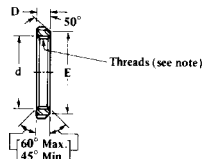
TN-065 to TAN-15 = .002 Max.

Surface Finish Note

TN-065 to TN-11, 100 $\mu$  in., max.  
TN-12 to TAN-15, 120 $\mu$  in., max.



N-00 through AN-15  
TN-065 through TAN-15



| BB & RB Nut No. | TRB Nut No. | Thds. per Inch | Thread Minor Deam. |        | Thread Pitch Dia. |        | Thd. Major Dia. <i>d</i> | Outside Dia. <i>C</i> | Face Dia. <i>E</i> |       | Slot dimension |      |                 | Thickness <i>D</i> |      |
|-----------------|-------------|----------------|--------------------|--------|-------------------|--------|--------------------------|-----------------------|--------------------|-------|----------------|------|-----------------|--------------------|------|
|                 |             |                | Min.               | Max.   | Min.              | Max.   |                          |                       | Min.               | Max.  | Width <i>G</i> |      | Height <i>H</i> | Min.               | Max. |
|                 |             |                |                    |        |                   |        |                          |                       |                    |       | Min.           | Max. |                 |                    |      |
| N-00            | —           | 32             | 0.3572             | 0.3606 | 0.3707            | 0.3733 | 0.391                    | 0.755                 | .605               | .625  | .120           | .130 | .073            | .209               | .229 |
| N-01            | —           | 32             | 0.4352             | 0.4386 | 0.4487            | 0.4513 | 0.469                    | 0.880                 | .699               | .719  | .120           | .130 | .073            | .303               | .323 |
| N-02            | —           | 32             | 0.5522             | 0.5556 | 0.5657            | 0.5687 | 0.586                    | 1.005                 | .793               | .813  | .120           | .130 | .104            | .303               | .323 |
| N-03            | —           | 32             | 0.6302             | 0.6336 | 0.6437            | 0.6467 | 0.664                    | 1.130                 | .918               | .938  | .120           | .130 | .104            | .334               | .354 |
| N-04            | —           | 32             | 0.7472             | 0.7506 | 0.7607            | 0.7641 | 0.781                    | 1.380                 | 1.105              | 1.125 | .178           | .198 | .104            | .365               | .385 |
| N-05            | —           | 32             | 0.9352             | 0.9386 | 0.9487            | 0.9521 | 0.969                    | 1.568                 | 1.261              | 1.281 | .178           | .198 | .104            | .396               | .416 |
| N-06            | —           | 18             | 1.1129             | 1.1189 | 1.1369            | 1.1409 | 1.173                    | 1.755                 | 1.480              | 1.500 | .178           | .198 | .104            | .396               | .416 |
|                 | TN-065      | 18             | 1.2524             | 1.2584 | 1.2764            | 1.2804 | 1.312                    | 2.068                 | 1.793              | 1.813 | .178           | .198 | .104            | .428               | .448 |
| N-07            | TN-07       | 18             | 1.3159             | 1.3219 | 1.3399            | 1.3439 | 1.376                    | 2.068                 | 1.793              | 1.813 | .178           | .198 | .104            | .428               | .448 |
| N-08            | TN-08       | 18             | 1.5029             | 1.5089 | 1.5269            | 1.5314 | 1.563                    | 2.255                 | 1.980              | 2.000 | .240           | .260 | .104            | .428               | .448 |
| N-09            | TN-09       | 18             | 1.7069             | 1.7129 | 1.7309            | 1.7354 | 1.767                    | 2.536                 | 2.261              | 2.281 | .240           | .260 | .104            | .428               | .448 |
| N-10            | TN-10       | 18             | 1.9069             | 1.9129 | 1.9309            | 1.9354 | 1.967                    | 2.693                 | 2.418              | 2.438 | .240           | .260 | .104            | .490               | .510 |
| N-11            | TN-11       | 18             | 2.0969             | 2.1029 | 2.1209            | 2.1260 | 2.157                    | 2.974                 | 2.636              | 2.656 | .240           | .260 | .135            | .490               | .510 |
| N-12            | TN-12       | 18             | 2.2999             | 2.3059 | 2.3239            | 2.3290 | 2.360                    | 3.161                 | 2.824              | 2.844 | .240           | .260 | .135            | .521               | .541 |
| N-13            | TN-13       | 18             | 2.4879             | 2.4949 | 2.5119            | 2.5170 | 2.548                    | 3.380                 | 3.043              | 3.063 | .240           | .260 | .135            | .553               | .573 |
| N-14            | TN-14       | 18             | 2.6909             | 2.6969 | 2.7149            | 2.7200 | 2.751                    | 3.630                 | 3.283              | 3.313 | .240           | .260 | .135            | .553               | .573 |
| AN-15           | TAN-15      | 12             | 2.8428             | 2.8518 | 2.8789            | 2.8843 | 2.933                    | 3.880                 | 3.533              | 3.563 | .360           | .385 | .135            | .584               | .604 |

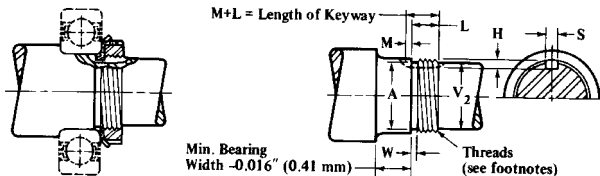
All dimensions in inches. For dimensions in millimeters, multiply inch values, except thread diameters, by 25.4 and round result to two decimal places.

Threads are American National form, Class 3.

Typical steels for locknuts are: AISI, C1015, C1018, C1020, C1025, C1035, C1117, C1118, C1212, C1213, and C1215. Minimum hardness, tensile strength, yield strength and elongation are given in ANSI/ABMA 8.2-1991 which also lists larger sizes of locknuts.



**Table 25. AFBMA Standard for Shafts for Locknuts (series N-00) for Ball Bearings and Cylindrical and Spherical Roller Bearings. Inch Design.**



Min. Bearing Width  $-0.016''$  (0.41 mm)

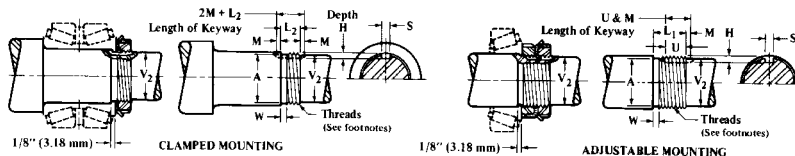
Threads (see footnotes)

| Locknut Number | Bearing Bore | $V_2$<br>Max. | Threads <sup>a</sup> |            |            |            |            | Relief   |           | Keyway    |           |       |
|----------------|--------------|---------------|----------------------|------------|------------|------------|------------|----------|-----------|-----------|-----------|-------|
|                |              |               | No. per inch         | Major Dia. | Pitch Dia. | Minor Dia. | Length $L$ | Dia. $A$ | Width $W$ | Depth $H$ | Width $S$ | $M$   |
|                |              |               |                      | Max.       | Max.       | Max.       | Max.       | Max.     | Max.      | Max.      | Min.      | Min.  |
| N-00           | 0.3937       | 0.312         | 32                   | 0.391      | 0.3707     | 0.3527     | 0.297      | 0.3421   | 0.078     | 0.062     | 0.125     | 0.094 |
| N-01           | 0.4724       | 0.406         | 32                   | 0.469      | 0.4487     | 0.4307     | 0.391      | 0.4201   | 0.078     | 0.062     | 0.125     | 0.094 |
| N-02           | 0.5906       | 0.500         | 32                   | 0.586      | 0.5657     | 0.5477     | 0.391      | 0.5371   | 0.078     | 0.078     | 0.125     | 0.094 |
| N-03           | 0.6693       | 0.562         | 32                   | 0.664      | 0.6437     | 0.6257     | 0.422      | 0.6151   | 0.078     | 0.078     | 0.125     | 0.094 |
| N-04           | 0.7874       | 0.719         | 32                   | 0.781      | 0.7607     | 0.7427     | 0.453      | 0.7321   | 0.078     | 0.078     | 0.188     | 0.094 |
| N-05           | 0.9843       | 0.875         | 32                   | 0.969      | 0.9487     | 0.9307     | 0.484      | 0.9201   | 0.078     | 0.094     | 0.188     | 0.125 |
| N-06           | 1.1811       | 1.062         | 18                   | 1.173      | 1.1369     | 1.1048     | 0.484      | 1.0942   | 0.109     | 0.094     | 0.188     | 0.125 |
| N-07           | 1.3780       | 1.250         | 18                   | 1.376      | 1.3399     | 1.3078     | 0.516      | 1.2972   | 0.109     | 0.094     | 0.188     | 0.125 |
| N-08           | 1.5748       | 1.469         | 18                   | 1.563      | 1.5269     | 1.4948     | 0.547      | 1.4842   | 0.109     | 0.094     | 0.312     | 0.125 |
| N-09           | 1.7717       | 1.688         | 18                   | 1.777      | 1.7309     | 1.6988     | 0.547      | 1.6882   | 0.141     | 0.094     | 0.312     | 0.156 |
| N-10           | 1.9685       | 1.875         | 18                   | 1.967      | 1.9309     | 1.8988     | 0.609      | 1.8882   | 0.141     | 0.094     | 0.312     | 0.156 |
| N-11           | 2.1654       | 2.062         | 18                   | 2.157      | 2.1209     | 2.0888     | 0.609      | 2.0782   | 0.141     | 0.125     | 0.312     | 0.156 |
| N-12           | 2.3622       | 2.250         | 18                   | 2.360      | 2.3239     | 2.2918     | 0.641      | 2.2812   | 0.141     | 0.125     | 0.312     | 0.156 |
| N-13           | 2.5591       | 2.438         | 18                   | 2.548      | 2.5119     | 2.4798     | 0.672      | 2.4692   | 0.141     | 0.125     | 0.312     | 0.156 |
| N-14           | 2.7559       | 2.625         | 18                   | 2.751      | 2.7149     | 2.6828     | 0.672      | 2.6722   | 0.141     | 0.125     | 0.312     | 0.250 |
| AN-15          | 2.9528       | 2.781         | 12                   | 2.933      | 2.8789     | 2.8308     | 0.703      | 2.8095   | 0.172     | 0.125     | 0.312     | 0.250 |
| AN-16          | 3.1496       | 3.000         | 12                   | 3.137      | 3.0829     | 3.0348     | 0.703      | 3.0135   | 0.172     | 0.125     | 0.375     | 0.250 |

<sup>a</sup>Threads are American National form Class 3.

All dimensions in inches. For dimensions in millimeters, multiply inch values, except thread diameters, by 25.4 and round result to two decimal places. See footnote to Table 26 for material other than steel. For sizes larger than shown, see ANSI/ABMA 8.2-1991.

Table 26. AFBMA Standard for Shafts for Tapered Roller Bearing Locknuts. Inch Design.



| Locknut Number | Bearing Bore | $V_2$<br>Max. | Threads <sup>a</sup> |            |            |            |       | Length |          | Relief    |           | Keyway    |       |       |      |
|----------------|--------------|---------------|----------------------|------------|------------|------------|-------|--------|----------|-----------|-----------|-----------|-------|-------|------|
|                |              |               | No. per inch         | Major Dia. | Pitch Dia. | Minor Dia. | $L_1$ | $L_2$  | Dia. $A$ | Width $W$ | Depth $H$ | Width $S$ | $M$   | $U$   |      |
|                |              |               |                      | Max.       | Max.       | Max.       |       |        |          |           |           |           |       |       | Max. |
| N-00           | 0.3937       | 0.312         | 32                   | 0.391      | 0.3707     | 0.3527     | 0.609 | 0.391  | 0.3421   | 0.078     | 0.094     | 0.125     | 0.094 | 0.469 |      |
| N-01           | 0.4724       | 0.406         | 32                   | 0.469      | 0.4487     | 0.4307     | 0.797 | 0.484  | 0.4201   | 0.078     | 0.094     | 0.125     | 0.094 | 0.562 |      |
| N-02           | 0.5906       | 0.500         | 32                   | 0.586      | 0.5657     | 0.5477     | 0.828 | 0.516  | 0.5371   | 0.078     | 0.094     | 0.125     | 0.094 | 0.594 |      |
| N-03           | 0.6693       | 0.562         | 32                   | 0.664      | 0.6437     | 0.6257     | 0.891 | 0.547  | 0.6151   | 0.078     | 0.094     | 0.125     | 0.094 | 0.625 |      |
| N-04           | 0.7874       | 0.703         | 32                   | 0.781      | 0.7607     | 0.7427     | 0.922 | 0.547  | 0.7321   | 0.078     | 0.094     | 0.188     | 0.094 | 0.625 |      |
| N-05           | 0.9843       | 0.875         | 32                   | 0.969      | 0.9487     | 0.9307     | 1.016 | 0.609  | 0.9201   | 0.078     | 0.125     | 0.188     | 0.125 | 0.719 |      |
| N-06           | 1.1811       | 1.062         | 18                   | 1.173      | 1.1369     | 1.1048     | 1.016 | 0.609  | 1.0942   | 0.109     | 0.125     | 0.188     | 0.125 | 0.719 |      |
| TN-065         | 1.3750       | 1.188         | 18                   | 1.312      | 1.2764     | 1.2443     | 1.078 | 0.641  | 1.2337   | 0.109     | 0.125     | 0.188     | 0.125 | 0.750 |      |
| TN-07          | 1.3780       | 1.250         | 18                   | 1.376      | 1.3399     | 1.3078     | 1.078 | 0.641  | 1.2972   | 0.109     | 0.125     | 0.188     | 0.125 | 0.750 |      |
| TN-08          | 1.5748       | 1.438         | 18                   | 1.563      | 1.5269     | 1.4948     | 1.078 | 0.641  | 1.4842   | 0.109     | 0.125     | 0.312     | 0.125 | 0.750 |      |
| TN-09          | 1.7717       | 1.656         | 18                   | 1.767      | 1.7309     | 1.6988     | 1.078 | 0.641  | 1.6882   | 0.141     | 0.125     | 0.312     | 0.156 | 0.781 |      |
| TN-10          | 1.9685       | 1.859         | 18                   | 1.967      | 1.9309     | 1.8988     | 1.203 | 0.703  | 1.882    | 0.141     | 0.125     | 0.312     | 0.156 | 0.844 |      |
| TN-11          | 2.1654       | 2.047         | 18                   | 2.157      | 2.1209     | 2.0888     | 1.203 | 0.703  | 2.0782   | 0.141     | 0.125     | 0.312     | 0.156 | 0.844 |      |
| TN-12          | 2.3622       | 2.250         | 18                   | 2.360      | 2.3239     | 2.2918     | 1.297 | 0.766  | 2.2812   | 0.141     | 0.156     | 0.312     | 0.156 | 0.906 |      |
| TN-13          | 2.5591       | 2.422         | 18                   | 2.548      | 2.5119     | 2.4798     | 1.359 | 0.797  | 2.4692   | 0.141     | 0.156     | 0.312     | 0.156 | 0.938 |      |
| TN-14          | 2.7559       | 2.625         | 18                   | 2.751      | 2.7149     | 2.6828     | 1.359 | 0.797  | 2.6722   | 0.141     | 0.156     | 0.312     | 0.250 | 1.000 |      |
| TAN-15         | 2.9528       | 2.781         | 12                   | 2.933      | 2.8789     | 2.8308     | 1.422 | 0.828  | 2.8095   | 0.172     | 0.188     | 0.312     | 0.250 | 1.031 |      |
| TAN-16         | 3.1496       | 3.000         | 12                   | 3.137      | 3.0829     | 3.0348     | 1.422 | 0.828  | 3.0135   | 0.172     | 0.188     | 0.375     | 0.250 | 1.031 |      |

<sup>a</sup>Threads are American National form Class 3.

All dimensions in inches. For dimensions in millimeters, multiply inch values, except thread diameters, by 25.4 and round results to two decimal places. These data apply to steel. When either the nut or the shaft is made of stainless steel, aluminum, or other material having a tendency to seize, it is recommended that the maximum thread diameter of the shaft, both major and pitch, be reduced by 20 per cent of the pitch diameter tolerance listed in the Standard. For sizes larger than shown, see ANSI/ABMA 8.2-1991.

**Bearing Closures.**—Shields, seals, labyrinths, and slingers are employed to retain the lubricant in the bearing and to prevent the entry of dirt, moisture, or other harmful substances. The type selected for a given application depends upon the lubricant, shaft, speed, and the atmospheric conditions in which the unit is to operate. The shields or seals may be located in the bearing itself. Shields differ from seals in that they are attached to one bearing race but there is a definite clearance between the shield and the other, usually the inner, race. When a shielded bearing is placed in a housing in which the grease space has been filled, the bearing in running will tend to expel excess grease past the shields or to accept grease from the housing when the amount in the bearing itself is low.

Seals of leather, rubber, cork, felt, or plastic composition may be used. Since they must bear against the rotating member, excessive pressure should be avoided and some lubricant must be allowed to flow into the area of contact in order to prevent seizing and burning of the seal and scoring of the rotating member. Some seals are made up in the form of cartridges which can be pressed into the end of the bearing housing.

Leather seals may be used over a wide range of speeds. Although lubricant is best retained with a leather cupped inward toward the bearing, this arrangement is not suitable at high speeds due to danger of burning the leather. At high speeds where abrasive dust is present, the seal should be arranged with the leather cupped outward to lead some lubricant into the contact area. Only light pressure of leather against the shaft should be maintained.

**Bearing Fits.**—The slipping or creeping of a bearing ring on a rotating shaft or in a rotating housing occurs when the fit of the ring on the shaft or in the housing is loose. Such slipping or creeping action may cause rapid wear of both shaft and bearing ring when the surfaces are dry and highly loaded. To prevent this action the bearing is customarily mounted with the rotating ring a press fit and the stationary ring a push fit, the tightness or looseness depending upon the service intended. Thus, where shock or vibratory loads are to be encountered, fits should be made somewhat tighter than for ordinary service. The stationary ring, if correctly fitted, is allowed to creep very slowly so that prolonged stressing of one part of the raceway is avoided.

To facilitate the assembly of a bearing on a shaft it may become necessary to expand the inner ring by heating. This should be done in clean oil or in a temperature-controlled furnace at a temperature of between 200 and 250°F. The utmost care must be used to make sure that the temperature does not exceed 250°F. as overheating will tend to reduce the hardness of the rings. Prelubricated bearings should not be mounted by this method.

### Design Considerations

**Friction Losses in Rolling Element Bearings.**—The static and kinematic torques of rolling element bearings are generally small and in many applications are not significant. Bearing torque is a measure of the frictional resistance of the bearing to rotation and is the sum of three components: the torque due to the applied load; the torque due to viscous forces in lubricated rolling element bearings; and the torque due to roller end motions, for example, thrust loads against flanges. The friction or torque data may be used to calculate power absorption or heat generation within the bearing and can be utilized in efficiency or system-cooling studies.

Empirical equations have been developed for each of the torque components. These equations are influenced by such factors as bearing load, lubrication environment, and bearing design parameters. These design parameters include sliding friction from contact between the rolling elements and separator surfaces or between adjacent rolling elements; rolling friction from material deformations during the passage of the rolling elements over the race path; skidding or sliding of the Hertzian contact; and windage friction as a function of speed.

Starting or breakaway torques are also of interest in some situations. Breakaway torques tend to be between 1.5 and 1.8 times the running or kinetic torques.

When evaluating the torque requirements of a system under design, it should be noted that other components of the bearing package, such as seals and closures, can increase the overall system torque significantly. Seal torques have been shown to vary from a fraction of the bearing torque to several times that torque. In addition, the torque values given can vary significantly when load, speed of rotation, temperature, or lubrication are outside normal ranges.

For small instrument bearings friction torque has implications more critical than for larger types of bearings. These bearings have three operating friction torques to consider: starting torque, normal running torque, and peak running torque. These torque levels may vary between manufacturers and among lots from a given manufacturer.

Instrument bearings are even more critically dependent on design features — radial play, retainer type, and race conformity — than larger bearings. Typical starting torque values for small bearings are given in the accompanying table, extracted from the New Departure General Catalog.

Finally, if accurate control of friction torque is critical to a particular application, tests of the selected bearings should be conducted to evaluate performance.

#### Starting Torque — ABEC7

| Bearing Bore<br>(in.) | Max. Starting<br>Torque<br>(g cm) | Thrust<br>Load<br>(g) | Minimum Radial Play Range (inches)             |                                      |
|-----------------------|-----------------------------------|-----------------------|--|--------------------------------------|
|                       |                                   |                       | High Carbon Chrome<br>Steel and All Miniatures | Stainless Steel<br>Except Miniatures |
| 0.125                 | 0.10                              | 75                    | 0.0003–0.0005                                  | —                                    |
|                       | 0.14                              | 75                    | 0.0002–0.0004                                  | 0.0004–0.0006                        |
|                       | 0.18                              | 75                    | 0.0001–0.0003                                  | 0.0003–0.0005                        |
|                       | 0.22                              | 75                    | 0.0001–0.0003                                  | 0.0001–0.0003                        |
| 0.1875–0.312          | 0.40                              | 400                   | 0.0005–0.0008                                  | —                                    |
|                       | 0.45                              | 400                   | 0.0004–0.0006                                  | 0.0005–0.0008                        |
|                       | 0.50                              | 400                   | 0.0003–0.0005                                  | 0.0003–0.0005                        |
|                       | 0.63                              | 400                   | 0.0001–0.0003                                  | 0.0002–0.0004                        |
| 0.375                 | 0.50                              | 400                   | 0.0005–0.0008                                  | 0.0008–0.0011                        |
|                       | 0.63                              | 400                   | 0.0004–0.0006                                  | 0.0005–0.0008                        |
|                       | 0.75                              | 400                   | 0.0003–0.0005                                  | 0.0004–0.0006                        |
|                       | 0.95                              | 400                   | 0.0002–0.0004                                  | 0.0003–0.0005                        |

**Selection of Ball and Roller Bearings.**—As compared with sleeve bearings, ball and roller bearings offer the following advantages: 1) Starting friction is low; 2) Less axial space is required; 3) Relatively accurate shaft alignment can be maintained; 4) Both radial and axial loads can be carried by certain types; 5) Angle of load application is not restricted; 6) Replacement is relatively easy; 7) Comparatively heavy overloads can be carried momentarily; 8) Lubrication is simple; and 9) Design and application can be made with the assistance of bearing supplier engineers.

In selecting a ball or roller bearing for a specific application five choices must be made: 1) the bearing series; 2) the type of bearing; 3) the size of bearing; 4) the method of lubrication; and 5) the type of mounting.

Naturally these considerations are modified or affected by the anticipated operating conditions, expected life, cost, and overhaul philosophy.

It is well to review the possible history of the bearing and its function in the machine it will be applied to, thus: 1) Will it be expected to endure removal and reapplication?; 2) Must it be free from maintenance attention during its useful life?; 3) Can wear of the housing or shaft be tolerated during the overhaul period?; 4) Must it be adjustable to take up wear, or to change shaft location?; 5) How accurately can the load spectrum be estimated? and; and 6) Will it be relatively free from abuse in operation?.

Though many cautions could be pointed out, it should always be remembered that inadequate design approaches limit the utilization of rolling element bearings, reduce customer satisfaction, and reduce reliability. Time spent in this stage of design is the most rewarding effort of the bearing engineer, and here again he can depend on the bearing manufacturers' field organization for assistance.

*Type:* Where loads are low, ball bearings are usually less expensive than roller bearings in terms of unit-carrying capacity. Where loads are high, the reverse is usually true.

For a purely radial load, almost any type of radial bearing can be used, the actual choice being determined by other factors. To support a combination of thrust and radial loads, several types of bearings may be considered. If the thrust load component is large, it may be most economical to provide a separate thrust bearing. When a separate thrust bearing cannot be used due to high speed, lack of space, or other factors, the following types may be considered: angular contact ball bearing, deep groove ball bearing without filling slot, tapered roller bearing with steep contact angle, and self-aligning bearing of the wide type. If movement or deflection in an axial direction must be held to a minimum, then a separate thrust bearing or a preloaded bearing capable of taking considerable thrust load is required. To minimize deflection due to a moment in an axial plane, a rigid bearing such as a double row angular contact type with outwardly converging load lines is required. In such cases, the resulting stresses must be taken into consideration in determining the proper size of the bearing.

For shock loads or heavy loads of short duration, roller bearings are usually preferred.

Special bearing designs may be required where accelerations are usually high as in planetary or crank motions.

Where the problem of excessive shaft deflection or misalignment between shaft and housing is present, a self-aligning type of bearing may be a satisfactory solution.

It should be kept in mind that a great deal of difficulty can be avoided if standard types of bearings are used in preference to special designs, wherever possible.

*Size:* The size of bearing required for a given application is determined by the loads that are to be carried and, in some cases, by the amount of rigidity that is necessary to limit deflection to some specified amount.

The forces to which a bearing will be subjected can be calculated by the laws of engineering mechanics from the known loads, power, operating pressure, etc. Where loads are irregular, varying, or of unknown magnitude, it may be difficult to determine the actual forces. In such cases, empirical determination of such forces, based on extensive experience in bearing design, may be needed to attack the problem successfully. Where such experience is lacking, the bearing manufacturer should be consulted or the services of a bearing expert obtained.

If a ball or roller bearing is to be subjected to a combination of radial and thrust loads, an *equivalent radial load* is computed in the case of radial or angular type bearings and an *equivalent thrust load* is computed in the case of thrust bearings.

**Method of Lubrication.**—If speeds are high, relubrication difficult, the shaft angle other than horizontal, the application environment incompatible with normal lubrication, leakage cannot be tolerated; if other elements of the mechanism establish the lubrication requirements, bearing selection must be made with these criteria as controlling influences. Modern bearing types cover a wide selection of lubrication means. Though the most popular type is the "cartridge" type of sealed grease ball bearing, many applications have requirements which dictate against them. Often, operating environments may subject bearings to temperatures too high for seals utilized in the more popular designs. If minute leakage or the accumulation of traces of dirt at seal lips cannot be tolerated by the application (as in baking industry machinery), then the selections of bearings must be made with other sealing and lubrication systems in mind.

High shaft speeds generally dictate bearing selection based on the need for cooling, the suppression of churning or aeration of conventional lubricants, and most important of all, the inherent speed limitations of certain bearing types. An example of the latter is the effect of cage design and of the roller-end thrust-flange contact on the lubrication requirements in commercial taper roller bearings, which limit the speed they can endure and the thrust load they can carry. Reference to the manufacturers' catalog and application-design manuals is recommended before making bearing selections.

See *Anti-friction Bearing Lubrication* on page 2339 for more information on this topic.

**Type of Mounting.**—Many bearing installations are complicated because the best adapted type was not selected. Similarly, performance, reliability, and maintenance operations are restricted because the mounting was not thoroughly considered. There is no universally adaptable bearing for all needs. Careful reviews of the machine requirements should be made before designs are implemented. In many cases complicated machining, redundant shaft and housings, and use of an oversize bearing can be eliminated if the proper bearing in a well-thought-out mounting is chosen.

Advantage should be taken of the many race variations available in "standard" series of bearings. Puller grooves, tapered sleeves, ranged outer races, split races, fully demountable rolling-element and cage assemblies, flexible mountings, hydraulic removal features, relubrication holes and grooves, and many other innovations are available beyond the obvious advantages which are inherent in the basic bearing types.

**Radial and Axial Clearance.**—In designing the bearing mounting, a major consideration is to provide running clearances consistent with the requirements of the application. Race fits must be expected to absorb some of the original bearing clearance so that allowance should be made for approximately 80 per cent of the actual interference showing up in the diameter of the race. This will increase for heavy, stiff housings or for extra light series races shrunk onto solid shafts, while light metal housings (aluminum, magnesium, or sheet metal) and tubular shafts with wall sections less than the race wall thickness will cause a lesser change in the race diameter.

Where the application will impose heat losses through housing or shaft, or where a temperature differential may be expected, allowances must be made in the proper direction to insure proper operating clearance. Some compromises are required in applications where the indicated modification cannot be fully accommodated without endangering the bearing performance at lower speeds, during starting, or under lower temperature conditions than anticipated. Some leeway can be relied on with ball bearings since they can run with moderate preloads (.0005 inch, max.) without affecting bearing life or temperature rise. Roller bearings, however, have a lesser tolerance for preloading, and must be carefully controlled to avoid overheating and resulting self-destruction.

In all critical applications axial and radial clearances should be checked with feeler gages or dial indicators to insure mounted clearances within tolerances established by the design engineer. Since chips, scores, race misalignment, shaft or housing denting, housing distortion, end cover (closure) off-squareness, and mismatch of rotor and housing axial dimensions can rob the bearing of clearance, careful checks of running clearance is recommended.

For precision applications, taper-sleeve mountings, opposed ball or tapered-roller bearings with adjustable or shimmed closures are employed to provide careful control of radial and/or axial clearances. This practice requires skill and experience as well as the initial assistance of the bearing manufacturer's field engineer.

Tapered bore bearings are often used in applications such as these, again requiring careful and well worked-out assembly procedures. They can be assembled on either tapered shafts or on adapter sleeves. Advancement of the inner race over the tapered shaft can be done either by controlled heating (to expand the race as required) or by the use of a hydraulic jack. The adapter sleeve is supplied with a lock-nut which is used to advance the race on

the tapered sleeve. With the heavier fits normally required to effect the clearance changes compatible with such mountings, hydraulic removal devices are normally recommended.

For the conventional application, with standard fits, clearances provided in the standard bearing are suitable for normal operation. To insure that the design conditions are "normal," a careful review of the application requirements, environments, operating speed range, anticipated abuses, and design parameters must be made.

**General Bearing Handling Precautions.**—To insure that rolling element bearings are capable of achieving their design life and that they perform without objectionable noise, temperature rise, or shaft excursions, the following precautions are recommended:

- 1) Use the best bearing available for the application, consistent with the value of the application. Remember, the cost of the best bearing is generally small compared to the replacement costs of the rotating components that can be destroyed if a bearing fails or malfunctions.
- 2) If questions arise in designing the bearing application, seek out the assistance of the bearing manufacturer's representative.
- 3) Handle bearings with care, keeping them in the sealed, original container until ready to use.
- 4) Follow the manufacturer's instructions in handling and assembling the bearings.
- 5) Work with clean tools, clean dry hands, and in clean surroundings.
- 6) Do not wash or wipe bearings prior to installation unless special instructions or requirements have been established to do so.
- 7) Place unwrapped bearings on clean paper and keep them similarly covered until applied, if they cannot be kept in the original container.
- 8) Don't use wooden mallets, brittle or chipped tools, or dirty fixtures and tools in mounting bearings.
- 9) Don't spin uncleaned bearings, nor spin *any* bearing with an air blast.
- 10) Use care not to scratch or nick bearings.
- 11) Don't strike or press on race flanges.
- 12) Use adapters for mounting which provide uniform steady pressure rather than hammering on a drift or sleeve.
- 13) Insure that races are started onto shafts and into housings evenly so as to prevent cocking.
- 14) Inspect shafts and housings before mounting bearing to insure that proper fits will be maintained.
- 15) When removing bearings, clean housings, covers, and shafts before exposing the bearings. All dirt can be considered an abrasive, dangerous to the reuse of any rolling bearing.
- 16) Treat used bearings, which may be reused, as new ones.
- 17) Protect dismantled bearings from dirt and moisture.
- 18) Use clean, lint-free rags if bearings are wiped.
- 19) Wrap bearings in clean, oil-proof paper when not in use.
- 20) Use clean filtered, water-free Stoddard's solvent or flushing oil to clean bearings.
- 21) In heating bearings for mounting onto shafts, follow manufacturer's instructions.
- 22) In assembling bearings onto shafts *never* strike the outer race, or press on it to force the inner race. Apply the pressure on the inner race only. In dismantling follow the same precautions.
- 23) Do not press, strike, or otherwise force the seal or shield on factory-sealed bearings.

**Bearing Failures, Deficiencies, and Their Origins.**—The general classifications of failures and deficiencies requiring bearing removal are:

1) Overheating due to a) Inadequate or insufficient lubrication; b) Excessive lubrication; c) Grease liquefaction or aeration; d) Oil foaming; e) Abrasive or corrosive action due to contaminants in bearing; f) Distortion of housing due to warping, or out-of-round; g) Seal rubbing or failure; h) Inadequate or blocked scavenge oil passages; i) Inadequate bearing-clearance or bearing-preload; j) Race turning; k) Cage wear; and l) Shaft expansion—loss of bearing or seal clearance.

2) Vibration due to a) Dirt or chips in bearing; b) Fatigued race or rolling elements; c) Race turning; d) Rotor unbalance; e) Out-of-round shaft; f) Race misalignment; g) Housing resonance; h) Cage wear; i) Flats on races or rolling elements; j) Excessive clearance; k) Corrosion; l) False-brinelling or indentation of races; m) Electrical discharge (similar to corrosion effects); n) Mixed rolling element diameters; and o) Out-of-square rolling paths in races.

3) Turning on shaft due to a) Growth of race due to overheating; b) Fretting wear; c) Improper initial fit; d) Excessive shaft deflection; e) Initially coarse shaft finish; and f) Seal rub on inner race.

4) Binding of the shaft due to a) Lubricant breakdown; b) Contamination by abrasive or corrosive matter; c) Housing distortion or out-of-round pinching bearing; d) Uneven shimming of housing with loss of clearance; e) Tight rubbing seals; f) Preloaded bearings; g) Cocked races; h) Loss of clearance due to excessive tightening of adapter; i) Thermal expansion of shaft or housing; and j) Cage failure.

5) Noisy bearing due to a) Lubrication breakdown, inadequate lubrication, stiff grease; b) Contamination; c) Pinched bearing; d) Seal rubbing; e) Loss of clearance and preload; f) Bearing slipping on shaft or in housing; g) Flatted roller or ball; h) Brinelling due to assembly abuse, handling, or shock loads; i) Variation in size of rolling elements; j) Out-of-round or lobular shaft; k) Housing bore waviness; and l) Chips or scores under bearing race seat.

6) Displaced shaft due to a) Bearing wear; b) Improper housing or closure assembly; c) Overheated and shifted bearing; d) Inadequate shaft or housing shoulder; e) Lubrication and cage failure permitting rolling elements to bunch; f) Loosened retainer nut or adapter; g) Excessive heat application in assembling inner race, causing growth and shifting on shaft; and h) Housing pounding out.

7) Lubricant leakage due to a) Overfilling of lubricant; b) Grease churning due to use of too soft a consistency; c) Grease deterioration due to excessive operating temperature; d) Operating life longer than grease life (grease breakdown, aeration, and purging); e) Seal wear; f) Wrong shaft attitude (bearing seals designed for horizontal mounting only); g) Seal failure; h) Clogged breather; i) Oil foaming due to churning or air flow through housing; j) Gasket (O-ring) failure or misapplication; k) Porous housing or closure; and l) Lubricator set at wrong flow rate.

### Load Ratings and Fatigue Life

**Ball and Roller Bearing Life.**—The performance of ball and roller bearings is a function of many variables. These include the bearing design, the characteristics of the material from which the bearings are made, the way in which they are manufactured, as well as many variables associated with their application. The only sure way to establish the satisfactory operation of a bearing selected for a specific application is by actual performance in the application. As this is often impractical, another basis is required to estimate the suitability of a particular bearing for a given application. Two factors are taken into consideration: the bearing fatigue life, and its ability to withstand static loading.

*Life Criterion:* Even if a ball or roller bearing is properly mounted, adequately lubricated, protected from foreign matter and not subjected to extreme operating conditions, it



can ultimately fatigue. Under ideal conditions, the repeated stresses developed in the contact areas between the balls or rollers and the raceways eventually can result in the fatigue of the material which manifests itself with the spalling of the load-carrying surfaces. In most applications the fatigue life is the maximum useful life of a bearing.

*Static Load Criterion:* A static load is a load acting on a non-rotating bearing. Permanent deformations appear in balls or rollers and raceways under a static load of moderate magnitude and increase gradually with increasing load. The permissible static load is, therefore, dependent upon the permissible magnitude of permanent deformation. It has been found that for ball and roller bearings suitably manufactured from hardened alloy steel, deformations occurring under maximum contact stress of 4,000 megapascals (580,000 pounds per square inch) acting at the center of contact (in the case of roller bearings, of a uniformly loaded roller) do not greatly impair smoothness or friction. Depending on requirements for smoothness of operation, friction, or sound level, higher or lower static load limits may be tolerated.

**Ball Bearing Types Covered.**—AFBMA and American National Standard ANSI/ABMA 9-1990 sets forth the method of determining ball bearing Rating Life and Static Load Rating and covers the following types:

1) *Radial, deep groove and angular contact ball bearings* whose inner ring raceways have a cross-sectional radius not larger than 52 percent of the ball diameter and whose outer ring raceways have a cross-sectional radius not larger than 53 percent of the ball diameter.

2) *Radial, self-aligning ball bearings* whose inner ring raceways have cross-sectional radii not larger than 53 percent of the ball diameter.

3) *Thrust ball bearings* whose washer raceways have cross-sectional radii not larger than 54 percent of the ball diameter.

4) *Double row, radial and angular contact ball bearings* and double direction thrust ball bearings are presumed to be symmetrical.

**Limitations for Ball Bearings.**—The following limitations apply:

1) *Truncated contact area.* This standard\* may not be safely applied to ball bearings subjected to loading which causes the contact area of the ball with the raceway to be truncated by the raceway shoulder. This limitation depends strongly on details of bearing design which are not standardized.

2) *Material.* This standard applies only to ball bearings fabricated from hardened good quality steel.

3) *Types.* The  $f_c$  factors specified in the basic load rating formulas are valid only for those ball bearing types specified above.

4) *Lubrication.* The Rating Life calculated according to this standard is based on the assumption that the bearing is adequately lubricated. The determination of adequate lubrication depends upon the bearing application.

5) *Ring support and alignment.* The Rating Life calculated according to this standard assumes that the bearing inner and outer rings are rigidly supported and the inner and outer ring axes are properly aligned.

6) *Internal clearance.* The radial ball bearing Rating Life calculated according to this standard is based on the assumption that only a nominal interior clearance occurs in the mounted bearing at operating speed, load and temperature.

7) *High speed effects.* The Rating Life calculated according to this standard does not account for high speed effects such as ball centrifugal forces and gyroscopic moments. These effects tend to diminish fatigue life. Analytical evaluation of these effects frequently requires the use of high speed digital computation devices and hence is not covered in the standard.

\* All references to "standard" are to AFBMA and American National Standard "Load Ratings and Fatigue Life for Ball Bearings" ANSI/ABMA 9-1990.

8) *Groove radii.* If groove radii are smaller than those specified in the bearing types covered, the ability of a bearing to resist fatigue is not improved; however, it is diminished by the use of larger radii.

**Ball Bearing Rating Life.**—According to the Anti-Friction Bearing Manufacturers Association standards the Rating Life  $L_{10}$  of a group of apparently identical ball bearings is the life in millions of revolutions that 90 percent of the group will complete or exceed. For a single bearing,  $L_{10}$  also refers to the life associated with 90 percent reliability.

*Radial and Angular Contact Ball Bearings:* The magnitude of the Rating Life  $L_{10}$  in millions of revolutions, for a radial or angular contact ball bearing application is given by the formula:

$$L_{10} = \left( \frac{C}{P} \right)^3 \quad (1)$$

where  $C$  = basic load rating, newtons (pounds). See Formulas (2), (3a) and (3b)

$P$  = equivalent radial load, newtons (pounds). See Formula (4)

**Table 27. Values of  $f_c$  for Radial and Angular Contact Ball Bearings**

| $\frac{D \cos \alpha}{d_m}$ | Single Row Radial Contact; Single and Double Row Angular Contact, Groove Type <sup>a</sup> |                   | Double Row Radial Contact Groove Type |                   | Self-Aligning       |                   |
|-----------------------------|--|-------------------|---------------------------------------|-------------------|---------------------|-------------------|
|                             | Metric <sup>b</sup>  | Inch <sup>c</sup> | Metric <sup>b</sup>                   | Inch <sup>c</sup> | Metric <sup>b</sup> | Inch <sup>c</sup> |
| 0.05                        | 46.7   | 3550              | 44.2                                  | 3360              | 17.3                | 1310              |
| 0.06                        | 49.1   | 3730              | 46.5                                  | 3530              | 18.6                | 1420              |
| 0.07                        | 51.1   | 3880              | 48.4                                  | 3680              | 19.9                | 1510              |
| 0.08                        | 52.8   | 4020              | 50.0                                  | 3810              | 21.1                | 1600              |
| 0.09                        | 54.3   | 4130              | 51.4                                  | 3900              | 22.3                | 1690              |
| 0.10                        | 55.5   | 4220              | 52.6                                  | 4000              | 23.4                | 1770              |
| 0.12                        | 57.5   | 4370              | 54.5                                  | 4140              | 25.6                | 1940              |
| 0.14                        | 58.8   | 4470              | 55.7                                  | 4230              | 27.7                | 2100              |
| 0.16                        | 59.6   | 4530              | 56.5                                  | 4290              | 29.7                | 2260              |
| 0.18                        | 59.9   | 4550              | 56.8                                  | 4310              | 31.7                | 2410              |
| 0.20                        | 59.9   | 4550              | 56.8                                  | 4310              | 33.5                | 2550              |
| 0.22                        | 59.6   | 4530              | 56.5                                  | 4290              | 35.2                | 2680              |
| 0.24                        | 59.0   | 4480              | 55.9                                  | 4250              | 36.8                | 2790              |
| 0.26                        | 58.2   | 4420              | 55.1                                  | 4190              | 38.2                | 2910              |
| 0.28                        | 57.1   | 4340              | 54.1                                  | 4110              | 39.4                | 3000              |
| 0.30                        | 56.0   | 4250              | 53.0                                  | 4030              | 40.3                | 3060              |
| 0.32                        | 54.6   | 4160              | 51.8                                  | 3950              | 40.9                | 3110              |
| 0.34                        | 53.2   | 4050              | 50.4                                  | 3840              | 41.2                | 3130              |
| 0.36                        | 51.7   | 3930              | 48.9                                  | 3730              | 41.3                | 3140              |
| 0.38                        | 50.0   | 3800              | 47.4                                  | 3610              | 41.0                | 3110              |
| 0.40                        | 48.4   | 3670              | 45.8                                  | 3480              | 40.4                | 3070              |

<sup>a</sup> A. When calculating the basic load rating for a unit consisting of two similar, single row, radial contact ball bearings, in a duplex mounting, the pair is considered as one, double row, radial contact ball bearing.

B. When calculating the basic load rating for a unit consisting of two, similar, single row, angular contact ball bearings in a duplex mounting, "face-to-face" or "back-to-back," the pair is considered as one, double row, angular contact ball bearing.

C. When calculating the basic load rating for a unit consisting of two or more similar, single angular contact ball bearings mounted "in tandem," properly manufactured and mounted for equal load distribution, the rating of the combination is the number of bearings to the 0.7 power times the rating of a single row ball bearing. If the unit may be treated as a number of individually interchangeable single row bearings, this footnote "C" does not apply.

<sup>b</sup> Use to obtain  $C$  in newtons when  $D$  is given in mm.

<sup>c</sup> Use to obtain  $C$  in pounds when  $D$  is given in inches.

**Table 28. Values of X and Y for Computing Equivalent Radial Load P of Radial and Angular Contact Ball Bearings**

| Contact Angle, $\alpha$               | Table Entering Factors <sup>a</sup>    |              |            | Single Row Bearings <sup>b</sup> |   |                       | Double Row Bearings |                    |      |                    |
|---------------------------------------|--|--------------|------------|----------------------------------|---|-----------------------|---------------------|--------------------|------|--------------------|
|                                       |  |              |            | $\frac{F_a}{F_r} > e$            | $\frac{F_a}{F_r} \leq e$  | $\frac{F_a}{F_r} > e$ |                     |                    |      |                    |
| <b>RADIAL CONTACT GROOVE BEARINGS</b> |  |              |            |                                  |   |                       |                     |                    |      |                    |
|                                       | $F_d/C_o$                              | $F_d/iZD^2$  |            | $e$                              | X   | Y                     | X                   | Y                  | X    | Y                  |
|                                       |  | Metric Units | Inch Units |                                  |   |                       |                     |                    |      |                    |
| 0°                                    | 0.014                                  | 0.172        | 25         | 0.19                             |   | 2.30                  |                     |                    |      | 2.30               |
|                                       | 0.028                                  | 0.345        | 50         | 0.22                             |   | 1.99                  |                     |                    |      | 1.99               |
|                                       | 0.056                                  | 0.689        | 100        | 0.26                             |   | 1.71                  |                     |                    |      | 1.71               |
|                                       | 0.084                                  | 1.03         | 150        | 0.28                             |   | 1.56                  |                     |                    |      | 1.55               |
|                                       | 0.11                                   | 1.38         | 200        | 0.30                             | 0.56  | 1.45                  | 1                   | 0                  | 0.56 | 1.45               |
|                                       | 0.17                                   | 2.07         | 300        | 0.34                             |   | 1.31                  |                     |                    |      | 1.31               |
|                                       | 0.28                                   | 3.45         | 500        | 0.38                             |   | 1.15                  |                     |                    |      | 1.15               |
|                                       | 0.42                                   | 5.17         | 750        | 0.42                             |   | 1.04                  |                     |                    |      | 1.04               |
|                                       | 0.56                                   | 6.89         | 1000       | 0.44                             |   | 1.00                  |                     |                    |      | 1.00               |
|                                       | <b>ANGULAR CONTACT GROOVE BEARINGS</b> |              |            |                                  |   |                       |                     |                    |      |                    |
|                                       | $iF_d/C_o$                             | $F_d/iZD^2$  |            | $e$                              | X   | Y                     | X                   | Y                  | X    | Y                  |
|                                       |  | Metric Units | Inch Units |                                  |   |                       |                     |                    |      |                    |
| 5°                                    | 0.014                                  | 0.172        | 25         | 0.23                             | For this type use the X, Y, and e values applicable to single row radial contact bearings |                       |                     | 2.78               | 0.78 | 3.74               |
|                                       | 0.028                                  | 0.345        | 50         | 0.26                             |   |                       | 2.40                |                    | 3.23 |                    |
|                                       | 0.056                                  | 0.689        | 100        | 0.30                             |   |                       | 2.07                |                    | 2.78 |                    |
|                                       | 0.085                                  | 1.03         | 150        | 0.34                             |   |                       | 1.87                |                    | 2.52 |                    |
|                                       | 0.11                                   | 1.38         | 200        | 0.36                             |   |                       | 1.75                | 1                  | 2.36 |                    |
|                                       | 0.17                                   | 2.07         | 300        | 0.40                             |   |                       | 1.58                |                    | 2.13 |                    |
|                                       | 0.28                                   | 3.45         | 500        | 0.45                             |   |                       | 1.39                |                    | 1.87 |                    |
|                                       | 0.42                                   | 5.17         | 750        | 0.50                             |   |                       | 1.26                |                    | 1.69 |                    |
|                                       | 0.56                                   | 6.89         | 1000       | 0.52                             |   |                       | 1.21                |                    | 1.63 |                    |
|                                       | 10°                                    | 0.014        | 0.172      | 25                               |   | 0.29                  |                     | 1.88               |      | 2.18               |
| 0.029                                 |  | 0.345        | 50         | 0.32                             |   | 1.71                  |                     | 1.98               | 2.78 |                    |
| 0.057                                 |  | 0.689        | 100        | 0.36                             |   | 1.52                  |                     | 1.76               | 2.47 |                    |
| 0.086                                 |  | 1.03         | 150        | 0.38                             |   | 1.41                  |                     | 1.63               | 2.20 |                    |
| 0.11                                  |  | 1.38         | 200        | 0.40                             | 0.46  | 1.34                  | 1                   | 1.55               | 0.75 | 2.18               |
| 0.17                                  |  | 2.07         | 300        | 0.44                             |   | 1.23                  |                     | 1.42               | 2.00 |                    |
| 0.29                                  |  | 3.45         | 500        | 0.49                             |   | 1.10                  |                     | 1.27               | 1.79 |                    |
| 0.43                                  |  | 5.17         | 750        | 0.54                             |   | 1.01                  |                     | 1.17               | 1.64 |                    |
| 0.57                                  |  | 6.89         | 1000       | 0.54                             |   | 1.00                  |                     | 1.16               | 1.63 |                    |
| 15°                                   |  | 0.015        | 0.172      | 25                               | 0.38  |                       | 1.47                |                    | 1.65 | 2.39               |
|                                       | 0.029                                  | 0.345        | 50         | 0.40                             |   | 1.40                  |                     | 1.57               | 2.28 |                    |
|                                       | 0.058                                  | 0.689        | 100        | 0.43                             |   | 1.30                  |                     | 1.46               | 2.11 |                    |
|                                       | 0.087                                  | 1.03         | 150        | 0.46                             |   | 1.23                  |                     | 1.38               | 2.00 |                    |
|                                       | 0.12                                   | 1.38         | 200        | 0.47                             | 0.44  | 1.19                  | 1                   | 1.34               | 0.72 | 1.93               |
|                                       | 0.17                                   | 2.07         | 300        | 0.50                             |   | 1.12                  |                     | 1.26               | 1.82 |                    |
|                                       | 0.29                                   | 3.45         | 500        | 0.55                             |   | 1.02                  |                     | 1.14               | 1.66 |                    |
|                                       | 0.44                                   | 5.17         | 750        | 0.56                             |   | 1.00                  |                     | 1.12               | 1.63 |                    |
|                                       | 0.58                                   | 6.89         | 1000       | 0.56                             |   | 1.00                  |                     | 1.12               | 1.63 |                    |
|                                       | 20°                                    | ...          | ...        | ...                              | 0.57  | 0.43                  | 1.00                | 1                  | 1.09 | 0.70               |
| 25°                                   | ...                                    | ...          | ...        | 0.68                             | 0.41  | 0.87                  | 1                   | 0.92               | 0.67 | 1.41               |
| 30°                                   | ...                                    | ...          | ...        | 0.80                             | 0.39  | 0.76                  | 1                   | 0.78               | 0.63 | 1.24               |
| 35°                                   | ...                                    | ...          | ...        | 0.95                             | 0.37  | 0.66                  | 1                   | 0.66               | 0.60 | 1.07               |
| 40°                                   | ...                                    | ...          | ...        | 1.14                             | 0.35  | 0.57                  | 1                   | 0.55               | 0.57 | 0.98               |
| Self-aligning Ball Bearings           |  |              |            | $1.5 \tan \alpha$                | 0.40  | $0.4 \cot \alpha$     | 1                   | $0.42 \cot \alpha$ | 0.65 | $0.65 \cot \alpha$ |

<sup>a</sup> Symbol definitions are given on the following page.

<sup>b</sup> For single row bearings when  $F_d/F_r \leq e$ , use  $X = 1, Y = 0$ . Two similar, single row, angular contact ball bearings mounted face-to-face or back-to-back are considered as one double row, angular contact bearing.

Values of X, Y, and e for a load or contact angle other than shown are obtained by linear interpolation. Values of X, Y, and e do not apply to filling slot bearings for applications in which ball-raceway

contact areas project substantially into the filling slot under load. Symbol Definitions:  $F_a$  is the applied axial load in newtons (pounds);  $C_o$  is the static load rating in newtons (pounds) of the bearing under consideration and is found by [Formula \(20\)](#);  $i$  is the number of rows of balls in the bearing;  $Z$  is the number of balls per row in a radial or angular contact bearing or the number of balls in a single row, single direction thrust bearing;  $D$  is the ball diameter in millimeters (inches); and  $F_r$  is the applied radial load in newtons (pounds).

For radial and angular contact ball bearings with balls not larger than 25.4 mm (1 inch) in diameter,  $C$  is found by the formula:

$$C = f_c (i \cos \alpha)^{0.7} Z^{2/3} D^{1.8} \quad (2)$$

and with balls larger than 25.4 mm (1 inch) in diameter  $C$  is found by the formula:

$$C = 3.647 f_c (i \cos \alpha)^{0.7} Z^{2/3} D^{1.4} \quad (\text{metric}) \quad (3a)$$

$$C = f_c (i \cos \alpha)^{0.7} Z^{2/3} D^{1.4} \quad (\text{inch}) \quad (3b)$$

where  $f_c$  = a factor which depends on the geometry of the bearing components, the accuracy to which the various bearing parts are made and the material. Values of  $f_c$  are given in [Table 27](#)

$i$  = number of rows of balls in the bearing

$\alpha$  = nominal contact angle, degrees

$Z$  = number of balls per row in a radial or angular contact bearing

$D$  = ball diameter, mm (inches)

The magnitude of the equivalent radial load,  $P$ , in newtons (pounds) for radial and angular contact ball bearings, under combined constant radial and constant thrust loads is given by the formula:

$$P = XF_r + YF_a \quad (4)$$

where  $F_r$  = the applied radial load in newtons (pounds)

$F_a$  = the applied axial load in newtons (pounds)

$X$  = radial load factor as given in [Table 30](#)

$Y$  = axial load factor as given in [Table 30](#)

**Thrust Ball Bearings:** The magnitude of the Rating Life  $L_{10}$  in millions of revolutions for a thrust ball bearing application is given by the formula:

$$L_{10} = \left( \frac{C_a}{P_a} \right)^3 \quad (5)$$

where  $C_a$  = the basic load rating, newtons (pounds). See [Formulas \(6\) to \(10\)](#)

$P_a$  = equivalent thrust load, newtons (pounds). See [Formula \(11\)](#)

For single row, single and double direction, thrust ball bearing with balls not larger than 25.4 mm (1 inch) in diameter,  $C_a$  is found by the formulas:

$$\text{for } \alpha = 90 \text{ degrees, } C_a = f_c Z^{2/3} D^{1.8} \quad (6)$$

$$\text{for } \alpha \neq 90 \text{ degrees, } C_a = f_c (\cos \alpha)^{0.7} Z^{2/3} D^{1.8} \tan \alpha \quad (7)$$

and with balls larger than 25.4 mm (1 inch) in diameter,  $C_a$  is found by the formulas:

$$\text{for } \alpha = 90 \text{ degrees, } C_a = 3.647 f_c Z^{2/3} D^{1.4} \quad (\text{metric}) \quad (8a)$$

$$C_a = f_c Z^{2/3} D^{1.4} \quad (\text{inch}) \quad (8b)$$

$$\text{for } \alpha \neq 90 \text{ degrees, } C_a = 3.647 f_c (\cos \alpha)^{0.7} Z^{2/3} D^{1.4} \tan \alpha \quad (\text{metric}) \quad (9a)$$

$$C_a = f_c (\cos \alpha)^{0.7} Z^{2/3} D^{1.4} \tan \alpha \quad (9b)$$

where  $f_c$  = a factor which depends on the geometry of the bearing components, the accuracy to which the various bearing parts are made, and the material. Values of  $f_c$  are given in Table 29

$Z$  = number of balls per row in a single row, single direction thrust ball bearing

$D$  = ball diameter, mm (inches)

$\alpha$  = nominal contact angle, degrees

**Table 29. Values of  $f_c$  for Thrust Ball Bearings**

| $\frac{D}{d_m}$ | $\alpha = 90^\circ$ |                   | $D \cos \alpha$ | $\alpha = 45^\circ$ |                   | $\alpha = 60^\circ$ |                   | $\alpha = 75^\circ$ |                   |
|-----------------|---------------------|-------------------|-----------------|---------------------|-------------------|---------------------|-------------------|---------------------|-------------------|
|                 | Metric <sup>a</sup> | Inch <sup>b</sup> |                 | Metric <sup>a</sup> | Inch <sup>b</sup> | Metric <sup>a</sup> | Inch <sup>b</sup> | Metric <sup>a</sup> | Inch <sup>b</sup> |
| 0.01            | 36.7                | 2790              | 0.01            | 42.1                | 3200              | 39.2                | 2970              | 37.3                | 2840              |
| 0.02            | 45.2                | 3430              | 0.02            | 51.7                | 3930              | 48.1                | 3650              | 45.9                | 3490              |
| 0.03            | 51.1                | 3880              | 0.03            | 58.2                | 4430              | 54.2                | 4120              | 51.7                | 3930              |
| 0.04            | 55.7                | 4230              | 0.04            | 63.3                | 4810              | 58.9                | 4470              | 56.1                | 4260              |
| 0.05            | 59.5                | 4520              | 0.05            | 67.3                | 5110              | 62.6                | 4760              | 59.7                | 4540              |
| 0.06            | 62.9                | 4780              | 0.06            | 70.7                | 5360              | 65.8                | 4990              | 62.7                | 4760              |
| 0.07            | 65.8                | 5000              | 0.07            | 73.5                | 5580              | 68.4                | 5190              | 65.2                | 4950              |
| 0.08            | 68.5                | 5210              | 0.08            | 75.9                | 5770              | 70.7                | 5360              | 67.3                | 5120              |
| 0.09            | 71.0                | 5390              | 0.09            | 78.0                | 5920              | 72.6                | 5510              | 69.2                | 5250              |
| 0.10            | 73.3                | 5570              | 0.10            | 79.7                | 6050              | 74.2                | 5630              | 70.7                | 5370              |
| 0.12            | 77.4                | 5880              | 0.12            | 82.3                | 6260              | 76.6                | 5830              | ...                 | ...               |
| 0.14            | 81.1                | 6160              | 0.14            | 84.1                | 6390              | 78.3                | 5950              | ...                 | ...               |
| 0.16            | 84.4                | 6410              | 0.16            | 85.1                | 6470              | 79.2                | 6020              | ...                 | ...               |
| 0.18            | 87.4                | 6640              | 0.18            | 85.5                | 6500              | 79.6                | 6050              | ...                 | ...               |
| 0.20            | 90.2                | 6854              | 0.20            | 85.4                | 6490              | 79.5                | 6040              | ...                 | ...               |
| 0.22            | 92.8                | 7060              | 0.22            | 84.9                | 6450              | ...                 | ...               | ...                 | ...               |
| 0.24            | 95.3                | 7240              | 0.24            | 84.0                | 6380              | ...                 | ...               | ...                 | ...               |
| 0.26            | 97.6                | 7410              | 0.26            | 82.8                | 6290              | ...                 | ...               | ...                 | ...               |
| 0.28            | 99.8                | 7600              | 0.28            | 81.3                | 6180              | ...                 | ...               | ...                 | ...               |
| 0.30            | 101.9               | 7750              | 0.30            | 79.6                | 6040              | ...                 | ...               | ...                 | ...               |
| 0.32            | 103.9               | 7900              | ...             | ...                 | ...               | ...                 | ...               | ...                 | ...               |
| 0.34            | 105.8               | 8050              | ...             | ...                 | ...               | ...                 | ...               | ...                 | ...               |

<sup>a</sup> Use to obtain  $C_a$  in newtons when  $D$  is given in mm.

<sup>b</sup> Use to obtain  $C_a$  in pounds when  $D$  is given in inches.

For thrust ball bearings with two or more rows of similar balls carrying loads in the same direction, the basic load rating,  $C_a$ , in newtons (pounds) is found by the formula:

$$C_a = (Z_1 + Z_2 + \dots + Z_n) \left[ \left( \frac{Z_1}{C_{a1}} \right)^{10/3} + \left( \frac{Z_2}{C_{a2}} \right)^{10/3} + \dots + \left( \frac{Z_n}{C_{an}} \right)^{10/3} \right]^{-0.3} \quad (10)$$

where  $Z_1, Z_2, \dots, Z_n$  = number of balls in respective rows of a single-direction multi-row thrust ball bearing

$C_{a1}, C_{a2}, \dots, C_{an}$  = basic load rating per row of a single-direction, multi-row thrust ball bearing, each calculated as a single-row bearing with  $Z_1, Z_2, \dots, Z_n$  balls, respectively

The magnitude of the equivalent thrust load,  $P_a$ , in newtons (pounds) for thrust ball bearings with  $\alpha \neq 90$  degrees under combined constant thrust and constant radial loads is found by the formula:

$$P_a = XF_r + YF_a \quad (11)$$

where  $F_r$  = the applied radial load in newtons (pounds)

$F_a$  = the applied axial load in newtons (pounds)

$X$  = radial load factor as given in Table 30

$Y$  = axial load factor as given in Table 30

**Table 30. Values of X and Y for Computing Equivalent Thrust Load  $P_a$  for Thrust Ball Bearings**

| Contact Angle<br>$\alpha$ | $e$  | Single Direction Bearings |   | Double Direction Bearings |      |                       |   |
|---------------------------|------|---------------------------|---|---------------------------|------|-----------------------|---|
|                           |      | $\frac{F_a}{F_r} > e$     |   | $\frac{F_a}{F_r} \leq e$  |      | $\frac{F_a}{F_r} > e$ |   |
|                           |      | X                         | Y | X                         | Y    | X                     | Y |
| 45°                       | 1.25 | 0.66                      | 1 | 1.18                      | 0.59 | 0.66                  | 1 |
| 60°                       | 2.17 | 0.92                      | 1 | 1.90                      | 0.54 | 0.92                  | 1 |
| 75°                       | 4.67 | 1.66                      | 1 | 3.89                      | 0.52 | 1.66                  | 1 |

For  $\alpha = 90^\circ$ ,  $F_r = 0$  and  $Y = 1$ .

**Roller Bearing Types Covered.**—This standard\* applies to *cylindrical, tapered and self-aligning radial and thrust roller bearings* and to *needle roller bearings*. These bearings are presumed to be within the size ranges shown in the AFBMA dimensional standards, of good quality and produced in accordance with good manufacturing practice.

Roller bearings vary considerably in design and execution. Since small differences in relative shape of contacting surfaces may account for distinct differences in load carrying ability, this standard does not attempt to cover all design variations, rather it applies to basic roller bearing designs.

The following limitations apply:

1) *Truncated contact area.* This standard may not be safely applied to roller bearings subjected to application conditions which cause the contact area of the roller with the raceway to be severely truncated by the edge of the raceway or roller.

2) *Stress concentrations.* A cylindrical, tapered or self-aligning roller bearing must be expected to have a basic load rating less than that obtained using a value of  $f_c$  taken from Table 31 or 32 if, under load, a stress concentration is present in some part of the roller-raceway contact. Such stress concentrations occur in the center of nominal point contacts, at the contact extremities for line contacts and at inadequately blended junctions of a rolling surface profile. Stress concentrations can also occur if the rollers are not accurately guided such as in bearings without cages and bearings not having rigid integral flanges. Values of  $f_c$  given in Tables 31 and 32 are based upon bearings manufactured to achieve optimized contact. For no bearing type or execution will the factor  $f_c$  be greater than that obtained in Tables 31 and 32.

3) *Material.* This standard applies only to roller bearings fabricated from hardened, good quality steel.

4) *Lubrication.* Rating Life calculated according to this standard is based on the assumption that the bearing is adequately lubricated. Determination of adequate lubrication depends upon the bearing application.

5) *Ring support and alignment.* Rating Life calculated according to this standard assumes that the bearing inner and outer rings are rigidly supported, and that the inner and outer ring axes are properly aligned.

6) *Internal clearance.* Radial roller bearing Rating Life calculated according to this standard is based on the assumption that only a nominal internal clearance occurs in the mounted bearing at operating speed, load, and temperature.

7) *High speed effects.* The Rating Life calculated according to this standard does not account for high speed effects such as roller centrifugal forces and gyroscopic moments: These effects tend to diminish fatigue life. Analytical evaluation of these effects frequently requires the use of high speed digital computation devices and hence, cannot be included.

\* All references to "standard" are to AFBMA and American National Standard "Load Ratings and Fatigue Life for Roller Bearings" ANSI/AFBMA Std 11-1990.

**Table 31. Values of  $f_c$  for Radial Roller Bearings**

| $D \cos \alpha$<br>$d_m$ | $f_c$               |                   | $D \cos \alpha$<br>$d_m$ | $f_c$               |                   | $D \cos \alpha$<br>$d_m$ | $f_c$               |                   |
|--------------------------|---------------------|-------------------|--------------------------|---------------------|-------------------|--------------------------|---------------------|-------------------|
|                          | Metric <sup>a</sup> | Inch <sup>b</sup> |                          | Metric <sup>a</sup> | Inch <sup>b</sup> |                          | Metric <sup>a</sup> | Inch <sup>b</sup> |
| 0.01                     | 52.1                | 4680              | 0.18                     | 88.8                | 7980              | 0.35                     | 79.5                | 7140              |
| 0.02                     | 60.8                | 5460              | 0.19                     | 88.8                | 7980              | 0.36                     | 78.6                | 7060              |
| 0.03                     | 66.5                | 5970              | 0.20                     | 88.7                | 7970              | 0.37                     | 77.6                | 6970              |
| 0.04                     | 70.7                | 6350              | 0.21                     | 88.5                | 7950              | 0.38                     | 76.7                | 6890              |
| 0.05                     | 74.1                | 6660              | 0.22                     | 88.2                | 7920              | 0.39                     | 75.7                | 6800              |
| 0.06                     | 76.9                | 6910              | 0.23                     | 87.9                | 7890              | 0.40                     | 74.6                | 6700              |
| 0.07                     | 79.2                | 7120              | 0.24                     | 87.5                | 7850              | 0.41                     | 73.6                | 6610              |
| 0.08                     | 81.2                | 7290              | 0.25                     | 87.0                | 7810              | 0.42                     | 72.5                | 6510              |
| 0.09                     | 82.8                | 7440              | 0.26                     | 86.4                | 7760              | 0.43                     | 71.4                | 6420              |
| 0.10                     | 84.2                | 7570              | 0.27                     | 85.8                | 7710              | 0.44                     | 70.3                | 6320              |
| 0.11                     | 85.4                | 7670              | 0.28                     | 85.2                | 7650              | 0.45                     | 69.2                | 6220              |
| 0.12                     | 86.4                | 7760              | 0.29                     | 84.5                | 7590              | 0.46                     | 68.1                | 6120              |
| 0.13                     | 87.1                | 7830              | 0.30                     | 83.8                | 7520              | 0.47                     | 67.0                | 6010              |
| 0.14                     | 87.7                | 7880              | 0.31                     | 83.0                | 7450              | 0.48                     | 65.8                | 5910              |
| 0.15                     | 88.2                | 7920              | 0.32                     | 82.2                | 7380              | 0.49                     | 64.6                | 5810              |
| 0.16                     | 88.5                | 7950              | 0.33                     | 81.3                | 7300              | 0.50                     | 63.5                | 5700              |
| 0.17                     | 88.7                | 7970              | 0.34                     | 80.4                | 7230              | ...                      | ...                 | ...               |

<sup>a</sup> For  $\alpha = 0^\circ$ ,  $F_a = 0$  and  $X = 1$ .

<sup>b</sup> Use to obtain  $C$  in pounds when  $l_{eff}$  and  $D$  are given in inches.

**Table 32. Values of  $f_c$  for Thrust Roller Bearings**

| $D \cos \alpha$<br>$d_m$ | $45^\circ < \alpha < 60^\circ$ |                   | $60^\circ < \alpha < 75^\circ$ |                   | $75^\circ \leq \alpha < 90^\circ$ |                   | $\frac{D}{d_m}$ | $\alpha = 90^\circ$ |                   |
|--------------------------|--------------------------------|-------------------|--------------------------------|-------------------|-----------------------------------|-------------------|-----------------|---------------------|-------------------|
|                          | $f_c$                          |                   |                                |                   |                                   |                   |                 | $f_c$               |                   |
|                          | Metric <sup>a</sup>            | Inch <sup>b</sup> | Metric <sup>a</sup>            | Inch <sup>b</sup> | Metric <sup>a</sup>               | Inch <sup>b</sup> |                 | Metric <sup>a</sup> | Inch <sup>b</sup> |
| 0.01                     | 109.7                          | 9840              | 107.1                          | 9610              | 105.6                             | 9470              | 0.01            | 105.4               | 9500              |
| 0.02                     | 127.8                          | 11460             | 124.7                          | 11180             | 123.0                             | 11030             | 0.02            | 122.9               | 11000             |
| 0.03                     | 139.5                          | 12510             | 136.2                          | 12220             | 134.3                             | 12050             | 0.03            | 134.5               | 12100             |
| 0.04                     | 148.3                          | 13300             | 144.7                          | 12980             | 142.8                             | 12810             | 0.04            | 143.4               | 12800             |
| 0.05                     | 155.2                          | 13920             | 151.5                          | 13590             | 149.4                             | 13400             | 0.05            | 150.7               | 13200             |
| 0.06                     | 160.9                          | 14430             | 157.0                          | 14080             | 154.9                             | 13890             | 0.06            | 156.9               | 14100             |
| 0.07                     | 165.6                          | 14850             | 161.6                          | 14490             | 159.4                             | 14300             | 0.07            | 162.4               | 14500             |
| 0.08                     | 169.5                          | 15200             | 165.5                          | 14840             | 163.2                             | 14640             | 0.08            | 167.2               | 15100             |
| 0.09                     | 172.8                          | 15500             | 168.7                          | 15130             | 166.4                             | 14930             | 0.09            | 171.7               | 15400             |
| 0.10                     | 175.5                          | 15740             | 171.4                          | 15370             | 169.0                             | 15160             | 0.10            | 175.7               | 15900             |
| 0.12                     | 179.7                          | 16120             | 175.4                          | 15730             | 173.0                             | 15520             | 0.12            | 183.0               | 16300             |
| 0.14                     | 182.3                          | 16350             | 177.9                          | 15960             | 175.5                             | 15740             | 0.14            | 189.4               | 17000             |
| 0.16                     | 183.7                          | 16480             | 179.3                          | 16080             | ...                               | ...               | 0.16            | 195.1               | 17500             |
| 0.18                     | 184.1                          | 16510             | 179.7                          | 16120             | ...                               | ...               | 0.18            | 200.3               | 18000             |
| 0.20                     | 183.7                          | 16480             | 179.3                          | 16080             | ...                               | ...               | 0.20            | 205.0               | 18500             |
| 0.22                     | 182.6                          | 16380             | ...                            | ...               | ...                               | ...               | 0.22            | 209.4               | 18800             |
| 0.24                     | 180.9                          | 16230             | ...                            | ...               | ...                               | ...               | 0.24            | 213.5               | 19100             |
| 0.26                     | 178.7                          | 16030             | ...                            | ...               | ...                               | ...               | 0.26            | 217.3               | 19600             |
| 0.28                     | ...                            | ...               | ...                            | ...               | ...                               | ...               | 0.28            | 220.9               | 19900             |
| 0.30                     | ...                            | ...               | ...                            | ...               | ...                               | ...               | 0.30            | 224.3               | 20100             |

<sup>a</sup> Use to obtain  $C_a$  in newtons when  $l_{eff}$  and  $D$  are given in mm.

<sup>b</sup> Use to obtain  $C_a$  in pounds when  $l_{eff}$  and  $D$  are given in inches.

**Roller Bearing Rating Life.**—The Rating Life  $L_{10}$  of a group of apparently identical roller bearings is the life in millions of revolutions that 90 percent of the group will complete or exceed. For a single bearing,  $L_{10}$  also refers to the life associated with 90 percent reliability.

**Radial Roller Bearings:** The magnitude of the Rating Life,  $L_{10}$ , in millions of revolutions, for a radial roller bearing application is given by the formula:

$$L_{10} = \left(\frac{C}{P}\right)^{10/3} \quad (12)$$

where  $C$  = the basic load rating in newtons (pounds), see [Formula \(13\)](#); and,  $P$  = equivalent radial load in newtons (pounds), see [Formula \(14\)](#).

For radial roller bearings,  $C$  is found by the formula:

$$C = f_c(i l_{eff} \cos \alpha)^{7/9} Z^{3/4} D^{29/27} \quad (13)$$

where  $f_c$  = a factor which depends on the geometry of the bearing components, the accuracy to which the various bearing parts are made, and the material. Maximum values of  $f_c$  are given in [Table 31](#)

$i$  = number of rows of rollers in the bearing

$l_{eff}$  = effective length, mm (inches)     $\alpha$  = nominal contact angle, degrees

$Z$  = number of rollers per row in a radial roller bearing

$D$  = roller diameter, mm (inches) (mean diameter for a tapered roller, major diameter for a spherical roller)

When rollers are longer than  $2.5D$ , a reduction in the  $f_c$  value must be anticipated. In this case, the bearing manufacturer may be expected to establish load ratings accordingly.

In applications where rollers operate directly on a shaft surface or a housing surface, such a surface must be equivalent in all respects to the raceway it replaces to achieve the basic load rating of the bearing.

When calculating the basic load rating for a unit consisting of two or more similar single-row bearings mounted "in tandem," properly manufactured and mounted for equal load distribution, the rating of the combination is the number of bearings to the  $7/9$  power times the rating of a single-row bearing. If, for some technical reason, the unit may be treated as a number of individually interchangeable single-row bearings, this consideration does not apply.

The magnitude of the equivalent radial load,  $P$ , in newtons (pounds), for radial roller bearings, under combined constant radial and constant thrust loads is given by the formula:

$$P = XF_r + YF_a \quad (14)$$

where  $F_r$  = the applied radial load in newtons (pounds)

$F_a$  = the applied axial load in newtons (pounds)

$X$  = radial load factor as given in [Table 33](#)

$Y$  = axial load factor as given in [Table 33](#)

**Table 33. Values of  $X$  and  $Y$  for Computing Equivalent Radial Load  $P$  for Radial Roller Bearing**

| Bearing Type   | $\frac{F_a}{F_r} \leq e$         |                    | $\frac{F_a}{F_r} > e$ |                    |
|--|----------------------------------|--------------------|-----------------------|--------------------|
|  | $X$                              | $Y$                | $X$                   | $Y$                |
| Self-Aligning<br>and<br>Tapered<br>Roller Bearings <sup>a</sup><br>$\alpha \neq 0^\circ$ | Single Row Bearings              |                    |                       |                    |
|  | 1                                | 0                  | 0.4                   | $0.4 \cot \alpha$  |
|  | Double Row Bearings <sup>a</sup> |                    |                       |                    |
|  | 1                                | $0.45 \cot \alpha$ | 0.67                  | $0.67 \cot \alpha$ |

<sup>a</sup> For  $\alpha = 0^\circ$ ,  $F_a = 0$  and  $X = 1$ .

$e = 1.5 \tan \alpha$



### Typical Bearing Life for Various Design Applications

| Uses   | Design life in hours | Uses  | Design life in hours |
|--|----------------------|---|----------------------|
| Agricultural equipment   | 3000 – 6000          | Gearing units   |                      |
| Aircraft equipment   | 500 – 2000           | Automotive  | 600 – 5000           |
| Automotive   |                      | Multipurpose  | 8000 – 15000         |
| Race car   | 500 – 800            | Machine tools   | 20000                |
| Light motor cycle  | 600 – 1200           | Rail Vehicles   | 15000 – 25000        |
| Heavy motor cycle  | 1000 – 2000          | Heavy rolling mill  | > 50000              |
| Light cars   | 1000 – 2000          | Machines  |                      |
| Heavy cars   | 1500 – 2500          | Beater mills  | 20000 – 30000        |
| Light trucks   | 1500 – 2500          | Briquette presses   | 20000 – 30000        |
| Heavy trucks   | 2000 – 2500          | Grinding spindles   | 1000 – 2000          |
| Buses  | 2000 – 5000          | Machine tools   | 10000 – 30000        |
| Electrical   |                      | Mining machinery  | 4000 – 15000         |
| Household appliances   | 1000 – 2000          | Paper machines  | 50000 – 80000        |
| Motors ≤ ½ hp  | 1000 – 2000          | Rolling mills   |                      |
| Motors ≤ 3 hp  | 8000 – 10000         | Small cold mills  | 5000 – 6000          |
| Motors, medium   | 10000 – 15000        | Large multipurpose mills  | 8000 – 10000         |
| Motors, large  | 20000 – 30000        | Rail vehicle axle   |                      |
| Elevator cables sheaves  | 40000 – 60000        | Mining cars   | 5000                 |
| Mine ventilation fans  | 40000 – 50000        | Motor rail cars   | 16000 – 20000        |
| Propeller thrust bearings  | 15000 – 25000        | Open-pit mining cars  | 20000 – 25000        |
| Propeller shaft bearings   | > 80000              | Streetcars  | 20000 – 25000        |
| Gear drives  |                      | Passenger cars  | 26000                |
| Boat gearing units   | 3000 – 5000          | Freight cars  | 35000                |
| Gear drives  | > 50000              | Locomotive outer bearings   | 20000 – 25000        |
| Ship gear drives   | 20000 – 30000        | Locomotive inner bearings   | 30000 – 40000        |
| Machinery for 8 hour service which are not always fully utilized | 14000 – 20000        | Machinery for short or intermittent operation where service interruption is of minor importance | 4000 – 8000          |
| Machinery for 8 hour service which are fully utilized            | 20000 – 30000        | Machinery for intermittent service where reliable operation is of great importance              | 8000 – 14000         |
| Machinery for continuous 24 hour service                         | 50000 – 60000        | Instruments and apparatus in frequent use   | 0 – 500              |

Roller bearings are generally designed to achieve optimized contact; however, they usually support loads other than the loading at which optimized contact is maintained. The  $10/3$  exponent in Rating Life Formulas (12) and (15) was selected to yield satisfactory Rating Life estimates for a broad spectrum from light to heavy loading. When loading exceeds that which develops optimized contact, e.g., loading greater than  $C/4$  or  $C_d/4$  to  $C_d/2$ , the user should consult the bearing manufacturer to establish the adequacy of the Rating Life formulas for the particular application.

**Thrust Roller Bearings:** The magnitude of the Rating Life,  $L_{10}$ , in millions of revolutions for a thrust roller bearing application is given by the formula:

$$L_{10} = \left( \frac{C_a}{P_a} \right)^{10/3} \quad (15)$$

where  $C_a$  = basic load rating, newtons (pounds). See Formulas (16) to (18)

$P_a$  = equivalent thrust load, newtons (pounds). See Formula (19)

For single row, single and double direction, thrust roller bearings, the magnitude of the basic load rating,  $C_a$ , in newtons (pounds), is found by the formulas:

$$\text{for } \alpha = 90^\circ, C_a = f_c l_{eff}^{7/9} Z^{3/4} D^{29/27} \quad (16)$$

$$\text{for } \alpha \neq 90^\circ, C_a = f_c (l_{eff} \cos \alpha)^{7/9} Z^{3/4} D^{29/27} \tan \alpha \quad (17)$$

where  $f_c$  = a factor which depends on the geometry of the bearing components, the accuracy to which the various parts are made, and the material. Values of  $f_c$  are given in [Table 32](#)

$l_{eff}$  = effective length, mm (inches)

$Z$  = number of rollers in a single row, single direction, thrust roller bearing

$D$  = roller diameter, mm (inches) (mean diameter for a tapered roller, major diameter for a spherical roller)

$\alpha$  = nominal contact angle, degrees

For thrust roller bearings with two or more rows of rollers carrying loads in the same direction the magnitude of  $C_a$  is found by the formula:

$$C_a = (Z_1 l_{eff1} + Z_2 l_{eff2} \dots Z_n l_{effn}) \left\{ \left[ \frac{Z_1 l_{eff1}}{C_{a1}} \right]^{9/2} + \left[ \frac{Z_2 l_{eff2}}{C_{a2}} \right]^{9/2} + \dots \right. \\ \left. \left[ \frac{Z_n l_{effn}}{C_{an}} \right]^{9/2} \right\}^{-2/9} \quad (18)$$

Where  $Z_1, Z_2 \dots Z_n$  = the number of rollers in respective rows of a single direction, multi-row bearing

$C_{a1}, C_{a2} \dots C_{an}$  = the basic load rating per row of a single direction, multi-row, thrust roller bearing, each calculated as a single row bearing with  $Z_1, Z_2 \dots Z_n$  rollers respectively

$l_{eff1}, l_{eff2} \dots l_{effn}$  = effective length, mm (inches), or rollers in the respective rows

In applications where rollers operate directly on a surface supplied by the user, such a surface must be equivalent in all respects to the washer raceway it replaces to achieve the basic load rating of the bearing.

In case the bearing is so designed that several rollers are located on a common axis, these rollers are considered as one roller of a length equal to the total effective length of contact of the several rollers. Rollers as defined above, or portions thereof which contact the same washer-raceway area, belong to one row.

When the ratio of the individual roller effective length to the pitch diameter (at which this roller operates) is too large, a reduction of the  $f_c$  value must be anticipated due to excessive slip in the roller-raceway contact.

When calculating the basic load rating for a unit consisting of two or more similar single row bearings mounted "in tandem," properly manufactured and mounted for equal load distribution, the rating of the combination is defined by [Formula \(18\)](#). If, for some technical reason, the unit may be treated as a number of individually interchangeable single-row bearings, this consideration does not apply.

The magnitude of the equivalent thrust load,  $P_a$ , in pounds, for thrust roller bearings with  $\alpha$  not equal to 90 degrees under combined constant thrust and constant radial loads is given by the formula:

$$P_a = XF_r + YF_a \quad (19)$$

where  $F_r$  = applied radial load, newtons (pounds)

$F_a$  = applied axial load, newtons (pounds)

$X$  = radial load factor as given in [Table 34](#)

$Y$  = axial load factor as given in [Table 34](#)

**Table 34. Values of X and Y for Computing Equivalent Thrust Load  $P_a$  for Thrust Roller Bearings**

| Bearing Type   | Single Direction Bearings |   | Double Direction Bearings |      |                       |   |
|--|---------------------------|---|---------------------------|------|-----------------------|---|
|  | $\frac{F_a}{F_r} > e$     |   | $\frac{F_a}{F_r} \leq e$  |      | $\frac{F_a}{F_r} > e$ |   |
|  | X                         | Y | X                         | Y    | X                     | Y |
| Self-Aligning Tapered Thrust Roller Bearings <sup>a</sup><br>$\alpha \neq 0$ | $\tan \alpha$             | 1 | $1.5 \tan \alpha$         | 0.67 | $\tan \alpha$         | 1 |

<sup>a</sup> For  $\alpha = 90^\circ$ ,  $F_r = 0$  and  $Y = 1$ .

$$e = 1.5 \tan \alpha$$

**Life Adjustment Factors.**—In certain applications of ball or roller bearings it is desirable to specify life for a reliability other than 90 per cent. In other cases the bearings may be fabricated from special bearing steels such as vacuum-degassed and vacuum-melted steels, and improved processing techniques. Finally, application conditions may indicate other than normal lubrication, load distribution, or temperature. For such conditions a series of life adjustment factors may be applied to the fatigue life formula. This is fully explained in AFBMA and American National Standard "Load Ratings and Fatigue Life for Ball Bearings" ANSI/AFBMA Std 9–1990 and AFBMA and American National Standard "Load Ratings and Fatigue Life for Roller Bearings" ANSI/AFBMA Std 11–1990. In addition to consulting these standards it may be advantageous to also obtain information from the bearing manufacturer.

*Life Adjustment Factor for Reliability:* For certain applications, it is desirable to specify life for a reliability greater than 90 per cent which is the basis of the Rating Life.

To determine the bearing life of ball or roller bearings for reliability greater than 90 per cent, the Rating Life must be adjusted by a factor  $a_1$  such that  $L_n = a_1 L_{10}$ . For a reliability of 95 per cent, designated as  $L_5$ , the life adjustment factor  $a_1$  is 0.62; for 96 per cent,  $L_4$ ,  $a_1$  is 0.53; for 97 per cent,  $L_3$ ,  $a_1$  is 0.44; for 98 per cent,  $L_2$ ,  $a_1$  is 0.33; and for 99 per cent,  $L_1$ ,  $a_1$  is 0.21.

*Life Adjustment Factor for Material:* For certain types of ball or roller bearings which incorporate improved materials and processing, the Rating Life can be adjusted by a factor  $a_2$  such that  $L_{10}' = a_2 L_{10}$ . Factor  $a_2$  depends upon steel analysis, metallurgical processes, forming methods, heat treatment, and manufacturing methods in general. Ball and roller bearings fabricated from consumable vacuum remelted steels and certain other special analysis steels, have demonstrated extraordinarily long endurance. These steels are of exceptionally high quality, and bearings fabricated from these are usually considered special manufacture. Generally,  $a_2$  values for such steels can be obtained from the bearing manufacturer. However, all of the specified limitations and qualifications for the application of the Rating Life formulas still apply.

*Life Adjustment Factor for Application Condition:* Application conditions which affect ball or roller bearing life include: 1) lubrication; 2) load distribution (including effects of clearance, misalignment, housing and shaft stiffness, type of loading, and thermal gradients); and 3) temperature.

Items 2 and 3 require special analytical and experimental techniques, therefore the user should consult the bearing manufacturer for evaluations and recommendations.

Operating conditions where the factor  $a_3$  might be less than 1 include: a) exceptionally low values of  $Nd_m$  (rpm times pitch diameter, in mm); e.g.,  $Nd_m < 10,000$ ; b) lubricant viscosity at less than 70 SSU for ball bearings and 100 SSU for roller bearings at operating temperature; and c) excessively high operating temperatures.

When  $a_3$  is less than 1 it may not be assumed that the deficiency in lubrication can be overcome by using an improved steel. When this factor is applied,  $L_{10}' = a_3 L_{10}$ .

In most ball and roller bearing applications, lubrication is required to separate the rolling surfaces, i.e., rollers and raceways, to reduce the retainer-roller and retainer-land friction and sometimes to act as a coolant to remove heat generated by the bearing.

*Factor Combinations:* A fatigue life formula embodying the foregoing life adjustment factors is  $L_{10}' = a_1 a_2 a_3 L_{10}$ . Indiscriminate application of the life adjustment factors in this formula may lead to serious overestimation of bearing endurance, since fatigue life is only one criterion for bearing selection. Care must be exercised to select bearings which are of sufficient size for the application.

**Ball Bearing Static Load Rating.**—For ball bearings suitably manufactured from hardened alloy steels, the static radial load rating is that uniformly distributed static radial bearing load which produces a maximum contact stress of 4,000 megapascals (580,000 pounds per square inch). In the case of a single row, angular contact ball bearing, the static radial load rating refers to the radial component of that load which causes a purely radial displacement of the bearing rings in relation to each other. The static axial load rating is that uniformly distributed static centric axial load which produces a maximum contact stress of 4,000 megapascals (580,000 pounds per square inch).

*Radial and Angular Contact Groove Ball Bearings:* The magnitude of the static load rating  $C_o$  in newtons (pounds) for radial ball bearings is found by the formula:

$$C_o = f_o i Z D^2 \cos \alpha \quad (20)$$

where  $f_o$  = a factor for different kinds of ball bearings given in [Table 35](#)

$i$  = number of rows of balls in bearing

$Z$  = number of balls per row

$D$  = ball diameter, mm (inches)

$\alpha$  = nominal contact angle, degrees

This formula applies to bearings with a cross sectional raceway groove radius not larger than  $0.52 D$  in radial and angular contact groove ball bearing inner rings and  $0.53 D$  in radial and angular contact groove ball bearing outer rings and self-aligning ball bearing inner rings.

The load carrying ability of a ball bearing is not necessarily increased by the use of a smaller groove radius but is reduced by the use of a larger radius than those indicated above.

*Radial or Angular Contact Ball Bearing Combinations:* The basic static load rating for two similar single row radial or angular contact ball bearings mounted side by side on the same shaft such that they operate as a unit (duplex mounting) in “back-to-back” or “face-to-face” arrangement is two times the rating of one single row bearing.

The basic static radial load rating for two or more single row radial or angular contact ball bearings mounted side by side on the same shaft such that they operate as a unit (duplex or stack mounting) in “tandem” arrangement, properly manufactured and mounted for equal load distribution, is the number of bearings times the rating of one single row bearing.

*Thrust Ball Bearings:* The magnitude of the static load rating  $C_{oa}$  for thrust ball bearings is found by the formula:

$$C_{oa} = f_o Z D^2 \cos \alpha \quad (21)$$

where  $f_o$  = a factor given in [Table 35](#)

$Z$  = number of balls carrying the load in one direction

$D$  = ball diameter, mm (inches)

$\alpha$  = nominal contact angle, degrees

This formula applies to thrust ball bearings with a cross sectional raceway radius not larger than  $0.54 D$ . The load carrying ability of a bearing is not necessarily increased by use of a smaller radius, but is reduced by use of a larger radius.

**Roller Bearing Static Load Rating:** For roller bearings suitably manufactured from hardened alloy steels, the static radial load rating is that uniformly distributed static radial bearing load which produces a maximum contact stress of 4,000 megapascals (580,000 pounds per square inch) acting at the center of contact of the most heavily loaded rolling element. The static axial load rating is that uniformly distributed static centric axial load which produces a maximum contact stress of 4,000 megapascals (580,000 pounds per square inch) acting at the center of contact of each rolling element.

**Table 35.  $f_o$  for Calculating Static Load Rating for Ball Bearings**

| $\frac{D \cos \alpha}{d_m}$ | Radial and Angular Contact Groove Type |                   | Radial Self-Aligning |                   | Thrust              |                   |
|-----------------------------|--|-------------------|----------------------|-------------------|---------------------|-------------------|
|                             | Metric <sup>a</sup>                    | Inch <sup>b</sup> | Metric <sup>a</sup>  | Inch <sup>b</sup> | Metric <sup>a</sup> | Inch <sup>b</sup> |
| 0.00                        | 12.7                                   | 1850              | 1.3                  | 187               | 51.9                | 7730              |
| 0.01                        | 13.0                                   | 1880              | 1.3                  | 191               | 52.6                | 7620              |
| 0.02                        | 13.2                                   | 1920              | 1.3                  | 195               | 51.7                | 7500              |
| 0.03                        | 13.5                                   | 1960              | 1.4                  | 198               | 50.9                | 7380              |
| 0.04                        | 13.7                                   | 1990              | 1.4                  | 202               | 50.2                | 7280              |
| 0.05                        | 14.0                                   | 2030              | 1.4                  | 206               | 49.6                | 7190              |
| 0.06                        | 14.3                                   | 2070              | 1.5                  | 210               | 48.9                | 7090              |
| 0.07                        | 14.5                                   | 2100              | 1.5                  | 214               | 48.3                | 7000              |
| 0.08                        | 14.7                                   | 2140              | 1.5                  | 218               | 47.6                | 6900              |
| 0.09                        | 14.5                                   | 2110              | 1.5                  | 222               | 46.9                | 6800              |
| 0.10                        | 14.3                                   | 2080              | 1.6                  | 226               | 46.4                | 6730              |
| 0.11                        | 14.1                                   | 2050              | 1.6                  | 231               | 45.9                | 6660              |
| 0.12                        | 13.9                                   | 2020              | 1.6                  | 235               | 45.5                | 6590              |
| 0.13                        | 13.6                                   | 1980              | 1.7                  | 239               | 44.7                | 6480              |
| 0.14                        | 13.4                                   | 1950              | 1.7                  | 243               | 44.0                | 6380              |
| 0.15                        | 13.2                                   | 1920              | 1.7                  | 247               | 43.3                | 6280              |
| 0.16                        | 13.0                                   | 1890              | 1.7                  | 252               | 42.6                | 6180              |
| 0.17                        | 12.7                                   | 1850              | 1.8                  | 256               | 41.9                | 6070              |
| 0.18                        | 12.5                                   | 1820              | 1.8                  | 261               | 41.2                | 5970              |
| 0.19                        | 12.3                                   | 1790              | 1.8                  | 265               | 40.4                | 5860              |
| 0.20                        | 12.1                                   | 1760              | 1.9                  | 269               | 39.7                | 5760              |
| 0.21                        | 11.9                                   | 1730              | 1.9                  | 274               | 39.0                | 5650              |
| 0.22                        | 11.6                                   | 1690              | 1.9                  | 278               | 38.3                | 5550              |
| 0.23                        | 11.4                                   | 1660              | 2.0                  | 283               | 37.5                | 5440              |
| 0.24                        | 11.2                                   | 1630              | 2.0                  | 288               | 37.0                | 5360              |
| 0.25                        | 11.0                                   | 1600              | 2.0                  | 293               | 36.4                | 5280              |
| 0.26                        | 10.8                                   | 1570              | 2.1                  | 297               | 35.8                | 5190              |
| 0.27                        | 10.6                                   | 1540              | 2.1                  | 302               | 35.0                | 5080              |
| 0.28                        | 10.4                                   | 1510              | 2.1                  | 307               | 34.4                | 4980              |
| 0.29                        | 10.3                                   | 1490              | 2.1                  | 311               | 33.7                | 4890              |
| 0.30                        | 10.1                                   | 1460              | 2.2                  | 316               | 33.2                | 4810              |
| 0.31                        | 9.9                                    | 1440              | 2.2                  | 321               | 32.7                | 4740              |
| 0.32                        | 9.7                                    | 1410              | 2.3                  | 326               | 32.0                | 4640              |
| 0.33                        | 9.5                                    | 1380              | 2.3                  | 331               | 31.2                | 4530              |
| 0.34                        | 9.3                                    | 1350              | 2.3                  | 336               | 30.5                | 4420              |
| 0.35                        | 9.1                                    | 1320              | 2.4                  | 341               | 30.0                | 4350              |
| 0.36                        | 8.9                                    | 1290              | 2.4                  | 346               | 29.5                | 4270              |
| 0.37                        | 8.7                                    | 1260              | 2.4                  | 351               | 28.8                | 4170              |
| 0.38                        | 8.5                                    | 1240              | 2.5                  | 356               | 28.0                | 4060              |
| 0.39                        | 8.3                                    | 1210              | 2.5                  | 361               | 27.2                | 3950              |
| 0.40                        | 8.1                                    | 1180              | 2.5                  | 367               | 26.8                | 3880              |
| 0.41                        | 8.0                                    | 1160              | 2.6                  | 372               | 26.2                | 3800              |
| 0.42                        | 7.8                                    | 1130              | 2.6                  | 377               | 25.7                | 3720              |
| 0.43                        | 7.6                                    | 1100              | 2.6                  | 383               | 25.1                | 3640              |
| 0.44                        | 7.4                                    | 1080              | 2.7                  | 388               | 24.6                | 3560              |
| 0.45                        | 7.2                                    | 1050              | 2.7                  | 393               | 24.0                | 3480              |

**Table 35. (Continued)  $f_o$  for Calculating Static Load Rating for Ball Bearings**

| $\frac{D \cos \alpha}{d_m}$ | Radial and Angular Contact Groove Type |                   | Radial Self-Aligning |                   | Thrust              |                   |
|-----------------------------|--|-------------------|----------------------|-------------------|---------------------|-------------------|
|                             | Metric <sup>a</sup>                    | Inch <sup>b</sup> | Metric <sup>a</sup>  | Inch <sup>b</sup> | Metric <sup>a</sup> | Inch <sup>b</sup> |
| 0.46                        | 7.1                                    | 1030              | 2.8                  | 399               | 23.5                | 3400              |
| 0.47                        | 6.9                                    | 1000              | 2.8                  | 404               | 22.9                | 3320              |
| 0.48                        | 6.7                                    | 977               | 2.8                  | 410               | 22.4                | 3240              |
| 0.49                        | 6.6                                    | 952               | 2.9                  | 415               | 21.8                | 3160              |
| 0.50                        | 6.4                                    | 927               | 2.9                  | 421               | 21.2                | 3080              |

<sup>a</sup> Use to obtain  $C_o$  or  $C_{oa}$  in newtons when  $D$  is given in mm.

<sup>b</sup> Use to obtain  $C_o$  or  $C_{oa}$  in pounds when  $D$  is given in inches.

Note: Based on modulus of elasticity =  $2.07 \times 10^5$  megapascals ( $30 \times 10^6$  pounds per square inch) and Poisson's ratio = 0.3.

**Radial Roller Bearings:** The magnitude of the static load rating  $C_o$  in newtons (pounds) for radial roller bearings is found by the formulas:

$$C_o = 44 \left( 1 - \frac{D \cos \alpha}{d_m} \right) i Z l_{eff} D \cos \alpha \quad (\text{metric}) \quad (22a)$$

$$C_o = 6430 \left( 1 - \frac{D \cos \alpha}{d_m} \right) i Z l_{eff} D \cos \alpha \quad (\text{inch}) \quad (22b)$$

where  $D$  = roller diameter, mm (inches); mean diameter for a tapered roller and major diameter for a spherical roller

$d_m$  = mean pitch diameter of the roller complement, mm (inches)

$i$  = number of rows of rollers in bearing

$Z$  = number of rollers per row

$l_{eff}$  = effective length, mm (inches); overall roller length minus roller chamfers or minus grinding undercuts at the ring where contact is shortest

$\alpha$  = nominal contact angle, degrees

**Radial Roller Bearing Combinations:** The static load rating for two similar single row roller bearings mounted side by side on the same shaft such that they operate as a unit is two times the rating of one single row bearing.

The static radial load rating for two or more similar single row roller bearings mounted side by side on the same shaft such that they operate as a unit (duplex or stack mounting) in "tandem" arrangement, properly manufactured and mounted for equal load distribution, is the number of bearings times the rating of one single row bearing.

**Thrust Roller Bearings:** The magnitude of the static load rating  $C_{oa}$  in newtons (pounds) for thrust roller bearings is found by the formulas:

$$C_{oa} = 220 \left( 1 - \frac{D \cos \alpha}{d_m} \right) Z l_{eff} D \sin \alpha \quad (\text{metric}) \quad (23a)$$

$$C_{oa} = 32150 \left( 1 - \frac{D \cos \alpha}{d_m} \right) Z l_{eff} D \sin \alpha \quad (\text{inch}) \quad (23b)$$

where the symbol definitions are the same as for **Formulas (22a) and (22b)**.

**Thrust Roller Bearing Combination:** The static axial load rating for two or more similar single direction thrust roller bearings mounted side by side on the same shaft such that they operate as a unit (duplex or stack mounting) in "tandem" arrangement, properly manufactured and mounted for equal load distribution, is the number of bearings times the rating of one single direction bearing. The accuracy of this formula decreases in the case of single direction bearings when  $F_r > 0.44 F_a \cot \alpha$  where  $F_r$  is the applied radial load in newtons (pounds) and  $F_a$  is the applied axial load in newtons (pounds).

**Ball Bearing Static Equivalent Load.**—For ball bearings the static equivalent radial load is that calculated static radial load which produces a maximum contact stress equal in magnitude to the maximum contact stress in the actual condition of loading. The static equivalent axial load is that calculated static centric axial load which produces a maximum contact stress equal in magnitude to the maximum contact stress in the actual condition of loading.

*Radial and Angular Contact Ball Bearings:* The magnitude of the static equivalent radial load  $P_o$  in newtons (pounds) for radial and angular contact ball bearings under combined thrust and radial loads is the greater of:

$$P_o = X_o F_r + Y_o F_a \quad (24)$$

$$P_o = F_r \quad (25)$$

where  $X_o$  = radial load factor given in [Table 36](#)

$Y_o$  = axial load factor given in [Table 36](#)

$F_r$  = applied radial load, newtons (pounds)

$F_a$  = applied axial load, newtons (pounds)

**Table 36. Values of  $X_o$  and  $Y_o$  for Computing Static Equivalent Radial Load  $P_o$  of Ball Bearings**

| Contact Angle                                 | Single Row Bearings <sup>a</sup> |                    | Double Row Bearings |                    |
|---|----------------------------------|--------------------|---------------------|--------------------|
|   | $X_o$                            | $Y_o$ <sup>b</sup> | $X_o$               | $Y_o$ <sup>b</sup> |
| RADIAL CONTACT GROOVE BEARINGS <sup>c,a</sup> |                                  |                    |                     |                    |
| $\alpha = 0^\circ$                            | 0.6                              | 0.5                | 0.6                 | 0.5                |
| ANGULAR CONTACT GROOVE BEARINGS               |                                  |                    |                     |                    |
| $\alpha = 15^\circ$                           | 0.5                              | 0.47               | 1                   | 0.94               |
| $\alpha = 20^\circ$                           | 0.5                              | 0.42               | 1                   | 0.84               |
| $\alpha = 25^\circ$                           | 0.5                              | 0.38               | 1                   | 0.76               |
| $\alpha = 30^\circ$                           | 0.5                              | 0.33               | 1                   | 0.66               |
| $\alpha = 35^\circ$                           | 0.5                              | 0.29               | 1                   | 0.58               |
| $\alpha = 40^\circ$                           | 0.5                              | 0.26               | 1                   | 0.52               |
| SELF-ALIGNING BEARINGS                        |                                  |                    |                     |                    |
| ...   | 0.5                              | $0.22 \cot \alpha$ | 1                   | $0.44 \cot \alpha$ |

<sup>a</sup>  $P_o$  is always  $\geq F_r$ .

<sup>b</sup> Values of  $Y_o$  for intermediate contact angles are obtained by linear interpolation.

<sup>c</sup> Permissible maximum value of  $F_d/C_o$  (where  $F_d$  is applied axial load and  $C_o$  is static radial load rating) depends on the bearing design (groove depth and internal clearance).

*Thrust Ball Bearings:* The magnitude of the static equivalent axial load  $P_{oa}$  in newtons (pounds) for thrust ball bearings with contact angle  $\alpha \neq 90^\circ$  under combined radial and thrust loads is found by the formula:

$$P_{oa} = F_a + 2.3 F_r \tan \alpha \quad (26)$$

where the symbol definitions are the same as for [Formulas \(24\)](#) and [\(25\)](#). This formula is valid for all load directions in the case of double direction ball bearings. For single direction ball bearings, it is valid where  $F_r/F_a \leq 0.44 \cot \alpha$  and gives a satisfactory but less conservative value of  $P_{oa}$  for  $F_r/F_a$  up to  $0.67 \cot \alpha$ .

Thrust ball bearings with  $\alpha = 90^\circ$  can support axial loads only. The static equivalent load for this type of bearing is  $P_{oa} = F_a$ .

**Roller Bearing Static Equivalent Load.**—The static equivalent radial load for roller bearings is that calculated, static radial load which produces a maximum contact stress acting at the center of contact of a uniformly loaded rolling element equal in magnitude to the maximum contact stress in the actual condition of loading. The static equivalent axial load is that calculated, static centric axial load which produces a maximum contact stress acting

at the center of contact of a uniformly loaded rolling element equal in magnitude to the maximum contact stress in the actual condition of loading.

**Radial Roller Bearings:** The magnitude of the static equivalent radial load  $P_o$  in newtons (pounds) for radial roller bearings under combined radial and thrust loads is the greater of:

$$P_o = X_o F_r + Y_o F_a \quad (27)$$

$$P_o = F_r \quad (28)$$

where  $X_o$  = radial factor given in Table 37

$Y_o$  = axial factor given in Table 37

$F_r$  = applied radial load, newtons (pounds)

$F_a$  = applied axial load, newtons (pounds)

**Table 37. Values of  $X_o$  and  $Y_o$  for Computing Static Equivalent Radial Load  $P_o$  for Self-Aligning and Tapered Roller Bearings**

| Bearing Type                                 | Single Row <sup>a</sup> |                    | Double Row |                    |
|--|-------------------------|--------------------|------------|--------------------|
|  | $X_o$                   | $Y_o$              | $X_o$      | $Y_o$              |
| Self-Aligning and Tapered<br>$\alpha \neq 0$ | 0.5                     | $0.22 \cot \alpha$ | 1          | $0.44 \cot \alpha$ |

<sup>a</sup>  $P_o$  is always  $\geq F_r$ .

The static equivalent radial load for radial roller bearings with  $\alpha = 0^\circ$  and subjected to radial load only is  $P_{or} = F_r$ .

Note: The ability of radial roller bearings with  $\alpha = 0^\circ$  to support axial loads varies considerably with bearing design and execution. The bearing user should therefore consult the bearing manufacturer for recommendations regarding the evaluation of equivalent load in cases where bearings with  $\alpha = 0^\circ$  are subjected to axial load.

**Radial Roller Bearing Combinations:** When calculating the static equivalent radial load for two similar single row angular contact roller bearings mounted side by side on the same shaft such that they operate as a unit (duplex mounting) in "back-to-back" or "face-to-face" arrangement, use the  $X_o$  and  $Y_o$  values for a double row bearing and the  $F_r$  and  $F_a$  values for the total loads on the arrangement.

When calculating the static equivalent radial load for two or more similar single row angular contact roller bearings mounted side by side on the same shaft such that they operate as a unit (duplex or stack mounting) in "tandem" arrangement, use the  $X_o$  and  $Y_o$  values for a single row bearing and the  $F_r$  and  $F_a$  values for the total loads on the arrangement.

**Thrust Roller Bearings:** The magnitude of the static equivalent axial load  $P_{oa}$  in newtons (pounds) for thrust roller bearings with contact angle  $\alpha \neq 90^\circ$ , under combined radial and thrust loads is found by the formula:

$$P_{oa} = F_a + 2.3 F_r \tan \alpha \quad (29)$$

where  $F_a$  = applied axial load, newtons (pounds)

$F_r$  = applied radial load, newtons (pounds)

$\alpha$  = nominal contact angle, degrees

The accuracy of this formula decreases for single direction thrust roller bearings when  $F_r > 0.44 F_a \cot \alpha$ .

**Thrust Roller Bearing Combinations:** When calculating the static equivalent axial load for two or more thrust roller bearings mounted side by side on the same shaft such that they operate as a unit (duplex or stack mounting) in "tandem" arrangement, use the  $F_r$  and  $F_a$  values for the total loads acting on the arrangement.



## STANDARD METAL BALLS

**Standard Metal Balls.**—American National Standard ANSI/AFBMA Std 10-1989 provides information for the user of metal balls permitting them to be described readily and accurately. It also covers certain measurable characteristics affecting ball quality.

On the following pages, tables taken from this Standard cover standard balls for bearings and other purposes by type of material, grade, and size range; preferred ball sizes; ball hardness corrections for curvature; various tolerances, marking increments, and maximum surface roughnesses by grades; total hardness ranges for various materials; and minimum case depths for carbon steel balls. The numbers of balls per pound and per kilogram for ferrous and nonferrous metals are also shown.

**Definitions and Symbols.**—The following definitions and symbols apply to American National Standard metal balls.

*Nominal Ball Diameter,  $D_w$ :* The diameter value that is used for the general identification of a ball size, e.g.,  $\frac{1}{4}$  inch, 6 mm, etc.

*Single Diameter of a Ball,  $D_{ws}$ :* The distance between two parallel planes tangent to the surface of a ball.

*Mean Diameter of a Ball,  $D_{wm}$ :* The arithmetical mean of the largest and smallest single diameters of a ball.

*Ball Diameter Variation,  $V_{Dws}$ :* The difference between the largest and smallest single diameters of one ball.

*Deviation from Spherical Form,  $\Delta R_w$ :* The greatest radial distance in any radial plane between a sphere circumscribed around the ball surface and any point on the ball surface.

*Lot:* A definite quantity of balls manufactured under conditions that are presumed uniform, considered and identified as an entirety.

*Lot Mean Diameter,  $D_{wmL}$ :* The arithmetical mean of the mean diameter of the largest ball and that of the smallest ball in the lot.

*Lot Diameter Variation,  $V_{DwL}$ :* The difference between the mean diameter of the largest ball and that of the smallest ball in the lot.

*Nominal Ball Diameter Tolerance:* The maximum allowable deviation of any ball lot mean diameter from the Nominal Ball Diameter.

*Container Marking Increment:* The Standard unit steps in millionths of an inch or in micrometers used to express the Specific Diameter.

*Specific Diameter:* The amount by which the lot mean diameter ( $D_{wmL}$ ) differs from the nominal diameter ( $D_w$ ), accurate to the container marking increment for that grade; the specific diameter should be marked on the unit container.

*Ball Gage Deviation,  $\Delta S$ :* The difference between the lot mean diameter and the sum of the nominal mean diameter and the ball gage.

*Surface Roughness,  $R_a$ :* Surface roughness consists of all those irregularities that form surface relief and are conventionally defined within the area where deviations of form and waviness are eliminated. (See Handbook Surface Texture Section.)

**Ordering Specifications.**—Unless otherwise agreed between producer and user, orders for metal balls should provide the following information: quantity, material, nominal ball diameter, grade, and ball gage. A *ball grade* embodies a specific combination of dimensional form, and surface roughness tolerances. A *ball gage(s)* is the prescribed small amount, expressed with the proper algebraic sign, by which the lot mean diameter (arithmetical mean of the mean diameters of the largest and smallest balls in the lot) should differ from the nominal diameter, this amount being one of an established series of amounts as shown in the table below. The 0 ball gage is commonly referred to as "OK".

## Preferred Ball Gages for Grades 3 to 200

| Grade  | Ball Gages (in 0.0001-in. units) |    |                        | Ball Gages (in 1 $\mu$ m units)    |    |                                    |
|--------|----------------------------------|----|------------------------|------------------------------------|----|------------------------------------|
|        | Minus                            | OK | Plus                   | Minus                              | OK | Plus                               |
| 3, 5   | - 3 - 2 - 1                      | 0  | + 1 + 2 + 3            | - 8 - 7 - 6 - 5<br>- 4 - 3 - 2 - 1 | 0  | + 1 + 2 + 3 + 4<br>+ 5 + 6 + 7 + 8 |
| 10, 16 | - 4 - 3 - 2 - 1                  | 0  | + 1 + 2 + 3 + 4        | - 10 - 8 - 6<br>- 4 - 2            | 0  | + 2 + 4 + 6<br>+ 8 + 10            |
| 24     | - 5 - 4 - 3<br>- 2 - 1           | 0  | + 1 + 2 + 3<br>+ 4 + 5 | - 12 - 10 - 8<br>- 6 - 4 - 2       | 0  | + 2 + 4 + 6<br>+ 8 + 10 + 12       |
| 48     | - 6 - 4 - 2                      | 0  | + 2 + 4 + 6            | - 16 - 12 - 8 - 4                  | 0  | + 4 + 8 + 12 + 16                  |
| 100    |                                  | 0  |                        |                                    | 0  |                                    |
| 200    |                                  | 0  |                        |                                    | 0  |                                    |

Table 1. AFBMA Standard Balls — Tolerances for Individual Balls and for Lots of Balls

| Grade       | Allowable Ball Diameter Variation | Allowable Deviation from Spherical Form | Maximum Surface Roughness $R_a$ | Allowable Lot Diameter Variation | Nominal Ball Diameter Tolerance ( $\pm$ ) | Container Marking Increments |
|-------------|-----------------------------------|---|---------------------------------|----------------------------------|---|------------------------------|
|             | For Individual Balls              |   |                                 | For Lots of Balls                |   |                              |
| Grade       | Millionths of an Inch             |   |                                 |                                  |   |                              |
| 3           | 3                                 | 3                                       | 0.5                             | 5                                | a   | 10                           |
| 5           | 5                                 | 5                                       | 0.8                             | 10                               | a   | 10                           |
| 10          | 10                                | 10                                      | 1                               | 20                               | a   | 10                           |
| 16          | 16                                | 16                                      | 1                               | 32                               | a   | 10                           |
| 24          | 24                                | 24                                      | 2                               | 48                               | a   | 10                           |
| 48          | 48                                | 48                                      | 3                               | 96                               | a   | 50                           |
| 100         | 100                               | 100                                     | 5                               | 200                              | 500                                       | a                            |
| 200         | 200                               | 200                                     | 8                               | 400                              | 1000                                      | a                            |
| 500         | 500                               | 500                                     | a                               | 1000                             | 2000                                      | a                            |
| 1000        | 1000                              | 1000                                    | a                               | 2000                             | 5000                                      | a                            |
| Micrometers |                                   |   |                                 |                                  |   |                              |
| 3           | 0.08                              | 0.08                                    | 0.012                           | 0.13                             | a   | 0.25                         |
| 5           | 0.13                              | 0.13                                    | 0.02                            | 0.25                             | a   | 0.25                         |
| 10          | 0.25                              | 0.25                                    | 0.025                           | 0.5                              | a   | 0.25                         |
| 16          | 0.4                               | 0.4                                     | 0.025                           | 0.8                              | a   | 0.25                         |
| 24          | 0.6                               | 0.6                                     | 0.05                            | 1.2                              | a   | 0.25                         |
| 48          | 1.2                               | 1.2                                     | 0.08                            | 2.4                              | a   | 1.25                         |
| 100         | 2.5                               | 2.5                                     | 0.125                           | 5                                | 12.5                                      | a                            |
| 200         | 5                                 | 5                                       | 0.2                             | 10                               | 25  | a                            |
| 500         | 13                                | 13                                      | a                               | 25                               | 50  | a                            |
| 1000        | 25                                | 25                                      | a                               | 50                               | 125                                       | a                            |

<sup>a</sup> Not applicable.

Allowable ball gage (see text) deviation is for Grade 3: + 0.000030, - 0.000030 inch (+0.75, - 0.75  $\mu$ m); for Grades 5, 10, and 16: + 0.000050, - 0.000040 inch (+ 1.25, - 1  $\mu$ m); and for Grade 24: + 0.000100, - 0.000100 inch (+ 2.5, - 2.5  $\mu$ m). Other grades not given.

*Examples:* A typical order, in inch units, might read as follows: 80,000 pieces, chrome alloy steel,  $\frac{1}{4}$ -inch Nominal Diameter, Grade 16, and Ball Gage to be -0.0002 inch.

A typical order, in metric units, might read as follows: 80,000 pieces, chrome alloy steel, 6 mm Nominal Diameter, Grade 16, and Ball Gage to be  $-4 \mu\text{m}$ .

**Package Marking:** The ball manufacturer or supplier will identify packages containing each lot with information provided on the orders, as given above. In addition, the specific diameter of the contents shall be stated. Container marking increments are listed in [Table 1](#).

**Examples:** Balls supplied to the order of the first of the previous examples would, if perfect size, be  $D_{wml} = 0.249800$  inch. In Grade 16 these balls would be acceptable with  $D_{wml}$  from 0.249760 to 0.249850 inch. If they actually measured 0.249823 (which would be rounded off to 0.249820), each package would be marked: 5,000 Balls, Chrome Alloy Steel,  $\frac{1}{4}$ " Nominal Diameter, Grade 16,  $-0.0002$  inch Ball Gage, and  $-0.000180$  inch Specific Diameter.

Balls supplied to the order of the second of the two previous examples would, if perfect size, be  $D_{wml} = 5.99600$  mm. In Grade 16 these balls would be acceptable with a  $D_{wml}$  from 5.99500 to 5.99725 mm. If they actually measured 5.99627 mm (which would be rounded off to 5.99625 mm), each package would be marked: 5,000 Balls, Chrome Alloy Steel, 6 mm Nominal Diameter, Grade 16,  $-4 \mu\text{m}$  Ball Gage, and  $-3.75 \mu\text{m}$  Specific Diameter.

For complete details as to material requirements, quality specifications, quality assurance provisions, and methods of hardness testing, reference should be made to the Standard.

**Table 2. AFBMA Standard Balls — Typical Nominal Size Ranges by Material and Grade**

| Steel Balls <sup>a</sup>              |                      |   |                            | Non-Ferrous Balls <sup>a</sup> |                       |  |                             |                            |
|---------------------------------------|----------------------|---|----------------------------|--------------------------------|-----------------------|--|-----------------------------|----------------------------|
| Material                              | Grade                | Size Range <sup>b</sup>                         |                            | Material Grade                 | Grade                 | Size Range <sup>b</sup>                                    |                             |                            |
|                                       |                      | Inch  | mm                         |                                |                       | Inch   | mm                          |                            |
| Chrome Alloy                          | 3                    | $\frac{1}{32}-1$                                | 0.8–25                     | Aluminum                       | 200                   | $\frac{1}{16}-1$   | 1.5–25                      |                            |
|                                       | 5,10,<br>16,24       | $\frac{1}{64}-1\frac{1}{2}$                     | 0.3–38                     | Aluminum<br>Bronze             | 200                   | $1\frac{3}{16}-4$  | 20–100                      |                            |
|                                       | 48, 100,<br>200, 500 | $\frac{1}{32}-2\frac{7}{8}$                     | 0.8–75                     |                                |                       |  |                             |                            |
|                                       | 1000                 | $\frac{3}{8}-4\frac{1}{2}$                      | 10–115                     | Brass                          | 100,200,<br>500, 1000 | $\frac{1}{16}-\frac{3}{4}$                                 | 1.5–19                      |                            |
| AISI M-50                             | 3                    | $\frac{1}{32}-\frac{1}{2}$                      | 0.8–12                     | Bronze                         | 200,500,<br>1000      | $\frac{1}{16}-\frac{3}{4}$                                 | 1.5–19                      |                            |
|                                       | 5,10,16<br>24,48     | $\frac{1}{32}-1\frac{5}{8}$                     | 0.8–40                     |                                |                       |  |                             |                            |
| Corrosion<br>Resisting<br>Hardened    | 3,5,10,16            | $\frac{1}{64}-\frac{3}{4}$                      | 0.3–19                     | Monel<br>Metal 400             | 100,200,<br>500       | $\frac{1}{16}-\frac{3}{4}$                                 | 1.5–19                      |                            |
|                                       | 24                   | $\frac{1}{32}-1$                                | 0.8–25                     |                                |                       |  |                             |                            |
|                                       | 48<br>100,200        | $\frac{1}{32}-2$<br>$\frac{1}{32}-4\frac{1}{2}$ | 0.8–50<br>0.8–115          |                                |                       |  |                             |                            |
| Corrosion-<br>Resisting<br>Unhardened | 100,200,<br>500      | $\frac{1}{16}-\frac{3}{4}$                      | 1.5–19                     | K-Monel<br>Metal 500           | 100<br>200            | $\frac{1}{16}-\frac{3}{4}$<br>$\frac{1}{16}-1\frac{1}{16}$ | 1.5–19<br>1.5–45            |                            |
|                                       |                      | Carbon<br>Steel <sup>c</sup>                    | 100,200,<br>500, 1000      | $\frac{1}{16}-1\frac{1}{2}$    | 1.5–38                | Tungsten<br>Carbide  | 5                           | $\frac{3}{64}-\frac{1}{2}$ |
| Silicon<br>Molybdenum                 | 200                  |   | $\frac{1}{4}-1\frac{1}{8}$ | 6.5–28                         | 10                    |  | $\frac{3}{64}-\frac{3}{4}$  | 1.2–19                     |
|                                       |                      |   |                            |                                | 16                    |  | $\frac{3}{64}-1$            | 1.2–25                     |
|                                       |                      |   |                            |                                | 24                    |  | $\frac{3}{64}-1\frac{1}{4}$ | 1.2–32                     |

<sup>a</sup> For hardness rages see [Table 3](#).

<sup>b</sup> For tolerances see [Table 1](#).

<sup>c</sup> For minimum case depths refer to the Standard.

**Table 3. AFBMA Standard Balls—Typical Hardness Ranges**

| Material                       | Common Standard            | SAE Unified Number | Rockwell Value <sup>a,b</sup> |
|--------------------------------|----------------------------|--------------------|-------------------------------|
| Steel—                         |                            |                    |                               |
| Alloy tool                     | AISI/SAE M50               | T11350             | 60–65 “C” <sup>c,d</sup>      |
| Carbon <sup>e</sup>            | AISI/SAE 1008              | G10080             | 60 Minimum “C” <sup>b</sup>   |
|                                | AISI/SAE 1013              | G10130             | 60 Minimum “C” <sup>b</sup>   |
|                                | AISI/SAE 1018              | G10180             | 60 Minimum “C” <sup>b</sup>   |
|                                | AISI/SAE 1022              | G10220             | 60 Minimum “C” <sup>b</sup>   |
| Chrome alloy                   | AISI/SAE E52100            | G52986             | 60–67 “C” <sup>c,d</sup>      |
|                                | AISI/SAE E51100            | G51986             | 60–67 “C” <sup>c,d</sup>      |
| Corrosion-resisting hardened   |                            |                    |                               |
|                                | AISI/SAE 440C              | S44004             | 58–65 “C” <sup>f,d</sup>      |
|                                | AISI/SAE 440B              | S44003             | 55–62 “C” <sup>f,d</sup>      |
|                                | AISI/SAE 420               | S42000             | 52 Minimum “C” <sup>f,d</sup> |
|                                | AISI/SAE 410               | S41000             | 97 “B”; 41 “C” <sup>f,d</sup> |
|                                | AISI/SAE 329               | S32900             | 45 Minimum “C” <sup>f,d</sup> |
| Corrosion-resisting unhardened |                            |                    |                               |
|                                | AISI/SAE 3025              | S30200             | 25–39 “C” <sup>d,g</sup>      |
|                                | AISI/SAE 304               | S30400             | 25–39 “C” <sup>d,g</sup>      |
|                                | AISI/SAE 305               | S30500             | 25–39 “C” <sup>d,g</sup>      |
|                                | AISI/SAE 316               | S31600             | 25–39 “C” <sup>d,g</sup>      |
|                                | AISI/SAE 430               | S43000             | 48–63 “A” <sup>d</sup>        |
| Silicon molybdenum             | AISI/SAE S2                | T41902             | 52–60 “C” <sup>c</sup>        |
| Aluminum                       | AA-2017                    | A92017             | 54–72 “B”                     |
| Aluminium bronze               | CDA-624                    | C62400             | 94–98 “B”                     |
|                                | CDA-630                    | C63000             | 94–98 “B”                     |
| Brass                          | CDA-260                    | C26000             | 75–87 “B”                     |
| Bronze                         | CDA-464                    | C46400             | 75–98 “B”                     |
| Monel 400                      | AMS-4730                   | N04400             | 85–95 “B”                     |
| Monel K-500                    | QA-N-286                   | N05500             | 24 Minimum “C”                |
| Tungsten carbide               | JIC Carbide Classification | ...                | 84–91.5 “A”                   |

<sup>a</sup> Rockwell Hardness Tests shall be conducted on parallel flats in accordance with ASTM Standard E18 unless otherwise specified.

<sup>b</sup> Hardness readings taken on spherical surfaces are subject to the corrections shown in Table 5. Hardness readings for carbon steel balls smaller than 5 mm (¼ inch) shall be taken by the microhardness method (detailed in ANSI/AFBMA Std 10-1989) or as agreed between manufacturer and purchaser.

<sup>c</sup> Hardness of balls in any one lot shall be within 3 points on Rockwell C scale.

<sup>d</sup> When microhardness method (see ANSI/AFBMA Std 10-1989) is used, the Rockwell hardness values given are converted to DPH in accordance with ASTM Standard E 140, “Standard Hardness Conversion Tables for Metals.”

<sup>e</sup> Choice of carbon steels shown to be at ball manufacturer's option.

<sup>f</sup> Hardness of balls in any one lot shall be within 4 points on Rockwell C scale.

<sup>g</sup> Annealed hardness of 75–90 “B” is available when specified.

## STANDARD METAL BALLS

Table 4. Preferred Ball Sizes

| Nominal Ball Sizes Metric | Diameter mm | Diameter Inches | Nominal Ball Sizes Inch | Nominal Ball Sizes Metric | Diameter mmm | Diameter Inches | Nominal Ball Sizes Inch |
|---------------------------|-------------|-----------------|-------------------------|---------------------------|--------------|-----------------|-------------------------|
| 0.3                       | 0.300 00    | 0.011 810       |                         |                           | 0.793 75     | 0.031 250       | $\frac{1}{32}$          |
|                           | 0.396 88    | 0.015 625       |                         | 0.8                       | 0.800 00     | 0.031 496       |                         |
| 0.4                       | 0.400 00    | 0.015 750       | $\frac{1}{64}$          | 1                         | 1.000 00     | 0.039 370       |                         |
| 0.5                       | 0.500 00    | 0.019 680       |                         |                           | 1.190 63     | 0.046 875       | $\frac{3}{64}$          |
|                           | 0.508 00    | 0.020 000       | 0.020                   | 1.2                       | 1.200 00     | 0.047 240       |                         |
| 0.6                       | 0.600 00    | 0.023 620       |                         | 1.5                       | 1.500 00     | 0.059 060       |                         |
|                           | 0.635 00    | 0.025 000       | 0.025                   |                           | 1.587 50     | 0.062 500       | $\frac{1}{16}$          |
| 0.7                       | 0.700 00    | 0.027 560       |                         |                           | 1.984 38     | 0.078 125       | $\frac{5}{64}$          |
| 2                         | 2.000 00    | 0.078 740       |                         | 21                        | 21.000 000   | 0.826 770       |                         |
|                           | 2.381 25    | 0.093 750       | $\frac{3}{32}$          |                           | 21.431 25    | 0.843 750       | $\frac{27}{32}$         |
| 2.5                       | 2.500 00    | 0.098 420       |                         | 22                        | 22.000 00    | 0.866 140       |                         |
|                           | 2.778 00    | 0.109 375       | $\frac{7}{64}$          |                           | 22.225 00    | 0.875 000       | $\frac{7}{8}$           |
| 3                         | 3.000 00    | 0.118 110       |                         | 23                        | 23.000 00    | 0.905 510       |                         |
|                           | 3.175 00    | 0.125 000       | $\frac{1}{8}$           |                           | 23.018 75    | 0.906 250       | $\frac{29}{32}$         |
| 3.5                       | 3.500 00    | 0.137 800       |                         |                           | 23.812 50    | 0.937 500       | $\frac{15}{16}$         |
|                           | 3.571 87    | 0.140 625       | $\frac{9}{64}$          | 24                        | 24.000 00    | 0.944 880       |                         |
|                           | 3.968 75    | 0.156 250       | $\frac{5}{32}$          |                           | 24.606 25    | 0.968 750       | $\frac{31}{32}$         |
| 4                         | 4.000 00    | 0.157 480       |                         | 25                        | 25.000 00    | 0.984 250       |                         |
|                           | 4.365 63    | 0.171 875       | $\frac{11}{64}$         |                           | 25.400 00    | 1.000 000       | 1                       |
| 4.5                       | 4.500 00    | 0.177 160       |                         | 26                        | 26.000 00    | 1.023 620       |                         |
|                           | 4.762 50    | 0.187 500       | $\frac{3}{16}$          |                           | 26.987 50    | 1.062 500       | $\frac{1}{16}$          |
| 5                         | 5.000 00    | 0.196 850       |                         | 28                        | 28.000 00    | 1.102 360       |                         |
| 5.5                       | 5.500 00    | 0.216 540       |                         |                           | 28.575 00    | 1.125 000       | $\frac{1}{8}$           |
|                           | 5.556 25    | 0.218 750       | $\frac{7}{32}$          | 30                        | 30.000 00    | 1.181 100       |                         |
|                           | 5.953 12    | 0.234 375       | $\frac{15}{64}$         |                           | 30.162 50    | 1.187 500       | $\frac{13}{16}$         |
| 6                         | 6.000 00    | 0.236 220       |                         |                           | 31.750 00    | 1.250 000       | $\frac{1}{4}$           |
|                           | 6.350 00    | 0.250 000       | $\frac{1}{4}$           | 32                        | 32.000 00    | 1.259 840       |                         |
| 6.5                       | 6.500 00    | 0.255 900       |                         |                           | 33.337 50    | 1.312 500       | $\frac{15}{16}$         |
|                           | 6.746 88    | 0.265 625       | $\frac{17}{64}$         | 34                        | 34.000 00    | 1.338 580       |                         |
| 7                         | 7.000 00    | 0.275 590       |                         |                           | 34.925 00    | 1.375 000       | $\frac{13}{8}$          |
|                           | 7.143 75    | 0.281 250       | $\frac{9}{32}$          | 35                        | 35.000 00    | 1.377 950       |                         |
| 7.5                       | 7.500 00    | 0.295 280       |                         | 36                        | 36.000 00    | 1.417 320       |                         |
|                           | 7.540 63    | 0.296 875       | $\frac{19}{64}$         |                           | 36.512 50    | 1.437 500       | $\frac{17}{16}$         |
|                           | 7.937 50    | 0.312 500       | $\frac{5}{16}$          | 38                        | 38.000 00    | 1.496 060       |                         |
| 8                         | 8.000 00    | 0.314 960       |                         |                           | 38.100 00    | 1.500 000       | $\frac{1}{2}$           |
| 8.5                       | 8.500 00    | 0.334 640       |                         |                           | 39.687 50    | 1.562 500       | $\frac{19}{16}$         |
|                           | 8.731 25    | 0.343 750       | $\frac{11}{32}$         | 40                        | 40.000 00    | 1.574 800       |                         |
| 9                         | 9.000 00    | 0.354 330       |                         |                           | 41.275 00    | 1.625 000       | $\frac{15}{8}$          |
|                           | 9.128 12    | 0.359 375       | $\frac{23}{64}$         |                           | 42.862 50    | 1.687 500       | $\frac{11}{16}$         |
|                           | 9.525 00    | 0.375 000       | $\frac{3}{8}$           |                           | 44.450 00    | 1.750 000       | $\frac{3}{4}$           |
|                           | 9.921 87    | 0.390 625       | $\frac{25}{64}$         | 45                        | 45.000 00    | 1.771 650       |                         |
| 10                        | 10.000 00   | 0.393 700       |                         |                           | 46.037 50    | 1.812 500       | $\frac{13}{16}$         |
|                           | 10.318 75   | 0.406 250       | $\frac{13}{32}$         |                           | 47.625 00    | 1.875 000       | $\frac{1}{6}$           |
| 11                        | 11.000 00   | 0.433 070       |                         |                           | 49.212 50    | 1.937 500       | $\frac{15}{16}$         |
|                           | 11.112 50   | 0.437 500       | $\frac{7}{16}$          | 50                        | 50.000 00    | 1.968 500       |                         |
| 11.5                      | 11.500 00   | 0.452 756       |                         |                           | 50.800 00    | 2.000 000       | 2                       |
|                           | 11.509 38   | 0.453 125       | $\frac{29}{64}$         |                           | 53.975 00    | 2.125 000       | $\frac{21}{8}$          |

**Table 4. (Continued) Preferred Ball Sizes**

| Nominal Ball Sizes Metric | Diameter mm | Diameter Inches | Nominal Ball Sizes Inch | Nominal Ball Sizes Metric | Diameter mmb | Diameter Inches | Nominal Ball Sizes Inch |
|---------------------------|-------------|-----------------|-------------------------|---------------------------|--------------|-----------------|-------------------------|
| 12                        | 11.906 25   | 0.468 750       | $\frac{15}{32}$         | 55                        | 55.000 00    | 2.165 354       |                         |
|                           | 12.000 00   | 0.472 440       |                         |                           | 57.150 00    | 2.250 000       | $\frac{2}{4}$           |
|                           | 12.303 12   | 0.484 375       | $\frac{31}{64}$         | 60                        | 60.000 00    | 2.362 205       |                         |
| 13                        | 12.700 00   | 0.500 000       | $\frac{1}{2}$           |                           | 60.325 00    | 2.375 00        | $\frac{23}{8}$          |
|                           | 13.000 00   | 0.511 810       |                         |                           | 63.500 00    | 2.500 000       | $\frac{21}{2}$          |
|                           | 13.493 75   | 0.531 250       | $\frac{17}{32}$         | 65                        | 65.000 00    | 2.559 055       |                         |
| 14                        | 14.000 00   | 0.551 180       |                         |                           | 66.675 00    | 2.625 000       | $\frac{25}{8}$          |
|                           | 14.287 50   | 0.562 500       | $\frac{9}{16}$          |                           | 69.850 00    | 2.750 000       | $\frac{23}{4}$          |
|                           | 15.000 00   | 0.590 550       |                         |                           | 73.025 00    | 2.875 000       | $\frac{27}{8}$          |
| 15                        | 15.081 25   | 0.593 750       | $\frac{19}{32}$         |                           | 76.200 00    | 3.000 000       | 3                       |
|                           | 15.875 00   | 0.625 000       | $\frac{5}{8}$           |                           | 79.375 00    | 3.125 000       | $3\frac{3}{8}$          |
|                           | 16.000 00   | 0.629 920       |                         |                           | 82.550 00    | 3.250 000       | $\frac{31}{4}$          |
| 16                        | 16.668 75   | 0.656 250       | $\frac{21}{32}$         |                           | 85.725 00    | 3.375 00        | $\frac{33}{8}$          |
|                           | 17.000 00   | 0.669 290       |                         |                           | 88.900 00    | 3.500 000       | $3\frac{1}{2}$          |
|                           | 17.462 50   | 0.687 500       | $\frac{11}{16}$         |                           | 92.075 00    | 3.625 000       | $\frac{35}{8}$          |
| 18                        | 18.000 00   | 0.708 660       |                         |                           | 95.250 00    | 3.750 000       | $\frac{37}{4}$          |
|                           | 18.256 25   | 0.718 750       | $\frac{23}{32}$         |                           | 98.425 00    | 3.875 000       | $\frac{37}{8}$          |
|                           | 19.000 00   | 0.748 030       |                         |                           | 101.600 00   | 4.000 000       | 4                       |
| 19                        | 19.050 00   | 0.750 000       | $\frac{3}{4}$           |                           | 104.775 00   | 4.125 000       | $4\frac{1}{8}$          |
|                           | 19.843 75   | 0.781 250       | $\frac{25}{32}$         |                           | 107.950 00   | 4.250 000       | $\frac{41}{4}$          |
|                           | 20.000 00   | 0.787 400       |                         |                           | 111.125 00   | 4.375 000       | $4\frac{3}{8}$          |
| 20                        | 20.637 50   | 0.812 500       | $\frac{13}{16}$         |                           | 114.300 00   | 4.500 000       | $4\frac{1}{2}$          |

**Table 5. Ball Hardness Corrections for Curvatures**

| Hardness Reading, Rockwell C | Ball Diameters, Inch  |                |               |               |               |               |     |
|------------------------------|-----------------------|----------------|---------------|---------------|---------------|---------------|-----|
|                              | $\frac{1}{4}$         | $\frac{5}{16}$ | $\frac{3}{8}$ | $\frac{1}{2}$ | $\frac{5}{8}$ | $\frac{3}{4}$ | 1   |
|                              | Correction—Rockwell C |                |               |               |               |               |     |
| 20                           | 12.1                  | 9.3            | 7.7           | 6.1           | 4.9           | 4.1           | 3.1 |
| 25                           | 11.0                  | 8.4            | 7.0           | 5.5           | 4.4           | 3.7           | 2.7 |
| 30                           | 9.8                   | 7.5            | 6.2           | 4.9           | 3.9           | 3.2           | 2.4 |
| 35                           | 8.6                   | 6.6            | 5.5           | 4.3           | 3.4           | 2.8           | 2.1 |
| 40                           | 7.5                   | 5.7            | 4.7           | 3.6           | 2.9           | 2.4           | 1.7 |
| 45                           | 6.3                   | 4.9            | 4.0           | 3.0           | 2.4           | 1.9           | 1.4 |
| 50                           | 5.2                   | 4.0            | 3.2           | 2.4           | 1.9           | 1.5           | 1.1 |
| 55                           | 4.1                   | 3.1            | 2.5           | 1.8           | 1.4           | 1.1           | 0.8 |
| 60                           | 2.9                   | 2.2            | 1.8           | 1.2           | 0.9           | 0.7           | 0.4 |
| 65                           | 1.8                   | 1.3            | 1.0           | 0.5           | 0.3           | 0.2           | 0.1 |
| 20                           | 12.8                  | 9.3            | 7.6           | 6.6           | 5.2           | 4.0           | 3.2 |
| 25                           | 11.7                  | 8.4            | 6.9           | 5.9           | 4.6           | 3.5           | 2.8 |
| 30                           | 10.5                  | 7.5            | 6.1           | 5.2           | 4.1           | 3.1           | 2.4 |
| 35                           | 9.4                   | 6.6            | 5.4           | 4.6           | 3.6           | 2.7           | 2.1 |
| 40                           | 8.0                   | 5.7            | 4.5           | 3.8           | 3.0           | 2.2           | 1.8 |
| 45                           | 6.7                   | 4.9            | 3.8           | 3.2           | 2.5           | 1.8           | 1.4 |
| 50                           | 5.5                   | 4.0            | 3.0           | 2.6           | 2.0           | 1.4           | 1.1 |
| 55                           | 4.3                   | 3.1            | 2.3           | 1.9           | 1.5           | 1.0           | 0.8 |
| 60                           | 3.0                   | 2.2            | 1.7           | 1.2           | 1.0           | 0.6           | 0.4 |
| 65                           | 1.9                   | 1.3            | 0.9           | 0.6           | 0.4           | 0.2           | 0.1 |

Corrections to be added to Rockwell C readings obtained on spherical surfaces of chrome alloy steel, corrosion resisting hardened and unhardened steel, and carbon steel balls. For other ball sizes and hardness readings, interpolate between correction values shown.

Table 6. Number of Metal Balls per Pound

| Nom. Dia., <sup>a</sup> Inches | Material Density, Pounds per Cubic Inch |         |         |         |         |         |         |         |         |         |         |         |         |
|--------------------------------|---|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|                                | .101                                    | .274    | .277    | .279    | .283    | .284    | .286    | .288    | .301    | .304    | .306    | .319    | .540    |
| 1/32                           | 620 000                                 | 228 000 | 226 000 | 224 000 | 221 000 | 220 000 | 219 000 | 217 000 | 208 000 | 206 000 | 205 000 | 196 000 | 116 000 |
| 1/16                           | 77 500                                  | 28 600  | 28 200  | 28 000  | 27 600  | 27 500  | 27 400  | 27 200  | 26 000  | 25 700  | 25 600  | 24 500  | 14 500  |
| 3/32                           | 22 900                                  | 8 460   | 8 370   | 8 310   | 8 190   | 8 160   | 8 100   | 8 050   | 7 700   | 7 620   | 7 570   | 7 270   | 4 290   |
| 1/8                            | 9 680                                   | 3 570   | 3 530   | 3 500   | 3 460   | 3 440   | 3 400   | 3 250   | 3 220   | 3 200   | 3 200   | 3 070   | 1 810   |
| 5/32                           | 4 960                                   | 1 830   | 1 810   | 1 790   | 1 770   | 1 760   | 1 750   | 1 740   | 1 660   | 1 650   | 1 640   | 1 570   | 927     |
| 3/16                           | 2 870                                   | 1 060   | 1 050   | 1 040   | 1 020   | 1 020   | 1 010   | 1 010   | 963     | 953     | 947     | 908     | 537     |
| 7/32                           | 1 810                                   | 666     | 659     | 654     | 645     | 642     | 638     | 634     | 606     | 600     | 596     | 572     | 338     |
| 1/4                            | 1 210                                   | 446     | 441     | 438     | 432     | 430     | 427     | 424     | 406     | 402     | 399     | 383     | 226     |
| 5/16                           | 850                                     | 313     | 310     | 308     | 303     | 302     | 300     | 298     | 285     | 282     | 281     | 269     | 159     |
| 3/8                            | 620                                     | 228     | 226     | 224     | 221     | 220     | 219     | 217     | 208     | 206     | 205     | 196     | 116     |
| 7/16                           | 466                                     | 172.    | 170.    | 169.    | 166.    | 166.    | 164.    | 163.    | 156.    | 155.    | 154.    | 147.    | 87.1    |
| 1/2                            | 359                                     | 132.    | 131.    | 130.    | 128.    | 128.    | 127.    | 126.    | 120.    | 119.    | 118.    | 114.    | 67.1    |
| 5/8                            | 282                                     | 104.    | 103.    | 102.    | 101.    | 100.    | 99.6    | 98.9    | 94.6    | 93.7    | 93.1    | 89.3    | 52.8    |
| 3/4                            | 226                                     | 83.2    | 82.3    | 81.7    | 80.6    | 80.3    | 79.7    | 79.2    | 75.8    | 75.0    | 74.5    | 71.5    | 42.2    |
| 7/8                            | 184                                     | 67.7    | 66.9    | 66.5    | 65.5    | 65.3    | 64.8    | 64.4    | 61.6    | 61.0    | 60.6    | 58.1    | 34.3    |
| 1 1/32                         | 151.                                    | 55.8    | 55.2    | 54.8    | 54.0    | 53.8    | 53.4    | 53.1    | 50.8    | 50.3    | 49.9    | 47.9    | 28.3    |
| 1 1/8                          | 126.                                    | 46.5    | 46.0    | 45.7    | 45.0    | 44.9    | 44.5    | 44.2    | 42.3    | 41.9    | 41.6    | 39.9    | 23.6    |
| 1 1/4                          | 106.                                    | 39.2    | 38.7    | 38.5    | 37.9    | 37.8    | 37.5    | 37.3    | 35.7    | 35.3    | 35.1    | 33.6    | 19.9    |
| 1 1/2                          | 90.3                                    | 33.3    | 32.9    | 32.7    | 32.2    | 32.1    | 31.9    | 31.7    | 30.3    | 30.0    | 29.8    | 28.6    | 16.9    |
| 1 3/8                          | 77.5                                    | 28.6    | 28.2    | 28.0    | 27.6    | 27.5    | 27.4    | 27.2    | 26.0    | 25.7    | 25.6    | 24.5    | 14.5    |
| 1 1/2                          | 66.9                                    | 24.7    | 24.4    | 24.2    | 23.9    | 23.8    | 23.6    | 23.5    | 22.5    | 22.2    | 22.1    | 21.2    | 12.5    |
| 1 5/8                          | 58.2                                    | 21.5    | 21.2    | 21.1    | 20.8    | 20.7    | 20.6    | 20.4    | 19.5    | 19.3    | 19.2    | 18.4    | 10.9    |
| 1 3/4                          | 50.9                                    | 18.8    | 18.6    | 18.4    | 18.2    | 18.1    | 18.0    | 17.9    | 17.1    | 16.9    | 16.8    | 16.1    | 9.53    |
| 1 7/8                          | 44.8                                    | 16.5    | 16.3    | 16.2    | 16.0    | 15.9    | 15.8    | 15.7    | 15.0    | 14.9    | 14.8    | 14.2    | 8.38    |
| 2                              | 39.7                                    | 14.6    | 14.5    | 14.4    | 14.2    | 14.1    | 14.0    | 13.9    | 13.3    | 13.2    | 13.1    | 12.6    | 7.42    |
| 2 1/8                          | 35.3                                    | 13.0    | 12.9    | 12.8    | 12.6    | 12.5    | 12.5    | 12.4    | 11.8    | 11.7    | 11.6    | 11.2    | 6.59    |
| 2 1/4                          | 31.5                                    | 11.6    | 11.5    | 11.4    | 11.2    | 11.2    | 11.1    | 11.0    | 10.6    | 10.5    | 10.4    | 9.97    | 5.89    |
| 2 3/8                          | 28.2                                    | 10.4    | 10.3    | 10.2    | 10.1    | 10.0    | 9.97    | 9.90    | 9.47    | 9.38    | 9.32    | 8.94    | 5.28    |
| 2 1/2                          | 25.4                                    | 9.37    | 9.26    | 9.20    | 9.07    | 9.04    | 8.97    | 8.91    | 8.53    | 8.44    | 8.39    | 8.04    | 4.75    |
| 2 5/8                          | 22.9                                    | 8.46    | 8.37    | 8.31    | 8.19    | 8.16    | 8.10    | 8.05    | 7.70    | 7.62    | 7.57    | 7.27    | 4.29    |
| 2 3/4                          | 20.8                                    | 7.67    | 7.58    | 7.53    | 7.42    | 7.40    | 7.35    | 7.29    | 6.98    | 6.91    | 6.87    | 6.59    | 3.89    |
| 3                              | 18.9                                    | 6.97    | 6.89    | 6.85    | 6.75    | 6.72    | 6.68    | 6.63    | 6.35    | 6.28    | 6.24    | 5.99    | 3.54    |

<sup>a</sup> For sizes above 1 in. diameter, use the following formula: No. balls per pound =  $1.91 \div [(\text{nom. dia., in.})^3 \times (\text{material density, lbs. per cubic in.})]$ .

Ball material densities in pounds per cubic inch: aluminum .101; aluminum bronze .274; corrosion resisting hardened steel .277; AISI M-50 and silicon molybdenum steels .279; chrome alloy steel .283; carbon steel .284; AISI 302 corrosion resisting unhardened steel .286; AISI 316 corrosion resisting unhardened steel .288; bronze .304; brass and K-Monel metal .306; Monel metal .319; and tungsten carbide .540.

Table 7. Number of Metal Balls per Kilogram

| Nom. Dia., <sup>a</sup><br>mm | Material Density, Grams per Cubic Centimeter |           |           |           |           |           |           |           |           |           |           |           |           |
|-------------------------------|--|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|                               | 2.796  | 7.584     | 7.667     | 7.723     | 7.833     | 7.861     | 7.916     | 7.972     | 8.332     | 8.415     | 8.470     | 8.830     | 14.947    |
| 0.3                           | 25 300 000                                   | 9 330 000 | 9 230 000 | 9 160 000 | 9 030 000 | 9 000 000 | 8 940 000 | 8 870 000 | 8 490 000 | 8 410 000 | 8 350 000 | 8 010 000 | 4 730 000 |
| 0.4                           | 10 670 000                                   | 3 930 000 | 3 890 000 | 3 860 000 | 3 810 000 | 3 800 000 | 3 770 000 | 3 740 000 | 3 580 000 | 3 550 000 | 3 520 000 | 3 380 000 | 2 000 000 |
| 0.5                           | 5 470 000                                    | 2 010 000 | 1 990 000 | 1 980 000 | 1 950 000 | 1 940 000 | 1 930 000 | 1 920 000 | 1 830 000 | 1 820 000 | 1 800 000 | 1 730 000 | 1 020 000 |
| 0.7                           | 1 990 000                                    | 734 000   | 726 000   | 721 000   | 711 000   | 708 000   | 703 000   | 698 000   | 668 000   | 662 000   | 657 000   | 631 000   | 373 000   |
| 0.8                           | 1 330 000                                    | 492 000   | 487 000   | 483 000   | 476 000   | 475 000   | 471 000   | 468 000   | 448 000   | 443 000   | 440 000   | 422 000   | 250 000   |
| 1.0                           | 683 000                                      | 252 000   | 249 000   | 247 000   | 244 000   | 243 000   | 241 000   | 240 000   | 229 000   | 227 000   | 225 000   | 216 000   | 128 000   |
| 1.2                           | 395 000                                      | 146 000   | 144 000   | 143 000   | 141 000   | 141 000   | 140 000   | 139 000   | 133 000   | 131 000   | 130 000   | 125 000   | 73 900    |
| 1.5                           | 202 000                                      | 74 600    | 73 800    | 73 300    | 72 200    | 72 000    | 71 500    | 71 000    | 67 900    | 67 200    | 66 800    | 64 100    | 37 900    |
| 2.0                           | 85 400                                       | 31 500    | 31 100    | 30 900    | 30 500    | 30 400    | 30 200    | 29 900    | 28 700    | 28 400    | 28 200    | 27 000    | 16 000    |
| 2.5                           | 43 700                                       | 16 100    | 15 900    | 15 800    | 15 600    | 15 500    | 15 400    | 15 300    | 14 700    | 14 500    | 14 400    | 13 800    | 8 180     |
| 3.0                           | 25 300                                       | 9 330     | 9 230     | 9 160     | 9 030     | 9 000     | 8 940     | 8 870     | 8 490     | 8 410     | 8 350     | 8 010     | 4 730     |
| 3.5                           | 15 900                                       | 5 870     | 5 810     | 5 770     | 5 690     | 5 670     | 5 630     | 5 590     | 5 350     | 5 290     | 5 260     | 5 040     | 2 980     |
| 4.0                           | 10 700                                       | 3 930     | 3 890     | 3 860     | 3 810     | 3 800     | 3 770     | 3 740     | 3 580     | 3 550     | 3 520     | 3 380     | 2 000     |
| 4.5                           | 7 500  | 2 760     | 2 730     | 2 710     | 2 680     | 2 670     | 2 650     | 2 630     | 2 520     | 2 490     | 2 470     | 2 370     | 1 400     |
| 5.0                           | 5 470  | 5 010     | 1 990     | 1 980     | 1 950     | 1 940     | 1 930     | 1 920     | 1 830     | 1 820     | 1 800     | 1 730     | 1 020     |
| 5.5                           | 4 110  | 1 510     | 1 500     | 1 490     | 1 470     | 1 460     | 1 450     | 1 440     | 1 380     | 1 360     | 1 360     | 1 300     | 768       |
| 6.0                           | 3 160  | 1 170     | 1 150     | 1 140     | 1 130     | 1 120     | 1 120     | 1 110     | 1 060     | 1 050     | 1 040     | 1 000     | 592       |
| 6.5                           | 2 490  | 917       | 907       | 901       | 888       | 885       | 878       | 872       | 835       | 826       | 821       | 788       | 465       |
| 7.0                           | 1 990  | 734       | 726       | 721       | 711       | 708       | 703       | 698       | 668       | 662       | 657       | 631       | 373       |
| 7.5                           | 1 620  | 597       | 590       | 586       | 578       | 576       | 572       | 568       | 543       | 538       | 534       | 513       | 303       |
| 8.0                           | 1 330  | 492       | 487       | 483       | 476       | 475       | 471       | 468       | 448       | 443       | 440       | 422       | 250       |
| 8.5                           | 1 110  | 410       | 406       | 403       | 397       | 396       | 393       | 390       | 373       | 370       | 367       | 352       | 208       |
| 9.0                           | 937  | 345       | 342       | 339       | 334       | 333       | 331       | 329       | 314       | 311       | 309       | 297       | 175       |
| 10.0                          | 683  | 252       | 249       | 247       | 244       | 243       | 241       | 240       | 229       | 227       | 225       | 216       | 128       |
| 11.0                          | 513.0  | 189.0     | 187.0     | 186.0     | 183.0     | 183.0     | 181.0     | 180.0     | 172.0     | 171.0     | 169.0     | 163.0     | 96.0      |
| 11.5                          | 449.0  | 166.0     | 164.0     | 163.0     | 160.0     | 160.0     | 159.0     | 158.0     | 151.0     | 149.0     | 148.0     | 142.0     | 84.0      |
| 12.0                          | 395.0  | 146.0     | 144.0     | 143.0     | 141.0     | 141.0     | 140.0     | 139.0     | 133.0     | 131.0     | 130.0     | 125.0     | 73.9      |
| 13.0                          | 311.0  | 115.0     | 113.0     | 113.0     | 111.0     | 111.0     | 110.0     | 109.0     | 104.0     | 103.0     | 103.0     | 98.5      | 58.2      |
| 14.0                          | 249.0  | 91.8      | 90.8      | 90.1      | 88.9      | 88.5      | 87.9      | 87.3      | 83.5      | 82.7      | 82.2      | 78.8      | 46.6      |
| 15.0                          | 202.0  | 74.6      | 73.8      | 73.3      | 72.2      | 72.0      | 71.5      | 71.0      | 67.9      | 67.2      | 66.8      | 64.1      | 37.9      |
| 16.0                          | 167.0  | 61.5      | 60.8      | 60.4      | 59.5      | 59.3      | 58.9      | 58.5      | 56.0      | 55.4      | 55.1      | 52.8      | 31.2      |
| 17.0                          | 139.0  | 51.3      | 50.7      | 50.3      | 49.6      | 49.5      | 49.1      | 48.8      | 46.7      | 46.2      | 45.9      | 44.0      | 26.0      |

<sup>a</sup>For sizes above 17 mm diameter, use the following formula: No. balls per kilogram =  $1,910,000 \div [(\text{nom. dia., mm})^3 \times (\text{material density, grams per cu. cm})]$ .

Ball material densities in grams per cubic centimeter: aluminum, 2.796; aluminum bronze, 7.584; corrosion-resisting hardened steel, 7.677; AISI M-50 and silicon molybdenum steel, 7.723; chrome alloy steel, 7.833; carbon steel, 7.861; AISI 302 corrosion-resisting unhardened steel, 7.916; AISI 316 corrosion-resisting unhardened steel, 7.972; bronze, 8.415; brass and K-Monel metal, 8.470; Monel metal, 8.830; tungsten carbide, 14.947.



**LUBRICANTS AND LUBRICATION**

A lubricant is used for one or more of the following purposes: to reduce friction; to prevent wear; to prevent adhesion; to aid in distributing the load; to cool the moving elements; and to prevent corrosion.

The range of materials used as lubricants has been greatly broadened over the years, so that in addition to oils and greases, many plastics and solids and even gases are now being applied in this role. The only limitations on many of these materials are their ability to replenish themselves, to dissipate frictional heat, their reaction to high environmental temperatures, and their stability in combined environments. Because of the wide selection of lubricating materials available, great care is advisable in choosing the material and the method of application. The following types of lubricants are available: petroleum fluids, synthetic fluids, greases, solid films, working fluids, gases, plastics, animal fat, metallic and mineral films, and vegetable oils.

**Lubricating Oils.**—The most versatile and best-known lubricant is mineral oil. When applied in well-designed applications that provide for the limitations of both mechanical and hydraulic elements, oil is recognized as the most reliable lubricant. Concurrently, it is offered in a wide selection of stocks, carefully developed to meet the requirements of the specific application.

Lubricating oils are seldom marketed without additives blended for a narrow range of applications. These “additive packages” are developed for particular applications, so it is advisable to consult the sales-engineering representatives of a reputable petroleum company on the proper selection for the conditions under consideration. The following are the most common types of additives: wear preventive, oxidation inhibitor, rust inhibitor, detergent-dispersant, viscosity index improver, defoaming agent, and pour-point depressant.

A more recent development in the field of additives is a series of organic compounds that leave no ash when heated to a temperature high enough to evaporate or burn off the base oil. Initially produced for internal-combustion-engine applications these additives have found ready acceptance in those other applications where metallic or mineral trace elements would promote catalytic, corrosive, deposition, or degradation effects on mechanism materials.

Additives usually are not stable over the entire temperature and shear-rate ranges considered acceptable for the base stock oil application. Because of this problem, additive type oils must be carefully monitored to ensure that they are not continued in service after their principal capabilities have been diminished or depleted. Of primary importance in this regard is the action of the detergent-dispersant additives that function so well to reduce and control degradation products that would otherwise deposit on the operating parts and oil cavity walls. Because the materials cause the oil to carry a higher than normal amount of the breakdown products in a fine suspension, they may cause an accelerated deposition rate or foaming when they have been depleted or degenerated by thermal or contamination action. Ingestion of water by condensation or leaking can cause markedly harmful effects.

Viscosity index improvers serve to modify oils so that their change in viscosity is reduced over the operating temperature range. These materials may be used to improve both a heavy or a light oil; however, the original stock will tend to revert to its natural state when the additive has been depleted or degraded due to exposure to high temperatures or to the high shear rates normally encountered in the load-carrying zones of bearings and gears. In heavy-duty installations, it is generally advisable to select a heavier or a more highly refined oil (and one that is generally more costly) rather than to rely on a less stable viscosity-index-improvement product. Viscosity-index-improved oils are generally used in applications where the shear rate is well below 1,000,000 reciprocal seconds, as determined by the following formula:

$$\text{Shear rate}(s^{-1}) = \frac{DN}{60t}$$

where  $D$  is the journal diameter in inches,  $N$  is the journal speed in rpm, and  $t$  is the film thickness in inches.

**Types of Oils.**—Aside from being aware of the many additives available to satisfy particular application requirements and improve the performance of fluids, the designer must also be acquainted with the wide variety of oils, natural and synthetic, which are also available. Each oil has its own special features that make it suitable for specific applications and limit its utility in others. Though a complete description of each oil and its application feasibility cannot be given here, reference to major petroleum and chemical company sales engineers will provide full descriptions and sound recommendations. In some applications, however, it must be accepted that the interrelation of many variables, including shear rate, load, and temperature variations, prohibit precise recommendations or predictions of fluid durability and performance. Thus, prototype and rig testing are often required to ensure the final selection of the most satisfactory fluid.

The following table lists the major classifications and properties of available commercial petroleum oils.

### Properties of Commercial Petroleum Oils and Their Applications

| Automotive. With increased additives, diesel and marine reciprocating engines. |                        |       |                       | Gear trains and transmissions. With E. P. additives, hypoid gears. |                        |       |                       |
|--|------------------------|-------|-----------------------|--|------------------------|-------|-----------------------|
| Type   | Viscosity, Centistokes |       | Density, g/cc at 60°F | Type   | Viscosity, Centistokes |       | Density, g/cc at 60°F |
|  | 100°F                  | 210°F |                       |  | 100°F                  | 210°F |                       |
| SAE 10 W   | 41                     | 6.0   | 0.870                 | General Purpose  | 22                     | 3.9   | 0.880                 |
| SAE 20 W   | 71                     | 8.5   | 0.885                 |  | 44                     | 6.0   | 0.898                 |
| SAE 30   | 114                    | 11.2  | 0.890                 |  | 66                     | 7.0   | 0.915                 |
| SAE 40   | 173                    | 14.5  | 0.890                 |  | 110                    | 9.9   | 0.915                 |
| SAE 50   | 270                    | 19.5  | 0.900                 |  | 200                    | 15.5  | 0.890                 |
| Machine tools and other industrial applications.                               |                        |       |                       | Marine propulsion and stationary power turbines.                   |                        |       |                       |
| SAE 75   | 47                     | 7.0   | 0.930, approx.        | Turbine Light  | 32                     | 5.5   | 0.871                 |
| SAE 80   | 69                     | 8.0   |                       | Medium   | 65                     | 8.1   | 0.876                 |
| SAE 90   | 285                    | 20.5  |                       | Heavy  | 99                     | 10.7  | 0.885                 |
| SAE 140  | 725                    | 34.0  |                       |  |                        |       |                       |
| SAE 250  | 1,220                  | 47.0  |                       |  |                        |       |                       |
| Turbojet engines.  |                        |       |                       | Reciprocating engines.   |                        |       |                       |
| Aviation   | 5                      | 1.5   | 0.858                 | Aviation   | 76                     | 9.3   | 0.875                 |
|  | 10                     | 2.5   | 0.864                 |  | 268                    | 20.0  | 0.891                 |
|  |                        |       |                       |  | 369                    | 25.0  | 0.892                 |

**Viscosity.**—As noted before, fluids used as lubricants are generally categorized by their viscosity at 100 and 210 deg. F. Absolute viscosity is defined as a fluid's resistance to shear or motion—its internal friction in other words. This property is described in several ways, but basically it is the force required to move a plane surface of unit area with unit speed parallel to a second plane and at unit distance from it. In the metric system, the unit of viscosity is called the "poise" and in the English system is called the "reyn." One reyn is equal to 68,950 poises. One poise is the viscosity of a fluid, such that one dyne force is required to move a surface of one square centimeter with a speed of one centimeter per second, the distance between surfaces being one centimeter. The range of kinematic viscosity for a series of typical fluids is shown in the table on page 2333. Kinematic viscosity is related directly to the flow time of a fluid through the viscosimeter capillary. By multiplying the kinematic viscosity by the density of the fluid at the test temperature, one can determine the absolute viscosity. Because, in the metric system, the mass density is equal to the specific gravity, the conversion from kinematic to absolute viscosity is generally made in this sys-

tem and then converted to English units where required. The densities of typical lubricating fluids with comparable viscosities at 100 deg. F and 210 deg. F are shown in this same table.

The following conversion table may be found helpful.

### Viscosity Conversion Factors

| Multiply   | By                                      | To Get   |
|--|---|--|
| Centipoises, $Z, \frac{\text{dyne-s}}{100 \text{ cm}^2}$ | $1.45 \times 10^{-7}$                   | Reyns, $\mu, \frac{\text{lb force-s}}{\text{in.}^2}$     |
| Centistokes, $v, \frac{\text{cm}^2}{100 \text{ s}}$      | Density in $\frac{\text{g}}{\text{cc}}$ | Centipoises, $Z, \frac{\text{dyne-s}}{100 \text{ cm}^2}$ |
| Saybolt Universal Seconds, $t_s$                         | $0.22 t_s - \frac{180}{t_s}$            | Centistokes, $v, \frac{\text{cm}^2}{100 \text{ s}}$      |

Also see page 2586 for addittional conversion factors.

**Finding Specific Gravity of Oils at Different Temperatures.**—The standard practice in the oil industry is to obtain a measure of specific gravity at 60 deg. F on an arbitrary scale, in degrees API, as specified by the American Petroleum Institute. As an example, API gravity,  $\rho_{\text{API}}$ , may be expressed as 27.5 degrees at 60 deg. F.

The relation between gravity in API degrees and specific gravity (grams of mass per cubic centimeter) at 60 deg. F,  $\rho_{60}$ , is

$$\rho_{60} = \frac{141.5}{131.5 + \rho_{\text{API}}}$$

The specific gravity,  $\rho_T$ , at some other temperature,  $T$ , is found from the equation

$$\rho_T = \rho_{60} - 0.00035(T - 60)$$

Normal values of specific gravity for sleeve-bearing lubricants range from 0.75 to 0.95 at 60 deg. F. If the API rating is not known, an assumed value of 0.85 may be used.

**Application of Lubricating Oils.**—In the selection and application of lubricating oils, careful attention must be given to the temperature in the critical operating area and its effect on oil properties. Analysis of each application should be made with detailed attention given to cooling, friction losses, shear rates, and contaminants.

Many oil selections are found to result in excessive operating temperatures because of a viscosity that is initially too high, which raises the friction losses. As a general rule, the lightest-weight oil that can carry the maximum load should be used. Where it is felt that the load carrying capacity is borderline, lubricity improvers may be employed rather than an arbitrarily higher viscosity fluid. It is well to remember that in many mechanisms the thicker fluid may increase friction losses sufficiently to lower the operating viscosity into the range provided by an initially lighter fluid. In such situations also, improved cooling, such as may be accomplished by increasing the oil flow, can improve the fluid properties in the load zone.

Similar improvements can be accomplished in many gear trains and other mechanisms by reducing churning and aeration through improved scavenging, direction of oil jets, and elimination of obstacles to the flow of the fluid. Many devices, such as journal bearings, are extremely sensitive to the effects of cooling flow and can be improved by greater flow rates with a lighter fluid. In other cases it is well to remember that the load carrying capacity of a petroleum oil is affected by pressure, shear rate, and bearing surface finish as well as initial viscosity and therefore these must be considered in the selection of the fluid. Detailed explanation of these factors is not within the scope of this text; however the technical representatives of the petroleum companies can supply practical guides for most applications.

Other factors to consider in the selection of an oil include the following: 1) Compatibility with system materials; 2) Water absorption properties; 3) Break-in requirements; 4) Detergent requirements; 5) Corrosion protection; 6) Low temperature properties; 7) Foaming tendencies; 8) Boundary lubrication properties; 9) Oxidation resistance (high temperature properties); and 10) Viscosity/temperature stability (Viscosity Temperature Index)..

Generally, the factors listed above are those which are usually modified by additives as described earlier. Since additives are used in limited amounts in most petroleum products, blended oils are not as durable as the base stock and must therefore be used in carefully worked-out systems. Maintenance procedures must be established to monitor the oil so that it may be replaced when the effect of the additive is noted or expected to degrade. In large systems supervised by a lubricating engineer, sampling and associated laboratory analysis can be relied on, while in customer-maintained systems as in automobiles and reciprocating engines, the design engineer must specify a safe replacement period which takes into account any variation in type of service or utilization.

Some large systems, such as turbine-power units, have complete oil systems which are designed to filter, cool, monitor, meter, and replenish the oil automatically. In such facilities, much larger oil quantities are used and they are maintained by regularly assigned lubricating personnel. Here reliance is placed on conservatively chosen fluids with the expectation that they will endure many months or even years of service.

**Centralized Lubrication Systems.**—Various forms of centralized lubrication systems are used to simplify and render more efficient the task of lubricating machines. In general, a central reservoir provides the supply of oil, which is conveyed to each bearing either through individual lines of tubing or through a single line of tubing that has branches extending to each of the different bearings. Oil is pumped into the lines either manually by a single movement of a lever or handle, or automatically by mechanical drive from some revolving shaft or other part of the machine. In either case, all bearings in the central system are lubricated simultaneously. Centralized force-feed lubrication is adaptable to various classes of machine tools such as lathes, planers, and milling machines and to many other types of machines. It permits the use of a lighter grade of oil, especially where complete coverage of the moving parts is assured.

**Gravity Lubrication Systems.**—Gravity systems of lubrication usually consist of a small number of distributing centers or manifolds from which oil is taken by piping as directly as possible to the various surfaces to be lubricated, each bearing point having its own independent pipe and set of connections. The aim of the gravity system, as of all lubrication systems, is to provide a reliable means of supplying the bearing surfaces with the proper amount of lubricating oil. The means employed to maintain this steady supply of oil include drip feeds, wick feeds, and the wiping type of oiler. Most manifolds are adapted to use either or both drip and wick feeds.

*Drip-feed Lubricators:* A drip feed consists of a simple cup or manifold mounted in a convenient position for filling and connected by a pipe or duct to each bearing to be oiled. The rate of feed in each pipe is regulated by a needle or conical valve. A loose-fitting cover is usually fitted to the manifold in order to prevent cinders or other foreign matter from becoming mixed with the oil. When a cylinder or other chamber operating under pressure is to be lubricated, the oil-cup takes the form of a lubricator having a tight-fitting screw cover and a valve in the oil line. To fill a lubricator of this kind, it is only necessary to close the valve and unscrew the cover.

*Operation of Wick Feeds:* For a wick feed, the siphoning effect of strands of worsted yarn is employed. The worsted wicks give a regular and reliable supply of oil and at the same time act as filters and strainers. A wick composed of the proper number of strands is fitted into each oil-tube. In order to insure using the proper sizes of wicks, a study should be made of the oil requirements of each installation, and the number of strands necessary to

meet the demands of bearings at different rates of speed should be determined. When the necessary data have been obtained, a table should be prepared showing the size of wick or the number of strands to be used for each bearing of the machine.

*Oil-conducting Capacity of Wicks:* With the oil level maintained at a point  $\frac{3}{8}$  to  $\frac{3}{4}$  inch below the top of an oil-tube, each strand of a clean worsted yarn will carry slightly more than one drop of oil a minute. A twenty-four-strand wick will feed approximately thirty drops a minute, which is ordinarily sufficient for operating a large bearing at high speed. The wicks should be removed from the oil-tubes when the machinery is idle. If left in place, they will continue to deliver oil to the bearings until the supply in the cup is exhausted, thus wasting a considerable quantity of oil, as well as flooding the bearing. When bearings require an extra supply of oil temporarily, it may be supplied by dipping the wicks or by pouring oil down the tubes from an oil-can or, in the case of drip feeds, by opening the needle valves. When equipment that has remained idle for some time is to be started up, the wicks should be dipped and the moving parts oiled by hand to insure an ample initial supply of oil. The oil should be kept at about the same level in the cup, as otherwise the rate of flow will be affected. Wicks should be lifted periodically to prevent dirt accumulations at the ends from obstructing the flow of oil.

*How Lubricating Wicks are Made:* Wicks for lubricating purposes are made by cutting worsted yarn into lengths about twice the height of the top of the oil-tube above the bottom of the oil-cup, plus 4 inches. Half the required number of strands are then assembled and doubled over a piece of soft copper wire, laid across the middle of the strands. The free ends are then caught together by a small piece of folded sheet lead, and the copper wire twisted together throughout its length. The lead serves to hold the lower end of the wick in place, and the wire assists in forcing the other end of the wick several inches into the tube. When the wicks are removed, the free end of the copper wire may be hooked over the tube end to indicate which tube the wick belongs to. Dirt from the oil causes the wick to become gummy and to lose its filtering effect. Wicks that have thus become clogged with dirt should be cleaned or replaced by new ones. The cleaning is done by boiling the wicks in soda water and then rinsing them thoroughly to remove all traces of the soda. Oil-pipes are sometimes fitted with openings through which the flow of oil can be observed. In some installations, a short glass tube is substituted for such an opening.

*Wiper-type Lubricating Systems:* Wiper-type lubricators are used for out-of-the-way oscillating parts. A wiper consists of an oil-cup with a central blade or plate extending above the cup, and is attached to a moving part. A strip of fibrous material fed with oil from a source of supply is placed on a stationary part in such a position that the cup in its motion scrapes along the fibrous material and wipes off the oil, which then passes to the bearing surfaces.

Oil manifolds, cups, and pipes should be cleaned occasionally with steam conducted through a hose or with boiling soda water. When soda water is used, the pipes should be disconnected, so that no soda water can reach the bearings.

**Oil Mist Systems.**—A very effective system for both lubricating and cooling many elements which require a limited quantity of fluid is found in a device which generates a mist of oil, separates out the denser and larger (wet) oil particles, and then distributes the mist through a piping or conduit system. The mist is delivered into the bearing, gear, or lubricated element cavity through a condensing or spray nozzle, which also serves to meter the flow. In applications which do not encounter low temperatures or which permit the use of visual devices to monitor the accumulation of solid oil, oil mist devices offer advantages in providing cooling, clean lubricant, pressurized cavities which prevent entrance of contaminants, efficient application of limited lubricant quantities, and near-automatic performance. These devices are supplied with fluid reservoirs holding from a few ounces up to several gallons of oil and with accommodations for either accepting shop air or working

from a self-contained compressor powered by electricity. With proper control of the fluid temperature, these units can atomize and dispense most motor and many gear oils.

**Lubricating Greases.**—In many applications, fluid lubricants cannot be used because of the difficulty of retention, relubrication, or the danger of churning. To satisfy these and other requirements such as simplification, greases are applied. These formulations are usually petroleum oils thickened by dispersions of soap, but may consist of synthetic oils with soap or inorganic thickeners, or oil with siliceous dispersions. In all cases, the thickener, which must be carefully prepared and mixed with the fluid, is used to immobilize the oil, serving as a storehouse from which the oil bleeds at a slow rate. Though the thickener very often has lubricating properties itself, the oil bleeding from the bulk of the grease is the determining lubricating function. Thus, it has been shown that when the oil has been depleted to the level of 50 per cent of the total weight of the grease, the lubricating ability of the material is no longer reliable. In some applications requiring an initially softer and wetter material, however, this level may be as high as 60 per cent.

**Grease Consistency Classifications.**—To classify greases as to mobility and oil content, they are divided into Grades by the NLGI (National Lubricating Grease Institute). These grades, ranging from 0, the softest, up through 6, the stiffest, are determined by testing in a penetrometer, with the depth of penetration of a specific cone and weight being the controlling criterion. To insure proper averaging of specimen resistance to the cone, most specifications include a requirement that the specimen be worked in a sieve-like device before being packed into the penetrometer cup for the penetration test. Since many greases exhibit thixotropic properties (they soften with working, as they often do in an application with agitation of the bulk of the grease by the working elements or accelerations), this penetration of the worked specimen should be used as a guide to compare the material to the original manufactured condition of it and other greases, rather than to the exact condition in which it will be found in the application. Conversely, many greases are found to stiffen when exposed to high shear rates at moderate loads as in automatic grease dispensing equipment. The application of a grease, therefore must be determined by a carefully planned cut-and-try procedure. Most often this is done by the original equipment manufacturer with the aid of the petroleum company representatives, but in many cases it is advisable to include the bearing engineer as well. In this general area it is well to remember that shock loads, axial or thrust movement within or on the grease cavity can cause the grease to contact the moving parts and initiate softening due to the shearing or working thus induced. To limit this action, grease-lubricated bearing assemblies often utilize dams or dividers to keep the bulk of the grease contained and unchanged by this working. Successful application of a grease depends however, on a relatively small amount of mobile lubricant (the oil bled out of the bulk) to replenish that small amount of lubricant in the element to be lubricated. If the space between the bulk of the mobile grease and the bearing is too large, then a critical delay period (which will be regulated by the grease bleed rate and the temperature at which it is held) will ensue before lubricant in the element can be resupplied. Since most lubricants undergo some attrition due to thermal degradation, evaporation, shearing, or decomposition in the bearing area to which applied, this delay can be fatal.

To prevent this from leading to failure, grease is normally applied so that the material in the cavity contacts the bearing in the lower quadrants, insuring that the excess originally packed into it impinges on the material in the reservoir. With the proper selection of a grease which does not slump excessively, and a reservoir construction to prevent churning, the initial action of the bearing when started into operation will be to purge itself of excess grease, and to establish a flow path for bleed oil to enter the bearing. For this purpose, most greases selected will be of a grade 2 or 3 consistency, falling into the "channelling" variety or designation.

**Types of Grease.**—Greases are made with a variety of soaps and are chosen for many particular characteristics. Most popular today, however, are the lithium, or soda-soap grease

and the modified-clay thickened materials. For high temperature applications (250 deg. F. and above) certain finely divided dyes and other synthetic thickeners are applied. For all-around use the lithium soap greases are best for moderate temperature applications (up to 225 deg. F.) while a number of soda-soap greases have been found to work well up to 285 deg. F. Since the major suppliers offer a number of different formulations for these temperature ranges it is recommended that the user contact the engineering representatives of a reputable petroleum company before choosing a grease. Greases also vary in volatility and viscosity according to the oil used. Since the former will affect the useful life of the bulk applied to the bearing and the latter will affect the load carrying capacity of the grease, they must both be considered in selecting a grease.

For application to certain gears and slow-speed journal bearings, a variety of greases are thickened with carbon, graphite, molybdenum disulfide, lead, or zinc oxide. Some of these materials are likewise used to inhibit fretting corrosion or wear in sliding or oscillating mechanisms and in screw or thread applications. One material used as a "gear grease" is a residual asphaltic compound which is known as a "Crater Compound." Being extremely stiff and having an extreme temperature-viscosity relationship, its application must also be made with careful consideration of its limitations and only after careful evaluation in the actual application. Its oxidation resistance is limited and its low mobility in winter temperature ranges make it a material to be used with care. However, it is used extensively in the railroad industry and in other applications where containment and application of lubricants is difficult. In such conditions its ability to adhere to gear and chain contact surfaces far outweighs its limitations and in some extremes it is "painted" onto the elements at regular intervals.

**Temperature Effects on Grease Life.**—Since most grease applications are made where long life is important and relubrication is not too practical, operating temperatures must be carefully considered and controlled. Being a hydro-carbon, and normally susceptible to oxidation, grease is subject to the general rule that: Above a critical threshold temperature, each 15- to 18-deg. F. rise in temperature reduces the oxidation life of the lubricant by half. For this reason, it is vital that all elements affecting the operating temperature of the application be considered, correlated, and controlled. With sealed-for-life bearings, in particular, grease life must be determined for representative bearings and limits must be established for all subsequent applications.

Most satisfactory control can be established by measuring bearing temperature rise during a controlled test, at a consistent measuring point or location. Once a base line and limiting range are determined, all deviating bearings should be dismantled, inspected, and reassembled with fresh lubricant for retest. In this manner mavericks or faulty assemblies will be ferreted out and the reliability of the application established. Generally, a well lubricated grease packed bearing will have a temperature rise above ambient, as measured at the outer race, of from 10 to 50 deg. F. In applications where heat is introduced into the bearing through the shaft or housing, a temperature rise must be added to that of the frame or shaft temperature.

In bearing applications care must be taken not to fill the cavity too full. The bearing should have a practical quantity of grease worked into it with the rolling elements thoroughly coated and the cage covered, but the housing (cap and cover) should be no more than 75 per cent filled; with softer greases, this should be no more than 50 per cent. Excessive packing is evidenced by overheating, churning, aerating, and eventual purging with final failure due to insufficient lubrication. In grease lubrication, *never* add a bit more for good luck — hold to the prescribed amount and determine this with care on a number of representative assemblies.

**Relubricating with Grease.**—In some applications, sealed-grease methods are not applicable and addition of grease at regular intervals is required. Where this is recommended by the manufacturer of the equipment, or where the method has been worked out as part of a development program, the procedure must be carefully followed. *First*, use the proper

lubricant — the same as recommended by the manufacturer or as originally applied (grease performance can be drastically impaired if contaminated with another lubricant). *Second*, clean the lubrication fitting thoroughly with materials which will not affect the mechanism or penetrate into the grease cavity. *Third*, remove the cap (and if applicable, the drain or purge plug). *Fourth*, clean and inspect the drain or scavenge cavity. *Fifth*, weigh the grease gun or calibrate it to determine delivery rate. *Sixth*, apply the directed quantity or fill until grease is detected coming out the drain or purge hole. *Seventh*, operate the mechanism with the drain open so that excess grease is purged. *Last*, continue to operate the mechanism while determining the temperature rise and insure that it is within limits. Where there is access to a laboratory, samples of the purged material may be analyzed to determine the deterioration of the lubricant and to search for foreign material which may be evidence of contamination or of bearing failure.

Normally, with modern types of grease and bearings, lubrication need only be considered at overhaul periods or over intervals of three to ten years.

**Solid Film Lubricants.**—Solids such as graphite, molybdenum disulfide, polytetrafluoroethylene, lead, babbitt, silver, or metallic oxides are used to provide dry film lubrication in high-load, slow-speed or oscillating load conditions. Though most are employed in conjunction with fluid or grease lubricants, they are often applied as the primary or sole lubricant where their inherent limitations are acceptable. Of foremost importance is their inability to carry away heat. Second, they cannot replenish themselves, though they generally do lay down an oriented film on the contacting interface. Third, they are relatively immobile and must be bonded to the substrate by a carrier, by plating, fusing, or by chemical or thermal deposition.

Though these materials do not provide the low coefficient of friction associated with fluid lubrication, they do provide coefficients in the range of 0.4 down to 0.02, depending on the method of application and the material against which they rub. Polytetrafluoroethylene, in normal atmospheres and after establishing a film on both surfaces has been found to exhibit a coefficient of friction down to 0.02. However, this material is subject to cold flow and must be supported by a filler or on a matrix to continue its function. Since it can now be cemented in thin sheets and is often supplied with a fine glass fiber filler, it is practical in a number of installations where the speed and load do not combine to melt the bond or cause the material to sublime.

Bonded films of molybdenum disulfide, using various resins and ceramic combinations as binders, are deposited over phosphate treated steel, aluminum, or other metals with good success. Since its action produces a gradual wear of the lubricant, its life is limited by the thickness which can be applied (not over a thousandth or two in the conventional application). In most applications this is adequate if the material is used to promote break-in, prevent galling or pick-up, and to reduce fretting or abrasion in contacts otherwise impossible to separate.

In all applications of solid film lubricants, the performance of the film is limited by the care and preparation of the surface to which they are applied. If they can't adhere properly, they cannot perform, coming off in flakes and often jamming under flexible components. The best advice is to seek the assistance of the supplier's field engineer and set up a close control of the surface preparation and solid film application procedure. It should be noted that the functions of a good solid film lubricant cannot overcome the need for better surface finishing. Contacting surfaces should be smooth and flat to insure long life and minimum friction forces. Generally, surfaces should be finished to no more than 24 micro-inches AA with wariness no greater than 0.00002 inch.

**Anti-friction Bearing Lubrication.**—The limiting factors in bearing lubrication are the load and the linear velocity of the centers of the balls or rollers. Since these are difficult to evaluate, a speed factor which consists of the inner race bore diameter  $\times$  RPM is used as a



criterion. This factor will be referred to as  $S_i$ , where the bore diameter is in inches and  $S_m$  where it is in millimeters.

For use in anti-friction bearings, grease must have the following properties:

- 1) Freedom from chemically or mechanically active ingredients such as uncombined metals or oxides, and similar mineral or solid contaminants.
- 2) The slightest possible tendency of change in consistency, such as thickening, separation of oil, evaporation or hardening.
- 3) A melting point considerably higher than the operating temperatures.

The choice of lubricating oils is easier. They are more uniform in their characteristics and if resistant to oxidation, gumming and evaporation, can be selected primarily with regard to a suitable viscosity.

*Grease Lubrication:* Anti-friction bearings are normally grease lubricated, both because grease is much easier than oil to retain in the housing over a long period and because it acts to some extent as a seal against the entry of dirt and other contaminants into the bearings. For almost all applications, a No. 2 soda-base grease or a mixed-base grease with up to 5 per cent calcium soap to give a smoother consistency, blended with an oil of around 250 to 300 SSU (Saybolt Universal Seconds) at 100 degrees F. is suitable. In cases where speeds are high, say  $S_i$  is 5000 or over, a grease made with an oil of about 150 SSU at 100 degrees F. may be more suitable especially if temperatures are also high. In many cases where bearings are exposed to large quantities of water, it has been found that a standard soda-base ball-bearing grease, although classed as water soluble gives better results than water-insoluble types. Greases are available that will give satisfactory lubrication over a temperature range of -40 degrees to +250 degrees F.

Conservative grease renewal periods will be found in the accompanying chart. Grease should not be allowed to remain in a bearing for longer than 48 months or if the service is very light and temperatures low, 60 months, irrespective of the number of hours' operation during that period as separation of the oil from the soap and oxidation continue whether the bearing is in operation or not.

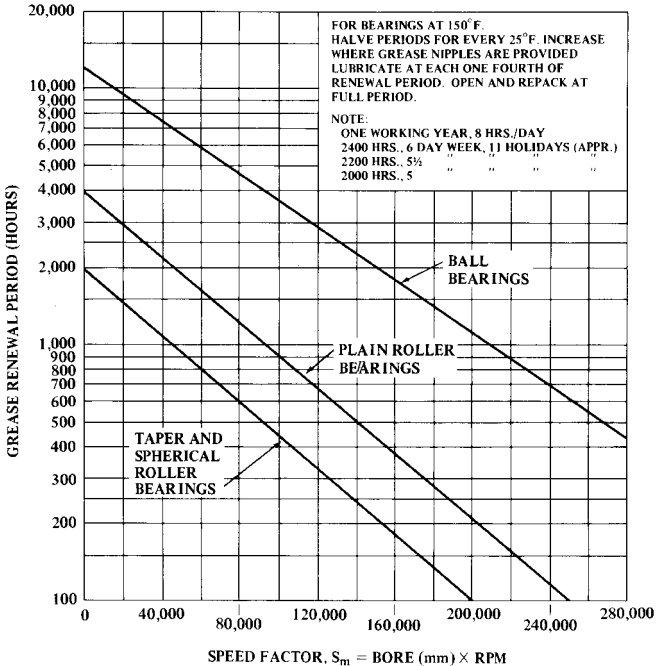
Before renewing the grease in a hand-packed bearing, the bearing assembly should be removed and washed in clean kerosene, degreasing fluid or other solvent. As soon as the bearing is quite clean it should be washed at once in clean light mineral oil, preferably rust-inhibited. The bearing should *not be spun* before or while it is being oiled. Caustic solutions may be used if the old grease is hard and difficult to remove, but the best method is to soak the bearing for a few hours in light mineral oil, preferably warmed to about 130 degrees F., and then wash in cleaning fluid as described above. The use of chlorinated solvents is best avoided.

When replacing the grease, it should be forced with the fingers between the balls or rollers, dismantling the bearing, if convenient. The available space inside the bearing should be filled completely and the bearing then spun by hand. Any grease thrown out should be wiped off. The space on each side of the bearing in the housing should be not more than half-filled. Too much grease will result in considerable churning, high bearing temperatures and the possibility of early failure. Unlike any other kind of bearing, anti-friction bearings more often give trouble due to over-rather than to under-lubrication.

Grease is usually not very suitable for speed factors over 12,000 for  $S_i$  or 300,000 for  $S_m$  (although successful applications have been made up to an  $S_i$  of 50,000) or for temperatures much over 210 degrees F., 300 degrees F. being the extreme practical upper limit, even if synthetics are used. For temperatures above 210 degrees F., the grease renewal periods are very short.

*Oil Lubrication:* Oil lubrication is usually adopted when speeds and temperatures are high or when it is desired to adopt a central oil supply for the machine as a whole. Oil for anti-friction bearing lubrication should be well refined with high film strength and good resistance to oxidation and good corrosion protection. Anti-oxidation additives do no harm

but are not really necessary at temperatures below about 200 degrees F. Anti-corrosion additives are always desirable. The accompanying table gives recommended viscosities of oil for ball bearing lubrication other than by an air-distributed oil mist. Within a given temperature and speed range, an oil towards the lighter end of the grade should be used, if convenient, as speeds increase. Roller bearings usually require an oil one grade heavier than do ball bearings for a given speed and temperature range. Cooled oil is sometimes circulated through an anti-friction bearing to carry off excess heat resulting from high speeds and heavy loads.



### Oil Viscosities and Temperature Ranges for Ball Bearing Lubrication

| Maximum Temperature Range Degrees F. | Optimum Temperature Range, Degrees F. | Speed Factor, $S_p^a$       |                            |
|--------------------------------------|---------------------------------------|-----------------------------|----------------------------|
|                                      |                                       | Under 1000                  | Over 1000                  |
|                                      |                                       | Viscosity                   |                            |
| -40 to +100                          | -40 to -10                            | 80 to 90 SSU <sup>b</sup>   | 70 to 80 SSU <sup>b</sup>  |
| -10 to +100                          | -10 to +30                            | 100 to 115 SSU <sup>b</sup> | 80 to 100 SSU <sup>b</sup> |
| +30 to +150                          | +30 to +150                           | SAE 20                      | SAE 10                     |
| +30 to +200                          | +150 to +200                          | SAE 40                      | SAE 30                     |
| +50 to +300                          | +200 to +300                          | SAE 70                      | SAE 60                     |

<sup>a</sup> Inner race bore diameter (inches)  $\times$  RPM.

<sup>b</sup> At 100 deg. F.

Not applicable to air-distributed oil mist lubrication.

### Aerodynamic Lubrication

A natural extension of hydrodynamic lubrication consists in using air or some other gas as the lubricant. The viscosity of air is 1,000 times smaller than that of a very thin mineral oil. Consequently, the viscous resistance to motion is very much less. However, the distance of nearest approach, i.e. the closest distance between the shaft and the bearing is also correspondingly smaller, so that special precautions must be taken.

To obtain full benefit from such aerodynamic lubrication, the surfaces must have a very fine finish, the alignment must be very good, the speeds must be high and the loading relatively low. If all these conditions are fulfilled extremely successful bearing system can be made to run at very low coefficients of friction. They may also operate at very high temperatures since chemical degradation of the lubricant need not occur. Furthermore, if air is used as the lubricant, it costs nothing. This type of lubrication mechanism is very important for oil-free compressors and gas turbines. Another area of growing application for aerodynamic bearings is in data recording heads for computers. Air is used as the lubricant for the recording heads which are designed to be separated from the magnetic recording disc by a thin air film. The need for high recording densities in magnetic discs necessitates the smallest possible air film thickness between the head and disc. A typical thickness is around  $1\mu\text{m}$ .

The analysis of aerodynamic bearings is very similar to liquid hydrodynamic bearings. The main difference, however, is that the gas compressibility is now a distinctive feature and has to be incorporated into the analysis.

**Elastohydrodynamic Lubrication.**—In the arrangement of the shaft and bearing it is usually assumed that the surfaces are perfectly rigid and retain their geometric shape during operation. However, a question might be posed: what is the situation if the geometry or mechanical properties of the materials are such that appreciable elastic deformation of the surfaces occurs? Suppose a steel shaft rests on a rubber block. It deforms the block elastically and provides an approximation to a half-bearing (see Figure 1 a).

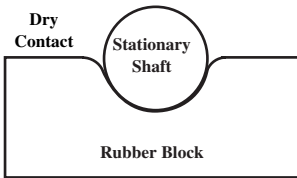


Fig. 1a.

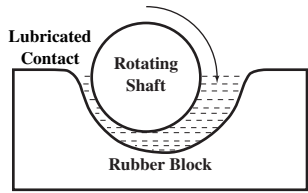


Fig. 1b.

If a lubricant is applied to the system it will be dragged into the interface and, if the conditions are right, it will form a hydrodynamic film. However, the pressures developed in the oil film will now have to match up with the elastic stresses in the rubber. In fact the shape of the rubber will be changed as indicated in Figure 1 b.

This type of lubrication is known as elastohydrodynamic lubrication. It occurs between rubber seals and shafts. It also occurs, rather surprisingly, in the contact between a windshield wiper blade and a windshield in the presence of rain. The geometry of the deformable member, its elastic properties, the load, the speed and the viscosity of the liquid and its dependence on the contact pressure are all important factors in the operation of elastohydrodynamic lubrication.

With conventional journals and bearings the average pressure over the bearing is of the order of  $7 \times 10^{-6} \text{ N/rn}^2$ . With elastohydrodynamic bearings using a material such as rubber the pressures are perhaps 10 to 20 times smaller. At the other end of pressure spectrum, for instance in gear teeth, contact pressures of the order of  $700 \times 10^6 \text{ N/in}^2$  may easily be

reached. Because the metals used for gears are very hard this may still be within the range of elastic deformation. With careful alignment of the engaging gear teeth and appropriate surface finish, gears can in fact run successfully under these conditions using an ordinary mineral oil as the lubricant. If the thickness of the elastohydrodynamic film formed at such pressures is calculated it will be found that it is less than an atomic diameter. Since even the smoothest metal surfaces are far rougher than this (a millionth of an inch is about 100 atomic diameters) it seems hard to understand why lubrication is effective in these circumstances.

The explanation was first provided by A.N. Grubin in 1949 and a little later (1958) by A.W. Crook. With most mineral oils the application of a high pressure can lead to an enormous increase in viscosity. For example, at a pressure of  $700 \times 10^6 \text{ N/m}^2$  the viscosity may be increased 10,000-fold. The oil entering the gap between the gear teeth is trapped between the surfaces and at the high pressures existing in the contact region behaves virtually like a solid separating layer. This process explains why many mechanisms in engineering practice operate under much severer conditions than the classical theory would allow.

This type of elastohydrodynamic lubrication becomes apparent only when the film thickness is less than about 0.25 to 1  $\mu\text{m}$ . To be exploited successfully it implies that the surfaces must be very smooth and very carefully aligned. If these conditions are met systems such as gears or cams and tappets can operate effectively at very high contact pressures without any metallic contact occurring. The coefficient of friction depends on the load, contact geometry, speed, etc., but generally it lies between about  $\mu = 0.01$  at the lightest pressures and  $\mu = 0.1$  at the highest pressures. The great success of elastohydrodynamic theory in explaining effective lubrication at very high contact pressures also raises a problem that has not yet been satisfactorily resolved: why do lubricants ever fail, since the harder they are squeezed the harder it is to extrude them? It is possible that high temperature flashes are responsible; alternatively the high rates of shear can actually fracture the lubricant film since when it is trapped between the surfaces it is, instantaneously, more like a wax than an oil.

It is clear that in this type of lubrication the effect of pressure on viscosity is a factor of major importance. It turns out that mineral oils have reasonably good pressure-viscosity characteristics. It appears that synthetic oils do not have satisfactory pressure-viscosity characteristics.

In engineering, two most frequently encountered types of contact are line contact and point contact.

The film thickness for line contact (gears, cam-tappet) can be estimated from:

$$h_o = 2.65 \frac{\alpha^{0.54} (\eta_o U)^{0.7} R_e^{0.43}}{w^{0.13} E_e^{0.03}}$$

In the case of point contact (ball bearings), the film thickness is given by:

$$h_o = 0.84 \alpha \eta_o U^{0.74} 0.41 R_e \left( \frac{E_e}{W} \right)^{0.074}$$

In the above equations the symbols used are defined as:

$\alpha$  = the pressure-viscosity coefficient. A typical value for mineral oil is  $1.8 \times 10^{-8} \text{ m}^2/\text{N}$

$\nu$  = the viscosity of the lubricant at atmospheric pressure  $\text{Ns/m}^2$

$U$  = the entraining surface velocity,  $U = (U_A + U_B)/2 \text{ m/s}$ , where the subscripts  $A$  and  $B$  refer to the velocities of bodies 'A' and 'B' respectively.

$W$  = the load on the contact,  $\text{N}$

$w$  = the load per unit width of line contact,  $\text{N/m}$

LUBRICANTS

$E_o$  = the reduced Young's modulus  $\frac{1}{E_e} = \frac{1}{2} \left( \frac{1 - \nu_A^2}{E_A} + \frac{1 - \nu_B^2}{E_B} \right)$  N/m<sup>2</sup> where ' $\nu_A$

and  $\nu_B$  are the Poisson's ratios of the contacting bodies 'A' and 'B' respectively;  $E_A$  and  $E_B$  are the Young's moduli of the contacting bodies 'A' and 'B' respectively.

$R_e$  = is the reduced radius of curvature (meters) and is given by different equations for different contact configurations.

In ball bearings (see Figure 2) the reduced radius is given by:

- contact between the ball and inner race:  $R_e = \frac{rR_1}{R_1 + r}$
- contact between the ball and outer race:  $R_e = \frac{r(R_1 + 2r)}{R_1 + r}$

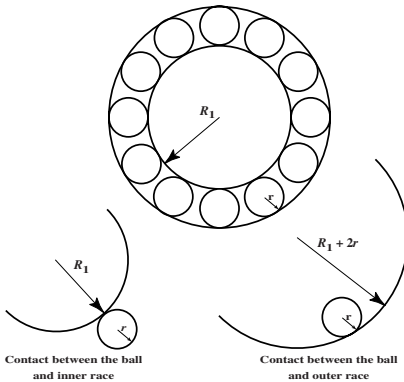


Fig. 2.

For involute gears it can readily be shown that the contact at a distance  $s$  from the pitch point can be represented by two cylinders of radii  $R_{1,2} \sin \psi + s$  rotating with the angular velocity of the wheels (see Fig. 3b). In the expression below  $R_1$  or  $R_2$  represent pitch radii of the wheels and  $\psi$  is the pressure angle. Thus,

$$R_e = \frac{(R_1 \sin \psi + s)(R_2 \sin \psi + s)}{(R_1 + R_2) \sin \psi}$$

The thickness of the film developed in the contact zone between smooth surfaces must be related to the topography of the actual surfaces. The most commonly used parameter for this purpose is the specific film thickness defined as the ratio of the minimum film thickness for smooth surfaces (given by the above equations) to the roughness parameter of the contacting surfaces.

$$\lambda = \frac{h_o}{\sqrt{R_{m1}^2 + R_{m2}^2}}$$

where  $R_m = 1.11R_a$  is the root-mean-square height of surface asperities, and  $R_a$  is the centre-line-average height of surface asperities.

If  $\lambda$  is greater than 3 then it is usually assumed that there is full separation of contacting bodies by an elastohydrodynamic film.

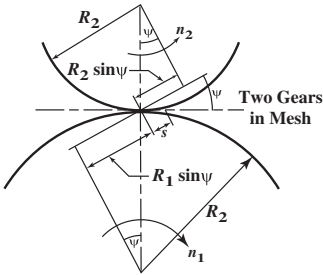


Fig. 3a.

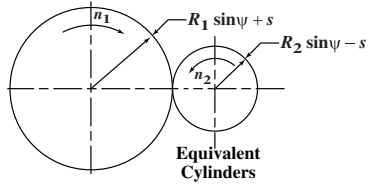


Fig. 3b.

**Viscosity-pressure relationship.**—Lubricant viscosity increases with pressure. For most lubricants this effect is considerably larger than the effect of temperature or shear when the pressure is appreciably above atmospheric. This is of fundamental importance in the lubrication of highly loaded concentrated contacts such as in rolling contact bearings, gears and cam-tappet systems.

The best known equation to calculate the viscosity of a lubricant at moderate pressures is the Barus equation.

$$\eta_p = \eta_o e^{\alpha p}$$

where  $\eta$  is the viscosity at pressure  $p$  ( $\text{Ns/m}^2$ ),  $\eta_o$  is the viscosity at atmospheric pressure ( $\text{Ns/in}^2$ ),  $\alpha$  is the pressure-viscosity coefficient ( $\text{m}^2/\text{N}$ ) which can be obtained by plotting the natural logarithm of dynamic viscosity  $\eta$  measured at pressure  $p$ . The slope of the graph is  $\alpha$  and  $p$  is the pressure of concern ( $\text{N/m}^2$ ).

Values of dynamic viscosity  $\eta$  and pressure-viscosity coefficient  $\alpha$  for most commonly used lubricants are given in Table 1.

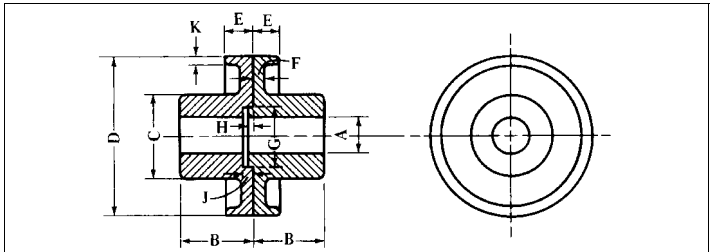
**Table 1. Dynamic Viscosity  $\eta$  and Pressure-viscosity Coefficient  $\alpha$  for Lubricants**

| Lubricant            | Dynamic viscosity $\eta$ measured at atmospheric pressure and room temperature $\eta \times 10^{-3}$ Ns/m <sup>2</sup> | Pressure-viscosity coefficient $\alpha$ measured at room temperature $\alpha \times 10^{-3}$ m <sup>2</sup> /N |
|----------------------|--|--|
| Light machine oil    | 45   | 28   |
| Heavy machine oil    | 153  | 23.7   |
| Cylinder oil         | 810  | 34   |
| Spindle oil          | 18.6   | 20   |
| Medicinal whale oil  | 107  | 29.5   |
| Castor oil           | 360  | 15.9   |
| Glycerol (glycerine) | 535  | 5.9  |

COUPLINGS AND CLUTCHES

**Connecting Shafts.**—For couplings to transmit up to about 150 horsepower, simple flange-type couplings of appropriate size, as shown in the table, are commonly used. The design shown is known as a safety flange coupling because the bolt heads and nuts are shrouded by the flange, but such couplings today are normally shielded by a sheet metal or other cover.

Safety Flange Couplings



| A      | B       | C      | D  | E       | F     | G      | H    | J     | K     | Bolts |         |
|--------|---------|--------|----|---------|-------|--------|------|-------|-------|-------|---------|
|        |         |        |    |         |       |        |      |       |       | No.   | Dia.    |
| 1      | 1 3/4   | 2 1/4  | 4  | 1 1/16  | 5/16  | 1 1/2  | 1/4  | 9/32  | 1/4   | 5     | 3/8     |
| 1 1/4  | 2 3/16  | 2 3/4  | 5  | 1 3/16  | 3/8   | 1 1/8  | 1/4  | 9/32  | 1/4   | 5     | 7/16    |
| 1 1/2  | 2 5/8   | 3 3/8  | 6  | 1 5/16  | 7/16  | 2 1/4  | 1/4  | 9/32  | 1/4   | 5     | 1/2     |
| 1 3/4  | 3 1/16  | 4      | 7  | 1 1/16  | 1/2   | 2 5/8  | 1/4  | 9/32  | 1/4   | 5     | 9/16    |
| 2      | 3 1/2   | 4 1/2  | 8  | 1 3/16  | 9/16  | 3      | 1/4  | 9/32  | 5/16  | 5     | 5/8     |
| 2 1/4  | 3 15/16 | 5 1/8  | 9  | 1 5/16  | 5/8   | 3 3/8  | 1/4  | 9/32  | 5/16  | 5     | 11/16   |
| 2 1/2  | 4 3/8   | 5 5/8  | 10 | 1 7/16  | 11/16 | 3 3/4  | 1/4  | 9/32  | 5/16  | 5     | 3/4     |
| 2 3/4  | 4 13/16 | 6 1/4  | 11 | 1 9/16  | 3/4   | 4 1/8  | 1/4  | 9/32  | 5/16  | 5     | 13/16   |
| 3      | 5 1/4   | 6 3/4  | 12 | 1 11/16 | 13/16 | 4 1/2  | 1/4  | 9/32  | 3/8   | 5     | 7/8     |
| 3 1/4  | 5 11/16 | 7 3/8  | 13 | 1 13/16 | 7/8   | 4 7/8  | 1/4  | 9/32  | 3/8   | 5     | 15/16   |
| 3 1/2  | 6 1/8   | 8      | 14 | 1 15/16 | 15/16 | 5 1/4  | 1/4  | 9/32  | 3/8   | 5     | 1       |
| 3 3/4  | 6 9/16  | 8 1/2  | 15 | 2 1/16  | 1     | 5 5/8  | 1/4  | 9/32  | 3/8   | 5     | 1 1/16  |
| 4      | 7       | 9      | 16 | 2 1/4   | 1 1/8 | 6      | 1/4  | 9/32  | 7/16  | 5     | 1 1/8   |
| 4 1/2  | 7 7/8   | 10 1/4 | 18 | 2 1/2   | 1 1/4 | 6 3/4  | 1/4  | 9/32  | 7/16  | 5     | 1 1/4   |
| 5      | 8 3/4   | 11 1/4 | 20 | 2 3/4   | 1 3/8 | 7 1/2  | 1/4  | 9/32  | 7/16  | 5     | 1 3/8   |
| 5 1/2  | 8 3/4   | 11 1/4 | 20 | 2 3/4   | 1 3/8 | 7 1/2  | 1/4  | 9/32  | 7/16  | 5     | 1 3/8   |
| 6      | 10 1/2  | 12 3/8 | 22 | 2 5/16  | 1 1/2 | 8 1/4  | 5/16 | 11/32 | 1/2   | 5     | 1 7/16  |
| 6 1/2  | 11 3/8  | 13 1/2 | 24 | 3 3/8   | 1 5/8 | 9      | 5/16 | 11/32 | 1/2   | 5     | 1 1/2   |
| 7      | 12 1/4  | 14 5/8 | 26 | 3 1/4   | 1 3/4 | 9 3/4  | 5/16 | 11/32 | 9/16  | 6     | 1 1/2   |
| 7 1/2  | 13      | 15 3/4 | 28 | 3 7/16  | 1 7/8 | 10 1/2 | 5/16 | 11/32 | 9/16  | 6     | 1 9/16  |
| 8      | 14      | 16 7/8 | 28 | 3 1/2   | 2     | 10 7/8 | 5/16 | 11/32 | 5/8   | 7     | 1 1/2   |
| 8 1/2  | 14 7/8  | 18     | 30 | 3 11/16 | 2 1/8 | 11 1/4 | 5/16 | 11/32 | 5/8   | 7     | 1 9/16  |
| 9      | 15 3/4  | 19 1/8 | 31 | 3 3/4   | 2 1/4 | 11 3/8 | 5/16 | 11/32 | 11/16 | 8     | 1 1/2   |
| 9 1/2  | 16 5/8  | 20 1/4 | 32 | 3 15/16 | 2 3/8 | 12     | 5/16 | 11/32 | 11/16 | 8     | 1 9/16  |
| 10     | 17 1/2  | 21 3/8 | 34 | 4 1/8   | 2 1/2 | 12 3/4 | 5/16 | 11/32 | 3/4   | 8     | 1 5/8   |
| 10 1/2 | 18 3/8  | 22 1/2 | 35 | 4 1/4   | 2 5/8 | 13 1/8 | 5/16 | 11/32 | 3/4   | 10    | 1 3/8   |
| 11     | 19 1/4  | 23 3/8 | 36 | 4 7/16  | 2 3/4 | 13 1/2 | 5/16 | 11/32 | 7/8   | 10    | 1 11/16 |
| 11 1/2 | 20 1/8  | 24 3/4 | 37 | 4 3/8   | 2 7/8 | 13 7/8 | 5/16 | 11/32 | 7/8   | 10    | 1 3/4   |
| 12     | 21      | 25 7/8 | 38 | 4 13/16 | 3     | 14 1/4 | 5/16 | 11/32 | 1     | 10    | 1 13/16 |

For small sizes and low power applications, a setscrew may provide the connection between the hub and the shaft, but higher power usually requires a key and perhaps two setscrews, one of them above the key. A flat on the shaft and some means of locking the set-screw(s) in position are advisable. In the AGMA Class I and II fits the shaft tolerances are  $-0.0005$  inch from  $\frac{1}{2}$  to  $1\frac{1}{2}$  inches diameter and  $-0.001$  inch on larger diameters up to 7 inches.

Class I coupling bore tolerances are  $+0.001$  inch up to  $1\frac{1}{2}$  inches diameter, then  $+0.0015$  inch to 7 inches diameter. Class II coupling bore tolerances are  $+0.002$  inch on sizes up to 3 inches diameter,  $+0.003$  inch on sizes from  $3\frac{1}{4}$  through  $3\frac{3}{4}$  inches diameter, and  $+0.004$  inch on larger diameters up to 7 inches.

**Interference Fits.**—Components of couplings transmitting over 150 horsepower often are made an interference fit on the shafts, which may reduce fretting corrosion. These couplings may or may not use keys, depending on the degree of interference. Keys may range in size from  $\frac{1}{8}$  inch wide by  $\frac{1}{16}$  inch high for  $\frac{1}{2}$ -inch diameter shafts to  $1\frac{3}{4}$  inches wide by  $\frac{7}{8}$  inch high for 7-inch diameter shafts. Couplings transmitting high torque or operating at high speeds or both may use two keys. Keys must be a good fit in their keyways to ensure good transmission of torque and prevent failure. AGMA standards provide recommendations for square parallel, rectangular section, and plain tapered keys, for shafts of  $\frac{5}{16}$  through 7 inches diameter, in three classes designated commercial, precision, and fitted. These standards also cover keyway offset, lead, parallelism, finish and radii, and face keys and splines. (See also ANSI and other Standards in Keys and Keyways section of this Handbook.)

**Double-cone Clamping Couplings.**—As shown in the table, double-cone clamping couplings are made in a range of sizes for shafts from  $1\frac{1}{16}$  to 6 inches in diameter, and are easily assembled to shafts. These couplings provide an interference fit, but they usually cost more and have larger overall dimensions than regular flanged couplings.

Double-cone Clamping Couplings

| A                | B               | C               | D               | E              | F             | G               | H                | J              | K              | L               | M             | No. of Bolts | No. of Keys |
|------------------|-----------------|-----------------|-----------------|----------------|---------------|-----------------|------------------|----------------|----------------|-----------------|---------------|--------------|-------------|
| $1\frac{1}{16}$  | $5\frac{1}{4}$  | $2\frac{3}{4}$  | $2\frac{1}{2}$  | $1\frac{3}{8}$ | $\frac{5}{8}$ | $2\frac{1}{2}$  | $4\frac{3}{4}$   | $1\frac{1}{8}$ | 1              | 5               | $\frac{1}{2}$ | 3            | 1           |
| $1\frac{15}{16}$ | 7               | $3\frac{1}{2}$  | $2\frac{7}{8}$  | $2\frac{1}{8}$ | $\frac{5}{8}$ | $2\frac{3}{4}$  | $6\frac{1}{4}$   | $1\frac{1}{8}$ | $1\frac{3}{8}$ | $6\frac{1}{4}$  | $\frac{1}{2}$ | 3            | 1           |
| $2\frac{1}{16}$  | $8\frac{3}{4}$  | $4\frac{7}{16}$ | $3\frac{3}{8}$  | 3              | $\frac{3}{4}$ | $3\frac{1}{2}$  | $7\frac{13}{16}$ | $1\frac{1}{2}$ | $1\frac{3}{4}$ | $7\frac{7}{8}$  | $\frac{5}{8}$ | 3            | 1           |
| 3                | $10\frac{1}{2}$ | $5\frac{1}{2}$  | $4\frac{3}{32}$ | $3\frac{1}{2}$ | $\frac{3}{4}$ | $4\frac{3}{16}$ | 9                | $2\frac{1}{4}$ | 2              | $9\frac{1}{2}$  | $\frac{5}{8}$ | 3            | 1           |
| $3\frac{1}{2}$   | $12\frac{1}{4}$ | 7               | $5\frac{5}{8}$  | $4\frac{3}{8}$ | $\frac{7}{8}$ | $5\frac{1}{16}$ | $11\frac{1}{4}$  | $2\frac{5}{8}$ | $2\frac{1}{2}$ | $11\frac{1}{4}$ | $\frac{3}{4}$ | 4            | 1           |
| 4                | 14              | 7               | $5\frac{1}{2}$  | $4\frac{3}{4}$ | $\frac{7}{8}$ | $5\frac{1}{2}$  | 12               | $3\frac{3}{4}$ | $2\frac{1}{2}$ | 12              | $\frac{3}{4}$ | 4            | 1           |
| $4\frac{1}{2}$   | $15\frac{1}{2}$ | 8               | $6\frac{1}{2}$  | $5\frac{1}{4}$ | $\frac{7}{8}$ | $6\frac{3}{4}$  | $13\frac{1}{2}$  | $3\frac{3}{4}$ | $2\frac{3}{4}$ | $14\frac{1}{2}$ | $\frac{3}{4}$ | 4            | 1           |
| 5                | 17              | 9               | $7\frac{1}{4}$  | $5\frac{3}{4}$ | $\frac{7}{8}$ | 7               | 15               | $3\frac{3}{4}$ | 3              | $15\frac{1}{4}$ | $\frac{3}{4}$ | 4            | 1           |
| $5\frac{1}{2}$   | $17\frac{1}{2}$ | $9\frac{1}{2}$  | $7\frac{3}{4}$  | $6\frac{1}{4}$ | 1             | 7               | $15\frac{1}{2}$  | $3\frac{3}{4}$ | 3              | $15\frac{3}{4}$ | $\frac{7}{8}$ | 4            | 1           |
| 6                | 18              | 10              | $8\frac{1}{4}$  | $6\frac{3}{4}$ | 1             | 7               | 16               | $3\frac{3}{4}$ | 3              | $15\frac{3}{4}$ | $\frac{7}{8}$ | 4            | 2           |



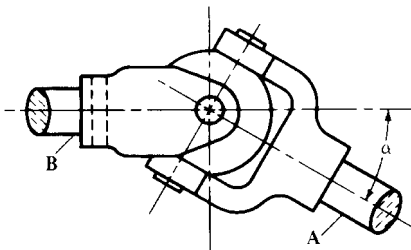
**Flexible Couplings.**—Shafts that are out of alignment laterally or angularly can be connected by any of several designs of flexible couplings. Such couplings also permit some degree of axial movement in one or both shafts. Some couplings use disks or diaphragms to transmit the torque. Another simple form of flexible coupling consists of two flanges connected by links or endless belts made of leather or other strong, pliable material. Alternatively, the flanges may have projections that engage spacers of molded rubber or other flexible materials that accommodate uneven motion between the shafts. More highly developed flexible couplings use toothed flanges engaged by correspondingly toothed elements, permitting relative movement. These couplings require lubrication unless one or more of the elements is made of a self-lubricating material. Other couplings use diaphragms or bellows that can flex to accommodate relative movement between the shafts.

**The Universal Joint.**—This form of coupling, originally known as a Cardan or Hooke's coupling, is used for connecting two shafts the axes of which are not in line with each other, but which merely intersect at a point. There are many different designs of universal joints or couplings, which are based on the principle embodied in the original design. One well-known type is shown by the accompanying diagram.

As a rule, a universal joint does not work well if the angle  $\alpha$  (see illustration) is more than 45 degrees, and the angle should preferably be limited to about 20 degrees or 25 degrees, excepting when the speed of rotation is slow and little power is transmitted.

*Variation in Angular Velocity of Driven Shaft:* Owing to the angularity between two shafts connected by a universal joint, there is a variation in the angular velocity of one shaft during a single revolution, and because of this, the use of universal couplings is sometimes prohibited. Thus, the angular velocity of the driven shaft will not be the same at all points of the revolution as the angular velocity of the driving shaft. In other words, if the driving shaft moves with a uniform motion, then the driven shaft will have a variable motion and, therefore, the universal joint should not be used when absolute uniformity of motion is essential for the driven shaft.

*Determining Maximum and Minimum Velocities:* If shaft *A* (see diagram) runs at a constant speed, shaft *B* revolves at maximum speed when shaft *A* occupies the position shown in the illustration, and the minimum speed of shaft *B* occurs when the fork of the driving shaft *A* has turned 90 degrees from the position illustrated. The maximum speed of the driven shaft may be obtained by multiplying the speed of the driving shaft by the secant of angle  $\alpha$ . The minimum speed of the driven shaft equals the speed of the driver multiplied by cosine  $\alpha$ . Thus, if the driver rotates at a constant speed of 100 revolutions per minute and the shaft angle is 25 degrees, the maximum speed of the driven shaft is at a rate equal to  $1.1034 \times 100 = 110.34$  rpm. The minimum speed rate equals  $0.9063 \times 100 = 90.63$ ; hence, the extreme variation equals  $110.34 - 90.63 = 19.71$  rpm.



**Use of Intermediate Shaft between Two Universal Joints.**—The lack of uniformity in the speed of the driven shaft resulting from the use of a universal coupling, as previously explained, is objectionable for some forms of mechanisms. This variation may be avoided if the two shafts are connected with an intermediate shaft and two universal joints, provided the latter are properly arranged or located. Two conditions are necessary to obtain a constant speed ratio between the driving and driven shafts. First, the shafts must make the same angle with the intermediate shaft; second, the universal joint forks (assuming that the fork design is employed) on the intermediate shaft must be placed relatively so that when the plane of the fork at the left end coincides with the center lines of the intermediate shaft and the shaft attached to the left-hand coupling, the plane of the right-hand fork must also coincide with the center lines of the intermediate shaft and the shaft attached to the right-hand coupling; therefore the driving and the driven shafts may be placed in a variety of positions. One of the most common arrangements is with the driving and driven shafts parallel. The forks on the intermediate shafts should then be placed in the same plane.

This intermediate connecting shaft is frequently made telescoping, and then the driving and driven shafts can be moved independently of each other within certain limits in longitudinal and lateral directions. The telescoping intermediate shaft consists of a rod which enters a sleeve and is provided with a suitable spline, to prevent rotation between the rod and sleeve and permit a sliding movement. This arrangement is applied to various machine tools.

**Knuckle Joints.**—Movement at the joint between two rods may be provided by knuckle joints, for which typical proportions are seen in the table *Proportions of Knuckle Joints* that follows.

**Friction Clutches.**—Clutches which transmit motion from the driving to the driven member by the friction between the engaging surfaces are built in many different designs, although practically all of them can be classified under four general types, namely, conical clutches; radially expanding clutches; contracting-band clutches; and friction disk clutches in single and multiple types. There are many modifications of these general classes, some of which combine the features of different types. The proportions of various sizes of cone clutches are given in the table "Cast-iron Friction Clutches." The multicone friction clutch is a further development of the cone clutch. Instead of having a single cone-shaped surface, there is a series of concentric conical rings which engage annular grooves formed by corresponding rings on the opposite clutch member. The internal-expanding type is provided with shoes which are forced outward against an enclosing drum by the action of levers connecting with a collar free to slide along the shaft. The engaging shoes are commonly lined with wood or other material to increase the coefficient of friction. Disk clutches are based on the principle of multiple-plane friction, and use alternating plates or disks so arranged that one set engages with an outside cylindrical case and the other set with the shaft. When these plates are pressed together by spring pressure, or by other means, motion is transmitted from the driving to the driven members connected to the clutch. Some disk clutches have a few rather heavy or thick plates and others a relatively large number of thinner plates. Clutches of the latter type are common in automobile transmissions. One set of disks may be of soft steel and the other set of phosphor-bronze, or some other combination may be employed. For instance, disks are sometimes provided with cork inserts, or one set or series of disks may be faced with a special friction material such as asbestos-wire fabric, as in "dry plate" clutches, the disks of which are not lubricated like the disks of a clutch having, for example, the steel and phosphor-bronze combination. It is common practice to hold the driving and driven members of friction clutches in engagement by means of spring pressure, although pneumatic or hydraulic pressure may be employed.

Proportions of Knuckle Joints

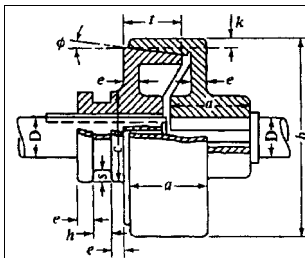
|          |          |          |          |          |          |          | For sizes not given below:<br>$a = 1.2 D$ $h = 2 D$<br>$b = 1.1 D$ $i = 0.5 D$<br>$c = 1.2 D$ $j = 0.25 D$<br>$e = 0.75 D$ $k = 0.5 D$<br>$f = 0.6 D$ $l = 1.5 D$<br>$g = 1.5 D$ |          |          |          |          |
|----------|----------|----------|----------|----------|----------|----------|--|----------|----------|----------|----------|
| <i>D</i> | <i>a</i> | <i>b</i> | <i>c</i> | <i>e</i> | <i>f</i> | <i>g</i> | <i>h</i>   | <i>i</i> | <i>j</i> | <i>k</i> | <i>l</i> |
| 1/2      | 5/8      | 9/16     | 5/8      | 3/8      | 5/16     | 3/4      | 1  | 1/4      | 1/8      | 1/4      | 3/4      |
| 3/4      | 7/8      | 3/4      | 7/8      | 9/16     | 7/16     | 1 1/8    | 1 1/2  | 3/8      | 3/16     | 3/8      | 1 1/8    |
| 1        | 1 1/4    | 1 1/8    | 1 1/4    | 3/4      | 5/8      | 1 1/2    | 2  | 1/2      | 1/4      | 1/2      | 1 1/2    |
| 1 1/4    | 1 1/2    | 1 3/8    | 1 1/2    | 15/16    | 3/4      | 1 7/8    | 2 1/2  | 5/8      | 5/16     | 3/8      | 1 7/8    |
| 1 1/2    | 1 3/4    | 1 5/8    | 1 3/4    | 1 1/8    | 7/8      | 2 1/4    | 3  | 3/4      | 3/8      | 3/4      | 2 1/4    |
| 1 3/4    | 2 1/8    | 2        | 2 1/8    | 1 5/16   | 1 1/16   | 2 5/8    | 3 1/2  | 7/8      | 7/16     | 7/8      | 2 5/8    |
| 2        | 2 3/8    | 2 1/4    | 2 3/8    | 1 1/2    | 1 3/16   | 3        | 4  | 1        | 1/2      | 1        | 3        |
| 2 1/4    | 2 3/4    | 2 1/2    | 2 3/4    | 1 11/16  | 1 3/8    | 3 3/8    | 4 1/2  | 1 1/8    | 9/16     | 1 1/8    | 3 3/8    |
| 2 1/2    | 3        | 2 3/4    | 3        | 1 7/8    | 1 1/2    | 3 3/4    | 5  | 1 1/4    | 5/8      | 1 1/4    | 3 3/4    |
| 2 3/4    | 3 1/4    | 3        | 3 1/4    | 2 1/16   | 1 5/8    | 4 1/8    | 5 1/2  | 1 3/8    | 1 1/16   | 1 3/8    | 4 1/8    |
| 3        | 3 3/8    | 3 1/4    | 3 3/8    | 2 1/4    | 1 13/16  | 4 1/2    | 6  | 1 1/2    | 3/4      | 1 1/2    | 4 1/2    |
| 3 1/4    | 4        | 3 5/8    | 4        | 2 7/16   | 2        | 4 7/8    | 6 1/2  | 1 5/8    | 13/16    | 1 5/8    | 4 7/8    |
| 3 1/2    | 4 1/4    | 3 7/8    | 4 1/4    | 2 5/8    | 2 1/8    | 5 1/4    | 7  | 1 3/4    | 7/8      | 1 3/4    | 5 1/4    |
| 3 3/4    | 4 1/2    | 4 1/8    | 4 1/2    | 2 13/16  | 2 1/4    | 5 5/8    | 7 1/2  | 1 7/8    | 15/16    | 1 7/8    | 5 5/8    |
| 4        | 4 3/4    | 4 3/8    | 4 3/4    | 3        | 2 3/8    | 6        | 8  | 2        | 1        | 2        | 6        |
| 4 1/4    | 5 1/8    | 4 3/4    | 5 1/8    | 3 3/16   | 2 9/16   | 6 3/8    | 8 1/2  | 2 1/8    | 1 1/16   | 2 1/8    | 6 3/8    |
| 4 1/2    | 5 1/2    | 5        | 5 1/2    | 3 3/8    | 2 3/4    | 6 3/4    | 9  | 2 1/4    | 1 1/8    | 2 1/4    | 6 3/4    |
| 4 3/4    | 5 3/4    | 5 1/4    | 5 3/4    | 3 7/16   | 2 7/8    | 7 1/8    | 9 1/2  | 2 3/8    | 1 3/16   | 2 3/8    | 7 1/8    |
| 5        | 6        | 5 1/2    | 6        | 3 3/4    | 3        | 7 1/2    | 10   | 2 1/2    | 1 1/4    | 2 1/2    | 7 1/2    |

**Power Transmitting Capacity of Friction Clutches.**—When selecting a clutch for a given class of service, it is advisable to consider any overloads that may be encountered and base the power transmitting capacity of the clutch upon such overloads. When the load varies or is subject to frequent release or engagement, the clutch capacity should be greater than the actual amount of power transmitted. If the power is derived from a gas or gasoline engine, the horsepower rating of the clutch should be 75 or 100 per cent greater than that of the engine.

**Power Transmitted by Disk Clutches.**—The approximate amount of power that a disk clutch will transmit may be determined from the following formula, in which *H* = horsepower transmitted by the clutch;  $\mu$  = coefficient of friction; *r* = mean radius of engaging surfaces; *F* = axial force in pounds (spring pressure) holding disks in contact; *N* = number of frictional surfaces; *S* = speed of shaft in revolutions per minute:

$$H = \frac{\mu r F N S}{63,000}$$

## Cast-iron Friction Clutches



For sizes not given below:

$$a = 2D$$

$$b = 4 \text{ to } 8D$$

$$c = 2\frac{1}{4}D$$

$$t = 1\frac{1}{2}D$$

$$e = \frac{3}{8}D$$

$$h = \frac{1}{2}D$$

$$s = \frac{5}{16}D, \text{ nearly}$$

$$k = \frac{1}{4}D$$

Note: The angle  $\phi$  of the cone may be from 4 to 10 degrees

| $D$            | $a$             | $b$   | $c$             | $t$            | $e$            | $h$            | $s$            | $k$              |
|----------------|-----------------|-------|-----------------|----------------|----------------|----------------|----------------|------------------|
| 1              | 2               | 4-8   | $2\frac{1}{4}$  | $1\frac{1}{2}$ | $\frac{3}{8}$  | $\frac{1}{2}$  | $\frac{5}{16}$ | $\frac{1}{4}$    |
| $1\frac{1}{4}$ | $2\frac{1}{2}$  | 5-10  | $2\frac{7}{8}$  | $1\frac{7}{8}$ | $\frac{1}{2}$  | $\frac{5}{8}$  | $\frac{3}{8}$  | $\frac{5}{16}$   |
| $1\frac{1}{2}$ | 3               | 6-12  | $3\frac{3}{8}$  | $2\frac{1}{4}$ | $\frac{5}{8}$  | $\frac{3}{4}$  | $\frac{1}{2}$  | $\frac{3}{8}$    |
| $1\frac{3}{4}$ | $3\frac{1}{2}$  | 7-14  | 4               | $2\frac{5}{8}$ | $\frac{5}{8}$  | $\frac{7}{8}$  | $\frac{5}{8}$  | $\frac{7}{16}$   |
| 2              | 4               | 8-16  | $4\frac{1}{2}$  | 3              | $\frac{3}{4}$  | 1              | $\frac{5}{8}$  | $\frac{1}{2}$    |
| $2\frac{1}{4}$ | $4\frac{1}{2}$  | 9-18  | 5               | $3\frac{3}{8}$ | $\frac{7}{8}$  | $1\frac{1}{8}$ | $\frac{5}{8}$  | $\frac{9}{16}$   |
| $2\frac{1}{2}$ | 5               | 10-20 | $5\frac{5}{8}$  | $3\frac{3}{4}$ | 1              | $1\frac{1}{4}$ | $\frac{3}{4}$  | $\frac{5}{8}$    |
| $2\frac{3}{4}$ | $5\frac{1}{2}$  | 11-22 | $6\frac{1}{4}$  | $4\frac{1}{8}$ | 1              | $1\frac{3}{8}$ | $\frac{7}{8}$  | $\frac{11}{16}$  |
| 3              | 6               | 12-24 | $6\frac{3}{4}$  | $4\frac{1}{2}$ | $1\frac{1}{8}$ | $1\frac{1}{2}$ | $\frac{7}{8}$  | $\frac{3}{4}$    |
| $3\frac{1}{4}$ | $6\frac{1}{2}$  | 13-26 | $7\frac{3}{8}$  | $4\frac{7}{8}$ | $1\frac{1}{4}$ | $1\frac{5}{8}$ | 1              | $\frac{13}{16}$  |
| $3\frac{1}{2}$ | 7               | 14-28 | $7\frac{7}{8}$  | $5\frac{1}{4}$ | $1\frac{3}{8}$ | $1\frac{3}{4}$ | 1              | $\frac{7}{8}$    |
| $3\frac{3}{4}$ | $7\frac{1}{2}$  | 15-30 | $8\frac{1}{2}$  | $5\frac{5}{8}$ | $1\frac{3}{8}$ | $1\frac{7}{8}$ | $1\frac{1}{4}$ | $\frac{15}{16}$  |
| 4              | 8               | 16-32 | 9               | 6              | $1\frac{1}{2}$ | 2              | $1\frac{1}{4}$ | 1                |
| $4\frac{1}{4}$ | $8\frac{1}{2}$  | 17-34 | $9\frac{1}{2}$  | $6\frac{3}{8}$ | $1\frac{5}{8}$ | $2\frac{1}{8}$ | $1\frac{3}{8}$ | $1\frac{1}{16}$  |
| $4\frac{1}{2}$ | 9               | 18-36 | $10\frac{1}{4}$ | $6\frac{3}{4}$ | $1\frac{3}{4}$ | $2\frac{1}{4}$ | $1\frac{3}{8}$ | $1\frac{1}{8}$   |
| $4\frac{3}{4}$ | $9\frac{1}{2}$  | 19-38 | $10\frac{3}{4}$ | $7\frac{1}{8}$ | $1\frac{3}{4}$ | $2\frac{3}{8}$ | $1\frac{1}{2}$ | $1\frac{13}{16}$ |
| 5              | 10              | 20-40 | $11\frac{1}{4}$ | $7\frac{1}{2}$ | $1\frac{7}{8}$ | $2\frac{1}{2}$ | $1\frac{1}{2}$ | $1\frac{1}{4}$   |
| $5\frac{1}{4}$ | $10\frac{1}{2}$ | 21-42 | $11\frac{3}{4}$ | $7\frac{7}{8}$ | 2              | $2\frac{5}{8}$ | $1\frac{5}{8}$ | $1\frac{5}{16}$  |
| $5\frac{1}{2}$ | 11              | 22-44 | $12\frac{3}{8}$ | $8\frac{1}{4}$ | 2              | $2\frac{3}{4}$ | $1\frac{3}{4}$ | $1\frac{3}{8}$   |
| $5\frac{3}{4}$ | $11\frac{1}{2}$ | 23-46 | 13              | $8\frac{5}{8}$ | $2\frac{1}{4}$ | $2\frac{7}{8}$ | $1\frac{3}{4}$ | $1\frac{7}{16}$  |
| 6              | 12              | 24-48 | $13\frac{1}{2}$ | 9              | $2\frac{1}{4}$ | 3              | $1\frac{7}{8}$ | $1\frac{1}{2}$   |

**Frictional Coefficients for Clutch Calculations.**—While the frictional coefficients used by designers of clutches differ somewhat and depend upon variable factors, the following values may be used in clutch calculations: For greasy leather on cast iron about 0.20 or 0.25, leather on metal that is quite oily 0.15; metal and cork on oily metal 0.32; the same on dry metal 0.35; metal on dry metal 0.15; disk clutches having lubricated surfaces 0.10.

**Formulas for Cone Clutches.**—In cone clutch design, different formulas have been developed for determining the horsepower transmitted. These formulas, at first sight, do not seem to agree, there being a variation due to the fact that in some of the formulas the friction clutch surfaces are assumed to engage without slip, whereas, in others, some allowance is made for slip. The following formulas include both of these conditions:

$H.P.$  = horsepower transmitted

$N$  = revolutions per minute

$r$  = mean radius of friction cone, in inches

$r_1$  = large radius of friction cone, in inches

$r_2$  = small radius of friction cone, in inches

$R_1$  = outside radius of leather band, in inches

$R_2$  = inside radius of leather band, in inches

$V$  = velocity of a point at distance  $r$  from the center, in feet per minute

$F$  = tangential force acting at radius  $r$ , in pounds

$P_n$  = total normal force between cone surfaces, in pounds

$P_s$  = spring force, in pounds

$\alpha$  = angle of clutch surface with axis of shaft = 7 to 13 degrees

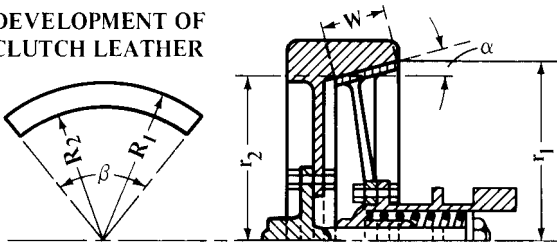
$\beta$  = included angle of clutch leather, when developed, in degrees

$f$  = coefficient of friction = 0.20 to 0.25 for greasy leather on iron

$p$  = allowable pressure per square inch of leather band = 7 to 8 pounds

$W$  = width of clutch leather, in inches

### DEVELOPMENT OF CLUTCH LEATHER



$$R_1 = \frac{r_1}{\sin \alpha} \quad R_2 = \frac{r_2}{\sin \alpha}$$

$$\beta = \sin \alpha \times 360 \quad r = \frac{r_1 + r_2}{2}$$

$$V = \frac{2\pi r N}{12}$$

$$F = \frac{HP \times 33,000}{V}$$

$$W = \frac{P_n}{2\pi r p}$$

$$HP = \frac{P_n f r N}{63,025}$$

For engagement with some slip:

$$P_n = \frac{P_s}{\sin \alpha}$$

$$P_s = \frac{HP \times 63,025 \sin \alpha}{f r N}$$

For engagement without slip:

$$P_n = \frac{P_s}{\sin \alpha + f \cos \alpha}$$

$$P_s = \frac{HP \times 63,025 (\sin \alpha + f \cos \alpha)}{f r N}$$

**Angle of Cone.**—If the angle of the conical surface of the cone type of clutch is too small, it may be difficult to release the clutch on account of the wedging effect, whereas, if the angle is too large, excessive spring force will be required to prevent slipping. The minimum angle for a leather-faced cone is about 8 or 9 degrees and the maximum angle about 13 degrees. An angle of  $12 \frac{1}{2}$  degrees appears to be the most common and is generally con-

sidered good practice. These angles are given with relation to the clutch axis and are one-half the included angle.

**Magnetic Clutches.**—Many disk and other clutches are operated electromagnetically with the magnetic force used only to move the friction disk(s) and the clutch disk(s) into or out of engagement against spring or other pressure. On the other hand, in a magnetic particle clutch, transmission of power is accomplished by magnetizing a quantity of metal particles enclosed between the driving and the driven components, forming a bond between them. Such clutches can be controlled to provide either a rigid coupling or uniform slip, useful in wire drawing and manufacture of cables.

Another type of magnetic clutch uses eddy currents induced in the input member which interact with the field in the output rotor. Torque transmitted is proportional to the coil current, so precise control of torque is provided. A third type of magnetic clutch relies on the hysteresis loss between magnetic fields generated by a coil in an input drum and a close-fitting cup on the output shaft, to transmit torque. Torque transmitted with this type of clutch also is proportional to coil current, so close control is possible.

Permanent-magnet types of clutches also are available, in which the engagement force is exerted by permanent magnets when the electrical supply to the disengagement coils is cut off. These types of clutches have capacities up to five times the torque-to-weight ratio of spring-operated clutches. In addition, if the controls are so arranged as to permit the coil polarity to be reversed instead of being cut off, the combined permanent magnet and electromagnetic forces can transmit even greater torque.

**Centrifugal and Free-wheeling Clutches.**—Centrifugal clutches have driving members that expand outward to engage a surrounding drum when speed is sufficient to generate centrifugal force. Free-wheeling clutches are made in many different designs and use balls, cams or sprags, ratchets, and fluids to transmit motion from one member to the other. These types of clutches are designed to transmit torque in only one direction and to take up the drive with various degrees of gradualness up to instantaneously.

**Slipping Clutch/Couplings.**—Where high shock loads are likely to be experienced, a slipping clutch or coupling or both should be used. The most common design uses a clutch plate that is clamped between the driving and driven plates by spring pressure that can be adjusted. When excessive load causes the driven member to slow, the clutch plate surfaces slip, allowing reduction of the torque transmitted. When the overload is removed, the drive is taken up automatically. Switches can be provided to cut off current supply to the driving motor when the driven shaft slows to a preset limit or to signal a warning or both. The slip or overload torque is calculated by taking 150 per cent of the normal running torque.

**Wrapped-spring Clutches.**—For certain applications, a simple steel spring sized so that its internal diameter is a snug fit on both driving and driven shafts will transmit adequate torque in one direction. The tightness of grip of the spring on the shafts increases as the torque transmitted increases. Disengagement can be effected by slight rotation of the spring, through a projecting tang, using electrical or mechanical means, to wind up the spring to a larger internal diameter, allowing one of the shafts to run free within the spring.

Normal running torque  $T_r$  in lb-ft = (required horsepower  $\times$  5250)  $\div$  rpm. For heavy shock load applications, multiply by a 200 per cent or greater overload factor. (See Motors, factors governing selection.)

The clutch starting torque  $T_c$ , in lb-ft, required to accelerate a given inertia in a specific time is calculated from the formula:

$$T_c = \frac{WR^2 \times \Delta N}{308t}$$

where  $WR^2$  = total inertia encountered by clutch in lb-ft<sup>2</sup> ( $W$  = weight and  $R$  = radius of gyration of rotating part)

$\Delta N$  = final rpm – initial rpm

308 = = constant (see *Factors Governing Motor Selection* on page 2473)

$t$  = time to required speed in seconds

Example: If the inertia is 80 lb-ft<sup>2</sup>, and the speed of the driven shaft is to be increased from 0 to 1500 rpm in 3 seconds, find the clutch starting torque in lb-ft.

$$T_c = \frac{80 \times 1500}{308 \times 3} = 130 \text{ lb-ft}$$

The heat  $E$ , in BTU, generated in one engagement of a clutch can be calculated from the formula:

$$E = \frac{T_c \times WR^2 \times (N_1^2 - N_2^2)}{(T_c - T_1) \times 4.7 \times 10^6}$$

where:  $WR^2$  = total inertia encountered by clutch in lb-ft.<sup>2</sup>

$N_1$  = final rpm     $N_2$  = initial rpm

$T_c$  = clutch torque in lb-ft     $T_1$  = torque load in lb-ft

Example: Calculate the heat generated for each engagement under the conditions cited for the first example.

$$E = \frac{130 \times 80 \times (1500)^2}{(130 - 10) \times 4.7 \times 10^6} = 41.5 \text{ BTU}$$

The preferred location for a clutch is on the high- rather than on the low-speed shaft because a smaller-capacity unit, of lower cost and with more rapid dissipation of heat, can be used. However, the heat generated may also be more because of the greater slippage at higher speeds, and the clutch may have a shorter life. For light-duty applications, such as to a machine tool, where cutting occurs after the spindle has reached operating speed, the calculated torque should be multiplied by a safety factor of 1.5 to arrive at the capacity of the clutch to be used. Heavy-duty applications such as frequent starting of a heavily loaded vibratory-finishing barrel require a safety factor of 3 or more.

**Positive Clutches.**—When the driving and driven members of a clutch are connected by the engagement of interlocking teeth or projecting lugs, the clutch is said to be “positive” to distinguish it from the type in which the power is transmitted by frictional contact. The positive clutch is employed when a sudden starting action is not objectionable and when the inertia of the driven parts is relatively small. The various forms of positive clutches differ merely in the angle or shape of the engaging surfaces. The least positive form is one having planes of engagement which incline backward, with respect to the direction of motion. The tendency of such a clutch is to disengage under load, in which case it must be held in position by axial pressure.

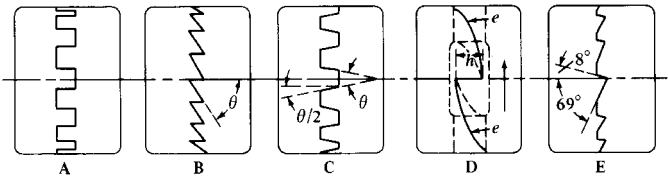


Fig. 1. Types of Clutch Teeth

This pressure may be regulated to perform normal duty, permitting the clutch to slip and disengage when over-loaded. Positive clutches, with the engaging planes parallel to the axis of rotation, are held together to obviate the tendency to jar out of engagement, but they provide no safety feature against over-load. So-called “under-cut” clutches engage more tightly the heavier the load, and are designed to be disengaged only when free from load. The teeth of positive clutches are made in a variety of forms, a few of the more common

styles being shown in Fig. 1. Clutch *A* is a straight-toothed type, and *B* has angular or saw-shaped teeth. The driving member of the former can be rotated in either direction: the latter is adapted to the transmission of motion in one direction only, but is more readily engaged. The angle  $\theta$  of the cutter for a saw-tooth clutch *B* is ordinarily 60 degrees. Clutch *C* is similar to *A*, except that the sides of the teeth are inclined to facilitate engagement and disengagement. Teeth of this shape are sometimes used when a clutch is required to run in either direction without backlash. Angle  $\theta$  is varied to suit requirements and should not exceed 16 or 18 degrees. The straight-tooth clutch *A* is also modified to make the teeth engage more readily, by rounding the corners of the teeth at the top and bottom. Clutch *D* (commonly called a "spiral-jaw" clutch) differs from *B* in that the surfaces *e* are helicoidal. The driving member of this clutch can transmit motion in only one direction.

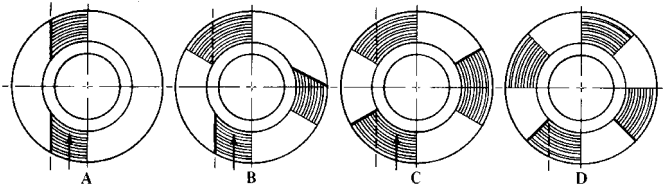


Fig. 2. Diagrammatic View Showing Method of Cutting Clutch Teeth

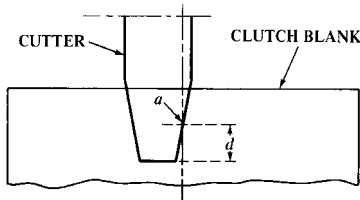


Fig. 3.

Clutches of this type are known as right- and left-hand, the former driving when turning to the right, as indicated by the arrow in the illustration. Clutch *E* is the form used on the back-shaft of the Brown & Sharpe automatic screw machines. The faces of the teeth are radial and incline at an angle of 8 degrees with the axis, so that the clutch can readily be disengaged. This type of clutch is easily operated, with little jar or noise. The 2-inch diameter size has 10 teeth. Height of working face,  $\frac{1}{8}$  inch.

**Cutting Clutch Teeth.**—A common method of cutting a straight-tooth clutch is indicated by the diagrams *A*, *B* and *C*, Fig. 2, which show the first, second and third cuts required for forming the three teeth. The work is held in the chuck of a dividing-head, the latter being set at right angles to the table. A plain milling cutter may be used (unless the corners of the teeth are rounded), the side of the cutter being set to exactly coincide with the center-line. When the number of teeth in the clutch is odd, the cut can be taken clear across the blank as shown, thus finishing the sides of two teeth with one passage of the cutter. When the number of teeth is even, as at *D*, it is necessary to mill all the teeth on one side and then set the cutter for finishing the opposite side. Therefore, clutches of this type commonly have an odd number of teeth. The maximum width of the cutter depends upon the width of the space at the narrow ends of the teeth. If the cutter must be quite narrow in order to pass the narrow ends, some stock may be left in the tooth spaces, which must be removed by a separate cut. If the tooth is of the modified form shown at *C*, Fig. 1, the cutter should be set as



indicated in Fig. 3; that is, so that a point *a* on the cutter at a radial distance *d* equal to one-half the depth of the clutch teeth lies in a radial plane. When it is important to eliminate all backlash, point *a* is sometimes located at a radial distance *d* equal to six-tenths of the depth of the tooth, in order to leave clearance spaces at the bottoms of the teeth; the two clutch members will then fit together tightly. Clutches of this type must be held in mesh.

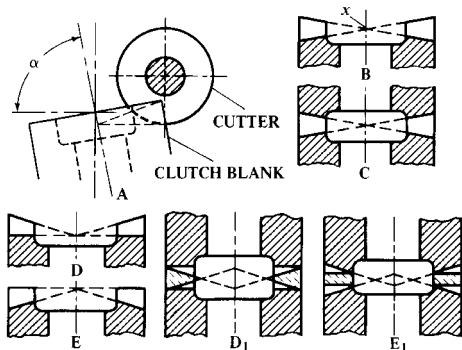
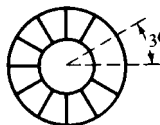


Fig. 4.

**Angle of Dividing-head for Milling V-shaped Teeth with Single-angle Cutter**



$$\cos \alpha = \frac{\tan(360^\circ/N) \times \cot \theta}{2}$$

$\alpha$  is the angle shown in Fig. 4 and is the angle shown by the graduations on the dividing head.  $\theta$  is the included angle of a single cutter, see Fig. 1.

| No. of Teeth, <i>N</i> | Angle of Single-angle Cutter, $\theta$ |       |           |           | No. of Teeth, <i>N</i> | Angle of Single-angle Cutter, $\theta$ |           |           |  |
|------------------------|--|-------|-----------|-----------|------------------------|--|-----------|-----------|--|
|                        | Dividing Head Angle, $\alpha$          |       |           |           |                        | Dividing Head Angle, $\alpha$          |           |           |  |
|                        | 60°                                    | 70°   | 80°       |           |                        | 60°                                    | 70°       | 80°       |  |
| 5                      | 27°                                    | 19.2' | 55° 56.3' | 74° 15.4' | 18                     | 83° 58.1'                              | 86° 12.1' | 88° 9.67' |  |
| 6                      | 60                                     |       | 71 37.6   | 81 13     | 19                     | 84 18.8                                | 86 25.1   | 88 15.9   |  |
| 7                      | 68                                     | 46.7  | 76 48.5   | 83 39.2   | 20                     | 84 37.1                                | 86 36.6   | 88 21.5   |  |
| 8                      | 73                                     | 13.3  | 79 30.9   | 84 56.5   | 21                     | 84 53.5                                | 86 46.9   | 88 26.5   |  |
| 9                      | 75                                     | 58.9  | 81 13     | 85 45.4   | 22                     | 85 8.26                                | 86 56.2   | 88 31     |  |
| 10                     | 77                                     | 53.6  | 82 24.1   | 86 19.6   | 23                     | 85 21.6                                | 87 4.63   | 88 35.1   |  |
| 11                     | 79                                     | 18.5  | 83 17     | 86 45.1   | 24                     | 85 33.8                                | 87 12.3   | 88 38.8   |  |
| 12                     | 80                                     | 24.4  | 83 58.1   | 87 4.94   | 25                     | 85 45                                  | 87 19.3   | 88 42.2   |  |
| 13                     | 81                                     | 17.1  | 84 31.1   | 87 20.9   | 26                     | 85 55.2                                | 87 25.7   | 88 45.3   |  |
| 14                     | 82                                     | .536  | 84 58.3   | 87 34     | 27                     | 86 4.61                                | 87 31.7   | 88 48.2   |  |
| 15                     | 82                                     | 36.9  | 85 21.2   | 87 45     | 28                     | 86 13.3                                | 87 37.2   | 88 50.8   |  |
| 16                     | 83                                     | 7.95  | 85 40.6   | 87 54.4   | 29                     | 86 21.4                                | 87 42.3   | 88 53.3   |  |
| 17                     | 83                                     | 34.7  | 85 57.4   | 88 2.56   | 30                     | 86 28.9                                | 87 47     | 88 55.6   |  |

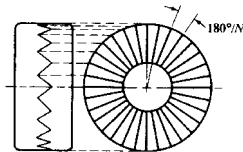
**Cutting Saw-tooth Clutches:** When milling clutches having angular teeth as shown at B, Fig. 1, the axis of the clutch blank should be inclined a certain angle  $\alpha$  as shown at A in Fig. 4. If the teeth were milled with the blank vertical, the tops of the teeth would incline towards the center as at D, whereas, if the blank were set to such an angle that the tops of the teeth were square with the axis, the bottoms would incline upwards as at E. In either case,

the two clutch members would not mesh completely: the engagement of the teeth cut as shown at  $D$  and  $E$  would be as indicated at  $D_1$  and  $E_1$  respectively. As will be seen, when the outer points of the teeth at  $D_1$  are at the bottom of the grooves in the opposite member, the inner ends are not together, the contact area being represented by the dotted lines. At  $E_1$  the inner ends of the teeth strike first and spaces are left between the teeth around the outside of the clutch. To overcome this objectionable feature, the clutch teeth should be cut as indicated at  $B$ , or so that the bottoms and tops of the teeth have the same inclination, converging at a central point  $x$ . The teeth of both members will then engage across the entire width as shown at  $C$ . The angle  $\alpha$  required for cutting a clutch as at  $B$  can be determined by the following formula in which  $\alpha$  equals the required angle,  $N$  = number of teeth,  $\theta$  = cutter angle, and  $360^\circ/N$  = angle between teeth:

$$\cos \alpha = \frac{\tan(360^\circ/N) \times \cot \theta}{2}$$

The angles  $\alpha$  for various numbers of teeth and for 60-, 70- or 80-degree single-angle cutters are given in the table on page 2356. The following table is for double-angle cutters used to cut V-shaped teeth.

#### Angle of Dividing-head for Milling V-shaped Teeth with Double-angle Cutter



$$\cos \alpha = \frac{\tan(180^\circ/N) \times \cot(\theta/2)}{2}$$

This is the angle ( $\alpha$ , Fig. 4) shown by graduations on the dividing-head.  $\theta$  is the included angle of a double-angle cutter, see Fig. 1.

| No. of Teeth, $N$ | Included Angle of Cutter, $\theta$ |         | No. of Teeth, $N$ | Included Angle of Cutter, $\theta$ |           |
|-------------------|------------------------------------|---------|-------------------|------------------------------------|-----------|
|                   | 60°                                | 90°     |                   | 60°                                | 90°       |
|                   | Dividing Head Angle, $\alpha$      |         |                   |                                    |           |
| 10                | 73° 39.4'                          | 80° 39' | 31                | 84° 56.9'                          | 87° 5.13' |
| 11                | 75 16.1                            | 81 33.5 | 32                | 85 6.42                            | 87 10.6   |
| 12                | 76 34.9                            | 82 18   | 33                | 85 15.4                            | 87 15.8   |
| 13                | 77 40.5                            | 82 55.3 | 34                | 85 23.8                            | 87 20.7   |
| 14                | 78 36                              | 83 26.8 | 35                | 85 31.8                            | 87 25.2   |
| 15                | 79 23.6                            | 83 54   | 36                | 85 39.3                            | 87 29.6   |
| 16                | 80 4.83                            | 84 17.5 | 37                | 85 46.4                            | 87 33.7   |
| 17                | 80 41                              | 84 38.2 | 38                | 85 53.1                            | 87 37.5   |
| 18                | 81 13                              | 84 56.5 | 39                | 85 59.5                            | 87 41.2   |
| 19                | 81 41.5                            | 85 12.8 | 40                | 86 5.51                            | 87 44.7   |
| 20                | 82 6.97                            | 85 27.5 | 41                | 86 11.3                            | 87 48     |
| 21                | 82 30                              | 85 40.7 | 42                | 86 16.7                            | 87 51.2   |
| 22                | 82 50.8                            | 85 52.6 | 43                | 86 22                              | 87 54.2   |
| 23                | 83 9.82                            | 86 3.56 | 44                | 86 26.9                            | 87 57     |
| 24                | 83 27.2                            | 86 13.5 | 45                | 86 31.7                            | 87 59.8   |
| 25                | 83 43.1                            | 86 22.7 | 46                | 86 36.2                            | 88 2.4    |
| 26                | 83 57.8                            | 26 31.2 | 47                | 86 40.6                            | 88 4.91   |
| 27                | 84 11.4                            | 86 39   | 48                | 86 44.8                            | 88 7.32   |
| 28                | 84 24                              | 86 46.2 | 49                | 86 48.8                            | 88 9.63   |
| 29                | 84 35.7                            | 86 53   | 50                | 86 52.6                            | 88 11.8   |
| 30                | 84 46.7                            | 86 59.3 | 51                | 86 56.3                            | 88 14     |

The angles given in the table above are applicable to the milling of V-shaped grooves in brackets, etc., which must have toothed surfaces to prevent the two members from turning relative to each other, except when unclamped for angular adjustment

**FRICION BRAKES**

**Formulas for Band Brakes.**—In any band brake, such as shown in Fig. 1, in the tabulation of formulas, where the brake wheel rotates in a clockwise direction, the tension in that part of the band marked *x* equals  $P \frac{1}{e^{\mu\theta} - 1}$

The tension in that part marked *y* equals  $P \frac{e^{\mu\theta}}{e^{\mu\theta} - 1}$ .

*P* = tangential force in pounds at rim of brake wheel

*e* = base of natural logarithms = 2.71828

$\mu$  = coefficient of friction between the brake band and the brake wheel

$\theta$  = angle of contact of the brake band with the brake wheel expressed in

radians (one radian =  $\frac{180 \text{ deg.}}{\pi \text{ radians}} = 57.296 \frac{\text{deg.}}{\text{radian}}$ ).

For simplicity in the formulas presented, the tensions at *x* and *y* (Fig. 1) are denoted by  $T_1$  and  $T_2$  respectively, for clockwise rotation. When the direction of the rotation is reversed, the tension in *x* equals  $T_2$ , and the tension in *y* equals  $T_1$ , which is the reverse of the tension in the clockwise direction.

The value of the expression  $e^{\mu\theta}$  in these formulas may be most easily found by using a hand-held calculator of the scientific type; that is, one capable of raising 2.71828 to the power  $\mu\theta$ . The following example outlines the steps in the calculations.

**Table of Values of  $e^{\mu\theta}$**

| Proportion of Contact to Whole Circumference, $\frac{\theta}{2\pi}$ | Steel Band on Cast Iron, $\mu = 0.18$ | Leather Belt on               |                           |                               |                    |
|---|---------------------------------------|-------------------------------|---------------------------|-------------------------------|--------------------|
|   |                                       | Wood                          | Cast Iron                 |                               |                    |
|   |                                       | Slightly Greasy; $\mu = 0.47$ | Very Greasy; $\mu = 0.12$ | Slightly Greasy; $\mu = 0.28$ | Damp; $\mu = 0.38$ |
| 0.1   | 1.12                                  | 1.34                          | 1.08                      | 1.19                          | 1.27               |
| 0.2   | 1.25                                  | 1.81                          | 1.16                      | 1.42                          | 1.61               |
| 0.3   | 1.40                                  | 2.43                          | 1.25                      | 1.69                          | 2.05               |
| 0.4   | 1.57                                  | 3.26                          | 1.35                      | 2.02                          | 2.60               |
| 0.425   | 1.62                                  | 3.51                          | 1.38                      | 2.11                          | 2.76               |
| 0.45  | 1.66                                  | 3.78                          | 1.40                      | 2.21                          | 2.93               |
| 0.475   | 1.71                                  | 4.07                          | 1.43                      | 2.31                          | 3.11               |
| 0.5   | 1.76                                  | 4.38                          | 1.46                      | 2.41                          | 3.30               |
| 0.525   | 1.81                                  | 4.71                          | 1.49                      | 2.52                          | 3.50               |
| 0.55  | 1.86                                  | 5.07                          | 1.51                      | 2.63                          | 3.72               |
| 0.6   | 1.97                                  | 5.88                          | 1.57                      | 2.81                          | 4.19               |
| 0.7   | 2.21                                  | 7.90                          | 1.66                      | 3.43                          | 5.32               |
| 0.8   | 2.47                                  | 10.60                         | 1.83                      | 4.09                          | 6.75               |
| 0.9   | 2.77                                  | 14.30                         | 1.97                      | 4.87                          | 8.57               |
| 1.0   | 3.10                                  | 19.20                         | 2.12                      | 5.81                          | 10.90              |

## Formulas for Simple and Differential Band Brakes

$F$  = force in pounds at end of brake handle;  $P$  = tangential force in pounds at rim of brake wheel;  $e$  = base of natural logarithms = 2.71828;  $\mu$  = coefficient of friction between the brake band and the brake wheel;  $\theta$  = angle of contact of the brake band with the brake wheel, expressed in radians (one radian = 57.296 degrees).

$$T_1 = P \frac{1}{e^{\mu\theta} - 1} \quad T_2 = P \frac{e^{\mu\theta}}{e^{\mu\theta} - 1}$$

## Simple Band Brake

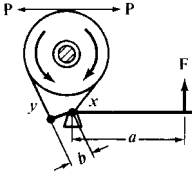


Fig. 1.

For clockwise rotation:

$$F = \frac{bT_2}{a} = \frac{Pb}{a} \left( \frac{e^{\mu\theta}}{e^{\mu\theta} - 1} \right)$$

For counter clockwise rotation:

$$F = \frac{bT_1}{a} = \frac{Pb}{a} \left( \frac{1}{e^{\mu\theta} - 1} \right)$$

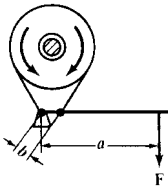


Fig. 2.

For clockwise rotation:

$$F = \frac{bT_1}{a} = \frac{Pb}{a} \left( \frac{1}{e^{\mu\theta} - 1} \right)$$

For counter clockwise rotation:

$$F = \frac{bT_2}{a} = \frac{Pb}{a} \left( \frac{e^{\mu\theta}}{e^{\mu\theta} - 1} \right)$$

## Differential Band Brake

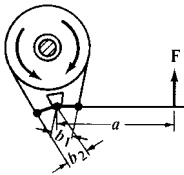


Fig. 3.

For clockwise rotation:

$$F = \frac{b_2T_2 - b_1T_1}{a} = \frac{P}{a} \left( \frac{b_2e^{\mu\theta} - b_1}{e^{\mu\theta} - 1} \right)$$

For counter clockwise rotation:

$$F = \frac{b_2T_1 - b_1T_2}{a} = \frac{P}{a} \left( \frac{b_2 - b_1e^{\mu\theta}}{e^{\mu\theta} - 1} \right)$$

In this case, if  $b_2$  is equal to, or less than,  $b_1e^{\mu\theta}$ , the force  $F$  will be 0 or negative and the band brake works automatically.

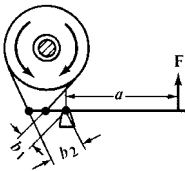


Fig. 4.

For clockwise rotation:

$$F = \frac{b_2T_2 + b_1T_1}{a} = \frac{P}{a} \left( \frac{b_2e^{\mu\theta} + b_1}{e^{\mu\theta} - 1} \right)$$

For counter clockwise rotation:

$$F = \frac{b_1T_2 + b_2T_1}{a} = \frac{P}{a} \left( \frac{b_1e^{\mu\theta} + b_2}{e^{\mu\theta} - 1} \right)$$

If  $b_2 = b_1$ , both of the above formulas reduce to  $F = \frac{Pb_1}{a} \left( \frac{e^{\mu\theta} + 1}{e^{\mu\theta} - 1} \right)$ .

In this case, the same force  $F$  is required for rotation in either direction.

*Example:* In a band brake of the type in Fig. 1, dimension  $a = 24$  inches, and  $b = 4$  inches; force  $P = 100$  pounds; coefficient  $\mu = 0.2$ , and angle of contact = 240 degrees, or

$$\theta = \frac{240}{180} \times \pi = 4.18$$

The rotation is clockwise. Find force  $F$  required.

$$\begin{aligned}
 F &= \frac{Pb}{a} \left( \frac{e^{\mu\theta}}{e^{\mu\theta} - 1} \right) \\
 &= \frac{100 \times 4}{24} \left( \frac{2.71828^{0.2 \times 4.18}}{2.71828^{0.2 \times 4.18} - 1} \right) \\
 &= \frac{400}{24} \times \frac{2.71828^{0.836}}{2.71828^{0.836} - 1} = 16.66 \times \frac{2.31}{2.31 - 1} = 29.4
 \end{aligned}$$

If a hand-held calculator is not used, determining the value of  $e^{\mu\theta}$  is rather tedious, and the table on page 2358 will save calculations.

**Coefficient of Friction in Brakes.**—The coefficients of friction that may be assumed for friction brake calculations are as follows: Iron on iron, 0.25 to 0.3 leather on iron, 0.3; cork on iron, 0.35. Values somewhat lower than these should be assumed when the velocities exceed 400 feet per minute at the beginning of the braking operation.

For brakes where wooden brake blocks are used on iron drums, poplar has proved the best brake-block material. The best material for the brake drum is wrought iron. Poplar gives a high coefficient of friction, and is little affected by oil. The average coefficient of friction for poplar brake blocks and wrought-iron drums is 0.6; for poplar on cast iron, 0.35 for oak on wrought iron, 0.5; for oak on cast iron, 0.3; for beech on wrought iron, 0.5; for beech on cast iron, 0.3; for elm on wrought iron, 0.6; and for elm on cast iron, 0.35. The objection to elm is that the friction decreases rapidly if the friction surfaces are oily. The coefficient of friction for elm and wrought iron, if oily, is less than 0.4.

**Calculating Horsepower from Dynamometer Tests.**—When a dynamometer is arranged for measuring the horsepower transmitted by a shaft, as indicated by the diagrammatic view in Fig. 5, the horsepower may be obtained by the formula:

$$HP = \frac{2\pi LPN}{33000}$$

in which H.P. = horsepower transmitted;  $N$  = number of revolutions per minute;  $L$  = distance (as shown in illustration) from center of pulley to point of action of weight  $P$ , in feet;  $P$  = weight hung on brake arm or read on scale.

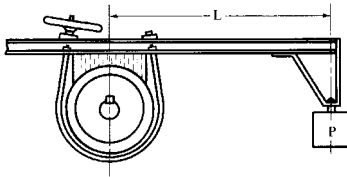


Fig. 5.

By adopting a length of brake arm equal to 5 feet 3 inches, the formula may be reduced to the simple form:

$$HP = \frac{NP}{1000}$$

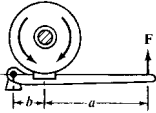
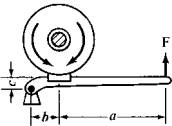
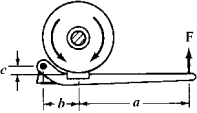
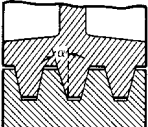
If a length of brake arm equal to 2 feet 7½ inches is adopted as a standard, the formula takes the form:

$$HP = \frac{NP}{2000}$$

The *transmission* type of dynamometer measures the power by transmitting it through the mechanism of the dynamometer from the apparatus in which it is generated, or to the

apparatus in which it is to be utilized. Dynamometers known as *indicators* operate by simultaneously measuring the pressure and volume of a confined fluid. This type may be used for the measurement of the power generated by steam or gas engines or absorbed by refrigerating machinery, air compressors, or pumps. An electrical dynamometer is for measuring the power of an electric current, based on the mutual action of currents flowing in two coils. It consists principally of one fixed and one movable coil, which, in the normal position, are at right angles to each other. Both coils are connected in series, and, when a current traverses the coils, the fields produced are at right angles; hence, the coils tend to take up a parallel position. The movable coil with an attached pointer will be deflected, the deflection measuring directly the electric current.

**Formulas for Block Brakes**

|  |  |
|--|--|
| <p><math>F</math> = force in pounds at end of brake handle;<br/> <math>P</math> = tangential force in pounds at rim of brake wheel;<br/> <math>\mu</math> = coefficient of friction between the brake block and brake wheel.</p> |  |
|  <p>Fig. 1.</p>   | <p>Block brake.<br/>                 For rotation in either direction:</p> $F = P \frac{b}{a+b} \times \frac{1}{\mu} = \frac{Pb}{a+b} \left( \frac{1}{\mu} \right)$  |
|  <p>Fig. 2.</p>   | <p>Block brake.<br/>                 For clockwise rotation:</p> $F = \frac{Pb - Pc}{a+b} = \frac{Pb}{a+b} \left( \frac{1}{\mu} - \frac{c}{b} \right)$ <p>For counter clockwise rotation:</p> $F = \frac{Pb + Pc}{a+b} = \frac{Pb}{a+b} \left( \frac{1}{\mu} + \frac{c}{b} \right)$  |
|  <p>Fig. 3.</p>   | <p>Block brake.<br/>                 For clockwise rotation:</p> $F = \frac{Pb + Pc}{a+b} = \frac{Pb}{a+b} \left( \frac{1}{\mu} + \frac{c}{b} \right)$ <p>For counter clockwise rotation:</p> $F = \frac{Pb - Pc}{a+b} = \frac{Pb}{a+b} \left( \frac{1}{\mu} - \frac{c}{b} \right)$  |
|  <p>Fig. 4.</p>   | <p>The brake wheel and friction block of the block brake are often grooved as shown in Fig. 4. In this case, substitute for <math>\mu</math> in the above equations the value <math>\frac{\mu}{\sin \alpha + \mu \cos \alpha}</math> where <math>\alpha</math> is one-half the angle included by the faces of the grooves.</p> |

**Friction Wheels for Power Transmission**

When a rotating member is driven intermittently and the rate of driving does not need to be positive, friction wheels are frequently used, especially when the amount of power to be transmitted is comparatively small. The driven wheels in a pair of friction disks should always be made of a harder material than the driving wheels, so that if the driven wheel

should be held stationary by the load, while the driving wheel revolves under its own pressure, a flat spot may not be rapidly worn on the driven wheel. The driven wheels, therefore, are usually made of iron, while the driving wheels are made of or covered with, rubber, paper, leather, wood or fiber. The safe working force per inch of face width of contact for various materials are as follows: Straw fiber, 150; leather fiber, 240; tarred fiber, 240; leather, 150; wood, 100 to 150; paper, 150. Coefficients of friction for different combinations of materials are given in the following table. Smaller values should be used for exceptionally high speeds, or when the transmission must be started while under load.

**Horsepower of Friction Wheels.**—Let  $D$  = diameter of friction wheel in inches;  $N$  = Number of revolutions per minute;  $W$  = width of face in inches;  $f$  = coefficient of friction;  $P$  = force in pounds, per inch width of face. Then:

$$\text{H.P.} = \frac{3.1416 \times D \times N \times P \times W \times f}{33,000 \times 12}$$

Assume

$$\frac{3.1416 \times P \times f}{33,000 \times 12} = C$$

then,

for  $P = 100$  and  $f = 0.20$ ,  $C = 0.00016$

for  $P = 150$  and  $f = 0.20$ ,  $C = 0.00024$

for  $P = 200$  and  $f = 0.20$ ,  $C = 0.00032$

**Working Values of Coefficient of Friction**

| Materials                   | Coefficient of Friction | Materials                 | Coefficient of Friction |
|-----------------------------|-------------------------|---------------------------|-------------------------|
| Straw fiber and cast iron   | 0.26                    | Tarred fiber and aluminum | 0.18                    |
| Straw fiber and aluminum    | 0.27                    | Leather and cast iron     | 0.14                    |
| Leather fiber and cast iron | 0.31                    | Leather and aluminum      | 0.22                    |
| Leather fiber and aluminum  | 0.30                    | Leather and typemetal     | 0.25                    |
| Tarred fiber and cast iron  | 0.15                    | Wood and metal            | 0.25                    |
| Paper and cast iron         | 0.20                    |                           |                         |

The horsepower transmitted is then:

$$\text{HP} = D \times N \times W \times C$$

*Example:* Find the horsepower transmitted by a pair of friction wheels; the diameter of the driving wheel is 10 inches, and it revolves at 200 revolutions per minute. The width of the wheel is 2 inches. The force per inch width of face is 150 pounds, and the coefficient of friction 0.20.

$$\text{HP} = 10 \times 200 \times 2 \times 0.00024 = 0.96 \text{ horsepower}$$

**Horsepower Which May be Transmitted by Means of a Clean Paper Friction Wheel of One-inch Face when Run Under a Force of 150 Pounds (Rockwood Mfg. Co.)**

| Dia. of Friction Wheel | Revolutions per Minute |       |       |       |       |       |       |       |       |      |       |
|------------------------|------------------------|-------|-------|-------|-------|-------|-------|-------|-------|------|-------|
|                        | 25                     | 50    | 75    | 100   | 150   | 200   | 300   | 400   | 600   | 800  | 1000  |
| 4                      | 0.023                  | 0.047 | 0.071 | 0.095 | 0.142 | 0.190 | 0.285 | 0.380 | 0.571 | 0.76 | 0.95  |
| 6                      | 0.035                  | 0.071 | 0.107 | 0.142 | 0.214 | 0.285 | 0.428 | 0.571 | 0.856 | 1.14 | 1.42  |
| 8                      | 0.047                  | 0.095 | 0.142 | 0.190 | 0.285 | 0.380 | 0.571 | 0.761 | 1.142 | 1.52 | 1.90  |
| 10                     | 0.059                  | 0.119 | 0.178 | 0.238 | 0.357 | 0.476 | 0.714 | 0.952 | 1.428 | 1.90 | 2.38  |
| 14                     | 0.083                  | 0.166 | 0.249 | 0.333 | 0.499 | 0.666 | 0.999 | 1.332 | 1.999 | 2.66 | 3.33  |
| 16                     | 0.095                  | 0.190 | 0.285 | 0.380 | 0.571 | 0.761 | 1.142 | 1.523 | 2.284 | 3.04 | 3.80  |
| 18                     | 0.107                  | 0.214 | 0.321 | 0.428 | 0.642 | 0.856 | 1.285 | 1.713 | 2.570 | 3.42 | 4.28  |
| 24                     | 0.142                  | 0.285 | 0.428 | 0.571 | 0.856 | 1.142 | 1.713 | 2.284 | 3.427 | 4.56 | 5.71  |
| 30                     | 0.178                  | 0.357 | 0.535 | 0.714 | 1.071 | 1.428 | 2.142 | 2.856 | 4.284 | 5.71 | 7.14  |
| 36                     | 0.214                  | 0.428 | 0.642 | 0.856 | 1.285 | 1.713 | 2.570 | 3.427 | 5.140 | 6.85 | 8.56  |
| 42                     | 0.249                  | 0.499 | 0.749 | 0.999 | 1.499 | 1.999 | 2.998 | 3.998 | 5.997 | 7.99 | 9.99  |
| 48                     | 0.285                  | 0.571 | 0.856 | 1.142 | 1.713 | 2.284 | 3.427 | 4.569 | 6.854 | 9.13 | 11.42 |
| 50                     | 0.297                  | 0.595 | 0.892 | 1.190 | 1.785 | 2.380 | 3.570 | 4.760 | 7.140 | 9.52 | 11.90 |

## KEYS AND KEYSEATS

**ANSI Standard Keys and Keyseats.**—American National Standard, B17.1 Keys and Keyseats, based on current industry practice, was approved in 1967, and reaffirmed in 1989. This standard establishes a uniform relationship between shaft sizes and key sizes for parallel and taper keys as shown in [Table 1](#). Other data in this standard are given in [Tables 2](#) and [3](#) through [7](#). The sizes and tolerances shown are for single key applications only.

The following definitions are given in the standard:

**Key:** A demountable machinery part which, when assembled into keyseats, provides a positive means for transmitting torque between the shaft and hub.

**Keyseat:** An axially located rectangular groove in a shaft or hub.

This standard recognizes that there are two classes of stock for parallel keys used by industry. One is a close, plus toleranced key stock and the other is a broad, negative toleranced bar stock. Based on the use of two types of stock, two classes of fit are shown:

**Class 1:** A clearance or metal-to-metal side fit obtained by using bar stock keys and keyseat tolerances as given in [Table 4](#). This is a relatively free fit and applies only to parallel keys.

**Class 2:** A side fit, with possible interference or clearance, obtained by using key stock and keyseat tolerances as given in [Table 4](#). This is a relatively tight fit.

**Class 3:** This is an interference side fit and is not tabulated in [Table 4](#) since the degree of interference has not been standardized. However, it is suggested that the top and bottom fit range given under Class 2 in [Table 4](#), for parallel keys be used.

**Table 1. Key Size Versus Shaft Diameter ANSI B17.1-1967 (R1998)**

| Nominal Shaft Diameter   |                | Nominal Key Size |                |                | Normal Keyseat Depth |                |
|--|----------------|------------------|----------------|----------------|----------------------|----------------|
| Over   | To (Incl.)     | Width, W         | Height, H      |                | H/2                  |                |
|  |                |                  | Square         | Rectangular    | Square               | Rectangular    |
| $\frac{3}{16}$   | $\frac{7}{16}$ | $\frac{3}{32}$   | $\frac{3}{32}$ | ...            | $\frac{3}{64}$       | ...            |
| $\frac{7}{16}$   | $\frac{9}{16}$ | $\frac{1}{8}$    | $\frac{1}{8}$  | $\frac{3}{32}$ | $\frac{1}{16}$       | $\frac{3}{64}$ |
| $\frac{9}{16}$   | $\frac{7}{8}$  | $\frac{3}{16}$   | $\frac{3}{16}$ | $\frac{1}{8}$  | $\frac{3}{32}$       | $\frac{1}{16}$ |
| $\frac{7}{8}$  | $1\frac{1}{4}$ | $\frac{1}{4}$    | $\frac{1}{4}$  | $\frac{3}{16}$ | $\frac{1}{8}$        | $\frac{3}{32}$ |
| $1\frac{1}{4}$   | $1\frac{3}{8}$ | $\frac{5}{16}$   | $\frac{5}{16}$ | $\frac{1}{4}$  | $\frac{5}{32}$       | $\frac{1}{8}$  |
| $1\frac{3}{8}$   | $1\frac{3}{4}$ | $\frac{3}{8}$    | $\frac{3}{8}$  | $\frac{1}{4}$  | $\frac{3}{16}$       | $\frac{1}{8}$  |
| $1\frac{3}{4}$   | $2\frac{1}{4}$ | $\frac{1}{2}$    | $\frac{1}{2}$  | $\frac{3}{8}$  | $\frac{1}{4}$        | $\frac{3}{16}$ |
| $2\frac{1}{4}$   | $2\frac{3}{4}$ | $\frac{5}{8}$    | $\frac{5}{8}$  | $\frac{7}{16}$ | $\frac{5}{16}$       | $\frac{7}{32}$ |
| $2\frac{3}{4}$   | $3\frac{1}{4}$ | $\frac{3}{4}$    | $\frac{3}{4}$  | $\frac{1}{2}$  | $\frac{3}{8}$        | $\frac{1}{4}$  |
| $3\frac{1}{4}$   | $3\frac{3}{4}$ | $\frac{7}{8}$    | $\frac{7}{8}$  | $\frac{5}{8}$  | $\frac{7}{16}$       | $\frac{5}{16}$ |
| $3\frac{3}{4}$   | $4\frac{1}{2}$ | 1                | 1              | $\frac{3}{4}$  | $\frac{1}{2}$        | $\frac{3}{8}$  |
| $4\frac{1}{2}$   | $5\frac{1}{2}$ | $1\frac{1}{4}$   | $1\frac{1}{4}$ | $\frac{7}{8}$  | $\frac{5}{8}$        | $\frac{7}{16}$ |
| $5\frac{1}{2}$   | $6\frac{1}{2}$ | $1\frac{1}{2}$   | $1\frac{1}{2}$ | 1              | $\frac{3}{4}$        | $\frac{1}{2}$  |
| Square Keys preferred for shaft diameters above this line; rectangular keys, below |                |                  |                |                |                      |                |
| $6\frac{1}{2}$   | $7\frac{1}{2}$ | $1\frac{3}{4}$   | $1\frac{3}{4}$ | $1\frac{1}{2}$ | $\frac{7}{8}$        | $\frac{3}{4}$  |
| $7\frac{1}{2}$   | 9              | 2                | 2              | $1\frac{1}{2}$ | 1                    | $\frac{3}{4}$  |
| 9  | 11             | $2\frac{1}{2}$   | $2\frac{1}{2}$ | $1\frac{3}{4}$ | $1\frac{1}{4}$       | $\frac{7}{8}$  |

<sup>a</sup> Some key standards show  $1\frac{1}{4}$  inches; preferred height is  $1\frac{1}{2}$  inches.

All dimensions are given in inches. For larger shaft sizes, see *ANSI Standard Woodruff Keys and Keyseats*.

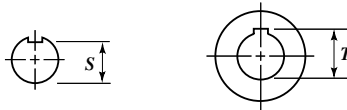
**Key Size vs. Shaft Diameter:** Shaft diameters are listed in [Table 1](#) for identification of various key sizes and are not intended to establish shaft dimensions, tolerances or selections. For a stepped shaft, the size of a key is determined by the diameter of the shaft at the



point of location of the key. Up through 6½-inch diameter shafts square keys are preferred; rectangular keys are preferred for larger shafts.

If special considerations dictate the use of a keyseat in the hub shallower than the preferred nominal depth shown, it is recommended that the tabulated preferred nominal standard keyseat always be used in the shaft.

**Keyseat Alignment Tolerances:** A tolerance of 0.010 inch, max is provided for offset (due to parallel displacement of keyseat centerline from centerline of shaft or bore) of keyseats in shaft and bore. The following tolerances for maximum lead (due to angular displacement of keyseat centerline from centerline of shaft or bore and measured at right angles to the shaft or bore centerline) of keyseats in shaft and bore are specified: 0.002 inch for keyseat length up to and including 4 inches; 0.0005 inch per inch of length for keyseat lengths above 4 inches to and including 10 inches; and 0.005 inch for keyseat lengths above 10 inches. For the effect of keyways on shaft strength, see *Effect of Keyways on Shaft Strength* on page 305.



**Table 2. Depth Control Values *S* and *T* for Shaft and Hub**  
*ANSI B17.1-1967 (R1998)*

| Nominal Shaft Diameter | Shafts, Parallel and Taper |             | Hubs, Parallel |             | Hubs, Taper |             |
|------------------------|----------------------------|-------------|----------------|-------------|-------------|-------------|
|                        | Square                     | Rectangular | Square         | Rectangular | Square      | Rectangular |
|                        | <i>S</i>                   | <i>S</i>    | <i>T</i>       | <i>T</i>    | <i>T</i>    | <i>T</i>    |
| ½                      | 0.430                      | 0.445       | 0.560          | 0.544       | 0.535       | 0.519       |
| ⅜                      | 0.493                      | 0.509       | 0.623          | 0.607       | 0.598       | 0.582       |
| ⅝                      | 0.517                      | 0.548       | 0.709          | 0.678       | 0.684       | 0.653       |
| ¾                      | 0.581                      | 0.612       | 0.773          | 0.742       | 0.748       | 0.717       |
| ⅞                      | 0.644                      | 0.676       | 0.837          | 0.806       | 0.812       | 0.781       |
| 1                      | 0.708                      | 0.739       | 0.900          | 0.869       | 0.875       | 0.844       |
| 1 ⅛                    | 0.771                      | 0.802       | 0.964          | 0.932       | 0.939       | 0.907       |
| 1 ¼                    | 0.796                      | 0.827       | 1.051          | 1.019       | 1.026       | 0.994       |
| 1 ⅝                    | 0.859                      | 0.890       | 1.114          | 1.083       | 1.089       | 1.058       |
| 1 ¾                    | 0.923                      | 0.954       | 1.178          | 1.146       | 1.153       | 1.121       |
| 1 ⅞                    | 0.986                      | 1.017       | 1.241          | 1.210       | 1.216       | 1.185       |
| 2                      | 1.049                      | 1.080       | 1.304          | 1.273       | 1.279       | 1.248       |
| 2 ⅛                    | 1.112                      | 1.144       | 1.367          | 1.336       | 1.342       | 1.311       |
| 2 ¼                    | 1.137                      | 1.169       | 1.455          | 1.424       | 1.430       | 1.399       |
| 2 ⅝                    | 1.201                      | 1.232       | 1.518          | 1.487       | 1.493       | 1.462       |
| 2 ¾                    | 1.225                      | 1.288       | 1.605          | 1.543       | 1.580       | 1.518       |
| 2 ⅞                    | 1.289                      | 1.351       | 1.669          | 1.606       | 1.644       | 1.581       |
| 3                      | 1.352                      | 1.415       | 1.732          | 1.670       | 1.707       | 1.645       |
| 3 ⅛                    | 1.416                      | 1.478       | 1.796          | 1.733       | 1.771       | 1.708       |
| 3 ¼                    | 1.479                      | 1.541       | 1.859          | 1.796       | 1.834       | 1.771       |
| 3 ⅝                    | 1.542                      | 1.605       | 1.922          | 1.860       | 1.897       | 1.835       |
| 3 ¾                    | 1.527                      | 1.590       | 2.032          | 1.970       | 2.007       | 1.945       |
| 3 ⅞                    | 1.591                      | 1.654       | 2.096          | 2.034       | 2.071       | 2.009       |
| 4                      | 1.655                      | 1.717       | 2.160          | 2.097       | 2.135       | 2.072       |
| 4 ⅛                    | 1.718                      | 1.781       | 2.223          | 2.161       | 2.198       | 2.136       |
| 4 ¼                    | 1.782                      | 1.844       | 2.287          | 2.224       | 2.262       | 2.199       |
| 4 ⅝                    | 1.845                      | 1.908       | 2.350          | 2.288       | 2.325       | 2.263       |
| 4 ¾                    | 1.909                      | 1.971       | 2.414          | 2.351       | 2.389       | 2.326       |
| 4 ⅞                    | 1.972                      | 2.034       | 2.477          | 2.414       | 2.452       | 2.389       |
| 5                      | 1.957                      | 2.051       | 2.587          | 2.493       | 2.562       | 2.468       |
| 5 ⅛                    | 2.021                      | 2.114       | 2.651          | 2.557       | 2.626       | 2.532       |

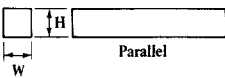
**Table 2. (Continued) Depth Control Values *S* and *T* for Shaft and Hub  
ANSI B17.1-1967 (R1998)**

| Nominal Shaft Diameter | Shafts, Parallel and Taper |                    | Hubs, Parallel |                    | Hubs, Taper |                    |
|------------------------|----------------------------|--------------------|----------------|--------------------|-------------|--------------------|
|                        | Square                     | Rectangular        | Square         | Rectangular        | Square      | Rectangular        |
|                        | <i>S</i>                   | <i>S</i>           | <i>T</i>       | <i>T</i>           | <i>T</i>    | <i>T</i>           |
| 2 $\frac{7}{16}$       | 2.084                      | 2.178              | 2.714          | 2.621              | 2.689       | 2.596              |
| 2 $\frac{1}{2}$        | 2.148                      | 2.242              | 2.778          | 2.684              | 2.753       | 2.659              |
| 2 $\frac{9}{16}$       | 2.211                      | 2.305              | 2.841          | 2.748              | 2.816       | 2.723              |
| 2 $\frac{5}{8}$        | 2.275                      | 2.369              | 2.905          | 2.811              | 2.880       | 2.786              |
| 2 $\frac{11}{16}$      | 2.338                      | 2.432              | 2.968          | 2.874              | 2.943       | 2.849              |
| 2 $\frac{3}{4}$        | 2.402                      | 2.495              | 3.032          | 2.938              | 3.007       | 2.913              |
| 2 $\frac{13}{16}$      | 2.387                      | 2.512              | 3.142          | 3.017              | 3.117       | 2.992              |
| 2 $\frac{7}{8}$        | 2.450                      | 2.575              | 3.205          | 3.080              | 3.180       | 3.055              |
| 2 $\frac{15}{16}$      | 2.514                      | 2.639              | 3.269          | 3.144              | 3.244       | 3.119              |
| 3                      | 2.577                      | 2.702              | 3.332          | 3.207              | 3.307       | 3.182              |
| 3 $\frac{1}{16}$       | 2.641                      | 2.766              | 3.396          | 3.271              | 3.371       | 3.246              |
| 3 $\frac{1}{8}$        | 2.704                      | 2.829              | 3.459          | 3.334              | 3.434       | 3.309              |
| 3 $\frac{3}{16}$       | 2.768                      | 2.893              | 3.523          | 3.398              | 3.498       | 3.373              |
| 3 $\frac{1}{4}$        | 2.831                      | 2.956              | 3.586          | 3.461              | 3.561       | 3.436              |
| 3 $\frac{5}{16}$       | 2.816                      | 2.941              | 3.696          | 3.571              | 3.671       | 3.546              |
| 3 $\frac{3}{8}$        | 2.880                      | 3.005              | 3.760          | 3.635              | 3.735       | 3.610              |
| 3 $\frac{7}{16}$       | 2.943                      | 3.068              | 3.823          | 3.698              | 3.798       | 3.673              |
| 3 $\frac{1}{2}$        | 3.007                      | 3.132              | 3.887          | 3.762              | 3.862       | 3.737              |
| 3 $\frac{9}{16}$       | 3.070                      | 3.195              | 3.950          | 3.825              | 3.925       | 3.800              |
| 3 $\frac{5}{8}$        | 3.134                      | 3.259              | 4.014          | 3.889              | 3.989       | 3.864              |
| 3 $\frac{11}{16}$      | 3.197                      | 3.322              | 4.077          | 3.952              | 4.052       | 3.927              |
| 3 $\frac{3}{4}$        | 3.261                      | 3.386              | 4.141          | 4.016              | 4.116       | 3.991              |
| 3 $\frac{13}{16}$      | 3.246                      | 3.371              | 4.251          | 4.126              | 4.226       | 4.101              |
| 3 $\frac{7}{8}$        | 3.309                      | 3.434              | 4.314          | 4.189              | 4.289       | 4.164              |
| 3 $\frac{15}{16}$      | 3.373                      | 3.498              | 4.378          | 4.253              | 4.353       | 4.228              |
| 4                      | 3.436                      | 3.561              | 4.441          | 4.316              | 4.416       | 4.291              |
| 4 $\frac{1}{16}$       | 3.627                      | 3.752              | 4.632          | 4.507              | 4.607       | 4.482              |
| 4 $\frac{1}{4}$        | 3.690                      | 3.815              | 4.695          | 4.570              | 4.670       | 4.545              |
| 4 $\frac{3}{8}$        | 3.817                      | 3.942              | 4.822          | 4.697              | 4.797       | 4.672              |
| 4 $\frac{1}{2}$        | 3.880                      | 4.005              | 4.885          | 4.760              | 4.860       | 4.735              |
| 4 $\frac{1}{2}$        | 3.944                      | 4.069              | 4.949          | 4.824              | 4.924       | 4.799              |
| 4 $\frac{3}{4}$        | 4.041                      | 4.229              | 5.296          | 5.109              | 5.271       | 5.084              |
| 4 $\frac{7}{8}$        | 4.169                      | 4.356              | 5.424          | 5.236              | 5.399       | 5.211              |
| 4 $\frac{15}{16}$      | 4.232                      | 4.422              | 5.487          | 5.300              | 5.462       | 5.275              |
| 5                      | 4.296                      | 4.483              | 5.551          | 5.363              | 5.526       | 5.338              |
| 5 $\frac{1}{16}$       | 4.486                      | 4.674              | 5.741          | 5.554              | 5.716       | 5.529              |
| 5 $\frac{1}{4}$        | 4.550                      | 4.737              | 5.805          | 5.617              | 5.780       | 5.592              |
| 5 $\frac{1}{8}$        | 4.740                      | 4.927              | 5.995          | 5.807              | 5.970       | 5.782              |
| 5 $\frac{1}{2}$        | 4.803                      | 4.991              | 6.058          | 5.871              | 6.033       | 5.846              |
| 5 $\frac{3}{4}$        | 4.900                      | 5.150              | 6.405          | 6.155              | 6.380       | 6.130              |
| 5 $\frac{15}{16}$      | 5.091                      | 5.341              | 6.596          | 6.346              | 6.571       | 6.321              |
| 6                      | 5.155                      | 5.405              | 6.660          | 6.410              | 6.635       | 6.385              |
| 6 $\frac{1}{4}$        | 5.409                      | 5.659              | 6.914          | 6.664              | 6.889       | 6.639              |
| 6 $\frac{1}{2}$        | 5.662                      | 5.912              | 7.167          | 6.917              | 7.142       | 6.892              |
| 6 $\frac{3}{4}$        | 5.760                      | <sup>a</sup> 5.885 | 7.515          | <sup>a</sup> 7.390 | 7.490       | <sup>a</sup> 7.365 |
| 7                      | 6.014                      | <sup>a</sup> 6.139 | 7.769          | <sup>a</sup> 7.644 | 7.744       | <sup>a</sup> 7.619 |
| 7 $\frac{1}{4}$        | 6.268                      | <sup>a</sup> 6.393 | 8.023          | <sup>a</sup> 7.898 | 7.998       | <sup>a</sup> 7.873 |
| 7 $\frac{1}{2}$        | 6.521                      | <sup>a</sup> 6.646 | 8.276          | <sup>a</sup> 8.151 | 8.251       | <sup>a</sup> 8.126 |
| 7 $\frac{3}{4}$        | 6.619                      | 6.869              | 8.624          | 8.374              | 8.599       | 8.349              |
| 8                      | 6.873                      | 7.123              | 8.878          | 8.628              | 8.853       | 8.603              |
| 9                      | 7.887                      | 8.137              | 9.892          | 9.642              | 9.867       | 9.617              |
| 10                     | 8.591                      | 8.966              | 11.096         | 10.721             | 11.071      | 10.696             |
| 11                     | 9.606                      | 9.981              | 12.111         | 11.736             | 12.086      | 11.711             |
| 12                     | 10.309                     | 10.809             | 13.314         | 12.814             | 13.289      | 12.789             |
| 13                     | 11.325                     | 11.825             | 14.330         | 13.830             | 14.305      | 13.805             |
| 14                     | 12.028                     | 12.528             | 15.533         | 15.033             | 15.508      | 15.008             |
| 15                     | 13.043                     | 13.543             | 16.548         | 16.048             | 16.523      | 16.023             |

<sup>a</sup> 1 $\frac{3}{4}$  × 1 $\frac{1}{2}$  inch key.

All dimensions are given in inches. See Table 4 for tolerances.

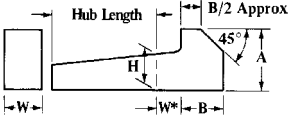
**Table 3. ANSI Standard Plain and Gib Head Keys ANSI B17.1-1967 (R1998)**



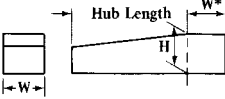
Parallel

Plain and Gib Head

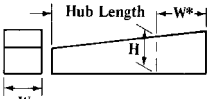
Taper Keys Have a 1/8" Taper in 12"



Gib Head Taper



Plain Taper



Alternate Plain Taper

| Key      |   |           | Nominal Key Size |            | Tolerance |        |           |        |           |
|----------|---|-----------|------------------|------------|-----------|--------|-----------|--------|-----------|
|          |   |           | Width W          |            | Width, W  |        |           |        | Height, H |
|          |   |           | Over             | To (Incl.) | Width, W  |        | Height, H |        |           |
| Parallel | Square                                  | Keystock  | ...              | 1¼         | +0.001    | -0.000 | +0.001    | -0.000 |           |
|          |   |           | 1¼               | 3          | +0.002    | -0.000 | +0.002    | -0.000 |           |
|          |   |           | 3                | 3½         | +0.003    | -0.000 | +0.003    | -0.000 |           |
|          |   | Bar Stock | ...              | ¾          | +0.000    | -0.002 | +0.000    | -0.002 |           |
|          |   |           | ¾                | 1½         | +0.000    | -0.003 | +0.000    | -0.003 |           |
|          |   |           | 1½               | 2½         | +0.000    | -0.004 | +0.000    | -0.004 |           |
|          | Rectangular                             | Keystock  | ...              | 1¼         | +0.001    | -0.000 | +0.005    | -0.005 |           |
|          |   |           | 1¼               | 3          | +0.002    | -0.000 | +0.005    | -0.005 |           |
|          |   |           | 3                | 7          | +0.003    | -0.000 | +0.005    | -0.005 |           |
|          |   | Bar Stock | ...              | ¾          | +0.000    | -0.003 | +0.000    | -0.003 |           |
|          |   |           | ¾                | 1½         | +0.000    | -0.004 | +0.000    | -0.004 |           |
|          |   |           | 1½               | 3          | +0.000    | -0.005 | +0.000    | -0.005 |           |
| Taper    | Plain or Gib Head Square or Rectangular | ...       | 1¼               | +0.001     | -0.000    | +0.005 | -0.000    |        |           |
|          |   | 1¼        | 3                | +0.002     | -0.000    | +0.005 | -0.000    |        |           |
|          |   | 3         | 7                | +0.003     | -0.000    | +0.005 | -0.000    |        |           |

| Gib Head Nominal Dimensions |        |       |      |             |      |      |                           |        |       |        |             |       |       |
|-----------------------------|--------|-------|------|-------------|------|------|---------------------------|--------|-------|--------|-------------|-------|-------|
| Nominal Key Size Width, W   | Square |       |      | Rectangular |      |      | Nominal Key Size Width, W | Square |       |        | Rectangular |       |       |
|                             | H      | A     | B    | H           | A    | B    |                           | H      | A     | B      | H           | A     | B     |
| 1/8                         | 1/8    | 1/4   | 1/4  | 3/32        | 3/16 | 1/8  | 1                         | 1      | 1 1/8 | 1 1/8  | 3/4         | 1 1/4 | 7/8   |
| 3/16                        | 3/16   | 5/16  | 5/16 | 1/8         | 1/4  | 1/4  | 1 1/4                     | 1 1/4  | 2     | 1 7/16 | 7/8         | 1 3/8 | 1     |
| 1/4                         | 1/4    | 7/16  | 3/8  | 3/16        | 5/16 | 5/16 | 1 1/2                     | 1 1/2  | 2 3/8 | 1 3/4  | 1           | 1 5/8 | 1 1/8 |
| 5/16                        | 5/16   | 1/2   | 7/16 | 1/4         | 7/16 | 3/8  | 1 3/4                     | 1 3/4  | 2 3/4 | 2      | 1 1/2       | 2 3/8 | 1 3/4 |
| 3/8                         | 3/8    | 5/8   | 1/2  | 1/4         | 7/16 | 3/8  | 2                         | 2      | 3 1/2 | 2 1/4  | 1 1/2       | 2 3/8 | 1 3/4 |
| 1/2                         | 1/2    | 7/8   | 3/8  | 3/8         | 5/8  | 1/2  | 2 1/2                     | 2 1/2  | 4     | 3      | 1 3/4       | 2 3/4 | 2     |
| 5/8                         | 5/8    | 1     | 3/4  | 7/16        | 3/4  | 9/16 | 3                         | 3      | 5     | 3 1/2  | 2           | 3 1/2 | 2 1/4 |
| 3/4                         | 3/4    | 1 1/4 | 7/8  | 1/2         | 7/8  | 5/8  | 3 1/2                     | 3 1/2  | 6     | 4      | 2 1/2       | 4     | 3     |
| 7/8                         | 7/8    | 1 3/8 | 1    | 5/8         | 1    | 3/4  | ...                       | ...    | ...   | ...    | ...         | ...   | ...   |

All dimensions are given in inches.

\*For locating position of dimension H. Tolerance does not apply.

For larger sizes the following relationships are suggested as guides for establishing A and B: A = 1.8H and B = 1.2H.

**Table 4. ANSI Standard Fits for Parallel and Taper Keys ANSI B17.1-1967 (R1998)**

| Type of Key                             | Key Width   |            | Side Fit         |                  |                        | Top and Bottom Fit |                  |                  |                        |                      |
|---|-------------|------------|------------------|------------------|------------------------|--------------------|------------------|------------------|------------------------|----------------------|
|   | Over        | To (Incl.) | Width Tolerance  |                  | Fit Range <sup>a</sup> | Depth Tolerance    |                  |                  | Fit Range <sup>a</sup> |                      |
|   |             |            | Key              | Key-Seat         |                        | Key                | Shaft Key-Seat   | Hub Key-Seat     |                        |                      |
| Class 1 Fit for Parallel Keys           |             |            |                  |                  |                        |                    |                  |                  |                        |                      |
| Square                                  | ...         | 1/2        | +0.000<br>-0.002 | +0.002<br>-0.000 | 0.004 CL<br>0.000      | +0.000<br>-0.002   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.032 CL<br>0.005 CL   |                      |
|   | 1/2         | 3/4        | +0.000<br>-0.002 | +0.003<br>-0.000 | 0.005 CL<br>0.000      | +0.000<br>-0.002   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.032 CL<br>0.005 CL   |                      |
|   | 3/4         | 1          | +0.000<br>-0.003 | +0.003<br>-0.000 | 0.006 CL<br>0.000      | +0.000<br>-0.003   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.033 CL<br>0.005 CL   |                      |
|   | 1           | 1 1/2      | +0.000<br>-0.003 | +0.004<br>-0.000 | 0.007 CL<br>0.000      | +0.000<br>-0.003   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.033 CL<br>0.005 CL   |                      |
|   | 1 1/2       | 2 1/2      | +0.000<br>-0.004 | +0.004<br>-0.000 | 0.008 CL<br>0.000      | +0.000<br>-0.004   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.034 CL<br>0.005 CL   |                      |
|   | 2 1/2       | 3 1/2      | +0.000<br>-0.006 | +0.004<br>-0.000 | 0.010 CL<br>0.000      | +0.000<br>-0.006   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.036 CL<br>0.005 CL   |                      |
|   | Rectangular | ...        | 1/2              | +0.000<br>-0.003 | +0.002<br>-0.000       | 0.005 CL<br>0.000  | +0.000<br>-0.003 | +0.000<br>-0.015 | +0.010<br>-0.000       | 0.033 CL<br>0.005 CL |
|   |             | 1/2        | 3/4              | +0.000<br>-0.003 | +0.003<br>-0.000       | 0.006 CL<br>0.000  | +0.000<br>-0.003 | +0.000<br>-0.015 | +0.010<br>-0.000       | 0.033 CL<br>0.005 CL |
| 3/4                                     |             | 1          | +0.000<br>-0.004 | +0.003<br>-0.000 | 0.007 CL<br>0.000      | +0.000<br>-0.004   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.034 CL<br>0.005 CL   |                      |
| 1                                       |             | 1 1/2      | +0.000<br>-0.004 | +0.004<br>-0.000 | 0.008 CL<br>0.000      | +0.000<br>-0.004   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.034 CL<br>0.005 CL   |                      |
| 1 1/2                                   |             | 3          | +0.000<br>-0.005 | +0.004<br>-0.000 | 0.009 CL<br>0.000      | +0.000<br>-0.005   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.035 CL<br>0.005 CL   |                      |
| 3                                       |             | 4          | +0.000<br>-0.006 | +0.004<br>-0.000 | 0.010 CL<br>0.000      | +0.000<br>-0.006   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.036 CL<br>0.005 CL   |                      |
| 4                                       |             | 6          | +0.000<br>-0.008 | +0.004<br>-0.000 | 0.012 CL<br>0.000      | +0.000<br>-0.008   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.038 CL<br>0.005 CL   |                      |
| 6                                       |             | 7          | +0.000<br>-0.013 | +0.004<br>-0.000 | 0.017 CL<br>0.000      | +0.000<br>-0.013   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.043 CL<br>0.005 CL   |                      |
| Class 2 Fit for Parallel and Taper Keys |             |            |                  |                  |                        |                    |                  |                  |                        |                      |
| Parallel Square                         | ...         | 1 1/4      | +0.001<br>-0.000 | +0.002<br>-0.000 | 0.002 CL<br>0.001 INT  | +0.001<br>-0.000   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.030 CL<br>0.004 CL   |                      |
|   | 1 1/4       | 3          | +0.002<br>-0.000 | +0.002<br>-0.000 | 0.002 CL<br>0.002 INT  | +0.002<br>-0.000   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.030 CL<br>0.003 CL   |                      |
|   | 3           | 3 1/2      | +0.003<br>-0.000 | +0.002<br>-0.000 | 0.002 CL<br>0.003 INT  | +0.003<br>-0.000   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.030 CL<br>0.002 CL   |                      |
| Parallel Rectangular                    | ...         | 1 1/4      | +0.001<br>-0.000 | +0.002<br>-0.000 | 0.002 CL<br>0.001 INT  | +0.005<br>-0.005   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.035 CL<br>0.000 CL   |                      |
|   | 1 1/4       | 3          | +0.002<br>-0.000 | +0.002<br>-0.000 | 0.002 CL<br>0.002 INT  | +0.005<br>-0.005   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.035 CL<br>0.000 CL   |                      |
|   | 3           | 7          | +0.003<br>-0.000 | +0.002<br>-0.000 | 0.002 CL<br>0.003 INT  | +0.005<br>-0.005   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.035 CL<br>0.000 CL   |                      |
| Taper                                   | ...         | 1 1/4      | +0.001<br>-0.000 | +0.002<br>-0.000 | 0.002 CL<br>0.001 INT  | +0.005<br>-0.000   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.005 CL<br>0.025 INT  |                      |
|   | 1 1/4       | 3          | +0.002<br>-0.000 | +0.002<br>-0.000 | 0.002 CL<br>0.002 INT  | +0.005<br>-0.000   | +0.000<br>-0.015 | +0.010<br>-0.000 | 0.005 CL<br>0.025 INT  |                      |
|   | 3           | b          | +0.003           | +0.002           | 0.002 CL               | +0.005             | +0.000           | +0.010           | 0.005 CL               |                      |
|   |             |            | -0.000           | -0.000           | 0.003 INT              | -0.000             | -0.015           | -0.000           | 0.025 INT              |                      |

<sup>a</sup>Limits of variation. CL = Clearance; INT = Interference.

<sup>b</sup>To (Incl.) 3 1/2-inch Square and 7-inch Rectangular key widths.

All dimensions are given in inches. See also text on page 2363.

KEYS AND KEYSEATS

**Table 5. Suggested Keyseat Fillet Radius and Key Chamfer**  
ANSI B17.1-1967 (R1998)

| Keyseat Depth, $H/2$ |               | Fillet Radius  | 45 deg. Chamfer | Keyseat Depth, $H/2$ |                | Fillet Radius  | 45 deg. Chamfer |
|----------------------|---------------|----------------|-----------------|----------------------|----------------|----------------|-----------------|
| Over                 | To (Incl.)    |                |                 | Over                 | To (Incl.)     |                |                 |
| $\frac{1}{8}$        | $\frac{1}{4}$ | $\frac{1}{32}$ | $\frac{3}{64}$  | $\frac{7}{8}$        | $1\frac{1}{4}$ | $\frac{3}{16}$ | $\frac{7}{32}$  |
| $\frac{1}{4}$        | $\frac{1}{2}$ | $\frac{1}{16}$ | $\frac{5}{64}$  | $1\frac{1}{4}$       | $1\frac{3}{4}$ | $\frac{1}{4}$  | $\frac{9}{32}$  |
| $\frac{1}{2}$        | $\frac{7}{8}$ | $\frac{1}{8}$  | $\frac{5}{32}$  | $1\frac{3}{4}$       | $2\frac{1}{2}$ | $\frac{3}{8}$  | $\frac{13}{32}$ |

All dimensions are given in inches.

**Table 6. ANSI Standard Keyseat Tolerances for Electric Motor and Generator Shaft Extensions** ANSI B17.1-1967 (R1998)

| Keyseat Width |                | Width Tolerance  | Depth Tolerance  |
|---------------|----------------|------------------|------------------|
| Over          | To (Incl.)     |                  |                  |
| ...           | $\frac{1}{4}$  | +0.001<br>-0.001 | +0.000<br>-0.015 |
| $\frac{1}{4}$ | $\frac{3}{4}$  | +0.000<br>-0.002 | +0.000<br>-0.015 |
| $\frac{3}{4}$ | $1\frac{1}{4}$ | +0.000<br>-0.003 | +0.000<br>-0.015 |

All dimensions are given in inches.

**Table 7. Set Screws for Use Over Keys** ANSI B17.1-1967 (R1998)

| Nom. Shaft Dia. |                | Nom. Key Width | Set Screw Dia. | Nom. Shaft Dia. |                | Nom. Key Width | Set Screw Dia. |
|-----------------|----------------|----------------|----------------|-----------------|----------------|----------------|----------------|
| Over            | To (Incl.)     |                |                | Over            | To (Incl.)     |                |                |
| $\frac{5}{16}$  | $\frac{7}{16}$ | $\frac{3}{32}$ | No. 10         | $2\frac{1}{4}$  | $2\frac{3}{4}$ | $\frac{5}{8}$  | $\frac{1}{2}$  |
| $\frac{7}{16}$  | $\frac{9}{16}$ | $\frac{1}{8}$  | No. 10         | $2\frac{3}{4}$  | $3\frac{1}{4}$ | $\frac{3}{4}$  | $\frac{5}{8}$  |
| $\frac{9}{16}$  | $\frac{7}{8}$  | $\frac{3}{16}$ | $\frac{1}{4}$  | $3\frac{1}{4}$  | $3\frac{3}{4}$ | $\frac{7}{8}$  | $\frac{3}{4}$  |
| $\frac{7}{8}$   | $1\frac{1}{4}$ | $\frac{1}{4}$  | $\frac{5}{16}$ | $3\frac{3}{4}$  | $4\frac{1}{2}$ | 1              | $\frac{3}{4}$  |
| $1\frac{1}{4}$  | $1\frac{3}{8}$ | $\frac{5}{16}$ | $\frac{3}{8}$  | $4\frac{1}{2}$  | $5\frac{1}{2}$ | $1\frac{1}{4}$ | $\frac{7}{8}$  |
| $1\frac{3}{8}$  | $1\frac{3}{4}$ | $\frac{3}{8}$  | $\frac{3}{8}$  | $5\frac{1}{2}$  | $6\frac{1}{2}$ | $1\frac{1}{2}$ | 1              |
| $1\frac{3}{4}$  | $2\frac{1}{4}$ | $\frac{1}{2}$  | $\frac{1}{2}$  | ...             | ...            | ...            | ...            |

All dimensions are given in inches.

These set screw diameter selections are offered as a guide but their use should be dependent upon design considerations.

**ANSI Standard Woodruff Keys and Keyseats.**—American National Standard B17.2 was approved in 1967, and reaffirmed in 1990. Data from this standard are shown in [Tables 8, 9, and 10](#).

Table 8. ANSI Standard Woodruff Keys ANSI B17.2-1967 (R1998)

| Key No. | Nominal Key Size $W \times B$      | Actual Length $F$<br>+0.000<br>-0.010 | Height of Key |       |       |       | Distance Below Center $E$ |
|---------|------------------------------------|---------------------------------------|---------------|-------|-------|-------|---------------------------|
|         |                                    |                                       | $C$           |       | $D$   |       |                           |
|         |                                    |                                       | Max.          | Min.  | Max.  | Min.  |                           |
| 202     | $\frac{1}{16} \times \frac{1}{4}$  | 0.248                                 | 0.109         | 0.104 | 0.109 | 0.104 | $\frac{1}{64}$            |
| 202.5   | $\frac{1}{16} \times \frac{5}{16}$ | 0.311                                 | 0.140         | 0.135 | 0.140 | 0.135 | $\frac{1}{64}$            |
| 302.5   | $\frac{3}{32} \times \frac{5}{16}$ | 0.311                                 | 0.140         | 0.135 | 0.140 | 0.135 | $\frac{1}{64}$            |
| 203     | $\frac{1}{16} \times \frac{3}{8}$  | 0.374                                 | 0.172         | 0.167 | 0.172 | 0.167 | $\frac{1}{64}$            |
| 303     | $\frac{3}{32} \times \frac{3}{8}$  | 0.374                                 | 0.172         | 0.167 | 0.172 | 0.167 | $\frac{1}{64}$            |
| 403     | $\frac{1}{8} \times \frac{3}{8}$   | 0.374                                 | 0.172         | 0.167 | 0.172 | 0.167 | $\frac{1}{64}$            |
| 204     | $\frac{1}{16} \times \frac{1}{2}$  | 0.491                                 | 0.203         | 0.198 | 0.194 | 0.188 | $\frac{3}{64}$            |
| 304     | $\frac{3}{32} \times \frac{1}{2}$  | 0.491                                 | 0.203         | 0.198 | 0.194 | 0.188 | $\frac{3}{64}$            |
| 404     | $\frac{1}{8} \times \frac{1}{2}$   | 0.491                                 | 0.203         | 0.198 | 0.194 | 0.188 | $\frac{3}{64}$            |
| 305     | $\frac{3}{32} \times \frac{5}{8}$  | 0.612                                 | 0.250         | 0.245 | 0.240 | 0.234 | $\frac{1}{16}$            |
| 405     | $\frac{1}{8} \times \frac{5}{8}$   | 0.612                                 | 0.250         | 0.245 | 0.240 | 0.234 | $\frac{1}{16}$            |
| 505     | $\frac{5}{32} \times \frac{5}{8}$  | 0.612                                 | 0.250         | 0.245 | 0.240 | 0.234 | $\frac{1}{16}$            |
| 605     | $\frac{3}{16} \times \frac{3}{8}$  | 0.612                                 | 0.250         | 0.245 | 0.240 | 0.234 | $\frac{1}{16}$            |
| 406     | $\frac{1}{8} \times \frac{3}{4}$   | 0.740                                 | 0.313         | 0.308 | 0.303 | 0.297 | $\frac{1}{16}$            |
| 506     | $\frac{5}{32} \times \frac{3}{4}$  | 0.740                                 | 0.313         | 0.308 | 0.303 | 0.297 | $\frac{1}{16}$            |
| 606     | $\frac{3}{16} \times \frac{3}{4}$  | 0.740                                 | 0.313         | 0.308 | 0.303 | 0.297 | $\frac{1}{16}$            |
| 806     | $\frac{1}{4} \times \frac{3}{4}$   | 0.740                                 | 0.313         | 0.308 | 0.303 | 0.297 | $\frac{1}{16}$            |
| 507     | $\frac{5}{32} \times \frac{7}{8}$  | 0.866                                 | 0.375         | 0.370 | 0.365 | 0.359 | $\frac{1}{16}$            |
| 607     | $\frac{3}{16} \times \frac{7}{8}$  | 0.866                                 | 0.375         | 0.370 | 0.365 | 0.359 | $\frac{1}{16}$            |
| 707     | $\frac{7}{32} \times \frac{7}{8}$  | 0.866                                 | 0.375         | 0.370 | 0.365 | 0.359 | $\frac{1}{16}$            |
| 807     | $\frac{1}{4} \times \frac{7}{8}$   | 0.866                                 | 0.375         | 0.370 | 0.365 | 0.359 | $\frac{1}{16}$            |
| 608     | $\frac{3}{16} \times 1$            | 0.992                                 | 0.438         | 0.433 | 0.428 | 0.422 | $\frac{1}{16}$            |
| 708     | $\frac{7}{32} \times 1$            | 0.992                                 | 0.438         | 0.433 | 0.428 | 0.422 | $\frac{1}{16}$            |
| 808     | $\frac{1}{4} \times 1$             | 0.992                                 | 0.438         | 0.433 | 0.428 | 0.422 | $\frac{1}{16}$            |
| 1008    | $\frac{5}{16} \times 1$            | 0.992                                 | 0.438         | 0.433 | 0.428 | 0.422 | $\frac{1}{16}$            |
| 1208    | $\frac{3}{8} \times 1$             | 0.992                                 | 0.438         | 0.433 | 0.428 | 0.422 | $\frac{1}{16}$            |
| 609     | $\frac{3}{16} \times 1\frac{1}{8}$ | 1.114                                 | 0.484         | 0.479 | 0.475 | 0.469 | $\frac{5}{64}$            |
| 709     | $\frac{7}{32} \times 1\frac{1}{8}$ | 1.114                                 | 0.484         | 0.479 | 0.475 | 0.469 | $\frac{5}{64}$            |
| 809     | $\frac{1}{4} \times 1\frac{1}{8}$  | 1.114                                 | 0.484         | 0.479 | 0.475 | 0.469 | $\frac{5}{64}$            |
| 1009    | $\frac{5}{16} \times 1\frac{1}{8}$ | 1.114                                 | 0.484         | 0.479 | 0.475 | 0.469 | $\frac{5}{64}$            |
| 610     | $\frac{3}{16} \times 1\frac{1}{4}$ | 1.240                                 | 0.547         | 0.542 | 0.537 | 0.531 | $\frac{5}{64}$            |
| 710     | $\frac{7}{32} \times 1\frac{1}{4}$ | 1.240                                 | 0.547         | 0.542 | 0.537 | 0.531 | $\frac{5}{64}$            |
| 810     | $\frac{1}{4} \times 1\frac{1}{4}$  | 1.240                                 | 0.547         | 0.542 | 0.537 | 0.531 | $\frac{5}{64}$            |
| 1010    | $\frac{5}{16} \times 1\frac{1}{4}$ | 1.240                                 | 0.547         | 0.542 | 0.537 | 0.531 | $\frac{5}{64}$            |
| 1210    | $\frac{3}{8} \times 1\frac{1}{4}$  | 1.240                                 | 0.547         | 0.542 | 0.537 | 0.531 | $\frac{5}{64}$            |
| 811     | $\frac{1}{4} \times 1\frac{3}{8}$  | 1.362                                 | 0.594         | 0.589 | 0.584 | 0.578 | $\frac{3}{32}$            |
| 1011    | $\frac{5}{16} \times 1\frac{3}{8}$ | 1.362                                 | 0.594         | 0.589 | 0.584 | 0.578 | $\frac{3}{32}$            |
| 1211    | $\frac{3}{8} \times 1\frac{3}{8}$  | 1.362                                 | 0.594         | 0.589 | 0.584 | 0.578 | $\frac{3}{32}$            |
| 812     | $\frac{1}{4} \times 1\frac{1}{2}$  | 1.484                                 | 0.641         | 0.636 | 0.631 | 0.625 | $\frac{7}{64}$            |
| 1012    | $\frac{5}{16} \times 1\frac{1}{2}$ | 1.484                                 | 0.641         | 0.636 | 0.631 | 0.625 | $\frac{7}{64}$            |
| 1212    | $\frac{3}{8} \times 1\frac{1}{2}$  | 1.484                                 | 0.641         | 0.636 | 0.631 | 0.625 | $\frac{7}{64}$            |

All dimensions are given in inches.

The Key numbers indicate normal key dimensions. The last two digits give the nominal diameter  $B$  in eighths of an inch and the digits preceding the last two give the nominal width  $W$  in thirty-seconds of an inch.

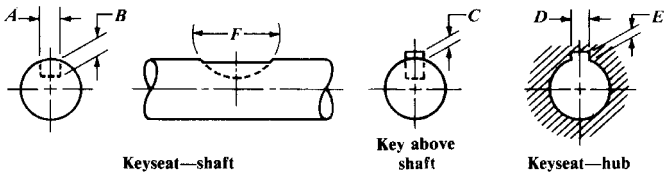
Table 9. ANSI Standard Woodruff Keys ANSI B17.2-1967 (R1998)

| Key No. | Nominal Key Size $W \times B$       | Actual Length $F$<br>+0.000<br>-0.010 | Height of Key |       |       |       | Distance Below Center $E$ |
|---------|-------------------------------------|---------------------------------------|---------------|-------|-------|-------|---------------------------|
|         |                                     |                                       | $C$           |       | $D$   |       |                           |
|         |                                     |                                       | Max.          | Min.  | Max.  | Min.  |                           |
| 617-1   | $\frac{3}{16} \times 2\frac{1}{8}$  | 1.380                                 | 0.406         | 0.401 | 0.396 | 0.390 | $\frac{2}{32}$            |
| 817-1   | $\frac{1}{4} \times 2\frac{1}{8}$   | 1.380                                 | 0.406         | 0.401 | 0.396 | 0.390 | $\frac{2}{32}$            |
| 1017-1  | $\frac{5}{16} \times 2\frac{1}{8}$  | 1.380                                 | 0.406         | 0.401 | 0.396 | 0.390 | $\frac{2}{32}$            |
| 1217-1  | $\frac{3}{8} \times 2\frac{1}{8}$   | 1.380                                 | 0.406         | 0.401 | 0.396 | 0.390 | $\frac{2}{32}$            |
| 617     | $\frac{3}{16} \times 2\frac{1}{8}$  | 1.723                                 | 0.531         | 0.526 | 0.521 | 0.515 | $\frac{17}{32}$           |
| 817     | $\frac{1}{4} \times 2\frac{1}{8}$   | 1.723                                 | 0.531         | 0.526 | 0.521 | 0.515 | $\frac{17}{32}$           |
| 1017    | $\frac{5}{16} \times 2\frac{1}{8}$  | 1.723                                 | 0.531         | 0.526 | 0.521 | 0.515 | $\frac{17}{32}$           |
| 1217    | $\frac{3}{8} \times 2\frac{1}{8}$   | 1.723                                 | 0.531         | 0.526 | 0.521 | 0.515 | $\frac{17}{32}$           |
| 822-1   | $\frac{1}{4} \times 2\frac{3}{4}$   | 2.000                                 | 0.594         | 0.589 | 0.584 | 0.578 | $\frac{25}{32}$           |
| 1022-1  | $\frac{5}{16} \times 2\frac{3}{4}$  | 2.000                                 | 0.594         | 0.589 | 0.584 | 0.578 | $\frac{25}{32}$           |
| 1222-1  | $\frac{3}{8} \times 2\frac{3}{4}$   | 2.000                                 | 0.594         | 0.589 | 0.584 | 0.578 | $\frac{25}{32}$           |
| 1422-1  | $\frac{7}{16} \times 2\frac{3}{4}$  | 2.000                                 | 0.594         | 0.589 | 0.584 | 0.578 | $\frac{25}{32}$           |
| 1622-1  | $\frac{1}{2} \times 2\frac{3}{4}$   | 2.000                                 | 0.594         | 0.589 | 0.584 | 0.578 | $\frac{25}{32}$           |
| 822     | $\frac{1}{4} \times 2\frac{3}{4}$   | 2.317                                 | 0.750         | 0.745 | 0.740 | 0.734 | $\frac{5}{8}$             |
| 1022    | $\frac{5}{16} \times 2\frac{3}{4}$  | 2.317                                 | 0.750         | 0.745 | 0.740 | 0.734 | $\frac{5}{8}$             |
| 1222    | $\frac{3}{8} \times 2\frac{3}{4}$   | 2.317                                 | 0.750         | 0.745 | 0.740 | 0.734 | $\frac{5}{8}$             |
| 1422    | $\frac{7}{16} \times 2\frac{3}{4}$  | 2.317                                 | 0.750         | 0.745 | 0.740 | 0.734 | $\frac{5}{8}$             |
| 1622    | $\frac{1}{2} \times 2\frac{3}{4}$   | 2.317                                 | 0.750         | 0.745 | 0.740 | 0.734 | $\frac{5}{8}$             |
| 1228    | $\frac{3}{8} \times 3\frac{1}{2}$   | 2.880                                 | 0.938         | 0.933 | 0.928 | 0.922 | $\frac{13}{16}$           |
| 1428    | $\frac{7}{16} \times 3\frac{1}{2}$  | 2.880                                 | 0.938         | 0.933 | 0.928 | 0.922 | $\frac{13}{16}$           |
| 1628    | $\frac{1}{2} \times 3\frac{1}{2}$   | 2.880                                 | 0.938         | 0.933 | 0.928 | 0.922 | $\frac{13}{16}$           |
| 1828    | $\frac{9}{16} \times 3\frac{1}{2}$  | 2.880                                 | 0.938         | 0.933 | 0.928 | 0.922 | $\frac{13}{16}$           |
| 2028    | $\frac{5}{8} \times 3\frac{1}{2}$   | 2.880                                 | 0.938         | 0.933 | 0.928 | 0.922 | $\frac{13}{16}$           |
| 2228    | $\frac{11}{16} \times 3\frac{1}{2}$ | 2.880                                 | 0.938         | 0.933 | 0.928 | 0.922 | $\frac{13}{16}$           |
| 2428    | $\frac{3}{4} \times 3\frac{1}{2}$   | 2.880                                 | 0.938         | 0.933 | 0.928 | 0.922 | $\frac{13}{16}$           |

All dimensions are given in inches.

The key numbers indicate nominal key dimensions. The last two digits give the nominal diameter  $B$  in eighths of an inch and the digits preceding the last two give the nominal width  $W$  in thirty-seconds of an inch.

The key numbers with the -1 designation, while representing the nominal key size have a shorter length  $F$  and due to a greater distance below center  $E$  are less in height than the keys of the same number without the -1 designation.



**Table 10. ANSI Keyseat Dimensions for Woodruff Keys**  
ANSI B17.2-1967 (R1998)

| Key No. | Nominal Size Key                   | Keyseat—Shaft  |        |                  |                   |       | Key Above Shaft  | Keyseat—Hub      |                  |
|---------|------------------------------------|----------------|--------|------------------|-------------------|-------|------------------|------------------|------------------|
|         |                                    | Width <i>A</i> |        | Depth <i>B</i>   | Diameter <i>F</i> |       | Height <i>C</i>  | Width <i>D</i>   | Depth <i>E</i>   |
|         |                                    | Min.           | Max.   | +0.005<br>-0.000 | Min.              | Max.  | +0.005<br>-0.005 | +0.002<br>-0.000 | +0.005<br>-0.000 |
| 202     | $\frac{1}{16} \times \frac{1}{4}$  | 0.0615         | 0.0630 | 0.0728           | 0.250             | 0.268 | 0.0312           | 0.0635           | 0.0372           |
| 202.5   | $\frac{1}{16} \times \frac{5}{16}$ | 0.0615         | 0.0630 | 0.1038           | 0.312             | 0.330 | 0.0312           | 0.0635           | 0.0372           |
| 302.5   | $\frac{3}{32} \times \frac{5}{16}$ | 0.0928         | 0.0943 | 0.0882           | 0.312             | 0.330 | 0.0469           | 0.0948           | 0.0529           |
| 203     | $\frac{1}{16} \times \frac{3}{8}$  | 0.0615         | 0.0630 | 0.1358           | 0.375             | 0.393 | 0.0312           | 0.0635           | 0.0372           |
| 303     | $\frac{3}{32} \times \frac{3}{8}$  | 0.0928         | 0.0943 | 0.1202           | 0.375             | 0.393 | 0.0469           | 0.0948           | 0.0529           |
| 403     | $\frac{1}{8} \times \frac{3}{8}$   | 0.1240         | 0.1255 | 0.1045           | 0.375             | 0.393 | 0.0625           | 0.1260           | 0.0685           |
| 204     | $\frac{1}{16} \times \frac{1}{2}$  | 0.0615         | 0.0630 | 0.1668           | 0.500             | 0.518 | 0.0312           | 0.0635           | 0.0372           |
| 304     | $\frac{3}{32} \times \frac{1}{2}$  | 0.0928         | 0.0943 | 0.1511           | 0.500             | 0.518 | 0.0469           | 0.0948           | 0.0529           |
| 404     | $\frac{1}{8} \times \frac{1}{2}$   | 0.1240         | 0.1255 | 0.1355           | 0.500             | 0.518 | 0.0625           | 0.1260           | 0.0685           |
| 305     | $\frac{3}{32} \times \frac{5}{8}$  | 0.0928         | 0.0943 | 0.1981           | 0.625             | 0.643 | 0.0469           | 0.0948           | 0.0529           |
| 405     | $\frac{1}{8} \times \frac{5}{8}$   | 0.1240         | 0.1255 | 0.1825           | 0.625             | 0.643 | 0.0625           | 0.1260           | 0.0685           |
| 505     | $\frac{5}{32} \times \frac{5}{8}$  | 0.1553         | 0.1568 | 0.1669           | 0.625             | 0.643 | 0.0781           | 0.1573           | 0.0841           |
| 605     | $\frac{3}{16} \times \frac{5}{8}$  | 0.1863         | 0.1880 | 0.1513           | 0.625             | 0.643 | 0.0937           | 0.1885           | 0.0997           |
| 406     | $\frac{1}{8} \times \frac{3}{4}$   | 0.1240         | 0.1255 | 0.2455           | 0.750             | 0.768 | 0.0625           | 0.1260           | 0.0685           |
| 506     | $\frac{5}{32} \times \frac{3}{4}$  | 0.1553         | 0.1568 | 0.2299           | 0.750             | 0.768 | 0.0781           | 0.1573           | 0.0841           |
| 606     | $\frac{3}{16} \times \frac{3}{4}$  | 0.1863         | 0.1880 | 0.2143           | 0.750             | 0.768 | 0.0937           | 0.1885           | 0.0997           |
| 806     | $\frac{1}{4} \times \frac{3}{4}$   | 0.2487         | 0.2505 | 0.1830           | 0.750             | 0.768 | 0.1250           | 0.2510           | 0.1310           |
| 507     | $\frac{5}{32} \times \frac{7}{8}$  | 0.1553         | 0.1568 | 0.2919           | 0.875             | 0.895 | 0.0781           | 0.1573           | 0.0841           |
| 607     | $\frac{3}{16} \times \frac{7}{8}$  | 0.1863         | 0.1880 | 0.2763           | 0.875             | 0.895 | 0.0937           | 0.1885           | 0.0997           |
| 707     | $\frac{7}{32} \times \frac{7}{8}$  | 0.2175         | 0.2193 | 0.2607           | 0.875             | 0.895 | 0.1093           | 0.2198           | 0.1153           |
| 807     | $\frac{1}{4} \times \frac{7}{8}$   | 0.2487         | 0.2505 | 0.2450           | 0.875             | 0.895 | 0.1250           | 0.2510           | 0.1310           |
| 608     | $\frac{3}{16} \times 1$            | 0.1863         | 0.1880 | 0.3393           | 1.000             | 1.020 | 0.0937           | 0.1885           | 0.0997           |
| 708     | $\frac{7}{32} \times 1$            | 0.2175         | 0.2193 | 0.3237           | 1.000             | 1.020 | 0.1093           | 0.2198           | 0.1153           |
| 808     | $\frac{1}{4} \times 1$             | 0.2487         | 0.2505 | 0.3080           | 1.000             | 1.020 | 0.1250           | 0.2510           | 0.1310           |
| 1008    | $\frac{5}{16} \times 1$            | 0.3111         | 0.3130 | 0.2768           | 1.000             | 1.020 | 0.1562           | 0.3135           | 0.1622           |
| 1208    | $\frac{3}{8} \times 1$             | 0.3735         | 0.3755 | 0.2455           | 1.000             | 1.020 | 0.1875           | 0.3760           | 0.1935           |
| 609     | $\frac{3}{16} \times 1\frac{1}{8}$ | 0.1863         | 0.1880 | 0.3853           | 1.125             | 1.145 | 0.0937           | 0.1885           | 0.0997           |
| 709     | $\frac{7}{32} \times 1\frac{1}{8}$ | 0.2175         | 0.2193 | 0.3697           | 1.125             | 1.145 | 0.1093           | 0.2198           | 0.1153           |
| 809     | $\frac{1}{4} \times 1\frac{1}{8}$  | 0.2487         | 0.2505 | 0.3540           | 1.125             | 1.145 | 0.1250           | 0.2510           | 0.1310           |
| 1009    | $\frac{5}{16} \times 1\frac{1}{8}$ | 0.3111         | 0.3130 | 0.3228           | 1.125             | 1.145 | 0.1562           | 0.3135           | 0.1622           |
| 610     | $\frac{3}{16} \times 1\frac{1}{4}$ | 0.1863         | 0.1880 | 0.4483           | 1.250             | 1.273 | 0.0937           | 0.1885           | 0.0997           |
| 710     | $\frac{7}{32} \times 1\frac{1}{4}$ | 0.2175         | 0.2193 | 0.4327           | 1.250             | 1.273 | 0.1093           | 0.2198           | 0.1153           |
| 810     | $\frac{1}{4} \times 1\frac{1}{4}$  | 0.2487         | 0.2505 | 0.4170           | 1.250             | 1.273 | 0.1250           | 0.2510           | 0.1310           |
| 1010    | $\frac{5}{16} \times 1\frac{1}{4}$ | 0.3111         | 0.3130 | 0.3858           | 1.250             | 1.273 | 0.1562           | 0.3135           | 0.1622           |
| 1210    | $\frac{3}{8} \times 1\frac{1}{4}$  | 0.3735         | 0.3755 | 0.3545           | 1.250             | 1.273 | 0.1875           | 0.3760           | 0.1935           |
| 811     | $\frac{1}{4} \times 1\frac{3}{8}$  | 0.2487         | 0.2505 | 0.4640           | 1.375             | 1.398 | 0.1250           | 0.2510           | 0.1310           |
| 1011    | $\frac{5}{16} \times 1\frac{3}{8}$ | 0.3111         | 0.3130 | 0.4328           | 1.375             | 1.398 | 0.1562           | 0.3135           | 0.1622           |



**Table 10. (Continued) ANSI Keyseat Dimensions for Woodruff Keys**  
ANSI B17.2-1967 (R1998)

| Key No. | Nominal Size Key                    | Keyseat—Shaft               |        |                  |                   |       | Key Above Shaft  | Keyseat—Hub      |                  |
|---------|-------------------------------------|-----------------------------|--------|------------------|-------------------|-------|------------------|------------------|------------------|
|         |                                     | Width <i>A</i> <sup>a</sup> |        | Depth <i>B</i>   | Diameter <i>F</i> |       | Height <i>C</i>  | Width <i>D</i>   | Depth <i>E</i>   |
|         |                                     | Min.                        | Max.   | +0.005<br>-0.000 | Min.              | Max.  | +0.005<br>-0.005 | +0.002<br>-0.000 | +0.005<br>-0.000 |
| 1211    | $\frac{3}{8} \times 1\frac{3}{8}$   | 0.3735                      | 0.3755 | 0.4015           | 1.375             | 1.398 | 0.1875           | 0.3760           | 0.1935           |
| 812     | $\frac{1}{4} \times 1\frac{1}{2}$   | 0.2487                      | 0.2505 | 0.5110           | 1.500             | 1.523 | 0.1250           | 0.2510           | 0.1310           |
| 1012    | $\frac{5}{16} \times 1\frac{1}{2}$  | 0.3111                      | 0.3130 | 0.4798           | 1.500             | 1.523 | 0.1562           | 0.3135           | 0.1622           |
| 1212    | $\frac{3}{8} \times 1\frac{1}{2}$   | 0.3735                      | 0.3755 | 0.4485           | 1.500             | 1.523 | 0.1875           | 0.3760           | 0.1935           |
| 617-1   | $\frac{3}{16} \times 2\frac{1}{8}$  | 0.1863                      | 0.1880 | 0.3073           | 2.125             | 2.160 | 0.0937           | 0.1885           | 0.0997           |
| 817-1   | $\frac{1}{4} \times 2\frac{1}{8}$   | 0.2487                      | 0.2505 | 0.2760           | 2.125             | 2.160 | 0.1250           | 0.2510           | 0.1310           |
| 1017-1  | $\frac{5}{16} \times 2\frac{1}{8}$  | 0.3111                      | 0.3130 | 0.2448           | 2.125             | 2.160 | 0.1562           | 0.3135           | 0.1622           |
| 1217-1  | $\frac{3}{8} \times 2\frac{1}{8}$   | 0.3735                      | 0.3755 | 0.2135           | 2.125             | 2.160 | 0.1875           | 0.3760           | 0.1935           |
| 617     | $\frac{3}{16} \times 2\frac{1}{8}$  | 0.1863                      | 0.1880 | 0.4323           | 2.125             | 2.160 | 0.0937           | 0.1885           | 0.0997           |
| 817     | $\frac{1}{4} \times 2\frac{1}{8}$   | 0.2487                      | 0.2505 | 0.4010           | 2.125             | 2.160 | 0.1250           | 0.2510           | 0.1310           |
| 1017    | $\frac{5}{16} \times 2\frac{1}{8}$  | 0.3111                      | 0.3130 | 0.3698           | 2.125             | 2.160 | 0.1562           | 0.3135           | 0.1622           |
| 1217    | $\frac{3}{8} \times 2\frac{1}{8}$   | 0.3735                      | 0.3755 | 0.3385           | 2.125             | 2.160 | 0.1875           | 0.3760           | 0.1935           |
| 822-1   | $\frac{1}{2} \times 2\frac{3}{4}$   | 0.2487                      | 0.2505 | 0.4640           | 2.750             | 2.785 | 0.1250           | 0.2510           | 0.1310           |
| 1022-1  | $\frac{5}{16} \times 2\frac{3}{4}$  | 0.3111                      | 0.3130 | 0.4328           | 2.750             | 2.785 | 0.1562           | 0.3135           | 0.1622           |
| 1222-1  | $\frac{3}{8} \times 2\frac{3}{4}$   | 0.3735                      | 0.3755 | 0.4015           | 2.750             | 2.785 | 0.1875           | 0.3760           | 0.1935           |
| 1422-1  | $\frac{7}{16} \times 2\frac{3}{4}$  | 0.4360                      | 0.4380 | 0.3703           | 2.750             | 2.785 | 0.2187           | 0.4385           | 0.2247           |
| 1622-1  | $\frac{1}{2} \times 2\frac{3}{4}$   | 0.4985                      | 0.5005 | 0.3390           | 2.750             | 2.785 | 0.2500           | 0.5010           | 0.2560           |
| 822     | $\frac{1}{4} \times 2\frac{3}{4}$   | 0.2487                      | 0.2505 | 0.6200           | 2.750             | 2.785 | 0.1250           | 0.2510           | 0.1310           |
| 1022    | $\frac{5}{16} \times 2\frac{3}{4}$  | 0.3111                      | 0.3130 | 0.5888           | 2.750             | 2.785 | 0.1562           | 0.3135           | 0.1622           |
| 1222    | $\frac{3}{8} \times 2\frac{3}{4}$   | 0.3735                      | 0.3755 | 0.5575           | 2.750             | 2.785 | 0.1875           | 0.3760           | 0.1935           |
| 1422    | $\frac{7}{16} \times 2\frac{3}{4}$  | 0.4360                      | 0.4380 | 0.5263           | 2.750             | 2.785 | 0.2187           | 0.4385           | 0.2247           |
| 1622    | $\frac{1}{2} \times 2\frac{3}{4}$   | 0.4985                      | 0.5005 | 0.4950           | 2.750             | 2.785 | 0.2500           | 0.5010           | 0.2560           |
| 1228    | $\frac{3}{8} \times 3\frac{1}{2}$   | 0.3735                      | 0.3755 | 0.7455           | 3.500             | 3.535 | 0.1875           | 0.3760           | 0.1935           |
| 1428    | $\frac{7}{16} \times 3\frac{1}{2}$  | 0.4360                      | 0.4380 | 0.7143           | 3.500             | 3.535 | 0.2187           | 0.4385           | 0.2247           |
| 1628    | $\frac{1}{2} \times 3\frac{1}{2}$   | 0.4985                      | 0.5005 | 0.6830           | 3.500             | 3.535 | 0.2500           | 0.5010           | 0.2560           |
| 1828    | $\frac{9}{16} \times 3\frac{1}{2}$  | 0.5610                      | 0.5630 | 0.6518           | 3.500             | 3.535 | 0.2812           | 0.5635           | 0.2872           |
| 2028    | $\frac{3}{8} \times 3\frac{1}{2}$   | 0.6235                      | 0.6255 | 0.6205           | 3.500             | 3.535 | 0.3125           | 0.6260           | 0.3185           |
| 2228    | $\frac{11}{16} \times 3\frac{1}{2}$ | 0.6860                      | 0.6880 | 0.5893           | 3.500             | 3.535 | 0.3437           | 0.6885           | 0.3497           |
| 2428    | $\frac{3}{4} \times 3\frac{1}{2}$   | 0.7485                      | 0.7505 | 0.5580           | 3.500             | 3.535 | 0.3750           | 0.7510           | 0.3810           |

<sup>a</sup> These Width *A* values were set with the maximum keyseat (shaft) width as that figure which will receive a key with the greatest amount of looseness consistent with assuring the key's sticking in the keyseat (shaft). Minimum keyseat width is that figure permitting the largest shaft distortion acceptable when assembling maximum key in minimum keyseat. Dimensions *A*, *B*, *C*, *D* are taken at side intersection.

All dimensions are given in inches.

The following definitions are given in this standard:

**Woodruff Key:** A demountable machinery part which, when assembled into key-seats, provides a positive means for transmitting torque between the shaft and hub.

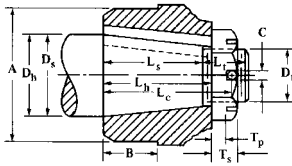
**Woodruff Key Number:** An identification number by which the size of key may be readily determined.

**Woodruff Keyseat—Shaft:** The circular pocket in which the key is retained.

**Woodruff Keyseat—Hub:** An axially located rectangular groove in a hub. (This has been referred to as a keyway.)

**Woodruff Keyseat Milling Cutter:** An arbor type or shank type milling cutter normally used for milling Woodruff keyseats in shafts (see page 820).

Taper Shaft Ends with Slotted Nuts SAE Standard



TAPER PER FOOT =  $1.500^{+0.002}$  IN.  
 H IS MEASURED PERPENDICULAR TO KEY.  
 C, COTTER-PIN HOLE HAS CENTERLINE  
 DISPLACED 90° FROM KEYWAY CENTER

| Nom. Dia. | Dia. of Shaft, $D_s$ |       | Dia. of Hole, $D_h$ |       | $L_c$   | $L_s$ | $L_h$ | $L_t$ | $T_s$ | $T_p$ | Nut Width, Flats |
|-----------|----------------------|-------|---------------------|-------|---------|-------|-------|-------|-------|-------|------------------|
|           | Max.                 | Min.  | Max.                | Min.  |         |       |       |       |       |       |                  |
| 1/4       | 0.250                | 0.249 | 0.248               | 0.247 | 9/16    | 5/16  | 3/8   | 5/16  | 7/32  | 9/64  | 5/16             |
| 3/8       | 0.375                | 0.374 | 0.373               | 0.372 | 7/16    | 7/16  | 1/2   | 23/64 | 17/64 | 3/16  | 1/2              |
| 1/2       | 0.500                | 0.499 | 0.498               | 0.497 | 63/64   | 11/16 | 3/4   | 23/64 | 17/64 | 3/16  | 3/4              |
| 5/8       | 0.625                | 0.624 | 0.623               | 0.622 | 13/32   | 11/16 | 3/4   | 17/32 | 7/16  | 1/4   | 3/4              |
| 3/4       | 0.750                | 0.749 | 0.748               | 0.747 | 113/128 | 15/16 | 1     | 17/32 | 7/16  | 1/4   | 3/4              |
| 7/8       | 0.875                | 0.874 | 0.873               | 0.872 | 111/16  | 15/16 | 1     | 11/16 | 1/2   | 5/16  | 15/16            |
| 1         | 1.001                | 0.999 | 0.997               | 0.995 | 115/16  | 15/16 | 1 1/8 | 11/16 | 1/2   | 5/16  | 1 1/16           |
| 1 1/8     | 1.126                | 1.124 | 1.122               | 1.120 | 115/16  | 15/16 | 1 3/8 | 11/16 | 1/2   | 5/16  | 1 1/4            |
| 1 1/4     | 1.251                | 1.249 | 1.247               | 1.245 | 115/16  | 15/16 | 1 3/8 | 11/16 | 1/2   | 5/16  | 1 7/16           |
| 1 3/8     | 1.376                | 1.374 | 1.372               | 1.370 | 27/16   | 1 7/8 | 2     | 11/16 | 1/2   | 5/16  | 1 7/16           |
| 1 1/2     | 1.501                | 1.499 | 1.497               | 1.495 | 27/16   | 1 7/8 | 2     | 11/16 | 1/2   | 5/16  | 1 7/16           |
| 1 5/8     | 1.626                | 1.624 | 1.622               | 1.620 | 213/16  | 2 1/8 | 2 1/4 | 13/16 | 5/8   | 7/16  | 2 3/16           |
| 1 3/4     | 1.751                | 1.749 | 1.747               | 1.745 | 213/16  | 2 1/8 | 2 1/4 | 13/16 | 5/8   | 7/16  | 2 3/16           |
| 1 7/8     | 1.876                | 1.874 | 1.872               | 1.870 | 31/16   | 2 3/8 | 2 3/2 | 13/16 | 5/8   | 7/16  | 2 3/16           |
| 2         | 2.001                | 1.999 | 1.997               | 1.995 | 39/16   | 2 7/8 | 3     | 13/16 | 5/8   | 7/16  | 2 3/16           |
| 2 1/4     | 2.252                | 2.248 | 2.245               | 2.242 | 39/16   | 2 7/8 | 3     | 13/16 | 5/8   | 7/16  | 2 3/8            |
| 2 1/2     | 2.502                | 2.498 | 2.495               | 2.492 | 49/32   | 3 3/8 | 3 1/2 | 1 1/4 | 1     | 5/8   | 3 3/8            |
| 2 3/4     | 2.752                | 2.748 | 2.745               | 2.742 | 49/32   | 3 3/8 | 3 1/2 | 1 1/4 | 1     | 5/8   | 3 3/8            |
| 3         | 3.002                | 2.998 | 2.995               | 2.992 | 225/32  | 3 7/8 | 4     | 1 1/4 | 1     | 5/8   | 3 3/8            |
| 3 1/4     | 3.252                | 3.248 | 3.245               | 3.242 | 51/32   | 4 1/8 | 4 1/4 | 1 1/4 | 1     | 5/8   | 3 7/8            |
| 3 1/2     | 3.502                | 3.498 | 3.495               | 3.492 | 57/16   | 4 3/8 | 4 1/2 | 1 3/8 | 1 1/8 | 3/4   | 3 7/8            |
| 4         | 4.002                | 3.998 | 3.995               | 3.992 | 67/16   | 5 3/8 | 5 1/2 | 1 3/8 | 1 1/8 | 3/4   | 3 7/8            |

| Nom. Dia. | $D_t$ | Thds. per Inch | Keyway |       |      |      | Square Key |        | A     | B     | C    |
|-----------|-------|----------------|--------|-------|------|------|------------|--------|-------|-------|------|
|           |       |                | W      |       | H    |      | Max.       | Min.   |       |       |      |
|           |       |                | Max.   | Min.  | Max. | Min. |            |        |       |       |      |
| 1/4       | #10   | 40             | 0.0625 | .0615 | .037 | .033 | 0.0635     | 0.0625 | 1/2   | 3/16  | 5/64 |
| 3/8       | 3/16  | 32             | 0.0937 | .0927 | .053 | .049 | 0.0947     | 0.0937 | 11/16 | 1/4   | 5/64 |
| 1/2       | 1/16  | 32             | 0.1250 | .1240 | .069 | .065 | 0.1260     | 0.1250 | 7/8   | 3/8   | 5/64 |
| 5/8       | 1/2   | 28             | 0.1562 | .1552 | .084 | .080 | 0.1572     | 0.1562 | 11/16 | 3/8   | 1/8  |
| 3/4       | 1/2   | 28             | 0.1875 | .1865 | .100 | .096 | 0.1885     | 0.1875 | 1 1/4 | 5/8   | 1/8  |
| 7/8       | 3/8   | 24             | 0.2500 | .2490 | .131 | .127 | 0.2510     | 0.2500 | 1 1/2 | 3/4   | 5/32 |
| 1         | 3/4   | 20             | 0.2500 | .2490 | .131 | .127 | 0.2510     | 0.2500 | 1 3/4 | 3/8   | 5/32 |
| 1 1/8     | 7/8   | 20             | 0.3125 | .3115 | .162 | .158 | 0.3135     | 0.3125 | 2     | 7/8   | 5/32 |
| 1 1/4     | 1     | 20             | 0.3125 | .3115 | .162 | .158 | 0.3135     | 0.3125 | 2 1/8 | 7/8   | 5/32 |
| 1 3/8     | 1     | 20             | 0.3750 | .3740 | .194 | .190 | 0.3760     | 0.3750 | 2 1/4 | 1     | 5/32 |
| 1 1/2     | 1     | 20             | 0.3750 | .3740 | .194 | .190 | 0.3760     | 0.3750 | 2 1/2 | 1     | 5/32 |
| 1 5/8     | 1 1/4 | 18             | 0.4375 | .4365 | .225 | .221 | 0.4385     | 0.4375 | 2 3/4 | 1 1/4 | 5/32 |
| 1 3/4     | 1 1/4 | 18             | 0.4375 | .4365 | .225 | .221 | 0.4385     | 0.4375 | 3     | 1 1/4 | 5/32 |
| 1 7/8     | 1 1/4 | 18             | 0.4375 | .4365 | .225 | .221 | 0.4385     | 0.4375 | 3 3/8 | 1 1/4 | 5/32 |
| 2         | 1 1/4 | 18             | 0.5000 | .4990 | .256 | .252 | 0.5010     | 0.5000 | 3 1/4 | 1 1/2 | 5/32 |
| 2 1/4     | 1 1/2 | 18             | 0.5625 | .5610 | .287 | .283 | 0.5640     | 0.5625 | 3 1/2 | 1 1/2 | 5/32 |
| 2 1/2     | 2     | 16             | 0.6250 | .6235 | .319 | .315 | 0.6265     | 0.6250 | 4     | 1 3/4 | 7/32 |
| 2 3/4     | 2     | 16             | 0.6875 | .6860 | .350 | .346 | 0.6890     | 0.6875 | 4 3/8 | 1 3/4 | 7/32 |
| 3         | 2     | 16             | 0.7500 | .7485 | .381 | .377 | 0.7515     | 0.7500 | 4 3/4 | 2     | 7/32 |
| 3 1/4     | 2     | 16             | 0.7500 | .7485 | .381 | .377 | 0.7515     | 0.7500 | 5     | 2 1/8 | 7/32 |
| 3 1/2     | 2 1/2 | 16             | 0.8750 | .8735 | .444 | .440 | 0.8765     | 0.8750 | 5 1/2 | 2 1/4 | 9/32 |
| 4         | 2 1/2 | 16             | 1.0000 | .9985 | .506 | .502 | 1.0015     | 1.0000 | 6 1/4 | 2 3/4 | 9/32 |

All dimensions in inches except where otherwise noted. © 1990, SAE.

**Chamfered Keys and Filleted Keyseats.**—In general practice, chamfered keys and filleted keyseats are not used. However, it is recognized that fillets in keyseats decrease stress concentration at corners. When used, fillet radii should be as large as possible without causing excessive bearing stresses due to reduced contact area between the key and its mating parts. Keys must be chamfered or rounded to clear fillet radii. Values in Table 5 assume general conditions and should be used only as a guide when critical stresses are encountered.

**Depths for Milling Keyseats.**—Table 11 on page 2375 has been compiled to facilitate the accurate milling of keyseats. This table gives the distance  $M$  (see illustration accompanying table) between the top of the shaft and a line passing through the upper corners or edges of the keyseat. Dimension  $M$  is calculated by the formula:  $M = \frac{1}{2}(S - \sqrt{S^2 - E^2})$  where  $S$  is diameter of shaft, and  $E$  is width of keyseat. A simple approximate formula that gives  $M$  to within 0.001 inch is  $M = E^2 \div 4S$ .

**Cotters.**—A cotter is a form of key that is used to connect rods, etc., that are subjected either to tension or compression or both, the cotter being subjected to shearing stresses at two transverse cross-sections. When taper cotters are used for drawing and holding parts together, if the cotter is held in place by the friction between the bearing surfaces, the taper should not be too great. Ordinarily a taper varying from  $\frac{1}{4}$  to  $\frac{1}{2}$  inch per foot is used for plain cotters. When a set-screw or other device is used to prevent the cotter from backing out of its slot, the taper may vary from  $1\frac{1}{2}$  to 2 inches per foot.

### British Keys and Keyways

**British Standard Metric Keys and Keyways.**—This British Standard, BS 4235:Part 1:1972 (1986), covers square and rectangular parallel keys and keyways, and square and rectangular taper keys and keyways. Plain and gib-head taper keys are specified. There are three classes of fit for the square and rectangular parallel keys and keyways, designated free, normal, and close. A *free fit* is applied when the application requires the hub of an assembly to slide over the key; a *normal fit* is employed when the key is to be inserted in the keyway with the minimum amount of fitting, as may be required in mass-production assembly work; and a *close fit* is applied when accurate fitting of the key is required under maximum material conditions, which may involve selection of components.

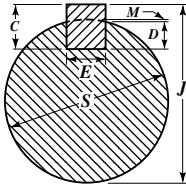
The Standard does not provide for misalignment or offset greater than can be accommodated within the dimensional tolerances. If an assembly is to be heavily stressed, a check should be made to ensure that the cumulative effect of misalignment or offset, or both, does not prevent satisfactory bearing on the key. Radii and chamfers are not normally provided on keybar and keys as supplied, but they can be produced during manufacture by agreement between the user and supplier.

Unless otherwise specified, keys in compliance with this Standard are manufactured from steel made to BS 970 having a tensile strength of not less than 550 MN/m<sup>2</sup> in the finished condition. BS 970, Part 1, lists the following steels and maximum section sizes, respectively, that meet this tensile strength requirement: 070M20, 25 × 14 mm; 070M26, 36 × 20 mm; 080M30, 90 × 45 mm; and 080M40, 100 × 50 mm.

At the time of publication of this Standard, the demand for metric keys was not sufficient to enable standard ranges of lengths to be established. The lengths given in the accompanying table are those shown as standard in ISO Recommendations R773: 1969, "Rectangular or Square Parallel Keys and their Corresponding Keyways (Dimensions in Millimeters)," and R 774: 1969, "Taper Keys and their Corresponding Keyways—with or without Gib Head (Dimensions in Millimeters)."

Tables 12 through 15 on the following pages cover the dimensions and tolerances of square and rectangular keys and keyways, and square and rectangular taper keys and keyways.

**Table 11. Finding Depth of Keyseat and Distance from Top of Key to Bottom of Shaft**



For milling keyseats, the total depth to feed cutter in from outside of shaft to bottom of keyseat is  $M + D$ , where  $D$  is depth of keyseat.

For checking an assembled key and shaft, caliper measurement  $J$  between top of key and bottom of shaft is used.

$$J = S - (M + D) + C$$

where  $C$  is depth of key. For Woodruff keys, dimensions  $C$  and  $D$  can be found in Tables 8 through 10. Assuming shaft diameter  $S$  is normal size, the tolerance on dimension  $J$  for Woodruff keys in keyslots are  $+0.000, -0.010$  inch.

| Dia. of Shaft, S, Inches | Width of Keyseat, E |       |       |       |       |       |       |       |       |       |       |       |       |       |       |     |
|--------------------------|---------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-----|
|                          | 1/16                | 3/32  | 1/8   | 5/32  | 3/16  | 7/32  | 1/4   | 5/16  | 3/8   | 7/16  | 1/2   | 9/16  | 5/8   | 11/16 | 3/4   |     |
|                          | Dimension M, Inch   |       |       |       |       |       |       |       |       |       |       |       |       |       |       |     |
| 0.3125                   | .0032               | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.3437                   | .0029               | .0065 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.3750                   | .0026               | .0060 | .0107 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.4060                   | .0024               | .0055 | .0099 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.4375                   | .0022               | .0051 | .0091 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.4687                   | .0021               | .0047 | .0085 | .0134 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.5000                   | .0020               | .0044 | .0079 | .0125 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.5625                   | ...                 | .0039 | .0070 | .0111 | .0161 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.6250                   | ...                 | .0035 | .0063 | .0099 | .0144 | .0198 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.6875                   | ...                 | .0032 | .0057 | .0090 | .0130 | .0179 | .0235 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.7500                   | ...                 | .0029 | .0052 | .0082 | .0119 | .0163 | .0214 | .0341 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.8125                   | ...                 | .0027 | .0048 | .0076 | .0110 | .0150 | .0197 | .0312 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.8750                   | ...                 | .0025 | .0045 | .0070 | .0102 | .0139 | .0182 | .0288 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 0.9375                   | ...                 | ...   | .0042 | .0066 | .0095 | .0129 | .0170 | .0263 | .0391 | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 1.0000                   | ...                 | ...   | .0039 | .0061 | .0089 | .0121 | .0159 | .0250 | .0365 | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 1.0625                   | ...                 | ...   | .0037 | .0058 | .0083 | .0114 | .0149 | .0235 | .0342 | ...   | ...   | ...   | ...   | ...   | ...   | ... |
| 1.1250                   | ...                 | ...   | .0035 | .0055 | .0079 | .0107 | .0141 | .0221 | .0322 | .0443 | ...   | ...   | ...   | ...   | ...   | ... |
| 1.1875                   | ...                 | ...   | .0033 | .0052 | .0074 | .0102 | .0133 | .0209 | .0304 | .0418 | ...   | ...   | ...   | ...   | ...   | ... |
| 1.2500                   | ...                 | ...   | .0031 | .0049 | .0071 | .0097 | .0126 | .0198 | .0288 | .0395 | ...   | ...   | ...   | ...   | ...   | ... |
| 1.3750                   | ...                 | ...   | ...   | .0045 | .0064 | .0088 | .0115 | .0180 | .0261 | .0357 | .0471 | ...   | ...   | ...   | ...   | ... |
| 1.5000                   | ...                 | ...   | ...   | .0041 | .0059 | .0080 | .0105 | .0165 | .0238 | .0326 | .0429 | ...   | ...   | ...   | ...   | ... |
| 1.6250                   | ...                 | ...   | ...   | .0038 | .0054 | .0074 | .0097 | .0152 | .0219 | .0300 | .0394 | .0502 | ...   | ...   | ...   | ... |
| 1.7500                   | ...                 | ...   | ...   | ...   | .0050 | .0069 | .0090 | .0141 | .0203 | .0278 | .0365 | .0464 | ...   | ...   | ...   | ... |
| 1.8750                   | ...                 | ...   | ...   | ...   | .0047 | .0064 | .0084 | .0131 | .0189 | .0259 | .0340 | .0432 | .0536 | ...   | ...   | ... |
| 2.0000                   | ...                 | ...   | ...   | ...   | .0044 | .0060 | .0078 | .0123 | .0177 | .0242 | .0318 | .0404 | .0501 | ...   | ...   | ... |
| 2.1250                   | ...                 | ...   | ...   | ...   | ...   | .0056 | .0074 | .0116 | .0167 | .0228 | .0298 | .0379 | .0470 | .0572 | .0684 | ... |
| 2.2500                   | ...                 | ...   | ...   | ...   | ...   | ...   | .0070 | .0109 | .0157 | .0215 | .0281 | .0357 | .0443 | .0538 | .0643 | ... |
| 2.3750                   | ...                 | ...   | ...   | ...   | ...   | ...   | ...   | .0103 | .0149 | .0203 | .0266 | .0338 | .0419 | .0509 | .0608 | ... |
| 2.5000                   | ...                 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | .0141 | .0193 | .0253 | .0321 | .0397 | .0482 | .0576 | ... |
| 2.6250                   | ...                 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | .0135 | .0184 | .0240 | .0305 | .0377 | .0457 | .0547 | ... |
| 2.7500                   | ...                 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | .0175 | .0229 | .0291 | .0360 | .0437 | .0521 | ... |
| 2.8750                   | ...                 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | .0168 | .0219 | .0278 | .0344 | .0417 | .0498 | ... |
| 3.0000                   | ...                 | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | .0210 | .0266 | .0329 | .0399 | .0476 | ... |

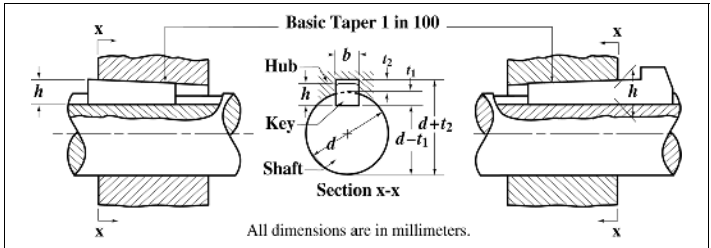
**Table 12. British Standard Metric Keyways for Square and Rectangular Parallel Keys BS 4235:Part 1:1972 (1986)**

| Shaft                                 |                | Key                |     | Keyway  |             |                  |            |                              |                    |             |           |           |           |            |           |      |      |
|---------------------------------------|----------------|--------------------|-----|---------|-------------|------------------|------------|------------------------------|--------------------|-------------|-----------|-----------|-----------|------------|-----------|------|------|
| Nominal Diameter $d$                  |                | Size, $b \times h$ |     | Nominal | Width, $b$  |                  |            |                              |                    | Depth       |           |           |           | Radius $r$ |           |      |      |
| Over                                  | Up to and Incl |                    |     |         | Free Fit    |                  | Normal Fit |                              | Close Fit          | Shaft $t_1$ |           | Hub $t_2$ |           | Max.       | Min.      |      |      |
|                                       |                |                    |     |         | Shaft (H9)  | Hub (D10)        | Shaft (N9) | Hub ( $J_8/9$ ) <sup>a</sup> | Shaft and Hub (P9) | Nominal     | Tolerance | Nominal   | Tolerance |            |           |      |      |
| Tolerances                            |                |                    |     |         |             |                  |            |                              |                    |             |           |           |           |            |           |      |      |
| Keyways for Square Parallel Keys      |                |                    |     |         |             |                  |            |                              |                    |             |           |           |           |            |           |      |      |
| 6                                     | 8              | 2 × 2              | 2   | }       | +0.025      | +0.060           | -0.004     | +0.012                       | -0.006             | 1.2         | }         | +0.1<br>0 | 1         | }          | +0.1<br>0 | 0.16 | 0.08 |
| 8                                     | 10             | 3 × 3              | 3   |         | 0           | +0.020           | -0.029     | -0.012                       | -0.031             | 1.8         |           |           | 1.4       |            |           | 0.16 | 0.08 |
| 10                                    | 12             | 4 × 4              | 4   | }       | +0.030<br>0 | +0.078<br>+0.030 | 0          | +0.015<br>-0.015             | -0.012<br>-0.042   | 2.5         | }         | }         | 1.8       | }          | }         | 0.16 | 0.08 |
| 12                                    | 17             | 5 × 5              | 5   |         |             |                  |            |                              |                    | 3           |           |           | 2.3       |            |           | 0.25 | 0.16 |
| 17                                    | 22             | 6 × 6              | 6   |         |             |                  |            |                              |                    | 3.5         |           |           | 2.8       |            |           | 0.25 | 0.16 |
| Keyways for Rectangular Parallel Keys |                |                    |     |         |             |                  |            |                              |                    |             |           |           |           |            |           |      |      |
| 22                                    | 30             | 8 × 7              | 8   | }       | +0.036      | +0.098           | 0          | +0.018                       | -0.015             | 4           | }         | }         | 3.3       | }          | }         | 0.25 | 0.16 |
| 30                                    | 38             | 10 × 8             | 10  |         | 0           | +0.040           | -0.036     | -0.018                       | -0.051             | 5           |           |           | 3.3       |            |           | 0.40 | 0.25 |
| 38                                    | 44             | 12 × 8             | 12  | }       | +0.043      | +0.120<br>+0.050 | 0          | +0.021<br>-0.021             | -0.018<br>-0.061   | 5.5         | }         | }         | 3.3       | }          | }         | 0.40 | 0.25 |
| 44                                    | 50             | 14 × 9             | 14  |         |             |                  |            |                              |                    | 5.5         |           |           | 3.8       |            |           | 0.40 | 0.25 |
| 50                                    | 58             | 16 × 10            | 16  |         |             |                  |            |                              |                    | 6           |           |           | 4.3       |            |           | 0.40 | 0.25 |
| 58                                    | 65             | 18 × 11            | 18  | }       | }           | }                | }          | }                            | }                  | }           | }         | }         | }         | }          | }         | }    | }    |
| 65                                    | 75             | 20 × 12            | 20  |         |             |                  |            |                              |                    |             |           |           |           |            |           |      |      |
| 75                                    | 85             | 22 × 14            | 22  | }       | +0.052      | +0.149<br>+0.065 | 0          | +0.026<br>-0.026             | -0.022<br>-0.074   | 7.5         | }         | }         | 4.9       | }          | }         | 0.60 | 0.40 |
| 85                                    | 95             | 25 × 14            | 25  |         |             |                  |            |                              |                    | 9           |           |           | 5.4       |            |           | 0.60 | 0.40 |
| 95                                    | 110            | 28 × 16            | 28  |         |             |                  |            |                              |                    | 10          |           |           | 6.4       |            |           | 0.60 | 0.40 |
| 110                                   | 130            | 32 × 18            | 32  | }       | }           | }                | }          | }                            | }                  | }           | }         | }         | }         | }          | }         | }    | }    |
| 130                                   | 150            | 36 × 20            | 36  |         |             |                  |            |                              |                    |             |           |           |           |            |           |      |      |
| 150                                   | 170            | 40 × 22            | 40  | }       | +0.062      | +0.180<br>-0.080 | 0          | +0.031<br>-0.031             | -0.026<br>-0.088   | 12          | }         | }         | 8.4       | }          | }         | 1.00 | 0.70 |
| 170                                   | 200            | 45 × 25            | 45  |         |             |                  |            |                              |                    | 13          |           |           | 9.4       |            |           | 1.00 | 0.70 |
| 200                                   | 230            | 50 × 28            | 50  |         |             |                  |            |                              |                    | 15          |           |           | 10.4      |            |           | 1.00 | 0.70 |
| 230                                   | 260            | 56 × 32            | 56  | }       | }           | }                | }          | }                            | }                  | }           | }         | }         | }         | }          | }         | }    | }    |
| 260                                   | 290            | 63 × 32            | 63  |         |             |                  |            |                              |                    |             |           |           |           |            |           |      |      |
| 290                                   | 330            | 70 × 36            | 70  | }       | +0.074      | +0.220<br>+0.100 | 0          | +0.037<br>-0.037             | -0.032<br>-0.106   | 20          | }         | }         | 12.4      | }          | }         | 1.60 | 1.20 |
| 330                                   | 380            | 80 × 40            | 80  |         |             |                  |            |                              |                    | 20          |           |           | 12.4      |            |           | 1.60 | 1.20 |
| 380                                   | 440            | 90 × 45            | 90  |         |             |                  |            |                              |                    | 22          |           |           | 14.4      |            |           | 1.60 | 1.20 |
| 440                                   | 500            | 100 × 50           | 100 | }       | }           | }                | }          | }                            | }                  | }           | }         | }         | }         | }          | }         | }    | }    |
| 500                                   | 500            | 100 × 50           | 100 |         |             |                  |            |                              |                    |             |           |           |           |            |           |      |      |
|                                       |                |                    |     | }       | }           | }                | }          | }                            | }                  | }           | }         | }         | }         | }          | }         | }    | }    |
|                                       |                |                    |     |         |             |                  |            |                              |                    |             |           |           |           |            |           |      |      |
|                                       |                |                    |     | }       | }           | }                | }          | }                            | }                  | }           | }         | }         | }         | }          | }         | }    | }    |
|                                       |                |                    |     |         |             |                  |            |                              |                    |             |           |           |           |            |           |      |      |

<sup>a</sup>Tolerance limits  $J_8/9$  are quoted from BS 4500, "ISO Limits and Fits," to three significant figures.

All dimensions in millimeters.

**Table 13. British Standard Metric Keyways for Square and Rectangular Taper Keys BS 4235:Part 1:1972 (1986)**



| Shaft                              |                 | Key                |                           | Keyway     |             |        |           |       |                         |      |       |      |      |
|------------------------------------|-----------------|--------------------|---------------------------|------------|-------------|--------|-----------|-------|-------------------------|------|-------|------|------|
| Nominal Diameter $d$               |                 | Size, $b \times h$ | Width $b$ , Shaft and Hub |            | Depth       |        |           |       | Corner Radius of Keyway |      |       |      |      |
| Over                               | Up to and Incl. |                    | Nom.                      | Tol. (D10) | Shaft $t_1$ |        | Hub $t_2$ |       | Max.                    | Min. |       |      |      |
| Keyways for Square Taper Keys      |                 |                    |                           |            |             |        |           |       |                         |      |       |      |      |
| 6                                  | 8               | 2 × 2              | 2                         | }          | +0.060      | 1.2    | }         | +0.10 | 0.5                     | }    | +0.10 | 0.16 | 0.08 |
| 8                                  | 10              | 3 × 3              | 3                         |            | +0.020      | 1.8    |           | 0.9   | 0.16                    |      | 0.08  |      |      |
| 10                                 | 12              | 4 × 4              | 4                         | }          | +0.078      | 2.5    | }         | +0.20 | 1.2                     | }    | +0.20 | 0.16 | 0.08 |
| 12                                 | 17              | 5 × 5              | 5                         |            | +0.030      | 3      |           | 1.7   | 0.25                    |      | 0.16  |      |      |
| 17                                 | 22              | 6 × 6              | 6                         |            | +0.030      | 3.5    |           | 2.2   | 0.25                    |      | 0.16  |      |      |
| Keyways for Rectangular Taper Keys |                 |                    |                           |            |             |        |           |       |                         |      |       |      |      |
| 22                                 | 30              | 8 × 7              | 8                         | }          | +0.098      | 4      | }         | +0.20 | 2.4                     | }    | +0.20 | 0.25 | 0.16 |
| 30                                 | 38              | 10 × 8             | 10                        |            | +0.040      | 5      |           | 2.4   | 0.40                    |      | 0.25  |      |      |
| 38                                 | 44              | 12 × 8             | 12                        | }          | }           | 5      | 2.4       | 0.40  | 0.25                    |      |       |      |      |
| 44                                 | 50              | 14 × 9             | 14                        |            |             | +0.120 | 5.5       | 2.9   | 0.40                    | 0.25 |       |      |      |
| 50                                 | 58              | 16 × 10            | 16                        |            |             | +0.050 | 6         | 3.4   | 0.40                    | 0.25 |       |      |      |
| 58                                 | 65              | 18 × 11            | 18                        | }          | }           | 7      | 3.4       | 0.40  | 0.25                    |      |       |      |      |
| 65                                 | 75              | 20 × 12            | 20                        |            |             | 7.5    | 3.9       | 0.60  | 0.40                    |      |       |      |      |
| 75                                 | 85              | 22 × 14            | 22                        | }          | }           | 9      | 4.4       | 0.60  | 0.40                    |      |       |      |      |
| 85                                 | 95              | 25 × 14            | 25                        |            |             | +0.149 | 9         | 4.4   | 0.60                    | 0.40 |       |      |      |
| 95                                 | 110             | 28 × 16            | 28                        |            |             | +0.065 | 10        | 5.4   | 0.60                    | 0.40 |       |      |      |
| 110                                | 130             | 32 × 18            | 32                        | }          | }           | 11     | 6.4       | 0.60  | 0.40                    |      |       |      |      |
| 130                                | 150             | 36 × 20            | 36                        |            |             | 12     | 7.1       | 1.00  | 0.70                    |      |       |      |      |
| 150                                | 170             | 40 × 22            | 40                        | }          | }           | 13     | 8.1       | 1.00  | 0.70                    |      |       |      |      |
| 170                                | 200             | 45 × 25            | 45                        |            |             | +0.180 | 15        | 9.1   | 1.00                    | 0.70 |       |      |      |
| 200                                | 230             | 50 × 28            | 50                        |            |             | +0.080 | 17        | 10.1  | 1.00                    | 0.70 |       |      |      |
| 230                                | 260             | 56 × 32            | 56                        | }          | }           | 20     | 11.1      | 1.60  | 1.20                    |      |       |      |      |
| 260                                | 290             | 63 × 32            | 63                        |            |             | +0.220 | 20        | 11.1  | 1.60                    | 1.20 |       |      |      |
| 290                                | 330             | 70 × 36            | 70                        | }          | }           | 22     | 13.1      | 1.60  | 1.20                    |      |       |      |      |
| 330                                | 380             | 80 × 40            | 80                        |            |             | +0.120 | 25        | 14.1  | 2.50                    | 2.00 |       |      |      |
| 380                                | 440             | 90 × 45            | 90                        |            |             | +0.260 | 28        | 16.1  | 2.50                    | 2.00 |       |      |      |
| 440                                | 500             | 100 × 50           | 100                       | }          | }           | 31     | 18.1      | 2.50  | 2.00                    |      |       |      |      |
|                                    |                 |                    |                           |            |             | +0.120 |           |       |                         |      |       |      |      |

**Table 14. British Standard Metric Square and Rectangular Parallel Keys BS 4235:Part 1:1972 (1986)**

| Width<br><i>b</i>         |                   | Thickness,<br><i>h</i> |                   | Chamfer,<br><i>s</i> |      | Length Range,<br><i>l</i> |     |
|---------------------------|-------------------|------------------------|-------------------|----------------------|------|---------------------------|-----|
| Nom.                      | Tol. <sup>a</sup> | Nom.                   | Tol. <sup>a</sup> | Min.                 | Max. | From                      | To  |
| Square Parallel Keys      |                   |                        |                   |                      |      |                           |     |
| 2                         | } 0<br>-0.025     | 2                      | } 0<br>-0.025     | 0.16                 | 0.25 | 6                         | 20  |
| 3                         |                   | 3                      |                   | 0.16                 | 0.25 | 6                         | 36  |
| 4                         | } 0<br>-0.030     | 4                      | } 0<br>-0.030     | 0.16                 | 0.25 | 8                         | 45  |
| 5                         |                   | 5                      |                   | 0.25                 | 0.40 | 10                        | 56  |
| 6                         |                   | 6                      |                   | 0.25                 | 0.40 | 14                        | 70  |
| Rectangular Parallel Keys |                   |                        |                   |                      |      |                           |     |
| 8                         | } 0<br>-0.036     | 7                      | } 0<br>-0.090     | 0.25                 | 0.40 | 18                        | 90  |
| 10                        |                   | 8                      |                   | 0.40                 | 0.60 | 22                        | 110 |
| 12                        | } 0<br>-0.043     | 8                      | } 0<br>-0.110     | 0.40                 | 0.60 | 28                        | 140 |
| 14                        |                   | 9                      |                   | 0.40                 | 0.60 | 36                        | 160 |
| 16                        |                   | 10                     |                   | 0.40                 | 0.60 | 45                        | 180 |
| 18                        | } 0<br>-0.052     | 11                     | } 0<br>-0.130     | 0.40                 | 0.60 | 50                        | 200 |
| 20                        |                   | 12                     |                   | 0.60                 | 0.80 | 56                        | 220 |
| 22                        |                   | 14                     |                   | 0.60                 | 0.80 | 63                        | 250 |
| 25                        |                   | 14                     |                   | 0.60                 | 0.80 | 70                        | 280 |
| 28                        | } 0<br>-0.062     | 16                     | } 0<br>-0.160     | 0.60                 | 0.80 | 80                        | 320 |
| 32                        |                   | 18                     |                   | 0.60                 | 0.80 | 90                        | 360 |
| 36                        |                   | 20                     |                   | 1.00                 | 1.20 | 100                       | 400 |
| 40                        |                   | 22                     |                   | 1.00                 | 1.20 | ...                       | ... |
| 45                        |                   | 25                     |                   | 1.00                 | 1.20 | ...                       | ... |
| 50                        | } 0<br>-0.074     | 28                     | } 0<br>-0.160     | 1.00                 | 1.20 | ...                       | ... |
| 56                        |                   | 32                     |                   | 1.60                 | 2.00 | ...                       | ... |
| 63                        |                   | 32                     |                   | 1.60                 | 2.00 | ...                       | ... |
| 70                        | } 0<br>-0.087     | 36                     | } 0<br>-0.160     | 1.60                 | 2.00 | ...                       | ... |
| 80                        |                   | 40                     |                   | 2.50                 | 3.00 | ...                       | ... |
| 90                        | } 0<br>-0.087     | 45                     | } 0<br>-0.160     | 2.50                 | 3.00 | ...                       | ... |
| 100                       |                   | 50                     |                   | 2.50                 | 3.00 | ...                       | ... |

<sup>a</sup>The tolerance on the width and thickness of square taper keys is h9, and on the width and thickness of rectangular keys, h9 and h11, respectively, in accordance with ISO metric limits and fits. All dimensions in millimeters.

**Table 15. British Standard Metric Square and Rectangular Taper Keys BS 4235:Part 1:1972 (1986)**

| Width $b$              |                   | Thickness $h$ |                   | Chamfer $s$ |      | Length Range $l$ |     | Gib head $h_1$ | Radius $r$ |
|------------------------|-------------------|---------------|-------------------|-------------|------|------------------|-----|----------------|------------|
| Nom.                   | Tol. <sup>a</sup> | Nom.          | Tol. <sup>a</sup> | Min.        | Max. | From             | To  | Nom.           | Nom.       |
| Square Taper Keys      |                   |               |                   |             |      |                  |     |                |            |
| 2                      | 0                 | 2             | 0                 | 0.16        | 0.25 | 6                | 20  | ...            | ...        |
| 3                      | -0.025            | 3             | -0.025            | 0.16        | 0.25 | 6                | 36  | ...            | ...        |
| 4                      | 0                 | 4             | 0                 | 0.16        | 0.25 | 8                | 45  | 7              | 0.25       |
| 5                      | -0.030            | 5             | -0.030            | 0.25        | 0.40 | 10               | 56  | 8              | 0.25       |
| 6                      |                   | 6             |                   | 0.25        | 0.40 | 14               | 70  | 10             | 0.25       |
| Rectangular Taper Keys |                   |               |                   |             |      |                  |     |                |            |
| 8                      | 0                 | 7             |                   | 0.25        | 0.40 | 18               | 90  | 11             | 1.5        |
| 10                     | -0.036            | 8             |                   | 0.40        | 0.60 | 22               | 110 | 12             | 1.5        |
| 12                     |                   | 8             | 0                 | 0.40        | 0.60 | 28               | 140 | 12             | 1.5        |
| 14                     | 0                 | 9             | -0.090            | 0.40        | 0.60 | 36               | 160 | 14             | 1.5        |
| 16                     | -0.043            | 10            |                   | 0.40        | 0.60 | 45               | 180 | 16             | 3.2        |
| 18                     |                   | 11            |                   | 0.40        | 0.60 | 50               | 200 | 18             | 3.2        |
| 20                     |                   | 12            |                   | 0.60        | 0.80 | 56               | 220 | 20             | 3.2        |
| 22                     | 0                 | 14            | 0                 | 0.60        | 0.80 | 63               | 250 | 22             | 3.2        |
| 25                     | -0.052            | 14            | -0.110            | 0.60        | 0.80 | 70               | 280 | 22             | 3.2        |
| 28                     |                   | 16            |                   | 0.60        | 0.80 | 80               | 320 | 25             | 3.2        |
| 32                     |                   | 18            |                   | 0.60        | 0.80 | 90               | 360 | 28             | 6.4        |
| 36                     |                   | 20            |                   | 1.00        | 1.20 | 100              | 400 | 32             | 6.4        |
| 40                     | 0                 | 22            | 0                 | 1.00        | 1.20 | ...              | ... | 36             | 6.4        |
| 45                     | -0.062            | 25            | -0.130            | 1.00        | 1.20 | ...              | ... | 40             | 6.4        |
| 50                     |                   | 28            |                   | 1.00        | 1.20 | ...              | ... | 45             | 6.4        |
| 56                     |                   | 32            |                   | 1.60        | 2.00 | ...              | ... | 50             | 9.5        |
| 63                     | 0                 | 32            |                   | 1.60        | 2.00 | ...              | ... | 50             | 9.5        |
| 70                     | -0.074            | 36            | 0                 | 1.60        | 2.00 | ...              | ... | 56             | 9.5        |
| 80                     |                   | 40            | -0.160            | 2.50        | 3.00 | ...              | ... | 63             | 9.5        |
| 90                     | 0                 | 45            |                   | 2.50        | 3.00 | ...              | ... | 70             | 9.5        |
| 100                    | -0.087            | 50            |                   | 2.50        | 3.00 | ...              | ... | 80             | 9.5        |

<sup>a</sup> The tolerance on the width and thickness of square taper keys is h9, and on the width and thickness of rectangular taper keys, h9 and h11 respectively, in accordance with ISO metric limits and fits. Does not apply to gib head dimensions.

*British Standard Keys and Keyways:* Tables 16 through 21 from BS 46:Part 1:1958 (1985) (obsolescent) provide data for rectangular parallel keys and keyways, square parallel keys and keyways, plain and gib head rectangular taper keys and keyways, plain and gib head square taper keys and keyways, and Woodruff keys and keyways.

*Parallel Keys:* These keys are used for transmitting unidirectional torques in transmissions not subject to heavy starting loads and where periodic withdrawal or sliding of the hub member may be required. In many instances, particularly couplings, a gib-head cannot be accommodated, and there is insufficient room to drift out the key from behind. It is then necessary to withdraw the component over the key and a parallel key is essential. Parallel square and rectangular keys are normally side fitting with top clearance and are usually retained in the shaft rather more securely than in the hub. The rectangular key is the general-purpose key for shafts greater than 1 inch in diameter; the square key is intended for



use with shafts up to and including 1-inch diameter or for shafts up to 6-inch diameter where it is desirable to have a greater key depth than is provided by rectangular keys. In stepped shafts, the larger diameters are usually required by considerations other than torque, e.g., resistance to bending. Where components such as fans, gears, impellers, etc., are attached to the larger shaft diameter, the use of a key smaller than standard for that diameter may be permissible. As this results in unequal disposition of the key in the shaft and its related hub, the dimensions  $H$  and  $h$  must be recalculated to maintain the  $T/2$  relationship.

**British Standard Preferred Lengths of Metric Keys BS 4235:Part 1:1972 (1986)**

| Length | Type of key |       |           |             | Length | Type of key |       |           |             |
|--------|-------------|-------|-----------|-------------|--------|-------------|-------|-----------|-------------|
|        | Sq.         | Rect. | Sq. Taper | Rect. Taper |        | Sq.         | Rect. | Sq. Taper | Rect. Taper |
| 6      | ●           |       | ●         |             | 63     | ●           | ●     | ●         | ●           |
| 8      | ●           |       | ●         |             | 70     | ●           | ●     | ●         | ●           |
| 10     | ●           |       | ●         |             | 80     |             | ●     |           | ●           |
| 12     | ●           |       | ●         |             | 90     |             | ●     |           | ●           |
| 14     | ●           |       | ●         |             | 100    |             | ●     |           | ●           |
| 16     | ●           |       | ●         |             | 110    |             | ●     |           | ●           |
| 18     | ●           | ●     | ●         | ●           | 125    |             | ●     |           | ●           |
| 20     | ●           | ●     | ●         | ●           | 140    |             | ●     |           | ●           |
| 22     | ●           | ●     | ●         | ●           | 160    |             | ●     |           | ●           |
| 25     | ●           | ●     | ●         | ●           | 180    |             | ●     |           | ●           |
| 28     | ●           | ●     | ●         | ●           | 200    |             | ●     |           | ●           |
| 32     | ●           | ●     | ●         | ●           | 220    |             | ●     |           | ●           |
| 36     | ●           | ●     | ●         | ●           | 250    |             | ●     |           | ●           |
| 40     | ●           | ●     | ●         | ●           | 280    |             | ●     |           | ●           |
| 45     | ●           | ●     | ●         | ●           | 320    |             | ●     |           | ●           |
| 50     | ●           | ●     | ●         | ●           | 360    |             | ●     |           | ●           |
| 56     | ●           | ●     | ●         | ●           | 400    |             | ●     |           | ●           |

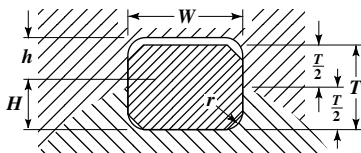
**Taper Keys:** These keys are used for transmitting heavy unidirectional, reversing, or vibrating torques and in applications where periodic withdrawal of the key may be necessary. Taper keys are usually top fitting, but may be top and side fitting where required, and the keyway in the hub should then have the same width value as the keyway in the shaft. Taper keys of rectangular section are used for general purposes and are of less depth than square keys; square sections are for use with shafts up to and including 1-inch diameter or for shafts up to 6-inch diameter where it is desirable to have greater key depth.

**Woodruff Keys:** These keys are used for light applications or the angular location of associated parts on tapered shaft ends. They are not recommended for other applications, but if so used, corner radii in the shaft and hub keyways are advisable to reduce stress concentration.

**Dimensions and Tolerances for British Parallel and Taper Keys and Keyways:** Dimensions and tolerances for key and keyway widths given in Tables 16, 17, 18, and 19 are based on the width of key  $W$  and provide a fitting allowance. The fitting allowance is designed to permit an interference between the key and the shaft keyway and a slightly easier condition between the key and the hub keyway. In shrink and heavy force fits, it may be found necessary to depart from the width and depth tolerances specified. Any variation in the width of the keyway should be such that the greatest width is at the end from which the key enters and any variation in the depth of the keyway should be such that the greatest depth is at the end from which the key enters.

Keys and keybar normally are not chamfered or radiused as supplied, but this may be done at the time of fitting. Radii and chamfers are given in Tables 16, 17, 18, and 19. Corner radii are recommended for keyways to alleviate stress concentration.

Table 16. British Standard Rectangular Parallel Keys, Keyways, and Keybars B.S. 46: Part I: 1958



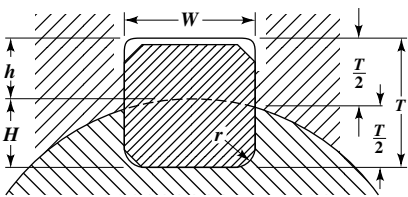
| Diameter of Shaft |                     | Key               |            |       |                | Keyway in Shaft |             |       |           | Keyway in Hub |             |       |           | Nominal Keyway Radius, $r^3$ | Keybar |       |       |       |       |
|-------------------|---------------------|-------------------|------------|-------|----------------|-----------------|-------------|-------|-----------|---------------|-------------|-------|-----------|------------------------------|--------|-------|-------|-------|-------|
| Over              | Up to and Including | Size $W \times T$ | Width, $W$ |       | Thickness, $T$ |                 | Width $W_s$ |       | Depth $H$ |               | Width $W_h$ |       | Depth $h$ |                              | Max.   | Min.  | Max.  | Min.  |       |
|                   |                     |                   | Max.       | Min.  | Max.           | Min.            | Min.        | Max.  | Min.      | Max.          | Min.        | Max.  | Min.      |                              |        |       |       |       | Max.  |
| 1                 | 1 1/4               | 5/16 x 1/4        | 0.314      | 0.312 | 0.253          | 0.250           | 0.311       | 0.312 | 0.146     | 0.152         | 0.312       | 0.313 | 0.112     | 0.118                        | 0.010  | 0.314 | 0.312 | 0.253 | 0.250 |
| 1 1/4             | 1 1/2               | 3/8 x 1/4         | 0.377      | 0.375 | 0.253          | 0.250           | 0.374       | 0.375 | 0.150     | 0.156         | 0.375       | 0.376 | 0.108     | 0.114                        | 0.010  | 0.377 | 0.375 | 0.253 | 0.250 |
| 1 1/2             | 1 3/4               | 7/16 x 3/16       | 0.440      | 0.438 | 0.315          | 0.312           | 0.437       | 0.438 | 0.186     | 0.192         | 0.438       | 0.439 | 0.135     | 0.141                        | 0.020  | 0.440 | 0.438 | 0.315 | 0.312 |
| 1 3/4             | 2                   | 1/2 x 3/16        | 0.502      | 0.500 | 0.315          | 0.312           | 0.499       | 0.500 | 0.190     | 0.196         | 0.500       | 0.501 | 0.131     | 0.137                        | 0.020  | 0.502 | 0.500 | 0.315 | 0.312 |
| 2                 | 2 1/2               | 5/8 x 7/16        | 0.627      | 0.625 | 0.441          | 0.438           | 0.624       | 0.625 | 0.260     | 0.266         | 0.625       | 0.626 | 0.185     | 0.191                        | 0.020  | 0.627 | 0.625 | 0.441 | 0.438 |
| 2 1/2             | 3                   | 3/4 x 1/2         | 0.752      | 0.750 | 0.503          | 0.500           | 0.749       | 0.750 | 0.299     | 0.305         | 0.750       | 0.751 | 0.209     | 0.215                        | 0.020  | 0.752 | 0.750 | 0.503 | 0.500 |
| 3                 | 3 1/2               | 7/8 x 5/8         | 0.877      | 0.875 | 0.629          | 0.625           | 0.874       | 0.875 | 0.370     | 0.376         | 0.875       | 0.876 | 0.264     | 0.270                        | 0.062  | 0.877 | 0.875 | 0.629 | 0.625 |
| 3 1/2             | 4                   | 1 x 3/4           | 1.003      | 1.000 | 0.754          | 0.750           | 0.999       | 1.000 | 0.441     | 0.447         | 1.000       | 1.001 | 0.318     | 0.324                        | 0.062  | 1.003 | 1.000 | 0.754 | 0.750 |
| 4                 | 5                   | 1 1/4 x 3/8       | 1.253      | 1.250 | 0.879          | 0.875           | 1.248       | 1.250 | 0.518     | 0.524         | 1.250       | 1.252 | 0.366     | 0.372                        | 0.062  | 1.253 | 1.250 | 0.879 | 0.875 |
| 5                 | 6                   | 1 1/2 x 1         | 1.504      | 1.500 | 1.006          | 1.000           | 1.498       | 1.500 | 0.599     | 0.605         | 1.500       | 1.502 | 0.412     | 0.418                        | 0.062  | 1.504 | 1.500 | 1.006 | 1.000 |
| 6                 | 7                   | 1 3/4 x 1 1/8     | 1.754      | 1.750 | 1.256          | 1.250           | 1.748       | 1.750 | 0.746     | 0.752         | 1.750       | 1.752 | 0.526     | 0.532                        | 0.125  |       |       |       |       |
| 7                 | 8                   | 2 x 1 3/8         | 2.005      | 2.000 | 1.381          | 1.375           | 1.998       | 2.000 | 0.818     | 0.824         | 2.000       | 2.002 | 0.573     | 0.579                        | 0.125  |       |       |       |       |
| 8                 | 9                   | 2 1/4 x 1 1/2     | 2.255      | 2.250 | 1.506          | 1.500           | 2.248       | 2.250 | 0.897     | 0.905         | 2.250       | 2.252 | 0.619     | 0.627                        | 0.125  |       |       |       |       |
| 9                 | 10                  | 2 1/2 x 1 5/8     | 2.505      | 2.500 | 1.631          | 1.625           | 2.498       | 2.500 | 0.975     | 0.983         | 2.500       | 2.502 | 0.666     | 0.674                        | 0.187  |       |       |       |       |
| 10                | 11                  | 2 3/4 x 1 7/8     | 2.755      | 2.750 | 1.881          | 1.875           | 2.748       | 2.750 | 1.114     | 1.122         | 2.750       | 2.752 | 0.777     | 0.785                        | 0.187  |       |       |       |       |
| 11                | 12                  | 3 x 2             | 3.006      | 3.000 | 2.008          | 2.000           | 2.998       | 3.000 | 1.195     | 1.203         | 3.000       | 3.002 | 0.823     | 0.831                        | 0.187  |       |       |       |       |
| 12                | 13                  | 3 1/4 x 2 1/8     | 3.256      | 3.250 | 2.133          | 2.125           | 3.248       | 3.250 | 1.273     | 1.281         | 3.250       | 3.252 | 0.870     | 0.878                        | 0.187  |       |       |       |       |
| 13                | 14                  | 3 1/2 x 2 3/8     | 3.506      | 3.500 | 2.383          | 2.375           | 3.498       | 3.500 | 1.413     | 1.421         | 3.500       | 3.502 | 0.980     | 0.988                        | 0.250  |       |       |       |       |
| 14                | 15                  | 3 3/4 x 2 1/2     | 3.756      | 3.750 | 2.508          | 2.500           | 3.748       | 3.750 | 1.492     | 1.502         | 3.750       | 3.752 | 1.026     | 1.036                        | 0.250  |       |       |       |       |
| 15                | 16                  | 4 x 2 5/8         | 4.008      | 4.000 | 2.633          | 2.625           | 3.998       | 4.000 | 1.571     | 1.581         | 4.000       | 4.002 | 1.072     | 1.082                        | 0.250  |       |       |       |       |
| 16                | 17                  | 4 1/4 x 2 7/8     | 4.258      | 4.250 | 2.883          | 2.875           | 4.248       | 4.250 | 1.711     | 1.721         | 4.250       | 4.252 | 1.182     | 1.192                        | 0.312  |       |       |       |       |
| 17                | 18                  | 4 1/2 x 3         | 4.508      | 4.500 | 3.010          | 3.000           | 4.498       | 4.500 | 1.791     | 1.801         | 4.500       | 4.502 | 1.229     | 1.239                        | 0.312  |       |       |       |       |
| 18                | 19                  | 4 3/4 x 3 1/8     | 4.758      | 4.750 | 3.135          | 3.125           | 4.748       | 4.750 | 1.868     | 1.878         | 4.750       | 4.752 | 1.277     | 1.287                        | 0.312  |       |       |       |       |
| 19                | 20                  | 5 x 3 3/8         | 5.008      | 5.000 | 3.385          | 3.375           | 4.998       | 5.000 | 2.010     | 2.020         | 5.000       | 5.002 | 1.385     | 1.395                        | 0.312  |       |       |       |       |

<sup>a</sup> The key chamfer shall be the minimum to clear the keyway radius. Nominal values are given.

Bright keybar is not normally available in sections larger than the above.

All dimensions in inches.

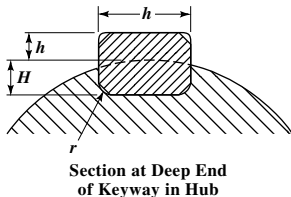
Table 17. British Standard Square Parallel Keys, Keyways, and Keybars B.S. 46: Part I: 1958



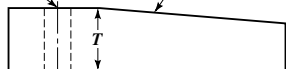
| Diameter of Shaft |                     | Key                                |                               |       | Keyway in Shaft |       |            |       | Keyway in Hub |       |            |       | Nominal Keyway Radius, $r^a$ | Bright Keybar                 |       |
|-------------------|---------------------|------------------------------------|-------------------------------|-------|-----------------|-------|------------|-------|---------------|-------|------------|-------|------------------------------|-------------------------------|-------|
| Over              | Up to and Including | Size, $W \times T$                 | Width, $W$ and Thickness, $T$ |       | Width, $W_s$    |       | Depth, $H$ |       | Width, $W_h$  |       | Depth, $h$ |       |                              | Width, $W$ and Thickness, $T$ |       |
|                   |                     |                                    | Max.                          | Min.  | Min.            | Max.  | Min.       | Max.  | Min.          | Max.  | Min.       | Max.  |                              | Max.                          | Min.  |
| $\frac{1}{4}$     | $\frac{1}{2}$       | $\frac{1}{8} \times \frac{1}{8}$   | 0.127                         | 0.125 | 0.124           | 0.125 | 0.072      | 0.078 | 0.125         | 0.126 | 0.060      | 0.066 | 0.010                        | 0.127                         | 0.125 |
| $\frac{1}{2}$     | $\frac{3}{4}$       | $\frac{3}{16} \times \frac{3}{16}$ | 0.190                         | 0.188 | 0.187           | 0.188 | 0.107      | 0.113 | 0.188         | 0.189 | 0.088      | 0.094 | 0.010                        | 0.190                         | 0.188 |
| $\frac{3}{4}$     | 1                   | $\frac{1}{4} \times \frac{1}{4}$   | 0.252                         | 0.250 | 0.249           | 0.250 | 0.142      | 0.148 | 0.250         | 0.251 | 0.115      | 0.121 | 0.010                        | 0.252                         | 0.250 |
| 1                 | $1\frac{1}{4}$      | $\frac{3}{8} \times \frac{3}{8}$   | 0.314                         | 0.312 | 0.311           | 0.312 | 0.177      | 0.183 | 0.312         | 0.313 | 0.142      | 0.148 | 0.010                        | 0.314                         | 0.312 |
| $1\frac{1}{4}$    | $1\frac{1}{2}$      | $\frac{3}{8} \times \frac{3}{8}$   | 0.377                         | 0.375 | 0.374           | 0.375 | 0.213      | 0.219 | 0.375         | 0.376 | 0.169      | 0.175 | 0.010                        | 0.377                         | 0.375 |
| $1\frac{1}{2}$    | $1\frac{3}{4}$      | $\frac{7}{16} \times \frac{7}{16}$ | 0.440                         | 0.438 | 0.437           | 0.438 | 0.248      | 0.254 | 0.438         | 0.439 | 0.197      | 0.203 | 0.020                        | 0.440                         | 0.438 |
| $1\frac{3}{4}$    | 2                   | $\frac{1}{2} \times \frac{1}{2}$   | 0.502                         | 0.500 | 0.499           | 0.500 | 0.283      | 0.289 | 0.500         | 0.501 | 0.224      | 0.230 | 0.020                        | 0.502                         | 0.500 |
| 2                 | $2\frac{1}{2}$      | $\frac{5}{8} \times \frac{5}{8}$   | 0.627                         | 0.625 | 0.624           | 0.625 | 0.354      | 0.360 | 0.625         | 0.626 | 0.278      | 0.284 | 0.020                        | 0.627                         | 0.625 |
| $2\frac{1}{2}$    | 3                   | $\frac{3}{4} \times \frac{3}{4}$   | 0.752                         | 0.750 | 0.749           | 0.750 | 0.424      | 0.430 | 0.750         | 0.751 | 0.333      | 0.339 | 0.020                        | 0.752                         | 0.750 |
| 3                 | $3\frac{1}{2}$      | $\frac{7}{8} \times \frac{7}{8}$   | 0.877                         | 0.875 | 0.874           | 0.875 | 0.495      | 0.501 | 0.875         | 0.876 | 0.387      | 0.393 | 0.062                        | 0.877                         | 0.875 |
| $3\frac{1}{2}$    | 4                   | $1 \times 1$                       | 1.003                         | 1.000 | 0.999           | 1.000 | 0.566      | 0.572 | 1.000         | 1.001 | 0.442      | 0.448 | 0.062                        | 1.003                         | 1.000 |
| 4                 | 5                   | $1\frac{1}{4} \times 1\frac{1}{4}$ | 1.253                         | 1.250 | 1.248           | 1.250 | 0.707      | 0.713 | 1.250         | 1.252 | 0.551      | 0.557 | 0.062                        | 1.253                         | 1.250 |
| 5                 | 6                   | $1\frac{1}{2} \times 1\frac{1}{2}$ | 1.504                         | 1.500 | 1.498           | 1.500 | 0.848      | 0.854 | 1.500         | 1.502 | 0.661      | 0.667 | 0.062                        | 1.504                         | 1.500 |

<sup>a</sup>The key chamfer shall be the minimum to clear the keyway radius. Nominal values are given. All dimensions in inches.

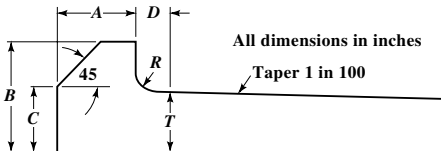
Table 18. British Standard Rectangular Taper Keys and Keyways, Gib-head and Plain B.S. 46: Part 1: 1958



Section at Deep End of Keyway in Hub



Plain Taper Key



Gib-Head Key

Alternative Design Showing a Parallel Hole Extension with a Drilled Hole To Facilitate Extraction

All dimensions in inches

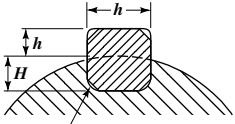
| Diameter of Shaft |                     | Key                |              |       |                |       |                 | Keyway in Shaft and Hub |               |       |                     |       |   |       |       | Nominal Keyway Radius, $r^a$ | Gib-head <sup>b</sup> |         |     |      | Radius, $R$ |
|-------------------|---------------------|--------------------|--------------|-------|----------------|-------|-----------------|-------------------------|---------------|-------|---------------------|-------|---|-------|-------|------------------------------|-----------------------|---------|-----|------|-------------|
| Over              | Up to and Including | Size, $W \times T$ | Width, $W$   |       | Thickness, $T$ |       | Keyway in Shaft |                         | Keyway in Hub |       | Depth in Shaft, $H$ |       | Depth in Hub at Deep End of Keyway, $h$ |       | A     |                              | B                     | C       | D   |      |             |
|                   |                     |                    | Max.         | Min.  | Max.           | Min.  | Min.            | Max.                    | Min.          | Max.  | Min.                | Max.  | Min.                                    | Max.  |       |                              |                       |         |     |      |             |
|                   |                     |                    | Width, $W_s$ |       | Width, $W_h$   |       | Min.            | Max.                    | Min.          | Max.  | Min.                | Max.  | Min.                                    | Max.  |       |                              |                       |         |     |      |             |
| 1                 | 1/4                 | 3/16 x 1/4         | 0.314        | 0.312 | 0.254          | 0.249 | 0.311           | 0.312                   | 0.312         | 0.313 | 0.146               | 0.152 | 0.090                                   | 0.096 | 0.010 | 3/8                          | 7/16                  | 1/4     | 0.3 | 1/16 |             |
| 1 1/4             | 1 1/2               | 3/8 x 3/4          | 0.377        | 0.375 | 0.254          | 0.249 | 0.374           | 0.375                   | 0.375         | 0.376 | 0.150               | 0.156 | 0.086                                   | 0.092 | 0.010 | 7/16                         | 7/16                  | 3/32    | 0.3 | 3/16 |             |
| 1 1/2             | 1 3/4               | 7/16 x 5/8         | 0.440        | 0.438 | 0.316          | 0.311 | 0.437           | 0.438                   | 0.438         | 0.439 | 0.186               | 0.192 | 0.112                                   | 0.118 | 0.020 | 1/2                          | 9/16                  | 5/16    | 0.4 | 1/16 |             |
| 1 3/4             | 2                   | 1/2 x 3/4          | 0.502        | 0.500 | 0.316          | 0.311 | 0.499           | 0.500                   | 0.500         | 0.501 | 0.190               | 0.196 | 0.108                                   | 0.114 | 0.020 | 5/8                          | 5/8                   | 3/8     | 0.4 | 3/16 |             |
| 2                 | 2 1/2               | 5/8 x 7/8          | 0.627        | 0.625 | 0.442          | 0.437 | 0.624           | 0.625                   | 0.625         | 0.626 | 0.260               | 0.266 | 0.162                                   | 0.168 | 0.020 | 11/16                        | 3/4                   | 7/16    | 0.5 | 1/8  |             |
| 2 1/2             | 3                   | 3/4 x 1/2          | 0.752        | 0.750 | 0.504          | 0.499 | 0.749           | 0.750                   | 0.750         | 0.751 | 0.299               | 0.305 | 0.185                                   | 0.191 | 0.020 | 13/16                        | 7/8                   | 11/32   | 0.5 | 1/8  |             |
| 3                 | 3 1/2               | 7/8 x 3/4          | 0.877        | 0.875 | 0.630          | 0.624 | 0.874           | 0.875                   | 0.875         | 0.876 | 0.370               | 0.376 | 0.239                                   | 0.245 | 0.062 | 15/16                        | 1                     | 21/32   | 0.6 | 3/8  |             |
| 3 1/2             | 4                   | 1 x 3/4            | 1.003        | 1.000 | 0.755          | 0.749 | 0.999           | 1.000                   | 1.000         | 1.001 | 0.441               | 0.447 | 0.293                                   | 0.299 | 0.062 | 1 1/16                       | 1 1/4                 | 23/32   | 0.6 | 1/4  |             |
| 4                 | 5                   | 1 1/4 x 3/8        | 1.253        | 1.250 | 0.880          | 0.874 | 1.248           | 1.250                   | 1.250         | 1.252 | 0.518               | 0.524 | 0.340                                   | 0.346 | 0.062 | 1 1/8                        | 1 1/2                 | 23/32   | 0.7 | 3/4  |             |
| 5                 | 6                   | 1 1/2 x 1          | 1.504        | 1.500 | 1.007          | 0.999 | 1.498           | 1.500                   | 1.500         | 1.502 | 0.599               | 0.605 | 0.384                                   | 0.390 | 0.062 | 1 3/8                        | 1 3/8                 | 1 1/2   | 0.7 | 1/2  |             |
| 6                 | 7                   | 1 3/4 x 1 1/4      | 1.754        | 1.750 | 1.257          | 1.249 | 1.748           | 1.750                   | 1.750         | 1.752 | 0.740               | 0.746 | 0.493                                   | 0.499 | 0.125 | 1 7/8                        | 2                     | 1 7/8   | 0.8 | 1/2  |             |
| 7                 | 8                   | 2 x 1 3/8          | 2.005        | 2.000 | 1.382          | 1.374 | 1.998           | 2.000                   | 2.000         | 2.002 | 0.818               | 0.824 | 0.539                                   | 0.545 | 0.125 | 2 1/16                       | 2 1/4                 | 1 13/32 | 0.8 | 3/4  |             |
| 8                 | 9                   | 2 1/4 x 1 1/2      | 2.255        | 2.250 | 1.509          | 1.499 | 2.248           | 2.250                   | 2.250         | 2.252 | 0.897               | 0.905 | 0.581                                   | 0.589 | 0.125 | 2 3/16                       | 2 3/2                 | 1 9/16  | 0.9 | 3/8  |             |
| 9                 | 10                  | 2 1/2 x 1 3/8      | 2.505        | 2.500 | 1.634          | 1.624 | 2.498           | 2.500                   | 2.500         | 2.502 | 0.975               | 0.983 | 0.628                                   | 0.636 | 0.187 | 2 7/16                       | 2 3/4                 | 1 11/16 | 0.9 | 3/8  |             |
| 10                | 11                  | 2 3/4 x 1 1/8      | 2.755        | 2.750 | 1.884          | 1.874 | 2.748           | 2.750                   | 2.750         | 2.752 | 1.114               | 1.122 | 0.738                                   | 0.746 | 0.187 | 2 11/16                      | 3                     | 1 15/16 | 1.0 | 3/8  |             |
| 11                | 12                  | 3 x 2              | 3.006        | 3.000 | 2.014          | 1.999 | 2.998           | 3.000                   | 3.000         | 3.002 | 1.195               | 1.203 | 0.782                                   | 0.790 | 0.187 | 3 1/16                       | 3 1/4                 | 2 1/16  | 1.0 | 3/8  |             |

<sup>a</sup>The key chamfer shall be the minimum to clear the keyway radius. Nominal values shall be given.

<sup>b</sup>Dimensions A, B, C, D, and R pertain to gib-head keys only.


All dimensions in inches.

Table 19. British Standard Square Taper Keys and Keyways, Gib-head or Plain B.S. 46: Part I: 1958

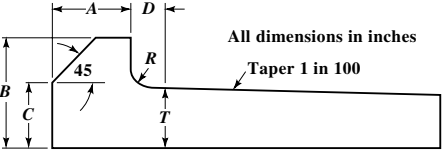


**Section at Deep End of Keyway in Hub**

**Alternative Design Showing a Parallel Hole Extension with a Drilled Hole To Facilitate Extraction**



**Plain Taper Key**



**Gib-Head Key**

All dimensions in inches

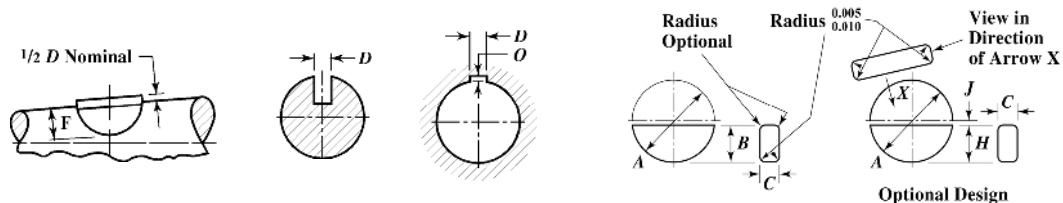
| Diameter of Shaft |                     | Key             |       |                     |       |                 |       | Keyway in Shaft and Hub |       |                          |       |  |       | Nominal Keyway Radius, <sup>a</sup> | Gib-head <sup>b</sup> |          |          |          |                  |      |
|-------------------|---------------------|-----------------|-------|---------------------|-------|-----------------|-------|-------------------------|-------|--------------------------|-------|--|-------|-------------------------------------|-----------------------|----------|----------|----------|------------------|------|
| Over              | Up to and Including | Width, <i>W</i> |       | Thickness, <i>T</i> |       | Keyway in Shaft |       | Keyway in Hub           |       | Depth in Shaft, <i>H</i> |       | Depth in Hub at Deep End of Keyway, <i>h</i> |       |                                     | <i>A</i>              | <i>B</i> | <i>C</i> | <i>D</i> | Radius, <i>R</i> |      |
|                   |                     | Max.            | Min.  | Max.                | Min.  | Min.            | Max.  | Min.                    | Max.  | Min.                     | Max.  | Min.   | Max.  |                                     |                       |          |          |          |                  |      |
| 1/4               | 1/2                 | 3/16 × 1/8      | 0.127 | 0.125               | 0.129 | 0.124           | 0.124 | 0.125                   | 0.125 | 0.126                    | 0.072 | 0.078  | 0.039 | 0.045                               | 0.010                 | 3/16     | 1/4      | 5/32     | 0.1              | 1/32 |
| 1/2               | 3/4                 | 3/16 × 3/16     | 0.190 | 0.188               | 0.192 | 0.187           | 0.187 | 0.188                   | 0.188 | 0.189                    | 0.107 | 0.113  | 0.067 | 0.073                               | 0.010                 | 1/4      | 3/8      | 7/32     | 0.2              | 1/32 |
| 3/4               | 1                   | 1/4 × 1/4       | 0.252 | 0.250               | 0.254 | 0.249           | 0.249 | 0.250                   | 0.250 | 0.251                    | 0.142 | 0.148  | 0.094 | 0.100                               | 0.010                 | 3/16     | 7/16     | 9/32     | 0.2              | 1/16 |
| 1                 | 1 1/4               | 5/16 × 5/16     | 0.314 | 0.312               | 0.316 | 0.311           | 0.311 | 0.312                   | 0.312 | 0.313                    | 0.177 | 0.183  | 0.121 | 0.127                               | 0.010                 | 3/8      | 9/16     | 11/32    | 0.3              | 1/16 |
| 1 1/4             | 1 1/2               | 3/8 × 3/8       | 0.377 | 0.379               | 0.379 | 0.374           | 0.374 | 0.375                   | 0.375 | 0.376                    | 0.213 | 0.219  | 0.148 | 0.154                               | 0.010                 | 7/16     | 3/8      | 13/32    | 0.3              | 1/16 |
| 1 1/2             | 1 3/4               | 7/16 × 7/16     | 0.440 | 0.438               | 0.442 | 0.437           | 0.437 | 0.438                   | 0.438 | 0.439                    | 0.248 | 0.254  | 0.175 | 0.181                               | 0.020                 | 1/2      | 3/4      | 15/32    | 0.4              | 1/16 |
| 1 3/4             | 2                   | 1/2 × 1/2       | 0.502 | 0.500               | 0.504 | 0.499           | 0.499 | 0.500                   | 0.500 | 0.501                    | 0.283 | 0.289  | 0.202 | 0.208                               | 0.020                 | 9/16     | 7/8      | 17/32    | 0.4              | 1/16 |
| 2                 | 2 1/2               | 5/8 × 5/8       | 0.627 | 0.625               | 0.630 | 0.624           | 0.624 | 0.625                   | 0.625 | 0.626                    | 0.354 | 0.360  | 0.256 | 0.262                               | 0.020                 | 11/16    | 1        | 21/32    | 0.5              | 1/8  |
| 2 1/2             | 3                   | 3/8 × 3/4       | 0.752 | 0.750               | 0.755 | 0.749           | 0.749 | 0.750                   | 0.750 | 0.751                    | 0.424 | 0.430  | 0.310 | 0.316                               | 0.020                 | 13/16    | 1 1/4    | 25/32    | 0.5              | 1/8  |
| 3                 | 3 1/2               | 7/8 × 7/8       | 0.877 | 0.875               | 0.880 | 0.874           | 0.874 | 0.875                   | 0.875 | 0.876                    | 0.495 | 0.501  | 0.364 | 0.370                               | 0.062                 | 15/16    | 1 3/8    | 29/32    | 0.6              | 1/8  |
| 3 1/2             | 4                   | 1 × 1           | 1.003 | 1.000               | 1.007 | 0.999           | 0.999 | 1.000                   | 1.000 | 1.001                    | 0.566 | 0.572  | 0.418 | 0.424                               | 0.062                 | 1 1/16   | 1 5/8    | 1 1/32   | 0.6              | 1/8  |
| 4                 | 5                   | 1 1/4 × 1 1/4   | 1.253 | 1.250               | 1.257 | 1.249           | 1.248 | 1.250                   | 1.250 | 1.252                    | 0.707 | 0.713  | 0.526 | 0.532                               | 0.062                 | 1 3/16   | 2        | 1 9/32   | 0.7              | 1/4  |
| 5                 | 6                   | 1 1/2 × 1 1/2   | 1.504 | 1.500               | 1.509 | 1.499           | 1.498 | 1.500                   | 1.500 | 1.502                    | 0.848 | 0.854  | 0.635 | 0.641                               | 0.062                 | 1 7/16   | 2 1/2    | 1 17/32  | 0.7              | 1/4  |

<sup>a</sup>The key chamfer shall be the minimum to clear the keyway radius. Nominal values shall be given.

<sup>b</sup>Dimensions *A*, *B*, *C*, *D*, and *R* pertain to gib-head keys only.

All dimensions in inches.

**Dimensions and Tolerances of British Woodruff Keys and Keyways.**—Dimensions and tolerances are shown in Table 20. An optional alternative design of the Woodruff key that differs from the normal form in its depth is given in the illustration accompanying the table. The method of designating British Woodruff Keys is the same as the American method explained in the footnote on page 2369.



**Table 20. British Standard Woodruff Keys and Keyways BS 46: Part 1: 1958**

| Key and Cutter No. | Key                     |               |            |       |         |       |             |       | Keyway            |       |                 |       |                   |       |                                |       | Optional Design |       |                |
|--------------------|-------------------------|---------------|------------|-------|---------|-------|-------------|-------|-------------------|-------|-----------------|-------|-------------------|-------|--------------------------------|-------|-----------------|-------|----------------|
|                    | Nominal Fractional Size |               | Diameter A |       | Depth B |       | Thickness C |       | Width in Shaft, D |       | Width in Hub, E |       | Depth in Shaft, F |       | Depth in Hub at Center Line, G |       | Depth of Key, H |       | Dimension, J   |
|                    | Width.                  | Dia.          | Max.       | Min.  | Max.    | Min.  | Max.        | Min.  | Min.              | Max.  | Min.            | Max.  | Min.              | Max.  | Min.                           | Max.  | Max.            | Min.  | Nom.           |
| 203                | $\frac{1}{16}$          | $\frac{3}{8}$ | 0.375      | 0.370 | 0.171   | 0.166 | 0.063       | 0.062 | 0.061             | 0.063 | 0.063           | 0.065 | 0.135             | 0.140 | 0.042                          | 0.047 | 0.162           | 0.156 | $\frac{1}{64}$ |
| 303                | $\frac{3}{32}$          | $\frac{3}{8}$ | 0.375      | 0.370 | 0.171   | 0.166 | 0.095       | 0.094 | 0.093             | 0.095 | 0.095           | 0.097 | 0.119             | 0.124 | 0.057                          | 0.062 | 0.162           | 0.156 | $\frac{1}{64}$ |
| 403                | $\frac{1}{8}$           | $\frac{3}{8}$ | 0.375      | 0.370 | 0.171   | 0.166 | 0.126       | 0.125 | 0.124             | 0.126 | 0.126           | 0.128 | 0.104             | 0.109 | 0.073                          | 0.078 | 0.162           | 0.156 | $\frac{1}{64}$ |
| 204                | $\frac{1}{16}$          | $\frac{1}{2}$ | 0.500      | 0.490 | 0.203   | 0.198 | 0.063       | 0.062 | 0.061             | 0.063 | 0.063           | 0.065 | 0.167             | 0.172 | 0.042                          | 0.047 | 0.194           | 0.188 | $\frac{3}{64}$ |
| 304                | $\frac{3}{32}$          | $\frac{1}{2}$ | 0.500      | 0.490 | 0.203   | 0.198 | 0.095       | 0.094 | 0.093             | 0.095 | 0.095           | 0.097 | 0.151             | 0.156 | 0.057                          | 0.062 | 0.194           | 0.188 | $\frac{3}{64}$ |
| 404                | $\frac{1}{8}$           | $\frac{1}{2}$ | 0.500      | 0.490 | 0.203   | 0.198 | 0.126       | 0.125 | 0.124             | 0.126 | 0.126           | 0.128 | 0.136             | 0.141 | 0.073                          | 0.078 | 0.194           | 0.188 | $\frac{3}{64}$ |
| 305                | $\frac{3}{32}$          | $\frac{5}{8}$ | 0.625      | 0.615 | 0.250   | 0.245 | 0.095       | 0.094 | 0.093             | 0.095 | 0.095           | 0.097 | 0.198             | 0.203 | 0.057                          | 0.062 | 0.240           | 0.234 | $\frac{1}{16}$ |
| 405                | $\frac{1}{8}$           | $\frac{5}{8}$ | 0.625      | 0.615 | 0.250   | 0.245 | 0.126       | 0.125 | 0.124             | 0.126 | 0.126           | 0.128 | 0.182             | 0.187 | 0.073                          | 0.078 | 0.240           | 0.234 | $\frac{1}{16}$ |
| 505                | $\frac{3}{32}$          | $\frac{5}{8}$ | 0.625      | 0.615 | 0.250   | 0.245 | 0.157       | 0.156 | 0.155             | 0.157 | 0.157           | 0.159 | 0.167             | 0.172 | 0.089                          | 0.094 | 0.240           | 0.234 | $\frac{1}{16}$ |
| 406                | $\frac{1}{8}$           | $\frac{3}{4}$ | 0.750      | 0.740 | 0.313   | 0.308 | 0.126       | 0.125 | 0.124             | 0.126 | 0.126           | 0.128 | 0.246             | 0.251 | 0.073                          | 0.078 | 0.303           | 0.297 | $\frac{1}{16}$ |

Table 20. (Continued) British Standard Woodruff Keys and Keyways BS 46: Part 1: 1958

| Key and Cutter No. | Key                     |                |            |       |         |       |             |       | Keyway            |       |                 |       |                   |       |                                |       | Optional Design |       |                |  |
|--------------------|-------------------------|----------------|------------|-------|---------|-------|-------------|-------|-------------------|-------|-----------------|-------|-------------------|-------|--------------------------------|-------|-----------------|-------|----------------|--|
|                    | Nominal Fractional Size |                | Diameter A |       | Depth B |       | Thickness C |       | Width in Shaft, D |       | Width in Hub, E |       | Depth in Shaft, F |       | Depth in Hub at Center Line, G |       | Depth of Key, H |       | Dimension, J   |  |
|                    | Width.                  | Dia.           | Max.       | Min.  | Max.    | Min.  | Max.        | Min.  | Min.              | Max.  | Min.            | Max.  | Min.              | Max.  | Min.                           | Max.  | Max.            | Min.  | Nom.           |  |
| 506                | $\frac{3}{32}$          | $\frac{3}{4}$  | 0.750      | 0.740 | 0.313   | 0.308 | 0.157       | 0.156 | 0.155             | 0.157 | 0.157           | 0.159 | 0.230             | 0.235 | 0.089                          | 0.094 | 0.303           | 0.297 | $\frac{1}{16}$ |  |
| 606                | $\frac{3}{16}$          | $\frac{3}{4}$  | 0.750      | 0.740 | 0.313   | 0.308 | 0.189       | 0.188 | 0.187             | 0.189 | 0.189           | 0.191 | 0.214             | 0.219 | 0.104                          | 0.109 | 0.303           | 0.297 | $\frac{1}{16}$ |  |
| 507                | $\frac{3}{32}$          | $\frac{7}{8}$  | 0.875      | 0.865 | 0.375   | 0.370 | 0.157       | 0.156 | 0.155             | 0.157 | 0.157           | 0.159 | 0.292             | 0.297 | 0.089                          | 0.094 | 0.365           | 0.359 | $\frac{1}{16}$ |  |
| 607                | $\frac{3}{16}$          | $\frac{7}{8}$  | 0.875      | 0.865 | 0.375   | 0.370 | 0.189       | 0.188 | 0.187             | 0.189 | 0.189           | 0.191 | 0.276             | 0.281 | 0.104                          | 0.109 | 0.365           | 0.359 | $\frac{1}{16}$ |  |
| 807                | $\frac{1}{4}$           | $\frac{7}{8}$  | 0.875      | 0.865 | 0.375   | 0.370 | 0.251       | 0.250 | 0.249             | 0.251 | 0.251           | 0.253 | 0.245             | 0.250 | 0.136                          | 0.141 | 0.365           | 0.359 | $\frac{1}{16}$ |  |
| 608                | $\frac{3}{16}$          | 1              | 1.000      | 0.990 | 0.438   | 0.433 | 0.189       | 0.188 | 0.187             | 0.189 | 0.189           | 0.191 | 0.339             | 0.344 | 0.104                          | 0.109 | 0.428           | 0.422 | $\frac{1}{16}$ |  |
| 808                | $\frac{1}{4}$           | 1              | 1.000      | 0.990 | 0.438   | 0.433 | 0.251       | 0.250 | 0.249             | 0.251 | 0.251           | 0.253 | 0.308             | 0.313 | 0.136                          | 0.141 | 0.428           | 0.422 | $\frac{1}{16}$ |  |
| 1008               | $\frac{3}{16}$          | 1              | 1.000      | 0.990 | 0.438   | 0.433 | 0.313       | 0.312 | 0.311             | 0.313 | 0.313           | 0.315 | 0.277             | 0.282 | 0.167                          | 0.172 | 0.428           | 0.422 | $\frac{1}{16}$ |  |
| 609                | $\frac{3}{16}$          | $1\frac{1}{8}$ | 1.125      | 1.115 | 0.484   | 0.479 | 0.189       | 0.188 | 0.187             | 0.189 | 0.189           | 0.191 | 0.385             | 0.390 | 0.104                          | 0.109 | 0.475           | 0.469 | $\frac{5}{64}$ |  |
| 809                | $\frac{1}{4}$           | $1\frac{1}{8}$ | 1.125      | 1.115 | 0.484   | 0.479 | 0.251       | 0.250 | 0.249             | 0.251 | 0.251           | 0.253 | 0.354             | 0.359 | 0.136                          | 0.141 | 0.475           | 0.469 | $\frac{5}{64}$ |  |
| 1009               | $\frac{3}{16}$          | $1\frac{1}{8}$ | 1.125      | 1.115 | 0.484   | 0.479 | 0.313       | 0.312 | 0.311             | 0.313 | 0.313           | 0.315 | 0.323             | 0.328 | 0.167                          | 0.172 | 0.475           | 0.469 | $\frac{5}{64}$ |  |
| 810                | $\frac{1}{4}$           | $1\frac{1}{4}$ | 1.250      | 1.240 | 0.547   | 0.542 | 0.251       | 0.250 | 0.249             | 0.251 | 0.251           | 0.253 | 0.417             | 0.422 | 0.136                          | 0.141 | 0.537           | 0.531 | $\frac{5}{64}$ |  |
| 1010               | $\frac{3}{16}$          | $1\frac{1}{4}$ | 1.250      | 1.240 | 0.547   | 0.542 | 0.313       | 0.312 | 0.311             | 0.313 | 0.313           | 0.315 | 0.386             | 0.391 | 0.167                          | 0.172 | 0.537           | 0.531 | $\frac{5}{64}$ |  |
| 1210               | $\frac{3}{8}$           | $1\frac{1}{4}$ | 1.250      | 1.240 | 0.547   | 0.542 | 0.376       | 0.375 | 0.374             | 0.376 | 0.376           | 0.378 | 0.354             | 0.359 | 0.198                          | 0.203 | 0.537           | 0.531 | $\frac{5}{64}$ |  |
| 1011               | $\frac{3}{16}$          | $1\frac{3}{8}$ | 1.375      | 1.365 | 0.594   | 0.589 | 0.313       | 0.312 | 0.311             | 0.313 | 0.313           | 0.315 | 0.433             | 0.438 | 0.167                          | 0.172 | 0.584           | 0.578 | $\frac{3}{32}$ |  |
| 1211               | $\frac{3}{8}$           | $1\frac{3}{8}$ | 1.375      | 1.365 | 0.594   | 0.589 | 0.376       | 0.375 | 0.374             | 0.376 | 0.376           | 0.378 | 0.402             | 0.407 | 0.198                          | 0.203 | 0.584           | 0.578 | $\frac{3}{32}$ |  |
| 812                | $\frac{1}{4}$           | $1\frac{1}{2}$ | 1.500      | 1.490 | 0.641   | 0.636 | 0.251       | 0.250 | 0.249             | 0.251 | 0.251           | 0.253 | 0.511             | 0.516 | 0.136                          | 0.141 | 0.631           | 0.625 | $\frac{7}{64}$ |  |
| 1012               | $\frac{3}{16}$          | $1\frac{1}{2}$ | 1.500      | 1.490 | 0.641   | 0.636 | 0.313       | 0.312 | 0.311             | 0.313 | 0.313           | 0.315 | 0.480             | 0.485 | 0.167                          | 0.172 | 0.631           | 0.625 | $\frac{7}{64}$ |  |
| 1212               | $\frac{3}{8}$           | $1\frac{1}{2}$ | 1.500      | 1.490 | 0.641   | 0.636 | 0.376       | 0.375 | 0.374             | 0.376 | 0.376           | 0.378 | 0.448             | 0.453 | 0.198                          | 0.203 | 0.631           | 0.625 | $\frac{7}{64}$ |  |

All dimensions are in inches.

KEYS AND KEYWAYS

**Table 21. British Preferred Lengths of Plain (Parallel or Taper) and Gib-head Keys, Rectangular and Square Section *BS 46:Part 1:1958 (1985) Appendix***

| Plain Key Size<br>$W \times T$     |   | Overall Length, $L$ |   |                |                |                |   |                |                |                |   |                |   |                |   |   |
|------------------------------------|---|---------------------|---|----------------|----------------|----------------|---|----------------|----------------|----------------|---|----------------|---|----------------|---|---|
|                                    |   | $\frac{3}{4}$       | 1 | $1\frac{1}{4}$ | $1\frac{1}{2}$ | $1\frac{3}{4}$ | 2 | $2\frac{1}{4}$ | $2\frac{1}{2}$ | $2\frac{3}{4}$ | 3 | $3\frac{1}{2}$ | 4 | $4\frac{1}{2}$ | 5 | 6 |
| $\frac{1}{8} \times \frac{1}{8}$   | • | •                   |   |                |                |                |   |                |                |                |   |                |   |                |   |   |
| $\frac{3}{16} \times \frac{3}{16}$ | • | •                   | • | •              | •              | •              | • | •              | •              | •              |   |                |   |                |   |   |
| $\frac{1}{4} \times \frac{1}{4}$   | • | •                   | • | •              | •              | •              | • | •              | •              | •              |   |                |   |                |   |   |
| $\frac{5}{16} \times \frac{1}{4}$  | • | •                   | • | •              | •              | •              | • | •              | •              | •              |   |                |   |                |   |   |
| $\frac{5}{16} \times \frac{5}{16}$ | • | •                   | • | •              | •              | •              | • | •              | •              | •              | • | •              | • |                |   |   |
| $\frac{3}{8} \times \frac{1}{4}$   |   | •                   | • | •              | •              | •              | • | •              | •              | •              |   | •              | • |                |   |   |
| $\frac{3}{8} \times \frac{3}{8}$   |   | •                   | • | •              | •              | •              | • | •              | •              | •              |   | •              | • |                |   |   |
| $\frac{7}{16} \times \frac{5}{16}$ |   |                     |   | •              | •              | •              | • | •              | •              | •              |   | •              | • |                |   |   |
| $\frac{7}{16} \times \frac{7}{16}$ |   |                     |   | •              | •              | •              | • | •              | •              | •              |   | •              | • |                |   |   |
| $\frac{1}{2} \times \frac{5}{16}$  |   |                     |   |                | •              | •              | • | •              | •              | •              |   | •              | • | •              | • |   |
| $\frac{1}{2} \times \frac{1}{2}$   |   |                     |   |                | •              | •              | • | •              | •              | •              |   | •              | • | •              | • |   |
| $\frac{5}{8} \times \frac{7}{16}$  |   |                     |   |                |                | •              | • | •              | •              | •              |   | •              | • | •              | • | • |
| $\frac{5}{8} \times \frac{5}{8}$   |   |                     |   |                |                | •              | • | •              | •              | •              |   | •              | • | •              | • | • |
| $\frac{3}{4} \times \frac{1}{2}$   |   |                     |   |                |                |                |   |                |                | •              |   | •              | • | •              | • | • |
| $\frac{3}{4} \times \frac{3}{4}$   |   |                     |   |                |                |                |   |                |                | •              |   | •              | • | •              | • | • |
| $\frac{7}{8} \times \frac{5}{8}$   |   |                     |   |                |                |                |   |                |                |                |   | •              | • | •              | • | • |

| Gib-head Key Size,<br>$W \times T$ |   | Overall Length, $L$ |                |   |                |                |                |   |                |   |                |   |                |   |                |   |                |   |
|------------------------------------|---|---------------------|----------------|---|----------------|----------------|----------------|---|----------------|---|----------------|---|----------------|---|----------------|---|----------------|---|
|                                    |   | $1\frac{1}{2}$      | $1\frac{3}{4}$ | 2 | $2\frac{1}{4}$ | $2\frac{1}{2}$ | $2\frac{3}{4}$ | 3 | $3\frac{1}{2}$ | 4 | $4\frac{1}{2}$ | 5 | $5\frac{1}{2}$ | 6 | $6\frac{1}{2}$ | 7 | $7\frac{1}{2}$ | 8 |
| $\frac{3}{16} \times \frac{3}{16}$ | • | •                   | •              | • | •              |                | •              |   |                |   |                |   |                |   |                |   |                |   |
| $\frac{1}{4} \times \frac{1}{4}$   | • | •                   | •              | • | •              |                | •              |   |                |   |                |   |                |   |                |   |                |   |
| $\frac{5}{16} \times \frac{1}{4}$  |   |                     | •              | • | •              |                | •              |   |                |   |                |   |                |   |                |   |                |   |
| $\frac{5}{16} \times \frac{5}{16}$ |   |                     | •              | • | •              |                | •              |   |                | • |                |   |                |   |                |   |                |   |
| $\frac{3}{8} \times \frac{1}{4}$   |   |                     | •              | • | •              |                | •              |   |                | • |                |   |                |   |                |   |                |   |
| $\frac{3}{8} \times \frac{3}{8}$   |   |                     | •              | • | •              |                | •              |   |                | • |                |   |                |   |                |   |                |   |
| $\frac{7}{16} \times \frac{5}{16}$ |   |                     |                | • | •              |                | •              |   |                | • |                |   |                |   |                |   |                |   |
| $\frac{7}{16} \times \frac{7}{16}$ |   |                     |                | • | •              |                | •              |   |                | • |                |   |                |   |                |   |                |   |
| $\frac{1}{2} \times \frac{5}{16}$  |   |                     |                |   | •              |                | •              |   |                | • |                |   |                |   |                |   |                |   |
| $\frac{1}{2} \times \frac{1}{2}$   |   |                     |                |   | •              |                | •              |   |                | • |                |   |                |   |                |   |                |   |
| $\frac{5}{8} \times \frac{7}{16}$  |   |                     |                |   |                |                | •              |   |                | • |                |   |                |   |                |   |                |   |
| $\frac{5}{8} \times \frac{5}{8}$   |   |                     |                |   |                |                | •              |   |                | • |                |   |                |   |                |   |                |   |
| $\frac{3}{4} \times \frac{1}{2}$   |   |                     |                |   |                |                |                |   |                | • |                |   |                |   |                |   |                |   |
| $\frac{3}{4} \times \frac{3}{4}$   |   |                     |                |   |                |                |                |   |                | • |                |   |                |   |                |   |                |   |
| $\frac{7}{8} \times \frac{5}{8}$   |   |                     |                |   |                |                |                |   |                |   |                |   |                |   |                |   |                |   |
| $\frac{7}{8} \times \frac{7}{8}$   |   |                     |                |   |                |                |                |   |                |   |                |   |                |   |                |   |                |   |
| $1 \times \frac{3}{4}$             |   |                     |                |   |                |                |                |   |                |   |                |   |                |   |                |   |                |   |
| $1 \times 1$                       |   |                     |                |   |                |                |                |   |                |   |                |   |                |   |                |   |                |   |

All dimension are in inches



**FLEXIBLE BELTS AND SHEAVES**

Flexible belt drives are used in industrial power transmission applications, especially when the speeds of the driver and driven shafts must be different or when shafts must be widely separated. The trend toward higher speed prime movers and the need to achieve a slower, useful driven speed are additional factors favoring the use of belts. Belts have numerous advantages over other means of power transmission; these advantages include overall economy, cleanliness, no need for lubrication, lower maintenance costs, easy installation, dampening of shock loads, and the abilities to be used for clutching and variable speed power transmission between widely spaced shafts.

**Calculations for Belts and Pulleys**

Belt speed plays an important role in the amount of load a friction drive system can transmit. Higher speeds will require higher preloads (increased belt tension) to compensate for the higher centrifugal force. In positive drive (toothed belt) systems, higher speeds generate dynamic forces caused by unavoidable tolerance errors that may result in increased tooth or pin stresses and shorter belt life.

**Pulley Diameters and Drive Ratios.**—Minimum pulley diameters determined by belt manufacturers are based on the minimum radius that a belt can wrap around a pulley without stressing the load-carrying members. For positive drive systems, minimum pulley diameters are also determined by the minimum number of teeth that must be engaged with the sprocket to guarantee the operating load.

Diameters of driving and driven pulleys determine the velocity ratio of the input relative to the output shaft and are derived from the following formulas: for all belt systems, velocity ratio  $V = D_{pi}/D_{po}$ , and for positive (toothed) drive systems, velocity ratio  $V = N_i/N_o$ , where  $D_{pi}$  is the pitch diameter of the driving pulley,  $D_{po}$  is the pitch diameter of the driven pulley,  $N_i$  is the number of teeth on the driving pulley, and  $N_o$  is the number of teeth on the driven pulley. For most drive systems, a velocity ratio of 8:1 is the largest that should be attempted with a single reduction drive, and 6:1 is a reasonable maximum.

**Wrap Angles and Center-to-Center Distances.**—The radial distance for which the belt is in contact with the pulley surface, or the number of teeth in engagement for positive drive belts, is called the wrap angle. Belt and sprocket combinations should be chosen to ensure a wrap angle of about  $120^\circ$  around the smaller pulley. The wrap angle should not be less than  $90^\circ$ , especially with positive drive belts, because if too few teeth are in engagement, the belt may jump a tooth or pin and timing or synchronization may be lost.

For flat belts, the minimum allowable center-to-center distance (CD) for any belt-and-sprocket combination should be chosen to ensure a minimum wrap angle around the smaller pulley. For high-velocity systems, a good rule of thumb is a minimum CD equal to the sum of the pitch diameter of the larger sprocket and one-half the pitch diameter of the smaller sprocket. This formula ensures a minimum wrap angle of approximately  $120^\circ$ , which is generally sufficient for friction drives and will ensure that positive drive belts do not jump teeth.

**Pulley Center Distances and Belt Lengths.**—Maximum center distances of pulleys should be about 15 to 20 times the pitch diameter of the smaller pulley. Greater spacing requires tight control of the belt tension because a small amount of stretch will cause a large drop in tension. Constant belt tension can be obtained by application of an adjustable tensioning pulley applied to the slack side of the belt. Friction drive systems using flat belts require much more tension than positive drive belt systems.

Belt length can be calculated from:  $L = 2C + \pi(D_2 + D_1)/2 + (D_2 - D_1)^2/4C$  for friction drives, and length  $L = 2C + \pi(D_2 + D_1)/2 + (D_2 + D_1)^2/4C$  for crossed belt friction belt drives, where  $C$  is the center distance,  $D_1$  is the pitch diameter of the small pulley, and  $D_2$  is

the pitch diameter of the large pulley. For serrated belt drives, the length determined by use of these equations should be divided by the serration pitch. The belt length must then be adjusted to provide a whole number of serrations.

**Pulley Diameters and Speeds.**—If  $D$  = diameter of driving pulley,  $d$  = diameter of driven pulley,  $S$  = speed of driving pulley, and  $s$  = speed of driven pulley:

$$D = \frac{d \times s}{S}, \quad d = \frac{D \times S}{s}, \quad S = \frac{d \times s}{D}, \quad \text{and} \quad s = \frac{D \times S}{d}$$

*Example 1:* If the diameter of the driving pulley  $D$  is 24 inches, its speed is 100 rpm, and the driven pulley is to run at 600 rpm, the diameter of the driven pulley,  $d = 24 \times 100/600 = 4$  inches.

*Example 2:* If the diameter of the driven pulley  $d$  is 36 inches, its required speed is to be 150 rpm, and the speed of the driving pulley is to be 600 rpm, the diameter of the driving pulley  $D = 36 \times 150/600 = 9$  inches.

*Example 3:* If the diameter of the driven pulley  $d$  is 4 inches, its required speed is 800 rpm, and the diameter of the driving pulley  $D$  is 26 inches, the speed of the driving pulley  $= 4 \times 800/26 = 123$  rpm.

*Example 4:* If the diameter of the driving pulley  $D$  is 15 inches and its speed is 180 rpm, and the diameter of the driven pulley  $d$  is 9 inches, then the speed of the driven pulley  $= 15 \times 180/9 = 300$  rpm.

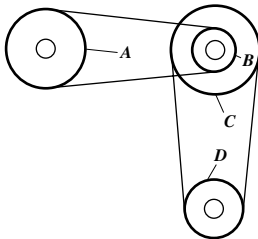
**Pulley Diameters in Compound Drive.**—If speeds of driving and driven pulleys,  $A$ ,  $B$ ,  $C$ , and  $D$  (see illustration) are known, the first step in finding their diameters is to form a fraction with the driving pulley speed as the numerator and the driven pulley speed as the denominator, and then reduce this fraction to its lowest terms. Resolve the numerator and the denominator into two pairs of factors (a pair being one factor in the numerator and one in the denominator) and, if necessary, multiply each pair by a trial number that will give pulleys of suitable diameters.

*Example 5:* If the speed of pulley  $A$  is 260 rpm and the required speed of pulley  $D$  is 720 rpm, find the diameters of the four pulleys. Reduced to its lowest terms, the fraction  $260/720 = 13/36$ , which represents the required speed ratio. Resolve this ratio  $13/36$  into two factors:

$$\frac{13}{36} = \frac{1 \times 13}{2 \times 18}$$

Multiply by trial numbers 12 and 1 to get:

$$\frac{(1 \times 12) \times (13 \times 1)}{(2 \times 12) \times (18 \times 1)} = \frac{12 \times 13}{24 \times 18}$$



Compound Drive with Four Pulleys.

The values 12 and 13 in the numerator represent the diameters of the *driven* pulleys,  $B$  and  $D$ , and the values 24 and 18 in the denominator represent the diameters of the *driving* pulleys,  $A$  and  $C$ , as shown in the illustration.

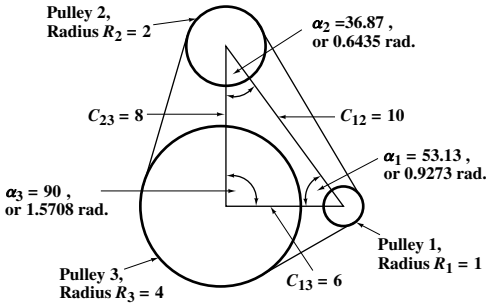
**Speed of Driven Pulley in Compound Drive.**—If diameters of pulleys  $A$ ,  $B$ ,  $C$ , and  $D$  (see illustration above), and speed of pulley  $A$  are known, the speed of the driven pulley  $D$  is found from:

$$\frac{\text{driving pulley diameter}}{\text{driven pulley diameter}} \times \frac{\text{driving pulley diameter}}{\text{driven pulley diameter}} \times \text{speed of first driving pulley}$$

*Example 6:* If the diameters of driving pulleys  $A$  and  $C$  are 18 and 24 inches, diameters of driven pulleys  $B$  and  $D$  are 12 and 13 inches, and the speed of driving pulley  $A$  is 260 rpm, speed of driven pulley

$$D = \frac{18 \times 24}{12 \times 13} \times 260 = 720 \text{ rpm}$$

**Length of Belt Traversing Three Pulleys.**—The length  $L$  of a belt traversing three pulleys, as shown in the diagram below, and touching them on one side only, can be found by the following formula.



Flat Belt Traversing Three Pulleys.

Referring to the diagram,  $R_1$ ,  $R_2$ , and  $R_3$  are the radii of the three pulleys;  $C_{12}$ ,  $C_{13}$ , and  $C_{23}$  are the center distances; and  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$  are the angles, in radians, of the triangle formed by the center distances. Then:

$$L = C_{12} + C_{13} + C_{23} + \frac{1}{2} \left[ \frac{(R_2 - R_1)^2}{C_{12}} + \frac{(R_3 - R_1)^2}{C_{13}} + \frac{(R_3 - R_2)^2}{C_{23}} \right] + \pi(R_1 + R_2 + R_3) - (\alpha_1 R_1 + \alpha_2 R_2 + \alpha_3 R_3)$$

*Example 7:* Assume  $R_1 = 1$ ,  $R_2 = 2$ ,  $R_3 = 4$ ,  $C_{12} = 10$ ,  $C_{13} = 6$ ,  $C_{23} = 8$ ,  $\alpha_1 = 53.13$  degrees or 0.9273 radian,  $\alpha_2 = 36.87$  degrees or 0.6435 radian, and  $\alpha_3 = 90$  degrees or 1.5708 radians. Then:

$$\begin{aligned} L &= 10 + 6 + 8 + \frac{1}{2} \left[ \frac{(2-1)^2}{10} + \frac{(4-1)^2}{6} + \frac{(4-2)^2}{8} \right] \\ &\quad + \pi(1 + 2 + 4) + (0.9273 \times 1 + 0.6435 \times 2 + 1.5708 \times 4) \\ &= 24 + 1.05 + 21.9911 - 8.4975 = 38.5436 \end{aligned}$$

**Power Transmitted By Belts.**—With belt drives, the force that produces work acts on the rim of a pulley or sheave and causes it to rotate. Since a belt on a drive must be tight enough to prevent slip, there is a belt pull on both sides of a driven wheel. When a drive is stationary or operating with no power transmitted, the pulls on both sides of the driven wheel are equal. When the drive is transmitting power, however, the pulls are not the same. There is a tight side tension  $T_T$  and a slack side tension,  $T_S$ . The difference between these two pulls ( $T_T - T_S$ ) is called *effective pull* or *net pull*. This effective pull is applied at the rim of the pulley and is the force that produces work.

Net pull equals horsepower (HP)  $\times$  33,000  $\div$  belt speed (fpm). Belt speed in fpm can be set by changing the pulley, sprocket, or sheave diameter. The shaft speeds remain the same. Belt speed is directly related to pulley diameter. Double the diameter and the total belt pull is cut in half, reducing the load on the shafts and bearings.

A belt experiences three types of tension as it rotates around a pulley: working tension (tight side – slack side), bending tension, and centrifugal tension.

The *tension ratio* ( $R$ ) equals tight side divided by slack side tension (measured in pounds). The larger  $R$  is, the closer a V-belt is to slipping—the belt is too loose. (Synchronous belts do not slip, because they depend on the tooth grip principle.)

In addition to working tension (tight side – slack side), two other tensions are developed in a belt when it is operating on a drive. *Bending tension*  $T_B$  occurs when the belt bends around the pulley. One part of the belt is in tension and the other is in compression, so compressive stresses also occur. The amount of tension depends on the belt's construction and the pulley diameter. *Centrifugal tension* ( $T_C$ ) occurs as the belt rotates around the drive and is calculated by  $T_C = MV^2$ , where  $T_C$  is centrifugal tension in pounds,  $M$  is a constant dependent on the belt's weight, and  $V$  is the belt velocity in feet per minute. Neither the bending nor centrifugal tensions are imposed on the pulley, shaft, or bearing—only on the belt.

Combining these three types of tension results in *peak tension* which is important in determining the degree of performance or belt life:  $T_{\text{peak}} = T_T + T_B + T_C$ .

**Measuring the Effective Length.**—The effective length of a V-belt is determined by placing the belt on a measuring device having two equal diameter sheaves with standard groove dimensions. The shaft of one of the sheaves is fixed. A specified measuring tension is applied to the housing for the shaft of the other sheave, moving it along a graduated scale. The belt is rotated around the sheaves at least two revolutions of the belt to seat it properly in the sheave grooves and to divide the total tension equally between the two strands of the belt.

The effective length of the belt is obtained by adding the effective (outside) circumference of one of the measuring sheaves to twice the center distance. Synchronous belts are measured in a similar manner.

The following sections cover common belts used in industrial applications for power transmission and specified in Rubber Manufacturers Association (RMA), Mechanical Power Transmission Association (MPTA), and The Rubber Association of Canada (RAC) standards. The information presented does not apply to automotive or agricultural drives, for which other standards exist. The belts covered in this section are Narrow, Classical, Double, and Light-Duty V-Belts, V-Ribbed Belts, Variable-Speed Belts, 60 deg V-Belts, and Synchronous (Timing) Belts.

### Flat Belting

Flat belting was originally made from leather because it was the most durable material available and could easily be cut and joined to make a driving belt suitable for use with cylindrical or domed pulleys. This type of belting was popular because it could be used to

transmit high torques over long distances and it was employed in factories to drive many small machines from a large common power source such as a steam engine. As electric motors became smaller, more efficient, and more powerful, and new types of belts and chains were made possible by modern materials and manufacturing processes, flat belts fell out of favor. Flat belts are still used for some drive purposes, but leather has been replaced by other natural and synthetic materials such as urethanes, which can be reinforced by high-strength polyamide or steel fabrics to provide properties such as resistance to stretching. The high modulus of elasticity in these flat belts eliminates the need for periodic retensioning that is usually necessary with V-belts.

Driving belts can be given a coating of an elastomer with a high coefficient of friction, to enable belts to grip pulleys without the degree of tension common with earlier materials. Urethanes are commonly used for driving belts where high resistance to abrasion is required, and also resist attack by chemical solvents of most kinds. Flat belts having good resistance to high temperatures are also available. Typical properties of polyurethane belts include tensile strength up to 40,000 psi, depending on reinforcement type and Shore hardness of 85 to 95. Most polyurethane belts are installed under tension. The amount of tension varies with the belt cross-section, being greater for belts of small section. Belt tension can be measured by marking lines 10 inches apart on an installed belt, then applying tension until the separation increases by the desired percentage. For 2 per cent tension, lines on the tensioned belt would be 10.2 inches apart. Mechanical failure may result when belt tensioning is excessive, and 2 to 2.5 per cent elongation should be regarded as the limit.

Flat belts offer high load capacities and are capable of transmitting power over long distances, maintaining relative rotational direction, can operate without lubricants, and are generally inexpensive to maintain or replace when worn. Flat belt systems will operate with little maintenance and only periodic adjustment. Because they transmit motion by friction, flat belts have the ability to slip under excessive loads, providing a fail-safe action to guard against malfunctions. This advantage is offset by the problem that friction belts can both slip and creep so that they do not offer exact, consistent velocity ratios nor precision timing between input and output shafts. Flat belts can be made to any desired length, being joined by reliable chemical bonding processes.

Increasing centrifugal force has less effect on the load-carrying capacity of flat belts at high speeds than it has on V-belts, for instance. The low thickness of a flat belt, compared with a V-belt, places its center of gravity near the pulley surface. Flat belts therefore may be run at surface speeds of up to 16,000 or even 20,000 ft/min (81.28 and 101.6 m/s), although ideal speeds are in the range of 3,000 to 10,000 ft/min (15.25 to 50.8 m/s). Elastomeric drive surfaces on flat belts have eliminated the need for belt dressings that were often needed to keep leather belts in place. These surface coatings can also contain antistatic materials. Belt pulley wear and noise are low with flat belts shock and vibration are damped, and efficiency is generally greater than 98 per cent compared with 96 per cent for V-belts.

Driving belt load capacities can be calculated from torque  $T = F(d/2)$  and horsepower  $HP = T \times rpm/396,000$ , where  $T$  is the torque in in-lb,  $F$  is the force transmitted in lb, and  $d$  is the pulley diameter in inches. Pulley width is usually about 10 per cent larger than the belt, and for good tracking, pulleys are often crowned by 0.012 to 0.10 inch for diameters in the range of 1.5 to 80 inches.

Before a belt specification is written, the system should be checked for excessive startup and shut-down loads, which sometimes are more than 10 per cent above operating conditions. In overcoming such loads, the belt will transmit considerably more force than during normal operation. Large starting and stopping forces will also shorten belt life unless they are taken into account during the design stage.

**Flat Belt Pulleys.**— Flat belt pulleys are usually made of cast iron, fabricated steel, paper, fiber, or various kinds of wood. They may be solid or split and in either case the hub may be split for clamping to the shaft.

Pulley face widths are nominally the same as the widths of the belts they are to carry. The pulley face should be approximately one inch more than the belt width for belts under 12 inches wide, 2 inches more for belts from 12 to 24 inches wide, and 3 inches more for belts over 24 inches in width.

Belts may be made to center themselves by the use of crowned pulleys. The usual amount of crowning is  $\frac{1}{8}$  inch per foot of pulley width. Thus, the difference in maximum and minimum radii of a crowned 6-inch wide pulley would be  $\frac{1}{16}$  inch. Crowned pulleys have a rim section either with a convex curve or a flat V form. Flanges on the sides of flat belt pulleys are in general undesirable as the belt tends to crawl against them. Too much crown is undesirable because of the tendency to "break the belt's back." This is particularly true for riding idlers close to driving pulleys where the curvature of the belt changes rapidly from one pulley to the other. Here, the idler should under no circumstances be crowned and the adjacent pulley should have very little crown. Pulleys carrying shifting belts are not crowned.

Open belt drives connecting pulleys on short centers with one pulley considerably larger than the other may be unsatisfactory due to the small angle of wrap on the smaller pulley. This angle may be increased by the use of idler pulleys on one or both sides of the belt.

### V-Belts

**Narrow V-Belts ANSI/RMA IP-22.**—Narrow V-belts serve the same applications as multiple, classical V-belts, but allow for a lighter, more compact drive. Three basic cross sections—3V and 3VX, 5V and 5VX, and 8V—are provided, as shown in Fig. 1. The 3VX and 5VX are molded, notched V-belts that have greater power capacity than conventional belts. Narrow V-belts are specified by cross section and effective length and have top widths ranging from  $\frac{3}{8}$  to 1 inch.

Narrow V-belts usually provide substantial weight and space savings over classical belts. Some narrow belts can transmit up to three times the horsepower of conventional belts in the same drive space, or the same horsepower in one-third to one-half the space. These belts are designed to operate in multiples and are also available in the joined configuration.

*Belt Cross Sections:* Nominal dimensions of the three cross sections are given in Fig. 1.

*Belt Size Designation:* Narrow V-belt sizes are identified by a standard belt number. The first figure of this number followed by the letter V denotes the belt cross section. An X following the V indicates a notched cross section. The remaining figures show the effective belt length in tenths of an inch. For example, the number 5VX1400 designates a notched V-belt with a 5V cross section and an effective length of 140.0 in. Standard effective lengths of narrow V-belts are shown in Table 1.

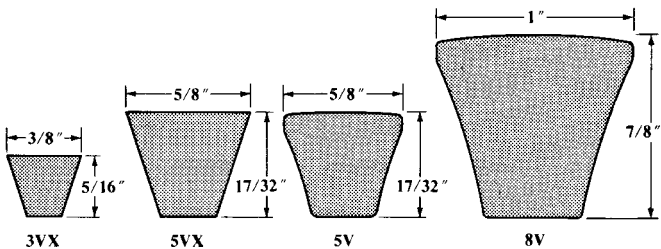


Fig. 1. Nominal Narrow V-Belt Dimensions

*Sheave Dimensions:* Groove angles and dimensions for sheaves and face widths of sheaves for multiple belt drives are given in Tables 2a and 2b, along with various tolerance values. Standard sheave outside diameters are given in Table 3.

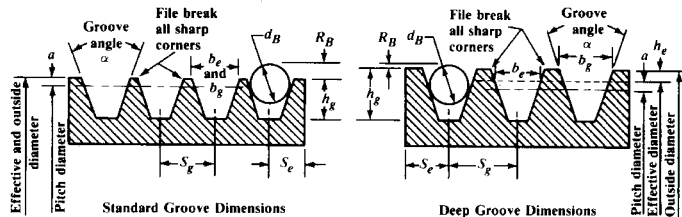
**Table 1. Narrow V-Belt Standard Effective Lengths ANSI/RMA IP-22 (1983)**

| Standard Length Designation <sup>a</sup> | Standard Effective Outside Length |       |       | Permissible Deviation from Standard Length | Matching Limits for One Set | Standard Length Designation <sup>a</sup> | Standard Effective Outside Length |       |       | Permissible Deviation from Standard Length | Matching Limits for One Set |
|--|-----------------------------------|-------|-------|--|-----------------------------|--|-----------------------------------|-------|-------|--|-----------------------------|
|  | Cross Section                     |       |       |  |                             |  | Cross Section                     |       |       |  |                             |
|  | 3V                                | 5V    | 8V    |  |                             |  | 3V                                | 5V    | 8V    |  |                             |
| 250                                      | 25.0                              | ...   | ...   | ±0.3                                       | 0.15                        | 1060                                     | 106.0                             | 106.0 | 106.0 | ±0.6                                       | 0.30                        |
| 265                                      | 26.5                              | ...   | ...   | ±0.3                                       | 0.15                        | 1120                                     | 112.0                             | 112.0 | 112.0 | ±0.6                                       | 0.30                        |
| 280                                      | 28.0                              | ...   | ...   | ±0.3                                       | 0.15                        | 1180                                     | 118.0                             | 118.0 | 118.0 | ±0.6                                       | 0.30                        |
| 300                                      | 30.0                              | ...   | ...   | ±0.3                                       | 0.15                        | 1250                                     | 125.0                             | 125.0 | 125.0 | ±0.6                                       | 0.30                        |
| 315                                      | 31.5                              | ...   | ...   | ±0.3                                       | 0.15                        | 1320                                     | 132.0                             | 132.0 | 132.0 | ±0.6                                       | 0.30                        |
| 335                                      | 33.5                              | ...   | ...   | ±0.3                                       | 0.15                        | 1400                                     | 140.0                             | 140.0 | 140.0 | ±0.6                                       | 0.30                        |
| 355                                      | 35.5                              | ...   | ...   | ±0.3                                       | 0.15                        | 1500                                     | ...                               | 150.0 | 150.0 | ±0.8                                       | 0.30                        |
| 375                                      | 37.5                              | ...   | ...   | ±0.3                                       | 0.15                        | 1600                                     | ...                               | 160.0 | 160.0 | ±0.8                                       | 0.45                        |
| 400                                      | 40.0                              | ...   | ...   | ±0.3                                       | 0.15                        | 1700                                     | ...                               | 170.0 | 170.0 | ±0.8                                       | 0.45                        |
| 425                                      | 42.5                              | ...   | ...   | ±0.3                                       | 0.15                        | 1800                                     | ...                               | 180.0 | 180.0 | ±0.8                                       | 0.45                        |
| 450                                      | 45.0                              | ...   | ...   | ±0.3                                       | 0.15                        | 1900                                     | ...                               | 190.0 | 190.0 | ±0.8                                       | 0.45                        |
| 475                                      | 47.5                              | ...   | ...   | ±0.3                                       | 0.15                        | 2000                                     | ...                               | 200.0 | 200.0 | ±0.8                                       | 0.45                        |
| 500                                      | 50.0                              | 50.0  | ...   | ±0.3                                       | 0.15                        | 2120                                     | ...                               | 212.0 | 212.0 | ±0.8                                       | 0.45                        |
| 530                                      | 53.0                              | 53.0  | ...   | ±0.4                                       | 0.15                        | 2240                                     | ...                               | 224.0 | 224.0 | ±0.8                                       | 0.45                        |
| 560                                      | 56.0                              | 56.0  | ...   | ±0.4                                       | 0.15                        | 2360                                     | ...                               | 236.0 | 236.0 | ±0.8                                       | 0.45                        |
| 600                                      | 60.0                              | 60.0  | ...   | ±0.4                                       | 0.15                        | 2500                                     | ...                               | 250.0 | 250.0 | ±0.8                                       | 0.45                        |
| 630                                      | 63.0                              | 63.0  | ...   | ±0.4                                       | 0.15                        | 2650                                     | ...                               | 265.0 | 265.0 | ±0.8                                       | 0.60                        |
| 670                                      | 67.0                              | 67.0  | ...   | ±0.4                                       | 0.30                        | 2800                                     | ...                               | 280.0 | 280.0 | ±0.8                                       | 0.60                        |
| 710                                      | 71.0                              | 71.0  | ...   | ±0.4                                       | 0.30                        | 3000                                     | ...                               | 300.0 | 300.0 | ±0.8                                       | 0.60                        |
| 750                                      | 75.0                              | 75.0  | ...   | ±0.4                                       | 0.30                        | 3150                                     | ...                               | 315.0 | 315.0 | ±1.0                                       | 0.60                        |
| 800                                      | 80.0                              | 80.0  | ...   | ±0.4                                       | 0.30                        | 3350                                     | ...                               | 335.0 | 335.0 | ±1.0                                       | 0.60                        |
| 850                                      | 85.0                              | 85.0  | ...   | ±0.5                                       | 0.30                        | 3550                                     | ...                               | 355.0 | 355.0 | ±1.0                                       | 0.60                        |
| 900                                      | 90.0                              | 90.0  | ...   | ±0.5                                       | 0.30                        | 3750                                     | ...                               | ...   | 375.0 | ±1.0                                       | 0.60                        |
| 950                                      | 95.0                              | 95.0  | ...   | ±0.5                                       | 0.30                        | 4000                                     | ...                               | ...   | 400.0 | ±1.0                                       | 0.75                        |
| 1000                                     | 100.0                             | 100.0 | 100.0 | ±0.5                                       | 0.30                        | 4250                                     | ...                               | ...   | 425.0 | ±1.2                                       | 0.75                        |

<sup>a</sup>To specify belt size, use the Standard Length Designation prefixed by the cross section, for example, 5 V850.

All dimensions in inches.

Table 2a. Narrow V-Belt Standard Sheave and Groove Dimensions ANSI/RMA IP-22 (1983)



Face Width of Standard and Deep Groove Sheaves =  $s_g(N_g - 1) + 2s_e$ , where  $N_g$  = number of grooves

| Cross Section | Standard Groove Outside Diameter     | Standard Groove Dimensions              |                      |                |                |                |                       |                        |                              | Design Factors     |       |
|---------------|--------------------------------------|---|----------------------|----------------|----------------|----------------|-----------------------|------------------------|------------------------------|--------------------|-------|
|               |                                      | Groove Angle, $\alpha$ , $\pm 0.25$ deg | $b_g$<br>$\pm 0.005$ | $b_e$<br>(Ref) | $h_g$<br>(Min) | $R_B$<br>(Min) | $d_B$<br>$\pm 0.0005$ | $S_g^a$<br>$\pm 0.015$ | $S_e$                        | Min Recommended OD | $2a$  |
| 3V            | Up through 3.49                      | 36                                      |                      |                |                | 0.181          |                       |                        |                              | 2.65               | 0.050 |
|               | Over 3.49 up to and including 6.00   | 38                                      | 0.350                | 0.350          | 0.340          | 0.183          | 0.3438                | 0.406                  | 0.344<br>(+0.099,<br>-0.031) |                    |       |
|               | Over 6.00 up to and including 12.00  | 40                                      |                      |                |                | 0.186          |                       |                        |                              |                    |       |
| 5V            | Over 12.00                           | 42                                      |                      |                |                | 0.188          |                       |                        |                              | 7.10               | 0.100 |
|               | Up through 9.99                      | 38                                      |                      |                |                | 0.329          |                       |                        |                              |                    |       |
|               | Over 9.99 up to and including 16.00  | 40                                      | 0.600                | 0.600          | 0.590          | 0.332          | 0.5938                | 0.688                  | 0.500<br>+0.125,<br>-0.047)  |                    |       |
| 8V            | Over 16.00                           | 42                                      |                      |                |                | 0.336          |                       |                        |                              | 12.50              | 0.200 |
|               | Up through 15.99                     | 38                                      |                      |                |                | 0.575          |                       |                        |                              |                    |       |
|               | Over 15.99 up to and including 22.40 | 40                                      | 1.000                | 1.000          | 0.990          | 0.580          | 1.0000                | 1.125                  | 0.750<br>(+0.250,<br>-0.062) |                    |       |
|               | Over 22.40                           | 42                                      |                      |                |                | 0.585          |                       |                        |                              |                    |       |

<sup>a</sup> See footnote <sup>b</sup> following Table 2b.



**Table 2b. Narrow V-Belt Standard Sheave and Groove Dimensions ANSI/RMA IP-22 (1983)**

| Cross Section | Deep Groove Outside Diameter         | Deep Groove Dimensions <sup>a</sup>     |                   |             |             |             |                    |                     |                  | Design Factors     |       |        |
|---------------|--------------------------------------|---|-------------------|-------------|-------------|-------------|--------------------|---------------------|------------------|--------------------|-------|--------|
|               |                                      | Groove Angle, $\alpha$ , $\pm 0.25$ deg | $b_g$ $\pm 0.005$ | $b_e$ (Ref) | $h_g$ (Min) | $R_B$ (Min) | $d_B$ $\pm 0.0005$ | $S_g^b$ $\pm 0.015$ | $S_e$            | Min Recommended OD | $2a$  | $2h_e$ |
| 3V            | Up through 3.71                      | 36                                      | 0.421             |             |             | 0.070       |                    |                     |                  | 2.87               | 0.050 | 0.218  |
|               | Over 3.71 up to and including 6.22   | 38                                      | 0.425             | 0.350       | 0.449       | 0.073       | 0.3438             | 0.500               | 0.375            |                    |       |        |
|               | Over 6.22 up to and including 12.22  | 40                                      | 0.429             |             |             | 0.076       |                    |                     | (+0.094, -0.031) |                    |       |        |
|               | Over 12.22                           | 42                                      | 0.434             |             |             | 0.078       |                    |                     |                  |                    |       |        |
| 5V            | Up through 10.31                     | 38                                      | 0.710             |             |             | 0.168       |                    |                     |                  | 7.42               | 0.100 | 0.320  |
|               | Over 10.31 up to and including 16.32 | 40                                      | 0.716             | 0.600       | 0.750       | 0.172       | 0.5938             | 0.812               | 0.562            |                    |       |        |
|               | Over 16.32                           | 42                                      | 0.723             |             |             | 0.175       |                    |                     | (+0.125, -0.047) |                    |       |        |
| 8V            | Up through 16.51                     | 38                                      | 1.180             |             |             | 0.312       |                    |                     |                  | 13.02              | 0.200 | 0.524  |
|               | Over 16.51 up to and including 22.92 | 40                                      | 1.191             | 1.000       | 1.252       | 0.316       | 1.0000             | 1.312               | 0.844            |                    |       |        |
|               | Over 22.92                           | 42                                      | 1.201             |             |             | 0.321       |                    |                     | (+0.250, -0.062) |                    |       |        |

<sup>a</sup>Deep groove sheaves are intended for drives with belt offset such as quarter-turn or vertical shaft drives. They may also be necessary where oscillations in the center distance may occur. Joined belts will not operate in deep groove sheaves.

<sup>b</sup>Summation of the deviations from  $S_g$  for all grooves in any one sheave should not exceed  $\pm 0.031$  in. The variations in pitch diameter between the grooves in any one sheave must be within the following limits: Up through 19.9 in. outside diameter and up through 6 grooves—0.010 in. (add 0.0005 in. for each additional groove). 20.0 in. and over on outside diameter and up through 10 grooves—0.015 in. (add 0.0005 in. for each additional groove). This variation can be obtained by measuring the distance across two measuring balls or rods placed in the grooves diametrically opposite each other. Comparing this “diameter over balls or rods” measurement between grooves will give the variation in pitch diameter.

| Other Sheave Tolerances  |   |   |
|--|---|---|
| Outside Diameter   | Radial Runout <sup>a</sup>  | Axial Runout <sup>a</sup>   |
| Up through 8.0 in. outside diameter $\pm 0.020$ in.<br>For each additional inch of outside diameter add $\pm 0.0025$ in. | Up through 10.0 in. outside diameter 0.010 in.<br>For each additional inch of outside diameter add 0.0005 in. | Up through 5.0 in. outside diameter 0.005 in.<br>For each additional inch of outside diameter add 0.001 in. |

<sup>a</sup>Total indicator reading.  
All dimensions in inches.

**Table 3. Standard Sheave Outside Diameters ANSI/RMA IP-22, 1983**

| 3V    |        |        | 5V    |        |        | 8V    |        |         |
|-------|--------|--------|-------|--------|--------|-------|--------|---------|
| Nom   | Min    | Max    | Nom   | Min    | Max    | Nom   | Min    | Max     |
| 2.65  | 2.638  | 2.680  | 7.10  | 7.087  | 7.200  | 12.50 | 12.402 | 12.600  |
| 2.80  | 2.795  | 2.840  | 7.50  | 7.480  | 7.600  | 13.20 | 13.189 | 13.400  |
| 3.00  | 2.953  | 3.000  | 8.00  | 7.874  | 8.000  | 14.00 | 13.976 | 14.200  |
| 3.15  | 3.150  | 3.200  | 8.50  | 8.346  | 8.480  | 15.00 | 14.764 | 15.000  |
| 3.35  | 3.346  | 3.400  | 9.00  | 8.819  | 8.960  | 16.00 | 15.748 | 16.000  |
| 3.55  | 3.543  | 3.600  | 9.25  | 9.291  | 9.440  | 17.00 | 16.732 | 17.000  |
| 3.65  | 3.642  | 3.700  | 9.75  | 9.567  | 9.720  | 18.00 | 17.717 | 18.000  |
| 4.00  | 3.937  | 4.000  | 10.00 | 9.843  | 10.000 | 19.00 | 18.701 | 19.000  |
| 4.12  | 4.055  | 4.120  | 10.30 | 10.157 | 10.320 | 20.00 | 19.685 | 20.000  |
| 4.50  | 4.409  | 4.480  | 10.60 | 10.433 | 10.600 | 21.20 | 20.866 | 21.200  |
| 4.75  | 4.646  | 4.720  | 10.90 | 10.709 | 10.880 | 22.40 | 22.047 | 22.400  |
| 5.00  | 4.921  | 5.000  | 11.20 | 11.024 | 11.200 | 23.60 | 23.622 | 24.000  |
| 5.30  | 5.197  | 5.280  | 11.80 | 11.811 | 12.000 | 24.80 | 24.803 | 25.200  |
| 5.60  | 5.512  | 5.600  | 12.50 | 12.402 | 12.600 | 30.00 | 29.528 | 30.000  |
| 6.00  | 5.906  | 6.000  | 13.20 | 13.189 | 13.400 | 31.50 | 31.496 | 32.000  |
| 6.30  | 6.299  | 6.400  | 14.00 | 13.976 | 14.200 | 35.50 | 35.433 | 36.000  |
| 6.50  | 6.496  | 6.600  | 15.00 | 14.764 | 15.000 | 40.00 | 39.370 | 40.000  |
| 6.90  | 6.890  | 7.000  | 16.00 | 15.748 | 16.000 | 44.50 | 44.094 | 44.800  |
| 8.00  | 7.874  | 8.000  | 18.70 | 18.701 | 19.000 | 50.00 | 49.213 | 50.000  |
| 10.00 | 9.843  | 10.000 | 20.00 | 19.685 | 20.000 | 52.00 | 51.969 | 52.800  |
| 10.60 | 10.433 | 10.600 | 21.20 | 20.866 | 21.200 | 63.00 | 62.992 | 64.000  |
| 12.50 | 12.402 | 12.600 | 23.60 | 23.622 | 24.000 | 71.00 | 70.866 | 72.000  |
| 14.00 | 13.976 | 14.200 | 25.00 | 24.803 | 25.200 | 79.00 | 78.740 | 80.000  |
| 16.00 | 15.748 | 16.000 | 28.00 | 27.953 | 28.400 | 99.00 | 98.425 | 100.000 |
| 19.00 | 18.701 | 19.000 | 31.50 | 31.496 | 32.000 | ...   | ...    | ...     |
| 20.00 | 19.685 | 20.000 | 37.50 | 37.402 | 38.000 | ...   | ...    | ...     |
| 25.00 | 24.803 | 25.200 | 40.00 | 39.370 | 40.000 | ...   | ...    | ...     |
| 31.50 | 31.496 | 32.000 | 44.50 | 44.094 | 44.800 | ...   | ...    | ...     |
| 33.50 | 33.465 | 34.000 | 50.00 | 49.213 | 50.000 | ...   | ...    | ...     |
| ...   | ...    | ...    | 63.00 | 62.992 | 64.000 | ...   | ...    | ...     |
| ...   | ...    | ...    | 71.00 | 70.866 | 72.000 | ...   | ...    | ...     |

All dimensions in inches. The nominal diameters were selected from R40 and R80 preferred numbers (see page 689).

**Minimum Sheave Size:** The recommended minimum sheave size depends on the rpm of the faster shaft. Minimum sheave diameters for each belt cross-section are listed in [Table 3](#).

**Cross Section Selection:** The chart ([Fig. 2](#), on page 2398) is a guide to the V-belt cross section to use for any combination of design horsepower and speed of the faster shaft. When the intersection of the design horsepower and speed of the faster shaft falls near a line between two areas on the chart, it is advisable to investigate the possibilities in both areas. Special circumstances (such as space limitations) may lead to a choice of belt cross section different from that indicated in the chart.

**Horsepower Ratings:** The horsepower ratings of narrow V-belts can be calculated using the following formula:

$$HP = d_p r [K_1 - K_2/d_p - K_3(d_p r)^2 - K_4 \log(d_p r)] + K_{SR} r$$

where  $d_p$  = the pitch diameter of the small sheave, in.;  $r$  = rpm of the faster shaft divided by 1000;  $K_{SR}$ , speed ratio correction factor ([Table 4](#)), and  $K_1$ ,  $K_2$ ,  $K_3$ , and  $K_4$ , cross section parameters, are listed in the accompanying [Table 5](#). This formula gives the basic horsepower rating, corrected for the speed ratio. To obtain the horsepower per belt for an arc of contact other than 180° and for belts shorter or longer than average length, multiply the horsepower obtained from this formula by the length correction factor ([Table 7](#)) and the arc of contact correction factor ([Table 6](#)).

NARROW V-BELTS

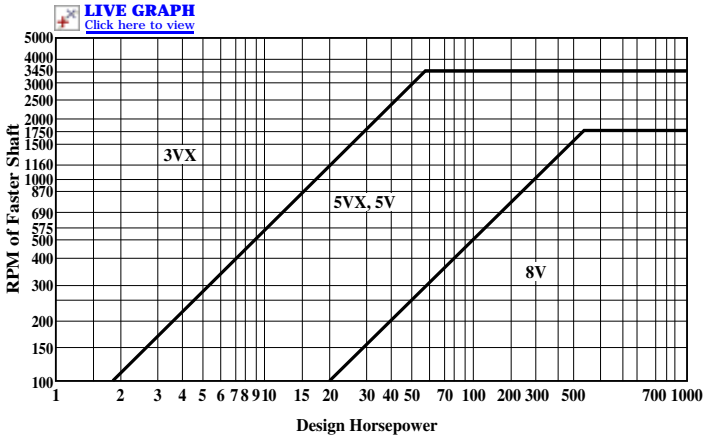


Fig. 2. Selection of Narrow V-Belt Cross Section

**Table 4. Speed Ratio Correction Factors**

| Speed Ratio <sup>a</sup> Range | $K_{SR}$      |        | Speed Ratio <sup>a</sup> Range | $K_{SR}$      |        |
|--------------------------------|---------------|--------|--------------------------------|---------------|--------|
|                                | Cross Section |        |                                | Cross Section |        |
|                                | 3VX           | 5VX    |                                | 5V            | 8V     |
| 1.00–1.01                      | 0.0000        | 0.0000 | 1.00–1.01                      | 0.0000        | 0.0000 |
| 1.02–1.03                      | 0.0157        | 0.0801 | 1.02–1.05                      | 0.0963        | 0.4690 |
| 1.04–1.06                      | 0.0315        | 0.1600 | 1.06–1.11                      | 0.2623        | 1.2780 |
| 1.07–1.09                      | 0.0471        | 0.2398 | 1.12–1.18                      | 0.4572        | 2.2276 |
| 1.10–1.13                      | 0.0629        | 0.3201 | 1.19–1.26                      | 0.6223        | 3.0321 |
| 1.14–1.18                      | 0.0786        | 0.4001 | 1.27–1.38                      | 0.7542        | 3.6747 |
| 1.19–1.25                      | 0.0944        | 0.4804 | 1.39–1.57                      | 0.8833        | 4.3038 |
| 1.26–1.35                      | 0.1101        | 0.5603 | 1.58–1.94                      | 0.9941        | 4.8438 |
| 1.36–1.57                      | 0.1259        | 0.6405 | 1.95–3.38                      | 1.0830        | 5.2767 |
| Over 1.57                      | 0.1416        | 0.7202 | Over 3.38                      | 1.1471        | 5.5892 |

<sup>a</sup>  $D_p/d_p$ , where  $D_p$  ( $d_p$ ) is the pitch diameter of the large (small) sheave.

**Table 5. Cross Section Correction Factors**

| Cross Section | $K_1$  | $K_2$  | $K_3$                   | $K_4$   |
|---------------|--------|--------|-------------------------|---------|
| 3VX           | 1.1691 | 1.5295 | $1.5229 \times 10^{-4}$ | 0.15960 |
| 5VX           | 3.3038 | 7.7810 | $3.6432 \times 10^{-4}$ | 0.43343 |
| 5V            | 3.3140 | 10.123 | $5.8758 \times 10^{-4}$ | 0.46527 |
| 8V            | 8.6628 | 49.323 | $1.5804 \times 10^{-3}$ | 1.1669  |

*Arc of Contact:* Arc of contact on the small sheave may be determined by the formulas.

*Exact formula:* Arc of Contact (deg) =  $2 \cos^{-1} \left( \frac{D_e - d_e}{2C} \right)$

*Approximate formula:* Arc of Contact (deg) =  $180 - \frac{(D_e - d_e)60}{C}$

where:  $D_e$  = Effective diameter of large sheave, inch

$d_e$  = Effective diameter of small sheave, inch

$C$  = Center distance, inch

**Table 6. Arc of Contact Correction Factors**

| $\frac{D_e - d_e}{C}$ | Arc of Contact, $\theta$ ,<br>on Small Sheave<br>(deg) | Correction<br>Factor | $\frac{D_e - d_e}{C}$ | Arc of Contact, $\theta$ ,<br>on Small Sheave<br>(deg) | Correction<br>Factor |
|-----------------------|--|----------------------|-----------------------|--|----------------------|
| 0.00                  | 180  | 1.00                 | 0.80                  | 133  | 0.87                 |
| 0.10                  | 174  | 0.99                 | 0.90                  | 127  | 0.85                 |
| 0.20                  | 169  | 0.97                 | 1.00                  | 120  | 0.82                 |
| 0.30                  | 163  | 0.96                 | 1.10                  | 113  | 0.80                 |
| 0.40                  | 157  | 0.94                 | 1.20                  | 106  | 0.77                 |
| 0.50                  | 151  | 0.93                 | 1.30                  | 99   | 0.73                 |
| 0.60                  | 145  | 0.91                 | 1.40                  | 91   | 0.70                 |
| 0.70                  | 139  | 0.89                 | 1.50                  | 83   | 0.65                 |

**Table 7. Length Correction Factors**

| Standard Length<br>Designation | Cross Section |      |      | Standard Length<br>Designation | Cross Section |      |      |
|--------------------------------|---------------|------|------|--------------------------------|---------------|------|------|
|                                | 3V            | 5V   | 8V   |                                | 3V            | 5V   | 8V   |
| 250                            | 0.83          |      |      | 1180                           | 1.12          | 0.99 | 0.89 |
| 265                            | 0.84          |      |      | 1250                           | 1.13          | 1.00 | 0.90 |
| 280                            | 0.85          |      |      | 1320                           | 1.14          | 1.01 | 0.91 |
| 300                            | 0.86          |      |      | 1400                           | 1.15          | 1.02 | 0.92 |
| 315                            | 0.87          |      |      | 1500                           |               | 1.03 | 0.93 |
| 335                            | 0.88          |      |      | 1600                           |               | 1.04 | 0.94 |
| 355                            | 0.89          |      |      | 1700                           |               | 1.05 | 0.94 |
| 375                            | 0.90          |      |      | 1800                           |               | 1.06 | 0.95 |
| 400                            | 0.92          |      |      | 1900                           |               | 1.07 | 0.96 |
| 425                            | 0.93          |      |      | 2000                           |               | 1.08 | 0.97 |
| 450                            | 0.94          |      |      | 2120                           |               | 1.09 | 0.98 |
| 475                            | 0.95          |      |      | 2240                           |               | 1.09 | 0.98 |
| 500                            | 0.96          | 0.85 |      | 2360                           |               | 1.10 | 0.99 |
| 530                            | 0.97          | 0.86 |      | 2500                           |               | 1.11 | 1.00 |
| 560                            | 0.98          | 0.87 |      | 2650                           |               | 1.12 | 1.01 |
| 600                            | 0.99          | 0.88 |      | 2800                           |               | 1.13 | 1.02 |
| 630                            | 1.00          | 0.89 |      | 3000                           |               | 1.14 | 1.03 |
| 670                            | 1.01          | 0.90 |      | 3150                           |               | 1.15 | 1.03 |
| 710                            | 1.02          | 0.91 |      | 3350                           |               | 1.16 | 1.04 |
| 750                            | 1.03          | 0.92 |      | 3550                           |               | 1.17 | 1.05 |
| 800                            | 1.04          | 0.93 |      | 3750                           |               |      | 1.06 |
| 850                            | 1.06          | 0.94 |      | 4000                           |               |      | 1.07 |
| 900                            | 1.07          | 0.95 |      | 4250                           |               |      | 1.08 |
| 950                            | 1.08          | 0.96 |      | 4500                           |               |      | 1.09 |
| 1000                           | 1.09          | 0.96 | 0.87 | 4750                           |               |      | 1.09 |
| 1060                           | 1.10          | 0.97 | 0.88 | 5000                           |               |      | 1.10 |
| 1120                           | 1.11          | 0.98 | 0.88 | ...                            |               |      | ...  |

**Number of Belts:** The number of belts required for an application is obtained by dividing the design horsepower by the corrected horsepower rating for one belt.

**Classical V-Belts ANSI/RMA IP-20.**—Classical V-belts are most commonly used in heavy-duty applications and include these standard cross sections: A, AX, B, BX, C, CX, D, and DX (Fig. 3, page 2403). Top widths range from  $\frac{1}{2}$  to  $1\frac{1}{4}$  in. and are specified by cross section and nominal length. Classical belts can be teamed in multiples of two or more. These multiple drives can transmit up to several hundred horsepower continuously and absorb reasonable shock loads.

**Belt Cross Sections:** Nominal dimensions of the four cross sections are given in Fig. 3.

**Belt Size Designation:** Classical V-belt sizes are identified by a standard belt number consisting of a letter-numeral combination. The letter identifies the cross section; the numeral identifies the length as shown in Table 8. For example, A60 indicates an A cross section and a standard length designation of 60. An X following the section letter designation indicates a molded notch cross section, for example, AX60.

*Sheave Dimensions:* Groove angles and dimensions for sheaves and the face widths of sheaves for multiple belt drives are given in Table 9, along with various tolerance values.

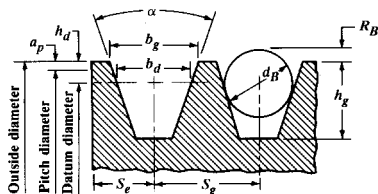
**Table 8. Classical V-Belt Standard Datum Length ANSI/RMA IP-20, 1988**

| Standard Length Designation <sup>a</sup> | Standard Datum lengths |       |       |       | Permissible Deviations from Std. Datum Length | Matching Limits for One Set |
|--|------------------------|-------|-------|-------|---|-----------------------------|
|  | Cross Section          |       |       |       |   |                             |
|  | A, AX                  | B, BX | C, CX | D     |   |                             |
| 26                                       | 27.3                   | ...   | ...   | ...   | +0.6, -0.6                                    | 0.15                        |
| 31                                       | 32.3                   | ...   | ...   | ...   | +0.6, -0.6                                    | 0.15                        |
| 35                                       | 36.3                   | 36.8  | ...   | ...   | +0.6, -0.6                                    | 0.15                        |
| 38                                       | 39.3                   | 39.8  | ...   | ...   | +0.7, -0.7                                    | 0.15                        |
| 42                                       | 43.3                   | 43.8  | ...   | ...   | +0.7, -0.7                                    | 0.15                        |
| 46                                       | 47.3                   | 47.8  | ...   | ...   | +0.7, -0.7                                    | 0.15                        |
| 51                                       | 52.3                   | 52.8  | 53.9  | ...   | +0.7, -0.7                                    | 0.15                        |
| 55                                       | 56.3                   | 56.8  | ...   | ...   | +0.7, -0.7                                    | 0.15                        |
| 60                                       | 61.3                   | 61.8  | 62.9  | ...   | +0.7, -0.7                                    | 0.15                        |
| 68                                       | 69.3                   | 69.8  | 70.9  | ...   | +0.7, -0.7                                    | 0.30                        |
| 75                                       | 75.3                   | 76.8  | 77.9  | ...   | +0.7, -0.7                                    | 0.30                        |
| 80                                       | 81.3                   | ...   | ...   | ...   | +0.7, -0.7                                    | 0.30                        |
| 81                                       | ...                    | 82.8  | 83.9  | ...   | +0.7, -0.7                                    | 0.30                        |
| 85                                       | 86.3                   | 86.8  | 87.9  | ...   | +0.7, -0.7                                    | 0.30                        |
| 90                                       | 91.3                   | 91.8  | 92.9  | ...   | +0.8, -0.8                                    | 0.30                        |
| 96                                       | 97.3                   | ...   | 98.9  | ...   | +0.8, -0.8                                    | 0.30                        |
| 97                                       | ...                    | 98.8  | ...   | ...   | +0.8, -0.8                                    | 0.30                        |
| 105                                      | 106.3                  | 106.8 | 107.9 | ...   | +0.8, -0.8                                    | 0.30                        |
| 112                                      | 113.3                  | 113.8 | 114.9 | ...   | +0.8, -0.8                                    | 0.30                        |
| 120                                      | 121.3                  | 121.8 | 122.9 | 123.3 | +0.8, -0.8                                    | 0.30                        |
| 128                                      | 129.3                  | 129.8 | 130.9 | 131.3 | +0.8, -0.8                                    | 0.30                        |
| 144                                      | ...                    | 145.8 | 146.9 | 147.3 | +0.8, -0.8                                    | 0.30                        |
| 158                                      | ...                    | 159.8 | 160.9 | 161.3 | +1.0, -1.0                                    | 0.45                        |
| 173                                      | ...                    | 174.8 | 175.9 | 176.3 | +1.0, -1.0                                    | 0.45                        |
| 180                                      | ...                    | 181.8 | 182.9 | 183.3 | +1.0, -1.0                                    | 0.45                        |
| 195                                      | ...                    | 196.8 | 197.9 | 198.3 | +1.1, -1.1                                    | 0.45                        |
| 210                                      | ...                    | 211.8 | 212.9 | 213.3 | +1.1, -1.1                                    | 0.45                        |
| 240                                      | ...                    | 240.3 | 240.9 | 240.8 | +1.3, -1.3                                    | 0.45                        |
| 270                                      | ...                    | 270.3 | 270.9 | 270.8 | +1.6, -1.6                                    | 0.60                        |
| 300                                      | ...                    | 300.3 | 300.0 | 300.8 | +1.6, -1.6                                    | 0.60                        |
| 330                                      | ...                    | ...   | 330.9 | 330.8 | +2.0, -2.0                                    | 0.60                        |
| 360                                      | ...                    | ...   | 380.9 | 360.8 | +2.0, -2.0                                    | 0.60                        |
| 540                                      | ...                    | ...   | ...   | 540.8 | +3.3, -3.3                                    | 0.90                        |
| 390                                      | ...                    | ...   | 390.9 | 390.8 | +2.0, -2.0                                    | 0.75                        |
| 420                                      | ...                    | ...   | 420.9 | 420.8 | +3.3, -3.3                                    | 0.75                        |
| 480                                      | ...                    | ...   | ...   | 480.8 | +3.3, -3.3                                    | 0.75                        |
| 600                                      | ...                    | ...   | ...   | 600.8 | +3.3, -3.3                                    | 0.90                        |
| 660                                      | ...                    | ...   | ...   | 660.8 | +3.3, -3.3                                    | 0.90                        |

<sup>a</sup>To specify belt size use the Standard Length Designation prefixed by the letter indicating the cross section, e.g., B90.

All dimensions in inches.

Table 9. Classical V-Belt Sheave and Groove Dimensions ANSI/RMA IP-20, 1988



Face Width of Standard and Deep Groove Sheaves =  $S_g (N_g - 1) + 2S_e$ , where  $N_g$  = number of grooves

| Standard Groove Dimensions |                                   |  |                    |                   |           |                    |                    |                    |                     |       | Design Factors               |        |                  |
|----------------------------|-----------------------------------|--|--------------------|-------------------|-----------|--------------------|--------------------|--------------------|---------------------|-------|------------------------------|--------|------------------|
| Cross Section              | Datum <sup>a</sup> Diameter Range | $\alpha$ Groove Angle $\pm 0.33^\circ$ | $b_d$ Ref          | $b_g$             | $h_g$ Min | $2h_d$             | $R_B$ Min          | $d_B$ $\pm 0.0005$ | $S_g^b$ $\pm 0.025$ | $S_e$ | Min Recom. Datum Diameter    | $2a_p$ |                  |
| A, AX                      | Through 5.4<br>Over 5.4           | 34                                     | 0.418              | 0.494             | 0.460     | 0.250              | 0.148              | 0.4375             | 0.625               | 0.375 | A 3.0<br>AX 2.2              | 0      |                  |
|                            |                                   | 38                                     |                    | $0.504 \pm 0.005$ |           |                    | 0.149              |                    |                     |       |                              |        | -0.062           |
| B, BX                      | Through 7.0<br>Over 7.0           | 34                                     | 0.530              | 0.637             | 0.550     | 0.350              | 0.189              | 0.5625             | 0.750               | 0.500 | B 5.4<br>BX 4.0              | 0      |                  |
|                            |                                   | 38                                     |                    | $0.650 \pm 0.006$ |           |                    | 0.190              |                    |                     |       |                              |        | +0.120<br>-0.065 |
| Combination                | A, AX Belt                        | Through 7.4 <sup>c</sup>               | 0.508 <sup>d</sup> | 0.612             | 0.612     | 0.634 <sup>e</sup> | 0.230              | 0.5625             | 0.750               | 0.500 | A 3.6 <sup>c</sup><br>AX 2.8 | 0.37   |                  |
|                            |                                   | Over 7.4                               |                    | 0.625             |           |                    | 0.226              |                    |                     |       |                              |        |                  |
|                            | B, BX Belt                        | Through 7.4 <sup>c</sup>               |                    | 0.612             |           |                    | 0.333 <sup>c</sup> |                    |                     |       |                              |        | 0.230            |
|                            |                                   | Over 7.4                               |                    | 0.625             |           |                    | 0.334 <sup>e</sup> |                    |                     |       |                              |        | 0.226            |
| C, CX                      | Through 7.99                      | 34                                     | 0.757              | 0.879             | 0.750     | 0.400              | 0.274              | 0.7812             | 1.000               | 0.688 | C 9.0<br>CX 6.8              | 0      |                  |
|                            | Over 7.99 to and incl. 12.0       | 36                                     |                    | 0.887             |           |                    | 0.276              |                    |                     |       |                              |        | $(\frac{2}{32})$ |
|                            | Over 12.0                         | 38                                     |                    | $0.895 \pm 0.007$ |           |                    | 0.277              |                    |                     |       |                              |        |                  |
| D                          | Through 12.99                     | 34                                     | 1.076              | 1.259             | 1.020     | 0.600              | 0.410              | 1.1250             | 1.438               | 0.875 | 13.0                         | 0      |                  |
|                            | Over 12.99 to and incl. 17.0      | 36                                     |                    | $1.271 \pm 0.008$ |           |                    | 0.411              |                    |                     |       |                              |        |                  |
|                            | Over 17.0                         | 38                                     |                    | 1.283             |           |                    |                    |                    |                     |       |                              |        |                  |

**Table 9. (Continued) Classical V-Belt Sheave and Groove Dimensions ANSI/RMA IP-20, 1988**

| Deep Groove Dimensions <sup>f</sup> |                               |  |           |                   |           |            |           |                               |                     |       | Design Factors          |        |        |                      |        |
|-------------------------------------|-------------------------------|--|-----------|-------------------|-----------|------------|-----------|-------------------------------|---------------------|-------|-------------------------|--------|--------|----------------------|--------|
| Cross Section                       | Datum <sup>a</sup> Dia. Range | $\alpha$ Groove Angle $\pm 0.33^\circ$ | $b_g$ Ref | $b_g$             | $h_g$ Min | $2h_d$ Ref | $R_B$ Min | $d_B$ $\pm 0.0005$            | $S_g^b$ $\pm 0.025$ | $S_e$ | Min Rec. Datum Diameter | $2a_p$ |        |                      |        |
| B, BX                               | Through 7.0                   | 34                                     | 0.530     | 0.747             | 0.730     | 0.710      | 0.007     | 0.5625                        | 0.875               | 0.562 | B 5.4                   | 0.36   |        |                      |        |
|                                     | Over 7.0                      | 38                                     |           | $0.774 \pm 0.006$ |           |            |           |                               |                     |       |                         |        | 0.008  | $+0.120$<br>$-0.065$ | BX 4.0 |
| C, CX                               | Through 7.99                  | 34                                     | 0.757     | 1.066             | 1.055     | 1.010      | -0.035    | 0.7812<br>( $\frac{25}{32}$ ) | 1.250               | 0.812 | C 9.0                   | 0.61   |        |                      |        |
|                                     | Over 7.99 to and incl. 12.0   | 36                                     |           | $1.085 \pm 0.007$ |           |            |           |                               |                     |       |                         |        | -0.032 | $+0.160$<br>$-0.070$ | CX 6.8 |
|                                     | Over 12.0                     | 38                                     |           | 1.105             |           |            |           |                               |                     |       |                         |        | -0.031 |                      |        |
| D                                   | Through 12.99                 | 34                                     | 1.076     | 1.513             | 1.435     | 1.430      | -0.010    | 1.1250<br>( $1\frac{1}{2}$ )  | 1.750               | 1.062 | 13.0                    | 0.83   |        |                      |        |
|                                     | Over 12.99 to and incl. 17.0  | 36                                     |           | $1.514 \pm 0.008$ |           |            |           |                               |                     |       |                         |        | -0.009 | $+0.220$<br>$-0.080$ |        |
|                                     | Over 17.0                     | 38                                     |           | 1.569             |           |            |           |                               |                     |       |                         |        | -0.008 |                      |        |

<sup>a</sup> The A/AX, B/BX combination groove should be used when deep grooves are required for A or AX belts.

<sup>b</sup> Summation of the deviations from  $S_g$  for all grooves in any one sheave should not exceed  $\pm 0.050$  in. The variation in datum diameter between the grooves in any one sheave must be within the following limits: Through 19.9 in. outside diameter and through 6 grooves: 0.010 in. (add 0.0005 in. for each additional groove). 20.0 in. and over on outside diameter and through 10 grooves: 0.015 in. (add 0.0005 in. for each additional groove). This variation can be obtained by measuring the distance across two measuring balls or rods placed diametrically opposite each other in a groove. Comparing this "diameter over balls or rods" measurement between grooves will give the variation in datum diameter.

<sup>c</sup> Diameters shown for combination grooves are outside diameters. A specific datum diameter does not exist for either A or B belts in combination grooves.

<sup>d</sup> The  $b_d$  value shown for combination grooves is the "constant width" point, but does not represent a datum width for either A or B belts ( $2h_d = 0.340$  ref).

<sup>e</sup>  $2h_d$  values for combination grooves are calculated based on  $b_d$  for A and B grooves.

<sup>f</sup> Deep groove sheaves are intended for drives with belt offset such as quarter-turn or vertical shaft drives. Joined belts will not operate in deep groove sheaves. Also, A and AX joined belts will not operate in A/AX and B/BX combination grooves.

| Other Sheave Tolerances   |   |   |
|---|---|---|
| Outside Diameter  | Radial Runout <sup>a</sup>  | Axial Runout <sup>a</sup>   |
| Through 8.0 in. outside diameter $\pm 0.020$ in. For each additional inch of outside diameter add $\pm 0.005$ in. | Through 10.0 in. outside diameter 0.010 in. For each additional inch of outside diameter add 0.0005 in. | Through 5.0 in. outside diameter 0.005 in. For each additional inch of outside diameter add 0.001 in. |

<sup>a</sup> Total indicator readings.

**A, AX & B, BX Combin.** All dimensions in inches.

**Minimum Sheave Size:** The recommended minimum sheave size depends on the rpm of the faster shaft. Minimum sheave diameters for each cross-section belt are listed in Table 9.

**Cross Section Selection:** Use the chart (Fig. 4) as a guide to the Classical V-belt cross section for any combination of design horsepower and speed of the faster shaft. When the intersection of the design horsepower and speed of the faster shaft falls near a line between two areas on the chart, the possibilities in both areas should be investigated. Special circumstances (such as space limitations) may lead to a choice of belt cross section different from that indicated in the chart.

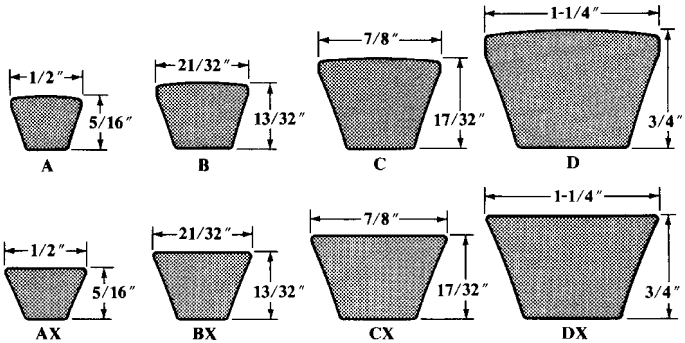


Fig. 3. Classical V-Belt Cross Sections

**Horsepower Ratings:** The horsepower rating formulas for classical V-belts are:

$$\begin{aligned} \mathbf{A:HP} = d_p r \left[ 1.004 - \frac{1.652}{d_p} - 1.547 \times 10^{-4} (d_p r)^2 - 0.2126 \log(d_p r) \right] \\ + 1.652 r \left( 1 - \frac{1}{K_{SR}} \right) \end{aligned}$$

$$\begin{aligned} \mathbf{AX:HP} = d_p r \left[ 1.462 - \frac{2.239}{d_p} - 2.198 \times 10^{-4} (d_p r)^2 - 0.4238 \log(d_p r) \right] \\ + 2.239 r \left( 1 - \frac{1}{K_{SR}} \right) \end{aligned}$$

$$\begin{aligned} \mathbf{B:HP} = d_p r \left[ 1.769 - \frac{4.372}{d_p} - 3.081 \times 10^{-4} (d_p r)^2 - 0.3658 \log(d_p r) \right] \\ + 4.372 r \left( 1 - \frac{1}{K_{SR}} \right) \end{aligned}$$



## CLASSICAL V-BELTS

$$\text{BX:HP} = d_p r \left[ 2.051 - \frac{3.532}{d_p} - 3.097 \times 10^{-4} (d_p r)^2 - 0.5735 \log(d_p r) \right] + 3.532 r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$\text{C:HP} = d_p r \left[ 3.325 - \frac{12.07}{d_p} - 5.828 \times 10^{-4} (d_p r)^2 - 0.6886 \log(d_p r) \right] + 12.07 r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$\text{CX:HP} = d_p r \left[ 3.272 - \frac{6.655}{d_p} - 5.298 \times 10^{-4} (d_p r)^2 - 0.8637 \log(d_p r) \right] + 6.655 r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$\text{D:HP} = d_p r \left[ 7.160 - \frac{43.21}{d_p} - 1.384 \times 10^{-3} (d_p r)^2 - 1.454 \log(d_p r) \right] + 43.21 r \left( 1 - \frac{1}{K_{SR}} \right)$$

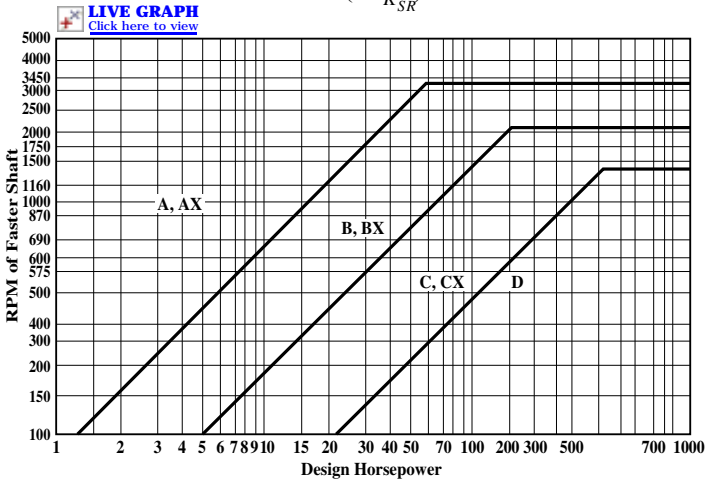


Fig. 4. Selection of Classic V-Belt Cross Sections

In these equations,  $d_p$  = pitch diameter of small sheave, in.;  $r$  = rpm of the faster shaft divided by 1000;  $K_{SR}$  = speed ratio factor given in the accompanying Table 10. These formulas give the basic horsepower rating, corrected for the speed ratio. To obtain the horsepower per belt for an arc of contact other than 180 degrees and for belts shorter or longer than average length, multiply the horsepower obtained from these formulas by the length correction factor (Table 11) and the arc of contact correction factor (Table 12).

**Table 10. Speed Ratio Correction Factors**

| Speed Ratio <sup>a</sup> Range | $K_{SR}$ | Speed Ratio <sup>a</sup> Range | $K_{SR}$ |
|--------------------------------|----------|--------------------------------|----------|
| 1.00–1.01                      | 1.0000   | 1.15–1.20                      | 1.0586   |
| 1.02–1.04                      | 1.0112   | 1.21–1.27                      | 1.0711   |
| 1.05–1.07                      | 1.0226   | 1.28–1.39                      | 1.0840   |
| 1.08–1.10                      | 1.0344   | 1.40–1.64                      | 1.0972   |
| 1.11–1.14                      | 1.0463   | Over 1.64                      | 1.1106   |

<sup>a</sup>  $D_p/d_p$ , where  $D_p$  ( $d_p$ ) is the pitch diameter of the large (small) sheave.

**Table 11. Length Correction Factors**

| Std. Length Designation | Cross Section |       |       |      |
|-------------------------|---------------|-------|-------|------|
|                         | A, AX         | B, BX | C, CX | D    |
| 26                      | 0.78          | ...   | ...   | ...  |
| 31                      | 0.82          | ...   | ...   | ...  |
| 35                      | 0.85          | 0.80  | ...   | ...  |
| 38                      | 0.87          | 0.82  | ...   | ...  |
| 42                      | 0.89          | 0.84  | ...   | ...  |
| 46                      | 0.91          | 0.86  | ...   | ...  |
| 51                      | 0.93          | 0.88  | 0.80  | ...  |
| 55                      | 0.95          | 0.89  | ...   | ...  |
| 60                      | 0.97          | 0.91  | 0.83  | ...  |
| 68                      | 1.00          | 0.94  | 0.85  | ...  |
| 75                      | 1.02          | 0.96  | 0.87  | ...  |
| 80                      | 1.04          | ...   | ...   | ...  |
| 81                      | ...           | 0.98  | 0.89  | ...  |
| 85                      | 1.05          | 0.99  | 0.90  | ...  |
| 90                      | 1.07          | 1.00  | 0.91  | ...  |
| 96                      | 1.08          | ...   | 0.92  | ...  |
| 97                      | ...           | 1.02  | ...   | ...  |
| 105                     | 1.10          | 1.03  | 0.94  | ...  |
| 112                     | 1.12          | 1.05  | 0.95  | ...  |
| 120                     | 1.13          | 1.06  | 0.96  | 0.88 |
| 128                     | 1.15          | 1.08  | 0.98  | 0.89 |
| 144                     | ...           | 1.10  | 1.00  | 0.91 |
| 158                     | ...           | 1.12  | 1.02  | 0.93 |
| 173                     | ...           | 1.14  | 1.04  | 0.94 |
| 180                     | ...           | 1.15  | 1.05  | 0.95 |
| 195                     | ...           | 1.17  | 1.08  | 0.96 |
| 210                     | ...           | 1.18  | 1.07  | 0.98 |
| 240                     | ...           | 1.22  | 1.10  | 1.00 |
| 270                     | ...           | 1.24  | 1.13  | 1.02 |
| 300                     | ...           | 1.27  | 1.15  | 1.04 |
| 330                     | ...           | ...   | 1.17  | 1.06 |
| 360                     | ...           | ...   | 1.18  | 1.07 |
| 390                     | ...           | ...   | 1.20  | 1.09 |
| 420                     | ...           | ...   | 1.21  | 1.10 |
| 480                     | ...           | ...   | ...   | 1.13 |
| 540                     | ...           | ...   | ...   | 1.15 |
| 600                     | ...           | ...   | ...   | 1.17 |
| 660                     | ...           | ...   | ...   | 1.18 |

**Number of Belts:** The number of belts required for an application is obtained by dividing the design horsepower by the corrected horsepower rating for one belt.

**Arc of Contact:** Arc of contact on the small sheave may be determined by the formulas.

$$\text{Exact formula: Arc of Contact (deg)} = 2 \cos^{-1} \left( \frac{D_d - d_d}{2C} \right)$$

$$\text{Approximate formula: Arc of Contact (deg)} = 180 - \left( \frac{(D_d - d_d)60}{C} \right)$$

where  $D_d$  = Datum diameter of large sheave or flat pulley, inch;  $d_d$  = Datum diameter of small sheave, inch; and,  $C$  = Center distance, inch.

**Table 12. Arc of Contact Correction Factors**

| $\frac{D_d - d_d}{C}$ | Arc of Contact,<br>$\theta$ , Small<br>Sheave (deg) | Correction Factor |                     | $\frac{D_d - d_d}{C}$ | Arc of Contact,<br>$\theta$ Small<br>Sheave (deg) | Correction Factor |                     |
|-----------------------|---|-------------------|---------------------|-----------------------|---|-------------------|---------------------|
|                       |   | V-V               | V-Flat <sup>a</sup> |                       |   | V-V               | V-Flat <sup>a</sup> |
| 0.00                  | 180   | 1.00              | 0.75                | 0.80                  | 133   | 0.87              | 0.85                |
| 0.10                  | 174   | 0.99              | 0.76                | 0.90                  | 127   | 0.85              | 0.85                |
| 0.20                  | 169   | 0.97              | 0.78                | 1.00                  | 120   | 0.82              | 0.82                |
| 0.30                  | 163   | 0.96              | 0.79                | 1.10                  | 113   | 0.80              | 0.80                |
| 0.40                  | 157   | 0.94              | 0.80                | 1.20                  | 106   | 0.77              | 0.77                |
| 0.50                  | 151   | 0.93              | 0.81                | 1.30                  | 99  | 0.73              | 0.73                |
| 0.60                  | 145   | 0.91              | 0.83                | 1.40                  | 91  | 0.70              | 0.70                |
| 0.70                  | 139   | 0.89              | 0.84                | 1.50                  | 83  | 0.65              | 0.65                |

<sup>a</sup> A V-flat drive is one using a small sheave and a large diameter flat pulley.

**Double V-Belts ANSI/RMA IP-21.**—Double V-belts or hexagonal belts are used when power input or takeoff is required on both sides of the belt. Designed for use on “serpentine” drives, which consist of sheaves rotating in opposite directions, the belts are available in AA, BB, CC, and DD cross sections and operate in standard classical sheaves. They are specified by cross section and nominal length.

*Belt Cross Sections:* Nominal dimensions of the four cross sections are given in Fig. 5.

*Belt Size Designation:* Double V-belt sizes are identified by a standard belt number, consisting of a letter-numeral combination. The letters identify the cross section; the numbers identify length as shown in Column 1 of Table 13. For example, AA51 indicates an AA cross section and a standard length designation of 51.

**Table 13. Double V-Belt Standard Effective Lengths ANSI/RMA IP-21, 1984**

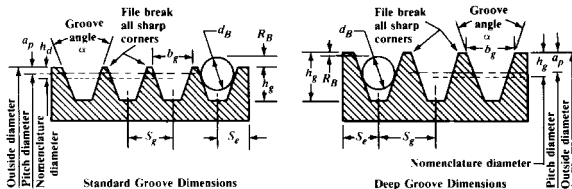
| Standard Length Designation <sup>a</sup> | Standard Effective Length |       |       |       | Permissible Deviation from Standard Effective Length | Matching Limits for One Set |
|--|---------------------------|-------|-------|-------|--|-----------------------------|
|  | Cross Section             |       |       |       |  |                             |
|  | AA                        | BB    | CC    | DD    |  |                             |
| 51                                       | 53.1                      | 53.9  | ...   | ...   | ±0.7   | 0.15                        |
| 55                                       | ...                       | 57.9  | ...   | ...   | ±0.7   | 0.15                        |
| 60                                       | 62.1                      | 62.9  | ...   | ...   | ±0.7   | 0.15                        |
| 68                                       | 70.1                      | 70.9  | ...   | ...   | ±0.7   | 0.30                        |
| 75                                       | 77.1                      | 77.9  | ...   | ...   | ±0.7   | 0.30                        |
| 80                                       | 82.1                      | ...   | ...   | ...   | ±0.7   | 0.30                        |
| 81                                       | ...                       | 83.9  | 85.2  | ...   | ±0.7   | 0.30                        |
| 85                                       | 87.1                      | 87.9  | 89.2  | ...   | ±0.7   | 0.30                        |
| 90                                       | 92.1                      | 92.9  | 94.2  | ...   | ±0.8   | 0.30                        |
| 96                                       | 98.1                      | ...   | 100.2 | ...   | ±0.8   | 0.30                        |
| 97                                       | ...                       | 99.9  | ...   | ...   | ±0.8   | 0.30                        |
| 105                                      | 107.1                     | 107.9 | 109.2 | ...   | ±0.8   | 0.30                        |
| 112                                      | 114.1                     | 114.9 | 116.2 | ...   | ±0.8   | 0.30                        |
| 120                                      | 122.1                     | 122.9 | 124.2 | 125.2 | ±0.8   | 0.30                        |
| 128                                      | 130.1                     | 130.9 | 132.2 | 133.2 | ±0.8   | 0.30                        |
| 144                                      | ...                       | 146.9 | 148.2 | 149.2 | ±0.8   | 0.30                        |
| 158                                      | ...                       | 160.9 | 162.2 | 163.2 | ±1.0   | 0.45                        |
| 173                                      | ...                       | 175.9 | 177.2 | 178.2 | ±1.0   | 0.45                        |
| 180                                      | ...                       | 182.9 | 184.2 | 185.2 | ±1.0   | 0.45                        |
| 195                                      | ...                       | 197.9 | 199.2 | 200.2 | ±1.1   | 0.45                        |
| 210                                      | ...                       | 212.9 | 214.2 | 215.2 | ±1.1   | 0.45                        |
| 240                                      | ...                       | 241.4 | 242.2 | 242.7 | ±1.3   | 0.45                        |
| 270                                      | ...                       | 271.4 | 272.2 | 272.7 | ±1.6   | 0.60                        |
| 300                                      | ...                       | 301.4 | 302.2 | 302.7 | ±1.6   | 0.60                        |
| 330                                      | ...                       | ...   | 332.2 | 332.7 | ±2.0   | 0.60                        |
| 360                                      | ...                       | ...   | 362.2 | 362.7 | ±2.0   | 0.60                        |

<sup>a</sup> To specify belt size use the Standard Length Designation prefixed by the letters indicating cross section; for example, BB90.

All dimensions in inches.

*Sheave Dimensions:* Groove angles and dimensions for sheaves and face widths of sheaves for multiple belt drives are given in Table 14, along with various tolerance values.

Table 14. Double V-Belt Sheave and Groove Dimensions ANSI/RMA IP-21, 1984



Face Width of Standard and Deep Groove Sheaves =  $S_g(N_g - 1) + 2S_e$ , where  $N_g$  = number of grooves

| Standard Groove Dimensions |                                      |  |                   |                 |           |                 |                       |                        |       |                           | Drive Design Factors |           |           |                   |        |
|----------------------------|--------------------------------------|--|-------------------|-----------------|-----------|-----------------|-----------------------|------------------------|-------|---------------------------|----------------------|-----------|-----------|-------------------|--------|
| Cross Section              | Outside Diameter Range               | Groove Angle, $\alpha$<br>$\pm 0.33^\circ$ | $b_g$             | $h_g$<br>(Min.) | $2h_d$    | $R_B$<br>(Min.) | $d_B$<br>$\pm 0.0005$ | $S_g^a$<br>$\pm 0.025$ | $S_e$ | Min. Recomm. Outside Dia. | $2a_p^b$             |           |           |                   |        |
| AA                         | Up through 5.65                      | 34   | 0.494             | 0.460           | 0.250     | 0.148           | 0.4375                | 0.625                  | 0.375 | +0.090                    | 3.25                 | 0.0       |           |                   |        |
|                            | Over 5.65                            | 38   | 0.504 $\pm 0.005$ |                 |           |                 |                       |                        |       | -0.062                    |                      |           |           |                   |        |
| BB                         | Up through 7.35                      | 34   | 0.637             | 0.550           | 0.350     | 0.189           | 0.5625                | 0.750                  | 0.500 | +0.120                    | 5.75                 | 0.0       |           |                   |        |
|                            | Over 7.35                            | 38   | 0.650 $\pm 0.006$ |                 |           |                 |                       |                        |       | -0.065                    |                      |           |           |                   |        |
| AA-BB                      | Up through 7.35                      | 34   | 0.612             | 0.612           | A = 0.750 | 0.230           | 0.5625                | 0.750                  | 0.500 | +0.120                    | A = 3.620            | A = 0.370 |           |                   |        |
|                            | Over 7.35                            | 38   | 0.625 $\pm 0.006$ |                 | B = 0.350 |                 |                       |                        |       | 0.226                     | $(\frac{5}{16})$     | -0.065    | B = 5.680 | B = -0.070        |        |
| CC                         | Up through 8.39                      | 34   | 0.879             | 0.750           | 0.400     | 0.274           | 0.7812                | 1.000                  | 0.688 | +0.160                    | 9.4                  | 0.0       |           |                   |        |
|                            | Over 8.39 up to and including 12.40  | 36   | 0.887 $\pm 0.007$ |                 |           |                 |                       |                        |       |                           |                      |           | 0.276     | $(\frac{25}{32})$ | -0.070 |
|                            | Over 12.40                           | 38   | 0.895             |                 |           |                 |                       |                        |       |                           |                      |           | 0.277     |                   |        |
| DD                         | Up through 13.59                     | 34   | 1.259             | 1.020           | 0.600     | 0.410           | 1.1250                | 1.438                  | 0.875 | +0.220                    | 13.6                 | 0.0       |           |                   |        |
|                            | Over 13.59 up to and including 17.60 | 36   | 1.271 $\pm 0.008$ |                 |           |                 |                       |                        |       |                           |                      |           | 0.410     | $(1\frac{1}{8})$  |        |
|                            | Over 17.60                           | 38   | 1.283             |                 |           |                 |                       |                        |       |                           |                      |           | 0.411     |                   |        |

**Table 14. (Continued) Double V-Belt Sheave and Groove Dimensions ANSI/RMA IP-21, 1984**

| Deep Groove Dimensions <sup>c</sup> |                                      |  |       |                 |        |                 |                       |                              |       |                                      | Drive Design Factors |       |       |
|-------------------------------------|--------------------------------------|--|-------|-----------------|--------|-----------------|-----------------------|------------------------------|-------|--------------------------------------|----------------------|-------|-------|
| Cross Section                       | Outside Diameter Range               | Groove Angle, $\alpha$<br>$\pm 0.33^\circ$ | $b_g$ | $h_g$<br>(Min.) | $2h_d$ | $R_B$<br>(Min.) | $d_B$<br>$\pm 0.0005$ | $S_g^a$<br>$\pm 0.025$       | $S_e$ | Minimum Recommended Outside Diameter | $2a_p$               |       |       |
| AA                                  | Up through 5.96                      | 34   | 0.589 | $\pm 0.005$     | 0.615  | 0.560           | -0.009                | 0.4375<br>( $7/16$ )         | 0.750 | 0.438                                | +0.090               | 3.56  | 0.310 |
|                                     | Over 5.96                            | 38   | 0.611 |                 |        |                 | -0.008                |                              |       |                                      | -0.062               |       |       |
| BB                                  | Up through 7.71                      | 34   | 0.747 | $\pm 0.006$     | 0.730  | 0.710           | +0.007                | 0.5625<br>( $9/16$ )         | 0.875 | 0.562                                | +0.120               | 6.11  | 0.360 |
|                                     | Over 7.71                            | 38   | 0.774 |                 |        |                 | +0.008                |                              |       |                                      | -0.065               |       |       |
| CC                                  | Up through 9.00                      | 34   | 1.066 | $\pm 0.007$     | 1.055  | 1.010           | -0.035                | 0.7812<br>( $25/32$ )        | 1.250 | 0.812                                | +0.160               | 10.01 | 0.610 |
|                                     | Over 9.00 up to and including 13.01  | 36   | 1.085 |                 |        |                 | -0.032                |                              |       |                                      | -0.070               |       |       |
|                                     | Over 13.01                           | 38   | 1.105 |                 |        |                 | -0.031                |                              |       |                                      |                      |       |       |
| DD                                  | Up through 14.42                     | 34   | 1.513 | $\pm 0.008$     | 1.435  | 1.430           | -0.010                | 1.1250<br>( $1\frac{1}{8}$ ) | 1.750 | 1.062                                | +0.220               | 14.43 | 0.830 |
|                                     | Over 14.42 up to and including 18.43 | 36   | 1.541 |                 |        |                 | -0.009                |                              |       |                                      | -0.080               |       |       |
|                                     | Over 18.43                           | 38   | 1.569 |                 |        |                 | -0.008                |                              |       |                                      |                      |       |       |

<sup>a</sup> Summation of the deviations from  $S_g$  for all grooves in any one sheave shall not exceed  $\pm 0.050$  in. The variation in pitch diameter between the grooves in any one sheave must be within the following limits: Up through 19.9 in. outside diameter and up through 6 grooves: 0.010 in. (add 0.005 in. for each additional groove). 20.0 in. and over on outside diameter and up through 10 grooves: 0.015 in. (add 0.0005 in. for each additional groove). This variation can be obtained easily by measuring the distance across two measuring balls or rods placed diametrically opposite each other in a groove. Comparing this "diameter over balls or rods" measurement between grooves will give the variation in pitch diameter.

<sup>b</sup> The  $a_p$  values shown for the A/B combination sheaves are the geometrically derived values. These values may be different from those shown in manufacturer's catalogs.

<sup>c</sup> Deep groove sheaves are intended for drives with belt offset such as quarter-turn or vertical shaft drives.

| Other Sheave Tolerances   |   |   |
|---|---|---|
| Outside Diameter  | Radial Runout <sup>a</sup>  | Axial Runout <sup>a</sup>   |
| Up through 4.0 in. outside diameter $\pm 0.020$ in.<br>For each additional inch of outside diameter add $\pm 0.005$ in. | Up through 10.0 in. outside diameter $\pm 0.010$ in.<br>For each additional inch of outside diameter add 0.0005 in. | Up through 5.0 in. outside diameter 0.005 in.<br>For each additional inch of outside diameter add 0.001 in. |

<sup>a</sup> Total indicator reading.  
All dimensions in inches.

**Cross Section Selection:** Use the chart (Fig. 6) as a guide to the double V-belt cross section for any combination of design horsepower and speed of the faster shaft. When the intersection of the design horsepower and speed of the faster shaft falls near a line between two areas on the chart, it is best to investigate the possibilities in both areas. Special circumstances (such as space limitations) may lead to a choice of belt cross section different from that indicated in the chart.

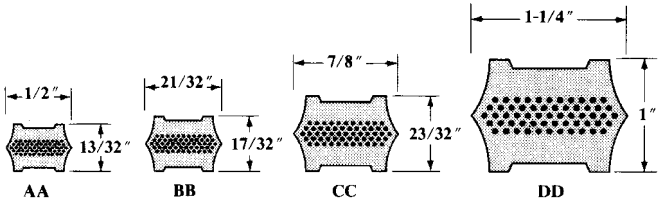


Fig. 5. Double-V Belt Cross Section

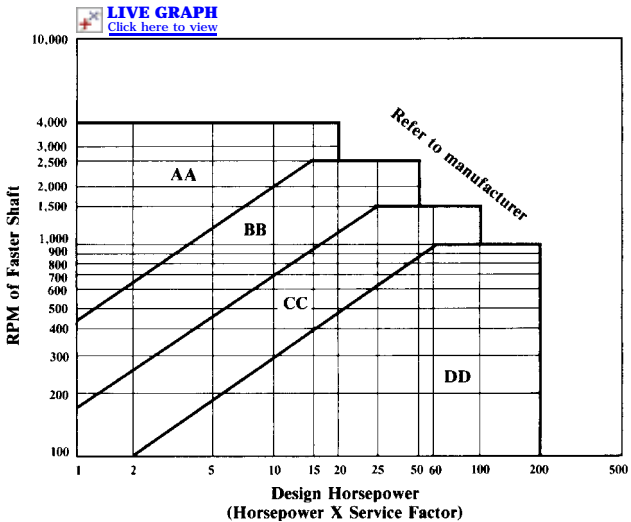


Fig. 6. Selection of Double V-Belt Cross Section

**Effective Diameter Determination:** Fig. 6 shows the relationship of effective diameter, outside diameter, and nomenclature diameter. Nomenclature diameter is used when ordering sheaves for double V-belt drives. The effective diameter is determined as follows:

$$\text{Effective diameter} = \text{Nomenclature diameter} + 2h_d - 2a_p$$

The values of  $2h_d$  and  $2a_p$  are given in Table 14.

**Double V-belt Length Determination:** The effective belt length of a specific drive may be determined by making a scaled layout of the drive. Draw the sheaves in terms of their effective diameters and in the position when a new belt is applied and first brought to driv-

ing tension. Next, measure the tangents and calculate the effective arc length ( $AL_e$ ) of each sheave (see Table 15 for a glossary of terms):

$$AL_e = \frac{d_e \theta}{115}$$

The effective length of the belt will then be the sum of the tangents and the connecting arc lengths. Manufacturers may be consulted for mathematical calculation of effective belt length for specific drive applications.

**Table 15. Glossary of Terms for Double V-belt Calculations**

|  |  |
|--|--|
| $AL_e$ = Length, arc, effective, in.   | $R$ = Ratio, tight side to slack side tension  |
| $2a_p$ = Diameter, differential, pitch to outside, in.                             | $R/(R - 1)$ = Factor, tension ratio            |
| $d$ = Diameter, pitch, in. (same as effective diameter)                            | $r$ = Angular velocity, faster shaft, rpm/1000 |
| $d_e$ = Diameter, effective, in.   | $S$ = Speed, belt, fpm/1000                    |
| $2h_d$ = Diameter differential, nomenclature to outside, in.                       | $T_e$ = Tension, effective pull, lbf           |
| $K_f$ = Factor, length - flex correction   | $T_r$ = Tension, allowable tight side, lbf     |
| $L_e$ = Length, effective, in.   | $T_s$ = Tension, slack side, lbf               |
| $n$ = Sheaves, number on drive   | $T_T$ = Tension, tight side, lbf               |
| $P_d$ = Power, design, horsepower (transmitted horsepower $\times$ service factor) | $\theta$ = Angle, arc of belt contact, deg     |

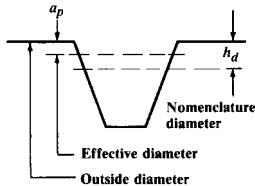


Fig. 7. Effective, Outside, and Nomenclature Sheave Diameters

**Number of Belts Determination:** The number of belts required may be determined on the basis of allowable tight side tension rating ( $T_r$ ) at the most severe sheave. The allowable tight side tensions per belt are given in Tables 16 through 19, and must be multiplied by the length-flex correction factors ( $K_f$ ) listed in Table 20. To select the allowable tight side tension from the tables for a given sheave, the belt speed and effective diameter of the sheave in question are required.

**Double V-Belt Drive Design Method:** The fourteen drive design steps are as follows:

1) Number the sheaves starting from the driver in the opposite direction to belt rotation; include the idlers.

2) Select the proper service factor for each loaded driven unit.

3) Multiply the horsepower requirement for each loaded driven sheave by the corresponding service factor. This is the design horsepower at each sheave.

4) Calculate driver design horsepower. This hp is equal to the sum of all the driven design horsepower.

5) Calculate belt speed ( $S$ ) in thousands of feet per minute:  $S = rd/3.820$ .

6) Calculate effective tension ( $T_e$ ) for each loaded sheave:  $T_e = 33P_d/S$ .

7) Determine minimum  $R/(R - 1)$  for each loaded sheave from Table 21 using the arc of contact determined from the drive layout.

8) In most drives, slippage will occur first at the driver sheave. Assume this to be true and calculate  $T_T$  and  $T_S$  for the driver:  $T_T = T_e [R/(R - 1)]$  and  $T_S = T_T - T_e$ . Use  $R/(R - 1)$  from Step 7 and  $T_e$  from Step 6 for the driver sheave.

9) Starting with the first driven sheave, determine  $T_T$  and  $T_S$  for each segment of the drive. The  $T_T$  for the driver becomes  $T_S$  for that sheave and is equal to  $T_T - T_e$ . Proceed around the drive in like manner.

10) Calculate actual  $R/(R - 1)$  for each sheave using:  $R/(R - 1) = T_T/T_e = T_T/(T_T - T_S)$ . The  $T_T$  and  $T_S$  values are for those determined in Step 9. If these values are equal to or greater than those determined in Step 7, the assumption that slippage will first occur at the driver is correct and the next two steps are not necessary. If the value is less, the assumption was not correct, so proceed with Step 11.

11) Take the sheave where the actual value  $R/(R - 1)$  (Step 10) is less than the minimum, as determined in Step 7, and calculate a new  $T_T$  and  $T_S$  for this sheave using the minimum  $R/(R - 1)$  as determined in Step 7:  $T_T = T_e [R/(R - 1)]$  and  $T_S = T_T - T_e$ .

12) Start with this sheave and recalculate the tension in each segment of the drive as in Step 9.

13) The length-flex factor ( $K_f$ ) is taken from Table 20. Before using this table, calculate the value of  $L_e/n$ . Be sure to use the appropriate belt cross-section column when selecting the correction factor.

14) Beginning with the driver sheave, determine the number of belts ( $N_b$ ) needed to satisfy the conditions at each loaded sheave using:  $N_b = T_T/T_r K_f$ . Note:  $T_T$  is tight side tension as determined in Step 9 or 11 and 12.  $T_r$  is allowable tight side tension as shown in Tables 18-21.  $K_f$  is the length-flex correction factor from Table 20. The sheave that requires the largest number of belts is the number of belts required for the drive. Any fraction of a belt should be treated as a whole belt.

**Table 16. Allowable Tight Side Tension for an AA Section**

| Belt Speed<br>(fpm) | Sheave Effective Diameter (in.) |     |     |     |     |     |     |     |
|---------------------|---------------------------------|-----|-----|-----|-----|-----|-----|-----|
|                     | 3.0                             | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 |
| 200                 | 30                              | 46  | 57  | 66  | 73  | 79  | 83  | 88  |
| 400                 | 23                              | 38  | 49  | 58  | 65  | 71  | 76  | 80  |
| 600                 | 18                              | 33  | 44  | 53  | 60  | 66  | 71  | 75  |
| 800                 | 14                              | 30  | 41  | 50  | 57  | 63  | 67  | 72  |
| 1000                | 12                              | 27  | 38  | 47  | 54  | 60  | 65  | 69  |
| 1200                | 9                               | 24  | 36  | 45  | 52  | 57  | 62  | 66  |
| 1400                | 7                               | 22  | 34  | 42  | 49  | 55  | 60  | 64  |
| 1600                | 5                               | 20  | 32  | 40  | 47  | 53  | 58  | 62  |
| 1800                | 3                               | 18  | 30  | 38  | 46  | 51  | 56  | 60  |
| 2000                | 1                               | 16  | 28  | 37  | 44  | 50  | 54  | 58  |
| 2200                | ...                             | 15  | 26  | 35  | 42  | 48  | 53  | 57  |
| 2400                | ...                             | 13  | 24  | 33  | 40  | 46  | 51  | 55  |
| 2600                | ...                             | 11  | 23  | 31  | 39  | 44  | 49  | 53  |
| 2800                | ...                             | 9   | 21  | 30  | 37  | 43  | 47  | 51  |
| 3000                | ...                             | 8   | 19  | 28  | 35  | 41  | 46  | 50  |
| 3200                | ...                             | 6   | 17  | 26  | 33  | 39  | 44  | 48  |
| 3400                | ...                             | 4   | 16  | 24  | 31  | 37  | 42  | 46  |
| 3600                | ...                             | 2   | 14  | 23  | 30  | 35  | 40  | 44  |
| 3800                | ...                             | 1   | 12  | 21  | 28  | 34  | 38  | 43  |
| 4000                | ...                             | ... | 10  | 19  | 26  | 32  | 37  | 41  |
| 4200                | ...                             | ... | 8   | 17  | 24  | 30  | 35  | 39  |
| 4400                | ...                             | ... | 6   | 15  | 22  | 28  | 33  | 37  |
| 4600                | ...                             | ... | 4   | 13  | 20  | 26  | 31  | 35  |
| 4800                | ...                             | ... | 2   | 11  | 18  | 24  | 29  | 33  |
| 5000                | ...                             | ... | ... | 9   | 16  | 22  | 27  | 31  |
| 5200                | ...                             | ... | ... | 7   | 14  | 20  | 24  | 28  |
| 5400                | ...                             | ... | ... | 4   | 12  | 17  | 22  | 26  |
| 5600                | ...                             | ... | ... | 2   | 9   | 15  | 20  | 24  |
| 5800                | ...                             | ... | ... | ... | 7   | 13  | 18  | 22  |

The allowable tight side tension must be evaluated for each sheave in the system (see Step 14). Values must be corrected by  $K_f$  from Table 20.



**Table 17. Allowable Tight Side Tension for a BB Section**

| Belt Speed<br>(fpm) | Sheave Effective Diameter (in.) |     |     |     |     |     |     |     |     |
|---------------------|---------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
|                     | 5.0                             | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 | 8.5 | 9.0 |
| 200                 | 81                              | 93  | 103 | 111 | 119 | 125 | 130 | 135 | 140 |
| 400                 | 69                              | 81  | 91  | 99  | 107 | 113 | 118 | 123 | 128 |
| 600                 | 61                              | 74  | 84  | 92  | 99  | 106 | 111 | 116 | 121 |
| 800                 | 56                              | 68  | 78  | 87  | 94  | 101 | 106 | 111 | 115 |
| 1000                | 52                              | 64  | 74  | 83  | 90  | 96  | 102 | 107 | 111 |
| 1200                | 48                              | 60  | 71  | 79  | 86  | 93  | 98  | 103 | 107 |
| 1400                | 45                              | 57  | 67  | 76  | 83  | 89  | 95  | 100 | 104 |
| 1600                | 42                              | 54  | 64  | 73  | 80  | 86  | 92  | 97  | 101 |
| 1800                | 39                              | 51  | 61  | 70  | 77  | 84  | 89  | 94  | 98  |
| 2000                | 36                              | 49  | 59  | 67  | 74  | 81  | 86  | 91  | 96  |
| 2200                | 34                              | 46  | 56  | 64  | 72  | 78  | 84  | 89  | 93  |
| 2400                | 31                              | 43  | 53  | 62  | 69  | 75  | 81  | 86  | 90  |
| 2600                | 29                              | 41  | 51  | 59  | 67  | 73  | 78  | 83  | 88  |
| 2800                | 26                              | 38  | 48  | 57  | 64  | 70  | 76  | 81  | 85  |
| 3000                | 23                              | 35  | 45  | 54  | 61  | 68  | 73  | 78  | 82  |
| 3200                | 21                              | 33  | 43  | 51  | 59  | 65  | 70  | 75  | 80  |
| 3400                | 18                              | 30  | 40  | 49  | 56  | 62  | 68  | 73  | 77  |
| 3600                | 15                              | 27  | 37  | 46  | 53  | 59  | 65  | 70  | 74  |
| 3800                | 12                              | 24  | 35  | 43  | 50  | 57  | 62  | 67  | 71  |
| 4000                | 9                               | 22  | 32  | 40  | 47  | 54  | 59  | 64  | 69  |
| 4200                | 7                               | 19  | 29  | 37  | 45  | 51  | 56  | 61  | 66  |
| 4400                | 4                               | 16  | 26  | 34  | 42  | 48  | 53  | 58  | 63  |
| 4600                | 1                               | 13  | 23  | 31  | 39  | 45  | 50  | 55  | 60  |
| 4800                | ...                             | 10  | 20  | 28  | 35  | 42  | 47  | 52  | 57  |
| 5000                | ...                             | 6   | 16  | 25  | 32  | 39  | 44  | 49  | 53  |
| 5200                | ...                             | 3   | 13  | 22  | 29  | 35  | 41  | 46  | 50  |
| 5400                | ...                             | ... | 10  | 18  | 26  | 32  | 38  | 42  | 47  |
| 5600                | ...                             | ... | 6   | 15  | 22  | 29  | 34  | 39  | 43  |
| 5800                | ...                             | ... | 3   | 11  | 19  | 25  | 31  | 36  | 40  |

The allowable tight side tension must be evaluated for each sheave in the system (see Step 14). Values must be corrected by  $K_f$  from Table 20.

**Table 18. Allowable Tight Side Tension for a CC Section**

| Belt Speed<br>(fpm) | Sheave Effective Diameter (in.) |     |     |      |      |      |      |      |      |
|---------------------|---------------------------------|-----|-----|------|------|------|------|------|------|
|                     | 7.0                             | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 | 15.0 |
| 200                 | 121                             | 158 | 186 | 207  | 228  | 244  | 257  | 268  | 278  |
| 400                 | 99                              | 135 | 164 | 187  | 206  | 221  | 234  | 246  | 256  |
| 600                 | 85                              | 122 | 151 | 173  | 192  | 208  | 221  | 232  | 242  |
| 800                 | 75                              | 112 | 141 | 164  | 182  | 198  | 211  | 222  | 232  |
| 1000                | 67                              | 104 | 133 | 155  | 174  | 190  | 203  | 214  | 224  |
| 1200                | 60                              | 97  | 126 | 149  | 167  | 183  | 196  | 207  | 217  |
| 1400                | 54                              | 91  | 120 | 142  | 161  | 177  | 190  | 201  | 211  |
| 1600                | 48                              | 85  | 114 | 137  | 155  | 171  | 184  | 196  | 205  |
| 1800                | 43                              | 80  | 108 | 131  | 150  | 166  | 179  | 190  | 200  |
| 2000                | 38                              | 75  | 103 | 126  | 145  | 160  | 174  | 185  | 195  |
| 2200                | 33                              | 70  | 98  | 121  | 140  | 155  | 169  | 180  | 190  |
| 2400                | 28                              | 65  | 93  | 116  | 135  | 150  | 164  | 175  | 185  |
| 2600                | 23                              | 60  | 88  | 111  | 130  | 145  | 159  | 170  | 180  |
| 2800                | 18                              | 55  | 83  | 106  | 125  | 140  | 154  | 165  | 175  |
| 3000                | 13                              | 50  | 78  | 101  | 120  | 135  | 149  | 160  | 170  |
| 3200                | 8                               | 45  | 73  | 96   | 115  | 130  | 144  | 155  | 165  |
| 3400                | 3                               | 39  | 68  | 91   | 110  | 125  | 138  | 150  | 160  |
| 3600                | ...                             | 34  | 63  | 86   | 104  | 120  | 133  | 145  | 154  |
| 3800                | ...                             | 29  | 58  | 80   | 99   | 115  | 128  | 139  | 149  |
| 4000                | ...                             | 24  | 52  | 75   | 94   | 109  | 123  | 134  | 144  |
| 4200                | ...                             | 18  | 47  | 70   | 88   | 104  | 117  | 128  | 138  |
| 4400                | ...                             | 12  | 41  | 64   | 83   | 98   | 112  | 123  | 133  |
| 4600                | ...                             | 7   | 35  | 58   | 77   | 93   | 106  | 117  | 127  |
| 4800                | ...                             | 1   | 29  | 52   | 71   | 87   | 100  | 111  | 121  |
| 5000                | ...                             | ... | 23  | 46   | 65   | 81   | 94   | 105  | 115  |
| 5200                | ...                             | ... | 17  | 40   | 59   | 75   | 88   | 99   | 109  |
| 5400                | ...                             | ... | 11  | 34   | 53   | 68   | 81   | 93   | 103  |
| 5600                | ...                             | ... | 5   | 27   | 46   | 62   | 75   | 86   | 96   |
| 5800                | ...                             | ... | ... | 21   | 40   | 55   | 68   | 80   | 90   |

The allowable tight side tension must be evaluated for each sheave in the system (see Step 14). Values must be corrected by  $K_f$  from Table 20.

**Table 19. Allowable Tight Side Tension for a DD Section**

| Belt Speed<br>(fpm) | Sheave Effective Diameter (in.) |      |      |      |      |      |      |      |      |
|---------------------|---------------------------------|------|------|------|------|------|------|------|------|
|                     | 12.0                            | 13.0 | 14.0 | 15.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 |
| 200                 | 243                             | 293  | 336  | 373  | 405  | 434  | 459  | 482  | 503  |
| 400                 | 195                             | 245  | 288  | 325  | 358  | 386  | 412  | 434  | 455  |
| 600                 | 167                             | 217  | 259  | 297  | 329  | 358  | 383  | 406  | 426  |
| 800                 | 146                             | 196  | 239  | 276  | 308  | 337  | 362  | 385  | 405  |
| 1000                | 129                             | 179  | 222  | 259  | 291  | 320  | 345  | 368  | 389  |
| 1200                | 114                             | 164  | 207  | 244  | 277  | 305  | 331  | 353  | 374  |
| 1400                | 101                             | 151  | 194  | 231  | 263  | 292  | 318  | 340  | 361  |
| 1600                | 89                              | 139  | 182  | 219  | 251  | 280  | 305  | 328  | 349  |
| 1800                | 78                              | 128  | 170  | 207  | 240  | 269  | 294  | 317  | 337  |
| 2000                | 67                              | 117  | 159  | 196  | 229  | 258  | 283  | 306  | 326  |
| 2200                | 56                              | 106  | 149  | 186  | 218  | 247  | 272  | 295  | 316  |
| 2400                | 45                              | 95   | 138  | 175  | 208  | 236  | 262  | 284  | 305  |
| 2600                | 35                              | 85   | 128  | 165  | 197  | 226  | 251  | 274  | 294  |
| 2800                | 24                              | 74   | 117  | 154  | 187  | 215  | 241  | 263  | 284  |
| 3000                | 14                              | 64   | 106  | 144  | 176  | 205  | 230  | 253  | 273  |
| 3200                | 3                               | 53   | 96   | 133  | 165  | 194  | 219  | 242  | 263  |
| 3400                | ...                             | 42   | 85   | 122  | 155  | 183  | 209  | 231  | 252  |
| 3600                | ...                             | 31   | 74   | 111  | 144  | 172  | 198  | 220  | 241  |
| 3800                | ...                             | 20   | 63   | 100  | 132  | 161  | 186  | 209  | 230  |
| 4000                | ...                             | 9    | 51   | 89   | 121  | 150  | 175  | 198  | 218  |
| 4200                | ...                             | ...  | 40   | 77   | 109  | 138  | 163  | 186  | 207  |
| 4400                | ...                             | ...  | 28   | 65   | 97   | 126  | 152  | 174  | 195  |
| 4600                | ...                             | ...  | 16   | 53   | 85   | 114  | 139  | 162  | 183  |
| 4800                | ...                             | ...  | 3    | 40   | 73   | 102  | 127  | 150  | 170  |
| 5000                | ...                             | ...  | ...  | 28   | 60   | 89   | 114  | 137  | 158  |
| 5200                | ...                             | ...  | ...  | 15   | 47   | 76   | 101  | 124  | 145  |
| 5400                | ...                             | ...  | ...  | 1    | 34   | 62   | 88   | 111  | 131  |
| 5600                | ...                             | ...  | ...  | ...  | 20   | 49   | 74   | 97   | 118  |
| 5800                | ...                             | ...  | ...  | ...  | 6    | 35   | 60   | 83   | 104  |

The allowable tight side tension must be evaluated for each sheave in the system (see Step 14). Values must be corrected by  $K_f$  from Table 20.

**Table 20. Length-Flex Correction Factors  $K_f$** 

| $\frac{L_e}{n}$ | Belt Cross Section |      |      |      | $\frac{L_e}{n}$ | Belt Cross Section |      |      |      |
|-----------------|--------------------|------|------|------|-----------------|--------------------|------|------|------|
|                 | AA                 | BB   | CC   | DD   |                 | AA                 | BB   | CC   | DD   |
| 10              | 0.64               | 0.58 | ...  | ...  | 70              | ...                | 1.03 | 0.95 | 0.91 |
| 15              | 0.74               | 0.68 | ...  | ...  | 80              | ...                | 1.06 | 0.98 | 0.94 |
| 20              | 0.82               | 0.74 | 0.68 | ...  | 90              | ...                | 1.09 | 1.00 | 0.96 |
| 25              | 0.87               | 0.79 | 0.73 | 0.70 | 100             | ...                | 1.11 | 1.03 | 0.99 |
| 30              | 0.92               | 0.84 | 0.77 | 0.74 | 110             | ...                | ...  | 1.05 | 1.00 |
| 35              | 0.96               | 0.87 | 0.80 | 0.77 | 120             | ...                | ...  | 1.06 | 1.02 |
| 40              | 0.99               | 0.90 | 0.83 | 0.80 | 130             | ...                | ...  | 1.08 | 1.04 |
| 45              | 1.02               | 0.93 | 0.86 | 0.82 | 140             | ...                | ...  | 1.10 | 1.05 |
| 50              | 1.05               | 0.95 | 0.88 | 0.84 | 150             | ...                | ...  | 1.11 | 1.07 |
| 60              | ...                | 0.99 | 0.92 | 0.88 | ...             | ...                | ...  | ...  | ...  |

**Tension Ratings:** The tension rating formulas are:

$$\text{AA } T_r = 118.5 - \frac{318.2}{d} - 0.8380S^2 - 25.76 \log S$$

$$\text{BB } T_r = 186.3 - \frac{665.1}{d} - 1.269S^2 - 39.02 \log S$$

$$CC \quad T_r = 363.9 - \frac{2060}{d} - 2.400S^2 - 73.77 \log S$$

$$DD \quad T_r = 783.1 - \frac{7790}{d} - 5.078S^2 - 156.1 \log S$$

where  $T_r$  = The allowable tight side tension for a double-V belt drive, lbf (not corrected for tension ratio or length-flex correction factor)

$d$  = Pitch diameter of small sheave, inch

$S$  = Belt speed, fpm/1000

**Table 21. Tension Ratio/Arc of Contact Factors**

| Arc of Contact,<br>$\theta$ (deg.) | Design<br>$\frac{R}{R-1}$ | Arc of Contact,<br>$\theta$ (deg.) | Design<br>$\frac{R}{R-1}$ |
|------------------------------------|---------------------------|------------------------------------|---------------------------|
| 300                                | 1.07                      | 170                                | 1.28                      |
| 290                                | 1.08                      | 160                                | 1.31                      |
| 280                                | 1.09                      | 150                                | 1.35                      |
| 270                                | 1.10                      | 140                                | 1.40                      |
| 260                                | 1.11                      | 130                                | 1.46                      |
| 250                                | 1.12                      | 120                                | 1.52                      |
| 240                                | 1.13                      | 110                                | 1.60                      |
| 230                                | 1.15                      | 100                                | 1.69                      |
| 220                                | 1.16                      | 90                                 | 1.81                      |
| 210                                | 1.18                      | 80                                 | 1.96                      |
| 200                                | 1.20                      | 70                                 | 2.15                      |
| 190                                | 1.22                      | 60                                 | 2.41                      |
| 180                                | 1.25                      | 50                                 | 2.77                      |

**Minimum Sheave Size:** The recommended minimum sheave size depends on the rpm of the faster shaft. Minimum groove diameters for each belt cross section are listed in [Table 14](#).

**Light Duty V-Belts ANSI/RMA IP-23.**—Light duty V-belts are typically used with fractional horsepower motors or small engines, and are designed primarily for fractional horsepower service. These belts are intended and specifically designed for use with small diameter sheaves and drives of loads and service requirements that are within the capacity of a single belt.

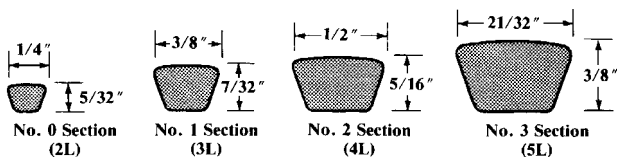


Fig. 8. Light Duty V-Belt Cross Sections

The four belt cross sections and sheave groove sizes are 2L, 3L, 4L, and 5L. The 2L is generally used only by OEMs and is not covered in the RMA standards.

**Belt Cross Sections.**—Nominal dimensions of the four cross sections are given in [Fig. 8](#).

**Belt Size Designation.**—V-belt sizes are identified by a standard belt number, consisting of a letter-numeral combination. The first number and letter identify the cross section; the remaining numbers identify length as shown in [Table 22](#). For example, a 3L520 belt has a 3L cross section and a length of 52.0 in.

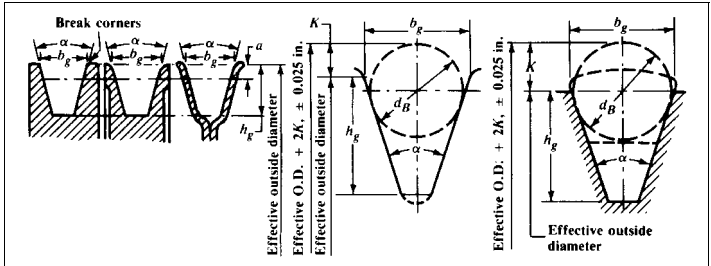
**Table 22. Light Duty V-Belt Standard Dimensions ANSI/RMA IP-23, 1968**

| Standard Effective Outside Length (in.) |     |     |     | Permissible Deviation From Standard Effective Length (in.) | Standard Effective Outside Length (in.) |     |     |     | Permissible Deviation From Standard Effective Length (in.) |
|---|-----|-----|-----|--|---|-----|-----|-----|--|
| Cross Section                           |     |     |     |  | Cross Section                           |     |     |     |  |
| 2L                                      | 3L  | 4L  | 5L  |  | 2L                                      | 3L  | 4L  | 5L  |  |
| 8                                       | ... | ... | ... | +0.12, -0.38   | ...                                     | ... | 53  | 53  | +0.25, -0.62   |
| 9                                       | ... | ... | ... | +0.12, -0.38   | ...                                     | 54  | 54  | 54  | +0.25, -0.62   |
| 10                                      | ... | ... | ... | +0.12, -0.38   | ...                                     | ... | 55  | 55  | +0.25, -0.62   |
| 11                                      | ... | ... | ... | +0.12, -0.38   | ...                                     | 56  | 56  | 56  | +0.25, -0.62   |
| 12                                      | ... | ... | ... | +0.12, -0.38   | ...                                     | ... | 57  | 57  | +0.25, -0.62   |
| 13                                      | ... | ... | ... | +0.12, -0.38   | ...                                     | 58  | 58  | 58  | +0.25, -0.62   |
| 14                                      | 14  | ... | ... | +0.12, -0.38   | ...                                     | ... | 59  | 59  | +0.25, -0.62   |
| 15                                      | 15  | ... | ... | +0.12, -0.38   | ...                                     | 60  | 60  | 60  | +0.25, -0.62   |
| 16                                      | 16  | ... | ... | +0.12, -0.38   | ...                                     | ... | 61  | 61  | +0.31, -0.69   |
| 17                                      | 17  | ... | ... | +0.12, -0.38   | ...                                     | ... | 62  | 62  | +0.31, -0.69   |
| 18                                      | 18  | 18  | ... | +0.12, -0.38   | ...                                     | ... | 63  | 63  | +0.31, -0.69   |
| 19                                      | 19  | 19  | ... | +0.12, -0.38   | ...                                     | ... | 64  | 64  | +0.31, -0.69   |
| 20                                      | 20  | 20  | ... | +0.12, -0.38   | ...                                     | ... | 65  | 65  | +0.31, -0.69   |
| ...                                     | 21  | 21  | ... | +0.25, -0.62   | ...                                     | ... | 66  | 66  | +0.31, -0.69   |
| ...                                     | 22  | 22  | ... | +0.25, -0.62   | ...                                     | ... | 67  | 67  | +0.31, -0.69   |
| ...                                     | 23  | 23  | ... | +0.25, -0.62   | ...                                     | ... | 68  | 68  | +0.31, -0.69   |
| ...                                     | 24  | 24  | ... | +0.25, -0.62   | ...                                     | ... | 69  | 69  | +0.31, -0.69   |
| ...                                     | 25  | 25  | 25  | +0.25, -0.62   | ...                                     | ... | 70  | 70  | +0.31, -0.69   |
| ...                                     | 26  | 26  | 26  | +0.25, -0.62   | ...                                     | ... | 71  | 71  | +0.31, -0.69   |
| ...                                     | 27  | 27  | 27  | +0.25, -0.62   | ...                                     | ... | 72  | 72  | +0.31, -0.69   |
| ...                                     | 28  | 28  | 28  | +0.25, -0.62   | ...                                     | ... | 73  | 73  | +0.31, -0.69   |
| ...                                     | 29  | 29  | 29  | +0.25, -0.62   | ...                                     | ... | 74  | 74  | +0.31, -0.69   |
| ...                                     | 30  | 30  | 30  | +0.25, -0.62   | ...                                     | ... | 75  | 75  | +0.31, -0.69   |
| ...                                     | 31  | 31  | 31  | +0.25, -0.62   | ...                                     | ... | 76  | 76  | +0.31, -0.69   |
| ...                                     | 32  | 32  | 32  | +0.25, -0.62   | ...                                     | ... | 77  | 77  | +0.31, -0.69   |
| ...                                     | 33  | 33  | 33  | +0.25, -0.62   | ...                                     | ... | 78  | 78  | +0.31, -0.69   |
| ...                                     | 34  | 34  | 34  | +0.25, -0.62   | ...                                     | ... | 79  | 79  | +0.31, -0.69   |
| ...                                     | 35  | 35  | 35  | +0.25, -0.62   | ...                                     | ... | 80  | 80  | +0.62, -0.88   |
| ...                                     | 36  | 36  | 36  | +0.25, -0.62   | ...                                     | ... | 82  | 82  | +0.62, -0.88   |
| ...                                     | 37  | 37  | 37  | +0.25, -0.62   | ...                                     | ... | 84  | 84  | +0.62, -0.88   |
| ...                                     | 38  | 38  | 38  | +0.25, -0.62   | ...                                     | ... | 86  | 86  | +0.62, -0.88   |
| ...                                     | 39  | 39  | 39  | +0.25, -0.62   | ...                                     | ... | 88  | 88  | +0.62, -0.88   |
| ...                                     | 40  | 40  | 40  | +0.25, -0.62   | ...                                     | ... | 90  | 90  | +0.62, -0.88   |
| ...                                     | 41  | 41  | 41  | +0.25, -0.62   | ...                                     | ... | 92  | 92  | +0.62, -0.88   |
| ...                                     | 42  | 42  | 42  | +0.25, -0.62   | ...                                     | ... | 94  | 94  | +0.62, -0.88   |
| ...                                     | 43  | 43  | 43  | +0.25, -0.62   | ...                                     | ... | 96  | 96  | +0.62, -0.88   |
| ...                                     | 44  | 44  | 44  | +0.25, -0.62   | ...                                     | ... | 98  | 98  | +0.62, -0.88   |
| ...                                     | 45  | 45  | 45  | +0.25, -0.62   | ...                                     | ... | 100 | 100 | +0.62, -0.88   |
| ...                                     | 46  | 46  | 46  | +0.25, -0.62   | ...                                     | ... | ... | ... | ...  |
| ...                                     | 47  | 47  | 47  | +0.25, -0.62   | ...                                     | ... | ... | ... | ...  |
| ...                                     | 48  | 48  | 48  | +0.25, -0.62   | ...                                     | ... | ... | ... | ...  |
| ...                                     | 49  | 49  | 49  | +0.25, -0.62   | ...                                     | ... | ... | ... | ...  |
| ...                                     | 50  | 50  | 50  | +0.25, -0.62   | ...                                     | ... | ... | ... | ...  |
| ...                                     | ... | 51  | 51  | +0.25, -0.62   | ...                                     | ... | ... | ... | ...  |
| ...                                     | 52  | 52  | 52  | +0.25, -0.62   | ...                                     | ... | ... | ... | ...  |

All dimensions in inches.

*Sheave Dimensions:* Groove angles and dimensions for sheaves and various sheave tolerances are given in [Table 23](#).

**Table 23. Light Duty V-Belt Sheave and Groove Dimensions**  
ANSI/RMA IP-23, 1968



| Belt Section | Effective Outside Diameter |                | $\alpha$ Groove Angle $\pm 0^\circ 20'$ (deg) | $d_B$ Ball Diameter $\pm 0.0005$ | $2K$  | $b_g$ (Ref) | $h_g$ (min) | $2a^a$ |
|--------------|----------------------------|----------------|---|----------------------------------|-------|-------------|-------------|--------|
|              | Min. Recomm.               | Range          |   |                                  |       |             |             |        |
| 2L           | 0.8                        | Less Than 1.50 | 32  | 0.2188                           | 0.176 | 0.240       | 0.250       | 0.04   |
|              |                            | 1.50 to 1.99   | 34  |                                  | 0.182 |             |             |        |
|              |                            | 2.00 to 2.50   | 36  |                                  | 0.188 |             |             |        |
|              |                            | Over 2.50      | 38  |                                  | 0.194 |             |             |        |
| 3L           | 1.5                        | Less Than 2.20 | 32  | 0.3125                           | 0.177 | 0.364       | 0.406       | 0.06   |
|              |                            | 2.20 to 3.19   | 34  |                                  | 0.191 |             |             |        |
|              |                            | 3.20 to 4.20   | 36  |                                  | 0.203 |             |             |        |
|              |                            | Over 4.20      | 38  |                                  | 0.215 |             |             |        |
| 4L           | 2.5                        | Less Than 2.65 | 30  | 0.4375                           | 0.299 | 0.490       | 0.490       | 0.10   |
|              |                            | 2.65 to 3.24   | 32  |                                  | 0.316 |             |             |        |
|              |                            | 3.25 to 5.65   | 34  |                                  | 0.331 |             |             |        |
|              |                            | Over 5.65      | 38  |                                  | 0.358 |             |             |        |
| 5L           | 3.5                        | Less Than 3.95 | 30  | 0.5625                           | 0.385 | 0.630       | 0.580       | 0.16   |
|              |                            | 3.95 to 4.94   | 32  |                                  | 0.406 |             |             |        |
|              |                            | 4.95 to 7.35   | 34  |                                  | 0.426 |             |             |        |
|              |                            | Over 7.35      | 38  |                                  | 0.461 |             |             |        |

<sup>a</sup>The diameter used in calculating speed ratio and belt speed is obtained by subtracting the  $2a$  value from the Effective Outside Diameter of the sheave.

| Other Sheave Tolerances                               |  |   |
|---|--|---|
| Outside Diameters                                     | Outside Diameter Eccentricity <sup>a</sup>                   | Groove Side Wobble & Runout <sup>a</sup>  |
| For outside diameters under 6.0 in. $\pm 0.015$ in.   | For outside diameters 10.0 in. and under 0.010 in.           | For outside diameters 20.0 in. and under 0.0015 in. per inch of outside diameter. |
| For outside diameters 6.0 to 12.0 in. $\pm 0.020$ in. | For each additional inch of outside diameter, add 0.0005 in. | For each additional inch of outside diameter, add 0.0005 in.                      |
| For outside diameters over 12.0 in. $\pm 0.040$ in.   |  |   |

<sup>a</sup>Total indicator reading.

All dimensions in inches.

**Horsepower Ratings:** The horsepower ratings for light duty V-belts can be calculated from the following formulas:

$$3L \quad \text{HP} = r \left( \frac{0.2164d^{0.91}}{r^{0.09}} - 0.2324 - 0.0001396r^2d^3 \right)$$

$$4L \quad \text{HP} = r \left( \frac{0.4666d^{0.91}}{r^{0.09}} - 0.7231 - 0.0002286r^2d^3 \right)$$

$$5L \quad \text{HP} = r \left( \frac{0.7748d^{0.91}}{r^{0.09}} - 1.727 - 0.0003641r^2d^3 \right)$$

where  $d = d_0 - 2a$ ;  $d_0$  = effective outside diameter of small sheave, in.;  $r$  = rpm of the faster shaft divided by 1000. The corrected horsepower rating is obtained by dividing the horsepower rating by the combined correction factor (Table 24), which accounts for drive geometry and service factor requirements.

**Table 24. Combined Correction Factors**

| Type of Driven Unit       | Speed Ratio   |              |
|---------------------------|---------------|--------------|
|                           | Less than 1.5 | 1.5 and Over |
| Fans and blowers          | 1.0           | 0.9          |
| Domestic laundry machines | 1.1           | 1.0          |
| Centrifugal pumps         | 1.1           | 1.0          |
| Generators                | 1.2           | 1.1          |
| Rotary compressors        | 1.2           | 1.1          |
| Machine tools             | 1.3           | 1.2          |
| Reciprocating pumps       | 1.4           | 1.3          |
| Reciprocating compressors | 1.4           | 1.3          |
| Wood working machines     | 1.4           | 1.3          |

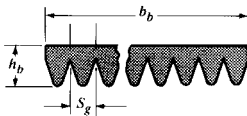
**V-Ribbed Belts ANSI/RMA IP-26.**—V-ribbed belts are a cross between flat belts and V-belts. The belt is basically flat with V-shaped ribs projecting from the bottom, which guide the belt and provide greater stability than that found in a flat belt. The ribs operate in grooved sheaves.

V-ribbed belts do not have the wedging action of a V-belt and thus operate at higher tensions. This design provides excellent performance in high-speed and serpentine applications, and in drives that utilize small diameter sheaves. The V-ribbed belt comes in five cross sections: H, J, K, L, and M, specified by effective length, cross section and number of ribs.

*Belt Cross Sections:* Nominal dimensions of the five cross sections are given in Table 25.

**Table 25. Nominal Dimensions of V-Ribbed Belt Cross Sections**  
ANSI/RMA IP-26, 1977

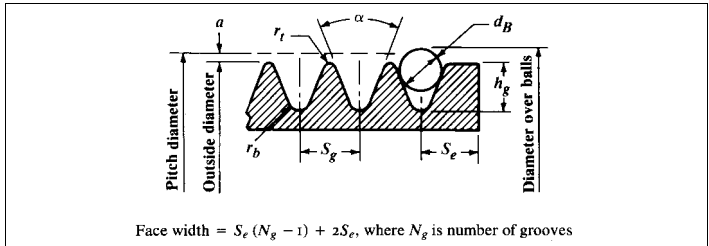
| Cross Section | $h_b$ | $S_g$ | Standard Number of Ribs      |
|---------------|-------|-------|------------------------------|
| H             | 0.12  | 0.063 | ...                          |
| J             | 0.16  | 0.092 | 4, 6, 10, 16, 20             |
| K             | 0.24  | 0.140 | ...                          |
| L             | 0.38  | 0.185 | 6, 8, 10, 12, 14, 16, 18, 20 |
| M             | 0.66  | 0.370 | 6, 8, 10, 12, 14, 16, 18, 20 |



$b_b = N_r \times S_g$ , where  $N_r$  = number of ribs and  $S_g$  is sheave groove spacing

All dimensions in inches.

**Table 26. V-Ribbed Belt Sheave and Groove Dimensions ANSI/RMA IP-26, 1977**



| Cross Section | Minimum Recommended Outside Diameter | $\alpha$ Groove Angle $\pm 0.25$ (deg) | $S_g^a$           | $r_t$ +0.005, -0.000 | $2a$  | $r_b$               | $h_g$ (min) | $d_B$ $\pm 0.0005$ | $S_e$               |
|---------------|--------------------------------------|--|-------------------|----------------------|-------|---------------------|-------------|--------------------|---------------------|
| H             | 0.50                                 | 40                                     | 0.063 $\pm 0.001$ | 0.005                | 0.020 | 0.013 +0.000 -0.005 | 0.041       | 0.0469             | 0.080 +0.020 -0.010 |
| J             | 0.80                                 | 40                                     | 0.092 $\pm 0.001$ | 0.008                | 0.030 | 0.015 +0.000 -0.005 | 0.071       | 0.0625             | 0.125 +0.030 -0.015 |
| K             | 1.50                                 | 40                                     | 0.140 $\pm 0.002$ | 0.010                | 0.038 | 0.020 +0.000 -0.005 | 0.122       | 0.1093             | 0.125 +0.050 -0.000 |
| L             | 3.00                                 | 40                                     | 0.185 $\pm 0.002$ | 0.015                | 0.058 | 0.015 +0.000 -0.005 | 0.183       | 0.1406             | 0.375 +0.075 -0.030 |
| M             | 7.00                                 | 40                                     | 0.370 $\pm 0.003$ | 0.030                | 0.116 | 0.030 +0.000 -0.010 | 0.377       | 0.2812             | 0.500 +0.100 -0.040 |

<sup>a</sup> Summation of the deviations from  $S_g$  for all grooves in any one sheave shall not exceed  $\pm 0.010$  in.

| Other Sheave Tolerances <sup>a</sup>  |  |  |
|---|--|--|
| Outside Diameter  | Radial Runout <sup>b</sup>   | Axial Runout <sup>b</sup>              |
| Up through 2.9 in. outside diameter $\pm 0.010$ in.                             | Up through 2.9 in. outside diameter 0.005 in.                              | 0.001 in. per inch of outside diameter |
| Over 2.9 in. to and including 8.0 in. outside diameter $\pm 0.020$ in.          | Over 2.9 in. to and including 10.0 in. outside diameter 0.010 in.          |  |
| For each additional inch of outside diameter over 8.0 in., add $\pm 0.0025$ in. | For each additional inch of outside diameter over 10.0 in., add 0.0005 in. |  |

<sup>a</sup> Variations in pitch diameter between the grooves in any one sheave must be within the following limits: Up through 2.9 in. outside diameter and up through 6 grooves, 0.002 in. (add 0.001 in. for each additional groove); over 2.9 in. to and including 19.9 in. and up through 10 grooves, 0.005 in. (add 0.0002 in. for each additional groove); over 19.9 in. and up through 10 grooves, 0.010 in. (add 0.0005 in. for each additional groove). This variation can be obtained by measuring the distance across two measuring balls or rods placed in the grooves diametrically opposite each other. Comparing this "diameter-over-balls or -rods" measurement between grooves will give the variation in pitch diameter.

<sup>b</sup> Total indicator reading.

All dimensions in inches

**Belt Size Designation:** Belt sizes are identified by a standard belt number, which consists of belt effective length to the nearest tenth of an inch, a letter designating cross section, and the number of ribs. For example, 540L6 signifies a 54.0 in. effective length, L belt, six ribs wide.

**Sheave Dimensions.:** Groove angles and dimensions for sheaves and face widths of sheaves for multiple belt drives are given in Table 26, along with various tolerance values.

**Cross Section Selection.:** Use the chart (Fig. 9) as a guide to the V-ribbed belt cross section for any combination of design horsepower and speed of the faster shaft. When the intersection of the design horsepower and speed of the faster shaft falls near a line between two areas on the chart, the possibilities in both areas should be explored. Special circumstances (such as space limitations) may lead to a choice of belt cross section different from that indicated in the chart. H and K cross sections are not included because of their specialized use. Belt manufacturers should be contacted for specific data.

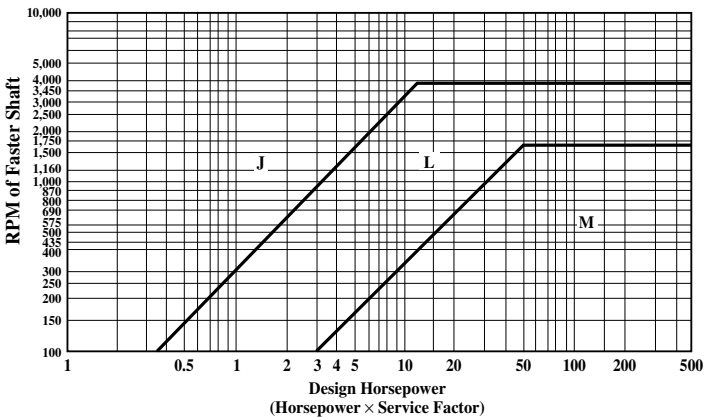


Fig. 9. Selection of V-Ribbed Belt Cross Section

**Horsepower Ratings.:** The horsepower rating formulas are:

$$\mathbf{J:HP} = d_p r \left[ \frac{0.1240}{(d_p r)^{0.09}} - \frac{0.08663}{d_p} - 0.2318 \times 10^{-4} (d_p r)^2 \right] + 0.08663 r \left[ 1 - \frac{1}{K_{SR}} \right]$$

$$\mathbf{L:HP} = d_p r \left[ \frac{0.5761}{(d_p r)^{0.09}} - \frac{0.8987}{d_p} - 1.018 \times 10^{-4} (d_p r)^2 \right] + 0.8987 r \left[ 1 - \frac{1}{K_{SR}} \right]$$

$$\mathbf{M:HP} = d_p r \left[ \frac{1.975}{(d_p r)^{0.09}} - \frac{6.597}{d_p} - 3.922 \times 10^{-4} (d_p r)^2 \right] + 6.597 r \left[ 1 - \frac{1}{K_{SR}} \right]$$

In these equations,  $d_p$  = pitch diameter of the small sheave, in.;  $r$  = rpm of the faster shaft divided by 1000;  $K_{SR}$  = speed ratio factor given in the accompanying Table 30. These formulas give the maximum horsepower per rib recommended, corrected for the speed ratio. To obtain the horsepower per rib for an arc of contact other than 180 degrees, and for belts longer or shorter than the average length, multiply the horsepower obtained from these formulas by the length correction factor (Table 28) and the arc of contact correction factor (Table 29).



**Table 27. V-Ribbed Belt Standard Effective Lengths ANSI/RMA IP-26, 1977**

| J Cross Section                          |                           |  | L Cross Section                          |                           |  | M Cross Section                          |                           |  |
|--|---------------------------|--|--|---------------------------|--|--|---------------------------|--|
| Standard Length Designation <sup>a</sup> | Standard Effective Length | Permissible Deviation From Standard Length | Standard Length Designation <sup>a</sup> | Standard Effective Length | Permissible Deviation From Standard Length | Standard Length Designation <sup>a</sup> | Standard Effective Length | Permissible Deviation From Standard Length |
| 180                                      | 18.0                      | +0.2, -0.2                                 | 500                                      | 50.0                      | +0.2, -0.4                                 | 900                                      | 90.0                      | +0.4, -0.7                                 |
| 190                                      | 19.0                      | +0.2, -0.2                                 | 540                                      | 54.0                      | +0.2, -0.4                                 | 940                                      | 94.0                      | +0.4, -0.8                                 |
| 200                                      | 20.0                      | +0.2, -0.2                                 | 560                                      | 56.0                      | +0.2, -0.4                                 | 990                                      | 99.0                      | +0.4, -0.8                                 |
| 220                                      | 22.0                      | +0.2, -0.2                                 | 615                                      | 61.5                      | +0.2, -0.5                                 | 1060                                     | 106.0                     | +0.4, -0.8                                 |
| 240                                      | 24.0                      | +0.2, -0.2                                 | 635                                      | 63.5                      | +0.2, -0.5                                 | 1115                                     | 111.5                     | +0.4, -0.9                                 |
| 260                                      | 26.0                      | +0.2, -0.2                                 | 655                                      | 65.5                      | +0.2, -0.5                                 | 1150                                     | 115.0                     | +0.4, -0.9                                 |
| 280                                      | 28.0                      | +0.2, -0.2                                 | 675                                      | 67.5                      | +0.3, -0.6                                 | 1185                                     | 118.5                     | +0.4, -0.9                                 |
| 300                                      | 30.0                      | +0.2, -0.3                                 | 695                                      | 69.5                      | +0.3, -0.6                                 | 1230                                     | 123.0                     | +0.4, -1.0                                 |
| 320                                      | 32.0                      | +0.2, -0.3                                 | 725                                      | 72.5                      | +0.3, -0.6                                 | 1310                                     | 131.0                     | +0.5, -1.1                                 |
| 340                                      | 34.0                      | +0.2, -0.3                                 | 765                                      | 76.5                      | +0.3, -0.6                                 | 1390                                     | 139.0                     | +0.5, -1.1                                 |
| 360                                      | 36.0                      | +0.2, -0.3                                 | 780                                      | 78.0                      | +0.3, -0.6                                 | 1470                                     | 147.0                     | +0.6, -1.2                                 |
| 380                                      | 38.0                      | +0.2, -0.3                                 | 795                                      | 79.5                      | +0.3, -0.6                                 | 1610                                     | 161.0                     | +0.6, -1.2                                 |
| 400                                      | 40.0                      | +0.2, -0.4                                 | 815                                      | 81.5                      | +0.3, -0.7                                 | 1650                                     | 165.0                     | +0.6, -1.3                                 |
| 430                                      | 43.0                      | +0.2, -0.4                                 | 840                                      | 84.0                      | +0.3, -0.7                                 | 1760                                     | 176.0                     | +0.7, -1.4                                 |
| 460                                      | 46.0                      | +0.2, -0.4                                 | 865                                      | 86.5                      | +0.3, -0.7                                 | 1830                                     | 183.0                     | +0.7, -1.4                                 |
| 490                                      | 49.0                      | +0.2, -0.4                                 | 915                                      | 91.5                      | +0.4, -0.7                                 | 1980                                     | 198.0                     | +0.8, -1.6                                 |
| 520                                      | 52.0                      | +0.2, -0.4                                 | 975                                      | 97.5                      | +0.4, -0.8                                 | 2130                                     | 213.0                     | +0.8, -1.6                                 |
| 550                                      | 55.0                      | +0.2, -0.4                                 | 990                                      | 99.0                      | +0.4, -0.8                                 | 2410                                     | 241.0                     | +0.9, -1.6                                 |
| 580                                      | 58.0                      | +0.2, -0.5                                 | 1065                                     | 106.5                     | +0.4, -0.8                                 | 2560                                     | 256.0                     | +1.0, -1.8                                 |
| 610                                      | 61.0                      | +0.2, -0.5                                 | 1120                                     | 112.0                     | +0.4, -0.9                                 | 2710                                     | 271.0                     | +1.1, -2.2                                 |
| 650                                      | 65.0                      | +0.2, -0.5                                 | 1150                                     | 115.0                     | +0.4, -0.9                                 | 3010                                     | 301.0                     | +1.2, -2.4                                 |

<sup>a</sup>To specify belt size, use the standard length designation, followed by the letter indicating belt cross section and the number of ribs desired. For example: 865L10.

All dimensions in inches.

**Table 28. Length Correction Factors**

| Std. Length Designation | Cross Section |      |      | Std. Length Designation | Cross Section |      |       |
|-------------------------|---------------|------|------|-------------------------|---------------|------|-------|
|                         | J             | L    | M    |                         | J             | L    | M     |
| 180                     | 0.83          | ...  | ...  | 1230                    | ...           | 1.08 | 0.94  |
| 200                     | 0.85          | ...  | ...  | 1310                    | ...           | 1.10 | 0.96  |
| 240                     | 0.89          | ...  | ...  | 1470                    | ...           | 1.12 | 0.098 |
| 280                     | 0.92          | ...  | ...  | 1610                    | ...           | 1.14 | 1.00  |
| 320                     | 0.95          | ...  | ...  | 1830                    | ...           | 1.17 | 1.03  |
| 360                     | 0.98          | ...  | ...  | 1980                    | ...           | 1.19 | 1.05  |
| 400                     | 1.00          | ...  | ...  | 2130                    | ...           | 1.21 | 1.06  |
| 440                     | 1.02          | ...  | ...  | 2410                    | ...           | 1.24 | 1.09  |
| 500                     | 1.05          | 0.89 | ...  | 2710                    | ...           | ...  | 1.12  |
| 550                     | 1.07          | 0.91 | ...  | 3010                    | ...           | ...  | 1.14  |
| 610                     | 1.09          | 0.93 | ...  | 3310                    | ...           | ...  | 1.16  |
| 690                     | 1.12          | 0.96 | ...  | 3610                    | ...           | ...  | 1.18  |
| 780                     | 1.16          | 0.98 | ...  | 3910                    | ...           | ...  | 1.20  |
| 910                     | 1.18          | 1.02 | 0.88 | 4210                    | ...           | ...  | 1.22  |
| 940                     | 1.19          | 1.02 | 0.89 | 4810                    | ...           | ...  | 1.25  |
| 990                     | 1.20          | 1.04 | 0.90 | 5410                    | ...           | ...  | 1.28  |
| 1060                    | ...           | 1.05 | 0.91 | 6000                    | ...           | ...  | 1.30  |
| 1150                    | ...           | 1.07 | 0.93 | ...                     | ...           | ...  | ...   |

**Table 29. Arc of Contact Correction Factors**

| $\frac{D_o - d_o}{C}$ | Arc of Contact, $\theta$ ,<br>on Small Sheave, (deg) | Correction Factor |
|-----------------------|--|-------------------|
| 0.00                  | 180  | 1.00              |
| 0.10                  | 174  | 0.98              |
| 0.20                  | 169  | 0.97              |
| 0.30                  | 163  | 0.95              |
| 0.40                  | 157  | 0.94              |
| 0.50                  | 151  | 0.92              |
| 0.60                  | 145  | 0.90              |
| 0.70                  | 139  | 0.88              |
| 0.80                  | 133  | 0.85              |
| 0.90                  | 127  | 0.83              |
| 1.00                  | 120  | 0.80              |
| 1.10                  | 113  | 0.77              |
| 1.20                  | 106  | 0.74              |
| 1.30                  | 99   | 0.71              |
| 1.40                  | 91   | 0.67              |
| 1.50                  | 83   | 0.63              |

*Number of Ribs:* The number of ribs required for an application is obtained by dividing the design horsepower by the corrected horsepower rating for one rib.

Arc of contact on the small sheave may be determined by the following formulas:

$$\text{Exact Formula: Arc of Contact (deg)} = 2 \cos^{-1} \left( \frac{D_o - d_o}{2C} \right)$$

$$\text{Approximate Formula: Arc of Contact (deg)} = 180 - \frac{(D_o - d_o)60}{C} \text{ where}$$

$D_o$  = Effective outside diameter of large sheave, in;  $d_o$  = Effective outside diameter of small sheave, in; and,  $C$  = Center distance, inch.

**Table 30. Speed Ratio Correction Factors**

| Speed Ratio <sup>a</sup>    | $K_{SR}$ |
|-----------------------------|----------|
| 1.00 to and incl. 1.10      | 1.0000   |
| Over 1.01 to and incl. 1.04 | 1.0136   |
| Over 1.04 to and incl. 1.08 | 1.0276   |
| Over 1.08 to and incl. 1.12 | 1.0419   |
| Over 1.12 to and incl. 1.18 | 1.0567   |
| Over 1.18 to and incl. 1.24 | 1.0719   |
| Over 1.24 to and incl. 1.34 | 1.0875   |
| Over 1.34 to and incl. 1.51 | 1.1036   |
| Over 1.51 to and incl. 1.99 | 1.1202   |
| Over 1.99                   | 1.1373   |

<sup>a</sup>  $D_p/d_p$ , where  $D_p$  ( $d_p$ ) is the pitch diameter of the large (small) sheave.

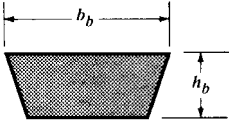
**Variable Speed Belts ANSI/RMA IP-25.**—For drives that require more speed variation than can be obtained with conventional industrial V-belts, standard-line variable-speed drives are available. These drives use special wide, thin belts. Package units of standard-line variable-speed belts and sheaves, combined with the motor and output gearbox are available in ranges from approximately  $\frac{1}{2}$  through 100 horsepower.

The speed ranges of variable-speed drives can be much greater than those drives using classical V-belts. Speed ranges up to 10:1 can be obtained on lower horsepower units.

This section covers 12 variable speed belt cross sections and sheave groove sizes designed 1422V, 1922V, 2322V 1926V, 2926V, 3226V, 2530V, 3230V, 4430V, 4036V, 4436V, and 4836V. The industry supplies many other sizes that are not listed in this section.

*Belt Cross Sections and Lengths:* Nominal dimensions of the 12 cross sections are given in [Table 31](#), and lengths in [Table 32](#).

**Table 31. Normal Variable-Speed Belt Dimensions ANSI/RMA IP-25, 1982**

|  |       |       |           |               |       |       |           |
|---|-------|-------|-----------|---------------|-------|-------|-----------|
| Cross Section   | $b_b$ | $h_b$ | $h_b/b_b$ | Cross Section | $b_b$ | $h_b$ | $h_b/b_b$ |
| 1422V   | 0.88  | 0.31  | 0.35      | 2530V         | 1.56  | 0.59  | 0.38      |
| 1922V   | 1.19  | 0.38  | 0.32      | 3230V         | 2.00  | 0.62  | 0.31      |
| 2322V   | 1.44  | 0.44  | 0.31      | 4430V         | 2.75  | 0.69  | 0.25      |
| 1926V   | 1.19  | 0.44  | 0.37      | 4036V         | 2.50  | 0.69  | 0.28      |
| 2926V   | 1.81  | 0.50  | 0.28      | 4436V         | 2.75  | 0.72  | 0.26      |
| 3226V   | 2.0   | 0.53  | 0.27      | 4836V         | 3.00  | 0.75  | 0.25      |

All dimensions in inches.

**Table 32. Variable-Speed V-Belt Standard Belt Lengths ANSI/RMA IP-25, 1982**

| Standard Pitch Length Designation | Standard Effective Lengths |       |       |       |       |       |       |       |       |       |       |       | Permissible Deviations From Standard Length |
|-----------------------------------|----------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---|
|                                   | Cross Section              |       |       |       |       |       |       |       |       |       |       |       |   |
|                                   | 1422V                      | 1922V | 2322V | 1926V | 2926V | 3226V | 2530V | 3230V | 4430V | 4036V | 4436V | 4836V |   |
| 315                               | 32.1                       | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ±0.7  |
| 335                               | 34.1                       | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ±0.7  |
| 355                               | 36.1                       | 36.2  | ...   | 36.3  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ±0.7  |
| 375                               | 38.1                       | 38.2  | ...   | 38.3  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ±0.7  |
| 400                               | 40.6                       | 40.7  | 40.8  | 40.8  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ±0.7  |
| 425                               | 43.1                       | 43.2  | 43.3  | 43.3  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ±0.8  |
| 450                               | 45.6                       | 45.7  | 45.8  | 45.8  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ±0.8  |
| 475                               | 48.1                       | 48.2  | 48.3  | 48.3  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ±0.8  |
| 500                               | 50.6                       | 50.7  | 50.8  | 50.8  | ...   | ...   | 50.9  | ...   | ...   | ...   | ...   | ...   | ±0.8  |
| 530                               | 53.6                       | 53.7  | 53.8  | 53.8  | 53.9  | ...   | 53.9  | ...   | ...   | ...   | ...   | ...   | ±0.8  |
| 560                               | 56.6                       | 56.7  | 56.8  | 56.8  | 56.9  | 56.9  | 56.9  | 57.1  | 57.3  | 57.3  | 57.3  | 57.4  | ±0.9  |
| 600                               | 60.6                       | 60.7  | 60.8  | 60.8  | 60.9  | 60.9  | 60.9  | 61.1  | 61.3  | 61.3  | 61.3  | 61.4  | ±0.9  |
| 630                               | 63.6                       | 63.7  | 63.8  | 63.8  | 63.9  | 63.9  | 63.9  | 64.1  | 64.3  | 64.3  | 64.3  | 64.4  | ±0.9  |
| 670                               | 67.6                       | 67.7  | 67.8  | 67.8  | 67.9  | 67.9  | 67.9  | 68.1  | 68.3  | 68.3  | 68.3  | 68.4  | ±0.9  |
| 710                               | 71.6                       | 71.7  | 71.8  | 71.8  | 71.9  | 71.9  | 71.9  | 72.1  | 72.3  | 72.3  | 72.3  | 72.4  | ±0.9  |
| 750                               | 75.6                       | 75.7  | 75.8  | 75.8  | 75.9  | 75.9  | 75.9  | 76.1  | 76.3  | 76.3  | 76.3  | 76.4  | ±1.0  |
| 800                               | ...                        | 80.7  | 80.8  | 80.8  | 80.9  | 80.9  | 80.9  | 81.1  | 81.3  | 81.3  | 81.3  | 81.4  | ±1.0  |
| 850                               | ...                        | 85.7  | 85.8  | 85.8  | 85.9  | 85.9  | 85.9  | 86.1  | 86.3  | 86.3  | 86.3  | 86.4  | ±1.1  |
| 900                               | ...                        | 90.7  | 90.8  | 90.8  | 90.9  | 90.9  | 90.9  | 91.1  | 91.3  | 91.3  | 91.3  | 91.4  | ±1.1  |
| 950                               | ...                        | 95.7  | 95.8  | 95.8  | 95.9  | 95.9  | 95.9  | 96.1  | 96.3  | 96.3  | 96.3  | 96.4  | ±1.1  |
| 1000                              | ...                        | 100.7 | 100.8 | 100.8 | 100.9 | 100.9 | 100.9 | 101.1 | 101.3 | 101.3 | 101.3 | 101.4 | ±1.2  |
| 1060                              | ...                        | 106.7 | 106.8 | 106.8 | 106.9 | 106.9 | 106.9 | 107.1 | 107.3 | 107.3 | 107.3 | 107.4 | ±1.2  |
| 1120                              | ...                        | 112.7 | 112.8 | 112.8 | 112.9 | 112.9 | 112.9 | 113.1 | 113.3 | 113.3 | 113.3 | 113.4 | ±1.2  |
| 1180                              | ...                        | 118.7 | 118.8 | 118.8 | 118.9 | 118.9 | 118.9 | 119.1 | 119.3 | 119.3 | 119.3 | 119.4 | ±1.3  |
| 1250                              | ...                        | ...   | ...   | ...   | 125.9 | 125.9 | 125.9 | 126.1 | 126.3 | 126.3 | 126.3 | 126.4 | ±1.3  |
| 1320                              | ...                        | ...   | ...   | ...   | ...   | 132.9 | ...   | 133.1 | 133.3 | 133.3 | 133.3 | 133.4 | ±1.3  |

All dimensions in inches.

The lengths given in this table are not necessarily available from all manufacturers. Availability should be investigated prior to design commitment.

Table 33. Variable-Speed Sheave and Groove Dimensions

| Cross Section | Standard Groove Dimensions                   |                                    |                         |                 |                     |  |                      |              |                     | Drive Design Factors              |      |              |             |
|---------------|--|------------------------------------|-------------------------|-----------------|---------------------|--|----------------------|--------------|---------------------|-----------------------------------|------|--------------|-------------|
|               | Variable                                     |                                    |                         |                 |                     | Companion                                    |                      |              |                     |                                   |      |              |             |
|               | $\alpha$<br>Groove Angle<br>$\pm 0.67$ (deg) | $b_g^a$ Closed<br>+0.000<br>-0.030 | $b_{go}$<br>Open<br>Max | $h_{gv}$<br>Min | $S_g$<br>$\pm 0.03$ | $\alpha$ Groove<br>Angle $\pm 0.33$<br>(deg) | $b_g$<br>$\pm 0.010$ | $h_g$<br>Min | $S_g$<br>$\pm 0.03$ | Min. Recomm.<br>Pitch<br>Diameter | $2a$ | $2av$<br>Max | $CL$<br>Min |
| 1422V         | 22   | 0.875                              | 1.63                    | 2.33            | 1.82                | 22   | 0.875                | 0.500        | 1.82                | 2.0                               | 0.20 | 3.88         | 0.08        |
| 1922V         | 22   | 1.188                              | 2.23                    | 3.14            | 2.42                | 22   | 1.188                | 0.562        | 2.42                | 3.0                               | 0.22 | 5.36         | 0.08        |
| 2322V         | 22   | 1.438                              | 2.71                    | 3.78            | 2.89                | 22   | 1.438                | 0.625        | 2.89                | 3.5                               | 0.25 | 6.52         | 0.08        |
| 1926V         | 26   | 1.188                              | 2.17                    | 2.65            | 2.36                | 26   | 1.188                | 0.625        | 2.36                | 3.0                               | 0.25 | 4.26         | 0.08        |
| 2926V         | 26   | 1.812                              | 3.39                    | 4.00            | 3.58                | 26   | 1.812                | 0.750        | 3.58                | 3.5                               | 0.30 | 6.84         | 0.08        |
| 3226V         | 26   | 2.000                              | 3.75                    | 4.41            | 3.96                | 26   | 2.000                | 0.781        | 3.96                | 4.0                               | 0.30 | 7.60         | 0.08        |
| 2530V         | 30   | 1.562                              | 2.81                    | 3.01            | 2.98                | 30   | 1.562                | 0.844        | 2.98                | 4.0                               | 0.30 | 4.64         | 0.10        |
| 3230V         | 30   | 2.000                              | 3.67                    | 3.83            | 3.85                | 30   | 2.000                | 0.875        | 3.85                | 4.5                               | 0.35 | 6.22         | 0.10        |
| 4430V         | 30   | 2.750                              | 5.13                    | 5.23            | 5.38                | 30   | 2.750                | 0.938        | 5.38                | 5.0                               | 0.40 | 8.88         | 0.10        |
| 4036V         | 36   | 2.500                              | 4.55                    | 3.95            | 4.80                | 36   | 2.500                | 0.938        | 4.80                | 4.5                               | 0.40 | 6.32         | 0.10        |
| 4436V         | 36   | 2.750                              | 5.03                    | 4.33            | 5.30                | 36   | 2.750                | 0.969        | 5.30                | 5.0                               | 0.40 | 7.02         | 0.10        |
| 4836V         | 36   | 3.000                              | 5.51                    | 4.72            | 5.76                | 36   | 3.000                | 1.000        | 5.76                | 6.0                               | 0.45 | 7.74         | 0.10        |

<sup>a</sup>The effective width ( $b_e$ ), a reference dimension, is the same as the ideal top width of closed variable-speed sheave ( $b_g$ ) and the ideal top width of the companion sheave ( $b_g$ ).

| Other Sheave Tolerances  |                 |   |  |
|--|-----------------|---|--|
| Outside Diameter   |                 | Radial Runout <sup>a</sup>                                  | Axial Runout <sup>a</sup>                                  |
| Up through 4.0 in. outside diameter                              | $\pm 0.020$ in. | Up through 10.0 in. outside diameter                        | 0.010 in.  |
| For each additional inch of outside diameter add $\pm 0.005$ in. |                 | For each additional inch of outside diameter add 0.0005 in. | Up through 5.0 in. outside diameter                        |
|  |                 |   | For each additional inch of outside diameter add 0.001 in. |

<sup>a</sup>Total indicator reading.

| Surface Finish                    |   |  |   |
|-----------------------------------|---|--|---|
| Machined Surface Area             | Max Surface Roughness Height, $R_v$ (AA) ( $\mu$ in.) | Machined Surface Area  | Max Surface Roughness Height, $R_v$ (AA) ( $\mu$ in.) |
| V-Sheave groove sidewalls         | 125   | Straight bores with 0.002 in. or less total tolerance        | 125   |
| Rim edges and ID, Hub ends and OD | 500   | Taper and straight bores with total tolerance over 0.002 in. | 250   |

All dimensions in inches, except where noted.

**Belt Size Designation:** Variable-speed belt sizes are identified by a standard belt number. The first two digits denote the belt top width in sixteenths of an inch; the third and fourth digits indicate the angle of the groove in which the belt is designed to operate. Letter V (for variable) follows the first four digits. The digits after the V indicate pitch length to the nearest 0.1 in. For example, 1422V450 is a belt of  $\frac{7}{8}$  in. ( $\frac{14}{16}$  in.) nominal top width designed to operate in a sheave of 22 degree groove angle and having a pitch length of 45.0 in.

**Sheave Groove Data:** A variable speed sheave is an assembly of movable parts, designed to permit one or both flanges of the sheave to be moved axially causing a radial movement of the variable speed belt in the sheave groove. This radial movement permits stepless speed variation within the physical limits of the sheave and the belt. A companion sheave may be a solid sheave having a constant diameter and groove profile or another variable sheave. Variable speed sheave designs should conform to the dimensions in Table 33 and Fig. 10. The included angle of the sheaves, top width, and clearance are boundary dimensions. Groove angles and dimensions of companion sheaves should conform to Table 33 and Fig. 11. Various tolerance values are also given in Table 33.

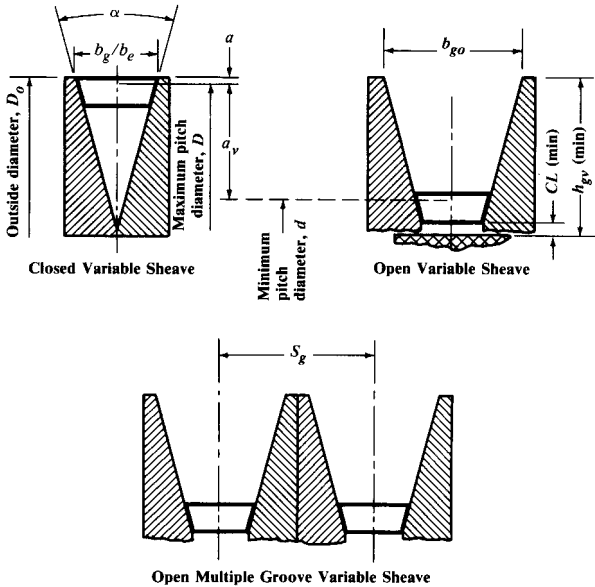


Fig. 10. Variable Sheaves

**Variable-Speed Drive Design:** Variable-speed belts are designed to operate in sheaves that are an assembly of movable parts. The sheave design permits one or both flanges of the sheave to be moved axially, causing a radial movement of the variable-speed belt in the sheave groove. The result is a stepless speed variation within the physical limits of the sheave and the variable-speed belt. Therefore, besides transmitting power, variable-speed belt drives provide speed variation.

## VARIABLE SPEED BELTS

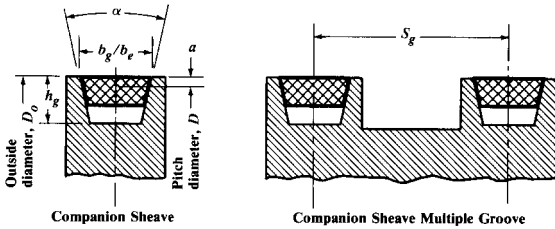


Fig. 11. Companion Sheaves

The factors that determine the amount of pitch diameter change on variable-speed sheaves are belt top width, belt thickness, and sheave angle. This pitch diameter change, combined with the selected operating pitch diameters for a sheave, determines the possible speed variation.

The range of output speeds from a variable-speed sheave drive is established by the companion sheave and is a function of the ratio of the pitch diameter of the companion sheave to the maximum and minimum pitch diameters of the variable sheave. Speed variation is usually obtained by varying the center distance between the two sheaves. This type of drive seldom exceeds a speed variation of 3:1.

For a single variable-speed sheave drive, the speed variation

$$\text{Speed variation} = \frac{\text{PD Max}}{\text{PD Min}} \quad (\text{of variable sheave})$$

For a dual variable-speed sheave drive, which is frequently referred to as a compound drive because both sheaves are variable, the speed variation is

$$\text{Speed variation} = \frac{DR(DN)}{dr(dn)}$$

where  $DR$  = Max driver PD

$DN$  = Max driven PD

$dr$  = Min driver PD

$dn$  = Min driven PD

With this design, the center distance is generally fixed and speed variation is usually accomplished by mechanically altering the pitch diameter of one sheave. In this type of drive, the other sheave is spring loaded to make an opposite change in the pitch diameter and to provide the correct belt tension. Speed variations of up to 10:1 are common on this type of drive.

**Speed Ratio Adjustment:** All speed ratio changes must be made while the drives are running. Attempting to make adjustments while the unit is stopped creates unnecessary and possibly destructive forces on both the belt and sheaves. In stationary control drives, the belt tension should be released to allow the flanges to adjust without belt force interference.

**Cross Section Selection:** Selection of a variable speed belt cross section is based on the drive design horsepower and speed variation. Table 33 shows the maximum pitch diameter variation ( $2av$ ) that each cross section can attain.

**Horsepower Ratings:** The general horsepower formulas for variable-speed belts are:

$$1422 \text{ V HP} = d_p r \left[ 0.4907 (d_p r)^{-0.09} - \frac{0.8378}{d_p} - 0.000337 (d_p r)^2 \right] + 0.8378 r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$1922 \text{ VHP} = d_p r \left[ 0.8502(d_p r)^{-0.09} - \frac{1.453}{d_p} - 0.000538(d_p r)^2 \right] + 1.453r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$2322 \text{ VHP} = d_p r \left[ 1.189(d_p r)^{-0.09} - \frac{2.356}{d_p} - 0.000777(d_p r)^2 \right] + 2.356r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$1926 \text{ VHP} = d_p r \left[ 1.046(d_p r)^{-0.09} - \frac{1.833}{d_p} - 0.000589(d_p r)^2 \right] + 1.833r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$2926 \text{ VHP} = d_p r \left[ 1.769(d_p r)^{-0.09} - \frac{4.189}{d_p} - 0.001059(d_p r)^2 \right] + 4.189r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$3226 \text{ VHP} = d_p r \left[ 2.073(d_p r)^{-0.09} - \frac{5.236}{d_p} - 0.001217(d_p r)^2 \right] + 5.236r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$2530 \text{ VHP} = d_p r \left[ 2.395(d_p r)^{-0.09} - \frac{6.912}{d_p} - 0.001148(d_p r)^2 \right] + 6.912r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$3230 \text{ VHP} = d_p r \left[ 2.806(d_p r)^{-0.09} - \frac{7.854}{d_p} - 0.001520(d_p r)^2 \right] + 7.854r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$4430 \text{ VHP} = d_p r \left[ 3.454(d_p r)^{-0.09} - \frac{7.854}{d_p} - 0.002196(d_p r)^2 \right] + 9.818r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$4036 \text{ VHP} = d_p r \left[ 3.566(d_p r)^{-0.09} - \frac{9.687}{d_p} - 0.002060(d_p r)^2 \right] + 9.687r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$4436 \text{ VHP} = d_p r \left[ 4.041(d_p r)^{-0.09} - \frac{11.519}{d_p} - 0.002297(d_p r)^2 \right] + 11.519r \left( 1 - \frac{1}{K_{SR}} \right)$$

$$4836 \text{ VHP} = d_p r \left[ 4.564(d_p r)^{-0.09} - \frac{13.614}{d_p} - 0.002634(d_p r)^2 \right] + 13.614r \left( 1 - \frac{1}{K_{SR}} \right)$$

In these equations,  $d_p$  = pitch diameter of small sheave, in.;  $r$  = rpm of faster shaft divided by 1000;  $K_{SR}$  = speed ratio factor given in the accompanying Table 34. These formulas give the basic horsepower rating, corrected for the speed ratio. To obtain the horsepower for arcs of contact other than 180 degrees and for belts longer or shorter than average length, multiply the horsepower obtained from these formulas by the arc of contact correction factor (Table 36) and the length correction factor (Table 35).

**Table 34. Speed Ratio Correction Factors**

| Speed Ratio <sup>a</sup> | $K_{SR}$ | Speed Ratio <sup>a</sup> | $K_{SR}$ |
|--------------------------|----------|--------------------------|----------|
| 1.00–1.01                | 1.0000   | 1.19–1.24                | 1.0719   |
| 1.02–1.04                | 1.0136   | 1.25–1.34                | 1.0875   |
| 1.05–1.08                | 1.0276   | 1.35–1.51                | 1.1036   |
| 1.09–1.12                | 1.0419   | 1.52–1.99                | 1.1202   |
| 1.13–1.18                | 1.0567   | 2.0 and over             | 1.1373   |

<sup>a</sup>  $D_p/d_p$ , where  $D_p$  ( $d_p$ ) is the pitch diameter of the large (small) sheave.



Table 35. Length Correction Factors

| Standard Pitch Length Designation | Cross Section |       |       |       |       |       |       |       |       |       |       |       |
|-----------------------------------|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                                   | 1422V         | 1922V | 2322V | 1926V | 2926V | 3226V | 2530V | 3230V | 4430V | 4036V | 4436V | 4836V |
| 315                               | 0.93          | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
| 335                               | 0.94          | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
| 355                               | 0.95          | 0.90  | ...   | 0.90  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
| 375                               | 0.96          | 0.91  | ...   | 0.91  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
| 400                               | 0.97          | 0.92  | 0.90  | 0.92  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
| 425                               | 0.98          | 0.93  | 0.91  | 0.93  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
| 450                               | 0.99          | 0.94  | 0.92  | 0.94  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
| 475                               | 1.00          | 0.95  | 0.93  | 0.95  | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
| 500                               | 1.01          | 0.95  | 0.94  | 0.95  | ...   | ...   | 0.90  | ...   | ...   | ...   | ...   | ...   |
| 530                               | 1.02          | 0.96  | 0.95  | 0.96  | 0.92  | ...   | 0.92  | ...   | ...   | ...   | ...   | ...   |
| 560                               | 1.03          | 0.97  | 0.96  | 0.97  | 0.93  | 0.92  | 0.93  | 0.91  | 0.90  | 0.91  | 0.91  | 0.92  |
| 600                               | 1.04          | 0.98  | 0.97  | 0.98  | 0.94  | 0.93  | 0.94  | 0.93  | 0.92  | 0.93  | 0.92  | 0.93  |
| 630                               | 1.05          | 0.99  | 0.98  | 0.99  | 0.95  | 0.94  | 0.95  | 0.94  | 0.93  | 0.94  | 0.93  | 0.94  |
| 670                               | 1.06          | 1.00  | 0.99  | 1.00  | 0.97  | 0.95  | 0.96  | 0.95  | 0.94  | 0.95  | 0.95  | 0.95  |
| 710                               | 1.07          | 1.01  | 1.00  | 1.01  | 0.98  | 0.96  | 0.98  | 0.96  | 0.96  | 0.96  | 0.96  | 0.96  |
| 750                               | 1.08          | 1.02  | 1.01  | 1.02  | 0.99  | 0.98  | 0.99  | 0.97  | 0.97  | 0.97  | 0.97  | 0.98  |
| 800                               | ...           | 1.03  | 1.02  | 1.03  | 1.00  | 0.99  | 1.00  | 0.99  | 0.99  | 0.99  | 0.99  | 0.99  |
| 850                               | ...           | 1.04  | 1.03  | 1.04  | 1.01  | 1.00  | 1.01  | 1.00  | 1.00  | 1.00  | 1.00  | 1.00  |
| 900                               | ...           | 1.05  | 1.04  | 1.05  | 1.02  | 1.01  | 1.02  | 1.01  | 1.01  | 1.01  | 1.01  | 1.01  |
| 950                               | ...           | 1.06  | 1.05  | 1.06  | 1.03  | 1.02  | 1.04  | 1.02  | 1.03  | 1.02  | 1.02  | 1.02  |
| 1000                              | ...           | 1.07  | 1.06  | 1.07  | 1.04  | 1.03  | 1.05  | 1.03  | 1.04  | 1.03  | 1.04  | 1.03  |
| 1060                              | ...           | 1.08  | 1.07  | 1.07  | 1.06  | 1.04  | 1.06  | 1.05  | 1.06  | 1.05  | 1.05  | 1.04  |
| 1120                              | ...           | 1.09  | 1.08  | 1.08  | 1.07  | 1.06  | 1.07  | 1.06  | 1.07  | 1.06  | 1.06  | 1.06  |
| 1180                              | ...           | 1.09  | 1.09  | 1.09  | 1.08  | 1.07  | 1.08  | 1.07  | 1.08  | 1.07  | 1.07  | 1.07  |
| 1250                              | ...           | ...   | ...   | ...   | 1.09  | 1.08  | 1.10  | 1.08  | 1.10  | 1.08  | 1.09  | 1.08  |
| 1320                              | ...           | ...   | ...   | ...   | ...   | 1.09  | ...   | 1.09  | 1.11  | 1.09  | 1.10  | 1.09  |

**Rim Speed:** The material and design selected for sheaves must be capable of withstanding the high rim speeds that may occur in variable-speed drives. The rim speed is calculated as follows: Rim speed (fpm) =  $(\pi/12) (D_o)$  (rpm).

**Arc of Contact:** Arc of contact on the small sheave may be determined by the formulas:

$$\text{Exact Formula: Arc of Contact (deg)} = 2 \cos^{-1} \left( \frac{D-d}{2C} \right)$$

$$\text{Approximate Formula: Arc of Contact (deg)} = 180 - \frac{(D-d)60}{C}$$

where  $D$  = Pitch diameter of large sheave or flat pulley, inch

$d$  = Pitch diameter of small sheave, inch

$C$  = Center distance, inch

**Table 36. Arc of Contact Correction Factors**

| $\frac{D-d}{C}$ | Arc of Contact, $\theta$ ,<br>on Small Sheave,<br>(deg) | Correction<br>Factor | $\frac{D-d}{C}$ | Arc of Contact, $\theta$ ,<br>on Small Sheave,<br>(deg) | Correction<br>Factor |
|-----------------|---|----------------------|-----------------|---|----------------------|
| 0.00            | 180   | 1.00                 | 0.80            | 0.80  | 0.87                 |
| 0.10            | 174   | 0.99                 | 0.90            | 0.90  | 0.85                 |
| 0.20            | 169   | 0.97                 | 1.00            | 1.00  | 0.82                 |
| 0.30            | 163   | 0.96                 | 1.10            | 1.10  | 0.80                 |
| 0.40            | 157   | 0.94                 | 1.20            | 1.20  | 0.77                 |
| 0.50            | 151   | 0.93                 | 1.30            | 1.30  | 0.73                 |
| 0.60            | 145   | 0.91                 | 1.40            | 1.40  | 0.70                 |
| 0.70            | 139   | 0.89                 | 1.50            | 1.50  | 0.65                 |

**60 Degree V-Belts.**—60 degree V-belts are ideal for compact drives. Their 60 degree angle and ribbed top are specifically designed for long life on small diameter sheaves. These belts offer extremely smooth operation at high speeds (in excess of 10,000 rpm) and can be used on drives with high speed ratios. They are available in 3M, 5M, 7M, and 11M (3, 5, 7, 11 mm) cross sections (top widths) and are commonly found in the joined configuration, which provides extra stability and improved performance. They are specified by cross section and nominal length; for example, a 5M315 designation indicates a belt having a 5 mm cross section and an effective length of 315 mm.

Industry standards have not yet been published for 60 degree V-belts. Therefore, belt manufacturers should be contacted for specific applications, specifications, and additional information.

**SAE Standard V-Belts.**—The data for V-belts and pulleys shown in Table 37 cover nine sizes, three of which — 0.250, 0.315, and 0.440 — were added in 1977 to conform to existing practice. This standard was reaffirmed in 1987.

V-belts are produced in a variety of constructions in a basic trapezoidal shape and are to be dimensioned in such a way that they are functional in pulleys dimensioned as described in the standard. Standard belt lengths are in increments of  $\frac{1}{2}$  inch up to and including 80 inches. Standard lengths above 80 inches up to and including 100 inches are in increments of 1 inch, without fractions. Standard belt length tolerances are based on the center distance and are as follows: For belt lengths of 50 inches or less,  $\pm 0.12$  inch; over 50 to 60 inches, inclusive,  $\pm 0.16$  inch; over 60 to 80 inches, inclusive,  $\pm 0.19$ ; and over 80 to 100 inches, inclusive,  $\pm 0.22$ .

**Belt Storage and Handling.**—To achieve maximum belt performance, proper belt storage procedures should always be practiced. If belts are not stored properly, their performance can be adversely affected. Four key rules are:

- 1) Do not store belts on floors unless they are protected by appropriate packaging.
- 2) Do not store belts near windows where the belts may be exposed to direct sunlight or moisture.

Table 37. SAE V-Belt and Pulley Dimensions

| SAE Size                       | Recommended Min. Eff Dia <sup>a</sup> | A Groove Angle (deg) ±0.5 | W Eff. Groove Width | D Groove Depth Min | d Ball or Rod Dia (±0.0005) | 2K 2 × Ball Extension | 2X <sup>b</sup> | S Groove <sup>c</sup> Spacing (±0.015) |
|--------------------------------|---------------------------------------|---------------------------|---------------------|--------------------|-----------------------------|-----------------------|-----------------|--|
| 0.250                          | 2.25                                  | 36                        | 0.248               | 0.276              | 0.2188                      | 0.164                 | 0.04            | 0.315                                  |
| 0.315                          | 2.25                                  | 36                        | 0.315               | 0.354              | 0.2812                      | 0.222                 | 0.05            | 0.413                                  |
| 0.380                          | 2.40                                  | 36                        | 0.380               | 0.433              | 0.3125                      | 0.154                 | 0.06            | 0.541                                  |
| 0.440                          | 2.75                                  | 36                        | 0.441               | 0.512              | 0.3750                      | 0.231                 | 0.07            | 0.591                                  |
| 0.500                          | 3.00                                  | 36                        | 0.500               | 0.551              | 0.4375                      | 0.314                 | 0.08            | 0.661                                  |
| 1 <sup>1</sup> / <sub>16</sub> | 3.00                                  | 34                        | 0.597               | 0.551              | 0.500                       | 0.258                 | 0.00            | 0.778                                  |
|                                | Over 4.00                             | 36                        |                     |                    |                             | 0.280                 |                 |  |
|                                | Over 6.00                             | 38                        |                     |                    |                             | 0.302                 |                 |  |
| 3/4                            | 3.00                                  | 34                        | 0.660               | 0.630              | 0.5625                      | 0.328                 | 0.02            | 0.841                                  |
|                                | Over 4.00                             | 36                        |                     |                    |                             | 0.352                 |                 |  |
|                                | Over 6.00                             | 38                        |                     |                    |                             | 0.374                 |                 |  |
| 7/8                            | 3.50                                  | 34                        | 0.785               | 0.709              | 0.6875                      | 0.472                 | 0.04            | 0.966                                  |
|                                | Over 4.50                             | 36                        |                     |                    |                             | 0.496                 |                 |  |
|                                | Over 6.00                             | 38                        |                     |                    |                             | 0.520                 |                 |  |
| 1                              | 4.00                                  | 34                        | 0.910               | 0.827              | 0.8125                      | 0.616                 | 0.06            | 1.091                                  |
|                                | Over 6.00                             | 36                        |                     |                    |                             | 0.642                 |                 |  |
|                                | Over 8.00                             | 38                        |                     |                    |                             | 0.666                 |                 |  |

All dimensions in inches.

<sup>a</sup> Pulley effective diameters below those recommended should be used with caution, because power transmission and belt life may be reduced.

<sup>b</sup> The  $X$  dimension is radial;  $2X$  is to be subtracted from the effective diameter to obtain "pitch diameter" for speed ratio calculations.

<sup>c</sup> These values are intended for adjacent grooves of the same effective width ( $W$ ). Choice of pulley manufacture or belt design parameter may justify variance from these values. The  $S$  dimension should be the same on all multiple groove pulleys in a drive using matched belts. © 1990, SAE, Inc.

3) Do not store belts near electrical devices that may generate ozone (transformers, electric motors, etc.).

4) Do not store belts in areas where solvents or chemicals are present in the atmosphere.

Belts should be stored in a cool, dry environment. When stacked on shelves, the stacks should be short enough to avoid excess weight on the bottom belts, which may cause distortion. When stored in containers, the container size and contents should be sufficiently limited to avoid distortion.

**V-Belts:** A common method is to hang the belts on pegs or pin racks. Very long belts stored this way should use sufficiently large pins or crescent shaped "saddles" to prevent their weight from causing distortion.

**Table 38. Service Factors for V-Belts**

|              |   |   |                                      |   |
|--------------|---|---|--------------------------------------|---|
| Driving Unit | <i>AC Motors:</i> Normal Torque, Squirrel Cage, Synchronous and Split Phase.<br><i>DC Motors:</i> Shunt Wound.<br><i>Engines:</i> Multiple Cylinder Internal Combustion.  |   |                                      |   |
|              | Types of Driven Machines  | Intermittent Service<br>(3–5 hours daily or seasonal) | Normal Service<br>(8–10 hours daily) | Continuous Service<br>(16–24 hours daily) |
|              | Agitators for liquids; Blowers and exhausters; Centrifugal pumps & compressors; Fans up to 10 horsepower; Light duty conveyors  | 1.1   | 1.2                                  | 1.3                                       |
|              | Belt conveyors for sand, grain, etc.; Dough mixers; Fans over 10 horsepower; Generators; Line shafts; Laundry machinery; Machine tools; Punches, presses, shears; Printing machinery; Positive displacement rotary pumps; Revolving and vibrating screens | 1.2   | 1.3                                  | 1.4                                       |
|              | Brick machinery; Bucket elevators; Exciters; Piston compressors; Conveyors (drag, pan, screw); Hammer mills; Paper mill beaters; Piston pumps; Positive displacement blowers; Pulverizers; Saw mill and woodworking machinery; Textile machinery          | 1.4   | 1.5                                  | 1.6                                       |
|              | Crushers (gyratory, jaw, roll); Mills (ball, rod, tube); Hoists; Rubber calendars, extruders, mills   | 1.5   | 1.6                                  | 1.8                                       |
| Driving Unit | <i>AC Motors:</i> High Torque, High Slip, Repulsion-Induction, Single Phase, Series Wound, Slip Ring.<br><i>DC Motors:</i> Series Wound, Compound Wound.<br><i>Engines:</i> Single Cylinder Internal Combustion. <i>Line Shafts, Clutches</i>             |   |                                      |   |
|              | Types of Driven Machines  | Intermittent Service<br>(3–5 hours daily or seasonal) | Normal Service<br>(8–10 hours daily) | Continuous Service<br>(16–24 hours daily) |
|              | Agitators for liquids; Blowers and exhausters; Centrifugal pumps & compressors; Fans up to 10 horsepower; Light duty conveyors  | 1.1   | 1.2                                  | 1.3                                       |
|              | Belt conveyors for sand, grain, etc.; Dough mixers; Fans over 10 horsepower; Generators; Line shafts; Laundry machinery; Machine tools; Punches, presses, shears; Printing machinery; Positive displacement rotary pumps; Revolving and vibrating screens | 1.2   | 1.3                                  | 1.4                                       |
|              | Brick machinery; Bucket elevators; Exciters; Piston compressors; Conveyors (drag, pan, screw); Hammer mills; Paper mill beaters; Piston pumps; Positive displacement blowers; Pulverizers; Saw mill and woodworking machinery; Textile machinery          | 1.4   | 1.5                                  | 1.6                                       |
|              | Crushers (gyratory, jaw, roll); Mills (ball, rod, tube); Hoists; Rubber calendars, extruders, mills   | 1.5   | 1.6                                  | 1.8                                       |

The machines listed above are representative samples only. Select the group listed above whose load characteristics most closely approximate those of the machine being considered.

**Joined V-belts, Synchronous Belts, V-Ribbed Belts:** Like V-belts, these belts may be stored on pins or saddles with precautions taken to avoid distortion. However, belts of this type up to approximately 120 in. are normally shipped in a “nested” configuration and should be stored in the same manner. Nests are formed by laying a belt on its side on a flat surface and placing as many belts inside the first belt as possible without undue force. When the nests are tight and are stacked with each rotated 180° from the one below, they may be stacked without damage.

Belts of this type over 120 in. may be “rolled up” and tied for shipment. These rolls may be stacked for easy storage. Care should be taken to avoid small bend radii which could damage the belts.

**Variable Speed Belts:** Variable speed belts are more sensitive to distortion than most other belts, and should not be hung from pins or racks but stored on shelves in the sleeves in which they are shipped.

**Service Factors:** Service factors for V-belts are listed in [Table 38](#).

### Synchronous Belts

**Synchronous Belts ANSI/RMA IP-24.**—Synchronous belts are also known as timing belts. These belts have evenly spaced teeth on their surfaces, which mesh with teeth on pulleys or sprockets to produce a positive, no-slip transmission of power. Such designs should not be confused with molded notched V-belts, which transmit power by means of the wedging action of the V-shape. Synchronous belts are used where driven shaft speeds must be synchronized to the rotation of the driver shaft and to eliminate the noise and maintenance problems of chain drives.

**Standard Timing Belts:** Conventional trapezoidal, or rectangular tooth, timing belts come in six cross sections, which relate to the pitch of the belt. Pitch is the distance from center to center of the teeth. The six basic cross sections or pitches are MXL (mini extra light), XL (extra light), L (light), H (heavy), XH (extra heavy), and XXH (double extra heavy) (Fig. 12). Belts are specified by pitch length, cross section (pitch), and width.

Double-sided timing belts have identical teeth on both sides of the belt and are used where synchronization is required from each belt face. They are available in XL, L, and H cross sections.

**Size Designations:** Synchronous belt sizes are identified by a standard number. The first digits specify the belt length to 0.1 in. followed by the belt section (pitch) designation. The digits following the belt section designation represent the nominal belt width times 100. For example, an L section belt 30.000 in. pitch length and 0.75 in. in width would be specified as a 300L075 synchronous belt.

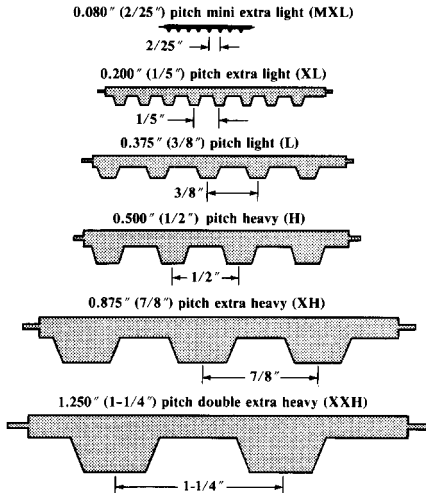


Fig. 12. Standard Synchronous Belt Sections

The RMA nomenclature for double-sided belts is the same as for single-sided belts with the addition of the prefix "D" in front of the belt section. However, some manufacturers use their own designation system for double-sided belts.

**Standard Sections:** Belt sections are specified in terms of pitch. Table 40 gives the Standard Belt Sections and their corresponding pitches.

**Table 39. Service Factors for Synchronous Belt Drives**

| Driving Units  | <i>AC Motors:</i> Normal Torque, Squirrel Cage, Synchronous and Split Phase.<br><i>DC Motors:</i> Shunt Wound. <i>Engines:</i> Multiple Cylinder Internal Combustion.   |   |                                      |   |
|--|---|---|--------------------------------------|---|
| Types of Driven Machines   |   | Intermittent Service<br>(3–5 hours daily or seasonal) | Normal Service<br>(8–10 hours daily) | Continuous Service<br>(16–24 hours daily) |
| Display, Dispensing, Projection, Medical equipment; Instrumentation; Measuring devices   |   | 1.0   | 1.2                                  | 1.4                                       |
| Appliances, sweepers, sewing machines; Office equipment; Wood lathes, band saws  |   | 1.2   | 1.4                                  | 1.6                                       |
| Conveyors: belt, light package, oven, screens, drums, conical  |   | 1.3   | 1.5                                  | 1.7                                       |
| Agitators for liquids; Dough mixers; Drill presses, lathes; Screw machines, jointers; Circular saws, planes; Laundry, Paper, Printing machinery  |   | 1.4   | 1.6                                  | 1.8                                       |
| Agitators for semiliquids; Brick machinery (except pug mills); Conveyor belt: ore, coal, sand; Line shafts; Machine tools: grinder, shaper, boring mill, milling machines; Pumps: centrifugal, gear, rotary  |   | 1.5   | 1.7                                  | 1.9                                       |
| Conveyor: apron, pan, bucket, elevator; Extractors, washers; Fans, blowers; centrifugal, induced draft exhausters; Generators & exciters; Hoists, elevators; Rubber calenders, mills, extruders; Saw mill, Textile machinery inc. looms, spinning frames, twisters |   | 1.6   | 1.8                                  | 2.0                                       |
| Centrifuges; Conveyors: flight, screw; Hammer mills; Paper pulpers   |   | 1.7   | 1.9                                  | 2.1                                       |
| Brick & clay pug mills; Fans, blowers, propeller mine fans, positive blowers   |   | 1.8   | 2.0                                  | 2.2                                       |
| Driving Units  | <i>AC Motors:</i> High Torque, High Slip, Repulsion-Induction, Single Phase Series Wound and Slip Ring.<br><i>DC Motors:</i> Series Wound and Compound Wound. <i>Engines:</i> Single Cylinder Internal Combustion.<br><i>Line Shafts. Clutches.</i> |   |                                      |   |
| Types of Driven Machines   |   | Intermittent Service<br>(3–5 hours daily or seasonal) | Normal Service<br>(8–10 hours daily) | Continuous Service<br>(16–24 hours daily) |
| Display, Dispensing, Projection, Medical equipment; Instrumentation; Measuring devices   |   | 1.2   | 1.4                                  | 1.6                                       |
| Appliances, sweepers, sewing machines; Office equipment; Wood lathes, band saws  |   | 1.4   | 1.6                                  | 1.8                                       |
| Conveyors: belt, light package, oven, screens, drums, conical  |   | 1.5   | 1.7                                  | 1.9                                       |
| Agitators for liquids; Dough mixers; Drill presses, lathes; Screw machines, jointers; Circular saws, planes; Laundry, Paper, Printing machinery  |   | 1.6   | 1.8                                  | 2.0                                       |
| Agitators for semiliquids; Brick machinery (except pug mills); Conveyor belt: ore, coal, sand; Line shafts; Machine tools: grinder, shaper, boring mill, milling machines; Pumps: centrifugal, gear, rotary  |   | 1.7   | 1.9                                  | 2.1                                       |
| Conveyor: apron, pan, bucket, elevator; Extractors, washers; Fans, blowers; centrifugal, induced draft exhausters; Generators & exciters; Hoists, elevators; Rubber calenders, mills, extruders; Saw mill, Textile machinery inc. looms, spinning frames, twisters |   | 1.8   | 2.0                                  | 2.2                                       |
| Centrifuges; Conveyors: flight, screw; Hammer mills; Paper pulpers   |   | 1.9   | 2.1                                  | 2.3                                       |
| Brick & clay pug mills; Fans, blowers, propeller mine fans, positive blowers   |   | 2.0   | 2.2                                  | 2.4                                       |

Synchronous belts will not slip, and therefore must be belted for the highest loadings anticipated in the system. A minimum service factor of 2.0 is recommended for equipment subject to chocking.

**Pitch Lengths:** Standard belt pitch lengths, belt length designations, and numbers of teeth are shown in [Table 42](#). Belt length tolerances are also given in this table; these tolerances apply to all belt sections and represent the total manufacturing tolerance on belt length.

**Nominal Tooth Dimensions:** [Table 40](#) shows the nominal tooth dimensions for each of the standard belt sections. Tooth dimensions for single- and double-sided belts are identical.

SYNCHRONOUS BELTS

**Table 40. Synchronous Belt Nominal Tooth and Section Dimensions**  
ANSI/RMA IP-24, 1983

| Belt Section (Pitch) | Tooth Angle | Single-Sided Belts |       |       |       |       |       | Double-Sided Belts |       |       |       |       |       |      |       |
|----------------------|-------------|--------------------|-------|-------|-------|-------|-------|--------------------|-------|-------|-------|-------|-------|------|-------|
|                      |             | $h_t$              | $b_t$ | $r_a$ | $r_r$ | $h_s$ | $h_d$ | $h_t$              | $b_t$ | $r_a$ | $r_r$ | $h_s$ | $h_d$ |      |       |
| MXL (0.080)          | 40          | 0.020              | 0.045 | 0.005 | 0.005 | 0.045 | ...   | XXH (1.250)        | 40    | 0.375 | 0.750 | 0.060 | 0.090 | 0.62 | ...   |
| XL (0.200)           | 50          | 0.050              | 0.101 | 0.015 | 0.015 | 0.090 | ...   | DXL (0.200)        | 50    | 0.050 | 0.101 | 0.015 | 0.015 | ...  | 0.120 |
| L (0.375)            | 40          | 0.075              | 0.183 | 0.020 | 0.020 | 0.14  | ...   | DL (0.375)         | 40    | 0.075 | 0.183 | 0.020 | 0.020 | ...  | 0.180 |
| H (0.500)            | 40          | 0.090              | 0.241 | 0.040 | 0.040 | 0.16  | ...   | DH (0.500)         | 40    | 0.090 | 0.241 | 0.040 | 0.040 | ...  | 0.234 |
| XH (0.875)           | 40          | 0.250              | 0.495 | 0.047 | 0.062 | 0.44  | ...   |                    |       |       |       |       |       |      |       |

All dimensions in inches.

**Table 41. Synchronous Belt Standard Pulley and Flange Dimensions**  
ANSI/RMA IP-24, 1983

| Belt Section | Standard Nominal Pulley Width | Standard Pulley Width Designation | Minimum Pulley Width |                  | Flange          |                           |
|--------------|-------------------------------|-----------------------------------|----------------------|------------------|-----------------|---------------------------|
|              |                               |                                   | Flanged $b_f$        | Unflanged $b'_f$ | Thickness (min) | Height <sup>a</sup> (min) |
| MXL          | 0.25                          | 025                               | 0.28                 | 0.35             | 0.023           | 0.020                     |
| XL           | 0.38                          | 037                               | 0.41                 | 0.48             | 0.029           | 0.040                     |
| L            | 0.50                          | 050                               | 0.55                 | 0.67             | 0.050           | 0.065                     |
|              | 0.75                          | 075                               | 0.80                 | 0.92             |                 |                           |
|              | 1.00                          | 100                               | 1.05                 | 1.17             |                 |                           |
| H            | 1.00                          | 100                               | 1.05                 | 1.23             | 0.050           | 0.080                     |
|              | 1.50                          | 150                               | 1.55                 | 1.73             |                 |                           |
|              | 2.00                          | 200                               | 2.08                 | 2.26             |                 |                           |
|              | 3.00                          | 300                               | 3.11                 | 3.29             |                 |                           |
| XH           | 2.00                          | 200                               | 2.23                 | 2.46             | 0.098           | 0.190                     |
|              | 3.00                          | 300                               | 3.30                 | 3.50             |                 |                           |
|              | 4.00                          | 400                               | 4.36                 | 4.59             |                 |                           |
| XXH          | 2.00                          | 200                               | 2.23                 | 2.52             | 0.127           | 0.245                     |
|              | 3.00                          | 300                               | 3.30                 | 3.59             |                 |                           |
|              | 4.00                          | 400                               | 4.36                 | 4.65             |                 |                           |
|              | 5.00                          | 500                               | 5.42                 | 5.72             |                 |                           |

**Table 42. Synchronous Belt Standard Pitch Lengths and Tolerances ANSI/RMA IP-24, 1983**

| Belt Length Designation | Pitch Length | Permissible Deviation From Standard Length | Number of Teeth for Standard Lengths |            |           |           |            |             | Belt Length Designation | Pitch Length | Permissible Deviation From Standard Length | Number of Teeth for Standard Lengths |            |           |           |            |             |  |
|-------------------------|--------------|--|--------------------------------------|------------|-----------|-----------|------------|-------------|-------------------------|--------------|--|--------------------------------------|------------|-----------|-----------|------------|-------------|--|
|                         |              |  | MXL (0.080)                          | XL (0.200) | L (0.375) | H (0.500) | XH (0.875) | XXH (1.250) |                         |              |  | MXL (0.080)                          | XL (0.200) | L (0.375) | H (0.500) | XH (0.875) | XXH (1.250) |  |
| 36                      | 3.600        | ±0.016                                     | 45                                   |            |           |           |            |             | 230                     | 23.000       | ±0.024                                     | ...                                  | 115        | ...       | ...       | ...        |             |  |
| 40                      | 4.000        | ±0.016                                     | 50                                   |            |           |           |            |             | 240                     | 24.000       | ±0.024                                     | ...                                  | 120        | 64        | 48        |            |             |  |
| 44                      | 4.400        | ±0.016                                     | 55                                   |            |           |           |            |             | 250                     | 25.000       | ±0.024                                     | ...                                  | 125        | ...       | ...       |            |             |  |
| 48                      | 4.800        | ±0.016                                     | 60                                   |            |           |           |            |             | 255                     | 25.500       | ±0.024                                     | ...                                  | ...        | 68        | ...       |            |             |  |
| 56                      | 5.600        | ±0.016                                     | 70                                   |            |           |           |            |             | 260                     | 26.000       | ±0.024                                     | ...                                  | 130        | ...       | ...       |            |             |  |
| 60                      | 6.000        | ±0.016                                     | 75                                   | 30         |           |           |            |             | 270                     | 27.000       | ±0.024                                     | ...                                  | ...        | 72        | 54        |            |             |  |
| 64                      | 6.400        | ±0.016                                     | 80                                   | ...        |           |           |            |             | 285                     | 28.500       | ±0.024                                     | ...                                  | ...        | 76        | ...       |            |             |  |
| 70                      | 7.000        | ±0.016                                     | ...                                  | 35         |           |           |            |             | 300                     | 30.000       | ±0.024                                     | ...                                  | ...        | 80        | 60        |            |             |  |
| 72                      | 7.200        | ±0.016                                     | 90                                   | ...        |           |           |            |             | 322                     | 32.250       | ±0.026                                     | ...                                  | ...        | 86        | ...       |            |             |  |
| 80                      | 8.000        | ±0.016                                     | 100                                  | 40         |           |           |            |             | 330                     | 33.000       | ±0.026                                     | ...                                  | ...        | ...       | 66        |            |             |  |
| 88                      | 8.800        | ±0.016                                     | 110                                  | ...        |           |           |            |             | 345                     | 34.500       | ±0.026                                     |                                      |            | 92        | ...       |            |             |  |
| 90                      | 9.000        | ±0.016                                     | ...                                  | 45         |           |           |            |             | 360                     | 36.000       | ±0.026                                     |                                      |            | ...       | 72        |            |             |  |
| 100                     | 10.000       | ±0.016                                     | 125                                  | 50         |           |           |            |             | 367                     | 36.750       | ±0.026                                     |                                      |            | 98        | ...       |            |             |  |
| 110                     | 11.000       | ±0.018                                     | ...                                  | 55         |           |           |            |             | 390                     | 39.000       | ±0.026                                     |                                      |            | 104       | 78        |            |             |  |
| 112                     | 11.200       | ±0.018                                     | 140                                  | ...        |           |           |            |             | 420                     | 42.000       | ±0.030                                     |                                      |            | 112       | 84        |            |             |  |
| 120                     | 12.000       | ±0.018                                     | ...                                  | 60         | ...       |           |            |             | 450                     | 45.000       | ±0.030                                     |                                      |            | 120       | 90        | ...        |             |  |
| 124                     | 12.375       | ±0.018                                     | ...                                  | ...        | 33        |           |            |             | 480                     | 48.000       | ±0.030                                     |                                      |            | 128       | 96        | ...        |             |  |
| 124                     | 12.400       | ±0.018                                     | 155                                  | ...        | ...       |           |            |             | 507                     | 50.750       | ±0.032                                     |                                      |            | ...       | ...       | 58         |             |  |
| 130                     | 13.000       | ±0.018                                     | ...                                  | 65         | ...       |           |            |             | 510                     | 51.000       | ±0.032                                     |                                      |            | 136       | 102       | ...        |             |  |
| 140                     | 14.000       | ±0.018                                     | 175                                  | 70         | ...       |           |            |             | 540                     | 54.000       | ±0.032                                     |                                      |            | 144       | 108       | ...        |             |  |
| 150                     | 15.000       | ±0.018                                     | ...                                  | 75         | 40        |           |            |             | 560                     | 56.000       | ±0.032                                     |                                      |            | ...       | ...       | 64         |             |  |
| 160                     | 16.000       | ±0.020                                     | 200                                  | 80         | ...       |           |            |             | 570                     | 57.000       | ±0.032                                     |                                      |            | ...       | 114       | ...        |             |  |
| 170                     | 17.000       | ±0.020                                     | ...                                  | 85         | ...       |           |            |             | 600                     | 60.000       | ±0.032                                     |                                      |            | 160       | 120       | ...        |             |  |
| 180                     | 18.000       | ±0.020                                     | 225                                  | 90         | ...       |           |            |             | 630                     | 63.000       | ±0.034                                     |                                      |            | ...       | 126       | 72         |             |  |
| 187                     | 18.750       | ±0.020                                     | ...                                  | ...        | 50        |           |            |             | 660                     | 66.000       | ±0.034                                     |                                      |            | ...       | 132       | ...        |             |  |
| 190                     | 19.000       | ±0.020                                     | ...                                  | 95         | ...       |           |            |             | 700                     | 70.000       | ±0.034                                     |                                      |            |           | 140       | 80         | 56          |  |
| 200                     | 20.000       | ±0.020                                     | 250                                  | 100        | ...       |           |            |             | 750                     | 75.000       | ±0.036                                     |                                      |            |           | 150       | ...        | ...         |  |
| 210                     | 21.000       | ±0.024                                     | ...                                  | 105        | 56        |           |            |             | 770                     | 77.000       | ±0.036                                     |                                      |            |           | ...       | 88         | ...         |  |
| 220                     | 22.000       | ±0.024                                     | ...                                  | 110        | ...       |           |            |             | 800                     | 80.000       | ±0.036                                     |                                      |            |           | 160       | ...        | 64          |  |
| 225                     | 22.500       | ±0.024                                     | ...                                  | ...        | 60        |           |            |             | 840                     | 84.000       | ±0.038                                     |                                      |            |           | ...       | 96         | ...         |  |

All dimensions in inches.



**Table 43. Synchronous Belt Standard Widths and Tolerances**  
ANSI/RMA IP-24, 1983

| Belt Section | Standard Belt Widths |            | Tolerances on Width for Belt Pitch Lengths |  |                |
|--------------|----------------------|------------|--|--|----------------|
|              | Designation          | Dimensions | Up to and including 33 in.                 | Over 33 in. up to and including 66 in. | Over 66 in.    |
| MXL (0.080)  | 012                  | 0.12       | +0.02<br>-0.03                             | ...                                    | ...            |
|              | 019                  | 0.19       |  |  |                |
|              | 025                  | 0.25       |  |  |                |
| XL (0.200)   | 025                  | 0.25       | +0.02<br>-0.03                             | ...                                    | ...            |
|              | 037                  | 0.38       |  |  |                |
| L (0.375)    | 050                  | 0.50       | +0.03<br>-0.03                             | +0.03<br>-0.05                         | ...            |
|              | 075                  | 0.75       |  |  |                |
|              | 100                  | 1.00       |  |  |                |
| H (0.500)    | 075                  | 0.75       | +0.03<br>-0.03                             | +0.03<br>-0.05                         | +0.03<br>-0.05 |
|              | 100                  | 1.00       |  |  |                |
|              | 150                  | 1.50       |  |  |                |
|              | 200                  | 2.00       | +0.03<br>-0.05                             | +0.05<br>-0.05                         | +0.05<br>-0.06 |
|              | 300                  | 3.00       |  |  |                |
| XH (0.875)   | 200                  | 2.00       | ...  | +0.19<br>-0.19                         | +0.19<br>-0.19 |
|              | 300                  | 3.00       |  |  |                |
|              | 400                  | 4.00       |  |  |                |
| XXH (1.250)  | 200                  | 2.00       | ...  | ...                                    | +0.19<br>-0.19 |
|              | 300                  | 3.00       |  |  |                |
|              | 400                  | 4.00       |  |  |                |
|              | 500                  | 5.00       |  |  |                |

*Widths.*: Standard belt widths, width designations, and width tolerances are shown in Table 43.

*Length Determination.*: The pitch length of a synchronous belt is determined by placing the belt on a measuring fixture having two pulleys of equal diameter, a method of applying force, and a means of measuring the center distance between the two pulleys. The position of one of the two pulleys is fixed and the other is movable along a graduated scale.

*Synchronous Belt Pulley Diameters:* Table 44 lists the standard pulley diameters by belt section (pitch). Fig. 13 defines the pitch, pitch diameter, outside diameter and pitch line differential.

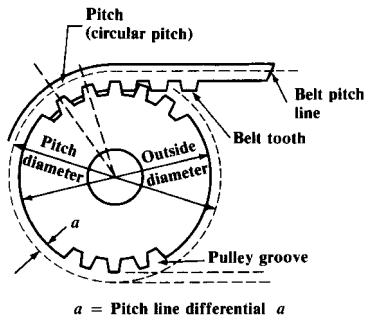


Fig. 13. Synchronous Belt Pulley Dimensions

**Table 44. Synchronous Belt Standard Pulley Diameters ANSI/RMA IP-24, 1983**

| Number of Grooves | Belt Section |         |            |         |                    |         |                    |         |            |         |             |         |
|-------------------|--------------|---------|------------|---------|--------------------|---------|--------------------|---------|------------|---------|-------------|---------|
|                   | MXL (0.080)  |         | XL (0.200) |         | L (0.375)          |         | H (0.500)          |         | XH (0.875) |         | XXH (1.250) |         |
|                   | Diameters    |         | Diameters  |         | Diameters          |         | Diameters          |         | Diameters  |         | Diameters   |         |
|                   | Pitch        | Outside | Pitch      | Outside | Pitch              | Outside | Pitch              | Outside | Pitch      | Outside | Pitch       | Outside |
| 10                | 0.255        | 0.235   | 0.637      | 0.617   | 1.194 <sup>a</sup> | 1.164   | ...                | ...     | ...        | ...     | ...         | ...     |
| 12                | 0.306        | 0.286   | 0.764      | 0.744   | 1.432 <sup>a</sup> | 1.402   | ...                | ...     | ...        | ...     | ...         | ...     |
| 14                | 0.357        | 0.337   | 0.891      | 0.871   | 1.671              | 1.641   | 2.228 <sup>a</sup> | 2.174   | ...        | ...     | ...         | ...     |
| 16                | 0.407        | 0.387   | 1.019      | 0.999   | 1.910              | 1.880   | 2.546              | 2.492   | ...        | ...     | ...         | ...     |
| 18                | 0.458        | 0.438   | 1.146      | 1.126   | 2.149              | 2.119   | 2.865              | 2.811   | 5.013      | 4.903   | 7.162       | 7.042   |
| 20                | 0.509        | 0.489   | 1.273      | 1.253   | 2.387              | 2.357   | 3.183              | 3.129   | 5.570      | 5.460   | 7.958       | 7.838   |
| 22                | 0.560        | 0.540   | 1.401      | 1.381   | 2.626              | 2.596   | 3.501              | 3.447   | 6.127      | 6.017   | 8.754       | 8.634   |
| 24                | 0.611        | 0.591   | 1.528      | 1.508   | 2.865              | 2.835   | 3.820              | 3.766   | 6.685      | 6.575   | 9.549       | 9.429   |
| 26                | 0.662        | 0.642   | ...        | ...     | 3.104              | 3.074   | 4.138              | 4.084   | 7.242      | 7.132   | 10.345      | 10.225  |
| 28                | 0.713        | 0.693   | 1.783      | 1.763   | 3.342              | 3.312   | 4.456              | 4.402   | 7.799      | 7.689   | ...         | ...     |
| 30                | 0.764        | 0.744   | 1.910      | 1.890   | 3.581              | 3.551   | 4.775              | 4.721   | 8.356      | 8.246   | 11.937      | 11.817  |
| 32                | 0.815        | 0.795   | 2.037      | 2.017   | 3.820              | 3.790   | 5.093              | 5.039   | 8.913      | 8.803   | ...         | ...     |
| 34                | 0.866        | 0.846   | ...        | ...     | ...                | ...     | ...                | ...     | ...        | ...     | 13.528      | 13.408  |
| 36                | 0.917        | 0.897   | 2.292      | 2.272   | 4.297              | 4.267   | 5.730              | 5.676   | ...        | ...     | ...         | ...     |
| 40                | 1.019        | 0.999   | 2.546      | 2.526   | 4.775              | 4.745   | 6.366              | 6.312   | 11.141     | 11.031  | 15.915      | 15.795  |
| 42                | 1.070        | 1.050   | 2.674      | 2.654   | ...                | ...     | ...                | ...     | ...        | ...     | ...         | ...     |
| 44                | 1.120        | 1.100   | 2.801      | 2.781   | 5.252              | 5.222   | 7.003              | 6.949   | ...        | ...     | ...         | ...     |
| 48                | 1.222        | 1.202   | 3.056      | 3.036   | 5.730              | 5.700   | 7.639              | 7.585   | 13.369     | 13.259  | 19.099      | 18.979  |
| 60                | 1.528        | 1.508   | 3.820      | 3.800   | 7.162              | 7.132   | 9.549              | 9.495   | 16.711     | 16.601  | 23.873      | 23.753  |
| 72                | 1.833        | 1.813   | 4.584      | 4.564   | 8.594              | 8.564   | 11.459             | 11.405  | 20.054     | 19.944  | 28.648      | 28.528  |
| 84                | ...          | ...     | ...        | ...     | 10.027             | 9.997   | 13.369             | 13.315  | 23.396     | 23.286  | ...         | ...     |
| 90                | ...          | ...     | ...        | ...     | ...                | ...     | ...                | ...     | ...        | ...     | 35.810      | 35.690  |
| 96                | ...          | ...     | ...        | ...     | ...                | ...     | 15.279             | 15.225  | 26.738     | 26.628  | ...         | ...     |
| 120               | ...          | ...     | ...        | ...     | ...                | ...     | 19.099             | 19.045  | 33.423     | 33.313  | ...         | ...     |

All dimensions in inches.

\* Usually not available in all widths — consult supplier.

**Widths:** Standard pulley widths for each belt section are shown in Table 41. The nominal pulley width is specified in terms of the maximum standard belt width the pulley will accommodate. The minimum pulley width, whether flanged or unflanged, is also shown in Table 41, along with flange dimensions and various pulley tolerances.

**Pulley Size Designation:** Synchronous belt pulleys are designated by the number of grooves, the belt section, and a number representing 100 times the nominal width. For example, a 30 groove L section pulley with a nominal width of 0.75 in. would be designated by 30L075. Pulley tolerances are shown in Table 45.

**Table 45. Pulley Tolerances (All Sections)**

| Outside Diameter Range   | Outside Diameter Tolerance | Pitch to Pitch Tolerance   |                              |
|--|----------------------------|--|------------------------------|
|  |                            | Adjacent Grooves   | Accumulative Over 90 Degrees |
| Up thru 1.000  | +0.002<br>-0.000           | ±0.001   | ±0.003                       |
| Over 1.000 to and including 2.000  | +0.003<br>-0.000           | ±0.001   | ±0.004                       |
| Over 2.000 to and including 4.000  | +0.004<br>-0.000           | ±0.001   | ±0.005                       |
| Over 4.000 to and including 7.000  | +0.005<br>-0.000           | ±0.001   | ±0.005                       |
| Over 7.000 to and including 12.000   | +0.006<br>-0.000           | ±0.001   | ±0.006                       |
| Over 12.000 to and including 20.000  | +0.007<br>-0.000           | ±0.001   | ±0.007                       |
| Over 20.000  | +0.008<br>-0.000           | ±0.001   | ±0.008                       |
| Radial Runout <sup>a</sup>   |                            | Axial Runout <sup>b</sup>  |                              |
| For outside diameters 8.0 in. and under 0.005 in.<br>For each additional inch of outside diameter add 0.0005 in. |                            | For outside diameters 1.0 in. and under 0.001 in.<br>For each additional inch of outside diameter up through 10.0 in., add 0.001 in.<br>For each additional inch of outside diameter over 10.0 in., add 0.0005 in. |                              |

<sup>a</sup> Flange outside diameter equals pulley outside diameter plus twice flange height.

<sup>b</sup> Total indicator reading.

All dimensions in inches.

**Cross Section Selection:** The chart (Fig. 14) may be used as a guide to the selection of a synchronous belt for any combination of design horsepower and speed of the faster shaft. When the intersection of the design horsepower and speed of the faster shaft falls near a line between two areas on the chart, the possibilities in both areas should be explored. Special circumstances (such as space limitations) may result in selection of a belt cross section different from that indicated in the chart. Belt manufacturers should be contacted for specific data.

**Torque Ratings:** It is customary to use torque load requirements rather than horsepower load when designing drives using the small pitch MXL section belts. These belts operate on small diameters resulting in relatively low belt speeds, so torque is essentially constant for all rpm. The torque rating formulas for MXL sections are:

$$Q_r = d[1.13 - 1.38 \times 10^{-3} d^2] \text{ for belt width} = 0.12 \text{ in.}$$

$$Q_r = d[1.88 - 2.30 \times 10^{-3} d^2] \text{ for belt width} = 0.19 \text{ in.}$$

$$Q_r = d[2.63 - 3.21 \times 10^{-3} d^2] \text{ for belt width} = 0.25 \text{ in.}$$

where  $Q_r$  = the maximum torque rating (lbf-in.) for a belt of specified width having six or more teeth in mesh and a pulley surface speed of 6500 fpm or less. Torque ratings for drives with less than six teeth in mesh must be corrected as shown in Table 46.  $d$  = pitch diameter of smaller pulley, inch.

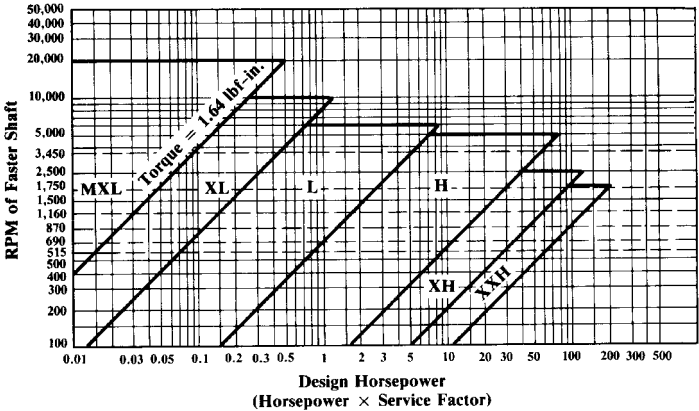


Fig. 14. Selection of Synchronous Belt Cross Section

Table 46. Teeth in Mesh Factor

| Teeth in Mesh | Factor $K_z$ | Teeth in Mesh | Factor $K_z$ |
|---------------|--------------|---------------|--------------|
| 6 or more     | 1.00         | 3             | 0.40         |
| 5             | 0.80         | 2             | 0.20         |
| 4             | 0.60         |               |              |

**Horsepower Rating Formulas:** The horsepower rating formulas for synchronous belts, other than the MLX section, are determined from the following formulas, where the number in parentheses is the belt width in inches.

$$XL(0.38)HP = dr[0.0916 - 7.07 \times 10^{-5}(dr)^2]$$

$$L(1.00)HP = dr[0.436 - 3.01 \times 10^{-4}(dr)^2]$$

$$H(3.00)HP = dr[3.73 - 1.41 \times 10^{-3}(dr)^2]$$

$$XH(4.00)HP = dr[7.21 - 4.68 \times 10^{-3}(dr)^2]$$

$$XXH(5.00)HP = dr[11.4 - 7.81 \times 10^{-3}(dr)^2]$$

where HP = the maximum horsepower rating recommended for the specified standard belt width having six or more teeth in mesh and a pulley surface speed of 6500 fpm or less. Horsepower ratings for drives with less than six teeth in mesh must be corrected as shown in Table 46.  $d$  = pitch diameter of smaller pulley, in.  $r$  = rpm of faster shaft divided by 1000. Total horsepower ratings are the same for double-sided as for single-sided belts. Contact manufacturers for percentage of horsepower available for each side of the belt.

**Finding the Required Belt Width:** The belt width should not exceed the small pulley diameter or excessive side thrust will result.

**Torque Rating Method (MXL Section):** Divide the design torque by the teeth in mesh factor to obtain the corrected design torque. Compare the corrected design torque with the torque rating given in Table 47 for the pulley diameter being considered. Select the narrowest belt width that has a torque rating equal to or greater than the corrected design torque.

**Table 47. Torque Rating for MXL Section (0.080 in. Pitch)**

| Belt Width, (in.) | Rated Torque (lbf-in.) for Small Pulley (Number of Grooves and Pitch Diameter, in.) |                |                |                |                |                |                |                |                |                |
|-------------------|---|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
|                   | 10MXL<br>0.255  | 12MXL<br>0.306 | 14MXL<br>0.357 | 16MXL<br>0.407 | 18MXL<br>0.458 | 20MXL<br>0.509 | 22MXL<br>0.560 | 24MXL<br>0.611 | 28MXL<br>0.713 | 30MXL<br>0.764 |
| 0.12              | 0.29  | 0.35           | 0.40           | 0.46           | 0.52           | 0.57           | 0.63           | 0.69           | 0.81           | 0.86           |
| 0.19              | 0.48  | 0.58           | 0.67           | 0.77           | 0.86           | 0.96           | 1.05           | 1.15           | 1.34           | 1.44           |
| 0.25              | 0.67  | 0.80           | 0.94           | 1.07           | 1.20           | 1.34           | 1.47           | 1.61           | 1.87           | 2.01           |

**Horsepower Rating Method (XL, L, H, XH, and XXH Sections):** Multiply the horsepower rating for the widest standard belt of the selected section by the teeth in mesh factor to obtain the corrected horsepower rating. Divide the design horsepower by the corrected horsepower rating to obtain the required belt width factor. Compare the required belt width factor with those shown in [Table 48](#). Select the narrowest belt width that has a width factor equal to or greater than the required belt width factor.

**Table 48. Belt Width Factor**

| Belt Section | Belt Width (in.) |      |      |      |      |      |      |      |      |      |      |      |
|--------------|------------------|------|------|------|------|------|------|------|------|------|------|------|
|              | 0.12             | 0.19 | 0.25 | 0.38 | 0.50 | 0.75 | 1.00 | 1.50 | 2.00 | 3.00 | 4.00 | 5.00 |
| MXL (0.080)  | 0.43             | 0.73 | 1.00 | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
| XL (0.200)   | ...              | ...  | 0.62 | 1.00 | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...  |
| L (0.375)    | ...              | ...  | ...  | ...  | 0.45 | 0.72 | 1.00 | ...  | ...  | ...  | ...  | ...  |
| H (0.500)    | ...              | ...  | ...  | ...  | ...  | 0.21 | 0.29 | 0.45 | 0.63 | 1.00 | ...  | ...  |
| XH (0.875)   | ...              | ...  | ...  | ...  | ...  | ...  | ...  | ...  | 0.45 | 0.72 | 1.00 | ...  |
| XXH (1.250)  | ...              | ...  | ...  | ...  | ...  | ...  | ...  | ...  | 0.35 | 0.56 | 0.78 | 1.00 |

**Drive Selection:** Information on design and selection of synchronous belt drives is available in engineering manuals published by belt manufacturers. Manufacturers should be consulted on such matters as preferred stock sizes, desirable speeds, center distances, etc.

**Minimum Pulley Size:** The recommended minimum pulley size depends on the rpm of the faster shaft. Minimum sheave diameters for each cross-section belt are listed in [Table 44](#).

**Selection of Flanged Pulleys:** To determine when to use flanged pulleys, consider the following conditions:

1) On all two-pulley drives, the minimum flanging requirements are two flanges on one pulley, or one flange on each pulley on opposite sides.

2) On drives where the center distance is more than eight times the diameter of the small pulley, both pulleys should be flanged on both sides.

3) On vertical shaft drives, one pulley should be flanged on both sides and other pulleys in the system should be flanged on the bottom side only.

4) On drives with more than two pulleys, the minimum flanging requirements are two flanges on every other pulley, or one flange on every pulley, alternating sides around the system.

**Service Factors:** Service factors for synchronous belts in [Table 39](#).

## TRANSMISSION CHAINS

### Types of Chains

In addition to the standard roller and inverted tooth types, a wide variety of drive chains of different construction is available. Such chains are manufactured to various degrees of precision ranging from unfinished castings or forgings to chains having certain machined parts. Practically all of these chains as well as standard roller chains can be equipped with attachments to fit them for conveyor use. A few such types are briefly described in the following paragraphs. Detailed information about them can be obtained from the manufacturers.

**Types of Chains.**—*Detachable Chains:* The links of this type of chain, which are identical, are easily detachable. Each has a hook-shaped end in which the bar of the adjacent link articulates. These chains are available in malleable iron or pressed steel. The chief advantage is the ease with which any link can be removed.

*Cast Roller Chains:* Cast roller chains are constructed, wholly or partly, of cast metal parts and are available in various styles. In general the rollers and side bars are accurately made castings without machine finish. The links are usually connected by means of forged pins secured by nuts or cotters. Such chains are used for slow speeds and moderate loads, or where the precision of standard roller chains is not required.

*Pintle Chains:* Unlike the roller chain, the pintle chain is composed of hollow-cored cylinders cast or forged integrally with two offset side bars and each link identical. The links are joined by pins inserted in holes in the ends of the side bars and through the cored holes in the adjacent links. Lugs prevent turning of the pins in the side bars ensuring articulation of the chain between the pin and the cored cylinder.

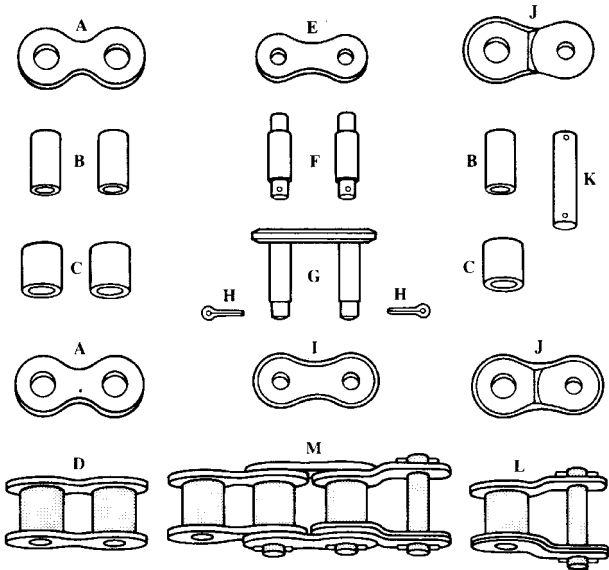
### Standard Roller Transmission Chains

A roller chain is made up of two kinds of links: roller links and pin links alternately spaced throughout the length of the chain as shown in [Table 1](#).

Roller chains are manufactured in several types, each designed for the particular service required. All roller chains are so constructed that the rollers are evenly spaced throughout the chain. The outstanding advantage of this type of chain is the ability of the rollers to rotate when contacting the teeth of the sprocket. Two arrangements of roller chains are in common use: the single-strand type and the multiple-strand type. In the latter type, two or more chains are joined side by side by means of common pins which maintain the alignment of the rollers in the different strands.

**Types of Roller Chains.**—*Standard roller chains* are manufactured to the specifications in the American National Standard for precision power transmission roller chains, attachments, and sprockets ANSI/ASME B29.1M-1993 and, where indicated, the data in the subsequent tables have been taken from this standard. These roller chains and sprockets are commonly used for the transmission of power in industrial machinery, machine tools, motor trucks, motorcycles, tractors, and similar applications. In tabulating the dimensional information in ANSI/ASME B29.1M, customary inch-pound units were used. Metric (SI) units are given in separate tabulations in the Standard.

*Nonstandard roller chains*, developed individually by various manufacturers prior to the adoption of the ANSI standard, are similar in form and construction to standard roller chains but do not conform dimensionally to standard chains. Some sizes are still available from the originating manufacturers for replacement on existing equipment. They are not recommended for new installations, since their manufacture is being discontinued as rapidly as possible.

**Table 1. ANSI Nomenclature for Roller Chain Parts** ANSI/ASME B29.1M-1993

*Roller Link D.* — An inside link consisting of two inside plates, two bushings, and two rollers.

*Pin Link G and E.* — An outside link consisting of two pin-link plates assembled with two pins.

*Inside Plate A.* — One of the plates forming the tension members of a roller link.

*Pin Link Plate E.* — One of the plates forming the tension members of a pin link.

*Pin F.* — A stud articulating within a bushing of an inside link and secured at its ends by the pin-link plates.

*Bushing B.* — A cylindrical bearing in which the pin turns.

*Roller C.* — A ring or thimble which turns over a bushing.

*Assembled Pins G.* — Two pins assembled with one pin-link plate.

*Connecting-Link G and I.* — A pin link having one side plate detachable.

*Connecting-Link Plate I.* — The detachable pin-link plate belonging to a connecting link. It is retained by cotter pins or by a one-piece spring clip (not shown).

*Connecting Link Assembly M.* — A unit designed to connect two roller links.

*Offset Link L.* — A link consisting of two offset plates assembled with a bushing and roller at one end and an offset link pin at the other.

*Offset Plate J.* — One of the plates forming the tension members of the offset link.

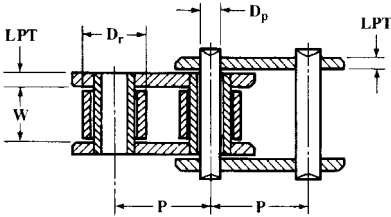
*Offset Link Pin K.* — A pin used in offset links.

*Standard double-pitch roller chains* are like standard roller chains, except that their link plates have twice the pitch of the corresponding standard-pitch chain. Their design conforms to specifications in the ANSI Standard for double-pitch power transmission roller chains and sprockets ANSI/ASME B29.3M-1994. They are especially useful for low speeds, moderate loads, or long center distances.

## Transmission Roller Chain

**Standard Roller Chain Nomenclature, Dimensions and Loads.**—Standard nomenclature for roller chain parts are given in Table 1. Dimensions for Standard Series roller chain are given in Table 2.

Table 2. ANSI Roller Chain Dimensions ASME/ANSI B29.1M-1986



| Pitch<br>$P$ | Max. Roller Diameter<br>$D_r$ | Standard Series    |              |                       |                                   |                                     | Heavy Series                      |
|--------------|-------------------------------|--------------------|--------------|-----------------------|-----------------------------------|-------------------------------------|-----------------------------------|
|              |                               | Standard Chain No. | Width<br>$W$ | Pin Diameter<br>$D_p$ | Thickness of Link Plates<br>$LPT$ | Measuring Load, <sup>†</sup><br>Lb. | Thickness of Link Plates<br>$LPT$ |
| 0.250        | <sup>a</sup> 0.130            | 25                 | 0.125        | 0.0905                | 0.030                             | 18                                  | ...                               |
| 0.375        | <sup>a</sup> 0.200            | 35                 | 0.188        | 0.141                 | 0.050                             | 18                                  | ...                               |
| 0.500        | 0.306                         | 41                 | 0.250        | 0.141                 | 0.050                             | 18                                  | ...                               |
| 0.500        | 0.312                         | 40                 | 0.312        | 0.156                 | 0.060                             | 31                                  | ...                               |
| 0.625        | 0.400                         | 50                 | 0.375        | 0.200                 | 0.080                             | 49                                  | ...                               |
| 0.750        | 0.469                         | 60                 | 0.500        | 0.234                 | 0.094                             | 70                                  | 0.125                             |
| 1.000        | 0.625                         | 80                 | 0.625        | 0.312                 | 0.125                             | 125                                 | 0.156                             |
| 1.250        | 0.750                         | 100                | 0.750        | 0.375                 | 0.156                             | 195                                 | 0.187                             |
| 1.500        | 0.875                         | 120                | 1.000        | 0.437                 | 0.187                             | 281                                 | 0.219                             |
| 1.750        | 1.000                         | 140                | 1.000        | 0.500                 | 0.219                             | 383                                 | 0.250                             |
| 2.000        | 1.125                         | 160                | 1.250        | 0.562                 | 0.250                             | 500                                 | 0.281                             |
| 2.250        | 1.406                         | 180                | 1.406        | 0.687                 | 0.281                             | 633                                 | 0.312                             |
| 2.500        | 1.562                         | 200                | 1.500        | 0.781                 | 0.312                             | 781                                 | 0.375                             |
| 3.000        | 1.875                         | 240                | 1.875        | 0.937                 | 0.375                             | 1000                                | 0.500                             |

<sup>a</sup> Bushing diameter. This size chain has no rollers.

All dimensions are in inches.

Roller Diameters  $D_r$  are approximately  $\frac{5}{8}P$ .

The width  $W$  is defined as the distance between the link plates. It is approximately  $\frac{5}{8}$  of the chain pitch.

Pin Diameters  $D_p$  are approximately  $\frac{5}{16}P$  or  $\frac{1}{2}$  of the roller diameter.

Thickness  $LPT$  of Inside and Outside Link Plates for the standard series is approximately  $\frac{1}{8}P$ .

Thickness of Link Plates for the heavy series of any pitch is approximately that of the next larger pitch Standard Series chain.

Maximum Height of Roller Link Plates =  $0.95P$ .

Maximum Height of Pin Link Plates =  $0.82P$ .

Maximum Pin Diameter = nominal pin diameter + 0.0005 inch.

Minimum Hole in Bushing = nominal pin diameter + 0.0015 inch.

Maximum Width of Roller Link = nominal width of chain +  $(2.12 \times \text{nominal link plate thickness.})$

Minimum Distance between Pin Link Plates = maximum width of roller link + 0.002 inch.



**Chain Pitch:** Distance in inches between centers of adjacent joint members. Other dimensions are proportional to the pitch.

**Tolerances for Chain Length:** New chains, under standard measuring load, must not be underlength. Overlength tolerance is  $0.001/(\text{pitch in inches})^2 + 0.015$  inch per foot. Length measurements are to be taken over a length of at least 12 inches.

**Measuring Load:** The load in pounds under which a chain should be measured for length. It is equal to one per cent of the ultimate tensile strength, with a minimum of 18 pounds and a maximum of 1000 pounds for both single and multiple-strand chain.

**Minimum Ultimate Tensile Strength:** For single-strand chain, equal to or greater than  $12,500 \times (\text{pitch in inches})^2$  pounds. The minimum tensile strength or breaking strength of a multiple-strand chain is equal to that of a single-strand chain multiplied by the number of strands. Minimum ultimate tensile strength is indicative only of the tensile strength quality of the chain, not the maximum load that can be applied.

**Standard Roller Chain Numbers.**—The right-hand figure in the chain number is zero for roller chains of the usual proportions, 1 for a lightweight chain, and 5 for a rollerless bushing chain. The numbers to the left of the right-hand figure denote the number of  $\frac{1}{8}$  inches in the pitch. The letter *H* following the chain number denotes the heavy series; thus the number 80 *H* denotes a 1-inch pitch heavy chain. The hyphenated number 2 suffixed to the chain number denotes a double strand, 3 a triple strand, 4 a quadruple strand chain and so on.

**Heavy Series:** These chains, made in  $\frac{3}{4}$ -inch and larger pitches, have thicker link plates than those of the regular standard. Their value is only in the acceptance of higher loads at lower speeds.

**Light-weight Machinery Chain:** This chain is designated as No. 41. It is  $\frac{1}{2}$  inch pitch;  $\frac{1}{4}$  inch wide; has 0.306-inch diameter rollers and a 0.141-inch pin diameter. The minimum ultimate tensile strength is 1500 pounds.

**Multiple-strand Chain:** This is essentially an assembly of two or more single-strand chains placed side by side with pins that extend through the entire width to maintain alignment of the different strands.

**Types of Sprockets.**—Four different designs or types of roller-chain sprockets are shown by the sectional views, Fig. 1. Type *A* is a plain plate; type *B* has a hub on one side only; type *C*, a hub on both sides; and type *D*, a detachable hub. Also used are shear pin and slip clutch sprockets designed to prevent damage to the drive or to other equipment caused by overloads or stalling.

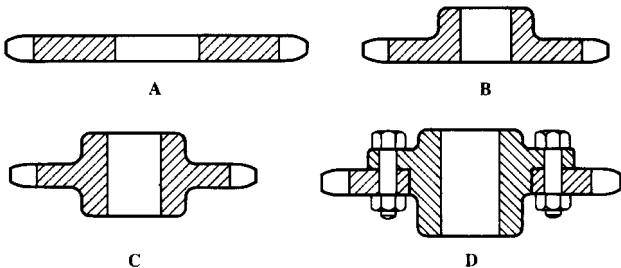
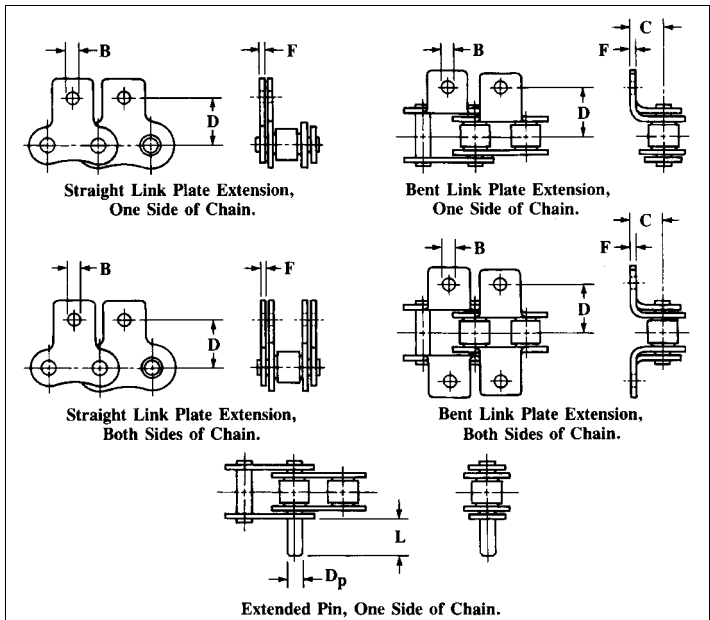


Fig. 1. Types of Sprockets

**Attachments.**—Modifications to standard chain components to adapt the chain for use in conveying, elevating, and timing operations are known as "attachments." The components commonly modified are: 1) the link plates, which are provided with extended lugs which may be straight or bent; and 2) the chain pins, which are extended in length so as to project substantially beyond the outer surface of the pin link plates.

Hole diameters, thicknesses, hole locations and offset dimensions for straight link and bent link plate extensions and lengths and diameters of extended pins are given in Table 3.

**Table 3. Straight and Bent Link Plate Extensions and Extended Pin Dimensions**  
ANSI/ASME B29.1M-1993



| Chain No. | Straight Link Plate Extension |          |          | Bent Link Plate Extension |          |          |          | Extended Pin                 |          |
|-----------|-------------------------------|----------|----------|---------------------------|----------|----------|----------|------------------------------|----------|
|           | <i>B</i> min.                 | <i>D</i> | <i>F</i> | <i>B</i> min.             | <i>C</i> | <i>D</i> | <i>F</i> | <i>D<sub>p</sub></i> Nominal | <i>L</i> |
| 35        | 0.102                         | 0.375    | 0.050    | 0.102                     | 0.250    | 0.375    | 0.050    | 0.141                        | 0.375    |
| 40        | 0.131                         | 0.500    | 0.060    | 0.131                     | 0.312    | 0.500    | 0.060    | 0.156                        | 0.375    |
| 50        | 0.200                         | 0.625    | 0.080    | 0.200                     | 0.406    | 0.625    | 0.080    | 0.200                        | 0.469    |
| 60        | 0.200                         | 0.719    | 0.094    | 0.200                     | 0.469    | 0.750    | 0.094    | 0.234                        | 0.562    |
| 80        | 0.261                         | 0.969    | 0.125    | 0.261                     | 0.625    | 1.000    | 0.125    | 0.312                        | 0.750    |
| 100       | 0.323                         | 1.250    | 0.156    | 0.323                     | 0.781    | 1.250    | 0.156    | 0.375                        | 0.938    |
| 120       | 0.386                         | 1.438    | 0.188    | 0.386                     | 0.906    | 1.500    | 0.188    | 0.437                        | 1.125    |
| 140       | 0.448                         | 1.750    | 0.219    | 0.448                     | 1.125    | 1.750    | 0.219    | 0.500                        | 1.312    |
| 160       | 0.516                         | 2.000    | 0.250    | 0.516                     | 1.250    | 2.000    | 0.250    | 0.562                        | 1.500    |
| 200       | 0.641                         | 2.500    | 0.312    | 0.641                     | 1.688    | 2.500    | 0.312    | 0.781                        | 1.875    |

All dimensions are in inches.

**Sprocket Classes.**—The American National Standard ANSI/ASME B29.1M-1993 provides for two classes of sprockets designated as Commercial and Precision. The selection of either is a matter of drive application judgment. The usual moderate to slow speed commercial drive is adequately served by Commercial sprockets. Where extreme high speed in combination with high load is involved, or where the drive involves fixed centers, critical timing, or register problems, or close clearance with outside interference, then the use of Precision sprockets may be more appropriate.

As a general guide, drives requiring Type A or Type B lubrication (see page 2463) would be served by Commercial sprockets. Drives requiring Type C lubrication may require Precision sprockets; the manufacturer should be consulted.

**Keys, Keyways, and Set Screws.**—To secure sprockets to the shaft, both keys and set screws should be used. The key is used to prevent rotation of the sprocket on the shaft. Keys should be fitted carefully in the shaft and sprocket keyways to eliminate all backlash, especially on the fluctuating loads. A set screw should be located over a flat key to secure it against longitudinal displacement.

Where a set screw is to be used with a parallel key, the following sizes are recommended by the American Chain Association. For a sprocket bore and shaft diameter in the range of

$\frac{1}{2}$  through  $\frac{7}{8}$  inch, a  $\frac{1}{4}$ -inch set screw

$\frac{15}{16}$  through  $1\frac{3}{4}$  inches, a  $\frac{3}{8}$ -inch set screw

$1\frac{13}{16}$  through  $2\frac{1}{4}$  inches, a  $\frac{1}{2}$ -inch set screw

$2\frac{5}{16}$  through  $3\frac{1}{4}$  inches, a  $\frac{5}{8}$ -inch set screw

$3\frac{3}{8}$  through  $4\frac{1}{2}$  inches, a  $\frac{3}{4}$ -inch set screw

$4\frac{3}{4}$  through  $5\frac{1}{2}$  inches, a  $\frac{7}{8}$ -inch set screw

$5\frac{3}{4}$  through  $7\frac{3}{8}$  inches, a 1-inch set screw

$7\frac{1}{2}$  through  $12\frac{1}{2}$  inches, a  $1\frac{1}{4}$ -inch set screw

**Sprocket Diameters.**—The various diameters of roller chain sprockets are shown in Fig. 2. These are defined as follows.

*Pitch Diameter:* The pitch diameter is the diameter of the pitch circle that passes through the centers of the link pins as the chain is wrapped on the sprocket.

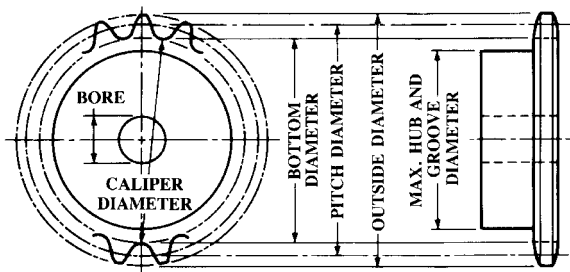


Fig. 2. Sprocket Diameters

Because the chain pitch is measured on a straight line between the centers of adjacent pins, the chain pitch lines form a series of chords of the sprocket pitch circle. Sprocket pitch diameters for one-inch pitch and for 9 to 108 teeth are given in Table 4. For lower (5 to 8) or higher (109 to 200) numbers of teeth use the following formula in which  $P$  = pitch,  $N$  = number of teeth: Pitch Diameter =  $P \div \sin(180^\circ \div N)$ .

**Table 4. ANSI Roller Chain Sprocket Diameters ANSI/ASME B29.1M-1993**

These diameters and caliper factors apply only to chain of 1-inch pitch. For any other pitch, multiply the values given below by the pitch.

Caliper Dia. (even teeth) = Pitch Diameter – Roller Dia.

Caliper Dia. (odd teeth) = Caliper factor × Pitch – Roller Dia.

See Table 5 for tolerances on Caliper Diameters.

| No. Teeth <sup>a</sup> | Pitch Diameter | Outside Diameter |                 | Caliper Factor | No. Teeth <sup>a</sup> | Pitch Diameter | Outside Diameter |                 | Caliper Factor |
|------------------------|----------------|------------------|-----------------|----------------|------------------------|----------------|------------------|-----------------|----------------|
|                        |                | Turned           | Topping Hob Cut |                |                        |                | Turned           | Topping Hob Cut |                |
| 9                      | 2.9238         | 3.348            | 3.364           | 2.8794         | 59                     | 18.7892        | 19.363           | 19.361          | 18.7825        |
| 10                     | 3.2361         | 3.678            | 3.676           |                | 60                     | 19.1073        | 19.681           | 19.680          |                |
| 11                     | 3.5495         | 4.006            | 3.990           | 3.5133         | 61                     | 19.4255        | 20.000           | 19.998          | 19.4190        |
| 12                     | 3.8637         | 4.332            | 4.352           |                | 62                     | 19.7437        | 20.318           | 20.316          |                |
| 13                     | 4.1786         | 4.657            | 4.666           | 4.1481         | 63                     | 20.0618        | 20.637           | 20.634          | 20.0556        |
| 14                     | 4.4940         | 4.981            | 4.982           |                | 64                     | 20.3800        | 20.956           | 20.952          |                |
| 15                     | 4.8097         | 5.304            | 5.298           | 4.7834         | 65                     | 20.6982        | 21.274           | 21.270          | 20.6921        |
| 16                     | 5.1258         | 5.627            | 5.614           |                | 66                     | 21.0164        | 21.593           | 21.588          |                |
| 17                     | 5.4422         | 5.949            | 5.930           | 5.4190         | 67                     | 21.3346        | 21.911           | 21.907          | 21.3287        |
| 18                     | 5.7588         | 6.271            | 6.292           |                | 68                     | 21.6528        | 22.230           | 22.225          |                |
| 19                     | 6.0755         | 6.593            | 6.609           | 6.0548         | 69                     | 21.9710        | 22.548           | 22.543          | 21.9653        |
| 20                     | 6.3924         | 6.914            | 6.926           |                | 70                     | 22.2892        | 22.867           | 22.861          |                |
| 21                     | 6.7095         | 7.235            | 7.243           | 6.6907         | 71                     | 22.6074        | 23.185           | 23.179          | 22.6018        |
| 22                     | 7.0267         | 7.555            | 7.560           |                | 72                     | 22.9256        | 23.504           | 23.498          |                |
| 23                     | 7.3439         | 7.876            | 7.877           | 7.3268         | 73                     | 23.2438        | 23.822           | 23.816          | 7.32384        |
| 24                     | 7.6613         | 8.196            | 8.195           |                | 74                     | 23.5620        | 24.141           | 24.134          |                |
| 25                     | 7.9787         | 8.516            | 8.512           | 7.9630         | 75                     | 23.8802        | 24.459           | 24.452          | 23.8750        |
| 26                     | 8.2962         | 8.836            | 8.829           |                | 76                     | 24.1984        | 24.778           | 24.770          |                |
| 27                     | 8.6138         | 9.156            | 9.147           | 8.5992         | 77                     | 24.5166        | 25.096           | 25.089          | 24.5116        |
| 28                     | 8.9314         | 9.475            | 9.465           |                | 78                     | 24.8349        | 25.415           | 25.407          |                |
| 29                     | 9.2491         | 9.795            | 9.782           | 9.2355         | 79                     | 25.1531        | 25.733           | 25.725          | 25.1481        |
| 30                     | 9.5668         | 10.114           | 10.100          |                | 80                     | 25.4713        | 26.052           | 26.043          |                |
| 31                     | 9.8845         | 10.434           | 10.418          | 9.8718         | 81                     | 25.7896        | 26.370           | 26.362          | 25.7847        |
| 32                     | 10.2023        | 10.753           | 10.736          |                | 82                     | 26.1078        | 26.689           | 26.680          |                |
| 33                     | 10.5201        | 11.073           | 11.053          | 10.5082        | 83                     | 26.4260        | 27.007           | 26.998          | 26.4213        |
| 34                     | 10.8379        | 11.392           | 11.371          |                | 84                     | 26.7443        | 27.326           | 27.316          |                |
| 35                     | 11.1558        | 11.711           | 11.728          | 11.1446        | 85                     | 27.0625        | 27.644           | 27.635          | 27.0579        |
| 36                     | 11.4737        | 12.030           | 12.046          |                | 86                     | 27.3807        | 27.962           | 27.953          |                |
| 37                     | 11.7916        | 12.349           | 12.364          | 11.7810        | 87                     | 27.6990        | 28.281           | 28.271          | 27.6945        |
| 38                     | 12.1095        | 12.668           | 12.682          |                | 88                     | 28.0172        | 28.599           | 28.589          |                |
| 39                     | 12.4275        | 12.987           | 13.000          | 12.4174        | 89                     | 28.3354        | 28.918           | 28.907          | 28.3310        |
| 40                     | 12.7455        | 13.306           | 13.318          |                | 90                     | 28.6537        | 29.236           | 29.226          |                |
| 41                     | 13.0635        | 13.625           | 13.636          | 13.0539        | 91                     | 28.9719        | 29.555           | 29.544          | 28.9676        |
| 42                     | 13.3815        | 13.944           | 13.954          |                | 92                     | 29.2902        | 29.873           | 29.862          |                |
| 43                     | 13.6995        | 14.263           | 14.272          | 13.6904        | 93                     | 29.6084        | 30.192           | 30.180          | 29.6042        |
| 44                     | 14.0175        | 14.582           | 14.590          |                | 94                     | 29.9267        | 30.510           | 30.499          |                |
| 45                     | 14.3355        | 14.901           | 14.908          | 14.3269        | 95                     | 30.2449        | 30.828           | 30.817          | 30.2408        |
| 46                     | 14.6535        | 15.219           | 15.226          |                | 96                     | 30.5632        | 31.147           | 31.135          |                |
| 47                     | 14.9717        | 15.538           | 15.544          | 14.9634        | 97                     | 30.8815        | 31.465           | 31.454          | 30.8774        |
| 48                     | 15.2898        | 15.857           | 15.862          |                | 98                     | 31.1997        | 31.784           | 31.772          |                |
| 49                     | 15.6079        | 16.176           | 16.180          | 15.5999        | 99                     | 31.5180        | 32.102           | 32.090          | 31.5140        |
| 50                     | 15.9260        | 16.495           | 16.498          |                | 100                    | 31.8362        | 32.421           | 32.408          |                |
| 51                     | 16.2441        | 16.813           | 16.816          | 16.2364        | 101                    | 32.1545        | 32.739           | 32.727          | 32.1506        |
| 52                     | 16.5622        | 17.132           | 17.134          |                | 102                    | 32.4727        | 33.057           | 33.045          |                |
| 53                     | 16.8803        | 17.451           | 17.452          | 16.8729        | 103                    | 32.7910        | 33.376           | 33.363          | 32.7872        |
| 54                     | 17.1984        | 17.769           | 17.770          |                | 104                    | 33.1093        | 33.694           | 33.681          |                |
| 55                     | 17.5165        | 18.088           | 18.089          | 17.5094        | 105                    | 33.4275        | 34.013           | 34.000          | 33.4238        |
| 56                     | 17.8347        | 18.407           | 18.407          |                | 106                    | 33.7458        | 34.331           | 34.318          |                |
| 57                     | 18.1528        | 18.725           | 18.725          | 18.1459        | 107                    | 34.0641        | 34.649           | 34.636          | 34.0604        |
| 58                     | 18.4710        | 19.044           | 19.043          |                | 108                    | 34.3823        | 34.968           | 34.954          |                |

<sup>a</sup> For 5 – 8 and 109–200 teeth see text, pages 2446, 2448.

**Bottom Diameter:** The bottom diameter is the diameter of a circle tangent to the curve (called the seating curve) at the bottom of the tooth gap. It equals the pitch diameter minus the diameter of the roller.

**Caliper Diameter:** The caliper diameter is the same as the bottom diameter for a sprocket with an even number of teeth. For a sprocket with an odd number of teeth, it is defined as the distance from the bottom of one tooth gap to that of the nearest opposite tooth gap. The caliper diameter for an even tooth sprocket is equal to pitch diameter–roller diameter. The caliper diameter for an odd tooth sprocket is equal to caliper factor–roller diameter. Here, the caliper factor =  $PD[\cos(90^\circ \div N)]$ , where  $PD$  = pitch diameter and  $N$  = number of teeth. Caliper factors for 1-in. pitch and sprockets having 9–108 teeth are given in Table 4. For other tooth numbers use above formula. Caliper diameter tolerances are minus only and are equal to  $0.002P\sqrt{N} + 0.006$  inch for the Commercial sprockets and  $0.001P\sqrt{N} + 0.003$  inch for Precision sprockets. Tolerances are given in Table 5.

**Table 5. Minus Tolerances on the Caliper Diameters of Precision Sprockets**  
ANSI/ASME B29.1M-1993

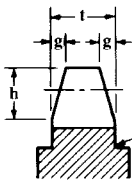
| Pitch | Number of Teeth |        |         |         |        |
|-------|-----------------|--------|---------|---------|--------|
|       | Up to 15        | 16–24  | 25–35   | 36–48   | 49–63  |
| 0.250 | 0.004           | 0.004  | 0.004   | 0.005   | 0.005  |
| 0.375 | 0.004           | 0.004  | 0.004   | 0.005   | 0.005  |
| 0.500 | 0.004           | 0.005  | 0.0055  | 0.006   | 0.0065 |
| 0.625 | 0.005           | 0.0055 | 0.006   | 0.007   | 0.008  |
| 0.750 | 0.005           | 0.006  | 0.007   | 0.008   | 0.009  |
| 1.000 | 0.006           | 0.007  | 0.008   | 0.009   | 0.010  |
| 1.250 | 0.007           | 0.008  | 0.009   | 0.010   | 0.012  |
| 1.500 | 0.007           | 0.009  | 0.0105  | 0.012   | 0.013  |
| 1.750 | 0.008           | 0.010  | 0.012   | 0.013   | 0.015  |
| 2.000 | 0.009           | 0.011  | 0.013   | 0.015   | 0.017  |
| 2.250 | 0.010           | 0.012  | 0.014   | 0.016   | 0.018  |
| 2.500 | 0.010           | 0.013  | 0.015   | 0.018   | 0.020  |
| 3.000 | 0.012           | 0.015  | 0.018   | 0.021   | 0.024  |
| Pitch | Number of Teeth |        |         |         |        |
|       | 64–80           | 81–99  | 100–120 | 121–143 | 144 up |
| 0.250 | 0.005           | 0.005  | 0.006   | 0.006   | 0.006  |
| 0.375 | 0.006           | 0.006  | 0.006   | 0.007   | 0.007  |
| 0.500 | 0.007           | 0.0075 | 0.008   | 0.0085  | 0.009  |
| 0.625 | 0.009           | 0.009  | 0.009   | 0.010   | 0.011  |
| 0.750 | 0.010           | 0.010  | 0.011   | 0.012   | 0.013  |
| 1.000 | 0.011           | 0.012  | 0.013   | 0.014   | 0.015  |
| 1.250 | 0.013           | 0.014  | 0.016   | 0.017   | 0.018  |
| 1.500 | 0.015           | 0.016  | 0.018   | 0.019   | 0.021  |
| 1.750 | 0.017           | 0.019  | 0.020   | 0.022   | 0.024  |
| 2.000 | 0.019           | 0.021  | 0.023   | 0.025   | 0.027  |
| 2.250 | 0.021           | 0.023  | 0.025   | 0.028   | 0.030  |
| 2.500 | 0.023           | 0.025  | 0.028   | 0.030   | 0.033  |
| 3.000 | 0.027           | 0.030  | 0.033   | 0.036   | 0.039  |

Minus tolerances for Commercial sprockets are twice those shown in this table.

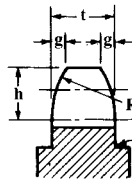
**Outside Diameter:** OD is the diameter over the tips of teeth. Sprocket ODs for 1-in. pitch and 9–108 teeth are given in Table 4. For other tooth numbers the OD may be determined by the following formulas in which  $O$  = approximate OD;  $P$  = pitch of chain;  $N$  = number of sprocket teeth:  $O = P[0.6 + \cot(180^\circ \div N)]$ , for turned sprocket;  $O$  = pitch diameter – roller diameter +  $2 \times$  whole depth of topping hob cut, for topping hob cut sprocket.\*

**Table 6. American National Standard Roller Chain Sprocket Flange Thickness and Tooth Section Profile Dimension ANSI/ASME B29.1M-1993**

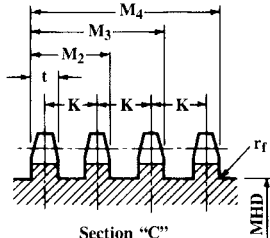
Flange chamfer may be either as in Section "A" or Section "B" or anything in between.



**Section "A"**



**Section "B"**



**Section "C"**

| Sprocket Flange Thickness |                   |                                      |                 |              |                      |           |                          |                      |                                    |           |
|---------------------------|-------------------|--------------------------------------|-----------------|--------------|----------------------|-----------|--------------------------|----------------------|------------------------------------|-----------|
| Std. Chain No.            | Width of Chain, W | Maximum Sprocket Flange Thickness, t |                 |              | Minus Tolerance on t |           | Tolerance on M           |                      | Max. Variation of t on Each Flange |           |
|                           |                   | Single                               | Double & Triple | Quad. & Over | Commercial           | Precision | Commercial Plus or Minus | Precision Minus Only | Commercial                         | Precision |
| 25                        | 0.125             | 0.110                                | 0.106           | 0.096        | 0.021                | 0.007     | 0.007                    | 0.007                | 0.021                              | 0.004     |
| 35                        | 0.188             | 0.169                                | 0.163           | 0.150        | 0.027                | 0.008     | 0.008                    | 0.008                | 0.027                              | 0.004     |
| 41                        | 0.250             | 0.226                                | ...             | ...          | 0.032                | 0.009     | ...                      | ...                  | 0.032                              | 0.004     |
| 40                        | 0.312             | 0.284                                | 0.275           | 0.256        | 0.035                | 0.009     | 0.009                    | 0.009                | 0.035                              | 0.004     |
| 50                        | 0.375             | 0.343                                | 0.332           | 0.310        | 0.036                | 0.010     | 0.010                    | 0.010                | 0.036                              | 0.005     |
| 60                        | 0.500             | 0.459                                | 0.444           | 0.418        | 0.036                | 0.011     | 0.011                    | 0.011                | 0.036                              | 0.006     |
| 80                        | 0.625             | 0.575                                | 0.556           | 0.526        | 0.040                | 0.012     | 0.012                    | 0.012                | 0.040                              | 0.006     |
| 100                       | 0.750             | 0.692                                | 0.669           | 0.633        | 0.046                | 0.014     | 0.014                    | 0.014                | 0.046                              | 0.007     |
| 120                       | 1.000             | 0.924                                | 0.894           | 0.848        | 0.057                | 0.016     | 0.016                    | 0.016                | 0.057                              | 0.008     |
| 140                       | 1.000             | 0.924                                | 0.894           | 0.848        | 0.057                | 0.016     | 0.016                    | 0.016                | 0.057                              | 0.008     |
| 160                       | 1.250             | 1.156                                | 1.119           | 1.063        | 0.062                | 0.018     | 0.018                    | 0.018                | 0.062                              | 0.009     |
| 180                       | 1.406             | 1.302                                | 1.259           | 1.198        | 0.068                | 0.020     | 0.020                    | 0.020                | 0.068                              | 0.010     |
| 200                       | 1.500             | 1.389                                | 1.344           | 1.278        | 0.072                | 0.021     | 0.021                    | 0.021                | 0.072                              | 0.010     |
| 240                       | 1.875             | 1.738                                | 1.682           | 1.602        | 0.087                | 0.025     | 0.025                    | 0.025                | 0.087                              | 0.012     |

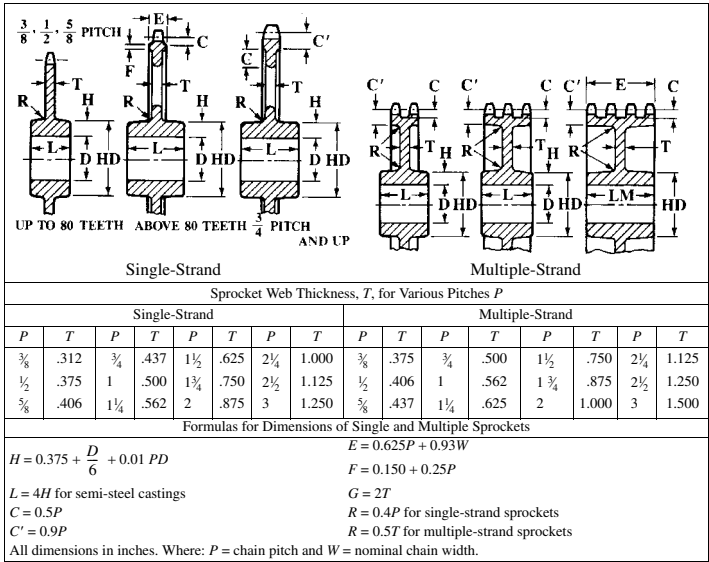
| Sprocket Tooth Section Profile Dimensions |               |                    |                    |                   |                    |              |
|---|---------------|--------------------|--------------------|-------------------|--------------------|--------------|
| Std. Chain No.                            | Chain Pitch P | Depth of Chamfer h | Width of Chamfer g | Minimum Radius Rc | Transverse Pitch K |              |
|   |               |                    |                    |                   | Standard Series    | Heavy Series |
| 25  | 0.250         | 0.125              | 0.031              | 0.265             | 0.252              | ...          |
| 35  | 0.375         | 0.188              | 0.047              | 0.398             | 0.399              | ...          |
| 41  | 0.500         | 0.250              | 0.062              | 0.531             | ...                | ...          |
| 40  | 0.500         | 0.250              | 0.062              | 0.531             | 0.566              | ...          |
| 50  | 0.625         | 0.312              | 0.078              | 0.664             | 0.713              | ...          |
| 60  | 0.750         | 0.375              | 0.094              | 0.796             | 0.897              | 1.028        |
| 80  | 1.000         | 0.500              | 0.125              | 1.062             | 1.153              | 1.283        |
| 100                                       | 1.250         | 0.625              | 0.156              | 1.327             | 1.408              | 1.539        |
| 120                                       | 1.500         | 0.750              | 0.188              | 1.593             | 1.789              | 1.924        |
| 140                                       | 1.750         | 0.875              | 0.219              | 1.858             | 1.924              | 2.055        |
| 160                                       | 2.000         | 1.000              | 0.250              | 2.124             | 2.305              | 2.437        |
| 180                                       | 2.250         | 1.125              | 0.281              | 2.392             | 2.592              | 2.723        |
| 200                                       | 2.500         | 1.250              | 0.312              | 2.654             | 2.817              | 3.083        |
| 240                                       | 3.000         | 1.500              | 0.375              | 3.187             | 3.458              | 3.985        |

All dimensions are in inches.  $r_f \text{ max} = 0.04 P$  for max. hub diameter.

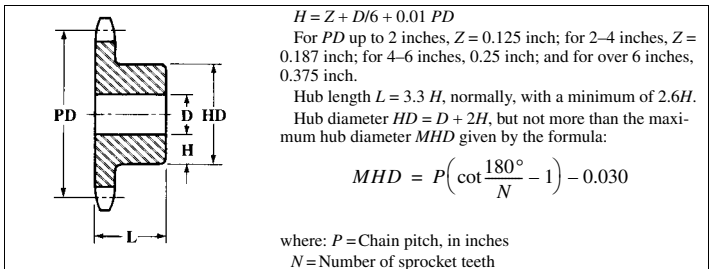
\*This dimension was added in 1984 as a desirable goal for the future. It should in no way obsolete existing tools or sprockets. The whole depth  $WD$  is found from the formula:  $WD = \frac{1}{2}D_r + P[0.3 - \frac{1}{2} \tan(90 \text{ deg} \div N_a)]$ , where  $N_a$  is the intermediate number of teeth for the topping hob. For teeth range 5,  $N_a = 5$ ; 6, 6; 7-8, 7.47; 9-11, 9.9; 12-17, 14.07; 18-34, 23.54; 35 and over, 56.

**Proportions of Sprockets.**—Typical proportions of single-strand and multiple-strand cast roller chain sprockets, as provided by the American Chain Association, are shown in Table 7. Typical proportions of roller chain bar-steel sprockets, also provided by this association, are shown in Table 8.

**Table 7. Typical Proportions of Single-Strand and Multiple-Strand Cast Roller Chain Sprockets**



**Table 8. Typical Proportions of Roller Chain Bar-steel Sprockets**



When sprocket wheels are designed with spokes, the usual assumptions made in order to determine suitable proportions are as follows: 1) That the maximum torque load acting on a sprocket is the chain tensile strength times the sprocket pitch radius; 2) That the torque load is equally divided between the arms by the rim; and 3) That each arm acts as a cantilever beam.

The arms are generally elliptical in cross section, the major axis twice the minor axis.

**Selection of Chain and Sprockets.**—The smallest applicable pitch of roller chain is desirable for quiet operation and high speed. The horsepower capacity varies with the chain pitch as shown in Table 9. However, short pitch with high working load can often be obtained by the use of multiple-strand chain.

The small sprocket selected must be large enough to accommodate the shaft. Table 10 gives maximum bore and hub diameters consistent with commercial practice for sprockets with up to 25 teeth.

After selecting the small sprocket, the number of teeth in the larger sprocket is determined by the desired ratio of the shaft speed. Overemphasis on the exactness in the speed ratio may result in a cumbersome and expensive installation. In most cases, satisfactory operation can be obtained with a minor change in speed of one or both shafts.

**Table 9. Horsepower Ratings for Roller Chain—1986**

|   |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
|---|--|------|------|------|------|------|------|--------|------|------|------|------|------|------|
| To properly use this table the following factors must be taken into consideration:  |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| 1) Service factors  |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| 2) Multiple Strand Factors  |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| 3) Lubrication  |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| Service Factors: See Table 15.  |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| Multiple Strand Factors: For two strands, the multiple strand factor is 1.7; for three strands, it is 2.5; and for four strands, it is 3.3.                           |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| Lubrication:  |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| Required type of lubrication is indicated at the bottom of each roller chain size section of the table. For a description of each type of lubrication, see page 2463. |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| Type A — Manual or Drip Lubrication   |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| Type B — Bath or Disc Lubrication   |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| Type C — Oil Stream Lubrication   |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| To find the required horsepower table rating, use the following formula:  |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| $\text{Required hp Table Rating} = \frac{\text{hp to be Transmitted} \times \text{Service Factor}}{\text{Multiple-Strand Factor}}$                                    |  |      |      |      |      |      |      |        |      |      |      |      |      |      |
| 1/2-inch Pitch Standard Single-Strand Roller Chain — No. 25   | Revolutions per Minute — Small Sprocket <sup>a</sup> |      |      |      |      |      |      |        |      |      |      |      |      |      |
|   |  | 50   | 100  | 300  | 500  | 700  | 900  | 1200   | 1500 | 1800 | 2100 | 2500 | 3000 | 3500 |
|   | Horsepower Rating                                    |      |      |      |      |      |      |        |      |      |      |      |      |      |
|   | 11   | 0.03 | 0.05 | 0.14 | 0.23 | 0.31 | 0.39 | 0.50   | 0.62 | 0.73 | 0.83 | 0.98 | 1.15 | 1.32 |
|   | 12   | 0.03 | 0.06 | 0.16 | 0.25 | 0.34 | 0.43 | 0.55   | 0.68 | 0.80 | 0.92 | 1.07 | 1.26 | 1.45 |
|   | 13   | 0.04 | 0.06 | 0.17 | 0.27 | 0.37 | 0.47 | 0.60   | 0.74 | 0.87 | 1.00 | 1.17 | 1.38 | 1.58 |
|   | 14   | 0.04 | 0.07 | 0.19 | 0.30 | 0.40 | 0.50 | 0.65   | 0.80 | 0.94 | 1.08 | 1.27 | 1.49 | 1.71 |
|   | 15   | 0.04 | 0.08 | 0.20 | 0.32 | 0.43 | 0.54 | 0.70   | 0.86 | 1.01 | 1.17 | 1.36 | 1.61 | 1.85 |
|   | 16   | 0.04 | 0.08 | 0.22 | 0.34 | 0.47 | 0.58 | 0.76   | 0.92 | 1.09 | 1.25 | 1.46 | 1.72 | 1.98 |
|   | 17   | 0.05 | 0.09 | 0.23 | 0.37 | 0.50 | 0.62 | 0.81   | 0.99 | 1.16 | 1.33 | 1.56 | 1.84 | 2.11 |
|   | 18   | 0.05 | 0.09 | 0.25 | 0.39 | 0.53 | 0.66 | 0.86   | 1.05 | 1.24 | 1.42 | 1.66 | 1.96 | 2.25 |
|   | 19   | 0.05 | 0.10 | 0.26 | 0.41 | 0.56 | 0.70 | 0.91   | 1.11 | 1.31 | 1.50 | 1.76 | 2.07 | 2.38 |
|   | 20   | 0.06 | 0.10 | 0.28 | 0.44 | 0.59 | 0.74 | 0.96   | 1.17 | 1.38 | 1.59 | 1.86 | 2.19 | 2.52 |
|   | 21   | 0.06 | 0.11 | 0.29 | 0.46 | 0.62 | 0.78 | 1.01   | 1.24 | 1.46 | 1.68 | 1.96 | 2.31 | 2.66 |
| 22  | 0.06   | 0.11 | 0.31 | 0.48 | 0.66 | 0.82 | 1.07 | 1.30   | 1.53 | 1.76 | 2.06 | 2.43 | 2.79 |      |
| 23  | 0.06   | 0.12 | 0.32 | 0.51 | 0.69 | 0.86 | 1.12 | 1.37   | 1.61 | 1.85 | 2.16 | 2.55 | 2.93 |      |
| 24  | 0.07   | 0.13 | 0.34 | 0.53 | 0.72 | 0.90 | 1.17 | 1.43   | 1.69 | 1.94 | 2.27 | 2.67 | 3.07 |      |
| 25  | 0.07   | 0.13 | 0.35 | 0.56 | 0.75 | 0.94 | 1.22 | 1.50   | 1.76 | 2.02 | 2.37 | 2.79 | 3.21 |      |
| 26  | 0.07   | 0.14 | 0.37 | 0.58 | 0.79 | 0.98 | 1.28 | 1.56   | 1.84 | 2.11 | 2.47 | 2.91 | 3.34 |      |
| 28  | 0.08   | 0.15 | 0.40 | 0.63 | 0.85 | 1.07 | 1.38 | 1.69   | 1.99 | 2.29 | 2.68 | 3.15 | 3.62 |      |
| 30  | 0.08   | 0.16 | 0.43 | 0.68 | 0.92 | 1.15 | 1.49 | 1.82   | 2.15 | 2.46 | 2.88 | 3.40 | 3.90 |      |
| 32  | 0.09   | 0.17 | 0.46 | 0.73 | 0.98 | 1.23 | 1.60 | 1.95   | 2.30 | 2.64 | 3.09 | 3.64 | 4.18 |      |
| 35  | 0.10   | 0.19 | 0.51 | 0.80 | 1.08 | 1.36 | 1.76 | 2.15   | 2.53 | 2.91 | 3.41 | 4.01 | 4.61 |      |
| 40  | 0.12   | 0.22 | 0.58 | 0.92 | 1.25 | 1.57 | 2.03 | 2.48   | 2.93 | 3.36 | 3.93 | 4.64 | 5.32 |      |
| 45  | 0.13   | 0.25 | 0.66 | 1.05 | 1.42 | 1.78 | 2.31 | 2.82   | 3.32 | 3.82 | 4.47 | 5.26 | 6.05 |      |
|   | Type A   |      |      |      |      |      |      | Type B |      |      |      |      |      |      |



**Table 9. (Continued) Horsepower Ratings for Roller Chain—1986**

|   | No. of Teeth Small Splt. | Revolutions per Minute — Small Sprocket <sup>a</sup> |      |      |        |      |      |      |      |      |        |      |      |      |
|---|--------------------------|--|------|------|--------|------|------|------|------|------|--------|------|------|------|
|   |                          | 50   | 100  | 300  | 500    | 700  | 900  | 1200 | 1500 | 1800 | 2100   | 2500 | 3000 | 3500 |
|   |                          | Horsepower Rating                                    |      |      |        |      |      |      |      |      |        |      |      |      |
| 3/8-inch Pitch Standard Single-Strand Roller Chain — No. 35 | 11                       | 0.10   | 0.18 | 0.49 | 0.77   | 1.05 | 1.31 | 1.70 | 2.08 | 2.45 | 2.82   | 3.30 | 2.94 | 2.33 |
|   | 12                       | 0.11   | 0.20 | 0.54 | 0.85   | 1.15 | 1.44 | 1.87 | 2.29 | 2.70 | 3.10   | 3.62 | 3.35 | 2.66 |
|   | 13                       | 0.12   | 0.22 | 0.59 | 0.93   | 1.26 | 1.57 | 2.04 | 2.49 | 2.94 | 3.38   | 3.95 | 3.77 | 3.00 |
|   | 14                       | 0.13   | 0.24 | 0.63 | 1.01   | 1.36 | 1.71 | 2.21 | 2.70 | 3.18 | 3.66   | 4.28 | 4.22 | 3.35 |
|   | 15                       | 0.14   | 0.25 | 0.68 | 1.08   | 1.47 | 1.84 | 2.38 | 2.91 | 3.43 | 3.94   | 4.61 | 4.68 | 3.71 |
|   | 16                       | 0.15   | 0.27 | 0.73 | 1.16   | 1.57 | 1.97 | 2.55 | 3.12 | 3.68 | 4.22   | 4.94 | 5.15 | 4.09 |
|   | 17                       | 0.16   | 0.29 | 0.78 | 1.24   | 1.68 | 2.10 | 2.73 | 3.33 | 3.93 | 4.51   | 5.28 | 5.64 | 4.48 |
|   | 18                       | 0.17   | 0.31 | 0.83 | 1.32   | 1.78 | 2.24 | 2.90 | 3.54 | 4.18 | 4.80   | 5.61 | 6.15 | 4.88 |
|   | 19                       | 0.18   | 0.33 | 0.88 | 1.40   | 1.89 | 2.37 | 3.07 | 3.76 | 4.43 | 5.09   | 5.95 | 6.67 | 5.29 |
|   | 20                       | 0.19   | 0.35 | 0.93 | 1.48   | 2.00 | 2.51 | 3.25 | 3.97 | 4.68 | 5.38   | 6.29 | 7.20 | 5.72 |
|   | 21                       | 0.20   | 0.37 | 0.98 | 1.56   | 2.11 | 2.64 | 3.42 | 4.19 | 4.93 | 5.67   | 6.63 | 7.75 | 6.15 |
|   | 22                       | 0.21   | 0.38 | 1.03 | 1.64   | 2.22 | 2.78 | 3.60 | 4.40 | 5.19 | 5.96   | 6.97 | 8.21 | 6.59 |
|   | 23                       | 0.22   | 0.40 | 1.08 | 1.72   | 2.33 | 2.92 | 3.78 | 4.62 | 5.44 | 6.25   | 7.31 | 8.62 | 7.05 |
|   | 24                       | 0.23   | 0.42 | 1.14 | 1.80   | 2.44 | 3.05 | 3.96 | 4.84 | 5.70 | 6.55   | 7.66 | 9.02 | 7.51 |
|   | 25                       | 0.24   | 0.44 | 1.19 | 1.88   | 2.55 | 3.19 | 4.13 | 5.05 | 5.95 | 6.84   | 8.00 | 9.43 | 7.99 |
|   | 26                       | 0.25   | 0.46 | 1.24 | 1.96   | 2.66 | 3.33 | 4.31 | 5.27 | 6.21 | 7.14   | 8.35 | 9.84 | 8.47 |
|   | 28                       | 0.27   | 0.50 | 1.34 | 2.12   | 2.88 | 3.61 | 4.67 | 5.71 | 6.73 | 7.73   | 9.05 | 10.7 | 9.47 |
|   | 30                       | 0.29   | 0.54 | 1.45 | 2.29   | 3.10 | 3.89 | 5.03 | 6.15 | 7.25 | 8.33   | 9.74 | 11.5 | 10.5 |
| 32  | 0.31                     | 0.58   | 1.55 | 2.45 | 3.32   | 4.17 | 5.40 | 6.60 | 7.77 | 8.93 | 10.4   | 12.3 | 11.6 |      |
| 35  | 0.34                     | 0.64   | 1.71 | 2.70 | 3.66   | 4.59 | 5.95 | 7.27 | 8.56 | 9.84 | 11.5   | 13.6 | 13.2 |      |
| 40  | 0.39                     | 0.73   | 1.97 | 3.12 | 4.23   | 5.30 | 6.87 | 8.40 | 9.89 | 11.4 | 13.3   | 15.7 | 16.2 |      |
| 45  | 0.45                     | 0.83   | 2.24 | 3.55 | 4.80   | 6.02 | 7.80 | 9.53 | 11.2 | 12.9 | 15.1   | 17.8 | 19.3 |      |
|   |                          | Type A   |      |      | Type B |      |      |      |      |      | Type C |      |      |      |
| 1/2-inch Pitch Standard Single-Strand Roller Chain — No. 40 |                          | Revolutions per Minute — Small Sprocket <sup>a</sup> |      |      |        |      |      |      |      |      |        |      |      |      |
|   |                          | 50   | 100  | 200  | 300    | 400  | 500  | 700  | 900  | 1000 | 1200   | 1400 | 1600 | 1800 |
|   |                          | Horsepower Rating                                    |      |      |        |      |      |      |      |      |        |      |      |      |
|   | 11                       | 0.23   | 0.43 | 0.80 | 1.16   | 1.50 | 1.83 | 2.48 | 3.11 | 3.42 | 4.03   | 4.63 | 5.22 | 4.66 |
|   | 12                       | 0.25   | 0.47 | 0.88 | 1.27   | 1.65 | 2.01 | 2.73 | 3.42 | 3.76 | 4.43   | 5.09 | 5.74 | 5.31 |
|   | 13                       | 0.28   | 0.52 | 0.96 | 1.39   | 1.80 | 2.20 | 2.97 | 3.73 | 4.10 | 4.83   | 5.55 | 6.26 | 5.99 |
|   | 14                       | 0.30   | 0.56 | 1.04 | 1.50   | 1.95 | 2.38 | 3.22 | 4.04 | 4.44 | 5.23   | 6.01 | 6.78 | 6.70 |
|   | 15                       | 0.32   | 0.60 | 1.12 | 1.62   | 2.10 | 2.56 | 3.47 | 4.35 | 4.78 | 5.64   | 6.47 | 7.30 | 7.43 |
|   | 16                       | 0.35   | 0.65 | 1.20 | 1.74   | 2.25 | 2.75 | 3.72 | 4.66 | 5.13 | 6.04   | 6.94 | 7.83 | 8.18 |
|   | 17                       | 0.37   | 0.69 | 1.29 | 1.85   | 2.40 | 2.93 | 3.97 | 4.98 | 5.48 | 6.45   | 7.41 | 8.36 | 8.96 |
|   | 18                       | 0.39   | 0.73 | 1.37 | 1.97   | 2.55 | 3.12 | 4.22 | 5.30 | 5.82 | 6.86   | 7.88 | 8.89 | 9.76 |
|   | 19                       | 0.42   | 0.78 | 1.45 | 2.09   | 2.71 | 3.31 | 4.48 | 5.62 | 6.17 | 7.27   | 8.36 | 9.42 | 10.5 |
|   | 20                       | 0.44   | 0.82 | 1.53 | 2.21   | 2.86 | 3.50 | 4.73 | 5.94 | 6.53 | 7.69   | 8.83 | 9.96 | 11.1 |
|   | 21                       | 0.46   | 0.87 | 1.62 | 2.33   | 3.02 | 3.69 | 4.99 | 6.26 | 6.88 | 8.11   | 9.31 | 10.5 | 11.7 |
|   | 22                       | 0.49   | 0.91 | 1.70 | 2.45   | 3.17 | 3.88 | 5.25 | 6.58 | 7.23 | 8.52   | 9.79 | 11.0 | 12.3 |
|   | 23                       | 0.51   | 0.96 | 1.78 | 2.57   | 3.33 | 4.07 | 5.51 | 6.90 | 7.59 | 8.94   | 10.3 | 11.6 | 12.9 |
|   | 24                       | 0.54   | 1.00 | 1.87 | 2.69   | 3.48 | 4.26 | 5.76 | 7.23 | 7.95 | 9.36   | 10.8 | 12.1 | 13.5 |
|   | 25                       | 0.56   | 1.05 | 1.95 | 2.81   | 3.64 | 4.45 | 6.02 | 7.55 | 8.30 | 9.78   | 11.2 | 12.7 | 14.1 |
| 26  | 0.58                     | 1.09   | 2.04 | 2.93 | 3.80   | 4.64 | 6.28 | 7.88 | 8.66 | 10.2 | 11.7   | 13.2 | 14.7 |      |
| 28  | 0.63                     | 1.18   | 2.20 | 3.18 | 4.11   | 5.03 | 6.81 | 8.54 | 9.39 | 11.1 | 12.7   | 14.3 | 15.9 |      |
| 30  | 0.68                     | 1.27   | 2.38 | 3.42 | 4.43   | 5.42 | 7.33 | 9.20 | 10.1 | 11.9 | 13.7   | 15.4 | 17.2 |      |
| 32  | 0.73                     | 1.36   | 2.55 | 3.67 | 4.75   | 5.81 | 7.86 | 9.86 | 10.8 | 12.8 | 14.7   | 16.5 | 18.4 |      |
| 35  | 0.81                     | 1.50   | 2.81 | 4.04 | 5.24   | 6.40 | 8.66 | 10.9 | 11.9 | 14.1 | 16.2   | 18.2 | 20.3 |      |
| 40  | 0.93                     | 1.74   | 3.24 | 4.67 | 6.05   | 7.39 | 10.0 | 12.5 | 13.8 | 16.3 | 18.7   | 21.1 | 23.4 |      |
| 45  | 1.06                     | 1.97   | 3.68 | 5.30 | 6.87   | 8.40 | 11.4 | 14.2 | 15.7 | 18.5 | 21.2   | 23.9 | 26.6 |      |
|   |                          | Type A   |      |      | Type B |      |      |      |      |      | Type C |      |      |      |

**Table 9. (Continued) Horsepower Ratings for Roller Chain—1986**

|   | No. of Teeth Small Spkt. | Revolutions per Minute — Small Sprocket <sup>a</sup> |      |      |      |        |      |      |      |      |        |      |      |      |
|---|--------------------------|--|------|------|------|--------|------|------|------|------|--------|------|------|------|
|   |                          | 10   | 25   | 50   | 100  | 200    | 300  | 400  | 500  | 700  | 900    | 1000 | 1200 | 1400 |
|   |                          | Horsepower Rating                                    |      |      |      |        |      |      |      |      |        |      |      |      |
| 1/2-inch Pitch Light Weight Machinery Roller Chain — No. 41 | 11                       | 0.03   | 0.07 | 0.13 | 0.24 | 0.44   | 0.64 | 0.82 | 1.01 | 1.37 | 1.71   | 1.88 | 1.71 | 1.36 |
|   | 12                       | 0.03   | 0.07 | 0.14 | 0.26 | 0.49   | 0.70 | 0.91 | 1.11 | 1.50 | 1.88   | 2.07 | 1.95 | 1.55 |
|   | 13                       | 0.04   | 0.08 | 0.15 | 0.28 | 0.53   | 0.76 | 0.99 | 1.21 | 1.63 | 2.05   | 2.25 | 2.20 | 1.75 |
|   | 14                       | 0.04   | 0.09 | 0.16 | 0.31 | 0.57   | 0.83 | 1.07 | 1.31 | 1.77 | 2.22   | 2.44 | 2.46 | 1.95 |
|   | 15                       | 0.04   | 0.09 | 0.18 | 0.33 | 0.62   | 0.89 | 1.15 | 1.41 | 1.91 | 2.39   | 2.63 | 2.73 | 2.17 |
|   | 16                       | 0.04   | 0.10 | 0.19 | 0.36 | 0.66   | 0.95 | 1.24 | 1.51 | 2.05 | 2.57   | 2.82 | 3.01 | 2.39 |
|   | 17                       | 0.05   | 0.11 | 0.20 | 0.38 | 0.71   | 1.02 | 1.32 | 1.61 | 2.18 | 2.74   | 3.01 | 3.29 | 2.61 |
|   | 18                       | 0.05   | 0.12 | 0.22 | 0.40 | 0.75   | 1.08 | 1.40 | 1.72 | 2.32 | 2.91   | 3.20 | 3.59 | 2.85 |
|   | 19                       | 0.05   | 0.12 | 0.23 | 0.43 | 0.80   | 1.15 | 1.49 | 1.82 | 2.46 | 3.09   | 3.40 | 3.89 | 3.09 |
|   | 20                       | 0.06   | 0.13 | 0.24 | 0.45 | 0.84   | 1.21 | 1.57 | 1.92 | 2.60 | 3.26   | 3.59 | 4.20 | 3.33 |
|   | 21                       | 0.06   | 0.14 | 0.26 | 0.48 | 0.89   | 1.28 | 1.66 | 2.03 | 2.74 | 3.44   | 3.78 | 4.46 | 3.59 |
|   | 22                       | 0.06   | 0.14 | 0.27 | 0.50 | 0.93   | 1.35 | 1.74 | 2.13 | 2.89 | 3.62   | 3.98 | 4.69 | 3.85 |
|   | 23                       | 0.06   | 0.15 | 0.28 | 0.53 | 0.98   | 1.41 | 1.83 | 2.24 | 3.03 | 3.80   | 4.17 | 4.92 | 4.11 |
|   | 24                       | 0.07   | 0.16 | 0.29 | 0.55 | 1.03   | 1.48 | 1.92 | 2.34 | 3.17 | 3.97   | 4.37 | 5.15 | 4.38 |
|   | 25                       | 0.07   | 0.17 | 0.31 | 0.57 | 1.07   | 1.55 | 2.00 | 2.45 | 3.31 | 4.15   | 4.57 | 5.38 | 4.66 |
|   | 26                       | 0.07   | 0.17 | 0.32 | 0.60 | 1.12   | 1.61 | 2.09 | 2.55 | 3.46 | 4.33   | 4.76 | 5.61 | 4.94 |
|   | 28                       | 0.08   | 0.19 | 0.35 | 0.65 | 1.21   | 1.75 | 2.26 | 2.77 | 3.74 | 4.69   | 5.16 | 6.08 | 5.52 |
|   | 30                       | 0.08   | 0.20 | 0.38 | 0.70 | 1.31   | 1.88 | 2.44 | 2.98 | 4.03 | 5.06   | 5.56 | 6.55 | 6.13 |
|   | 32                       | 0.09   | 0.22 | 0.40 | 0.75 | 1.40   | 2.02 | 2.61 | 3.20 | 4.33 | 5.42   | 5.96 | 7.03 | 6.75 |
| 35  | 0.10                     | 0.24   | 0.44 | 0.83 | 1.54 | 2.22   | 2.88 | 3.52 | 4.76 | 5.97 | 6.57   | 7.74 | 7.72 |      |
| 40  | 0.12                     | 0.27   | 0.51 | 0.96 | 1.78 | 2.57   | 3.33 | 4.07 | 5.50 | 6.90 | 7.59   | 8.94 | 9.43 |      |
| 45  | 0.14                     | 0.31   | 0.58 | 1.08 | 2.02 | 2.92   | 3.78 | 4.62 | 6.25 | 7.84 | 8.62   | 10.2 | 11.3 |      |
|   |                          | Type A   |      |      |      | Type B |      |      |      |      | Type C |      |      |      |
|   | No. of Teeth Small Spkt. | Revolutions per Minute — Small Sprocket <sup>a</sup> |      |      |      |        |      |      |      |      |        |      |      |      |
|   |                          | 25   | 50   | 100  | 200  | 300    | 400  | 500  | 700  | 900  | 1000   | 1200 | 1400 | 1600 |
|   |                          | Horsepower Rating                                    |      |      |      |        |      |      |      |      |        |      |      |      |
| 5/8-inch Pitch Standard Single-Strand Roller Chain — No. 50 | 11                       | 0.24   | 0.45 | 0.84 | 1.56 | 2.25   | 2.92 | 3.57 | 4.83 | 6.06 | 6.66   | 7.85 | 8.13 | 6.65 |
|   | 12                       | 0.26   | 0.49 | 0.92 | 1.72 | 2.47   | 3.21 | 3.92 | 5.31 | 6.65 | 7.31   | 8.62 | 9.26 | 7.58 |
|   | 13                       | 0.29   | 0.54 | 1.00 | 1.87 | 2.70   | 3.50 | 4.27 | 5.78 | 7.25 | 7.97   | 9.40 | 10.4 | 8.55 |
|   | 14                       | 0.31   | 0.58 | 1.09 | 2.03 | 2.92   | 3.79 | 4.63 | 6.27 | 7.86 | 8.64   | 10.2 | 11.7 | 9.55 |
|   | 15                       | 0.34   | 0.63 | 1.17 | 2.19 | 3.15   | 4.08 | 4.99 | 6.75 | 8.47 | 9.31   | 11.0 | 12.6 | 10.6 |
|   | 16                       | 0.36   | 0.67 | 1.26 | 2.34 | 3.38   | 4.37 | 5.35 | 7.24 | 9.08 | 9.98   | 11.8 | 13.5 | 11.7 |
|   | 17                       | 0.39   | 0.72 | 1.34 | 2.50 | 3.61   | 4.67 | 5.71 | 7.73 | 9.69 | 10.7   | 12.6 | 14.4 | 12.8 |
|   | 18                       | 0.41   | 0.76 | 1.43 | 2.66 | 3.83   | 4.97 | 6.07 | 8.22 | 10.3 | 11.3   | 13.4 | 15.3 | 13.9 |
|   | 19                       | 0.43   | 0.81 | 1.51 | 2.82 | 4.07   | 5.27 | 6.44 | 8.72 | 10.9 | 12.0   | 14.2 | 16.3 | 15.1 |
|   | 20                       | 0.46   | 0.86 | 1.60 | 2.98 | 4.30   | 5.57 | 6.80 | 9.21 | 11.5 | 12.7   | 15.0 | 17.2 | 16.3 |
|   | 21                       | 0.48   | 0.90 | 1.69 | 3.14 | 4.53   | 5.87 | 7.17 | 9.71 | 12.2 | 13.4   | 15.8 | 18.1 | 17.6 |
|   | 22                       | 0.51   | 0.95 | 1.77 | 3.31 | 4.76   | 6.17 | 7.54 | 10.2 | 12.8 | 14.1   | 16.6 | 19.1 | 18.8 |
|   | 23                       | 0.53   | 1.00 | 1.86 | 3.47 | 5.00   | 6.47 | 7.91 | 10.7 | 13.4 | 14.8   | 17.4 | 20.0 | 20.1 |
|   | 24                       | 0.56   | 1.04 | 1.95 | 3.63 | 5.23   | 6.78 | 8.29 | 11.2 | 14.1 | 15.5   | 18.2 | 20.9 | 21.4 |
|   | 25                       | 0.58   | 1.09 | 2.03 | 3.80 | 5.47   | 7.08 | 8.66 | 11.7 | 14.7 | 16.2   | 19.0 | 21.9 | 22.8 |
|   | 26                       | 0.61   | 1.14 | 2.12 | 3.96 | 5.70   | 7.39 | 9.03 | 12.2 | 15.3 | 16.9   | 19.9 | 22.8 | 24.2 |
|   | 28                       | 0.66   | 1.23 | 2.30 | 4.29 | 6.18   | 8.01 | 9.79 | 13.2 | 16.6 | 18.3   | 21.5 | 24.7 | 27.0 |
|   | 30                       | 0.71   | 1.33 | 2.48 | 4.62 | 6.66   | 8.63 | 10.5 | 14.3 | 17.9 | 19.7   | 23.2 | 26.6 | 30.0 |
|   | 32                       | 0.76   | 1.42 | 2.66 | 4.96 | 7.14   | 9.25 | 11.3 | 15.3 | 19.2 | 21.1   | 24.9 | 28.6 | 32.2 |
| 35  | 0.84                     | 1.57   | 2.93 | 5.46 | 7.86 | 10.2   | 12.5 | 16.9 | 21.1 | 23.2 | 27.4   | 31.5 | 35.5 |      |
| 40  | 0.97                     | 1.81   | 3.38 | 6.31 | 9.08 | 11.8   | 14.4 | 19.5 | 24.4 | 26.8 | 31.6   | 36.3 | 41.0 |      |
| 45  | 1.10                     | 2.06   | 3.84 | 7.16 | 10.3 | 13.4   | 16.3 | 22.1 | 27.7 | 30.5 | 35.9   | 41.3 | 46.5 |      |
|   |                          | Type A   |      |      |      | Type B |      |      |      |      | Type C |      |      |      |

TRANSMISSION ROLLER CHAIN

Table 9. (Continued) Horsepower Ratings for Roller Chain—1986

| No. of<br>Teeth<br>Small<br>Spkt.                           | Revolutions per Minute — Small Sprocket <sup>a</sup> |        |      |      |      |      |        |      |      |      |      |      |      |      |
|---|--|--------|------|------|------|------|--------|------|------|------|------|------|------|------|
|   | 25   | 50     | 100  | 150  | 200  | 300  | 400    | 500  | 600  | 700  | 800  | 900  | 1000 |      |
|   | Horsepower Rating                                    |        |      |      |      |      |        |      |      |      |      |      |      |      |
| 3/8-inch Pitch Standard Single-Strand Roller Chain — No. 60 | 11   | 0.41   | 0.77 | 1.44 | 2.07 | 2.69 | 3.87   | 5.02 | 6.13 | 7.23 | 8.30 | 9.36 | 10.4 | 11.4 |
|   | 12   | 0.45   | 0.85 | 1.58 | 2.28 | 2.95 | 4.25   | 5.51 | 6.74 | 7.94 | 9.12 | 10.3 | 11.4 | 12.6 |
|   | 13   | 0.50   | 0.92 | 1.73 | 2.49 | 3.22 | 4.64   | 6.01 | 7.34 | 8.65 | 9.94 | 11.2 | 12.5 | 13.7 |
|   | 14   | 0.54   | 1.00 | 1.87 | 2.69 | 3.49 | 5.02   | 6.51 | 7.96 | 9.37 | 10.8 | 12.1 | 13.5 | 14.8 |
|   | 15   | 0.58   | 1.08 | 2.01 | 2.90 | 3.76 | 5.41   | 7.01 | 8.57 | 10.1 | 11.6 | 13.1 | 14.5 | 16.0 |
|   | 16   | 0.62   | 1.16 | 2.16 | 3.11 | 4.03 | 5.80   | 7.52 | 9.19 | 10.8 | 12.4 | 14.0 | 15.6 | 17.1 |
|   | 17   | 0.66   | 1.24 | 2.31 | 3.32 | 4.30 | 6.20   | 8.03 | 9.81 | 11.6 | 13.3 | 15.0 | 16.7 | 18.3 |
|   | 18   | 0.70   | 1.31 | 2.45 | 3.53 | 4.58 | 6.59   | 8.54 | 10.4 | 12.3 | 14.1 | 15.9 | 17.7 | 19.5 |
|   | 19   | 0.75   | 1.39 | 2.60 | 3.74 | 4.85 | 6.99   | 9.05 | 11.1 | 13.0 | 15.0 | 16.9 | 18.8 | 20.6 |
|   | 20   | 0.79   | 1.47 | 2.75 | 3.96 | 5.13 | 7.38   | 9.57 | 11.7 | 13.8 | 15.8 | 17.9 | 19.8 | 21.8 |
|   | 21   | 0.83   | 1.55 | 2.90 | 4.17 | 5.40 | 7.78   | 10.1 | 12.3 | 14.5 | 16.7 | 18.8 | 20.9 | 23.0 |
|   | 22   | 0.87   | 1.63 | 3.05 | 4.39 | 5.68 | 8.19   | 10.6 | 13.0 | 15.3 | 17.5 | 19.8 | 22.0 | 24.2 |
|   | 23   | 0.92   | 1.71 | 3.19 | 4.60 | 5.96 | 8.59   | 11.1 | 13.6 | 16.0 | 18.4 | 20.8 | 23.1 | 25.4 |
|   | 24   | 0.96   | 1.79 | 3.35 | 4.82 | 6.24 | 8.99   | 11.6 | 14.2 | 16.8 | 19.3 | 21.7 | 24.2 | 26.6 |
|   | 25   | 1.00   | 1.87 | 3.50 | 5.04 | 6.52 | 9.40   | 12.2 | 14.9 | 17.5 | 20.1 | 22.7 | 25.3 | 27.8 |
|   | 26   | 1.05   | 1.95 | 3.65 | 5.25 | 6.81 | 9.80   | 12.7 | 15.5 | 18.3 | 21.0 | 23.7 | 26.4 | 29.0 |
|   | 28   | 1.13   | 2.12 | 3.95 | 5.69 | 7.37 | 10.6   | 13.8 | 16.8 | 19.8 | 22.8 | 25.7 | 28.5 | 31.4 |
|   | 30   | 1.22   | 2.28 | 4.26 | 6.13 | 7.94 | 11.4   | 14.8 | 18.1 | 21.4 | 24.5 | 27.7 | 30.8 | 33.8 |
| 32  | 1.31   | 2.45   | 4.56 | 6.57 | 8.52 | 12.3 | 15.9   | 19.4 | 22.9 | 26.3 | 29.7 | 33.0 | 36.3 |      |
| 35  | 1.44   | 2.69   | 5.03 | 7.24 | 9.38 | 13.5 | 17.5   | 21.4 | 25.2 | 29.0 | 32.7 | 36.3 | 39.9 |      |
| 40  | 1.67   | 3.11   | 5.81 | 8.37 | 10.8 | 15.6 | 20.2   | 24.7 | 29.1 | 33.5 | 37.7 | 42.0 | 46.1 |      |
| 45  | 1.89   | 3.53   | 6.60 | 9.50 | 12.3 | 17.7 | 23.0   | 28.1 | 33.1 | 38.0 | 42.9 | 47.7 | 52.4 |      |
|   | Type A   | Type B |      |      |      |      | Type C |      |      |      |      |      |      |      |
| No. of<br>Teeth<br>Small<br>Spkt.                           | Revolutions per Minute — Small Sprocket <sup>a</sup> |        |      |      |      |      |        |      |      |      |      |      |      |      |
|   | 25   | 50     | 100  | 150  | 200  | 300  | 400    | 500  | 600  | 700  | 800  | 900  | 1000 |      |
|   | Horsepower Ratings                                   |        |      |      |      |      |        |      |      |      |      |      |      |      |
| 1-inch Pitch Standard Single-Strand Roller Chain — No. 80   | 11   | 0.97   | 1.80 | 3.36 | 4.84 | 6.28 | 9.04   | 11.7 | 14.3 | 16.9 | 19.4 | 21.9 | 23.0 | 19.6 |
|   | 12   | 1.06   | 1.98 | 3.69 | 5.32 | 6.89 | 9.93   | 12.9 | 15.7 | 18.5 | 21.3 | 24.0 | 26.2 | 22.3 |
|   | 13   | 1.16   | 2.16 | 4.03 | 5.80 | 7.52 | 10.8   | 14.0 | 17.1 | 20.2 | 23.2 | 26.2 | 29.1 | 25.2 |
|   | 14   | 1.25   | 2.34 | 4.36 | 6.29 | 8.14 | 11.7   | 15.2 | 18.6 | 21.9 | 25.1 | 28.4 | 31.5 | 28.2 |
|   | 15   | 1.35   | 2.52 | 4.70 | 6.77 | 8.77 | 12.6   | 16.4 | 20.0 | 23.6 | 27.1 | 30.6 | 34.0 | 31.2 |
|   | 16   | 1.45   | 2.70 | 5.04 | 7.26 | 9.41 | 13.5   | 17.6 | 21.5 | 25.3 | 29.0 | 32.8 | 36.4 | 34.4 |
|   | 17   | 1.55   | 2.88 | 5.38 | 7.75 | 10.0 | 14.5   | 18.7 | 22.9 | 27.0 | 31.0 | 35.0 | 38.9 | 37.7 |
|   | 18   | 1.64   | 3.07 | 5.72 | 8.25 | 10.7 | 15.4   | 19.9 | 24.4 | 28.7 | 33.0 | 37.2 | 41.4 | 41.1 |
|   | 19   | 1.74   | 3.25 | 6.07 | 8.74 | 11.3 | 16.3   | 21.1 | 25.8 | 30.4 | 35.0 | 39.4 | 43.8 | 44.5 |
|   | 20   | 1.84   | 3.44 | 6.41 | 9.24 | 12.0 | 17.2   | 22.3 | 27.3 | 32.2 | 37.0 | 41.7 | 46.3 | 48.1 |
|   | 21   | 1.94   | 3.62 | 6.76 | 9.74 | 12.6 | 18.2   | 23.5 | 28.8 | 33.9 | 39.0 | 43.9 | 48.9 | 51.7 |
|   | 22   | 2.04   | 3.81 | 7.11 | 10.2 | 13.3 | 19.1   | 24.8 | 30.3 | 35.7 | 41.0 | 46.2 | 51.4 | 55.5 |
|   | 23   | 2.14   | 4.00 | 7.46 | 10.7 | 13.9 | 20.1   | 26.0 | 31.8 | 37.4 | 43.0 | 48.5 | 53.9 | 59.3 |
|   | 24   | 2.24   | 4.19 | 7.81 | 11.3 | 14.6 | 21.0   | 27.2 | 33.2 | 39.2 | 45.0 | 50.8 | 56.4 | 62.0 |
|   | 25   | 2.34   | 4.37 | 8.16 | 11.8 | 15.2 | 21.9   | 28.4 | 34.7 | 40.9 | 47.0 | 53.0 | 59.0 | 64.8 |
|   | 26   | 2.45   | 4.56 | 8.52 | 12.3 | 15.9 | 22.9   | 29.7 | 36.2 | 42.7 | 49.1 | 55.3 | 61.5 | 67.6 |
|   | 28   | 2.65   | 4.94 | 9.23 | 13.3 | 17.2 | 24.8   | 32.1 | 39.3 | 46.3 | 53.2 | 59.9 | 66.7 | 73.3 |
|   | 30   | 2.85   | 5.33 | 9.94 | 14.3 | 18.5 | 26.7   | 34.6 | 42.3 | 49.9 | 57.3 | 64.6 | 71.8 | 78.9 |
| 32  | 3.06   | 5.71   | 10.7 | 15.3 | 19.9 | 28.6 | 37.1   | 45.4 | 53.5 | 61.4 | 69.2 | 77.0 | 84.6 |      |
| 35  | 3.37   | 6.29   | 11.7 | 16.9 | 21.9 | 31.6 | 40.9   | 50.0 | 58.9 | 67.6 | 76.3 | 84.8 | 93.3 |      |
| 40  | 3.89   | 7.27   | 13.6 | 19.5 | 25.3 | 36.4 | 47.2   | 57.7 | 68.0 | 78.1 | 88.1 | 99.0 | 108  |      |
| 45  | 4.42   | 8.25   | 15.4 | 22.2 | 28.7 | 41.4 | 53.6   | 65.6 | 77.2 | 88.7 | 100  | 111  | 122  |      |
|   | Type A   | Type B |      |      |      |      | Type C |      |      |      |      |      |      |      |

Table 9. (Continued) Horsepower Ratings for Roller Chain—1986

| No. of<br>Teeth<br>Small<br>Spkt.                            | Revolutions per Minute — Small Sprocket <sup>a</sup> |        |      |      |      |        |      |      |      |      |      |      |      |      |
|--|--|--------|------|------|------|--------|------|------|------|------|------|------|------|------|
|  | 10   | 25     | 50   | 100  | 150  | 200    | 300  | 400  | 500  | 600  | 700  | 800  | 900  |      |
|  | Horsepower Rating                                    |        |      |      |      |        |      |      |      |      |      |      |      |      |
| 1/2-inch Pitch Standard Single-Strand Roller Chain — No. 100 | 11   | 0.81   | 1.85 | 3.45 | 6.44 | 9.28   | 12.0 | 17.3 | 22.4 | 27.4 | 32.3 | 37.1 | 32.8 | 27.5 |
|  | 12   | 0.89   | 2.03 | 3.79 | 7.08 | 10.2   | 13.2 | 19.0 | 24.6 | 30.1 | 35.5 | 40.8 | 37.3 | 31.3 |
|  | 13   | 0.97   | 2.22 | 4.13 | 7.72 | 11.1   | 14.4 | 20.7 | 26.9 | 32.8 | 38.7 | 44.5 | 42.1 | 35.3 |
|  | 14   | 1.05   | 2.40 | 4.48 | 8.36 | 12.0   | 15.6 | 22.5 | 29.1 | 35.6 | 41.9 | 48.2 | 47.0 | 39.4 |
|  | 15   | 1.13   | 2.59 | 4.83 | 9.01 | 13.0   | 16.8 | 24.2 | 31.4 | 38.3 | 45.2 | 51.9 | 52.2 | 43.7 |
|  | 16   | 1.22   | 2.77 | 5.17 | 9.66 | 13.9   | 18.0 | 26.0 | 33.6 | 41.1 | 48.4 | 55.6 | 57.5 | 48.2 |
|  | 17   | 1.30   | 2.96 | 5.52 | 10.3 | 14.8   | 19.2 | 27.7 | 35.9 | 43.9 | 51.7 | 59.4 | 63.0 | 52.8 |
|  | 18   | 1.38   | 3.15 | 5.88 | 11.0 | 15.8   | 20.5 | 29.5 | 38.2 | 46.7 | 55.0 | 63.2 | 68.6 | 57.5 |
|  | 19   | 1.46   | 3.34 | 6.23 | 11.6 | 16.7   | 21.7 | 31.2 | 40.5 | 49.5 | 58.3 | 67.0 | 74.4 | 62.3 |
|  | 20   | 1.55   | 3.53 | 6.58 | 12.3 | 17.7   | 22.9 | 33.0 | 42.8 | 52.3 | 61.6 | 70.8 | 79.8 | 67.3 |
|  | 21   | 1.63   | 3.72 | 6.94 | 13.0 | 18.7   | 24.2 | 34.8 | 45.1 | 55.1 | 65.0 | 74.6 | 84.2 | 72.4 |
|  | 22   | 1.71   | 3.91 | 7.30 | 13.6 | 19.6   | 25.4 | 36.6 | 47.4 | 58.0 | 68.3 | 78.5 | 88.5 | 77.7 |
|  | 23   | 1.80   | 4.10 | 7.66 | 14.3 | 20.6   | 26.7 | 38.4 | 49.8 | 60.8 | 71.7 | 82.3 | 92.8 | 83.0 |
|  | 24   | 1.88   | 4.30 | 8.02 | 15.0 | 21.5   | 27.9 | 40.2 | 52.1 | 63.7 | 75.0 | 86.2 | 97.2 | 88.5 |
|  | 25   | 1.97   | 4.49 | 8.38 | 15.6 | 22.5   | 29.2 | 42.0 | 54.4 | 66.6 | 78.4 | 90.1 | 102  | 94.1 |
|  | 26   | 2.05   | 4.68 | 8.74 | 16.3 | 23.5   | 30.4 | 43.8 | 56.8 | 69.4 | 81.8 | 94.0 | 106  | 99.8 |
|  | 28   | 2.22   | 5.07 | 9.47 | 17.7 | 25.5   | 33.0 | 47.5 | 61.5 | 75.2 | 88.6 | 102  | 115  | 112  |
|  | 30   | 2.40   | 5.47 | 10.2 | 19.0 | 27.4   | 35.5 | 51.2 | 66.3 | 81.0 | 95.5 | 110  | 124  | 124  |
|  | 32   | 2.57   | 5.86 | 10.9 | 20.4 | 29.4   | 38.1 | 54.9 | 71.1 | 86.9 | 102  | 118  | 133  | 136  |
|  | 35   | 2.83   | 6.46 | 12.0 | 22.5 | 32.4   | 42.0 | 60.4 | 78.3 | 95.7 | 113  | 130  | 146  | 156  |
| 40   | 3.27   | 7.46   | 13.9 | 26.0 | 37.4 | 48.5   | 69.8 | 90.4 | 111  | 130  | 150  | 169  | 188  |      |
| 45   | 3.71   | 8.47   | 15.8 | 29.5 | 42.5 | 55.0   | 79.3 | 103  | 126  | 148  | 170  | 192  | 213  |      |
|  | Type A   | Type B |      |      |      | Type C |      |      |      |      |      |      |      |      |
| No. of<br>Teeth<br>Small<br>Spkt.                            | Revolutions per Minute — Small Sprocket <sup>a</sup> |        |      |      |      |        |      |      |      |      |      |      |      |      |
|  | 10   | 25     | 50   | 100  | 150  | 200    | 300  | 400  | 500  | 600  | 700  | 800  | 900  |      |
|  | Horsepower Rating                                    |        |      |      |      |        |      |      |      |      |      |      |      |      |
| 1/2-inch Pitch Standard Single-Strand Roller Chain — No. 120 | 11   | 1.37   | 3.12 | 5.83 | 10.9 | 15.7   | 20.3 | 29.2 | 37.9 | 46.3 | 54.6 | 46.3 | 37.9 | 31.8 |
|  | 12   | 1.50   | 3.43 | 6.40 | 11.9 | 17.2   | 22.3 | 32.1 | 41.6 | 50.9 | 59.9 | 52.8 | 43.2 | 36.2 |
|  | 13   | 1.64   | 3.74 | 6.98 | 13.0 | 18.8   | 24.3 | 35.0 | 45.4 | 55.5 | 65.3 | 59.5 | 48.7 | 40.8 |
|  | 14   | 1.78   | 4.05 | 7.56 | 14.1 | 20.3   | 26.3 | 37.9 | 49.1 | 60.1 | 70.8 | 66.5 | 54.4 | 45.6 |
|  | 15   | 1.91   | 4.37 | 8.15 | 15.2 | 21.9   | 28.4 | 40.9 | 53.0 | 64.7 | 76.3 | 73.8 | 60.4 | 50.6 |
|  | 16   | 2.05   | 4.68 | 8.74 | 16.3 | 23.5   | 30.4 | 43.8 | 56.8 | 69.4 | 81.8 | 81.3 | 66.5 | 55.7 |
|  | 17   | 2.19   | 5.00 | 9.33 | 17.4 | 25.1   | 32.5 | 46.8 | 60.6 | 74.1 | 87.3 | 89.0 | 72.8 | 61.0 |
|  | 18   | 2.33   | 5.32 | 9.92 | 18.5 | 26.7   | 34.6 | 49.8 | 64.5 | 78.8 | 92.9 | 97.0 | 79.4 | 66.5 |
|  | 19   | 2.47   | 5.64 | 10.5 | 19.6 | 28.3   | 36.6 | 52.8 | 68.4 | 83.6 | 98.5 | 105  | 86.1 | 72.1 |
|  | 20   | 2.61   | 5.96 | 11.1 | 20.7 | 29.9   | 38.7 | 55.8 | 72.2 | 88.3 | 104  | 114  | 92.9 | 77.9 |
|  | 21   | 2.75   | 6.28 | 11.7 | 21.9 | 31.5   | 40.8 | 58.8 | 76.2 | 93.1 | 110  | 122  | 100  | 83.8 |
|  | 22   | 2.90   | 6.60 | 12.3 | 23.0 | 33.1   | 42.9 | 61.8 | 80.1 | 97.9 | 115  | 131  | 107  | 89.9 |
|  | 23   | 3.04   | 6.93 | 12.9 | 24.1 | 34.8   | 45.0 | 64.9 | 84.0 | 103  | 121  | 139  | 115  | 96.1 |
|  | 24   | 3.18   | 7.25 | 13.5 | 25.3 | 36.4   | 47.1 | 67.9 | 88.0 | 108  | 127  | 146  | 122  | 102  |
|  | 25   | 3.32   | 7.58 | 14.1 | 26.4 | 38.0   | 49.3 | 71.0 | 91.9 | 112  | 132  | 152  | 130  | 109  |
|  | 26   | 3.47   | 7.91 | 14.8 | 27.5 | 39.7   | 51.4 | 74.0 | 95.9 | 117  | 138  | 159  | 138  | 115  |
|  | 28   | 3.76   | 8.57 | 16.0 | 29.8 | 43.0   | 55.7 | 80.2 | 104  | 127  | 150  | 172  | 154  | 129  |
|  | 30   | 4.05   | 9.23 | 17.2 | 32.1 | 46.3   | 60.0 | 86.4 | 112  | 137  | 161  | 185  | 171  | 143  |
|  | 32   | 4.34   | 9.90 | 18.5 | 34.5 | 49.6   | 64.3 | 92.6 | 120  | 147  | 173  | 199  | 188  | 158  |
|  | 35   | 4.78   | 10.9 | 20.3 | 38.0 | 54.7   | 70.9 | 102  | 132  | 162  | 190  | 219  | 215  | 180  |
| 40   | 5.52   | 12.6   | 23.5 | 43.9 | 63.2 | 81.8   | 118  | 153  | 187  | 220  | 253  | ...  | ...  |      |
| 45   | 6.27   | 14.3   | 26.7 | 49.8 | 71.7 | 92.9   | 134  | 173  | 212  | 250  | 287  | ...  | ...  |      |
|  | Type A   | Type B |      |      |      | Type C |      |      |      |      |      |      |      |      |

<sup>a</sup> For lower or higher rpm, larger chain sizes, and rpm above 3500, see B29.1M-1993.

For use of table see page 2451.

**Table 10. Recommended Roller Chain Sprocket Maximum Bore and Hub Diameters**

| Roller Chain Pitch |                  |                  |                  |                   |                  |                   |                  |                   |                  |                   |
|--------------------|------------------|------------------|------------------|-------------------|------------------|-------------------|------------------|-------------------|------------------|-------------------|
| No. of Teeth       | $\frac{3}{8}$    |                  | $\frac{1}{2}$    |                   | $\frac{5}{8}$    |                   | $\frac{3}{4}$    |                   | 1                |                   |
|                    | Max. Bore        | Max. Hub Dia.    | Max. Bore        | Max. Hub Dia.     | Max. Bore        | Max. Hub Dia.     | Max. Bore        | Max. Hub Dia.     | Max. Bore        | Max. Hub Dia.     |
| 11                 | $\frac{19}{32}$  | $\frac{55}{64}$  | $\frac{25}{32}$  | $\frac{11}{16}$   | $\frac{31}{32}$  | $\frac{15}{32}$   | $\frac{1}{4}$    | $\frac{1}{16}$    | $\frac{15}{8}$   | $\frac{23}{8}$    |
| 12                 | $\frac{5}{8}$    | $\frac{63}{64}$  | $\frac{7}{8}$    | $\frac{121}{64}$  | $\frac{15}{32}$  | $\frac{19}{64}$   | $\frac{19}{32}$  | $\frac{2}{64}$    | $\frac{125}{32}$ | $\frac{245}{64}$  |
| 13                 | $\frac{3}{4}$    | $\frac{17}{64}$  | 1                | $\frac{1}{2}$     | $\frac{19}{32}$  | $\frac{1}{8}$     | $\frac{1}{2}$    | 2                 | 2                | $\frac{31}{64}$   |
| 14                 | $\frac{27}{32}$  | $\frac{15}{64}$  | $\frac{15}{32}$  | $\frac{13}{32}$   | $\frac{13}{16}$  | $\frac{25}{64}$   | $\frac{13}{4}$   | $\frac{2}{2}$     | $\frac{29}{32}$  | $\frac{31}{32}$   |
| 15                 | $\frac{7}{8}$    | $\frac{123}{64}$ | $\frac{1}{4}$    | $\frac{113}{16}$  | $\frac{17}{32}$  | $\frac{29}{32}$   | $\frac{125}{32}$ | $\frac{23}{4}$    | $\frac{213}{32}$ | $\frac{343}{64}$  |
| 16                 | $\frac{31}{32}$  | $\frac{15}{32}$  | $\frac{19}{32}$  | $\frac{63}{64}$   | $\frac{11}{16}$  | $\frac{23}{64}$   | $\frac{131}{32}$ | $\frac{263}{64}$  | $\frac{223}{32}$ | $\frac{363}{64}$  |
| 17                 | $\frac{13}{32}$  | $\frac{19}{32}$  | $\frac{13}{8}$   | $\frac{29}{64}$   | $\frac{125}{32}$ | $\frac{21}{16}$   | $\frac{27}{32}$  | $\frac{37}{32}$   | $\frac{213}{16}$ | $\frac{45}{16}$   |
| 18                 | $\frac{17}{32}$  | $\frac{123}{32}$ | $\frac{17}{32}$  | $\frac{29}{64}$   | $\frac{1}{8}$    | $\frac{257}{64}$  | $\frac{29}{32}$  | $\frac{315}{32}$  | $\frac{31}{8}$   | $\frac{441}{64}$  |
| 19                 | $\frac{1}{4}$    | $\frac{127}{32}$ | $\frac{11}{16}$  | $\frac{229}{64}$  | $\frac{2}{16}$   | $\frac{35}{64}$   | $\frac{27}{16}$  | $\frac{345}{64}$  | $\frac{35}{16}$  | $\frac{461}{64}$  |
| 20                 | $\frac{19}{32}$  | $\frac{161}{64}$ | $\frac{125}{32}$ | $\frac{25}{8}$    | $\frac{2}{4}$    | $\frac{39}{32}$   | $\frac{211}{16}$ | $\frac{361}{64}$  | $\frac{31}{2}$   | $\frac{59}{32}$   |
| 21                 | $\frac{15}{16}$  | $\frac{25}{64}$  | $\frac{129}{32}$ | $\frac{225}{32}$  | $\frac{29}{32}$  | $\frac{31}{64}$   | $\frac{213}{16}$ | $\frac{43}{16}$   | $\frac{33}{4}$   | $\frac{59}{32}$   |
| 22                 | $\frac{17}{16}$  | $\frac{213}{16}$ | $\frac{115}{16}$ | $\frac{215}{16}$  | $\frac{2}{16}$   | $\frac{317}{16}$  | $\frac{215}{16}$ | $\frac{47}{16}$   | $\frac{37}{8}$   | $\frac{539}{64}$  |
| 23                 | $\frac{19}{16}$  | $\frac{25}{16}$  | $\frac{23}{32}$  | $\frac{33}{32}$   | $\frac{25}{8}$   | $\frac{357}{64}$  | $\frac{31}{8}$   | $\frac{443}{64}$  | $\frac{43}{16}$  | $\frac{615}{64}$  |
| 24                 | $\frac{11}{16}$  | $\frac{27}{16}$  | $\frac{2}{4}$    | $\frac{317}{64}$  | $\frac{213}{16}$ | $\frac{45}{64}$   | $\frac{31}{4}$   | $\frac{429}{32}$  | $\frac{49}{16}$  | $\frac{69}{16}$   |
| 25                 | $\frac{13}{4}$   | $\frac{29}{16}$  | $\frac{29}{32}$  | $\frac{327}{64}$  | $\frac{227}{32}$ | $\frac{49}{32}$   | $\frac{33}{8}$   | $\frac{53}{32}$   | $\frac{411}{16}$ | $\frac{67}{8}$    |
| Roller Chain Pitch |                  |                  |                  |                   |                  |                   |                  |                   |                  |                   |
| No. of Teeth       | $\frac{1}{4}$    |                  | $\frac{1}{2}$    |                   | $\frac{3}{4}$    |                   | 2                |                   | $2\frac{1}{2}$   |                   |
|                    | Max. Bore        | Max. Hub Dia.    | Max. Bore        | Max. Hub Dia.     | Max. Bore        | Max. Hub Dia.     | Max. Bore        | Max. Hub Dia.     | Max. Bore        | Max. Hub Dia.     |
| 11                 | $\frac{131}{32}$ | $\frac{231}{32}$ | $\frac{25}{16}$  | $\frac{337}{64}$  | $\frac{213}{16}$ | $\frac{411}{64}$  | $\frac{39}{32}$  | $\frac{425}{32}$  | $\frac{315}{16}$ | $\frac{563}{64}$  |
| 12                 | $\frac{29}{32}$  | $\frac{33}{8}$   | $\frac{23}{4}$   | $\frac{41}{16}$   | $\frac{31}{4}$   | $\frac{43}{4}$    | $\frac{33}{8}$   | $\frac{527}{64}$  | $\frac{423}{32}$ | $\frac{611}{64}$  |
| 13                 | $\frac{27}{32}$  | $\frac{325}{32}$ | $\frac{3}{16}$   | $\frac{435}{64}$  | $\frac{39}{16}$  | $\frac{51}{16}$   | $\frac{4}{16}$   | $\frac{65}{64}$   | $\frac{53}{32}$  | $\frac{739}{64}$  |
| 14                 | $\frac{21}{16}$  | $\frac{43}{16}$  | $\frac{35}{16}$  | $\frac{51}{32}$   | $\frac{37}{8}$   | $\frac{57}{8}$    | $\frac{411}{16}$ | $\frac{623}{32}$  | $\frac{523}{32}$ | $\frac{827}{64}$  |
| 15                 | $\frac{33}{32}$  | $\frac{419}{32}$ | $\frac{33}{4}$   | $\frac{533}{64}$  | $\frac{47}{16}$  | $\frac{629}{64}$  | $\frac{47}{8}$   | $\frac{73}{8}$    | $\frac{61}{4}$   | $\frac{97}{32}$   |
| 16                 | $\frac{39}{32}$  | 5                | 4                | 6                 | $\frac{411}{16}$ | $\frac{71}{64}$   | $\frac{51}{2}$   | $\frac{81}{64}$   | 7                | $\frac{101}{32}$  |
| 17                 | $\frac{321}{32}$ | $\frac{513}{32}$ | $\frac{415}{32}$ | $\frac{631}{64}$  | $\frac{51}{16}$  | $\frac{73}{64}$   | $\frac{511}{16}$ | $\frac{821}{32}$  | $\frac{77}{16}$  | $\frac{1027}{32}$ |
| 18                 | $\frac{325}{32}$ | $\frac{551}{64}$ | $\frac{421}{32}$ | $\frac{631}{32}$  | $\frac{55}{8}$   | $\frac{87}{64}$   | $\frac{61}{4}$   | $\frac{951}{16}$  | $\frac{81}{8}$   | $\frac{1141}{64}$ |
| 19                 | $\frac{43}{16}$  | $\frac{613}{64}$ | $\frac{415}{16}$ | $\frac{729}{64}$  | $\frac{511}{16}$ | $\frac{85}{64}$   | $\frac{67}{8}$   | $\frac{961}{64}$  | 9                | $\frac{123}{16}$  |
| 20                 | $\frac{419}{32}$ | $\frac{639}{64}$ | $\frac{57}{16}$  | $\frac{715}{16}$  | $\frac{61}{4}$   | $\frac{917}{64}$  | 7                | $\frac{1019}{32}$ | $\frac{93}{4}$   | $\frac{131}{4}$   |
| 21                 | $\frac{411}{16}$ | 7                | $\frac{511}{16}$ | $\frac{827}{64}$  | $\frac{613}{16}$ | $\frac{933}{64}$  | $\frac{73}{4}$   | $\frac{1115}{64}$ | 10               | $\frac{143}{64}$  |
| 22                 | $\frac{47}{8}$   | $\frac{713}{32}$ | $\frac{57}{8}$   | $\frac{857}{64}$  | $\frac{71}{4}$   | $\frac{1025}{64}$ | $\frac{83}{8}$   | $\frac{117}{8}$   | $\frac{107}{8}$  | $\frac{1427}{32}$ |
| 23                 | $\frac{51}{16}$  | $\frac{713}{16}$ | $\frac{63}{8}$   | $\frac{93}{8}$    | $\frac{77}{16}$  | $\frac{1015}{16}$ | 9                | $\frac{1233}{64}$ | $\frac{113}{8}$  | $\frac{1521}{32}$ |
| 24                 | $\frac{511}{16}$ | $\frac{813}{64}$ | $\frac{613}{16}$ | $\frac{955}{64}$  | 8                | $\frac{111}{2}$   | $\frac{95}{8}$   | $\frac{133}{32}$  | 13               | $\frac{1629}{64}$ |
| 25                 | $\frac{523}{32}$ | $\frac{839}{64}$ | $\frac{71}{4}$   | $\frac{1011}{32}$ | $\frac{89}{16}$  | $\frac{121}{16}$  | $\frac{101}{4}$  | $\frac{1351}{64}$ | $\frac{131}{2}$  | $\frac{171}{4}$   |

All dimensions in inches.

For standard key dimensions see pages 2363 through 2364.

Source: American Chain Association.

**Center Distance between Sprockets.**—The center-to-center distance between sprockets, as a general rule, should not be less than  $1\frac{1}{2}$  times the diameter of the larger sprocket and not less than thirty times the pitch nor more than about 50 times the pitch, although much depends upon the speed and other conditions. A center distance equivalent to 80 pitches may be considered an approved maximum. Very long center distances result in catenary tension in the chain. If roller-chain drives are designed correctly, the center-to-center distance for some transmissions may be so short that the sprocket teeth nearly touch each other, assuming that the load is not too great and the number of teeth is not too small. To

avoid interference of the sprocket teeth, the center distance must, of course, be somewhat greater than one-half the sum of the outside diameters of the sprockets. The chain should extend around at least 120 degrees of the pinion circumference, and this minimum amount of contact is obtained for all center distances provided the ratio is less than  $3\frac{1}{2}$  to 1. Other things being equal, a fairly long chain is recommended in preference to the shortest one allowed by the sprocket diameters, because the rate of chain elongation due to natural wear is inversely proportional to the length, and also because the greater elasticity of the longer strand tends to absorb irregularities of motion and to decrease the effect of shocks.

If possible, the center distance should be adjustable in order to take care of slack due to elongation from wear and this range of adjustment should be at least one and one-half pitches. A little slack is desirable as it allows the chain links to take the best position on the sprocket teeth and reduces the wear on the bearings. Too much sag or an excessive distance between the sprockets may cause the chain to whip up and down — a condition detrimental to smooth running and very destructive to the chain. The sprockets should run in a vertical plane, the sprocket axes being approximately horizontal, unless an idler is used on the slack side to keep the chain in position. The most satisfactory results are obtained when the slack side of the chain is on the bottom.

**Center Distance for a Given Chain Length.**—When the distance between the driving and driven sprockets can be varied to suit the length of the chain, this center distance for a tight chain may be determined by the following formula, in which  $c$  = center-to-center distance in inches;  $L$  = chain length in pitches;  $P$  = pitch of chain;  $N$  = number of teeth in large sprocket;  $n$  = number of teeth in small sprocket.

$$c = \frac{P}{8}(2L - N - n + \sqrt{(2L - N - n)^2 - 0.810(N - n)^2})$$

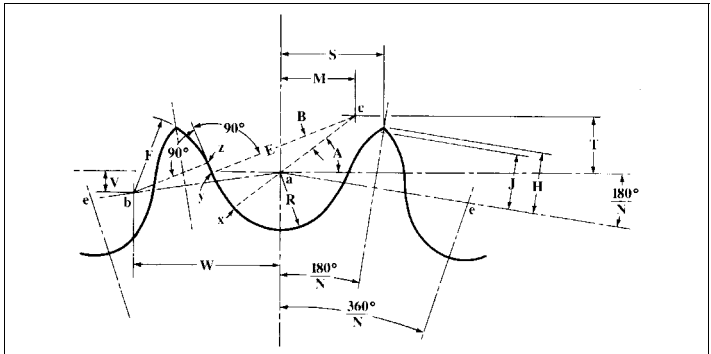
This formula is approximate, but the error is less than the variation in the length of the best chains. The length  $L$  in pitches should be an even number for a roller chain, so that the use of an offset connecting link will not be necessary.

**Idler Sprockets.**—When sprockets have a fixed center distance or are non-adjustable, it may be advisable to use an idler sprocket for taking up the slack. The idler should preferably be placed against the slack side between the two strands of the chain. When a sprocket is applied to the tight side of the chain to reduce vibration, it should be on the lower side and so located that the chain will run in a straight line between the two main sprockets. A sprocket will wear excessively if the number of teeth is too small and the speed too high, because there is impact between the teeth and rollers even though the idler carries practically no load.

**Length of Driving Chain.**—The total length of a block chain should be given in multiples of the pitch, whereas for a roller chain, the length should be in multiples of twice the pitch, because the ends must be connected with an outside and inside link. The length of a chain can be calculated accurately enough for ordinary practice by the use of the following formula, in which  $L$  = chain length in pitches;  $C$  = center distance in pitches;  $N$  = number of teeth in large sprocket;  $n$  = number of teeth in small sprocket:

$$L = 2C + \frac{N}{2} + \frac{n}{2} + \left(\frac{N-n}{2\pi}\right)^2 \times \frac{1}{C}$$

**Table 11. ANSI Sprocket Tooth Form for Roller Chain ANSI/ASME B29.1M-1993**



Seating Curve Data—Inches

| $P$   | $D_r$ | Min. $R$ | Min. $D_s$ | $D_s$ Tol. <sup>a</sup> | $P$   | $D_r$ | Min. $R$ | Min. $D_s$ | $D_s$ Tol. <sup>a</sup> |
|-------|-------|----------|------------|-------------------------|-------|-------|----------|------------|-------------------------|
| 0.250 | 0.130 | 0.0670   | 0.134      | 0.0055                  | 1.250 | 0.750 | 0.3785   | 0.757      | 0.0070                  |
| 0.375 | 0.200 | 0.1020   | 0.204      | 0.0055                  | 1.500 | 0.875 | 0.4410   | 0.882      | 0.0075                  |
| 0.500 | 0.306 | 0.1585   | 0.317      | 0.0060                  | 1.750 | 1.000 | 0.5040   | 1.008      | 0.0080                  |
| 0.500 | 0.312 | 0.1585   | 0.317      | 0.0060                  | 2.000 | 1.125 | 0.5670   | 1.134      | 0.0085                  |
| 0.625 | 0.400 | 0.2025   | 0.405      | 0.0060                  | 2.250 | 1.406 | 0.7080   | 1.416      | 0.0090                  |
| 0.750 | 0.469 | 0.2370   | 0.474      | 0.0065                  | 2.500 | 1.562 | 0.7870   | 1.573      | 0.0095                  |
| 1.000 | 0.625 | 0.3155   | 0.631      | 0.0070                  | 3.000 | 1.875 | 0.9435   | 1.887      | 0.0105                  |

<sup>a</sup> Plus tolerance only.

$P$  = pitch ( $ae$ )

$N$  = number of teeth  $D_r$  = nominal roller diameter

$D_s$  = seating curve diameter =  $1.005 D_r + 0.003$  (in inches)

$R = \frac{1}{2} D_s$  ( $D_s$  has only plus tolerance)

$A = 35^\circ + (60^\circ \div N)$   $B = 18^\circ - (56^\circ \div N)$   $ac = 0.8 D_r$

$M = 0.8 D_r \cos(35^\circ + (60^\circ \div N))$

$T = 0.8 D_r \sin(35^\circ + (60^\circ \div N))$

$E = 1.3025 D_r + 0.0015$  (in inches)

Chord  $xy = (2.605 D_r + 0.003) \sin 9^\circ - (28^\circ \div N)$  (in inches)

$yz = D_r [1.4 \sin(17^\circ - (64^\circ \div N)) - 0.8 \sin(18^\circ - (56^\circ \div N))]$

Length of a line between  $a$  and  $b = 1.4 D_r$

$W = 1.4 D_r \cos(180^\circ \div N)$ ;  $V = 1.4 D_r \sin(180^\circ \div N)$

$F = D_r [0.8 \cos(18^\circ - (56^\circ \div N)) + 1.4 \cos(17^\circ - (64^\circ \div N)) - 1.3025] - 0.0015$  inch

$H = \sqrt{F^2 - (1.4 D_r - 0.5 P)^2}$

$S = 0.5 P \cos(180^\circ \div N) + H \sin(180^\circ \div N)$

Approximate O.D. of sprocket when  $J$  is  $0.3 P = P [0.6 + \cot(180^\circ \div N)]$

O.D. of sprocket when tooth is pointed  $+ P \cot(180^\circ \div N) + \cos(180^\circ \div N) (D_s - D_r) + 2H$

Pressure angle for new chain =  $xab = 35^\circ - (120^\circ \div N)$

Minimum pressure angle =  $xab - B = 17^\circ - (64^\circ \div N)$ ;

Average pressure angle =  $26^\circ - (92^\circ \div N)$

Table 12. Standard Hob Design for Roller Chain Sprockets

**Section Normal to Hob Teeth**

Data for Laying Out Hob Outlines — Inches

| <i>P</i> | <i>P<sub>n</sub></i> | <i>H</i> | <i>E</i> | O.D.  | <i>W</i> | Bore  | Keyway     | No. Gashes |
|----------|----------------------|----------|----------|-------|----------|-------|------------|------------|
| 1/4      | 0.2527               | 0.0675   | 0.0075   | 2 3/8 | 2 1/2    | 1.250 | 1/4 × 1/8  | 13         |
| 3/8      | 0.379                | 0.101    | 0.012    | 3 1/8 | 2 1/2    | 1.250 | 1/4 × 1/8  | 13         |
| 1/2      | 0.506                | 0.135    | 0.015    | 3 3/8 | 2 1/2    | 1.250 | 1/4 × 1/8  | 12         |
| 5/8      | 0.632                | 0.170    | 0.018    | 3 3/8 | 2 1/2    | 1.250 | 1/4 × 1/8  | 12         |
| 3/4      | 0.759                | 0.202    | 0.023    | 3 3/4 | 2 3/4    | 1.250 | 1/4 × 1/8  | 11         |
| 1        | 1.011                | 0.270    | 0.030    | 4 3/8 | 3 3/4    | 1.250 | 1/4 × 1/8  | 11         |
| 1 1/4    | 1.264                | 0.337    | 0.038    | 4 3/4 | 4 1/2    | 1.250 | 1/4 × 1/8  | 10         |
| 1 1/2    | 1.517                | 0.405    | 0.045    | 5 3/8 | 5 1/4    | 1.250 | 1/4 × 1/8  | 10         |
| 1 3/4    | 1.770                | 0.472    | 0.053    | 6 3/8 | 6        | 1.500 | 3/8 × 3/16 | 9          |
| 2        | 2.022                | 0.540    | 0.060    | 6 7/8 | 6 3/4    | 1.500 | 3/8 × 3/16 | 9          |
| 2 1/4    | 2.275                | 0.607    | 0.068    | 8     | 8 1/2    | 1.750 | 3/8 × 3/16 | 8          |
| 2 1/2    | 2.528                | 0.675    | 0.075    | 8 3/8 | 9 3/8    | 1.750 | 3/8 × 3/16 | 8          |
| 3        | 3.033                | 0.810    | 0.090    | 9 3/4 | 11 1/4   | 2.000 | 1/2 × 3/8  | 8          |

Hobs designed for a given roller diameter ( $D_r$ ) and chain pitch ( $P$ ) will cut any number of teeth.

$P$  = Pitch of Chain

$P_n$  = Normal Pitch of Hob = 1.011  $P$  inches

$D_s$  = Minimum Diameter of Seating Curve = 1.005  $D_r$  + 0.003 inches

$F$  = Radius Center for Arc  $GK$ ;  $TO = OU = P_n \div 2$

$H = 0.27 P$ ;  $E = 0.03 P$  = Radius of Fillet Circle

$Q$  is located on line passing through  $F$  and  $J$ . Point  $J$  is intersection of line  $XY$  with circle of diameter  $D_s$ .  $R$  is found by trial and the arc of this radius is tangent to arc  $GK$  at  $K$  and to fillet radius.

$OD$  = Outside Diameter = 1.7 (Bore +  $D_r$  + 0.7  $P$ ) approx.

$D_n$  = Pitch Diameter =  $OD - D_s$ ;  $M$  = Helix Angle;  $\sin M = P_n \div \pi D_n$

$L$  = Lead =  $P_n \div \cos M$ ;  $W$  = Width = Not less than  $2 \times$  Bore, or  $6 D_r$ , or  $3.2 P$

To the length obtained by this formula, add enough to make a whole number (and for a roller chain, an even number) of pitches. If a roller chain has an odd number of pitches, it will be necessary to use an offset connecting link.

Another formula for obtaining chain length in which  $D$  = distance between centers of shafts;  $R$  = pitch radius of large sprocket;  $r$  = pitch radius of small sprocket;  $N$  = number of teeth in large sprocket;  $n$  = number of teeth in small sprocket;  $P$  = pitch of chain and sprockets; and  $l$  = required chain length in inches, is:

$$l = \frac{180^\circ + 2\alpha}{360^\circ} NP + \frac{180^\circ - 2\alpha}{360^\circ} nP + 2D \cos \alpha \quad \text{where } \sin \alpha = \frac{R - r}{D}$$



**Cutting Standard Sprocket Tooth Form.**—The proportions and seating curve data for the standard sprocket tooth form for roller chain are given in Table 11. Either formed or generating types of sprocket cutters may be employed.

**Hobs:** Only one hob will be required to cut any number of teeth for a given pitch and roller diameter. All hobs should be marked with pitch and roller diameter to be cut. Formulas and data for standard hob design are given in Table 12.

**Space Cutters:** Five cutters of this type will be required to cut from 7 teeth up for any given roller diameter. The ranges are, respectively, 7–8, 9–11, 12–17, 18–34, and 35 teeth and over. If less than 7 teeth is necessary, special cutters conforming to the required number of teeth should be used.

The regular cutters are based upon an intermediate number of teeth  $N_a$ , equal to  $2N_1N_2 \div (N_1 + N_2)$  in which  $N_1$  = minimum number of teeth and  $N_2$  = maximum number of teeth for which cutter is intended; but the topping curve radius  $F$  (see diagram in Table 13) is designed to produce adequate tooth height on a sprocket of  $N_2$  teeth. The values of  $N_a$  for the several cutters are, respectively, 7.47, 9.9, 14.07, 23.54, and 56. Formulas and construction data for space cutter layout are given in Table 13 and recommended cutter sizes are given in Table 14.

**Table 13. Standard Space Cutters for Roller-Chain Sprockets**

| Data for Laying Out Space Cutter |                       |                       |              |                |
|----------------------------------|-----------------------|-----------------------|--------------|----------------|
| Range of Teeth                   | M                     | T                     | W            | V              |
| 7-8                              | $0.5848 D_r$          | $0.5459 D_r$          | $1.2790 D_r$ | $0.5694 D_r$   |
| 9-11                             | $0.6032 D_r$          | $0.5255 D_r$          | $1.3302 D_r$ | $0.4365 D_r$   |
| 12-17                            | $0.6194 D_r$          | $0.5063 D_r$          | $1.3694 D_r$ | $0.2911 D_r$   |
| 18-34                            | $0.6343 D_r$          | $0.4875 D_r$          | $1.3947 D_r$ | $0.1220 D_r$   |
| 35 up                            | $0.6466 D_r$          | $0.4710 D_r$          | $1.4000 D_r$ | 0              |
| Range of Teeth                   | F                     | Chord xy              | yz           | Angle Yab      |
| 7-8                              | $0.8686 D_r - 0.0015$ | $0.2384 D_r + 0.0003$ | $0.0618 D_r$ | $24^\circ$     |
| 9-11                             | $0.8554 D_r - 0.0015$ | $0.2800 D_r + 0.0003$ | $0.0853 D_r$ | $18^\circ 10'$ |
| 12-17                            | $0.8364 D_r - 0.0015$ | $0.3181 D_r + 0.0004$ | $0.1269 D_r$ | $12^\circ$     |
| 18-34                            | $0.8073 D_r - 0.0015$ | $0.3540 D_r + 0.0004$ | $0.1922 D_r$ | $5^\circ$      |
| 35 up                            | $0.7857 D_r - 0.0015$ | $0.3850 D_r + 0.0004$ | $0.2235 D_r$ | $0^\circ$      |

$E$  (same for all ranges) =  $1.3025 D_r + 0.0015$ ;  $G$  (same for all ranges) =  $1.4 D_r$

See Table 14 for recommended cutter sizes.

Angle  $Yab$  is equal to  $180^\circ \div N$  when the cutter is made for a specific number of teeth. For the design of cutters covering a range of teeth, angle  $Yab$  was determined by layout to ensure chain roller clearance and to avoid pointed teeth on the larger sprockets of each range. It has values as given below for cutters covering the range of teeth shown. The following formulas are for cutters covering the standard ranges of teeth where  $N_a$  equals intermediate values given on page 2460.

$$W = 1.4D_r \cos Yab \quad V = 1.4D_r \sin Yab$$

$$yz = D_r \left[ 1.4 \sin \left( 17^\circ + \frac{116^\circ}{N_a} - Yab \right) - 0.8 \sin \left( 18^\circ - \frac{56^\circ}{N_a} \right) \right]$$

$$F = D_r \left[ 0.8 \cos \left( 18^\circ - \frac{56^\circ}{N_a} \right) + 1.4 \cos \left( 17^\circ + \frac{116^\circ}{N_a} - Yab \right) - 1.3025 \right] - 0.0015 \text{ in.}$$

For other points, use the value of  $N_a$  for  $N$  in the standard formulas in Table 11.

**Table 14. Recommended Space Cutter Sizes for Roller-Chain Sprockets**

| Pitch | Roller Dia. | Number of Teeth           |      |      |       |       |       |
|-------|-------------|---------------------------|------|------|-------|-------|-------|
|       |             | 6                         | 7-8  | 9-11 | 12-17 | 18-34 | 35 up |
|       |             | Cutter Diameter (Minimum) |      |      |       |       |       |
| 0.250 | 0.130       | 2.75                      | 2.75 | 2.75 | 2.75  | 2.75  | 2.75  |
| 0.375 | 0.200       | 2.75                      | 2.75 | 2.75 | 2.75  | 2.75  | 2.75  |
| 0.500 | 0.312       | 3.00                      | 3.00 | 3.12 | 3.12  | 3.12  | 3.12  |
| 0.625 | 0.400       | 3.12                      | 3.12 | 3.25 | 3.25  | 3.25  | 3.25  |
| 0.725 | 0.469       | 3.25                      | 3.25 | 3.38 | 3.38  | 3.38  | 3.38  |
| 1.000 | 0.625       | 3.88                      | 4.00 | 4.12 | 4.12  | 4.25  | 4.25  |
| 1.250 | 0.750       | 4.25                      | 4.38 | 4.50 | 4.50  | 4.62  | 4.62  |
| 1.500 | 0.875       | 4.38                      | 4.50 | 4.62 | 4.62  | 4.75  | 4.75  |
| 1.750 | 1.000       | 5.00                      | 5.12 | 5.25 | 5.38  | 5.50  | 5.50  |
| 2.000 | 1.125       | 5.38                      | 5.50 | 5.62 | 5.75  | 5.88  | 5.88  |
| 2.250 | 1.406       | 5.88                      | 6.00 | 6.25 | 6.38  | 6.50  | 6.50  |
| 2.500 | 1.563       | 6.38                      | 6.62 | 6.75 | 6.88  | 7.00  | 7.12  |
| 3.000 | 1.875       | 7.50                      | 7.75 | 7.88 | 8.00  | 8.00  | 8.25  |
| Pitch | Roller Dia. | Cutter Width (Minimum)    |      |      |       |       |       |
| 0.250 | 0.130       | 0.31                      | 0.31 | 0.31 | 0.31  | 0.28  | 0.28  |
| 0.375 | 0.200       | 0.47                      | 0.47 | 0.47 | 0.44  | 0.44  | 0.41  |
| 0.500 | 0.312       | 0.75                      | 0.75 | 0.75 | 0.75  | 0.72  | 0.69  |
| 0.625 | 0.400       | 0.75                      | 0.75 | 0.75 | 0.75  | 0.72  | 0.69  |
| 0.750 | 0.469       | 0.91                      | 0.91 | 0.91 | 0.88  | 0.84  | 0.81  |
| 1.000 | 0.625       | 1.50                      | 1.50 | 1.47 | 1.47  | 1.41  | 1.34  |
| 1.250 | 0.750       | 1.81                      | 1.81 | 1.78 | 1.75  | 1.69  | 1.62  |
| 1.500 | 0.875       | 1.81                      | 1.81 | 1.78 | 1.75  | 1.69  | 1.62  |
| 1.750 | 1.000       | 2.09                      | 2.09 | 2.06 | 2.03  | 1.97  | 1.88  |
| 2.000 | 1.125       | 2.41                      | 2.41 | 2.38 | 2.31  | 2.25  | 2.16  |
| 2.250 | 1.406       | 2.69                      | 2.69 | 2.66 | 2.59  | 2.47  | 2.41  |
| 2.500 | 1.563       | 3.00                      | 3.00 | 2.94 | 2.91  | 2.75  | 2.69  |
| 3.000 | 1.875       | 3.59                      | 3.59 | 3.53 | 3.47  | 3.34  | 3.22  |

Where the same roller diameter is commonly used with chains of two different pitches it is recommended that stock cutters be made wide enough to cut sprockets for both chains.

**Marking of Cutters.**—All cutters are to be marked, giving pitch, roller diameter and range of teeth to be cut.

**Bores for Sprocket Cutters** (recommended practice) are approximately as calculated from the formula:

$$\text{Bore} = 0.7 \sqrt{(\text{Width of Cutter} + \text{Roller Diameter} + 0.7 \text{ Pitch})}$$

and are equal to 1 inch for  $\frac{1}{4}$ - through  $\frac{3}{4}$ -inch pitches;  $1\frac{1}{4}$  inches for 1- through  $1\frac{1}{2}$ -inch for  $1\frac{3}{4}$ - through  $2\frac{1}{4}$ -inch pitches;  $1\frac{3}{4}$  inches for  $2\frac{1}{2}$ -inch pitch; and 2 inches for 3-inch pitch.

**Minimum Outside Diameters of Space Cutters** for 35 teeth and over (recommended practice) are approximately as calculated from the formula:

$$\text{Outside Diameter} = 1.2(\text{Bore} + \text{Roller Diameter} + 0.7 \text{ Pitch}) + 1 \text{ in.}$$

**Shaper Cutters:** Only one will be required to cut any number of teeth for a given pitch and roller diameter. The manufacturer should be referred to for information concerning the cutter form design to be used.

**Sprocket Manufacture.**—Cast sprockets have cut teeth, and the rim, hub face, and bore are machined. The smaller sprockets are generally cut from steel bar stock, and are finished all over. Sprockets are often made from forgings or forged bars. The extent of finishing depends on the particular specifications that are applicable. Many sprockets are made by welding a steel hub to a steel plate. This process produces a one-piece sprocket of desired proportions and one that can be heat-treated.

**Sprocket Materials.**—For large sprockets, cast iron is commonly used, especially in drives with large speed ratios, since the teeth of the larger sprocket are subjected to fewer chain engagements in a given time. For severe service, cast steel or steel plate is preferred.

The smaller sprockets of a drive are usually made of steel. With this material the body of the sprocket can be heat-treated to produce toughness for shock resistance, and the tooth surfaces can be hardened to resist wear.

Stainless steel or bronze may be used for corrosion resistance, and Formica, nylon or other suitable plastic materials for special applications.

**Roller Chain Drive Ratings.**—In 1961, under auspices of The American Sprocket Chain Manufacturers Association (now called American Chain Association), a joint research program was begun to study pin-bushing interaction at high speeds and to gain further data on the phenomenon of chain joint galling among other research areas. These studies have shown that a separating film of lubricant is formed in chain joints in a manner similar to that found in journal bearings. These developments appear in ANSI/ASME B29.1M-1993, and are contained in Table 9. The ratings shown in Table 9 are below the galling range.

The horsepower ratings in Table 9 apply to lubricated, single-pitch, single-strand roller chains, both ANSI Standard and Heavy series. To obtain ratings of multiple-strand chains, a multiple-strand factor is applied.

The ratings in Table 9 are based upon: 1) A service factor of 1.; 2) A chain length of approximately 100 pitches.; 3) Use of recommended lubrication methods.; and 4) A drive arrangement where two aligned sprockets are mounted on parallel shafts in a horizontal plane.

Under these conditions, approximately 15,000 hours of service life at full load operation may be expected.

**Table 15. Roller Chain Drive Service Factors**

| Type of Driven Load | Type of Input Power                             |                           |  |
|---------------------|---|---------------------------|--|
|                     | Internal Combustion Engine with Hydraulic Drive | Electric Motor or Turbine | Internal Combustion Engine with Mechanical Drive |
| Smooth              | 1.0   | 1.0                       | 1.2  |
| Moderate Shock      | 1.2   | 1.3                       | 1.4  |
| Heavy Shock         | 1.4   | 1.5                       | 1.7  |

Substantial increases in rated speed loads can be utilized, as when a service life of less than 15,000 hours is satisfactory, or when full load operation is encountered only during a portion of the required service life. Chain manufacturers should be consulted for assistance with any special application requirements.

The horsepower ratings shown in Table 9 relate to the speed of the smaller sprocket and drive selections are made on this basis, whether the drive is speed reducing or speed increasing. Drives with more than two sprockets, idlers, composite duty cycles, or other unusual conditions often require special consideration. Where quietness or extra smooth operation are of special importance, small-pitch chain operating over large diameter sprockets will minimize noise and vibration.

When making drive selection, consideration is given to the loads imposed on the chain by the type of input power and the type of equipment to be driven. Service factors are used to compensate for these loads and the *required* horsepower rating of the chain is determined by the following formula:

$$\text{Required hp Table Rating} = \frac{\text{hp to be Transmitted} \times \text{Service Factor}}{\text{Multiple-Strand Factor}}$$

*Service Factors:* The service factors in Table 15 are for normal chain loading. For unusual or extremely severe operating conditions not shown in this table, it is desirable to use larger service factors.

*Multiple-Strand Factors:* The horsepower ratings for multiple-strand chains equal single-strand ratings multiplied by these factors: for two strands, a factor of 1.7; for three strands, 2.5; and for four strands, 3.3.

**Lubrication.**—It has been shown that a separating wedge of fluid lubricant is formed in operating chain joints much like that formed in journal bearings. Therefore, fluid lubricant must be applied to ensure an oil supply to the joints and minimize metal-to-metal contact. If supplied in sufficient volume, lubrication also provides effective cooling and impact damping at higher speeds. For this reason, it is important that lubrication recommendations be followed. *The ratings in Table 9 apply only to drives lubricated in the manner specified in this table.*

Chain drives should be protected against dirt and moisture and the oil supply kept free of contamination. Periodic oil change is desirable. A good grade of non-detergent petroleum base oil is recommended. Heavy oils and greases are generally too stiff to enter and fill the chain joints. The following lubricant viscosities are recommended: For temperatures of 20° to 40°F, use SAE 20 lubricant; for 40° to 100°, use SAE 30; for 100° to 120°, use SAE 40; and for 120° to 140°, use SAE 50.

There are three basic types of lubrication for roller chain drives. The recommended type shown in Table 9 as Type A, Type B, or Type C is influenced by the chain speed and the amount of power transmitted. These are *minimum* lubrication requirements and the use of a better type (for example, Type C instead of Type B) is acceptable and may be beneficial. Chain life can vary appreciably depending upon the way the drive is lubricated. The better the chain lubrication, the longer the chain life. For this reason, it is important that the lubrication recommendations be followed when using the ratings given in Table 9. The types of lubrication are as follows:

*Type A — Manual or Drip Lubrication:* In manual lubrication, oil is applied copiously with a brush or spout can at least once every eight hours of operation. Volume and frequency should be sufficient to prevent overheating of the chain or discoloration of the chain joints. In drip lubrication, oil drops from a drip lubricator are directed between the link plate edges. The volume and frequency should be sufficient to prevent discoloration of the lubricant in the chain joints. Precautions must be taken against misdirection of the drops by windage.

*Type B — Bath or Disc Lubrication:* In bath lubrication, the lower strand of the chain runs through a sump of oil in the drive housing. The oil level should reach the pitch line of the chain at its lowest point while operating. In disc lubrication, the chain operates above the oil level. The disc picks up oil from the sump and deposits it onto the chain, usually by means of a trough. The diameter of the disc should be such as to produce rim speeds of between 600 and 8000 feet per minute.

*Type C — Oil Stream Lubrication:* The lubricant is usually supplied by a circulating pump capable of supplying each chain drive with a continuous stream of oil. The oil should be applied inside the chain loop evenly across the chain width, and directed at the slack strand.

The chain manufacturer should be consulted when it appears desirable to use a type of lubricant other than that recommended.

**Installation and Alignment.**—Sprockets should have the tooth form, thickness, profile, and diameters conforming to ASME/ANSI B29.1M. For maximum service life small sprockets operating at moderate to high speeds, or near the rated horsepower, should have hardened teeth. Normally, large sprockets should not exceed 120 teeth.

In general a center distance of 30 to 50 chain pitches is most desirable. The distance between sprocket centers should provide at least a 120 degree chain wrap on the smaller sprocket. Drives may be installed with either adjustable or fixed center distances. Adjustable centers simplify the control of chain slack. Sufficient housing clearance must always be provided for the chain slack to obtain full chain life.

Accurate alignment of shafts and sprocket tooth faces provides uniform distribution of the load across the entire chain width and contributes substantially to optimum drive life.

Shafting, bearings, and foundations should be suitable to maintain the initial alignment. Periodic maintenance should include an inspection of alignment.

**Example of Roller Chain Drive Design Procedure.**—The selection of a roller chain and sprockets for a specific design requirement is best accomplished by a systematic step-by-step procedure such as is used in the following example.

*Example:* Select a roller chain drive to transmit 10 horsepower from a countershaft to the main shaft of a wire drawing machine. The countershaft is  $1\frac{5}{16}$ -inches diameter and operates at 1000 rpm. The main shaft is also  $1\frac{5}{16}$ -inches diameter and must operate between 378 and 382 rpm. Shaft centers, once established, are fixed and by initial calculations must be approximately  $22\frac{1}{2}$  inches. The load on the main shaft is uneven and presents “peaks,” which place it in the heavy shock load category. The input power is supplied by an electric motor. The driving head is fully enclosed and all parts are lubricated from a central system.

*Step 1. Service Factor:* From Table 15 the service factor for heavy shock load and an electric motor drive is 1.5.

*Step 2. Design Horsepower:* The horsepower upon which the chain selection is based (design horsepower) is equal to the specified horsepower multiplied by the service factor,  $10 \times 1.5 = 15$  hp.

*Step 3. Chain Pitch and Small Sprocket Size for Single-Strand Drive:* In Table 9 under 1000 rpm, a  $\frac{5}{8}$ -inch pitch chain with a 24-tooth sprocket or a  $\frac{3}{4}$ -inch pitch chain with a 15-tooth sprocket are possible choices.

*Step 4. Check of Chain Pitch and Sprocket Selection:* From Table 10 it is seen that only the 24-tooth sprocket in Step 3 can be bored to fit the  $1\frac{5}{16}$ -inch diameter main shaft. In Table 9 a  $\frac{5}{8}$ -pitch chain at a small sprocket speed of 1000 rpm is rated at 15.5 hp for a 24-tooth sprocket.

*Step 5. Selection of Large Sprocket:* Since the driver is to operate at 1000 rpm and the driven at a minimum of 378 rpm, the speed ratio  $1000/378 = 2.646$ . Therefore the large sprocket should have  $24 \times 2.646 = 63.5$  (use 63) teeth.

This combination of 24 and 63 teeth will produce a main drive shaft speed of 381 rpm which is within the limitation of 378 to 382 rpm established in the original specification.

*Step 6. Computation of Chain Length:* Since the 24- and 63-tooth sprockets are to be placed on  $22\frac{1}{2}$ -inch centers, the chain length is determined from the formula:

$$L = 2C + \frac{N}{2} + \frac{n}{2} + \left(\frac{N-n}{2\pi}\right)^2 \times \frac{1}{C}$$

where  $L$  = chain length in pitches;  $C$  = shaft center distance in pitches;  $N$  = number of teeth in large sprocket; and  $n$  = number of teeth in small sprocket.

$$L = 2 \times 36 + \frac{63 + 24}{2} + \left(\frac{63 - 24}{6.28}\right)^2 \times \frac{1}{36} = 116.57 \text{ pitches}$$

*Step 7. Correction of Center Distance:* Since the chain is to couple at a whole number of pitches, 116 pitches will be used and the center distance recomputed based on this figure using the formula on page 2457 where  $c$  is the center distance in inches and  $P$  is the pitch.

$$c = \frac{P}{8}(2L - N - n + \sqrt{(2L - N - n)^2 - 0.810(N - n)^2})$$

$$c = \frac{5}{64}(2 \times 116 - 63 - 24 + \sqrt{(2 \times 116 - 63 - 24)^2 - 0.810(63 - 24)^2})$$

$$c = \frac{5}{64}(145 + 140.69) = 22.32 \text{ inches, say } 22\frac{3}{8} \text{ inches}$$

## STANDARDS FOR ELECTRIC MOTORS

**Classes of NEMA Standards.**—National Electrical Manufacturers Association Standards, available from the Association at 2101 L Street, NW, Washington, DC 20037, are of two classes: 1) *NEMA Standard*, which relates to a product commercially standardized and subject to repetitive manufacture, which standard has been approved by at least 90 per cent of the members of the Subdivision eligible to vote thereon; and 2) *Suggested Standard for Future Design*, which may not have been regularly applied to a commercial product, but which suggests a sound engineering approach to future development and has been approved by at least two-thirds of the members of the Subdivision eligible to vote thereon.

*Authorized Engineering Information* consists of explanatory data and other engineering information of an informative character not falling within the classification of NEMA Standard or Suggested Standard for Future Design.

**Mounting Dimensions and Frame Sizes for Electric Motors.**—Dimensions for foot-mounted electric motors as standardized in the United States by the National Electrical Manufacturers Association (NEMA) include the spacing of bolt holes in the feet of the motor, the distance from the bottom of the feet to the center-line of the motor shaft, the size of the conduit, the length and diameter of shaft, and other dimensions likely to be required by designers or manufacturers of motor-driven equipment. The Standard provides dimensions for face-mounted and flange-mounted motors by means of standard motor frame numbers.

Standard dimensions also are given where the motor is to be mounted upon a belt-tightening base or upon rails.

The NEMA standards also prescribe lettering for dimension drawings, mounting and terminal housing locations and dimensions, symbols and terminal connections, and provision for grounding of field wiring. In addition, the standards give recommended knock-out and clearance hole dimensions; tolerances on shaft extension diameters and keyseats; methods of measuring shaft run-out and eccentricity, also face runout of mounting surfaces; and tolerances of face-mounted and flanged-mounted motors.

**Design Letters of Polyphase Integral-horsepower Motors.**—Designs A, B, C, and D motors are squirrel-cage motors designed to withstand full voltage starting and developing locked-rotor torque and breakdown torque, drawing locked-rotor current, and having a slip as specified below:

*Design A:* Locked-rotor torque as shown in [Table 2](#), breakdown torque as shown in [Table 3](#), locked-rotor current higher than the values shown in [Table 1](#), and a slip at rated load of less than 5 per cent. Motors with 10 or more poles may have a slightly greater slip.

**Table 1. NEMA Standard Locked-rotor Current of 3-phase 60-hertz Integral-horsepower Squirrel-cage Induction Motors Rated at 230 Volts**

| Horse-power | Locked-rotor Current, Amps. | Design Letters | Horse-power | Locked-rotor Current, Amps. | Design Letters | Horse-power | Locked-rotor Current, Amps. | Design Letters |
|-------------|-----------------------------|----------------|-------------|-----------------------------|----------------|-------------|-----------------------------|----------------|
| ½           | 20                          | B, D           | 7½          | 127                         | B, C, D        | 50          | 725                         | B, C, D        |
| ¾           | 25                          | B, D           | 10          | 162                         | B, C, D        | 60          | 870                         | B, C, D        |
| 1           | 30                          | B, D           | 15          | 232                         | B, C, D        | 75          | 1085                        | B, C, D        |
| 1½          | 40                          | B, D           | 20          | 290                         | B, C, D        | 100         | 1450                        | B, C, D        |
| 2           | 50                          | B, D           | 25          | 365                         | B, C, D        | 125         | 1815                        | B, C, D        |
| 3           | 64                          | B, C, D        | 30          | 435                         | B, C, D        | 150         | 2170                        | B, C, D        |
| 5           | 92                          | B, C, D        | 40          | 580                         | B, C, D        | 200         | 2900                        | B, C           |

*Note:* The locked-rotor current of a motor is the steady-state current taken from the line with the rotor locked and with rated voltage and frequency applied to the motor.

For motors designed for voltages other than 230 volts, the locked-rotor current is inversely proportional to the voltages. For motors larger than 200 hp, see NEMA Standard MG 1-12.34.

**Table 2. NEMA Standard Locked-rotor Torque of Single-speed Polyphase 60- and 50-hertz Squirrel-cage Integral-horsepower Motors with Continuous Ratings**

| Hp                                       | Designs A and B        |      |      |      |     |     |     |                                    | Design C |      |     |
|--|------------------------|------|------|------|-----|-----|-----|------------------------------------|----------|------|-----|
|  | Synchronous Speed, rpm |      |      |      |     |     |     |                                    |          |      |     |
|  | 60 hertz               | 3600 | 1800 | 1200 | 900 | 720 | 600 | 514                                | 1800     | 1200 | 900 |
|  | 50 hertz               | 3000 | 1500 | 1000 | 750 | ... | ... | ...                                | 1500     | 1000 | 750 |
| Percent of Full-load Torque <sup>a</sup> |                        |      |      |      |     |     |     |                                    |          |      |     |
| 1/2                                      | ...                    | ...  | ...  | 140  | 140 | 115 | 110 | ...                                | ...      | ...  | ... |
| 3/4                                      | ...                    | ...  | 175  | 135  | 135 | 115 | 110 | ...                                | ...      | ...  | ... |
| 1  | ...                    | 275  | 170  | 135  | 135 | 115 | 110 | ...                                | ...      | ...  | ... |
| 1 1/2                                    | 175                    | 250  | 165  | 130  | 130 | 115 | 110 | ...                                | ...      | ...  | ... |
| 2  | 170                    | 235  | 160  | 130  | 125 | 115 | 110 | ...                                | ...      | ...  | ... |
| 3  | 160                    | 215  | 155  | 130  | 125 | 115 | 110 | ...                                | 250      | 250  | 225 |
| 5  | 150                    | 185  | 150  | 130  | 125 | 115 | 110 | 250                                | 250      | 250  | 225 |
| 7 1/2                                    | 140                    | 175  | 150  | 125  | 120 | 115 | 110 | 250                                | 225      | 200  | ... |
| 10                                       | 135                    | 165  | 150  | 125  | 120 | 115 | 110 | 250                                | 225      | 200  | ... |
| 15                                       | 130                    | 160  | 140  | 125  | 120 | 115 | 110 | 225                                | 200      | 200  | ... |
| 20                                       | 130                    | 150  | 135  | 125  | 120 | 115 | 110 | 200 for all sizes above 15 hp.     |          |      |     |
| 25                                       | 130                    | 150  | 135  | 125  | 120 | 115 | 110 |                                    |          |      |     |
| 30                                       | 130                    | 150  | 135  | 125  | 120 | 115 | 110 |                                    |          |      |     |
| 40                                       | 125                    | 140  | 135  | 125  | 120 | 115 | 110 |                                    |          |      |     |
| 50                                       | 120                    | 140  | 135  | 125  | 120 | 115 | 110 |                                    |          |      |     |
| 60                                       | 120                    | 140  | 135  | 125  | 120 | 115 | 110 |                                    |          |      |     |
| 75                                       | 105                    | 140  | 135  | 125  | 120 | 115 | 110 |                                    |          |      |     |
| 100                                      | 105                    | 125  | 125  | 125  | 120 | 115 | 110 |                                    |          |      |     |
| 125                                      | 100                    | 110  | 125  | 120  | 115 | 115 | 110 |                                    |          |      |     |
| 150                                      | 100                    | 110  | 120  | 120  | 115 | 115 | ... |                                    |          |      |     |
| 200                                      | 100                    | 100  | 120  | 120  | 115 | ... | ... |                                    |          |      |     |
|  |                        |      |      |      |     |     |     | For Design D motors, see footnote. |          |      |     |

<sup>a</sup> These values represent the upper limit of application for these motors.

*Note:* The locked-rotor torque of a motor is the minimum torque which it will develop at rest for all angular positions of the rotor, with rated voltage applied at rated frequency.

The locked-rotor torque of Design D, 60- and 50-hertz 4-, 6-, and 8-pole single-speed, polyphase squirrel-cage motors rated 150 hp and smaller, with rated voltage and frequency applied is 275 per cent of full-load torque, which represents the upper limit of application for these motors.

For motors larger than 200 hp, see NEMA Standard MG 1-12.37.

**Table 3. NEMA Standard Breakdown Torque of Single-speed Polyphase Squirrel-cage, Integral-horsepower Motors with Continuous Ratings**

| Horsepower                   | Synchronous Speed, rpm       |      |      |      |     |     |     |     |     |     |
|------------------------------|------------------------------|------|------|------|-----|-----|-----|-----|-----|-----|
|                              | 60 hertz                     | 3600 | 1800 | 1200 | 900 | 720 | 600 | 514 | ... |     |
|                              | 50 hertz                     | 3000 | 1500 | 1000 | 750 | ... | ... | ... | ... |     |
|                              | Per Cent of Full Load Torque |      |      |      |     |     |     |     |     |     |
| Designs A and B <sup>a</sup> |                              |      |      |      |     |     |     |     |     |     |
| 1/2                          | ...                          | ...  | ...  | 225  | 200 | 200 | 200 | 200 | 200 | 200 |
| 3/4                          | ...                          | ...  | 275  | 220  | 200 | 200 | 200 | 200 | 200 | 200 |
| 1                            | ...                          | 300  | 265  | 215  | 200 | 200 | 200 | 200 | 200 | 200 |
| 1 1/2                        | 250                          | 280  | 250  | 210  | 200 | 200 | 200 | 200 | 200 | 200 |
| 2                            | 240                          | 270  | 240  | 210  | 200 | 200 | 200 | 200 | 200 | 200 |
| 3                            | 230                          | 250  | 230  | 205  | 200 | 200 | 200 | 200 | 200 | 200 |
| 5                            | 215                          | 225  | 215  | 205  | 200 | 200 | 200 | 200 | 200 | 200 |
| 7 1/2                        | 200                          | 215  | 205  | 200  | 200 | 200 | 200 | 200 | 200 | 200 |
| 10-125, incl.                | 200                          | 200  | 200  | 200  | 200 | 200 | 200 | 200 | 200 | 200 |
| 150                          | 200                          | 200  | 200  | 200  | 200 | 200 | 200 | 200 | ... | ... |
| 200                          | 200                          | 200  | 200  | 200  | 200 | 200 | ... | ... | ... | ... |
| Design C                     |                              |      |      |      |     |     |     |     |     |     |
| 3                            | ...                          | ...  | 225  | 200  | ... | ... | ... | ... | ... | ... |
| 5                            | ...                          | 200  | 200  | 200  | ... | ... | ... | ... | ... | ... |
| 7 1/2-200, incl.             | ...                          | 190  | 190  | 190  | ... | ... | ... | ... | ... | ... |

<sup>a</sup> Design A values are in excess of those shown.

These values represent the upper limit of the range of application for these motors. For above 200 hp, see NEMA Standard MG1-12.38.

*Design B:* Locked-rotor torque as shown in Table 2, breakdown torque as shown in Table 3, locked-rotor current not exceeding that in Table 1, and a slip at rated load of less than 5 per cent. Motors with 10 or more poles may have a slightly greater slip.

*Design C:* Locked-rotor torque for special high-torque applications up to values shown in Table 2, breakdown torque up to values shown in Table 3, locked-rotor current not exceeding values shown in Table 1 and a slip at rated load of less than 5 per cent.

*Design D:* Locked-rotor torque as indicated in Table 2, locked-rotor current not greater than that shown in Table 1 and a slip at rated load of 5 per cent or more.

**Torque and Current Definitions.**—The definitions which follow have been adopted as standard by the National Electrical Manufacturers Association.

*Locked-Rotor or Static Torque:* The locked-rotor torque of a motor is the minimum torque which it will develop at rest for all angular positions of the rotor, with rated voltage applied at rated frequency.

*Breakdown Torque:* The breakdown torque of a motor is the maximum torque which the motor will develop, with rated voltage applied at rated frequency, without an abrupt drop in speed (see Table 4).

*Full-Load Torque:* The full-load torque of a motor is the torque necessary to produce its rated horsepower at full load speed. In pounds at 1-foot radius, it is equal to the horsepower times 5252 divided by the full-load speed.

*Pull-Out Torque:* The pull-out torque of a synchronous motor is the maximum sustained torque which the motor will develop at synchronous speed with rated voltage applied at rated frequency and with normal excitation.

*Pull-In Torque:* The pull-in torque of a synchronous motor is the maximum constant torque under which the motor will pull its connected inertia load into synchronism at rated voltage and frequency, when its field excitation is applied.

*Pull-Up Torque:* The pull-up torque of an alternating current motor is the minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown torque occurs. For motors which do not have a definite breakdown torque, the pull-up torque is the minimum torque developed up to rated speed.

*Locked Rotor Current:* The locked rotor current of a motor is the steady-state current taken from the line with the rotor locked and with rated voltage (and rated frequency in the case of alternating-current motors) applied to the motor.

**Table 4. NEMA Standard Breakdown Torque of Polyphase Wound-rotor Motors with Continuous Ratings — 60- and 50-hertz**

| Horsepower | Speed, rpm                   |      |     | Horsepower    | Speed, rpm                   |      |     |
|------------|------------------------------|------|-----|---------------|------------------------------|------|-----|
|            | 1800                         | 1200 | 900 |               | 1800                         | 1200 | 900 |
|            | Per cent of Full-load Torque |      |     |               | Per cent of Full-load Torque |      |     |
| 1          | ...                          | ...  | 250 | 7½            | 275                          | 250  | 225 |
| 1½         | ...                          | ...  | 250 | 10            | 275                          | 250  | 225 |
| 2          | 275                          | 275  | 250 | 15            | 250                          | 225  | 225 |
| 3          | 275                          | 275  | 250 | 20–200, incl. | 225                          | 225  | 225 |
| 5          | 275                          | 275  | 250 | ...           | ...                          | ...  | ... |

These values represent the upper limit of the range of application for these motors.

**Standard Direction of Motor Rotation.**—The standard direction of rotation for all non-reversing direct-current motors, all alternating-current single-phase motors, all synchronous motors, and all universal motors, is *counterclockwise* when facing that end of the motor opposite the drive.

This rule does not apply to two- and three-phase induction motors, as in most applications the phase sequence of the power lines is rarely known.



**Motor Types According to Variability of Speed.**—Five types of motors classified according to variability of speed are:

*Constant-speed Motors:* In this type of motor the normal operating speed is constant or practically constant; for example, a synchronous motor, an induction motor with small slip, or a direct-current shunt-wound motor.

*Varying-speed Motor:* In this type of motor, the speed varies with the load, ordinarily decreasing when the load increases; such as a series-wound or repulsion motor.

*Adjustable-speed Motor:* In this type of motor, the speed can be varied gradually over a considerable range, but when once adjusted remains practically unaffected by the load; such as a direct-current shunt-wound motor with field resistance control designed for a considerable range of speed adjustment.

The base speed of an adjustable-speed motor is the lowest rated speed obtained at rated load and rated voltage at the temperature rise specified in the rating.

*Adjustable Varying-speed Motor:* This type of motor is one in which the speed can be adjusted gradually, but when once adjusted for a given load will vary in considerable degree with the change in load; such as a direct-current compound-wound motor adjusted by field control or a wound-rotor induction motor with rheostatic speed control.

*Multispeed Motor:* This type of motor is one which can be operated at any one of two or more definite speeds, each being practically independent of the load; such as a direct-current motor with two armature windings or an induction motor with windings capable of various pole groupings. In the case of multispeed permanent-split capacitor and shaded pole motors, the speeds are dependent upon the load.

**Pull-up Torque.**—NEMA Standard pull up torques for single-speed, polyphase, squirrel-cage integral-horsepower motors, Designs A and B, with continuous ratings and with rated voltage and frequency applied are as follows: When the locked-rotor torque given in Table 2 is 110 per cent or less, the pull-up torque is 90 per cent of the locked-rotor torque; when the locked-rotor torque is greater than 110 per cent but less than 145 per cent, the pull-up torque is 100 per cent of full-load torque; and when the locked-rotor torque is 145 per cent or more, the pull-up torque is 70 per cent of the locked-rotor torque.

For Design C motors, with rated voltage and frequency applied, the pull-up torque is not less than 70 per cent of the locked-rotor torque as given in Table 2.

### Types and Characteristics of Electric Motors

**Types of Direct-Current Motors.**—Direct-current motors may be grouped into three general classes: series-wound; shunt-wound; and compound-wound.

In the *series-wound motor* the field windings, which are fixed in the stator frame, and the armature windings, which are placed around the rotor, are connected in series so that all current passing through the armature also passes through the field. In the *shunt-wound motor*, both armature and field are connected across the main power supply so that the armature and field currents are separate. In the *compound-wound motor*, both series and shunt field windings are provided and these may be connected so that the currents in both are flowing in the same direction, called *cumulative compounding*, or so that the currents in each are flowing in opposite directions, called *differential compounding*.

**Characteristics of Series-wound Direct-Current Motors.**—In the series-wound motor, any increase in load results in more current passing through the armature and the field windings. As the field is strengthened by this increased current, the motor speed decreases. Conversely, as the load is decreased the field is weakened and the speed increases and at very light loads may become excessive. For this reason, series-wound direct-current motors are usually directly connected or geared to the load to prevent “run-away.” (A series-wound motor, designated as series-shunt wound, is sometimes provided with a light shunt field winding to prevent dangerously high speeds at light loads.) The increase in armature current with increasing load produces increased torque, so that the

series-wound motor is particularly suited to heavy starting duty and where severe overloads may be expected. Its speed may be adjusted by means of a variable resistance placed in series with the motor, but due to variation with load, the speed cannot be held at any constant value. This variation of speed with load becomes greater as the speed is reduced. Series-wound motors are used where the load is practically constant and can easily be controlled by hand. They are usually limited to traction and lifting service.

**Shunt-wound Direct-Current Motors.**—In the shunt-wound motor, the strength of the field is not affected appreciably by change in the load, so that a fairly constant speed (about 10 to 12 per cent drop from no load to full load speed) is obtainable. This type of motor may be used for the operation of machines requiring an approximately constant speed and imposing low starting torque and light overload on the motor.

The shunt-wound motor becomes an adjustable-speed motor by means of field control or by armature control. If a variable resistance is placed in the field circuit, the amount of current in the field windings and hence the speed of rotation can be controlled. As the speed increases, the torque decreases proportionately, resulting in nearly constant horsepower. A speed range of 6 to 1 is possible using field control, but 4 to 1 is more common. Speed regulation is somewhat greater than in the constant-speed shunt-wound motors, ranging from about 15 to 22 per cent. If a variable resistance is placed in the armature circuit, the voltage applied to the armature can be reduced and hence the speed of rotation can be reduced over a range of about 2 to 1. With armature control, speed regulation becomes poorer as speed is decreased, and is about 100 per cent for a 2 to 1 speed range. Since the current through the field remains unchanged, the torque remains constant.

*Machine Tool Applications:* The adjustable-speed shunt-wound motors are useful on larger machines of the boring mill, lathe, and planer type and are particularly adapted to spindle drives because constant horsepower characteristics permit heavy cuts at low speed and light or finishing cuts at high speed. They have long been used for planer drives because they can provide an adjustable low speed for the cutting stroke and a high speed for the return stroke. Their application has been limited, however, to plants in which direct-current power is available.

**Adjustable-voltage Shunt-wound Motor Drive.**—More extensive use of the shunt-wound motor has been made possible by a combination drive that includes a means of converting alternating current to direct current. This conversion may be effected by a self-contained unit consisting of a separately excited direct-current generator driven by a constant speed alternating-current motor connected to the regular alternating-current line, or by an electronic rectifier with suitable controls connected to the regular alternating-current supply lines. The latter has the advantage of causing no vibration when mounted directly on the machine tool, an important factor in certain types of grinders.

In this type of adjustable-speed, shunt-wound motor drive, speed control is effected by varying the voltage applied to the armature while supplying constant voltage to the field. In addition to providing for the adjustment of the voltage supplied by the conversion unit to the armature of the shunt-wound motor, the amount of current passing through the motor field may also be controlled. In fact, a single control may be provided to vary the motor speed from minimum to base speed (speed of the motor at full load with rated voltage on armature and field) by varying the voltage applied to the armature and from base speed to maximum speed by varying the current flowing through the field. When so controlled, the motor operates at constant torque up to base speed and at constant horsepower above base speed.

*Speed Range:* Speed ranges of at least 20 to 1 below base speed and 4 or 5 to 1 above base speed (a total range of 100 to 1, or more) are obtainable as compared with about 2 to 1 below normal speed and 3 or 4 to 1 above normal speed for the conventional type of control. Speed regulation may be as great as 25 per cent at high speeds. Special electronic controls, when used with this type shunt motor drive, make possible maintenance of motor

speeds with as little variation as  $\frac{1}{2}$  to 1 per cent of full load speed from full load to no load over a line voltage variation of  $\pm 10$  per cent and over any normal variation in motor temperature and ambient temperature.

*Applications:* These direct-current, adjustable-voltage drives, as they are sometimes called, have been applied successfully to such machine tools as planers, milling machines, boring mills and lathes, as well as to other industrial machines where wide, stepless speed control, uniform speed under all operating conditions, constant torque acceleration and adaptability to automatic operation are required.

**Compound-wound Motors.**—In the compound-wound motor, the speed variation due to load changes is much less than in the series-wound motor, but greater than in the shunt-wound motor (ranging up to 25 per cent from full load to no load). It has a greater starting torque than the shunt-wound motor, is able to withstand heavier overloads, but has a narrower adjustable speed range. Standard motors of this type have a cumulative-compound winding, the differential-compound winding being limited to special applications. They are used where the starting load is very heavy or where the load changes suddenly and violently as with reciprocating pumps, printing presses and punch presses.

**Types of Polyphase Alternating-Current Motors.**—The most widely used polyphase motors are of the induction type. The “*squirrel cage*” induction motor consists of a wound stator which is connected to an external source of alternating-current power and a laminated steel core rotor with a number of heavy aluminum or copper conductors set into the core around its periphery and parallel to its axis. These conductors are connected together at each end of the rotor by a heavy ring, which provides closed paths for the currents induced in the rotor to circulate. The rotor bars form, in effect, a “squirrel cage” from which the motor takes its name.

*Wound-rotor type of Induction motor:* This type has in addition to a squirrel cage, a series of coils set into the rotor which are connected through slip-rings to external variable resistors. By varying the resistance of the wound-rotor circuits, the amount of current flowing in these circuits and hence the speed of the motor can be controlled. Since the rotor of an induction motor is not connected to the power supply, the motor is said to operate by transfer action and is analogous to a transformer with a short-circuited secondary that is free to rotate. Induction motors are built with a wide range of speed and torque characteristics which are discussed under “Operating Characteristics of Squirrel-cage Induction Motors.”

*Synchronous Motor:* The other type of polyphase alternating-current motor used industrially is the *synchronous motor*. In contrast to the induction motor, the rotor of the synchronous motor is connected to a direct-current supply which provides a field that rotates in step with the alternating-current field in the stator. After having been brought up to synchronous speed, which is governed by the frequency of the power supply and the number of poles in the rotor, the synchronous motor operates at this constant speed throughout its entire load range.

**Operating Characteristics of Squirrel-cage Induction Motors.**—In general, squirrel-cage induction motors are simple in design and construction and offer rugged service. They are essentially constant-speed motors, their speed changing very little with load and not being subject to adjustment. They are used for a wide range of industrial applications calling for integral horsepower ratings. According to the NEMA (National Electrical Manufacturers Association) Standards, there are four classes of squirrel-cage induction motors designated respectively as *A*, *B*, *C*, and *D*.

*Design A* motors are not commonly used since *Design B* has similar characteristics with the advantage of lower starting current.

*Design B:* motors may be designated as a general purpose type suitable for the majority of polyphase alternating-current applications such as blowers, compressors, drill presses, grinders, hammer mills, lathes, planers, polishers, saws, screw machines, shakers, stokers,

etc. The starting torque at 1800 R.P.M. is 250 to 275 per cent of full load torque for 3 H.P. and below; for 5 H.P. to 75 H. P. ratings the starting torque ranges from 185 to 150 per cent of full load torque. They have low starting current requirements, usually no more than 5 to 6 times full load current and can be started at full voltage. Their slip (difference between synchronous speed and actual speed at rated load) is relatively low.

*Design C:* motors have high starting torque (up to 250 per cent of full load torque) but low starting current. They can be started at full voltage. Slip at rated load is relatively low. They are used for compressors requiring a loaded start, heavy conveyors, reciprocating pumps and other applications requiring high starting torque.

*Design D:* motors have high slip at rated load, that is, the motor speed drops off appreciably as the load increases, permitting use of the stored energy of a flywheel. They provide heavy starting torque, up to 275 per cent of full load torque, are quiet in operation and have relatively low starting current. Applications are for impact, shock and other high peak loads or flywheel drives such as trains, elevators, hoists, punch and drawing presses, shears, etc.

*Design F:* motors are no longer standard. They had low starting torque, about 125 per cent of full-load torque, and low starting current. They were used to drive machines which required infrequent starting at no load or at very light load.

**Multiple-Speed Induction Motors.**—This type has a number of windings in the stator so arranged and connected that the number of effective poles and hence the speed can be changed. These motors are for the same types of starting conditions as the conventional squirrel-cage induction motors and are available in designs that provide constant horsepower at all rated speeds and in designs that provide constant torque at all rated speeds.

Typical speed combinations obtainable in these motors are 600, 900, 1200 and 1800 R.P.M.; 450, 600, 900 and 1200 R.P.M.; and 600, 720, 900 and 1200 R.P.M.

Where a gradual change in speed is called for, a wound rotor may be provided in addition to the multiple stator windings.

**Wound-Rotor Induction Motors.**—These motors are designed for applications where extremely low starting current with high starting torque are called for, such as in blowers, conveyors, compressors, fans and pumps. They may be employed for adjustable-varying speed service where the speed range does not extend below 50 per cent of synchronous speed, as for steel plate-forming rolls, printing presses, cranes, blowers, stokers, lathes and milling machines of certain types. The speed regulation of a wound rotor induction motor ranges from 5 to 10 per cent at maximum speed and from 18 to 30 per cent at low speed. They are also employed for reversing service as in cranes, gates, hoists and elevators.

**High-Frequency Induction Motors.**—This type is used in conjunction with frequency changers when very high speeds are desired, as on grinders, drills, routers, portable tools or woodworking machinery. These motors have an advantage over the series-wound or universal type of high speed motor in that they operate at a relatively constant speed over the entire load range. A motor-generator set, a two-unit frequency converter or a single unit inductor frequency converter may be used to supply three-phase power at the frequency required. The single unit frequency converter may be obtained for delivering any one of a number of frequencies ranging from 360 to 2160 cycles and it is self-driven and self-excited from the general polyphase power supply.

**Synchronous Motors.**—These are widely used in electric timing devices; to drive machines that must operate in synchronism; and also to operate compressors, rolling mills, crushers which are started without load, paper mill screens, shredders, vacuum pumps and motor-generator sets. Synchronous motors have an inherently high power factor and are often employed to make corrections for the low power factor of other types of motors on the same system.

**Types of Single-Phase Alternating-Current Motors.**—Most of the single-phase alternating-current motors are basically induction motors distinguished by different arrangements for starting. (A single-phase induction motor with only a squirrel-cage rotor has no starting torque.) In the *capacitor-start* single-phase motor, an auxiliary winding in the stator is connected in series with a capacitor and a centrifugal switch. During the starting and accelerating period the motor operates as a two-phase induction motor. At about two-thirds full-load speed, the auxiliary circuit is disconnected by the switch and the motor then runs as a single-phase induction motor. In the *capacitor-start, capacitor-run* motor, the auxiliary circuit is arranged to provide high effective capacity for high starting torque and to remain connected to the line but with reduced capacity during the running period. In the *single-value capacitor* or *capacitor split-phase* motor, a relatively small continuously-rated capacitor is permanently connected in one of the two stator windings and the motor both starts and runs like a two-phase motor.

In the *repulsion-start* single-phase motor, a drum-wound rotor circuit is connected to a commutator with a pair of short-circuited brushes set so that the magnetic axis of the rotor winding is inclined to the magnetic axis of the stator winding. The current flowing in this rotor circuit reacts with the field to produce starting and accelerating torques. At about two-thirds full load speed the brushes are lifted, the commutator is short circuited and the motor runs as a single-phase squirrel-cage motor. The *repulsion* motor employs a repulsion winding on the rotor for both starting and running. The *repulsion-induction* motor has an outer winding on the rotor acting as a repulsion winding and an inner squirrel-cage winding. As the motor comes up to speed, the induced rotor current partially shifts from the repulsion winding to the squirrel-cage winding and the motor runs partly as an induction motor.

In the *split-phase* motor, an auxiliary winding in the stator is used for starting with either a resistance connected in series with the auxiliary winding (*resistance-start*) or a reactor in series with the main winding (*reactor-start*).

The *series-wound* single-phase motor has a rotor winding in series with the stator winding as in the series-wound direct-current motor. Since this motor may also be operated on direct current, it is called a *universal* motor.

**Characteristics of Single-Phase Alternating-Current Motors.**—Single-phase motors are used in sizes up to about  $7\frac{1}{2}$  horsepower for heavy starting duty chiefly in home and commercial appliances for which polyphase power is not available. The *capacitor-start* motor is available in normal starting torque designs for such applications as centrifugal pumps, fans, and blowers and in high-starting torque designs for reciprocating compressors, pumps, loaded conveyors, or belts. The *capacitor-start, capacitor-run* motor is exceptionally quiet in operation when loaded to at least 50 per cent of capacity. It is available in low-torque designs for fans and centrifugal pumps and in high-torque designs for applications similar to those of the capacitor-start motor.

The *capacitor split-phase* motor requires the least maintenance of all single-phase motors, but has very low starting torque. Its high maximum torque makes it potentially useful in floor sanders or in grinders where momentary overloads due to excessive cutting pressure are experienced. It is also used for slow-speed direct connected fans.

The *repulsion-start, induction-run* motor has higher starting torque than the capacitor motors, although for the same current, the capacitor motors have equivalent pull-up and maximum torque. Electrical and mechanical noise and the extra maintenance sometimes required are disadvantages. These motors are used for compressors, conveyors and stokers starting under full load. The *repulsion-induction* motor has relatively high starting torque and low starting current. It also has a smooth speed-torque curve with no break and a greater ability to withstand long accelerating periods than capacitor type motors. It is particularly suitable for severe starting and accelerating duty and for high inertia loads such as laundry extractors. Brush noise is, however, continuous.

The *repulsion* motor has no limiting synchronous speed and the speed changes with the load. At certain loads, slight changes in load cause wide changes in speed. A brush shifting arrangement may be provided to adjust the speed which may have a range of 4 to 1 if full rated constant torque is applied but a decreasing range as the torque falls below this value. This type of motor may be reversed by shifting the brushes beyond the neutral point. These motors are suitable for machines requiring constant-torque and adjustable speed.

The *split-phase* and *universal* motors are limited to about  $\frac{1}{2}$  H.P. ratings and are used chiefly for small appliance and office machine applications.

**Motors with Built-in Speed Reducers.**—Electric motors having built-in speed-changing units are compact and the design of these motorized speed reducers tends to improve the appearance of the machines which they drive. There are several types of these speed reducers; they may be classified according to whether they are equipped with worm gearing, a regular gear train with parallel shafts, or planetary gearing.

The claims made for the worm gearing type of reduction unit are that the drive is quiet in operation and well adapted for use where the slow-speed shaft must be at right angles to the motor shaft and where a high speed ratio is essential.

For very low speeds, the double reduction worm gearing units are suitable. In these units two sets of worm gearing form the gear train, and both the slow-speed shaft and the armature shaft are parallel. The intermediate worm gear shaft can be built to extend from the housing, if required, so as to make two countershaft speeds available on the same unit.

In the parallel-shaft type of speed reducer, the slow-speed shaft is parallel with the armature shaft. The slow-speed shaft is rotated by a pinion on the armature shaft, this pinion meshing with a larger gear on the slow-speed shaft.

Geared motors having built-in speed-changing units are available with constant-mesh change gears for varying the speed ratio.

Planetary gearing permits a large speed reduction with few parts; hence, it is well adapted for geared-head motor units where economy and compactness are essential. The slow-speed shaft is in line with the armature shaft.

### Factors Governing Motor Selection

**Speed, Horsepower, Torque and Inertia Requirements.**—Where more than one speed or a range of speeds are called for, one of the following types of motors may be selected, depending upon other requirements: For direct-current, the standard shunt-wound motor with field control has a 2 to 1 range in some designs; the adjustable speed motor may have a range of from 3 to 1 up to 6 to 1; the shunt motor with adjustable voltage supply has a range up to 20 to 1 or more below base speed and 4 or 5 to 1 above base speed, making a total range of up to 100 to 1 or more. For polyphase alternating current, multi-speed squirrel-cage induction motors have 2, 3 or 4 fixed speeds; the wound-rotor motor has a 2 to 1 range. The two-speed wound-rotor motor has a 4 to 1 range. The brush-shifting shunt motor has a 4 to 1 range. The brush-shifting series motor has a 3 to 1 range; and the squirrel-cage motor with a variable-frequency supply has a very wide range. For single-phase alternating current, the brush-shifting repulsion motor has a  $2\frac{1}{2}$  to 1 range; the capacitor motor with tapped winding has a 2 to 1 range and the multi-speed capacitor motor has 2 or 3 fixed speeds. Speed regulation (variation in speed from no load to full load) is greatest with motors having series field windings and entirely absent with synchronous motors.

**Horsepower:** Where the load to be carried by the motor is not constant but follows a definite cycle, a horsepower-time curve enables the peak horsepower to be determined as well as the root-mean-square-average horsepower, which indicates the proper motor rating from a heating standpoint. Where the load is maintained at a constant value for a period of from 15 minutes to 2 hours depending on the size, the horsepower rating required will usually not be less than this constant value. When selecting the size of an induction motor, it should be kept in mind that this type of motor operates at maximum efficiency when it is

loaded to full capacity. Where operation is to be at several speeds, the horsepower requirement for each speed should be considered.

*Torque:* Starting torque requirements may vary from 10 per cent of full load to 250 per cent of full load torque depending upon the type of machine being driven. Starting torque may vary for a given machine because of frequency of start, temperature, type and amount of lubricant, etc., and such variables should be taken into account. The motor torque supplied to the machine must be well above that required by the driven machine at all points up to full speed. The greater the excess torque, the more rapid the acceleration. The approximate time required for acceleration from rest to full speed is given by the formula:

$$\text{Time} = \frac{N \times WR^2}{T_a \times 308} \text{ seconds}$$

where  $N$  = Full load speed in R.P.M.

$T_a$  = Torque = average foot-pounds available for acceleration.

$WR^2$  = Inertia of rotating part in pounds feet squared ( $W$  = weight and  $R$  = radius of gyration of rotating part).

308 = Combined constant converting minutes into seconds, weight into mass and radius into circumference.

If the time required for acceleration is greater than 20 seconds, special motors or starters may be required to avoid overheating.

The running torque  $T_r$  is found by the formula:

$$T_r = \frac{5250 \times \text{HP}}{N} \text{ foot pounds}$$

where  $H.P.$  = Horsepower being supplied to the driven machine

$N$  = Running speed in R.P.M.

5250 = Combined constant converting horsepower to foot-pounds per minute and work per revolution into torque.

The peak horsepower determines the maximum torque required by the driven machine and the motor must have a maximum running torque in excess of this value.

*Inertia:* The inertia or flywheel effect of the rotating parts of a driven machine will, if large, appreciably affect the accelerating time and, hence, the amount of heating in the motor. If synchronous motors are used, the inertia ( $WR^2$ ) of both the motor rotor and the rotating parts of the machine must be known since the pull-in torque (torque required to bring the driven machine up to synchronous speed) varies approximately as the square root of the total inertia of motor and load.

**Space Limitations in Motor Selection.**—If the motor is to become an integral part of the machine which it drives and space is at a premium, a partial motor may be called for. A complete motor is one made up of a stator, a rotor, a shaft, and two end shields with bearings. A *partial motor* is without one or more of these elements. One common type is furnished without drive-end end shield and bearing and is directly connected to the end or side of the machine which it drives, such as the headstock of a lathe. A so-called *shaftless type of motor* is supplied without shaft, end shields or bearings and is intended for built-in application in such units as multiple drilling machines, precision grinders, deep well pumps, compressors and hoists where the rotor is actually made a part of the driven machine. Where a partial motor is used, however, proper ventilation, mounting, alignment and bearings must be arranged for by the designer of the machine to which it is applied.

Sometimes it is possible to use a motor having a smaller frame size and wound with Class B insulation, permitting it to be subjected to a higher temperature rise than the larger-frame Class A insulated motor having the same horsepower rating.

**Temperatures.**—The applicability of a given motor is limited not only by its load starting and carrying ability, but also by the temperature which it reaches under load. Motors are given temperature ratings which are based upon the type of insulation (Class A or Class B are the most common) used in their construction and their type of frame (open, semien-closed, or enclosed).

*Insulating Materials:* Class A materials are: cotton, silk, paper, and similar organic materials when either impregnated or immersed in a liquid dielectric; molded and laminated materials with cellulose filler, phenolic resins, and other resins of similar properties; films and sheets of cellulose acetate and other cellulose derivatives of similar properties; and varnishes (enamel) as applied to conductors.

Class B insulating materials are: materials or combinations of materials such as mica, glass fiber, asbestos, etc., with suitable bonding substances. Other materials shown capable of operation at Class B temperatures may be included.

*Ambient Temperature and Allowable Temperature Rise:* Normal ambient temperature is taken to be 40°C (104°F). For open general-purpose motors with Class A insulation, the normal temperature rise on which the performance guarantees are based is 40°C (104°F).

Motors with Class A insulation having protected, semiprotected, drip-proof, or splash-proof, or drip-proof protected enclosures have a 50°C (122°F) rise rating.

Motors with Class A insulation and having totally enclosed, fan-cooled, explosion-proof, waterproof, dust-tight, submersible, or dust-explosion-proof enclosures have a 55°C (131°F) rise rating.

Motors with Class B insulation are permissible for total temperatures up to 110 degrees C (230°F) for open motors and 115°C (239°F) for enclosed motors.

**Motors Exposed to Injurious Conditions.**—Where motors are to be used in locations imposing unusual operating conditions, the manufacturer should be consulted, especially where any of the following conditions apply: exposure to chemical fumes; operation in damp places; operation at speeds in excess of specified overspeed; exposure to combustible or explosive dust; exposure to gritty or conducting dust; exposure to lint; exposure to steam; operation in poorly ventilated rooms; operation in pits, or where entirely enclosed in boxes; exposure to inflammable or explosive gases; exposure to temperatures below 10°C (50°F); exposure to oil vapor; exposure to salt air; exposure to abnormal shock or vibration from external sources; where the departure from rated voltage is excessive; and or where the alternating-current supply voltage is unbalanced.

Improved insulating materials and processes and greater mechanical protection against falling materials and liquids make it possible to use general-purpose motors in many locations where special-purpose motors were previously considered necessary. *Splash-proof motors* having well-protected ventilated openings and specially treated windings are used where they are to be subjected to falling and splashing water or are to be washed down as with a hose. Where climatic conditions are not severe, this type of motor is also successfully used in unprotected outdoor installations.

If the surrounding atmosphere carries abnormal quantities of metallic, abrasive, or non-explosive dust or acid or alkali fumes, a *totally enclosed fan-cooled motor* may be called for. In this type, the motor proper is completely enclosed but air is blown through an outer shell that completely or partially surrounds the inner case. If the dust in the atmosphere tends to pack or solidify and close the air passages of open splash-proof or totally enclosed fan-cooled motors, *totally enclosed (nonventilated) motors* are used. This type, which is limited to low horsepower ratings, is also used for outdoor service in mild or severe climates.



**Table 1. Characteristics and Applications of D.C. Motors, 1–300 hp**

| Type                                    | Starting Duty   | Maximum Momentary Running Torque    | Speed Regulation   | Speed Control <sup>a</sup>   | Applications  |
|---|---|-------------------------------------|--|--|---|
| Shunt-wound, constant-speed             | Medium starting torque. Varies with voltage supplied to armature, and is limited by starting resistor to 125 to 200% full-load torque | 125 to 200%. Limited by commutation | 8 to 12%   | Basic speed to 200% basic speed by field control                         | Drives where starting requirements are not severe. Use constant-speed or adjustable-speed, depending on speed required. Centrifugal pumps, fans, blowers, conveyors, elevators, wood- and metalworking machines |
| Shunt-wound, adjustable speed           |   |                                     | 10 to 20%, increases with weak fields                              | Basic speed to 60% basic speed (lower for some ratings) by field control |   |
| Shunt-wound, adjustable voltage control |   |                                     | Up to 25%. Less than 5% obtainable with special rotating regulator | Basic speed to 2% basic speed and basic speed to 200% basic speed        | Drives where wide, stepless speed control, uniform speed, constant-torque acceleration and adaptability to automatic operation are required. Planers, milling machines, boring machines, lathes, etc.           |
| Compound wound, constant-speed          | Heavy starting torque, Limited by starting resistor to 130 to 260% of full-load torque  | 130 to 260%. Limited by commutation | Standard compounding 25%. Depends on amount of series winding      | Basic speed to 125% basic speed by field control                         | Drives requiring high starting torque and fairly constant speed. Pulsating loads. Shears, bending rolls, pumps, conveyors, crushers, etc.   |
| Series-wound, varying-speed             | Very heavy starting torque. Limited to 300 to 350% full-load torque   | 300 to 350%. Limited by commutation | Very high. Infinite no-load speed                                  | From zero to maximum speed, depending on control and load                | Drives where very high starting torque is required and speed can be regulated. Cranes, hoists, gates, bridges, car dumpers, etc.  |

<sup>a</sup>Minimum speed below basic speed by armature control limited by heating.

**Table 2. Characteristics and Applications of Polyphase AC Motors**

| Polyphase Type  | Ratings hp              | Speed Regulation  | Speed Control   | Starting Torque  | Breakdown Torque   | Applications   |
|---|-------------------------|---|---|--|--|--|
| General-purpose squirrel cage, normal stg current, normal stg torque. Design B      | 0.5 to 200              | Less than 5%  | None, except multi-speed types, designed for two to four fixed speeds                         | 100 to 250% of full-load   | 200 to 300% of full-load   | Constant-speed service where starting torque is not excessive. Fans, blowers, rotary compressors, centrifugal pumps, woodworking machines, machine tools, line shafts  |
| Full-voltage starting, high stg torque, normal stg current, squirrel-cage, Design C | 3 to 150                | Less than 5%  | None except multi-speed types, designed for two to four fixed speeds                          | 200 to 250% of full-load   | 190 to 225% of full-load   | Constant-speed service where fairly high starting torque is required at infrequent intervals with starting current of about 500% full-load. Reciprocating pumps and compressors, conveyors, crushers, pulverizers, agitators, etc. |
| Full-voltage starting, high stg-torque, high-slip squirrel cage, Design D           | 0.5 to 150              | Drops about 7 to 12% from no load to full load                                  | None, except multi-speed types, designed for two to four fixed speeds                         | 275% of full-load depending on speed and rotor resistance                                | 275% of full-load<br>Will usually not stall until loaded to its maximum torque, which occurs at standstill | Constant-speed service and high-starting torque if starting not too frequent, and for taking high-peak loads with or without flywheels. Punch presses, die stamping, shears, bulldozers, bailers, hoists, cranes, elevators, etc.  |
| Wound-rotor, external-resistance starting   | 0.5 to several thousand | With rotor rings short-circuited drops about 3% for large to 5% for small sizes | Speed can be reduced to 50% of normal by rotor resistance. Speed varies inversely as the load | Up to 300% depending on external resistance in rotor circuit and how distributed         | 200% when rotor slip rings are short circuited   | Where high-starting torque with low-starting current or where limited speed control is required. Fans, centrifugal and plunger pumps, compressors, conveyors, hoists, cranes, ball mills, gate hoists, etc.                        |
| Synchronous   | 25 to several thousand  | Constant  | None, except special motors designed for two fixed speeds                                     | 40% for slow speed to 160% for medium speed 80% p-f designs. Special high-torque designs | Pull-out torque of unity-p-f motors 170%; 80%-p-f motors 225%. Special designs up to 300%                  | For constant-speed service, direct connection to slow-speed machines and where power-factor correction is required.  |

In addition to these special-purpose motors, there are two types of *explosion-proof motors* designed for hazardous locations. One type is for operation in hazardous dust locations (Class II, Group *G* of the National Electrical Code) and the other is for atmospheres containing explosive vapors and fumes classified as Class I, Group *D* (gasoline, naphtha, alcohols, acetone, lacquer-solvent vapors, natural gas).

### Electric Motor Maintenance

**Electric Motor Inspection Schedule.**—Frequency and thoroughness of inspection depend upon such factors as 1) importance of the motor in the production scheme; 2) percentage of days the motor operates; 3) nature of service; and 4) winding conditions.

The following schedules, recommended by the General Electric Company, and covering both AC and DC motors are based on average conditions in so far as duty and dirt are concerned.

**Weekly Inspection.**—1) *Surroundings.* Check to see if the windings are exposed to any dripping water, acid or alcoholic fumes; also, check for any unusual amount of dust, chips, or lint on or about the motor. See if any boards, covers, canvas, etc., have been misplaced that might interfere with the motor ventilation or jam moving parts.

2) *Lubrication of sleeve-bearing motors.* In sleeve-bearing motors check oil level, if a gage is used, and fill to the specified line. If the journal diameter is less than 2 inches, the motor should be stopped before checking the oil level. For special lubricating systems, such as wool-packed, forced lubrication, flood and disk lubrication, follow instruction book. Oil should be added to bearing housing only when motor is at rest. A check should be made to see if oil is creeping along the shaft toward windings where it may harm the insulation.

3) *Mechanical condition.* Note any unusual noise that may be caused by metal-to-metal contact or any odor as from scorching insulation varnish.

4) *Ball or roller bearings.* Feel ball- or roller-bearing housings for evidence of vibration, and listen for any unusual noise. Inspect for creepage of grease on inside of motor.

5) *Commutators and brushes.* Check brushes and commutator for sparking. If the motor is on cyclic duty it should be observed through several cycles. Note color and surface condition of the commutator. A stable copper oxide-carbon film (as distinguished from a pure copper surface) on the commutator is an essential requirement for good commutation. Such a film may vary in color all the way from copper to straw, chocolate to black. It should be clean and smooth and have a high polish. All brushes should be checked for wear and pigtail connections for looseness. The commutator surface may be cleaned by using a piece of dry canvas or other hard, nonlinting material that is wound around and securely fastened to a wooden stick, and held against the rotating commutator.

6) *Rotors and armatures.* The air gap on sleeve-bearing motors should be checked, especially if they have been recently overhauled. After installing new bearings, make sure that the average reading is within 10 per cent, provided reading should be less than 0.020 inch. Check air passages through punchings and make sure they are free of foreign matter.

7) *Windings.* If necessary clean windings by suction or mild blowing. After making sure that the motor is dead, wipe off windings with dry cloth, note evidence of moisture, and see if any water has accumulated in the bottom of frame. Check if any oil or grease has worked its way up to the rotor or armature windings. Clean with carbon tetrachloride in a well-ventilated room.

8) *General.* This is a good time to check the belt, gears, flexible couplings, chain, and sprockets for excessive wear or improper location. The motor starting should be checked to make sure that it comes up to proper speed each time power is applied.

**Monthly or Bimonthly Inspection.**—1) *Windings.* Check shunt, series, and commutating field windings for tightness. Try to move field spools on the poles, as drying out may have caused some play. If this condition exists, a service shop should be consulted. Check motor cable connections for tightness.

2) *Brushes.* Check brushes in holders for fit and free play. Check the brush-spring pressure. Tighten brush studs in holders to take up slack from drying out of washers, making sure that studs are not displaced, particularly on DC motors. Replace brushes that are worn down almost to the brush rivet, examine brush faces for chipped toes or heels, and for heat cracks. Damaged brushes should be replaced immediately.

3) *Commutators.* Examine commutator surface for high bars and high mica, or evidence of scratches or roughness. See that the risers are clean and have not been damaged.

4) *Ball or roller bearings.* On hard-driven, 24-hour service ball- or roller-bearing motors, purge out old grease through drain hole and apply new grease. Check to make sure grease or oil is not leaking out of the bearing housing. If any leakage is present, correct the condition before continuing to operate.

5) *Sleeve bearings.* Check sleeve bearings for wear, including end-play bearing surfaces. Clean out oil wells if there is evidence of dirt or sludge. Flush with lighter oil before refilling.

6) *Enclosed gears.* For motors with enclosed gears, open drain plug and check oil flow for presence of metal scale, sand, or water. If condition of oil is bad, drain, flush, and refill as directed. Rock rotor to see if slack or backlash is increasing.

7) *Loads.* Check loads for changed conditions, bad adjustment, poor handling, or control.

8) *Couplings and other drive details.* Note if belt-tightening adjustment is all used up. Shorten belt if this condition exists. See if belt runs steadily and close to inside (motor edge) of pulley. Chain should be checked for evidence of wear and stretch. Clean inside of chain housing. Check chain-lubricating system. Note inclination of slanting base to make sure it does not cause oil rings to rub on housing.

**Annual or Biannual Inspection.**—1) *Windings.* Check insulation resistance by using either a megohmmeter or a voltmeter having a resistance of about 100 ohms per volt. Check insulation surfaces for dry cracks and other evidence of need for coatings of insulating material. Clean surfaces and ventilating passages thoroughly if inspection shows accumulation of dust. Check for mold or water standing in frame to determine if windings need to be dried out, varnished, and baked.

2) *Air gap and bearings.* Check air gap to make sure that average reading is within 10 per cent, provided reading should be less than 0.020 inch. All bearings, ball, roller, and sleeve should be thoroughly checked and defective ones replaced. Waste-packed and wick-oiled bearings should have waste or wicks renewed, if they have become glazed or filled with metal or dirt, making sure that new waste bears well against shaft.

3) *Rotors (squirrel-cage).* Check squirrel-cage rotors for broken or loose bars and evidence of local heating. If fan blades are not cast in place, check for loose blades. Look for marks on rotor surface indicating foreign matter in air gap or a worn bearing.

4) *Rotors (wound).* Clean wound rotors thoroughly around collector rings, washers, and connections. Tighten connections if necessary. If rings are rough, spotted, or eccentric, refer to service shop for refinishing. See that all top sticks or wedges are tight. If any are loose, refer to service shop.

5) *Armatures.* Clean all armature air passages thoroughly if any are obstructed. Look for oil or grease creeping along shaft, checking back to bearing. Check commutator for surface condition, high bars, high mica, or eccentricity. If necessary, remachine the commutator to secure a smooth fresh surface.

6) *Loads.* Read load on motor with instruments at no load, full load, or through an entire cycle, as a check on the mechanical condition of the driven machine.

## ADHESIVES AND SEALANTS

By strict definition, an adhesive is any substance that fastens or bonds materials to be joined (adherends) by means of surface attachment. The bond durability depends on the strength of the adhesive to the substrate (adhesion) and the strength within the adhesive (cohesion). Besides bonding a joint, an adhesive may serve as a seal against foreign matter. When an adhesive performs both bonding and sealing functions, it is usually referred to as an adhesive sealant. Joining materials with adhesives offers significant benefits compared with mechanical methods of uniting two materials.

Among these benefits are that an adhesive distributes a load over an area rather than concentrating it at a point, resulting in a more even distribution of stresses. The adhesive bonded joint is therefore more resistant to flexural and vibrational stresses than, for example, a bolted, riveted, or welded joint. Another benefit is that an adhesive forms a seal as well as a bond. This seal prevents the corrosion that may occur with dissimilar metals, such as aluminum and magnesium, or mechanically fastened joints, by providing a dielectric insulation between the substrates. An adhesive also joins irregularly shaped surfaces more easily than does a mechanical fastener. Other benefits include negligible weight addition and virtually no change to part dimensions or geometry.

Most adhesives are available in liquids, gels, pastes, and tape forms. The growing variety of adhesives available can make the selection of the proper adhesive or sealant a challenging experience. In addition to the technical requirements of the adhesive, time and costs are also important considerations. Proper choice of an adhesive is based on knowledge of the suitability of the adhesive or sealant for the particular substrates. Appropriate surface preparation, curing parameters, and matching the strength and durability characteristics of the adhesive to its intended use are essential. The performance of an adhesive-bonded joint depends on a wide range of these factors, many of them quite complex. Adhesive suppliers can usually offer essential expertise in the area of appropriate selection.

Adhesives can be classified as structural or nonstructural. In general, an adhesive can be considered structural when it is capable of supporting heavy loads; nonstructural when it cannot support such loads. Many adhesives and sealants, under various brand names, may be available for a particular bonding application. It is always advisable to check the adhesive manufacturers' information before making an adhesive sealant selection. Also, testing under end-use conditions is always suggested to help ensure bonded or sealed joints meet or exceed expected performance requirements.

Though not meant to be all-inclusive, the following information correlates the features of some successful adhesive compositions available in the marketplace.

### Bonding Adhesives

Reactive-type bonding adhesives are applied as liquids and react (cure) to solids under appropriate conditions. The cured adhesive is either a thermosetting or thermoplastic polymer. These adhesives are supplied as two-component no-mix, two-component mix, and one-component no-mix types, which are discussed in the following paragraphs.

### Two-Component No-Mix Adhesives

**Types of Adhesives.**—*Anaerobic (Urethane Methacrylate Ester) Structural Adhesives:* Anaerobic structural adhesives are mixtures of acrylic esters that remain liquid when exposed to air but harden when confined between metal substrates. These adhesives can be used for large numbers of industrial purposes where high reliability of bond joints is required. Benefits include: no mixing is required (no pot-life or waste problems), flexible/durable bonds are made that withstand thermal cycling, have excellent resistance to solvents and severe environments, and rapid cure at room temperatures (eliminating

expensive ovens). The adhesives are easily dispensed with automatic equipment. An activator is usually required to be present on one surface to initiate the cure for these adhesives. Applications for these adhesives include bonding of metals, magnets (ferrites), glass, thermosetting plastics, ceramics, and stone.

*Acrylic Adhesives:* Acrylic adhesives are composed of a polyurethane polymer backbone with acrylate end groups. They can be formulated to cure through heat or the use of an activator applied to the substrate surface, but many industrial acrylic adhesives are cured by light. Light-cured adhesives are used in applications where the bond geometry allows light to reach the adhesive and the production rate is high enough to justify the capital expense of a light source. Benefits include: no mixing is required (no pot-life or waste problems); formulations cure (solidify) with activator, heat, or light; the adhesive will bond to a variety of substrates, including metal and most thermoplastics; and tough and durable bonds are produced with a typical resistance to the effects of temperatures up to 180°C. Typical applications include automobile body parts (steel stiffeners), assemblies subjected to paint-baking cycles, speaker magnets to pole plates, and bonding of motor magnets, sheet steel, and many other structural applications. Other applications include bonding glass, sheet metal, magnets (ferrite), thermosetting and thermoplastic plastics, wood, ceramics, and stone.

### Two-Component Mix Adhesives

**Types of Adhesives.**—*Epoxy Adhesives:* Two-component epoxy adhesives are well-established adhesives that offer many benefits in manufacturing. The reactive components of these adhesives are separated prior to use, so they usually have a good shelf life without refrigeration. Polymerization begins upon mixing, and a thermoset polymer is formed. Epoxy adhesives cure to form thermosetting polymers made up of a base side with the polymer resin and a second part containing the catalyst. The main benefit of these systems is that the depth of cure is unlimited. As a result, large volume can be filled for work such as potting, without the cure being limited by the need for access to an external influence such as moisture or light to activate the curing process.

For consistent adhesive performance, it is important that the mix ratio remain constant to eliminate variations in adhesive performance. Epoxies can be handled automatically, but the equipment involves initial and maintenance costs. Alternatively, adhesive components can be mixed by hand. However, this approach involves labor costs and the potential for human error. The major disadvantage of epoxies is that they tend to be very rigid and consequently have low peel strength. This lack of peel strength is less of a problem when bonding metal to metal than it is when bonding flexible substrates such as plastics.

Applications of epoxy adhesives include bonding, potting, and coating of metals, bonding of glass, rigid plastics, ceramics, wood, and stone.

*Polyurethane Adhesives:* Like epoxies, polyurethane adhesives are available as two-part systems or as one-component frozen premixes. They are also available as one-part moisture-cured systems. Polyurethane adhesives can provide a wide variety of physical properties. Their flexibility is greater than that of most epoxies. Coupled with the high cohesive strength, this flexibility provides a tough polymer able to achieve better peel strength and lower flexural modulus than most epoxy systems. This superior peel resistance allows use of polyurethanes in applications that require high flexibility. Polyurethanes bond very well to a variety of substrates, though a primer may be needed to prepare the substrate surface. These primers are moisture-reactive and require several hours to react sufficiently for the parts to be used. Such a time requirement may cause a production bottleneck if the bond-strength requirements are such that a primer is needed.

Applications for polyurethane adhesives include bonding of metals, glass, rubber, thermosetting and thermoplastic plastics, and wood.

**One-Component No-Mix Adhesives**

**Types of Adhesives.**—*Light-Curable Adhesives:* Light-curing systems use a unique curing mechanism. The adhesives contain photoinitiators that absorb light energy and dissociate to form radicals. These radicals then initiate the polymerization of the polymers, oligomers, and monomers in the adhesive. The photoinitiator acts as a chemical solar cell, converting the light energy into chemical energy for the curing process. Typically, these systems are formulated for use with ultraviolet light sources. However, newer products have been formulated for use with visible light sources.

One of the biggest benefits that light-curing adhesives offer to the manufacturer is the elimination of the work time to work-in-progress trade-off, which is embodied in most adhesive systems. With light-curing systems, the user can take as much time as needed to position the part without fear of the adhesive curing. Upon exposure to the appropriate light source, the adhesive then can be fully cured in less than 1 minute, minimizing the costs associated with work in progress. Adhesives that utilize light as the curing mechanism are often one-part systems with good shelf life, which makes them even more attractive for manufacturing use.

Applications for light-curable adhesives include bonding of glass, and glass to metal, tacking of wires, surface coating, thin-film encapsulation, clear substrate bonding, and potting of components,

*Cyanoacrylate Adhesives (Instant Adhesives):* Cyanoacrylates or instant adhesives are often called Superglue™. Cyanoacrylates are one-part adhesives that cure rapidly, as a result of the presence of surface moisture, to form high-strength bonds, when confined between two substrates. Cyanoacrylates have excellent adhesion to many substrates, including most plastics and they achieve fixture strength in seconds and full strength within 24 hours. These qualities make cyanoacrylates suitable for use in automated production environments. They are available in viscosities ranging from water-thin liquids to thixotropic gels.

Because cyanoacrylates are a relatively mature adhesive family, a wide variety of specialty formulations is now available to help the user address difficult assembly problems. One of the best examples is the availability of polyolefin primers, which allow users to obtain high bond strengths on difficult-to-bond plastics such as polyethylene and polypropylene. One common drawback of cyanoacrylates is that they form a very rigid polymer matrix, resulting in very low peel strengths. To address this problem, formulations have been developed that are rubber-toughened. Although the rubber toughening improves the peel strength of the system to some extent, peel strength remains a weak point for this system, and, therefore, cyanoacrylates are poor candidates for joint designs that require high peel resistance. In manufacturing environments with low relative humidity, the cure of the cyanoacrylate can be significantly retarded.

This problem can be addressed in one of two ways. One approach is to use accelerators that deposit active species on the surface to initiate the cure of the product. The other approach is to use specialty cyanoacrylate formulations that have been engineered to be surface-insensitive. These formulations can cure rapidly even on dry or slightly acidic surfaces.

Applications for cyanoacrylate adhesives include bonding of thermoplastic and thermosetting plastics, rubber, metals, wood, and leather, also strain relief of wires.

*Hot-Melt Adhesives:* Hot-melt adhesives are widely used in assembly applications. In general, hot-melt adhesives permit fixturing speeds that are much faster than can be achieved with water- or solvent-based adhesives. Usually supplied in solid form, hot-melt adhesives liquify when exposed to elevated temperatures. After application, they cool quickly, solidifying and forming a bond between two mating substrates. Hot-melt adhesives have been used successfully for a wide variety of adherends and can greatly reduce both the need for clamping and the length of time for curing. Some drawbacks with hot-

melt adhesives are their tendency to string during dispensing and relatively low-temperature resistance.

Applications for hot-melt adhesives are bonding of fabrics, wood, paper, plastics, and cardboard.

**Rubber-Based Solvent Cements:** Rubber-based solvent cements are adhesives made by combining one or more rubbers or elastomers in a solvent. These solutions are further modified with additives to improve the tack or stickiness, the degree of peel strength, flexibility, and the viscosity or body. Rubber-based adhesives are used in a wide variety of applications such as contact adhesive for plastics laminates like counter tops, cabinets, desks, and tables. Solvent-based rubber cements have also been the mainstay of the shoe and leather industry for many years.

Applications for rubber-based solvent cements include bonding of plastics laminates, wood, paper, carpeting, fabrics, and leather.

**Moisture-Cured Polyurethane Adhesives:** Like heat-curing systems, moisture-cured polyurethanes have the advantage of a very simple curing process. These adhesives start to cure when moisture from the atmosphere diffuses into the adhesive and initiates the polymerization process. In general, these systems will cure when the relative humidity is above 25 per cent, and the rate of cure will increase as the relative humidity increases.

The dependence of these systems on the permeation of moisture through the polymer is the source of their most significant process limitations. As a result of this dependence, depth of cure is limited to between 0.25 and 0.5 in. (6.35 and 12.7 mm). Typical cure times are in the range of 12 to 72 hours. The biggest use for these systems is for windshield bonding in automobile bodies.

Applications for moisture-cured polyurethane adhesives include bonding of metals, glass, rubber, thermosetting and thermoplastic plastics, and wood.

### Retaining Compounds

The term *retaining compounds* is used to describe adhesives used in circumferential assemblies joined by inserting one part into the other. In general, retaining compounds are anaerobic adhesives composed of mixtures of acrylic esters that remain liquid when exposed to air but harden when confined between cylindrical machine components. A typical example is a bearing held in an electric motor housing with a retaining compound. The first retaining compounds were launched in 1963, and the reaction among users of bearings was very strong because these retaining compounds enabled buyers of new bearings to salvage worn housings and minimize their scrap rate.

The use of retaining compounds has many benefits, including elimination of bulk needed for high friction forces, ability to produce more accurate assemblies and to augment or replace press fits, increased strength in heavy press fits, and reduction of machining costs. Use of these compounds also helps in dissipating heat through assembly, and eliminating distortion when installing drill bushings, fretting corrosion and backlash in keys and splines, and bearing seizure during operation.

The major advantages of retaining compounds for structural assemblies are that they require less severe machining tolerances and no securing of parts. Components are assembled quickly and cleanly, and they transmit high forces and torques, including dynamic forces. Retaining compounds also seal, insulate, and prevent micromovements so that neither fretting corrosion nor stress corrosion occurs. The adhesive joint can be taken apart easily after heating above 450°F (230°C) for a specified time.

Applications for retaining compounds include mounting of bearings in housings or on shafts, avoiding distortion of precision tooling and machines, mounting of rotors on shafts, inserting drill jig bushings, retaining cylinder linings, holding oil filter tubes in castings, retaining engine-core plugs, restoring accuracy to worn machine tools, and eliminating keys and set screws.



### Threadlocking

The term *threadlocker* is used to describe adhesives used in threaded assemblies for locking the threaded fasteners by filling the spaces between the nut and bolt threads with a hard, dense material that prevents loosening. In general, thread-lockers are anaerobic adhesives comprising mixtures of acrylic esters that remain liquid when exposed to air but harden when confined between threaded components. A typical example is a mounting bolt on a motor or a pump. Threadlocker strengths range from very low strength (removable) to high strength (permanent).

It is important that the total length of the thread is coated and that there is no restriction to the curing of the threadlocker material. (Certain oils or cleaning systems can impede or even completely prevent the adhesive from curing by anaerobic reaction.) The liquid threadlocker may be applied by hand or with special dispensing devices. Proper coating (wetting) of a thread is dependent on the size of the thread, the viscosity of the adhesive, and the geometry of the parts. With blind-hole threads, it is essential that the adhesive be applied all the way to the bottom of the threaded hole. The quantity must be such that after assembly, the displaced adhesive fills the whole length of the thread.

Some threadlocking products cured by anaerobic reaction have a positive influence on the coefficient of friction in the thread. The values are comparable with those of oiled bolts. Prestress and installation torque therefore can be defined exactly. This property allows threadlocking products cured by anaerobic reaction to be integrated into automated production lines using existing assembly equipment. The use of thread-lockers has many benefits including ability to lock and seal all popular bolt and nut sizes with all industrial finishes, and to replace mechanical locking devices. The adhesive can seal against most industrial fluids and will lubricate threads so that the proper clamp load is obtained. The materials also provide vibration-resistant joints that require handtool dismantling for servicing, prevent rusting of threads, and cure (solidify) without cracking or shrinking.

The range of applications includes such uses as locking and sealing nuts on hydraulic pistons, screws on vacuum cleaner bell housings, track bolts on bulldozers, hydraulic-line fittings, screws on typewriters, oil-pressure switch assembly, screws on carburetors, rocker nuts, machinery driving keys, and on construction equipment.

### Sealants

The primary role of a sealant composition is the prevention of leakage from or access by dust, fluids, and other materials to assembly structures. Acceptable leak rates can range from a slight drip to bubbletight to molecular diffusion through the base materials. Equipment users in the industrial market want trouble-free operation, but it is not always practical to specify zero leak rates. Factors influencing acceptable leak rates are toxicity, product or environmental contamination, combustibility, economics, and personnel considerations. All types of fluid seals perform the same basic function: they seal the process fluid (gas, liquid, or vapor) and keep it where it belongs. A general term for these assembly approaches is gasketing. Many products are being manufactured that are capable of sealing a variety of substrates.

**Types of Sealants.**—*Anaerobic Formed-in-Place Gasketing Materials:* Mechanical assemblies that require the joining of metal-to-metal flange surfaces have long been designed with prefabricated, precut materials required to seal the imperfect surfaces of the assembly. Numerous gasket materials that have been used to seal these assemblies include paper, cork, asbestos, wood, metals, dressings, and even plastics. Fluid seals are divided into static and dynamic systems, depending on whether or not the parts move in relationship to each other. Flanges are classed as static systems, although they may be moved relative to each other by vibration, temperature, and/or pressure changes, shocks, and impacts.

The term *anaerobic formed-in-place gasketing* is used to describe sealants that are used in flanged assemblies to compensate for surface imperfections of metal-to-metal compo-

nents by filling the space between the substrates with a flexible, nonrunning material. In general, anaerobic formed-in-place gaskets are sealants made up of mixtures of acrylic esters that remain liquid when exposed to air but harden when confined between components. A typical example is sealing two halves of a split crankcase.

The use of anaerobic formed-in-place gaskets has many benefits, including the ability to seal all surface imperfections, allow true metal-to-metal contact, eliminate compression set and fastener loosening, and add structural strength to assemblies. These gaskets also help improve torque transmission between bolted flange joints, eliminate bolt retorquing needed with conventional gaskets, permit use of smaller fasteners and lighter flanges, and provide for easy disassembly and cleaning.

Applications in which formed-in-place gasketing can be used to produce leakproof joints include pipe flanges, split crankcases, pumps, compressors, power takeoff covers, and axle covers. These types of gaskets may also be used for repairing damaged conventional gaskets and for coating soft gaskets.

*Silicone Rubber Formed-in-Place Gasketing:* Another type of formed-in-place gasket uses room-temperature vulcanizing (RTV) silicone rubbers. These materials are one-component sealants that cure on exposure to atmospheric moisture. They have excellent properties for vehicle use such as flexibility, low volatility, good adhesion, and high resistance to most automotive fluids. The materials will also withstand temperatures up to 600°F (320°C) for intermittent operation.

RTV silicones are best suited for fairly thick section (gap) gasketing applications where flange flexing is greatest. In the form of a very thin film, for a rigid metal-to-metal seal, the cured elastomer may abrade and eventually fail under continual flange movement. The RTV silicone rubber does not unitize the assembly, and it requires relatively clean, oil-free surfaces for sufficient adhesion and leakproof seals.

Because of the silicone's basic polymeric structure, RTV silicone elastomers have several inherent characteristics that make them useful in a wide variety of applications. These properties include outstanding thermal stability at temperatures from 400 to 600°F (204 to 320°C), and good low-temperature flexibility at -85 to -165°F (-65 to -115°C). The material forms an instant seal, as is required of all liquid gaskets, and will fill large gaps up to 0.250 in. (6.35 mm) for stamped metal parts and flanges. The rubber also has good stability in ultraviolet light and excellent weathering resistance.

Applications for formed-in-place RTV silicones in the automotive field are valve, camshaft and rocker covers, manual transmission (gearbox) flanges, oil pans, sealing panels, rear axle housings, timing chain covers, and window plates. The materials are also used on oven doors and flues.

### **Tapered Pipe-thread Sealing**

Thread sealants are used to prevent leakage of gases and liquids from pipe joints. All joints of this type are considered to be dynamic because of vibration, changing pressures, or changing temperatures.

Several types of sealants are used on pipe threads including noncuring pipe dopes, which are one of the oldest methods of sealing the spiral leak paths of threaded joints. In general, pipe dopes are pastes made from oils and various fillers. They lubricate joints and jam threads but provide no locking advantage. They also squeeze out under pressure, and have poor solvent resistance. Noncuring pipe dopes are not suitable for use on straight threads.

Another alternative is solvent-drying pipe dopes, which are an older method of sealing tapered threaded joints. These types of sealant offer the advantages of providing lubrication and orifice jamming and they also extrude less easily than noncuring pipe dopes. One disadvantage is that they shrink during cure as the solvents evaporate and fittings must be retorqued to minimize voids. These materials generally lock the threaded joint together by friction. A third type of sealer is the trapped elastomer supplied in the form of a thin tape

incorporating polytetrafluorethylene (PTFE). This tape gives a good initial seal and resists chemical attack, and is one of the only materials used for sealing systems that will seal against oxygen gas.

Some other advantages of PTFE are that it acts as a lubricant, allows for high torquing, and has a good resistance to various solvents. Some disadvantages are that it may not provide a true seal between the two threaded surfaces, and it lubricates in the off direction, so it may allow fittings to loosen. In dynamic joints, tape may allow creep, resulting in leakage over time. The lubrication effect may allow overtightening, which can add stress or lead to breakage. Tape also may be banned in some hydraulic systems due to shredding, which may cause clogging of key orifices.

**Anaerobic Pipe Sealants.**—*Anaerobic Pipe Sealants:* The term *anaerobic pipe sealants* is used to describe anaerobic sealants used in tapered threaded assemblies for sealing and locking threaded joints. Sealing and locking are accomplished by filling the space between the threads with the sealant. In general, these pipe sealants are anaerobic adhesives consisting of mixtures of acrylic esters that remain liquid when exposed to air but harden when confined between threaded components to form an insoluble tough plastics. The strength of anaerobic pipe sealants is between that of elastomers and yielding metal.

Clamp loads need be only tight enough to prevent separation in use. Because they develop strength by curing after they are in place, these sealants are generally forgiving of tolerances, tool marks, and slight misalignment. These sealants are formulated for use on metal substrates. If the materials are used on plastics, an activator or primer should be used to prepare the surfaces.

Among the advantages of these anaerobic sealers are that they lubricate during assembly, they seal regardless of assembly torque, and they make seals that correspond with the burst rating of the pipe. They also provide controlled disassembly torque, do not cure outside the joint, and are easily dispensed on the production line. These sealants also have the lowest cost per sealed fitting. Among the disadvantages are that the materials are not suitable for oxygen service, for use with strong oxidizing agents, or for use at temperatures above 200°C. The sealants also are typically not suitable for diameters over M80 (approximately 3 inches).

The many influences faced by pipe joints during service should be known and understood at the design stage, when sealants are selected. Sealants must be chosen for reliability and long-term quality. Tapered pipe threads must remain leak-free under the severest vibration and chemical attack, also under heat and pressure surges.

Applications of aerobic sealants are found in industrial plant fluid power systems, the textile industry, chemical processing, utilities and power generation facilities, petroleum refining, and in marine, automotive, and industrial equipment. The materials are also used in the pulp and paper industries, in gas compression and distribution, and in waste-treatment facilities.

## MOTION CONTROL

The most important factor in the manufacture of accurately machined components is the control of motion, whatever power source is used. For all practical purposes, motion control is accomplished by electrical or electronic circuits, energizing or deenergizing actuators such as electric motors or solenoid valves connected to hydraulic or pneumatic cylinders or motors. The accuracy with which a machine tool slide, for example, may be brought to a required position, time after time, controls the dimensions of the part being machined. This accuracy is governed by the design of the motion control system in use.

There is a large variety of control systems, with power outputs from milliwatts to megawatts, and they are used for many purposes besides motion control. Such a system may control a mechanical positioning unit, which may be linear or rotary, its velocity, acceleration, or combinations of these motion parameters. A control system may also be used to set voltage, tension, and other manufacturing process variables and to actuate various types of solenoid-operated valves. The main factors governing design of control systems are whether they are to be open- or closed-loop; what kinds and amounts of power are available; and the function requirements.

Factors governing selection of control systems are listed in [Table 1](#).

**Table 1. Control System Application Factors**

|                          |   |
|--------------------------|---|
| Type of System           | Nature of required control motion, i.e., position, velocity, acceleration   |
| Accuracy                 | Controlled output versus input  |
| Mechanical Load          | Viscous friction, coulomb friction, starting friction, load inertia   |
| Impact Loads             | Hitting mechanical stops and load disturbances  |
| Ratings                  | Torque or force, and speed  |
| Torque                   | Peak instantaneous torque   |
| Duty Cycle               | Load response, torque level, and duration and effect on thermal response  |
| Ambient Temperature      | Relation to duty cycle and internal temperature rise, and to the effect of temperature on the sensor  |
| Speed of Response        | Time to reach commanded condition. Usually defined by a response to a stepped command   |
| Frequency Response       | Output to input ratio versus frequency, for varying frequency and specified constant input amplitude. Usually expressed in decibels   |
| No-Load Speed            | Frequently applies to maximum kinetic energy and to impact on stops; avoiding overspeeding  |
| Backdriving              | With power off, can the load drive the motor? Is a fail-safe brake required? Can the load backdrive with power on without damage to the control electronics? (Electric motor acting as a generator) |
| Power Source             | Range of voltage and frequency within which the system must work. Effect of line transients   |
| Environmental Conditions | Range of nonoperating and operating conditions, reliability and serviceability, scheduled maintenance   |

**Open-Loop Systems.**—The term open-loop typically describes use of a rheostat or variable resistance to vary the input voltage and thereby adjust the speed of an electric motor, a low-accuracy control method because there is no output sensor to measure the performance. However, use of stepper motors (see [Table 2](#), and page 2493) in open-loop systems can make them very accurate. Shafts of stepper motors are turned through a fixed angle for every electrical pulse transmitted to them. The maximum pulse rate can be high, and the shaft can be coupled with step-down gear drives to form inexpensive, precise drive units

with wide speed ranges. Although average speed with stepper motors is exact, speed modulation can occur at low pulse rates and drives can incur serious resonance problems.

**Table 2. Control Motor Types**

|                            |   |
|----------------------------|---|
| AC Motors                  | Induction motors, simplest, lowest cost, most rugged, can work directly off the ac line or through an inexpensive, efficient, and compact thyristor controller. Useful in fan and other drives where power increases rapidly with speed as well as in simple speed regulation. Ac motors are larger than comparable permanent-magnet motors |
| Two-Phase Induction Motors | Often used as control motors in small electromechanical control systems. Power outputs range from a few milliwatts to tens of watts   |
| Split-Field Series Motors  | Work on both ac and dc. Feature high starting torque, low cost, uniform power output over a wide speed range, and are easily reversed with a single-pole three-position switch. Very easy to use with electric limit switches for controlling angle of travel   |
| Permanent-Magnet Motors    | Operate on dc, with high power output and high efficiency. The most powerful units use rare-earth magnets and are more expensive than conventional types. Lower-cost ferrite magnets are much less expensive and require higher gear-reduction ratios, but at their higher rated speeds are very efficient                                  |
| Brushless DC Motors        | Use electrical commutation and may be applied as simple drive motors or as four-quadrant control motors. The absence of brushes for commutation ensures high reliability and low electromagnetic interference   |
| Stepper Motors             | Index through a fixed angle for each input pulse so that speed is in exact proportion to pulse rate and the travel angle increases uniformly with the number of pulses. Proper application in systems with backlash and load inertia requires special care  |
| Wound-Field DC Motors      | For subfractional to integral horsepower applications where size is not significant. Cost is moderate because permanent magnets are not required. Depending on the windings, output characteristics can be adjusted for specific applications   |

Open-loop systems are only as accurate as the input versus output requirement can be calibrated, including the effects of changes in line voltage, temperature, and other operating conditions.

**Closed-Loop Systems.**—Table 3 shows some parameters and characteristics of closed-loop systems, and a simple example of such a system is shown below. A command may be input by a human operator, it may be derived from another piece of system equipment, or it may be generated by a computer. Generally, the command is in the form of an electrical signal. The system response is converted by the output sensor to a compatible, scaled electrical signal that may be compared with the input command, the difference constituting an error signal. It is usually required that the error be small, so it is amplified and applied to an appropriate driving unit. The driver may take many forms, but for motion control it is usually a motor.

The amplified error voltage drives the motor to correct the error. If the input command is constant, the system is a closed-loop regulator.

Closed-loop systems use feedback sensors that measure system output and give instructions to the power drive components, based on the measured values. A typical closed-loop speed control, for instance, uses a tachometer as a feedback sensor and will correct automatically for differences between the tachometer output and the commanded speed. All motion control systems require careful design to achieve good practical performance. Closed-loop systems generally cost more than open-loop systems because of the extra cost

of the tachometer or transducer used for output measurement. Faster response components also increase cost.

**Table 3. Closed-Loop System Parameters and Characteristics**

|  |  |
|--|--|
| Step Response                                | The response of the system to a step change in the input command. The response to a large step, which can saturate the system amplifier, is different from the response to a small nonsaturating step. Initial overshoots may not be permissible in some types of equipment  |
| Frequency Response                           | System response to a specified small-amplitude sinusoidal command where frequency is varied over the range of interest. The response is in decibels (dB), where $\text{dB} = 20 \log_{10}(\text{output}/\text{input})$ . This characteristic determines whether the system is responsive enough to meet requirements                                 |
| Bandwidth                                    | The effective range of input frequencies within which the control system responds well. The bandwidth is often described by the point where the frequency response is down by three decibels. Bandwidth is usually defined in Hz (cycles/sec) or $\omega = 2\pi \times \text{Hz}$ (radians/sec)  |
| Loading                                      | The torque required to drive the load and the load inertia. The amplifier must supply enough power to meet acceleration as well as output power requirements. If the load is nonlinear, its effect on error must be within specifications. Behavior may vary considerably, depending on whether the load aids or opposes motor torque, as in a hoist |
| Output Stiffness                             | A measure of the system's response to load disturbances. Dynamic stiffness measures the system's response to a rapidly varying load  |
| Resonant Peaks                               | Can show up in frequency-response testing as sharp (undamped) resonances. These resonances cannot be tolerated in the normal frequency range of the control system because they can lead to oscillation and vibration  |
| No load, or maximum speed and maximum torque | Can be controlled by voltage or current limiting in the electronic amplifier. A slip clutch can also be used for torque limiting, particularly to avoid impact damage  |

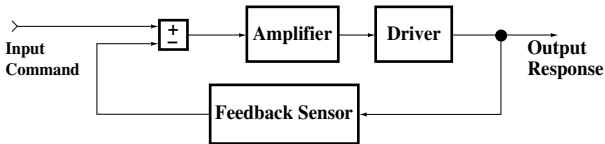


Fig. 1. General Arrangement of a Closed-Loop Control System

Accuracy of closed-loop systems is directly related to the accuracy of the sensor, so that choosing between open-loop and closed-loop controls may mean choosing between low price and consistent, accurate repeatability. In the closed-loop arrangement in Fig. 1, the sensor output is compared with the input command and the difference is amplified and applied to the motor to produce a correction. When the amplifier gain is high (the difference is greatly enlarged), even a small error will generate a correction. However, a high gain can lead to an unstable system due to inherent delays between the electrical inputs and outputs, especially with the motor.

Response accuracy depends not only on the precision of the feedback sensor and the gain of the amplifier, but also on the rate at which the command signal changes. The ability of the control system to follow rapidly changing inputs is naturally limited by the maximum motor speed and acceleration.

Amplified corrections cannot be applied to the motor instantaneously, and the motor does not respond immediately. Overshoots and oscillations can occur and the system must be adjusted or tuned to obtain acceptable performance. This adjustment is called damping the system response. Table 4 lists a variety of methods of damping, some of which require specialized knowledge.

**Table 4. Means of Damping System Response**

|                    |   |
|--------------------|---|
| Network Damping    | Included in the electrical portion of the closed loop. The networks adjust amplitude and phase to minimize control system feedback oscillations. Notch networks are used to reduce gain at specific frequencies to avoid mechanical resonance oscillations  |
| Tachometer Damping | Feedback proportional to output velocity is added to the error signal for system stabilization  |
| Magnetic Damping   | Viscous or inertial dampers on the motor rear shaft extension for closed-loop stabilization. Similar dampers use silicone fluid instead of magnetic means to provide damping  |
| Nonlinear Damping  | Used for special characteristics. Inverse error damping provides low damping for large errors, permitting fast slewing toward zero and very stable operation at zero. Other nonlinearities meet specific needs, for example, coulomb friction damping works well in canceling backlash oscillations |
| Damping Algorithms | With information on output position or velocity, or both, sampled data may be used with appropriate algorithms to set motor voltage for an optimum system response  |

The best damping methods permit high error amplification and accuracy, combined with the desired degree of stability. Whatever form the output takes, it is converted by the output sensor to an electrical signal of compatible form that can be compared with the input command. The error signal thus generated is amplified before being applied to the driving unit.

**Drive Power.**—Power for the control system often depends on what is available and may vary from single- and three-phase ac 60 or 400 Hz, through dc and other types. Portable or mobile equipment is usually battery-powered dc or an engine-driven electrical generator. Hydraulic and pneumatic power may also be available. Cost is often the deciding factor in the choice.

**Table 5. Special Features of Controllers**

|                                 |  |
|---------------------------------|--|
| Linear or Pulse-Width Modulated | Linear is simpler, PWM is more complex and can generate electromagnetic interference, but is more efficient  |
| Current Limiting                | Sets limits to maximum line or motor current. Limits the torque output of permanent magnet motors. Can reduce starting transients and current surges |
| Voltage Limiting                | Sets limits to maximum motor speed. Permits more uniform motor performance over a wide range of line voltages  |
| Energy Absorption               | Ability of the controller to absorb energy from a dc motor drive, back-driven by the load  |
| EMI Filtering                   | Especially important when high electrical gain is required, as in thermocouple circuits, for example   |
| Isolation                       | Of input and output, sometimes using optoisolators, or transformers, when input and output circuits require a high degree of isolation               |

**Control Function.**—The function of the control is usually set by the designer of the equipment and needs careful definition because it is the basis for the overall design. For instance, in positioning a machine tool table, such aspects as speed of movement and permissible variations in speed, accuracy of positioning, repeatability, and overshoot are among dozens of factors that must be considered. Some special features of controllers are

listed in [Table 5](#). Complex electromechanical systems require more knowledge of design and debugging than are needed for strictly mechanical systems.

**Electromechanical Control Systems.**—Wiring is the simplest way to connect components, so electromechanical controls are more versatile than pure hydraulic or pneumatic controls. The key to this versatility is often in the controller, the fundamental characteristic of which is its power output. The power output must be compatible with motor and load requirements. Changes to computer chips or software can usually change system performance to suit the application.

When driving a dc motor, for instance, the controller must supply sufficient power to match load requirements as well as motor operating losses, at minimum line voltage and maximum ambient temperature. The system's wiring must not be greatly sensitive to transient or steady-state electrical interference, and power lines must be separated from control signal lines, or appropriately shielded and isolated to avoid cross-coupling. Main lines to the controller must often include electrical interference filters so that the control system does not affect the power source, which may influence other equipment connected to the same source. For instance, an abruptly applied step command can be smoothed out so that heavy motor inrush currents are avoided. The penalty is a corresponding delay in response.

Use of current limiting units in a controller will not only set limits to line currents, but will also limit motor torque. Electronic torque limiting can frequently avoid the need for mechanical torque limiting. An example of the latter is using a slip clutch to avoid damage due to overtravel, the impact of which usually includes the kinetic energy of the moving machine elements. In many geared systems, most of the kinetic energy is in the motor. Voltage limiting is less useful than current limiting but may be needed to isolate the motor from voltage transients on the power line, to prevent overspeeding, as well as to protect electronic components.

**Mechanical Stiffness.**—When output motion must respond to a rapidly changing input command, the control system must have a wide bandwidth. Where the load mass (in linear motion systems) or the polar moment of inertia (in rotary systems) is high, there is a possibility of resonant oscillations. For the most stable and reliable systems, with a defined load, a high system mechanical stiffness is preferred. To attain this stiffness requires strengthening shafts, preloading bearings, and minimizing free play or backlash. In the best-performing systems, motor and load are coupled without intervening compliant members. Even tightly bolted couplings can introduce compliant oscillations resulting from extremely minute slippages caused by the load motions.

Backlash is a factor in the effective compliance of any coupling but has little effect on the resonant frequency because little energy is exchanged as the load is moved through the backlash region. However, even in the absence of significant torsional resonance, a high-gain control system can “buzz” in the backlash region. Friction is often sufficient to eliminate this small-amplitude, high-frequency component.

The difficulty with direct-drive control systems lies in matching motor to load. Most electric motors deliver rated power at higher speeds than are required by the driven load, so that load power must be delivered by the direct-drive motor operating at a slow and relatively inefficient speed. Shaft power at low speed involves a correspondingly high torque, which requires a large motor and a high-power controller. Motor copper loss (heating) is high in delivering the high motor torque. However, direct-drive motors provide maximum load velocity and acceleration, and can position massive loads within seconds of arc (rotational) or tenths of thousandths of an inch (linear) under dynamic conditions.

Where performance requirements are moderate, the required load torque can be traded off against speed by using a speed-changing transmission, typically, a gear train. The transmission effectively matches the best operating region of the motor to the required operating region of the load, and both motor and controller can be much smaller than would be needed for a comparable direct drive.



**Torsional Vibration.**—Control system instabilities can result from insufficient stiffness between the motor and the inertia of the driven load. The behavior of such a system is similar to that of a torsional pendulum, easily excited by commanded motions of the control system. If frictional losses are moderate to low, sustained oscillations will occur. In spite of the complex dynamics of the closed-loop system, the resonant frequency, as for a torsional pendulum, is given to a high degree of accuracy by the formula:

$$f_n = \frac{1}{2\pi} \times \sqrt{\frac{K}{J_L}}$$

where  $f_n$  is in hertz,  $K$  is torsional stiffness in in.-lb/rad, and  $J_L$  is load inertia in in.-lb-sec<sup>2</sup>/rad. If this resonant frequency falls within the bandwidth of the control system, self-sustained oscillations are likely to occur. These oscillations are often overlooked by control systems analysts because they do not appear in simple control systems, and they are very difficult to correct.

Friction inherently reduces the oscillation by dissipating the energy in the system inertia. If there is backlash between motor and load, coulomb friction (opposing motion but independent of speed) is especially effective in damping out the oscillation. However, the required friction for satisfactory damping can be excessive, introducing positioning error and adding to motor (and controller) power requirements. Friction also varies with operating conditions and time.

The most common method of eliminating torsional oscillation is to introduce a filter in the error channel of the control system to shape the gain characteristic as a function of frequency. If the torsional resonance is within the required system bandwidth, little can be done except stiffening the mechanical system and increasing the resonant frequency. If the filter reduces the gain within the required bandwidth, it will reduce performance. This method will work only if the natural resonance is above the minimum required performance bandwidth.

The simplest shaping network is the notch network (Table 4, network damping), which, in effect, is a band-rejection filter that sharply reduces gain at the notch frequency. By locating the notch frequency so as to balance out the torsional resonance peak, the oscillation can be eliminated. Where there are several modes of oscillation, several filter networks can be connected in series.

**Electric Motors.**—Electric motors for control systems must suit the application. Motors used in open-loop systems (excluding stepper motors) need not respond quickly to input command changes. Where the command is set by a human, response times of hundreds of milliseconds to several seconds may be acceptable. Slow response does not lead to the instabilities that time delays can introduce into closed-loop systems.

Closed-loop systems need motors with fast response, of which the best are permanent-magnet dc units, used where wide bandwidth, efficient operation, and high power output are required. Table 2 lists some types of control motors and their characteristics. An important feature of high-performance, permanent-magnet motors using high-energy, rare-earth magnets is that their maximum torque output capacity can be 10 to 20 or more times higher than their rated torque. In intermittent or low-duty-cycle applications, very high torque loads can be driven by a given motor. However, when rare-earth magnets (samarium cobalt or neodymium) are not used, peak torque capability may be limited by the possibility of demagnetization. Rare-earth magnets are relatively expensive, so it is important to verify peak torque capabilities for lower-cost motors that may use weaker Alnico or ferrite magnets.

Duty-cycle calculations are an aspect of thermal analysis that are well understood and are not covered here. Motor manufacturers usually supply information on thermal characteristics including thermal time constants and temperature rise per watt of internal power dissipation.

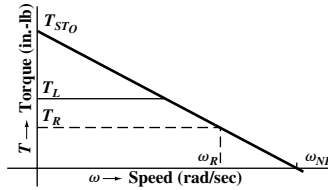


Fig. 2. Idealized Control Motor Characteristics for a Consistent Set of Units

Characteristics of permanent-magnet motors are defined with fair accuracy by relatively few parameters. The most important characteristics are:  $D_M$  motor damping in lb-in.-sec/rad;  $J_M$  motor inertia in lb-in.-sec<sup>2</sup>/rad; and  $R$  winding resistance in ohms. Fig. 1 shows other control motor characteristics,  $T_{STO}$  stall torque with no current limiting;  $T_L$  maximum torque with current limiting;  $\omega_{NL}$  no-load speed;  $\omega_R$  rated speed. Other derived motor parameters include  $V$  rated voltage in volts;  $I_{STO} = V/R$  current in amperes at stall with no current limiting;  $I_L$  ampere limit, adjusted in amplifier;  $I_R$  rated current;  $K_T = T_{STO}/I_{STO}$  torque constant in in.-lb/ampere;  $K_E = V/\omega_{NL}$  voltage constant in volt/rad/sec;

$K_M = K_T/\sqrt{R}$ , torque per square root of winding resistance;  $D_M = T_{STO}/\omega_{NL}$  motor damping in in.-lb/rad/sec; and  $T_M = J_M/D_M$  motor mechanical time constant in seconds.

**Stepper Motors.**—In a stepper motor, power is applied to a wound stator, causing the brushless rotor to change position to correspond with the internal magnetic field. The rotor maintains its position relative to the internal magnetic field at all times. In its most common mode of operation, the stepper motor is energized by an electronic controller whose current output to the motor windings defines the position of the internally generated magnetic field. Applying a command pulse to the controller will change the motor currents to reposition the rotor. A series of pulses, accompanied by a direction command, will cause rotation in uniformly spaced steps in the specified direction.

If the pulses are applied at a sufficiently high frequency, the rotor will be carried along with the system's inertia and will rotate relatively uniformly but with a modulated velocity. At the other extreme, the response to a single pulse will be a step followed by an overshoot and a decaying oscillation. Where the application cannot permit the oscillation, damping can be included in the controller.

Stepper motors are often preferred because positions of the rotor are known from the number of pulses and the step size. An initial index point is required as an output position reference, and care is required in the electronic circuits to avoid introducing random pulses that will cause false positions. As a minimum, the output index point on an appropriate shaft can verify the step count during operation.

**Gearing.**—In a closed-loop system, gearing may be used to couple a high-speed, low-torque motor to a lower-speed, higher-torque load. The gearing must meet requirements for accuracy, strength, and reliability to suit the application. In addition, the closed loop requires minimum backlash at the point where the feedback sensor is coupled. In a velocity-controlled system, the feedback sensor is a tachometer that is usually coupled directly to the rotor shaft. Backlash between motor and tachometer, as well as torsional compliance, must be minimized for stable operation of a high-performance system. Units combining motor and tachometer on a single shaft can usually be purchased as an assembly.

By contrast, a positioning system may use a position feedback sensor that is closely coupled to the shaft being positioned. As with the velocity system, backlash between the motor and feedback sensor must be minimized for closed-loop stability. Antibacklash gearing is frequently used between the gearing and the position feedback sensor. When the position

feedback sensor is a limited rotation device, it may be coupled to a gear that turns faster than the output gear to allow use of its full range. Although this step-up gearing enhances it, accuracy is ultimately limited by the errors in the intermediate gearing between the position sensor and the output.

When an appreciable load inertia is being driven, it is important that the mechanical stiffness between the position sensor coupling point and the load be high enough to avoid natural torsional resonances in the passband.

**Feedback Transducers.**—Controlled variables are measured by feedback transducers and are the key to accuracy in operation of closed-loop systems. When the accuracy of a carefully designed control system approaches the accuracy of the feedback transducer, the need for precision in the other system components is reduced.

Transducers may measure the quantity being controlled in digital or analog form, and are available for many different parameters such as pressure and temperature, as well as distance traveled or degrees of rotation. Machine designers generally need to measure and control linear or rotary motion, velocity, position, and sometimes acceleration. Although some transducers are nonlinear, a linear relationship between the measured variable and the (usually electrical) output is most common.

Output characteristics of an analog linear-position transducer are shown in Fig. 2. By dividing errors into components, accuracy can be increased by external adjustments, and slope error and zero offsets are easily trimmed in. Nonlinearity is controlled by the manufacturer. In Fig. 2 are seen the discrete error components that can be distinguished because of the ease with which they can be canceled out individually by external adjustments. The most common compensation is for zero-position alignment, so that when the machine has been set to the start position for a sequence, the transducer can be positioned to read zero output. Alternatively, with all components in fixed positions, a small voltage can be inserted in series with the transducer output for a very accurate alignment of mechanical and electrical zeros. This method helps in canceling long-term drift, particularly in the mechanical elements.

The second most common adjustment of a position transducer is of its output gradient, that is, transducer output volts per degree. Depending on the type of analog transducer, it is usually possible to add a small adjustment to the electrical input, to introduce a proportional change in output gradient. As with the zero-position adjustment, the gradient may be set very accurately initially and during periodic maintenance. The remaining errors shown in Fig. 2, such as intrinsic nonlinearity or nonconformity, result from limitations in design and manufacture of the transducer.

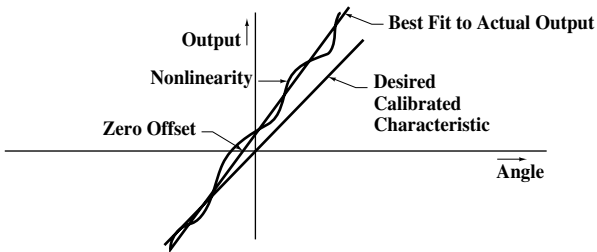


Fig. 3. Output Characteristics of a General Linear Position Transducer

Greater accuracy can be achieved in computer-controlled systems by using the computer to cancel out transducer errors. The system's mechanical values and corresponding transducer values are stored in a lookup table in the computer and referred to as necessary.

Accuracies approaching the inherent repeatability and stability of the system can thus be secured. If necessary, recalibration can be performed at frequent intervals.

**Analog Transducers.**—The simplest analog position transducer is the resistance potentiometer, the resistance element in which is usually a deposited-film rather than a wire-wound type. Very stable resistance elements based on conductive plastics, with resolution to a few microinches and operating lives in the 100 million rotations, are available, capable of working in severe environments with high vibrations and shock and at temperatures of 150 to 200°C. Accuracies of a few hundredths, and stability of thousandths, of a per cent, can be obtained from these units by trimming the plastics resistance element as a function of angle.

Performance of resistance potentiometers deteriorates when they operate at high speeds, and prolonged operation at speeds above 10 rpm causes excessive wear and increasing output noise. An alternative to the resistance potentiometer is the variable differential transformer, which uses electrical coupling between ac magnetic elements to measure angular or linear motion without sliding contacts. These units have unlimited resolution with accuracy comparable to the best resistance potentiometers but are more expensive and require compatible electronic circuits.

A variable differential transformer needs ac energization, so an ac source is required. A precision demodulator is frequently used to change the ac output to dc. Sometimes the ac output is balanced against an ac command signal whose input is derived from the same ac source. In dealing with ac signals, phase-angle matching and an accurate amplitude-scale factor are required for proper operation. Temperature compensation also may be required, primarily due to changes in resistance of the copper windings. Transducer manufacturers will supply full sets of compatible electronic controls.

**Synchros and Resolvers.**—Synchros and resolvers are transducers that are widely used for sensing of angles at accuracies down to 10 to 20 arc-seconds. More typically, and at much lower cost, their accuracies are 1 to 2 arc-minutes. Cost is further reduced when accuracies of 0.1 degree or higher are acceptable.

Synchros used as angle-position transducers are made as brush types with slip rings and in brushless types. These units can rotate continuously at high speeds, the operating life of brushless designs being limited only by the bearing life. Synchros have symmetrical three-wire stator windings that facilitate transmission of angle data over long distances (thousands of feet). Such a system is also highly immune to noise and coupled signals. Practically the only trimming required for very long line systems is matching the line-to-line capacitances.

Because synchros can rotate continuously, they can be used in multispeed arrangements, where, for example, full-scale system travel may be represented by 36 or 64 full rotations. When reduced by gearing to a single, full-scale turn, a synchro's electrical inaccuracy is the typical 0.1° error divided by 36 or 64 or whatever gear ratio is used. This error is insignificant compared with the error of the gearing coupling the high-speed synchro and the single speed (1 rotation for full scale) output shaft. The accuracy is dependable and stable, using standard synchros and gearing.

### Hydraulic and Pneumatic Systems

In Fig. 1 is shown a schematic of a hydraulic cylinder and the relationships between force and area that govern all hydraulic systems. Hydraulic actuators that drive the load may be cylinders or motors, depending on whether linear or rotary motion is required. The load must be defined by its torque-speed characteristics and inertia, and a suitable hydraulic actuator selected before the remaining system components can be chosen. Fluid under pressure and suitable valves are needed to control motion. Both single- and double-acting hydraulic cylinders are available, and the latter type is seen in Fig. 1.

Pressure can be traded off against velocity, if desired, by placing a different effective area at each side of the piston. The same pressure on a smaller area will move the piston at a higher speed but lower force for a given rate of fluid delivery. The cylinder shown in Fig. 1 can drive loads in either direction. The simple formulas of plane geometry relate cylinder areas, force, fluid flow, and rate of movement. Other configurations can develop equal forces and speeds in both directions.

The rotary equivalent of the cylinder is the hydraulic motor, which is defined by the fluid displacement required to turn the output shaft through one revolution, by the output torque, and by the load requirements of torque and speed. Output torque is proportional to fluid pressure, which can be as high as safety permits. Output speed is defined by the number of gallons per minute supplied to the motor. As an example, if 231 cu. in. = 1 gallon, an input of 6 gallons/min (gpm) with a 5-cu. in. displacement gives a mean speed of  $6 \times 231/5 = 277$  rpm. The motor torque must be defined by lb-in. per 100 lb<sub>f</sub>/in.<sup>2</sup> (typically) from which the required pressure can be determined. Various motor types are available.

**Hydraulic Pumps.**—The most-used hydraulic pump is the positive-displacement type, which delivers a fixed amount of fluid for every cycle. These pumps are also called hydrostatic because they deliver energy by static pressure rather than by the kinetic energy of a moving fluid. Positive-displacement pumps are rated by the gpm delivered at a stated speed and by the maximum pressure, which are the key parameters defining the power capacity of the hydraulic actuator. Delivered gpm are reduced under load due to leakage, and the reduction is described by the volumetric efficiency, which is the ratio of actual to theoretical output.

**Hydraulic Fluids.**—The hydraulic fluid is the basic means of transmitting power, and it also provides lubrication and cooling when passed through a heat exchanger. The fluid must be minimally compressible to avoid springiness and delay in response. The total system inertia reacts with fluid compliance to generate a resonant frequency, much as inertia and mechanical compliance react in an electromechanical system. Compliance must be low enough that resonances do not occur in the active bandwidth of the servomechanism, and that unacceptable transients do not occur under shock loads. Seal friction and fluid viscosity tend to damp out resonant vibrations. Shock-absorbing limit stops or cushions are usually located at the travel limits to minimize transient impact forces.

$$F = \text{force (lb)} = \text{pressure} \times \text{area}$$

$$P_1 \text{ and } P_2 = \text{line pressure on either side of piston in lb}_f/\text{in.}^2$$

$$d_1 \text{ and } d_2 = \text{diameters of piston rod and piston in in.}$$

$$F_1 = \frac{\pi}{4} (d_2^2 - d_1^2) \times P_1 = 0.7854 P_1 (d_2^2 - d_1^2)$$

$$F_2 = \frac{\pi}{4} d_2^2 P_2 = 0.7854 P_2 d_2^2$$

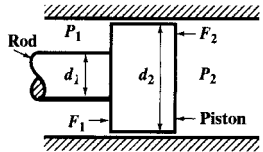


Fig. 1. Elementary Hydraulic Force/Area Formulas

Hydraulic fluids with special additives for lubrication minimize wear between moving parts. An auxiliary function is prevention of corrosion and pitting. Hydraulic fluids must also be compatible with gaskets, seals, and other nonmetallic materials.

Viscosity is another critical parameter of hydraulic fluids as high viscosity means high resistance to fluid flow with a corresponding power loss and heating of the fluid, pressure drop in the hydraulic lines, difficulty in removing bubbles, and sometimes overdamped operation. Unfortunately, viscosity falls very rapidly with increasing temperature, which can lead to reduction of the lubrication properties and excessive wear as well as increasing leakage. For hydraulic actuators operating at very low temperatures, the fluid pour point is important. Below this temperature, the hydraulic fluid will not flow. Design guidelines similar to those used with linear or rotating bearings are applicable in these conditions.

Fire-resistant fluids are available for use in certain conditions such as in die casting, where furnaces containing molten metal are often located near hydraulic systems.

A problem with hydraulic systems that is absent in electromechanical systems is that of dirt, air bubbles, and contaminants in the fluid. Enclosed systems are designed to keep out contaminants, but the main problem is with the reservoir or fluid storage unit. A suitable sealer must be used in the reservoir to prevent corrosion and a filter should be used during filling. Atmospheric pressure is required on the fluid surface in the reservoir except where a pressurized reservoir is used. Additional components include coarse and fine filters to remove contaminants and these filters may be rated to remove micron sized particles (1 micron = 0.00004 in.).

Very fine filters are sometimes used in high-pressure lines, where dirt might interfere with the operation of sensitive valves. Where a high-performance pump is used, a fine filter is a requirement. Usually, only coarse filters are used on fluid inlet lines because fine filters might introduce excessive pressure drop.

Aside from the reservoir used for hydraulic fluid storage, line connections, fittings, and couplings are needed. Expansion of these components under pressure increases the mechanical compliance of the system, reducing the frequencies of any resonances and possibly interfering with the response of wide-band systems.

Formulas relating fluid flow and mechanical power follow. These formulas supplement the general force, torque, speed, and power formulas of mechanical systems.

$$F = P \times A$$

$$A = 0.7854 \times d^2$$

$$hp = 0.000583q \times \text{pressure in lb}_f/\text{in.}^2$$

$$1 \text{ gallon of fluid flow/min at } 1 \text{ lb}_f/\text{in.}^2 \text{ pressure} = 0.000582 \text{ hp.}$$

For rotary outputs,

$$hp = \text{torque} \times \text{rpm}/63,025$$

where torque is in lb-in. (Theoretical hp output must be multiplied by the efficiency of the hydraulic circuits to determine actual output.)

In the preceding equations,

$$P = \text{pressure in lb}_f/\text{in.}^2$$

$$A = \text{piston area in in.}^2$$

$$F = \text{force in lb}$$

$$q = \text{fluid flow in gallons/min}$$

$$d = \text{piston diameter in inches}$$

**Hydraulic and Pneumatic Control Systems.**—Control systems for hydraulic and pneumatic circuits are more mature than those for electromechanical systems because they have been developed over many more years. Hydraulic components are available at moderate prices from many sources. Although their design is complex, application and servicing of these systems are usually more straightforward than with electromechanical systems.

Electromechanical and hydraulic/pneumatic systems may be analyzed by similar means. The mathematical requirements for accuracy and stability are analogous, as are most performance features, although nonlinearities are caused by different physical attributes. Nonlinear friction, backlash, and voltage and current limiting are common to both types of system, but hydraulic/pneumatic systems also have the behavior characteristics of fluid-driven systems such as thermal effects and fluid flow dynamics including turbulence, leakage caused by imperfect seals, and contamination.

Both control types require overhead equipment that does not affect performance but adds to overall cost and complexity. For instance, electromechanical systems require electrical power sources and power control components, voltage regulators, fuses and circuit breakers, relays and switches, connectors, wiring and related devices. Hydraulic/pneumatic sys-

tems require fluid stored under pressure, motor-driven pumps or compressors, valves, pressure regulators/limiters, piping and fasteners, as well as hydraulic/pneumatic motors and cylinders. Frequently, the optimum system is selected on the basis of overhead equipment already available.

Electromechanical systems are generally slower and heavier than hydraulic systems and less suited to controlling heavy loads. The bandwidths of hydraulic control systems can respond to input signals of well over 100 Hz as easily as an electromechanical system can respond to, say, 10 to 20 Hz. Hydraulic systems can drive very high torque loads without intermediate transmissions such as the gear trains often used with electromechanical systems. Also, hydraulic/pneumatic systems using servo valves and piston/cylinder arrangements are inherently suited to linear motion operation, whereas electromechanical controls based on conventional electrical machines are more naturally suited to driving rotational loads.

Until recently, electromechanical systems were limited to system bandwidths of about 10 Hz, with power outputs of a few hundred watts. However, their capabilities have now been sharply extended through the use of rare-earth motor magnets having much higher energies than earlier designs. Similarly, semiconductor power components deliver much higher output power at lower prices than earlier equipment. Electromechanical control systems are now suited to applications of more than 100 hp with bandwidths up to 40 Hz and sometimes up to 100 Hz.

Although much depends on the specific design, the edge in reliability, even for high-power, fast-response needs, is shifting toward electromechanical systems. Basically, there are more things that can go wrong in hydraulic/pneumatic systems, as indicated by the shift to more electrical systems in aircraft.

**Hydraulic Control Systems.**—Using essentially incompressible fluid, hydraulic systems are suited to a wide range of applications, whereas pneumatic power is generally limited to simpler uses. In Fig. 2 are shown the essential features of a simple linear hydraulic control system and a comparable system for driving a rotating load.

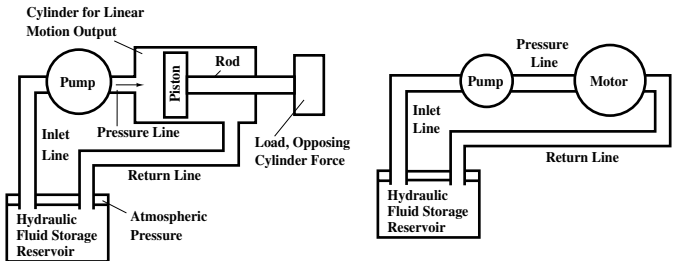


Fig. 2. (left) A Simple Linear Hydraulic Control System in Which the Load Force Returns the Piston and (right) a Comparable System for Driving a Rotating Load

Hydraulic controls of the type shown have fast response and very high load capacities. In a linear actuator, for example, each  $\text{lb}/\text{in}^2$  of system pressure acts against the area of the piston to generate the force applied. Hydraulic pressures of up to  $3000 \text{ lb}/\text{in}^2$  are readily obtained from hydraulic pumps, so that cylinders can exert forces of hundreds of tons without the need for speed-reducing transmission systems to increase the force. The hydraulic fluid distributes heat, so it helps cool the system.

Systems similar to those in Fig. 2 can be operated in open- or closed-loop modes. Open-loop operation can be controlled by programming units that initiate each step by operating relays, limit switches, solenoid valves, and other components to generate the forces over

the required travel ranges. Auxiliary components are used to ensure safe operation and make such systems flexible and reliable, as shown in Fig. 3.

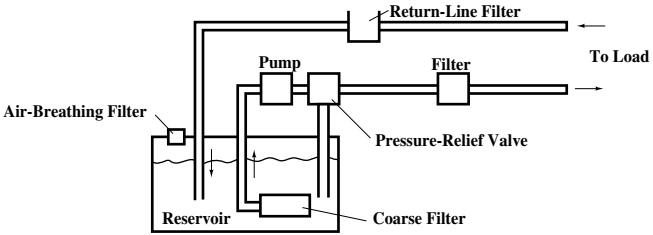


Fig. 3. Some of the Auxiliary Components Used in a Practical Hydraulic System

In the simplest mode, whether open- or closed-loop, hydraulic system operation may be discontinuous or proportional. Discontinuous operation, sometimes called bang-bang, or on-off, works well, is widely used in low- to medium-accuracy systems, and is easy to maintain. In this closed-loop mode, accuracy is limited; if the response to error is set too high, the system will oscillate between on-off modes, with average output at about the desired value. This oscillation, however, can be noisy, introduces system transients, and may cause rapid wear of system components.

Another factor to be considered in on-off systems is the shock caused by sudden opening and closing of high-pressure valves, which introduce transient pulses in the fluid flow and can cause high stresses in components. These problems can be addressed by the use of pressure-limiting relief valves and other units.

**Proportional Control Systems.**—Where the highest accuracy is required, perhaps in two directions, and with aiding or opposing forces or torques, a more sophisticated proportional control, closed-loop system is preferred. As shown in Fig. 4, the amplifier and electric servomotor used in electromechanical closed-loop systems is replaced in the closed-loop hydraulic system by an electronically controlled servo-valve. In its simplest form, the valve uses a linear motor to position the spool that determines the flow path for the hydraulic fluid. In some designs, the linear motor may be driven by a solenoid against a bias spring on the valve spool. In other arrangements, the motor may be a bidirectional unit that permits a fluid flow depending on the polarity and amplitude of the voltage supplied to the motor.

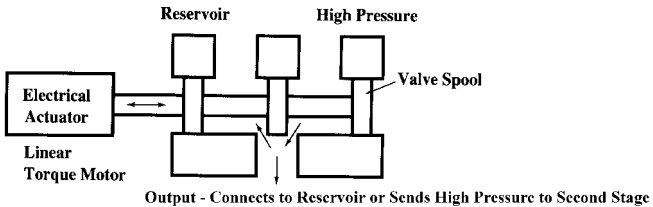


Fig. 4.

Such designs can be used in proportional control systems to achieve smooth operation and minimum nonlinearities, and will give the maximum accuracy required by the best machine tool applications. Where very high power must be controlled, use is often made of a two-stage valve in which the output from the first stage is used to drive the second-stage valve, as shown in Fig. 5.



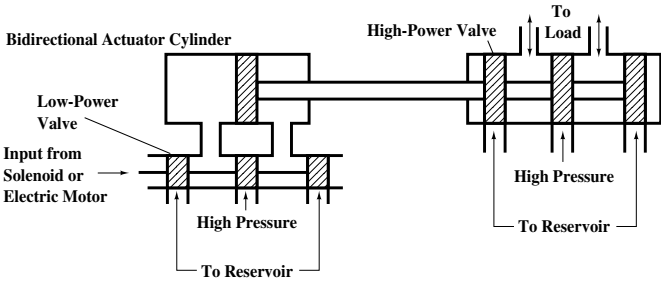


Fig. 5. Two-Stage Valve for Large-Power Control from a Low-Power Input

**Electronic Controls.**—An error-sensing electronic amplifier drives the solenoid motor of Fig. 5, which provides automatic output correction in a closed-loop system. The input is an ideal place to introduce electrical control features, adding greatly to the versatility of the control system. The electronic amplifier can provide the necessary driving power using pulse-width modulation as required, for minimum heating. The output can respond to signals in the low-microvolt range.

A major decision is whether to use analog or digital control. Although analog units are simple, they are much less versatile than their digital counterparts. Digital systems can be readjusted for total travel, speed, and acceleration by simple reprogramming. Use of appropriate feedback sensors can match accuracy to any production requirement, and a single digital system can be easily adapted to a great variety of similar applications. This adaptability is an important cost-saving feature for moderate-sized production runs. Modern microprocessors can integrate the operation of sets of systems.

Because nonlinearities and small incremental motions are easy to implement, digital systems are capable of very smooth acceleration, which avoids damaging shocks and induced leaks, and enhances reliability so that seals and hose connections last longer. The accuracy of digital control systems depends on transducer availability, and a full range of such devices has been developed and is now available.

Other features of digital controls are their capacity for self-calibration, easy digital read-out, and periodic self-compensation. For example, it is easy to incorporate backlash compensation. Inaccuracies can be corrected by using lookup tables that may themselves be updated as necessary. Digital outputs can be used as part of an inspection plan, to indicate need for tool changing, adjustment or sharpening, or for automatic record keeping. Despite continuing improvements in analog systems, digital control of hydraulic systems is favored in large plants.

**Pneumatic Systems.**—Hydraulic systems transmit power by means of the flow of an essentially incompressible fluid. Pneumatic systems use a highly compressible gas. For this reason, a pneumatic system is slower in responding to loads, especially sudden output loads, than a hydraulic system. Similarly, torque or force requires time and output motion to build up. Response to sudden output loads shows initial overshoot. Much more complex networks or other damping means are required to develop stable response in closed-loop systems. On the other hand, there are no harmful shock waves analogous to the transients that can occur in hydraulic systems, and pneumatic system components last comparatively longer.

Notwithstanding their performance deficiencies, pneumatic systems have numerous desirable features. Pneumatic systems avoid some fire hazards compared with the most preferred hydraulic fluids. Air can be vented to the atmosphere so a flow line only is needed, reducing the complexity, cost, and weight of the overall system. Pneumatic lines,

couplings, and fittings are lighter than their hydraulic counterparts, often a significant advantage. The gaseous medium also is lighter than hydraulic fluid, and pneumatic systems are usually easier to clean, assemble, and generally maintain. Fluid viscosity and its temperature variations are virtually negligible with pneumatic systems.

Among drawbacks with pneumatics are that lubrication must be carefully designed in, and more power is needed to achieve a desired pressure when the fluid medium is a compressible gas. Gas under high pressure can cause an explosion if its storage tank is damaged, so storage must have substantial safety margins. Gas compressibility makes pneumatic systems 1 or 2 orders of magnitude slower than hydraulic systems.

The low stiffness of pneumatic systems is another indicator of the long response time. Resonances occur between the compressible gas and equivalent system inertias at lower frequencies. Even the relatively low speed of sound in connecting lines contributes to response delay, adding to the difficulty of closed-loop stabilization. Fortunately, it is possible to construct pneumatic analogs to electrical networks to simplify stabilization at the exact point of the delays. Such pneumatic stabilizing means are commercially available and are important elements of closed-loop pneumatic control systems.

In contrast with hydraulic systems, where speed may be controlled by varying pump output, pneumatic system control is almost exclusively by valves, which control the flow from a pneumatic accumulator or pressure source. The pressure is maintained between limits by an intermittently operated pump. Low-pressure outlet ports must be large enough to accommodate the high volume of the expanded gas. In Fig. 6 is shown a simplified system for closed-loop position control applied to an air cylinder, in which static accuracy is controlled by the position sensor. Proper design requires a good theoretical analysis and attention to practical design if good, stable, closed-loop response is to be achieved.

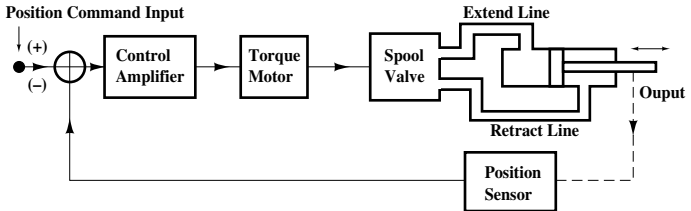


Fig. 6. A Pneumatic Closed-Loop Linear Control System

## O-RINGS

An O-ring is a one-piece molded elastomeric seal with a circular cross-section that seals by distortion of its resilient elastic compound. Dimensions of O-rings are given in ANSI/SAE AS568A, Aerospace Size Standard for O-rings. The standard ring sizes have been assigned identifying dash numbers that, in conjunction with the compound (ring material), completely specifies the ring. Although the ring sizes are standardized, ANSI/SAE AS568A does not cover the compounds used in making the rings; thus, different manufacturers will use different designations to identify various ring compounds. For example, 230-8307 represents a standard O-ring of size 230 (2.484 in. ID by 0.139 in. width) made with compound 8307, a general-purpose nitrile compound. O-ring material properties are discussed at the end of this section.

When properly installed in a groove, an O-ring is normally slightly deformed so that the naturally round cross-section is squeezed diametrically out of round prior to the application of pressure. This compression ensures that under static conditions, the ring is in contact with the inner and outer walls enclosing it, with the resiliency of the rubber providing a zero-pressure seal. When pressure is applied, it tends to force the O-ring across the groove, causing the ring to further deform and flow up to the fluid passage and seal it against leakage, as in Fig. 1(a). As additional pressure is applied, the O-ring deforms into a D shape, as in Fig. 1(b). If the clearance gap between the sealing surface and the groove corners is too large or if the pressure exceeds the deformation limits of the O-ring material (compound), the O-ring will extrude into the clearance gap, reducing the effective life of the seal. For very low-pressure static applications, the effectiveness of the seal can be improved by using a softer durometer compound or by increasing the initial squeeze on the ring, but at higher pressures, the additional squeeze may reduce the ring's dynamic sealing ability, increase friction, and shorten ring life.

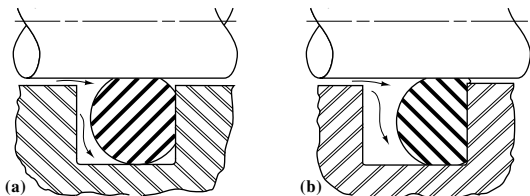


Fig. 1.

The initial diametral squeeze of the ring is very important in the success of an O-ring application. The squeeze is the difference between the ring width  $W$  and the gland depth  $F$  (Fig. 2) and has a great effect on the sealing ability and life of an O-ring application.

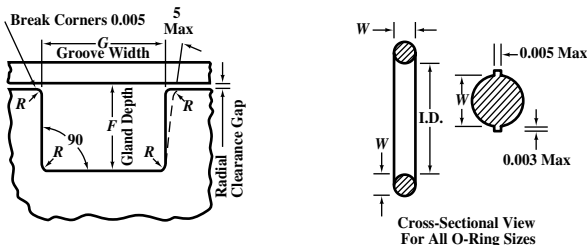


Fig. 2. Groove and Ring Details

The ideal squeeze varies according to the ring cross-section, with the average being about 20 per cent, i.e., the ring's cross-section  $W$  is about 20 per cent greater than the gland depth  $F$  (groove depth plus clearance gap). The groove width is normally about 1.5 times larger than the ring width  $W$ . When installed, an O-ring compresses slightly and distorts into the free space within the groove. Additional expansion or swelling may also occur due to contact of the ring with fluid or heat. The groove must be large enough to accommodate the maximum expansion of the ring or the ring may extrude into the clearance gap or rupture the assembly. In a dynamic application, the extruded ring material will quickly wear and fray, severely limiting seal life.

To prevent O-ring extrusion or to correct an O-ring application, reduce the clearance gap by modifying the dimensions of the system, reduce the system operating pressure, install antiextrusion backup rings in the groove with the O-ring, as in Fig. 3, or use a harder O-ring compound. A harder compound may result in higher friction and a greater tendency of the seal to leak at low pressures. Backup rings, frequently made of leather, Teflon, metal, phenolic, hard rubber, and other hard materials, prevent extrusion and nibbling where large clearance gaps and high pressure are necessary.

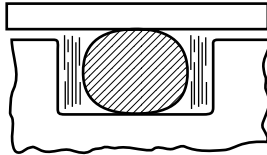


Fig. 3. Preferred Use of Backup Washers

The most effective and reliable sealing is generally provided by using the diametrical clearances given in manufacturers' literature. However, the information in Table 1 may be used to estimate the gland depth (groove depth plus radial clearance) required in O-ring applications. The radial clearance used (radial clearance equals one-half the diametrical clearance) also depends on the system pressure, the ring compound and hardness, and specific details of the application.

**Table 1. Gland Depth for O-Ring Applications**

| Standard O-Ring Cross-Sectional Diameter (in.) | Gland Depth (in.)   |                |
|--|---------------------|----------------|
|  | Reciprocating Seals | Static Seals   |
| 0.070  | 0.055 to 0.057      | 0.050 to 0.052 |
| 0.103  | 0.088 to 0.090      | 0.081 to 0.083 |
| 0.139  | 0.121 to 0.123      | 0.111 to 0.113 |
| 0.210  | 0.185 to 0.188      | 0.170 to 0.173 |
| 0.275  | 0.237 to 0.240      | 0.226 to 0.229 |

Source: Auburn Manufacturing Co. When possible, use manufacturer recommendations for clearance gaps and groove depth.

Fig. 4 indicates conditions where O-ring seals may be used, depending on the fluid pressure and the O-ring hardness. If the conditions of use fall to the right of the curve, extrusion of the O-ring into the surrounding clearance gap will occur, greatly reducing the life of the ring. If conditions fall to the left of the curve, no extrusion of the ring will occur, and the ring may be used under these conditions. For example, in an O-ring application with a 0.004-in. diametrical clearance and 2500-psi pressure, extrusion will occur with a 70 durometer O-ring but not with an 80 durometer O-ring. As the graph indicates, high-pressure applications require lower clearances and harder O-rings for effective sealing.

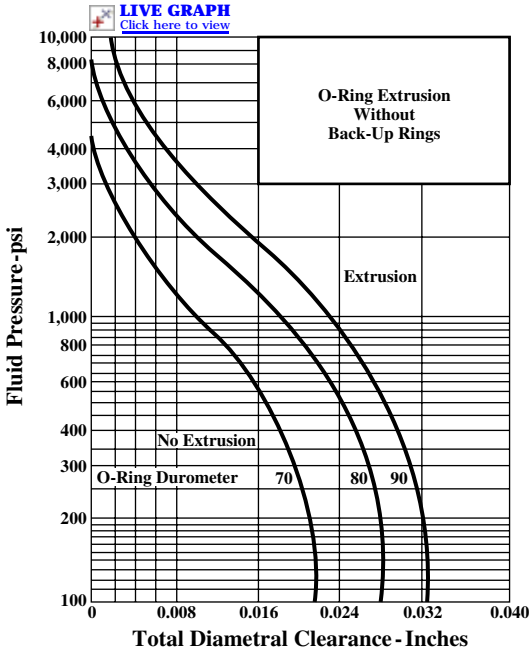


Fig. 4. Extrusion Potential of O-Rings as a Function of Hardness and Clearance

Recommended groove width, clearance dimensions, and bottom-of-groove radius for O-ring numbers up to 475 (25.940-in. ID by 0.275-in. width) can be found using Table 2 in conjunction with Fig. 5. In general, except for ring cross-sections smaller than  $\frac{1}{16}$  in., the groove width is approximately  $1.5W$ , where  $W$  is the ring cross-sectional diameter. Straight-sided grooves are best for preventing extrusion of the ring or nibbling; however, for low-pressure applications (less than 1500 psi) sloped sides with an angle up to  $5^\circ$  can be used to simplify machining of the groove. The groove surfaces should be free of burrs, nicks, or scratches. For static seals (i.e., no contact between the O-ring and any moving parts), the groove surfaces should have a maximum roughness of 32 to 63  $\mu\text{in. rms}$  for liquid-sealing applications and 16 to 32  $\mu\text{in. rms}$  for gaseous-sealing applications. In dynamic seals, relative motion exists between the O-ring and one or more parts and the maximum groove surface roughness should be 8 to 16  $\mu\text{in. rms}$  for sliding contact applications (reciprocating seals, for example) and 16 to 32  $\mu\text{in. rms}$  for rotary contact applications (rotating and oscillating seals).

In dynamic seal applications, the roughness of surfaces in contact with O-rings (bores, pistons, and shafts, for example) should be 8 to 16  $\mu\text{in. rms}$ , without longitudinal or circumferential scratches. Surface finishes of less than 5  $\mu\text{in. rms}$  are too smooth to give a good seal life because they wipe too clean, causing the ring to wear against the housing in the absence of a lubricating film. The best-quality surfaces are honed, burnished, or hard chromium plated. Soft and stringy metals such as aluminum, brass, bronze, Monel, or free machining stainless steel should not be used in contact with moving seals. In static applica-

tions, O-ring contacting surfaces should have a maximum surface roughness of 64 to 125  $\mu\text{in. rms}$ .

**Table 2. Diametral Clearance and Groove Sizes for O-Ring Applications**

| ANSI/SAE<br>AS568<br>Number | Tolerances       |                  | Diametral Clearance, $D$        |                      | Groove Width, $G$ |       |       | Bottom of<br>Groove<br>Radius, $R$ |
|-----------------------------|------------------|------------------|---------------------------------|----------------------|-------------------|-------|-------|------------------------------------|
|                             | A                | B                | Reciprocating &<br>Static Seals | Rotary<br>Seals      | Backup Rigs       |       |       |                                    |
|                             |                  |                  |                                 |                      | None              | One   | Two   |                                    |
| 001                         | +0.001<br>-0.000 | +0.000<br>-0.001 | 0.002 to 0.004                  | 0.012<br>to<br>0.016 | 0.063             |       |       | 0.005 to<br>0.015                  |
| 002                         |                  |                  |                                 |                      | 0.073             |       |       |                                    |
| 003                         |                  |                  |                                 |                      | 0.083             |       |       |                                    |
| 004 to 012                  |                  |                  |                                 |                      | 0.094             | 0.149 | 0.207 |                                    |
| 013 to 050                  | +0.002<br>-0.000 | +0.000<br>-0.002 | 0.002 to 0.005                  | 0.016<br>to<br>0.020 | 0.141             | 0.183 | 0.245 | 0.010 to<br>0.025                  |
| 102 to 129                  |                  |                  | 0.002 to 0.006                  |                      | 0.188             | 0.235 | 0.304 |                                    |
| 130 to 178                  |                  |                  | 0.003 to 0.007                  |                      | 0.281             | 0.334 | 0.424 | 0.020 to<br>0.035                  |
| 201 to 284                  |                  |                  | 0.004 to 0.010                  |                      | 0.375             | 0.475 | 0.579 |                                    |
| 309 to 395                  | +0.003           | +0.000           | 0.003 to 0.007                  |                      |                   |       |       |                                    |
| 425 to 475                  | -0.000           | -0.003           | 0.004 to 0.010                  |                      |                   |       |       |                                    |

Source: Auburn Manufacturing Co. All dimensions are in inches. Clearances listed are minimum and maximum values; standard groove widths may be reduced by about 10 per cent for use with ring compounds that free swell less than 15 per cent. Dimension A is the ID of any surface contacted by the outside circumference of the ring; B is the OD of any surface contacted by the inside circumference of the ring.

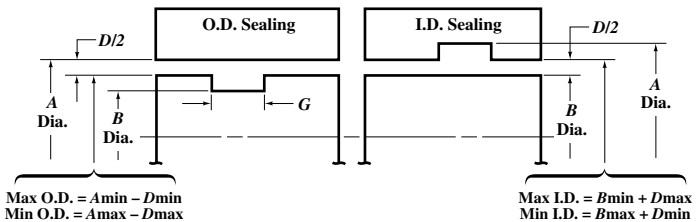


Fig. 5. Installation data for use with Table 2. Max and Min are maximum and minimum piston and bore diameters for O.D. and I.D., respectively.

The preferred bore materials are steel and cast iron, and pistons should be softer than the bore to avoid scratching them. The bore sections should be thick enough to resist expansion and contraction under pressure so that the radial clearance gap remains constant, reducing the chance of damage to the O-ring by extrusion and nibbling. Some compatibility problems may occur when O-rings are used with plastics parts because certain compounding ingredients may attack the plastics, causing crazing of the plastics surface.

O-rings are frequently used as driving belts in round bottom or V-grooves with light tension for low-power drive elements. Special compounds are available with high resistance to stress relaxation and fatigue for these applications. Best service is obtained in drive belt applications when the initial belt tension is between 80 and 200 psi and the initial installed stretch is between 8 and 25 per cent of the circumferential length. Most of the compounds used for drive belts operate best between 10 and 15 per cent stretch, although polyurethane has good service life when stretched as much as 20 to 25 per cent.

**Table 3. Typical O-Ring Compounds**

|                            |  |
|----------------------------|--|
| Nitrile                    | General-purpose compound for use with most petroleum oils, greases, gasoline, alcohols and glycols, LP gases, propane and butane fuels. Also for food service to resist vegetable and animal fats. Effective temperature range is about $-40^{\circ}$ to $250^{\circ}$ F. Excellent compression set, tear and abrasion resistance, but poor resistance to ozone, sunlight and weather. Higher-temperature nitrile compounds with similar properties are also available.  |
| Hydrogenated Nitrile       | Similar to general-purpose nitrile compounds with improved high-temperature performance, resistance to aging, and petroleum product compatibility.   |
| Polychloroprene (Neoprene) | General-purpose compound with low compression set and good resistance to elevated temperatures. Good resistance to sunlight, ozone, and weathering, and fair oil resistance. Frequently used for refrigerator gases such as Freon. Effective temperature range is about $-40^{\circ}$ to $250^{\circ}$ F.  |
| Ethylene Propylene         | General-purpose compound with excellent resistance to polar fluids such as water, steam, ketones, and phosphate esters, and brake fluids, but not resistant to petroleum oils and solvents. Excellent resistance to ozone and flexing. Recommended for belt-drive applications. Continuous duty service in temperatures up to $250^{\circ}$ F.   |
| Silicon                    | Widest temperature range ( $-150^{\circ}$ to $500^{\circ}$ F) and best low-temperature flexibility of all elastomeric compounds. Not recommended for dynamic applications, due to low strength, or for use with most petroleum oils. Shrinkage characteristics similar to organic rubber, allowing existing molds to be used.  |
| Polyurethane               | Toughest of the elastomers used for O-rings, characterized by high tensile strength, excellent abrasion resistance, and tear strength. Compression set and heat resistance are inferior to nitrile. Suitable for hydraulic applications that anticipate abrasive contaminants and shock loads. Temperature service range of $-65^{\circ}$ to $212^{\circ}$ F.  |
| Fluorosilicone             | Wide temperature range ( $-80^{\circ}$ to $450^{\circ}$ F) for continuous duty and excellent resistance to petroleum oils and fuels. Recommended for static applications only, due to limited strength and low abrasion resistance.  |
| Polyacrylate               | Heat resistance better than nitrile compounds, but inferior low temperature, compression set, and water resistance. Often used in power steering and transmission applications due to excellent resistance to oil, automatic transmission fluids, oxidation, and flex cracking. Temperature service range of $-20^{\circ}$ to $300^{\circ}$ F.   |
| Fluorocarbon (Viton)       | General-purpose compound suitable for applications requiring resistance to aromatic or halogenated solvents or to high temperatures ( $-20^{\circ}$ to $500^{\circ}$ F with limited service to $600^{\circ}$ F). Outstanding resistance to blended aromatic fuels, straight aromatics, and halogenated hydrocarbons and other petroleum products. Good resistance to strong acids (temperature range in acids $-20^{\circ}$ to $250^{\circ}$ F), but not effective for use with very hot water, steam, and brake fluids. |

**Ring Materials.**—Thousands of O-ring compounds have been formulated for specific applications. Some of the most common types of compounds and their typical applications are given in [Table 3](#). The Shore A durometer is the standard instrument used for measuring the hardness of elastomeric compounds. The softest O-rings are 50 and 60 Shore A and stretch more easily, exhibit lower breakout friction, seal better on rough surfaces, and need less clamping pressure than harder rings. For a given squeeze, the higher the durometer hardness of a ring, the greater the associated friction because a greater compressive force is exerted by hard rings than soft rings.

The most widely used rings are medium-hard O-rings with 70 Shore A hardness, which have the best wear resistance and frictional properties for running seals. Applications that involve oscillating or rotary motion frequently use 80 Shore A materials. Rings with a hardness above 85 Shore A often leak more because of less effective wiping action. These harder rings have a greater resistance to extrusion, but for small sizes may break easily during installation. O-ring hardness varies inversely with temperature, but when used for continuous service at high temperatures, the hardness may eventually increase after an initial softening of the compound.

O-ring compounds have thermal coefficients of expansion in the range of 7 to 20 times that of metal components, so shrinkage or expansion with temperature change can pose problems of leakage past the seal at low temperatures and excessive pressures at high temperatures when a ring is installed in a tight-fitting groove. Likewise, when an O-ring is immersed in a fluid, the compound usually absorbs some of the fluid and consequently increases in volume. Manufacturer's data give volumetric increase data for compounds completely immersed in various fluids. For confined rings (those with only a portion of the ring exposed to fluid), the size increase may be considerably lower than for rings completely immersed in fluid. Certain fluids can also cause ring shrinkage during "idle" periods, i.e., when the seal has a chance to dry out. If this shrinkage is more than 3 to 4 per cent, the seal may leak.

Excessive swelling due to fluid contact and high temperatures softens all compounds approximately 20 to 30 Shore A points from room temperature values and designs should anticipate the expected operating conditions. At low temperatures, swelling may be beneficial because fluid absorption may make the seal more flexible. However, the combination of low temperature and low pressure makes a seal particularly difficult to maintain. A soft compound should be used to provide a resilient seal at low temperatures. Below  $-65^{\circ}\text{F}$ , only compounds formulated with silicone are useful; other compounds are simply too stiff, especially for use with air and other gases.

Compression set is another material property and a very important sealing factor. It is a measure of the shape memory of the material, that is, the ability to regain shape after being deformed. Compression set is a ratio, expressed as a percentage, of the unrecovered to original thickness of an O-ring compressed for a specified period of time between two heated plates and then released. O-rings with excessive compressive set will fail to maintain a good seal because, over time, the ring will be unable to exert the necessary compressive force (squeeze) on the enclosing walls. Swelling of the ring due to fluid contact tends to increase the squeeze and may partially compensate for the loss due to compression set. Generally, compression set varies by compound and ring cross-sectional diameter, and increases with the operating temperature.



## ROLLED STEEL SECTIONS, WIRE, AND SHEET-METAL GAGES

### Rolled Steel Sections

**Lengths of Angles Bent to Circular Shape.**—To calculate the length of an angle-iron used either inside or outside of a tank or smokestack, the following table of constants may be used: Assume, for example, that a stand-pipe, 20 feet inside diameter, is provided with a 3 by 3 by  $\frac{3}{8}$  inch angle-iron on the inside at the top. The circumference of a circle 20 feet in diameter is 754 inches. From the table of constants, find the constant for a 3 by 3 by  $\frac{3}{8}$  inch angle-iron, which is 4.319. The length of the angle then is  $754 - 4.319 = 749.681$  inches. Should the angle be on the outside, add the constant instead of subtracting it; thus,  $754 + 4.319 = 758.319$  inches.

| Size of Angle  | Const. | Size of Angle   | Const. | Size of Angle                   | Const. |
|--|--------|---|--------|---------------------------------|--------|
| $\frac{1}{4} \times 2 \times 2$                        | 2.879  | $\frac{5}{16} \times 3 \times 3$                      | 4.123  | $\frac{1}{2} \times 5 \times 5$ | 6.804  |
| $\frac{5}{16} \times 2 \times 2$                       | 3.076  | $\frac{3}{8} \times 3 \times 3$                       | 4.319  | $\frac{3}{8} \times 6 \times 6$ | 7.461  |
| $\frac{3}{8} \times 2 \times 2$                        | 3.272  | $\frac{1}{2} \times 3 \times 3$                       | 4.711  | $\frac{1}{2} \times 6 \times 6$ | 7.854  |
| $\frac{1}{4} \times 2\frac{1}{2} \times 2\frac{1}{2}$  | 3.403  | $\frac{3}{8} \times 3\frac{1}{2} \times 3\frac{1}{2}$ | 4.843  | $\frac{3}{4} \times 6 \times 6$ | 8.639  |
| $\frac{5}{16} \times 2\frac{1}{2} \times 2\frac{1}{2}$ | 3.600  | $\frac{1}{2} \times 3\frac{1}{2} \times 3\frac{1}{2}$ | 5.235  | $\frac{1}{2} \times 8 \times 8$ | 9.949  |
| $\frac{3}{8} \times 2\frac{1}{2} \times 2\frac{1}{2}$  | 3.796  | $\frac{3}{8} \times 4 \times 4$                       | 5.366  | $\frac{3}{4} \times 8 \times 8$ | 10.734 |
| $\frac{1}{2} \times 2\frac{1}{2} \times 2\frac{1}{2}$  | 4.188  | $\frac{1}{2} \times 4 \times 4$                       | 5.758  | $1 \times 8 \times 8$           | 11.520 |
| $\frac{1}{4} \times 3 \times 3$                        | 3.926  | $\frac{3}{8} \times 5 \times 5$                       | 6.414  | ...                             | ...    |

**Standard Designations of Rolled Steel Shapes.**—Through a joint effort, the American Iron and Steel Institute (AISI) and the American Institute of Steel Construction (AISC) have changed most of the designations for their hot-rolled structural steel shapes. The present designations, standard for steel producing and fabricating industries, should be used when designing, detailing, and ordering steel. The accompanying Table 1 compares the present designations with the previous descriptions.

**Table 1. Hot-Rolled Structural Steel Shape Designations (AISI and AISC)**

| Present Designation                    | Type of Shape                   | Previous Designation                   |
|--|---------------------------------|--|
| W 24 × 76                              | W shape                         | 24 WF 76                               |
| W 14 × 26                              | W shape                         | 14 B 26                                |
| S 24 × 100                             | S shape                         | 24 I 100                               |
| M 8 × 18.5                             | M shape                         | 8 M 18.5                               |
| M 10 × 9                               | M shape                         | 10 JR 9.0                              |
| M 8 × 34.3                             | M shape                         | 8 × 8 M 34.3                           |
| C 12 × 20.7                            | American Standard Channel       | 12 [20.7                               |
| MC 12 × 45                             | Miscellaneous Channel           | 12 × 4 [45.0                           |
| MC 12 × 10.6                           | Miscellaneous Channel           | 12 JR [10.6                            |
| HP 14 × 73                             | HP shape                        | 14 BP 73                               |
| L 6 × 6 × $\frac{3}{4}$                | Equal Leg Angle                 | $\angle 6 \times 6 \times \frac{3}{4}$ |
| L 6 × 4 × $\frac{3}{8}$                | Unequal Leg Angle               | $\angle 6 \times 4 \times \frac{3}{8}$ |
| WT 12 × 38                             | Structural Tee cut from W shape | ST 12 WF 38                            |
| WT 7 × 13                              | Structural Tee cut from W shape | ST 7 B 13                              |
| St 12 × 50                             | Structural Tee cut from S shape | ST 12 I 50                             |
| MT 4 × 9.25                            | Structural Tee cut from M shape | ST 4 M 9.25                            |
| MT 5 × 4.5                             | Structural Tee cut from M shape | ST 5 JR 4.5                            |
| MT 4 × 17.15                           | Structural Tee cut from M shape | ST 4 M 17.15                           |
| PL $\frac{1}{2} \times 18$             | Plate                           | PL 18 × $\frac{1}{2}$                  |
| Bar 1                                  | Square Bar                      | Bar 1                                  |
| Bar 1 $\frac{1}{4} \varnothing$        | Round Bar                       | Bar 1 $\frac{1}{4} \varnothing$        |
| Bar 2 $\frac{1}{2} \times \frac{1}{2}$ | Flat Bar                        | Bar 2 $\frac{1}{2} \times \frac{1}{2}$ |
| Pipe 4 Std.                            | Pipe                            | Pipe 4 Std.                            |
| Pipe 4 X-Strong                        | Pipe                            | Pipe 4 X-Strong                        |
| Pipe 4 XX-Strong                       | Pipe                            | Pipe 4 XX-Strong                       |
| TS 4 × 4 × .375                        | Structural Tubing: Square       | Tube 4 × 4 × .375                      |
| TS 5 × 3 × .375                        | Structural Tubing: Rectangular  | Tube 5 × 3 × .375                      |
| TS 3 OD × .250                         | Structural Tubing: Circular     | Tube 3 OD × .250                       |

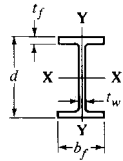
Data taken from the "Manual of Steel Construction," 8th Edition, 1980, with permission of the American Institute of Steel Construction.

Table 2a. Steel Wide-Flange Sections

Wide-flange sections are designated, in order, by a section letter, nominal depth of the member in inches, and the nominal weight in pounds per foot; thus:

**W 18 × 64**

indicates a wide-flange section having a nominal depth of 18 inches, and a nominal weight per foot of 64 pounds. Actual geometry for each section can be obtained from the values below.



| Designation       | Area, A<br>inch <sup>2</sup> | Depth, d<br>inch | Flange                        |                                   | Web Thickness, t <sub>w</sub><br>inch | Axis X-X               |                        |           | Axis Y-Y               |                        |           |
|-------------------|------------------------------|------------------|-------------------------------|-----------------------------------|---------------------------------------|------------------------|------------------------|-----------|------------------------|------------------------|-----------|
|                   |                              |                  | Width, b <sub>f</sub><br>inch | Thickness, t <sub>f</sub><br>inch |                                       | I<br>inch <sup>4</sup> | S<br>inch <sup>3</sup> | r<br>inch | I<br>inch <sup>4</sup> | S<br>inch <sup>3</sup> | r<br>inch |
| <b>W 27</b> × 178 | 52.3                         | 27.81            | 14.085                        | 1.190                             | 0.725                                 | 6990                   | 502                    | 11.6      | 555                    | 78.8                   | 3.26      |
| × 161             | 47.4                         | 27.59            | 14.020                        | 1.080                             | 0.660                                 | 6280                   | 455                    | 11.5      | 497                    | 70.9                   | 3.24      |
| × 146             | 42.9                         | 27.38            | 13.965                        | 0.975                             | 0.605                                 | 5630                   | 411                    | 11.4      | 443                    | 63.5                   | 3.21      |
| × 114             | 33.5                         | 27.29            | 10.070                        | 0.930                             | 0.570                                 | 4090                   | 299                    | 11.0      | 159                    | 31.5                   | 2.18      |
| × 102             | 30.0                         | 27.09            | 10.015                        | 0.830                             | 0.515                                 | 3620                   | 267                    | 11.0      | 139                    | 27.8                   | 2.15      |
| × 94              | 27.7                         | 26.92            | 9.990                         | 0.745                             | 0.490                                 | 3270                   | 243                    | 10.9      | 124                    | 24.8                   | 2.12      |
| × 84              | 24.8                         | 26.71            | 9.960                         | 0.640                             | 0.460                                 | 2850                   | 213                    | 10.7      | 106                    | 21.2                   | 2.07      |
| <b>W 24</b> × 162 | 47.7                         | 25.00            | 12.955                        | 1.220                             | 0.705                                 | 5170                   | 414                    | 10.4      | 443                    | 68.4                   | 3.05      |
| × 146             | 43.0                         | 24.74            | 12.900                        | 1.090                             | 0.650                                 | 4580                   | 371                    | 10.3      | 391                    | 60.5                   | 3.01      |
| × 131             | 38.5                         | 24.48            | 12.855                        | 0.960                             | 0.605                                 | 4020                   | 329                    | 10.2      | 340                    | 53.0                   | 2.97      |
| × 117             | 34.4                         | 24.26            | 12.800                        | 0.850                             | 0.550                                 | 3540                   | 291                    | 10.1      | 297                    | 46.5                   | 2.94      |
| × 104             | 30.6                         | 24.06            | 12.750                        | 0.750                             | 0.500                                 | 3100                   | 258                    | 10.1      | 259                    | 40.7                   | 2.91      |
| × 94              | 27.7                         | 24.31            | 9.065                         | 0.875                             | 0.515                                 | 2700                   | 222                    | 9.87      | 109                    | 24.0                   | 1.98      |
| × 84              | 24.7                         | 24.10            | 9.020                         | 0.770                             | 0.470                                 | 2370                   | 196                    | 9.79      | 94.4                   | 20.9                   | 1.95      |
| × 76              | 22.4                         | 23.92            | 8.990                         | 0.680                             | 0.440                                 | 2100                   | 176                    | 9.69      | 82.5                   | 18.4                   | 1.92      |
| × 68              | 20.1                         | 23.73            | 8.965                         | 0.585                             | 0.415                                 | 1830                   | 154                    | 9.55      | 70.4                   | 15.7                   | 1.87      |
| × 62              | 18.2                         | 23.74            | 7.040                         | 0.590                             | 0.430                                 | 1550                   | 131                    | 9.23      | 34.5                   | 9.80                   | 1.38      |
| × 55              | 16.2                         | 23.57            | 7.005                         | 0.505                             | 0.395                                 | 1350                   | 114                    | 9.11      | 29.1                   | 8.30                   | 1.34      |
| <b>W 21</b> × 147 | 43.2                         | 22.06            | 12.510                        | 1.150                             | 0.720                                 | 3630                   | 329                    | 9.17      | 376                    | 60.1                   | 2.95      |
| × 132             | 38.8                         | 21.83            | 12.440                        | 1.035                             | 0.650                                 | 3220                   | 295                    | 9.12      | 333                    | 53.5                   | 2.93      |
| × 122             | 35.9                         | 21.68            | 12.390                        | 0.960                             | 0.600                                 | 2960                   | 273                    | 9.09      | 305                    | 49.2                   | 2.92      |
| × 111             | 32.7                         | 21.51            | 12.340                        | 0.875                             | 0.550                                 | 2670                   | 249                    | 9.05      | 274                    | 44.5                   | 2.90      |
| × 101             | 29.8                         | 21.36            | 12.290                        | 0.800                             | 0.500                                 | 2420                   | 227                    | 9.02      | 248                    | 40.3                   | 2.89      |
| × 93              | 27.3                         | 21.62            | 8.420                         | 0.930                             | 0.580                                 | 2070                   | 192                    | 8.70      | 92.9                   | 22.1                   | 1.84      |
| × 83              | 24.3                         | 21.43            | 8.355                         | 0.835                             | 0.515                                 | 1830                   | 171                    | 8.67      | 81.4                   | 19.5                   | 1.83      |
| × 73              | 21.5                         | 21.24            | 8.295                         | 0.740                             | 0.455                                 | 1600                   | 151                    | 8.64      | 70.6                   | 17.0                   | 1.81      |
| × 68              | 20.0                         | 21.13            | 8.270                         | 0.685                             | 0.430                                 | 1480                   | 140                    | 8.60      | 64.7                   | 15.7                   | 1.80      |
| × 62              | 18.3                         | 20.99            | 8.240                         | 0.615                             | 0.400                                 | 1330                   | 127                    | 8.54      | 57.5                   | 13.9                   | 1.77      |
| × 57              | 16.7                         | 21.06            | 6.555                         | 0.650                             | 0.405                                 | 1170                   | 111                    | 8.36      | 30.6                   | 9.35                   | 1.35      |
| × 50              | 14.7                         | 20.83            | 6.530                         | 0.535                             | 0.380                                 | 984                    | 94.5                   | 8.18      | 24.9                   | 7.64                   | 1.30      |
| × 44              | 13.0                         | 20.66            | 6.500                         | 0.450                             | 0.350                                 | 843                    | 81.6                   | 8.06      | 20.7                   | 6.36                   | 1.26      |
| <b>W 18</b> × 119 | 35.1                         | 18.97            | 11.265                        | 1.060                             | 0.655                                 | 2190                   | 231                    | 7.90      | 253                    | 44.9                   | 2.69      |
| × 106             | 31.1                         | 18.73            | 11.200                        | 0.940                             | 0.590                                 | 1910                   | 204                    | 7.84      | 220                    | 39.4                   | 2.66      |
| × 97              | 28.5                         | 18.59            | 11.145                        | 0.870                             | 0.535                                 | 1750                   | 188                    | 7.82      | 201                    | 36.1                   | 2.65      |
| × 86              | 25.3                         | 18.39            | 11.090                        | 0.770                             | 0.480                                 | 1530                   | 166                    | 7.77      | 175                    | 31.6                   | 2.63      |
| × 76              | 22.3                         | 18.21            | 11.035                        | 0.680                             | 0.425                                 | 1330                   | 146                    | 7.73      | 152                    | 27.6                   | 2.61      |
| × 71              | 20.8                         | 18.47            | 7.635                         | 0.810                             | 0.495                                 | 1170                   | 127                    | 7.50      | 60.3                   | 15.8                   | 1.70      |
| × 65              | 19.1                         | 18.35            | 7.590                         | 0.750                             | 0.450                                 | 1070                   | 117                    | 7.49      | 54.8                   | 14.4                   | 1.69      |
| × 60              | 17.6                         | 18.24            | 7.555                         | 0.695                             | 0.415                                 | 984                    | 108                    | 7.47      | 50.1                   | 13.3                   | 1.69      |
| × 55              | 16.2                         | 18.11            | 7.530                         | 0.630                             | 0.390                                 | 890                    | 98.3                   | 7.41      | 44.9                   | 11.9                   | 1.67      |
| × 50              | 14.7                         | 17.99            | 7.495                         | 0.570                             | 0.355                                 | 800                    | 88.9                   | 7.38      | 40.1                   | 10.7                   | 1.65      |
| × 46              | 13.5                         | 18.06            | 6.060                         | 0.605                             | 0.360                                 | 712                    | 78.8                   | 7.25      | 22.5                   | 7.43                   | 1.29      |
| × 40              | 11.8                         | 17.90            | 6.015                         | 0.525                             | 0.315                                 | 612                    | 68.4                   | 7.21      | 19.1                   | 6.35                   | 1.27      |
| × 35              | 10.3                         | 17.70            | 6.000                         | 0.425                             | 0.300                                 | 510                    | 57.6                   | 7.04      | 15.3                   | 5.12                   | 1.22      |

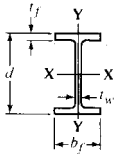
Consult the AISC Manual, noted above, for W steel shapes having nominal depths greater than 27 inches.

Symbols: I = moment of inertia; S = section modulus; r = radius of gyration.

Data taken from the "Manual of Steel Construction," 8th Edition, 1980, with permission of the American Institute of Steel Construction.

Table 2b. Steel Wide-Flange Sections

Wide-flange sections are designated, in order, by a section letter, nominal depth of the member in inches, and the nominal weight in pounds per foot. Thus:  
**W 16 × 78**  
 indicates a wide-flange section having a nominal depth of 16 inches, and a nominal weight per foot of 78 pounds. Actual geometry for each section can be obtained from the values below.



| Designation | Area, $A$<br>inch <sup>2</sup> | Depth, $d$<br>inch | Flange               |                          | Web Thickness, $t_w$<br>inch | Axis X-X                 |                          |             | Axis Y-Y                 |                          |             |
|-------------|--------------------------------|--------------------|----------------------|--------------------------|------------------------------|--------------------------|--------------------------|-------------|--------------------------|--------------------------|-------------|
|             |                                |                    | Width, $b_f$<br>inch | Thickness, $t_f$<br>inch |                              | $I$<br>inch <sup>4</sup> | $S$<br>inch <sup>3</sup> | $r$<br>inch | $I$<br>inch <sup>4</sup> | $S$<br>inch <sup>3</sup> | $r$<br>inch |
| W 16 × 100  | 29.4                           | 16.97              | 10.425               | 0.985                    | 0.585                        | 1490                     | 175                      | 7.10        | 186                      | 35.7                     | 2.51        |
| × 89        | 26.2                           | 16.75              | 10.365               | 0.875                    | 0.525                        | 1300                     | 155                      | 7.05        | 163                      | 31.4                     | 2.49        |
| × 77        | 22.6                           | 16.52              | 10.295               | 0.760                    | 0.455                        | 1110                     | 134                      | 7.00        | 138                      | 26.9                     | 2.47        |
| × 67        | 19.7                           | 16.33              | 10.235               | 0.665                    | 0.395                        | 954                      | 117                      | 6.96        | 119                      | 23.2                     | 2.46        |
| × 57        | 16.8                           | 16.43              | 7.120                | 0.715                    | 0.430                        | 758                      | 92.2                     | 6.72        | 43.1                     | 12.1                     | 1.60        |
| × 50        | 14.7                           | 16.26              | 7.070                | 0.630                    | 0.380                        | 659                      | 81.0                     | 6.68        | 37.2                     | 10.5                     | 1.59        |
| × 45        | 13.3                           | 16.13              | 7.035                | 0.565                    | 0.345                        | 586                      | 72.7                     | 6.65        | 32.8                     | 9.34                     | 1.57        |
| × 40        | 11.8                           | 16.01              | 6.995                | 0.505                    | 0.305                        | 518                      | 64.7                     | 6.63        | 28.9                     | 8.25                     | 1.57        |
| × 36        | 10.6                           | 15.86              | 6.985                | 0.430                    | 0.295                        | 448                      | 56.5                     | 6.51        | 24.5                     | 7.00                     | 1.52        |
| × 31        | 9.12                           | 15.88              | 5.525                | 0.440                    | 0.275                        | 375                      | 47.2                     | 6.41        | 12.4                     | 4.49                     | 1.17        |
| × 26        | 7.68                           | 15.69              | 5.500                | 0.345                    | 0.250                        | 301                      | 38.4                     | 6.26        | 9.59                     | 3.49                     | 1.12        |
| W 14 × 730  | 215.0                          | 22.42              | 17.890               | 4.910                    | 3.070                        | 14300                    | 1280                     | 8.17        | 4720                     | 527                      | 4.69        |
| × 665       | 196.0                          | 21.64              | 17.650               | 4.520                    | 2.830                        | 12400                    | 1150                     | 7.98        | 4170                     | 472                      | 4.62        |
| × 605       | 178.0                          | 20.92              | 17.415               | 4.160                    | 2.595                        | 10800                    | 1040                     | 7.80        | 3680                     | 423                      | 4.55        |
| × 550       | 162.0                          | 20.24              | 17.200               | 3.820                    | 2.380                        | 9430                     | 931                      | 7.63        | 3250                     | 378                      | 4.49        |
| × 500       | 147.0                          | 19.60              | 17.010               | 3.500                    | 2.190                        | 8210                     | 838                      | 7.48        | 2880                     | 339                      | 4.43        |
| × 455       | 134.0                          | 19.02              | 16.835               | 3.210                    | 2.015                        | 7190                     | 756                      | 7.33        | 2560                     | 304                      | 4.38        |
| × 426       | 125.0                          | 18.67              | 16.695               | 3.035                    | 1.875                        | 6600                     | 707                      | 7.26        | 2360                     | 283                      | 4.34        |
| × 398       | 117.0                          | 18.29              | 16.590               | 2.845                    | 1.770                        | 6000                     | 656                      | 7.16        | 2170                     | 262                      | 4.31        |
| × 370       | 109.0                          | 17.92              | 16.475               | 2.660                    | 1.655                        | 5440                     | 607                      | 7.07        | 1990                     | 241                      | 4.27        |
| × 342       | 101.0                          | 17.54              | 16.360               | 2.470                    | 1.540                        | 4900                     | 559                      | 6.98        | 1810                     | 221                      | 4.24        |
| × 311       | 91.4                           | 17.12              | 16.230               | 2.260                    | 1.410                        | 4330                     | 506                      | 6.88        | 1610                     | 199                      | 4.20        |
| × 283       | 83.3                           | 16.74              | 16.110               | 2.070                    | 1.290                        | 3840                     | 459                      | 6.79        | 1440                     | 179                      | 4.17        |
| × 257       | 75.6                           | 16.38              | 15.995               | 1.890                    | 1.175                        | 3400                     | 415                      | 6.71        | 1290                     | 161                      | 4.13        |
| × 233       | 68.5                           | 16.04              | 15.890               | 1.720                    | 1.070                        | 3010                     | 375                      | 6.63        | 1150                     | 145                      | 4.10        |
| × 211       | 62.0                           | 15.72              | 15.800               | 1.560                    | 0.980                        | 2660                     | 338                      | 6.55        | 1030                     | 130                      | 4.07        |
| × 193       | 56.8                           | 15.48              | 15.710               | 1.440                    | 0.890                        | 2400                     | 310                      | 6.50        | 931                      | 119                      | 4.05        |
| × 176       | 51.8                           | 15.22              | 15.650               | 1.310                    | 0.830                        | 2140                     | 281                      | 6.43        | 838                      | 107                      | 4.02        |
| × 159       | 46.7                           | 14.98              | 15.565               | 1.190                    | 0.745                        | 1900                     | 254                      | 6.38        | 748                      | 96.2                     | 4.00        |
| × 145       | 42.7                           | 14.78              | 15.500               | 1.090                    | 0.680                        | 1710                     | 232                      | 6.33        | 677                      | 87.3                     | 3.98        |

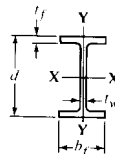
Symbols:  $I$  = moment of inertia;  $S$  = section modulus;  $r$  = radius of gyration.

Data taken from the "Manual of Steel Construction," 8th Edition, 1980, with permission of the American Institute of Steel Construction.

Table 2c. Steel Wide-Flange Sections

Wide-flange sections are designated, in order, by a section letter, nominal depth of the member in inches, and the nominal weight in pounds per foot. Thus:

**W 14 × 38**  
indicates a wide-flange section having a nominal depth of 14 inches, and a nominal weight per foot of 38 pounds. Actual geometry for each section can be obtained from the values below.



| Designation | Area, $A$<br>inch <sup>2</sup> | Depth, $d$<br>inch | Flange                  |                                  | Web<br>Thick-<br>ness,<br>$t_w$<br>inch | Axis X-X                 |                          |             | Axis Y-Y                 |                          |             |
|-------------|--------------------------------|--------------------|-------------------------|----------------------------------|---|--------------------------|--------------------------|-------------|--------------------------|--------------------------|-------------|
|             |                                |                    | Width,<br>$b_f$<br>inch | Thick-<br>ness,<br>$t_f$<br>inch |   | $I$<br>inch <sup>4</sup> | $S$<br>inch <sup>3</sup> | $r$<br>inch | $I$<br>inch <sup>4</sup> | $S$<br>inch <sup>3</sup> | $r$<br>inch |
| W 14 × 132  | 38.8                           | 14.66              | 14.725                  | 1.030                            | 0.645                                   | 1530                     | 209                      | 6.28        | 548                      | 74.5                     | 3.76        |
| × 120       | 35.3                           | 14.48              | 14.670                  | 0.940                            | 0.590                                   | 1380                     | 190                      | 6.24        | 495                      | 67.5                     | 3.74        |
| × 109       | 32.0                           | 14.32              | 14.605                  | 0.860                            | 0.525                                   | 1240                     | 173                      | 6.22        | 447                      | 61.2                     | 3.73        |
| × 99        | 29.1                           | 14.16              | 14.565                  | 0.780                            | 0.485                                   | 1110                     | 157                      | 6.17        | 402                      | 55.2                     | 3.71        |
| × 90        | 26.5                           | 14.02              | 14.520                  | 0.710                            | 0.440                                   | 999                      | 143                      | 6.14        | 362                      | 49.9                     | 3.70        |
| × 82        | 24.1                           | 14.31              | 10.130                  | 0.855                            | 0.510                                   | 882                      | 123                      | 6.05        | 148                      | 29.3                     | 2.48        |
| × 74        | 21.8                           | 14.17              | 10.070                  | 0.785                            | 0.450                                   | 796                      | 112                      | 6.04        | 134                      | 26.6                     | 2.48        |
| × 68        | 20.0                           | 14.04              | 10.035                  | 0.720                            | 0.415                                   | 723                      | 103                      | 6.01        | 121                      | 24.2                     | 2.46        |
| × 61        | 17.9                           | 13.89              | 9.995                   | 0.645                            | 0.375                                   | 640                      | 92.2                     | 5.98        | 107                      | 21.5                     | 2.45        |
| × 53        | 15.6                           | 13.92              | 8.060                   | 0.660                            | 0.370                                   | 541                      | 77.8                     | 5.89        | 57.7                     | 14.3                     | 1.92        |
| × 48        | 14.1                           | 13.79              | 8.030                   | 0.595                            | 0.340                                   | 485                      | 70.3                     | 5.85        | 51.4                     | 12.8                     | 1.91        |
| × 43        | 12.6                           | 13.66              | 7.995                   | 0.530                            | 0.305                                   | 428                      | 62.7                     | 5.82        | 45.2                     | 11.3                     | 1.89        |
| × 38        | 11.2                           | 14.10              | 6.770                   | 0.515                            | 0.310                                   | 385                      | 54.6                     | 5.87        | 26.7                     | 7.88                     | 1.55        |
| × 34        | 10.0                           | 13.98              | 6.745                   | 0.455                            | 0.285                                   | 340                      | 48.6                     | 5.83        | 23.3                     | 6.91                     | 1.53        |
| × 30        | 8.85                           | 13.84              | 6.730                   | 0.385                            | 0.270                                   | 291                      | 42.0                     | 5.73        | 19.6                     | 5.82                     | 1.49        |
| × 26        | 7.69                           | 13.91              | 5.025                   | 0.420                            | 0.255                                   | 245                      | 35.3                     | 5.65        | 8.91                     | 3.54                     | 1.08        |
| × 22        | 6.49                           | 13.74              | 5.000                   | 0.335                            | 0.230                                   | 199                      | 29.0                     | 5.54        | 7.00                     | 2.80                     | 1.04        |
| W 12 × 336  | 98.8                           | 16.82              | 13.385                  | 2.955                            | 1.775                                   | 4060                     | 483                      | 6.41        | 1190                     | 177                      | 3.47        |
| × 305       | 89.6                           | 16.32              | 13.235                  | 2.705                            | 1.625                                   | 3550                     | 435                      | 6.29        | 1050                     | 159                      | 3.42        |
| × 279       | 81.9                           | 15.85              | 13.140                  | 2.470                            | 1.530                                   | 3110                     | 393                      | 6.16        | 937                      | 143                      | 3.38        |
| × 252       | 74.1                           | 15.41              | 13.005                  | 2.250                            | 1.395                                   | 2720                     | 353                      | 6.06        | 828                      | 127                      | 3.34        |
| × 230       | 67.7                           | 15.05              | 12.895                  | 2.070                            | 1.285                                   | 2420                     | 321                      | 5.97        | 742                      | 115                      | 3.31        |
| × 210       | 61.8                           | 14.71              | 12.790                  | 1.900                            | 1.180                                   | 2140                     | 292                      | 5.89        | 664                      | 104                      | 3.28        |
| × 190       | 55.8                           | 14.38              | 12.670                  | 1.735                            | 1.060                                   | 1890                     | 263                      | 5.82        | 589                      | 93.0                     | 3.25        |
| × 170       | 50.0                           | 14.03              | 12.570                  | 1.560                            | 0.960                                   | 1650                     | 235                      | 5.74        | 517                      | 82.3                     | 3.22        |
| × 152       | 44.7                           | 13.71              | 12.480                  | 1.400                            | 0.870                                   | 1430                     | 209                      | 5.66        | 454                      | 72.8                     | 3.19        |
| × 136       | 39.9                           | 13.41              | 12.400                  | 1.250                            | 0.790                                   | 1240                     | 186                      | 5.58        | 398                      | 64.2                     | 3.16        |
| × 120       | 35.3                           | 13.12              | 12.320                  | 1.105                            | 0.710                                   | 1070                     | 163                      | 5.51        | 345                      | 56.0                     | 3.13        |
| × 106       | 31.2                           | 12.89              | 12.220                  | 0.990                            | 0.610                                   | 933                      | 145                      | 5.47        | 301                      | 49.3                     | 3.11        |
| × 96        | 28.2                           | 12.71              | 12.160                  | 0.900                            | 0.550                                   | 833                      | 131                      | 5.44        | 270                      | 44.4                     | 3.09        |
| × 87        | 25.6                           | 12.53              | 12.125                  | 0.810                            | 0.515                                   | 740                      | 118                      | 5.38        | 241                      | 39.7                     | 3.07        |
| × 79        | 23.2                           | 12.38              | 12.080                  | 0.735                            | 0.470                                   | 662                      | 107                      | 5.34        | 216                      | 35.8                     | 3.05        |
| × 72        | 21.1                           | 12.25              | 12.040                  | 0.670                            | 0.430                                   | 597                      | 97.4                     | 5.31        | 195                      | 32.4                     | 3.04        |
| × 65        | 19.1                           | 12.12              | 12.000                  | 0.605                            | 0.390                                   | 533                      | 87.9                     | 5.28        | 174                      | 29.1                     | 3.02        |
| × 58        | 17.0                           | 12.19              | 10.010                  | 0.640                            | 0.360                                   | 475                      | 78.0                     | 5.28        | 107                      | 21.4                     | 2.51        |
| × 53        | 15.6                           | 12.06              | 9.995                   | 0.575                            | 0.345                                   | 425                      | 70.6                     | 5.23        | 95.8                     | 19.2                     | 2.48        |
| × 50        | 14.7                           | 12.19              | 8.080                   | 0.640                            | 0.370                                   | 394                      | 64.7                     | 5.18        | 56.3                     | 13.9                     | 1.96        |
| × 45        | 13.2                           | 12.06              | 8.045                   | 0.575                            | 0.335                                   | 350                      | 58.1                     | 5.15        | 50.0                     | 12.4                     | 1.94        |
| × 40        | 11.8                           | 11.94              | 8.005                   | 0.515                            | 0.295                                   | 310                      | 51.9                     | 5.13        | 44.1                     | 11.0                     | 1.93        |
| × 35        | 10.3                           | 12.50              | 6.560                   | 0.520                            | 0.300                                   | 285                      | 45.6                     | 5.25        | 24.5                     | 7.47                     | 1.54        |
| × 30        | 8.79                           | 12.34              | 6.520                   | 0.440                            | 0.260                                   | 238                      | 38.6                     | 5.21        | 20.3                     | 6.24                     | 1.52        |
| × 26        | 7.65                           | 12.22              | 6.490                   | 0.380                            | 0.230                                   | 204                      | 33.4                     | 5.17        | 17.3                     | 5.34                     | 1.51        |
| × 22        | 6.48                           | 12.31              | 4.030                   | 0.425                            | 0.260                                   | 156                      | 25.4                     | 4.91        | 4.66                     | 2.31                     | 0.847       |
| × 19        | 5.57                           | 12.16              | 4.005                   | 0.350                            | 0.235                                   | 130                      | 21.3                     | 4.82        | 3.76                     | 1.88                     | 0.822       |
| × 16        | 4.71                           | 11.99              | 3.990                   | 0.265                            | 0.220                                   | 103                      | 17.1                     | 4.67        | 2.82                     | 1.41                     | 0.773       |
| × 14        | 4.16                           | 11.91              | 3.970                   | 0.225                            | 0.200                                   | 88.6                     | 14.9                     | 4.62        | 2.36                     | 1.19                     | 0.753       |

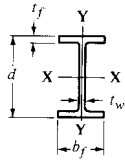
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Table 2d. Steel Wide-Flange Sections

Wide-flange sections are designated, in order, by a section letter, nominal depth of the member in inches, and the nominal weight in pounds per foot; thus:

**W 8 × 67**

indicates a wide-flange section having a nominal depth of 8 inches, and a nominal weight per foot of 67 pounds. Actual geometry for each section can be obtained from the values below.



| Designation | Area, A<br>inch <sup>2</sup> | Depth, d<br>inch | Flange                        |  | Web<br>Thick-<br>ness,<br>t <sub>w</sub><br>inch | Axis X-X               |                        |           | Axis Y-Y               |                        |           |
|-------------|------------------------------|------------------|-------------------------------|--|--|------------------------|------------------------|-----------|------------------------|------------------------|-----------|
|             |                              |                  | Width, b <sub>f</sub><br>inch | Thick-<br>ness, t <sub>f</sub><br>inch |  | I<br>inch <sup>4</sup> | S<br>inch <sup>3</sup> | r<br>inch | I<br>inch <sup>4</sup> | S<br>inch <sup>3</sup> | r<br>inch |
| W 10 × 112  | 32.9                         | 11.36            | 10.415                        | 1.250                                  | 0.755  | 716                    | 126                    | 4.66      | 236                    | 45.3                   | 2.68      |
| × 100       | 29.4                         | 11.10            | 10.340                        | 1.120                                  | 0.680  | 623                    | 112                    | 4.60      | 207                    | 40.0                   | 2.65      |
| × 88        | 25.9                         | 10.84            | 10.265                        | 0.990                                  | 0.605  | 534                    | 98.5                   | 4.54      | 179                    | 34.8                   | 2.63      |
| × 77        | 22.6                         | 10.60            | 10.190                        | 0.870                                  | 0.530  | 455                    | 85.9                   | 4.49      | 154                    | 30.1                   | 2.60      |
| × 68        | 20.0                         | 10.40            | 10.130                        | 0.770                                  | 0.470  | 394                    | 75.7                   | 4.44      | 134                    | 26.4                   | 2.59      |
| × 60        | 17.6                         | 10.22            | 10.080                        | 0.680                                  | 0.420  | 341                    | 66.7                   | 4.39      | 116                    | 23.0                   | 2.57      |
| × 54        | 15.8                         | 10.09            | 10.030                        | 0.615                                  | 0.370  | 303                    | 60.0                   | 4.37      | 103                    | 20.6                   | 2.56      |
| × 49        | 14.4                         | 9.98             | 10.000                        | 0.560                                  | 0.340  | 272                    | 54.6                   | 4.35      | 93.4                   | 18.7                   | 2.54      |
| × 45        | 13.3                         | 10.10            | 8.020                         | 0.620                                  | 0.350  | 248                    | 49.1                   | 4.32      | 53.4                   | 13.3                   | 2.01      |
| × 39        | 11.5                         | 9.92             | 7.985                         | 0.530                                  | 0.315  | 209                    | 42.1                   | 4.27      | 45.0                   | 11.3                   | 1.98      |
| × 33        | 9.71                         | 9.73             | 7.960                         | 0.435                                  | 0.290  | 170                    | 35.0                   | 4.19      | 36.6                   | 9.20                   | 1.94      |
| × 30        | 8.84                         | 10.47            | 5.810                         | 0.510                                  | 0.300  | 170                    | 32.4                   | 4.38      | 16.7                   | 5.75                   | 1.37      |
| × 26        | 7.61                         | 10.33            | 5.770                         | 0.440                                  | 0.260  | 144                    | 27.9                   | 4.35      | 14.1                   | 4.89                   | 1.36      |
| × 22        | 6.49                         | 10.17            | 5.750                         | 0.360                                  | 0.240  | 118                    | 23.2                   | 4.27      | 11.4                   | 3.97                   | 1.33      |
| × 19        | 5.62                         | 10.24            | 4.020                         | 0.395                                  | 0.250  | 96.3                   | 18.8                   | 4.14      | 4.29                   | 2.14                   | 0.874     |
| × 17        | 4.99                         | 10.11            | 4.010                         | 0.330                                  | 0.240  | 81.9                   | 16.2                   | 4.05      | 3.56                   | 1.78                   | 0.844     |
| × 15        | 4.41                         | 9.99             | 4.000                         | 0.270                                  | 0.230  | 68.9                   | 13.8                   | 3.95      | 2.89                   | 1.45                   | 0.810     |
| × 12        | 3.54                         | 9.87             | 3.960                         | 0.210                                  | 0.190  | 53.8                   | 10.9                   | 3.90      | 2.18                   | 1.10                   | 0.785     |
| W 8 × 67    | 19.7                         | 9.00             | 8.280                         | 0.935                                  | 0.570  | 272                    | 60.4                   | 3.72      | 88.6                   | 21.4                   | 2.12      |
| × 58        | 17.1                         | 8.75             | 8.220                         | 0.810                                  | 0.510  | 228                    | 52.0                   | 3.65      | 75.1                   | 18.3                   | 2.10      |
| × 48        | 14.1                         | 8.50             | 8.110                         | 0.685                                  | 0.400  | 184                    | 43.3                   | 3.61      | 60.9                   | 15.0                   | 2.08      |
| × 40        | 11.7                         | 8.25             | 8.070                         | 0.560                                  | 0.360  | 146                    | 35.5                   | 3.53      | 49.1                   | 12.2                   | 2.04      |
| × 35        | 10.3                         | 8.12             | 8.020                         | 0.495                                  | 0.310  | 127                    | 31.2                   | 3.51      | 42.6                   | 10.6                   | 2.03      |
| × 31        | 9.13                         | 8.00             | 7.995                         | 0.435                                  | 0.285  | 110                    | 27.5                   | 3.47      | 37.1                   | 9.27                   | 2.02      |
| × 28        | 8.25                         | 8.06             | 6.535                         | 0.465                                  | 0.285  | 98.0                   | 24.3                   | 3.45      | 21.7                   | 6.63                   | 1.62      |
| × 24        | 7.08                         | 7.93             | 6.495                         | 0.400                                  | 0.245  | 82.8                   | 20.9                   | 3.42      | 18.3                   | 5.63                   | 1.61      |
| × 21        | 6.16                         | 8.28             | 5.270                         | 0.400                                  | 0.250  | 75.3                   | 18.2                   | 3.49      | 9.77                   | 3.71                   | 1.26      |
| × 18        | 5.26                         | 8.14             | 5.250                         | 0.330                                  | 0.230  | 61.9                   | 15.2                   | 3.43      | 7.97                   | 3.04                   | 1.23      |
| × 15        | 4.44                         | 8.11             | 4.015                         | 0.315                                  | 0.245  | 48.0                   | 11.8                   | 3.29      | 3.41                   | 1.70                   | 0.876     |
| × 13        | 3.84                         | 7.99             | 4.000                         | 0.255                                  | 0.230  | 39.6                   | 9.91                   | 3.21      | 2.73                   | 1.37                   | 0.843     |
| × 10        | 2.96                         | 7.89             | 3.940                         | 0.205                                  | 0.170  | 30.8                   | 7.81                   | 3.22      | 2.09                   | 1.06                   | 0.841     |
| W 6 × 25    | 7.34                         | 6.38             | 6.080                         | 0.455                                  | 0.320  | 53.4                   | 16.7                   | 2.70      | 17.1                   | 5.61                   | 1.52      |
| × 20        | 5.87                         | 6.20             | 6.020                         | 0.365                                  | 0.260  | 41.4                   | 13.4                   | 2.66      | 13.3                   | 4.41                   | 1.50      |
| × 16        | 4.74                         | 6.28             | 4.030                         | 0.405                                  | 0.260  | 32.1                   | 10.2                   | 2.60      | 4.43                   | 2.20                   | 0.966     |
| × 15        | 4.43                         | 5.99             | 5.990                         | 0.260                                  | 0.230  | 29.1                   | 9.72                   | 2.56      | 9.32                   | 3.11                   | 1.46      |
| × 12        | 3.55                         | 6.03             | 4.000                         | 0.280                                  | 0.230  | 22.1                   | 7.31                   | 2.49      | 2.99                   | 1.50                   | 0.918     |
| × 9         | 2.68                         | 5.90             | 3.940                         | 0.215                                  | 0.170  | 16.4                   | 5.56                   | 2.47      | 2.19                   | 1.11                   | 0.905     |
| W 5 × 19    | 5.54                         | 5.15             | 5.030                         | 0.430                                  | 0.270  | 26.2                   | 10.2                   | 2.17      | 9.13                   | 3.63                   | 1.28      |
| × 16        | 4.68                         | 5.01             | 5.000                         | 0.360                                  | 0.240  | 21.3                   | 8.51                   | 2.13      | 7.51                   | 3.00                   | 1.27      |
| W 4 × 13    | 3.83                         | 4.16             | 4.060                         | 0.345                                  | 0.280  | 11.3                   | 5.46                   | 1.72      | 3.86                   | 1.90                   | 1.00      |

Symbols: I = moment of inertia; S = section modulus; r = radius of gyration.

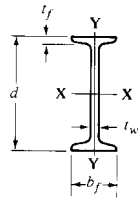
Data taken from the "Manual of Steel Construction," 8th Edition, 1980, with permission of the American Institute of Steel Construction.

Table 3. Steel S Sections

"S" is the section symbol for "I" Beams. S shapes are designated, in order, by their section letter, actual depth in inches, and nominal weight in pounds per foot. Thus:

**S 5 × 14.75**

indicates an S shape (or I beam) having a depth of 5 inches and a nominal weight of 14.75 pounds per foot.

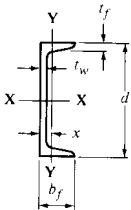


| Designation | Area<br>$A$<br>inch <sup>2</sup> | Depth,<br>$d$<br>inch | Flange                  |                                  | Web<br>Thickness,<br>$t_w$<br>inch | Axis-X-X                 |                          |             | Axis Y-Y                 |                          |             |
|-------------|----------------------------------|-----------------------|-------------------------|----------------------------------|------------------------------------|--------------------------|--------------------------|-------------|--------------------------|--------------------------|-------------|
|             |                                  |                       | Width,<br>$b_f$<br>inch | Thick-<br>ness,<br>$t_f$<br>inch |                                    | $I$<br>inch <sup>4</sup> | $S$<br>inch <sup>3</sup> | $r$<br>inch | $I$<br>inch <sup>4</sup> | $S$<br>inch <sup>3</sup> | $r$<br>inch |
| S 24 × 121  | 35.6                             | 24.50                 | 8.050                   | 1.090                            | 0.800                              | 3160                     | 258                      | 9.43        | 83.3                     | 20.7                     | 1.53        |
| × 106       | 31.2                             | 24.50                 | 7.870                   | 1.090                            | 0.620                              | 2940                     | 240                      | 9.71        | 77.1                     | 19.6                     | 1.57        |
| × 100       | 29.3                             | 24.00                 | 7.245                   | 0.870                            | 0.745                              | 2390                     | 199                      | 9.02        | 47.7                     | 13.2                     | 1.27        |
| × 90        | 26.5                             | 24.00                 | 7.125                   | 0.870                            | 0.625                              | 2250                     | 187                      | 9.21        | 44.9                     | 12.6                     | 1.30        |
| × 80        | 23.5                             | 24.00                 | 7.000                   | 0.870                            | 0.500                              | 2100                     | 175                      | 9.47        | 42.2                     | 12.1                     | 1.34        |
| S 20 × 96   | 28.2                             | 20.30                 | 7.200                   | 0.920                            | 0.800                              | 1670                     | 165                      | 7.71        | 50.2                     | 13.9                     | 1.33        |
| × 86        | 25.3                             | 20.30                 | 7.060                   | 0.920                            | 0.660                              | 1580                     | 155                      | 7.89        | 46.8                     | 13.3                     | 1.36        |
| × 75        | 22.0                             | 20.00                 | 6.385                   | 0.795                            | 0.635                              | 1280                     | 128                      | 7.62        | 29.8                     | 9.32                     | 1.16        |
| × 66        | 19.4                             | 20.00                 | 6.255                   | 0.795                            | 0.505                              | 1190                     | 119                      | 7.83        | 27.7                     | 8.85                     | 1.19        |
| S 18 × 70   | 20.6                             | 18.00                 | 6.251                   | 0.691                            | 0.711                              | 926                      | 103                      | 6.71        | 24.1                     | 7.72                     | 1.08        |
| × 54.7      | 16.1                             | 18.00                 | 6.001                   | 0.691                            | 0.461                              | 804                      | 89.4                     | 7.07        | 20.8                     | 6.94                     | 1.14        |
| S 15 × 50   | 14.7                             | 15.00                 | 5.640                   | 0.622                            | 0.550                              | 486                      | 64.8                     | 5.75        | 15.7                     | 5.57                     | 1.03        |
| × 42.9      | 12.6                             | 15.00                 | 5.501                   | 0.622                            | 0.411                              | 447                      | 59.6                     | 5.95        | 14.4                     | 5.23                     | 1.07        |
| S 12 × 50   | 14.7                             | 12.00                 | 5.477                   | 0.659                            | 0.687                              | 305                      | 50.8                     | 4.55        | 15.7                     | 5.74                     | 1.03        |
| × 40.8      | 12.0                             | 12.00                 | 5.252                   | 0.659                            | 0.462                              | 272                      | 45.4                     | 4.77        | 13.6                     | 5.16                     | 1.06        |
| × 35        | 10.3                             | 12.00                 | 5.078                   | 0.544                            | 0.428                              | 229                      | 38.2                     | 4.72        | 9.87                     | 3.89                     | 0.980       |
| × 31.8      | 9.35                             | 12.00                 | 5.000                   | 0.544                            | 0.350                              | 218                      | 36.4                     | 4.83        | 9.36                     | 3.74                     | 1.00        |
| S 10 × 35   | 10.3                             | 10.00                 | 4.944                   | 0.491                            | 0.594                              | 147                      | 29.4                     | 3.78        | 8.36                     | 3.38                     | 0.901       |
| × 25.4      | 7.46                             | 10.00                 | 4.661                   | 0.491                            | 0.311                              | 124                      | 24.7                     | 4.07        | 6.79                     | 2.91                     | 0.954       |
| S 8 × 23    | 6.77                             | 8.00                  | 4.171                   | 0.426                            | 0.441                              | 64.9                     | 16.2                     | 3.10        | 4.31                     | 2.07                     | 0.798       |
| × 18.4      | 5.41                             | 8.00                  | 4.001                   | 0.426                            | 0.271                              | 57.6                     | 14.4                     | 3.26        | 3.73                     | 1.86                     | 0.831       |
| S 7 × 20    | 5.88                             | 7.00                  | 3.860                   | 0.392                            | 0.450                              | 42.4                     | 12.1                     | 2.69        | 3.17                     | 1.64                     | 0.734       |
| × 15.3      | 4.50                             | 7.00                  | 3.662                   | 0.392                            | 0.252                              | 36.7                     | 10.5                     | 2.86        | 2.64                     | 1.44                     | 0.766       |
| S 6 × 17.25 | 5.07                             | 6.00                  | 3.565                   | 0.359                            | 0.465                              | 26.3                     | 8.77                     | 2.28        | 2.31                     | 1.30                     | 0.675       |
| × 12.5      | 3.67                             | 6.00                  | 3.332                   | 0.359                            | 0.232                              | 22.1                     | 7.37                     | 2.45        | 1.82                     | 1.09                     | 0.705       |
| S 5 × 14.75 | 4.34                             | 5.00                  | 3.284                   | 0.326                            | 0.494                              | 15.2                     | 6.09                     | 1.87        | 1.67                     | 1.01                     | 0.620       |
| × 10        | 2.94                             | 5.00                  | 3.004                   | 0.326                            | 0.214                              | 12.3                     | 4.92                     | 2.05        | 1.22                     | 0.809                    | 0.643       |
| S 4 × 9.5   | 2.79                             | 4.00                  | 2.796                   | 0.293                            | 0.326                              | 6.79                     | 3.39                     | 1.56        | 0.903                    | 0.646                    | 0.569       |
| × 7.7       | 2.26                             | 4.00                  | 2.663                   | 0.293                            | 0.193                              | 6.08                     | 3.04                     | 1.64        | 0.764                    | 0.574                    | 0.581       |
| S 3 × 7.5   | 2.21                             | 3.00                  | 2.509                   | 0.260                            | 0.349                              | 2.93                     | 1.95                     | 1.15        | 0.586                    | 0.468                    | 0.516       |
| × 5.7       | 1.67                             | 3.00                  | 2.330                   | 0.260                            | 0.170                              | 2.52                     | 1.68                     | 1.23        | 0.455                    | 0.390                    | 0.522       |

Data taken from the "Manual of Steel Construction," 8th Edition, 1980, with permission of the American Institute of Steel Construction.

Table 4. American Standard Steel Channels

American Standard Channels are designated, in order, by a section letter, actual depth in inches, and nominal weight per foot in pounds. Thus:  
**C 7 × 14.75**  
 indicates an American Standard Channel with a depth of 7 inches and a nominal weight of 14.75 pounds per foot.



| Designation | Area, $A$<br>inch <sup>2</sup> | Depth, $d$<br>inch | Flange                  |                                  | Web<br>Thick-<br>ness,<br>$t_w$<br>inch | Axis X-X                 |                          |             | Axis Y-Y                 |                          |             | $x$<br>inch |
|-------------|--------------------------------|--------------------|-------------------------|----------------------------------|---|--------------------------|--------------------------|-------------|--------------------------|--------------------------|-------------|-------------|
|             |                                |                    | Width,<br>$b_f$<br>inch | Thick-<br>ness,<br>$t_f$<br>inch |   | $I$<br>inch <sup>4</sup> | $S$<br>inch <sup>3</sup> | $r$<br>inch | $I$<br>inch <sup>4</sup> | $S$<br>inch <sup>3</sup> | $r$<br>inch |             |
| C 15 × 50   | 14.7                           | 15.00              | 3.716                   | 0.650                            | 0.716                                   | 404                      | 53.8                     | 5.24        | 11.0                     | 3.78                     | 0.867       | 0.798       |
| × 40        | 11.8                           | 15.00              | 3.520                   | 0.650                            | 0.520                                   | 349                      | 46.5                     | 5.44        | 9.23                     | 3.37                     | 0.886       | 0.777       |
| × 33.9      | 9.96                           | 15.00              | 3.400                   | 0.650                            | 0.400                                   | 315                      | 42.0                     | 5.62        | 8.13                     | 3.11                     | 0.904       | 0.787       |
| C 12 × 30   | 8.82                           | 12.00              | 3.170                   | 0.501                            | 0.510                                   | 162                      | 27.0                     | 4.29        | 5.14                     | 2.06                     | 0.763       | 0.674       |
| × 25        | 7.35                           | 12.00              | 3.047                   | 0.501                            | 0.387                                   | 144                      | 24.1                     | 4.43        | 4.47                     | 1.88                     | 0.780       | 0.674       |
| × 20.7      | 6.09                           | 12.00              | 2.942                   | 0.501                            | 0.282                                   | 129                      | 21.5                     | 4.61        | 3.88                     | 1.73                     | 0.799       | 0.698       |
| C 10 × 30   | 8.82                           | 10.00              | 3.033                   | 0.436                            | 0.673                                   | 103                      | 20.7                     | 3.42        | 3.94                     | 1.65                     | 0.669       | 0.649       |
| × 25        | 7.35                           | 10.00              | 2.886                   | 0.436                            | 0.526                                   | 91.2                     | 18.2                     | 3.52        | 3.36                     | 1.48                     | 0.676       | 0.617       |
| × 20        | 5.88                           | 10.00              | 2.739                   | 0.436                            | 0.379                                   | 78.9                     | 15.8                     | 3.66        | 2.81                     | 1.32                     | 0.692       | 0.606       |
| × 15.3      | 4.49                           | 10.00              | 2.600                   | 0.436                            | 0.240                                   | 67.4                     | 13.5                     | 3.87        | 2.28                     | 1.16                     | 0.713       | 0.634       |
| C 9 × 20    | 5.88                           | 9.00               | 2.648                   | 0.413                            | 0.448                                   | 60.9                     | 13.5                     | 3.22        | 2.42                     | 1.17                     | 0.642       | 0.583       |
| × 15        | 4.41                           | 9.00               | 2.485                   | 0.413                            | 0.285                                   | 51.0                     | 11.3                     | 3.40        | 1.93                     | 1.01                     | 0.661       | 0.586       |
| × 13.4      | 3.94                           | 9.00               | 2.433                   | 0.413                            | 0.233                                   | 47.9                     | 10.6                     | 3.48        | 1.76                     | 0.962                    | 0.669       | 0.601       |
| C 8 × 18.75 | 5.51                           | 8.00               | 2.527                   | 0.390                            | 0.487                                   | 44.0                     | 11.0                     | 2.82        | 1.98                     | 1.01                     | 0.599       | 0.565       |
| × 13.75     | 4.04                           | 8.00               | 2.343                   | 0.390                            | 0.303                                   | 36.1                     | 9.03                     | 2.99        | 1.53                     | 0.854                    | 0.615       | 0.553       |
| × 11.5      | 3.38                           | 8.00               | 2.260                   | 0.390                            | 0.220                                   | 32.6                     | 8.14                     | 3.11        | 1.32                     | 0.781                    | 0.625       | 0.571       |
| C 7 × 14.75 | 4.33                           | 7.00               | 2.299                   | 0.366                            | 0.419                                   | 27.2                     | 7.78                     | 2.51        | 1.38                     | 0.779                    | 0.564       | 0.532       |
| × 12.25     | 3.60                           | 7.00               | 2.194                   | 0.366                            | 0.314                                   | 24.2                     | 6.93                     | 2.60        | 1.17                     | 0.703                    | 0.571       | 0.525       |
| × 9.8       | 2.87                           | 7.00               | 2.090                   | 0.366                            | 0.210                                   | 21.3                     | 6.08                     | 2.72        | 0.968                    | 0.625                    | 0.581       | 0.540       |
| C 6 × 13    | 3.83                           | 6.00               | 2.157                   | 0.343                            | 0.437                                   | 17.4                     | 5.80                     | 2.13        | 1.05                     | 0.642                    | 0.525       | 0.514       |
| × 10.5      | 3.09                           | 6.00               | 2.034                   | 0.343                            | 0.314                                   | 15.2                     | 5.06                     | 2.22        | 0.866                    | 0.564                    | 0.529       | 0.499       |
| × 8.2       | 2.40                           | 6.00               | 1.920                   | 0.343                            | 0.200                                   | 13.1                     | 4.38                     | 2.34        | 0.693                    | 0.492                    | 0.537       | 0.511       |
| C 5 × 9     | 2.64                           | 5.00               | 1.885                   | 0.320                            | 0.325                                   | 8.90                     | 3.56                     | 1.83        | 0.632                    | 0.450                    | 0.489       | 0.478       |
| × 6.7       | 1.97                           | 5.00               | 1.750                   | 0.320                            | 0.190                                   | 7.49                     | 3.00                     | 1.95        | 0.479                    | 0.378                    | 0.493       | 0.484       |
| C 4 × 7.25  | 2.13                           | 4.00               | 1.721                   | 0.296                            | 0.321                                   | 4.59                     | 2.29                     | 1.47        | 0.433                    | 0.343                    | 0.450       | 0.459       |
| × 5.4       | 1.59                           | 4.00               | 1.584                   | 0.296                            | 0.184                                   | 3.85                     | 1.93                     | 1.56        | 0.319                    | 0.283                    | 0.449       | 0.457       |
| C 3 × 6     | 1.76                           | 3.00               | 1.596                   | 0.273                            | 0.356                                   | 2.07                     | 1.38                     | 1.08        | 0.305                    | 0.268                    | 0.416       | 0.455       |
| × 5         | 1.47                           | 3.00               | 1.498                   | 0.273                            | 0.258                                   | 1.85                     | 1.24                     | 1.12        | 0.247                    | 0.233                    | 0.410       | 0.438       |
| × 4.1       | 1.21                           | 3.00               | 1.410                   | 0.273                            | 0.170                                   | 1.66                     | 1.10                     | 1.17        | 0.197                    | 0.202                    | 0.404       | 0.436       |

Symbols:  $I$  = moment of inertia;  $S$  = section modulus;  $r$  = radius of gyration;  $x$  = distance from center of gravity of section to outer face of structural shape.

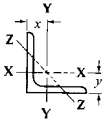
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**Table 5. Steel Angles with Equal Legs**

These angles are commonly designated by section symbol, width of each leg, and thickness, thus:

**L 3 × 3 × 1/4**

indicates a 3 × 3-inch angle of 1/4-inch thickness.



| Size inch     | Thickness inch | Weight per Foot lb. | Area inch <sup>2</sup> | Axis X-X & Y-Y      |        |             | Z-Z    |
|---------------|----------------|---------------------|------------------------|---------------------|--------|-------------|--------|
|               |                |                     |                        | I inch <sup>4</sup> | r inch | x or y inch | r inch |
| 8 × 8         | 1 1/8          | 56.9                | 16.7                   | 98.0                | 2.42   | 2.41        | 1.56   |
|               | 1              | 51.0                | 15.0                   | 89.0                | 2.44   | 2.37        | 1.56   |
|               | 7/8            | 45.0                | 13.2                   | 79.6                | 2.45   | 2.32        | 1.57   |
|               | 3/4            | 38.9                | 11.4                   | 69.7                | 2.47   | 2.28        | 1.58   |
|               | 5/8            | 32.7                | 9.61                   | 59.4                | 2.49   | 2.23        | 1.58   |
|               | 9/16           | 29.6                | 8.68                   | 54.1                | 2.50   | 2.21        | 1.59   |
|               | 1/2            | 26.4                | 7.75                   | 48.6                | 2.50   | 2.19        | 1.59   |
|               | 1              | 37.4                | 11.00                  | 35.5                | 1.80   | 1.86        | 1.17   |
| 6 × 6         | 7/8            | 33.1                | 9.73                   | 31.9                | 1.81   | 1.82        | 1.17   |
|               | 3/4            | 28.7                | 8.44                   | 28.2                | 1.83   | 1.78        | 1.17   |
|               | 5/8            | 24.2                | 7.11                   | 24.2                | 1.84   | 1.73        | 1.18   |
|               | 9/16           | 21.9                | 6.43                   | 22.1                | 1.85   | 1.71        | 1.18   |
|               | 1/2            | 19.6                | 5.75                   | 19.9                | 1.86   | 1.68        | 1.18   |
|               | 7/16           | 17.2                | 5.06                   | 17.7                | 1.87   | 1.66        | 1.19   |
|               | 3/8            | 14.9                | 4.36                   | 15.4                | 1.88   | 1.64        | 1.19   |
|               | 5/16           | 12.4                | 3.65                   | 13.0                | 1.89   | 1.62        | 1.20   |
| 5 × 5         | 7/8            | 27.2                | 7.98                   | 17.8                | 1.49   | 1.57        | .973   |
|               | 3/4            | 23.6                | 6.94                   | 15.7                | 1.51   | 1.52        | .975   |
|               | 5/8            | 20.0                | 5.86                   | 13.6                | 1.52   | 1.48        | .978   |
|               | 1/2            | 16.2                | 4.75                   | 11.3                | 1.54   | 1.43        | .983   |
|               | 7/16           | 14.3                | 4.18                   | 10.0                | 1.55   | 1.41        | .986   |
|               | 3/8            | 12.3                | 3.61                   | 8.74                | 1.56   | 1.39        | .990   |
|               | 5/16           | 10.3                | 3.03                   | 7.42                | 1.57   | 1.37        | .994   |
|               | 3/4            | 18.5                | 5.44                   | 7.67                | 1.19   | 1.27        | .778   |
| 4 × 4         | 5/8            | 15.7                | 4.61                   | 6.66                | 1.20   | 1.23        | .779   |
|               | 1/2            | 12.8                | 3.75                   | 5.56                | 1.22   | 1.18        | .782   |
|               | 7/16           | 11.3                | 3.31                   | 4.97                | 1.23   | 1.16        | .785   |
|               | 3/8            | 9.8                 | 2.86                   | 4.36                | 1.23   | 1.14        | .788   |
|               | 5/16           | 8.2                 | 2.40                   | 3.71                | 1.24   | 1.12        | .791   |
|               | 1/4            | 6.6                 | 1.94                   | 3.04                | 1.25   | 1.09        | .795   |
|               | 1/2            | 11.1                | 3.25                   | 3.64                | 1.06   | 1.06        | .683   |
|               | 7/16           | 9.8                 | 2.87                   | 3.26                | 1.07   | 1.04        | .684   |
| 3 1/2 × 3 1/2 | 3/8            | 8.5                 | 2.48                   | 2.87                | 1.07   | 1.01        | .687   |
|               | 5/16           | 7.2                 | 2.09                   | 2.45                | 1.08   | .990        | .690   |
|               | 1/4            | 5.8                 | 1.69                   | 2.01                | 1.09   | .968        | .694   |
|               | 1/2            | 9.4                 | 2.75                   | 2.22                | .898   | .932        | .584   |
|               | 7/16           | 8.3                 | 2.43                   | 1.99                | .905   | .910        | .585   |
|               | 3/8            | 7.2                 | 2.11                   | 1.76                | .913   | .888        | .587   |
|               | 5/16           | 6.1                 | 1.78                   | 1.51                | .922   | .865        | .589   |
|               | 1/4            | 4.9                 | 1.44                   | 1.24                | .930   | .842        | .592   |
| 2 1/2 × 2 1/2 | 3/16           | 3.71                | 1.09                   | .962                | .939   | .820        | .596   |
|               | 1/2            | 7.7                 | 2.25                   | 1.23                | .739   | .806        | .487   |
|               | 3/8            | 5.9                 | 1.73                   | .984                | .753   | .762        | .487   |
|               | 5/16           | 5.0                 | 1.46                   | .849                | .761   | .740        | .489   |
|               | 1/4            | 4.1                 | 1.19                   | .703                | .769   | .717        | .491   |
|               | 3/16           | 3.07                | .902                   | .547                | .778   | .694        | .495   |
|               | 3/8            | 4.7                 | 1.36                   | .479                | .594   | .636        | .389   |
|               | 5/16           | 3.92                | 1.15                   | .416                | .601   | .614        | .390   |
| 2 × 2         | 1/4            | 3.19                | .938                   | .348                | .609   | .592        | .391   |
|               | 3/16           | 2.44                | .715                   | .272                | .617   | .569        | .394   |
|               | 1/8            | 1.65                | .484                   | .190                | .626   | .546        | .398   |

Data taken from the "Manual of Steel Construction," 8th Edition, 1980, with permission of the American Institute of Steel Construction.



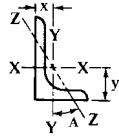
ROLLED STEEL SECTIONS

Table 6. Steel Angles with Unequal Legs

These angles are commonly designated by section symbol, width of each leg, and thickness, thus:

$$L\ 7 \times 4 \times \frac{1}{2}$$

indicates a 7 × 4-inch angle of 1/2-inch thickness.



| Size<br>inch | Thick-<br>ness<br>inch | Weight<br>per Ft.<br>lb. | Area<br>inch <sup>2</sup> | Axis X-X               |                        |           |           | Axis Y-Y               |                        |           | Axis Z-Z  |           |          |
|--------------|------------------------|--------------------------|---------------------------|------------------------|------------------------|-----------|-----------|------------------------|------------------------|-----------|-----------|-----------|----------|
|              |                        |                          |                           | I<br>inch <sup>4</sup> | S<br>inch <sup>3</sup> | r<br>inch | y<br>inch | I<br>inch <sup>4</sup> | S<br>inch <sup>3</sup> | r<br>inch | x<br>inch | r<br>inch | Tan<br>A |
| 9 × 4        | 5/8                    | 26.3                     | 7.73                      | 64.9                   | 11.5                   | 2.90      | 3.36      | 8.32                   | 2.65                   | 1.04      | .858      | .847      | .216     |
|              | 9/16                   | 23.8                     | 7.00                      | 59.1                   | 10.4                   | 2.91      | 3.33      | 7.63                   | 2.41                   | 1.04      | .834      | .850      | .218     |
|              | 1/2                    | 21.3                     | 6.25                      | 53.2                   | 9.34                   | 2.92      | 3.31      | 6.92                   | 2.17                   | 1.05      | .810      | .854      | .220     |
| 8 × 6        | 1                      | 44.2                     | 13.0                      | 80.8                   | 15.1                   | 2.49      | 2.65      | 38.8                   | 8.92                   | 1.73      | 1.65      | 1.28      | .543     |
|              | 7/8                    | 39.1                     | 11.5                      | 72.3                   | 13.4                   | 2.51      | 2.61      | 34.9                   | 7.94                   | 1.74      | 1.61      | 1.28      | .547     |
|              | 3/4                    | 33.8                     | 9.94                      | 63.4                   | 11.7                   | 2.53      | 2.56      | 30.7                   | 6.92                   | 1.76      | 1.56      | 1.29      | .551     |
|              | 5/8                    | 28.5                     | 8.36                      | 54.1                   | 9.87                   | 2.54      | 2.52      | 26.3                   | 5.88                   | 1.77      | 1.52      | 1.29      | .554     |
|              | 9/16                   | 7                        | 7.56                      | 49.3                   | 8.95                   | 2.55      | 2.50      | 24.0                   | 5.34                   | 1.78      | 1.50      | 1.30      | .556     |
|              | 1/2                    | 23.0                     | 6.75                      | 44.3                   | 8.02                   | 2.56      | 2.47      | 21.7                   | 4.79                   | 1.79      | 1.47      | 1.30      | .558     |
| 8 × 4        | 7/16                   | 20.2                     | 5.93                      | 39.2                   | 7.07                   | 2.57      | 2.45      | 19.3                   | 4.23                   | 1.80      | 1.45      | 1.31      | .560     |
|              | 1                      | 37.4                     | 11.0                      | 69.6                   | 14.1                   | 2.52      | 3.05      | 11.6                   | 3.94                   | 1.03      | 1.05      | .846      | .247     |
|              | 3/4                    | 28.7                     | 8.44                      | 54.9                   | 10.9                   | 2.55      | 2.95      | 9.36                   | 3.07                   | 1.05      | .953      | .852      | .258     |
|              | 9/16                   | 21.9                     | 6.43                      | 42.8                   | 8.35                   | 2.58      | 2.88      | 7.43                   | 2.38                   | 1.07      | .882      | .861      | .265     |
| 7 × 4        | 1/2                    | 19.6                     | 5.75                      | 38.5                   | 7.49                   | 2.59      | 2.86      | 6.74                   | 2.15                   | 1.08      | .859      | .865      | .267     |
|              | 3/4                    | 26.2                     | 7.69                      | 37.8                   | 8.42                   | 2.22      | 2.51      | 9.05                   | 3.03                   | 1.09      | 1.01      | .860      | .324     |
|              | 5/8                    | 22.1                     | 6.48                      | 32.4                   | 7.14                   | 2.24      | 2.46      | 7.84                   | 2.58                   | 1.10      | .963      | .865      | .329     |
| 6 × 4        | 1/2                    | 17.9                     | 5.25                      | 26.7                   | 5.81                   | 2.25      | 2.42      | 6.53                   | 2.12                   | 1.11      | .917      | .872      | .335     |
|              | 3/8                    | 13.6                     | 3.98                      | 20.6                   | 4.44                   | 2.27      | 2.37      | 5.10                   | 1.63                   | 1.13      | .870      | .880      | .340     |
|              | 7/8                    | 27.2                     | 7.98                      | 27.7                   | 7.15                   | 1.86      | 2.12      | 9.75                   | 3.39                   | 1.11      | 1.12      | .857      | .421     |
|              | 3/4                    | 23.6                     | 6.94                      | 24.5                   | 6.25                   | 1.88      | 2.08      | 8.68                   | 2.97                   | 1.12      | 1.08      | .860      | .428     |
|              | 5/8                    | 20.0                     | 5.86                      | 21.1                   | 5.31                   | 1.90      | 2.03      | 7.52                   | 2.54                   | 1.13      | 1.03      | .864      | .435     |
|              | 9/16                   | 18.1                     | 5.31                      | 19.3                   | 4.83                   | 1.90      | 2.01      | 6.91                   | 2.31                   | 1.14      | 1.01      | .866      | .438     |
| 6 × 3 1/2    | 1/2                    | 16.2                     | 4.75                      | 17.4                   | 4.33                   | 1.91      | 1.99      | 6.27                   | 2.08                   | 1.15      | .987      | .870      | .440     |
|              | 7/16                   | 14.3                     | 4.18                      | 15.5                   | 3.83                   | 1.92      | 1.96      | 5.60                   | 1.85                   | 1.16      | .964      | .873      | .443     |
|              | 3/8                    | 12.3                     | 3.61                      | 13.5                   | 3.32                   | 1.93      | 1.94      | 4.90                   | 1.60                   | 1.17      | .941      | .877      | .446     |
|              | 9/16                   | 10.3                     | 3.03                      | 11.4                   | 2.79                   | 1.94      | 1.92      | 4.18                   | 1.35                   | 1.17      | .918      | .882      | .448     |
|              | 1/2                    | 15.3                     | 4.50                      | 16.6                   | 4.24                   | 1.92      | 2.08      | 4.25                   | 1.59                   | .972      | .833      | .759      | .344     |
|              | 3/8                    | 11.7                     | 3.42                      | 12.9                   | 3.24                   | 1.94      | 2.04      | 3.34                   | 1.23                   | .988      | .787      | .676      | .350     |
|              | 5/16                   | 9.8                      | 2.87                      | 10.9                   | 2.73                   | 1.95      | 2.01      | 2.85                   | 1.04                   | .996      | .763      | .772      | .352     |
|              | 3/4                    | 19.8                     | 5.81                      | 13.9                   | 4.28                   | 1.55      | 1.75      | 5.55                   | 2.22                   | .977      | .996      | .748      | .464     |
| 5 × 3 1/2    | 5/8                    | 16.8                     | 4.92                      | 12.0                   | 3.65                   | 1.56      | 1.70      | 4.83                   | 1.90                   | .991      | .951      | .751      | .472     |
|              | 1/2                    | 13.6                     | 4.00                      | 9.99                   | 2.99                   | 1.58      | 1.66      | 4.05                   | 1.56                   | 1.01      | .906      | .755      | .479     |
|              | 7/16                   | 12.0                     | 3.53                      | 8.90                   | 2.64                   | 1.59      | 1.63      | 3.63                   | 1.39                   | 1.01      | .883      | .758      | .482     |
|              | 3/8                    | 10.4                     | 3.05                      | 7.78                   | 2.29                   | 1.60      | 1.61      | 3.18                   | 1.21                   | 1.02      | .861      | .762      | .486     |
|              | 5/16                   | 8.7                      | 2.56                      | 6.60                   | 1.94                   | 1.61      | 1.59      | 2.72                   | 1.02                   | 1.03      | .838      | .766      | .489     |
|              | 3/4                    | 7.0                      | 2.06                      | 5.39                   | 1.57                   | 1.62      | 1.56      | 2.23                   | .830                   | 1.04      | .814      | .770      | .492     |
|              | 5/8                    | 15.7                     | 4.61                      | 11.4                   | 3.55                   | 1.57      | 1.80      | 3.06                   | 1.39                   | .815      | .796      | .644      | .349     |
| 1/2          | 12.8                   | 3.75                     | 9.45                      | 2.91                   | 1.59                   | 1.75      | 2.58      | 1.15                   | .829                   | .750      | .648      | .357      |          |

Table 6. (Continued) Steel Angles with Unequal Legs

| Size<br>inch  | Thick-<br>ness<br>inch | Weight<br>per Ft.<br>lb. | Area<br>inch <sup>2</sup> | Axis X-X                      |                               |                  |                  | Axis Y-Y                      |                               |                  | Axis Z-Z         |                  |          |
|---------------|------------------------|--------------------------|---------------------------|-------------------------------|-------------------------------|------------------|------------------|-------------------------------|-------------------------------|------------------|------------------|------------------|----------|
|               |                        |                          |                           | <i>I</i><br>inch <sup>4</sup> | <i>S</i><br>inch <sup>3</sup> | <i>r</i><br>inch | <i>y</i><br>inch | <i>I</i><br>inch <sup>4</sup> | <i>S</i><br>inch <sup>3</sup> | <i>r</i><br>inch | <i>x</i><br>inch | <i>r</i><br>inch | Tan<br>A |
| 5 × 3         | 7/16                   | 11.3                     | 3.31                      | 8.43                          | 2.58                          | 1.60             | 1.73             | 2.32                          | 1.02                          | .837             | .727             | .651             | .361     |
|               | 3/8                    | 9.8                      | 2.86                      | 7.37                          | 2.24                          | 1.61             | 1.70             | 2.04                          | .888                          | .845             | .704             | .654             | .364     |
|               | 5/16                   | 8.2                      | 2.40                      | 6.26                          | 1.89                          | 1.61             | 1.68             | 1.75                          | .753                          | .853             | .681             | .658             | .368     |
|               | 1/4                    | 6.6                      | 1.94                      | 5.11                          | 1.53                          | 1.62             | 1.66             | 1.44                          | .614                          | .861             | .657             | .663             | .371     |
|               | 3/8                    | 14.7                     | 4.30                      | 6.37                          | 2.35                          | 1.22             | 1.29             | 4.52                          | 1.84                          | 1.03             | 1.04             | .719             | .745     |
|               | 1/2                    | 11.9                     | 3.50                      | 5.32                          | 1.94                          | 1.23             | 1.25             | 3.79                          | 1.52                          | 1.04             | 1.00             | .722             | .750     |
|               | 7/16                   | 10.6                     | 3.09                      | 4.76                          | 1.72                          | 1.24             | 1.23             | 3.40                          | 1.35                          | 1.05             | .978             | .724             | .753     |
|               | 3/8                    | 9.1                      | 2.67                      | 4.18                          | 1.49                          | 1.25             | 1.21             | 2.95                          | 1.17                          | 1.06             | .955             | .727             | .755     |
| 4 × 3 1/2     | 5/16                   | 7.7                      | 2.25                      | 3.56                          | 1.26                          | 1.26             | 1.18             | 2.55                          | .994                          | 1.07             | .932             | .730             | .757     |
|               | 1/4                    | 6.2                      | 1.81                      | 2.91                          | 1.03                          | 1.27             | 1.16             | 2.09                          | .808                          | 1.07             | .909             | .734             | .759     |
|               | 3/8                    | 13.6                     | 3.98                      | 6.03                          | 2.30                          | 1.23             | 1.37             | 2.87                          | 1.35                          | .849             | .871             | .637             | .534     |
|               | 1/2                    | 11.1                     | 3.25                      | 5.05                          | 1.89                          | 1.25             | 1.33             | 2.42                          | 1.12                          | .864             | .827             | .639             | .543     |
|               | 7/16                   | 9.8                      | 2.87                      | 4.52                          | 1.68                          | 1.25             | 1.30             | 2.18                          | .992                          | .871             | .804             | .641             | .547     |
|               | 3/8                    | 8.5                      | 2.48                      | 3.96                          | 1.46                          | 1.26             | 1.28             | 1.92                          | .866                          | .879             | .782             | .644             | .551     |
|               | 5/16                   | 7.2                      | 2.09                      | 3.38                          | 1.23                          | 1.27             | 1.26             | 1.65                          | .734                          | .887             | .759             | .647             | .554     |
|               | 1/4                    | 5.8                      | 1.69                      | 2.77                          | 1.00                          | 1.28             | 1.24             | 1.36                          | .599                          | .896             | .736             | .651             | .558     |
| 3 1/2 × 3     | 1/2                    | 10.2                     | 3.00                      | 3.45                          | 1.45                          | 1.07             | 1.13             | 2.33                          | 1.10                          | .881             | .875             | .621             | .714     |
|               | 7/16                   | 9.1                      | 2.65                      | 3.10                          | 1.29                          | 1.08             | 1.10             | 2.09                          | .975                          | .889             | .853             | .622             | .718     |
|               | 3/8                    | 7.9                      | 2.30                      | 2.72                          | 1.13                          | 1.09             | 1.08             | 1.85                          | .851                          | .897             | .830             | .625             | .721     |
|               | 5/16                   | 6.6                      | 1.93                      | 2.33                          | .954                          | 1.10             | 1.06             | 1.58                          | .722                          | .905             | .808             | .627             | .724     |
|               | 1/4                    | 5.4                      | 1.56                      | 1.91                          | .776                          | 1.11             | 1.04             | 1.30                          | .589                          | .914             | .785             | .631             | .727     |
|               | 1/2                    | 9.4                      | 2.75                      | 3.24                          | 1.41                          | 1.09             | 1.20             | 1.36                          | .760                          | .704             | .705             | .534             | .486     |
|               | 7/16                   | 8.3                      | 2.43                      | 2.91                          | 1.26                          | 1.09             | 1.18             | 1.23                          | .677                          | .711             | .682             | .535             | .491     |
|               | 3/8                    | 7.2                      | 2.11                      | 2.56                          | 1.09                          | 1.10             | 1.16             | 1.09                          | .592                          | .719             | .660             | .537             | .496     |
| 3 1/2 × 2 1/2 | 5/16                   | 6.1                      | 1.78                      | 2.19                          | .927                          | 1.11             | 1.14             | .939                          | .504                          | .727             | .637             | .540             | .501     |
|               | 1/4                    | 4.9                      | 1.44                      | 1.80                          | .755                          | 1.12             | 1.11             | .777                          | .412                          | .735             | .614             | .544             | .506     |
|               | 1/2                    | 8.5                      | 2.50                      | 2.08                          | 1.04                          | .913             | 1.00             | 1.30                          | .744                          | .722             | .750             | .520             | .667     |
|               | 7/16                   | 7.6                      | 2.21                      | 1.88                          | .928                          | .920             | .978             | 1.18                          | .664                          | .729             | .728             | .521             | .672     |
|               | 3/8                    | 6.6                      | 1.92                      | 1.66                          | .810                          | .928             | .956             | 1.04                          | .581                          | .736             | .706             | .522             | .676     |
|               | 5/16                   | 5.6                      | 1.62                      | 1.42                          | .688                          | .937             | .933             | .898                          | .494                          | .744             | .683             | .525             | .680     |
|               | 1/4                    | 4.5                      | 1.31                      | 1.17                          | .561                          | .945             | .911             | .743                          | .404                          | .753             | .661             | .528             | .684     |
|               | 3/16                   | 3.39                     | .996                      | .907                          | .430                          | .954             | .888             | .577                          | .310                          | .761             | .638             | .533             | .688     |
| 3 × 2         | 1/2                    | 7.7                      | 2.25                      | 1.92                          | 1.00                          | .924             | 1.08             | .672                          | .474                          | .546             | .583             | .428             | .414     |
|               | 7/16                   | 6.8                      | 2.00                      | 1.73                          | .894                          | .932             | 1.06             | .609                          | .424                          | .553             | .561             | .429             | .421     |
|               | 3/8                    | 5.9                      | 1.73                      | 1.53                          | .781                          | .940             | 1.04             | .543                          | .371                          | .559             | .539             | .430             | .428     |
|               | 5/16                   | 5.0                      | 1.46                      | 1.32                          | .664                          | .948             | 1.02             | .740                          | .317                          | .567             | .516             | .432             | .435     |
|               | 1/4                    | 4.1                      | 1.19                      | 1.09                          | .542                          | .957             | .993             | .392                          | .260                          | .574             | .493             | .435             | .440     |
|               | 3/16                   | 3.07                     | .902                      | .842                          | .415                          | .966             | .970             | .307                          | .200                          | .583             | .470             | .439             | .446     |
|               | 3/8                    | 5.3                      | 1.55                      | .912                          | .547                          | .768             | .831             | .514                          | .363                          | .577             | .581             | .420             | .614     |
|               | 5/16                   | 4.5                      | 1.31                      | .788                          | .466                          | .776             | .809             | .446                          | .310                          | .584             | .559             | .422             | .620     |
| 2 1/2 × 2     | 1/4                    | 3.62                     | 1.06                      | .654                          | .381                          | .784             | .787             | .372                          | .254                          | .592             | .537             | .424             | .626     |
|               | 3/16                   | 2.75                     | .809                      | .509                          | .293                          | .793             | .764             | .291                          | .196                          | .600             | .514             | .427             | .631     |

Symbols: *I* = moment of inertia; *S* = section modulus; *r* = radius of gyration; *x* = distance from center of gravity of section to outer face of structural shape.

Data taken from the "Manual of Steel Construction," 8th Edition, 1980, with permission of the American Institute of Steel Construction.

Table 7. Aluminum Association Standard Structural Shapes

| Depth           | Width | Weight per Foot | Area              | Flange Thickness | Web Thickness | Fillet Radius | Axis X-X          |                   |          | Axis Y-Y          |                   |          |          |
|-----------------|-------|-----------------|-------------------|------------------|---------------|---------------|-------------------|-------------------|----------|-------------------|-------------------|----------|----------|
|                 |       |                 |                   |                  |               |               | <i>I</i>          | <i>S</i>          | <i>r</i> | <i>I</i>          | <i>S</i>          | <i>r</i> | <i>x</i> |
| inch            | inch  | lb.             | inch <sup>2</sup> | inch             | inch          | inch          | inch <sup>4</sup> | inch <sup>3</sup> | inch     | inch <sup>4</sup> | inch <sup>3</sup> | inch     | inch     |
| <b>I-BEAMS</b>  |       |                 |                   |                  |               |               |                   |                   |          |                   |                   |          |          |
| 3.00            | 2.50  | 1.637           | 1.392             | 0.20             | 0.13          | 0.25          | 2.24              | 1.49              | 1.27     | 0.52              | 0.42              | 0.61     | ...      |
| 3.00            | 2.50  | 2.030           | 1.726             | 0.26             | 0.15          | 0.25          | 2.71              | 1.81              | 1.25     | 0.68              | 0.54              | 0.63     | ...      |
| 4.00            | 3.00  | 2.311           | 1.965             | 0.23             | 0.15          | 0.25          | 5.62              | 2.81              | 1.69     | 1.04              | 0.69              | 0.73     | ...      |
| 4.00            | 3.00  | 2.793           | 2.375             | 0.29             | 0.17          | 0.25          | 6.71              | 3.36              | 1.68     | 1.31              | 0.87              | 0.74     | ...      |
| 5.00            | 3.50  | 3.700           | 3.146             | 0.32             | 0.19          | 0.30          | 13.94             | 5.58              | 2.11     | 2.29              | 1.31              | 0.85     | ...      |
| 6.00            | 4.00  | 4.030           | 3.427             | 0.29             | 0.19          | 0.30          | 21.99             | 7.33              | 2.53     | 3.10              | 1.55              | 0.95     | ...      |
| 6.00            | 4.00  | 4.692           | 3.990             | 0.35             | 0.21          | 0.30          | 25.50             | 8.50              | 2.53     | 3.74              | 1.87              | 0.97     | ...      |
| 7.00            | 4.50  | 5.800           | 4.932             | 0.38             | 0.23          | 0.30          | 42.89             | 12.25             | 2.95     | 5.78              | 2.57              | 1.08     | ...      |
| 8.00            | 5.00  | 6.181           | 5.256             | 0.35             | 0.23          | 0.30          | 59.69             | 14.92             | 3.37     | 7.30              | 2.92              | 1.18     | ...      |
| 8.00            | 5.00  | 7.023           | 5.972             | 0.41             | 0.25          | 0.30          | 67.78             | 16.94             | 3.37     | 8.55              | 3.42              | 1.20     | ...      |
| 9.00            | 5.50  | 8.361           | 7.110             | 0.44             | 0.27          | 0.30          | 102.02            | 22.67             | 3.79     | 12.22             | 4.44              | 1.31     | ...      |
| 10.00           | 6.00  | 8.646           | 7.352             | 0.41             | 0.25          | 0.40          | 132.09            | 26.42             | 4.24     | 14.78             | 4.93              | 1.42     | ...      |
| 10.00           | 6.00  | 10.286          | 8.747             | 0.50             | 0.29          | 0.40          | 155.79            | 31.16             | 4.22     | 18.03             | 6.01              | 1.44     | ...      |
| 12.00           | 7.00  | 11.672          | 9.925             | 0.47             | 0.29          | 0.40          | 255.57            | 42.60             | 5.07     | 26.90             | 7.69              | 1.65     | ...      |
| 12.00           | 7.00  | 14.292          | 12.153            | 0.62             | 0.31          | 0.40          | 317.33            | 52.89             | 5.11     | 35.48             | 10.14             | 1.71     | ...      |
| <b>CHANNELS</b> |       |                 |                   |                  |               |               |                   |                   |          |                   |                   |          |          |
| 2.00            | 1.00  | 0.577           | 0.491             | 0.13             | 0.13          | 0.10          | 0.288             | 0.288             | 0.766    | 0.045             | 0.064             | 0.303    | 0.298    |
| 2.00            | 1.25  | 1.071           | 0.911             | 0.26             | 0.17          | 0.15          | 0.546             | 0.546             | 0.774    | 0.139             | 0.178             | 0.391    | 0.471    |
| 3.00            | 1.50  | 1.135           | 0.965             | 0.20             | 0.13          | 0.25          | 1.41              | 0.94              | 1.21     | 0.22              | 0.22              | 0.47     | 0.49     |
| 3.00            | 1.75  | 1.597           | 1.358             | 0.26             | 0.17          | 0.25          | 1.97              | 1.31              | 1.20     | 0.42              | 0.37              | 0.55     | 0.62     |
| 4.00            | 2.00  | 1.738           | 1.478             | 0.23             | 0.15          | 0.25          | 3.91              | 1.95              | 1.63     | 0.60              | 0.45              | 0.64     | 0.65     |
| 4.00            | 2.25  | 2.331           | 1.982             | 0.29             | 0.19          | 0.25          | 5.21              | 2.60              | 1.62     | 1.02              | 0.69              | 0.72     | 0.78     |
| 5.00            | 2.25  | 2.212           | 1.881             | 0.26             | 0.15          | 0.30          | 7.88              | 3.15              | 2.05     | 0.98              | 0.64              | 0.72     | 0.73     |
| 5.00            | 2.75  | 3.089           | 2.627             | 0.32             | 0.19          | 0.30          | 11.14             | 4.45              | 2.06     | 2.05              | 1.14              | 0.88     | 0.95     |
| 6.00            | 2.50  | 2.834           | 2.410             | 0.29             | 0.17          | 0.30          | 14.35             | 4.78              | 2.44     | 1.53              | 0.90              | 0.80     | 0.79     |
| 6.00            | 3.25  | 4.030           | 3.427             | 0.35             | 0.21          | 0.30          | 21.04             | 7.01              | 2.48     | 3.76              | 1.76              | 1.05     | 1.12     |
| 7.00            | 2.75  | 3.205           | 2.725             | 0.29             | 0.17          | 0.30          | 22.09             | 6.31              | 2.85     | 2.10              | 1.10              | 0.88     | 0.84     |
| 7.00            | 3.50  | 4.715           | 4.009             | 0.38             | 0.21          | 0.30          | 33.79             | 9.65              | 2.90     | 5.13              | 2.23              | 1.13     | 1.20     |
| 8.00            | 3.00  | 4.147           | 3.526             | 0.35             | 0.19          | 0.30          | 37.40             | 9.35              | 3.26     | 3.25              | 1.57              | 0.96     | 0.93     |
| 8.00            | 3.75  | 5.789           | 4.923             | 0.471            | 0.25          | 0.35          | 52.69             | 13.17             | 3.27     | 7.13              | 2.82              | 1.20     | 1.22     |
| 9.00            | 3.25  | 4.983           | 4.237             | 0.35             | 0.23          | 0.35          | 54.41             | 12.09             | 3.58     | 4.40              | 1.89              | 1.02     | 0.93     |
| 9.00            | 4.00  | 6.970           | 5.927             | 0.44             | 0.29          | 0.35          | 78.31             | 17.40             | 3.63     | 9.61              | 3.49              | 1.27     | 1.25     |
| 10.00           | 3.50  | 6.136           | 5.218             | 0.41             | 0.25          | 0.35          | 83.22             | 16.64             | 3.99     | 6.33              | 2.56              | 1.10     | 1.02     |
| 10.00           | 4.25  | 8.360           | 7.109             | 0.50             | 0.31          | 0.40          | 116.15            | 23.23             | 4.04     | 13.02             | 4.47              | 1.35     | 1.34     |
| 12.00           | 4.00  | 8.274           | 7.036             | 0.47             | 0.29          | 0.40          | 159.76            | 26.63             | 4.77     | 11.03             | 3.86              | 1.25     | 1.14     |
| 12.00           | 5.00  | 11.822          | 10.053            | 0.62             | 0.35          | 0.45          | 239.69            | 39.95             | 4.88     | 25.74             | 7.60              | 1.60     | 1.61     |

Structural sections are available in 6061-T6 aluminum alloy. Data supplied by The Aluminum Association.

**Wire and Sheet-Metal Gages**

The thicknesses of sheet metals and the diameters of wires conform to various gaging systems. These gage sizes are indicated by numbers, and the following tables give the decimal equivalents of the different gage numbers. Much confusion has resulted from the use of gage numbers, and in ordering materials it is preferable to give the exact dimensions in decimal fractions of an inch. While the dimensions thus specified should conform to the gage ordinarily used for a given class of material, any error in the specification due, for example, to the use of a table having "rounded off" or approximate equivalents, will be apparent to the manufacturer at the time the order is placed. Furthermore, the decimal method of indicating wire diameters and sheet metal thicknesses has the advantage of being self-explanatory, whereas arbitrary gage numbers are not. The decimal system of indicating gage sizes is now being used quite generally, and gage numbers are gradually being discarded. Unfortunately, there is considerable variation in the use of different gages. For example, a gage ordinarily used for copper, brass and other non-ferrous materials, may at times be used for steel, and vice versa. The gages specified in the following are the ones ordinarily employed for the materials mentioned, but there are some minor exceptions and variations in the different industries.

**Wire Gages.**—The wire gage system used by practically all of the steel producers in the United States is known by the name Steel Wire Gage or to distinguish it from the Standard Wire Gage (S.W.G.) used in Great Britain it is called the United States Steel Wire Gage. It is the same as the Washburn and Moen, American Steel and Wire Company, and Roebling Wire Gages. The name has the official sanction of the Bureau of Standards at Washington but is not legally effective. The only wire gage which has been recognized in Acts of Congress is the Birmingham Gage (also known as Stub's Iron Wire). The Birmingham Gage is, however, nearly obsolete in both the United States and Great Britain, where it originated. Copper and aluminum wires are specified in decimal fractions. They were formerly universally specified in the United States by the American or Brown & Sharpe Wire Gage. Music spring steel wire, one of the highest quality wires of several types used for mechanical springs, is specified by the piano or music wire gage.

In Great Britain one wire gage has been legalized. This is called the Standard Wire Gage (S.W.G.), formerly called Imperial Wire Gage.

**Gages for Rods.**—Steel wire rod sizes are designated by fractional or decimal parts of an inch and by the gage numbers of the United States Steel Wire Gage. Copper and aluminum rods are specified by decimal fractions and fractions. Drill rod may be specified in decimal fractions but in the carbon and alloy tool steel grades may also be specified in the Stub's Steel Wire Gage and in the high-speed steel drill rod grade may be specified by the Morse Twist Drill Gage (Manufacturers' Standard Gage for Twist Drills). For gage numbers with corresponding decimal equivalents see the tables of American Standard Straight Shank Twist Drills, for example, page 856, and Table 5a on page 2525.

**Gages for Wall Thicknesses of Tubing.**—At one time the Birmingham or Stub's Iron Wire Gage was used to specify the wall thickness of the following classes of tubing: seamless brass, seamless copper, seamless steel, and aluminum. The Brown & Sharpe Wire Gage was used for brazed brass and brazed copper tubing. Wall thicknesses are now specified by decimal parts of an inch but the wall thickness of steel pressure tubes and steel mechanical tubing may be specified by the Birmingham or Stub's Iron Wire Gage. In Great Britain the Standard Wire Gage (S.W.G.) is used to specify the wall thickness of some kinds of steel tubes.

Table 1. Wire Gages in Approximate Decimals of an Inch

| No. of Wire Gage | American Wire or Brown & Sharpe Gage | Steel Wire Gage (U.S.) <sup>a</sup> | British Standard Wire Gage (Imperial Wire Gage) | Music or Piano Wire Gage | Birmingham or Stub's Iron Wire Gage | Stub's Steel Wire Gage | No. of Wire Gage | Stub's Steel Wire Gage |
|------------------|--------------------------------------|-------------------------------------|---|--------------------------|-------------------------------------|------------------------|------------------|------------------------|
| 7/8              | ...                                  | 0.4900                              | 0.5000  | ...                      | ...                                 | ...                    | 51               | 0.066                  |
| %                | 0.5800                               | 0.4615                              | 0.4640  | 0.004                    | ...                                 | ...                    | 52               | 0.063                  |
| %                | 0.5165                               | 0.4305                              | 0.4320  | 0.005                    | 0.5000                              | ...                    | 53               | 0.058                  |
| %                | 0.4600                               | 0.3938                              | 0.4000  | 0.006                    | 0.4540                              | ...                    | 54               | 0.055                  |
| %                | 0.4096                               | 0.3625                              | 0.3720  | 0.007                    | 0.4250                              | ...                    | 55               | 0.050                  |
| %                | 0.3648                               | 0.3310                              | 0.3480  | 0.008                    | 0.3800                              | ...                    | 56               | 0.045                  |
| 1/8              | 0.3249                               | 0.3065                              | 0.3240  | 0.009                    | 0.3400                              | ...                    | 57               | 0.042                  |
| 1                | 0.2893                               | 0.2830                              | 0.3000  | 0.010                    | 0.3000                              | 0.227                  | 58               | 0.041                  |
| 2                | 0.2576                               | 0.2625                              | 0.2760  | 0.011                    | 0.2840                              | 0.219                  | 59               | 0.040                  |
| 3                | 0.2294                               | 0.2437                              | 0.2520  | 0.012                    | 0.2590                              | 0.212                  | 60               | 0.039                  |
| 4                | 0.2043                               | 0.2253                              | 0.2320  | 0.013                    | 0.2380                              | 0.207                  | 61               | 0.038                  |
| 5                | 0.1819                               | 0.2070                              | 0.2120  | 0.014                    | 0.2200                              | 0.204                  | 62               | 0.037                  |
| 6                | 0.1620                               | 0.1920                              | 0.1920  | 0.016                    | 0.2030                              | 0.201                  | 63               | 0.036                  |
| 7                | 0.1443                               | 0.1770                              | 0.1760  | 0.018                    | 0.1800                              | 0.199                  | 64               | 0.035                  |
| 8                | 0.1285                               | 0.1620                              | 0.1600  | 0.020                    | 0.1650                              | 0.197                  | 65               | 0.033                  |
| 9                | 0.1144                               | 0.1483                              | 0.1440  | 0.022                    | 0.1480                              | 0.194                  | 66               | 0.032                  |
| 10               | 0.1019                               | 0.1350                              | 0.1280  | 0.024                    | 0.1340                              | 0.191                  | 67               | 0.031                  |
| 11               | 0.0907                               | 0.1205                              | 0.1160  | 0.026                    | 0.1200                              | 0.188                  | 68               | 0.030                  |
| 12               | 0.0808                               | 0.1055                              | 0.1040  | 0.029                    | 0.1090                              | 0.185                  | 69               | 0.029                  |
| 13               | 0.0720                               | 0.0915                              | 0.0920  | 0.031                    | 0.0950                              | 0.182                  | 70               | 0.027                  |
| 14               | 0.0641                               | 0.0800                              | 0.0800  | 0.033                    | 0.0830                              | 0.180                  | 71               | 0.026                  |
| 15               | 0.0571                               | 0.0720                              | 0.0720  | 0.035                    | 0.0720                              | 0.178                  | 72               | 0.024                  |
| 16               | 0.0508                               | 0.0625                              | 0.0640  | 0.037                    | 0.0650                              | 0.175                  | 73               | 0.023                  |
| 17               | 0.0453                               | 0.0540                              | 0.0560  | 0.039                    | 0.0580                              | 0.172                  | 74               | 0.022                  |
| 18               | 0.0403                               | 0.0475                              | 0.0480  | 0.041                    | 0.0490                              | 0.168                  | 75               | 0.020                  |
| 19               | 0.0359                               | 0.0410                              | 0.0400  | 0.043                    | 0.0420                              | 0.164                  | 76               | 0.018                  |
| 20               | 0.0320                               | 0.0348                              | 0.0360  | 0.045                    | 0.0350                              | 0.161                  | 77               | 0.016                  |
| 21               | 0.0285                               | 0.0318                              | 0.0320  | 0.047                    | 0.0320                              | 0.157                  | 78               | 0.015                  |
| 22               | 0.0253                               | 0.0286                              | 0.0280  | 0.049                    | 0.0280                              | 0.155                  | 79               | 0.014                  |
| 23               | 0.0226                               | 0.0258                              | 0.0240  | 0.051                    | 0.0250                              | 0.153                  | 80               | 0.013                  |
| 24               | 0.0201                               | 0.0230                              | 0.0220  | 0.055                    | 0.0220                              | 0.151                  | ...              | ...                    |
| 25               | 0.0179                               | 0.0204                              | 0.0200  | 0.059                    | 0.0200                              | 0.148                  | ...              | ...                    |
| 26               | 0.0159                               | 0.0181                              | 0.0180  | 0.063                    | 0.0180                              | 0.146                  | ...              | ...                    |
| 27               | 0.0142                               | 0.0173                              | 0.0164  | 0.067                    | 0.0160                              | 0.143                  | ...              | ...                    |
| 28               | 0.0126                               | 0.0162                              | 0.0149  | 0.071                    | 0.0140                              | 0.139                  | ...              | ...                    |
| 29               | 0.0113                               | 0.0150                              | 0.0136  | 0.075                    | 0.0130                              | 0.134                  | ...              | ...                    |
| 30               | 0.0100                               | 0.0140                              | 0.0124  | 0.080                    | 0.0120                              | 0.127                  | ...              | ...                    |
| 31               | 0.00893                              | 0.0132                              | 0.0116  | 0.085                    | 0.0100                              | 0.120                  | ...              | ...                    |
| 32               | 0.00795                              | 0.0128                              | 0.0108  | 0.090                    | 0.0090                              | 0.115                  | ...              | ...                    |
| 33               | 0.00708                              | 0.0118                              | 0.0100  | 0.095                    | 0.0080                              | 0.112                  | ...              | ...                    |
| 34               | 0.00630                              | 0.0104                              | 0.0092  | 0.100                    | 0.0070                              | 0.110                  | ...              | ...                    |
| 35               | 0.00561                              | 0.0095                              | 0.0084  | 0.106                    | 0.0050                              | 0.108                  | ...              | ...                    |
| 36               | 0.00500                              | 0.0090                              | 0.0076  | 0.112                    | 0.0040                              | 0.106                  | ...              | ...                    |
| 37               | 0.00445                              | 0.0085                              | 0.0068  | 0.118                    | ...                                 | 0.103                  | ...              | ...                    |
| 38               | 0.00396                              | 0.0080                              | 0.0060  | 0.124                    | ...                                 | 0.101                  | ...              | ...                    |
| 39               | 0.00353                              | 0.0075                              | 0.0052  | 0.130                    | ...                                 | 0.099                  | ...              | ...                    |
| 40               | 0.00314                              | 0.0070                              | 0.0048  | 0.138                    | ...                                 | 0.097                  | ...              | ...                    |
| 41               | 0.00280                              | 0.0066                              | 0.0044  | 0.146                    | ...                                 | 0.095                  | ...              | ...                    |
| 42               | 0.00249                              | 0.0062                              | 0.0040  | 0.154                    | ...                                 | 0.092                  | ...              | ...                    |
| 43               | 0.00222                              | 0.0060                              | 0.0036  | 0.162                    | ...                                 | 0.088                  | ...              | ...                    |
| 44               | 0.00198                              | 0.0058                              | 0.0032  | 0.170                    | ...                                 | 0.085                  | ...              | ...                    |
| 45               | 0.00176                              | 0.0055                              | 0.0028  | 0.180                    | ...                                 | 0.081                  | ...              | ...                    |
| 46               | 0.00157                              | 0.0052                              | 0.0024  | ...                      | ...                                 | 0.079                  | ...              | ...                    |
| 47               | 0.00140                              | 0.0050                              | 0.0020  | ...                      | ...                                 | 0.077                  | ...              | ...                    |
| 48               | 0.00124                              | 0.0048                              | 0.0016  | ...                      | ...                                 | 0.075                  | ...              | ...                    |
| 49               | 0.00111                              | 0.0046                              | 0.0012  | ...                      | ...                                 | 0.072                  | ...              | ...                    |
| 50               | 0.00099                              | 0.0044                              | 0.0010  | ...                      | ...                                 | 0.069                  | ...              | ...                    |

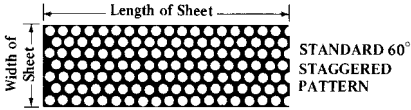
<sup>a</sup> Also known as Washburn and Moen, American Steel and Wire Co. and Roebling Wire Gages. A greater selection of sizes is available and is specified by what are known as split gage numbers. They can be recognized by  $\frac{1}{2}$  fractions which follow the gage number; i.e.,  $4\frac{1}{2}$ . The decimal equivalents of split gage numbers are in the Steel Products Manual entitled: *Wire and Rods, Carbon Steel* published by the American Iron and Steel Institute, Washington, DC.

**Strength and Stiffness of Perforated Metals.**—It is common practice to use perforated metals in equipment enclosures to provide cooling by the flow of air or fluids. If the perforated material is to serve also as a structural member, then calculations of stiffness and strength must be made that take into account the effect of the perforations on the strength of the panels.

The accompanying table provides equivalent or effective values of the yield strength  $S^*$ ; modulus of elasticity  $E^*$ ; and Poisson's ratio  $\nu^*$  of perforated metals in terms of the values for solid material. The  $S^*/S$  and  $E^*/E$  ratios, given in the accompanying table for the standard round hole staggered pattern, can be used to determine the safety margins or deflections for perforated metal use as compared to the unperforated metal for any geometry or loading condition.

Perforated material has different strengths depending on the direction of loading; therefore, values of  $S^*/S$  in the table are given for the width (strongest) and length (weakest) directions. Also, the effective elastic constants are for plane stress conditions and apply to the in-plane loading of thin perforated sheets; the bending stiffness is greater. However, since most loading conditions involve a combination of bending and stretching, it is more convenient to use the same effective elastic constants for these combined loading conditions. The plane stress effective elastic constants given in the table can be conservatively used for all loading conditions.

**Mechanical Properties of Materials Perforated with Round Holes in IPA Standard Staggered Hole Pattern**



| IPA No. | Perforation Diam. (in.) | Center Distance (in.) | Open Area (%) | $S^*/S$     |              | $E^*/E$ | $\nu^*$ |
|---------|-------------------------|-----------------------|---------------|-------------|--------------|---------|---------|
|         |                         |                       |               | Width (in.) | Length (in.) |         |         |
| 100     | 0.020                   | (625)                 | 20            | 0.530       | 0.465        | 0.565   | 0.32    |
| 106     | $\frac{1}{16}$          | $\frac{1}{8}$         | 23            | 0.500       | 0.435        | 0.529   | 0.33    |
| 107     | $\frac{5}{64}$          | $\frac{3}{64}$        | 46            | 0.286       | 0.225        | 0.246   | 0.38    |
| 108     | $\frac{5}{64}$          | $\frac{1}{8}$         | 36            | 0.375       | 0.310        | 0.362   | 0.35    |
| 109     | $\frac{3}{32}$          | $\frac{3}{32}$        | 32            | 0.400       | 0.334        | 0.395   | 0.34    |
| 110     | $\frac{3}{32}$          | $\frac{3}{16}$        | 23            | 0.500       | 0.435        | 0.529   | 0.33    |
| 112     | $\frac{1}{10}$          | $\frac{3}{32}$        | 36            | 0.360       | 0.296        | 0.342   | 0.35    |
| 113     | $\frac{1}{8}$           | $\frac{3}{16}$        | 40            | 0.333       | 0.270        | 0.310   | 0.36    |
| 114     | $\frac{1}{8}$           | $\frac{7}{32}$        | 29            | 0.428       | 0.363        | 0.436   | 0.33    |
| 115     | $\frac{1}{8}$           | $\frac{1}{4}$         | 23            | 0.500       | 0.435        | 0.529   | 0.33    |
| 116     | $\frac{5}{32}$          | $\frac{7}{32}$        | 46            | 0.288       | 0.225        | 0.249   | 0.38    |
| 117     | $\frac{5}{32}$          | $\frac{1}{4}$         | 36            | 0.375       | 0.310        | 0.362   | 0.35    |
| 118     | $\frac{3}{16}$          | $\frac{1}{4}$         | 51            | 0.250       | 0.192        | 0.205   | 0.42    |
| 119     | $\frac{3}{16}$          | $\frac{5}{16}$        | 33            | 0.400       | 0.334        | 0.395   | 0.34    |
| 120     | $\frac{1}{4}$           | $\frac{5}{16}$        | 58            | 0.200       | 0.147        | 0.146   | 0.47    |
| 121     | $\frac{1}{4}$           | $\frac{3}{8}$         | 40            | 0.333       | 0.270        | 0.310   | 0.36    |
| 122     | $\frac{1}{4}$           | $\frac{7}{16}$        | 30            | 0.428       | 0.363        | 0.436   | 0.33    |
| 123     | $\frac{1}{4}$           | $\frac{1}{2}$         | 23            | 0.500       | 0.435        | 0.529   | 0.33    |
| 124     | $\frac{3}{8}$           | $\frac{1}{2}$         | 51            | 0.250       | 0.192        | 0.205   | 0.42    |
| 125     | $\frac{3}{8}$           | $\frac{9}{16}$        | 40            | 0.333       | 0.270        | 0.310   | 0.36    |
| 126     | $\frac{3}{8}$           | $\frac{3}{8}$         | 33            | 0.400       | 0.334        | 0.395   | 0.34    |
| 127     | $\frac{7}{16}$          | $\frac{5}{8}$         | 45            | 0.300       | 0.239        | 0.265   | 0.38    |
| 128     | $\frac{1}{2}$           | $1\frac{1}{16}$       | 47            | 0.273       | 0.214        | 0.230   | 0.39    |
| 129     | $\frac{9}{16}$          | $\frac{3}{4}$         | 51            | 0.250       | 0.192        | 0.205   | 0.42    |

Value in parentheses specifies holes per square inch instead of center distance.  $S^*/S$  = ratio of yield strength of perforated to unperforated material;  $E^*/E$  = ratio of modulus of elasticity of perforated to unperforated material;  $\nu^*$  = Poisson's ratio for given percentage of open area.

IPA is Industrial Perforators Association.

**Sheet-Metal Gages.**—Thicknesses of steel sheets given in Table 2 are based upon a weight of 41.82 pounds per square foot per inch of thickness, which is known as the Manufacturers' Standard Gage for Sheet Steel. This gage differs from the older United States Standard Gage for iron and steel sheets and plates, established by Congress in 1893, based upon a weight of 40 pounds per square foot per inch of thickness which is the weight of wrought-iron plate.

**Table 2. Sheet-Metal Gages in Approximate Decimals of an Inch**

| Gage No. | Steel Gage <sup>a</sup> | B.G. <sup>b</sup> | Galvanized Sheet | Zinc Gage | Gage No. | Steel Gage <sup>a</sup> | B.G. <sup>b</sup> | Galvanized Sheet | Zinc Gage |
|----------|-------------------------|-------------------|------------------|-----------|----------|-------------------------|-------------------|------------------|-----------|
| 15/0     | ...                     | 1.000             | ...              | ...       | 20       | 0.0359                  | 0.0392            | 0.0396           | 0.070     |
| 14/0     | ...                     | 0.9583            | ...              | ...       | 21       | 0.0329                  | 0.0349            | 0.0366           | 0.080     |
| 13/0     | ...                     | 0.9167            | ...              | ...       | 22       | 0.0299                  | 0.03125           | 0.0336           | 0.090     |
| 12/0     | ...                     | 0.8750            | ...              | ...       | 23       | 0.0269                  | 0.02782           | 0.0306           | 0.100     |
| 11/0     | ...                     | 0.8333            | ...              | ...       | 24       | 0.0239                  | 0.02476           | 0.0276           | 0.125     |
| 10/0     | ...                     | 0.7917            | ...              | ...       | 25       | 0.0209                  | 0.02204           | 0.0247           | ...       |
| 9/0      | ...                     | 0.7500            | ...              | ...       | 26       | 0.0179                  | 0.01961           | 0.0217           | ...       |
| 8/0      | ...                     | 0.7083            | ...              | ...       | 27       | 0.0164                  | 0.01745           | 0.0202           | ...       |
| 7/0      | ...                     | 0.6666            | ...              | ...       | 28       | 0.0149                  | 0.01562           | 0.0187           | ...       |
| 6/0      | ...                     | 0.6250            | ...              | ...       | 29       | 0.0135                  | 0.01390           | 0.0172           | ...       |
| 5/0      | ...                     | 0.5883            | ...              | ...       | 30       | 0.0120                  | 0.01230           | 0.0157           | ...       |
| 4/0      | ...                     | 0.5416            | ...              | ...       | 31       | 0.0105                  | 0.01100           | 0.0142           | ...       |
| 3/0      | ...                     | 0.5000            | ...              | ...       | 32       | 0.0097                  | 0.00980           | 0.0134           | ...       |
| 2/0      | ...                     | 0.4452            | ...              | ...       | 33       | 0.0090                  | 0.00870           | ...              | ...       |
| 1/0      | ...                     | 0.3964            | ...              | ...       | 34       | 0.0082                  | 0.00770           | ...              | ...       |
| 1        | ...                     | 0.3532            | ...              | ...       | 35       | 0.0075                  | 0.00690           | ...              | ...       |
| 2        | ...                     | 0.3147            | ...              | ...       | 36       | 0.0067                  | 0.00610           | ...              | ...       |
| 3        | 0.2391                  | 0.2804            | ...              | 0.006     | 37       | 0.0064                  | 0.00540           | ...              | ...       |
| 4        | 0.2242                  | 0.2500            | ...              | 0.008     | 38       | 0.0060                  | 0.00480           | ...              | ...       |
| 5        | 0.2092                  | 0.2225            | ...              | 0.010     | 39       | ...                     | 0.00430           | ...              | ...       |
| 6        | 0.1943                  | 0.1981            | ...              | 0.012     | 40       | ...                     | 0.00386           | ...              | ...       |
| 7        | 0.1793                  | 0.1764            | ...              | 0.014     | 41       | ...                     | 0.00343           | ...              | ...       |
| 8        | 0.1644                  | 0.1570            | 0.1681           | 0.016     | 42       | ...                     | 0.00306           | ...              | ...       |
| 9        | 0.1495                  | 0.1398            | 0.1532           | 0.018     | 43       | ...                     | 0.00272           | ...              | ...       |
| 10       | 0.1345                  | 0.1250            | 0.1382           | 0.020     | 44       | ...                     | 0.00242           | ...              | ...       |
| 11       | 0.1196                  | 0.1113            | 0.1233           | 0.024     | 45       | ...                     | 0.00215           | ...              | ...       |
| 12       | 0.1046                  | 0.0991            | 0.1084           | 0.028     | 46       | ...                     | 0.00192           | ...              | ...       |
| 13       | .0897                   | 0.0882            | 0.0934           | 0.032     | 47       | ...                     | 0.00170           | ...              | ...       |
| 14       | 0.0747                  | 0.0785            | 0.0785           | 0.036     | 48       | ...                     | 0.00152           | ...              | ...       |
| 15       | 0.0673                  | 0.0699            | 0.0710           | 0.040     | 49       | ...                     | 0.00135           | ...              | ...       |
| 16       | 0.0598                  | 0.0625            | 0.0635           | 0.045     | 50       | ...                     | 0.00120           | ...              | ...       |
| 17       | 0.0538                  | 0.0556            | 0.0575           | 0.050     | 51       | ...                     | 0.00107           | ...              | ...       |
| 18       | .0478                   | 0.0495            | 0.0516           | 0.055     | 52       | ...                     | 0.00095           | ...              | ...       |
| 19       | 0.0418                  | 0.0440            | 0.0456           | 0.060     | ...      | ...                     | ...               | ...              | ...       |

<sup>a</sup> Manufacturers' Standard Gage for Sheet Steel

<sup>b</sup> B.G. is the Birmingham Gage for sheets and hoops.

*The United States Standard Gage* (not shown above) for iron and steel sheets and plates was established by Congress in 1893 and was primarily a *weight* gage rather than a thickness gage. The equivalent thicknesses were derived from the weight of wrought iron. The weight per cubic foot was taken at 480 pounds, thus making the weight of a plate 12 inches square and 1 inch thick, 40 pounds. In converting weight to equivalent thickness, gage tables formerly published contained thicknesses equivalent to the basic weights just mentioned. For example, a No. 3 U.S. gage represents a wrought-iron plate having a weight of 10 pounds per square foot; hence, if the weight per square foot per inch thick is 40 pounds, the plate thickness for a No. 3 gage =  $10 \div 40 = 0.25$  inch, which was the original thickness equivalent for this gage number. Because this and the other thickness equivalents were derived from the weight of wrought iron, they are not correct for steel.

Zinc sheets are usually ordered by specifying decimal thickness although a zinc gage exists and is shown in [Table 2](#).

Most sheet-metal products in Great Britain are specified by the British Standard Wire Gage (Imperial Wire Gage). Black iron and steel sheet and hooping, and galvanized flat and corrugated steel sheet, however, are specified by the Birmingham Gage (B.G.), which was legalized in 1914, and are also shown in [Table 2](#). This Birmingham Gage should not be confused with the Birmingham or Stub's Iron Wire Gage mentioned previously.

Thicknesses of aluminum, copper, and copper-base alloys were formerly designated by the American or Brown & Sharpe Wire Gage but now are specified in decimals or fractions of an inch. American National Standard B32.1-1952 (R1988) entitled Preferred Thicknesses for Uncoated Thin Flat Metals (see accompanying [Table 3](#)) gives thicknesses that are based on the 20- and 40-series of preferred numbers in American National Standard Preferred Numbers — ANSI Z17.1 (see Handbook page [689](#)) and are applicable to uncoated, thin, flat metals and alloys. Each number of the 20-series is approximately 12 percent greater than the next smaller one and each number of the 40-series is approximately 6 percent greater than the next smaller one.

**Table 3. Preferred Thicknesses for Uncoated Metals and Alloys—  
Under 0.250 Inch in Thickness ANSI B32.1-1952 (R1994)**

| Preferred Thickness, Inches |                       |                       |                       |                       |                       |                       |                       |
|-----------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Based on<br>20-Series       | Based on<br>40-Series | Based on<br>20-Series | Based on<br>40-Series | Based on<br>20-Series | Based on<br>40-Series | Based on<br>20-Series | Based on<br>40-Series |
| ...                         | 0.236                 | 0.100                 | 0.100                 | ...                   | 0.042                 | 0.018                 | 0.018                 |
| 0.224                       | 0.224                 | ...                   | 0.095                 | 0.040                 | 0.040                 | ...                   | 0.017                 |
| ...                         | 0.212                 | 0.090                 | 0.090                 | ...                   | 0.038                 | 0.016                 | 0.016                 |
| 0.200                       | 0.200                 | ...                   | 0.085                 | 0.036                 | 0.036                 | ...                   | 0.015                 |
| ...                         | 0.190                 | 0.080                 | 0.080                 | ...                   | 0.034                 | 0.014                 | 0.014                 |
| 0.180                       | 0.180                 | ...                   | 0.075                 | 0.032                 | 0.032                 | ...                   | 0.013                 |
| ...                         | 0.170                 | 0.071                 | 0.071                 | ...                   | 0.030                 | 0.012                 | 0.012                 |
| 0.160                       | 0.160                 | ...                   | 0.067                 | 0.028                 | 0.028                 | 0.011                 | 0.011                 |
| ...                         | 0.150                 | 0.063                 | 0.063                 | ...                   | 0.026                 | 0.010                 | 0.010                 |
| 0.140                       | 0.140                 | ...                   | 0.060                 | 0.025                 | 0.025                 | 0.009                 | 0.009                 |
| ...                         | 0.132                 | 0.056                 | 0.056                 | ...                   | 0.024                 | 0.008                 | 0.008                 |
| 0.125                       | 0.125                 | ...                   | 0.053                 | 0.022                 | 0.022                 | 0.007                 | 0.007                 |
| ...                         | 0.118                 | 0.050                 | 0.050                 | ...                   | 0.021                 | 0.006                 | 0.006                 |
| 0.112                       | 0.112                 | ...                   | 0.048                 | 0.020                 | 0.020                 | 0.005                 | 0.005                 |
| ...                         | 0.106                 | 0.045                 | 0.045                 | ...                   | 0.019                 | 0.004                 | 0.004                 |

The American National Standard ANSI B32.1-1952 (R1994) lists preferred thicknesses that are based on the 20- and 40-series of preferred numbers and states that those based on the 40-series should provide adequate coverage. However, where intermediate thicknesses are required, the Standard recommends that thicknesses be based on the 80-series of preferred numbers (see Handbook page [689](#)).

Thicknesses for copper and copper-base alloy flat products below  $\frac{1}{4}$  inch thick are specified by the 20-series of American National Standard Preferred Numbers given in ANSI B32.1. Although the table in ANSI B32.1 gives only the 20- and 40-series of numbers, it states that when intermediate thicknesses are required they should be selected from thicknesses based on the 80-series of numbers (see Handbook page [689](#)).

**Metric Sizes for Flat Metal Products.**—American National Standard B32.3M-1984, (R1994) establishes a preferred series of metric thicknesses, widths, and lengths for flat metal products of rectangular cross section; the thickness and width values are also applicable to base metals that may be coated in later operations. [Table 4a](#) lists the preferred thicknesses; [Table 4b](#) lists the preferred widths. Whenever possible, the Preferred Thick-



ness and Preferred Widths values should be used, with the Second or Third Preference chosen only if no suitable Preferred size is available. Since not all metals and grades are produced in each of the sizes given in Tables 4a and 4b, producers or distributors should be consulted to determine a particular product and size combination's availability.

**Table 4a. Preferred Metric Thicknesses for All Flat Metal Products**  
ANSI/ASME B32.3M-1984 (R1994)

| Preferred Thickness | Second Preference | Third Preference | Preferred Thickness | Second Preference | Third Preference | Preferred Thickness | Second Preference | Third Preference |
|---------------------|-------------------|------------------|---------------------|-------------------|------------------|---------------------|-------------------|------------------|
| 0.050               | ...               | ...              | ...                 | ...               | 1.5              | 12                  | ...               | ...              |
| 0.060               | ...               | ...              | 1.6                 | ...               | ...              | ...                 | 14                | ...              |
| 0.080               | ...               | ...              | ...                 | ...               | 1.7              | 16                  | ...               | ...              |
| 0.10                | ...               | ...              | ...                 | 1.8               | ...              | ...                 | 18                | ...              |
| 0.12                | ...               | ...              | ...                 | ...               | 1.9              | 20                  | ...               | ...              |
| ...                 | 0.14              | ...              | 2.0                 | ...               | ...              | ...                 | 22                | ...              |
| 0.16                | ...               | ...              | ...                 | ...               | 2.1              | 25                  | ...               | ...              |
| ...                 | 0.18              | ...              | ...                 | 2.2               | ...              | ...                 | 28                | ...              |
| 0.20                | ...               | ...              | ...                 | ...               | 2.4              | 30                  | ...               | ...              |
| ...                 | 0.22              | ...              | 2.5                 | ...               | ...              | ...                 | 32                | ...              |
| 0.25                | ...               | ...              | ...                 | ...               | 2.6              | 35                  | ...               | ...              |
| ...                 | 0.28              | ...              | ...                 | 2.8               | ...              | ...                 | 38                | ...              |
| 0.30                | ...               | ...              | 3.0                 | ...               | ...              | 40                  | ...               | ...              |
| ...                 | 0.35              | ...              | ...                 | 3.2               | ...              | ...                 | 45                | ...              |
| 0.40                | ...               | ...              | ...                 | ...               | 3.4              | 50                  | ...               | ...              |
| ...                 | 0.45              | ...              | 3.5                 | ...               | ...              | ...                 | 55                | ...              |
| 0.50                | ...               | ...              | ...                 | ...               | 3.6              | 60                  | ...               | ...              |
| ...                 | 0.55              | ...              | ...                 | 3.8               | ...              | ...                 | 70                | ...              |
| 0.60                | ...               | ...              | 4.0                 | ...               | ...              | 80                  | ...               | ...              |
| ...                 | 0.65              | ...              | ...                 | 4.2               | ...              | ...                 | 90                | ...              |
| ...                 | 0.70              | ...              | ...                 | 4.5               | ...              | 100                 | ...               | ...              |
| ...                 | ...               | 0.75             | ...                 | 4.8               | ...              | ...                 | 110               | ...              |
| 0.80                | ...               | ...              | 5.0                 | ...               | ...              | 120                 | ...               | ...              |
| ...                 | ...               | 0.85             | ...                 | 5.5               | ...              | ...                 | 130               | ...              |
| ...                 | 0.90              | ...              | 6.0                 | ...               | ...              | 140                 | ...               | ...              |
| ...                 | ...               | 0.95             | ...                 | ...               | 6.5              | ...                 | 150               | ...              |
| 1.0                 | ...               | ...              | ...                 | 7.0               | ...              | 160                 | ...               | ...              |
| ...                 | ...               | 1.05             | ...                 | ...               | 7.5              | 180                 | ...               | ...              |
| ...                 | 1.1               | ...              | 8.0                 | ...               | ...              | 200                 | ...               | ...              |
| 1.2                 | ...               | ...              | ...                 | 9.0               | ...              | 250                 | ...               | ...              |
| ...                 | ...               | 1.3              | 10                  | ...               | ...              | 300                 | ...               | ...              |
| ...                 | 1.4               | ...              | ...                 | 11                | ...              | ...                 | ...               | ...              |

**Table 4b. Preferred Metric Widths<sup>a</sup> for All Flat Metal Products**

| Preferred Widths | Second Preference | Preferred Widths | Second Preference | Preferred Widths | Second Preference | Preferred Widths | Second Preference |
|------------------|-------------------|------------------|-------------------|------------------|-------------------|------------------|-------------------|
| 10               | ...               | 60               | ...               | 180              | ...               | ...              | 900               |
| 12               | ...               | ...              | 70                | 200              | ...               | 1000             | ...               |
| 16               | ...               | 80               | ...               | ...              | 225               | 1200             | ...               |
| 20               | ...               | ...              | 90                | 250              | ...               | 1500             | ...               |
| 25               | ...               | 100              | ...               | ...              | 280               | 2000             | ...               |
| 30               | ...               | ...              | 110               | 300              | ...               | 2500             | ...               |
| 35               | ...               | 120              | ...               | 400              | ...               | 3000             | ...               |
| 40               | ...               | ...              | 130               | 500              | ...               | 3500             | ...               |
| ...              | 45                | 140              | ...               | 600              | ...               | 4000             | ...               |
| 50               | ...               | ...              | 150               | ...              | 700               | 5000             | ...               |
| ...              | 55                | 160              | ...               | 800              | ...               | ...              | ...               |

<sup>a</sup> These widths are applicable to bar, foil, flat wire, plate, ribbon, sheet, strip, etc. only where the width falls within the 100 to 500 mm range.

All dimensions are in millimeters.

**Table 5a. Decimal Equivalent of Numbered Drill Sizes**

| Drill Number | Decimal |       | Drill Number | Decimal |       | Drill Number | Decimal |       | Drill Number | Decimal |       |
|--------------|---------|-------|--------------|---------|-------|--------------|---------|-------|--------------|---------|-------|
|              | Inch    | mm    |              | Inch    | mm    |              | Inch    | mm    |              | Inch    | mm    |
| 1            | 0.2280  | 5.791 | 26           | 0.1470  | 3.734 | 51           | 0.0670  | 1.702 | 76           | 0.0200  | 0.508 |
| 2            | 0.2210  | 5.613 | 27           | 0.1440  | 3.658 | 52           | 0.0635  | 1.613 | 77           | 0.0180  | 0.457 |
| 3            | 0.2130  | 5.410 | 28           | 0.1405  | 3.569 | 53           | 0.0595  | 1.511 | 78           | 0.0160  | 0.406 |
| 4            | 0.2090  | 5.309 | 29           | 0.1360  | 3.454 | 54           | 0.0550  | 1.397 | 79           | 0.0145  | 0.368 |
| 5            | 0.2055  | 5.220 | 30           | 0.1285  | 3.264 | 55           | 0.0520  | 1.321 | 80           | 0.0135  | 0.343 |
| 6            | 0.2040  | 5.182 | 31           | 0.1200  | 3.048 | 56           | 0.0465  | 1.181 | 81           | 0.0130  | 0.330 |
| 7            | 0.2010  | 5.105 | 32           | 0.1160  | 2.946 | 57           | 0.0430  | 1.092 | 82           | 0.0125  | 0.318 |
| 8            | 0.1990  | 5.054 | 33           | 0.1130  | 2.870 | 58           | 0.0420  | 1.067 | 83           | 0.0120  | 0.305 |
| 9            | 0.1960  | 4.978 | 34           | 0.1110  | 2.819 | 59           | 0.0410  | 1.041 | 84           | 0.0115  | 0.292 |
| 10           | 0.1935  | 4.915 | 35           | 0.1100  | 2.794 | 60           | 0.0400  | 1.016 | 85           | 0.0110  | 0.280 |
| 11           | 0.1910  | 4.851 | 36           | 0.1065  | 2.705 | 61           | 0.0390  | 0.991 | 86           | 0.0105  | 0.267 |
| 12           | 0.1890  | 4.800 | 37           | 0.1040  | 2.642 | 62           | 0.0380  | 0.965 | 87           | 0.0100  | 0.254 |
| 13           | 0.1850  | 4.700 | 38           | 0.1015  | 2.578 | 63           | 0.0370  | 0.940 | 88           | 0.0095  | 0.241 |
| 14           | 0.1820  | 4.623 | 39           | 0.0995  | 2.527 | 64           | 0.0360  | 0.914 | 89           | 0.0091  | 0.231 |
| 15           | 0.1800  | 4.572 | 40           | 0.0980  | 2.489 | 65           | 0.0350  | 0.889 | 90           | 0.0087  | 0.221 |
| 16           | 0.1770  | 4.496 | 41           | 0.0960  | 2.438 | 66           | 0.0330  | 0.838 | 91           | 0.0083  | 0.211 |
| 17           | 0.1730  | 4.394 | 42           | 0.0935  | 2.375 | 67           | 0.0320  | 0.813 | 92           | 0.0079  | 0.200 |
| 18           | 0.1695  | 4.305 | 43           | 0.0890  | 2.261 | 68           | 0.0310  | 0.787 | 93           | 0.0075  | 0.190 |
| 19           | 0.1660  | 4.216 | 44           | 0.0860  | 2.184 | 69           | 0.0292  | 0.742 | 94           | 0.0071  | 0.180 |
| 20           | 0.1610  | 4.089 | 45           | 0.0820  | 2.083 | 70           | 0.0280  | 0.711 | 95           | 0.0067  | 0.170 |
| 21           | 0.1590  | 4.039 | 46           | 0.0810  | 2.057 | 71           | 0.0260  | 0.660 | 96           | 0.0063  | 0.160 |
| 22           | 0.1570  | 3.988 | 47           | 0.0785  | 1.994 | 72           | 0.0250  | 0.635 | 97           | 0.0059  | 0.150 |
| 23           | 0.1540  | 3.912 | 48           | 0.0760  | 1.930 | 73           | 0.0240  | 0.610 | ...          | ...     | ...   |
| 24           | 0.1520  | 3.861 | 49           | 0.0730  | 1.854 | 74           | 0.0225  | 0.572 | ...          | ...     | ...   |
| 25           | 0.1495  | 3.797 | 50           | 0.0700  | 1.778 | 75           | 0.0210  | 0.533 | ...          | ...     | ...   |

**Table 5b. Decimal Equivalent of Letter Drill Sizes**

| Drill Size | Decimal |       | Drill Size | Decimal |       | Drill Size | Decimal |       | Drill Size | Decimal |        | Drill Size | Decimal |        |
|------------|---------|-------|------------|---------|-------|------------|---------|-------|------------|---------|--------|------------|---------|--------|
|            | Inch    | mm    |            | Inch    | mm    |            | Inch    | mm    |            | Inch    | mm     |            | Inch    | mm     |
| A          | 0.234   | 5.944 | G          | 0.261   | 6.629 | M          | 0.295   | 7.493 | S          | 0.348   | 8.839  | Y          | 0.404   | 10.262 |
| B          | 0.238   | 6.045 | H          | 0.266   | 6.756 | N          | 0.302   | 7.671 | T          | 0.358   | 9.093  | Z          | 0.413   | 10.490 |
| C          | 0.242   | 6.147 | I          | 0.272   | 6.909 | O          | 0.316   | 8.026 | U          | 0.368   | 9.347  | ...        | ...     | ...    |
| D          | 0.246   | 6.248 | J          | 0.277   | 7.036 | P          | 0.323   | 8.204 | V          | 0.377   | 9.576  | ...        | ...     | ...    |
| E          | 0.250   | 6.350 | K          | 0.281   | 7.137 | Q          | 0.332   | 8.433 | W          | 0.386   | 9.804  | ...        | ...     | ...    |
| F          | 0.257   | 6.528 | L          | 0.290   | 7.366 | R          | 0.339   | 8.611 | X          | 0.397   | 10.084 | ...        | ...     | ...    |

## PIPE AND PIPE FITTINGS

**Wrought Steel Pipe.**—ANSI/ASME B36.10M-1995 covers dimensions of welded and seamless wrought steel pipe, for high or low temperatures or pressures.

The word *pipe* as distinguished from *tube* is used to apply to tubular products of dimensions commonly used for pipelines and piping systems. Pipe dimensions of sizes 12 inches and smaller have outside diameters numerically larger than the corresponding nominal sizes whereas outside diameters of tubes are identical to nominal sizes.

*Size:* The size of all pipe is identified by the nominal pipe size. The manufacture of pipe in the nominal sizes of  $\frac{1}{8}$  inch to 12 inches, inclusive, is based on a standardized outside diameter (OD). This OD was originally selected so that pipe with a standard OD and having a wall thickness which was typical of the period would have an inside diameter (ID) approximately equal to the nominal size. Although there is now no such relation between the existing standard thicknesses, ODs and nominal sizes, these nominal sizes and standard ODs continue in use as “standard.”

The manufacture of pipe in nominal sizes of 14-inch OD and larger proceeds on the basis of an OD corresponding to the nominal size.

*Weight:* The nominal weights of steel pipe are calculated values and are tabulated in [Table 1](#). They are based on the following formula:

$$W_{pe} = 10.68(D - t)t$$

where  $W_{pe}$  = nominal plain end weight to the nearest 0.01 lb/ft.

$D$  = outside diameter to the nearest 0.001 inch

$t$  = specified wall thickness rounded to the nearest 0.001 inch

*Wall thickness:* The nominal wall thicknesses are given in [Table 1](#) which also indicates the wall thicknesses in API Standard 5L.

The wall thickness designations “Standard,” “Extra-Strong,” and “Double Extra-Strong” have been commercially used designations for many years. The Schedule Numbers were subsequently added as a convenient designation for use in ordering pipe. “Standard” and Schedule 40 are identical for nominal pipe sizes up to 10 inches, inclusive. All larger sizes of “Standard” have  $\frac{3}{8}$ -inch wall thickness. “Extra-Strong” and Schedule 80 are identical for nominal pipe sizes up to 8 inch, inclusive. All larger sizes of “Extra-Strong” have  $\frac{1}{2}$ -inch-wall thickness.

*Wall Thickness Selection:* When the selection of wall thickness depends primarily on capacity to resist internal pressure under given conditions, the designer shall compute the exact value of wall thickness suitable for conditions for which the pipe is required as prescribed in the “ASME Boiler and Pressure Vessel Code,” “ANSI B31 Code for Pressure Piping,” or other similar codes, whichever governs the construction. A thickness can then be selected from [Table 1](#) to suit the value computed to fulfill the conditions for which the pipe is desired.

*Metric Weights and Mass:* Standard SI metric dimensions in millimeters for outside diameters and wall thicknesses may be found by multiplying the inch dimensions by 25.4. Outside diameters converted from those shown in [Table 1](#) should be rounded to the nearest 0.1 mm and wall thicknesses to the nearest 0.01 mm.

The following formula may be used to calculate the SI metric plain end mass in kg/m using the converted metric diameters and thicknesses:

$$W_{pe} = 0.02466(D - t)t$$

where  $W_{pe}$  = nominal plain end mass rounded to the nearest 0.01 kg/m.

$D$  = outside diameter to the nearest 0.1 mm for sizes shown in [Table 1](#).

$t$  = specified wall thickness rounded to the nearest 0.01 mm.

**Table 1. American National Standard Weights and Dimensions of Welded and Seamless Wrought Steel Pipe ANSI/ASME B36.10M-1995**

| Nom. Size and (O.D.), inch | Wall Thick., inch | Plain End Wgt., lb/ft | Identification |       |       | Nom. Size and (O.D.), inch | Wall Thick., inch | Plain End Wgt., lb/ft | Identification |       |     |     |
|----------------------------|-------------------|-----------------------|----------------|-------|-------|----------------------------|-------------------|-----------------------|----------------|-------|-----|-----|
|                            |                   |                       | Sch. No.       | Other |       |                            |                   |                       | Sch. No.       | Other |     |     |
| 1/8<br>(0.405)             | 0.057             | 0.21                  | 30             | ...   | ...   | 3<br>(3.500)               | 0.141             | 5.06                  | ...            | 5L    | ... |     |
|                            | 0.068             | 0.24                  | 40             | 5L    | STD   |                            | 0.156             | 5.57                  | ...            | 5L    | ... |     |
|                            | 0.095             | 0.31                  | 80             | 5L    | XS    |                            | 0.172             | 6.11                  | ...            | 5L    | ... |     |
| 1/4<br>(0.540)             | 0.073             | 0.36                  | 30             | ...   | ...   |                            | 0.188             | 6.65                  | ...            | 5L    | ... |     |
|                            | 0.088             | 0.42                  | 40             | 5L    | STD   |                            | 0.216             | 7.58                  | 40             | 5L    | STD |     |
|                            | 0.119             | 0.54                  | 80             | 5L    | XS    |                            | 0.250             | 8.68                  | ...            | 5L    | ... |     |
| 3/8<br>(0.675)             | 0.091             | 0.57                  | 40             | 5L    | STD   |                            | 0.281             | 9.66                  | ...            | 5L    | ... |     |
|                            | 0.126             | 0.74                  | 80             | 5L    | XS    |                            | 0.300             | 10.25                 | 80             | 5L    | XS  |     |
|                            | 0.095             | 0.76                  | 30             | ...   | ...   |                            | 0.438             | 14.32                 | 160            | ...   | ... |     |
| 1/2<br>(0.840)             | 0.109             | 0.85                  | 40             | 5L    | STD   |                            | 0.600             | 18.58                 | ...            | 5L    | XXS |     |
|                            | 0.147             | 1.09                  | 80             | 5L    | XS    |                            | 3 1/2<br>(4.000)  | 0.083                 | 3.47           | ...   | 5L  | ... |
|                            | 0.188             | 1.31                  | 160            | ...   | ...   |                            |                   | 0.109                 | 4.53           | ...   | 5L  | ... |
| 0.294                      | 1.71              | ...                   | 5L             | XXS   | 0.125 | 5.17                       |                   | ...                   | 5L             | ...   |     |     |
| 3/4<br>(1.050)             | 0.095             | 0.97                  | 30             | ...   | ...   | 0.141                      |                   | 5.81                  | ...            | 5L    | ... |     |
|                            | 0.113             | 1.13                  | 40             | 5L    | STD   | 0.156                      |                   | 6.40                  | ...            | 5L    | ... |     |
|                            | 0.154             | 1.47                  | 80             | 5L    | XS    | 0.172                      |                   | 7.03                  | ...            | 5L    | ... |     |
| 1<br>(1.315)               | 0.219             | 1.94                  | 160            | ...   | ...   | 0.188                      |                   | 7.65                  | ...            | 5L    | ... |     |
|                            | 0.308             | 2.44                  | ...            | 5L    | XXS   | 0.226                      |                   | 9.11                  | 40             | 5L    | STD |     |
|                            | 0.114             | 1.46                  | 30             | ...   | ...   | 0.250                      |                   | 10.01                 | ...            | 5L    | ... |     |
| 1 1/4<br>(1.660)           | 0.133             | 1.68                  | 40             | 5L    | STD   | 0.281                      |                   | 11.16                 | ...            | 5L    | ... |     |
|                            | 0.179             | 2.17                  | 80             | 5L    | XS    | 0.318                      |                   | 12.50                 | 80             | 5L    | XS  |     |
|                            | 0.250             | 2.84                  | 160            | ...   | ...   | 4<br>(4.500)               |                   | 0.083                 | 3.92           | ...   | 5L  | ... |
| 0.358                      | 3.66              | ...                   | 5L             | XXS   | 0.109 |                            | 5.11              | ...                   | 5L             | ...   |     |     |
| 1 1/2<br>(1.900)           | 0.117             | 1.93                  | 30             | ...   | ...   |                            | 0.125             | 5.84                  | ...            | 5L    | ... |     |
|                            | 0.140             | 2.27                  | 40             | 5L    | STD   |                            | 0.141             | 6.56                  | ...            | 5L    | ... |     |
|                            | 0.191             | 3.00                  | 80             | 5L    | XS    |                            | 0.156             | 7.24                  | ...            | 5L    | ... |     |
| 2<br>(2.375)               | 0.250             | 3.76                  | 160            | ...   | ...   |                            | 0.172             | 7.95                  | ...            | 5L    | ... |     |
|                            | 0.382             | 5.21                  | ...            | 5L    | XXS   |                            | 0.188             | 8.66                  | ...            | 5L    | ... |     |
|                            | 0.125             | 2.37                  | 30             | ...   | ...   |                            | 0.203             | 9.32                  | ...            | 5L    | ... |     |
| 2 1/2<br>(2.875)           | 0.145             | 2.72                  | 40             | 5L    | STD   |                            | 0.219             | 10.01                 | ...            | 5L    | ... |     |
|                            | 0.200             | 3.63                  | 80             | 5L    | XS    |                            | 0.237             | 10.79                 | 40             | 5L    | STD |     |
|                            | 0.281             | 4.86                  | 160            | ...   | ...   |                            | 0.250             | 11.35                 | ...            | 5L    | ... |     |
| 3<br>(3.500)               | 0.400             | 6.41                  | ...            | 5L    | XXS   |                            | 0.281             | 12.66                 | ...            | 5L    | ... |     |
|                            | 0.083             | 2.03                  | ...            | 5L    | ...   | 0.312                      | 13.96             | ...                   | 5L             | ...   |     |     |
|                            | 0.109             | 2.64                  | ...            | 5L    | ...   | 0.337                      | 14.98             | 80                    | 5L             | XS    |     |     |
| 3 1/2<br>(4.000)           | 0.125             | 3.00                  | ...            | 5L    | ...   | 0.438                      | 19.00             | 120                   | 5L             | ...   |     |     |
|                            | 0.141             | 3.36                  | ...            | 5L    | ...   | 0.531                      | 22.51             | 160                   | 5L             | ...   |     |     |
|                            | 0.154             | 3.65                  | 40             | 5L    | STD   | 0.674                      | 27.54             | ...                   | 5L             | XXS   |     |     |
| 4<br>(4.500)               | 0.172             | 4.05                  | ...            | 5L    | ...   | 5<br>(5.563)               | 0.083             | 4.86                  | ...            | 5L    | ... |     |
|                            | 0.188             | 4.39                  | ...            | 5L    | ...   |                            | 0.125             | 7.26                  | ...            | 5L    | ... |     |
|                            | 0.218             | 5.02                  | 80             | 5L    | XS    |                            | 0.156             | 9.01                  | ...            | 5L    | ... |     |
| 0.250                      | 5.67              | ...                   | 5L             | ...   | 0.188 |                            | 10.79             | ...                   | 5L             | ...   |     |     |
| 0.281                      | 6.28              | ...                   | ...            | ...   | 0.219 |                            | 12.50             | ...                   | 5L             | ...   |     |     |
| 0.344                      | 7.46              | 160                   | ...            | ...   | 0.258 |                            | 14.62             | 40                    | 5L             | STD   |     |     |
| 0.436                      | 9.03              | ...                   | ...            | XXS   | 0.281 |                            | 15.85             | ...                   | 5L             | ...   |     |     |
| 4 1/2<br>(5.063)           | 0.083             | 2.47                  | ...            | 5L    | ...   |                            | 0.312             | 17.50                 | ...            | 5L    | ... |     |
|                            | 0.109             | 3.22                  | ...            | 5L    | ...   |                            | 0.344             | 19.17                 | ...            | 5L    | ... |     |
|                            | 0.125             | 3.67                  | ...            | 5L    | ...   |                            | 0.375             | 20.78                 | 80             | 5L    | XS  |     |
| 5<br>(5.563)               | 0.141             | 4.12                  | ...            | 5L    | ...   |                            | 0.500             | 27.04                 | 120            | 5L    | ... |     |
|                            | 0.156             | 4.53                  | ...            | 5L    | ...   |                            | 0.625             | 32.96                 | 160            | 5L    | ... |     |
|                            | 0.172             | 4.97                  | ...            | 5L    | ...   | 0.750                      | 38.55             | ...                   | 5L             | XXS   |     |     |
| 5 1/2<br>(6.125)           | 0.188             | 5.40                  | ...            | 5L    | ...   | 6<br>(6.625)               | 0.083             | 5.80                  | ...            | 5L    | ... |     |
|                            | 0.203             | 5.79                  | 40             | 5L    | STD   |                            | 0.109             | 7.59                  | ...            | 5L    | ... |     |
|                            | 0.216             | 6.13                  | ...            | 5L    | ...   |                            | 0.125             | 8.68                  | ...            | 5L    | ... |     |
| 0.250                      | 7.01              | ...                   | 5L             | ...   | 0.141 |                            | 9.76              | ...                   | 5L             | ...   |     |     |
| 0.276                      | 7.66              | 80                    | 5L             | XS    | 0.156 |                            | 10.78             | ...                   | 5L             | ...   |     |     |
| 0.375                      | 10.01             | 160                   | ...            | ...   | 0.172 |                            | 11.85             | ...                   | 5L             | ...   |     |     |
| 0.552                      | 13.69             | ...                   | 5L             | XXS   |       |                            |                   |                       |                |       |     |     |

PIPE AND PIPE FITTINGS

**Table 1. (Continued) American National Standard Weights and Dimensions of Welded and Seamless Wrought Steel Pipe ANSI/ASME B36.10M-1995**

| Nom. Size and (O.D.), inch | Wall Thick., inch | Plain End Wgt., lb/ft | Identification |        | Nom. Size and (O.D.), inch | Wall Thick., inch | Plain End Wgt., lb/ft | Identification |         |        |
|----------------------------|-------------------|-----------------------|----------------|--------|----------------------------|-------------------|-----------------------|----------------|---------|--------|
|                            |                   |                       | Sch. No.       | Other  |                            |                   |                       | Sch. No.       | Other   |        |
| 6<br>(6.625)               | 0.188             | 12.92                 | ...            | 5L ... | 10<br>(10.750)             | 1.125             | 115.64                | 160            | ... ... |        |
|                            | 0.203             | 13.92                 | ...            | 5L ... |                            | 1.250             | 126.83                | ...            | 5L ...  |        |
|                            | 0.219             | 14.98                 | ...            | 5L ... |                            | 12<br>(12.750)    | 0.172                 | 23.11          | ...     | 5L ... |
|                            | 0.250             | 17.02                 | ...            | 5L ... |                            |                   | 0.188                 | 25.22          | ...     | 5L ... |
|                            | 0.280             | 18.97                 | 40             | 5L STD |                            |                   | 0.203                 | 27.20          | ...     | ...    |
|                            | 0.312             | 21.04                 | ...            | 5L ... |                            |                   | 0.219                 | 29.31          | ...     | 5L ... |
|                            | 0.344             | 23.08                 | ...            | 5L ... |                            |                   | 0.250                 | 33.38          | 20      | 5L ... |
|                            | 0.375             | 25.03                 | ...            | 5L ... |                            |                   | 0.281                 | 37.42          | ...     | 5L ... |
|                            | 0.432             | 28.57                 | 80             | 5L XS  |                            |                   | 0.312                 | 41.45          | ...     | 5L ... |
|                            | 0.500             | 32.71                 | ...            | 5L ... |                            |                   | 0.330                 | 43.77          | 30      | 5L ... |
|                            | 0.562             | 36.39                 | 120            | 5L ... |                            |                   | 0.344                 | 45.58          | ...     | 5L ... |
|                            | 0.625             | 40.05                 | ...            | 5L ... |                            |                   | 0.375                 | 49.56          | ...     | 5L STD |
|                            | 0.719             | 45.35                 | 160            | 5L ... |                            |                   | 0.406                 | 53.52          | 40      | 5L ... |
|                            | 0.750             | 47.06                 | ...            | 5L ... |                            |                   | 0.438                 | 57.59          | ...     | 5L ... |
|                            | 0.864             | 53.16                 | ...            | 5L XXS |                            |                   | 0.500                 | 65.42          | ...     | 5L XS  |
|                            | 0.875             | 53.73                 | ...            | 5L ... |                            |                   | 0.562                 | 73.15          | 60      | 5L ... |
|                            | 8<br>(8.625)      | 0.125                 | 11.35          | ...    |                            |                   | 5L ...                | 14<br>(14.000) | 0.625   | 80.93  |
| 0.156                      |                   | 14.11                 | ...            | 5L ... | 0.688                      |                   | 88.63                 |                | 80      | 5L ... |
| 0.188                      |                   | 16.94                 | ...            | 5L ... | 0.750                      | 96.12             | ...                   |                | 5L ...  |        |
| 0.203                      |                   | 18.26                 | ...            | 5L ... | 0.812                      | 103.53            | ...                   |                | 5L ...  |        |
| 0.219                      |                   | 19.66                 | ...            | 5L ... | 0.844                      | 107.32            | 100                   |                | ...     |        |
| 0.250                      |                   | 22.36                 | 20             | 5L ... | 0.875                      | 110.97            | ...                   |                | 5L ...  |        |
| 0.277                      |                   | 24.70                 | 30             | 5L ... | 0.938                      | 118.33            | ...                   |                | 5L ...  |        |
| 0.312                      |                   | 27.70                 | ...            | 5L ... | 1.000                      | 125.49            | 120                   |                | 5L XXS  |        |
| 0.322                      |                   | 28.55                 | 40             | 5L STD | 1.062                      | 132.57            | ...                   |                | 5L ...  |        |
| 0.344                      |                   | 30.42                 | ...            | 5L ... | 1.125                      | 139.67            | 140                   |                | 5L ...  |        |
| 0.375                      |                   | 33.04                 | ...            | 5L ... | 1.250                      | 153.53            | ...                   |                | 5L ...  |        |
| 0.406                      |                   | 35.64                 | 60             | ...    | 1.312                      | 160.27            | 160                   |                | 5L ...  |        |
| 0.438                      |                   | 38.30                 | ...            | 5L ... | 10<br>(10.750)             | 0.188             | 27.73                 |                | ...     | 5L ... |
| 0.500                      |                   | 43.39                 | 80             | 5L XS  |                            | 0.203             | 29.91                 |                | ...     | 5L ... |
| 0.562                      |                   | 48.40                 | ...            | 5L ... |                            | 0.210             | 30.93                 |                | ...     | 5L ... |
| 0.594                      |                   | 50.95                 | 100            | ...    |                            | 0.219             | 32.23                 |                | ...     | 5L ... |
| 0.625                      |                   | 53.40                 | ...            | 5L ... |                            | 0.250             | 36.71                 |                | 10      | 5L ... |
| 0.719                      | 60.71             | 120                   | 5L ...         | 0.281  |                            | 41.17             | ...                   | 5L ...         |         |        |
| 0.750                      | 63.08             | ...                   | 5L ...         | 0.312  |                            | 45.61             | 20                    | 5L ...         |         |        |
| 0.812                      | 67.76             | 140                   | 5L ...         | 0.344  |                            | 50.17             | ...                   | 5L ...         |         |        |
| 0.875                      | 72.42             | ...                   | 5L XXS         | 0.375  |                            | 54.57             | 30                    | 5L STD         |         |        |
| 0.906                      | 74.69             | 160                   | ...            | 0.406  |                            | 58.94             | ...                   | 5L ...         |         |        |
| 1.000                      | 81.44             | ...                   | 5L ...         | 0.438  |                            | 63.44             | 40                    | 5L ...         |         |        |
| 10<br>(10.750)             | 0.156             | 17.65                 | ...            | 5L ... |                            | 0.469             | 67.78                 | ...            | 5L ...  |        |
|                            | 0.188             | 21.21                 | ...            | 5L ... |                            | 0.500             | 72.09                 | ...            | 5L XS   |        |
|                            | 0.203             | 22.87                 | ...            | 5L ... |                            | 0.562             | 80.66                 | ...            | 5L ...  |        |
|                            | 0.219             | 24.63                 | ...            | 5L ... |                            | 0.594             | 85.05                 | 60             | ...     |        |
|                            | 0.250             | 28.04                 | 20             | 5L ... |                            | 0.625             | 89.28                 | ...            | 5L ...  |        |
|                            | 0.279             | 31.20                 | ...            | 5L ... | 0.688                      | 97.81             | ...                   | 5L ...         |         |        |
|                            | 0.307             | 34.24                 | 30             | 5L ... | 0.750                      | 106.13            | 80                    | 5L ...         |         |        |
|                            | 0.344             | 38.23                 | ...            | 5L ... | 0.812                      | 114.37            | ...                   | 5L ...         |         |        |
|                            | 0.365             | 40.48                 | 40             | 5L STD | 0.875                      | 122.65            | ...                   | 5L ...         |         |        |
|                            | 0.438             | 48.24                 | ...            | 5L ... | 0.938                      | 130.85            | 100                   | 5L ...         |         |        |
|                            | 0.500             | 54.74                 | 60             | 5L XS  | 1.000                      | 138.84            | ...                   | 5L ...         |         |        |
|                            | 0.562             | 61.15                 | ...            | 5L ... | 1.062                      | 146.74            | ...                   | 5L ...         |         |        |
|                            | 0.594             | 64.43                 | 80             | ...    | 1.094                      | 150.79            | 120                   | ...            |         |        |
|                            | 0.625             | 67.58                 | ...            | 5L ... | 1.125                      | 154.69            | ...                   | 5L ...         |         |        |
|                            | 0.719             | 77.03                 | 100            | 5L ... | 1.250                      | 170.21            | 140                   | 5L ...         |         |        |
|                            | 0.812             | 86.18                 | ...            | 5L ... | 1.406                      | 189.11            | 160                   | ...            |         |        |
|                            | 0.844             | 89.29                 | 120            | ...    | 2.000                      | 256.32            | ...                   | ...            |         |        |
| 0.875                      | 92.28             | ...                   | 5L ...         | 2.125  | 269.50                     | ...               | ...                   |                |         |        |
| 0.938                      | 98.30             | ...                   | 5L ...         | 2.200  | 277.25                     | ...               | ...                   |                |         |        |
| 1.000                      | 104.13            | 140                   | 5L XXS         | 2.500  | 307.05                     | ...               | ...                   |                |         |        |

**Table 2. Properties of American National Standard Schedule 40 Welded and Seamless Wrought Steel Pipe**

| Diameter, Inches |               |                | Wall Thickness, Inches | Cross-Sectional Area of Metal | Weight per Foot, Pounds |                  | Capacity per Foot of Length |            | Length of Pipe in Feet to Contain |            | Properties of Sections |                    |                 |
|------------------|---------------|----------------|------------------------|-------------------------------|-------------------------|------------------|-----------------------------|------------|-----------------------------------|------------|------------------------|--------------------|-----------------|
| Nominal          | Actual Inside | Actual Outside |                        |                               | Of Pipe                 | Of Water in Pipe | In Cubic Inches             | In Gallons | One Cubic Foot                    | One Gallon | Moment of Inertia      | Radius of Gyration | Section Modulus |
| 1/8              | 0.269         | 0.405          | 0.068                  | 0.072                         | 0.24                    | 0.025            | 0.682                       | 0.003      | 2532.                             | 338.7      | 0.00106                | 0.122              | 0.00525         |
| 1/4              | 0.364         | 0.540          | 0.088                  | 0.125                         | 0.42                    | 0.045            | 1.249                       | 0.005      | 1384.                             | 185.0      | 0.00331                | 0.163              | 0.01227         |
| 3/8              | 0.493         | 0.675          | 0.091                  | 0.167                         | 0.57                    | 0.083            | 2.291                       | 0.010      | 754.4                             | 100.8      | 0.00729                | 0.209              | 0.02160         |
| 1/2              | 0.622         | 0.840          | 0.109                  | 0.250                         | 0.85                    | 0.132            | 3.646                       | 0.016      | 473.9                             | 63.35      | 0.01709                | 0.261              | 0.4070          |
| 3/4              | 0.824         | 1.050          | 0.113                  | 0.333                         | 1.13                    | 0.231            | 6.399                       | 0.028      | 270.0                             | 36.10      | 0.03704                | 0.334              | 0.07055         |
| 1                | 1.049         | 1.315          | 0.133                  | 0.494                         | 1.68                    | 0.374            | 10.37                       | 0.045      | 166.6                             | 22.27      | 0.08734                | 0.421              | 0.1328          |
| 1 1/4            | 1.380         | 1.660          | 0.140                  | 0.669                         | 2.27                    | 0.648            | 17.95                       | 0.078      | 96.28                             | 12.87      | 0.1947                 | 0.539              | 0.2346          |
| 1 1/2            | 1.610         | 1.900          | 0.145                  | 0.799                         | 2.72                    | 0.882            | 24.43                       | 0.106      | 70.73                             | 9.456      | 0.3099                 | 0.623              | 0.3262          |
| 2                | 2.067         | 2.375          | 0.154                  | 1.075                         | 3.65                    | 1.454            | 40.27                       | 0.174      | 42.91                             | 5.737      | 0.6658                 | 0.787              | 0.5607          |
| 2 1/2            | 2.469         | 2.875          | 0.203                  | 1.704                         | 5.79                    | 2.074            | 57.45                       | 0.249      | 30.08                             | 4.021      | 1.530                  | 0.947              | 1.064           |
| 3                | 3.068         | 3.500          | 0.216                  | 2.228                         | 7.58                    | 3.202            | 88.71                       | 0.384      | 19.48                             | 2.604      | 3.017                  | 1.163              | 1.724           |
| 3 1/2            | 3.548         | 4.000          | 0.226                  | 2.680                         | 9.11                    | 4.283            | 118.6                       | 0.514      | 14.56                             | 1.947      | 4.788                  | 1.337              | 2.394           |
| 4                | 4.026         | 4.500          | 0.237                  | 3.174                         | 10.79                   | 5.515            | 152.8                       | 0.661      | 11.31                             | 1.512      | 7.233                  | 1.510              | 3.215           |
| 5                | 5.047         | 5.563          | 0.258                  | 4.300                         | 14.62                   | 8.666            | 240.1                       | 1.04       | 7.198                             | 0.9622     | 15.16                  | 1.878              | 5.451           |
| 6                | 6.065         | 6.625          | 0.280                  | 5.581                         | 18.97                   | 12.52            | 346.7                       | 1.50       | 4.984                             | 0.6663     | 28.14                  | 2.245              | 8.496           |
| 8                | 7.981         | 8.625          | 0.322                  | 8.399                         | 28.55                   | 21.67            | 600.3                       | 2.60       | 2.878                             | 0.3848     | 72.49                  | 2.938              | 16.81           |
| 10               | 10.020        | 10.750         | 0.365                  | 11.91                         | 40.48                   | 34.16            | 946.3                       | 4.10       | 1.826                             | 0.2441     | 160.7                  | 3.674              | 29.91           |
| 12               | 11.938        | 12.750         | 0.406                  | 15.74                         | 53.52                   | 48.49            | 1343.                       | 5.81       | 1.286                             | 0.1720     | 300.2                  | 4.364              | 47.09           |
| 16               | 15.000        | 16.000         | 0.500                  | 24.35                         | 82.77                   | 76.55            | 2121.                       | 9.18       | 0.8149                            | 0.1089     | 732.0                  | 5.484              | 91.50           |
| 18               | 16.876        | 18.000         | 0.562                  | 30.79                         | 104.7                   | 96.90            | 2684.                       | 11.62      | 0.6438                            | 0.0861     | 1172.                  | 6.168              | 130.2           |
| 20               | 18.812        | 20.000         | 0.594                  | 36.21                         | 123.1                   | 120.4            | 3335.                       | 14.44      | 0.5181                            | 0.0693     | 1706.                  | 6.864              | 170.6           |
| 24               | 22.624        | 24.000         | 0.688                  | 50.39                         | 171.3                   | 174.1            | 4824.                       | 20.88      | 0.3582                            | 0.0479     | 3426.                  | 8.246              | 285.5           |
| 32               | 30.624        | 32.000         | 0.688                  | 67.68                         | 230.1                   | 319.1            | 8839.                       | 38.26      | 0.1955                            | 0.0261     | 8299.                  | 11.07              | 518.7           |

Note: Torsional section modulus equals twice section modulus.

**Table 3. Properties of American National Standard Schedule 80 Welded and Seamless Wrought Steel Pipe**

| Diameter, Inches |                  |                   | Wall Thickness,<br>Inches | Cross-Sectional<br>Area of Metal | Weight per<br>Foot, Pounds |                     | Capacity per<br>Foot of Length |               | Length of Pipe in<br>Feet to Contain |               | Properties of Sections  |                          |                    |
|------------------|------------------|-------------------|---------------------------|----------------------------------|----------------------------|---------------------|--------------------------------|---------------|--------------------------------------|---------------|-------------------------|--------------------------|--------------------|
| Nominal          | Actual<br>Inside | Actual<br>Outside |                           |                                  | Of Pipe                    | Of Water<br>in Pipe | In Cubic<br>Inches             | In<br>Gallons | One<br>Cubic<br>Foot                 | One<br>Gallon | Moment<br>of<br>Inertia | Radius<br>of<br>Gyration | Section<br>Modulus |
| 1/8              | 0.215            | 0.405             | 0.095                     | 0.093                            | 0.315                      | 0.016               | 0.436                          | 0.0019        | 3966.                                | 530.2         | 0.00122                 | 0.115                    | 0.00600            |
| 1/4              | 0.302            | 0.540             | 0.119                     | 0.157                            | 0.537                      | 0.031               | 0.860                          | 0.0037        | 2010.                                | 268.7         | 0.00377                 | 0.155                    | 0.01395            |
| 3/8              | 0.423            | 0.675             | 0.126                     | 0.217                            | 0.739                      | 0.061               | 1.686                          | 0.0073        | 1025.                                | 137.0         | 0.00862                 | 0.199                    | 0.02554            |
| 1/2              | 0.546            | 0.840             | 0.147                     | 0.320                            | 1.088                      | 0.101               | 2.810                          | 0.0122        | 615.0                                | 82.22         | 0.02008                 | 0.250                    | 0.04780            |
| 3/4              | 0.742            | 1.050             | 0.154                     | 0.433                            | 1.474                      | 0.187               | 5.189                          | 0.0225        | 333.0                                | 44.52         | 0.04479                 | 0.321                    | 0.08531            |
| 1                | 0.957            | 1.315             | 0.179                     | 0.639                            | 2.172                      | 0.312               | 8.632                          | 0.0374        | 200.2                                | 26.76         | 0.1056                  | 0.407                    | 0.1606             |
| 1 1/4            | 1.278            | 1.660             | 0.191                     | 0.881                            | 2.997                      | 0.556               | 15.39                          | 0.0667        | 112.3                                | 15.01         | 0.2418                  | 0.524                    | 0.2913             |
| 1 1/2            | 1.500            | 1.900             | 0.200                     | 1.068                            | 3.631                      | 0.766               | 21.21                          | 0.0918        | 81.49                                | 10.89         | 0.3912                  | 0.605                    | 0.4118             |
| 2                | 1.939            | 2.375             | 0.218                     | 1.477                            | 5.022                      | 1.279               | 35.43                          | 0.1534        | 48.77                                | 6.519         | 0.8680                  | 0.766                    | 0.7309             |
| 2 1/2            | 2.323            | 2.875             | 0.276                     | 2.254                            | 7.661                      | 1.836               | 50.86                          | 0.2202        | 33.98                                | 4.542         | 1.924                   | 0.924                    | 1.339              |
| 3                | 2.900            | 3.500             | 0.300                     | 3.016                            | 10.25                      | 2.861               | 79.26                          | 0.3431        | 21.80                                | 2.914         | 3.895                   | 1.136                    | 2.225              |
| 3 1/2            | 3.364            | 4.000             | 0.318                     | 3.678                            | 12.50                      | 3.850               | 106.7                          | 0.4617        | 16.20                                | 2.166         | 6.280                   | 1.307                    | 3.140              |
| 4                | 3.826            | 4.500             | 0.337                     | 4.407                            | 14.98                      | 4.980               | 138.0                          | 0.5972        | 12.53                                | 1.674         | 9.611                   | 1.477                    | 4.272              |
| 5                | 4.813            | 5.563             | 0.375                     | 6.112                            | 20.78                      | 7.882               | 218.3                          | 0.9451        | 7.915                                | 1.058         | 20.67                   | 1.839                    | 7.432              |
| 6                | 5.761            | 6.625             | 0.432                     | 8.405                            | 28.57                      | 11.29               | 312.8                          | 1.354         | 5.524                                | 0.738         | 40.49                   | 2.195                    | 12.22              |
| 8                | 7.625            | 8.625             | 0.500                     | 12.76                            | 43.39                      | 19.78               | 548.0                          | 2.372         | 3.153                                | 0.422         | 105.7                   | 2.878                    | 24.52              |
| 10               | 9.562            | 10.750            | 0.594                     | 18.95                            | 64.42                      | 31.11               | 861.7                          | 3.730         | 2.005                                | 0.268         | 245.2                   | 3.597                    | 45.62              |
| 12               | 11.374           | 12.750            | 0.688                     | 26.07                            | 88.63                      | 44.02               | 1219.                          | 5.278         | 1.417                                | 0.189         | 475.7                   | 4.271                    | 74.62              |
| 14               | 12.500           | 14.000            | 0.750                     | 31.22                            | 106.1                      | 53.16               | 1473.                          | 6.375         | 1.173                                | 0.157         | 687.4                   | 4.692                    | 98.19              |
| 16               | 14.312           | 16.000            | 0.844                     | 40.19                            | 136.6                      | 69.69               | 1931.                          | 8.357         | 0.895                                | 0.120         | 1158.                   | 5.366                    | 144.7              |
| 18               | 16.124           | 18.000            | 0.938                     | 50.28                            | 170.9                      | 88.46               | 2450.                          | 10.61         | 0.705                                | 0.094         | 1835.                   | 6.041                    | 203.9              |
| 20               | 17.938           | 20.000            | 1.031                     | 61.44                            | 208.9                      | 109.5               | 3033.                          | 13.13         | 0.570                                | 0.076         | 2772.                   | 6.716                    | 277.2              |
| 22               | 19.750           | 22.000            | 1.125                     | 73.78                            | 250.8                      | 132.7               | 3676.                          | 15.91         | 0.470                                | 0.063         | 4031.                   | 7.391                    | 366.4              |

Note: Torsional section modulus equals twice section modulus.

**Table 4. Volume of Flow at 1 Foot Per-Minute Velocity in Pipe and Tube**

| Nominal Dia., Inches | Schedule 40 Pipe   |                    |                            | Schedule 80 Pipe   |                    |                            | Type K Copper Tube |                    |                            | Type L Copper Tube |                    |                            |
|----------------------|--------------------|--------------------|----------------------------|--------------------|--------------------|----------------------------|--------------------|--------------------|----------------------------|--------------------|--------------------|----------------------------|
|                      | Cu. Ft. per Minute | Gallons per Minute | Pounds 60 F Water per Min. | Cu. Ft. per Minute | Gallons per Minute | Pounds 60 F Water per Min. | Cu. Ft. per Minute | Gallons per Minute | Pounds 60 F Water per Min. | Cu. Ft. per Minute | Gallons per Minute | Pounds 60 F Water per Min. |
| 1/8                  | 0.0004             | 0.003              | 0.025                      | 0.0003             | 0.002              | 0.016                      | 0.0002             | 0.0014             | 0.012                      | 0.0002             | 0.002              | 0.014                      |
| 1/4                  | 0.0007             | 0.005              | 0.044                      | 0.0005             | 0.004              | 0.031                      | 0.0005             | 0.0039             | 0.033                      | 0.0005             | 0.004              | 0.034                      |
| 3/8                  | 0.0013             | 0.010              | 0.081                      | 0.0010             | 0.007              | 0.061                      | 0.0009             | 0.0066             | 0.055                      | 0.0010             | 0.008              | 0.063                      |
| 1/2                  | 0.0021             | 0.016              | 0.132                      | 0.0016             | 0.012              | 0.102                      | 0.0015             | 0.0113             | 0.094                      | 0.0016             | 0.012              | 0.101                      |
| 3/4                  | 0.0037             | 0.028              | 0.232                      | 0.0030             | 0.025              | 0.213                      | 0.0030             | 0.0267             | 0.189                      | 0.0034             | 0.025              | 0.210                      |
| 1                    | 0.0062             | 0.046              | 0.387                      | 0.0050             | 0.037              | 0.312                      | 0.0054             | 0.0404             | 0.338                      | 0.0057             | 0.043              | 0.358                      |
| 1 1/4                | 0.0104             | 0.078              | 0.649                      | 0.0088             | 0.067              | 0.555                      | 0.0085             | 0.0632             | 0.53                       | 0.0087             | 0.065              | 0.545                      |
| 1 1/2                | 0.0141             | 0.106              | 0.882                      | 0.0123             | 0.092              | 0.765                      | 0.0196             | 0.1465             | 1.22                       | 0.0124             | 0.093              | 0.770                      |
| 2                    | 0.0233             | 0.174              | 1.454                      | 0.0206             | 0.154              | 1.280                      | 0.0209             | 0.1565             | 1.31                       | 0.0215             | 0.161              | 1.34                       |
| 2 1/2                | 0.0332             | 0.248              | 2.073                      | 0.0294             | 0.220              | 1.830                      | 0.0323             | 0.2418             | 2.02                       | 0.0331             | 0.248              | 2.07                       |
| 3                    | 0.0514             | 0.383              | 3.201                      | 0.0460             | 0.344              | 2.870                      | 0.0461             | 0.3446             | 2.88                       | 0.0473             | 0.354              | 2.96                       |
| 3 1/2                | 0.0682             | 0.513              | 4.287                      | 0.0617             | 0.458              | 3.720                      | 0.0625             | 0.4675             | 3.91                       | 0.0640             | 0.479              | 4.00                       |
| 4                    | 0.0884             | 0.660              | 5.516                      | 0.0800             | 0.597              | 4.970                      | 0.0811             | 0.6068             | 5.07                       | 0.0841             | 0.622              | 5.20                       |
| 5                    | 0.1390             | 1.040              | 8.674                      | 0.1260             | 0.947              | 7.940                      | 0.1259             | 0.9415             | 7.87                       | 0.1296             | 0.969              | 8.10                       |
| 6                    | 0.2010             | 1.500              | 12.52                      | 0.1820             | 1.355              | 11.300                     | 0.1797             | 1.3440             | 11.2                       | 0.1862             | 1.393              | 11.6                       |
| 8                    | 0.3480             | 2.600              | 21.68                      | 0.3180             | 2.380              | 19.800                     | 0.3135             | 2.3446             | 19.6                       | 0.3253             | 2.434              | 20.3                       |
| 10                   | 0.5476             | 4.10               | 34.18                      | 0.5560             | 4.165              | 31.130                     | 0.4867             | 3.4405             | 30.4                       | 0.5050             | 3.777              | 21.6                       |
| 12                   | 0.7773             | 5.81               | 48.52                      | 0.7060             | 5.280              | 44.040                     | 0.6978             | 5.2194             | 43.6                       | 0.7291             | 5.454              | 45.6                       |
| 14                   | 0.9396             | 7.03               | 58.65                      | 0.8520             | 6.380              | 53.180                     | ...                | ...                | ...                        | ...                | ...                | ...                        |
| 16                   | 1.227              | 9.18               | 76.60                      | 1.1170             | 8.360              | 69.730                     | ...                | ...                | ...                        | ...                | ...                | ...                        |
| 18                   | 1.553              | 11.62              | 96.95                      | 1.4180             | 10.610             | 88.500                     | ...                | ...                | ...                        | ...                | ...                | ...                        |
| 20                   | 1.931              | 14.44              | 120.5                      | 1.7550             | 13.130             | 109.510                    | ...                | ...                | ...                        | ...                | ...                | ...                        |

To obtain volume of flow at any other velocity, multiply values in table by velocity in feet per minute.



**Plastics Pipe.**—Shortly after World War II, plastics pipe became an acceptable substitute, under certain service conditions, for other piping materials. Now, however, plastics pipe is specified on the basis of its own special capabilities and limitations. The largest volume of application has been for water piping systems.

Besides being light in weight, plastics pipe performs well in resisting deterioration from corrosive or caustic fluids. Even if the fluid borne is harmless, the chemical resistance of plastics pipe offers protection against a harmful exterior environment, such as when buried in a corrosive soil.

Generally, plastics pipe is limited by its temperature and pressure capacities. The higher the operating pressure of the pipe system, the less will be its temperature capability. The reverse is true, also. Since it is formed from organic resins, plastics pipe will burn. For various piping compositions, ignition temperatures vary from 700° to 800°F (370° to 430°C).

The following are accepted methods for joining plastics pipe:

*Solvent Welding* is usually accomplished by brushing a solvent cement on the end of the length of pipe and into the socket end of a fitting or the flange of the next pipe section. A chemical weld then joins and seals the pipe after connection.

*Threading* is a procedure not recommended for thin-walled plastics pipe or for specific grades of plastics. During connection of thicker-walled pipe, strap wrenches are used to avoid damaging and weakening the plastics.

*Heat Fusion* involves the use of heated air and plastics filler rods to weld plastics pipe assemblies. A properly welded joint can have a tensile strength equal to 90 percent that of the pipe material.

*Elastomeric Sealing* is used with bell-end piping. It is a recommended procedure for large diameter piping and for underground installations. The joints are set quickly and have good pressure capabilities.

**Table 5. Dimensions and Weights of Thermoplastics Pipe**

| Nominal Pipe Size |      | Outside Diameter |       | Schedule 40         |       |                |      | Schedule 80         |       |                |      |
|-------------------|------|------------------|-------|---------------------|-------|----------------|------|---------------------|-------|----------------|------|
|                   |      |                  |       | Nom. Wall Thickness |       | Nominal Weight |      | Nom. Wall Thickness |       | Nominal Weight |      |
| in.               | cm   | in.              | cm    | in.                 | cm    | lb/100'        | kg/m | in.                 | cm    | lb/100'        | kg/m |
| 1/8               | 0.3  | 0.405            | 1.03  | 0.072               | 0.18  | 3.27           | 0.05 | 0.101               | 0.256 | 4.18           | 0.06 |
| 1/4               | 0.6  | 0.540            | 1.37  | 0.093               | 0.24  | 5.66           | 0.08 | 0.126               | 0.320 | 7.10           | 0.11 |
| 3/8               | 1.0  | 0.675            | 1.71  | 0.096               | 0.24  | 7.57           | 0.11 | 0.134               | 0.340 | 9.87           | 0.15 |
| 1/2               | 1.3  | 0.840            | 2.13  | 0.116               | 0.295 | 11.4           | 0.17 | 0.156               | 0.396 | 14.5           | 0.22 |
| 3/4               | 2.0  | 1.050            | 2.67  | 0.120               | 0.305 | 15.2           | 0.23 | 0.163               | 0.414 | 19.7           | 0.29 |
| 1                 | 2.5  | 1.315            | 3.34  | 0.141               | 0.358 | 22.5           | 0.33 | 0.190               | 0.483 | 29.1           | 0.43 |
| 1 1/4             | 3.2  | 1.660            | 4.22  | 0.148               | 0.376 | 30.5           | 0.45 | 0.202               | 0.513 | 40.1           | 0.60 |
| 1 1/2             | 3.8  | 1.900            | 4.83  | 0.154               | 0.391 | 36.6           | 0.54 | 0.212               | 0.538 | 48.7           | 0.72 |
| 2                 | 5.1  | 2.375            | 6.03  | 0.163               | 0.414 | 49.1           | 0.73 | 0.231               | 0.587 | 67.4           | 1.00 |
| 2 1/2             | 6.4  | 2.875            | 7.30  | 0.215               | 0.546 | 77.9           | 1.16 | 0.293               | 0.744 | 103            | 1.5  |
| 3                 | 7.6  | 3.500            | 8.89  | 0.229               | 0.582 | 102            | 1.5  | 0.318               | 0.808 | 138            | 2.1  |
| 3 1/2             | 8.9  | 4.000            | 10.16 | 0.240               | 0.610 | 123            | 1.8  | 0.337               | 0.856 | 168            | 2.5  |
| 4                 | 10.2 | 4.500            | 11.43 | 0.251               | 0.638 | 145            | 2.2  | 0.357               | 0.907 | 201            | 3.0  |
| 5                 | 12.7 | 5.563            | 14.13 | 0.273               | 0.693 | 197            | 2.9  | 0.398               | 1.011 | 280            | 4.2  |
| 6                 | 15.2 | 6.625            | 16.83 | 0.297               | 0.754 | 256            | 3.8  | 0.458               | 1.163 | 385            | 5.7  |
| 8                 | 20.3 | 8.625            | 21.91 | 0.341               | 0.866 | 385            | 5.7  | 0.530               | 1.346 | 584            | 8.7  |
| 10                | 25.4 | 10.75            | 27.31 | 0.387               | 0.983 | 546            | 8.1  | 0.629               | 1.598 | 867            | 12.9 |
| 12                | 30.5 | 12.75            | 32.39 | 0.430               | 1.09  | 722            | 10.7 | 0.728               | 1.849 | 1192           | 17.7 |

The nominal weights of plastics pipe given in this table are based on an empirically chosen material density of 1.00 g/cm<sup>3</sup>. The nominal unit weight for a specific plastics pipe formulation can be

obtained by multiplying the weight values from the table by the density in  $\text{g/cm}^3$  or by the specific gravity of the particular plastics composition.

The following are ranges of density factors for various plastics pipe materials: PE, 0.93 to 0.96; PVC, 1.35 to 1.40; CPVC, 1.55; ABS, 1.04 to 1.08; SR, 1.05; PB, 0.91 to 0.92; and PP, 0.91. For meanings of abbreviations see [Table 6](#).

Information supplied by the Plastics Pipe Institute.

*Insert Fitting* is particularly useful for PE and PB pipe. For joining pipe sections, insert fittings are pushed into the pipe and secured by stainless steel clamps.

*Transition Fitting* involves specially designed connectors to join plastic pipe with other materials, such as cast iron, steel, copper, clay, and concrete.

Plastic pipe can be specified by means of Schedules 40, 80, and 120, which conform dimensionally to metal pipe, or through a Standard Dimension Ratio (SDR). The SDR is a rounded value obtained by dividing the average outside diameter of the pipe by the wall thickness. Within an individual SDR series of pipe, pressure ratings are uniform, regardless of pipe diameter.

[Table 5](#) provides the weights and dimensions for Schedule 40 and 80 thermoplastic pipe, [Table 6](#) gives properties of plastics pipe, [Table 7](#) gives maximum non-shock operating pressures for several varieties of Schedule 40 and 80 plastics pipe at 73°F, and [Table 8](#) gives correction factors to pressure ratings for elevated temperatures.

**Table 6. General Properties and Uses of Plastic Pipe**

| Plastic Pipe Material                    | Properties   | Common Uses   | Operating Temperature <sup>a</sup>           |                  | Joining Methods  |
|--|--|---|--|------------------|--|
|  |  |   | With Pressure                                | Without Pressure |  |
| ABS<br>(Acrylonitrilebutadiene styrene)  | Rigid; excellent impact strength at low temperatures; maintains rigidity at higher temperatures. | Water, Drain, Waste, Vent, Sewage.                  | 100°F (38°C)                                 | 180°F (82°C)     | Solvent cement, Threading, Transition fitting.                             |
| PE<br>(Polyethylene)                     | Flexible; excellent impact strength; good performance at low temperatures.                       | Water, Gas, Chemical, Irrigation.                   | 100°F (38°C)                                 | 180°F (82°C)     | Heat fusion, Insert and Transition fitting.                                |
| PVC<br>(Polyvinylchloride)               | Rigid; fire self-extinguishing; high impact and tensile strength.                                | Water, Gas, Sewage, Industrial process, Irrigation. | 100°F (38°C)                                 | 180°F (82°C)     | Solvent cement, Elastomeric seal, Mechanical coupling, Transition fitting. |
| CPVC<br>(Chlorinated polyvinyl chloride) | Rigid; fire self-extinguishing; high impact and tensile strength.                                | Hot and cold water, Chemical.                       | 180°F (82°C) at 100 psig (690kPa) for SDR-11 |                  | Solvent cement, Threading, Mechanical coupling, Transition fitting.        |
| PB<br>(Polybutylene)                     | Flexible; good performance at elevated temperatures.   | Water, Gas, Irrigation.                             | 180°F (82°C)                                 | 200°F (93°C)     | Insert fitting, Heat fusion, Transition fitting.                           |
| PP<br>(Polypropylene)                    | Rigid; very light; high chemical resistance, particularly to sulfur-bearing compounds.           | Chemical waste and processing.                      | 100°F (38°C)                                 | 180°F (82°C)     | Mechanical coupling, Heat fusion, Threading.                               |
| SR<br>(Styrene rubber plastic)           | Rigid; moderate chemical resistance; fair impact strength.                                       | Drainage, Septic fields.                            | 150°F (66°C)                                 | ...              | Solvent cement, Transition fitting, Elastomeric seal.                      |

<sup>a</sup>The operating temperatures shows are general guide points. For specific operating temperature and pressure data for various grades of the types of plastic pipe given, please consult the pipe manufacturer or the Plastics Pipe Institute.

From information supplied by the Plastics Pipe Institute.

## PIPE AND PIPE FITTINGS

**Table 7. Maximum Nonshock Operating Pressure (psi) for Thermoplastic Piping at 73°F**

| Nominal Pipe Size (inch) | Schedule 40             |     | Schedule 80      |              |                  |                           |                  |              |     |
|--------------------------|-------------------------|-----|------------------|--------------|------------------|---------------------------|------------------|--------------|-----|
|                          | PVC & CPVC (Socket End) | ABS | PVC & CPVC       |              | Polypropylene    |                           | PVDF             |              | ABS |
|                          |                         |     | Socket End       | Threaded End | Thermoseal Joint | Threaded End <sup>a</sup> | Thermoseal Joint | Threaded End |     |
| 1/2                      | 600                     | 476 | 850              | 420          | 410              | 20                        | 580              | 290          | 678 |
| 3/4                      | 480                     | 385 | 690              | 340          | 330              | 20                        | 470              | 230          | 550 |
| 1                        | 450                     | 360 | 630              | 320          | 310              | 20                        | 430              | 210          | 504 |
| 1 1/4                    | 370                     | 294 | 520              | 260          | 260              | 20                        | ...              | ...          | 416 |
| 1 1/2                    | 330                     | 264 | 470              | 240          | 230              | 20                        | 326              | 160          | 376 |
| 2                        | 280                     | 222 | 400              | 200          | 200              | ...                       | 270              | 140          | 323 |
| 2 1/2                    | 300                     | 243 | 420              | 210          | ...              | 20                        | ...              | ...          | 340 |
| 3                        | 260                     | 211 | 370              | 190          | 160              | 20                        | 250              | NR           | 297 |
| 4                        | 220                     | 177 | 320              | 160          | 140              | NR                        | 220              | NR           | 259 |
| 6                        | 180                     | 141 | 280              | NR           | ...              | ...                       | 190              | NR           | 222 |
| 8                        | 160                     | ... | 250 <sup>b</sup> | NR           | ...              | ...                       | ...              | ...          | ... |
| 10                       | 140                     | ... | 230              | NR           | ...              | ...                       | ...              | ...          | ... |
| 12                       | 130                     | ... | 230              | NR           | ...              | ...                       | ...              | ...          | ... |

<sup>a</sup> Recommended for intermittent drainage pressure not exceeding 20 psi.

<sup>b</sup> 8-inch CPVC Tee, 90° Ell, and 45° Ell are rated at half the pressure shown.

ABS pressures refer to unthreaded pipe only.

For service at higher temperature, multiply the pressure obtained from this table by the correction factor from [Table 6](#).

NR is not recommended.

**Table 8. Temperature-Correction Factors for Thermoplastic Piping Operating Pressures**

| Operating Temperature, °F | Pipe Material |      |               |      |
|---------------------------|---------------|------|---------------|------|
|                           | PVC           | CPVC | Polypropylene | PVDF |
| 70                        | 1             | 1    | 1             | 1    |
| 80                        | 0.90          | 0.96 | 0.97          | 0.95 |
| 90                        | 0.75          | 0.92 | 0.91          | 0.87 |
| 100                       | 0.62          | 0.85 | 0.85          | 0.80 |
| 110                       | 0.50          | 0.77 | 0.80          | 0.75 |
| 115                       | 0.45          | 0.74 | 0.77          | 0.71 |
| 120                       | 0.40          | 0.70 | 0.75          | 0.68 |
| 125                       | 0.35          | 0.66 | 0.71          | 0.66 |
| 130                       | 0.30          | 0.62 | 0.68          | 0.62 |
| 140                       | 0.22          | 0.55 | 0.65          | 0.58 |
| 150                       | NR            | 0.47 | 0.57          | 0.52 |
| 160                       | NR            | 0.40 | 0.50          | 0.49 |
| 170                       | NR            | 0.32 | 0.26          | 0.45 |
| 180                       | NR            | 0.25 | <sup>a</sup>  | 0.42 |
| 200                       | NR            | 0.18 | NR            | 0.36 |
| 210                       | NR            | 0.15 | NR            | 0.33 |
| 240                       | NR            | NR   | NR            | 0.25 |
| 280                       | NR            | NR   | NR            | 0.18 |

<sup>a</sup> Recommended for intermittent drainage pressure not exceeding 20 psi.

NR = not recommended.

For more detailed information concerning the properties of a particular plastic pipe formulation, consult the pipe manufacturer or Plastics Pipe Institute, 1825 Connecticut Ave. NW, Washington, D.C. 20009.

**Pipe and Tube Bending.**—In bending a pipe or tube, the outer part of the bend is stretched and the inner section compressed, and as the result of opposite and unequal stresses, the pipe or tube tends to flatten or collapse. To prevent such distortion, the common practice is to support the wall of the pipe or tube in some manner during the bending operation. This support may be in the form of a filling material, or, when a bending machine or fixture is used, an internal mandrel or ball-shaped member may support the inner wall when required.

If a filling material is used, it is melted and poured into the pipe or tube. Many filler materials made up from combinations of bismuth, lead, tin, and cadmium, with melting points around 160 degrees F are commercially available. With this material, tubes having very thin walls have been bent to small radii. The metal filler conforms to the inside of the tube so closely that the tube can be bent just as though it were a solid rod. The filler is removed readily by melting.

This method has been applied to the bending of copper, brass, duralumin, plain steel, and stainless steel tubes with uniform success. Tubes plated with chromium or nickel can often be bent without danger of the plate flaking off. Other filling materials such as resin, tar, lead, and dry sand have also been used.

Pipes are often bent to avoid the use of fittings, thus eliminating joints, providing a smooth unobstructed passage for fluids, and resulting in certain other advantages.

*Minimum Radius:* The safe minimum radius for a given diameter, material, and method of bending depends upon the thickness of the pipe wall, it being possible, for example, to bend extra heavy pipe to a smaller radius than pipe of standard weight. As a general rule, wrought iron or steel pipe of standard weight may readily be bent to a radius equal to five or six times the nominal pipe diameter. The minimum radius for standard weight pipe should, as a rule, be three and one-half to four times the diameter. It will be understood, however, that the minimum radius may vary considerably, depending upon the method of bending. Extra heavy pipe may be bent to radii varying from two and one-half times the diameter for smaller sizes to three and one-half to four times the diameter for larger sizes.

*Rules for Finding Lengths of Bends:* In determining the required length of a pipe or tube before bending, the lengths of the straight sections are, of course, added to the lengths required for the curved sections in order to make the proper allowance for bends. The following rules are for finding the lengths of the curved sections.

*Length of 90-Degree Bend:* To find the length of a 90-degree or right-angle bend, multiply the radius of the bend by 1.57. The radius is measured to the center of the pipe, or to a point midway between the inner and outer walls.

*Length of 180-Degree Bend:* Multiply the radius of the bend by 3.14.

*Length of other than 90- or 180-Degree Bend:* Multiply the radius of the bend by the included angle, and then multiply the product by the constant 0.01745. The result is the length of the curved section.

**Definitions of Pipe Fittings.**—The following definitions for various pipe fittings are given by the National Tube Co.:

*Armstrong Joint:* A two-bolt, flanged or lugged connection for high pressures. The ends of the pipes are peculiarly formed to properly hold a gutta-percha ring. It was originally made for cast-iron pipe. The two-bolt feature has much to recommend it. There are various substitutes for this joint, many of which employ rubber in place of gutta-percha; others use more bolts in order to reduce the cost.

*Bell and Spigot Joint:* a) The usual term for the joint in cast-iron pipe. Each piece is made with an enlarged diameter or bell at one end into which the plain or spigot end of another piece is inserted when laying. The joint is then made tight by cement, oakum, lead, rubber or other suitable substance, which is driven in or calked into the bell and around the spigot. When a similar joint is made in wrought pipe by means of a cast bell (or hub), it is at times

called hub and spigot joint (poor usage). Matheson joint is the name applied to a similar joint in wrought pipe which has the bell formed from the pipe.

b) Applied to fittings or valves, means that one end of the run is a "bell," and the other end is a "spigot," similar to those used on regular cast-iron pipe.

*Bonnet:* a) A cover used to guide and enclose the tail end of a valve spindle.

b) A cap over the end of a pipe (poor usage).

*Branch:* The outlet or inlet of a fitting not in line with the run, but which may make any angle.

*Branch Ell:* a) Used to designate an elbow having a back outlet in line with one of the outlets of the "run." It is also called a heel outlet elbow.

b) Incorrectly used to designate side outlet or back outlet elbow.

*Branch Pipe:* A very general term used to signify a pipe either cast or wrought, that is equipped with one or more branches. Such pipes are used so frequently that they have acquired common names such as tees, crosses, side or back outlet elbows, manifolds, double-branch elbows, etc. The term branch pipe is generally restricted to such as do not conform to usual dimensions.

*Branch Tee or Header:* A tee having many side branches. (See *Manifold*.)

*Bull Head Tee:* A tee the branch of which is larger than the run.

*Bushing:* A pipe fitting for the purpose of connecting a pipe with a fitting of larger size, being a hollow plug with internal and external threads to suit the different diameters.

*Card Weight Pipe:* A term used to designate standard or full weight pipe, which is the Briggs' standard thickness of pipe.

*Close Nipple:* One the length of which is about twice the length of a standard pipe thread and is without any shoulder.

*Coupling:* A threaded sleeve used to connect two pipes. Commercial couplings are threaded inside to suit the exterior thread of the pipe. The term coupling is occasionally used to mean any jointing device and may be applied to either straight or reducing sizes.

*Cross:* A pipe fitting with four branches arranged in pairs, each pair on one axis, and the axes at right angles. When the outlets are otherwise arranged the fittings are branch pipes or specials.

*Cross-over:* A small fitting with a double offset, or shaped like the letter U with the ends turned out. It is only made in small sizes and used to pass the flow of one pipe past another when the pipes are in the same plane.

*Cross-over Tee:* A fitting made along lines similar to the cross-over, but having at one end two openings in a tee-head the plane of which is at right angles to the plane of the cross-over bend.

*Cross Valve:* a) A valve fitted on a transverse pipe so as to open communication at will between two parallel lines of piping. Much used in connection with oil and water pumping arrangements, especially on ship board.

b) Usually considered as an angle valve with a back outlet in the same plane as the other two openings.

*Crotch:* A fitting that has the general shape of the letter Y. Caution should be exercised not to confuse the crotch and wye.

*Double-branch Elbow:* A fitting that, in a manner, looks like a tee, or as if two elbows had been shaved and then placed together, forming a shape something like the letter Y or a crotch.

*Double Sweep Tee:* A tee made with easy curves between body and branch, i.e., the center of the curve between run and branch lies outside the body.

*Drop Elbow:* A small sized ell that is frequently used where gas is put into a building. These fittings have wings cast on each side. The wings have small countersunk holes so that they may be fastened by wood screws to a ceiling or wall or framing timbers.

*Drop Tee:* One having the same peculiar wings as the drop elbow.

*Dry Joint:* One made without gasket or packing or smear of any kind, as a ground joint.

**Elbow (ELL):** A fitting that makes an angle between adjacent pipes. The angle is always 90 degrees, unless another angle is stated. (See *Branch Ell*, *Service Ell*, and *Union Ell*.)

**Extra Heavy:** When applied to pipe, means pipe thicker than standard pipe; when applied to valves and fittings, indicates goods suitable for a working pressure of 250 pounds per square inch.

**Header:** A large pipe into which one set of boilers is connected by suitable nozzles or tees, or similar large pipes from which a number of smaller ones lead to consuming points. Headers are often used for other purposes—for heaters or in refrigeration work. Headers are essentially branch pipes with many outlets, which are usually parallel. Largely used for tubes of water-tube boilers.

**Hydrostatic Joint:** Used in large water mains, in which sheet lead is forced tightly into the bell of a pipe by means of the hydrostatic pressure of a liquid.

**Kewanee Union:** A patented pipe union having one pipe end of brass and the other of malleable iron, with a ring or nut of malleable iron, in which the arrangement and finish of the several parts is such as to provide a non-corrosive ball-and-socket joint at the junction of the pipe ends, and a non-corrosive connection between the ring and brass pipe end.

**Lead Joint:** a) Generally used to signify the connection between pipes which is made by pouring molten lead into the annular space between a bell and spigot, and then making the lead tight by calking.

b) Rarely used to mean the joint made by pressing the lead between adjacent pieces, as when a lead gasket is used between flanges.

**Lead Wool:** A material used in place of molten lead for making pipe joints. It is lead fiber, about as coarse as fine excelsior, and when made in a strand, it can be calked into the joints, making them very solid.

**Line Pipe:** Special brand of pipe that employs recessed and taper thread couplings, and usually greater length of thread than Briggs' standard. The pipe is also subjected to higher test.

**Lip Union:** a) A special form of union characterized by the lip that prevents the gasket from being squeezed into the pipe so as to obstruct the flow.

b) A ring union, unless flange is specified.

**Manifold:** a) A fitting with numerous branches used to convey fluids between a large pipe and several smaller pipes. (See *Branch Tee* or *Header*.)

b) A header for a coil.

**Matheson Joint:** A wrought pipe joint made by enlarging one end of the pipe to form a suitable lead recess, similar to the bell end of a cast-iron pipe, and which receives the male or spigot end of the next length. Practically the same style of a joint as used for cast-iron pipe.

**Medium Pressure:** When applied to valves and fittings, means suitable for a working pressure of from 125 to 175 pounds per square inch.

**Needle Valve:** A valve provided with a long tapering point in place of the ordinary valve disk. The tapering point permits fine graduation of the opening. At times called a needle point valve.

**Nipple:** A tubular pipe fitting usually threaded on both ends and under 12 inches in length. Pipe over 12 inches long is regarded as cut pipe. (See *Close Nipple*, *Short Nipple*, *Shoulder Nipple*, and *Space Nipple*.)

**Reducer:** a) A fitting having a larger size at one end than at the other. Some have tried to establish the term "increaser" — thinking of direction of flow — but this has been due to a misunderstanding of the trade custom of always giving the largest size of run of a fitting first; hence, all fittings having more than one size are reducers. They are always threaded inside, unless specified flanged or for some special joint.

b) Threaded type, made with abrupt reduction.

c) Flanged pattern with taper body.

d) Flanged eccentric pattern with taper body, but flanges at 90 degrees to one side of body.

e) Misapplied at times, to a reducing coupling.

*Run:* a) A length of pipe that is made of more than one piece of pipe.

b) The portion of any fitting having its ends "in line" or nearly so, in contradistinction to the branch or side opening, as of a tee. The two main openings of an ell also indicate its run, and when there is a third opening on an eli, the fitting is a "side outlet" or "back outlet" elbow, except that when all three openings are in one plane and the back outlet is in line with one of the run openings, the fitting is a "heel outlet elbow" or a "single sweep tee" or sometimes a "branch tee."

*Rust Joint:* Employed to secure rigid connection. The joint is made by packing an intervening space tightly with a stiff paste which oxidizes the iron, the whole rusting together and hardening into a solid mass. It generally cannot be separated except by destroying some of the pieces. One recipe is 80 pounds cast-iron borings or filings, 1 pound sal-ammoniac, 2 pounds flowers of sulphur, mixed to a paste with water.

*Service Ell:* An elbow having an outside thread on one end. Also known as street ell.

*Service Pipe:* A pipe connecting mains with a dwelling.

*Service Tee:* A tee having inside thread on one end and on branch, but outside thread on other end of run. Also known as street tee.

*Short Nipple:* One whose length is a little greater than that of two threaded lengths or somewhat longer than a close nipple. It always has some unthreaded portion between the two threads.

*Shoulder Nipple:* A nipple of any length, which has a portion of pipe between two pipe threads. As generally used, however, it is a nipple about halfway between the length of a close nipple and a short nipple.

*Space Nipple:* A nipple with a portion of pipe or shoulder between the two threads. It may be of any length long enough to allow a shoulder.

*Standard Pressure:* A term applied to valves and fittings suitable for a working steam pressure of 125 pounds per square inch.

*Tee:* A fitting, either cast or wrought, that has one side outlet at right angles to the run. A single outlet branch pipe. (See *Branch Tee or Header*, *Bull Head Tee*, *Cross-over Tee*, *Double Sweep Tee*, *Drop Tee*, *Service Tee*, and *Union Tee*.)

*Union:* The usual trade term for a device used to connect pipes. It commonly consists of three pieces which are, first, the thread end fitted with exterior and interior threads; second, the bottom end fitted with interior threads and a small exterior shoulder; and third, the ring which has an inside flange at one end while the other end has an inside thread like that on the exterior of the thread end. A gasket is placed between the thread and bottom ends, which are drawn together by the ring. Unions are very extensively used, because they permit of connections with little disturbance of the pipe positions.

*Union Ell:* An ell with a male or female union at one end.

*Union Joint:* A pipe coupling, usually threaded, which permits disconnection without disturbing other sections.

*Union Tee:* A tee with male or female union at connection on one end of run.

*Wiped Joint:* A lead joint in which the molten solder is poured upon the desired place, after scraping and fitting the parts together, and the joint is wiped up by hand with a moleskin or cloth pad while the metal is in a plastic condition.

*Wye (Y):* A fitting either cast or wrought that has one side outlet at any angle other than 90 degrees. The angle is usually 45 degrees, unless another angle is specified. The fitting is usually indicated by the letter Y.

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## SYMBOLS AND ABBREVIATIONS

## Greek Letters and Standard Abbreviations

The Greek letters are frequently used in mathematical expressions and formulas. The Greek alphabet is given below.

|          |            |         |           |           |        |          |            |         |            |            |         |
|----------|------------|---------|-----------|-----------|--------|----------|------------|---------|------------|------------|---------|
| A        | $\alpha$   | Alpha   | H         | $\eta$    | Eta    | N        | $\nu$      | Nu      | T          | $\tau$     | Tau     |
| B        | $\beta$    | Beta    | $\Theta$  | $\theta$  | Theta  | $\Xi$    | $\xi$      | Xi      | $\Upsilon$ | $\upsilon$ | Upsilon |
| $\Gamma$ | $\gamma$   | Gamma   | I         | $\iota$   | Iota   | O        | $\omicron$ | Omicron | $\Phi$     | $\phi$     | Phi     |
| $\Delta$ | $\delta$   | Delta   | K         | $\kappa$  | Kappa  | $\Pi$    | $\pi$      | Pi      | X          | $\chi$     | Chi     |
| E        | $\epsilon$ | Epsilon | $\Lambda$ | $\lambda$ | Lambda | R        | $\rho$     | Rho     | $\Psi$     | $\psi$     | Psi     |
| Z        | $\zeta$    | Zeta    | M         | $\mu$     | Mu     | $\Sigma$ | $\sigma$   | Sigma   | $\Omega$   | $\omega$   | Omega   |

## ANSI Abbreviations for Scientific and Engineering Terms

ANSI Y1.1-1972, (R 1984)

|                                 |                          |                            |                   |
|---------------------------------|--------------------------|----------------------------|-------------------|
| Absolute                        | abs                      | Decibel                    | dB                |
| Alternating current             | ac                       | Degree                     | deg or $^{\circ}$ |
| Ampere                          | amp                      | Degree Centigrade          | $^{\circ}$ C      |
| Ampere-hour                     | amp hr                   | Degree Fahrenheit          | $^{\circ}$ F      |
| Angstrom unit                   | Å                        | Degree Kelvin              | K                 |
| Antilogarithm                   | antilog                  | Diameter                   | dia               |
| Arithmetical average            | aa                       | Direct current             | dc                |
| Atmosphere                      | atm                      | Dozen                      | doz               |
| Atomic weight                   | at wt                    | Dram                       | dr                |
| Avoirdupois                     | avdp                     | Efficiency                 | eff               |
| Barometer                       | baro                     | Electric                   | elec              |
| Board feet (feet board measure) | fbm                      | Electromotive force        | emf               |
| Boiler pressure                 | bopress                  | Elevation                  | el                |
| Boiling point                   | bp                       | Engine                     | eng               |
| Brinell hardness number         | Bhn                      | Engineer                   | engr              |
| British thermal unit            | Btu or B                 | Engineering                | enrg              |
| Bushel                          | bu                       | Equation                   | eq                |
| Calorie                         | cal                      | External                   | ext               |
| Candle                          | cd                       | Fluid                      | fl                |
| Center to center                | c to c                   | Foot                       | ft                |
| Centimeter                      | cm                       | Foot-candle                | fc                |
| Centimeter-gram-second (system) | cgs                      | Foot-Lambert               | fL or fl          |
| Chemical                        | chem                     | Foot per minute            | fpm               |
| Chemically pure                 | cp                       | Foot per second            | fps               |
| Circular                        | circ                     | Foot-pound                 | ft lb             |
| Circular mil                    | cmil                     | Foot-pound-second (system) | fps               |
| Coefficient                     | coef                     | Free on board              | fob               |
| Cologarithm                     | colog                    | Freezing point             | fp                |
| Concentrate                     | conc                     | Frequency                  | freq              |
| Conductivity                    | condct                   | Fusion point               | fnpt              |
| Constant                        | const                    | Gallon                     | gal               |
| Cord                            | cd                       | Gallon per minute          | gpm               |
| Cosecant                        | csc                      | Gallon per second          | gps               |
| Cosine                          | cos                      | Grain                      | gr                |
| Cost, insurance, and freight    | cif                      | Gram                       | g                 |
| Cotangent                       | ctn                      | Greatest common divisor    | gcd               |
| Counter electromotive force     | cemf                     | High pressure              | hp                |
| Cubic                           | cu                       | Horsepower                 | hp                |
| Cubic centimeter                | cm <sup>3</sup> or cc    | Horsepower-hour            | hp hr             |
| Cubic foot                      | ft <sup>3</sup> or cu ft | Hour                       | h or hr           |
| Cubic feet per second           | ft <sup>3</sup> or cfs   | Hyperbolic cosine          | cosh              |
| Cubic inch                      | in <sup>3</sup> or cu in | Hyperbolic sine            | sinh              |
| Cubic meter                     | m <sup>3</sup> or cu m   | Hyperbolic tangent         | tanh              |
| Cubic millimeter                | mm <sup>3</sup> or cumm  | Inch                       | in                |
| Cubic yard                      | yd <sup>3</sup> or cu yd | Inch per second            | in/s or ips       |
| Current density                 | cd                       | Inch-pound                 | in lb             |
| Cylinder                        | cyl                      |                            |                   |

## ANSI Abbreviations for Scientific and Engineering Terms (Continued)

ANSI Y1.1-1972, (R 1984)

|                           |               |                             |                               |
|---------------------------|---------------|-----------------------------|-------------------------------|
| Indicated horsepower-hour | iph           | Pound-force foot            | lb <sub>f</sub> · ft or lb ft |
| Intermediate pressure     | ip            | Pound-force inch            | lb <sub>f</sub> · in or lb in |
| Internal                  | intl          | pound-force per square foot | lb/ft <sup>2</sup> or psf     |
| Kilovolt-ampere/hour      | KVA-h or kVAh | pound-force per square inch | lb/in <sup>2</sup> or psi     |
| Kilowatt-hour meter       | kwhm          | pound per horsepower        | lb/hp or hp                   |
| Latitude                  | lat           | Power factor                | pf                            |
| Least common multiple     | lcm           | Quart                       | qt                            |
| Liquid                    | liq           | Reactive volt-ampere meter  | rva                           |
| Logarithm (common)        | log           | Revolution per minute       | r/min or rpm                  |
| Logarithm (natural)       | ln            | Revolution per second       | r/s or rps                    |
| Low pressure              | lp            | Root mean square            | rms                           |
| Lumen per watt            | lm/W or lpw   | Round                       | rnd                           |
| Magnetomotive force       | mmf           | Secant                      | sec                           |
| Mathematics (ical)        | math          | Second                      | s or sec                      |
| Maximum                   | max           | Sine                        | sin                           |
| Mean effective pressure   | mep           | Specific gravity            | sp gr                         |
| Melting point             | mp            | Specific heat               | sp ht                         |
| Meter                     | m             | Square                      | sq                            |
| Meter-kilogram-second     | mks           | Square centimeter           | cm <sup>2</sup> or sq cm      |
| Microfarad                | μF            | Square foot                 | ft <sup>2</sup> or sq ft      |
| Mile                      | mi            | Square inch                 | in <sup>2</sup> or sq in      |
| Mile per hour             | mi/h or mph   | Square kilometer            | km <sup>2</sup> or sq km      |
| Milliampere               | m/A           | Square root of mean square  | rms                           |
| Minimum                   | min           | Standard                    | std                           |
| Molecular weight          | mol wt        | Tangent                     | tan                           |
| Molecule                  | mo            | Temperature                 | temp                          |
| National Electrical Code  | NEC           | Tensile strength            | ts                            |
| Ounce                     | oz            | Versed sine                 | vers                          |
| Ounce-inch                | oz in         | Volt                        | V                             |
| Pennyweight               | dwt           | Watt                        | W                             |
| Pint                      | pt            | Watt-hour                   | Wh                            |
| Potential                 | pot           | Week                        | wk                            |
| Potential difference      | pd            | Weight                      | wt                            |
| Pound                     | lb            | Yard                        | yd                            |

Alternative abbreviations conforming to the practice of the International Electrotechnical Commission.

|             |    |                 |     |             |    |              |    |
|-------------|----|-----------------|-----|-------------|----|--------------|----|
| Ampere      | A  | Kilovolt-ampere | kVA | Microfarad  | μF | Milliampere  | mA |
| Ampere-hour | Ah | Kilowatt        | kW  | Microwatt   | μW | Volt         | V  |
| Coulomb     | C  |                 |     | Milliampere | mA | Volt-ampere  | VA |
| Farad       | F  | Kilowatthour    | kWh | Millifarad  | mF | Volt-coulomb | VC |
| Henry       | H  | Megawatt        | MW  | Millihenry  | mH | Watt         | W  |
| Joule       | J  | Megohm          | MΩ  | Millivolt   | mV | Watt-hour    | Wh |
| Kilovolt    | kV | Microampere     | μA  | Ohm         | Ω  | Volt         | VA |

Only the most commonly used terms have been included. These forms are recommended for those whose familiarity with the terms used makes possible a maximum of abbreviations. For others, less contracted combinations made up from this list may be used. For example, the list gives the abbreviation of the term "feet per second" as "fps." To some, however, ft per sec will be more easily understood.

Abbreviations should be used sparingly and only where their meaning will be clear. If there is any doubt, then spell out the term or unit of measurement.

The following points are good practice when preparing engineering documentation. Terms denoting units of measurement should be abbreviated in text only when preceded by the amounts indicated in numerals: "several inches," "one inch," "12 in." A sentence should not begin with a numeral followed by an abbreviation. The use of conventional signs for abbreviations in text should be avoided: use "lb," not "#" or "in," not ".

Symbols for the chemical elements are listed in the table on page 398.

Mathematical Signs and Commonly Used Abbreviations

|                      |                                      |                        |   |
|----------------------|--------------------------------------|------------------------|---|
| +                    | Plus (sign of addition)              | $\pi$                  | Pi (3.1416)   |
| +                    | Positive                             | $\Sigma$               | Sigma (sign of summation)   |
| -                    | Minus (sign of subtraction)          | $\omega$               | Omega (angles measured in radians)  |
| -                    | Negative                             | $g$                    | Acceleration due to gravity (32.16 ft/s <sup>2</sup> or 9.81 m/s <sup>2</sup> ) |
| $\pm$ ( $\mp$ )      | Plus or minus (minus or plus)        | $i$ (or $j$ )          | Imaginary quantity ( $\sqrt{-1}$ )  |
| $\times$             | Multiplied by (multiplication sign)  | sin                    | Sine  |
| $\cdot$              | Multiplied by (multiplication sign)  | cos                    | Cosine  |
| $\div$               | Divided by (division sign)           | tan                    | Tangent   |
| /                    | Divided by (division sign)           | cot                    | Cotangent   |
| :                    | Is to (in proportion)                | sec                    | Secant  |
| =                    | Equals                               | csc                    | Cosecant  |
| $\neq$               | Is not equal to                      | vers                   | Versed sine   |
| $\equiv$             | Is identical to                      | covers                 | Covered sine  |
| $\cong$ or $\approx$ | Approximately equals                 | $\sin^{-1} a$          | Arc the sine of which is $a$  |
| >                    | Greater than                         | arcsin $a$ or asin $a$ |   |
| <                    | Less than                            | $(\sin a)^{-1}$        | Reciprocal of sin $a$ ( $1 \div \sin a$ )                                       |
| $\geq$               | Greater than or equal to             | $\sin^n x$             | $n$ th power of sin $x$   |
| $\leq$               | Less than or equal to                | sinh $x$               | Hyperbolic sine of $x$  |
| $\rightarrow$        | Approaches as a limit                | cosh $x$               | Hyperbolic cosine of $x$  |
| $\propto$            | Varies directly as                   | $\Delta$               | Delta (increment of)  |
| $\therefore$         | Therefore                            | $\delta$               | Delta (variation of)  |
| $::$                 | Equals (in proportion)               | $d$                    | Differential (in calculus)  |
| $\sqrt{\quad}$       | Square root                          | $\partial$             | Partial differentiation (in calculus)   |
| $\sqrt[3]{\quad}$    | Cube root                            | $\int$                 | Integral (in calculus)  |
| $\sqrt[4]{\quad}$    | 4th root                             | $\int_a^b$             | Integral between the limits $a$ and $b$   |
| $\sqrt[n]{\quad}$    | $n$ th root                          | !                      | $5! = 1 \times 2 \times 3 \times 4 \times 5$ (Factorial)                        |
| $a^2$                | $a$ squared (2nd power of $a$ )      | $\sphericalangle$      | Angle   |
| $a^3$                | $a$ cubed (3rd power of $a$ )        | $\perp$                | Right angle   |
| $a^4$                | 4th power of $a$                     | $\perp$                | Perpendicular to  |
| $a^n$                | $n$ th power of $a$                  | $\triangle$            | Triangle  |
| $a^{-n}$             | $1 \div a^n$                         | $\bigcirc$             | Circle  |
| $\frac{1}{n}$        | Reciprocal value of $n$              | $\square$              | Parallelogram   |
| log                  | Logarithm                            | $^\circ$               | Degree (circular arc or temperature)  |
| $\log_e$             | Natural or Napierian logarithm       | '                      | Minutes or feet   |
| ln                   | Natural or Napierian logarithm       | "                      | Seconds or inches   |
| $e$                  | Base of natural logarithms (2.71828) | $a'$                   | $a$ prime   |
| lim                  | Limit value (of an expression)       | $a''$                  | $a$ double prime  |
| $\infty$             | Infinity                             | $a_1$                  | $a$ sub one   |
| $\alpha$             | Alpha                                | $a_2$                  | $a$ sub two   |
| $\beta$              | Beta                                 | $a_n$                  | $a$ sub $n$   |
| $\gamma$             | Gamma                                | ( )                    | Parentheses   |
| $\theta$             | Theta                                | [ ]                    | Brackets  |
| $\phi$               | Phi                                  | { }                    | Braces  |
| $\mu$                | Mu (coefficient of friction)         | $K$                    | Absolute value of $K$ , size of $K$ irrespective of sign                        |

commonly used to denote angles

**Letter Symbols for Mechanics and Time-Related Phenomena**  
ANSI/ASME Y10.3M-1984

|  |                                  |  |                             |
|--|----------------------------------|--|-----------------------------|
| Acceleration, angular                            | $\alpha$ (alpha)                 | Height   | $h$                         |
| Acceleration, due to gravity                     | $g$                              | Inertia, moment of   | $I$ or $J$                  |
| Acceleration, linear                             | $a$                              | Inertia, polar (area) moment of <sup>a</sup>               | $J$                         |
| Amplitude <sup>a</sup>                           | $A$                              | Inertia, product (area) moment of <sup>a</sup>             | $I_{xy}$                    |
|  |                                  | Length   | $L$ or $l$                  |
|  | $\alpha$ (alpha)                 | Load per unit distance <sup>a</sup>                        | $q$ or $w$                  |
|  | $\beta$ (beta)                   | Load, total <sup>a</sup>                                   | $P$ or $W$                  |
| Angle  | $\gamma$ (gamma)                 | Mass   | $m$                         |
|  | $\theta$ (theta)                 | Moment of force, including bending moment                  | $M$                         |
|  | $\phi$ (phi)                     | Neutral axis, distance to extreme fiber from <sup>a</sup>  | $c$                         |
|  | $\psi$ (psi)                     | Period   | $T$                         |
| Angle, solid                                     | $\Omega$ (omega)                 | Poisson's ratio  | $\mu$ (mu) or $\nu$ (nu)    |
| Angular frequency                                | $\omega$ (omega)                 | Power  | $P$                         |
| Angular momentum                                 | $L$                              | Pressure, normal force per unit area                       | $p$                         |
| Angular velocity                                 | $\omega$ (omega)                 | Radius   | $r$                         |
| Arc length                                       | $s$                              | Revolutions per unit of time                               | $n$                         |
| Area   | $A$                              | Second moment of area (second axial moment of area)        | $I_a$                       |
| Axes, through any point <sup>a</sup>             | $X-X, Y-Y, \text{ or } Z-Z$      | Second polar moment of area                                | $I_p$ or $J$                |
| Bulk modulus                                     | $K$                              | Section modulus  | $Z$                         |
| Breadth (width)                                  | $b$                              | Shear force in beam section <sup>a</sup>                   | $V$                         |
| Coefficient of expansion, linear <sup>a</sup>    | $\alpha$ (alpha)                 | Spring constant (load per unit deflection) <sup>a</sup>    | $k$                         |
| Coefficient of friction                          | $\mu$ (mu)                       | Statcal moment of any area about a given axis <sup>a</sup> | $Q$                         |
| Concentrated load (same as force)                | $F$                              | Strain, normal   | $\epsilon$ (epsilon)        |
| Deflection of beam, max <sup>a</sup>             | $\delta$ (delta)                 | Strain, shear  | $\gamma$ (gamma)            |
| Density  | $\rho$ (rho)                     | Stress, concentration factor <sup>a</sup>                  | $K$                         |
| Depth  | $d, \delta$ (delta), or $t$      | Stress, normal   | $\sigma$ (sigma)            |
| Diameter   | $D$ or $d$                       | Stress, shear  | $\tau$ (tau)                |
| Displacement <sup>a</sup>                        | $u, v, w$                        | Temperature, absolute <sup>b</sup>                         | $T$ , or $\theta$ (theta)   |
| Distance, linear <sup>a</sup>                    | $s$                              | Temperature <sup>b</sup>                                   | $t$ , or $\theta$ (theta)   |
| Eccentricity of application of load <sup>a</sup> | $e$                              | Thickness  | $d, \delta$ (delta), or $t$ |
| Efficiency <sup>a</sup>                          | $\eta$ (eta)                     | Time   | $t$                         |
| Elasticity, modulus of                           | $E$                              | Torque   | $T$                         |
| Elasticity, modulus of, in shear                 | $G$                              | Velocity, linear   | $v$                         |
| Elongation, total <sup>a</sup>                   | $\delta$ (delta)                 | Volume   | $V$                         |
| Energy, kinetic                                  | $E_k, K, T$                      | Wavelength   | $\lambda$ (lambda)          |
| Energy, potential                                | $E_p, V, \text{ or } \Phi$ (phi) | Weight   | $W$                         |
| Factor of safety <sup>a</sup>                    | $N, \text{ or } n$               | Weight per unit volume                                     | $\gamma$ (gamma)            |
| Force or load, concentrated                      | $F$                              | Work   | $W$                         |
| Frequency  | $f$                              |  |                             |
| Gyration, radius of <sup>a</sup>                 | $k$                              |  |                             |

<sup>a</sup> Not specified in Standard<sup>b</sup> Specified in ANSI Y10.4-1982 (R1988)

## MEASURING UNITS

## Metric Systems Of Measurement

A metric system of measurement was first established in France in the years following the French Revolution, and various systems of metric units have been developed since that time. All metric unit systems are based, at least in part, on the International Metric Standards, which are the meter and kilogram, or decimal multiples or submultiples of these standards.

In 1795, a metric system called the centimeter-gram-second (cgs) system was proposed, and was adopted in France in 1799. In 1873, the British Association for the Advancement of Science recommended the use of the cgs system, and since then it has been widely used in all branches of science throughout the world. From the base units in the cgs system are derived the following:

*Unit of velocity* = 1 centimeter per second

*Acceleration due to gravity (at Paris)* = 981 centimeters per second per second

*Unit of force* = 1 dyne =  $\frac{1}{981}$  gram

*Unit of work* = 1 erg = 1 dyne-centimeter

*Unit of power* = 1 watt = 10,000,000 ergs per second

Another metric system called the MKS (meter-kilogram-second) system of units was proposed by Professor G. Giorgi in 1902. In 1935, the International Electro-technical Commission (IEC) accepted his recommendation that this system of units of mechanics should be linked with the electromagnetic units by the adoption of a fourth base unit. In 1950, the IEC adopted the ampere, the unit of electric current, as the fourth unit, and the MKSA system thus came into being.

A gravitational system of metric units, known as the technical system, is based on the meter, the kilogram as a force, and the second. It has been widely used in engineering. Because the standard of force is defined as the weight of the mass of the standard kilogram, the fundamental unit of force varies due to the difference in gravitational pull at different locations around the earth. By international agreement, a standard value for acceleration due to gravity was chosen (9.81 meters per second squared) that for all practical measurements is approximately the same as the local value at the point of measurement.

**The International System of Units (SI).**—The Conference Generale des Poids et Mesures (CGPM), which is the body responsible for all international matters concerning the metric system, adopted in 1954, a rationalized and coherent system of units, based on the four MKSA units (see above), and including the *kelvin* as the unit of temperature and the *candela* as the unit of luminous intensity. In 1960, the CGPM formally named this system the *Système International d'Unites*, for which the abbreviation is SI in all languages. In 1971, the 14th CGPM adopted a seventh base unit, the *mole*, which is the unit of quantity ("amount of substance").

In the period since the first metric system was established in France toward the end of the 18th century, most of the countries of the world have adopted a metric system. At the present time, most of the industrially advanced metric-using countries are changing from their traditional metric system to SI. Those countries that are currently changing or considering change from the English system of measurement to metric have the advantage that they can convert directly to the modernized system. The United Kingdom, which can be said to have led the now worldwide move to change from the English system, went straight to SI.

The use of SI units instead of the traditional metric units has little effect on everyday life or trade. The units of linear measurement, mass, volume, and time remain the same, viz. meter, kilogram, liter, and second.

The SI, like the traditional metric system, is based on decimal arithmetic. For each physical quantity, units of different sizes are formed by multiplying or dividing a single base value by powers of 10. Thus, changes can be made very simply by adding zeros or shifting decimal points. For example, the meter is the basic unit of length; the kilometer is a multiple (1000 meters); and the millimeter is a sub-multiple (one-thousandth of a meter).

In the older metric systems, the simplicity of a series of units linked by powers of ten is an advantage for plain quantities such as length, but this simplicity is lost as soon as more complex units are encountered. For example, in different branches of science and engineering, energy may appear as the erg, the calorie, the kilogram-meter, the liter-atmosphere, or the horsepower-hour. In contrast, the SI provides only one basic unit for each physical quantity, and universality is thus achieved.

As mentioned before, there are seven base units, which are for the basic quantities of length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity, expressed as the meter (m), the kilogram (kg), the second (s), the ampere (A), the kelvin (K), the mole (mol), and the candela (cd). The units are defined in the accompanying [Table 1](#).

The SI is a coherent system. A system is said to be coherent if the product or quotient of any two unit quantities in the system is the unit of the resultant quantity. For example, in a coherent system in which the foot is the unit of length, the square foot is the unit of area, whereas the acre is not.

Other physical quantities are derived from the base units. For example, the unit of velocity is the meter per second (m/s), which is a combination of the base units of length and time. The unit of acceleration is the meter per second squared ( $\text{m/s}^2$ ). By applying Newton's second law of motion—force is proportional to mass multiplied by acceleration—the unit of force is obtained that is the kilogram-meter per second squared ( $\text{kg}\cdot\text{m/s}^2$ ). This unit is known as the newton, or N. Work, or force times distance is the kilogram-meter squared per second squared ( $\text{kg}\cdot\text{m}^2/\text{s}^2$ ), which is the joule (1 joule = 1 newton-meter), and energy is also expressed in these terms. The abbreviation for joule is J. Power or work per unit time is the kilogram-meter squared per second cubed ( $\text{kg}\cdot\text{m}^2/\text{s}^3$ ), which is the watt (1 watt = 1 joule per second = 1 newton-meter per second). The abbreviation for watt is W. The term horsepower is not used in the SI and is replaced by the watt, which together with multiples and submultiples—kilowatt and milliwatt, for example—is the same unit as that used in electrical work.

The use of the newton as the unit of force is of particular interest to engineers. In practical work using the English or traditional metric systems of measurements, it is a common practice to apply weight units as force units. Thus, the unit of force in those systems is that force that when applied to unit mass produces an acceleration  $g$  rather than unit acceleration. The value of gravitational acceleration  $g$  varies around the earth, and thus the weight of a given mass also varies. In an effort to account for this minor error, the kilogram-force and pound-force were introduced, which are defined as the forces due to “standard gravity” acting on bodies of one kilogram or one pound mass, respectively. The standard gravitational acceleration is taken as 9.80665 meters per second squared or 32.174 feet per second squared. The newton is defined as “that force, which when applied to a body having a mass of one kilogram, gives it an acceleration of one meter per second squared.” It is independent of  $g$ . As a result, the factor  $g$  disappears from a wide range of formulas in dynamics. However, in some formulas in statics, where the weight of a body is important rather than its mass,  $g$  does appear where it was formerly absent (the weight of a mass of  $W$  kilograms is equal to a force of  $Wg$  newtons, where  $g$  = approximately 9.81 meters per second squared). Details concerning the use of SI units in mechanics calculations are given on [page 142](#) and throughout the Mechanics section in this Handbook. The use of SI units in strength of materials calculations is covered in the section on that subject.

Decimal multiples and sub-multiples of the SI units are formed by means of the prefixes given in the following table, which represent the numerical factors shown.

### Factors and Prefixes for Forming Decimal Multiples of SI Units

| Factor by which the unit is multiplied | Prefix | Symbol | Factor by which the unit is multiplied | Prefix | Symbol |
|--|--------|--------|--|--------|--------|
| $10^{12}$                              | tera   | T      | $10^{-2}$                              | centi  | c      |
| $10^9$                                 | giga   | G      | $10^{-3}$                              | milli  | m      |
| $10^6$                                 | mega   | M      | $10^{-6}$                              | micro  | $\mu$  |
| $10^3$                                 | kilo   | k      | $10^{-9}$                              | nano   | n      |
| $10^2$                                 | hecto  | h      | $10^{-12}$                             | pico   | p      |
| 10                                     | deka   | da     | $10^{-15}$                             | femto  | f      |
| $10^{-1}$                              | deci   | d      | $10^{-18}$                             | atto   | a      |

For more information on SI practice, the reader is referred to the following publications: *Metric Practice Guide*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, PA 19103.

*ISO International Standard 1000*. This publication covers the rules for use of SI units, their multiples and sub-multiples. It can be obtained from the American National Standards Institute 11 West 42nd Street, New York, NY 10036.

*The International System of Units*, Special Publication 330 of the National Bureau of Standards—available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

**Binary Multiples.**—The International Electrotechnical Commission has assigned the following prefixes to represent exponential binary multiples. This avoids confusion with standard SI decimal prefixes when representing powers of 2, as in bits and bytes.

| Symbol | Name | Binary Power | Symbol | Name | Binary Power | Symbol | Name | Binary Power |
|--------|------|--------------|--------|------|--------------|--------|------|--------------|
| Ki     | kibi | $2^{10}$     | Gi     | gibi | $2^{30}$     | Pi     | pebi | $2^{50}$     |
| Mi     | mebi | $2^{20}$     | Ti     | tebi | $2^{40}$     | Ei     | exbi | $2^{60}$     |

*Example 1:*  $2 \text{ Ki} = 2 \times 2^{10} = 2 \times 1,024 = 2,048$ . This does *not* equal  $2 \text{ K} = 2 \times 10^3 = 2,000$ .

*Example 2:*  $1 \text{ mebibyte} = 1 \times 2^{20} = 1,048,576$  bytes. Again this does *not* equal  $1 \text{ megabyte} = 1 \times 10^6 = 1,000,000$  bytes, a value that is often confused with 1,048,576 bytes.

**Table 1. International System (SI) Units**

| Physical Quantity         | Name of Unit  | Unit Symbol | Definition   |
|---------------------------|---------------|-------------|--|
| <b>Basic SI Units</b>     |               |             |  |
| Length                    | meter         | m           | Distance traveled by light in vacuo during $1/299,792,458$ of a second.  |
| Mass                      | kilogram      | kg          | Mass of the international prototype which is in the custody of the Bureau International des Poids et Mesures (BIPM) at Sèvres, near Paris.   |
| Time                      | second        | s           | The duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.  |
| Electric Current          | ampere        | A           | The constant current which, if maintained in two parallel rectilinear conductors of infinite length, of negligible circular cross section, and placed at a distance of one meter apart in a vacuum, would produce between these conductors a force equal to $2 \times 10^{-7}$ N/m length. |
| Thermodynamic Temperature | degree kelvin | K           | The fraction $1/273.16$ of the thermodynamic temperature of the triple point of water.   |
| Amount of Substance       | mole          | mol         | The amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.  |
| Luminous Intensity        | candela       | cd          | Luminous intensity, in the perpendicular direction, of a surface of $1/600,000$ square meter of a black body at the temperature of freezing platinum under a pressure of 101,325 newtons per square meter.   |

**Table 1. (Continued) International System (SI) Units**

| Physical Quantity                    | Name of Unit | Unit Symbol                             | Definition  |
|--------------------------------------|--------------|---|---|
| <b>SI Units Having Special Names</b> |              |   |   |
| Force                                | newton       | $N = \text{kg}\cdot\text{m}/\text{s}^2$ | That force which, when applied to a body having a mass of one kilogram, gives it an acceleration of one meter per second squared.   |
| Work, Energy, Quantity of Heat       | joule        | $J = N\cdot\text{m}$                    | The work done when the point of application of a force of one newton is displaced through a distance of one meter in the direction of the force.  |
| Electric Charge                      | coulomb      | $C = A\cdot\text{s}$                    | The quantity of electricity transported in one second by a current of one ampere.   |
| Electric Potential                   | volt         | $V = W/A$                               | The difference of potential between two points of a conducting wire carrying a constant current of one ampere, when the power dissipated between these points is equal to one watt.   |
| Electric Capacitance                 | farad        | $F = C/V$                               | The capacitance of a capacitor between the plates of which there appears a difference of potential of one volt when it is charged by a quantity of electricity equal to one coulomb.  |
| Electric Resistance                  | ohm          | $\Omega = V/A$                          | The resistance between two points of a conductor when a constant difference of potential of one volt, applied between these two points, produces in this conductor a current of one ampere, this conductor not being the source of any electromotive force. |
| Magnetic Flux                        | weber        | $\text{Wb} = V\cdot\text{s}$            | The flux which, linking a circuit of one turn produces in it an electromotive force of one volt as it is reduced to zero at a uniform rate in one second.   |
| Inductance                           | henry        | $H = V\cdot\text{s}/A$                  | The inductance of a closed circuit in which an electromotive force of one volt is produced when the electric current in the circuit varies uniformly at the rate of one ampere per second.  |
| Luminous Flux                        | lumen        | $1\text{m} = \text{cd}\cdot\text{sr}$   | The flux emitted within a unit solid angle of one steradian by a point source having a uniform intensity of one candela.  |
| Illumination                         | lux          | $1\text{x} = 1\text{m}/\text{m}^2$      | An illumination of one lumen per square meter.  |

**Table 2. International System (SI) Units with Complex Names**

| Physical Quantity                    | SI Unit                         | Unit Symbol                              |
|--------------------------------------|---------------------------------|--|
| <b>SI Units Having Complex Names</b> |                                 |  |
| Area                                 | square meter                    | $\text{m}^2$                             |
| Volume                               | cubic meter                     | $\text{m}^3$                             |
| Frequency                            | hertz <sup>a</sup>              | Hz                                       |
| Density (Mass Density)               | kilogram per cubic meter        | $\text{kg}/\text{m}^3$                   |
| Velocity                             | meter per second                | $\text{m}/\text{s}$                      |
| Angular Velocity                     | radian per second               | $\text{rad}/\text{s}$                    |
| Acceleration                         | meter per second squared        | $\text{m}/\text{s}^2$                    |
| Angular Acceleration                 | radian per second squared       | $\text{rad}/\text{s}^2$                  |
| Pressure                             | pascal <sup>b</sup>             | Pa                                       |
| Surface Tension                      | newton per meter                | $\text{N}/\text{m}$                      |
| Dynamic Viscosity                    | newton second per meter squared | $\text{N}\cdot\text{s}/\text{m}^2$       |
| Kinematic Viscosity                  | } meter squared per second      | $\text{m}^2/\text{s}$                    |
| Diffusion Coefficient                |                                 |  |
| Thermal Conductivity                 | watt per meter degree Kelvin    | $\text{W}/(\text{m}\cdot^\circ\text{K})$ |
| Electric Field Strength              | volt per meter                  | $\text{V}/\text{m}$                      |
| Magnetic Flux Density                | tesla <sup>c</sup>              | T  |
| Magnetic Field Strength              | ampere per meter                | $\text{A}/\text{m}$                      |
| Luminance                            | candela per square meter        | $\text{cd}/\text{m}^2$                   |

<sup>a</sup> Hz = cycle/second<sup>b</sup> Pa = newton/meter<sup>2</sup><sup>c</sup> T = weber/meter<sup>2</sup>



**Standard of Length.**—In 1866 the United States, by act of Congress, passed a law making legal the meter, the only measure of length that has been legalized by the United States Government. The United States yard is defined by the relation: 1 yard =  $\frac{3600}{9937}$  meter. The legal equivalent of the meter for commercial purposes was fixed as 39.37 inches, by law, in July, 1866, and experience having shown that this value was exact within the error of observation, the United States Office of Standard Weights and Measures was, in 1893, authorized to derive the yard from the meter by the use of this relation. The United States prototype meters Nos. 27 and 21 were received from the International Bureau of Weights and Measures in 1889. Meter No. 27, sealed in its metal case, is preserved in a fireproof vault at the Bureau of Standards.

Comparisons made prior to 1893 indicated that the relation of the yard to the meter, fixed by the Act of 1866, was by chance the exact relation between the international meter and the British imperial yard, within the error of observation. A subsequent comparison made between the standards just mentioned indicates that the legal relation adopted by Congress is in error 0.0001 inch; but, in view of the fact that certain comparisons made by the English Standards Office between the imperial yard and its authentic copies show variations as great if not greater than this, it cannot be said with certainty that there is a difference between the imperial yard of Great Britain and the United States yard derived from the meter. The bronze yard No. 11, which was an exact copy of the British imperial yard both in form and material, had shown changes when compared with the imperial yard in 1876 and 1888, which could not reasonably be said to be entirely due to changes in Bronze No. 11. On the other hand, the new meters represented the most advanced ideas of standards, and it therefore seemed that greater stability as well as higher accuracy would be secured by accepting the international meter as a fundamental standard of length.

### U.S. Customary Unit System

The USCS is originated from the foot-pound-second unit system or English unit system. The USCS system and English unit system are same for the measures of length and mass, but it varies for the measure of capacity. The U.S. gallon is defined as 231 cubic inches and bushel as 2,150.42 cubic inches where as the corresponding English units are 277.42 cubic inches and 2,219.36 cubic inches.

### Fundamental Constants

| Name                      | Symbol | USCS units   | SI units   |
|---------------------------|--------|--|--|
| Avogadro's number         | $N_A$  |  | $6.022 \times 10^{23} \text{ mol}^{-1}$                      |
| Boltzman constant         | $k$    | $5.65 \times 10^{-24} \text{ ft}\cdot\text{lb}_f/\text{R}$       | $1.38065 \times 10^{-23} \text{ J}/\text{K}$                 |
| Faraday Constant          | $F$    |  | 96487 C/mol  |
| Gravitational constant    | $g$    | $32.174 \text{ lb}_m\cdot\text{ft}/\text{lb}_f\cdot\text{sec}^2$ | $9.80667 \text{ m}/\text{sec}^2$                             |
| Gravitational constant    | $G$    | $5.65 \times 10^{-24} \text{ ft}\cdot\text{lb}_f/\text{R}$       | $6.672 \times 10^{-11} \text{ N}\cdot\text{m}^2/\text{kg}^2$ |
| Specific gas constant     | $R$    | $53.3 \text{ ft}\cdot\text{lb}_f/\text{lb}_m\cdot\text{R}$       | $287 \text{ J}/\text{kg}\cdot\text{K}$                       |
| Universal gas constant    | $R$    | $1545 \text{ ft}\cdot\text{lb}_f/\text{lbmol}\cdot\text{R}$      | $8314 \text{ J}/\text{kmol}\cdot\text{K}$                    |
| Volume (molal ideal gas)  | $V$    | $359 \text{ ft}^3/\text{lbmol}$                                  | $22.41 \text{ m}^3/\text{kmol}$                              |
| Pressure, atmospheric     | $P$    | $14.696 \text{ lb}_f/\text{in}^2$                                | $101330 \text{ Pa (n/m}^2)$                                  |
| Temperature, standard     | $T$    | $32^\circ\text{F}$   | $0^\circ\text{C}$  |
| Density                   |        |  |  |
| Air at 32°F (0°C)         |        | $0.0805 \text{ lb}_m/\text{ft}^3$                                | $1.29 \text{ kg}/\text{m}^3$                                 |
| Air at 70°F (20°C), 1 atm |        | $0.0749 \text{ lb}_m/\text{ft}^3$                                | $1.20 \text{ kg}/\text{m}^3$                                 |
| Sea water                 |        | $64 \text{ lb}_m/\text{ft}^3$                                    | $1025 \text{ kg}/\text{m}^3$                                 |
| Fresh water               |        | $62.4 \text{ lb}_m/\text{ft}^3$                                  | $1000 \text{ kg}/\text{m}^3$                                 |
| Mercury                   |        | $849 \text{ lb}_m/\text{ft}^3$                                   | $13600 \text{ kg}/\text{m}^3$                                |
| Earth                     |        | $345 \text{ lb}_m/\text{ft}^3$                                   | $5520 \text{ kg}/\text{m}^3$                                 |

## U.S. SYSTEM AND METRIC SYSTEM CONVERSIONS

## Units of Length

Table 1. Linear Measure Conversion Factors

| Metric  | US Customary  |
|---|---|
| <i>1 kilometer (km) =</i><br><b>1000</b> meters<br><b>100,000</b> centimeters<br><b>1,000,000</b> millimeters<br>0.539956 nautical mile<br>0.621371 mile<br>1093.61 yards<br>3280.83 feet<br>39,370.08 inches | <i>1 mile (mi) =</i><br>0.868976 nautical mile<br><b>1760</b> yards<br><b>5280</b> feet<br><b>63,360</b> inches<br><b>1.609344</b> kilometers<br><b>1609.344</b> meters<br><b>160,934.4</b> centimeters<br><b>1,609,344</b> millimeters |
| <i>1 meter (m) =</i><br><b>10</b> decimeters<br><b>100</b> centimeters<br><b>1000</b> millimeters<br>1.09361 yards<br>3.28084 feet<br>39.37008 inches   | <i>1 yard (yd) =</i><br><b>3</b> feet<br><b>36</b> inches<br><b>0.9144</b> meter<br><b>91.44</b> centimeter<br><b>914.4</b> millimeter  |
| <i>1 decimeter (dm) = 10</i> centimeters  | <i>1 foot (international) (ft) =</i><br><b>12</b> inches = $\frac{1}{3}$ yard<br><b>0.3048</b> meter<br><b>30.48</b> centimeter<br><b>304.8</b> millimeters   |
| <i>1 centimeter (cm) =</i><br><b>0.01</b> meter<br><b>10</b> millimeters<br>0.0328 foot<br>0.3937 inch  | <i>1 survey foot =</i><br>1.000002 international feet<br>$\frac{12}{39.37} = 0.3048006096012$ meter   |
| <i>1 millimeter (mm) =</i><br><b>0.001</b> meter<br><b>0.1</b> centimeter<br><b>1000</b> micron<br>0.03937 inch   | <i>1 inch (in) =</i><br><b>1000</b> mils<br><b>1,000,000</b> micro-inch<br><b>2.54</b> centimeters<br><b>25.4</b> millimeters<br><b>25,400</b> microns  |
| <i>1 micrometer or micron (<math>\mu\text{m}</math>) =</i><br><b>0.000001</b> meter = one millionth meter<br><b>0.0001</b> centimeter<br><b>0.001</b> millimeter<br>0.00003937 inch<br>39.37 micro-inches     | <i>1 mil =</i><br><b>0.001</b> inch<br><b>1000</b> micro-inches<br><b>0.0254</b> millimeters  |
|   | <i>1 micro-inch (<math>\mu\text{in}</math>) =</i><br><b>0.000001</b> inch = one millionth inch<br><b>0.0254</b> micrometer (micron)   |

Note: Figures in **Bold** indicate exact conversion values

| Surveyors Measure   | Nautical Measure  |
|---|---|
| <i>1 mile = 8</i> furlongs = <b>80</b> chains   | <i>1 league = 3</i> nautical miles  |
| <i>1 furlong = 10</i> chains = <b>220</b> yards   | <i>1 nautical mile =</i><br>1.1508 statute miles<br><b>6076.11549</b> feet<br>1.8516 kilometers                                     |
| <i>1 chain =</i><br><b>4</b> rods = <b>22</b> yards = <b>66</b> feet = <b>100</b> links | <i>1 fathom = 2</i> yards = <b>6</b> feet   |
| <i>1 rod =</i><br><b>5.5</b> yards = <b>16.5</b> feet = <b>25</b> links<br>5.0292 meter | <i>1 knot =</i> nautical unit of speed =<br>1 nautical mile per hour<br>1.1508 statute miles per hour<br>1.8516 kilometers per hour |
| <i>1 link = 7.92</i> inches   |   |
| <i>1 span = 9</i> inches  |   |
| <i>1 hand = 4</i> inches  |   |

**Table 1. (Continued) Linear Measure Conversion Factors**

|  |  |
|--|--|
| One degree at the equator =<br>60 nautical miles<br>69,047 statute miles<br>111,098 kilometers | 360 degrees at the equator =<br>circumference at equator<br>21,600 nautical miles<br>24,856.8 statute miles<br>39,995.4 kilometers |
| One minute at the equator =<br>1 nautical mile<br>1.1508 statute miles<br>1.8516 kilometers    |  |

**Table 2. Circular and Angular Measure Conversion Factors**

|  |  |
|--|--|
| circumference of circle =<br>360 degrees = $2\pi$ radian = 6.283185 radian | 1 degree (°) = 60 minutes = 3600 seconds =<br>$\pi/180$ radian = 0.017453 radian |
| 1 quadrant = 90 degrees = $\pi/2$ radian =<br>1.570796 radian              | 1 minute (') = 60 seconds = 0.016667 degrees =<br>0.000291 radian                |
| 1 radian = 57.2957795 degrees  | $\pi = 3.141592654$  |

**Table 3. Feet and Inches to Inches Conversion**

| Inches → | 0      | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   |
|----------|--------|------|------|------|------|------|------|------|------|------|------|------|
| Feet ↓   | Inches |      |      |      |      |      |      |      |      |      |      |      |
| 0        | 0      | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   |
| 1        | 12     | 13   | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   |
| 2        | 24     | 25   | 26   | 27   | 28   | 29   | 30   | 31   | 32   | 33   | 34   | 35   |
| 3        | 36     | 37   | 38   | 39   | 40   | 41   | 42   | 43   | 44   | 45   | 46   | 47   |
| 4        | 48     | 49   | 50   | 51   | 52   | 53   | 54   | 55   | 56   | 57   | 58   | 59   |
| 5        | 60     | 61   | 62   | 63   | 64   | 65   | 66   | 67   | 68   | 69   | 70   | 71   |
| 6        | 72     | 73   | 74   | 75   | 76   | 77   | 78   | 79   | 80   | 81   | 82   | 83   |
| 7        | 84     | 85   | 86   | 87   | 88   | 89   | 90   | 91   | 92   | 93   | 94   | 95   |
| 8        | 96     | 97   | 98   | 99   | 100  | 101  | 102  | 103  | 104  | 105  | 106  | 107  |
| 9        | 108    | 109  | 110  | 111  | 112  | 113  | 114  | 115  | 116  | 117  | 118  | 119  |
| 10       | 120    | 121  | 122  | 123  | 124  | 125  | 126  | 127  | 128  | 129  | 130  | 131  |
| 20       | 240    | 241  | 242  | 243  | 244  | 245  | 246  | 247  | 248  | 249  | 250  | 251  |
| 30       | 360    | 361  | 362  | 363  | 364  | 365  | 366  | 367  | 368  | 369  | 370  | 371  |
| 40       | 480    | 481  | 482  | 483  | 484  | 485  | 486  | 487  | 488  | 489  | 490  | 491  |
| 50       | 600    | 601  | 602  | 603  | 604  | 605  | 606  | 607  | 608  | 609  | 610  | 611  |
| 60       | 720    | 721  | 722  | 723  | 724  | 725  | 726  | 727  | 728  | 729  | 730  | 731  |
| 70       | 840    | 841  | 842  | 843  | 844  | 845  | 846  | 847  | 848  | 849  | 850  | 851  |
| 80       | 960    | 961  | 962  | 963  | 964  | 965  | 966  | 967  | 968  | 969  | 970  | 971  |
| 90       | 1080   | 1081 | 1082 | 1083 | 1084 | 1085 | 1086 | 1087 | 1088 | 1089 | 1090 | 1091 |
| 100      | 1200   | 1201 | 1202 | 1203 | 1204 | 1205 | 1206 | 1207 | 1208 | 1209 | 1210 | 1211 |

*Example:* A tape measure reads 17 feet 8 inches. How many inches is this? *Solution:* Read down the first column of Table 3 to find 10 ft 0 in = 120 inches. Next, find the intersection of the 7 ft row and the 8 inch column to get 92 inches. Add both results to get 120 inches + 92 inches = 212 inches.

**Table 4. Inches to Feet and Yards Conversion**

| inch | feet    | yard    | inch | feet   | yard   | inch | feet   | yard   | inch | feet   | yard   | inch | feet   | yard   |
|------|---------|---------|------|--------|--------|------|--------|--------|------|--------|--------|------|--------|--------|
| 100  | 8.3333  | 2.7778  | 10   | 0.8333 | 0.2778 | 1    | 0.0833 | 0.0278 | 0.1  | 0.0083 | 0.0028 | 0.01 | 0.0008 | 0.0003 |
| 200  | 16.6667 | 5.5556  | 20   | 1.6667 | 0.5556 | 2    | 0.1667 | 0.0556 | 0.2  | 0.0167 | 0.0056 | 0.02 | 0.0017 | 0.0006 |
| 300  | 25      | 8.3333  | 30   | 2.5    | 0.8333 | 3    | 0.25   | 0.0833 | 0.3  | 0.025  | 0.0083 | 0.03 | 0.0025 | 0.0008 |
| 400  | 33.3333 | 11.1111 | 40   | 3.3333 | 1.1111 | 4    | 0.3333 | 0.1111 | 0.4  | 0.0333 | 0.0111 | 0.04 | 0.0033 | 0.0011 |
| 500  | 41.6667 | 13.8889 | 50   | 4.1667 | 1.3889 | 5    | 0.4167 | 0.1389 | 0.5  | 0.0417 | 0.0139 | 0.05 | 0.0042 | 0.0014 |
| 600  | 50      | 16.6667 | 60   | 5      | 1.6667 | 6    | 0.5    | 0.1667 | 0.6  | 0.05   | 0.0167 | 0.06 | 0.005  | 0.0017 |
| 700  | 58.3333 | 19.4444 | 70   | 5.8333 | 1.9444 | 7    | 0.5833 | 0.1944 | 0.7  | 0.0583 | 0.0194 | 0.07 | 0.0058 | 0.0019 |
| 800  | 66.6667 | 22.2222 | 80   | 6.6667 | 2.2222 | 8    | 0.6667 | 0.2222 | 0.8  | 0.0667 | 0.0222 | 0.08 | 0.0067 | 0.0022 |
| 900  | 75      | 25.0000 | 90   | 7.5    | 2.5000 | 9    | 0.75   | 0.2500 | 0.9  | 0.075  | 0.0250 | 0.09 | 0.0075 | 0.0025 |
| 1000 | 83.3333 | 27.7778 | 100  | 8.3333 | 2.7778 | 10   | 0.8333 | 0.2778 | 1    | 0.0833 | 0.0278 | 0.1  | 0.0083 | 0.0028 |

**Table 5. Fractional Inches to Decimal Feet for 0 to 1 Foot**

| Inches<br>↓ | Feet   |        |        |        |        |        |        |        |        |        |        |        |
|-------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|             | 0      | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      | 10     | 11     |
| 0           | 0.0000 | 0.0833 | 0.1667 | 0.2500 | 0.3333 | 0.4167 | 0.5000 | 0.5833 | 0.6667 | 0.7500 | 0.8333 | 0.9167 |
| 1/64        | 0.0013 | 0.0846 | 0.1680 | 0.2513 | 0.3346 | 0.4180 | 0.5013 | 0.5846 | 0.6680 | 0.7513 | 0.8346 | 0.9180 |
| 1/32        | 0.0026 | 0.0859 | 0.1693 | 0.2526 | 0.3359 | 0.4193 | 0.5026 | 0.5859 | 0.6693 | 0.7526 | 0.8359 | 0.9193 |
| 3/64        | 0.0039 | 0.0872 | 0.1706 | 0.2539 | 0.3372 | 0.4206 | 0.5039 | 0.5872 | 0.6706 | 0.7539 | 0.8372 | 0.9206 |
| 1/16        | 0.0052 | 0.0885 | 0.1719 | 0.2552 | 0.3385 | 0.4219 | 0.5052 | 0.5885 | 0.6719 | 0.7552 | 0.8385 | 0.9219 |
| 5/64        | 0.0065 | 0.0898 | 0.1732 | 0.2565 | 0.3398 | 0.4232 | 0.5065 | 0.5898 | 0.6732 | 0.7565 | 0.8398 | 0.9232 |
| 3/32        | 0.0078 | 0.0911 | 0.1745 | 0.2578 | 0.3411 | 0.4245 | 0.5078 | 0.5911 | 0.6745 | 0.7578 | 0.8411 | 0.9245 |
| 7/64        | 0.0091 | 0.0924 | 0.1758 | 0.2591 | 0.3424 | 0.4258 | 0.5091 | 0.5924 | 0.6758 | 0.7591 | 0.8424 | 0.9258 |
| 1/8         | 0.0104 | 0.0938 | 0.1771 | 0.2604 | 0.3438 | 0.4271 | 0.5104 | 0.5938 | 0.6771 | 0.7604 | 0.8438 | 0.9271 |
| 9/64        | 0.0117 | 0.0951 | 0.1784 | 0.2617 | 0.3451 | 0.4284 | 0.5117 | 0.5951 | 0.6784 | 0.7617 | 0.8451 | 0.9284 |
| 5/32        | 0.0130 | 0.0964 | 0.1797 | 0.2630 | 0.3464 | 0.4297 | 0.5130 | 0.5964 | 0.6797 | 0.7630 | 0.8464 | 0.9297 |
| 11/64       | 0.0143 | 0.0977 | 0.1810 | 0.2643 | 0.3477 | 0.4310 | 0.5143 | 0.5977 | 0.6810 | 0.7643 | 0.8477 | 0.9310 |
| 3/16        | 0.0156 | 0.0990 | 0.1823 | 0.2656 | 0.3490 | 0.4323 | 0.5156 | 0.5990 | 0.6823 | 0.7656 | 0.8490 | 0.9323 |
| 13/64       | 0.0169 | 0.1003 | 0.1836 | 0.2669 | 0.3503 | 0.4336 | 0.5169 | 0.6003 | 0.6836 | 0.7669 | 0.8503 | 0.9336 |
| 7/32        | 0.0182 | 0.1016 | 0.1849 | 0.2682 | 0.3516 | 0.4349 | 0.5182 | 0.6016 | 0.6849 | 0.7682 | 0.8516 | 0.9349 |
| 15/64       | 0.0195 | 0.1029 | 0.1862 | 0.2695 | 0.3529 | 0.4362 | 0.5195 | 0.6029 | 0.6862 | 0.7695 | 0.8529 | 0.9362 |
| 1/4         | 0.0208 | 0.1042 | 0.1875 | 0.2708 | 0.3542 | 0.4375 | 0.5208 | 0.6042 | 0.6875 | 0.7708 | 0.8542 | 0.9375 |
| 17/64       | 0.0221 | 0.1055 | 0.1888 | 0.2721 | 0.3555 | 0.4388 | 0.5221 | 0.6055 | 0.6888 | 0.7721 | 0.8555 | 0.9388 |
| 3/8         | 0.0234 | 0.1068 | 0.1901 | 0.2734 | 0.3568 | 0.4401 | 0.5234 | 0.6068 | 0.6901 | 0.7734 | 0.8568 | 0.9401 |
| 19/64       | 0.0247 | 0.1081 | 0.1914 | 0.2747 | 0.3581 | 0.4414 | 0.5247 | 0.6081 | 0.6914 | 0.7747 | 0.8581 | 0.9414 |
| 5/16        | 0.0260 | 0.1094 | 0.1927 | 0.2760 | 0.3594 | 0.4427 | 0.5260 | 0.6094 | 0.6927 | 0.7760 | 0.8594 | 0.9427 |
| 21/64       | 0.0273 | 0.1107 | 0.1940 | 0.2773 | 0.3607 | 0.4440 | 0.5273 | 0.6107 | 0.6940 | 0.7773 | 0.8607 | 0.9440 |
| 11/32       | 0.0286 | 0.1120 | 0.1953 | 0.2786 | 0.3620 | 0.4453 | 0.5286 | 0.6120 | 0.6953 | 0.7786 | 0.8620 | 0.9453 |
| 23/64       | 0.0299 | 0.1133 | 0.1966 | 0.2799 | 0.3633 | 0.4466 | 0.5299 | 0.6133 | 0.6966 | 0.7799 | 0.8633 | 0.9466 |
| 3/8         | 0.0313 | 0.1146 | 0.1979 | 0.2813 | 0.3646 | 0.4479 | 0.5313 | 0.6146 | 0.6979 | 0.7813 | 0.8646 | 0.9479 |
| 25/64       | 0.0326 | 0.1159 | 0.1992 | 0.2826 | 0.3659 | 0.4492 | 0.5326 | 0.6159 | 0.6992 | 0.7826 | 0.8659 | 0.9492 |
| 13/32       | 0.0339 | 0.1172 | 0.2005 | 0.2839 | 0.3672 | 0.4505 | 0.5339 | 0.6172 | 0.7005 | 0.7839 | 0.8672 | 0.9505 |
| 27/64       | 0.0352 | 0.1185 | 0.2018 | 0.2852 | 0.3685 | 0.4518 | 0.5352 | 0.6185 | 0.7018 | 0.7852 | 0.8685 | 0.9518 |
| 7/16        | 0.0365 | 0.1198 | 0.2031 | 0.2865 | 0.3698 | 0.4531 | 0.5365 | 0.6198 | 0.7031 | 0.7865 | 0.8698 | 0.9531 |
| 29/64       | 0.0378 | 0.1211 | 0.2044 | 0.2878 | 0.3711 | 0.4544 | 0.5378 | 0.6211 | 0.7044 | 0.7878 | 0.8711 | 0.9544 |
| 15/32       | 0.0391 | 0.1224 | 0.2057 | 0.2891 | 0.3724 | 0.4557 | 0.5391 | 0.6224 | 0.7057 | 0.7891 | 0.8724 | 0.9557 |
| 31/64       | 0.0404 | 0.1237 | 0.2070 | 0.2904 | 0.3737 | 0.4570 | 0.5404 | 0.6237 | 0.7070 | 0.7904 | 0.8737 | 0.9570 |
| 1/2         | 0.0417 | 0.1250 | 0.2083 | 0.2917 | 0.3750 | 0.4583 | 0.5417 | 0.6250 | 0.7083 | 0.7917 | 0.8750 | 0.9583 |
| 33/64       | 0.0430 | 0.1263 | 0.2096 | 0.2930 | 0.3763 | 0.4596 | 0.5430 | 0.6263 | 0.7096 | 0.7930 | 0.8763 | 0.9596 |
| 17/32       | 0.0443 | 0.1276 | 0.2109 | 0.2943 | 0.3776 | 0.4609 | 0.5443 | 0.6276 | 0.7109 | 0.7943 | 0.8776 | 0.9609 |
| 35/64       | 0.0456 | 0.1289 | 0.2122 | 0.2956 | 0.3789 | 0.4622 | 0.5456 | 0.6289 | 0.7122 | 0.7956 | 0.8789 | 0.9622 |
| 9/16        | 0.0469 | 0.1302 | 0.2135 | 0.2969 | 0.3802 | 0.4635 | 0.5469 | 0.6302 | 0.7135 | 0.7969 | 0.8802 | 0.9635 |
| 37/64       | 0.0482 | 0.1315 | 0.2148 | 0.2982 | 0.3815 | 0.4648 | 0.5482 | 0.6315 | 0.7148 | 0.7982 | 0.8815 | 0.9648 |
| 19/32       | 0.0495 | 0.1328 | 0.2161 | 0.2995 | 0.3828 | 0.4661 | 0.5495 | 0.6328 | 0.7161 | 0.7995 | 0.8828 | 0.9661 |
| 39/64       | 0.0508 | 0.1341 | 0.2174 | 0.3008 | 0.3841 | 0.4674 | 0.5508 | 0.6341 | 0.7174 | 0.8008 | 0.8841 | 0.9674 |
| 5/8         | 0.0521 | 0.1354 | 0.2188 | 0.3021 | 0.3854 | 0.4688 | 0.5521 | 0.6354 | 0.7188 | 0.8021 | 0.8854 | 0.9688 |
| 41/64       | 0.0534 | 0.1367 | 0.2201 | 0.3034 | 0.3867 | 0.4701 | 0.5534 | 0.6367 | 0.7201 | 0.8034 | 0.8867 | 0.9701 |
| 21/32       | 0.0547 | 0.1380 | 0.2214 | 0.3047 | 0.3880 | 0.4714 | 0.5547 | 0.6380 | 0.7214 | 0.8047 | 0.8880 | 0.9714 |
| 43/64       | 0.0560 | 0.1393 | 0.2227 | 0.3060 | 0.3893 | 0.4727 | 0.5560 | 0.6393 | 0.7227 | 0.8060 | 0.8893 | 0.9727 |
| 11/16       | 0.0573 | 0.1406 | 0.2240 | 0.3073 | 0.3906 | 0.4740 | 0.5573 | 0.6406 | 0.7240 | 0.8073 | 0.8906 | 0.9740 |
| 45/64       | 0.0586 | 0.1419 | 0.2253 | 0.3086 | 0.3919 | 0.4753 | 0.5586 | 0.6419 | 0.7253 | 0.8086 | 0.8919 | 0.9753 |
| 23/32       | 0.0599 | 0.1432 | 0.2266 | 0.3099 | 0.3932 | 0.4766 | 0.5599 | 0.6432 | 0.7266 | 0.8099 | 0.8932 | 0.9766 |
| 47/64       | 0.0612 | 0.1445 | 0.2279 | 0.3112 | 0.3945 | 0.4779 | 0.5612 | 0.6445 | 0.7279 | 0.8112 | 0.8945 | 0.9779 |
| 3/4         | 0.0625 | 0.1458 | 0.2292 | 0.3125 | 0.3958 | 0.4792 | 0.5625 | 0.6458 | 0.7292 | 0.8125 | 0.8958 | 0.9792 |
| 49/64       | 0.0638 | 0.1471 | 0.2305 | 0.3138 | 0.3971 | 0.4805 | 0.5638 | 0.6471 | 0.7305 | 0.8138 | 0.8971 | 0.9805 |
| 25/32       | 0.0651 | 0.1484 | 0.2318 | 0.3151 | 0.3984 | 0.4818 | 0.5651 | 0.6484 | 0.7318 | 0.8151 | 0.8984 | 0.9818 |
| 51/64       | 0.0664 | 0.1497 | 0.2331 | 0.3164 | 0.3997 | 0.4831 | 0.5664 | 0.6497 | 0.7331 | 0.8164 | 0.8997 | 0.9831 |
| 13/16       | 0.0677 | 0.1510 | 0.2344 | 0.3177 | 0.4010 | 0.4844 | 0.5677 | 0.6510 | 0.7344 | 0.8177 | 0.9010 | 0.9844 |
| 53/64       | 0.0690 | 0.1523 | 0.2357 | 0.3190 | 0.4023 | 0.4857 | 0.5690 | 0.6523 | 0.7357 | 0.8190 | 0.9023 | 0.9857 |
| 27/32       | 0.0703 | 0.1536 | 0.2370 | 0.3203 | 0.4036 | 0.4870 | 0.5703 | 0.6536 | 0.7370 | 0.8203 | 0.9036 | 0.9870 |
| 55/64       | 0.0716 | 0.1549 | 0.2383 | 0.3216 | 0.4049 | 0.4883 | 0.5716 | 0.6549 | 0.7383 | 0.8216 | 0.9049 | 0.9883 |
| 7/8         | 0.0729 | 0.1563 | 0.2396 | 0.3229 | 0.4063 | 0.4896 | 0.5729 | 0.6563 | 0.7396 | 0.8229 | 0.9063 | 0.9896 |
| 57/64       | 0.0742 | 0.1576 | 0.2409 | 0.3242 | 0.4076 | 0.4909 | 0.5742 | 0.6576 | 0.7409 | 0.8242 | 0.9076 | 0.9909 |
| 29/32       | 0.0755 | 0.1589 | 0.2422 | 0.3255 | 0.4089 | 0.4922 | 0.5755 | 0.6589 | 0.7422 | 0.8255 | 0.9089 | 0.9922 |
| 59/64       | 0.0768 | 0.1602 | 0.2435 | 0.3268 | 0.4102 | 0.4935 | 0.5768 | 0.6602 | 0.7435 | 0.8268 | 0.9102 | 0.9935 |
| 15/16       | 0.0781 | 0.1615 | 0.2448 | 0.3281 | 0.4115 | 0.4948 | 0.5781 | 0.6615 | 0.7448 | 0.8281 | 0.9115 | 0.9948 |
| 61/64       | 0.0794 | 0.1628 | 0.2461 | 0.3294 | 0.4128 | 0.4961 | 0.5794 | 0.6628 | 0.7461 | 0.8294 | 0.9128 | 0.9961 |
| 31/32       | 0.0807 | 0.1641 | 0.2474 | 0.3307 | 0.4141 | 0.4974 | 0.5807 | 0.6641 | 0.7474 | 0.8307 | 0.9141 | 0.9974 |
| 63/64       | 0.0820 | 0.1654 | 0.2487 | 0.3320 | 0.4154 | 0.4987 | 0.5820 | 0.6654 | 0.7487 | 0.8320 | 0.9154 | 0.9987 |
| 1           | 0.0833 | 0.1667 | 0.2500 | 0.3333 | 0.4167 | 0.5000 | 0.5833 | 0.6667 | 0.7500 | 0.8333 | 0.9167 | 1.0000 |

Example: Convert 78 $\frac{3}{4}$  inches to feet. Solution: From Table 4, find 70 inches = 5.8333 feet and add to that 8 $\frac{3}{4}$  inches = 0.7292 feet found in Table 8a at the intersection of the  $\frac{3}{4}$  inch row and the 8 inch column. Thus, 78 $\frac{3}{4}$  inches = 5.8333 + 0.7292 = 6.5625 feet.

**Table 6. Feet to Inches Conversion**

| feet | inch  | feet | inch | feet | inch | feet | inch | feet | inch | feet  | inch  |
|------|-------|------|------|------|------|------|------|------|------|-------|-------|
| 100  | 1200  | 10   | 120  | 1    | 12   | 0.1  | 1.2  | 0.01 | 0.12 | 0.001 | 0.012 |
| 200  | 2400  | 20   | 240  | 2    | 24   | 0.2  | 2.4  | 0.02 | 0.24 | 0.002 | 0.024 |
| 300  | 3600  | 30   | 360  | 3    | 36   | 0.3  | 3.6  | 0.03 | 0.36 | 0.003 | 0.036 |
| 400  | 4800  | 40   | 480  | 4    | 48   | 0.4  | 4.8  | 0.04 | 0.48 | 0.004 | 0.048 |
| 500  | 6000  | 50   | 600  | 5    | 60   | 0.5  | 6    | 0.05 | 0.6  | 0.005 | 0.06  |
| 600  | 7200  | 60   | 720  | 6    | 72   | 0.6  | 7.2  | 0.06 | 0.72 | 0.006 | 0.072 |
| 700  | 8400  | 70   | 840  | 7    | 84   | 0.7  | 8.4  | 0.07 | 0.84 | 0.007 | 0.084 |
| 800  | 9600  | 80   | 960  | 8    | 96   | 0.8  | 9.6  | 0.08 | 0.96 | 0.008 | 0.096 |
| 900  | 10800 | 90   | 1080 | 9    | 108  | 0.9  | 10.8 | 0.09 | 1.08 | 0.009 | 0.108 |
| 1000 | 12000 | 100  | 1200 | 10   | 120  | 1    | 12   | 0.1  | 1.2  | 0.01  | 0.12  |

**Table 7. Fractional Inch to Decimal Inch and Millimeter**

| Fractional Inch | Decimal Inch | Millimeters | Fractional Inch | Decimal Inch | Millimeters |
|-----------------|--------------|-------------|-----------------|--------------|-------------|
| 1/64            | 0.015625     | 0.396875    |                 | 0.511811024  | 13          |
| 1/32            | 0.03125      | 0.79375     | 33/64           | 0.515625     | 13.096875   |
|                 | 0.039370079  | 1           | 17/32           | 0.53125      | 13.49375    |
| 3/64            | 0.046875     | 1.190625    | 35/64           | 0.546875     | 13.890625   |
| 1/16            | 0.0625       | 1.5875      |                 | 0.551181102  | 14          |
| 5/64            | 0.078125     | 1.984375    | 9/16            | 0.5625       | 14.2875     |
|                 | 0.078740157  | 2           | 37/64           | 0.578125     | 14.684375   |
| 3/32            | 0.09375      | 2.38125     |                 | 0.590551181  | 15          |
| 7/64            | 0.109375     | 2.778125    | 19/32           | 0.59375      | 15.08125    |
|                 | 0.118110236  | 3           | 39/64           | 0.609375     | 15.478125   |
| 1/8             | 0.125        | 3.175       | 5/8             | 0.625        | 15.875      |
| 9/64            | 0.140625     | 3.571875    |                 | 0.62992126   | 16          |
| 5/32            | 0.15625      | 3.96875     | 41/64           | 0.640625     | 16.271875   |
|                 | 0.157480315  | 4           | 21/32           | 0.65625      | 16.66875    |
| 11/64           | 0.171875     | 4.365625    |                 | 0.669291339  | 17          |
| 3/16            | 0.1875       | 4.7625      | 43/64           | 0.671875     | 17.065625   |
|                 | 0.196850394  | 5           | 11/16           | 0.6875       | 17.4625     |
| 13/64           | 0.203125     | 5.159375    | 45/64           | 0.703125     | 17.859375   |
| 7/32            | 0.21875      | 5.55625     |                 | 0.708661417  | 18          |
| 15/64           | 0.234375     | 5.953125    | 23/32           | 0.71875      | 18.25625    |
|                 | 0.236220472  | 6           | 47/64           | 0.734375     | 18.653125   |
| 1/4             | 0.25         | 6.35        |                 | 0.748031496  | 19          |
| 17/64           | 0.265625     | 6.746875    | 3/4             | 0.75         | 19.05       |
|                 | 0.275590551  | 7           | 49/64           | 0.765625     | 19.446875   |
| 9/32            | 0.28125      | 7.14375     | 25/32           | 0.78125      | 19.84375    |
| 19/64           | 0.296875     | 7.540625    |                 | 0.787401575  | 20          |
| 5/16            | 0.3125       | 7.9375      | 51/64           | 0.796875     | 20.240625   |
|                 | 0.31496063   | 8           | 13/16           | 0.8125       | 20.6375     |
| 21/64           | 0.328125     | 8.334375    |                 | 0.826771654  | 21          |
| 11/32           | 0.34375      | 8.73125     | 53/64           | 0.828125     | 21.034375   |
|                 | 0.354330709  | 9           | 27/32           | 0.84375      | 21.43125    |
| 23/64           | 0.359375     | 9.128125    | 55/64           | 0.859375     | 21.828125   |
| 3/8             | 0.375        | 9.525       |                 | 0.866141732  | 22          |
| 25/64           | 0.390625     | 9.921875    | 7/8             | 0.875        | 22.225      |
|                 | 0.393700787  | 10          | 57/64           | 0.890625     | 22.621875   |
| 13/32           | 0.40625      | 10.31875    |                 | 0.905511811  | 23          |
| 27/64           | 0.421875     | 10.715625   | 29/32           | 0.90625      | 23.01875    |
|                 | 0.433070866  | 11          | 59/64           | 0.921875     | 23.415625   |
| 7/16            | 0.4375       | 11.1125     | 15/16           | 0.9375       | 23.8125     |
| 29/64           | 0.453125     | 11.509375   |                 | 0.94488189   | 24          |
| 15/32           | 0.46875      | 11.90625    | 61/64           | 0.953125     | 24.209375   |
|                 | 0.472440945  | 12          | 31/32           | 0.96875      | 24.60625    |
| 31/64           | 0.484375     | 12.303125   |                 | 0.984251969  | 25          |
| 1/2             | 0.5          | 12.7        | 63/64           | 0.984375     | 25.003125   |

**Table 8a. Inch to Millimeters Conversion**

| inch | mm          | inch | mm        | inch | mm       | inch | mm      | inch  | mm      | inch   | mm      |
|------|-------------|------|-----------|------|----------|------|---------|-------|---------|--------|---------|
| 10   | 254.00000   | 1    | 25.40000  | 0.1  | 2.54000  | .01  | 0.25400 | 0.001 | 0.02540 | 0.0001 | 0.00254 |
| 20   | 508.00000   | 2    | 50.80000  | 0.2  | 5.08000  | .02  | 0.50800 | 0.002 | 0.05080 | 0.0002 | 0.00508 |
| 30   | 762.00000   | 3    | 76.20000  | 0.3  | 7.62000  | .03  | 0.76200 | 0.003 | 0.07620 | 0.0003 | 0.00762 |
| 40   | 1,016.00000 | 4    | 101.60000 | 0.4  | 10.16000 | .04  | 1.01600 | 0.004 | 0.10160 | 0.0004 | 0.01016 |
| 50   | 1,270.00000 | 5    | 127.00000 | 0.5  | 12.70000 | .05  | 1.27000 | 0.005 | 0.12700 | 0.0005 | 0.01270 |
| 60   | 1,524.00000 | 6    | 152.40000 | 0.6  | 15.24000 | .06  | 1.52400 | 0.006 | 0.15240 | 0.0006 | 0.01524 |
| 70   | 1,778.00000 | 7    | 177.80000 | 0.7  | 17.78000 | .07  | 1.77800 | 0.007 | 0.17780 | 0.0007 | 0.01778 |
| 80   | 2,032.00000 | 8    | 203.20000 | 0.8  | 20.32000 | .08  | 2.03200 | 0.008 | 0.20320 | 0.0008 | 0.02032 |
| 90   | 2,286.00000 | 9    | 228.60000 | 0.9  | 22.86000 | .09  | 2.28600 | 0.009 | 0.22860 | 0.0009 | 0.02286 |
| 100  | 2,540.00000 | 10   | 254.00000 | 1.0  | 25.40000 | .10  | 2.54000 | 0.010 | 0.25400 | 0.0010 | 0.02540 |

All values in this table are exact. For inches to centimeters, shift decimal point in mm column one place to left and read centimeters, thus, for example, 40 in. = 1016 mm = 101.6 cm.

**Table 8b. Millimeters to Inch Conversion**

| mm    | inch     | mm  | inch    | mm | inch    | mm  | inch    | mm   | inch    | mm    | inch    |
|-------|----------|-----|---------|----|---------|-----|---------|------|---------|-------|---------|
| 100   | 3.93701  | 10  | 0.39370 | 1  | 0.03937 | 0.1 | 0.00394 | 0.01 | .000039 | 0.001 | 0.00004 |
| 200   | 7.87402  | 20  | 0.78740 | 2  | 0.07874 | 0.2 | 0.00787 | 0.02 | .000079 | 0.002 | 0.00008 |
| 300   | 11.81102 | 30  | 1.18110 | 3  | 0.11811 | 0.3 | 0.01181 | 0.03 | .00118  | 0.003 | 0.00012 |
| 400   | 15.74803 | 40  | 1.57480 | 4  | 0.15748 | 0.4 | 0.01575 | 0.04 | .00157  | 0.004 | 0.00016 |
| 500   | 19.68504 | 50  | 1.96850 | 5  | 0.19685 | 0.5 | 0.01969 | 0.05 | .00197  | 0.005 | 0.00020 |
| 600   | 23.62205 | 60  | 2.36220 | 6  | 0.23622 | 0.6 | 0.02362 | 0.06 | .00236  | 0.006 | 0.00024 |
| 700   | 27.55906 | 70  | 2.75591 | 7  | 0.27559 | 0.7 | 0.02756 | 0.07 | .00276  | 0.007 | 0.00028 |
| 800   | 31.49606 | 80  | 3.14961 | 8  | 0.31496 | 0.8 | 0.03150 | 0.08 | .00315  | 0.008 | 0.00031 |
| 900   | 35.43307 | 90  | 3.54331 | 9  | 0.35433 | 0.9 | 0.03543 | 0.09 | .00354  | 0.009 | 0.00035 |
| 1,000 | 39.37008 | 100 | 3.93701 | 10 | 0.39370 | 1.0 | 0.03937 | 0.10 | .00394  | 0.010 | 0.00039 |

Based on 1 inch = 25.4 millimeters, exactly. For centimeters to inches, shift decimal point of centimeter value one place to right and enter mm column, thus, for example, 70 cm = 700 mm = 27.55906 inches.

**Table 9. Feet to Millimeters Conversion**

| feet  | mm      | feet | mm     | feet | mm      | feet | mm     | feet | mm     |
|-------|---------|------|--------|------|---------|------|--------|------|--------|
| 100   | 30,480  | 10   | 3,048  | 1    | 304.8   | 0.1  | 30.48  | 0.01 | 3.048  |
| 200   | 60,960  | 20   | 6,096  | 2    | 609.6   | 0.2  | 60.96  | 0.02 | 6.096  |
| 300   | 91,440  | 30   | 9,144  | 3    | 914.4   | 0.3  | 91.44  | 0.03 | 9.144  |
| 400   | 121,920 | 40   | 12,192 | 4    | 1,219.2 | 0.4  | 121.92 | 0.04 | 12.192 |
| 500   | 152,400 | 50   | 15,240 | 5    | 1,524.0 | 0.5  | 152.40 | 0.05 | 15.240 |
| 600   | 182,880 | 60   | 18,288 | 6    | 1,828.8 | 0.6  | 182.88 | 0.06 | 18.288 |
| 700   | 213,360 | 70   | 21,336 | 7    | 2,133.6 | 0.7  | 213.36 | 0.07 | 21.336 |
| 800   | 243,840 | 80   | 24,384 | 8    | 2,438.4 | 0.8  | 243.84 | 0.08 | 24.384 |
| 900   | 274,320 | 90   | 27,432 | 9    | 2,743.2 | 0.9  | 274.32 | 0.09 | 27.432 |
| 1,000 | 304,800 | 100  | 30,480 | 10   | 3,048.0 | 1.0  | 304.80 | 0.10 | 30.480 |

Based on 1 inch = 25.4 millimeters, exactly. All values in this table are exact.

*Example 1:* Convert 293 feet,  $5\frac{47}{64}$  inches to mm.

|                         |      |          |            |    |
|-------------------------|------|----------|------------|----|
| 200 ft                  | =    | 60,960.0 | mm         |    |
| 90 ft                   | =    | 27,432.0 | mm         |    |
| 3 ft                    | =    | 914.4    | mm         |    |
| 5                       | inch | =        | 127.0      | mm |
| $\frac{47}{64}$         | inch | =        | 18.653     | mm |
| <hr/>                   |      |          |            |    |
| 293 ft $5\frac{47}{64}$ | inch | =        | 89,452.053 | mm |

*Example 2:* Convert 71.86 feet to mm.

|       |      |   |            |    |
|-------|------|---|------------|----|
| 70.0  | feet | = | 21,336.0   | mm |
| 1.0   | feet | = | 304.8      | mm |
| 0.80  | feet | = | 243.84     | mm |
| 0.06  | feet | = | 18.288     | mm |
| <hr/> |      |   |            |    |
| 71.86 | feet | = | 21,902.928 | mm |

Table 10. Mixed Fractional Inches to Millimeters Conversion for 0 to 41 Inches in  $\frac{1}{64}$ -Inch Increments

| →<br>Inches↓ | 0           | 1         | 2         | 3         | 4          | 5          | 6          | 7          | 8          | 9          | 10         | 20         | 30         | 40          |
|--------------|-------------|-----------|-----------|-----------|------------|------------|------------|------------|------------|------------|------------|------------|------------|-------------|
|              | Millimeters |           |           |           |            |            |            |            |            |            |            |            |            |             |
| 0            | 0           | 25.4      | 50.8      | 76.2      | 101.6      | 127.0      | 152.4      | 177.8      | 203.2      | 228.6      | 254.0      | 508.0      | 762.0      | 1016.0      |
| 1/64         | 0.396875    | 25.796875 | 51.196875 | 76.596875 | 101.996875 | 127.396875 | 152.796875 | 178.196875 | 203.596875 | 228.996875 | 254.396875 | 508.396875 | 762.396875 | 1016.396875 |
| 1/32         | 0.79375     | 26.19375  | 51.59375  | 76.99375  | 102.39375  | 127.79375  | 153.19375  | 178.59375  | 203.99375  | 229.39375  | 254.79375  | 508.79375  | 762.79375  | 1016.79375  |
| 3/64         | 1.190625    | 26.590625 | 51.990625 | 77.390625 | 102.790625 | 128.190625 | 153.590625 | 178.990625 | 204.390625 | 229.790625 | 255.190625 | 509.190625 | 763.190625 | 1017.190625 |
| 1/16         | 1.5875      | 26.9875   | 52.3875   | 77.7875   | 103.1875   | 128.5875   | 153.9875   | 179.3875   | 204.7875   | 230.1875   | 255.5875   | 509.5875   | 763.5875   | 1017.5875   |
| 5/64         | 1.984375    | 27.384375 | 52.784375 | 78.184375 | 103.584375 | 128.984375 | 154.384375 | 179.784375 | 205.184375 | 230.584375 | 255.984375 | 509.984375 | 763.984375 | 1017.984375 |
| 3/32         | 2.38125     | 27.78125  | 53.18125  | 78.58125  | 103.98125  | 129.38125  | 154.78125  | 180.18125  | 205.58125  | 230.98125  | 256.38125  | 510.38125  | 764.38125  | 1018.38125  |
| 7/64         | 2.778125    | 28.178125 | 53.578125 | 78.978125 | 104.378125 | 129.778125 | 155.178125 | 180.578125 | 205.978125 | 231.378125 | 256.778125 | 510.778125 | 764.778125 | 1018.778125 |
| 1/8          | 3.175       | 28.575    | 53.975    | 79.375    | 104.775    | 130.175    | 155.575    | 180.975    | 206.375    | 231.775    | 257.175    | 511.175    | 765.175    | 1019.175    |
| 9/64         | 3.571875    | 28.971875 | 54.371875 | 79.771875 | 105.171875 | 130.571875 | 155.971875 | 181.371875 | 206.771875 | 232.171875 | 257.571875 | 511.571875 | 765.571875 | 1019.571875 |
| 5/32         | 3.96875     | 29.36875  | 54.76875  | 80.16875  | 105.56875  | 130.96875  | 156.36875  | 181.76875  | 207.16875  | 232.56875  | 257.96875  | 511.96875  | 765.96875  | 1019.96875  |
| 11/64        | 4.365625    | 29.765625 | 55.165625 | 80.565625 | 105.965625 | 131.365625 | 156.765625 | 182.165625 | 207.565625 | 232.965625 | 258.365625 | 512.365625 | 766.365625 | 1020.365625 |
| 3/16         | 4.7625      | 30.1625   | 55.5625   | 80.9625   | 106.3625   | 131.7625   | 157.1625   | 182.5625   | 207.9625   | 233.3625   | 258.7625   | 512.7625   | 766.7625   | 1020.7625   |
| 13/64        | 5.159375    | 30.559375 | 55.959375 | 81.359375 | 106.759375 | 132.159375 | 157.559375 | 182.959375 | 208.359375 | 233.759375 | 259.159375 | 513.159375 | 767.159375 | 1021.159375 |
| 7/32         | 5.55625     | 30.95625  | 56.35625  | 81.75625  | 107.15625  | 132.55625  | 157.95625  | 183.35625  | 208.75625  | 234.15625  | 259.55625  | 513.55625  | 767.55625  | 1021.55625  |
| 15/64        | 5.953125    | 31.353125 | 56.753125 | 82.153125 | 107.553125 | 132.953125 | 158.353125 | 183.753125 | 209.153125 | 234.553125 | 259.953125 | 513.953125 | 767.953125 | 1021.953125 |
| 1/4          | 6.35        | 31.75     | 57.15     | 82.55     | 107.95     | 133.35     | 158.75     | 184.15     | 209.55     | 234.95     | 260.35     | 514.35     | 768.35     | 1022.35     |
| 17/64        | 6.746875    | 32.146875 | 57.546875 | 82.946875 | 108.346875 | 133.746875 | 159.146875 | 184.546875 | 209.946875 | 235.346875 | 260.746875 | 514.746875 | 768.746875 | 1022.746875 |
| 9/32         | 7.14375     | 32.54375  | 57.94375  | 83.34375  | 108.74375  | 134.14375  | 159.54375  | 184.94375  | 210.34375  | 235.74375  | 261.14375  | 515.14375  | 769.14375  | 1023.14375  |
| 19/64        | 7.540625    | 32.940625 | 58.340625 | 83.740625 | 109.140625 | 134.540625 | 159.940625 | 185.340625 | 210.740625 | 236.140625 | 261.540625 | 515.540625 | 769.540625 | 1023.540625 |
| 5/16         | 7.9375      | 33.3375   | 58.7375   | 84.1375   | 109.5375   | 134.9375   | 160.3375   | 185.7375   | 211.1375   | 236.5375   | 261.9375   | 515.9375   | 769.9375   | 1023.9375   |
| 21/64        | 8.334375    | 33.734375 | 59.134375 | 84.534375 | 109.934375 | 135.334375 | 160.734375 | 186.134375 | 211.534375 | 236.934375 | 262.334375 | 516.334375 | 770.334375 | 1024.334375 |
| 11/32        | 8.73125     | 34.13125  | 59.53125  | 84.93125  | 110.33125  | 135.73125  | 161.13125  | 186.53125  | 211.93125  | 237.33125  | 262.73125  | 516.73125  | 770.73125  | 1024.73125  |
| 23/64        | 9.128125    | 34.528125 | 59.928125 | 85.328125 | 110.728125 | 136.128125 | 161.528125 | 186.928125 | 212.328125 | 237.728125 | 263.128125 | 517.128125 | 771.128125 | 1025.128125 |
| 3/8          | 9.525       | 34.925    | 60.325    | 85.725    | 111.125    | 136.525    | 161.925    | 187.325    | 212.725    | 238.125    | 263.525    | 517.525    | 771.525    | 1025.525    |
| 25/64        | 9.921875    | 35.321875 | 60.721875 | 86.121875 | 111.521875 | 136.921875 | 162.321875 | 187.721875 | 213.121875 | 238.521875 | 263.921875 | 517.921875 | 771.921875 | 1025.921875 |
| 13/32        | 10.31875    | 35.71875  | 61.11875  | 86.51875  | 111.91875  | 137.31875  | 162.71875  | 188.11875  | 213.51875  | 238.91875  | 264.31875  | 518.31875  | 772.31875  | 1026.31875  |
| 27/64        | 10.715625   | 36.115625 | 61.515625 | 86.915625 | 112.315625 | 137.715625 | 163.115625 | 188.515625 | 213.915625 | 239.315625 | 264.715625 | 518.715625 | 772.715625 | 1026.715625 |
| 7/16         | 11.1125     | 36.5125   | 61.9125   | 87.3125   | 112.7125   | 138.1125   | 163.5125   | 188.9125   | 214.3125   | 239.7125   | 265.1125   | 519.1125   | 773.1125   | 1027.1125   |
| 29/64        | 11.509375   | 36.909375 | 62.309375 | 87.709375 | 113.109375 | 138.509375 | 163.909375 | 189.309375 | 214.709375 | 240.109375 | 265.509375 | 519.509375 | 773.509375 | 1027.509375 |
| 15/32        | 11.90625    | 37.30625  | 62.70625  | 88.10625  | 113.50625  | 138.90625  | 164.30625  | 189.70625  | 215.10625  | 240.50625  | 265.90625  | 519.90625  | 773.90625  | 1027.90625  |
| 31/64        | 12.303125   | 37.703125 | 63.103125 | 88.503125 | 113.903125 | 139.303125 | 164.703125 | 190.103125 | 215.503125 | 240.903125 | 266.303125 | 520.303125 | 774.303125 | 1028.303125 |
| 1/2          | 12.7        | 38.1      | 63.5      | 88.9      | 114.3      | 139.7      | 165.1      | 190.5      | 215.9      | 241.3      | 266.7      | 520.7      | 774.7      | 1028.7      |

Table 10. (Continued) Mixed Fractional Inches to Millimeters Conversion for 0 to 41 Inches in  $\frac{1}{64}$ -Inch Increments

| →<br>Inches↓ | Millimeters |           |           |            |            |            |            |            |            |            |            |            |            |             |
|--------------|-------------|-----------|-----------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|-------------|
|              | 0           | 1         | 2         | 3          | 4          | 5          | 6          | 7          | 8          | 9          | 10         | 20         | 30         | 40          |
| 33/64        | 13.096875   | 38.496875 | 63.896875 | 89.296875  | 114.696875 | 140.096875 | 165.496875 | 190.896875 | 216.296875 | 241.696875 | 267.096875 | 521.096875 | 775.096875 | 1029.096875 |
| 17/32        | 13.49375    | 38.89375  | 64.29375  | 89.69375   | 115.09375  | 140.49375  | 165.89375  | 191.29375  | 216.69375  | 242.09375  | 267.49375  | 521.49375  | 775.49375  | 1029.49375  |
| 35/64        | 13.890625   | 39.290625 | 64.690625 | 90.090625  | 115.490625 | 140.890625 | 166.290625 | 191.690625 | 217.090625 | 242.490625 | 267.890625 | 521.890625 | 775.890625 | 1029.890625 |
| 9/16         | 14.2875     | 39.6875   | 65.0875   | 90.4875    | 115.8875   | 141.2875   | 166.6875   | 192.0875   | 217.4875   | 242.8875   | 268.2875   | 522.2875   | 776.2875   | 1030.2875   |
| 37/64        | 14.684375   | 40.084375 | 65.484375 | 90.884375  | 116.284375 | 141.684375 | 167.084375 | 192.484375 | 217.884375 | 243.284375 | 268.684375 | 522.684375 | 776.684375 | 1030.684375 |
| 19/32        | 15.08125    | 40.48125  | 65.88125  | 91.28125   | 116.68125  | 142.08125  | 167.48125  | 192.88125  | 218.28125  | 243.68125  | 269.08125  | 523.08125  | 777.08125  | 1031.08125  |
| 39/64        | 15.478125   | 40.878125 | 66.278125 | 91.678125  | 117.078125 | 142.478125 | 167.878125 | 193.278125 | 218.678125 | 244.078125 | 269.478125 | 523.478125 | 777.478125 | 1031.478125 |
| 5/8          | 15.875      | 41.275    | 66.675    | 92.075     | 117.475    | 142.875    | 168.275    | 193.675    | 219.075    | 244.475    | 269.875    | 523.875    | 777.875    | 1031.875    |
| 41/64        | 16.271875   | 41.671875 | 67.071875 | 92.471875  | 117.871875 | 143.271875 | 168.671875 | 194.071875 | 219.471875 | 244.871875 | 270.271875 | 524.271875 | 778.271875 | 1032.271875 |
| 21/32        | 16.66875    | 42.06875  | 67.46875  | 92.86875   | 118.26875  | 143.66875  | 169.06875  | 194.46875  | 219.86875  | 245.26875  | 270.66875  | 524.66875  | 778.66875  | 1032.66875  |
| 43/64        | 17.065625   | 42.465625 | 67.865625 | 93.265625  | 118.665625 | 144.065625 | 169.465625 | 194.865625 | 220.265625 | 245.665625 | 271.065625 | 525.065625 | 779.065625 | 1033.065625 |
| 11/16        | 17.4625     | 42.8625   | 68.2625   | 93.6625    | 119.0625   | 144.4625   | 169.8625   | 195.2625   | 220.6625   | 246.0625   | 271.4625   | 525.4625   | 779.4625   | 1033.4625   |
| 45/64        | 17.859375   | 43.259375 | 68.659375 | 94.059375  | 119.459375 | 144.859375 | 170.259375 | 195.659375 | 221.059375 | 246.459375 | 271.859375 | 525.859375 | 779.859375 | 1033.859375 |
| 23/32        | 18.25625    | 43.65625  | 69.05625  | 94.45625   | 119.85625  | 145.25625  | 170.65625  | 196.05625  | 221.45625  | 246.85625  | 272.25625  | 526.25625  | 780.25625  | 1034.25625  |
| 47/64        | 18.653125   | 44.053125 | 69.453125 | 94.853125  | 120.253125 | 145.653125 | 171.053125 | 196.453125 | 221.853125 | 247.253125 | 272.653125 | 526.653125 | 780.653125 | 1034.653125 |
| 3/4          | 19.05       | 44.45     | 69.85     | 95.25      | 120.65     | 146.05     | 171.45     | 196.85     | 222.25     | 247.65     | 273.05     | 527.05     | 781.05     | 1035.05     |
| 49/64        | 19.446875   | 44.846875 | 70.246875 | 95.646875  | 121.046875 | 146.446875 | 171.846875 | 197.246875 | 222.646875 | 248.046875 | 273.446875 | 527.446875 | 781.446875 | 1035.446875 |
| 25/32        | 19.84375    | 45.24375  | 70.64375  | 96.04375   | 121.44375  | 146.84375  | 172.24375  | 197.64375  | 223.04375  | 248.44375  | 273.84375  | 527.84375  | 781.84375  | 1035.84375  |
| 51/64        | 20.240625   | 45.640625 | 71.040625 | 96.440625  | 121.840625 | 147.240625 | 172.640625 | 198.040625 | 223.440625 | 248.840625 | 274.240625 | 528.240625 | 782.240625 | 1036.240625 |
| 13/16        | 20.6375     | 46.0375   | 71.4375   | 96.8375    | 122.2375   | 147.6375   | 173.0375   | 198.4375   | 223.8375   | 249.2375   | 274.6375   | 528.6375   | 782.6375   | 1036.6375   |
| 53/64        | 21.034375   | 46.434375 | 71.834375 | 97.234375  | 122.634375 | 148.034375 | 173.434375 | 198.834375 | 224.234375 | 249.634375 | 275.034375 | 529.034375 | 783.034375 | 1037.034375 |
| 27/32        | 21.43125    | 46.83125  | 72.23125  | 97.63125   | 123.03125  | 148.43125  | 173.83125  | 199.23125  | 224.63125  | 250.03125  | 275.43125  | 529.43125  | 783.43125  | 1037.43125  |
| 55/64        | 21.828125   | 47.228125 | 72.628125 | 98.028125  | 123.428125 | 148.828125 | 174.228125 | 199.628125 | 225.028125 | 250.428125 | 275.828125 | 529.828125 | 783.828125 | 1037.828125 |
| 7/8          | 22.225      | 47.625    | 73.025    | 98.425     | 123.825    | 149.225    | 174.625    | 200.025    | 225.425    | 250.825    | 276.225    | 530.225    | 784.225    | 1038.225    |
| 57/64        | 22.621875   | 48.021875 | 73.421875 | 98.821875  | 124.221875 | 149.621875 | 175.021875 | 200.421875 | 225.821875 | 251.221875 | 276.621875 | 530.621875 | 784.621875 | 1038.621875 |
| 29/32        | 23.01875    | 48.41875  | 73.81875  | 99.21875   | 124.61875  | 150.01875  | 175.41875  | 200.81875  | 226.21875  | 251.61875  | 277.01875  | 531.01875  | 785.01875  | 1039.01875  |
| 59/64        | 23.415625   | 48.815625 | 74.215625 | 99.615625  | 125.015625 | 150.415625 | 175.815625 | 201.215625 | 226.615625 | 252.015625 | 277.415625 | 531.415625 | 785.415625 | 1039.415625 |
| 15/16        | 23.8125     | 49.2125   | 74.6125   | 100.0125   | 125.4125   | 150.8125   | 176.2125   | 201.6125   | 227.0125   | 252.4125   | 277.8125   | 531.8125   | 785.8125   | 1039.8125   |
| 61/64        | 24.209375   | 49.609375 | 75.009375 | 100.409375 | 125.809375 | 151.209375 | 176.609375 | 202.009375 | 227.409375 | 252.809375 | 278.209375 | 532.209375 | 786.209375 | 1040.209375 |
| 31/32        | 24.60625    | 50.00625  | 75.40625  | 100.80625  | 126.20625  | 151.60625  | 177.00625  | 202.40625  | 227.80625  | 253.20625  | 278.60625  | 532.60625  | 786.60625  | 1040.60625  |
| 63/64        | 25.003125   | 50.403125 | 75.803125 | 101.203125 | 126.603125 | 152.003125 | 177.403125 | 202.803125 | 228.203125 | 253.603125 | 279.003125 | 533.003125 | 787.003125 | 1041.003125 |
| 1            | 25.4        | 50.8      | 76.2      | 101.6      | 127        | 152.4      | 177.8      | 203.2      | 228.6      | 254        | 279.4      | 533.4      | 787.4      | 1041.4      |

Based on 1 inch = 25.4 millimeters, exactly. All values in this table are exact. Example: Convert  $21\frac{23}{64}$  inches to millimeters. Solution: From the first page of this table, find 20 inches = 508.0 millimeters and add to that  $1\frac{23}{64}$  inches = 34.528125 millimeters found at the intersection of the 1- inch column and the row containing  $\frac{23}{64}$  inch. Thus,  $21\frac{23}{64}$  inches = 508.0 + 34.528125 = 542.528125 mm, exactly.



Table 11. Decimals of an Inch to Millimeters Conversion

| →<br>Inches<br>↓ | 0.000       | 0.001   | 0.002   | 0.003   | 0.004   | 0.005   | 0.006   | 0.007   | 0.008   | 0.009   |
|------------------|-------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|                  | Millimeters |         |         |         |         |         |         |         |         |         |
| 0.000            | ...         | 0.0254  | 0.0508  | 0.0762  | 0.1016  | 0.1270  | 0.1524  | 0.1778  | 0.2032  | 0.2286  |
| 0.010            | 0.2540      | 0.2794  | 0.3048  | 0.3302  | 0.3556  | 0.3810  | 0.4064  | 0.4318  | 0.4572  | 0.4826  |
| 0.020            | 0.5080      | 0.5334  | 0.5588  | 0.5842  | 0.6096  | 0.6350  | 0.6604  | 0.6858  | 0.7112  | 0.7366  |
| 0.030            | 0.7620      | 0.7874  | 0.8128  | 0.8382  | 0.8636  | 0.8890  | 0.9144  | 0.9398  | 0.9652  | 0.9906  |
| 0.040            | 1.0160      | 1.0414  | 1.0668  | 1.0922  | 1.1176  | 1.1430  | 1.1684  | 1.1938  | 1.2192  | 1.2446  |
| 0.050            | 1.2700      | 1.2954  | 1.3208  | 1.3462  | 1.3716  | 1.3970  | 1.4224  | 1.4478  | 1.4732  | 1.4986  |
| 0.060            | 1.5240      | 1.5494  | 1.5748  | 1.6002  | 1.6256  | 1.6510  | 1.6764  | 1.7018  | 1.7272  | 1.7526  |
| 0.070            | 1.7780      | 1.8034  | 1.8288  | 1.8542  | 1.8796  | 1.9050  | 1.9304  | 1.9558  | 1.9812  | 2.0066  |
| 0.080            | 2.0320      | 2.0574  | 2.0828  | 2.1082  | 2.1336  | 2.1590  | 2.1844  | 2.2098  | 2.2352  | 2.2606  |
| 0.090            | 2.2860      | 2.3114  | 2.3368  | 2.3622  | 2.3876  | 2.4130  | 2.4384  | 2.4638  | 2.4892  | 2.5146  |
| 0.100            | 2.5400      | 2.5654  | 2.5908  | 2.6162  | 2.6416  | 2.6670  | 2.6924  | 2.7178  | 2.7432  | 2.7686  |
| 0.110            | 2.7940      | 2.8194  | 2.8448  | 2.8702  | 2.8956  | 2.9210  | 2.9464  | 2.9718  | 2.9972  | 3.0226  |
| 0.120            | 3.0480      | 3.0734  | 3.0988  | 3.1242  | 3.1496  | 3.1750  | 3.2004  | 3.2258  | 3.2512  | 3.2766  |
| 0.130            | 3.3020      | 3.3274  | 3.3528  | 3.3782  | 3.4036  | 3.4290  | 3.4544  | 3.4798  | 3.5052  | 3.5306  |
| 0.140            | 3.5560      | 3.5814  | 3.6068  | 3.6322  | 3.6576  | 3.6830  | 3.7084  | 3.7338  | 3.7592  | 3.7846  |
| 0.150            | 3.8100      | 3.8354  | 3.8608  | 3.8862  | 3.9116  | 3.9370  | 3.9624  | 3.9878  | 4.0132  | 4.0386  |
| 0.160            | 4.0640      | 4.0894  | 4.1148  | 4.1402  | 4.1656  | 4.1910  | 4.2164  | 4.2418  | 4.2672  | 4.2926  |
| 0.170            | 4.3180      | 4.3434  | 4.3688  | 4.3942  | 4.4196  | 4.4450  | 4.4704  | 4.4958  | 4.5212  | 4.5466  |
| 0.180            | 4.5720      | 4.5974  | 4.6228  | 4.6482  | 4.6736  | 4.6990  | 4.7244  | 4.7498  | 4.7752  | 4.8006  |
| 0.190            | 4.8260      | 4.8514  | 4.8768  | 4.9022  | 4.9276  | 4.9530  | 4.9784  | 5.0038  | 5.0292  | 5.0546  |
| 0.200            | 5.0800      | 5.1054  | 5.1308  | 5.1562  | 5.1816  | 5.2070  | 5.2324  | 5.2578  | 5.2832  | 5.3086  |
| 0.210            | 5.3340      | 5.3594  | 5.3848  | 5.4102  | 5.4356  | 5.4610  | 5.4864  | 5.5118  | 5.5372  | 5.5626  |
| 0.220            | 5.5880      | 5.6134  | 5.6388  | 5.6642  | 5.6896  | 5.7150  | 5.7404  | 5.7658  | 5.7912  | 5.8166  |
| 0.230            | 5.8420      | 5.8674  | 5.8928  | 5.9182  | 5.9436  | 5.9690  | 5.9944  | 6.0198  | 6.0452  | 6.0706  |
| 0.240            | 6.0960      | 6.1214  | 6.1468  | 6.1722  | 6.1976  | 6.2230  | 6.2484  | 6.2738  | 6.2992  | 6.3246  |
| 0.250            | 6.3500      | 6.3754  | 6.4008  | 6.4262  | 6.4516  | 6.4770  | 6.5024  | 6.5278  | 6.5532  | 6.5786  |
| 0.260            | 6.6040      | 6.6294  | 6.6548  | 6.6802  | 6.7056  | 6.7310  | 6.7564  | 6.7818  | 6.8072  | 6.8326  |
| 0.270            | 6.8580      | 6.8834  | 6.9088  | 6.9342  | 6.9596  | 6.9850  | 7.0104  | 7.0358  | 7.0612  | 7.0866  |
| 0.280            | 7.1120      | 7.1374  | 7.1628  | 7.1882  | 7.2136  | 7.2390  | 7.2644  | 7.2898  | 7.3152  | 7.3406  |
| 0.290            | 7.3660      | 7.3914  | 7.4168  | 7.4422  | 7.4676  | 7.4930  | 7.5184  | 7.5438  | 7.5692  | 7.5946  |
| 0.300            | 7.6200      | 7.6454  | 7.6708  | 7.6962  | 7.7216  | 7.7470  | 7.7724  | 7.7978  | 7.8232  | 7.8486  |
| 0.310            | 7.8740      | 7.8994  | 7.9248  | 7.9502  | 7.9756  | 8.0010  | 8.0264  | 8.0518  | 8.0772  | 8.1026  |
| 0.320            | 8.1280      | 8.1534  | 8.1788  | 8.2042  | 8.2296  | 8.2550  | 8.2804  | 8.3058  | 8.3312  | 8.3566  |
| 0.330            | 8.3820      | 8.4074  | 8.4328  | 8.4582  | 8.4836  | 8.5090  | 8.5344  | 8.5598  | 8.5852  | 8.6106  |
| 0.340            | 8.6360      | 8.6614  | 8.6868  | 8.7122  | 8.7376  | 8.7630  | 8.7884  | 8.8138  | 8.8392  | 8.8646  |
| 0.350            | 8.8900      | 8.9154  | 8.9408  | 8.9662  | 8.9916  | 9.0170  | 9.0424  | 9.0678  | 9.0932  | 9.1186  |
| 0.360            | 9.1440      | 9.1694  | 9.1948  | 9.2202  | 9.2456  | 9.2710  | 9.2964  | 9.3218  | 9.3472  | 9.3726  |
| 0.370            | 9.3980      | 9.4234  | 9.4488  | 9.4742  | 9.4996  | 9.5250  | 9.5504  | 9.5758  | 9.6012  | 9.6266  |
| 0.380            | 9.6520      | 9.6774  | 9.7028  | 9.7282  | 9.7536  | 9.7790  | 9.8044  | 9.8298  | 9.8552  | 9.8806  |
| 0.390            | 9.9060      | 9.9314  | 9.9568  | 9.9822  | 10.0076 | 10.0330 | 10.0584 | 10.0838 | 10.1092 | 10.1346 |
| 0.400            | 10.1600     | 10.1854 | 10.2108 | 10.2362 | 10.2616 | 10.2870 | 10.3124 | 10.3378 | 10.3632 | 10.3886 |
| 0.410            | 10.4140     | 10.4394 | 10.4648 | 10.4902 | 10.5156 | 10.5410 | 10.5664 | 10.5918 | 10.6172 | 10.6426 |
| 0.420            | 10.6680     | 10.6934 | 10.7188 | 10.7442 | 10.7696 | 10.7950 | 10.8204 | 10.8458 | 10.8712 | 10.8966 |
| 0.430            | 10.9220     | 10.9474 | 10.9728 | 10.9982 | 11.0236 | 11.0490 | 11.0744 | 11.0998 | 11.1252 | 11.1506 |
| 0.440            | 11.1760     | 11.2014 | 11.2268 | 11.2522 | 11.2776 | 11.3030 | 11.3284 | 11.3538 | 11.3792 | 11.4046 |
| 0.450            | 11.4300     | 11.4554 | 11.4808 | 11.5062 | 11.5316 | 11.5570 | 11.5824 | 11.6078 | 11.6332 | 11.6586 |
| 0.460            | 11.6840     | 11.7094 | 11.7348 | 11.7602 | 11.7856 | 11.8110 | 11.8364 | 11.8618 | 11.8872 | 11.9126 |
| 0.470            | 11.9380     | 11.9634 | 11.9888 | 12.0142 | 12.0396 | 12.0650 | 12.0904 | 12.1158 | 12.1412 | 12.1666 |
| 0.480            | 12.1920     | 12.2174 | 12.2428 | 12.2682 | 12.2936 | 12.3190 | 12.3444 | 12.3698 | 12.3952 | 12.4206 |
| 0.490            | 12.4460     | 12.4714 | 12.4968 | 12.5222 | 12.5476 | 12.5730 | 12.5984 | 12.6238 | 12.6492 | 12.6746 |
| 0.500            | 12.7000     | 12.7254 | 12.7508 | 12.7762 | 12.8016 | 12.8270 | 12.8524 | 12.8778 | 12.9032 | 12.9286 |

Table 11. (Continued) Decimals of an Inch to Millimeters Conversion

| Inches<br>↓ | 0.000       | 0.001   | 0.002   | 0.003   | 0.004   | 0.005   | 0.006   | 0.007   | 0.008   | 0.009   |
|-------------|-------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|             | Millimeters |         |         |         |         |         |         |         |         |         |
| 0.510       | 12.9540     | 12.9794 | 13.0048 | 13.0302 | 13.0556 | 13.0810 | 13.1064 | 13.1318 | 13.1572 | 13.1826 |
| 0.520       | 13.2080     | 13.2334 | 13.2588 | 13.2842 | 13.3096 | 13.3350 | 13.3604 | 13.3858 | 13.4112 | 13.4366 |
| 0.530       | 13.4620     | 13.4874 | 13.5128 | 13.5382 | 13.5636 | 13.5890 | 13.6144 | 13.6398 | 13.6652 | 13.6906 |
| 0.540       | 13.7160     | 13.7414 | 13.7668 | 13.7922 | 13.8176 | 13.8430 | 13.8684 | 13.8938 | 13.9192 | 13.9446 |
| 0.550       | 13.9700     | 13.9954 | 14.0208 | 14.0462 | 14.0716 | 14.0970 | 14.1224 | 14.1478 | 14.1732 | 14.1986 |
| 0.560       | 14.2240     | 14.2494 | 14.2748 | 14.3002 | 14.3256 | 14.3510 | 14.3764 | 14.4018 | 14.4272 | 14.4526 |
| 0.570       | 14.4780     | 14.5034 | 14.5288 | 14.5542 | 14.5796 | 14.6050 | 14.6304 | 14.6558 | 14.6812 | 14.7066 |
| 0.580       | 14.7320     | 14.7574 | 14.7828 | 14.8082 | 14.8336 | 14.8590 | 14.8844 | 14.9098 | 14.9352 | 14.9606 |
| 0.590       | 14.9860     | 15.0114 | 15.0368 | 15.0622 | 15.0876 | 15.1130 | 15.1384 | 15.1638 | 15.1892 | 15.2146 |
| 0.600       | 15.2400     | 15.2654 | 15.2908 | 15.3162 | 15.3416 | 15.3670 | 15.3924 | 15.4178 | 15.4432 | 15.4686 |
| 0.610       | 15.4940     | 15.5194 | 15.5448 | 15.5702 | 15.5956 | 15.6210 | 15.6464 | 15.6718 | 15.6972 | 15.7226 |
| 0.620       | 15.7480     | 15.7734 | 15.7988 | 15.8242 | 15.8496 | 15.8750 | 15.9004 | 15.9258 | 15.9512 | 15.9766 |
| 0.630       | 16.0020     | 16.0274 | 16.0528 | 16.0782 | 16.1036 | 16.1290 | 16.1544 | 16.1798 | 16.2052 | 16.2306 |
| 0.640       | 16.2560     | 16.2814 | 16.3068 | 16.3322 | 16.3576 | 16.3830 | 16.4084 | 16.4338 | 16.4592 | 16.4846 |
| 0.650       | 16.5100     | 16.5354 | 16.5608 | 16.5862 | 16.6116 | 16.6370 | 16.6624 | 16.6878 | 16.7132 | 16.7386 |
| 0.660       | 16.7640     | 16.7894 | 16.8148 | 16.8402 | 16.8656 | 16.8910 | 16.9164 | 16.9418 | 16.9672 | 16.9926 |
| 0.670       | 17.0180     | 17.0434 | 17.0688 | 17.0942 | 17.1196 | 17.1450 | 17.1704 | 17.1958 | 17.2212 | 17.2466 |
| 0.680       | 17.2720     | 17.2974 | 17.3228 | 17.3482 | 17.3736 | 17.3990 | 17.4244 | 17.4498 | 17.4752 | 17.5006 |
| 0.690       | 17.5260     | 17.5514 | 17.5768 | 17.6022 | 17.6276 | 17.6530 | 17.6784 | 17.7038 | 17.7292 | 17.7546 |
| 0.700       | 17.7800     | 17.8054 | 17.8308 | 17.8562 | 17.8816 | 17.9070 | 17.9324 | 17.9578 | 17.9832 | 18.0086 |
| 0.710       | 18.0340     | 18.0594 | 18.0848 | 18.1102 | 18.1356 | 18.1610 | 18.1864 | 18.2118 | 18.2372 | 18.2626 |
| 0.720       | 18.2880     | 18.3134 | 18.3388 | 18.3642 | 18.3896 | 18.4150 | 18.4404 | 18.4658 | 18.4912 | 18.5166 |
| 0.730       | 18.5420     | 18.5674 | 18.5928 | 18.6182 | 18.6436 | 18.6690 | 18.6944 | 18.7198 | 18.7452 | 18.7706 |
| 0.740       | 18.7960     | 18.8214 | 18.8468 | 18.8722 | 18.8976 | 18.9230 | 18.9484 | 18.9738 | 18.9992 | 19.0246 |
| 0.750       | 19.0500     | 19.0754 | 19.1008 | 19.1262 | 19.1516 | 19.1770 | 19.2024 | 19.2278 | 19.2532 | 19.2786 |
| 0.760       | 19.3040     | 19.3294 | 19.3548 | 19.3802 | 19.4056 | 19.4310 | 19.4564 | 19.4818 | 19.5072 | 19.5326 |
| 0.770       | 19.5580     | 19.5834 | 19.6088 | 19.6342 | 19.6596 | 19.6850 | 19.7104 | 19.7358 | 19.7612 | 19.7866 |
| 0.780       | 19.8120     | 19.8374 | 19.8628 | 19.8882 | 19.9136 | 19.9390 | 19.9644 | 19.9898 | 20.0152 | 20.0406 |
| 0.790       | 20.0660     | 20.0914 | 20.1168 | 20.1422 | 20.1676 | 20.1930 | 20.2184 | 20.2438 | 20.2692 | 20.2946 |
| 0.800       | 20.3200     | 20.3454 | 20.3708 | 20.3962 | 20.4216 | 20.4470 | 20.4724 | 20.4978 | 20.5232 | 20.5486 |
| 0.810       | 20.5740     | 20.5994 | 20.6248 | 20.6502 | 20.6756 | 20.7010 | 20.7264 | 20.7518 | 20.7772 | 20.8026 |
| 0.820       | 20.8280     | 20.8534 | 20.8788 | 20.9042 | 20.9296 | 20.9550 | 20.9804 | 21.0058 | 21.0312 | 21.0566 |
| 0.830       | 21.0820     | 21.1074 | 21.1328 | 21.1582 | 21.1836 | 21.2090 | 21.2344 | 21.2598 | 21.2852 | 21.3106 |
| 0.840       | 21.3360     | 21.3614 | 21.3868 | 21.4122 | 21.4376 | 21.4630 | 21.4884 | 21.5138 | 21.5392 | 21.5646 |
| 0.850       | 21.5900     | 21.6154 | 21.6408 | 21.6662 | 21.6916 | 21.7170 | 21.7424 | 21.7678 | 21.7932 | 21.8186 |
| 0.860       | 21.8440     | 21.8694 | 21.8948 | 21.9202 | 21.9456 | 21.9710 | 21.9964 | 22.0218 | 22.0472 | 22.0726 |
| 0.870       | 22.0980     | 22.1234 | 22.1488 | 22.1742 | 22.1996 | 22.2250 | 22.2504 | 22.2758 | 22.3012 | 22.3266 |
| 0.880       | 22.3520     | 22.3774 | 22.4028 | 22.4282 | 22.4536 | 22.4790 | 22.5044 | 22.5298 | 22.5552 | 22.5806 |
| 0.890       | 22.6060     | 22.6314 | 22.6568 | 22.6822 | 22.7076 | 22.7330 | 22.7584 | 22.7838 | 22.8092 | 22.8346 |
| 0.900       | 22.8600     | 22.8854 | 22.9108 | 22.9362 | 22.9616 | 22.9870 | 23.0124 | 23.0378 | 23.0632 | 23.0886 |
| 0.910       | 23.1140     | 23.1394 | 23.1648 | 23.1902 | 23.2156 | 23.2410 | 23.2664 | 23.2918 | 23.3172 | 23.3426 |
| 0.920       | 23.3680     | 23.3934 | 23.4188 | 23.4442 | 23.4696 | 23.4950 | 23.5204 | 23.5458 | 23.5712 | 23.5966 |
| 0.930       | 23.6220     | 23.6474 | 23.6728 | 23.6982 | 23.7236 | 23.7490 | 23.7744 | 23.7998 | 23.8252 | 23.8506 |
| 0.940       | 23.8760     | 23.9014 | 23.9268 | 23.9522 | 23.9776 | 24.0030 | 24.0284 | 24.0538 | 24.0792 | 24.1046 |
| 0.950       | 24.1300     | 24.1554 | 24.1808 | 24.2062 | 24.2316 | 24.2570 | 24.2824 | 24.3078 | 24.3332 | 24.3586 |
| 0.960       | 24.3840     | 24.4094 | 24.4348 | 24.4602 | 24.4856 | 24.5110 | 24.5364 | 24.5618 | 24.5872 | 24.6126 |
| 0.970       | 24.6380     | 24.6634 | 24.6888 | 24.7142 | 24.7396 | 24.7650 | 24.7904 | 24.8158 | 24.8412 | 24.8666 |
| 0.980       | 24.8920     | 24.9174 | 24.9428 | 24.9682 | 24.9936 | 25.0190 | 25.0444 | 25.0698 | 25.0952 | 25.1206 |
| 0.990       | 25.1460     | 25.1714 | 25.1968 | 25.2222 | 25.2476 | 25.2730 | 25.2984 | 25.3238 | 25.3492 | 25.3746 |
| 1.000       | 25.4000     | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     |

Based on 1 inch = 25.4 millimeters, exactly. All values in this table are exact. Use Table 8a to obtain whole inch and other decimal equivalents to add to decimal equivalents above. Example: Convert 10.9983 in. to mm. Solution: 10.9983 in. = 254.0 + 25.3492 + 0.00762 = 279.35682 mm.

## MILLIMETER TO INCH CONVERSION

Table 12. Millimeters to Inches Conversion

| →<br>Millimeters<br>↓ | 0       | 1       | 2       | 3       | 4        | 5       | 6       | 7       | 8       | 9       |
|-----------------------|---------|---------|---------|---------|----------|---------|---------|---------|---------|---------|
|                       | Inches  |         |         |         |          |         |         |         |         |         |
| 0                     | ...     | 0.03937 | 0.07874 | 0.11811 | 0.15748  | 0.19685 | 0.23622 | 0.27559 | 0.31496 | 0.35433 |
| 10                    | 0.39370 | 0.43307 | 0.47244 | 0.51181 | 0.55118  | 0.59055 | 0.62992 | 0.66929 | 0.70866 | 0.74803 |
| 20                    | 0.78740 | 0.82677 | 0.86614 | 0.90551 | 0.94488  | 0.98425 | 1.02362 | 1.06299 | 1.10236 | 1.14173 |
| 30                    | 1.18110 | 1.22047 | 1.25984 | 1.29921 | 1.33858  | 1.37795 | 1.41732 | 1.45669 | 1.49606 | 1.53543 |
| 40                    | 1.57480 | 1.61417 | 1.65354 | 1.69291 | 1.73228  | 1.77165 | 1.81102 | 1.85039 | 1.88976 | 1.92913 |
| 50                    | 1.96850 | 2.00787 | 2.04724 | 2.08661 | 2.12598  | 2.16535 | 2.20472 | 2.24409 | 2.28346 | 2.32283 |
| 60                    | 2.36220 | 2.40157 | 2.44094 | 2.48031 | 2.51969  | 2.55906 | 2.59843 | 2.63780 | 2.67717 | 2.71654 |
| 70                    | 2.75591 | 2.79528 | 2.83465 | 2.87402 | 2.91339  | 2.95276 | 2.99213 | 3.03150 | 3.07087 | 3.11024 |
| 80                    | 3.14961 | 3.18898 | 3.22835 | 3.26772 | 3.30709  | 3.34646 | 3.38583 | 3.42520 | 3.46457 | 3.50394 |
| 90                    | 3.54331 | 3.58268 | 3.62205 | 3.66142 | 3.70079  | 3.74016 | 3.77953 | 3.81890 | 3.85827 | 3.89764 |
| 100                   | 3.93701 | 3.97638 | 4.01575 | 4.05512 | 4.09449  | 4.13386 | 4.17323 | 4.21260 | 4.25197 | 4.29134 |
| 110                   | 4.33071 | 4.37008 | 4.40945 | 4.44882 | 4.48819  | 4.52756 | 4.56693 | 4.60630 | 4.64567 | 4.68504 |
| 120                   | 4.72441 | 4.76378 | 4.80315 | 4.84252 | 4.88189  | 4.92126 | 4.96063 | 5.00000 | 5.03937 | 5.07874 |
| 130                   | 5.11811 | 5.15748 | 5.19685 | 5.23622 | 5.27559  | 5.31496 | 5.35433 | 5.39370 | 5.43307 | 5.47244 |
| 140                   | 5.51181 | 5.55118 | 5.59055 | 5.62992 | 5.66929  | 5.70866 | 5.74803 | 5.78740 | 5.82677 | 5.86614 |
| 150                   | 5.90551 | 5.94488 | 5.98425 | 6.02362 | 6.06299  | 6.10236 | 6.14173 | 6.18110 | 6.22047 | 6.25984 |
| 160                   | 6.29921 | 6.33858 | 6.37795 | 6.41732 | 6.45669  | 6.49606 | 6.53543 | 6.57480 | 6.61417 | 6.65354 |
| 170                   | 6.69291 | 6.73228 | 6.77165 | 6.81102 | 6.85039  | 6.88976 | 6.92913 | 6.96850 | 7.00787 | 7.04724 |
| 180                   | 7.08661 | 7.12598 | 7.16535 | 7.20472 | 7.24409  | 7.28346 | 7.32283 | 7.36220 | 7.40157 | 7.44094 |
| 190                   | 7.48031 | 7.51969 | 7.55906 | 7.59843 | 7.63780  | 7.67717 | 7.71654 | 7.75591 | 7.79528 | 7.83465 |
| 200                   | 7.87402 | 7.91339 | 7.95276 | 7.99213 | 8.03150  | 8.07087 | 8.11024 | 8.14961 | 8.18898 | 8.22835 |
| 210                   | 8.26772 | 8.30709 | 8.34646 | 8.38583 | 8.42520  | 8.46457 | 8.50394 | 8.54331 | 8.58268 | 8.62205 |
| 220                   | 8.66142 | 8.70079 | 8.74016 | 8.77953 | 8.81890  | 8.85827 | 8.89764 | 8.93701 | 8.97638 | 9.01575 |
| 230                   | 9.05512 | 9.09449 | 9.13386 | 9.17323 | 9.21260  | 9.25197 | 9.29134 | 9.33071 | 9.37008 | 9.40945 |
| 240                   | 9.44882 | 9.48819 | 9.52756 | 9.56693 | 9.60630  | 9.64567 | 9.68504 | 9.72441 | 9.76378 | 9.80315 |
| 250                   | 9.84252 | 9.88189 | 9.92126 | 9.96063 | 10.00000 | 10.0394 | 10.0787 | 10.1181 | 10.1575 | 10.1969 |
| 260                   | 10.2362 | 10.2756 | 10.3150 | 10.3543 | 10.3937  | 10.4331 | 10.4724 | 10.5118 | 10.5512 | 10.5906 |
| 270                   | 10.6299 | 10.6693 | 10.7087 | 10.7480 | 10.7874  | 10.8268 | 10.8661 | 10.9055 | 10.9449 | 10.9843 |
| 280                   | 11.0236 | 11.0630 | 11.1024 | 11.1417 | 11.1811  | 11.2205 | 11.2598 | 11.2992 | 11.3386 | 11.3780 |
| 290                   | 11.4173 | 11.4567 | 11.4961 | 11.5354 | 11.5748  | 11.6142 | 11.6535 | 11.6929 | 11.7323 | 11.7717 |
| 300                   | 11.8110 | 11.8504 | 11.8898 | 11.9291 | 11.9685  | 12.0079 | 12.0472 | 12.0866 | 12.1260 | 12.1654 |
| 310                   | 12.2047 | 12.2441 | 12.2835 | 12.3228 | 12.3622  | 12.4016 | 12.4409 | 12.4803 | 12.5197 | 12.5591 |
| 320                   | 12.5984 | 12.6378 | 12.6772 | 12.7165 | 12.7559  | 12.7953 | 12.8346 | 12.8740 | 12.9134 | 12.9528 |
| 330                   | 12.9921 | 13.0315 | 13.0709 | 13.1102 | 13.1496  | 13.1890 | 13.2283 | 13.2677 | 13.3071 | 13.3465 |
| 340                   | 13.3858 | 13.4252 | 13.4646 | 13.5039 | 13.5433  | 13.5827 | 13.6220 | 13.6614 | 13.7008 | 13.7402 |
| 350                   | 13.7795 | 13.8189 | 13.8583 | 13.8976 | 13.9370  | 13.9764 | 14.0157 | 14.0551 | 14.0945 | 14.1339 |
| 360                   | 14.1732 | 14.2126 | 14.2520 | 14.2913 | 14.3307  | 14.3701 | 14.4094 | 14.4488 | 14.4882 | 14.5276 |
| 370                   | 14.5669 | 14.6063 | 14.6457 | 14.6850 | 14.7244  | 14.7638 | 14.8031 | 14.8425 | 14.8819 | 14.9213 |
| 380                   | 14.9606 | 15.0000 | 15.0394 | 15.0787 | 15.1181  | 15.1575 | 15.1969 | 15.2362 | 15.2756 | 15.3150 |
| 390                   | 15.3543 | 15.3937 | 15.4331 | 15.4724 | 15.5118  | 15.5512 | 15.5906 | 15.6299 | 15.6693 | 15.7087 |
| 400                   | 15.7480 | 15.7874 | 15.8268 | 15.8661 | 15.9055  | 15.9449 | 15.9843 | 16.0236 | 16.0630 | 16.1024 |
| 410                   | 16.1417 | 16.1811 | 16.2205 | 16.2598 | 16.2992  | 16.3386 | 16.3780 | 16.4173 | 16.4567 | 16.4961 |
| 420                   | 16.5354 | 16.5748 | 16.6142 | 16.6535 | 16.6929  | 16.7323 | 16.7717 | 16.8110 | 16.8504 | 16.8898 |
| 430                   | 16.9291 | 16.9685 | 17.0079 | 17.0472 | 17.0866  | 17.1260 | 17.1654 | 17.2047 | 17.2441 | 17.2835 |
| 440                   | 17.3228 | 17.3622 | 17.4016 | 17.4409 | 17.4803  | 17.5197 | 17.5591 | 17.5984 | 17.6378 | 17.6772 |
| 450                   | 17.7165 | 17.7559 | 17.7953 | 17.8346 | 17.8740  | 17.9134 | 17.9528 | 17.9921 | 18.0315 | 18.0709 |
| 460                   | 18.1102 | 18.1496 | 18.1890 | 18.2283 | 18.2677  | 18.3071 | 18.3465 | 18.3858 | 18.4252 | 18.4646 |
| 470                   | 18.5039 | 18.5433 | 18.5827 | 18.6220 | 18.6614  | 18.7008 | 18.7402 | 18.7795 | 18.8189 | 18.8583 |
| 480                   | 18.8976 | 18.9370 | 18.9764 | 19.0157 | 19.0551  | 19.0945 | 19.1339 | 19.1732 | 19.2126 | 19.2520 |
| 490                   | 19.2913 | 19.3307 | 19.3701 | 19.4094 | 19.4488  | 19.4882 | 19.5276 | 19.5669 | 19.6063 | 19.6457 |

Table 12. (Continued) Millimeters to Inches Conversion

| →<br>Millimeters<br>↓ | 0       | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | 9       |
|-----------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|                       | Inches  |         |         |         |         |         |         |         |         |         |
| 500                   | 19.6850 | 19.7244 | 19.7638 | 19.8031 | 19.8425 | 19.8819 | 19.9213 | 19.9606 | 20.0000 | 20.0394 |
| 510                   | 20.0787 | 20.1181 | 20.1575 | 20.1969 | 20.2362 | 20.2756 | 20.3150 | 20.3543 | 20.3937 | 20.4331 |
| 520                   | 20.4724 | 20.5118 | 20.5512 | 20.5906 | 20.6299 | 20.6693 | 20.7087 | 20.7480 | 20.7874 | 20.8268 |
| 530                   | 20.8661 | 20.9055 | 20.9449 | 20.9843 | 21.0236 | 21.0630 | 21.1024 | 21.1417 | 21.1811 | 21.2205 |
| 540                   | 21.2598 | 21.2992 | 21.3386 | 21.3780 | 21.4173 | 21.4567 | 21.4961 | 21.5354 | 21.5748 | 21.6142 |
| 550                   | 21.6535 | 21.6929 | 21.7323 | 21.7717 | 21.8110 | 21.8504 | 21.8898 | 21.9291 | 21.9685 | 22.0079 |
| 560                   | 22.0472 | 22.0866 | 22.1260 | 22.1654 | 22.2047 | 22.2441 | 22.2835 | 22.3228 | 22.3622 | 22.4016 |
| 570                   | 22.4409 | 22.4803 | 22.5197 | 22.5591 | 22.5984 | 22.6378 | 22.6772 | 22.7165 | 22.7559 | 22.7953 |
| 580                   | 22.8346 | 22.8740 | 22.9134 | 22.9528 | 22.9921 | 23.0315 | 23.0709 | 23.1102 | 23.1496 | 23.1890 |
| 590                   | 23.2283 | 23.2677 | 23.3071 | 23.3465 | 23.3858 | 23.4252 | 23.4646 | 23.5039 | 23.5433 | 23.5827 |
| 600                   | 23.6220 | 23.6614 | 23.7008 | 23.7402 | 23.7795 | 23.8189 | 23.8583 | 23.8976 | 23.9370 | 23.9764 |
| 610                   | 24.0157 | 24.0551 | 24.0945 | 24.1339 | 24.1732 | 24.2126 | 24.2520 | 24.2913 | 24.3307 | 24.3701 |
| 620                   | 24.4094 | 24.4488 | 24.4882 | 24.5276 | 24.5669 | 24.6063 | 24.6457 | 24.6850 | 24.7244 | 24.7638 |
| 630                   | 24.8031 | 24.8425 | 24.8819 | 24.9213 | 24.9606 | 25.0000 | 25.0394 | 25.0787 | 25.1181 | 25.1575 |
| 640                   | 25.1969 | 25.2362 | 25.2756 | 25.3150 | 25.3543 | 25.3937 | 25.4331 | 25.4724 | 25.5118 | 25.5512 |
| 650                   | 25.5906 | 25.6299 | 25.6693 | 25.7087 | 25.7480 | 25.7874 | 25.8268 | 25.8661 | 25.9055 | 25.9449 |
| 660                   | 25.9843 | 26.0236 | 26.0630 | 26.1024 | 26.1417 | 26.1811 | 26.2205 | 26.2598 | 26.2992 | 26.3386 |
| 670                   | 26.3780 | 26.4173 | 26.4567 | 26.4961 | 26.5354 | 26.5748 | 26.6142 | 26.6535 | 26.6929 | 26.7323 |
| 680                   | 26.7717 | 26.8110 | 26.8504 | 26.8898 | 26.9291 | 26.9685 | 27.0079 | 27.0472 | 27.0866 | 27.1260 |
| 690                   | 27.1654 | 27.2047 | 27.2441 | 27.2835 | 27.3228 | 27.3622 | 27.4016 | 27.4409 | 27.4803 | 27.5197 |
| 700                   | 27.5591 | 27.5984 | 27.6378 | 27.6772 | 27.7165 | 27.7559 | 27.7953 | 27.8346 | 27.8740 | 27.9134 |
| 710                   | 27.9528 | 27.9921 | 28.0315 | 28.0709 | 28.1102 | 28.1496 | 28.1890 | 28.2283 | 28.2677 | 28.3071 |
| 720                   | 28.3465 | 28.3858 | 28.4252 | 28.4646 | 28.5039 | 28.5433 | 28.5827 | 28.6220 | 28.6614 | 28.7008 |
| 730                   | 28.7402 | 28.7795 | 28.8189 | 28.8583 | 28.8976 | 28.9370 | 28.9764 | 29.0157 | 29.0551 | 29.0945 |
| 740                   | 29.1339 | 29.1732 | 29.2126 | 29.2520 | 29.2913 | 29.3307 | 29.3701 | 29.4094 | 29.4488 | 29.4882 |
| 750                   | 29.5276 | 29.5669 | 29.6063 | 29.6457 | 29.6850 | 29.7244 | 29.7638 | 29.8031 | 29.8425 | 29.8819 |
| 760                   | 29.9213 | 29.9606 | 30.0000 | 30.0394 | 30.0787 | 30.1181 | 30.1575 | 30.1969 | 30.2362 | 30.2756 |
| 770                   | 30.3150 | 30.3543 | 30.3937 | 30.4331 | 30.4724 | 30.5118 | 30.5512 | 30.5906 | 30.6299 | 30.6693 |
| 780                   | 30.7087 | 30.7480 | 30.7874 | 30.8268 | 30.8661 | 30.9055 | 30.9449 | 30.9843 | 31.0236 | 31.0630 |
| 790                   | 31.1024 | 31.1417 | 31.1811 | 31.2205 | 31.2598 | 31.2992 | 31.3386 | 31.3780 | 31.4173 | 31.4567 |
| 800                   | 31.4961 | 31.5354 | 31.5748 | 31.6142 | 31.6535 | 31.6929 | 31.7323 | 31.7717 | 31.8110 | 31.8504 |
| 810                   | 31.8898 | 31.9291 | 31.9685 | 32.0079 | 32.0472 | 32.0866 | 32.1260 | 32.1654 | 32.2047 | 32.2441 |
| 820                   | 32.2835 | 32.3228 | 32.3622 | 32.4016 | 32.4409 | 32.4803 | 32.5197 | 32.5591 | 32.5984 | 32.6378 |
| 830                   | 32.6772 | 32.7165 | 32.7559 | 32.7953 | 32.8346 | 32.8740 | 32.9134 | 32.9528 | 32.9921 | 33.0315 |
| 840                   | 33.0709 | 33.1102 | 33.1496 | 33.1890 | 33.2283 | 33.2677 | 33.3071 | 33.3465 | 33.3858 | 33.4252 |
| 850                   | 33.4646 | 33.5039 | 33.5433 | 33.5827 | 33.6220 | 33.6614 | 33.7008 | 33.7402 | 33.7795 | 33.8189 |
| 860                   | 33.8583 | 33.8976 | 33.9370 | 33.9764 | 34.0157 | 34.0551 | 34.0945 | 34.1339 | 34.1732 | 34.2126 |
| 870                   | 34.2520 | 34.2913 | 34.3307 | 34.3701 | 34.4094 | 34.4488 | 34.4882 | 34.5276 | 34.5669 | 34.6063 |
| 880                   | 34.6457 | 34.6850 | 34.7244 | 34.7638 | 34.8031 | 34.8425 | 34.8819 | 34.9213 | 34.9606 | 35.0000 |
| 890                   | 35.0394 | 35.0787 | 35.1181 | 35.1575 | 35.1969 | 35.2362 | 35.2756 | 35.3150 | 35.3543 | 35.3937 |
| 900                   | 35.4331 | 35.4724 | 35.5118 | 35.5512 | 35.5906 | 35.6299 | 35.6693 | 35.7087 | 35.7480 | 35.7874 |
| 910                   | 35.8268 | 35.8661 | 35.9055 | 35.9449 | 35.9843 | 36.0236 | 36.0630 | 36.1024 | 36.1417 | 36.1811 |
| 920                   | 36.2205 | 36.2598 | 36.2992 | 36.3386 | 36.3780 | 36.4173 | 36.4567 | 36.4961 | 36.5354 | 36.5748 |
| 930                   | 36.6142 | 36.6535 | 36.6929 | 36.7323 | 36.7717 | 36.8110 | 36.8504 | 36.8898 | 36.9291 | 36.9685 |
| 940                   | 37.0079 | 37.0472 | 37.0866 | 37.1260 | 37.1654 | 37.2047 | 37.2441 | 37.2835 | 37.3228 | 37.3622 |
| 950                   | 37.4016 | 37.409  | 37.4803 | 37.5197 | 37.5591 | 37.5984 | 37.6378 | 37.6772 | 37.7165 | 37.7559 |
| 960                   | 37.7953 | 37.8346 | 37.8740 | 37.9134 | 37.9528 | 37.9921 | 38.0315 | 38.0709 | 38.1102 | 38.1496 |
| 970                   | 38.1800 | 38.2283 | 38.2677 | 38.3071 | 38.3465 | 38.3858 | 38.4252 | 38.4646 | 38.5039 | 38.5433 |
| 980                   | 38.5827 | 38.6220 | 38.6614 | 38.7008 | 38.7402 | 38.7795 | 38.8189 | 38.8583 | 38.8976 | 38.9370 |
| 990                   | 38.9764 | 39.0157 | 39.0551 | 39.0945 | 39.1339 | 39.1732 | 39.2126 | 39.2520 | 39.2913 | 39.3307 |
| 1000                  | 39.3701 | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     |

Based on 1 inch = 25.4 millimeters, exactly.

**Table 13a. Microinches to Micrometers (microns) Conversion**

| →<br>Microinches<br>↓ | 0                     | 1       | 2       | 3       | 4       | 5      | 6       | 7       | 8       | 9       |
|-----------------------|-----------------------|---------|---------|---------|---------|--------|---------|---------|---------|---------|
|                       | Micrometers (microns) |         |         |         |         |        |         |         |         |         |
| 0                     | 0                     | 0.0254  | 0.0508  | 0.0762  | 0.1016  | 0.127  | 0.1524  | 0.1778  | 0.2032  | 0.2286  |
| 10                    | 0.254                 | 0.2794  | 0.3048  | 0.3302  | 0.3556  | 0.381  | 0.4064  | 0.4318  | 0.4572  | 0.4826  |
| 20                    | 0.508                 | 0.5334  | 0.5588  | 0.5842  | 0.6096  | 0.635  | 0.6604  | 0.6858  | 0.7112  | 0.7366  |
| 30                    | 0.762                 | 0.7874  | 0.8128  | 0.8382  | 0.8636  | 0.889  | 0.9144  | 0.9398  | 0.9652  | 0.9906  |
| 40                    | 1.016                 | 1.0414  | 1.0668  | 1.0922  | 1.1176  | 1.143  | 1.1684  | 1.1938  | 1.2192  | 1.2446  |
| 50                    | 1.27                  | 1.2954  | 1.3208  | 1.3462  | 1.3716  | 1.397  | 1.4224  | 1.4478  | 1.4732  | 1.4986  |
| 60                    | 1.524                 | 1.5494  | 1.5748  | 1.6002  | 1.6256  | 1.651  | 1.6764  | 1.7018  | 1.7272  | 1.7526  |
| 70                    | 1.778                 | 1.8034  | 1.8288  | 1.8542  | 1.8796  | 1.905  | 1.9304  | 1.9558  | 1.9812  | 2.0066  |
| 80                    | 2.032                 | 2.0574  | 2.0828  | 2.1082  | 2.1336  | 2.159  | 2.1844  | 2.2098  | 2.2352  | 2.2606  |
| 90                    | 2.286                 | 2.3114  | 2.3368  | 2.3622  | 2.3876  | 2.413  | 2.4384  | 2.4638  | 2.4892  | 2.5146  |
| 100                   | 2.54                  | 2.5654  | 2.5908  | 2.6162  | 2.6416  | 2.667  | 2.6924  | 2.7178  | 2.7432  | 2.7686  |
| 110                   | 2.794                 | 2.8194  | 2.8448  | 2.8702  | 2.8956  | 2.921  | 2.9464  | 2.9718  | 2.9972  | 3.0226  |
| 120                   | 3.048                 | 3.0734  | 3.0988  | 3.1242  | 3.1496  | 3.175  | 3.2004  | 3.2258  | 3.2512  | 3.2766  |
| 130                   | 3.302                 | 3.3274  | 3.3528  | 3.3782  | 3.4036  | 3.429  | 3.4544  | 3.4798  | 3.5052  | 3.5306  |
| 140                   | 3.556                 | 3.5814  | 3.6068  | 3.6322  | 3.6576  | 3.683  | 3.7084  | 3.7338  | 3.7592  | 3.7846  |
| 150                   | 3.81                  | 3.8354  | 3.8608  | 3.8862  | 3.9116  | 3.937  | 3.9624  | 3.9878  | 4.0132  | 4.0386  |
| 160                   | 4.064                 | 4.0894  | 4.1148  | 4.1402  | 4.1656  | 4.191  | 4.2164  | 4.2418  | 4.2672  | 4.2926  |
| 170                   | 4.318                 | 4.3434  | 4.3688  | 4.3942  | 4.4196  | 4.445  | 4.4704  | 4.4958  | 4.5212  | 4.5466  |
| 180                   | 4.572                 | 4.5974  | 4.6228  | 4.6482  | 4.6736  | 4.699  | 4.7244  | 4.7498  | 4.7752  | 4.8006  |
| 190                   | 4.826                 | 4.8514  | 4.8768  | 4.9022  | 4.9276  | 4.953  | 4.9784  | 5.0038  | 5.0292  | 5.0546  |
| 200                   | 5.08                  | 5.1054  | 5.1308  | 5.1562  | 5.1816  | 5.207  | 5.2324  | 5.2578  | 5.2832  | 5.3086  |
| 210                   | 5.334                 | 5.3594  | 5.3848  | 5.4102  | 5.4356  | 5.461  | 5.4864  | 5.5118  | 5.5372  | 5.5626  |
| 220                   | 5.588                 | 5.6134  | 5.6388  | 5.6642  | 5.6896  | 5.715  | 5.7404  | 5.7658  | 5.7912  | 5.8166  |
| 230                   | 5.842                 | 5.8674  | 5.8928  | 5.9182  | 5.9436  | 5.969  | 5.9944  | 6.0198  | 6.0452  | 6.0706  |
| 240                   | 6.096                 | 6.1214  | 6.1468  | 6.1722  | 6.1976  | 6.223  | 6.2484  | 6.2738  | 6.2992  | 6.3246  |
| 250                   | 6.35                  | 6.3754  | 6.4008  | 6.4262  | 6.4516  | 6.477  | 6.5024  | 6.5278  | 6.5532  | 6.5786  |
| 260                   | 6.604                 | 6.6294  | 6.6548  | 6.6802  | 6.7056  | 6.731  | 6.7564  | 6.7818  | 6.8072  | 6.8326  |
| 270                   | 6.858                 | 6.8834  | 6.9088  | 6.9342  | 6.9596  | 6.985  | 7.0104  | 7.0358  | 7.0612  | 7.0866  |
| 280                   | 7.112                 | 7.1374  | 7.1628  | 7.1882  | 7.2136  | 7.239  | 7.2644  | 7.2898  | 7.3152  | 7.3406  |
| 290                   | 7.366                 | 7.3914  | 7.4168  | 7.4422  | 7.4676  | 7.493  | 7.5184  | 7.5438  | 7.5692  | 7.5946  |
| 300                   | 7.62                  | 7.6454  | 7.6708  | 7.6962  | 7.7216  | 7.747  | 7.7724  | 7.7978  | 7.8232  | 7.8486  |
| 310                   | 7.874                 | 7.8994  | 7.9248  | 7.9502  | 7.9756  | 8.001  | 8.0264  | 8.0518  | 8.0772  | 8.1026  |
| 320                   | 8.128                 | 8.1534  | 8.1788  | 8.2042  | 8.2296  | 8.255  | 8.2804  | 8.3058  | 8.3312  | 8.3566  |
| 330                   | 8.382                 | 8.4074  | 8.4328  | 8.4582  | 8.4836  | 8.509  | 8.5344  | 8.5598  | 8.5852  | 8.6106  |
| 340                   | 8.636                 | 8.6614  | 8.6868  | 8.7122  | 8.7376  | 8.763  | 8.7884  | 8.8138  | 8.8392  | 8.8646  |
| 350                   | 8.89                  | 8.9154  | 8.9408  | 8.9662  | 8.9916  | 9.017  | 9.0424  | 9.0678  | 9.0932  | 9.1186  |
| 360                   | 9.144                 | 9.1694  | 9.1948  | 9.2202  | 9.2456  | 9.271  | 9.2964  | 9.3218  | 9.3472  | 9.3726  |
| 370                   | 9.398                 | 9.4234  | 9.4488  | 9.4742  | 9.4996  | 9.525  | 9.5504  | 9.5758  | 9.6012  | 9.6266  |
| 380                   | 9.652                 | 9.6774  | 9.7028  | 9.7282  | 9.7536  | 9.779  | 9.8044  | 9.8298  | 9.8552  | 9.8806  |
| 390                   | 9.906                 | 9.9314  | 9.9568  | 9.9822  | 10.0076 | 10.033 | 10.0584 | 10.0838 | 10.1092 | 10.1346 |
| 400                   | 10.16                 | 10.1854 | 10.2108 | 10.2362 | 10.2616 | 10.287 | 10.3124 | 10.3378 | 10.3632 | 10.3886 |
| 410                   | 10.414                | 10.4394 | 10.4648 | 10.4902 | 10.5156 | 10.541 | 10.5664 | 10.5918 | 10.6172 | 10.6426 |
| 420                   | 10.668                | 10.6934 | 10.7188 | 10.7442 | 10.7696 | 10.795 | 10.8204 | 10.8458 | 10.8712 | 10.8966 |
| 430                   | 10.922                | 10.9474 | 10.9728 | 10.9982 | 11.0236 | 11.049 | 11.0744 | 11.0998 | 11.1252 | 11.1506 |
| 440                   | 11.176                | 11.2014 | 11.2268 | 11.2522 | 11.2776 | 11.303 | 11.3284 | 11.3538 | 11.3792 | 11.4046 |
| 450                   | 11.43                 | 11.4554 | 11.4808 | 11.5062 | 11.5316 | 11.557 | 11.5824 | 11.6078 | 11.6332 | 11.6586 |
| 460                   | 11.684                | 11.7094 | 11.7348 | 11.7602 | 11.7856 | 11.811 | 11.8364 | 11.8618 | 11.8872 | 11.9126 |
| 470                   | 11.938                | 11.9634 | 11.9888 | 12.0142 | 12.0396 | 12.065 | 12.0904 | 12.1158 | 12.1412 | 12.1666 |
| 480                   | 12.192                | 12.2174 | 12.2428 | 12.2682 | 12.2936 | 12.319 | 12.3444 | 12.3698 | 12.3952 | 12.4206 |
| 490                   | 12.446                | 12.4714 | 12.4968 | 12.5222 | 12.5476 | 12.573 | 12.5984 | 12.6238 | 12.6492 | 12.6746 |
| 500                   | 12.7                  | 12.7254 | 12.7508 | 12.7762 | 12.8016 | 12.827 | 12.8524 | 12.8778 | 12.9032 | 12.9286 |

Use the small table below to convert microinches to micrometers for ranges higher than given in the main table above. Appropriate quantities chosen from both tables are simply added to obtain the higher converted value:

| µin. | µm    | µin. | µm    | µin. | µm    | µin. | µm    | µin. | µm    |
|------|-------|------|-------|------|-------|------|-------|------|-------|
| 600  | 15.24 | 800  | 20.32 | 1000 | 25.4  | 1500 | 38.1  | 2100 | 53.34 |
| 700  | 17.78 | 900  | 22.86 | 1200 | 30.48 | 1800 | 45.72 | 2400 | 60.96 |

Both tables based on 1 microinch = 0.0254 micrometers, exactly. All values in both parts of this table are exact; figures to the right of the last place figures are all zeros.

*Example:* Convert 1375 µin. to µm:

$$\begin{array}{rcl}
 \text{From lower portion of Table 13a:} & 1200 \text{ } \mu\text{in.} & = & 30.48 \text{ } \mu\text{m} \\
 \text{From upper portion of Table 13a:} & 175 \text{ } \mu\text{in.} & = & 4.445 \text{ } \mu\text{m} \\
 & \underline{1375 \text{ } \mu\text{in.}} & = & \underline{34.925 \text{ } \mu\text{m}}
 \end{array}$$

**Table 13b. Micrometers (microns) to Microinches Conversion**

| →<br>Microns<br>↓ | 0           | 0.01     | 0.02     | 0.03     | 0.04     | 0.05     | 0.06     | 0.07     | 0.08     | 0.09     |
|-------------------|-------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|                   | Microinches |          |          |          |          |          |          |          |          |          |
| 0.00              | 0.0000      | 0.3937   | 0.7874   | 1.1811   | 1.5748   | 1.9685   | 2.3622   | 2.7559   | 3.1496   | 3.5433   |
| 0.10              | 3.9370      | 4.3307   | 4.7244   | 5.1181   | 5.5118   | 5.9055   | 6.2992   | 6.6929   | 7.0866   | 7.4803   |
| 0.20              | 7.8740      | 8.2677   | 8.6614   | 9.0551   | 9.4488   | 9.8425   | 10.2362  | 10.6299  | 11.0236  | 11.4173  |
| 0.30              | 11.8110     | 12.2047  | 12.5984  | 12.9921  | 13.3858  | 13.7795  | 14.1732  | 14.5669  | 14.9606  | 15.3543  |
| 0.40              | 15.7480     | 16.1417  | 16.5354  | 16.9291  | 17.3228  | 17.7165  | 18.1102  | 18.5039  | 18.8976  | 19.2913  |
| 0.50              | 19.6850     | 20.0787  | 20.4724  | 20.8661  | 21.2598  | 21.6535  | 22.0472  | 22.4409  | 22.8346  | 23.2283  |
| 0.60              | 23.6220     | 24.0157  | 24.4094  | 24.8031  | 25.1969  | 25.5906  | 25.9843  | 26.3780  | 26.7717  | 27.1654  |
| 0.70              | 27.5591     | 27.9528  | 28.3465  | 28.7402  | 29.1339  | 29.5276  | 29.9213  | 30.3150  | 30.7087  | 31.1024  |
| 0.80              | 31.4961     | 31.8898  | 32.2835  | 32.6772  | 33.0709  | 33.4646  | 33.8583  | 34.2520  | 34.6457  | 35.0394  |
| 0.90              | 35.4331     | 35.8268  | 36.2205  | 36.6142  | 37.0079  | 37.4016  | 37.7953  | 38.1890  | 38.5827  | 38.9764  |
| 1.00              | 39.3701     | 39.7638  | 40.1575  | 40.5512  | 40.9449  | 41.3386  | 41.7323  | 42.1260  | 42.5197  | 42.9134  |
| 1.10              | 43.3071     | 43.7008  | 44.0945  | 44.4882  | 44.8819  | 45.2756  | 45.6693  | 46.0630  | 46.4567  | 46.8504  |
| 1.20              | 47.2441     | 47.6378  | 48.0315  | 48.4252  | 48.8189  | 49.2126  | 49.6063  | 50.0000  | 50.3937  | 50.7874  |
| 1.30              | 51.1811     | 51.5748  | 51.9685  | 52.3622  | 52.7559  | 53.1496  | 53.5433  | 53.9370  | 54.3307  | 54.7244  |
| 1.40              | 55.1181     | 55.5118  | 55.9055  | 56.2992  | 56.6929  | 57.0866  | 57.4803  | 57.8740  | 58.2677  | 58.6614  |
| 1.50              | 59.0551     | 59.4488  | 59.8425  | 60.2362  | 60.6299  | 61.0236  | 61.4173  | 61.8110  | 62.2047  | 62.5984  |
| 1.60              | 62.9921     | 63.3858  | 63.7795  | 64.1732  | 64.5669  | 64.9606  | 65.3543  | 65.7480  | 66.1417  | 66.5354  |
| 1.70              | 66.9291     | 67.3228  | 67.7165  | 68.1102  | 68.5039  | 68.8976  | 69.2913  | 69.6850  | 70.0787  | 70.4724  |
| 1.80              | 70.8661     | 71.2598  | 71.6535  | 72.0472  | 72.4409  | 72.8346  | 73.2283  | 73.6220  | 74.0157  | 74.4094  |
| 1.90              | 74.8031     | 75.1969  | 75.5906  | 75.9843  | 76.3780  | 76.7717  | 77.1654  | 77.5591  | 77.9528  | 78.3465  |
| 2.00              | 78.7402     | 79.1339  | 79.5276  | 79.9213  | 80.3150  | 80.7087  | 81.1024  | 81.4961  | 81.8898  | 82.2835  |
| 2.10              | 82.6772     | 83.0709  | 83.4646  | 83.8583  | 84.2520  | 84.6457  | 85.0394  | 85.4331  | 85.8268  | 86.2205  |
| 2.20              | 86.6142     | 87.0079  | 87.4016  | 87.7953  | 88.1890  | 88.5827  | 88.9764  | 89.3701  | 89.7638  | 90.1575  |
| 2.30              | 90.5512     | 90.9449  | 91.3386  | 91.7323  | 92.1260  | 92.5197  | 92.9134  | 93.3071  | 93.7008  | 94.0945  |
| 2.40              | 94.4882     | 94.8819  | 95.2756  | 95.6693  | 96.0630  | 96.4567  | 96.8504  | 97.2441  | 97.6378  | 98.0315  |
| 2.50              | 98.4252     | 98.8189  | 99.2126  | 99.6063  | 100.0000 | 100.3937 | 100.7874 | 101.1811 | 101.5748 | 101.9685 |
| 2.60              | 102.3622    | 102.7559 | 103.1496 | 103.5433 | 103.9370 | 104.3307 | 104.7244 | 105.1181 | 105.5118 | 105.9055 |
| 2.70              | 106.2992    | 106.6929 | 107.0866 | 107.4803 | 107.8740 | 108.2677 | 108.6614 | 109.0551 | 109.4488 | 109.8425 |
| 2.80              | 110.2362    | 110.6299 | 111.0236 | 111.4173 | 111.8110 | 112.2047 | 112.5984 | 112.9921 | 113.3858 | 113.7795 |
| 2.90              | 114.1732    | 114.5669 | 114.9606 | 115.3543 | 115.7480 | 116.1417 | 116.5354 | 116.9291 | 117.3228 | 117.7165 |
| 3.00              | 118.1102    | 118.5039 | 118.8976 | 119.2913 | 119.6850 | 120.0787 | 120.4724 | 120.8661 | 121.2598 | 121.6535 |
| 3.10              | 122.0472    | 122.4409 | 122.8346 | 123.2283 | 123.6220 | 124.0157 | 124.4094 | 124.8031 | 125.1969 | 125.5906 |
| 3.20              | 125.9843    | 126.3780 | 126.7717 | 127.1654 | 127.5591 | 127.9528 | 128.3465 | 128.7402 | 129.1339 | 129.5276 |
| 3.30              | 129.9213    | 130.3150 | 130.7087 | 131.1024 | 131.4961 | 131.8898 | 132.2835 | 132.6772 | 133.0709 | 133.4646 |
| 3.40              | 133.8583    | 134.2520 | 134.6457 | 135.0394 | 135.4331 | 135.8268 | 136.2205 | 136.6142 | 137.0079 | 137.4016 |
| 3.50              | 137.7953    | 138.1890 | 138.5827 | 138.9764 | 139.3701 | 139.7638 | 140.1575 | 140.5512 | 140.9449 | 141.3386 |
| 3.60              | 141.7323    | 142.1260 | 142.5197 | 142.9134 | 143.3071 | 143.7008 | 144.0945 | 144.4882 | 144.8819 | 145.2756 |
| 3.70              | 145.6693    | 146.0630 | 146.4567 | 146.8504 | 147.2441 | 147.6378 | 148.0315 | 148.4252 | 148.8189 | 149.2126 |
| 3.80              | 149.6063    | 150.0000 | 150.3937 | 150.7874 | 151.1811 | 151.5748 | 151.9685 | 152.3622 | 152.7559 | 153.1496 |
| 3.90              | 153.5433    | 153.9370 | 154.3307 | 154.7244 | 155.1181 | 155.5118 | 155.9055 | 156.2992 | 156.6929 | 157.0866 |
| 4.00              | 157.4803    | 157.8740 | 158.2677 | 158.6614 | 159.0551 | 159.4488 | 159.8425 | 160.2362 | 160.6299 | 161.0236 |
| 4.10              | 161.4173    | 161.8110 | 162.2047 | 162.5984 | 162.9921 | 163.3858 | 163.7795 | 164.1732 | 164.5669 | 164.9606 |
| 4.20              | 165.3543    | 165.7480 | 166.1417 | 166.5354 | 166.9291 | 167.3228 | 167.7165 | 168.1102 | 168.5039 | 168.8976 |
| 4.30              | 169.2913    | 169.6850 | 170.0787 | 170.4724 | 170.8661 | 171.2598 | 171.6535 | 172.0472 | 172.4409 | 172.8346 |
| 4.40              | 173.2283    | 173.6220 | 174.0157 | 174.4094 | 174.8031 | 175.1969 | 175.5906 | 175.9843 | 176.3780 | 176.7717 |
| 4.50              | 177.1654    | 177.5591 | 177.9528 | 178.3465 | 178.7402 | 179.1339 | 179.5276 | 179.9213 | 180.3150 | 180.7087 |
| 4.60              | 181.1024    | 181.4961 | 181.8898 | 182.2835 | 182.6772 | 183.0709 | 183.4646 | 183.8583 | 184.2520 | 184.6457 |
| 4.70              | 185.0394    | 185.4331 | 185.8268 | 186.2205 | 186.6142 | 187.0079 | 187.4016 | 187.7953 | 188.1890 | 188.5827 |
| 4.80              | 188.9764    | 189.3701 | 189.7638 | 190.1575 | 190.5512 | 190.9449 | 191.3386 | 191.7323 | 192.1260 | 192.5197 |
| 4.90              | 192.9134    | 193.3071 | 193.7008 | 194.0945 | 194.4882 | 194.8819 | 195.2756 | 195.6693 | 196.0630 | 196.4567 |
| 5.00              | 196.8504    | 197.2441 | 197.6378 | 198.0315 | 198.4252 | 198.8189 | 199.2126 | 199.6063 | 200.0000 | 200.3937 |

The table given below can be used with the preceding main table to obtain higher converted values, simply by adding appropriate quantities chosen from each table:

| µm | µin.     | µm | µin.     | µm | µin.       | µm | µin.       |
|----|----------|----|----------|----|------------|----|------------|
| 10 | 393.7008 | 20 | 787.4016 | 30 | 1,181.1024 | 40 | 1,574.8032 |
| 15 | 590.5512 | 25 | 984.2520 | 35 | 1,378.9528 | 45 | 1,771.6535 |
|    |          |    |          |    |            | 50 | 1,968.5039 |
|    |          |    |          |    |            | 55 | 2,165.3543 |

Both portions of Table 13b are based on 1 microinch = 0.0254 micrometers, exactly.

*Example:* Convert 23.55 µm to µin.:

From above table: 20.00 µm = 787.4016 µin

From main table: 3.55 µm = 139.7638 µin

23.55 µm = 927.1654 µin

## FEET TO METERS CONVERSION

**Table 14a. Feet to Meters Conversion**

| feet  | meters | feet | meters | feet | meters | feet | meters  | feet | meters   |
|-------|--------|------|--------|------|--------|------|---------|------|----------|
| 100   | 30.48  | 10   | 3.048  | 1    | 0.3048 | 0.1  | 0.03048 | 0.01 | 0.003048 |
| 200   | 60.96  | 20   | 6.096  | 2    | 0.6096 | 0.2  | 0.06096 | 0.02 | 0.006096 |
| 300   | 91.44  | 30   | 9.144  | 3    | 0.9144 | 0.3  | 0.09144 | 0.03 | 0.009144 |
| 400   | 121.92 | 40   | 12.192 | 4    | 1.2192 | 0.4  | 0.12192 | 0.04 | 0.012192 |
| 500   | 152.4  | 50   | 15.24  | 5    | 1.524  | 0.5  | 0.1524  | 0.05 | 0.01524  |
| 600   | 182.88 | 60   | 18.288 | 6    | 1.8288 | 0.6  | 0.18288 | 0.06 | 0.018288 |
| 700   | 213.36 | 70   | 21.336 | 7    | 2.1336 | 0.7  | 0.21336 | 0.07 | 0.021336 |
| 800   | 243.84 | 80   | 24.384 | 8    | 2.4384 | 0.8  | 0.24384 | 0.08 | 0.024384 |
| 900   | 274.32 | 90   | 27.432 | 9    | 2.7432 | 0.9  | 0.27432 | 0.09 | 0.027432 |
| 1,000 | 304.8  | 100  | 30.48  | 10   | 3.048  | 1.0  | 0.3048  | 0.10 | 0.03048  |

1 ft = 0.3048 m, exactly

**Table 14b. Meters to Feet Conversion**

| meters | feet      | meters | feet    | meters | feet   | meters | feet  | meters | feet  |
|--------|-----------|--------|---------|--------|--------|--------|-------|--------|-------|
| 100    | 328.084   | 10     | 32.808  | 1      | 3.281  | 0.1    | 0.328 | 0.01   | 0.033 |
| 200    | 656.168   | 20     | 65.617  | 2      | 6.562  | 0.2    | 0.656 | 0.02   | 0.066 |
| 300    | 984.252   | 30     | 98.425  | 3      | 9.843  | 0.3    | 0.984 | 0.03   | 0.098 |
| 400    | 1,312.336 | 40     | 131.234 | 4      | 13.123 | 0.4    | 1.312 | 0.04   | 0.131 |
| 500    | 1,640.420 | 50     | 164.042 | 5      | 16.404 | 0.5    | 1.640 | 0.05   | 0.164 |
| 600    | 1,968.504 | 60     | 196.850 | 6      | 19.685 | 0.6    | 1.969 | 0.06   | 0.197 |
| 700    | 2,296.588 | 70     | 229.659 | 7      | 22.966 | 0.7    | 2.297 | 0.07   | 0.230 |
| 800    | 2,624.672 | 80     | 262.467 | 8      | 26.247 | 0.8    | 2.625 | 0.08   | 0.262 |
| 900    | 2,952.756 | 90     | 295.276 | 9      | 29.528 | 0.9    | 2.953 | 0.09   | 0.295 |
| 1,000  | 3,280.840 | 100    | 328.084 | 10     | 32.808 | 1.0    | 3.281 | 0.10   | 0.328 |

1 m = 3.280840 ft

**Table 15a. Miles to Kilometers Conversion**

| miles  | km        | miles | km       | miles | km     | miles | km    | miles | km   |
|--------|-----------|-------|----------|-------|--------|-------|-------|-------|------|
| 1,000  | 1,609.34  | 100   | 160.93   | 10    | 16.09  | 1     | 1.61  | 0.1   | 0.16 |
| 2,000  | 3,218.69  | 200   | 321.87   | 20    | 32.19  | 2     | 3.22  | 0.2   | 0.32 |
| 3,000  | 4,828.03  | 300   | 482.80   | 30    | 48.28  | 3     | 4.83  | 0.3   | 0.48 |
| 4,000  | 6,437.38  | 400   | 643.74   | 40    | 64.37  | 4     | 6.44  | 0.4   | 0.64 |
| 5,000  | 8,046.72  | 500   | 804.67   | 50    | 80.47  | 5     | 8.05  | 0.5   | 0.80 |
| 6,000  | 9,656.06  | 600   | 965.61   | 60    | 96.56  | 6     | 9.66  | 0.6   | 0.97 |
| 7,000  | 11,265.41 | 700   | 1,126.54 | 70    | 112.65 | 7     | 11.27 | 0.7   | 1.13 |
| 8,000  | 12,874.75 | 800   | 1,287.48 | 80    | 128.75 | 8     | 12.87 | 0.8   | 1.29 |
| 9,000  | 14,484.10 | 900   | 1,448.41 | 90    | 144.84 | 9     | 14.48 | 0.9   | 1.45 |
| 10,000 | 16,093.44 | 1,000 | 1,609.34 | 100   | 160.93 | 10    | 16.09 | 1.0   | 1.61 |

1 mile = 1.609344 km, exactly

**Table 15b. Kilometers to Miles Conversion**

| km     | miles    | km    | miles  | km  | miles | km | miles | km  | miles |
|--------|----------|-------|--------|-----|-------|----|-------|-----|-------|
| 1,000  | 621.37   | 100   | 62.14  | 10  | 6.21  | 1  | 0.62  | 0.1 | 0.06  |
| 2,000  | 1,242.74 | 200   | 124.27 | 20  | 12.43 | 2  | 1.24  | 0.2 | 0.12  |
| 3,000  | 1,864.11 | 300   | 186.41 | 30  | 18.64 | 3  | 1.86  | 0.3 | 0.19  |
| 4,000  | 2,485.48 | 400   | 248.55 | 40  | 24.85 | 4  | 2.49  | 0.4 | 0.25  |
| 5,000  | 3,106.86 | 500   | 310.69 | 50  | 31.07 | 5  | 3.11  | 0.5 | 0.31  |
| 6,000  | 3,728.23 | 600   | 372.82 | 60  | 37.28 | 6  | 3.73  | 0.6 | 0.37  |
| 7,000  | 4,349.60 | 700   | 434.96 | 70  | 43.50 | 7  | 4.35  | 0.7 | 0.43  |
| 8,000  | 4,970.97 | 800   | 497.10 | 80  | 49.71 | 8  | 4.97  | 0.8 | 0.50  |
| 9,000  | 5,592.34 | 900   | 559.23 | 90  | 55.92 | 9  | 5.59  | 0.9 | 0.56  |
| 10,000 | 6,213.71 | 1,000 | 621.37 | 100 | 62.14 | 10 | 6.21  | 1.0 | 0.62  |

1 km = 0.6213712 mile

## Units of Area

Table 16. Square Measure and Conversion Factors

| Metric System  | U.S. System   |
|--|---|
| 1 square kilometer (km <sup>2</sup> ) =<br>100 hectares<br>1,000,000 square meters<br>0.3861 square mile<br>247.1 acres  | 1 square mile (mi <sup>2</sup> ) =<br>640 acres<br>6400 square yards<br>2.5899 square kilometers  |
| 1 hectare (ha) =<br>0.01 square kilometer<br>100 ares<br>10,000 square meters<br>2.471 acres<br>107,639 square feet  | 1 acre =<br>10 square chains<br>4840 square yards<br>43,560 square feet<br>a square, 208.71 feet on a side<br>0.4046856 hectare<br>40.47 ares<br>4046.856 square meters   |
| 1 are (a) =<br>0.0001 square kilometer<br>100 square meters<br>0.0247 acre<br>1076.4 square feet   | 1 square chain =<br>16 square rods<br>484 square yards<br>4356 square feet  |
| 1 square meter (m <sup>2</sup> ) =<br>0.000001 square kilometer<br>100 square decimeters<br>10000 square centimeters<br>1,000,000 square millimeters<br>10.764 square feet<br>1.196 square yards | 1 square rod =<br>30.25 square yards<br>272.25 square feet<br>625 square links  |
| 1 square decimeter (dm <sup>2</sup> ) =<br>100 square centimeters  | 1 square yard (yd <sup>2</sup> ) =<br>9 square feet<br>1296 square inches<br>0.83612736 square meter<br>8361.2736 square centimeter<br>836,127.36 square millimeter       |
| 1 square centimeter (cm <sup>2</sup> ) =<br>0.0001 square meters<br>100 square millimeters<br>0.001076 square foot<br>0.155 square inch  | 1 square foot (ft <sup>2</sup> ) =<br>0.111111 square yard<br>144 square inches<br>0.09290304 square meter<br>929.0304 square centimeters<br>92,903.04 square millimeters |
| 1 square millimeter (mm <sup>2</sup> ) =<br>0.01 square centimeters<br>1,000,000 square microns<br>0.00155 square inch   | 1 square inch (in <sup>2</sup> ) =<br>0.0007716 square yard<br>0.006944 square foot<br>0.00064516 square meter<br>6.4516 square centimeters<br>645.16 square millimeters  |
| 1 square micrometer (micron) (μm <sup>2</sup> ) =<br>1 × 10 <sup>-12</sup> square meter<br>0.000001 square millimeters<br>1 × 10 <sup>-9</sup> square inch<br>1549.997 square micro-inch         | 1 square mil (mil <sup>2</sup> ) =<br>0.000001 square inch<br>0.00064516 square millimeter  |
|  | 1 square micro-inch (μin <sup>2</sup> ) =<br>1 × 10 <sup>-12</sup> square inch<br>0.00064516 square micrometer (micron)   |

Note: Figures in **Bold** indicate exact conversion values

## Measure Used for Diameters and Areas of Electric Wires

|  |   |
|--|---|
| 1 circular inch =<br>area of 1-inch diameter circle<br>¾ square inch<br>0.7854 square inch<br>5.067 square centimeter<br>1,000,000 circular mils | 1 circular mil =<br>area of 0.001-inch diameter circle<br>¼ square mill<br>1 square inch =<br>1.2732 circular inch<br>1,273,239 circular mils |
|--|---|



**Table 17a. Square Inches to Square Centimeters Conversion**

| inch <sup>2</sup> | cm <sup>2</sup> | inch <sup>2</sup> | cm <sup>2</sup> | inch <sup>2</sup> | cm <sup>2</sup> | inch <sup>2</sup> | cm <sup>2</sup> | inch <sup>2</sup> | cm <sup>2</sup> |
|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|
| 100               | 645.16          | 10                | 64.516          | 1                 | 6.4516          | 0.1               | 0.64516         | 0.01              | 0.064516        |
| 200               | 1,290.32        | 20                | 129.032         | 2                 | 12.9032         | 0.2               | 1.29032         | 0.02              | 0.129032        |
| 300               | 1,935.48        | 30                | 193.548         | 3                 | 19.3548         | 0.3               | 1.93548         | 0.03              | 0.135489        |
| 400               | 2,580.64        | 40                | 258.064         | 4                 | 25.8064         | 0.4               | 2.58064         | 0.04              | 0.258064        |
| 500               | 3,225.80        | 50                | 322.58          | 5                 | 32.258          | 0.5               | 3.2258          | 0.05              | 0.32258         |
| 600               | 30,870.96       | 60                | 387.096         | 6                 | 38.7096         | 0.6               | 3.87096         | 0.06              | 0.387096        |
| 700               | 4,516.12        | 70                | 451.612         | 7                 | 45.1612         | 0.7               | 4.51612         | 0.07              | 0.451612        |
| 800               | 5,161.28        | 80                | 516.128         | 8                 | 51.6128         | 0.8               | 5.16128         | 0.08              | 0.516128        |
| 900               | 5,806.44        | 90                | 580.644         | 9                 | 58.0644         | 0.9               | 5.80644         | 0.09              | 0.580644        |
| 1,000             | 6,451.60        | 100               | 645.16          | 10                | 64.516          | 1.0               | 6.4516          | 0.10              | 0.64516         |

Based on 1 inch = 2.54 centimeters, exactly, 1 inch<sup>2</sup> = 6.4516 cm<sup>2</sup>, exactly.

**Table 17b. Square Centimeters to Square Inches Conversion**

| cm <sup>2</sup> | inch <sup>2</sup> | cm <sup>2</sup> | inch <sup>2</sup> | cm <sup>2</sup> | inch <sup>2</sup> | cm <sup>2</sup> | inch <sup>2</sup> | cm <sup>2</sup> | inch <sup>2</sup> |
|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|
| 100             | 15.500            | 10              | 1.550             | 1               | 0.155             | 0.1             | 0.016             | 0.01            | 0.002             |
| 200             | 31.000            | 20              | 3.100             | 2               | 0.310             | 0.2             | 0.031             | 0.02            | 0.003             |
| 300             | 46.500            | 30              | 4.650             | 3               | 0.465             | 0.3             | 0.047             | 0.03            | 0.005             |
| 400             | 62.000            | 40              | 6.200             | 4               | 0.620             | 0.4             | 0.062             | 0.04            | 0.006             |
| 500             | 77.500            | 50              | 7.750             | 5               | 0.75              | 0.5             | 0.078             | 0.05            | 0.008             |
| 600             | 93.000            | 60              | 9.300             | 6               | 0.930             | 0.6             | 0.093             | 0.06            | 0.009             |
| 700             | 108.500           | 70              | 10.850            | 7               | 1.085             | 0.7             | 0.109             | 0.07            | 0.011             |
| 800             | 124.000           | 80              | 12.400            | 8               | 1.240             | 0.8             | 0.124             | 0.08            | 0.012             |
| 900             | 139.500           | 90              | 13.950            | 9               | 1.395             | 0.9             | 0.140             | 0.09            | 0.014             |
| 1,000           | 155.000           | 100             | 15.500            | 10              | 1.550             | 1.0             | 0.155             | 0.10            | 0.016             |

Based on 1 inch = 2.54 centimeters, exactly, 1 cm<sup>2</sup> = 0.1550003 inch<sup>2</sup>.

**Table 18a. Square Feet to Square Meters Conversion**

| ft <sup>2</sup> | m <sup>2</sup> | ft <sup>2</sup> | m <sup>2</sup> | ft <sup>2</sup> | m <sup>2</sup> | ft <sup>2</sup> | m <sup>2</sup> | ft <sup>2</sup> | m <sup>2</sup> |
|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|
| 1,000           | 92.903         | 100             | 9.290          | 10              | 0.929          | 1               | 0.093          | 0.1             | 0.009          |
| 2,000           | 185.806        | 200             | 18.581         | 20              | 1.858          | 2               | 0.186          | 0.2             | 0.019          |
| 3,000           | 278.709        | 300             | 27.871         | 30              | 2.787          | 3               | 0.279          | 0.3             | 0.028          |
| 4,000           | 371.612        | 400             | 37.161         | 40              | 3.716          | 4               | 0.372          | 0.4             | 0.037          |
| 5,000           | 464.515        | 500             | 46.452         | 50              | 4.645          | 5               | 0.465          | 0.5             | 0.046          |
| 6,000           | 557.418        | 600             | 55.742         | 60              | 5.574          | 6               | 0.557          | 0.6             | 0.056          |
| 7,000           | 650.321        | 700             | 65.032         | 70              | 6.503          | 7               | 0.650          | 0.7             | 0.065          |
| 8,000           | 743.224        | 800             | 74.322         | 80              | 7.432          | 8               | 0.743          | 0.8             | 0.074          |
| 9,000           | 836.127        | 900             | 83.613         | 90              | 8.361          | 9               | 0.836          | 0.9             | 0.084          |
| 10,000          | 929.030        | 1,000           | 92.903         | 100             | 9.290          | 10              | 0.929          | 1.0             | 0.093          |

Based on 1 inch = 2.54 centimeters, exactly, 1 ft<sup>2</sup> = 0.09290304 m<sup>2</sup>, exactly.

**Table 18b. Square Meters to Square Feet Conversion**

| m <sup>2</sup> | ft <sup>2</sup> | m <sup>2</sup> | ft <sup>2</sup> | m <sup>2</sup> | ft <sup>2</sup> | m <sup>2</sup> | ft <sup>2</sup> | m <sup>2</sup> | ft <sup>2</sup> |
|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|
| 100            | 1,076.39        | 10             | 107.64          | 1              | 10.76           | 0.1            | 1.08            | 0.01           | 0.11            |
| 200            | 2,152.78        | 20             | 215.28          | 2              | 21.53           | 0.2            | 2.15            | 0.02           | 0.22            |
| 300            | 3,229.17        | 30             | 322.92          | 3              | 32.29           | 0.3            | 3.23            | 0.03           | 0.32            |
| 400            | 4,305.56        | 40             | 430.56          | 4              | 43.06           | 0.4            | 4.31            | 0.04           | 0.43            |
| 500            | 5,381.96        | 50             | 538.20          | 5              | 53.82           | 0.5            | 5.38            | 0.05           | 0.54            |
| 600            | 6,458.35        | 60             | 645.83          | 6              | 64.58           | 0.6            | 6.46            | 0.06           | 0.65            |
| 700            | 7,534.74        | 70             | 753.47          | 7              | 75.35           | 0.7            | 7.53            | 0.07           | 0.75            |
| 800            | 8,611.13        | 80             | 861.11          | 8              | 86.11           | 0.8            | 8.61            | 0.08           | 0.86            |
| 900            | 9,687.52        | 90             | 968.75          | 9              | 96.88           | 0.9            | 9.69            | 0.09           | 0.97            |
| 1,000          | 10,763.91       | 100            | 1,076.39        | 10             | 107.64          | 1.0            | 10.76           | 0.10           | 1.08            |

Based on 1 inch = 2.54 centimeters, exactly, 1 m<sup>2</sup> = 10.76391 ft<sup>2</sup>.

**Table 19a. Square Yard to Square Meter Conversion**

| yd <sup>2</sup> | m <sup>2</sup> | yd <sup>2</sup> | m <sup>2</sup> | yd <sup>2</sup> | m <sup>2</sup> | yd <sup>2</sup> | m <sup>2</sup> | yd <sup>2</sup> | m <sup>2</sup> |
|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|
| 1000            | 836.12736      | 100             | 83.612736      | 10              | 8.3612736      | 1               | 0.83612736     | 0.1             | 0.083612736    |
| 2000            | 1672.25472     | 200             | 167.225472     | 20              | 16.7225472     | 2               | 1.67225472     | 0.2             | 0.167225472    |
| 3000            | 2508.38208     | 300             | 250.838208     | 30              | 25.0838208     | 3               | 2.50838208     | 0.3             | 0.250838208    |
| 4000            | 3344.50944     | 400             | 334.450944     | 40              | 33.4450944     | 4               | 3.34450944     | 0.4             | 0.334450944    |
| 5000            | 4180.6368      | 500             | 418.06368      | 50              | 41.806368      | 5               | 4.1806368      | 0.5             | 0.41806368     |
| 6000            | 5016.76416     | 600             | 501.676416     | 60              | 50.1676416     | 6               | 5.01676416     | 0.6             | 0.501676416    |
| 7000            | 5852.89152     | 700             | 585.289152     | 70              | 58.5289152     | 7               | 5.85289152     | 0.7             | 0.585289152    |
| 8000            | 6689.01888     | 800             | 668.901888     | 80              | 66.8901888     | 8               | 6.68901888     | 0.8             | 0.668901888    |
| 9000            | 7525.14624     | 900             | 752.514624     | 90              | 75.2514624     | 9               | 7.52514624     | 0.9             | 0.752514624    |
| 10000           | 8361.2736      | 1000            | 836.12736      | 100             | 83.612736      | 10              | 8.3612736      | 1               | 0.83612736     |

Based on 1 inch = 2.54 centimeters, exactly, 1 yd<sup>2</sup> = 0.83612736 m<sup>2</sup>, exactly

**Table 19b. Square Meter to Square Yard Conversion**

| m <sup>2</sup> | yd <sup>2</sup> | m <sup>2</sup> | yd <sup>2</sup> | m <sup>2</sup> | yd <sup>2</sup> | m <sup>2</sup> | yd <sup>2</sup> | m <sup>2</sup> | yd <sup>2</sup> |
|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|
| 1000           | 1195.990046     | 100            | 119.5990046     | 10             | 11.95990046     | 1              | 1.195990046     | 0.1            | 0.119599005     |
| 2000           | 2391.980093     | 200            | 239.1980093     | 20             | 23.91980093     | 2              | 2.391980093     | 0.2            | 0.239198009     |
| 3000           | 3587.970139     | 300            | 358.7970139     | 30             | 35.87970139     | 3              | 3.587970139     | 0.3            | 0.358797014     |
| 4000           | 4783.960185     | 400            | 478.3960185     | 40             | 47.83960185     | 4              | 4.783960185     | 0.4            | 0.478396019     |
| 5000           | 5979.950232     | 500            | 597.9950232     | 50             | 59.79950232     | 5              | 5.979950232     | 0.5            | 0.597995023     |
| 6000           | 7175.940278     | 600            | 717.5940278     | 60             | 71.75940278     | 6              | 7.175940278     | 0.6            | 0.717594028     |
| 7000           | 8371.930324     | 700            | 837.1930324     | 70             | 83.71930324     | 7              | 8.371930324     | 0.7            | 0.837193032     |
| 8000           | 9567.92037      | 800            | 956.792037      | 80             | 95.6792037      | 8              | 9.56792037      | 0.8            | 0.956792037     |
| 9000           | 10763.91042     | 900            | 1076.391042     | 90             | 107.6391042     | 9              | 10.76391042     | 0.9            | 1.076391042     |
| 10000          | 11959.90046     | 1000           | 1195.990046     | 100            | 119.5990046     | 10             | 11.95990046     | 1              | 1.195990046     |

Based on 1 inch = 2.54 centimeters, exactly, 1 m<sup>2</sup> = 1.195990046 yd<sup>2</sup>.

**Table 20a. Acres to Hectares Conversion**

| →<br>acres<br>↓ | 0        | 10      | 20      | 30      | 40      | 50      | 60      | 70      | 80      | 90      |
|-----------------|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|                 | hectares |         |         |         |         |         |         |         |         |         |
| 0               | ...      | 4.047   | 8.094   | 12.141  | 16.187  | 20.234  | 24.281  | 28.328  | 32.375  | 36.422  |
| 100             | 40.469   | 44.515  | 48.562  | 52.609  | 56.656  | 60.703  | 64.750  | 68.797  | 72.843  | 76.890  |
| 200             | 80.937   | 84.984  | 89.031  | 93.078  | 97.125  | 101.171 | 105.218 | 109.265 | 113.312 | 117.359 |
| 300             | 121.406  | 125.453 | 129.499 | 133.546 | 137.593 | 141.640 | 145.687 | 149.734 | 153.781 | 157.827 |
| 400             | 161.874  | 165.921 | 169.968 | 174.015 | 178.062 | 182.109 | 186.155 | 190.202 | 194.249 | 198.296 |
| 500             | 202.343  | 206.390 | 240.437 | 214.483 | 218.530 | 222.577 | 226.624 | 230.671 | 234.718 | 238.765 |
| 600             | 242.811  | 246.858 | 250.905 | 254.952 | 258.999 | 263.046 | 267.092 | 271.139 | 275.186 | 279.233 |
| 700             | 283.280  | 287.327 | 291.374 | 295.420 | 299.467 | 303.514 | 307.561 | 311.608 | 315.655 | 319.702 |
| 800             | 323.748  | 327.795 | 331.842 | 335.889 | 339.936 | 343.983 | 348.030 | 352.076 | 356.123 | 360.170 |
| 900             | 364.217  | 368.264 | 372.311 | 376.358 | 380.404 | 384.451 | 388.498 | 392.545 | 396.592 | 400.639 |
| 1000            | 404.686  | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     |

1 acre = 0.4046856 hectare

**Table 20b. Hectares to Acres Conversion**

| →<br>hectares<br>↓ | 0       | 10      | 20      | 30      | 40      | 50      | 60      | 70      | 80      | 90      |
|--------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|                    | acres   |         |         |         |         |         |         |         |         |         |
| 0                  | ...     | 24.71   | 49.42   | 74.13   | 98.84   | 123.55  | 148.26  | 172.97  | 197.68  | 222.39  |
| 100                | 247.11  | 271.82  | 296.53  | 321.24  | 345.95  | 370.66  | 395.37  | 420.08  | 444.79  | 469.50  |
| 200                | 494.21  | 518.92  | 543.63  | 568.34  | 593.05  | 617.76  | 642.47  | 667.18  | 691.90  | 716.61  |
| 300                | 741.32  | 766.03  | 790.74  | 815.45  | 840.16  | 864.87  | 889.58  | 914.29  | 939.00  | 963.71  |
| 400                | 988.42  | 1013.13 | 1037.84 | 1062.55 | 1087.26 | 1111.97 | 1136.68 | 1161.40 | 1186.11 | 1210.82 |
| 500                | 1235.53 | 1260.24 | 1284.95 | 1309.66 | 1334.37 | 1359.08 | 1383.79 | 1408.50 | 1433.21 | 1457.92 |
| 600                | 1482.63 | 1507.34 | 1532.05 | 1556.76 | 1581.47 | 1606.19 | 1630.90 | 1655.61 | 1680.32 | 1705.03 |
| 700                | 1729.74 | 1754.45 | 1779.16 | 1803.87 | 1828.58 | 1853.29 | 1878.00 | 1902.71 | 1927.42 | 1952.13 |
| 800                | 1976.84 | 2001.55 | 2026.26 | 2050.97 | 2075.69 | 2100.40 | 2125.11 | 2149.82 | 2174.53 | 2199.24 |
| 900                | 2223.95 | 2248.66 | 2273.37 | 2298.08 | 2322.79 | 2347.50 | 2372.21 | 2396.92 | 2421.63 | 2446.34 |
| 1000               | 2471.05 | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     |

1 hectare = 2.471054 acres

## Units of Volume

Table 21. Cubic Measure and Conversion Factors

| Metric System  | U.S. System  |
|--|--|
| <i>1 cubic meter (m<sup>3</sup>) =</i>                     | <i>1 cubic yard (yd<sup>3</sup>) =</i>   |
| <b>1000</b> cubic decimeters (liters)                      | <b>27</b> cubic feet   |
| <b>1,000,000</b> cubic centimeters                         | 201.97403 U.S. gallons   |
| 1.30795 cubic yards  | <b>46,656</b> cubic inch   |
| 35.314667 cubic feet                                       | 0.7646 cubic meter   |
| 61,023.74 cubic inches                                     | <i>1 cubic foot (ft<sup>3</sup>) =</i>   |
| 264.17205 U.S. gallons                                     | <b>1728</b> cubic inches   |
| 219.96925 British Imperial gallons                         | 7.4805 U.S. gallons  |
| <i>1 liter (l) or 1 cubic decimeter (dm<sup>3</sup>) =</i> | 6.23 British Imperial gallons  |
| <b>1</b> liter = volume of 1 kg water at 39.2°F            | 0.02831685 cubic meter   |
| <b>0.001</b> cubic meter                                   | 28.31685 liters  |
| <b>1000</b> cubic centimeters                              | <i>1 cubic inch (in<sup>3</sup>) =</i>   |
| <b>10</b> deciliters                                       | 0.55411256 U.S. fluid ounces   |
| 0.03531466 cubic foot                                      | <b>16.387064</b> cubic centimeters   |
| 61.023744 cubic inches                                     |  |
| 0.2642 U.S. gallon   |  |
| 0.21997 British Imperial gallon                            |  |
| 1.0566882 U.S. quarts                                      |  |
| 33.814 U.S. fluid ounces                                   |  |
| <i>1 cubic centimeter (cm<sup>3</sup>) =</i>               |  |
| <b>0.001</b> liter   |  |
| <b>1000</b> cubic millimeters                              |  |
| 0.061024 cubic inch  |  |
| <i>1 cubic millileter = 0.001</i> cubic centimeters        |  |
| <i>1 hectoliter (hl) = 100</i> liters                      |  |
| <i>1 deciliter (dl) = 10</i> centiliters                   |  |
| <i>1 centiliter (cl) = 10</i> milliliters                  |  |
|  | <b>Shipping Measure</b>  |
|  | For measuring internal capacity of a vessel:   |
|  | <i>1 register ton = 100</i> cubic feet   |
|  | For measurement of cargo:  |
|  | <i>1 shipping ton =</i>  |
|  | Approximately 40 cubic feet of merchandise is considered a shipping ton, unless that bulk would weigh more than 2000 pounds, in which case the freight charge may be based upon weight |
|  | <i>40 cubic feet =</i>   |
|  | 32.143 U.S. bushels  |
|  | 31.16 Imperial bushels   |
|  | <b>U.S. Liquid Measure</b>   |
| <i>1 British Imperial gallon =</i>                         | <i>1 U.S. gallon =</i>   |
| 0.1605 cubic foot  | 0.13368 cubic foot   |
| 277.42 cubic inches  | <b>231</b> cubic inches  |
| 1.2009 U.S. gallon   | <b>128</b> U.S. fluid ounces   |
| <b>160</b> Imperial fluid ounces                           | <b>4</b> U.S. quarts   |
| <b>4</b> Imperial quarts                                   | <b>8</b> U.S. pints  |
| <b>8</b> Imperial pints                                    | 0.8327 British Imperial gallon   |
| <b>4,54609</b> liters                                      | <b>3,785411784</b> liters  |
| <i>1 quart =</i>   | <i>1 quart =</i>   |
| <b>2</b> Imperial pints                                    | <b>2</b> U.S. pints  |
| <b>8</b> Imperial gills                                    | <b>8</b> U.S. gills  |
| <b>40</b> Imperial fluid ounces                            | <b>32</b> U.S. fluid ounces  |
| 69.354 cubic inches  | <b>57.75</b> cubic inches  |
| <b>1.1365225</b> liters                                    | 0.9463529 liters   |
| <i>1 pint =</i>  | <i>1 pint =</i>  |
| <b>4</b> Imperial gills                                    | <b>4</b> U.S. gills  |
| <b>20</b> Imperial fluid ounces                            | <b>16</b> U.S. fluid ounces  |
| 34.678 cubic inches  | <b>28.875</b> cubic inches   |
| <b>568.26125</b> milliliters                               | 473.176 milliliters  |
| <i>1 gill =</i>  | <i>1 gill =</i>  |
| <b>5</b> Imperial fluid ounces                             | <b>1/2</b> cup = <b>4</b> U.S. fluid ounces  |
| 8.669 cubic inches   | <b>7.21875</b> cubic inches  |
| 142.07 milliliters   | 118.29 milliliters   |

Note: Figures in **Bold** indicate exact conversion values

**Table 21. (Continued) Cubic Measure and Conversion Factors**

| British (Imperial) Liquid and Dry Measure                 |   | Apothecaries' Fluid Measure                   |  |
|---|---|---|--|
| <i>1 British Imperial fluid ounce =</i>                   | <i>1.733871 cubic inch</i>                          | <i>1 U.S. fluid ounce =</i>                   | <b>1.8046875</b> cubic inch  |
| <i><math>\frac{1}{160}</math> British Imperial gallon</i> | <i>28.41306 milliliters</i>                         | <i><math>\frac{1}{128}</math> U.S. gallon</i> | <b>8</b> drachms   |
| <i>1 British Imperial bushel =</i>                        | <b>8</b> Imperial gallons = 1.284 cubic feet        |   | 0.02957353 liter   |
|   | 2219.36 cubic inches                                |   | 29.57353 milliliters   |
|   |   | <i>1 fluid drachm =</i>                       | <b>60</b> minims   |
| U.S. Dry Measure  |   | Old Liquid Measure                            |  |
| <i>1 bushel (U.S. or Winchester struck bushel) =</i>      | <i>1.2445 cubic feet</i>                            | <i>1 barrel (bbl) =</i>                       | $31\frac{1}{2}$ gallons  |
|   | <b>2150.42</b> cubic inches                         | <i>1 hogshead =</i>                           | 2 barrels = 63 gallons   |
|   | a cylinder 18.5 inches dia., 8 inches deep          | <i>1 pipe or butt =</i>                       | 2 hogsheads = 4 barrels = 126 gallons  |
|   | a cylinder 47.0 cm dia., 20.3 cm deep               | <i>1 tierce =</i>                             | 42 gallons   |
| <i>1 bushel =</i>   | <b>4</b> pecks = <b>32</b> quarts = <b>64</b> pints | <i>1 puncheon =</i>                           | 2 tierces = 84 gallons   |
| <i>1 peck =</i>   | <b>8</b> quarts = <b>16</b> pints                   | <i>1 tun =</i>                                | 2 pipes = 3 puncheons  |
| <i>1 dry quart =</i>                                      | <b>2</b> pints =                                    |   |  |
|   | <b>67.200625</b> cubic inches                       | Other Cubic Measure                           |  |
|   | 1.101221 liters                                     | The following are used for wood and masonry:  |  |
| <i>1 heaped bushel =</i>                                  | $1\frac{1}{4}$ struck bushel                        | <i>1 cord of wood =</i>                       | $4 \times 4 \times 8$ feet = 128 cubic feet                                    |
| <i>1 cubic foot =</i>                                     | 0.8036 struck bushel                                | <i>1 perch of masonry =</i>                   | $16\frac{1}{2} \times 1\frac{1}{2} \times 1$ foot = $24\frac{3}{4}$ cubic feet |
| Barrel Measure  |   |   |  |
| <i>1 drum =</i>   | <b>55</b> U.S. gallon                               | <i>1 petroleum barrel (bo) =</i>              | <b>42</b> U.S. gallons   |
|   | 7.3524 cubic feet                                   |   | 5.614583 cubic feet  |
|   | 208.19765 liters                                    |   | 158.98729 liters   |

Note: Figures in **Bold** indicate exact conversion values

**Table 22a. Cubic Inches to Cubic Centimeters Conversion**

| inch <sup>3</sup> | cm <sup>3</sup> | inch <sup>3</sup> | cm <sup>3</sup> | inch <sup>3</sup> | cm <sup>3</sup> | inch <sup>3</sup> | cm <sup>3</sup> | inch <sup>3</sup> | cm <sup>3</sup> |
|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|
| 100               | 1,638.71        | 10                | 163.87          | 1                 | 16.39           | 0.1               | 1.64            | 0.01              | 0.16            |
| 200               | 3,277.41        | 20                | 327.74          | 2                 | 32.77           | 0.2               | 3.28            | 0.02              | 0.33            |
| 300               | 4,916.12        | 30                | 491.61          | 3                 | 49.16           | 0.3               | 4.92            | 0.03              | 0.49            |
| 400               | 6,554.82        | 40                | 655.48          | 4                 | 65.55           | 0.4               | 6.55            | 0.04              | 0.66            |
| 500               | 8,193.53        | 50                | 819.35          | 5                 | 81.94           | 0.5               | 8.19            | 0.05              | 0.82            |
| 600               | 9,832.24        | 60                | 983.22          | 6                 | 98.32           | 0.6               | 9.83            | 0.06              | 0.98            |
| 700               | 11,470.94       | 70                | 1,147.09        | 7                 | 114.71          | 0.7               | 11.47           | 0.07              | 1.15            |
| 800               | 13,109.65       | 80                | 1,310.96        | 8                 | 131.10          | 0.8               | 13.11           | 0.08              | 1.31            |
| 900               | 14,748.35       | 90                | 1,474.84        | 9                 | 147.48          | 0.9               | 14.75           | 0.09              | 1.47            |
| 1,000             | 16,387.06       | 100               | 1,638.71        | 10                | 163.87          | 1.0               | 16.39           | 0.10              | 1.64            |

Based on 1 inch = 2.54 centimeters, exactly. 1 inch<sup>3</sup> = 16.387064 cm<sup>3</sup>, exactly

**Table 22b. Cubic Centimeters to Cubic Inches Conversion**

| cm <sup>3</sup> | inch <sup>3</sup> | cm <sup>3</sup> | inch <sup>3</sup> | cm <sup>3</sup> | inch <sup>3</sup> | cm <sup>3</sup> | inch <sup>3</sup> |
|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|-------------------|
| 1,000           | 61.024            | 100             | 6.102             | 10              | 0.610             | 1               | 0.061             |
| 2,000           | 122.048           | 200             | 12.205            | 20              | 1.220             | 2               | 0.122             |
| 3,000           | 183.071           | 300             | 18.307            | 30              | 1.831             | 3               | 0.183             |
| 4,000           | 244.095           | 400             | 24.410            | 40              | 2.441             | 4               | 0.244             |
| 5,000           | 305.119           | 500             | 30.512            | 50              | 3.051             | 5               | 0.305             |
| 6,000           | 366.143           | 600             | 36.614            | 60              | 3.661             | 6               | 0.366             |
| 7,000           | 427.166           | 700             | 42.717            | 70              | 4.272             | 7               | 0.427             |
| 8,000           | 488.190           | 800             | 48.819            | 80              | 4.882             | 8               | 0.488             |
| 9,000           | 549.214           | 900             | 54.921            | 90              | 5.492             | 9               | 0.549             |
| 10,000          | 610.238           | 1,000           | 61.024            | 100             | 6.102             | 10              | 0.610             |

Based on 1 inch = 2.54 centimeters, exactly. 1 cm<sup>3</sup> = 0.06102376 inch<sup>3</sup>

**Table 23a. Cubic Feet to Cubic Meters Conversion**

| ft <sup>3</sup> | m <sup>3</sup> | ft <sup>3</sup> | m <sup>3</sup> | ft <sup>3</sup> | m <sup>3</sup> | ft <sup>3</sup> | m <sup>3</sup> | ft <sup>3</sup> | m <sup>3</sup> |
|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|
| 1,000           | 28.317         | 100             | 2.832          | 10              | 0.283          | 1               | 0.028          | 0.1             | 0.003          |
| 2,000           | 56.634         | 200             | 5.663          | 20              | 0.566          | 2               | 0.057          | 0.2             | 0.006          |
| 3,000           | 84.951         | 300             | 8.495          | 30              | 0.850          | 3               | 0.085          | 0.3             | 0.008          |
| 4,000           | 113.267        | 400             | 11.327         | 40              | 1.133          | 4               | 0.113          | 0.4             | 0.011          |
| 5,000           | 141.584        | 500             | 14.158         | 50              | 1.416          | 5               | 0.142          | 0.5             | 0.014          |
| 6,000           | 169.901        | 600             | 16.990         | 60              | 1.699          | 6               | 0.170          | 0.6             | 0.017          |
| 7,000           | 198.218        | 700             | 19.822         | 70              | 1.982          | 7               | 0.198          | 0.7             | 0.020          |
| 8,000           | 226.535        | 800             | 22.653         | 80              | 2.265          | 8               | 0.227          | 0.8             | 0.023          |
| 9,000           | 254.852        | 900             | 25.485         | 90              | 2.549          | 9               | 0.255          | 0.9             | 0.025          |
| 10,000          | 283.168        | 1,000           | 28.317         | 100             | 2.832          | 10              | 0.283          | 1.0             | 0.028          |

Based on 1 inch = 2.54 centimeters, exactly. 1 ft<sup>3</sup> = 0.02831685 m<sup>3</sup>**Table 23b. Cubic Meters to Cubic Feet Conversion**

| m <sup>3</sup> | ft <sup>3</sup> | m <sup>3</sup> | ft <sup>3</sup> | m <sup>3</sup> | ft <sup>3</sup> | m <sup>3</sup> | ft <sup>3</sup> | m <sup>3</sup> | ft <sup>3</sup> |
|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|
| 100            | 3,531.47        | 10             | 353.15          | 1              | 35.31           | 0.1            | 3.53            | 0.01           | 0.35            |
| 200            | 7,062.93        | 20             | 706.29          | 2              | 70.63           | 0.2            | 7.06            | 0.02           | 0.71            |
| 300            | 10,594.40       | 30             | 1,059.44        | 3              | 105.94          | 0.3            | 10.59           | 0.03           | 1.06            |
| 400            | 14,125.86       | 40             | 4,412.59        | 4              | 141.26          | 0.4            | 14.13           | 0.04           | 1.41            |
| 500            | 17,657.33       | 50             | 1,756.73        | 5              | 176.57          | 0.5            | 17.66           | 0.05           | 1.77            |
| 600            | 21,188.80       | 60             | 2,118.88        | 6              | 211.89          | 0.6            | 21.19           | 0.06           | 2.12            |
| 700            | 24,720.26       | 70             | 2,472.03        | 7              | 247.20          | 0.7            | 24.72           | 0.07           | 2.47            |
| 800            | 28,251.73       | 80             | 2,825.17        | 8              | 282.52          | 0.8            | 28.25           | 0.08           | 2.83            |
| 900            | 31,783.19       | 90             | 3,178.32        | 9              | 317.83          | 0.9            | 31.78           | 0.09           | 3.18            |
| 1,000          | 35,314.66       | 100            | 3,531.47        | 10             | 353.15          | 1.0            | 35.311          | 0.10           | 3.53            |

Based on 1 inch = 2.54 centimeters, exactly. 1 m<sup>3</sup> = 35.31466 ft<sup>3</sup>**Table 24a. Cubic Feet to Liters Conversion**

| ft <sup>3</sup> | liters    | ft <sup>3</sup> | liters   | ft <sup>3</sup> | liters | ft <sup>3</sup> | liters | ft <sup>3</sup> | liters |
|-----------------|-----------|-----------------|----------|-----------------|--------|-----------------|--------|-----------------|--------|
| 100             | 2,831.68  | 10              | 283.17   | 1               | 28.32  | 0.1             | 2.83   | 0.01            | 0.28   |
| 200             | 5,663.37  | 20              | 566.34   | 2               | 56.63  | 0.2             | 5.66   | 0.02            | 0.57   |
| 300             | 8,495.06  | 30              | 849.51   | 3               | 84.95  | 0.3             | 8.50   | 0.03            | 0.85   |
| 400             | 11,326.74 | 40              | 1,132.67 | 4               | 113.27 | 0.4             | 11.33  | 0.04            | 1.13   |
| 500             | 14,158.42 | 50              | 1,415.84 | 5               | 141.58 | 0.5             | 14.16  | 0.05            | 1.42   |
| 600             | 16,990.11 | 60              | 1,699.01 | 6               | 169.90 | 0.6             | 16.99  | 0.06            | 1.70   |
| 700             | 19,821.80 | 70              | 1,982.18 | 7               | 198.22 | 0.7             | 19.82  | 0.07            | 1.98   |
| 800             | 22,653.48 | 80              | 2,263.35 | 8               | 226.53 | 0.8             | 22.65  | 0.08            | 2.27   |
| 900             | 25,485.16 | 90              | 2,548.52 | 9               | 254.85 | 0.9             | 25.49  | 0.09            | 2.55   |
| 1,000           | 28,316.85 | 100             | 2,831.68 | 10              | 283.17 | 1.0             | 28.32  | 0.10            | 2.83   |

1 ft<sup>3</sup> = 28.31685 liters**Table 24b. Liters to Cubic Feet Conversion**

| liters | ft <sup>3</sup> | liters | ft <sup>3</sup> | liters | ft <sup>3</sup> | liters | ft <sup>3</sup> | liters | ft <sup>3</sup> |
|--------|-----------------|--------|-----------------|--------|-----------------|--------|-----------------|--------|-----------------|
| 1,000  | 35.315          | 100    | 3.531           | 10     | 0.353           | 1      | 0.035           | 0.1    | 0.004           |
| 2,000  | 70.629          | 200    | 7.063           | 20     | 0.706           | 2      | 0.071           | 0.2    | 0.007           |
| 3,000  | 105.944         | 300    | 10.594          | 30     | 1.059           | 3      | 0.106           | 0.3    | 0.011           |
| 4,000  | 141.259         | 400    | 14.126          | 40     | 1.413           | 4      | 0.141           | 0.4    | 0.014           |
| 5,000  | 176.573         | 500    | 17.657          | 50     | 1.766           | 5      | 0.177           | 0.5    | 0.018           |
| 6,000  | 211.888         | 600    | 21.189          | 60     | 2.119           | 6      | 0.212           | 0.6    | 0.021           |
| 7,000  | 247.203         | 700    | 24.720          | 70     | 2.472           | 7      | 0.247           | 0.7    | 0.025           |
| 8,000  | 282.517         | 800    | 28.252          | 80     | 2.825           | 8      | 0.283           | 0.8    | 0.028           |
| 9,000  | 317.832         | 900    | 31.783          | 90     | 3.178           | 9      | 0.318           | 0.9    | 0.032           |
| 10,000 | 353.147         | 1,000  | 35.315          | 100    | 3.531           | 10     | 0.353           | 1.0    | 0.035           |

1 liter = 0.03531466 ft<sup>3</sup>

**Table 25a. U.K. (Imperial) Gallons to Liters Conversion**

| Imp. gals | 0       | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | 9       |
|-----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|           | liters  |         |         |         |         |         |         |         |         |         |
| 0         | ...     | 4.546   | 9.092   | 13.638  | 18.184  | 22.730  | 27.277  | 31.823  | 36.369  | 40.915  |
| 10        | 45.461  | 50.007  | 54.553  | 59.099  | 63.645  | 68.191  | 72.737  | 77.284  | 81.830  | 86.376  |
| 20        | 90.922  | 95.468  | 100.014 | 104.560 | 109.106 | 113.652 | 118.198 | 122.744 | 127.291 | 131.837 |
| 30        | 136.383 | 140.929 | 145.475 | 150.021 | 154.567 | 159.113 | 163.659 | 168.205 | 172.751 | 177.298 |
| 40        | 181.844 | 186.390 | 190.936 | 195.482 | 200.028 | 204.574 | 209.120 | 213.666 | 218.212 | 222.759 |
| 50        | 227.305 | 231.851 | 236.397 | 240.943 | 245.489 | 250.035 | 254.581 | 259.127 | 263.673 | 268.219 |
| 60        | 272.766 | 277.312 | 281.858 | 286.404 | 290.950 | 295.496 | 300.042 | 304.588 | 309.134 | 313.680 |
| 70        | 318.226 | 322.773 | 327.319 | 331.865 | 336.411 | 340.957 | 345.503 | 350.049 | 354.595 | 359.141 |
| 80        | 363.687 | 368.233 | 372.780 | 377.326 | 381.872 | 386.418 | 390.964 | 395.510 | 400.056 | 404.602 |
| 90        | 409.148 | 413.694 | 418.240 | 422.787 | 427.333 | 431.879 | 436.425 | 440.971 | 445.517 | 450.063 |
| 100       | 454.609 | 459.155 | 463.701 | 468.247 | 472.794 | 477.340 | 481.886 | 486.432 | 490.978 | 495.524 |

1 U.K. gallon = 4.546092 liters

**Table 25b. Liters to U.K. (Imperial) Gallons Conversion**

| liters | 0                | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      |
|--------|------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|        | Imperial gallons |        |        |        |        |        |        |        |        |        |
| 0      | ...              | 0.220  | 0.440  | 0.660  | 0.880  | 1.100  | 1.320  | 1.540  | 1.760  | 1.980  |
| 10     | 2.200            | 2.420  | 2.640  | 2.860  | 3.080  | 3.300  | 3.520  | 3.739  | 3.959  | 4.179  |
| 20     | 4.399            | 4.619  | 4.839  | 5.059  | 5.279  | 5.499  | 5.719  | 5.939  | 6.159  | 6.379  |
| 30     | 6.599            | 6.819  | 7.039  | 7.259  | 7.479  | 7.699  | 7.919  | 8.139  | 8.359  | 8.579  |
| 40     | 8.799            | 9.019  | 9.239  | 9.459  | 9.679  | 9.899  | 10.119 | 10.339 | 10.559 | 10.778 |
| 50     | 10.998           | 11.218 | 11.438 | 11.658 | 11.878 | 12.098 | 12.318 | 12.538 | 12.758 | 12.978 |
| 60     | 13.198           | 13.418 | 13.638 | 13.858 | 14.078 | 14.298 | 14.518 | 14.738 | 14.958 | 15.178 |
| 70     | 15.398           | 15.618 | 15.838 | 16.058 | 16.278 | 16.498 | 16.718 | 16.938 | 17.158 | 17.378 |
| 80     | 17.598           | 17.818 | 18.037 | 18.257 | 18.477 | 18.697 | 18.917 | 19.137 | 19.357 | 19.577 |
| 90     | 19.797           | 20.017 | 20.237 | 20.457 | 20.677 | 20.897 | 21.117 | 21.337 | 21.557 | 21.777 |
| 100    | 21.997           | 22.217 | 22.437 | 22.657 | 22.877 | 23.097 | 23.317 | 23.537 | 23.757 | 23.977 |

1 liter = 0.2199692 U.K. gallons

**Table 26a. U.S. Gallons to Liters Conversion**

| gals   | liters    | gals  | liters   | gals | liters | gals | liters | gals | liters |
|--------|-----------|-------|----------|------|--------|------|--------|------|--------|
| 1,000  | 3,785.41  | 100   | 378.54   | 10   | 37.85  | 1    | 3.79   | 0.1  | 0.38   |
| 2,000  | 7,570.82  | 200   | 757.08   | 20   | 75.71  | 2    | 7.57   | 0.2  | 0.76   |
| 3,000  | 11,356.24 | 300   | 1,135.62 | 30   | 113.56 | 3    | 11.36  | 0.3  | 1.14   |
| 4,000  | 15,141.65 | 400   | 1,514.16 | 40   | 151.42 | 4    | 15.14  | 0.4  | 1.51   |
| 5,000  | 18,927.06 | 500   | 1,892.71 | 50   | 189.27 | 5    | 18.93  | 0.5  | 1.89   |
| 6,000  | 22,712.47 | 600   | 2,271.25 | 60   | 227.12 | 6    | 22.71  | 0.6  | 2.27   |
| 7,000  | 26,497.88 | 700   | 2,649.79 | 70   | 264.98 | 7    | 26.50  | 0.7  | 2.65   |
| 8,000  | 30,283.30 | 800   | 3,028.33 | 80   | 302.83 | 8    | 30.28  | 0.8  | 3.03   |
| 9,000  | 34,068.71 | 900   | 3,406.87 | 90   | 340.69 | 9    | 34.07  | 0.9  | 3.41   |
| 10,000 | 37,854.12 | 1,000 | 3,785.41 | 100  | 378.54 | 10   | 37.85  | 1.0  | 3.79   |

1 U.S. gallon = 3.785412 liters

**Table 26b. Liters to U.S. Gallons Conversion**

| liters | gals     | liters | gals   | liters | gals  | liters | gals | liters | gals |
|--------|----------|--------|--------|--------|-------|--------|------|--------|------|
| 1,000  | 264.17   | 100    | 26.42  | 10     | 2.64  | 1      | 0.26 | 0.1    | 0.03 |
| 2,000  | 528.34   | 200    | 52.83  | 20     | 5.28  | 2      | 0.53 | 0.2    | 0.05 |
| 3,000  | 792.52   | 300    | 79.25  | 30     | 7.93  | 3      | 0.79 | 0.3    | 0.08 |
| 4,000  | 1,056.69 | 400    | 105.67 | 40     | 10.57 | 4      | 1.06 | 0.4    | 0.11 |
| 5,000  | 1,320.86 | 500    | 132.09 | 50     | 13.21 | 5      | 1.32 | 0.5    | 0.13 |
| 6,000  | 1,585.03 | 600    | 158.50 | 60     | 15.85 | 6      | 1.59 | 0.6    | 0.16 |
| 7,000  | 1,849.20 | 700    | 184.92 | 70     | 18.49 | 7      | 1.85 | 0.7    | 0.18 |
| 8,000  | 2,113.38 | 800    | 211.34 | 80     | 21.13 | 8      | 2.11 | 0.8    | 0.21 |
| 9,000  | 2,377.55 | 900    | 237.75 | 90     | 23.78 | 9      | 2.38 | 0.9    | 0.24 |
| 10,000 | 2,641.72 | 1,000  | 264.17 | 100    | 26.42 | 10     | 2.64 | 1.0    | 0.26 |

1 liter = 0.2641720 U.S. gallon

FLOW CONVERSION FACTORS

**Table 27a. U.S. Fluid Ounces to Milliliters Conversion**

| oz   | mL        | oz  | mL        | oz | mL        | oz  | mL        | oz   | mL        |
|------|-----------|-----|-----------|----|-----------|-----|-----------|------|-----------|
| 100  | 2957.353  | 10  | 295.7353  | 1  | 29.57353  | 0.1 | 2.957353  | 0.01 | 0.2957353 |
| 200  | 5914.706  | 20  | 591.4706  | 2  | 59.14706  | 0.2 | 5.914706  | 0.02 | 0.5914706 |
| 300  | 8872.059  | 30  | 887.2059  | 3  | 88.72059  | 0.3 | 8.872059  | 0.03 | 0.8872059 |
| 400  | 11829.412 | 40  | 1182.9412 | 4  | 118.29412 | 0.4 | 11.829412 | 0.04 | 1.1829412 |
| 500  | 14786.765 | 50  | 1478.6765 | 5  | 147.86765 | 0.5 | 14.786765 | 0.05 | 1.4786765 |
| 600  | 17744.118 | 60  | 1774.4118 | 6  | 177.44118 | 0.6 | 17.744118 | 0.06 | 1.7744118 |
| 700  | 20701.471 | 70  | 2070.1471 | 7  | 207.01471 | 0.7 | 20.701471 | 0.07 | 2.0701471 |
| 800  | 23658.824 | 80  | 2365.8824 | 8  | 236.58824 | 0.8 | 23.658824 | 0.08 | 2.3658824 |
| 900  | 26616.177 | 90  | 2661.6177 | 9  | 266.16177 | 0.9 | 26.616177 | 0.09 | 2.6616177 |
| 1000 | 29573.53  | 100 | 2957.353  | 10 | 295.7353  | 1   | 29.57353  | 0.1  | 2.957353  |

1 U.S. fluid ounce = 29.57353 milliliters

**Table 27b. Milliliters to U.S. Fluid Ounces Conversion**

| mL   | oz      | mL  | oz      | mL | oz       | mL  | oz        | mL   | oz         |
|------|---------|-----|---------|----|----------|-----|-----------|------|------------|
| 100  | 3.3814  | 10  | 0.33814 | 1  | 0.033814 | 0.1 | 0.0033814 | 0.01 | 0.00033814 |
| 200  | 6.7628  | 20  | 0.67628 | 2  | 0.067628 | 0.2 | 0.0067628 | 0.02 | 0.00067628 |
| 300  | 10.1442 | 30  | 1.01442 | 3  | 0.101442 | 0.3 | 0.0101442 | 0.03 | 0.00101442 |
| 400  | 13.5256 | 40  | 1.35256 | 4  | 0.135256 | 0.4 | 0.0135256 | 0.04 | 0.00135256 |
| 500  | 16.907  | 50  | 1.6907  | 5  | 0.16907  | 0.5 | 0.016907  | 0.05 | 0.0016907  |
| 600  | 20.2884 | 60  | 2.02884 | 6  | 0.202884 | 0.6 | 0.0202884 | 0.06 | 0.00202884 |
| 700  | 23.6698 | 70  | 2.36698 | 7  | 0.236698 | 0.7 | 0.0236698 | 0.07 | 0.00236698 |
| 800  | 27.0512 | 80  | 2.70512 | 8  | 0.270512 | 0.8 | 0.0270512 | 0.08 | 0.00270512 |
| 900  | 30.4326 | 90  | 3.04326 | 9  | 0.304326 | 0.9 | 0.0304326 | 0.09 | 0.00304326 |
| 1000 | 33.814  | 100 | 3.3814  | 10 | 0.33814  | 1   | 0.033814  | 0.1  | 0.0033814  |

1 milliliter = 0.003814 U.S. fluid ounce

**Units of Volumetric Flow Rate**

**Table 28a. Volume Flow per Second Conversion**

| To Convert ↓            | Multiply By Factor To Obtain ↓ | Cm <sup>3</sup> /sec      | Meter <sup>3</sup> /sec   | Foot <sup>3</sup> /sec | Liter/sec                | Gallon/sec (US) | Gallon/sec (UK)          |
|-------------------------|--------------------------------|---------------------------|---------------------------|------------------------|--------------------------|-----------------|--------------------------|
| Cm <sup>3</sup> /sec    |                                | 1                         | 1                         | 1 × 10 <sup>-6</sup>   | 3.531 × 10 <sup>-5</sup> | 0.001           | 2.642 × 10 <sup>-4</sup> |
| Meter <sup>3</sup> /sec | 1 × 10 <sup>6</sup>            | 1                         | 1                         | 35.31466               | 1,000                    | 264.172         | 219.9692                 |
| Foot <sup>3</sup> /sec  | 28,316.846                     | 0.028316                  | 0.028316                  | 1                      | 28.3168                  | 7.480519        | 6.22883                  |
| Liter/sec               | 1000                           | 0.001                     | 0.001                     | 0.0353146              | 1                        | 0.264172        | 0.21996                  |
| Gallon/sec (US)         | 3,785.412                      | 3.7854 × 10 <sup>-3</sup> | 3.7854 × 10 <sup>-3</sup> | 0.133368               | 3.785412                 | 1               | 0.8326739                |
| Gallon/sec (UK)         | 4,546.092                      | 4.546 × 10 <sup>-3</sup>  | 4.546 × 10 <sup>-3</sup>  | 0.1605432              | 4.546092                 | 1.2009504       | 1                        |

**Table 28b. Volume Flow per Minute Conversion**

| To Convert ↓           | →         | Foot <sup>3</sup> /min | Liter/min | Gallon/min (US) | Gallon/min (UK) |
|------------------------|-----------|------------------------|-----------|-----------------|-----------------|
| Foot <sup>3</sup> /min | 1         | 1                      | 28.316846 | 7.480519        | 6.2288327       |
| Liter/min              | 0.035314  | 0.035314               | 1         | 0.264172        | 0.2199692       |
| Gallon/min (US)        | 0.133680  | 0.133680               | 3.785412  | 1               | 0.832673        |
| Gallon/min (UK)        | 0.1605437 | 0.1605437              | 4.546092  | 1.20095         | 1               |

**Pitot Tube.**— A pitot tube is a small, transparent, open tube bent at right angle. It is a hollow tube that is placed longitudinally in the direction of fluid flow, allowing the flow to enter one end at the fluids velocity of approach. When the fluids enter the pitot tube, it comes to a stop, all of the velocity head is converted to pressure head. The difference between the total and static energies is the kinetic energy of the fluid. The velocity of the fluid can be calculated by using the Bernoulli equation.

$$\frac{p_1}{\rho} + \frac{v_1^2}{2} = \frac{p_2}{\rho} \qquad v_1 = \sqrt{\frac{2(p_2 - p_1)}{\rho}} \text{ (SI)} \qquad v_1 = \sqrt{\frac{2(p_2 - p_1)g_c}{\rho}} \text{ (US)}$$

## Units of Mass and Weight

Table 29. Mass and Weight Conversion Factors

| Metric System                             | Avoirdupois or Commercial Weight        |
|---|---|
| <i>1 metric ton (t) =</i>                 | <i>1 gross or long ton =</i>            |
| <b>1000</b> kilograms                     | <b>2240</b> pounds                      |
| 2204.6223 pounds                          | 1.016 metric ton                        |
| 0.9842 gross or long ton (of 2240 pounds) | 1016 kilograms                          |
| 0.9072 net or short ton (of 2000 pounds)  | <i>1 net or short ton = 2000</i> pounds |
| <i>1 kilogram (kg) =</i>                  | <i>1 pound = 16</i> ounces              |
| <b>1000</b> grams = <b>10</b> hectograms  | <b>7000</b> grains                      |
| 2.2046 pounds                             | <b>0.45359237</b> kilogram              |
| 35.274 ounces avoirdupois                 | 453.6 grams                             |
| <i>1 hectogram (hg) = 10</i> dekagrams    | <i>1 ounce =</i>                        |
| <i>1 dekagram (dag) = 10</i> grams        | $\frac{1}{16}$ pound                    |
| <i>1 gram (g) =</i>                       | 16 drachms                              |
| <b>10</b> decigrams                       | <b>437.5</b> grains                     |
| 0.0022046 pound                           | 28.3495 grams                           |
| 0.03215 ounce Troy                        | 0.2780139 newton                        |
| 0.03527 ounce avoirdupois                 | <i>1 grain Avoirdupois =</i>            |
| 15.432 grains                             | <b>1</b> grain apothecaries' weight =   |
| <i>1 decigram (dg) = 10</i> centigrams    | <b>1</b> grain Troy weight              |
| <i>1 centigram (cg) = 10</i> milligrams   | 0.064799 gram                           |

| Troy Weight  | Apothecaries' Weight                                  |
|--|---|
| Used for Weighing Gold and Silver                                    | <i>1 pound = 12</i> ounces = 5760 grains              |
| <i>1 pound Troy =</i>  | <i>1 ounce =</i>                                      |
| 12 ounces Troy = 5760 grains   | 8 drachms = 480 grains                                |
| $\frac{144}{175}$ Avoirdupois pound                                  | 31.103 grams  |
| <i>1 ounce Troy =</i>  | <i>1 drachm = 3</i> scruples = 60 grains              |
| 20 pennyweights = 480 grains   | <i>1 scruple = 20</i> grains                          |
| 31.103 grams   | <b>Old Weight Measures</b>                            |
| <i>1 pennyweight = 24</i> grains                                     | Measures for weight seldom used in the United States: |
| <i>1 grain Troy =</i>  | <i>1 gross or long ton = 20</i> hundred-weights       |
| <b>1</b> grain avoirdupois   | <i>1 hundred-weight = 4</i> quarters = 112 pounds     |
| <b>1</b> grain apothecaries' weight                                  | <i>1 quarter = 28</i> pounds                          |
| 0.0648 gram  | <i>1 stone = 14</i> pounds                            |
| <i>1 carat (used in weighing diamonds) =</i>                         | <i>1 quintal = 100</i> pounds                         |
| 3.086 grains   |   |
| <b>200</b> milligrams = $\frac{1}{5}$ gram                           |   |
| <i>1 gold karat = <math>\frac{1}{24}</math></i> proportion pure gold |   |

Note: Figures in **Bold** indicate exact conversion values

Table 30a. Pounds to Kilograms Conversion

| lb     | kg       | lb    | kg     | lb  | kg    | lb | kg   | lb  | kg   |
|--------|----------|-------|--------|-----|-------|----|------|-----|------|
| 1,000  | 453.59   | 100   | 45.36  | 10  | 4.54  | 1  | 0.45 | 0.1 | 0.05 |
| 2,000  | 907.18   | 200   | 90.72  | 20  | 9.07  | 2  | 0.91 | 0.2 | 0.09 |
| 3,000  | 1,360.78 | 300   | 136.08 | 30  | 13.61 | 3  | 1.36 | 0.3 | 0.14 |
| 4,000  | 1,814.37 | 400   | 181.44 | 40  | 18.14 | 4  | 1.81 | 0.4 | 0.18 |
| 5,000  | 2,267.96 | 500   | 226.80 | 50  | 22.68 | 5  | 2.27 | 0.5 | 0.23 |
| 6,000  | 2,721.55 | 600   | 272.16 | 60  | 27.22 | 6  | 2.72 | 0.6 | 0.27 |
| 7,000  | 3,175.15 | 700   | 317.51 | 70  | 31.75 | 7  | 3.18 | 0.7 | 0.32 |
| 8,000  | 3,628.74 | 800   | 362.87 | 80  | 36.29 | 8  | 3.63 | 0.8 | 0.36 |
| 9,000  | 4,082.33 | 900   | 408.23 | 90  | 40.82 | 9  | 4.08 | 0.9 | 0.41 |
| 10,000 | 4,535.92 | 1,000 | 453.59 | 100 | 45.36 | 10 | 4.54 | 1.0 | 0.45 |

1 pound = 0.4535924 kilogram



DENSITY CONVERSION FACTORS

**Table 30b. Kilograms to Pounds Conversion**

| kg     | lb        | kg    | lb       | kg  | lb     | kg | lb    | kg  | lb   |
|--------|-----------|-------|----------|-----|--------|----|-------|-----|------|
| 1,000  | 2,204.62  | 100   | 220.46   | 10  | 22.05  | 1  | 2.20  | 0.1 | 0.22 |
| 2,000  | 4,409.24  | 200   | 440.92   | 20  | 44.09  | 2  | 4.41  | 0.2 | 0.44 |
| 3,000  | 6,613.87  | 300   | 661.39   | 30  | 66.14  | 3  | 6.61  | 0.3 | 0.66 |
| 4,000  | 8,818.49  | 400   | 881.85   | 40  | 88.18  | 4  | 8.82  | 0.4 | 0.88 |
| 5,000  | 11,023.11 | 500   | 1,102.31 | 50  | 110.23 | 5  | 11.02 | 0.5 | 1.10 |
| 6,000  | 13,227.73 | 600   | 1,322.77 | 60  | 132.28 | 6  | 13.23 | 0.6 | 1.32 |
| 7,000  | 15,432.35 | 700   | 1,543.24 | 70  | 154.32 | 7  | 15.43 | 0.7 | 1.54 |
| 8,000  | 17,636.98 | 800   | 1,763.70 | 80  | 176.37 | 8  | 17.64 | 0.8 | 1.76 |
| 9,000  | 19,841.60 | 900   | 1,984.16 | 90  | 198.42 | 9  | 19.84 | 0.9 | 1.98 |
| 10,000 | 22,046.22 | 1,000 | 2,204.62 | 100 | 220.46 | 10 | 22.05 | 1.0 | 2.20 |

1 kilogram = 2.204622 pounds

**Table 31a. Ounces to Grams Conversion**

| oz  | g        | oz | g      | oz  | g     | oz   | g    | oz    | g    |
|-----|----------|----|--------|-----|-------|------|------|-------|------|
| 10  | 283.50   | 1  | 28.35  | 0.1 | 2.83  | 0.01 | 0.28 | 0.001 | 0.03 |
| 20  | 566.99   | 2  | 56.70  | 0.2 | 5.67  | 0.02 | 0.57 | 0.002 | 0.06 |
| 30  | 850.49   | 3  | 85.05  | 0.3 | 8.50  | 0.03 | 0.85 | 0.003 | 0.09 |
| 40  | 1,133.98 | 4  | 113.40 | 0.4 | 11.34 | 0.04 | 1.13 | 0.004 | 0.11 |
| 50  | 1,417.48 | 5  | 141.75 | 0.5 | 14.17 | 0.05 | 1.42 | 0.005 | 0.14 |
| 60  | 1,700.97 | 6  | 170.10 | 0.6 | 17.01 | 0.06 | 1.70 | 0.006 | 0.17 |
| 70  | 1,984.47 | 7  | 198.45 | 0.7 | 19.84 | 0.07 | 1.98 | 0.007 | 0.20 |
| 80  | 2,267.96 | 8  | 226.80 | 0.8 | 22.68 | 0.08 | 2.27 | 0.008 | 0.23 |
| 90  | 2,551.46 | 9  | 255.15 | 0.9 | 25.51 | 0.09 | 2.55 | 0.009 | 0.26 |
| 100 | 2,834.95 | 10 | 283.50 | 1.0 | 28.35 | 0.10 | 2.83 | 0.010 | 0.28 |

1 ounce = 28.34952 grams

**Table 31b. Grams to Ounces Conversion**

| g     | oz     | g   | oz    | g  | oz    | g   | oz    | g    | oz    |
|-------|--------|-----|-------|----|-------|-----|-------|------|-------|
| 100   | 3.527  | 10  | 0.353 | 1  | 0.035 | 0.1 | 0.004 | 0.01 | 0.000 |
| 200   | 7.055  | 20  | 0.705 | 2  | 0.071 | 0.2 | 0.007 | 0.02 | 0.001 |
| 300   | 10.582 | 30  | 1.058 | 3  | 0.106 | 0.3 | 0.011 | 0.03 | 0.001 |
| 400   | 14.110 | 40  | 1.411 | 4  | 0.141 | 0.4 | 0.014 | 0.04 | 0.001 |
| 500   | 17.637 | 50  | 1.764 | 5  | 0.176 | 0.5 | 0.018 | 0.05 | 0.002 |
| 600   | 21.164 | 60  | 2.116 | 6  | 0.212 | 0.6 | 0.021 | 0.06 | 0.002 |
| 700   | 24.692 | 70  | 2.469 | 7  | 0.247 | 0.7 | 0.025 | 0.07 | 0.002 |
| 800   | 28.219 | 80  | 2.822 | 8  | 0.282 | 0.8 | 0.028 | 0.08 | 0.003 |
| 900   | 31.747 | 90  | 3.175 | 9  | 0.317 | 0.9 | 0.032 | 0.09 | 0.003 |
| 1,000 | 35.274 | 100 | 3.527 | 10 | 0.353 | 1.0 | 0.035 | 0.10 | 0.004 |

1 gram = 0.03527397 ounce

**Table 32. Density Conversion Factors**

| To Convert<br>↓         | Multiply<br>By This<br>Factor,<br>To Obtain<br>↓ | Gram/mL      | Gram/cm <sup>3</sup> | Kg/m <sup>3</sup> | Lb/inch <sup>3</sup>    | Lb/feet <sup>3</sup> | Lb/gallon (US) | Ton/yard <sup>3</sup>  |
|-------------------------|--|--------------|----------------------|-------------------|-------------------------|----------------------|----------------|------------------------|
| Grams/mL                |  | 1            | 1                    | <b>1000</b>       | 0.036128                | 62.43                | 8.345          | 0.8428                 |
| Grams/cm <sup>3</sup>   |  | 1            | 1                    | <b>1000</b>       | 0.036128                | 62.43                | 8.345          | 0.8428                 |
| Kilogram/m <sup>3</sup> |  | <b>0.001</b> | <b>0.001</b>         | 1                 | $3.6128 \times 10^{-5}$ | 0.06243              | 0.008345       | $8.428 \times 10^{-4}$ |
| Lb/inch <sup>3</sup>    |  | 27.67788     | 27.67788             | 27677.83          | 1                       | 1728.0               | 230.9718       | 23.32687               |
| Lb/feet <sup>3</sup>    |  | 0.01602      | 0.01602              | 16.02             | $5.787 \times 10^{-4}$  | 1                    | 0.1337         | 0.01349                |
| Lb/gallon (US)          |  | 0.11983      | 0.11983              | 119.83            | 0.004329                | 7.481126             | 1              | 0.10099                |
| Ton/yard <sup>3</sup>   |  | 1.18652      | 1.18652              | 1186.52           | 0.042869                | 74.07451             | 9.9015         | 1                      |

**Table 33a. Pounds per Cubic Inch to Grams per Cubic Centimeter Conversion**

| lb/in <sup>3</sup> | g/cm <sup>3</sup> | lb/in <sup>3</sup> | g/cm <sup>3</sup> | lb/in <sup>3</sup> | g/cm <sup>3</sup> | lb/in <sup>3</sup> | g/cm <sup>3</sup> | lb/in <sup>3</sup> | g/cm <sup>3</sup> |
|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|
| 100                | 2,767.99          | 10                 | 276.80            | 1                  | 27.68             | 0.1                | 2.77              | 0.01               | 0.28              |
| 200                | 5,535.98          | 20                 | 553.60            | 2                  | 55.36             | 0.2                | 5.54              | 0.02               | 0.55              |
| 300                | 8,303.97          | 30                 | 830.40            | 3                  | 83.04             | 0.3                | 8.30              | 0.03               | 0.83              |
| 400                | 11,071.96         | 40                 | 1,107.20          | 4                  | 110.72            | 0.4                | 11.07             | 0.04               | 1.11              |
| 500                | 13,839.95         | 50                 | 1,384.00          | 5                  | 138.40            | 0.5                | 13.84             | 0.05               | 1.38              |
| 600                | 16,607.94         | 60                 | 1,660.79          | 6                  | 166.08            | 0.6                | 16.61             | 0.06               | 1.66              |
| 700                | 19,375.93         | 70                 | 1,937.59          | 7                  | 193.76            | 0.7                | 19.38             | 0.07               | 1.94              |
| 800                | 22,143.92         | 80                 | 2,214.39          | 8                  | 221.44            | 0.8                | 22.14             | 0.08               | 2.21              |
| 900                | 24,911.91         | 90                 | 2,491.19          | 9                  | 249.12            | 0.9                | 24.91             | 0.09               | 2.49              |
| 1,000              | 27,679.90         | 100                | 2,767.99          | 10                 | 276.80            | 1.0                | 27.68             | 0.10               | 2.77              |

$$1 \text{ lb/in}^3 = 27.67990 \text{ g/cm}^3$$

**Table 33b. Grams per Cubic Centimeter to Pounds per Cubic Inch Conversion**

| g/cm <sup>3</sup> | lb/in <sup>3</sup> | g/cm <sup>3</sup> | lb/in <sup>3</sup> | g/cm <sup>3</sup> | lb/in <sup>3</sup> | g/cm <sup>3</sup> | lb/in <sup>3</sup> | g/cm <sup>3</sup> | lb/in <sup>3</sup> |
|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|
| 1,000             | 36.127             | 100               | 3.613              | 10                | 0.361              | 1                 | 0.036              | 0.1               | 0.004              |
| 2,000             | 72.255             | 200               | 7.225              | 20                | 0.723              | 2                 | 0.072              | 0.2               | 0.007              |
| 3,000             | 108.382            | 300               | 10.838             | 30                | 1.084              | 3                 | 0.108              | 0.3               | 0.011              |
| 4,000             | 144.509            | 400               | 14.451             | 40                | 1.445              | 4                 | 0.145              | 0.4               | 0.014              |
| 5,000             | 180.636            | 500               | 18.064             | 50                | 1.806              | 5                 | 0.181              | 0.5               | 0.018              |
| 6,000             | 216.764            | 600               | 21.676             | 60                | 2.168              | 6                 | 0.217              | 0.6               | 0.022              |
| 7,000             | 252.891            | 700               | 25.289             | 70                | 2.529              | 7                 | 0.253              | 0.7               | 0.025              |
| 8,000             | 289.018            | 800               | 28.902             | 80                | 2.890              | 8                 | 0.289              | 0.8               | 0.029              |
| 9,000             | 325.146            | 900               | 32.515             | 90                | 3.251              | 9                 | 0.325              | 0.9               | 0.033              |
| 10,000            | 361.273            | 1,000             | 36.127             | 100               | 3.613              | 10                | 0.361              | 1.0               | 0.036              |

$$1 \text{ g/cm}^3 = 0.03612730 \text{ lb/in}^3$$

**Table 34a. Pounds per Cubic Foot to Kilograms per Cubic Meter Conversion**

| lb/ft <sup>3</sup> | kg/m <sup>3</sup> | lb/ft <sup>3</sup> | kg/m <sup>3</sup> | lb/ft <sup>3</sup> | kg/m <sup>3</sup> | lb/ft <sup>3</sup> | kg/m <sup>3</sup> | lb/ft <sup>3</sup> | kg/m <sup>3</sup> |
|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|
| 100                | 1,601.85          | 10                 | 160.18            | 1                  | 16.02             | 0.1                | 1.60              | 0.01               | 0.16              |
| 200                | 3,203.69          | 20                 | 320.37            | 2                  | 32.04             | 0.2                | 3.20              | 0.02               | 0.32              |
| 300                | 4,805.54          | 30                 | 480.55            | 3                  | 48.06             | 0.3                | 4.81              | 0.03               | 0.48              |
| 400                | 6,407.38          | 40                 | 640.74            | 4                  | 64.07             | 0.4                | 6.41              | 0.04               | 0.64              |
| 500                | 8,009.23          | 50                 | 800.92            | 5                  | 80.09             | 0.5                | 8.01              | 0.05               | 0.80              |
| 600                | 9,611.08          | 60                 | 961.11            | 6                  | 96.11             | 0.6                | 9.61              | 0.06               | 0.96              |
| 700                | 11,212.92         | 70                 | 1,121.29          | 7                  | 112.13            | 0.7                | 11.21             | 0.07               | 1.12              |
| 800                | 12,814.77         | 80                 | 1,281.48          | 8                  | 128.15            | 0.8                | 12.81             | 0.08               | 1.28              |
| 900                | 14,416.61         | 90                 | 1,441.66          | 9                  | 144.17            | 0.9                | 14.42             | 0.09               | 1.44              |
| 1,000              | 16,018.46         | 100                | 1,601.85          | 10                 | 160.18            | 1.0                | 16.02             | 0.10               | 1.60              |

$$1 \text{ lb/ft}^3 = 16.01846 \text{ kg/m}^3$$

**Table 34b. Kilograms per Cubic Meter to Pounds per Cubic Foot Conversion**

| kg/m <sup>3</sup> | lb/ft <sup>3</sup> | kg/m <sup>3</sup> | lb/ft <sup>3</sup> | kg/m <sup>3</sup> | lb/ft <sup>3</sup> | kg/m <sup>3</sup> | lb/ft <sup>3</sup> | kg/m <sup>3</sup> | lb/ft <sup>3</sup> |
|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|
| 1,000             | 62.428             | 100               | 6.243              | 10                | 0.624              | 1                 | 0.062              | 0.1               | 0.006              |
| 2,000             | 124.856            | 200               | 12.486             | 20                | 1.249              | 2                 | 0.125              | 0.2               | 0.012              |
| 3,000             | 187.284            | 300               | 18.728             | 30                | 1.873              | 3                 | 0.187              | 0.3               | 0.019              |
| 4,000             | 249.712            | 400               | 24.971             | 40                | 2.497              | 4                 | 0.250              | 0.4               | 0.025              |
| 5,000             | 312.140            | 500               | 31.214             | 50                | 3.121              | 5                 | 0.312              | 0.5               | 0.031              |
| 6,000             | 374.568            | 600               | 37.457             | 60                | 3.746              | 6                 | 0.375              | 0.6               | 0.037              |
| 7,000             | 436.996            | 700               | 43.700             | 70                | 4.370              | 7                 | 0.437              | 0.7               | 0.044              |
| 8,000             | 499.424            | 800               | 49.942             | 80                | 4.994              | 8                 | 0.499              | 0.8               | 0.050              |
| 9,000             | 561.852            | 900               | 56.185             | 90                | 5.619              | 9                 | 0.562              | 0.9               | 0.056              |
| 10,000            | 624.280            | 1,000             | 62.428             | 100               | 6.243              | 10                | 0.624              | 1.0               | 0.062              |

$$1 \text{ kg/m}^3 = 0.06242797 \text{ lb/ft}^3$$

Units of Pressure and Stress

**Table 35. Pressure and Stress Conversion Factors**

|  |   |
|--|---|
| <i>1 kilogram per sq. millimeter (kg<sub>f</sub>/mm<sup>2</sup>) =</i><br>1422.32 pounds per square inch   | <i>1 pound per square inch =</i><br>144 pounds per square foot<br>0.068 atmosphere<br>2.042 inches of mercury at 62°F<br>27.7 inches of water at 62°F<br>2.31 feet of water at 62°F<br>0.0703 kilogram per square centimeter<br>6.894757 kilopascals<br>6894.757 pascal |
| <i>1 kilogram per sq. centimeter (kg<sub>f</sub>/cm<sup>2</sup>) =</i><br>14.223 pounds per square inch  | <i>1 atmosphere =</i><br>30 inches of mercury at 62°F<br>14.7 pounds per square inch<br>2116.3 pounds per square foot<br>33.95 feet of water at 62°F  |
| <i>1 bar =</i><br><b>1,000,000</b> dynes per square centimeter<br><b>1000</b> millibars<br><b>100</b> kilopascals<br>750.06168 torr<br>1.0197162 kilogram force per sq. centimeter | <i>1 foot of water at 62°F =</i><br>62.355 pounds per square foot<br>0.433 pound per square inch  |
| <i>1 millibar =</i><br><b>100,000</b> dynes per square centimeter<br><b>100</b> pascal   | <i>1 inch of mercury at 62°F =</i><br>1.132 foot of water<br>13.58 inches of water<br>0.491 pound per square inch   |
| <i>1 torr =</i><br><b>760</b> millimeters mercury<br>$\frac{1}{760}$ atmosphere<br>133.224 pascal<br>1.333224 millibar   | <i>1 inch of water =</i><br>0.0735559 inch mercury at 0°C<br>1.8683205 torr<br>0.5780367 ounce force per square inch<br>0.0024583 atmosphere  |

**Table 36a. Pounds per Square Inch to Kilograms per Square Centimeter Conversion**

| lb/in <sup>2</sup> | kg/cm <sup>2</sup> | lb/in <sup>2</sup> | kg/cm <sup>2</sup> | lb/in <sup>2</sup> | kg/cm <sup>2</sup> | lb/in <sup>2</sup> | kg/cm <sup>2</sup> | lb/in <sup>2</sup> | kg/cm <sup>2</sup> |
|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| 1,000              | 70.307             | 100                | 7.031              | 10                 | 0.703              | 1                  | 0.070              | 0.1                | 0.007              |
| 2,000              | 140.614            | 200                | 14.061             | 20                 | 1.406              | 2                  | 0.141              | 0.2                | 0.014              |
| 3,000              | 210.921            | 300                | 21.092             | 30                 | 2.109              | 3                  | 0.211              | 0.3                | 0.021              |
| 4,000              | 281.228            | 400                | 28.123             | 40                 | 2.812              | 4                  | 0.281              | 0.4                | 0.028              |
| 5,000              | 351.535            | 500                | 35.153             | 50                 | 3.515              | 5                  | 0.352              | 0.5                | 0.035              |
| 6,000              | 421.842            | 600                | 42.184             | 60                 | 4.218              | 6                  | 0.422              | 0.6                | 0.042              |
| 7,000              | 492.149            | 700                | 49.215             | 70                 | 4.921              | 7                  | 0.492              | 0.7                | 0.049              |
| 8,000              | 562.456            | 800                | 56.246             | 80                 | 5.625              | 8                  | 0.562              | 0.8                | 0.056              |
| 9,000              | 632.763            | 900                | 63.276             | 90                 | 6.328              | 9                  | 0.633              | 0.9                | 0.063              |
| 10,000             | 703.070            | 1,000              | 70.307             | 100                | 7.031              | 10                 | 0.703              | 1.0                | 0.070              |

1 lb/in<sup>2</sup> = 0.07030697 kg/cm<sup>2</sup>

**Table 36b. Kilogram per Square Centimeter to Pounds per Square Inch Conversion**

| kg/cm <sup>2</sup> | lb/in <sup>2</sup> | kg/cm <sup>2</sup> | lb/in <sup>2</sup> | kg/cm <sup>2</sup> | lb/in <sup>2</sup> | kg/cm <sup>2</sup> | lb/in <sup>2</sup> | kg/cm <sup>2</sup> | lb/in <sup>2</sup> |
|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| 100                | 1,422.33           | 10                 | 142.23             | 1                  | 14.22              | 0.1                | 1.42               | 0.01               | 0.14               |
| 200                | 2,844.67           | 20                 | 284.47             | 2                  | 28.45              | 0.2                | 2.84               | 0.02               | 0.28               |
| 300                | 4,267.00           | 30                 | 426.70             | 3                  | 42.67              | 0.3                | 4.27               | 0.03               | 0.43               |
| 400                | 5,689.34           | 40                 | 568.93             | 4                  | 56.89              | 0.4                | 5.69               | 0.04               | 0.57               |
| 500                | 7,111.67           | 50                 | 711.17             | 5                  | 71.12              | 0.5                | 7.11               | 0.05               | 0.71               |
| 600                | 8,534.00           | 60                 | 853.40             | 6                  | 85.34              | 0.6                | 8.53               | 0.06               | 0.85               |
| 700                | 9,956.34           | 70                 | 995.63             | 7                  | 99.56              | 0.7                | 9.96               | 0.07               | 1.00               |
| 800                | 11,378.67          | 80                 | 1,137.87           | 8                  | 113.79             | 0.8                | 11.38              | 0.08               | 1.14               |
| 900                | 12,801.01          | 90                 | 1,280.10           | 9                  | 128.01             | 0.9                | 12.80              | 0.09               | 1.28               |
| 1,000              | 14,223.34          | 100                | 1,422.33           | 10                 | 142.23             | 1.0                | 14.22              | 0.10               | 1.42               |

1 kg/cm<sup>2</sup> = 14.22334 lb/in<sup>2</sup>

**Table 37a. Pounds per Square Foot to Kilograms per Square Meter Conversion**

| lb/ft <sup>2</sup> | kg/m <sup>2</sup> | lb/ft <sup>2</sup> | kg/m <sup>2</sup> | lb/ft <sup>2</sup> | kg/m <sup>2</sup> | lb/ft <sup>2</sup> | kg/m <sup>2</sup> | lb/ft <sup>2</sup> | kg/m <sup>2</sup> |
|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|
| 1,000              | 4,882.43          | 100                | 488.24            | 10                 | 48.82             | 1                  | 4.88              | 0.1                | 0.49              |
| 2,000              | 9,764.86          | 200                | 976.49            | 20                 | 97.65             | 2                  | 9.76              | 0.2                | 0.98              |
| 3,000              | 14,647.29         | 300                | 1,464.73          | 30                 | 146.47            | 3                  | 14.65             | 0.3                | 1.46              |
| 4,000              | 19,529.72         | 400                | 1,952.97          | 40                 | 195.30            | 4                  | 19.53             | 0.4                | 1.95              |
| 5,000              | 24,412.14         | 500                | 2,441.21          | 50                 | 244.12            | 5                  | 24.41             | 0.5                | 2.44              |
| 6,000              | 29,294.57         | 600                | 2,929.46          | 60                 | 292.95            | 6                  | 29.29             | 0.6                | 2.93              |
| 7,000              | 34,177.00         | 700                | 3,417.70          | 70                 | 341.77            | 7                  | 34.18             | 0.7                | 3.42              |
| 8,000              | 39,059.43         | 800                | 3,905.94          | 80                 | 390.59            | 8                  | 39.06             | 0.8                | 3.91              |
| 9,000              | 43,941.86         | 900                | 4,394.19          | 90                 | 439.42            | 9                  | 43.94             | 0.9                | 4.39              |
| 10,000             | 48,824.28         | 1,000              | 4,882.43          | 100                | 488.24            | 10                 | 48.82             | 1.0                | 4.88              |

1 lb/ft<sup>2</sup> = 4.882429 kg/m<sup>2</sup>

**Table 37b. Kilograms per Square Meter to Pounds per Square Foot Conversion**

| kg/m <sup>2</sup> | lb/ft <sup>2</sup> | kg/m <sup>2</sup> | lb/ft <sup>2</sup> | kg/m <sup>2</sup> | lb/ft <sup>2</sup> | kg/m <sup>2</sup> | lb/ft <sup>2</sup> | kg/m <sup>2</sup> | lb/ft <sup>2</sup> |
|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|-------------------|--------------------|
| 1,000             | 204.82             | 100               | 20.48              | 10                | 2.05               | 1                 | 0.20               | 0.1               | 0.02               |
| 2,000             | 409.63             | 200               | 40.96              | 20                | 4.10               | 2                 | 0.41               | 0.2               | 0.04               |
| 3,000             | 614.45             | 300               | 61.44              | 30                | 6.14               | 3                 | 0.61               | 0.3               | 0.06               |
| 4,000             | 819.26             | 400               | 81.93              | 40                | 8.19               | 4                 | 0.82               | 0.4               | 0.08               |
| 5,000             | 1,024.08           | 500               | 102.41             | 50                | 10.24              | 5                 | 1.02               | 0.5               | 0.10               |
| 6,000             | 1,228.90           | 600               | 122.89             | 60                | 12.29              | 6                 | 1.23               | 0.6               | 0.12               |
| 7,000             | 1,433.71           | 700               | 143.37             | 70                | 14.34              | 7                 | 1.43               | 0.7               | 0.14               |
| 8,000             | 1,638.53           | 800               | 163.85             | 80                | 16.39              | 8                 | 1.64               | 0.8               | 0.16               |
| 9,000             | 1,843.34           | 900               | 184.33             | 90                | 18.43              | 9                 | 1.84               | 0.9               | 0.18               |
| 10,000            | 2,048.16           | 1,000             | 204.82             | 100               | 20.48              | 10                | 2.05               | 1.0               | 0.20               |

1 kg/m<sup>2</sup> = 0.2048161 lb/ft<sup>2</sup>

**Table 38a. Pounds Per Square Inch to Kilopascals Conversion**

| →<br>lb/in <sup>2</sup> ↓ | 0           | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | 9       |
|---------------------------|-------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|                           | kilopascals |         |         |         |         |         |         |         |         |         |
| 0                         | ...         | 6.895   | 13.790  | 20.684  | 27.579  | 34.474  | 41.369  | 48.263  | 55.158  | 62.053  |
| 10                        | 68.948      | 75.842  | 82.737  | 89.632  | 96.527  | 103.421 | 110.316 | 117.211 | 124.106 | 131.000 |
| 20                        | 137.895     | 144.790 | 151.685 | 158.579 | 165.474 | 172.369 | 179.264 | 186.158 | 193.053 | 199.948 |
| 30                        | 206.843     | 213.737 | 220.632 | 227.527 | 234.422 | 241.316 | 248.211 | 255.106 | 262.001 | 268.896 |
| 40                        | 275.790     | 282.685 | 289.580 | 296.475 | 303.369 | 310.264 | 317.159 | 324.054 | 330.948 | 337.843 |
| 50                        | 344.738     | 351.633 | 358.527 | 365.422 | 372.317 | 379.212 | 386.106 | 393.001 | 399.896 | 406.791 |
| 60                        | 413.685     | 420.580 | 427.475 | 434.370 | 441.264 | 448.159 | 455.054 | 461.949 | 468.843 | 475.738 |
| 70                        | 482.633     | 489.528 | 496.423 | 503.317 | 510.212 | 517.107 | 524.002 | 530.896 | 537.791 | 544.686 |
| 80                        | 551.581     | 558.475 | 565.370 | 572.265 | 579.160 | 586.054 | 592.949 | 599.844 | 606.739 | 613.633 |
| 90                        | 620.528     | 627.423 | 634.318 | 641.212 | 648.107 | 655.002 | 661.897 | 668.791 | 675.686 | 682.581 |
| 100                       | 689.476     | 696.370 | 703.265 | 710.160 | 717.055 | 723.949 | 730.844 | 737.739 | 744.634 | 751.529 |

1 lb/in<sup>2</sup> = 6.894757 kPa. Note: 1 kilopascal = 1 kilonewton/meter<sup>2</sup>.

**Table 38b. Kilopascals to Pounds Per Square Inch Conversion**

| →<br>kPa ↓ | 0                  | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      |
|------------|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|            | lb/in <sup>2</sup> |        |        |        |        |        |        |        |        |        |
| 0          | ...                | 0.145  | 0.290  | 0.435  | 0.580  | 0.725  | 0.870  | 1.015  | 1.160  | 1.305  |
| 10         | 1.450              | 1.595  | 1.740  | 1.885  | 2.031  | 2.176  | 2.321  | 2.466  | 2.611  | 2.756  |
| 20         | 2.901              | 3.046  | 3.191  | 3.336  | 3.481  | 3.626  | 3.771  | 3.916  | 4.061  | 4.206  |
| 30         | 4.351              | 4.496  | 4.641  | 4.786  | 4.931  | 5.076  | 5.221  | 5.366  | 5.511  | 5.656  |
| 40         | 5.802              | 5.947  | 6.092  | 6.237  | 6.382  | 6.527  | 6.672  | 6.817  | 6.962  | 7.107  |
| 50         | 7.252              | 7.397  | 7.542  | 7.687  | 7.832  | 7.977  | 8.122  | 8.267  | 8.412  | 8.557  |
| 60         | 8.702              | 8.847  | 8.992  | 9.137  | 9.282  | 9.427  | 9.572  | 9.718  | 9.863  | 10.008 |
| 70         | 10.153             | 10.298 | 10.443 | 10.588 | 10.733 | 10.878 | 11.023 | 11.168 | 11.313 | 11.458 |
| 80         | 11.603             | 11.748 | 11.893 | 12.038 | 12.183 | 12.328 | 12.473 | 12.618 | 12.763 | 12.908 |
| 90         | 13.053             | 13.198 | 13.343 | 13.489 | 13.634 | 13.779 | 13.924 | 14.069 | 14.214 | 14.359 |
| 100        | 14.504             | 14.649 | 14.794 | 14.939 | 15.084 | 15.229 | 15.374 | 15.519 | 15.664 | 15.809 |

1 kPa = 0.1450377 lb/in<sup>2</sup>. Note: 1 kilopascal = 1 kilonewton/meter<sup>2</sup>.

Table 39. Pressure and Stress Conversion Factors

| To Convert<br>↓                  | Atmosphere                | Pascal<br>(n/m <sup>2</sup> ) | Dyne/cm <sup>2</sup>      | Bar                        | Kg/cm <sup>2</sup>         | Kg/m <sup>2</sup> | Psia<br>(Lb/inch <sup>2</sup> ) | Pound/ft <sup>2</sup> | Inch of<br>Water | Inch of<br>Mercury      | Millimeter<br>of Mercury | Ton/ft <sup>2</sup>      |
|----------------------------------|---------------------------|-------------------------------|---------------------------|----------------------------|----------------------------|-------------------|---------------------------------|-----------------------|------------------|-------------------------|--------------------------|--------------------------|
| Atmosphere                       | 1                         | 101325                        | 1.0133 × 10 <sup>6</sup>  | 1.01325                    | 1.03319076                 | 10,331.9076       | 14.6959488                      | 2,116.216             | 407.1893         | 29.9212                 | 760                      | 0.9597354                |
| Pascal (n/m <sup>2</sup> )       | 9.8692 × 10 <sup>-6</sup> | <b>1</b>                      | <b>10</b>                 | <b>1 × 10<sup>-5</sup></b> | 1.01968 × 10 <sup>-5</sup> | 0.101968          | 0.00014504                      | 0.02088               | 0.004019         | 0.0002953               | 0.0075                   | 9.472 × 10 <sup>-6</sup> |
| Dyne/cm <sup>2</sup>             | 9.8692 × 10 <sup>-7</sup> | <b>0.1</b>                    | <b>1</b>                  | <b>1 × 10<sup>-6</sup></b> | 1.01968 × 10 <sup>-6</sup> | 0.0101968         | 1.4504 × 10 <sup>-5</sup>       | 0.002088              | 0.000402         | 2.95 × 10 <sup>-5</sup> | 0.00075                  | 9.472 × 10 <sup>-7</sup> |
| Bar                              | 0.98692327                | <b>1 × 10<sup>5</sup></b>     | <b>1 × 10<sup>6</sup></b> | <b>1</b>                   | 1.01968                    | 10194.8           | 14.5037256                      | 2088.5434             | 401.8646         | 29.5299                 | 750.06168                | 0.9471852                |
| Kilogram/centimeter <sup>2</sup> | 0.96784111                | 98,069.982                    | 980,699.83                | 0.9807                     | <b>1</b>                   | <b>10000</b>      | 14.2232691                      | 2048.6123             | 394.0945         | 28.9653                 | 735.58536                | 0.9289043                |
| Kilogram/meter <sup>2</sup>      | 9.6787 × 10 <sup>-5</sup> | 9.80699                       | 98.06998                  | 9.807 × 10 <sup>-5</sup>   | <b>0.0001</b>              | <b>1</b>          | 0.001422                        | 0.204823              | 0.039409         | 0.002896                | 0.0735585                | 9.289 × 10 <sup>-5</sup> |
| Psi (Lb/inch <sup>2</sup> )      | 0.06804596                | 6,894.7572                    | 68,947.573                | 0.068947                   | 0.07029148                 | 703.0446          | <b>1</b>                        | <b>144</b>            | 27.70768         | 2.03602                 | 51.71493                 | 0.0653061                |
| Pound/ft <sup>2</sup>            | 4.7254 × 10 <sup>-4</sup> | 47.88025                      | 478.80258                 | 0.000478                   | 0.00048813                 | 4.88225           | 0.006944                        | <b>1</b>              | 0.19241          | 0.014139                | 0.3591314                | 0.0004535                |
| Inch of Water                    | 0.00245586                | 248.8400                      | 2488.4003                 | 0.002488                   | 0.00253690                 | 25.3737           | 0.036091                        | 5.19713               | <b>1</b>         | 0.073482                | 1.866453                 | 0.002356                 |
| Inch of Mercury                  | 0.03342112                | 3386.3949                     | 33,863.949                | 0.033863                   | 0.03452401                 | 345.3039          | 0.491153                        | 70.72632              | 13.6087          | <b>1</b>                | <b>25.4</b>              | 0.0320754                |
| Millimeter of Mercury            | 0.00131579                | 133.32236                     | 1333.22368                | 0.001333                   | 0.00135921                 | 13.594615         | 0.019336                        | 2.784495              | 0.53577          | 0.03937                 | <b>1</b>                 | 0.0012628                |
| Ton/ft <sup>2</sup> (US)         | 1.04195382                | 105575.970                    | 1055759.70                | 1.055759                   | 1.076537                   | 10765.3706        | 15.3125                         | 2205                  | 424.2724         | 31.1765                 | 791.8849                 | <b>1</b>                 |

## Units of Force

Table 40. Force Conversion Factors

| To Convert<br>↓ | Dyne                      | Gram-force               | Joule/cm                 | Newton         | Kg <sub>f</sub>            | Lb <sub>f</sub>            | Kip                       | Poundal                     | Ounce-force                |
|-----------------|---------------------------|--------------------------|--------------------------|----------------|----------------------------|----------------------------|---------------------------|-----------------------------|----------------------------|
| Dyne            | 1                         | 0.00101968               | <b>0.001</b>             | <b>0.00001</b> | 1.01968 × 10 <sup>-6</sup> | 2.24809 × 10 <sup>-6</sup> | 2.2481 × 10 <sup>-9</sup> | 7.233013 × 10 <sup>-5</sup> | 3.59694 × 10 <sup>-5</sup> |
| Gram-force      | 980.7                     | <b>1</b>                 | 0.9807                   | 0.009807       | <b>0.001</b>               | 0.0022047                  | 2.2047 × 10 <sup>-6</sup> | 0.0709341                   | 0.03527521                 |
| Joule/cm        | <b>1000</b>               | 1.0196798                | <b>1</b>                 | <b>0.01</b>    | 0.00101968                 | 0.002248                   | 2.2481 × 10 <sup>-6</sup> | 0.0723301                   | 0.03596942                 |
| Newton          | <b>1 × 10<sup>5</sup></b> | 101.96798                | <b>100</b>               | <b>1</b>       | 0.101967982                | 0.2248089                  | 2.2481 × 10 <sup>-4</sup> | 7.23301                     | 3.596942                   |
| Kg-force        | 9.807 × 10 <sup>5</sup>   | <b>1000</b>              | 980.7                    | 9.807          | <b>1</b>                   | 2.2047                     | 0.0022047                 | 70.934129                   | 35.2752102                 |
| Lb <sub>f</sub> | 4.4482 × 10 <sup>5</sup>  | 453.57627                | 444.822                  | 4.44822        | 0.45357626                 | <b>1</b>                   | <b>0.001</b>              | 32.174038                   | 16                         |
| Kip             | 4.4482 × 10 <sup>8</sup>  | 4.5357 × 10 <sup>5</sup> | 4.4482 × 10 <sup>5</sup> | 4448.2224      | 453.5762688                | <b>1000</b>                | <b>1</b>                  | 32174.038                   | 16000                      |
| Poundal         | 13825.50                  | 14.097586                | 13.8255                  | 0.1382555      | 0.014097586                | 0.0310809                  | 3.1081 × 10 <sup>-5</sup> | <b>1</b>                    | 0.497296                   |
| Ounce-force     | 27801.39                  | 28.348519                | 27.8013                  | 0.278013       | 0.02834852                 | 0.06250                    | 6.25 × 10 <sup>-5</sup>   | 2.010877                    | <b>1</b>                   |

Figures in **bold face** indicate the conversion is exact

**Table 41a. Pounds-Force to Newtons Conversion**

| lb <sub>f</sub> →<br>↓ | 0       | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | 9       |
|------------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|                        | newtons |         |         |         |         |         |         |         |         |         |
| 0                      | ...     | 4.448   | 8.896   | 13.345  | 17.793  | 22.241  | 26.689  | 31.138  | 35.586  | 40.034  |
| 10                     | 44.482  | 48.930  | 53.379  | 57.827  | 62.275  | 66.723  | 71.172  | 75.620  | 80.068  | 84.516  |
| 20                     | 88.964  | 93.413  | 97.861  | 102.309 | 106.757 | 111.206 | 115.654 | 120.102 | 124.550 | 128.998 |
| 30                     | 133.447 | 137.895 | 142.343 | 146.791 | 151.240 | 155.688 | 160.136 | 164.584 | 169.032 | 173.481 |
| 40                     | 177.929 | 182.377 | 186.825 | 191.274 | 195.722 | 200.170 | 204.618 | 209.066 | 213.515 | 217.963 |
| 50                     | 222.411 | 226.859 | 231.308 | 235.756 | 240.204 | 244.652 | 249.100 | 253.549 | 257.997 | 262.445 |
| 60                     | 266.893 | 271.342 | 275.790 | 280.238 | 284.686 | 289.134 | 293.583 | 298.031 | 302.479 | 306.927 |
| 70                     | 311.376 | 315.824 | 320.272 | 324.720 | 329.168 | 333.617 | 338.065 | 342.513 | 346.961 | 351.410 |
| 80                     | 355.858 | 360.306 | 364.754 | 369.202 | 373.651 | 378.099 | 382.547 | 386.995 | 391.444 | 395.892 |
| 90                     | 400.340 | 404.788 | 409.236 | 413.685 | 418.133 | 422.581 | 427.029 | 431.478 | 435.926 | 440.374 |
| 100                    | 444.822 | 449.270 | 453.719 | 458.167 | 462.615 | 467.063 | 471.512 | 475.960 | 480.408 | 484.856 |

1 pound-force = 4.448222 newtons

**Table 41b. Newtons to Pounds-Force Conversion**

| N →<br>↓ | 0            | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | 9       |
|----------|--------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|          | pounds-force |         |         |         |         |         |         |         |         |         |
| 0        | ...          | 0.22481 | 0.44962 | 0.67443 | 0.89924 | 1.12404 | 1.34885 | 1.57366 | 1.79847 | 2.02328 |
| 10       | 2.24809      | 2.47290 | 2.69771 | 2.92252 | 3.14732 | 3.37213 | 3.59694 | 3.82175 | 4.04656 | 4.27137 |
| 20       | 4.49618      | 4.72099 | 4.94580 | 5.17060 | 5.39541 | 5.62022 | 5.84503 | 6.06984 | 6.29465 | 6.51946 |
| 30       | 6.74427      | 6.96908 | 7.19388 | 7.41869 | 7.64350 | 7.86831 | 8.09312 | 8.31793 | 8.54274 | 8.76755 |
| 40       | 8.99236      | 9.21716 | 9.44197 | 9.66678 | 9.89159 | 10.1164 | 10.3412 | 10.5660 | 10.7908 | 11.0156 |
| 50       | 11.2404      | 11.4653 | 11.6901 | 11.9149 | 12.1397 | 12.3645 | 12.5893 | 12.8141 | 13.0389 | 13.2637 |
| 60       | 13.4885      | 13.7133 | 13.9382 | 14.1630 | 14.3878 | 14.6126 | 14.8374 | 15.0622 | 15.2870 | 15.5118 |
| 70       | 15.7366      | 15.9614 | 16.1862 | 16.4110 | 16.6359 | 16.8607 | 17.0855 | 17.3103 | 17.5351 | 17.7599 |
| 80       | 17.9847      | 18.2095 | 18.4343 | 18.6591 | 18.8839 | 19.1088 | 19.3336 | 19.5584 | 19.7832 | 20.0080 |
| 90       | 20.2328      | 20.4576 | 20.6824 | 20.9072 | 21.1320 | 21.3568 | 21.5817 | 21.8065 | 22.0313 | 22.2561 |
| 100      | 22.4809      | 22.7057 | 22.9305 | 23.1553 | 23.3801 | 23.6049 | 23.8297 | 24.0546 | 24.2794 | 24.5042 |

1 newton = 0.2248089 pound-force

**Units of Moment and Torque**

**Table 42. Bending Moment or Torque Conversion Factors**

| To Convert<br>↓   | →                   | Dyne-centimeter           | Kilogram-meter             | Newton-millimeter | Newton-meter               | Ounce-inch               | Pound-foot               |
|-------------------|---------------------|---------------------------|----------------------------|-------------------|----------------------------|--------------------------|--------------------------|
| Dyne-centimeter   | Multiply By Factor. | 1                         | <b>1 × 10<sup>-7</sup></b> | <b>0.0001</b>     | <b>1 × 10<sup>-7</sup></b> | 1.416 × 10 <sup>-5</sup> | 7.375 × 10 <sup>-8</sup> |
| Kilogram-meter    |                     | 9.80665 × 10 <sup>7</sup> | 1                          | 9806.65           | 9.80665                    | 1388.78818707            | 7.233271722              |
| Newton-millimeter |                     | <b>10,000</b>             | 0.000101968                | 1                 | <b>0.001</b>               | 0.14161193               | 0.000737562              |
| Newton-meter      |                     | <b>1 × 10<sup>7</sup></b> | 0.101967982                | <b>1000</b>       | 1                          | 141.61192894             | 0.737562121              |
| Ounce-inch        |                     | 70615.52                  | 0.000720052                | 7.061552          | 0.007061552                | 1                        | 0.005208333              |
| Pound-foot        |                     | 13,558,180                | 0.138250025                | 1355.818          | 1.355818                   | 192                      | 1                        |

Figures in **bold face** indicate the conversion is exact

**Table 43a. Pound-Inches to Newton-Meters Conversion**

| lb <sub>f</sub> -in | N-m     | lb <sub>f</sub> -in | N-m    | lb <sub>f</sub> -in | N-m   | lb <sub>f</sub> -in | N-m   | lb <sub>f</sub> -in | N-m   |
|---------------------|---------|---------------------|--------|---------------------|-------|---------------------|-------|---------------------|-------|
| 100                 | 11.298  | 10                  | 1.130  | 1                   | 0.113 | 0.1                 | 0.011 | 0.01                | 0.001 |
| 200                 | 22.597  | 20                  | 2.260  | 2                   | 0.226 | 0.2                 | 0.023 | 0.02                | 0.002 |
| 300                 | 33.895  | 30                  | 3.390  | 3                   | 0.339 | 0.3                 | 0.034 | 0.03                | 0.003 |
| 400                 | 45.194  | 40                  | 4.519  | 4                   | 0.452 | 0.4                 | 0.045 | 0.04                | 0.005 |
| 500                 | 56.492  | 50                  | 5.649  | 5                   | 0.565 | 0.5                 | 0.056 | 0.05                | 0.006 |
| 600                 | 67.791  | 60                  | 6.779  | 6                   | 0.678 | 0.6                 | 0.068 | 0.06                | 0.007 |
| 700                 | 79.089  | 70                  | 7.909  | 7                   | 0.791 | 0.7                 | 0.079 | 0.07                | 0.008 |
| 800                 | 90.388  | 80                  | 9.039  | 8                   | 0.904 | 0.8                 | 0.090 | 0.08                | 0.009 |
| 900                 | 101.686 | 90                  | 10.169 | 9                   | 1.017 | 0.9                 | 0.102 | 0.09                | 0.010 |
| 1000                | 112.985 | 100                 | 11.298 | 10                  | 1.130 | 1.0                 | 0.113 | 0.10                | 0.011 |

1 pound-inch = 0.1129848 newton-meter

**Table 43b. Newton-Meters to Pound-Inches Conversion**

| N·m  | lb <sub>f</sub> -in | N·m | lb <sub>f</sub> -in | N·m | lb <sub>f</sub> -in | N·m | lb <sub>f</sub> -in | N·m  | lb <sub>f</sub> -in |
|------|---------------------|-----|---------------------|-----|---------------------|-----|---------------------|------|---------------------|
| 100  | 885.07              | 10  | 88.51               | 1   | 8.85                | 0.1 | 0.89                | 0.01 | 0.09                |
| 200  | 1770.15             | 20  | 177.01              | 2   | 17.70               | 0.2 | 1.77                | 0.02 | 0.18                |
| 300  | 2655.22             | 30  | 265.52              | 3   | 26.55               | 0.3 | 2.66                | 0.03 | 0.27                |
| 400  | 3540.30             | 40  | 354.03              | 4   | 35.40               | 0.4 | 3.54                | 0.04 | 0.35                |
| 500  | 4425.37             | 50  | 442.54              | 5   | 44.25               | 0.5 | 4.43                | 0.05 | 0.44                |
| 600  | 5310.45             | 60  | 531.04              | 6   | 53.10               | 0.6 | 5.31                | 0.06 | 0.53                |
| 700  | 6195.52             | 40  | 619.55              | 7   | 61.96               | 0.7 | 6.20                | 0.07 | 0.62                |
| 800  | 7080.60             | 80  | 708.06              | 8   | 70.81               | 0.8 | 7.08                | 0.08 | 0.71                |
| 900  | 7965.67             | 90  | 796.57              | 9   | 79.66               | 0.9 | 7.97                | 0.09 | 0.80                |
| 1000 | 8850.75             | 100 | 885.07              | 10  | 88.51               | 1.0 | 8.85                | 0.10 | 0.89                |

1 newton meter = 8.850748 pound-inches

**Poundal.**—The expression “poundal” is sometimes used in connection with calculations in mechanics. Many mechanical handbooks, however, do not define it, because of its limited use. A poundal is a unit of force, and is defined as that force which, acting on a mass of one pound for one second, produces a velocity of one foot per second. A foot-poundal is a unit of energy equal to the energy resulting when a force of one poundal acts through a distance of one foot. In order to reduce foot-poundals to foot-pounds, multiply the number of foot-poundals by 0.03108. Dividing the number of foot-poundals by 32.16 (acceleration due to gravity) will also give foot-pounds.

### Units of Energy, Power, and Heat

1 horsepower-hour =

0.746 kilowatt-hour

1,980,000 foot-pounds

2545 Btu (British thermal units)

2.64 pounds of water evaporated at 212°F

17 pounds of water raised from 62° to 212°F

1 kilowatt-hour =

100 watt-hours

1.34 horsepower-hour

2,655,200 foot-pounds

3,600,000 joules

3415 Btu

3.54 pounds of water evaporated at 212°F

22.8 pounds of water raised from 62° to 212°F

**Table 43c. Power Conversion Factors**

1 horsepower =

746 watts

0.746 kilowatt

33,000 foot-pounds/minute

550 foot-pounds/second

2545 Btu/hour

42.4 Btu/minute

0.71 Btu/second

2.64 pounds of water evaporated per hour at 212°F

1 kilowatt =

1000 watts

1.34 horsepower

2,654,200 foot-pounds/hour

44,200 foot-pounds/minute

737 foot-pounds/second

3415 Btu/hour

57 Btu/minute

0.95 Btu/second

3.54 pounds of water evaporated per hour at 212°F

1 watt =

1 joule/second

0.00134 horsepower

0.001 kilowatt

3.42 Btu/hour

44.22 foot-pounds/minute

0.74 foot-pounds/second

0.0035 pound of water evaporated per hour at 212°F

**Table 43d. Heat Conversion Factors**

1 Btu (British thermal unit) =

1052 watt-seconds

778 foot-pounds

0.252 kilogram-calorie

0.000292 kilowatt-hour

0.000393, horsepower-hour

0.00104 pound of water evaporated at 212°F

1 kilogram calorie = 3.968 Btu

1 foot-pound =

1.36 joules

0.000000377 kilowatt-hour

0.00129 Btu

0.0000005 horsepower-hour

1 kilogram-meter =

7.233 foot-pounds

1 joule =

1 watt-second

0.00000078 kilowatt-hour

0.00095 Btu

0.74 foot-pound

**Table 44a. British Thermal Units to Foot-Pounds**

| Btu   | Ft-lb   | Btu | Ft-lb  | Btu | Ft-lb | Btu | Ft-lb | Btu  | Ft-lb |
|-------|---------|-----|--------|-----|-------|-----|-------|------|-------|
| 100   | 77,826  | 10  | 7,783  | 1   | 778   | 0.1 | 78    | 0.01 | 8     |
| 200   | 155,652 | 20  | 15,565 | 2   | 1,557 | 0.2 | 156   | 0.02 | 16    |
| 300   | 233,478 | 30  | 23,348 | 3   | 2,335 | 0.3 | 233   | 0.03 | 23    |
| 400   | 311,304 | 40  | 31,130 | 4   | 3,113 | 0.4 | 311   | 0.04 | 31    |
| 500   | 389,130 | 50  | 38,913 | 5   | 3,891 | 0.5 | 389   | 0.05 | 39    |
| 600   | 466,956 | 60  | 46,696 | 6   | 4,670 | 0.6 | 467   | 0.06 | 47    |
| 700   | 544,782 | 70  | 54,478 | 7   | 5,448 | 0.7 | 545   | 0.07 | 54    |
| 800   | 622,608 | 80  | 62,261 | 8   | 6,226 | 0.8 | 623   | 0.08 | 62    |
| 900   | 700,434 | 90  | 70,043 | 9   | 7,004 | 0.9 | 700   | 0.09 | 70    |
| 1,000 | 778,260 | 100 | 77,826 | 10  | 7,783 | 1.0 | 778   | 0.10 | 78    |

1 Btu = 778.26 ft-lb, conversion factor defined by International Steam Table Conference, 1929.

**Table 44b. Foot-Pounds to British Thermal Units**

| Ft-lb   | Btu     | Ft-lb  | Btu    | Ft-lb | Btu   | Ft-lb | Btu   | Ft-lb | Btu   |
|---------|---------|--------|--------|-------|-------|-------|-------|-------|-------|
| 10,000  | 12.849  | 1,000  | 1.285  | 100   | 0.128 | 10    | 0.013 | 1     | 0.001 |
| 20,000  | 25.698  | 2,000  | 2.570  | 200   | 0.257 | 20    | 0.026 | 2     | 0.003 |
| 30,000  | 38.548  | 3,000  | 3.855  | 300   | 0.385 | 30    | 0.039 | 3     | 0.004 |
| 40,000  | 51.397  | 4,000  | 5.140  | 400   | 0.514 | 40    | 0.051 | 4     | 0.005 |
| 50,000  | 64.246  | 5,000  | 6.425  | 500   | 0.642 | 50    | 0.064 | 5     | 0.006 |
| 60,000  | 77.095  | 6,000  | 7.710  | 600   | 0.771 | 60    | 0.077 | 6     | 0.008 |
| 70,000  | 89.944  | 7,000  | 8.994  | 700   | 0.899 | 70    | 0.090 | 7     | 0.009 |
| 80,000  | 102.794 | 8,000  | 10.279 | 800   | 1.028 | 80    | 0.103 | 8     | 0.010 |
| 90,000  | 115.643 | 9,000  | 11.564 | 900   | 1.156 | 90    | 0.116 | 9     | 0.012 |
| 100,000 | 128.492 | 10,000 | 12.849 | 1,000 | 1.285 | 100   | 0.128 | 10    | 0.013 |

1 ft-lb = 0.00128492 Btu, conversion factor defined by International Steam Table Conference, 1929.

**Table 45a. British Thermal Units to Kilojoules**

| Btu →<br>↓ | 0          | 100     | 200     | 300     | 400     | 500     | 600     | 700     | 800     | 900     |
|------------|------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|            | kilojoules |         |         |         |         |         |         |         |         |         |
| 0          | ...        | 105.51  | 211.01  | 316.52  | 422.02  | 527.53  | 633.03  | 738.54  | 844.04  | 949.55  |
| 1000       | 1055.06    | 1160.56 | 1266.07 | 1371.57 | 1477.08 | 1582.58 | 1688.09 | 1793.60 | 1899.10 | 2004.61 |
| 2000       | 2110.11    | 2215.62 | 2321.12 | 2426.63 | 2532.13 | 2637.64 | 2743.15 | 2848.65 | 2954.16 | 3059.66 |
| 3000       | 3165.17    | 3270.67 | 3376.18 | 3481.68 | 3587.19 | 3692.70 | 3798.20 | 3903.71 | 4009.21 | 4114.72 |
| 4000       | 4220.22    | 4325.73 | 4431.24 | 4536.74 | 4642.25 | 4747.75 | 4853.26 | 4958.76 | 5064.27 | 5169.77 |
| 5000       | 5275.28    | 5380.79 | 5486.29 | 5591.80 | 5697.30 | 5802.81 | 5908.31 | 6013.82 | 6119.32 | 6224.83 |
| 6000       | 6330.34    | 6435.84 | 6541.35 | 6646.85 | 6752.36 | 6857.86 | 6963.37 | 7068.88 | 7174.38 | 7279.89 |
| 7000       | 7385.39    | 7490.90 | 7596.40 | 7701.91 | 7807.41 | 7912.92 | 8018.43 | 8123.93 | 8229.44 | 8334.94 |
| 8000       | 8440.45    | 8545.95 | 8651.46 | 8756.96 | 8862.47 | 8967.98 | 9073.48 | 9178.99 | 9284.49 | 9390.00 |
| 9000       | 9495.50    | 9601.01 | 9706.52 | 9812.02 | 9917.53 | 10023.0 | 10128.5 | 10234.0 | 10339.5 | 10445.1 |
| 10000      | 10550.6    | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     |

1 Btu = 1055.056 joules

**Table 45b. Kilojoules to British Thermal Units**

| kJ →<br>↓ | 0                     | 100     | 200     | 300     | 400     | 500     | 600     | 700     | 800     | 900     |
|-----------|-----------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|           | British Thermal Units |         |         |         |         |         |         |         |         |         |
| 0         | ...                   | 94.78   | 189.56  | 284.35  | 379.13  | 473.91  | 568.69  | 663.47  | 758.25  | 853.04  |
| 1000      | 947.82                | 1042.60 | 1137.38 | 1232.16 | 1326.94 | 1421.73 | 1516.51 | 1611.29 | 1706.07 | 1800.85 |
| 2000      | 1895.63               | 1990.42 | 2085.20 | 2179.98 | 2274.76 | 2369.54 | 2464.32 | 2559.11 | 2653.89 | 2748.67 |
| 3000      | 2843.45               | 2938.23 | 3033.01 | 3127.80 | 3222.58 | 3317.36 | 3412.14 | 3506.92 | 3601.70 | 3696.49 |
| 4000      | 3791.27               | 3886.05 | 3980.83 | 4075.61 | 4170.39 | 4265.18 | 4359.96 | 4454.74 | 4549.52 | 4644.30 |
| 5000      | 4739.08               | 4833.87 | 4928.65 | 5023.43 | 5118.21 | 5212.99 | 5307.78 | 5402.56 | 5497.34 | 5592.12 |
| 6000      | 5686.90               | 5781.68 | 5876.47 | 5971.25 | 6066.03 | 6160.81 | 6255.59 | 6350.37 | 6445.16 | 6539.94 |
| 7000      | 6634.72               | 6729.50 | 6824.28 | 6919.06 | 7013.85 | 7108.63 | 7203.41 | 7298.19 | 7392.97 | 7487.75 |
| 8000      | 7582.54               | 7677.32 | 7772.10 | 7866.88 | 7961.66 | 8056.44 | 8151.23 | 8246.01 | 8340.79 | 8435.57 |
| 9000      | 8530.35               | 8625.13 | 8719.92 | 8814.70 | 8909.48 | 9004.26 | 9099.04 | 9193.82 | 9288.61 | 9383.39 |
| 10000     | 9478.17               | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     |

1 joule = 0.0009478170 Btu



**Table 46a. Horsepower to Kilowatts Conversion**

| hp     | kW      | hp    | kW    | hp  | kW   | hp | kW  | hp  | kW   |
|--------|---------|-------|-------|-----|------|----|-----|-----|------|
| 1,000  | 745.7   | 100   | 74.6  | 10  | 7.5  | 1  | 0.7 | 0.1 | 0.07 |
| 2,000  | 1,491.4 | 200   | 149.1 | 20  | 14.9 | 2  | 1.5 | 0.2 | 0.15 |
| 3,000  | 2,237.1 | 300   | 223.7 | 30  | 22.4 | 3  | 2.2 | 0.3 | 0.22 |
| 4,000  | 2,982.8 | 400   | 298.3 | 40  | 29.8 | 4  | 3.0 | 0.4 | 0.30 |
| 5,000  | 3,728.5 | 500   | 372.8 | 50  | 37.3 | 5  | 3.7 | 0.5 | 0.37 |
| 6,000  | 4,474.2 | 600   | 447.4 | 60  | 44.7 | 6  | 4.5 | 0.6 | 0.45 |
| 7,000  | 5,219.9 | 700   | 522.0 | 70  | 52.2 | 7  | 5.2 | 0.7 | 0.52 |
| 8,000  | 5,965.6 | 800   | 596.6 | 80  | 59.7 | 8  | 6.0 | 0.8 | 0.60 |
| 9,000  | 6,711.3 | 900   | 671.1 | 90  | 67.1 | 9  | 6.7 | 0.9 | 0.67 |
| 10,000 | 7,457.0 | 1,000 | 745.7 | 100 | 74.6 | 10 | 7.5 | 1.0 | 0.75 |

1 hp = 0.7456999 kW, based on 1 horsepower = 550 foot-pounds per second.

**Table 46b. Kilowatts to Horsepower Conversion**

| kW     | hp       | kW    | hp      | kW  | hp    | kW | hp   | kW  | hp   |
|--------|----------|-------|---------|-----|-------|----|------|-----|------|
| 1,000  | 1,341.0  | 100   | 134.1   | 10  | 13.4  | 1  | 1.3  | 0.1 | 0.13 |
| 2,000  | 2,682.0  | 200   | 268.2   | 20  | 26.8  | 2  | 2.7  | 0.2 | 0.27 |
| 3,000  | 4,023.1  | 300   | 402.3   | 30  | 40.2  | 3  | 4.0  | 0.3 | 0.40 |
| 4,000  | 5,364.1  | 400   | 536.4   | 40  | 53.6  | 4  | 5.4  | 0.4 | 0.54 |
| 5,000  | 6,705.1  | 500   | 670.5   | 50  | 67.1  | 5  | 6.7  | 0.5 | 0.67 |
| 7,000  | 9,387.2  | 700   | 938.7   | 70  | 93.9  | 7  | 9.4  | 0.7 | 0.94 |
| 8,000  | 10,728.2 | 800   | 1,072.8 | 80  | 107.3 | 8  | 10.7 | 0.8 | 1.07 |
| 9,000  | 12,069.2 | 900   | 1,206.9 | 90  | 120.7 | 9  | 12.1 | 0.9 | 1.21 |
| 10,000 | 13,410.2 | 1,000 | 1,341.0 | 100 | 134.1 | 10 | 13.4 | 1.0 | 1.34 |

1 kW = 1.341022 hp, based on 1 horsepower = 550 foot-pounds per second.

**Table 47a. Foot-Pounds to Joules Conversion**

| ft-lb →<br>↓ | 0       | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | 9       |
|--------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|              | joules  |         |         |         |         |         |         |         |         |         |
| 0            | ...     | 1.356   | 2.712   | 4.067   | 5.423   | 6.779   | 8.135   | 9.491   | 10.847  | 12.202  |
| 10           | 13.558  | 14.914  | 16.270  | 17.626  | 18.981  | 20.337  | 21.693  | 23.049  | 24.405  | 25.761  |
| 20           | 27.116  | 28.472  | 29.828  | 31.184  | 32.540  | 33.895  | 35.251  | 36.607  | 37.963  | 39.319  |
| 30           | 40.675  | 42.030  | 43.386  | 44.742  | 46.098  | 47.454  | 48.809  | 50.165  | 51.521  | 52.877  |
| 40           | 54.233  | 55.589  | 56.944  | 58.300  | 59.656  | 61.012  | 62.368  | 63.723  | 65.079  | 66.435  |
| 50           | 67.791  | 69.147  | 70.503  | 71.858  | 73.214  | 74.570  | 75.926  | 77.282  | 78.637  | 79.993  |
| 60           | 81.349  | 82.705  | 84.061  | 85.417  | 86.772  | 88.128  | 89.484  | 90.840  | 92.196  | 93.551  |
| 70           | 94.907  | 96.263  | 97.619  | 98.975  | 100.331 | 101.686 | 103.042 | 104.398 | 105.754 | 107.110 |
| 80           | 108.465 | 109.821 | 111.177 | 112.533 | 113.889 | 115.245 | 116.600 | 117.956 | 119.312 | 120.668 |
| 90           | 122.024 | 123.379 | 124.735 | 126.091 | 127.447 | 128.803 | 130.159 | 131.514 | 132.870 | 134.226 |
| 100          | 135.582 | 136.938 | 138.293 | 139.649 | 141.005 | 142.361 | 143.717 | 145.073 | 146.428 | 147.784 |

1 foot-pound = 1.355818 joules

**Table 47b. Joules to Foot-Pounds Conversion**

| J →<br>↓ | 0           | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | 9       |
|----------|-------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|          | foot-pounds |         |         |         |         |         |         |         |         |         |
| 0        | ...         | 0.7376  | 1.4751  | 2.2127  | 2.9502  | 3.6878  | 4.4254  | 5.1629  | 5.9005  | 6.6381  |
| 10       | 7.3756      | 8.1132  | 8.8507  | 9.5883  | 10.3259 | 11.0634 | 11.8010 | 12.5386 | 13.2761 | 14.0137 |
| 20       | 14.7512     | 15.4888 | 16.2264 | 16.9639 | 17.7015 | 18.4391 | 19.1766 | 19.9142 | 20.6517 | 21.3893 |
| 30       | 22.1269     | 22.8644 | 23.6020 | 24.3395 | 25.0771 | 25.8147 | 26.5522 | 27.2898 | 28.0274 | 28.7649 |
| 40       | 29.5025     | 30.2400 | 30.9776 | 31.7152 | 32.4527 | 33.1903 | 33.9279 | 34.6654 | 35.4030 | 36.1405 |
| 50       | 36.8781     | 37.6157 | 38.3532 | 39.0908 | 39.8284 | 40.5659 | 41.3035 | 42.0410 | 42.7786 | 43.5162 |
| 60       | 44.2537     | 44.9913 | 45.7289 | 46.4664 | 47.2040 | 47.9415 | 48.6791 | 49.4167 | 50.1542 | 50.8918 |
| 70       | 51.6293     | 52.3669 | 53.1045 | 53.8420 | 54.5796 | 55.3172 | 56.0547 | 56.7923 | 57.5298 | 58.2674 |
| 80       | 59.0050     | 59.7425 | 60.4801 | 61.2177 | 61.9552 | 62.6928 | 63.4303 | 64.1679 | 64.9055 | 65.6430 |
| 90       | 66.3806     | 67.1182 | 67.8557 | 68.5933 | 69.3308 | 70.0684 | 70.8060 | 71.5435 | 72.2811 | 73.0186 |
| 100      | 73.7562     | 74.4938 | 75.2313 | 75.9689 | 76.7065 | 77.4440 | 78.1816 | 78.9191 | 79.6567 | 80.3943 |

1 joule = 0.7375621 foot-pound

Table 48. Power Conversion Factors

| To Convert<br>↓         | →                                       | Horsepower                | Watts       | Kilowatts                 | HP (metric)                | Kg <sub>f</sub> /m/s | Ft-Lb <sub>f</sub> /s | Ft-Lb <sub>f</sub> /min | Calories/sec | Btu/sec                   | Btu/hr      |
|-------------------------|---|---------------------------|-------------|---------------------------|----------------------------|----------------------|-----------------------|-------------------------|--------------|---------------------------|-------------|
| Horsepower              | Multiply By This Factor, To Obtain<br>↓ | 1                         | 745.699     | 0.745699                  | 1.0138681                  | 76.04                | <b>550</b>            | <b>33000</b>            | 178.1        | 0.7068                    | 2544.48     |
| Watts                   |   | 0.00134024                | 1           | <b>0.001</b>              | 0.0013596                  | 0.1019714            | 0.7375630             | 44.253727               | 0.2388363    | 0.0009478                 | 3.4122      |
| Kilowatts               |   | 1.34102365                | <b>1000</b> | 1                         | 1.3596196                  | 101.9713158          | 737.563011            | 44253.727270            | 238.836025   | 0.9478344                 | 3412.20     |
| HP (metric)             |   | 0.9863215                 | 735.499     | 0.735499                  | 1                          | <b>75</b>            | 542.476857            | 32548.61114             | 175.663869   | 0.6971321                 | 2509.6754   |
| Kg <sub>f</sub> -m/s    |   | 0.01315097                | 9.8066      | 0.0098067                 | 0.0133334                  | 1                    | 7.2330352             | 433.982114              | 2.3421883    | 0.0092951                 | 33.4623     |
| Ft-lb <sub>f</sub> /s   |   | 0.00181818                | 1.35581     | 0.0013558                 | 0.0018434                  | 0.1382545            | 1                     | <b>60</b>               | 0.3238181    | 0.0012851                 | 4.6263      |
| Ft-lb <sub>f</sub> /min |   | 3.0303 × 10 <sup>-5</sup> | 0.02259     | 2.2596 × 10 <sup>-5</sup> | 3.07233 × 10 <sup>-5</sup> | 0.0023042            | 0.0166667             | 1                       | 0.0053969    | 2.1418 × 10 <sup>-5</sup> | 0.077105    |
| Calories/sec            |   | 0.00561482                | 4.18696     | 0.0041869                 | 0.0056927                  | 0.4269512            | 3.0881527             | 185.288916              | 1            | 0.0039686                 | 14.2868     |
| Btu/sec                 |   | 1.41482739                | 1055.035    | 1.0550353                 | 1.4344484                  | 107.5834748          | 778.155065            | 46689.3039              | <b>252</b>   | 1                         | <b>3600</b> |
| Btu/hr                  |   | 0.0003930                 | 0.29306     | 0.0002931                 | 0.0003985                  | 0.0298843            | 0.2161542             | 12.969251               | 0.069994     | 0.0002778                 | 1           |

Figures in **bold face** indicate the conversion is exact

Table 49. Energy and Work Conversion Factors

| To Convert<br>↓    | →                                       | Joules                     | Ft-lb <sub>f</sub>       | Ft-Poundal               | Btu                       | Kg-m                      | Calories                  | Watt-hour                 | Erg                       | Therm                     | HP-hours                  | HP-hours (m)              |
|--------------------|---|----------------------------|--------------------------|--------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| Joules             | Multiply By This Factor, To Obtain<br>↓ | 1                          | 0.73756                  | 23.7303                  | 0.0009478                 | 0.101972                  | 0.2388458                 | 0.00027778                | <b>1 × 10<sup>7</sup></b> | 9.478 × 10 <sup>-9</sup>  | 3.725 × 10 <sup>-7</sup>  | 3.7764 × 10 <sup>-7</sup> |
| Ft-lb <sub>f</sub> |   | 1.355818                   | 1                        | 32.1740                  | 0.00128506                | 0.138255                  | 0.3238316                 | 0.00037661                | 1.356 × 10 <sup>7</sup>   | 1.285 × 10 <sup>-8</sup>  | 5.0505 × 10 <sup>-7</sup> | 5.1201 × 10 <sup>-7</sup> |
| Ft-Poundal         |   | 0.04214                    | 0.03108                  | 1                        | 3.994 × 10 <sup>-5</sup>  | 0.0042971                 | 0.010065                  | 1.1705 × 10 <sup>-5</sup> | 4.214 × 10 <sup>5</sup>   | 3.994 × 10 <sup>-10</sup> | 1.5697 × 10 <sup>-8</sup> | 1.5914 × 10 <sup>-8</sup> |
| Btu                |   | 1055.055                   | 778.1692                 | 25036.8174               | 1                         | 107.5875                  | 252                       | 0.29307071                | 1.055 × 10 <sup>10</sup>  | 1 × 10 <sup>-5</sup>      | 0.0003930                 | 0.0003984                 |
| Kg-m               |   | 9.80665                    | 7.233013                 | 232.714987               | 0.00929524                | 1                         | 2.342278                  | 0.00272416                | 9.807 × 10 <sup>7</sup>   | 9.294 × 10 <sup>-8</sup>  | 3.653 × 10 <sup>-6</sup>  | 3.703 × 10 <sup>-6</sup>  |
| Calories           |   | 4.1868                     | 3.088025                 | 99.35427                 | 0.00396832                | 0.42691934                | 1                         | 0.001163                  | 4.187 × 10 <sup>7</sup>   | 3.968 × 10 <sup>-8</sup>  | 1.5596 × 10 <sup>-6</sup> | 1.5811 × 10 <sup>-6</sup> |
| Watt-Hour          |   | <b>3600</b>                | 2655.2237                | 85429.168                | 3.4121416                 | 367.09783                 | 859.845227                | 1                         | 3.6 × 10 <sup>10</sup>    | 3.412 × 10 <sup>-5</sup>  | 0.001341                  | 0.0013595                 |
| Erg                |   | <b>1 × 10<sup>-7</sup></b> | 7.375 × 10 <sup>-8</sup> | 2.373 × 10 <sup>-6</sup> | 9.478 × 10 <sup>-11</sup> | 1.0197 × 10 <sup>-8</sup> | 2.3884 × 10 <sup>-8</sup> | 2.778 × 10 <sup>-11</sup> | 1                         | 9.478 × 10 <sup>-16</sup> | 3.725 × 10 <sup>-14</sup> | 3.776 × 10 <sup>-14</sup> |
| Therm              |   | 1.055 × 10 <sup>8</sup>    | 7.781 × 10 <sup>7</sup>  | 2.503 × 10 <sup>7</sup>  | <b>1 × 10<sup>5</sup></b> | 1.0758 × 10 <sup>7</sup>  | 2.5196 × 10 <sup>7</sup>  | 29307.222                 | 1.055 × 10 <sup>15</sup>  | 1                         | 39.3020                   | 39.843655                 |
| HP-hours           |   | 2.6845 × 10 <sup>6</sup>   | 1.9799 × 10 <sup>6</sup> | 6.3704 × 10 <sup>7</sup> | 2544.4150                 | 2.7374 × 10 <sup>5</sup>  | 6.4118 × 10 <sup>5</sup>  | 745.6944                  | 2.685 × 10 <sup>13</sup>  | 0.025444                  | 1                         | 1.0137839                 |
| HP-hours (m)       |   | 2.648 × 10 <sup>6</sup>    | 1.953 × 10 <sup>6</sup>  | 6.2837 × 10 <sup>7</sup> | 2509.8197                 | 2.70 × 10 <sup>5</sup>    | 6.3246 × 10 <sup>5</sup>  | 735.555                   | 2.648 × 10 <sup>13</sup>  | 0.025098                  | 0.9864034                 | 1                         |

Figures in **bold face** indicate the conversion is exact

Table 50. Thermal Conductance Conversion Factors

| To Convert<br>↓                  | →                                  | Btu-ft/(h-ft <sup>2</sup> -°F) | Btu-in/(h-ft <sup>2</sup> -°F) | Btu-in/(sec-ft <sup>2</sup> -°F) | Cal/(cm-s-°C)             | Kcal/(cm-s-°C)             | Kcal/(m-h-°C)             | Erg/(cm-s-°C)             | Joules/(m-h-°C)          | Watt/(ft-°C)              | Watt/(m-°K)               |
|----------------------------------|------------------------------------|--------------------------------|--------------------------------|----------------------------------|---------------------------|----------------------------|---------------------------|---------------------------|--------------------------|---------------------------|---------------------------|
| Btu-ft/(h-ft <sup>2</sup> -°F)   | Multiply By This Factor, To Obtain | 1                              | <b>12</b>                      | 0.00333333                       | 0.00413385                | 4.13386 × 10 <sup>-6</sup> | 1.488188976               | 173076.378                | 6230.0055                | 0.5274738                 | 1.73056                   |
| Btu-in/(h-ft <sup>2</sup> -°F)   |                                    | 0.0833333                      | 1                              | 0.000277778                      | 0.00034448                | 3.44448 × 10 <sup>-7</sup> | 0.124015748               | 14423.0315                | 519.25573                | 0.04395615                | 0.14421                   |
| Btu-in/(sec-ft <sup>2</sup> -°F) |                                    | <b>300</b>                     | <b>3600</b>                    | 1                                | 1.24001574                | 0.001240157                | 446.4566929               | 5.1925 × 10 <sup>7</sup>  | 1.8693 × 10 <sup>6</sup> | 158.24214                 | 519.167                   |
| Cal/(cm-s-°C)                    |                                    | 241.9047                       | 2902.8571                      | 0.806349                         | 1                         | <b>0.001</b>               | <b>360</b>                | 4.1868 × 10 <sup>7</sup>  | 1.507 × 10 <sup>6</sup>  | 127.598424                | 418.63                    |
| Kcal/(cm-s-°C)                   |                                    | 2.419 × 10 <sup>5</sup>        | 2.902 × 10 <sup>6</sup>        | 806.3492                         | <b>1000</b>               | 1                          | <b>360000</b>             | 4.1868 × 10 <sup>10</sup> | 1.507 × 10 <sup>9</sup>  | 1.276 × 10 <sup>5</sup>   | 4.1863 × 10 <sup>5</sup>  |
| Kcal/(m-h-°C)                    |                                    | 0.671957                       | 8.063349                       | 0.00223985                       | 0.00277778                | 2.77778 × 10 <sup>-6</sup> | 1                         | 116300                    | 4186.8                   | 0.35444                   | 1.16286                   |
| Erg/(cm-s-°C)                    |                                    | 5.7778 × 10 <sup>-6</sup>      | 6.933 × 10 <sup>-5</sup>       | 1.92593 × 10 <sup>-8</sup>       | 2.3884 × 10 <sup>-8</sup> | 2.3884 × 10 <sup>-11</sup> | 8.5984 × 10 <sup>-6</sup> | 1                         | 0.036                    | 3.0476 × 10 <sup>-6</sup> | 1 × 10 <sup>-5</sup>      |
| Joules/(m-h-°C)                  |                                    | 1.6051 × 10 <sup>-4</sup>      | 0.00192616                     | 5.35045 × 10 <sup>-7</sup>       | 6.6354 × 10 <sup>-7</sup> | 6.6354 × 10 <sup>-10</sup> | 0.000238874               | 27.781095                 | 1                        | 8.4666 × 10 <sup>-5</sup> | 2.7777 × 10 <sup>-4</sup> |
| Watt/(ft-°C)                     |                                    | 1.895828                       | 22.75                          | 0.006319429                      | 0.00783708                | 7.83709 × 10 <sup>-6</sup> | 2.821351461               | 328123.1749               | 11811.024                | 1                         | 3.28                      |
| Watt/(m-°K)                      |                                    | 0.5778486                      | 6.934183                       | 0.001926162                      | 0.002388744               | 2.38874 × 10 <sup>-6</sup> | 0.859947925               | <b>1 × 10<sup>5</sup></b> | <b>3600</b>              | 0.304878                  | 1                         |

Figures in **bold face** indicate the conversion is exact

**Conduction.**—Whenever the molecules of a working substance, whether liquid, solid, or vapor, are restrained so that no appreciable relative translatory motion occurs among them, the kinetic energies of the various molecules will be largely due to vibration. If a temperature difference exists in the working substance, some adjacent molecules will necessarily be at different temperatures hence will possess different degrees of vibratory motion. In this case the molecule which is vibrating most rapidly will transfer some of its motion to the slower-moving molecule next to it, the one then undergoing a decrease in temperature and the other an increase. In this way, thermal energy will be transferred by the mechanism of conduction from the region of higher to the region of lower temperature. The process will continue spontaneously until the entire system has reached a uniform equilibrium temperature.

In contrast to radiation, conduction only occurs when a working substance is present and when the molecules of that working substance retain

practically fixed positions with respect to one another. Thus, conductive heat flow would always occur through solids, but would take place in liquids and vapors only if special conditions prevented or greatly reduced the normal translatory motion of the molecules within these materials.

**Fuel Oil, Coal and Gas Equivalents.**—One gallon of fuel oil equals 13.1 pounds of coal, equals 160 cubic feet of natural gas. One barrel of fuel oil equals 0.278 ton of coal, equals 680.6 cubic feet of natural gas. One pound of fuel oil equals 1.75 pounds of coal, equals 21.3 cubic feet of natural gas. One pound of coal equals 0.763 gallon of oil, equals 12.2 cubic feet of natural gas. One ton of coal equals 3.6 barrels of oil, equals 24,500 cubic feet of natural gas. The heating value of the average mid-continent fuel oil having a Baume gravity of 26.9 is 19,376 British thermal units per pound of oil, and 143,950 British thermal units per gallon of oil. The specific gravity and the heat value may be expressed approximately by means of a simple formula, as follows: BTU per pound = 18,650 + 40 × (Degrees Baume - 10).

## Units of Temperature

**Thermometer Scales.**—There are two thermometer scales in general use: the Fahrenheit (F), which is used in the United States and in other countries still using the English system of units, and the Celsius (C) or Centigrade used throughout the rest of the world.

In the Fahrenheit thermometer, the freezing point of water is marked at 32 degrees on the scale and the boiling point, at atmospheric pressure, at 212 degrees. The distance between these two points is divided into 180 degrees. On the Celsius scale, the freezing point of water is at 0 degrees and the boiling point at 100 degrees. The following formulas may be used for converting temperatures given on any one of the scales to the other scale:

$$\text{Degrees Fahrenheit} = \frac{9 \times \text{degrees C}}{5} + 32$$

$$\text{Degrees Celsius} = \frac{5 \times (\text{degrees F} - 32)}{9}$$

Tables on the pages that follow can be used to convert degrees Celsius into degrees Fahrenheit or vice versa. In the event that the conversions are not covered in the tables, use those applicable portions of the formulas given above for converting.

Table 51. Temperature Conversion Formulas

| To Convert        | To                         | Use Formula                | To Convert     | To                         | Use Formula                     |
|-------------------|----------------------------|----------------------------|----------------|----------------------------|---------------------------------|
| Celsius, $t_C$    | $^{\circ}\text{K}$ , $t_K$ | $t_K = t_C + 273.15$       | Kelvin, $t_K$  | $^{\circ}\text{C}$ , $t_C$ | $t_C = t_K - 273.15$            |
|                   | $^{\circ}\text{F}$ , $t_F$ | $t_F = 1.8 t_C + 32$       |                | $^{\circ}\text{F}$ , $t_F$ | $t_F = 1.8 t_K - 459.67$        |
|                   | $^{\circ}\text{R}$ , $t_R$ | $t_R = 9(t_C + 273.15)/5$  |                | $^{\circ}\text{R}$ , $t_R$ | $t_R = 9/5 \times t_K$          |
| Fahrenheit, $t_F$ | $^{\circ}\text{K}$ , $t_K$ | $t_K = (t_F + 459.67)/1.8$ | Rankine, $t_R$ | $^{\circ}\text{K}$ , $t_K$ | $t_K = 5/9 \times t_R$          |
|                   | $^{\circ}\text{C}$ , $t_C$ | $t_C = (t_F - 32)/1.8$     |                | $^{\circ}\text{C}$ , $t_C$ | $t_C = 5/9 \times t_R - 273.15$ |
|                   | $^{\circ}\text{R}$ , $t_R$ | $t_K = t_F - 459.67$       |                | $^{\circ}\text{F}$ , $t_F$ | $t_F = t_R - 459.67$            |

**Absolute Temperature and Absolute Zero.**—A point has been determined on the thermometer scale, by theoretical considerations, that is called the absolute zero and beyond which a further decrease in temperature is inconceivable. This point is located at  $-273.15$  degrees Celsius or  $-459.67$  degrees F. A temperature reckoned from this point, instead of from the zero on the ordinary thermometers, is called absolute temperature. Absolute temperature in degrees C is known as “degrees Kelvin” or the “Kelvin scale” (K) and absolute temperature in degrees F is known as “degrees Rankine” or the “Rankine scale” (R).

$$\text{Degrees Kelvin} = \text{degrees C} + 273.15$$

$$\text{Degrees Rankine} = \text{degrees F} + 459.67$$

**Measures of the Quantity of Thermal Energy.**—The unit of quantity of thermal energy used in the United States is the British thermal unit, which is the quantity of heat or thermal energy required to raise the temperature of one pound of pure water one degree F. (American National Standard abbreviation, Btu; conventional British symbol, B.Th.U.) The French thermal unit, or *kilogram calorie*, is the quantity of heat or thermal energy required to raise the temperature of one kilogram of pure water one degree C. One kilogram calorie = 3.968 British thermal units = 1000 gram calories. The number of foot-pounds of mechanical energy equivalent to one British thermal unit is called the *mechanical equivalent of heat*, and equals 778 foot-pounds.

In the modern metric or SI system of units, the unit for thermal energy is the *joule* (J); a commonly used multiple being the kilojoule (kJ), or 1000 joules. See page 2544 for an explanation of the SI System. One kilojoule = 0.9478 Btu. Also in the SI System, the *watt* (W), equal to joule per second (J/s), is used for power, where one watt = 3.412 Btu per hour.

Table 52. °C → °F and °R Temperature Conversion °F → °C and °K

| °K    | °C     | °F     | °R     | °K    | °C    | °F   | °R   | °K    | °C    | °F    | °R   |       |       |       |
|-------|--------|--------|--------|-------|-------|------|------|-------|-------|-------|------|-------|-------|-------|
| 0.0   | -273.2 | -459.7 | ...    | 261.5 | -11.7 | 11   | 51.8 | 511.5 | 293.7 | 20.6  | 69   | 156.2 | 615.9 |       |
| 5.4   | -267.8 | -450   | ...    | 262.0 | -11.1 | 12   | 53.6 | 513.3 | 294.3 | 21.1  | 70   | 158.0 | 617.7 |       |
| 10.9  | -262.2 | -440   | ...    | 262.6 | -10.6 | 13   | 55.4 | 515.1 | 294.8 | 21.7  | 71   | 159.8 | 619.5 |       |
| 16.5  | -256.7 | -430   | ...    | 263.2 | -10.0 | 14   | 57.2 | 516.9 | 295.4 | 22.2  | 72   | 161.6 | 621.3 |       |
| 22.0  | -251.1 | -420   | ...    | 263.7 | -9.4  | 15   | 59.0 | 518.7 | 295.9 | 22.8  | 73   | 163.4 | 623.1 |       |
| 27.6  | -245.6 | -410   | ...    | 264.3 | -8.9  | 16   | 60.8 | 520.5 | 296.5 | 23.3  | 74   | 165.2 | 624.9 |       |
| 33.2  | -240.0 | -400   | ...    | 264.8 | -8.3  | 17   | 62.6 | 522.3 | 297.0 | 23.9  | 75   | 167.0 | 626.7 |       |
| 38.7  | -234.4 | -390   | ...    | 265.4 | -7.8  | 18   | 64.4 | 524.1 | 297.6 | 24.4  | 76   | 168.8 | 628.5 |       |
| 44.3  | -228.9 | -380   | ...    | 265.9 | -7.2  | 19   | 66.2 | 525.9 | 298.2 | 25.0  | 77   | 170.6 | 630.3 |       |
| 49.8  | -223.3 | -370   | ...    | 266.5 | -6.7  | 20   | 68.0 | 527.7 | 298.7 | 25.6  | 78   | 172.4 | 632.1 |       |
| 55.4  | -217.8 | -360   | ...    | 267.0 | -6.1  | 21   | 69.8 | 529.5 | 299.3 | 26.1  | 79   | 174.2 | 633.9 |       |
| 60.9  | -212.2 | -350   | ...    | 267.6 | -5.6  | 22   | 71.6 | 531.3 | 299.8 | 26.7  | 80   | 176.0 | 635.7 |       |
| 66.5  | -206.7 | -340   | ...    | 268.2 | -5.0  | 23   | 73.4 | 533.1 | 300.4 | 27.2  | 81   | 177.8 | 637.5 |       |
| 72.0  | -201.1 | -330   | ...    | 268.7 | -4.4  | 24   | 75.2 | 534.9 | 300.9 | 27.8  | 82   | 179.6 | 639.3 |       |
| 77.6  | -195.6 | -320   | ...    | 269.3 | -3.9  | 25   | 77.0 | 536.7 | 301.5 | 28.3  | 83   | 181.4 | 641.1 |       |
| 83.2  | -190.0 | -310   | ...    | 269.8 | -3.3  | 26   | 78.8 | 538.5 | 302.0 | 28.9  | 84   | 183.2 | 642.9 |       |
| 88.7  | -184.4 | -300   | ...    | 270.4 | -2.8  | 27   | 80.6 | 540.3 | 302.6 | 29.4  | 85   | 185.0 | 644.7 |       |
| 94.3  | -178.9 | -290   | ...    | 270.9 | -2.2  | 28   | 82.4 | 542.1 | 303.2 | 30.0  | 86   | 186.8 | 646.5 |       |
| 99.8  | -173.3 | -280   | ...    | 271.5 | -1.7  | 29   | 84.2 | 543.9 | 303.7 | 30.6  | 87   | 188.6 | 648.3 |       |
| 103.6 | -169.5 | -273.2 | -459.7 | 0.0   | 272.0 | -1.1 | 30   | 86.0  | 545.7 | 304.3 | 31.1 | 88    | 190.4 | 650.1 |
| 105.4 | -167.8 | -270   | -454.0 | 5.7   | 272.6 | -0.6 | 31   | 87.8  | 547.5 | 304.8 | 31.7 | 89    | 192.2 | 651.9 |
| 110.9 | -162.2 | -260   | -436.0 | 23.7  | 273.2 | 0.0  | 32   | 89.6  | 549.3 | 305.4 | 32.2 | 90    | 194.0 | 653.7 |
| 116.5 | -156.7 | -250   | -418.0 | 41.7  | 273.7 | 0.6  | 33   | 91.4  | 551.1 | 305.9 | 32.8 | 91    | 195.8 | 655.5 |
| 122.0 | -151.1 | -240   | -400.0 | 59.7  | 274.3 | 1.1  | 34   | 93.2  | 552.9 | 306.5 | 33.3 | 92    | 197.6 | 657.3 |
| 127.6 | -145.6 | -230   | -382.0 | 77.7  | 274.8 | 1.7  | 35   | 95.0  | 554.7 | 307.0 | 33.9 | 93    | 199.4 | 659.1 |
| 133.2 | -140.0 | -220   | -364.0 | 95.7  | 275.4 | 2.2  | 36   | 96.8  | 556.5 | 307.6 | 34.4 | 94    | 201.2 | 660.9 |
| 138.7 | -134.4 | -210   | -346.0 | 113.7 | 275.9 | 2.8  | 37   | 98.6  | 558.3 | 308.2 | 35.0 | 95    | 203.0 | 662.7 |
| 144.3 | -128.9 | -200   | -328.0 | 131.7 | 276.5 | 3.3  | 38   | 100.4 | 560.1 | 308.7 | 35.6 | 96    | 204.8 | 664.5 |
| 149.8 | -123.3 | -190   | -310.0 | 149.7 | 277.0 | 3.9  | 39   | 102.2 | 561.9 | 309.3 | 36.1 | 97    | 206.6 | 666.3 |
| 155.4 | -117.8 | -180   | -292.0 | 167.7 | 277.6 | 4.4  | 40   | 104.0 | 563.7 | 309.8 | 36.7 | 98    | 208.4 | 668.1 |
| 160.9 | -112.2 | -170   | -274.0 | 185.7 | 278.2 | 5.0  | 41   | 105.8 | 565.5 | 310.4 | 37.2 | 99    | 210.2 | 669.9 |
| 166.5 | -106.7 | -160   | -256.0 | 203.7 | 278.7 | 5.6  | 42   | 107.6 | 567.3 | 310.9 | 37.8 | 100   | 212.0 | 671.7 |
| 172.0 | -101.1 | -150   | -238.0 | 221.7 | 279.3 | 6.1  | 43   | 109.4 | 569.1 | 311.5 | 38.3 | 101   | 213.8 | 673.5 |
| 177.6 | -95.6  | -140   | -220.0 | 239.7 | 279.8 | 6.7  | 44   | 111.2 | 570.9 | 312.0 | 38.9 | 102   | 215.6 | 675.3 |
| 183.2 | -90.0  | -130   | -202.0 | 257.7 | 280.4 | 7.2  | 45   | 113.0 | 572.7 | 312.6 | 39.4 | 103   | 217.4 | 677.1 |
| 188.7 | -84.4  | -120   | -184.0 | 275.7 | 280.9 | 7.8  | 46   | 114.8 | 574.5 | 313.2 | 40.0 | 104   | 219.2 | 678.9 |
| 194.3 | -78.9  | -110   | -166.0 | 293.7 | 281.5 | 8.3  | 47   | 116.6 | 576.3 | 313.7 | 40.6 | 105   | 221.0 | 680.7 |
| 199.8 | -73.3  | -100   | -148.0 | 311.7 | 282.0 | 8.9  | 48   | 118.4 | 578.1 | 314.3 | 41.1 | 106   | 222.8 | 682.5 |
| 205.4 | -67.8  | -90    | -130.0 | 329.7 | 282.6 | 9.4  | 49   | 120.2 | 579.9 | 314.8 | 41.7 | 107   | 224.6 | 684.3 |
| 210.9 | -62.2  | -80    | -112.0 | 347.7 | 283.2 | 10.0 | 50   | 122.0 | 581.7 | 315.4 | 42.2 | 108   | 226.4 | 686.1 |
| 216.5 | -56.7  | -70    | -94.0  | 365.7 | 283.7 | 10.6 | 51   | 123.8 | 583.5 | 315.9 | 42.8 | 109   | 228.2 | 687.9 |
| 222.0 | -51.1  | -60    | -76.0  | 383.7 | 284.3 | 11.1 | 52   | 125.6 | 585.3 | 316.5 | 43.3 | 110   | 230.0 | 689.7 |
| 227.6 | -45.6  | -50    | -58.0  | 401.7 | 284.8 | 11.7 | 53   | 127.4 | 587.1 | 317.0 | 43.9 | 111   | 231.8 | 691.5 |
| 233.2 | -40.0  | -40    | -40.0  | 419.7 | 285.4 | 12.2 | 54   | 129.2 | 588.9 | 317.6 | 44.4 | 112   | 233.6 | 693.3 |
| 238.7 | -34.4  | -30    | -22.0  | 437.7 | 285.9 | 12.8 | 55   | 131.0 | 590.7 | 318.2 | 45.0 | 113   | 235.4 | 695.1 |
| 244.3 | -28.9  | -20    | -4.0   | 455.7 | 286.5 | 13.3 | 56   | 132.8 | 592.5 | 318.7 | 45.6 | 114   | 237.2 | 696.9 |
| 249.8 | -23.3  | -10    | 14.0   | 473.7 | 287.0 | 13.9 | 57   | 134.6 | 594.3 | 319.3 | 46.1 | 115   | 239.0 | 698.7 |
| 255.4 | -17.8  | 0      | 32.0   | 491.7 | 287.6 | 14.4 | 58   | 136.4 | 596.1 | 319.8 | 46.7 | 116   | 240.8 | 700.5 |
| 255.9 | -17.2  | 1      | 33.8   | 493.5 | 288.2 | 15.0 | 59   | 138.2 | 597.9 | 320.4 | 47.2 | 117   | 242.6 | 702.3 |
| 256.5 | -16.7  | 2      | 35.6   | 495.3 | 288.7 | 15.6 | 60   | 140.0 | 599.7 | 320.9 | 47.8 | 118   | 244.4 | 704.1 |
| 257.0 | -16.1  | 3      | 37.4   | 497.1 | 289.3 | 16.1 | 61   | 141.8 | 601.5 | 321.5 | 48.3 | 119   | 246.2 | 705.9 |
| 257.6 | -15.6  | 4      | 39.2   | 498.9 | 289.8 | 16.7 | 62   | 143.6 | 603.3 | 322.0 | 48.9 | 120   | 248.0 | 707.7 |
| 258.2 | -15.0  | 5      | 41.0   | 500.7 | 290.4 | 17.2 | 63   | 145.4 | 605.1 | 322.6 | 49.4 | 121   | 249.8 | 709.5 |
| 258.7 | -14.4  | 6      | 42.8   | 502.5 | 290.9 | 17.8 | 64   | 147.2 | 606.9 | 323.2 | 50.0 | 122   | 251.6 | 711.3 |
| 259.3 | -13.9  | 7      | 44.6   | 504.3 | 291.5 | 18.3 | 65   | 149.0 | 608.7 | 323.7 | 50.6 | 123   | 253.4 | 713.1 |
| 259.8 | -13.3  | 8      | 46.4   | 506.1 | 292.0 | 18.9 | 66   | 150.8 | 610.5 | 324.3 | 51.1 | 124   | 255.2 | 714.9 |
| 260.4 | -12.8  | 9      | 48.2   | 507.9 | 292.6 | 19.4 | 67   | 152.6 | 612.3 | 324.8 | 51.7 | 125   | 257.0 | 716.7 |
| 260.9 | -12.2  | 10     | 50.0   | 509.7 | 293.2 | 20.0 | 68   | 154.4 | 614.1 | 325.4 | 52.2 | 126   | 258.8 | 718.5 |

Table 52. (Continued) °C → °F and °R Temperature Conversion °F → °C and °K

| °K    | °C   | °F         | °R    | °K    | °C    | °F    | °R         | °K     | °C     | °F     | °R     |             |        |        |
|-------|------|------------|-------|-------|-------|-------|------------|--------|--------|--------|--------|-------------|--------|--------|
| 325.9 | 52.8 | <b>127</b> | 260.6 | 720.3 | 357.6 | 84.4  | <b>184</b> | 363.2  | 822.9  | 741.5  | 468.3  | <b>875</b>  | 1607.0 | 2066.7 |
| 326.5 | 53.3 | <b>128</b> | 262.4 | 722.1 | 358.2 | 85.0  | <b>185</b> | 365.0  | 824.7  | 755.4  | 482.2  | <b>900</b>  | 1652.0 | 2111.7 |
| 327.0 | 53.9 | <b>129</b> | 264.2 | 723.9 | 358.7 | 85.6  | <b>186</b> | 366.8  | 826.5  | 769.3  | 496.1  | <b>925</b>  | 1697.0 | 2156.7 |
| 327.6 | 54.4 | <b>130</b> | 266.0 | 725.7 | 359.3 | 86.1  | <b>187</b> | 368.6  | 828.3  | 783.2  | 510.0  | <b>950</b>  | 1742.0 | 2201.7 |
| 328.2 | 55.0 | <b>131</b> | 267.8 | 727.5 | 359.8 | 86.7  | <b>188</b> | 370.4  | 830.1  | 797.0  | 523.9  | <b>975</b>  | 1787.0 | 2246.7 |
| 328.7 | 55.6 | <b>132</b> | 269.6 | 729.3 | 360.4 | 87.2  | <b>189</b> | 372.2  | 831.9  | 810.9  | 537.8  | <b>1000</b> | 1832.0 | 2291.7 |
| 329.3 | 56.1 | <b>133</b> | 271.4 | 731.1 | 360.9 | 87.8  | <b>190</b> | 374.0  | 833.7  | 838.7  | 565.6  | <b>1050</b> | 1922.0 | 2381.7 |
| 329.8 | 56.7 | <b>134</b> | 273.2 | 732.9 | 361.5 | 88.3  | <b>191</b> | 375.8  | 835.5  | 866.5  | 593.3  | <b>1100</b> | 2012.0 | 2471.7 |
| 330.4 | 57.2 | <b>135</b> | 275.0 | 734.7 | 362.0 | 88.9  | <b>192</b> | 377.6  | 837.3  | 894.3  | 621.1  | <b>1150</b> | 2102.0 | 2561.7 |
| 330.9 | 57.8 | <b>136</b> | 276.8 | 736.5 | 362.6 | 89.4  | <b>193</b> | 379.4  | 839.1  | 922.0  | 648.9  | <b>1200</b> | 2192.0 | 2651.7 |
| 331.5 | 58.3 | <b>137</b> | 278.6 | 738.3 | 363.2 | 90.0  | <b>194</b> | 381.2  | 840.9  | 949.8  | 676.7  | <b>1250</b> | 2282.0 | 2741.7 |
| 332.0 | 58.9 | <b>138</b> | 280.4 | 740.1 | 363.7 | 90.6  | <b>195</b> | 383.0  | 842.7  | 977.6  | 704.4  | <b>1300</b> | 2372.0 | 2831.7 |
| 332.6 | 59.4 | <b>139</b> | 282.2 | 741.9 | 364.3 | 91.1  | <b>196</b> | 384.8  | 844.5  | 1005.4 | 732.2  | <b>1350</b> | 2462.0 | 2921.7 |
| 333.2 | 60.0 | <b>140</b> | 284.0 | 743.7 | 364.8 | 91.7  | <b>197</b> | 386.6  | 846.3  | 1033.2 | 760.0  | <b>1400</b> | 2552.0 | 3011.7 |
| 333.7 | 60.6 | <b>141</b> | 285.8 | 745.5 | 365.4 | 92.2  | <b>198</b> | 388.4  | 848.1  | 1060.9 | 787.8  | <b>1450</b> | 2642.0 | 3101.7 |
| 334.3 | 61.1 | <b>142</b> | 287.6 | 747.3 | 365.9 | 92.8  | <b>199</b> | 390.2  | 849.9  | 1088.7 | 815.6  | <b>1500</b> | 2732.0 | 3191.7 |
| 334.8 | 61.7 | <b>143</b> | 289.4 | 749.1 | 366.5 | 93.3  | <b>200</b> | 392.0  | 851.7  | 1116.5 | 843.3  | <b>1550</b> | 2822.0 | 3281.7 |
| 335.4 | 62.2 | <b>144</b> | 291.2 | 750.9 | 367.0 | 93.9  | <b>201</b> | 393.8  | 853.5  | 1144.3 | 871.1  | <b>1600</b> | 2912.0 | 3371.7 |
| 335.9 | 62.8 | <b>145</b> | 293.0 | 752.7 | 367.6 | 94.4  | <b>202</b> | 395.6  | 855.3  | 1172.0 | 898.9  | <b>1650</b> | 3002.0 | 3461.7 |
| 336.5 | 63.3 | <b>146</b> | 294.8 | 754.5 | 368.2 | 95.0  | <b>203</b> | 397.4  | 857.1  | 1199.8 | 926.7  | <b>1700</b> | 3092.0 | 3551.7 |
| 337.0 | 63.9 | <b>147</b> | 296.6 | 756.3 | 368.7 | 95.6  | <b>204</b> | 399.2  | 858.9  | 1227.6 | 954.4  | <b>1750</b> | 3182.0 | 3641.7 |
| 337.6 | 64.4 | <b>148</b> | 298.4 | 758.1 | 369.3 | 96.1  | <b>205</b> | 401.0  | 860.7  | 1255.4 | 982.2  | <b>1800</b> | 3272.0 | 3731.7 |
| 338.2 | 65.0 | <b>149</b> | 300.2 | 759.9 | 369.8 | 96.7  | <b>206</b> | 402.8  | 862.5  | 1283.2 | 1010.0 | <b>1850</b> | 3362.0 | 3821.7 |
| 338.7 | 65.6 | <b>150</b> | 302.0 | 761.7 | 370.4 | 97.2  | <b>207</b> | 404.6  | 864.3  | 1310.9 | 1037.8 | <b>1900</b> | 3452.0 | 3911.7 |
| 339.3 | 66.1 | <b>151</b> | 303.8 | 763.5 | 370.9 | 97.8  | <b>208</b> | 406.4  | 866.1  | 1338.7 | 1065.6 | <b>1950</b> | 3542.0 | 4001.7 |
| 339.8 | 66.7 | <b>152</b> | 305.6 | 765.3 | 371.5 | 98.3  | <b>209</b> | 408.2  | 867.9  | 1366.5 | 1093.3 | <b>2000</b> | 3632.0 | 4091.7 |
| 340.4 | 67.2 | <b>153</b> | 307.4 | 767.1 | 372.0 | 98.9  | <b>210</b> | 410.0  | 869.7  | 1394.3 | 1121.1 | <b>2050</b> | 3722.0 | 4181.7 |
| 340.9 | 67.8 | <b>154</b> | 309.2 | 768.9 | 372.6 | 99.4  | <b>211</b> | 411.8  | 871.5  | 1422.0 | 1148.9 | <b>2100</b> | 3812.0 | 4271.7 |
| 341.5 | 68.3 | <b>155</b> | 311.0 | 770.7 | 373.2 | 100.0 | <b>212</b> | 413.6  | 873.3  | 1449.8 | 1176.7 | <b>2150</b> | 3902.0 | 4361.7 |
| 342.0 | 68.9 | <b>156</b> | 312.8 | 772.5 | 373.7 | 104.4 | <b>220</b> | 428.0  | 887.7  | 1477.6 | 1204.4 | <b>2200</b> | 3992.0 | 4451.7 |
| 342.6 | 69.4 | <b>157</b> | 314.6 | 774.3 | 383.2 | 110.0 | <b>230</b> | 446.0  | 905.7  | 1505.4 | 1232.2 | <b>2250</b> | 4082.0 | 4541.7 |
| 343.2 | 70.0 | <b>158</b> | 316.4 | 776.1 | 388.7 | 115.6 | <b>240</b> | 464.0  | 923.7  | 1533.2 | 1260.0 | <b>2300</b> | 4172.0 | 4631.7 |
| 343.7 | 70.6 | <b>159</b> | 318.2 | 777.9 | 394.3 | 121.1 | <b>250</b> | 482.0  | 941.7  | 1560.9 | 1287.8 | <b>2350</b> | 4262.0 | 4721.7 |
| 344.3 | 71.1 | <b>160</b> | 320.0 | 779.7 | 408.2 | 135.0 | <b>275</b> | 527.0  | 986.7  | 1588.7 | 1315.6 | <b>2400</b> | 4352.0 | 4811.7 |
| 344.8 | 71.7 | <b>161</b> | 321.8 | 781.5 | 422.0 | 148.9 | <b>300</b> | 572.0  | 1031.7 | 1616.5 | 1343.3 | <b>2450</b> | 4442.0 | 4901.7 |
| 345.4 | 72.2 | <b>162</b> | 323.6 | 783.3 | 435.9 | 162.8 | <b>325</b> | 617.0  | 1076.7 | 1644.3 | 1371.1 | <b>2500</b> | 4532.0 | 4991.7 |
| 345.9 | 72.8 | <b>163</b> | 325.4 | 785.1 | 449.8 | 176.7 | <b>350</b> | 662.0  | 1121.7 | 1672.0 | 1398.9 | <b>2550</b> | 4622.0 | 5081.7 |
| 346.5 | 73.3 | <b>164</b> | 327.2 | 786.9 | 463.7 | 190.6 | <b>375</b> | 707.0  | 1166.7 | 1699.8 | 1426.7 | <b>2600</b> | 4712.0 | 5171.7 |
| 347.0 | 73.9 | <b>165</b> | 329.0 | 788.7 | 477.6 | 204.4 | <b>400</b> | 752.0  | 1211.7 | 1727.6 | 1454.4 | <b>2650</b> | 4802.0 | 5261.7 |
| 347.6 | 74.4 | <b>166</b> | 330.8 | 790.5 | 491.5 | 218.3 | <b>425</b> | 797.0  | 1256.7 | 1755.4 | 1482.2 | <b>2700</b> | 4892.0 | 5351.7 |
| 348.2 | 75.0 | <b>167</b> | 332.6 | 792.3 | 505.4 | 232.2 | <b>450</b> | 842.0  | 1301.7 | 1783.2 | 1510.0 | <b>2750</b> | 4982.0 | 5441.7 |
| 348.7 | 75.6 | <b>168</b> | 334.4 | 794.1 | 519.3 | 246.1 | <b>475</b> | 887.0  | 1346.7 | 1810.9 | 1537.8 | <b>2800</b> | 5072.0 | 5531.7 |
| 349.3 | 76.1 | <b>169</b> | 336.2 | 795.9 | 533.2 | 260.0 | <b>500</b> | 932.0  | 1391.7 | 1838.7 | 1565.6 | <b>2850</b> | 5162.0 | 5621.7 |
| 349.8 | 76.7 | <b>170</b> | 338.0 | 797.7 | 547.0 | 273.9 | <b>525</b> | 977.0  | 1436.7 | 1866.5 | 1593.3 | <b>2900</b> | 5252.0 | 5711.7 |
| 350.4 | 77.2 | <b>171</b> | 339.8 | 799.5 | 560.9 | 287.8 | <b>550</b> | 1022.0 | 1481.7 | 1894.3 | 1621.1 | <b>2950</b> | 5342.0 | 5801.7 |
| 350.9 | 77.8 | <b>172</b> | 341.6 | 801.3 | 574.8 | 301.7 | <b>575</b> | 1067.0 | 1526.7 | 1922.0 | 1648.9 | <b>3000</b> | 5432.0 | 5891.7 |
| 351.5 | 78.3 | <b>173</b> | 343.4 | 803.1 | 588.7 | 315.6 | <b>600</b> | 1112.0 | 1571.7 | 2033.2 | 1760.0 | <b>3200</b> | 5792.0 | 6251.7 |
| 352.0 | 78.9 | <b>174</b> | 345.2 | 804.9 | 602.6 | 329.4 | <b>625</b> | 1157.0 | 1616.7 | 2144.3 | 1871.1 | <b>3400</b> | 6152.0 | 6611.7 |
| 352.6 | 79.4 | <b>175</b> | 347.0 | 806.7 | 616.5 | 343.3 | <b>650</b> | 1202.0 | 1661.7 | 2255.4 | 1982.2 | <b>3600</b> | 6512.0 | 6971.7 |
| 353.2 | 80.0 | <b>176</b> | 348.8 | 808.5 | 630.4 | 357.2 | <b>675</b> | 1247.0 | 1706.7 | 2366.5 | 2093.3 | <b>3800</b> | 6872.0 | 7331.7 |
| 353.7 | 80.6 | <b>177</b> | 350.6 | 810.3 | 644.3 | 371.1 | <b>700</b> | 1292.0 | 1751.7 | 2477.6 | 2204.4 | <b>4000</b> | 7232.0 | 7691.7 |
| 354.3 | 81.1 | <b>178</b> | 352.4 | 812.1 | 658.2 | 385.0 | <b>725</b> | 1337.0 | 1796.7 | 2588.7 | 2315.6 | <b>4200</b> | 7592.0 | 8051.7 |
| 354.8 | 81.7 | <b>179</b> | 354.2 | 813.9 | 672.0 | 398.9 | <b>750</b> | 1382.0 | 1841.7 | 2699.8 | 2426.7 | <b>4400</b> | 7952.0 | 8411.7 |
| 355.4 | 82.2 | <b>180</b> | 356.0 | 815.7 | 685.9 | 412.8 | <b>775</b> | 1427.0 | 1886.7 | 2810.9 | 2537.8 | <b>4600</b> | 8312.0 | 8771.7 |
| 355.9 | 82.8 | <b>181</b> | 357.8 | 817.5 | 699.8 | 426.7 | <b>800</b> | 1472.0 | 1931.7 | 2922.0 | 2648.9 | <b>4800</b> | 8672.0 | 9131.7 |
| 356.5 | 83.3 | <b>182</b> | 359.6 | 819.3 | 713.7 | 440.6 | <b>825</b> | 1517.0 | 1976.7 | 3033.2 | 2760.0 | <b>5000</b> | 9032.0 | 9491.7 |
| 357.0 | 83.9 | <b>183</b> | 361.4 | 821.1 | 727.6 | 454.4 | <b>850</b> | 1562.0 | 2021.7 | ...    | ...    | ...         | ...    | ...    |

Table converts °C → °F and °R, or °F → °C and °K. Find "convert from" temperature in bold column and read result from °F and °R or °C and °K columns. Example 1: 183 °C = 361.4 °F and 821.1 °R. Example 2: 183 °F = 83.9 °C and 357.0 °K.

Units of Velocity and Acceleration

Table 53. Velocity Conversion Factors

| To Convert ↓ | Multiply By Factor, To Obtain ↓ | cm/sec                | m/sec                 | km/hr                 | ft/sec    | ft/min      | ft/hr                | knot <sup>a</sup>     | mile/hr |
|--------------|---------------------------------|-----------------------|-----------------------|-----------------------|-----------|-------------|----------------------|-----------------------|---------|
| cm/sec       |                                 | 1                     | <b>0.01</b>           | <b>0.036</b>          | 0.032808  | 1.9685      | 118.110236           | 0.01944               | 0.02237 |
| m/sec        | <b>100</b>                      | 1                     | <b>3.6</b>            | 3.2808                | 196.8504  | 11811.0236  | 1.94384              | 2.236936              |         |
| km/hr        | 27.77778                        | 0.27778               | 1                     | 0.911344              | 54.6806   | 3280.8399   | 0.53995              | 0.621371              |         |
| ft/sec       | 30.48                           | 0.3048                | 1.09728               | 1                     | <b>60</b> | <b>3600</b> | 0.59248              | 0.681818              |         |
| ft/min       | 0.5080                          | 0.00508               | 0.018288              | 0.016667              | 1         | <b>60</b>   | $9.8 \times 10^{-3}$ | 0.011364              |         |
| ft/hr        | 0.008467                        | $8.47 \times 10^{-5}$ | $3.05 \times 10^{-4}$ | $2.78 \times 10^{-4}$ | 0.01666   | 1           | $1.6 \times 10^{-4}$ | $1.89 \times 10^{-4}$ |         |
| knot         | 51.444                          | 0.51444               | 1.852                 | 1.687808              | 101.2686  | 6076.11549  | 1                    | 1.15167               |         |
| mile/hr      | 44.704                          | 0.447040              | 1.609344              | 1.466667              | <b>88</b> | <b>5280</b> | 0.8689               | 1                     |         |

<sup>a</sup> Knot means nautical miles per hour

Figures in **bold face** indicate the conversion is exact

Table 54. Acceleration Conversion Factors

| To Convert ↓         | Multiply By Factor, To Obtain ↓ | cm/sec <sup>2</sup>   | m/sec <sup>2</sup>     | km/hr <sup>2</sup>     | feet/sec <sup>2</sup> | ft/hr <sup>2</sup>     | Knot/sec               | miles/hr <sup>2</sup> |
|----------------------|---------------------------------|-----------------------|------------------------|------------------------|-----------------------|------------------------|------------------------|-----------------------|
| cm/sec <sup>2</sup>  |                                 | 1                     | <b>0.01</b>            | 129.6                  | 0.0328                | $4.252 \times 10^5$    | 0.0194384              | 80.529                |
| m/sec <sup>2</sup>   | <b>100</b>                      | 1                     | 12960                  | 3.280                  | $4.252 \times 10^7$   | 1.943844               | 8052.970               |                       |
| km/hr <sup>2</sup>   | 0.007716                        | $7.72 \times 10^{-5}$ | 1                      | $2.532 \times 10^{-4}$ | 3280.84               | 0.0001499              | 0.6213                 |                       |
| ft/sec <sup>2</sup>  | 30.48                           | 0.3048                | 3950.20                | 1                      | $1.296 \times 10^7$   | 0.592483               | 2454.545               |                       |
| ft/hr <sup>2</sup>   | $2.35 \times 10^{-6}$           | $2.35 \times 10^{-5}$ | $3.048 \times 10^{-4}$ | $7.716 \times 10^{-8}$ | 1                     | $4.571 \times 10^{-8}$ | $1.893 \times 10^{-4}$ |                       |
| Knot/sec             | 51.44444                        | 0.514444              | 6667.2                 | 1.687809               | $2.187 \times 10^7$   | 1                      | 4142.8060              |                       |
| mile/hr <sup>2</sup> | 0.0124                          | 0.000124              | 1.609                  | $4.074 \times 10^{-4}$ | <b>5280</b>           | 0.00024138             | 1                      |                       |

Figures in **bold face** indicate the conversion is exact.

Units of Viscosity

Table 55a. Oil Viscosity Conversion Factors

| To Convert ↓   | Multiply By This Factor, To Obtain ↓   | Poise (P)  | Centi-poise (Z)   | Reyn (μ)                   | Stoke (S)                      | Centistoke (v)                 |
|----------------|--|--|-------------------|----------------------------|--------------------------------|--------------------------------|
| Poise (P)      |  | $\frac{\text{dyne-s}}{\text{cm}^2} = \frac{\text{gram mass}}{\text{cm-s}}$ | 1                 | 100                        | $1.45 \times 10^{-5}$          | $\frac{1}{\rho}$               |
| Centipoise (Z) | $\frac{\text{dyne-s}}{100 \text{ cm}^2} = \frac{\text{gram mass}}{100 \text{ cm-s}}$ | 0.01   | 1                 | $1.45 \times 10^{-7}$      | $\frac{0.01}{\rho}$            | $\frac{1}{\rho}$               |
| Reyn (μ)       | $\frac{\text{lb force-s}}{\text{in}^2}$  | $6.9 \times 10^4$  | $6.9 \times 10^6$ | 1                          | $\frac{6.9 \times 10^4}{\rho}$ | $\frac{6.9 \times 10^6}{\rho}$ |
| Stoke (S)      | $\frac{\text{cm}^2}{\text{s}}$   | ρ  | 100 ρ             | $1.45 \times 10^{-5} \rho$ | 1                              | 100                            |
| Centistoke (v) | $\frac{\text{cm}^2}{100 \text{ s}}$  | 0.01 ρ   | ρ                 | $1.45 \times 10^{-7} \rho$ | 0.01                           | 1                              |

Table 55b. Additional Viscosity Conversion Factors

| Multiply   | By              | To Obtain                                      | Multiply      | By          | To Obtain            |
|------------|-----------------|--|---------------|-------------|----------------------|
| centipoise | <b>0.001</b>    | pascal-second (Pa · s)                         | pascal-second | <b>1000</b> | centipoise           |
| centistoke | <b>0.000001</b> | meter <sup>2</sup> /second (m <sup>2</sup> /s) | pascal-second | <b>10</b>   | poise                |
| stoke      | <b>0.0001</b>   | meter <sup>2</sup> /second (m <sup>2</sup> /s) | poise         | <b>0.1</b>  | pascal-second (Pa-s) |

ρ = Specific gravity of the oil.

Figures in **bold face** indicate the conversion is exact

## Units of Moment of Inertia and Momentum

Table 56. Moment of Inertia Conversion Factors

| Multiply                                     | By            | To Obtain  |
|--|---------------|--|
| Moment of Inertia and Section Modulus        |               |  |
| moment of inertia [kg · m <sup>2</sup> ]     | 23.73036      | pound-foot <sup>2</sup>                            |
| moment of inertia [kg · m <sup>2</sup> ]     | 3417.171      | pound-inch <sup>2</sup>                            |
| moment of inertia [lb · ft <sup>2</sup> ]    | 0.04214011    | kilogram-meter <sup>2</sup> (kg · m <sup>2</sup> ) |
| moment of inertia [lb · inch <sup>2</sup> ]  | 0.0002926397  | kilogram-meter <sup>2</sup> (kg · m <sup>2</sup> ) |
| moment of section [foot <sup>4</sup> ]       | 0.008630975   | meter <sup>4</sup> (m <sup>4</sup> )               |
| moment of section [inch <sup>4</sup> ]       | 41.62314      | centimeter <sup>4</sup>                            |
| moment of section [meter <sup>4</sup> ]      | 115.8618      | foot <sup>4</sup>                                  |
| moment of section [centimeter <sup>4</sup> ] | 0.02402510    | inch <sup>4</sup>                                  |
| section modulus [foot <sup>3</sup> ]         | 0.02831685    | meter <sup>3</sup> (m <sup>3</sup> )               |
| section modulus [inch <sup>3</sup> ]         | 0.00001638706 | meter <sup>3</sup> (m <sup>3</sup> )               |
| section modulus [meter <sup>3</sup> ]        | 35.31466      | foot <sup>3</sup>                                  |
| section modulus [meter <sup>3</sup> ]        | 61,023.76     | inch <sup>3</sup>                                  |

Table 57. Momentum Conversion Factors

| Multiply              | By         | To Obtain                        |
|-----------------------|------------|----------------------------------|
| Momentum              |            |                                  |
| kilogram-meter/second | 7.233011   | pound-foot/second                |
| kilogram-meter/second | 86.79614   | pound-inch/second                |
| pound-foot/second     | 0.1382550  | kilogram-meter/second (kg · m/s) |
| pound-inch/second     | 0.01152125 | kilogram-meter/second (kg · m/s) |

## Miscellaneous Measuring Units

1 great gross = 12 gross = 144 dozen

1 gross = 12 dozen = 144 units

1 dozen = 12 units

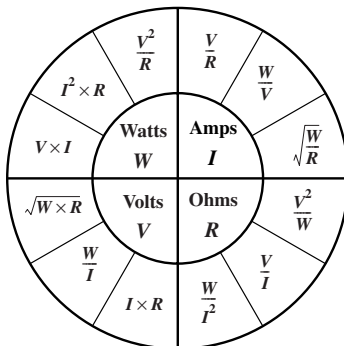
1 quire = 24 sheets

1 ream = 20 quires = 480 sheets

1 ream printing paper = 500 sheets

1 score = 20 units

**Ohm's Law.**—The following figure represents basic electrical relationships. This chart has been formatted in such a way that each variable has been related to the other three variables. This figure is simply for reference.



Key to variables:

V = Voltage (Volts)

R = Resistance (Ohms)

I = Current (Amps)

W = Power (Watts)

Circular Model of Electrical Relations



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| 304L (S30403)          | 1032, 1050, 1067       | 305 (S30500)           | 404, 448, 458-459, 472, 536 |
| 305 (S30500)           | 1032, 1050, 1067       | 308 (S30800)           | 404, 448, 458, 472          |
| 308 (S30800)           | 1032, 1050, 1067       | 309 (S30309)           | 448, 458, 460, 472, 536     |
| 309 (S30309)           | 1032, 1050, 1067       | 309 (S30900)           | 404, 448, 458, 472, 536     |
| 309 (S30900)           | 1032, 1050, 1067       | 309S (S30908)          | 404, 448, 458, 472          |
| 309S (S30908)          | 1032, 1050, 1067       | 310 (S31000)           | 404, 448, 458, 472, 536     |
| 310 (S31000)           | 1032, 1050, 1067       | 310S (S31008)          | 404, 448, 458, 472          |
| 310S (S31008)          | 1032, 1050, 1067       | 314 (S31400)           | 448, 458, 472               |
| 314 (S31400)           | 1032, 1050, 1067       | 316 (S31600)           | 404, 448, 458-459, 472, 536 |
| 316 (S31600)           | 1032, 1050, 1067       | 316F (S31620)          | 448, 458                    |
| 316L (S31603)          | 1032, 1050             | 316L (S31603)          | 448, 458, 472               |
| 317 (S31700)           | 1032, 1050             | 316N (S31651)          | 448, 458                    |
| 321 (S32100)           | 1032, 1050, 1067       | 317 (S31700)           | 404, 448, 459, 472, 536     |
| 330 (N08330)           | 1032, 1050             | 317 (S31703)           | 404                         |
| 347 (S34700)           | 1032, 1050, 1067       | 317L (S31703)          | 448, 459                    |
| 348 (S34800)           | 1032, 1050, 1067       | 321 (S32100)           | 404, 448, 459, 472, 536     |
| 403 (S40300)           | 1032, 1050, 1067       | 329 (S32900)           | 448, 459                    |
| 405 (S40500)           | 1032, 1050, 1067       | 330 (N08330)           | 448, 459                    |
| 409 (S40900)           | 1032, 1050, 1067       | 347 (S34700)           | 404, 448, 459, 472, 536     |
| 410 (S41000)           | 1032, 1050, 1067       | 348 (S34800)           | 404, 448, 459, 472          |
| 414 (S41400)           | 1032, 1051, 1067       | 384 (S38400)           | 404, 448, 459               |
| 416 (S41600)           | 1032, 1050, 1067       | 403 (S40300)           | 404, 449, 459, 472          |
| 416Se (S41623)         | 1032, 1050, 1067       | 405 (S40500)           | 404, 448, 459, 473          |
| 420 (S42000)           | 1032, 1050, 1067       | 409 (S40900)           | 448, 459                    |
| 420F (S42020)          | 1032, 1050, 1067       | 410 (S41000)           | 404, 449, 459, 472, 537     |
| 420FSe ()              | 1032, 1050, 1067       | 414 (S41400)           | 404, 449, 459, 473, 537     |
| 429 (S42900)           | 1032, 1050, 1067       | 416 (S41600)           | 404, 449, 459, 472, 537     |
| 430 (S43000)           | 1032, 1050, 1067       | 416Se (S41623)         | 404, 449, 459, 472          |
| 430F (S43020)          | 1032, 1050             | 420 (S42000)           | 404, 449, 459-460, 473, 537 |
| 430FSe (S43023)        | 1032, 1050, 1067       | 422 (S42200)           | 404, 449, 459               |
| 431 (S43100)           | 1032, 1051, 1067       | 429 (S42900)           | 404, 448, 459               |
| 434 (S43400)           | 1032, 1050, 1067       | 430 (S43000)           | 404, 448, 459-460, 473, 537 |
| 436 (S43600)           | 1032, 1050             | 430F (S43020)          | 404, 448, 459, 473          |
| 440A (S44002)          | 1032, 1051, 1067       | 430FSe (S43023)        | 448, 459, 473               |
| 440B (S44003)          | 1032, 1051, 1067       | 430Se (S43023)         | 404                         |
| 440C (S44004)          | 1032, 1051, 1067       |                        |                             |
| 440FSe ()              | 1032, 1050, 1067       |                        |                             |
| 442 (S44200)           | 1032, 1050             |                        |                             |
| 446 (S44600)           | 1032, 1050             |                        |                             |

| Stainless steel alloys       | <i>(continued)</i>      | Steel                        | <i>(continued)</i>   |
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| AISI (UNS) number            |                         | alloy, AISI-SAE (UNS) number |  |
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| 434 (S43400)                 | 448, 459-460            | E51100 (G51986)              | 442, 447   |
| 436 (S43600)                 | 404, 448, 460           | E51100 (G52986)              | 457  |
| 440A (S44002)                | 404, 449, 460, 473, 537 | E52100 (G52986)              | 442, 447, 451-452,<br>457, 474, 535, 1029, 1047, 1063,<br>1086       |
| 440B (S44003)                | 404, 449, 460, 473, 537 | 10B46 (G10461)               | 445  |
| 440C (S44004)                | 404, 449, 460, 473, 537 | 1045 (G10450)                | 444, 453-454, 465,<br>474, 1028, 1046, 1061                          |
| 440F (S44020)                | 473                     | 10956 ( )                    | 452  |
| 442 (S44200)                 | 448, 460, 537           | 1108 (G11080)                | 1027, 1045, 1061, 1086   |
| 446 (S44600)                 | 404, 448, 460, 473, 537 | 1320 (G13200)                | 451-452, 456, 533  |
| 501 (S50100)                 | 404, 449, 460, 473, 537 | 1330 (G13300)                | 442, 446, 456-457,<br>469, 474, 535, 1029, 1047, 1054,<br>1063, 1086 |
| 502 (S50200)                 | 404, 449, 460, 473      | 1335 (G13350)                | 442, 446, 457, 535,<br>1029, 1047, 1063, 1086                        |
| coefficient of expansion     | 404                     | 1340 (G13400)                | 442, 446, 457, 467,<br>469, 535, 1029, 1047, 1054, 1063,<br>1086     |
| density                      | 404                     | 1345 (G13450)                | 442, 446, 1029, 1047,<br>1063  |
| elastic properties           |                         | 2317 (G23170)                | 451, 456, 533  |
| 18-8                         | 420                     | 2330 (G23300)                | 451-452, 457, 535  |
| investment casting alloys    |                         | 2340 (G23400)                | 451-452, 457, 535  |
| austenitic                   |                         | 2512 (G25120)                | 533  |
| CF-16F                       | 418                     | 2515 (G25150)                | 451, 456   |
| CF-20                        | 418                     | 2517 (G25170)                | 533  |
| CF-3                         | 418                     | 30905 ( )                    | 451-452  |
| CF-3M                        | 418                     | 3115 (G31150)                | 451-452, 456, 533  |
| CF-8                         | 418                     | 3120 (G31200)                | 451-452, 456, 533  |
| CF-8C                        | 418                     | 3130 (G31300)                | 451-452, 457, 535  |
| CF-8M                        | 418                     | 3135 (G31350)                | 451-452, 456-457, 535  |
| CH-20                        | 418                     | 3140 (G31400)                | 451-452, 457, 467, 474   |
| CK-20                        | 418                     | 3141 (G31410)                | 451-452, 457, 535  |
| CN-7M                        | 418                     | 3145 (G31450)                | 451, 457, 535  |
| IC 316F                      | 418                     | 3150 (G31500)                | 451, 457, 535  |
| IC 321                       | 418                     | 3240 (G32400)                | 451  |
| hardenable                   |                         | 3310 (G33100)                | 451, 456, 474, 533   |
| Am-355                       | 418                     | 3316 (G33160)                | 533  |
| CA-15                        | 418                     | 4012 (G40120)                | 1029, 1047, 1054, 1062   |
| CA-40                        | 418                     | 4017 (G40170)                | 533  |
| CD-4M Cu                     | 418                     | 4023 (G40230)                | 442, 446, 451-452,<br>456, 474, 1029, 1047, 1054, 1062,<br>1086      |
| IC 15-5                      | 418                     | 4024 (G40240)                | 442, 446, 456-457,<br>1029, 1047, 1062, 1086                         |
| IC 17-4                      | 418                     | 4027 (G40270)                | 442, 446, 451, 456,<br>1054, 1086                                    |
| IC 416                       | 418                     | 4028 (G40280)                | 442, 446, 456-457,<br>1029, 1047, 1062, 1086                         |
| IC 431                       | 418                     | 4032 (G40320)                | 451, 456, 533, 1029,<br>1047, 1054, 1063, 1086                       |
| melting point                | 404                     | 4037 (G40370)                | 442, 446, 457, 469,<br>535, 1029, 1047, 1054, 1063, 1086             |
| powder metal alloys          |                         | 4042 (G40420)                | 451-452, 457, 469,<br>535, 1029, 1047, 1063, 1086                    |
| SS-303N1                     | 419                     | 4047 (G40470)                | 442, 446, 457, 535,<br>1029, 1047, 1063, 1086                        |
| SS-304N1                     | 419                     |                              |  |
| SS-316L                      | 419                     |                              |  |
| SS-410                       | 419                     |                              |  |
| specific heat                | 404                     |                              |  |
| thermal conductivity and     |                         |                              |  |
| conductance                  | 404                     |                              |  |
| 15-5PH                       | 1032, 1051              |                              |  |
| 17-4PH                       | 1032, 1051              |                              |  |
| 17-7PH                       | 1032, 1051              |                              |  |
| 18-8                         |                         |                              |  |
| wire                         |                         |                              |  |
| tensile strength             | 421                     |                              |  |
| Steam                        |                         |                              |  |
| specific heat                | 400                     |                              |  |
| Steel                        |                         |                              |  |
| alloy, AISI-SAE (UNS) number |                         |                              |  |
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| 41L40 (G41404)               | 447, 1029, 1047, 1062  | 50B44 (G50441)               | 442, 447, 1029, 1047, 1063  |
| 41L47 ( )                    | 1029, 1047, 1062   | 50B46 (G50461)               | 442, 447, 470, 1029, 1047, 1063                                     |
| 41L50 (G41405)               | 1029, 1047, 1062   | 50B50 (G50501)               | 442, 447, 1029, 1047, 1063  |
| 4118 (G41180)                | 442, 446, 1029, 1047, 1054, 1062   | 50B60 (G50601)               | 442, 447, 470, 1029, 1047, 1054, 1063                               |
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| 4125 (G41250)                | 451, 534   | 5045 (G50450)                | 535   |
| 4130 (G41300)                | 442, 446, 457, 467, 469, 474, 535, 1029, 1047, 1054, 1063, 1086                        | 5046 (G50460)                | 470, 535  |
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| 4137 (G41370)                | 442, 446, 456-457, 535, 1029, 1047, 1063, 1086   | 51B60 (G51601)               | 442, 447, 470, 1029, 1047, 1054, 1063                               |
| 4140 (G41400)                | 442, 446, 451-452, 456-457, 467, 469, 535, 1028-1029, 1046-1047, 1054, 1062-1063, 1086 | 51100 (G51986)               | 535   |
| 4142 (G41420)                | 442, 446, 1029, 1047, 1063, 1086   | 5115 (G51150)                | 534   |
| 4145 (G41450)                | 442, 446, 456-457, 535, 1029, 1047, 1063, 1086   | 5117 (G51170)                | 442, 446, 1029, 1047, 1062  |
| 4147 (G13300)                | 442  | 5120 (G51200)                | 442, 446, 456, 534, 1029, 1047, 1054, 1062, 1086                    |
| 4147 (G41470)                | 446, 1029, 1047, 1063, 1086  | 5130 (G51300)                | 442, 446, 457, 470, 535, 1029, 1047, 1054, 1063, 1086               |
| 4150 (G41500)                | 442, 446, 457, 467, 469, 535, 1028-1029, 1046-1047, 1054, 1062-1063, 1086              | 5132 (G51320)                | 442, 446, 457, 535, 1029, 1047, 1063, 1086                          |
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| 43L47 ( )                    | 1029, 1047, 1062   | 5135 (G51350)                | 442, 446, 457, 535, 1086  |
| 4317 (G43170)                | 534  | 5140 (G51400)                | 442, 446, 451-452, 457, 467, 470, 1029, 1047, 1063, 1086            |
| 4320 (G43200)                | 442, 446, 451, 456, 467, 534, 1029, 1047, 1054, 1062, 1086                             | 5145 (G51450)                | 535, 1029, 1047, 1063, 1086   |
| 4337 (G43370)                | 1029, 1047, 1063   | 5147 (G51470)                | 535, 1029, 1047, 1063   |
| 4340 (G43400)                | 442, 446, 451-452, 457, 467, 469, 474, 535, 1029, 1047, 1054, 1063, 1086               | 5150 (G51500)                | 442   |
| 4419 (G44190)                | 1029, 1047, 1062   | 5152 (G51520)                | 535   |
| 4422 (G44220)                | 1029, 1047, 1054, 1062   | 5155 (G51550)                | 442, 446  |
| 4427 (G44270)                | 1029, 1047, 1054, 1062   | 5160 (G51600)                | 442, 446, 467, 470, 1029, 1047, 1063                                |
| 4608 (G46080)                | 534  | 51710 ( )                    | 451   |
| 4615 (G46150)                | 442, 446, 451-452, 456, 1029, 1047, 1054, 1062, 1086                                   | 6118 (G51986)                | 447, 1029, 1047, 1054, 1062, 1086                                   |
| 4620 (G46200)                | 442, 446, 451-452, 456, 467, 1029, 1047, 1054, 1062, 1086                              | 6118 (G61180)                | 442   |
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| 4720 (G47200)                | 442, 446, 1029, 1047, 1054, 1062   | 6424 ( )                     | 1030, 1048, 1063  |

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| 86B45 (G86451) 471                   |                    | 9442 (G94420) 535                      |                    |
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| 86L40 ( ) 1029, 1047, 1062           |                    | 9840 (G98400) 535                      |                    |
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| 8641 (G86410) 457, 535               |                    | cobalt-tungsten                        |                    |
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| 8645 (G86450) 442, 447, 457, 1029,   |                    | 18-4-2-12 484                          |                    |
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**Guide to the Use of Tables and  
Formulas in  
Machinery's Handbook  
27th Edition**

BY JOHN M. AMISS, FRANKLIN D. JONES, AND  
HENRY H. RYFFEL

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**MACHINERY'S HANDBOOK GUIDE**

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## **THE PURPOSE OF THIS BOOK**

An engineering handbook is an essential part of the equipment of practically all engineers, machine designers, draftsmen, tool engineers and skilled mechanics in machine shops and toolrooms. The daily use of such a book, with its various tables and general data, saves a lot of time and labor. To obtain the full value of any handbook, however, the user must know enough about the contents to apply the tables, formulas, and other data, whenever they can be used to advantage.

One purpose of this Guide, which is based on MACHINERY'S HANDBOOK, is to show by examples, solutions, and test questions typical applications of handbook information in both drafting rooms and machine shops. Another function is to familiarize engineering students or other users with the HANDBOOK'S contents. A third objective is to provide test questions and drill work that will enable the HANDBOOK user, through practice, to obtain the required information quickly and easily.

MACHINERY'S HANDBOOK, as with all other handbooks, presents information in condensed form so that a large variety of subjects can be covered in a single volume. Because of this condensed treatment, any engineering handbook must be primarily a work of reference rather than a textbook, and the practical application of some parts will not always be apparent, especially to those who have had little experience in engineering work. The questions and examples in this book are intended not only to supplement some of the HANDBOOK material, but also to stimulate interest both in those parts that are used frequently and in the more special sections that may be very valuable even though seldom required.

## THE METRIC SYSTEM

MACHINERY'S HANDBOOK contains a considerable amount of metric material in terms of texts, tables, and formulas. This material is included because much of the world now uses the metric system, also known as the *Système International (SI)*, and the movement in that direction continues in all countries that intend to compete in the international marketplace, including the United States.

An explanation of the SI metric system is found on Handbook [pages 142 to 144](#) and [2544 to 2548](#). A brief history is given of the development of this system, and a description is provided for each of its seven basic units. Factors and prefixes for forming decimal multiples and submultiples of the SI units also are shown. Another table lists SI units with complex names and provides symbols for them.

Tables of SI units and conversion factors appear on [pages 2549 through 2587](#). Factors are provided for converting English units to metric units, or vice versa, and cover units of length, area, volume (including capacity), velocity, acceleration, flow, mass, density, force, force per unit length, bending moment or torque, moment of inertia, section modulus, momentum, pressure, stress, energy, work, power, and viscosity. By using the factors in these tables, it is a simple matter of multiplication to convert from one system of units to the other. Where the conversion factors are exact, they are given to only 3 or 4 significant figures, but where they are not exact they are given to 7 significant figures to permit the maximum degree of accuracy to be obtained that is ordinarily required in the metalworking field.

To avoid the need to use some of the conversion factors, various conversion tables are given on [pages 2550 through 2579](#). The tables for length conversion on [pages 2550 to 2562](#) will probably be the most frequently used. Two different types of tables are shown. The two tables on [page 2553](#) facilitate converting lengths

up to 100 inches into millimeters, in steps of one ten-thousandth of an inch; and up to 1000 millimeters to inches, in steps of a thousandth of a millimeter.

The table starting on **page 2554** enables converting fractions and mixed number lengths up to 41 inches into millimeters, in steps of one sixty-fourth of an inch.

To make possible such a wide range in a compact table, the reader often must take two or more numbers from the table and add them together, as is explained in the accompanying text. The tables starting on **page 2556** and **2558** have a much more limited range of conversion for inches to millimeters and millimeters to inches. However, these tables have the advantage of being direct-reading; that is, only a single value is taken from the table, and no addition is required.

For those who are engaged in design work where it is necessary to do computations in the fields of mechanics and strength of materials, a considerable amount of guidance will be found for the use of metric units. Thus, beginning on Handbook **page 141**, the use of the metric SI system in mechanics calculations is explained in detail. In succeeding pages, boldface type is used to highlight references to metric units in the combined Mechanics and Strength of Materials section. Metric formulas are provided also, to parallel the formulas for English units.

As another example, on **page 213**, it is explained in boldface type that SI metric units can be applied in the calculations in place of the English units of measurement without changes to the formulas for simple stresses.

The reader also should be aware that certain tables in the Handbook, such as that on **page 71**, which gives values for segments of circles for a radius = 1, can be used for either English or metric units, as is indicated directly under the table heading. There are other instances, however, where separate tables are needed, such as are shown on **pages 1018** to **1021** for the conversion of revolutions per minute, into cutting speed in feet per minute on **pages 1018** and **1019**, and into cutting speed in meters per minute on **pages 1020** and **1021**.



The metric material in the Handbook will provide considerable useful data and assistance to engineers and technicians who are required to use metric units of measurements. It is strongly suggested that all readers, whether or not they are using metric units at the present time, become familiar with the SI System by reading the explanatory material in the Handbook and by studying the SI units and the ways of converting English units to them.

# **Machinery's Handbook Guide 27th Edition**

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## SECTION 1

### DIMENSIONS AND AREAS OF CIRCLES

HANDBOOK Pages **66** and **76**

Circumferences of circles are used in calculating speeds of rotating machine parts, including drills, reamers, milling cutters, grinding wheels, gears, and pulleys. These speeds are variously referred to as surface speed, circumferential speed, and peripheral speed; meaning for each, the distance that a point on the surface or circumference would travel in one minute. This distance usually is expressed as feet per minute. Circumferences are also required in calculating the circular pitch of gears, laying out involute curves, finding the lengths of arcs, and in solving many geometrical problems. Letters from the Greek alphabet frequently are used to designate angles, and the Greek letter  $\pi$  (pi) always is used to indicate the ratio between the circumference and the diameter of a circle:

$$\pi = 3.14159265\dots = \frac{\text{circumference of circle}}{\text{diameter of circle}}$$

For most practical purposes the value of  $\pi = 3.1416$  may be used.

*Example 1:* Find the circumference and area of a circle whose diameter is 8 inches.

On Handbook **page 66**, the circumference  $C$  of a circle is given as  $3.1416d$ . Therefore,  $3.1416 \times 8 = 25.1328$  inches.

On the same page, the area is given as  $0.7854d^2$ . Therefore,  $A$  (area) =  $0.7854 \times 8^2 = 0.7854 \times 64 = 50.2656$  square inches.

*Example 2:* From **page 76** of the Handbook, the area of a cylindrical surface equals  $S = 3.1416 \times d \times h$ . For a diameter of 8 inches and a height of 10 inches, the area is  $3.1416 \times 8 \times 10 = 251.328$  square inches.

*Example 3:* For the cylinder in **Example 2** but with the area of both ends included, the total area is the sum of the area found in **Example 2** plus two times the area found in **Example 1**. Thus,

## 2 DIMENSIONS AND AREAS OF CIRCLES

$251.328 + 2 \times 50.2656 = 351.8592$  square inches. The same result could have been obtained by using the formula for total area given on Handbook [page 76](#):  $A = 3.1416 \times d \times (\frac{1}{2}d + h) = 3.1416 \times 8 \times (\frac{1}{2} \times 8 + 10) = 351.8592$  square inches.

*Example 4:* If the circumference of a tree is 96 inches, what is its diameter? Since the circumference of a circle  $C = 3.1416 \times d$ ,  $96 = 3.1416 \times d$  so that  $d = 96 \div 3.1416 = 30.558$  inches.

*Example 5:* The tables starting on [page 1018](#) of the Handbook provides values of revolutions per minute required producing various cutting speeds for workpieces of selected diameters. How are these speeds calculated? Cutting speed in feet per minute is calculated by multiplying the circumference in feet of a workpiece by the rpm of the spindle: cutting speed in fpm = circumference in feet  $\times$  rpm. By transposing this formula as explained in *Formulas And Their Rearrangement* starting on [page 8](#),

$$\text{rpm} = \frac{\text{cutting speed, fpm}}{\text{circumference in feet}}$$

For a 3-inch diameter workpiece ( $\frac{1}{4}$ -foot diameter) and for a cutting speed of 40 fpm,  $\text{rpm} = 40 \div (3.1416 \times \frac{1}{4}) = 50.92 = 51$  rpm, approximately, which is the same as the value given on [page 1018](#) of the Handbook.

### PRACTICE EXERCISES FOR SECTION 1

(See *Answers to Practice Exercises For Section 1* on page 221)

- 1) Find the area and circumference of a circle 10 mm in diameter.
- 2) On Handbook [page 1020](#), for a 5-mm diameter tool or workpiece rotating at 318 rpm, the corresponding cutting speed is given as 5 meters per minute. Check this value.
- 3) For a cylinder 100 mm in diameter and 10 mm high, what is the surface area not including the top or bottom?
- 4) A steel column carrying a load of 10,000 pounds has a diameter of 10 inches. What is the pressure on the floor in pounds per square inch?
- 5) What is the ratio of the area of a square of any size to the area of a circle having the same diameter as one side of the square?

6) What is the ratio of the area of a square of any size to the area of a circle having the same diameter as one side of the square?

7) The drilling speed for cast iron is assumed to be 70 feet per minute. Find the time required to drill two holes in each of 500 castings if each hole has a diameter of  $\frac{3}{4}$  inch and is 1 inch deep. Use 0.010 inch feed and allow one-fourth minute per hole for setup.

8) Find the weight of a cast-iron column 10 inches in diameter and 10 feet high. Cast iron weighs 0.26 pound per cubic inch.

9) If machine steel has a tensile strength of 55,000 pounds per square inch, what should be the diameter of a rod to support 36,000 pounds if the safe working stress is assumed to be one-fifth of the tensile strength?

10) Moving the circumference of a 16-inch automobile flywheel 2 inches moves the camshaft through how many degrees? (The camshaft rotates at one-half the flywheel speed.)

11) The tables beginning on Handbook [page 990](#) give lengths of chords for spacing off circumferences of circles into equal parts. Is another method available?

## SECTION 2

### CHORDAL DIMENSIONS, SEGMENTS, AND SPHERES

HANDBOOK Pages 78, 71, and 989—991

A chord of a circle is the distance along a straight line from one point to any other point on the circumference. A segment of a circle is that part or area between a chord and the arc it intercepts. The lengths of chords and the dimensions and areas of segments are often required in mechanical work.

**Lengths of Chords.**—The table of chords, Handbook page 990, can be applied to a circle of any diameter as explained and illustrated by examples on that page. This table is given to six decimal places so that it can be used in connection with precision tool work.

*Example 1:* A circle has 56 equal divisions and the chordal distance from one division to the next is 2.156 inches. What is the diameter of the circle?

The chordal length in the table for 56 divisions and a diameter of 1 equals 0.05607; therefore, in this example,

$$2.156 = 0.05607 \times \text{diameter}$$

$$\text{Diameter} = \frac{2.156}{0.05607} = 38.452 \text{ inches}$$

*Example 2:* A drill jig is to have eight holes equally spaced around a circle 6 inches in diameter. How can the chordal distance between adjacent holes be determined when the table, Handbook page 990, is not available?

One-half the angle between the radial center lines of adjacent holes =  $180 \div \text{number of holes}$ . If the sine of this angle is multiplied by the diameter of the circle, the product equals the chordal distance. In this example, we have  $180 \div 8 = 22.5$  degrees. The sine of 22.5 degrees from a calculator is 0.38268; hence, the

chordal distance =  $0.38268 \times 6 = 2.296$  inches. The result is the same as would be obtained with the table on Handbook [page 990](#) because the figures in the column "Length of the Chord" represent the sines of angles equivalent to 180 divided by the different numbers of spaces.

**Use of the Table of Segments of Circles—Handbook [page 71](#).**—This table is of the unit type in that the values all apply to a radius of 1. As explained above the table, the value for any other radius can be obtained by multiplying the figures in the table by the given radius. For areas, the *square* of the given radius is used. Thus, the unit type of table is universal in its application.

*Example 3:* Find the area of a segment of a circle, the center angle of which is 57 degrees, and the radius  $2\frac{1}{2}$  inches.

First locate 57 degrees in the center angle column; opposite this figure in the area column will be found 0.0781. Since the area is required, this number is multiplied by the square of  $2\frac{1}{2}$ . Thus,  $0.0781 \times (2\frac{1}{2})^2 = 0.488$  square inch

*Example 4:* A cylindrical oil tank is  $4\frac{1}{2}$  feet in diameter, 10 feet long, and is in a horizontal position. When the depth of the oil is 3 feet, 8 inches, what is the number of gallons of oil?

The total capacity of the tank equals  $0.7854 \times (4\frac{1}{2})^2 \times 10 = 159$  cubic feet. One U.S. gallon equals 0.1337 cubic foot (see Handbook [page 2566](#)); hence, the total capacity of the tank equals  $159 \div 0.1337 = 1190$  gallons.

The unfilled area at the top of the tank is a segment having a height of 10 inches or  $\frac{10}{27}$  (0.37037) of the tank radius. The nearest decimal equivalent to  $\frac{10}{27}$  in Column *h* of the table starting on [page 71](#) is 0.3707; hence, the number of cubic feet in the segment-shaped space =  $(27^2 \times 0.401 \times 120) \div 1728 = 20.3$  cubic feet and  $20.3 \div 0.1337 = 152$  gallons. Therefore, when the depth of oil is 3 feet, 8 inches, there are  $1190 - 152 = 1038$  gallons. (See also Handbook [page 61](#) for additional information on the capacity of cylindrical tanks.)

**Spheres.**—Handbook [page 78](#) gives formulas for calculating spherical volumes.

*Example 5:* If the diameter of a sphere is  $24\frac{5}{8}$  inches, what is the volume, given the formula:

$$\text{Volume} = 0.5236d^3$$

The cube of  $24\frac{5}{8} = 14,932.369$ ; hence, the volume of this sphere =  $0.5236 \times 14,932.369 = 7818.5$  cubic inches

### PRACTICE EXERCISES FOR SECTION 2

(See *Answers to Practice Exercises For Section 2* on page 221)

1) Find the lengths of chords when the number of divisions of a circumference and the radii are as follows: 30 and 4; 14 and  $2\frac{1}{2}$ ; 18 and  $3\frac{1}{2}$ .

2) Find the chordal distance between the graduations for thousandths on the following dial indicators: (a) Starrett has 100 divisions and  $1\frac{3}{8}$ -inch dial. (b) Brown & Sharpe has 100 divisions and  $1\frac{3}{4}$  inch dial. (c) Ames has 50 divisions and  $1\frac{5}{8}$  - inch dial.

3) The teeth of gears are evenly spaced on the pitch circumference. In making a drawing of a gear, how wide should the dividers be set to space 28 teeth on a 3-inch diameter pitch circle?

4) In a drill jig, 8 holes, each  $\frac{1}{2}$  inch diameter, were spaced evenly on a 6-inch diameter circle. To test the accuracy of the jig, plugs were placed in adjacent holes, and the distance over the plugs was measured with a micrometer. What should be the micrometer reading?

5) In the preceding problem, what should be the distance over plugs placed in alternate holes?

6) What is the length of the arc of contact of a belt over a pulley 2 feet, 3 inches in diameter if the arc of contact is 215 degrees?

7) Find the areas, lengths, and heights of chords of the following segments: (a) radius 2 inches, angle 45 degrees; (b) radius 6 inches, angle 27 degrees.



CHORDS AND SEGMENTS

7

8) Find the number of gallons of oil in a tank 6 feet in diameter and 12 feet long if the tank is in a horizontal position, and the oil measures 2 feet deep.

9) Find the surface area of the following spheres, the diameters of which are:  $1\frac{1}{2}$ ;  $3\frac{3}{8}$ ; 65;  $20\frac{3}{4}$ .

10) Find the volume of each sphere in the above exercise.

11) The volume of a sphere is 1,802,725 cubic inches. What are its surface area and diameter?

## SECTION 3

### FORMULAS AND THEIR REARRANGEMENT

HANDBOOK Page 29

A formula may be defined as a mathematical rule expressed by signs and symbols instead of in actual words. In formulas, letters are used to represent numbers or *quantities*, the term “quantity” being used to designate any number involved in a mathematical process. The use of letters in formulas, in place of the actual numbers, simplifies the solution of problems and makes it possible to condense into small space the information that otherwise would be imparted by long and cumbersome rules. The figures or values for a given problem are inserted in the formula according to the requirements in each specific case. When the values are thus inserted, in place of the letters, the result or answer is obtained by ordinary arithmetical methods. There are two reasons why a formula is preferable to a rule expressed in words. 1.) The formula is more concise, it occupies less space, and it is possible to see at a glance the whole meaning of the rule laid down. 2.) It is easier to remember a brief formula than a long rule, and it is, therefore, of greater value and convenience.

*Example 1:* In spur gears, the outside diameter of the gear can be found by adding 2 to the number of teeth and dividing the sum obtained by the diametral pitch of the gear. This rule can be expressed very simply by a formula. Assume that we write  $D$  for the outside diameter of the gear,  $N$  for the number of teeth, and  $P$  for the diametral pitch. Then the formula would be:

$$D = \frac{N + 2}{P}$$

This formula reads exactly as the rule given above. It says that the outside diameter ( $D$ ) of the gear equals 2 added to the number of teeth ( $N$ ), and this sum is divided by the pitch ( $P$ ).

If the number of teeth in a gear is 16 and the diametral pitch 6, then simply put these figures in the place of  $N$  and  $P$  in the formula, and the outside diameter as in ordinary arithmetic.

$$D = \frac{16 + 2}{6} = \frac{18}{6} = 3 \text{ inches}$$

*Example 2:* The formula for the horsepower generated by a steam engine is as follows:

$$H = \frac{P \times L \times A \times N}{33,000}$$

in which  $H$  = indicated horsepower of engine;

$P$  = mean effective pressure on piston in pounds per square inch;

$L$  = length of piston stroke in feet;

$A$  = area of piston in square inches;

$N$  = number of strokes of piston per minute.

Assume that  $P = 90$ ,  $L = 2$ ,  $A = 320$ , and  $N = 110$ ; what would be the horsepower?

If we insert the given values in the formula, we have:

$$H = \frac{90 \times 2 \times 320 \times 110}{33,000} = 192$$

From the examples given, we may formulate the following general rule: *In formulas, each letter stands for a certain dimension or quantity; when using a formula for solving a problem, replace the letters in the formula by the figures given for a certain problem, and find the required answer as in ordinary arithmetic.*

**Omitting Multiplication Signs in Formulas.**—In formulas, the sign for multiplication ( $\times$ ) is often left out between letters the values of which are to be multiplied. Thus  $AB$  means  $A \times B$ , and the formula  $H = \frac{P \times L \times A \times N}{33,000}$  can also be written  $H = \frac{PLAN}{33,000}$ .

If  $A = 3$ , and  $B = 5$ , then:  $AB = A \times B = 3 \times 5 = 15$ .

It is only the multiplication sign ( $\times$ ) that can be thus left out between the symbols or letters in a formula. All other signs must be indicated the same as in arithmetic. The multiplication sign can never be left out between two figures: 35 always means thirty-five, and “three times five” must be written  $3 \times 5$  but “three times  $A$ ”

may be written  $3A$ . As a general rule, the figure in an expression such as " $3A$ " is written first and is known as the *coefficient* of  $A$ . If the letter is written first, the multiplication sign is not left out, but the expression is written " $A \times 3$ ."

**Rearrangement of Formulas.**—A formula can be rearranged or "transposed" to determine the values represented by different letters of the formula. To illustrate by a simple example, the formula for determining the speed ( $s$ ) of a driven pulley when its diameter ( $d$ ), and the diameter ( $D$ ) and speed ( $S$ ) of the driving pulley are known is as follows:  $s = (S \times D)/d$ . If the speed of the driven pulley is known, and the problem is to find its diameter or the value of  $d$  instead of  $s$ , this formula can be rearranged or changed. Thus:

$$d = (S \times D)/s$$

Rearranging a formula in this way is governed by four general rules.

*Rule 1.* An independent term preceded by a plus sign (+) may be transposed to the other side of the equals sign (=) if the plus sign is changed to a minus sign (-).

*Rule 2.* An independent term preceded by a minus sign may be transposed to the other side of the equals sign if the minus sign is changed to a plus sign.

As an illustration of these rules, if  $A = B - C$ , then  $C = B - A$ , and if  $A = C + D - B$ , then  $B = C + D - A$ . That the foregoing are correct may be proved by substituting numerical values for the different letters and then transposing them as shown.

*Rule 3.* A term that multiplies all the other terms on one side of the equals sign may be moved to the other side if it is made to divide all the terms on that side.

As an illustration of this rule, if  $A = BCD$ , then  $A/(BC) = D$  or according to the common arrangement  $D = A/(BC)$ . Suppose, in the preceding formula, that  $B = 10$ ,  $C = 5$ , and  $D = 3$ ; then  $A = 10 \times 5 \times 3 = 150$  and  $150/(10 \times 5) = 3$ .

*Rule 4.* A term that divides all the other terms on one side of the equals sign may be moved to the other side if it is made to multiply all the terms on that side.

To illustrate, if  $s = SD/d$ , then  $sd = SD$ , and, according to *Rule 3.*,  $d = SD/s$ . This formula may also be rearranged for determining the values of  $S$  and  $D$ ; thus  $ds/D = S$ , and  $ds/S = D$ .

If, in the rearrangement of formulas, minus signs precede quantities, the signs may be changed to obtain positive rather than minus quantities. All the signs on both sides of the equals sign or on both sides of the equation may be changed. For example, if  $-2A = -B + C$ , then  $2A = B - C$ . The same result would be obtained by placing all the terms on the opposite side of the equals sign, which involves changing signs. For instance, if  $-2A = -B + C$ , then  $B - C = 2A$ .

**Fundamental Laws Governing Rearrangement.**—After a few fundamental laws that govern any formula or equation are understood, its solution usually is very simple. An equation states that one quantity equals another quantity. So long as both parts of the equation are treated exactly alike, the values remain equal. Thus, in the equation  $A = \frac{1}{2}ab$ , which states that the area  $A$  of a triangle equals one-half the product of the base  $a$  times the altitude  $b$ , each side of the equation would remain equal if we added the same amount:  $A + 6 = \frac{1}{2}ab + 6$ ; or we could subtract an equal amount from both sides:  $A - 8 = \frac{1}{2}ab - 8$ ; or multiply both parts by the same number:  $7A = 7(\frac{1}{2}ab)$ ; or we could divide both parts by the same number, and we would still have a true equation.

One formula for the total area  $T$  of a cylinder is:  $T = 2\pi r^2 + 2\pi rh$ , where  $r$  = radius and  $h$  = height of the cylinder. Suppose we want to solve this equation for  $h$ . Transposing the part that does not contain  $h$  to the other side by changing its sign, we get:  $2\pi rh = T - 2\pi r^2$ . To obtain  $h$ , we can divide both sides of the equation by any quantity that will leave  $h$  on the left-hand side; thus:

$$\frac{2\pi rh}{2\pi r} = \frac{T - 2\pi r^2}{2\pi r}$$

It is clear that, in the left-hand member, the  $2\pi r$  will cancel out, leaving:  $h = (T - 2\pi r^2)/(2\pi r)$ . The expression  $2\pi r$  in the right-hand member cannot be cancelled because it is not an independent factor, since the numerator equals the difference between  $T$  and  $2\pi r^2$ .

*Example 3:* Rearrange the formula for a trapezoid (Handbook page 64) to obtain  $h$ .

$$A = \frac{(a + b)h}{2}$$

$$2A = (a + b)h \quad (\text{multiply both members by } 2)$$

$$(a + b)h = 2A \quad (\text{transpose both members so as to get the multiple of } h \text{ on the left-hand side})$$

$$\frac{(a + b)h}{a + b} = \frac{2A}{a + b} \quad (\text{divide both members by } a + b)$$

$$h = \frac{2A}{a + b} \quad (\text{cancel } a + b \text{ from the left-hand member})$$

*Example 4:* The formula for determining the radius of a sphere (Handbook page 78) is as follows:

$$r = 3\sqrt[3]{\frac{3V}{4\pi}}$$

Rearrange to obtain a formula for finding the volume  $V$ .

$$r^3 = \frac{3V}{4\pi} \quad (\text{cube each side})$$

$$4\pi r^3 = 3V \quad (\text{multiply each side by } 4\pi)$$

$$3V = 4\pi r^3 \quad (\text{transpose both members})$$

$$\frac{3V}{3} = \frac{4\pi r^3}{3} \quad (\text{divide each side by } 3)$$

$$V = \frac{4\pi r^3}{3} \quad (\text{cancel } 3 \text{ from left-hand member})$$

The procedure has been shown in detail to indicate the underlying principles involved. The rearrangement could be simplified somewhat by direct application of the rules previously given. To illustrate:

$$r^3 = \frac{3V}{4\pi} \quad (\text{cube each side})$$

$$4\pi r^3 = 3V \text{ (applying Rule 4. move } 4\pi \text{ to left-hand side)}$$

$$\frac{4\pi r^3}{3} = V \text{ (move 3 to left-hand side—Rule 3.)}$$

This final equation would, of course, be reversed to locate  $V$  at the left of the equals sign as this is the usual position for whatever letter represents the quantity or value to be determined.

*Example 5:* It is required to determine the diameter of cylinder and length of stroke of a steam engine to deliver 150 horsepower. The mean effective steam pressure is 75 pounds, and the number of strokes per minute is 120. The length of the stroke is to be 1.4 times the diameter of the cylinder.

First, insert the known values into the horsepower formula (**Example 2**):

$$150 = \frac{75 \times L \times A \times 120}{33,000} = \frac{3 \times L \times A}{11}$$

The last expression is found by cancellation.

Assume now that the diameter of the cylinder in inches equals  $D$ . Then,  $L = 1.4D/12 = 0.117D$  according to the requirements in the problem; the divisor 12 is introduced to change the inches to feet,  $L$  being in feet in the horsepower formula. The area  $A = D^2 \times 0.7854$ . If we insert these values in the last expression in our formula, we have:

$$150 = \frac{3 \times 0.117D \times 0.7854D^2}{11} = \frac{0.2757D^3}{11}$$

$$0.2757D^3 = 150 \times 11 = 1650$$

$$D^3 = \frac{1650}{0.2757} \quad D = \sqrt[3]{\frac{1650}{0.2757}} = \sqrt[3]{5984.8} = 18.15$$

Hence, the diameter of the cylinder should be about  $18\frac{1}{4}$  inches, and the length of the stroke  $18.15 \times 1.4 = 25.41$ , or, say,  $25\frac{1}{2}$  inches.

**Solving Equations or Formulas by Trial.**—One of the equations used for spiral gear calculations, when the shafts are at right angles, the ratios are unequal, and the center distance must be exact, is as follows:

$$R \sec \alpha + \csc \alpha = \frac{2CP_n}{n}$$

In this equation

$R$  = ratio of number of teeth in large gear to number in small gear

$C$  = exact center distance

$P_n$  = normal diametral pitch

$n$  = number of teeth in small gear

The exact spiral angle  $\alpha$  of the large gear is found by trial using the equation just given.

Equations of this form are solved by trial by selecting an angle assumed to be approximately correct and inserting the secant and cosecant of this angle in the equation, adding the values thus obtained, and comparing the sum with the known value to the right of the equals sign in the equation. An example will show this more clearly. By using the problem given in Machinery's Handbook (bottom of [page 2104](#)) as an example,  $R = 3$ ;  $C = 10$ ;  $P_n = 8$ ;  $n = 28$ .

$$\text{Hence, the whole expression } \frac{2CP_n}{n} = \frac{2 \times 10 \times 8}{28} = 5.714$$

from which it follows that:

$$R \sec \alpha + \csc \alpha = 5.714$$

In the problem given, the spiral angle required is 45 degrees. The spiral gears, however, would not meet all the conditions given in the problem if the angle could not be slightly modified. To determine whether the angle should be greater or smaller than 45 degrees, insert the values of the secant and cosecant of 45 degrees in the formula. The secant of 45 degrees is 1.4142, and the cosecant is 1.4142. Then,

$$3 \times 1.4142 + 1.4142 = 5.6568$$

The value 5.6568 is too small, as it is less than 5.714 which is the required value. Hence, try 46 degrees. The secant of 46 degrees is 1.4395, and the cosecant, 1.3902. Then,



$$3 \times 1.4395 + 1.3902 = 5.7087$$

Obviously, an angle of 46 degrees is too small. Proceed, therefore, to try an angle of 46 degrees, 30 minutes. This angle will be found too great. Similarly 46 degrees, 15 minutes, if tried, will be found too great, and by repeated trials it will finally be found that an angle of 46 degrees, 6 minutes, the secant of which is 1.4422, and the cosecant, 1.3878, meets the requirements. Then,

$$3 \times 1.4422 + 1.3878 = 5.7144$$

which is as close to the required value as necessary.

In general, when an equation must be solved by the trial-and-error method, all the known quantities may be written on the right-hand side of the equal sign, and all the unknown quantities on the left-hand side. A value is assumed for the unknown quantity. This value is substituted in the equation, and all the values thus obtained on the left-hand side are added. In general, if the result is greater than the values on the right-hand side, the assumed value of the unknown quantity is too great. If the result obtained is smaller than the sum of the known values, the assumed value for the unknown quantity is too small. By thus adjusting the value of the unknown quantity until the left-hand member of the equation with the assumed value of the unknown quantity will just equal the known quantities on the right-hand side of the equal sign, the correct value of the unknown quantity may be determined.

**Derivation of Formulas.**—Most formulas in engineering handbooks are given without showing how they have been derived or originated, because engineers and designers usually want only the final results; moreover, such derivations would require considerable additional space, and they belong in textbooks rather than in handbooks, which are primarily works of reference. Although Machinery's Handbook contains thousands of standard and special formulas, it is apparent that no handbook can include every kind of formula, because a great many formulas apply only to local designing or manufacturing problems. Such special formulas are derived by engineers and designers for their own use. The exact methods of deriving formulas are based upon mathematical principles as they are related to the particular factors that apply. A few examples will be given to show how several different types of special formulas have been derived.

*Example 6:* The problem is to deduce the general formula for finding the point of intersection of two tapers with reference to measured diameters on those tapers. In the diagram, **Fig. 1**,

$L$  = the distance between the two measured diameters,  $D$  and  $d$ ;

$X$  = the required distance from one measured diameter to the intersection of tapers;

$a$  = angle of long taper as measured from center line;

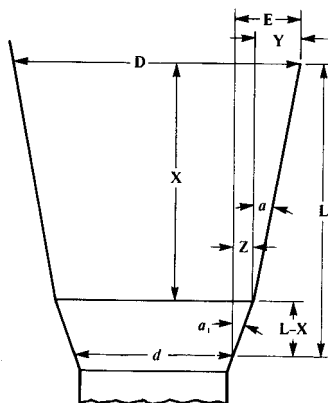
$a_1$  = angle of short taper as measured from center line.

Then,

$$E = \frac{D-d}{2} = Z + Y$$

$$Z = (L - X) \tan a_1$$

$$Y = X \tan a$$



**Fig. 1. To find Dimension  $X$  from a Given Diameter  $D$  to the Intersection of Two Conical Surfaces**

Therefore:

$$\frac{D-d}{2} = (L-X) \tan a_1 + X \tan a$$

and

$$D - d = 2 \tan a_1 (L - X) + 2X \tan a \tag{1}$$

But

$$2 \tan a_1 = T_1 \quad \text{and} \quad 2 \tan a = T$$

in which  $T$  and  $T_1$  represent the long and short tapers per inch, respectively.

Therefore, from **Equation (1)**,

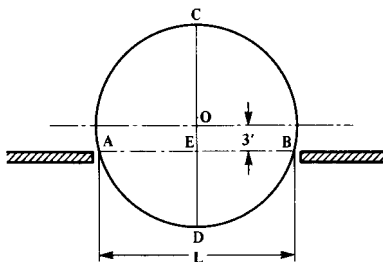
$$D - d = T_1(L - X) + TX$$

$$D - d = T_1L - T_1X + TX$$

$$X(T_1 - T) = T_1L - (D - d)$$

$$X = \frac{T_1L - (D - d)}{T_1 - T}$$

*Example 7:* A flywheel is 16 feet in diameter (outside measurement), and the center of its shaft is 3 feet above the floor. Derive a formula for determining how long the hole in the floor must be to permit the flywheel to turn.



**Fig. 2. To Find Length of Hole in Floor for Flywheel**

The conditions are as represented in **Fig. 2**. The line  $AB$  is the floor level and is a chord of the arc  $ABD$ ; it is parallel to the horizontal diameter through the center  $O$ .  $CD$  is the vertical diameter and is perpendicular to  $AB$ . It is shown in geometry that the diameter  $CD$  bisects the chord  $AB$  at the point of intersection  $E$ . One of the most useful theorems of geometry is that when a diameter bisects a chord, the product of the two parts of the diameter is equal to the square of one half the chord; in other words,  $(AE)^2 =$

$ED \times EC$ . If  $AB$  is represented by  $L$  and  $OE$  by  $a$ ,  $ED = r - a$  and  $EC = r + a$ , in which  $r =$  the radius  $OC$ ; hence,

$$\left(\frac{L}{2}\right)^2 = (r - a)(r + a) = r^2 - a^2$$

$$\frac{L}{2} = \sqrt{r^2 - a^2} \text{ and } L = 2\sqrt{r^2 - a^2}$$

By substituting the values given,

$$L = 2\sqrt{8^2 - 3^2} = 14.8324 \text{ feet} = 14 \text{ feet, } 10 \text{ inches.}$$

The length of the hole, therefore, should be at least 15 feet, to allow sufficient clearance.

**Empirical Formulas.**—Many formulas used in engineering calculations cannot be established fully by mathematical derivation but must be based upon actual tests instead of relying upon mere theories or assumptions that might introduce excessive errors. These formulas are known as “empirical formulas.” Usually such a formula contains a constant (or constants) that represents the result of the tests; consequently, the value obtained by the formula is consistent with these tests or with actual practice.

A simple example of an empirical formula will be found on Handbook [page 386](#). This particular formula contains the constant 54,000, which was established by tests, and the formula is used to obtain the breaking load of wrought-iron crane chains to which a factor of safety of 3, 4, or 5 is then applied to obtain the working load. Other examples of empirical formulas will be found on Handbook [page 281](#).

Handbook [page 299](#) contains an example of an empirical formula based upon experiments made with power-transmitting shafts. This formula gives the diameter of shaft required to prevent excessive twisting during transmission of power.

**Parentheses.**—Two important rules relating to the use of parentheses are based upon the principles of positive and negative numbers:

1) If a parenthesis is preceded by a + sign, it may be removed, if the terms within the parentheses retain their signs.

$$a + (b - c) = a + b - c$$

2) If a parenthesis is preceded by a  $-$  sign, it may be removed, if the signs preceding each of the terms inside of the parentheses are changed ( $+$  changed to  $-$ , and  $-$  to  $+$ ). Multiplication and division signs are not affected.

$$a - (b - c) = a - b + c$$

$$a - (-b + c) = a + b - c$$

Knowledge of algebra is not necessary to make successful use of formulas of the general type such as are found in engineering handbooks; it is only necessary to understand thoroughly the use of letters or symbols in place of numbers, and to be well versed in the methods, rules, and processes of ordinary arithmetic. Knowledge of algebra becomes necessary only where a general rule or formula that gives the answer to a problem directly is not available. In other words, algebra is useful in *developing* or originating a general rule or formula, but the formula can be *used* without recourse to algebraic processes.

**Constants.**—A constant is a value that does not change or is not variable. Constants at one stage of a mathematical investigation may be variables at another stage, but an *absolute constant* has the same value under all circumstances. The ratio of the circumference to the diameter of a circle, or 3.1416, is a simple example of an absolute constant. In a common formula used for determining the indicated horsepower of a reciprocating steam engine, the product of the mean effective pressure in psi, the length of the stroke in feet, the area of the piston in square inches, and the number of piston strokes per minute is divided by the constant 33,000, which represents the number of foot-pounds of work per minute equivalent to 1 horsepower. Constants occur in many mathematical formulas.

**Mathematical Signs and Abbreviations.**—Every division of mathematics has its traditions, customs, and signs that are frequently of ancient origin. Hence, we encounter Greek letters in many problems where it would seem that English letters would do as well or better. Most of the signs on Handbook [page 2542](#) will be used frequently. They should, therefore, be understood.

**Conversion Tables.**—It may sometimes be necessary to convert English units of measurement into metric units and vice versa. The tables provided at the back of the Handbook will be found useful in this connection.

### PRACTICE EXERCISES FOR SECTION 3

(See *Answers to Practice Exercises For Section 3* on page 222)

1) An approximate formula for determining the horsepower  $H$  of automobile engines is:  $H = D^2SN/3$ , where  $D$  = diameter of bore, inches;  $S$  = length of stroke, inches; and  $N$  = number of cylinders. Find the horsepower of the following automobile engine: a) bore,  $3\frac{1}{2}$  inches; stroke,  $4\frac{1}{4}$  inches. b) By using the reciprocal of 3, how could this formula be stated?

2) Using the right-angle triangle formula:  $C = \sqrt{a^2 + b^2}$ , where  $a$  = one side,  $b$  = the other side, and  $C$  = the hypotenuse, find the hypotenuse of a right triangle whose sides are 16 inches and 63 inches.

3) The formula for finding the blank diameter of a cylindrical shell is:  $D = \sqrt{d \times (d + 4h)}$ , where  $D$  = blank diameter;  $d$  = diameter of the shell;  $h$  = height of the shell. Find the diameter of the blank to form a cylindrical shell of 3 inches diameter and 2 inches high.

4) If  $D$  = diagonal of a cube;  $d$  = diagonal of face of a cube;  $s$  = side of a cube; and  $V$  = volume of a cube; then  $d = \sqrt{2D^2/3}$ ;  $s = \sqrt{D^2/3}$ ; and  $V = s^3$ . Find the side, volume of a cube, and diagonal of the face of a cube if the diagonal of the cube is 10.

5) The area of an equilateral triangle equals one fourth of the square of the side times the square root of 3, or  $A = (S^2/4)\sqrt{3} = 0.43301S^2$ . Find the area of an equilateral triangle the side of which is 14.5 inches.

6) The formula for the volume of a sphere is:  $4\pi r^3/3$  or  $\pi d^3/6$ . What constants may be used in place of  $4\pi/3$  and  $\pi/6$ ?

7) The formula for the volume of a solid ring is  $2\pi^2Rr^2$ , where  $r$  = radius of cross section and  $R$  = radius from the center of the ring to the center of the cross section. Find the volume of a solid ring made from 2-inch round stock if the mean diameter of the ring is 6 inches.

8) Explain these signs:  $\pm$ ,  $>$ ,  $<$ ,  $\sin^{-1}a$ ,  $\tan$ ,  $\angle$ ,  $\sqrt[4]{}$ ,  $\log$ ,  $\theta$ ,  $\beta$ ,  $::$

9) The area  $A$  of a trapezoid (see Handbook [page 64](#)) is found by the formula:

$$A = \frac{(a + b)h}{2}$$

Transpose the formula for determining width  $a$ .

10)  $R = \sqrt{r^2 + s^2}/4$ ; solve for  $r$ .

11)  $P = 3.1416\sqrt{2(a^2 + b^2)}$ ; solve for  $a$ .

12)  $\cos A = \sqrt{1 - \sin^2 A}$ ; solve for  $\sin A$ .

13)  $a/\sin A = b/\sin B$ ; solve for  $a$ ,  $b$ ,  $\sin A$ ,  $\sin B$ .

## SECTION 4

### SPREADSHEET CALCULATIONS

Spreadsheet computer programs or spreadsheets are versatile, powerful tools for doing repetitive or complicated algebraic calculations. They are used in diverse technological fields including manufacturing, design, and finance. Spreadsheets blend the power of high level computer languages with the simplicity of hand calculators. They are ideal for doing "what-if" calculations such as changing a problem's parameters and comparing the new result to the initial answer. The visual nature of spreadsheets allows the user to grasp quickly and simultaneously the interaction of many variables in a given problem.

Generally only 5 to 10% of a spreadsheet program functionality needs to be understood to begin doing productive spreadsheet calculations. Since the underlying concepts of all spreadsheets are the same, it is easy transfer this basic understanding from one spreadsheet program to another with very little learning curve. Only a small percentage of the actual spreadsheet commands will be covered in this section but understanding these core concepts will allow the reader to do productive work immediately.

There are many varieties of spreadsheet programs. It is impossible to cover all these spreadsheet programs individually in this brief overview. The formulas listed below are for conceptual understanding and may not work when plugged directly into a particular program. The user should consult the spreadsheet's manual or built in help system for examples. Generally for any given topic a spreadsheet's help system will list a properly constructed example of what the user is trying to do. The reader can use this as a guide and template to get started.

**Spreadsheet Basic Concepts.**—To begin using spreadsheets, several key spreadsheet concepts must be understood.



*Cell Content:* The basic calculating unit of all spreadsheets are cells. Cells may either contain formulas, which are discussed further on; or numbers, words, dates, percentages, and currency. A cell normally has to be formatted using the spreadsheet's cell format commands to display its contents correctly. The formatting usually does not affect the internal representation of the cell, e.g. the actual value of the number. For example, a cell formatted as a *percentage* such as 12% would actually contain a value of "0.12" in the cell. If the cell were left unformatted "0.12" would be displayed. A cell formatted for currency would display "3.4" as "\$3.40."

| Number  | Currency | Text      | Percentage  |
|---------|----------|-----------|-------------|
| 12.7854 | \$12.05  | Feed Rate | 12% or 0.12 |

Cells containing numbers may be formatted to display an arbitrary level of precision. Again the displayed precision has no effect on actual calculations. For example, the contents of a particular cell containing "3.1415" could be formatted to display "3.141" or "3.14" or "3". Regardless of what is displayed "3.1415" will be used internally by the program for all calculations that refer to that cell.

Formatting cells while not absolutely necessary, is usually a good idea for several reasons. Formatted cells help others understand your spreadsheet. 12% is easily identifiable as an interest rate, ".12" is not. Formatting can also help to avoid input mistakes in large spreadsheets such as accidentally placing an interest rate percentage in a payment currency-formatted cell. The interest rate will be displayed as "\$0.12" immediately telling the user something is wrong. For quick "back of the envelope calculations" formatting can be dispensed with to save time.

*Cell Address:* In addition to content, cells also have addresses. A cell address is created by combining the column and row names of that cell. In the spreadsheet in **Table 1a**, *Parts* would have an address of *A1*, *Machine 2* would be *C1*, and "\$13.76" would be *B3*. Spreadsheets use these cell addresses to combine and manipulate the cell contents using formulas.

**Table 1a. Machine Cost Spreadsheet (Display)**

|   | A        | B         | C         | D        |
|---|----------|-----------|-----------|----------|
| 1 | Parts    | Machine 1 | Machine 2 | Total    |
| 2 | Motor    | 12.89     | \$18.76   | \$31.65  |
| 3 | Controls | 13.76     | \$19.56   | \$33.32  |
| 4 | Chassis  | 15        | \$21.87   | \$36.87  |
| 5 | Rebate   | -7.5      | -\$10.00  | -\$17.50 |
| 6 | Total    | 34.15     | \$50.19   | \$84.34  |

*Formulas:* Instead of containing values, a cell may have a formula assigned to it. Spreadsheets use these formulas to manipulate, combine, and chain cells mathematically. The specific format or syntax for properly constructing a formula varies from spreadsheet to spreadsheet. The two most common formula construction techniques are illustrated using the spreadsheet in **Table 1b**.

**Table 1b. Machine Cost Spreadsheet (Formulas)**

|   | A        | B  | C                                      | D   |
|---|----------|--|--|---|
| 1 | Parts    | Machine 1  | Machine 2                              | Total   |
| 2 | Motor    | 12.89 <sup>a</sup>   | \$18.76                                | = +B2+C2 <sup>b</sup><br>= \$31.65                                    |
| 3 | Controls | 13.76 <sup>a</sup>   | \$19.56                                | = Sum(B3:C3) <sup>b</sup><br>= \$33.32                                |
| 4 | Chassis  | 15 <sup>a</sup>  | \$21.87                                | = Sum(B4:C4) <sup>b</sup><br>= \$36.87                                |
| 5 | Rebate   | -7.5 <sup>a</sup>  | -\$10.00                               | = Sum (B5:C5) <sup>b</sup><br>= -\$17.50                              |
| 6 | Total    | =+B2+B3+B4<br>+B5 <sup>b</sup><br>= Sum(B2:B5)<br>= 34.15 <sup>a</sup> | = Sum(C2:C5) <sup>b</sup><br>= \$50.19 | = Sum(D2:D5) <sup>b,c</sup><br>= Sum(B6:C6) <sup>d</sup><br>= \$84.34 |

<sup>a</sup> This cell is unformatted. This does not change the value of the intermediate calculations or final results.

<sup>b</sup> Cells cannot contain more than one value or formula. The double values and formulas listed in this cell are for illustration only and would not be allowed in a working spreadsheet.

<sup>c</sup> Sum of the machine *Parts*.

<sup>d</sup> Sum of *Machine 1* and *Machine 2*.

*Cell by Cell:* Each cell is added, subtracted, multiplied or divided individually. For example in **Table 1b**, the total cost of *Machine 1*

would be the values of each individual part cost in column *B* added vertically in cell *B6*.

$$B6 = +B2+B3+B4+B5 = \$34.15$$

*Sum Function:* For long columns or rows of cells, individual cell addition becomes cumbersome. Built-in functions simplify multiple cell manipulation by applying a specific function, like addition, over a range of cells. All spreadsheets have a summation or *Sum* function that adds all the cells that are called out in the function's address range. The *Sum* function adds cells horizontally or vertically. Again in **Table 1b**, the total cost of *Machine 1* using the *Sum* function would be:

$$B6 = \text{Sum}(B2:B5) = \$34.15$$

Either method yields the same result and may be used interchangeably. The cell by cell method must be used for cells that are not aligned horizontally or vertically. The compact *Sum* method is useful for long chains or ranges of cells. Spreadsheets contain many, many built-in functions that work with math, text strings, dates etc..

*Adding Formulas:* Cells containing formulas can themselves be combined, i.e. formulas containing formulas. In **Table 1b**, the total of the *motor* parts (row 2) for *Machine 1* and *Machine 2*, is calculated by the formula in cell *D2*, the total of the *control* parts *D3*, the total of all *chassis* parts *D4*, and the total of the *rebates* in *D5*. These formulas are summed together vertically in the first formula in cell *D6* to get the total cost of all the parts, in this case \$84.34. Note that a spreadsheet cell may only contain one formula or value. The multiple formulas in *D6* are for illustration only.

Alternatively, the cost of *Machine 1*, *B6* and *Machine 2*, *C6* could be added together horizontally to get the cost of all the machines which, in this case, equals the cost of all parts \$84.34. This illustrates that it is possible to set up a spreadsheet to find a solution in more than one way. In this case the total cost of all machines was calculated by adding the parts' subtotals or the individual machines' subtotals.

*Positive and Negative:* Spreadsheets usually display negative numbers with a minus sign “-” in front of them. Sometimes a negative cell number may be formatted to display parentheses around

a number instead of a minus sign. For example,  $-12.874$  would be equivalent to  $(12.874)$ . As with general formatting, this has no effect on the actual cell value.

It is extremely important to treat positive and negative cell values consistently. For example, cell values representing a loan amount of \$22,000.00 and a payment of \$500.00 might be entered as  $+\$22,000.00$  and  $-\$500.00$  if you are receiving a loan or  $-\$22,000.00$  and  $+\$500.00$  if you are loaning the money to someone. Switching one of the signs will create an error in the spreadsheet.

Generally it doesn't matter how positive and negative numbers are assigned, so long as the user is consistent throughout the spreadsheet and the people using the spreadsheet understand the positive-negative frame of reference. Failure to be consistent will lead to errors in your results.

*Basic Mathematical Operators:* Spreadsheets generally use the following conventions for basic mathematical operators. These operators may be applied to cell values or cell formulas.

#### Basic Spreadsheet Mathematical Operators

| Function | Operator                              | Function    | Operator    |
|----------|---------------------------------------|-------------|-------------|
| Add      | +                                     | Divide      | /           |
| Subtract | -                                     | Square      | $\wedge 2$  |
| Multiply | *                                     | Square Root | $\wedge .5$ |
| Grouping | $((5+B2)/A2) -(6*((9+16)\wedge 0.5))$ |             |             |

Consult the spreadsheet's help system to properly construct other mathematical operations such as sine, cosine, tangent, logarithms, etc..

*Built-In Functions:* As previously mentioned, spreadsheets contain many built-in functions to aid the user in setting up equations. For example, most spreadsheets have built-in interest functions sometimes referred to as Time Value of Money or *TVM* equations. Generally the names of the variables in the built-in equations do not always exactly match the generally accepted mathematical names used in particular field such as economics.

To illustrate this point, let's compare the *TVM* terms found in [Interest Formulas](#) on [page 125](#) to the variable names found in a

spreadsheet's Future Value (*FV*) built-in function. Then redo the *Compound Interest* problem found on Handbook [page 126](#).

*Example 1, Compound Interest:* At 10 per cent interest compounded annually for 3 years, a principal amount *P* of \$1000 becomes a sum  $F = 1000(1 + 10 / 100)^3 = \$1,331.93$ .

To solve this problem using a spreadsheet use the Future Value, *FV* built-in equation.  $FV(\text{Rate}, Nper, Pmt, Pv)$

where

*FV* = *F* or the Future Value of the amount owed or received.

*Rate* = *I* or nominal annual interest rate per period. In this yearly case divide by 1, for monthly payments divide by 12.

*Nper* = *n* or number of interest periods. In this case 3. If the interest were compounded monthly then  $Nper = 3 \text{ years} \times 12 \text{ periods/yr.} = 36 \text{ periods}$

*Pmt* = *R* or the payments made or received. For a compound interest loan  $Pmt = \$0.00$

*PV* = *P* or principle amount lent or borrowed.

Plugging in the appropriate values give the answer. Again note that leaving column *B* unformatted or formatting column *C* makes no difference for the final answer but does make it easier to understand the spreadsheet values.

**Table 2. Compound Interest Calculations Spreadsheet**

|   | A           | B  | C                          | D |
|---|-------------|--|----------------------------|---|
| 1 |             | Value  | Value                      |   |
| 2 | <i>Rate</i> | .1 <sup>a</sup>                                      | 10% <sup>b</sup>           |   |
| 3 | <i>Nper</i> | 3 <sup>a</sup>                                       | 3 <sup>b</sup>             |   |
| 4 | <i>Pmt</i>  | 0 <sup>a</sup>                                       | \$0.00 <sup>b</sup>        |   |
| 5 | <i>PV</i>   | -1000 <sup>a,c</sup>                                 | -\$1,000.00 <sup>b,c</sup> |   |
| 6 | <i>FV</i>   | = <i>FV</i> (B2,B3,B4,B5)<br>= 1,331.93 <sup>a</sup> | = \$1,331.93 <sup>b</sup>  |   |

<sup>a</sup> Unformatted cell.

<sup>b</sup> Formatted cell.

<sup>c</sup> This number is negative because you are loaning the money out to collect interest.

**Spreadsheet Advanced Concepts.**—One of the great strengths of spreadsheets is their ability to quickly and easily do what-if calculations. The two key concepts required to do this are cell content

and formula "copying and pasting" and "relative and absolute" cell addressing.

*Copying and Pasting:* Spreadsheets allow cells to be moved, or copied and pasted into new locations. Since a chain of cells can represent a complete problem and solution, copying these chains and pasting them repeatedly into adjacent areas allows several experimental "what-if" scenarios to be set up. It is then easy to vary the initial conditions of the problem and compare the results side by side. This is illustrated in the following example.

*Example 2, What-if Compound Interest Comparison:* Referring back to the compound interest problem in **Example 1**, compare the effects of different interest rates from three banks using the same loan amount and loan period. The banks offer a 10%, 11%, and 12% rate. In the spreadsheet, enter 10%, 11%, and 12% into B2, C2, and D2 respectively. Instead of typing in the initial amounts and formulas for the other values for other banks type them in once in, B3, B4, B5 and B6. Copy these cells one column over, into column C and column D. The spreadsheet will immediately solve all three interest rate solutions.

**Table 3. Interest Calculations Spreadsheet Using Relative Addressing**

|   | A    | B                               | C                               | D                               | E                              |
|---|------|---------------------------------|---------------------------------|---------------------------------|--------------------------------|
| 1 | Term | Bank A                          | Bank B                          | Bank C                          |                                |
| 2 | Rate | 10%                             | 11%                             | 12%                             | 4 cells above "relative" to E5 |
| 3 | Nper | 3                               | 3                               | 3                               | 3                              |
| 4 | Pmt  | \$0.00                          | \$0.00                          | \$0.00                          | 2                              |
| 5 | PV   | -\$1,000                        | -\$1,000                        | -\$1,000                        | 1                              |
| 6 | FV   | =FV(B2,B3,B4,B5)<br>=\$1,331.93 | =FV(C2,C3,C4,C5)<br>=\$1,367.63 | =FV(D2,D3,D4,D5)<br>=\$1,404.93 | Cell E5                        |

*Relative vs. Absolute Address:* Notice in row 6 of **Table 3** how the FV function cell addresses were changed as they were copied

from *B* column and pasted into the *C* and *D* columns. The formula cell addresses were changed from **B** to **C** in column *C* and **B** to **D** in column *D*. This is known as relative addressing. Instead of the formulas pointing to the original or "absolute" locations in the *B* column they were changed by the spreadsheet program as they were pasted to match a cell location with the same relative distance and direction as the original cell. To clarify, In column *E*, the cell *E2* is 4 cells up relative to *E5*. This is known as "relative" addressing. Relative addressing while pasting allows spreadsheets users to easily copy and paste multiple copies of a series of calculations. This easy what-if functionality is a cornerstone of spreadsheet usefulness.

*Absolute Addressing:* For large complicated spreadsheets the user may want to examine several what-if conditions while varying one basic parameter. For this type of problem it is useful to use "absolute" addressing. There are several formats for creating absolute addresses. Some spreadsheets require a "\$" be placed in front of each address. The relative address "B2" would become an absolute address when entered as "\$B\$2." When a formula with an absolute address is copied and pasted the copied formula maintains the same address as the original. The power of this is best illustrated by an example.

*Example 3, Absolute and Relative Addressing :* Suppose in **Example 1** we wanted to find the future value of \$1,000, \$1,500 and \$2,000 for 10% and 11% interest rates. Using the previous example as a starting point we enter values for *Rate*, *Nper*, *Pmt*, and *Pv*. We also enter the function *FV* into cell *B6*. This time we enter the absolute address *\$B\$2* for the *Rate* variable. Now when we copy cell *B6* into *C6* and *D6*, the *Rate* variable continues to point to cell *B2* (absolute addresses) while the other variables *Nper*, *Pmt*, and *Pv* point to locations in columns *C* and *D* (relative addresses).

**Table 4a. 10% Interest Rate Calculations Spreadsheet Using Absolute Addressing**

|   | A    | B                                   | C                                   | D                                   |
|---|------|-------------------------------------|-------------------------------------|-------------------------------------|
| 1 | Term | Loan Amount A                       | Loan Amount B                       | Loan Amount C                       |
| 2 | Rate | 10%                                 |                                     |                                     |
| 3 | Nper | 5                                   | 4                                   | 3                                   |
| 4 | Pmt  | \$0.00                              | \$0.00                              | \$0.00                              |
| 5 | PV   | -\$1,000                            | -\$1,500                            | -\$2,000                            |
| 6 | FV   | =FV(\$B\$2,B3,B4,B5)<br>=\$1,610.51 | =FV(\$B\$2,C3,C4,C5)<br>=\$2,196.15 | =FV(\$B\$2,D3,D4,D5)<br>=\$2,662.00 |

**Table 4b. 11% Interest Rate Calculations Spreadsheet Using Absolute Addressing**

|   | A    | B                                   | C                                   | D                                   |
|---|------|-------------------------------------|-------------------------------------|-------------------------------------|
| 1 | Term | Loan Amount A                       | Loan Amount B                       | Loan Amount C                       |
| 2 | Rate | 11%                                 |                                     |                                     |
| 3 | Nper | 5                                   | 4                                   | 3                                   |
| 4 | Pmt  | \$0.00                              | \$0.00                              | \$0.00                              |
| 5 | PV   | -\$1,000                            | -\$1,500                            | -\$2,000                            |
| 6 | FV   | =FV(\$B\$2,B3,B4,B5)<br>=\$1,685.06 | =FV(\$B\$2,C3,C4,C5)<br>=\$2,277.11 | =FV(\$B\$2,D3,D4,D5)<br>=\$2,735.26 |

From the **Table 4a** we find the future value for different starting amounts for a 10% rate. We change cell B2 from 10% to 11% and the spreadsheet updates all the loan calculations based on the new interest rate. These new values are displayed in **Table 4b**. All we had to do was change one cell to try a new "what-if." By combining relative and absolute addresses we were able to compare the effects of three different loan amounts using two interest rates by changing one cell value.

*Other Capabilities:* In addition to mathematical manipulations, most spreadsheets can create graphs, work with dates and text strings, link results to other spreadsheets, create conditional programming algorithms to name a few advanced capabilities. While these features may be useful in some situations, many real world



problems can be solved using spreadsheets by using a few simple operators and concepts.

### PRACTICE EXERCISES FOR SECTION 4

(See *Answers to Practice Exercises For Section 4* on page 223)

1) Use a spreadsheet to format a cell in different ways. Enter the number 0.34 in the first cell. Using the spreadsheet menu bar and online help, change the formatting of the cell to display this number as a percentage, a dollar amount, and then back to a general number.

2) Use a spreadsheet to create a times table. Enter the numbers 1-10 in the first column (A) and the first row (1). In cell B2 enter the formula for cell B1  $\times$  A2. Repeat this operation down the column. Use the spreadsheet's copy and paste function to copy all the formulas in column B, rows 2-10 and successively paste them into columns C-J making sure not to paste over the values in row 1. Use your spreadsheet to look up the value of  $2 \times 2$ ,  $5 \times 7$ , and  $8 \times 9$ .

|    | A  | B | C | D | E | F | G | H | I | J  |
|----|----|---|---|---|---|---|---|---|---|----|
| 1  | 1  | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 2  | 2  |   |   |   |   |   |   |   |   |    |
| 3  | 3  |   |   |   |   |   |   |   |   |    |
| 4  | 4  |   |   |   |   |   |   |   |   |    |
| 5  | 5  |   |   |   |   |   |   |   |   |    |
| 6  | 6  |   |   |   |   |   |   |   |   |    |
| 7  | 7  |   |   |   |   |   |   |   |   |    |
| 8  | 8  |   |   |   |   |   |   |   |   |    |
| 9  | 9  |   |   |   |   |   |   |   |   |    |
| 10 | 10 |   |   |   |   |   |   |   |   |    |

3) Using a spreadsheet to recreate Table 1b on **page 24**. Make sure to format currency cells where required.

4) Using your spreadsheet's online help for guidance, recreate the compound interest calculation, Table 2 on **page 27** using the spreadsheet's *Future Value* interest rate function. Make sure to format currency and percentage cells correctly.

5) Using the spreadsheet you created in the previous question, calculate the *Future Value* of \$2,500 compounded annually for 12 years at 7.5% interest. What would the *Future Value* be if the interest was compounded monthly?

## SECTION 5

### CALCULATIONS INVOLVING LOGARITHMS OF NUMBERS

HANDBOOK Pages **111** to **118**

The purpose of logarithms is to facilitate and shorten calculations involving multiplication and division, obtaining the powers of numbers, and extracting the roots of numbers. By means of logarithms, long multiplication problems become simple addition of logarithms; cumbersome division problems are easily solved by simple subtraction of logarithms; the fourth root or, say, the 10.4th root of a number can be extracted easily, and any number can be raised to the twelfth power as readily as it can be squared.

The availability of inexpensive hand-held calculators, and computers, has eliminated much of the need to use logarithms for such purposes; there are, however, many applications in which the logarithm of a number is used in obtaining the solution of a problem. For example, in the Handbook section, *Compound Interest* on **page 125**, there is a formula to find the number of years  $n$  required for a sum of money to grow a specified amount. The example accompanying the formula shows the necessary calculations that include the logarithms 3, 2.69897, and 0.025306, which correspond to the numbers 1000, 500, and 1.06, respectively. These logarithms were obtained directly from a hand-held electronic calculator and are the common or *Briggs* system logarithms, which have a base 10. Any other system of logarithms such as that of base  $e$  ( $e = 2.71828\dots$ ) could have been used in this problem with the same result. Base  $e$  logarithms are sometimes referred to as “natural logarithms.”

There are other types of problems in which logarithms of a specific base, usually 10 or  $e$ , must be used to obtain the correct result. On the logarithm keys of most calculators, the base 10 logs are identified by the word “log” and those of base  $e$  are referred to as “ln.”

In the common or Briggs system of logarithms, which is used ordinarily, the base of the logarithms is 10; that is, the logarithm is the *exponent* that would be affixed to 10 to produce the number corresponding to the logarithm. To illustrate, by taking simple numbers:

$$\text{Logarithm of } 10 = 1 \text{ because } 10^1 = 10$$

$$\text{Logarithm of } 100 = 2 \text{ because } 10^2 = 100$$

$$\text{Logarithm of } 1000 = 3 \text{ because } 10^3 = 1000$$

In each case, it will be seen that the exponent of 10 equals the logarithm of the number. The logarithms of all numbers between 10 and 100 equal 1 plus some fraction. For example: The logarithm of 20 = 1.301030.

The logarithms of all numbers between 100 and 1000 = 2 plus some fraction; between 1000 and 10,000 = 3 plus some fraction; and so on. The tables of logarithms in engineering handbooks give only this fractional part of a logarithm, which is called the *mantissa*. The whole number part of a logarithm, which is called the *characteristic*, is not given in the tables because it can easily be determined by simple rules. The logarithm of 350 is 2.544068. The whole number 2 is the characteristic (see Handbook [page 111](#)) and the decimal part 0.544068, or the mantissa, is found in the table (Handbook [page 115](#)).

**Principles Governing the Application of Logarithms.**—When logarithms are used, the product of two numbers can be obtained as follows: Add the logarithms of the two numbers; the sum equals the logarithm of the product. For example: The logarithm of 10 (commonly abbreviated log 10) equals 1; log 100 = 2; 2 + 1 = 3, which is the logarithm of 1000 or the product of 100 × 10.

Logarithms would not be used for such a simple example of multiplication; these particular numbers are employed merely to illustrate the principle involved.

For division by logarithms, subtract the logarithm of the divisor from the logarithm of the dividend to obtain the logarithm of the quotient. To use another simple example, divide 1000 by 100 using logarithms. As the respective logarithms of these numbers are 3 and 2, the difference of equals the logarithm of the quotient 10.

In using logarithms to raise a number to any power, simply multiply the logarithm of the number by the exponent of the number; the product equals the logarithm of the power. To illustrate, find the value of  $10^3$  using logarithms. The logarithm of  $10 = 1$  and the exponent is 3; hence,  $3 \times 1 = 3 = \log$  of 1000; hence,  $10^3 = 1000$ .

To extract any root of a number, merely divide the logarithm of this number by the index of the root; the quotient is the logarithm of the root. Thus, to obtain the cube root of 1000 divide 3 (log 1000) by 3 (index of root); the quotient equals 1 which is the logarithm of 10. Therefore,

$$\sqrt[3]{1000} = 10$$

Logarithms are of great value in many engineering and shop calculations because they make it possible to solve readily cumbersome and also difficult problems that otherwise would require complicated formulas or higher mathematics. Keep constantly in mind that logarithms are merely exponents. Any number might be the base of a system of logarithms. Thus, if 2 were selected as a base, then the logarithm of 256 would equal 8 because  $2^8 = 256$ . However, unless otherwise mentioned, the term "logarithm" is used to apply to the common or Briggs system, which has 10 for a base.

The tables of common logarithms are found on Handbook [pages 115](#) and [116](#). The natural logarithms, [pages 117](#) and [118](#), are based upon the number 2.71828. These logarithms are used in higher mathematics and also in connection with the formula to determine the mean effective pressure of steam in engine cylinders.

**Finding the Logarithms of Numbers.**—There is nothing complicated about the use of logarithms, but a little practice is required to locate readily the logarithm of a given number or to reverse this process and find the number corresponding to a given logarithm. These corresponding numbers are sometimes called "antilogarithms."

Study carefully the rules for finding logarithms given on Handbook [pages 111](#) to [114](#). Although the characteristic or whole-number part of a logarithm is easily determined, the following table will assist the beginner in memorizing the rules.

### Sample Numbers and Their Characteristics

| Characteristic | Number    | Characteristic | Number |
|----------------|-----------|----------------|--------|
| 0.008          | $\bar{3}$ | 88             | 1      |
| 0.08           | $\bar{2}$ | 888            | 2      |
| 0.8            | $\bar{1}$ | 8888           | 3      |
| 8.0            | 0         | 88888          | 4      |

Example of the use of the table of numbers and their characteristics: What number corresponds to the  $\log \bar{2}.55145$ ? Find 0.551450 in the log tables to correspond to 356. From the table of characteristics, note that a  $\bar{2}$  characteristic calls for one zero in front of the first integer; hence, point off 0.0356 as the number corresponding to the  $\log 2.55145$ . Evaluating logarithms with negative characteristics is explained more thoroughly later.

*Example 1:* Find the logarithm of 46.8.

The mantissa of this number is 0.670246. When there are two whole-number places, the characteristic is 1; hence, the log of 46.8 is 1.670246.

After a little practice with the above table, one becomes familiar with the rules governing the characteristic so that reference to the table is no longer necessary.

**Obtaining More Accurate Values Than Given Directly by Tables.**—The method of using the tables of logarithms to obtain more accurate values than are given directly, by means of interpolation, is explained on Handbook [page 112](#). These instructions should be read carefully in order to understand the procedure in connection with the following example:

*Example 2:*

$$\frac{76824 \times 52.076}{435.21} =$$

$$\log 76824 = 4.88549 \quad \log \text{numerator} = 6.60213$$

$$\log 52.076 = \underline{1.71664} \quad - \log 435.21 = \underline{2.63870}$$

$$\log \text{numerator} = 6.60213 \quad \log \text{quotient} = 3.96343$$

The number corresponding to the logarithm 3.96343 is 9192.4. The logarithms just given for the dividend and divisor are obtained by interpolation in the following manner:

In the log tables on **page 116** of the Handbook, find the mantissa corresponding to the first three digits of the number 76824, and the mantissa of the next higher 3-digit number in the table, 769. The mantissa of 76824 is the mantissa of 768 plus  $\frac{24}{100}$  times the difference between the mantissas of 769 and 768.

$$\text{Mantissa } 769 = .885926$$

$$\text{Mantissa } 768 = \underline{.885361}$$

$$\text{Difference} = .000565$$

Thus,  $\log 76824 = 0.24 \times 0.000565 + \log 76800 = 4.885497$ . The characteristic 4 is obtained as previously illustrated in the table on **page 35**. By again using interpolation as explained in the Handbook, the corrected mantissas are found for the logarithms of 52.076 and 435.21.

After obtaining the logarithm of the quotient, which is 3.96343, interpolation is again used to determine the corresponding number more accurately than would be possible otherwise. The mantissa .96343 (see Handbook **page 116**) is found, in the table, between 0.963316 and 0.963788, the mantissas corresponding to 919 and 920, respectively.

$$0.963788 - 0.963316 = 0.000472$$

$$0.96343 - 0.963316 = 0.000114$$

Note that the first line gives the difference between the two mantissas nearest .96343, and the second line gives the difference between the mantissa of the quotient and the nearest smaller mantissa in the Handbook table. The characteristic 3 in the quotient 3.96343 indicates 4 digits before the decimal point in the answer, thus the number sought is  $9190 + \frac{114}{472}(9200 - 9190) = 9192.4$ .

**Changing Form of Logarithm Having Negative Characteristic.**—The characteristic is frequently rearranged for easier manipulation. Note that  $8 - 8$  is the same as 0; hence, the log of 4.56 could be stated: 0.658965 or  $8.658965 - 8$ . Similarly, the log of 0.075 =  $\bar{2}.875061$  or  $8.875061 - 10$  or  $7.875061 - 9$ . Any similar

arrangement could be made, as determined by case in multiplication or division.

*Example 3:*

$$\sqrt[3]{0.47} = ?$$

$$\log 0.47 = \bar{1}.672098 \text{ or } 8.672098 - 9$$

$$\log \sqrt[3]{0.47} = (8.672098 - 9) \div 3 = 2.890699 \div 3 = \bar{1}.89070$$

In the first line above,  $9 - 9$  was added to  $\log 0.47$  because 3 (the index of the root) will divide evenly into 9;  $11 - 12$  or  $5 - 6$  could have been used as well. (Refer to Example 2 on Handbook [page 114](#). The procedure differs from that just described but the same result is obtained.)

To find the number corresponding to  $\bar{1}.89070$ , locate the nearest mantissa. Mantissa .890421 is found in the table and corresponds to 777. The  $\bar{1}$  characteristic indicates that the decimal point immediately precedes the first integer; therefore, the number equivalent to the  $\log 1.89070$  is 0.777. If desired, additional accuracy can be obtained by interpolation, as explained previously. Thus,

$$\sqrt[3]{0.47} = 0.777.$$

**Cologarithms.**—The cologarithm of a number is the logarithm of the reciprocal of that number. “Cologs” have no properties different from those of ordinary logarithms, but they enable division to be earned out by addition because the addition of a colog is the same as the subtraction of a logarithm.

$$\text{Example 4: } \frac{742 \times 6.31}{55 \times 0.92} = ?$$

Note that this problem could be stated:  $742 \times 6.31 \times 1/55 \times 1/0.92$ . Then the logs of each number could be added because the process is one of multiplication only.

$\log 1/55$  can be obtained readily in two ways

$$\log 1/55 = \log 1 - \log 55$$

$$\log 1 = 10.000000 \quad - 10$$

$$-\log 55 = -1.740363$$

$$\hline 8.259637 \quad - 10 \quad = \bar{2}.259637$$

or

$$\log 1/55 = \log 0.0181818 \text{ (see reciprocals)}$$

$$\log 0.0181818 = \bar{2}.25964$$

This number  $\bar{2}.259637$  is called the colog of 55; hence, to find the colog of any number, subtract the logarithm of that number from  $10.000000 - 10$ ; this is the same as dividing 1 by the number whose colog is sought.

To find the colog of 0.92, subtract  $\log 0.92$  (or  $\bar{1}.96379$ ) from  $10.00000 - 10$ ; thus:

$$\begin{array}{r} 10.000000 \quad - 10 \\ \log 0.92 = \quad \bar{1}.963788 \\ \hline \text{colog } 0.92 = \quad 9.963788 \quad - 10 = 0.036212 \end{array}$$

(In subtracting negative characteristics, change the sign of the lower one and add.)

Another method is to use  $\log 0.92 = \bar{1}.96379$  or  $9.96379 - 10$ , and proceeding as above:

$$\begin{array}{r} \log 0.92 = \quad \bar{1}.96378 = \quad 9.963788 - 10 \\ \text{colog } 0.92 \quad \quad \quad = \quad \underline{0.036212} \end{array}$$

**Example 4** may then be solved by adding logs; thus:

$$\begin{array}{r} \log 742 \quad \quad \quad = \quad 2.870404 \\ \log 6.31 \quad \quad \quad = \quad 0.800029 \\ \text{colog } 55 \quad \quad \quad = \quad \bar{2}.259637 \\ \text{colog } 0.92 \quad \quad \quad = \quad 0.036212 \\ \log \text{ quotient} \quad \quad = \quad \underline{1.966282} \end{array}$$

The number corresponding to the logarithm of the quotient = 92.53.

*Example 5:* The initial absolute pressure of the steam in a steam engine cylinder is 120 psi; the length of the stroke is 26 inches; the clearance  $1\frac{1}{2}$  inches; and the period of admission, measured from



the beginning of the stroke, 8 inches. Find the mean effective pressure.

The mean effective pressure is found by the formula:

$$p = \frac{P(1 + \log_e R)}{R}$$

in which  $p$  = mean effective pressure in pounds per square inch;  
 $P$  = initial absolute pressure in pounds per square inch;  
 $R$  = ratio of expansion, which in turn is found from the formula:

$$R = \frac{L + C}{l + C}$$

in which  $L$  = length of stroke in inches;  
 $l$  = period of admission in inches;  
 $C$  = clearance in inches.

The given values are  $P = 120$ ;  $L = 26$ ;  $l = 8$ ; and  $C = 1\frac{1}{2}$ . By inserting the last three values in the formula for  $R$ , we have:

$$R = \frac{26 + 1\frac{1}{2}}{8 + 1\frac{1}{2}} = \frac{27.5}{9.5} = 2.89$$

If we now insert the value of  $P$  and the found value of  $R$  in the formula for  $p$ , we have:

$$p = \frac{120(1 + \log_e 2.89)}{2.89}$$

The natural logarithm (hyp. log.) may be found from tables or a calculator. The natural logarithm for 2.89 is 1.061257 (see Handbook [page 117](#)). Inserting this value in the formula, we have:

$$p = \frac{120(1 + 1.061257)}{2.89} = \frac{120 \times 2.061257}{2.89} = 85.6 \text{ lb/in}^2$$

### PRACTICE EXERCISES FOR SECTION 5

(See *Answers to Practice Exercises For Section 5* on page 223)

- 1) What are the rules governing the characteristics?
- 2) Find the mantissas of: 762; 478; 26; 0.0098; 6743; 24.82.
- 3) What are the characteristics of the numbers just given?

4) What numbers could correspond to the following mantissas: 0.085016; 0.88508; 0.22763?

5) (a) If the characteristic of each of the mantissas just given is 1, what would the corresponding numbers be? (b) Using the following characteristics (2, 0, 3) for each mantissa, find the antilogarithms or corresponding numbers.

6)  $\log 765.4 = ?$   $\log 87.2 = ?$ ;  $\log 0.00874 = ?$

7) What are the antilogarithms of: 2.89894; 1.24279; 0.18013; 2.68708?

8) Find by interpolation the logarithm of: 75186; 42.037.

9) Find the numbers corresponding to the following logarithms: 1.82997; 0.67712.

10)  $(2.71)^5 = ?$   $(4.23)^{2.5} = ?$

11)  $\sqrt{97.65} = ?$   $\sqrt[5]{4687} = ?$   $2.3\sqrt[3]{44.5} = ?$

12)  $\frac{62876 \times 54.2 \times 0.0326}{1728 \times 231} = ?$

13)  $(2/19)^7 = ?$

14)  $(9.16)^{2.47} = ?$

15)  $\sqrt[3]{\frac{(75)^2 \times (5.23)^{2/3}}{0.00036 \times \sqrt{51.7}}} =$

16) The area of a circular sector =  $0.008727ar^2$  where  $a$  = angle in degrees and  $r$  = radius of the circle. Find the area of a circular sector the radius of which is 6.25 inches and the central angle is  $42^\circ 15'$ .

17) The diameter of a lineshaft carrying pulleys may be found from the formula:  $d = \sqrt[3]{53.5\text{hp/rpm}}$ . Find the diameter of shafting necessary to transmit 50 hp at 250 rpm.

18) The horsepower of a steam engine is found from the formula:  $hp = PLAN/33000$ , where

LOGARITHMS

$P$  = mean effective pressure in pounds per square inch;

$L$  = length of stroke in feet;

$A$  = area of piston in square inches;

$N$  = number of strokes per minute = revolutions per minute  $\times 2$ .

Find the horsepower of a steam engine if the pressure is 120 pounds, stroke 18 inches, piston 10 inches in diameter, and the number of revolutions per minute is 125.

19) Can the tables of logarithms be used for addition and subtraction?

20) Can logarithms be used to solve gear-ratio problems?

## SECTION 6

### DIMENSIONS, AREAS, AND VOLUMES OF GEOMETRICAL FIGURES

HANDBOOK Pages 36 to 74

The formulas given for the solution of different problems relating to the areas of surfaces and volumes of various geometrical figures are derived from plane and solid geometry. For purposes of shop mathematics, all that is necessary is to select the appropriate figure and use the formula given. Keep in mind the tables that have been studied and use them in the solution of the formulas whenever such usage can be done to advantage.

Many rules may be developed directly from the table for polygons on Handbook page 69. These rules will permit easy solution of nearly every problem involving a regular polygon. For instance, in the first "A" columns at the left,  $A/S^2 = 7.6942$  for a decagon; by transposition,  $S = \sqrt{A \div 7.6942}$ . In the first "R" column,  $R = 1.3066S$  for an octagon; hence,  $S = R \div 1.3066$ .

The frequent occurrence of such geometrical figures as squares, hexagons, spheres, and spherical segments in shop calculations makes the tables dealing with these figures very useful.

*Example 1:* A rectangle 12 inches long has an area of 120 square inches; what is the length of its diagonal?

The area of a rectangle equals the product of the two sides; hence, the unknown side of this rectangle equals  $\frac{120}{12} = 10$  inches.

$$\text{Length of diagonal} = \sqrt{12^2 + 10^2} = \sqrt{244} = 15.6205$$

*Example 2:* If the diameter of a sphere, the diameter of the base, and the height of a cone are all equal, find the volume of the sphere if the volume of the cone is 250 cubic inches.

The formula on Handbook [page 77](#) for the volume of a cone shows that the value for  $250 = 0.2618d^2h$ , in which  $d$  = diameter of cone base and  $h$  = vertical height of cone; hence,

$$d^2 = \frac{250}{0.2618h}$$

Since in this example  $d$  and  $h$  are equal,

$$d^3 = \frac{250}{0.2618}$$

and

$$d = \sqrt[3]{\frac{250}{0.2618}} = 9.8474 \text{ inches}$$

By referring to the formula on Handbook [page 78](#), the volume of a sphere =  $0.5236d^3 = 0.5236 \times (9.8474)^3 = 500$  cubic inches.

In solving the following exercises, first, construct the figure carefully, and then apply the formula. Use the examples in the Handbook as models.

### PRACTICE EXERCISES FOR SECTION 6

(See [Answers to Practice Exercises For Section 6](#) on page 224)

- 1) Find the volume of a cylinder having a base radius of 12.5 and a height of 16.3 inches.
- 2) Find the area of a triangle with sides that are 12, 14, and 18 inches in length.
- 3) Find the volume of a torus or circular ring made from  $1\frac{1}{2}$  inch round stock if its outside diameter is 14 inches.
- 4) A bar of hexagonal screw stock measures 0.750 inch per side. What is the largest diameter that can be turned from this bar?
- 5) Using the prismoidal formula (Handbook [page 59](#)), find the volume of the frustum of a regular triangular pyramid if its lower base is 6 inches per side, upper base 2 inches per side, and height 3 inches. (Use the table on Handbook [page 69](#) for areas. The side of the midsection equals one-half the sum of one side of the lower base and one side of the upper base.)

6) What is the diameter of a circle the area of which is equivalent to that of a spherical zone whose radius is 4 inches and height 2 inches?

7) Find the volume of a steel ball  $\frac{3}{8}$  inch in diameter.

8) What is the length of the side of a cube if the volume equals the volume of a frustum of a pyramid with square bases, 4 inches and 6 inches per side, and 3 inches high?

9) Find the volume of a bronze bushing if its inside diameter is inch, outside diameter is  $1\frac{1}{2}$  inches, and length is 2 inches.

10) Find the volume of material making up a hollow sphere with an outside diameter of 10 inches and an inside diameter of 6 inches.

11) Find the area of a 10-equal-sided polygon inscribed in a 6-inch diameter circle.

12) What is the radius of a fillet if its chord is 2 inches? What is its area?

13) Find the area of the conical surface and volume of a frustum of a cone if the diameter of its lower base is 3 feet, diameter of upper base 1 foot, and height 3 feet.

14) Find the total area of the sides and the volume of a triangular prism 10 feet high, having a base width of 8 feet.

15) The diagonal of a square is 16 inches. What is the length of its side?

16) How many gallons can be contained in a barrel having the following dimensions: height  $2\frac{1}{2}$  feet; bottom diameter 18 inches; bilge diameter 21 inches? (The sides are formed to the arc of a circle.)

17) Find the area of a sector of a circle if the radius is 8 inches and the central angle is 32 degrees.

18) Find the height of a cone if its volume is 17.29 cubic inches and the radius of its base is 4 inches.

19) Find the volume of a rectangular pyramid having a base  $4 \times 5$  inches and height 6 inches.

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20) Find the distance across the corners of both hexagons and squares when the distance across flats in each case is:  $\frac{1}{2}$ ;  $1\frac{5}{8}$ ;  $3\frac{3}{10}$ ; 5; 8.

21) The diagonal of one square is 2.0329 and of the other square is 4.6846. Find the lengths of the sides of both squares.

22) In measuring the distance over plugs in a die that has six  $\frac{3}{4}$ -inch holes equally spaced on a circle, what should be the micrometer reading over opposite plugs if the distance over alternate plugs is  $4\frac{1}{2}$  inches?

23) To what diameter should a shaft be turned in order to mill on one end a hexagon 2 inches on a side; an octagon 2 inches on a side?

## SECTION 7

### GEOMETRICAL PROPOSITIONS AND CONSTRUCTIONS

HANDBOOK Pages 49 to 58

Geometry is the branch of mathematics that deals with the relations of lines, angles, surfaces, and solids. Plane geometry treats the relations of lines, angles, and surfaces in one plane only, and since this branch of geometry is of special importance in mechanical work, the various propositions or fundamental principles are given in the Handbook, as well as various problems or constructions. This information is particularly useful in mechanical drafting and in solving problems in mensuration.

*Example 1:* A segment-shaped casting (see **Fig. 1**) has a chordal length of 12 inches, and the height of the chord is 2 inches; determine by the application of a geometrical principle the radius  $R$  of the segment.

This problem may be solved by the application of the second geometrical proposition given on Handbook **page 53**. In this example, one chord consists of two sections  $a$  and  $b$ , each 6 inches long; the other intersecting chord consists of one section  $d$ , 2 inches long; and the length of section  $c$  is to be determined in order to find radius  $R$ . Since  $a \times b = c \times d$ , it follows that:

$$c = \frac{a \times b}{d} = \frac{6 \times 6}{2} = 18 \text{ inches}$$

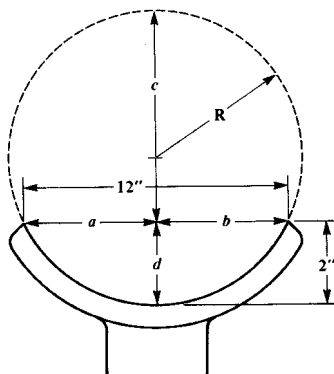
therefore,

$$R = \frac{c + d}{2} = \frac{18 + 2}{2} = 10 \text{ inches}$$

In this example, one chordal dimension,  $c + d =$  the diameter; but, the geometrical principle given in the Handbook applies regardless of the relative lengths of the intersecting chords.



*Example 2:* The center lines of three holes in a jig plate form a triangle. The angle between two of these intersecting center lines is 52 degrees. Another angle between adjacent center lines is 63 degrees. What is the third angle?



**Fig. 1.**

This problem is solved by application of the first geometrical principle on Handbook [page 49](#). The unknown angle =  $180 - (63 + 52) = 65$  degrees.

*Example 3:* The center lines of four holes in a jig plate form a four-sided figure. Three of the angles between the different intersecting center lines are 63 degrees, 105 degrees, and 58 degrees, respectively. What is the fourth angle?

According to the geometrical principle at the bottom of Handbook page 45, the unknown angle =  $360 - (63 + 105 + 58) = 134$  degrees.

*Example 4:* The centers of three holes are located on a circle. The angle between the radial center lines of the first and second holes is 22 degrees, and the center-to-center distance measured along the circle is  $2\frac{1}{2}$  inches. The angle between the second and third holes is 44 degrees. What is the center-to-center distance along the circle?

This problem is solved by application of the fourth principle on Handbook [page 53](#). Since the lengths of the arcs are proportional to the angles, the center distance between the second and third

holes =  $(44 \times 2\frac{1}{2})/22 = 5$  inches. (See also rules governing proportion starting on Handbook [page 5](#).)

The following practice exercises relate to the propositions and constructions given and should be answered without the aid of the Handbook.

### PRACTICE EXERCISES FOR SECTION 7

(See *Answers to Practice Exercises For Section 7* on page 224)

1) If any two angles of a triangle are known, how can the third angle be determined?

2) State three instances where one triangle is equal to another.

3) When are triangles similar?

4) What is the purpose of proving triangles similar?

5) If a triangle is equilateral, what follows?

6) What are the properties of the bisector of any angle of an equilateral triangle?

7) What is an isosceles triangle?

8) How do the size of an angle and the length of a side of a triangle compare?

9) Can you draw a triangle whose sides are 5, 6, and 11 inches?

10) What is the length of the hypotenuse of a right triangle the sides of which are 12 and 16 inches?

11) What is the value of the exterior angle of any triangle?

12) What are the relations of angles formed by two intersecting lines?

13) Draw two intersecting straight lines and a circle tangent to these lines.

14) Construct a right triangle given the hypotenuse and one side.

15) When are the areas of two parallelograms equal?

16) When are the areas of two triangles equal?

17) If a radius of a circle is perpendicular to a chord, what follows?

18) What is the relation between the radius and tangent of a circle?

19) What lines pass through the point of tangency of two tangent circles?

20) What are the attributes to two tangents drawn to a circle from an external point?

21) What is the value of an angle between a tangent and a chord drawn from the point of tangency?

22) Are all angles equal if their vertices are on the circumference of a circle, and they are subtended by the same chord?

23) If two chords intersect within a circle, what is the value of the product of their respective segments?

24) How can a right angle be drawn using a semicircle?

25) Upon what does the length of circular arcs in the same circle depend?

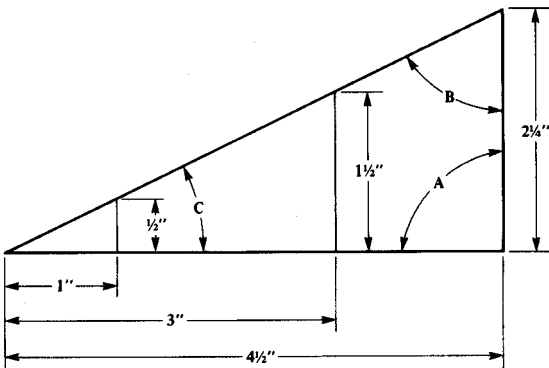
26) To what are the circumferences and areas of two circles proportional?

## SECTION 8

### FUNCTIONS OF ANGLES

HANDBOOK Pages 88 to 107

The basis of trigonometry is proportion. If the sides of any angle are indefinitely extended and perpendiculars from various points on one side are drawn to intersect the other side, right triangles will be formed, and the ratios of the respective sides and hypotenuses will be identical. If the base of the smallest triangle thus formed is 1 inch, and the altitude is  $\frac{1}{2}$  inch (see Fig. 1), the ratio between these sides is  $1 \div \frac{1}{2} = 2$  or  $\frac{1}{2} \div 1 = \frac{1}{2}$  depending upon how the ratio is stated. If the next triangle is measured, the ratio between the base and altitude will likewise be either 2 or  $\frac{1}{2}$ , and this will always be true for any number of triangles, if the angle remains unchanged. For example,  $3 \div 1\frac{1}{2} = 2$  and  $4\frac{1}{2} \div 2\frac{1}{4} = 2$  or  $1\frac{1}{2} \div 3 = \frac{1}{2}$  and  $2\frac{1}{4} \div 4\frac{1}{2} = \frac{1}{2}$ .



**Fig. 1. For a Given Angle, the Ratio of the Base to the Altitude Is the Same for All Triangle Sizes**

This relationship explains why rules can be developed to find the length of any side of a triangle when the angle and one side are known or to find the angle when any two sides are known. Since there are two relations between any two sides of a triangle, there can be, therefore, a total of six ratios with three sides. These ratios are defined and explained in the Handbook. Refer to **pages 88** and **89** and note explanations of the terms *side adjacent*, *side opposite*, and *hypotenuse*.

The abbreviations of the trigonometric functions begin with a small letter and are not followed by periods.

**Functions of Angles and Use of Trigonometric Tables.**—On **page 88** of the Handbook are given certain rules for determining the functions of angles. These rules, which should be memorized, may also be expressed as simple formulas:

$$\begin{array}{ll} \text{sine} = \frac{\text{side opposite}}{\text{hypotenuse}} & \text{cosecant} = \frac{\text{hypotenuse}}{\text{side opposite}} \\ \text{cosine} = \frac{\text{side adjacent}}{\text{hypotenuse}} & \text{secant} = \frac{\text{hypotenuse}}{\text{side adjacent}} \\ \text{tangent} = \frac{\text{side opposite}}{\text{side adjacent}} & \text{cotangent} = \frac{\text{side adjacent}}{\text{side opposite}} \end{array}$$

Note that these functions are arranged in pairs to include sine and cosecant, cosine and secant, tangent and cotangent, and that each pair consists of a function and its reciprocal. Also, note that the different functions are merely ratios, the sine being the ratio of the *side opposite* to the *hypotenuse*, cosine the ratio of the *side adjacent* to the *hypotenuse*, etc. Tables of trigonometric functions are, therefore, tables of ratios and these functions can be obtained easily and quickly from most pocket calculators. For example,  $\tan 20^\circ 30' = 0.37388$ ; this means that in any right triangle having an acute angle of  $20^\circ 30'$ , the side opposite that angle is equal in length to 0.37388 times the length of the side adjacent.  $\cos 50^\circ 22' = 0.63787$ ; this means that in any right triangle having an angle of  $50^\circ 22'$ , if the hypotenuse equals a certain length, say, 8, the side adjacent to the angle will equal  $0.63787 \times 8$  or 5.10296.

Referring to **Fig. 1**,  $\tan C = 2\frac{1}{4} \div 4\frac{1}{2} = 1\frac{1}{2} \div 3 = \frac{1}{2} \div 1 = 0.5$ ; therefore, for this particular angle  $C$ , the *side opposite* is always equal to 0.5 times *side adjacent*, thus:  $1 \times 0.5 = \frac{1}{2}$ ;  $3 \times 0.5 = 1\frac{1}{2}$ ; and  $4\frac{1}{2} \times 0.5 = 2\frac{1}{4}$ . The side opposite angle  $B$  equals  $4\frac{1}{2}$ ; hence,  $\tan B = 4\frac{1}{2} \div 2\frac{1}{4} = 2$ .

**Finding Angle Equivalent to Given Function.**—After determining the tangent of angle  $C$  or of angle  $B$ , the values of these angles can be determined readily. As  $\tan C = 0.5$ , find the number nearest to this in the tangent column. On Handbook **page 101** will be found 0.498582, corresponding to 26 degrees, 30 minutes, and 0.502219 corresponding to the angle 26 degrees, 40 minutes. Because 0.5 is approximately midway between 0.498582 and 0.502219, angle  $C$  can be accurately estimated as 26 degrees, 35 minutes. This degree of accuracy is usually sufficient, however, improved accuracy may be obtained by interpolation, as explained in the examples to follow.

Since angle  $A = 90$  degrees, and, as the sum of three angles of a triangle always equals 180 degrees, it is evident that angle  $C + B = 90$  degrees; therefore,  $B = 90$  degrees minus 26 degrees, 35 minutes = 63 degrees, 25 minutes. The table on Handbook **page 101** also shows that  $\tan 63$  degrees, 25 minutes is midway between 1.991164 and 2.005690, or approximately 2 within 0.0002.

Note that for angles  $45^\circ$  to  $90^\circ$ , Handbook **pages 100 to 102**, the table is used by reading from the bottom up, using the function labels across the bottom of the table, as explained on Handbook **page 99**.

In the foregoing example, the tangent is used to determine the unknown angles because the known sides are the side adjacent and the side opposite the unknown angles, these being the sides required for determining the tangent. If the side adjacent and the length of hypotenuse had been given instead, the unknown angles might have been determined by first finding the cosine because the cosine equals the side adjacent divided by the hypotenuse.

The acute angles (like  $B$  and  $C$ , **Fig. 1**) of any right triangle must be complementary, so the function of any angle equals the cofunction of its complement; thus, the sine of angle  $B =$  the cosine of

angle  $C$ ; the tangent of angle  $B$  = the cotangent of angle  $C$ ; etc. Thus,  $\tan b = 4\frac{1}{2} \div 2\frac{1}{4}$  and cotangent  $C$  also equals  $4\frac{1}{2} \div 2\frac{1}{4}$ . The tangent of  $20^\circ 30' = 0.37388$ , which also equals the cotangent of  $20^\circ 30'$ . For this reason, it is only necessary to calculate the trigonometric ratios to  $45^\circ$  when making a table of trigonometric functions for angles between  $45^\circ$  and  $90^\circ$ , and this is why the functions of angles between  $45^\circ$  and  $90^\circ$  are located in the table by reading it backwards or in reverse order, as previously mentioned.

*Example 1:* Find the tangent of 44 degrees, 59 minutes.

Following instructions given on [page 99](#) of the Handbook, find 44 degrees, 50 minutes, and 45 degrees, 0 minutes at the bottom of [page 102](#); and find their respective tangents, 0.994199 and 1.000000, in the column "tan" labeled across the top of the table. The tangent of  $44^\circ 59'$  is  $0.994199 + 0.9 \times (1 - 0.994199) = 0.99942$ .

*Example 2:* Find the tangent of 45 degrees, 5 minutes.

At the bottom of Handbook page 97, and above "tan" at the bottom of the table, are the tangents of  $45^\circ 0'$  and  $45^\circ 10'$ , 1.000000 and 1.005835, respectively. The required tangent is midway between these two values and can be found from  $1.000000 + 0.5 \times (1.005835 - 1) = 1.00292$ .

**How to Find More Accurate Functions and Angles Than Are Given in the Table.**—In the Handbook, the values of trigonometric functions are given to degrees and 10-minute increments; hence, if the given angle is in degrees, minutes, and seconds, the value of the function is determined from the nearest given values by interpolation.

*Example 3:* Assume that the sine of  $14^\circ 22' 26''$  is to be determined. It is evident that this value lies between the sine of  $14^\circ 20'$  and the sine of  $14^\circ 30'$ .

Sine  $14^\circ 20' = 0.247563$  and Sine  $14^\circ 30' = 0.250380$ ; the difference =  $0.250380 - 0.247563 = 0.002817$ . Consider this difference as a whole number (2817) and multiply it by a fraction having as its numerator the number of additional minutes and fractions of minutes (number of seconds divided by 60) in the given angle ( $2 + \frac{26}{60}$ ), and as its denominator the number of minutes in the interval between  $14^\circ 20'$  and the sine of  $14^\circ 30'$ . Thus,  $(2 + \frac{26}{60})/10 \times 2817$

$= [(2 \times 60) + 26]/(10 \times 60) \times 2817 = 685.47$ ; hence, by adding 0.000685 to sine of  $14^\circ 20'$ , we find that  $\text{sine } 14^\circ 22' 26'' = 0.247563 + 0.000685 = 0.24825$ .

The correction value (represented in this example by 0.000685) is *added* to the function of the *smaller* angle nearest the given angle in dealing with sines or tangents, but this correction value is *subtracted* in dealing with cosines or cotangents.

*Example 4:* Find the angle whose cosine is 0.27052.

The table of trigonometric functions shows that the desired angle is between  $74^\circ 10'$  and  $74^\circ 20'$  because the cosines of these angles are, respectively, 0.272840 and 0.270040. The difference  $= 0.272840 - 0.270040 = 0.00280'$ . From the cosine of the smaller angle (i.e., the larger cosine) or 0.272840, subtract the given cosine; thus,  $0.272840 - 0.27052 = 0.00232$ ; hence  $232/280 \times 10 = 8.28571'$  or the number of minutes to add to the smaller angle to obtain the required angle. Thus, the angle for a cosine of 0.27052 is  $74^\circ 18.28571'$ , or  $74^\circ 18' 17''$ . Angles corresponding to given sines, tangents, or cotangents may be determined by the same method.

**Trigonometric Functions of Angles Greater Than 90 Degrees.**—In obtuse triangles, one angle is greater than 90 degrees, and the Handbook tables can be used for finding the functions of angles larger than 90 degrees, but the angle must be first expressed in terms of an angle less than 90 degrees.

The sine of an angle greater than 90 degrees but less than 180 degrees equals the sine of an angle that is the difference between 180 degrees and the given angle.

*Example 5:* Find the sine of 118 degrees.

$\sin 118^\circ = \sin (180^\circ - 118^\circ) = \sin 62^\circ$ . By referring to [page 101](#), it will be seen that the sine given for 62 degrees is 0.882948.

The cosine, tangent, and cotangent of an angle greater than 90 but less than 180 degrees equals, respectively, the cosine, tangent, and cotangent of the difference between 180 degrees and the given angle; but the angular function has a negative value and must be preceded by a minus sign.

*Example 6:* Find  $\tan 123$  degrees, 20 minutes.

$$\tan 123^\circ 20' = -\tan (180^\circ - 123^\circ 20') = -\tan 56^\circ 40' = -1.520426$$



*Example 7:* Find  $\csc 150$  degrees.

Cosecant, abbreviated  $\csc$  or cosec, equals  $1/\sin$ , and is positive for angles 90 to 180 degrees (see Handbook [page 99](#))

$$\csc 15^\circ = 1/\sin(180^\circ - 150^\circ) = 1/\sin 30^\circ = 1/0.5 = 2.0$$

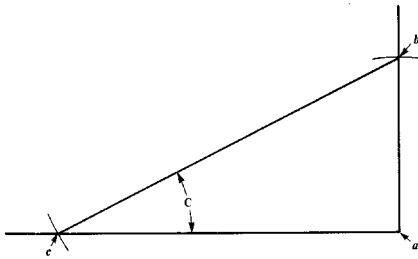
In the calculation of triangles, it is very important to include the minus sign in connection with the sines, cosines, tangents, and cotangents of angles greater than 90 degrees. The diagram, *Signs of Trigonometric Functions, Fractions of  $\pi$ , and Degree–Radian Conversion* on [page 98](#) of the Handbook, shows clearly the negative and positive values of different functions and angles between 0 and 360 degrees. The table, *Useful Relationships Among Angles* on [page 99](#), is also helpful in determining the function, sign, and angle less than 90 degrees that is equivalent to the function of an angle greater than 90 degrees.

**Use of Functions for Laying Out Angles.**—Trigonometric functions may be used for laying out angles accurately either on drawings or in connection with template work, etc. The following example illustrates the general method:

*Example 8:* Construct or lay out an angle of 27 degrees, 29 minutes by using its sine instead of a protractor.

First, draw two lines at right angles, as in [Fig. 2](#), and to any convenient length. Find, from a calculator, the sine of 27 degrees, 29 minutes, which equals 0.46149. If there is space enough, lay out the diagram to an enlarged scale to obtain greater accuracy. Assume that the scale is to be 10 to 1: therefore, multiply the sine of the angle by 10, obtaining 4.6149 or about  $4\frac{39}{64}$ . Set the dividers or the compass to this dimension and with  $a$  ([Fig. 2](#)) as a center, draw an arc, thus obtaining one side of the triangle  $ab$ . Now set the compass to 10 inches (since the scale is 10 to 1) and, with  $b$  as the center, describe an arc so as to obtain intersection  $c$ . The hypotenuse of the triangle is now drawn through the intersections  $c$  and  $b$ , thus obtaining an angle  $C$  of 27 degrees, 29 minutes within fairly close limits. The angle  $C$ , laid out in this way, equals 27 degrees, 29 minutes because:

$$\frac{\text{Side Opposite}}{\text{Hypotenuse}} = \frac{4.6149}{10} = 0.46149 = \sin 27^\circ 29'$$



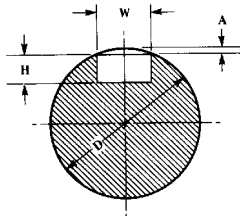
**Fig. 2. Method of Laying out Angle by Using Its Sine Tables of Functions Used in Conjunction with Formulas.—**

When milling keyways, it is often desirable to know the total depth from the outside of the shaft to the bottom of the keyway. With this depth known, the cutter can be fed down to the required depth without taking any measurements other than that indicated by the graduations on the machine. To determine the total depth, it is necessary to calculate the height of the arc, which is designated as dimension *A* in Fig. 3. The formula usually employed to determine *A* for a given diameter of shaft *D* and width of key *W* is as follows:

$$A = \frac{D}{2} - \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{W}{2}\right)^2}$$

Another formula, which is simpler than the one above, is used in conjunction with a calculator, as follows:

$$A = \frac{D}{2} \times \text{versed sine of an angle whose sine is } \frac{W}{D}$$



**Fig. 3. To Find Height *A* for Arc of Given Radius and Width *W***

*Example 9:* To illustrate the application of this formula, let it be required to find the height  $A$  when the shaft diameter is  $\frac{7}{8}$  inch and the width  $W$  of the key is  $\frac{7}{32}$  inch. Then,  $W/D = (\frac{7}{32})/(\frac{7}{8}) = \frac{7}{32} \times \frac{8}{7} = 0.25$ . Using the formula at the bottom of Handbook [page 103](#) for versed  $\sin \theta = 1 - \cos \theta$ , and a calculator, the angle corresponding to  $\sin 0.25 = 14.4775$  degrees, or 14 degrees, 28 minutes, 39 seconds. The cosine of this angle is 0.9682, and subtracting this value from 1 gives 0.03175 for the versed sine. Then, the height of the circular segment  $A = D/2 \times 0.03175 = (7 \times 0.03175)/(8 \times 2) = 0.01389$ , so the total depth of the keyway equals dimension  $H$  plus 0.01389 inch.

### PRACTICE EXERCISES FOR SECTION 8

(See *Answers to Practice Exercises For Section 8* on page 225)

- 1) How should a scientific pocket calculator be used to solve triangles?
- 2) Explain the meaning of  $\sin 30^\circ = 0.50000$ .
- 3) Find  $\sin 18^\circ 26' 30''$ ;  $\tan 27^\circ 16' 15''$ ;  $\cos 32^\circ 55' 17''$ .
- 4) Find the angles that correspond to the following tangents: 0.52035; 0.13025; to the following cosines: 0.06826; 0.66330.
- 5) Give two rules for finding the *side opposite* a given angle.
- 6) Give two rules for finding the *side adjacent* to a given angle.
- 7) Explain the following terms: equilateral; isosceles; acute angle; obtuse angle; oblique angle.
- 8) What is meant by complement; side adjacent; side opposite?
- 9) Can the elements referred to in Exercise 8 be used in solving an isosceles triangle?
- 10) Without referring to the Handbook, show the relationship between the six trigonometric functions and an acute angle, using the terms *side opposite*, *side adjacent*, and *hypotenuse* or abbreviations *SO*, *SA*, and *Hyp*.
- 11) Construct by use of tangents an angle of  $42^\circ 20'$ .
- 12) Construct by use of sines an angle of  $68^\circ 15'$ .
- 13) Construct by use of cosines an angle of  $55^\circ 5'$ .

## SECTION 9

### SOLUTION OF RIGHT-ANGLE TRIANGLES

HANDBOOK Page 91 to 92

A thorough knowledge of the solution of triangles or trigonometry is essential in drafting, layout work, bench work, and for convenient and rapid operation of some machine tools. Calculations concerning gears, screw threads, dovetails, angles, tapers, solution of polygons, gage design, cams, dies, and general inspection work are dependent upon trigonometry. Many geometrical problems may be solved more rapidly by trigonometry than by geometry.

In shop trigonometry, it is not necessary to develop and memorize the various rules and formulas, but it is essential that the six trigonometric functions be mastered thoroughly. It is well to remember that a thorough, working knowledge of trigonometry depends upon drill work; hence a large number of problems should be solved.

The various formulas for the solution of right-angle triangles are given on Handbook [page 91](#) and examples showing their application on [page 92](#). These formulas may, of course, be applied to a large variety of practical problems in drafting rooms, tool rooms, and machine shops, as indicated by the following examples.

Whenever two sides of a right-angle triangle are given, the third side can always be found by a simple arithmetical calculation, as shown by the second and third examples on Handbook [page 92](#). To find the angles, however, it is necessary to use tables of sines, cosines, tangents, and cotangents, or a calculator, and, if only one side and one of the acute angles are given, the natural trigonometric functions must be used for finding the lengths of the other sides.

*Example 1:* The Jarno taper is 0.600 inch per foot for all numbers. What is the included angle?

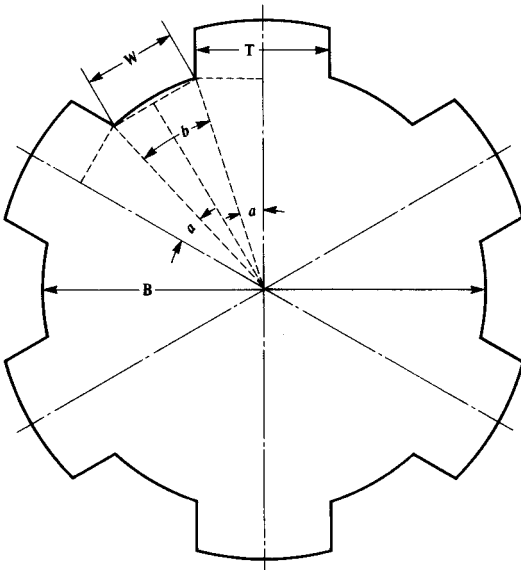
As the angle measured from the axis or center line is  $0.600 \div 2 = 0.300$  inch per foot, the tangent of one-half the included angle =  $0.300 \div 12 = 0.025 = \tan 1^\circ 26'$ ; hence the included angle =  $2^\circ 52'$ . A more direct method is to find the angle whose tangent equals the taper per foot divided by 24 as explained on Handbook [page 715](#).

*Example 2:* Determine the width  $W$  (see [Fig. 1](#)) of a cutter for milling a splined shaft having 6 splines 0.312 inch wide, and a diameter  $B$  of 1.060 inches.

This dimension  $W$  may be computed by using the following formula:

$$W = \sin \left( \frac{\frac{360^\circ}{N} - 2a}{2} \right) \times B$$

in which  $N$  = number of splines;  $B$  = diameter of body or of the shaft at the root of the spline groove.



**Fig. 1. To Find Width  $W$  of Spline-Groove Milling Cutter**

Angle  $a$  must first be computed, as follows:

$$\sin a = \frac{T}{2} \div \frac{B}{2} \quad \text{or} \quad \sin a = \frac{T}{B}$$

where  $T$  = width of spline;  $B$  = diameter at the root of the spline groove. In this example,

$$\sin a = \frac{0.312}{1.060} = 0.29434$$

$$a = 17^{\circ}7'; \text{ hence}$$

$$W = \left( \frac{\sin \frac{360^{\circ}}{6} - 2 \times 17^{\circ}7'}{2} \right) \times 1.060 = 0.236 \text{ inch}$$

This formula has also been used frequently in connection with broach design, but it is capable of a more general application. If the splines are to be ground on the sides, suitable deduction must be made from dimension  $W$  to leave sufficient stock for grinding.

If the angle  $b$  is known or is first determined, then

$$W = B \times \sin \frac{b}{2}$$

As there are 6 splines in this example, angle  $b = 60^{\circ} - 2a = 60^{\circ} - 34^{\circ}14' = 25^{\circ}46'$ ; hence,

$$W = 1.060 \times \sin 12^{\circ}53' = 1.060 \times 0.22297 = 0.236 \text{ inch}$$

*Example 3:* In sharpening the teeth of thread milling cutters, if the teeth have rake, it is necessary to position each tooth for the grinding operation so that the outside tip of the tooth is at a horizontal distance  $x$  from the vertical center line of the milling cutter as shown in **Fig. 2b**. What must this distance  $x$  be if the outside radius to the tooth tip is  $r$ , and the rake angle is to be  $A$ ? What distance  $x$  off center must a  $4\frac{1}{2}$ -inch diameter cutter be set if the teeth are to have a 3-degree rake angle?

In **Fig. 2a**, it will be seen that, assuming the tooth has been properly sharpened to rake angle  $A$ , if a line is drawn extending the front edge of the tooth, it will be at a perpendicular distance  $x$  from the center of the cutter. Let the cutter now be rotated until the tip of the tooth is at a horizontal distance  $x$  from the vertical center line

of the cutter as shown in Fig. 2b. It will be noted that an extension of the front edge of the cutter is still at perpendicular distance  $x$  from the center of the cutter, indicating that the cutter face is parallel to the vertical center line or is itself vertical, which is the desired position for sharpening using a vertical wheel. Thus,  $x$  is the proper offset distance for grinding the tooth to rake angle  $A$  if the radius to the tooth tip is  $r$ . Since  $r$  is the hypotenuse, and  $x$  is one side of a right-angled triangle,

$$x = r \sin A$$

For a cutter diameter of  $4\frac{1}{2}$  inches and a rake angle of 3 degrees,

$$\begin{aligned} x &= (4.5 \div 2) \sin 3^\circ = 2.25 \times 0.05234 \\ &= 0.118 \text{ inch} \end{aligned}$$

#### To Find Horizontal Distance for Positioning Milling Cutter Tooth for Grinding Rake Angle $A$

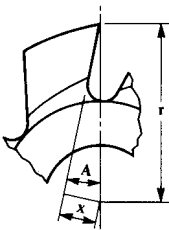


Fig. 2a.

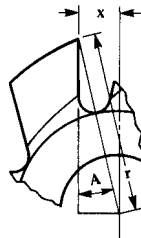


Fig. 2b.

*Example 4:* Forming tools are to be made for different sizes of poppet valve heads, and a general formula is required for finding angle  $x$  from dimensions given in Fig. 3.

The values for  $b$ ,  $h$ , and  $r$  can be determined easily from the given dimensions. Angle  $x$  can then be found in the following manner:

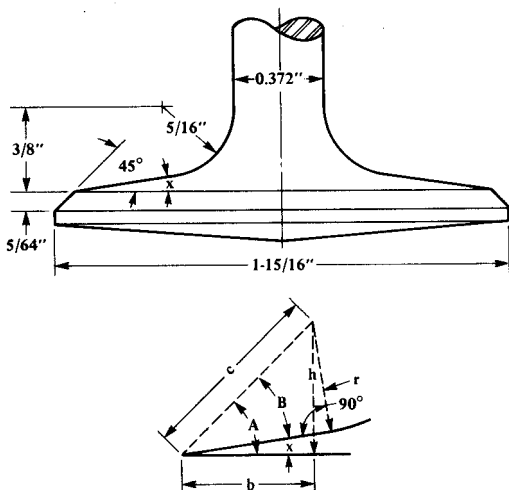
Referring to the lower diagram,

$$\tan A = \frac{h}{b} \quad (1)$$

$$c = \frac{h}{\sin A} \quad (2)$$

Also,

$$c = \frac{r}{\sin B} = \frac{r}{\sin(A - x)} \quad (3)$$



**Fig. 3. To Find Angle  $x$ , Having the Dimensions Given on the Upper Diagram**

From Equations (2) and (3) by comparison,

$$\frac{r}{\sin(A - x)} = \frac{h}{\sin A} \quad (4a)$$

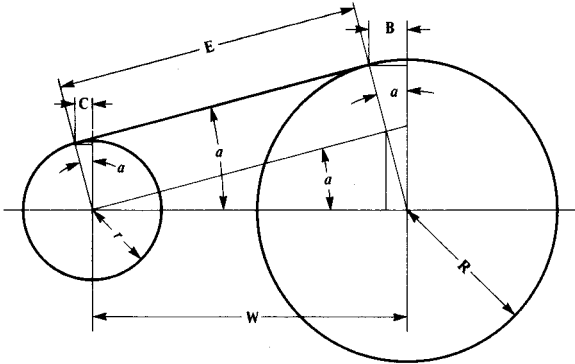
$$\sin(A - x) = \frac{r \sin A}{h} \quad (4b)$$

From the dimensions given, it is obvious that  $b = 0.392125$  inch,  $h = 0.375$  inch, and  $r = 0.3125$  inch. Substituting these values in Equation (1) and (4b) and solving, angle  $A$  will be found to be 43 degrees, 43 minutes and angle  $(A - x)$  to be 35 degrees, 10 minutes. By subtracting these two values, angle  $x$  will be found to equal 8 degrees, 33 minutes.

*Example 5:* In tool designing, it frequently becomes necessary to determine the length of a tangent to two circles. In Fig. 4,  $R =$



radius of large circle =  $1\frac{13}{16}$  inch;  $r$  = radius of small circle =  $\frac{3}{8}$  inch;  
 $W$  = center distance between circles =  $1\frac{11}{16}$  inches.



**Fig. 4. To Find Dimension E or Distance Between Points of Tangency**

With the values given, it is required to find the following:  $E$  = length of tangent,  $B$  = length of horizontal line from point of tangency on large circle to the vertical line, and  $C$  = length of horizontal line from point of tangency on small circle to the vertical center line.

$$\sin a = \frac{R-r}{W} = \frac{1\frac{13}{16} - \frac{3}{8}}{1\frac{11}{16}} = 0.25925$$

$$\text{Angle } a = 15^\circ 1' \text{ nearly}$$

$$E = W \cos a = 1\frac{11}{16} \times 0.9658 = 1.63 \text{ inches}$$

$$B = R \sin a \quad \text{and} \quad C = r \sin a$$

*Example 6:* A circle is inscribed in a right triangle having the dimensions shown in **Fig. 5**. Find the radius of the circle.

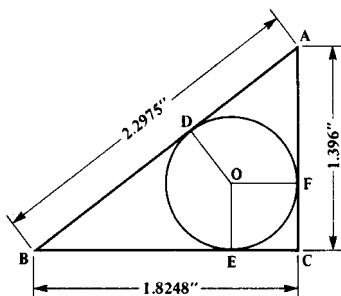
In **Fig. 5**,  $BD = BE$  and  $AD = AF$ , because “tangents drawn to a circle from the same point are equal.”  $EC = CF$ , and  $EC =$  radius  $OF$ . Then, let  $R =$  radius of inscribed circle.  $AC - R = AD$  and  $BC - R = DB$ . Adding,

$$AC + BC - 2R = AD + DB$$

$$AD + DB = AB$$

hence,

$$AC + BC - AB = 2R$$



**Fig. 5. To Find Radius of Circle Inscribed in Triangle**

Stated as a rule: *The diameter of a circle inscribed in a right triangle is equal to the difference between the lengths of the hypotenuse and the sum of the lengths of the other sides.* Substituting the given dimensions, we have  $1.396 + 1.8248 - 2.2975 = 0.9233 = 2R$ , and  $R = 0.4616$ .

*Example 7:* A part is to be machined to an angle  $b$  of 30 degrees (**Fig. 6**) by using a vertical forming tool having a clearance angle  $a$  of 10 degrees. Calculate the angle of the forming tool as measured in a plane  $Z-Z$ , which is perpendicular to the front or clearance surface of the tool.

Assume that  $B$  represents the angle in plane  $Z-Z$ .

$$\tan B = \frac{Y}{X} \text{ and } Y = y \times \cos a \tag{1}$$

Also,

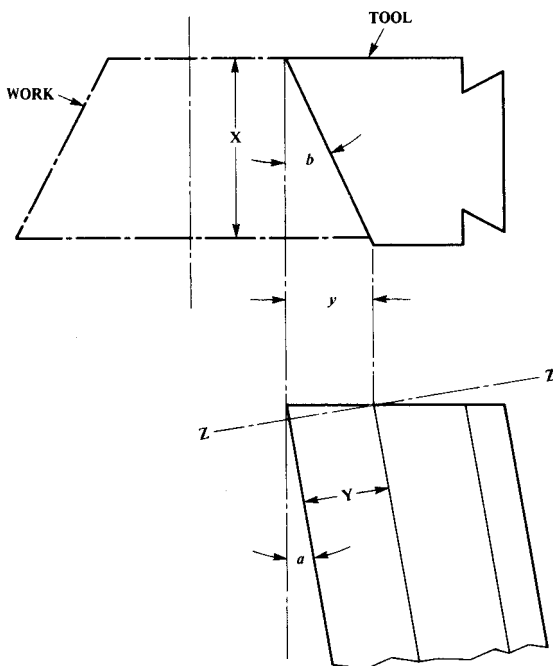
$$y = X \times \tan b \text{ and } X = \frac{y}{\tan b} \tag{2}$$

Now substituting the values of  $Y$  and  $X$  in **Equation (1)**, we have:

$$\tan B = \frac{y \times \cos a}{\frac{y}{\tan b}}$$

Clearing this equation of fractions,

$$\tan B = \cos a \times \tan b$$



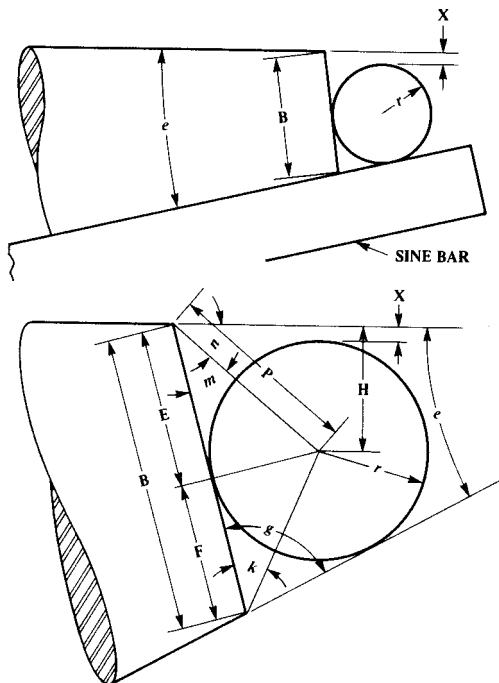
**Fig. 6. The Problem is to Determine Angle of Forming Tool in Plane Z-Z**

In this example,  $\tan B = 0.98481 \times 0.57735 = 0.56858$  ;  
hence,  $B = 29^{\circ}37'$  nearly.

*Example 8:* A method of checking the diameter at the small end of a taper plug gage is shown by **Fig. 7**. The gage is first mounted on a sine bar so that the top of the gage is parallel with the surface

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plate. A disk of known radius  $r$  is then placed in the corner formed by the end of the plug gage and the top side of the sine bar. Now by determining the difference  $X$  in height between the top of the gage and the top edge of the disk, the accuracy of the diameter  $B$  can be checked readily. Derive formulas for determining dimension  $X$ .



**Fig. 7. The Problem is to Determine Height  $X$  in Order to Check Diameter  $B$  of Taper Plug**

The known dimensions are:

$e$  = angle of taper

$r$  = radius of disk

$B$  = required diameter at end of plug gage

$g = 90 \text{ degrees} - \frac{1}{2}e$  and  $k = \frac{1}{2}g$

By trigonometry,

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$$F = \frac{r}{\tan k}; E = B - F; \text{ and } \tan m = \frac{r}{E}$$

Also

$$P = \frac{r}{\sin m}; n = g - m; \text{ and } H = P \sin n$$

Therefore,  $X = H - r$  or  $r - H$ , depending on whether or not the top edge of the disk is above or below the top of the plug gage. In **Fig. 7**, the top of the disk is below the top surface of the plug gage so that it is evident that  $X = H - r$ .

To illustrate the application of these formulas, assume that  $e = 6$  degrees,  $r = 1$  inch, and  $B = 2.400$  inches. The dimension  $X$  is then found as follows:

$$g = 90 - \frac{6}{2} = 87^\circ; \text{ and } k = 43^\circ 30'$$

By trigonometry,

$$F = \frac{1}{0.9896} = 1.0538"; E = 2.400 - 1.0538 = 1.3462 \text{ inches}$$

$$\tan m = \frac{1}{1.3462} = 0.74283 \text{ and } m = 36^\circ 36' 22''$$

$$P = \frac{1}{0.59631} = 1.6769"; n = 87^\circ - 36^\circ 36' 22'' = 50^\circ 23' 38''$$

and  $H = 1.6769 \times 0.77044 = 1.2920$  inches

Therefore,  $X = H - r = 1.2920 - 1 = 0.2920$  inch

The disk here is below the top surface of the plug gage; hence, the formula  $X = H - r$  was applied.

*Example 9:* In **Fig. 8**,  $a = 1\frac{1}{4}$  inches,  $h = 4$  inches, and angle  $A = 12$  degrees. Find dimension  $x$  and angle  $B$ .

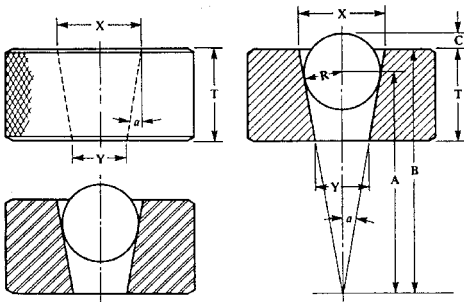
Draw an arc through points  $E$ ,  $F$ , and  $G$ , as shown, with  $r$  as a radius. According to a well-known theorem of geometry, which is given on Handbook **page 52**, if an angle at the circumference of a circle, between two chords, is subtended by the same arc as the angle at the center, between two radii, then the angle at the circumference is equal to one-half the angle at the center. This being true, angle  $C$  is twice the magnitude of angle  $A$ , and angle  $D = \text{angle } A = 12$  degrees. Thus,



*Example 10:* A steel ball is placed inside a taper gage as shown in **Fig. 9**. If the angle of the taper, length of taper, radius of ball, and its position in the gage are known, how can the end diameters  $X$  and  $Y$  of the gage be determined by measuring dimension  $C$ ?

The ball should be of such size as to project above the face of the gage. Although not necessary, this projection is preferable, as it permits the required measurements to be obtained more readily. After measuring the distance  $C$ , the calculation of dimension  $X$  is as follows: First obtain dimension  $A$ , which equals  $R$  multiplied by  $\csc a$ . Then adding  $R$  to  $A$  and subtracting  $C$  we obtain dimension  $B$ . Dimension  $X$  may then be obtained by multiplying  $2B$  by the tangent of angle  $a$ . The formulas for  $X$  and  $Y$  can therefore be written as follows:

$$\begin{aligned} X &= 2(R \csc a + R - C) \tan a \\ &= 2(R \sec a + 2 \tan a (R - C)) \\ Y &= X - 2T \tan a \end{aligned}$$



**Fig. 9. Checking Dimensions  $X$  and  $Y$  by Using One Ball of Given Size**

If, in **Fig. 9**, angle  $a = 9$  degrees,  $T = 1.250$  inches,  $C = 0.250$  inch and  $R = 0.500$  inch, what are the dimensions  $X$  and  $Y$ ? Applying the formula,

$$X = 2 \times 0.500 \times 1.0125 + 2 \times 0.15838(0.500 - 0.250)$$

By solving this equation,  $X = 1.0917$  inches. Then

$$Y = 1.0917 - (2.500 \times 0.15838) = 0.6957$$

*Example 11:* In designing a motion of the type shown in **Fig. 10**, it is essential, usually, to have link *E* swing equally above and below the center line *M-M*. A mathematical solution of this problem follows. In the illustration, *G* represents the machine frame; *F*, a lever shown in extreme positions; *E*, a link; and *D*, a slide. The distances *A* and *B* are fixed, and the problem is to obtain  $A + X$ , or the required length of the lever. In the right triangle:

$$A + X = \sqrt{(A - X)^2 + \left(\frac{B}{2}\right)^2}$$

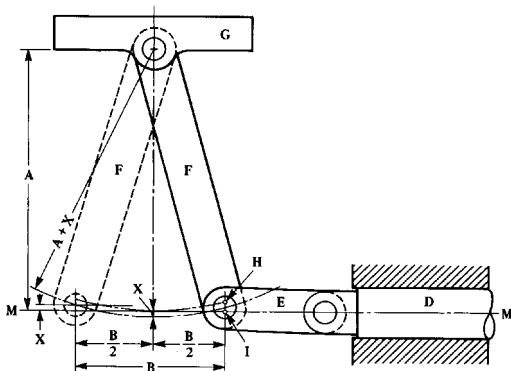
Squaring, we have:

$$A^2 + 2AX + X^2 = A^2 - 2AX + X^2 + \frac{B^2}{4}$$

$$4AX = \frac{B^2}{4}$$

$$X = \frac{B^2}{16A}$$

$$A + X = A + \frac{B^2}{16A} = \text{length of lever}$$



**Fig. 10. Determining Length *F* so that Link *E* will Swing Equally Above and Below the Center Line**

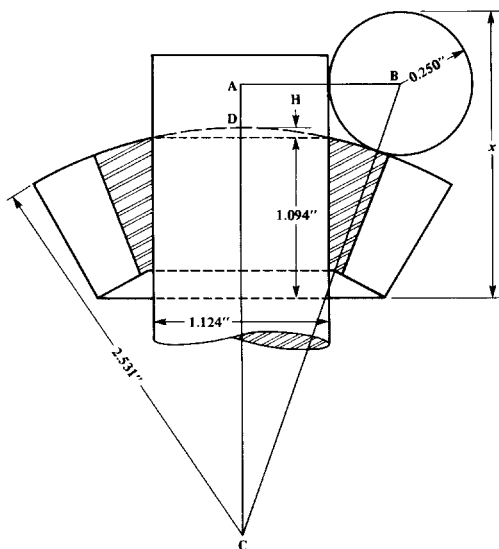


To illustrate the application of this formula, assume that the length of a lever is required when the distance  $A = 10$  inches, and the stroke  $B$  of the slide is 4 inches.

$$\begin{aligned} \text{Length of lever} &= A + \frac{B^2}{16A} = 10 + \frac{16}{16 \times 10} \\ &= 10.100 \text{ inches} \end{aligned}$$

Thus, it is evident that the pin in the lower end of the lever will be 0.100 inch below the center line  $M-M$  when half the stroke has been made, and, at each end of the stroke, the pin will be 0.100 inch above this center line.

*Example 12:* The spherical hubs of bevel gears are checked by measuring the distance  $x$  (Fig. 11) over a ball or plug placed against a plug gage that fits into the bore. Determine this distance  $x$ .



**Fig. 11. Method of Checking the Spherical Hub of a Bevel Gear with Plug Gages**

First find  $H$  by means of the formula for circular segments on Handbook page 62.

$$H = 2.531 - 1/2\sqrt{4 \times (2.531)^2 - (1.124)^2} = 0.0632 \text{ inch}$$

$$AB = \frac{1.124}{2} + 0.25 = 0.812 \text{ inch}$$

$$BC = 2.531 + 0.25 = 2.781 \text{ inches}$$

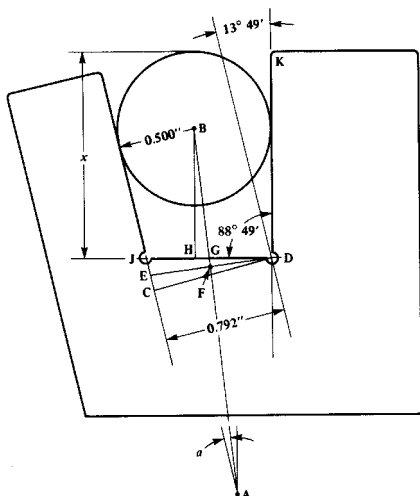
Applying one of the formulas for right triangles, on Handbook page 88,

$$AC = \sqrt{(2.781)^2 - (0.812)^2} = 2.6599 \text{ inches}$$

$$AD = AC - DC = 2.6599 - 2.531 = 0.1289 \text{ inch}$$

$$x = 1.094 + 0.0632 + 0.1289 + 0.25 = 1.536 \text{ inches}$$

*Example 13:* The accuracy of a gage is to be checked by placing a ball or plug between the gage jaws and measuring to the top of the ball or plug as shown by Fig. 12. Dimension  $x$  is required, and the known dimensions and angles are shown by the illustration.



**Fig. 12. Finding Dimension  $x$  to Check Accuracy of Gage**

One-half of the included angle between the gage jaws equals one-half of  $13^\circ \times 49'$  or  $6^\circ \times 54\frac{1}{2}'$ , and the latter equals angle  $a$ .

$$AB = \frac{0.500}{\sin 6^\circ 54\frac{1}{2}'} = 4.1569 \text{ inches}$$

$DE$  is perpendicular to  $AB$  and angle  $CDE =$  angle  $a$ ; hence,

$$DE = \frac{CD}{\cos 6^\circ 54\frac{1}{2}'} = \frac{0.792}{\cot 6^\circ 54\frac{1}{2}'} = 0.79779 \text{ inch}$$

$$AF = \frac{DE}{2} \times \cot 6^\circ 54\frac{1}{2}' = 3.2923 \text{ inches}$$

$$\text{Angle } CDK = 90^\circ + 13^\circ 49' = 103^\circ 49'$$

$$\text{Angle } CDJ = 103^\circ 49' - 88^\circ 49' = 15^\circ$$

$$\text{Angle } EDJ = 15^\circ - 6^\circ 54\frac{1}{2}' = 8^\circ 5\frac{1}{2}'$$

$$GF = \frac{DE}{2} \times \tan 8^\circ 5\frac{1}{2}' = 0.056711 \text{ inch}$$

$$\text{Angle } HBG = \text{angle } EDJ = 8^\circ 5\frac{1}{2}'$$

$$BG = AB - (GF + AF) = 0.807889 \text{ inch}$$

$$BH = BG \times \cos 8^\circ 5\frac{1}{2}' = 0.79984 \text{ inch}$$

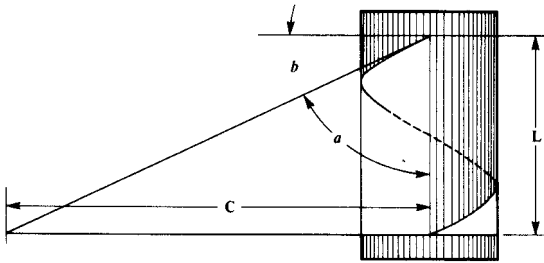
$$x = BH + 0.500 = 1.2998 \text{ inches}$$

If surface  $JD$  is parallel to the bottom surface of the gage, the distance between these surfaces might be added to  $x$  to make it possible to use a height gage from a surface plate.

### Helix Angles of Screw Threads, Hobs, and Helical Gears.—

The terms "helical" and "spiral" often are used interchangeably in drafting rooms and shops, although the two curves are entirely different. As the illustration on Handbook [page 58](#) shows, every point on a helix is equidistant from the axis, and the curve advances at a uniform rate around a cylindrical area. The helix is illustrated by the springs shown on Handbook [page 321](#). A spiral is flat like a clock spring. A spiral may be defined mathematically as a curve having a constantly increasing radius of curvature.

## RIGHT-ANGLE TRIANGLES



**Fig. 13. Helix Represented by a Triangular Piece of Paper Wound Upon a Cylinder**

If a piece of paper is cut in the form of a right triangle and wrapped around a cylinder, as indicated by the diagram (Fig. 13), the hypotenuse will form a helix. The curvature of a screw thread represents a helix. From the properties of a right triangle, simple formulas can be derived for determining helix angles. Thus, if the circumference of a part is divided by the lead or distance that the helix advances axially in one turn, the quotient equals the tangent of the helix angle as measured from the axis. The angles of helical curves usually (but not always) are measured from the axis. The helix angle of a helical or “spiral” gear is measured from the axis, but the helix angle of a screw thread is measured from a plane perpendicular to the axis. In a helical gear, the angle is  $a$  (Fig. 13), whereas for a screw thread, the angle is  $b$ ; hence, for helical gears,  $\tan a$  of helix angle =  $C/L$ ; for screw threads,  $\tan b$  of helix angle =  $L/C$ . The helix angle of a hob, such as is used for gear cutting, also is measured as indicated at  $b$  and often is known as the “end angle” because it is measured from the plane of the end surface of the hob. In calculating helix angles of helical gears, screw threads, and hobs, the pitch circumference is used.

*Example 14:* If the pitch diameter of a helical gear = 3.818 inches and the lead = 12 inches, what is the helix angle?

$\tan$  helix angle =  $(3.818 \times 3.1416)/12 = 1$  very nearly; hence the angle = 45 degrees.

## PRACTICE EXERCISES FOR SECTION 9

(See *Answers to Practice Exercises For Section 9* on page 226)

1) The No. 4 Morse taper is 0.6233 inch per foot; calculate the included angle.

2) ANSI Standard pipe threads have a taper of  $\frac{3}{4}$  inch per foot. What is the angle on each side of the center line?

3) To what dimension should the dividers be set to space 8 holes evenly on a circle of 6 inches diameter?

4) Explain the derivation of the formula

$$W = \sin\left(\frac{\frac{360^\circ}{N} - 2a}{2}\right) \times B$$

For notation, see **Example 2** on **page 59** and the diagram **Fig. 1**.

5) The top of a male dovetail is 4 inches wide. If the angle is degrees, and the depth is  $\frac{5}{8}$  inch, what is the width at the bottom of the dovetail?

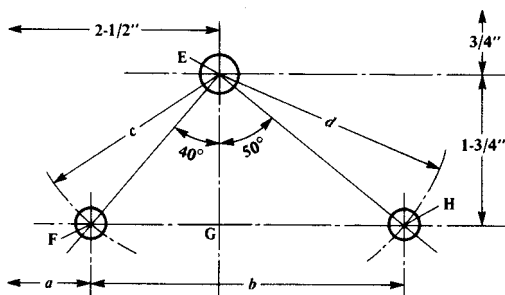
6) Angles may be laid out accurately by describing an arc with a radius of given length and then determining the length of a chord of this arc. In laying out an angle of 25 degrees, 20 minutes, using a radius of 8 inches, what should the length of the chord opposite the named angle be?

7) What is the largest square that may be milled on the end of a  $2\frac{1}{2}$ -inch bar of round stock?

8) A guy wire from a smoke stack is 120 feet long. How high is the stack if the wire is attached to feet from the top and makes an angle of 57 degrees with the stack?

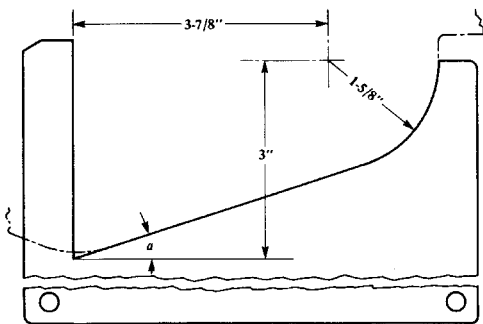
9) In laying out a master jig plate, it is required that holes *F* and *H*, **Fig. 14**, shall be on a straight line that is  $1\frac{3}{4}$  inch distant from hole *E*. The holes must also be on lines making, respectively, 40- and so-degree angles with line *EG*, drawn at right angles to the sides of the jig plate through *E*, as shown in the figure. Find the dimensions *a*, *b*, *c*, and *d*.

RIGHT-ANGLE TRIANGLES



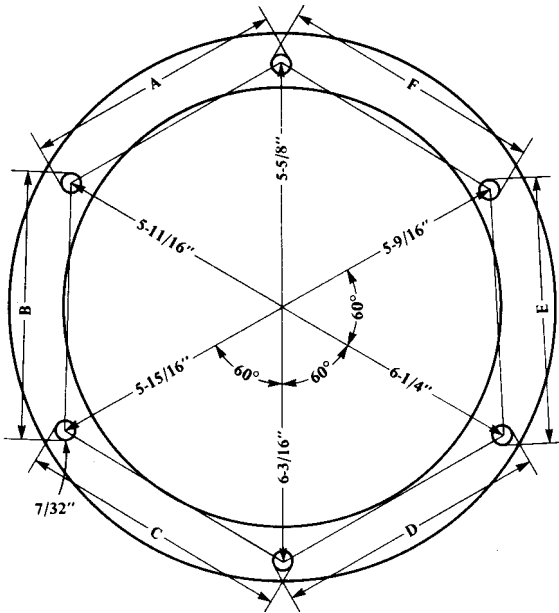
**Fig. 14. Find Dimensions a, b, c, and d**

10) Figure 15 shows a template for locating a pump body on a milling fixture, the inside contour of the template corresponding with the contour of the pump flange. Find the angle  $a$  from the values given.



**Fig. 15. To find Angle a Having the Dimensions Given**

11) Find the chordal distances as measured over plugs placed in holes located at different radii in the taximeter drive ring shown in Fig. 16. All holes are  $\frac{7}{32}$  inch diameter; the angle between the center line of each pair of holes is 60 degrees.



**Fig. 16. To Find the Chordal Distances of Irregularly Spaced Holes Drilled in a Taximeter Drive Ring**

12) An Acme screw thread has an outside diameter of  $1\frac{1}{4}$  inches and has 6 threads per inch. Find the helix angle using the pitch diameter as a base. Find, also, the helix angle if a double thread is cut on the screw.

13) What is the lead of the flutes in a  $\frac{7}{8}$ -inch drill if the helix angle, measured from the center line of the drill, is  $27^\circ 30'$ ?

14) A 4-inch diameter milling cutter has a lead of 68.57 inches. What is the helix angle measured from the axis?

## SECTION 10

### SOLUTION OF OBLIQUE TRIANGLES

HANDBOOK Pages 94–95

In solving problems for dimensions or angles, it is often convenient to work with oblique triangles. In an oblique triangle, none of the angles is a right angle. One of the angles may be over 90 degrees, or each of the three angles may be less than 90 degrees. Any oblique triangle may be solved by constructing perpendiculars to the sides from appropriate vertices, thus forming right triangles. The methods, previously explained, for solving right triangles, will then solve the oblique triangles. The objection to this method of solving oblique triangles is that it is a long, tedious process.

Two of the examples in the Handbook on [page 94](#), which are solved by the formulas for oblique triangles, will be solved by the right-angle triangle method. These triangles have been solved to show that all oblique triangles can be solved thus and to give an opportunity to compare the two methods. There are four classes of oblique triangles:

- 1) Given one side and two angles
- 2) Given two sides and the included angle
- 3) Given two sides and the angle opposite one of them
- 4) Given the three sides

*Example 1:* Solve the first example on Handbook [page 94](#) by the right-angle triangle method. By referring to the accompanying [Fig. 1](#):

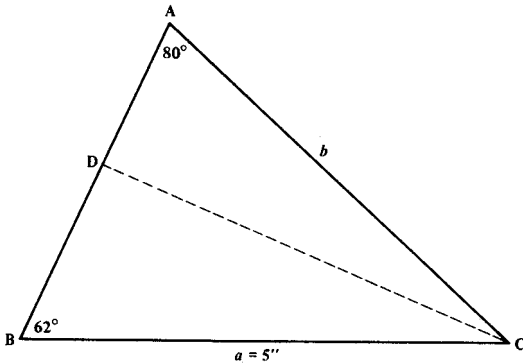
$$\text{Angle } C = 180^\circ - (62^\circ + 80^\circ) = 38^\circ$$

Draw a line  $DC$  perpendicular to  $AB$ .

In the right triangle  $BDC$ ,  $DC/BC = \sin 62^\circ$ .

$$\frac{DC}{5} = 0.88295; DC = 5 \times 0.88295 = 4.41475$$





**Fig. 1. Oblique Triangle Solved by Right-Angle Triangle Method**

Angle  $BCD = 90^\circ - 62^\circ = 28^\circ$ ;  $DCA = 38^\circ - 28^\circ = 10^\circ$

$$\frac{BD}{5} = \cos 62^\circ; BD = 5 \times 0.46947 = 2.34735$$

In triangle  $ADC$ ,  $AC/DC = \sec 10^\circ$ .

$$AC = 4.41475 \times 1.0154 = 4.4827$$

$$\frac{AD}{4.41475} = \tan 10^\circ; AD = 4.41475 \times 0.17633 = 0.7785$$

$$\text{and } AB = AD + BD = 0.7785 + 2.34735 = 3.1258$$

$$C = 38^\circ; b = 4.4827; c = 3.1258$$

*Example 2:* Apply the right-angle triangle method to the solution of the second example on Handbook [page 94](#).

Referring to [Fig. 2](#), draw a line  $BD$  perpendicular to  $CA$ .

In the right triangle  $BDC$ ,  $BD/9 = \sin 35^\circ$ .

$$BD = 9 \times 0.57358 = 5.16222$$

$$\frac{CD}{9} = \cos 35^\circ; CD = 9 \times 0.81915 = 7.37235$$

$$DA = 8 - 7.37235 = 0.62765$$

$$\text{In the right triangle } BDA, \frac{BD}{DA} = \frac{5.16222}{0.62765} = \tan A .$$

$$\tan A = 8.2246 \text{ and } A = 83^\circ 4'$$

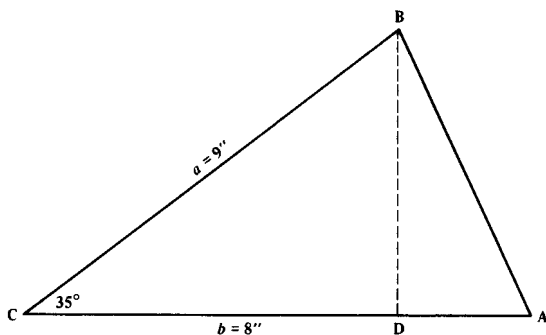
$$B = 180^\circ - (83^\circ 4' + 35^\circ) = 61^\circ 56'$$

$$\frac{BA}{BD} = \frac{BA}{5.1622} = \csc 83^\circ 4'; \quad BA = 5.1622 \times 1.0074 = 5.2004$$

$$BA = 5.1622 \times 1.0074 = 5.2004$$

$$A = 83^\circ 4'; B = 61^\circ 56'; C = 35^\circ$$

$$a = 9; b = 8; c = 5.2004$$



**Fig. 2. Another Example of the Right-Angle Triangle Solution of an Oblique Triangle Equation**

**Use of Formulas for Oblique Triangles.**—Oblique triangles are not encountered as frequently as right triangles, and, therefore, the methods of solving the latter may be fresh in the memory whereas methods for solving the former may be forgotten. All the formulas involved in the solution of the four classes of oblique triangles are derived from: (1) the law of sines; (2) the law of cosines; and (3) the sum of angles of a triangle equal  $180^\circ$ .

The law of sines is that, in any triangle, the lengths of the sides are proportional to the sines of the opposite angles. (See diagrams on Handbook [page 94](#).)

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C} \tag{1}$$

Solving this equation, we get:

## OBLIQUE TRIANGLES

$$\frac{a}{\sin A} = \frac{b}{\sin B}; \text{ then } a \times \sin B = b \times \sin A \text{ and}$$

$$a = \frac{b \times \sin A}{\sin B}; \sin B = \frac{b \times \sin A}{a}$$

$$b = \frac{a \times \sin B}{\sin A}; \sin A = \frac{a \times \sin B}{b}$$

$$\text{In like manner, } \frac{a}{\sin A} = \frac{c}{\sin C} \text{ and}$$

$$a \times \sin C = c \times \sin A; \text{ hence } \sin A = \frac{a \times \sin C}{c}$$

$$\text{and } \frac{b}{\sin B} = \frac{c}{\sin C} \text{ or } b \times \sin C = c \times \sin B$$

Thus, twelve formulas may be derived. As a general rule, only **Formula (1)** is remembered, and special formulas are derived from it as required.

The law of cosines states that, in any triangle, the square of any side equals the sum of the squares of the other two sides minus twice their product multiplied by the cosine of the angle between them. These relations are stated as formulas thus:

$$a^2 = b^2 + c^2 - 2bc \times \cos A \quad \text{or} \tag{1}$$

$$a = \sqrt{b^2 + c^2 - 2bc \times \cos A}$$

$$b^2 = a^2 + c^2 - 2ac \times \cos B \quad \text{or} \tag{2}$$

$$b = \sqrt{a^2 + c^2 - 2ac \times \cos B}$$

$$c^2 = a^2 + b^2 - 2ab \times \cos C \quad \text{or} \tag{3}$$

$$c = \sqrt{a^2 + b^2 - 2ab \times \cos C}$$

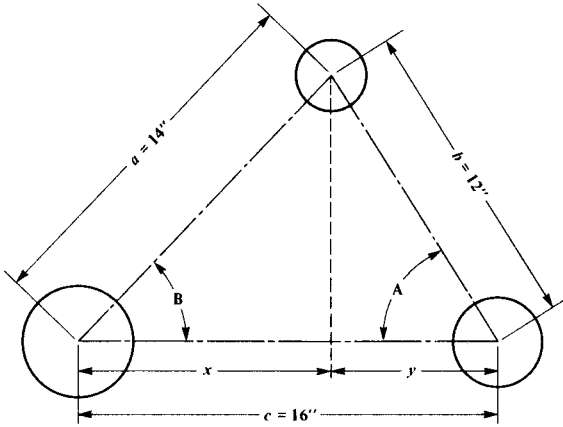
By solving **(1)**,  $a^2 = b^2 + c^2 - 2bc \times \cos A$  for  $\cos A$ ,

$$2bc \times \cos A = b^2 + c^2 - a^2 \quad (\text{transposing})$$

OBLIQUE TRIANGLES

$$\cos A = \frac{b^2 + c^2 - a^2}{2bc}$$

In like manner, formulas for  $\cos B$  and  $\cos C$  may be found.



**Fig. 3. Diagram Illustrating Example 3**

*Example 3:* A problem quite often encountered in layout work is illustrated in **Fig. 3**. It is required to find the dimensions  $x$  and  $y$  between the holes, these dimensions being measured from the intersection of the perpendicular line with the center line of the two lower holes. The three center-to-center distances are the only known values.

The method that might first suggest itself is to find the angle  $A$  (or  $B$ ) by some such formulas as:

$$\cos A = \frac{b^2 + c^2 - a^2}{2bc}$$

and then solve the right triangle for  $y$  by the formula

$$y = b \cos A$$

**Formulas (1)** and **(2)** can be combined as follows:

$$y = \frac{b^2 + c^2 - a^2}{2c}$$

The value of  $x$  can be determined in a similar manner.

The second solution of this problem involves the following geometrical proposition: In any oblique triangle where the three sides are known, the ratio of the length of the base to the sum of the other two sides equals the ratio of the difference between the length of the two sides to the difference between the lengths  $x$  and  $y$ . Therefore, if  $a = 14$ ,  $b = 12$ , and  $c = 16$  inches, then

$$c:(a+b) = (a-b):(x-y)$$

$$16:26 = 2:(x-y)$$

$$(x-y) = \frac{26 \times 2}{16} = 3\frac{1}{4} \text{ inches}$$

$$x = \frac{(x+y) + (x-y)}{2} = \frac{16 + 3\frac{1}{4}}{2} = 9.625 \text{ inches}$$

$$y = \frac{(x+y) - (x-y)}{2} = \frac{16 - 3\frac{1}{4}}{2} = 6.375 \text{ inches}$$

**When Angles Have Negative Values.**—In the solution of oblique triangles having one angle larger than 90 degrees, it is sometimes necessary to use angles whose functions are negative. (Review Handbook [pages 4](#) and [99](#).) Notice that for angles between 90 degrees and 180 degrees, the cosine, tangent, cotangent, and secant are negative.

*Example 4:* By referring to [Fig. 4](#), two sides and the angle between them are shown. Find angles  $A$  and  $B$ . (See Handbook [page 94](#).)

$$\tan A = \frac{4 \times \sin 20^\circ}{3 - 4 \times \cos 20^\circ} = \frac{4 \times 0.34202}{3 - 4 \times 0.93969} = \frac{1.36808}{3 - 3.75876}$$

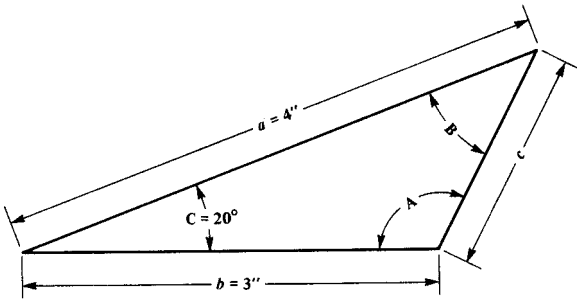
It will be seen that in the denominator of the fraction above, the number to be subtracted from 3 is greater than 3; the numbers are therefore reversed, 3 being subtracted from 3.75876, the remainder then being negative. Hence:

$$\tan A = \frac{1.36808}{3 - 3.75876} = \frac{1.36808}{-0.75876} = -1.80305$$

The final result is negative because a positive number (1.36808) is divided by a negative number (-0.75876). The tangents of

angles greater than 90 degrees and smaller than 180 degrees are negative. To illustrate an angle whose tangent is negative, enter the value  $-1.80305$  in the calculator and find the corresponding angle, which  $-60.986558$  degrees, or  $-60$  degrees,  $59$  minutes,  $59$  seconds. Because the tangent is negative, angle  $A$  must be subtracted from  $180$  degrees, giving  $119.01344$  degrees, or  $119$  degrees,  $0$  minutes,  $49$  seconds as the angle. Now angle  $B$  is found from the formula,

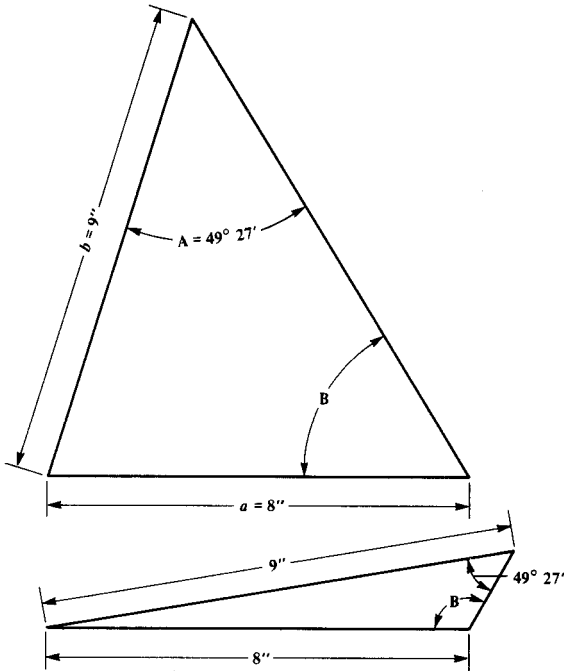
$$\begin{aligned} B &= 180^\circ - (A + C) = 180^\circ - (119^\circ 0' 11'' + 20^\circ) \\ &= 180^\circ - 139^\circ 0' 11'' = 40^\circ 59' 49'' \end{aligned}$$



**Fig. 4. Finding Angles  $A$  and  $B$  from the Dimensions Given**

**When Either of Two Triangles Conforms to the Given Dimensions.**—When two sides and the angle opposite one of the given sides are known, *if the side opposite the given angle is shorter than the other given side*, two triangles can be drawn, having sides of the required length (as shown by **Fig. 5**) and the required angle opposite one of the sides. The lengths of the two known sides of each triangle are  $8$  and  $9$  inches, and the angle opposite the  $8$ -inch side is  $49$  degrees,  $27$  minutes in each triangle; but it will be seen that the angle  $B$  of the lower triangle is very much larger than the corresponding angle of the upper triangle, and there is a great difference in the area. When two sides and one of the opposite angles are given, the problem is capable of two solutions when (and only when) the side opposite the given angle is shorter than the other given side. When the triangle to be calculated is drawn to scale, it

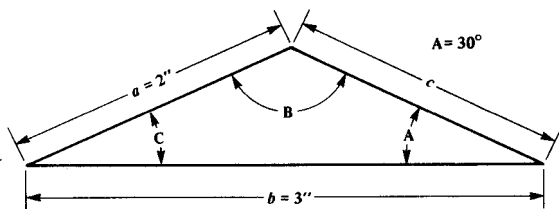
is possible to determine from the shape of the triangle which of the two solutions applies.



**Fig. 5. Diagrams Showing Two Possible Solutions of the Same Problem, Which Is to Find Angle  $B$**

*Example 5:* Find angle  $B$ , **Fig. 5**, from the formula,  $\sin B = (b \times \sin A)/a$ , where  $b = 9$  inches;  $A = 49$  degrees, 27 minutes;  $a$  is the side opposite angle  $A = 8$  inches.

$\sin B = 9 \times 0.75984/8 = 0.85482 = \sin 58^\circ 44' 34''$  or  $\sin B = 121^\circ 15' 36''$ . The practical requirements of the problem doubtless will indicate which of the two triangles shown in **Fig. 5** is the correct one.



**Fig. 6. Another Example that Has Two Possible Solutions**

*Example 6:* In **Fig. 6**,  $a = 2$  inches,  $b = 3$  inches, and  $A = 30$  degrees. Find  $B$ .

$$\sin B = \frac{b \times \sin A}{a} = \frac{\sin 30^\circ}{2} = 0.75000$$

We find from the calculator that sine 0.75000 is the sine of  $48^\circ 35'$ . From **Fig. 6** it is apparent, however, that  $B$  is greater than 90 degrees, and as 0.75000 is the sine not only of  $48^\circ 35'$ , but also of  $180^\circ - 48^\circ 35' = 131^\circ 25'$ , angle  $B$  in this triangle equals  $131^\circ 25'$ .

This example illustrates how the practical requirements of the problem indicate which of two angles is correct.

### PRACTICE EXERCISES FOR SECTION 10

(See *Answers to Practice Exercises For Section 10* on page 227)

1) Three holes in a jig are located as follows:

Hole No. 1 is 3.375 inches from hole No. 2 and 5.625 inches from hole No. 3; the distance between No. 2 and No. 3 is 6.250 inches. What three angles between the center lines are thus formed?

2) In **Fig. 7** is shown a triangle one side of which is 6.5 feet, and the two angles  $A$  and  $C$  are 78 and 73 degrees, respectively. Find angle  $B$ , sides  $b$  and  $c$ , and the area.

3) In **Fig. 8**, side  $a$  equals 3.2 inches, angle  $A$ , 118 degrees, and angle  $B$ , 40 degrees. Find angle  $C$ , sides  $b$  and  $c$ , and the area.

4) In **Fig. 9**, side  $b = 0.3$  foot, angle  $B = 35^\circ 40'$ , and angle  $C = 24^\circ 10'$ . Find angle  $A$ , sides  $a$  and  $c$ , and the area.

5) Give two general rules for finding the areas of triangles.



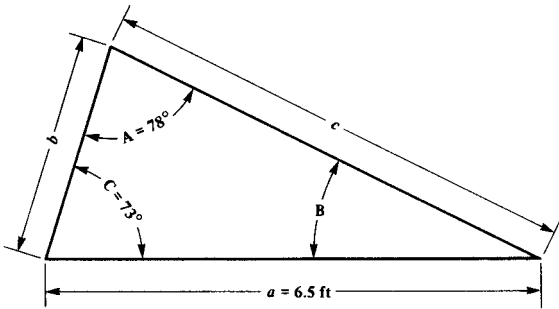


Fig. 7. Example for Practice Exercise No. 2

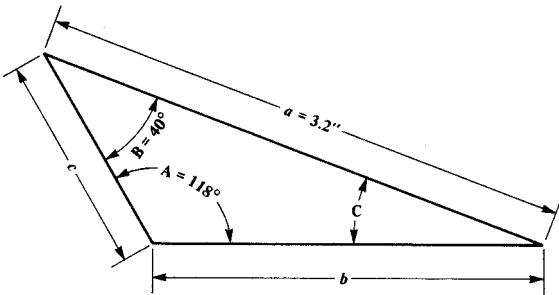


Fig. 8. Example for Practice Exercise No. 3

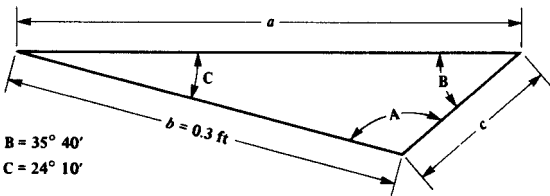


Fig. 9. Example for Practice Exercise No. 4

## SECTION 11

### FIGURING TAPERS

HANDBOOK Pages **698 – 716**

The term “taper,” as applied in shops and drafting rooms, means the difference between the large and small dimensions where the increase in size is uniform. Since tapering parts generally are conical, taper means the difference between the large and small diameters. Taper is ordinarily expressed as a certain number of inches per foot; thus,  $\frac{1}{2}$ " per ft;  $\frac{3}{4}$ " per ft; etc. In certain kinds of work, taper is also expressed as a decimal part of an inch per inch, as: 0.050" per inch. The length of the work is always measured parallel to the center line (axis) of the work, and never along the tapered surface.

Suppose that the diameter at one end of a tapering part is 1 inch, and the diameter at the other end, 1.5 inches, and that the length of the part is 1 foot. This piece, then, tapers  $\frac{1}{2}$  inch per foot, because the difference between the diameters at the ends is  $\frac{1}{2}$  inch. If the diameters at the ends of a part are  $\frac{7}{16}$  inch and  $\frac{1}{2}$  inch, and the length is 1 inch, this piece tapers  $\frac{1}{16}$  inch per inch. The usual problems met when figuring tapers may be divided into seven classes. The rule to be used is found on Handbook **page 715**.

*Example 1:* The diameter at the large end of a part is  $2\frac{5}{8}$  inches, the diameter at the small end,  $2\frac{3}{16}$  inches, and the length of the work, 7 inches. Find the taper per foot.

By referring to the third rule on Handbook **page 715**,

$$\text{Taper per foot} = \frac{2\frac{5}{8} - 2\frac{3}{16}}{7} \times 12 = \frac{3}{4} \text{ inch}$$

*Example 2:* The diameter at the large end of a tapering part is  $1\frac{5}{8}$  inches, the length is  $3\frac{1}{2}$  inches, and the taper is  $\frac{3}{4}$  inch per foot. The problem is to find the diameter at the small end.

By applying the fourth rule on Handbook [page 715](#),

$$\text{Diameter at small end} = 1\frac{5}{8} - \left(\frac{3}{4} \times 3\frac{1}{2}\right) = 1\frac{13}{32}$$

*Example 3:* What is the length of the taper if the two end diameter are 2.875 inches and 2.542 inches, the taper being 1 inch per foot?

By applying the sixth rule on Handbook [page 715](#),

$$\begin{aligned} \text{Distance between the two diameters} &= \frac{2.875 - 2.542}{1} \times 12 \\ &= 4 \text{ inches nearly} \end{aligned}$$

*Example 4:* If the length of the taper is 10 inches, and the taper is  $\frac{3}{4}$  inch per foot, what is the taper in the given length?

By applying the last rule on Handbook [page 715](#),

$$\text{Taper in given length} = \frac{3}{4} \times 10 = 0.625 \text{ inch}$$

*Example 5:* The small diameter is 1.636 inches, the length of the work is 5 inches, and the taper is  $\frac{1}{4}$  inch per foot; what is the large diameter?

By referring to the fifth rule on Handbook [page 715](#),

*Example 6:* Sketch A, [Fig. 1](#), shows a part used as a clamp bolt. The diameter,  $3\frac{1}{4}$  inches, is given 3 inches from the large end of the taper. The total length of the taper is 10 inches. The taper is  $\frac{3}{8}$  inch per foot. Find the diameter at the large and small ends of the taper.

First find the diameter of the large and using the fifth rule on Handbook [page 715](#).

$$\text{Diameter at large end} = \left(\frac{3}{8} \times 3\right) + 3\frac{1}{4} = 3\frac{11}{32} \text{ inches}$$

To find the diameter at the small end, use the fourth rule on Handbook [page 715](#).

FIGURING TAPERS

$$\text{Diameter at small end} = 3\frac{11}{32} - \left(\frac{3}{8} \times 10\right) = 3\frac{1}{32} \text{ inches}$$

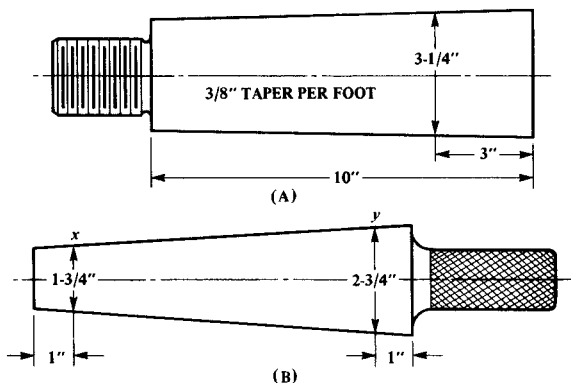


Fig. 1. Illustrations for Examples 6 and 7

*Example 7:* At B, Fig. 1, is shown a taper master gage intended for inspecting taper ring gages of various dimensions. The smallest diameter of the smallest ring gage is  $1\frac{3}{4}$  inches, and the largest diameter of the largest ring gage is  $2\frac{3}{4}$  inches. The taper is  $1\frac{1}{2}$  inches per foot. It is required that the master gage extend 1 inch outside of the ring gages at both the small and the large ends, when these ring gages are tested. How long should the taper be on the master gage?

The sixth rule on Handbook page 715 may be applied here.

$$\begin{aligned} \text{Distance between the two diameters} &= \frac{2\frac{3}{4} - 1\frac{3}{4}}{1\frac{1}{2}} \times 12 \\ &= 8 \text{ inches} \end{aligned}$$

$$\text{Total length of taper} = 8 + 2 = 10 \text{ inches}$$

**Table for Converting Taper per Foot to Degrees.**— Some types of machines, such as milling machines, are graduated in degrees, making it necessary to convert the taper per foot to the corresponding angle in degrees. This conversion is quickly done by means of the table, Handbook page 715.

*Example 8:* If a taper of  $1\frac{1}{2}$  inches per foot is to be milled on a piece of work, at what angle must the machine table be set if the taper is measured from the axis of the work?

By referring to the table on Handbook [page 715](#), the angle corresponding to a taper of  $1\frac{1}{2}$  inches to the foot is  $3^{\circ} 34' 35''$  as measured from the center line.

Note that the taper per foot varies directly as *the tangent of one-half the included angle*. Two mistakes frequently made in figuring tapers are assuming that the taper per foot varies directly as the included angle or that it varies directly as the tangent of the included angle. In order to verify this point, refer to the table on Handbook [page 714](#), where it will be seen that the included angle for a taper of 4 inches per foot ( $18^{\circ} 55' 29''$ ) is not twice the included angle for a taper of 2 inches per foot ( $9^{\circ} 31' 38''$ ). Neither is the tangent of  $18^{\circ} 55' 29''$  (0.3428587) twice the tangent of  $9^{\circ} 31' 38''$  (0.1678311).

**Tapers for Machine Tool Spindles.**—The holes in machine tool spindles, for receiving tool shanks, arbors, and centers, are tapered to ensure a tight grip, accuracy of location, and to facilitate removal of arbors, cutters, etc. The most common tapers are the Morse, the Brown & Sharpe, and the Jarno. The Morse has been very generally adopted for drilling machine spindles. Most engine lathe spindles also have the Morse taper, but some lathes have the Jarno or a modification of it, and others, a modified Morse taper, which is longer than the standard. A standard milling machine spindle was adopted in 1927 by the milling machine manufacturers of the National Machine Tool Builders' Association. A comparatively steep taper of  $3\frac{1}{2}$  inches per foot was adopted in connection with this standard spindle to ensure instant release of arbors. Prior to the adoption of the standard spindle, the Brown & Sharpe taper was used for practically all milling machines and is also the taper for dividing-head spindles. There is considerable variation in grinding machine spindles. The Brown & Sharpe taper is the most common, but the Morse and the Jarno have also been used. Tapers of  $\frac{5}{8}$  inch per foot and  $\frac{3}{4}$  inch per foot also have been used to some extent on miscellaneous classes of machines requiring a taper hole in the spindle.

## PRACTICE EXERCISES FOR SECTION 11

(See *Answers to Practice Exercises For Section 11* on page 227)

1) What tapers, per foot, are used with the following tapers: a) Morse taper; b) Jarno taper; c) milling machine spindle; d) and taper pin?

2) What is the taper per foot on a part if the included angle is  $10^{\circ} 30'$ ;  $55^{\circ} 45'$ ?

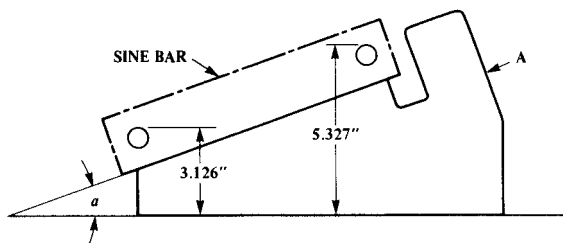
3) In setting up a taper gage like that shown on Handbook [page 713](#), what should be the center distance between 1.75-inch and 2-inch disks to check either the taper per foot or angle of a No. 4 Morse taper?

4) If it is required to check an angle of  $14\frac{1}{2}^{\circ}$ , using two disks in contact, and the smaller disk is 1-inch diameter, what should the diameter of the larger disk be?

5) What should be the center distance, using disks of 2-inch and 3-inch diameter, to check an angle of  $18^{\circ} 30'$  if the taper is measured from one side?

6) In grinding a reamer shank to fit a standard No. 2 Morse taper gage, it was found that the reamer stopped  $\frac{3}{8}$  inch short of going into the gage to the gage mark. How much should be ground off the diameter?

7) A milling machine arbor has a shank  $6\frac{1}{2}$  inches long with a No. 10 B. & S. taper. What is the total taper in this length?



**Fig. 2. Finding Angle  $a$  by Means of a Sine Bar and Handbook Instructions**

FIGURING TAPERS

8) A taper bushing for a grinding machine has a small inside diameter of  $\frac{7}{8}$  inch. It is 3 inches long with  $\frac{1}{2}$ -inch taper per foot. Find the large inside diameter.

9) If a 5-inch sine bar is used for finding the angle of the tapering bloc A (**Fig. 2**), and the heights of the sine-bar plug are as shown, find the corresponding angle  $a$  by means of the instructions beginning on Handbook **page 696**.

## SECTION 12

### TOLERANCES AND ALLOWANCES FOR MACHINE PARTS

HANDBOOK Pages **645 – 690**

In manufacturing machine parts according to modern methods, certain maximum and minimum dimensions are established, particularly for the more important members of whatever machine or mechanism is to be constructed. These limiting dimensions serve two purposes: they prevent both unnecessary accuracy and excessive inaccuracies. A certain degree of accuracy is essential to the proper functioning of the assembled parts of a mechanism, but it is useless and wasteful to make parts more precise than needed to meet practical requirements. Hence, the use of proper limiting dimensions promotes efficiency in manufacturing and ensures standards of accuracy and quality that are consistent with the functions of the different parts of a mechanical device.

Parts made to specified limits usually are considered interchangeable or capable of use without selection, but there are several degrees of interchangeability in machinery manufacture. Strictly speaking, interchangeability consists of making the different parts of a mechanism so uniform in size and contour that each part of a certain model will fit any mating part of the same model, regardless of the lot to which it belongs or when it was made. However, as often defined, interchangeability consists in making each part fit any mating part in a certain series; that is, the interchangeability exists only in the same series. Selective assembly is sometimes termed interchangeability, but it involves a selection or sorting of parts as explained later. It will be noted that the strict definition of interchangeability does not imply that the parts must always be assembled without handwork, although that is usually considered desirable. It does mean, however, that when whatever process finishes the mating parts, they must assemble and function properly without fitting individual parts one to the other.



When a machine having interchangeable parts has been installed, possibly at some distant point, a broken part can readily be replaced by a new one sent by the manufacturer, but this feature is secondary as compared with the increased efficiency in manufacturing on an interchangeable basis. To make parts interchangeable, it is necessary to use gages and measuring tools, to provide some system of inspection, and to adopt suitable tolerances. Whether absolute interchangeability is practicable or not may depend upon the tolerances adopted the relation between the different parts, and their form.

**Meanings of the Terms “Limit”, “Tolerance”, and “Allowance”.**—The terms “limit” and “tolerance” and “allowance” are often used interchangeably, but each of these three terms has a distinct meaning and refers to different dimensions. As shown by **Fig. 1**, the *limits* of a hole or shaft are its diameters. *Tolerance* is the difference between two *limits* and limiting dimensions of a given part, and the term means that a certain amount of error is tolerated for practical reasons. *Allowance* is the difference between limiting dimensions on mating parts that are to be assembled either loosely or tightly, depending upon the amount allowed for the fit.

*Example 1:* Limits and fits for cylindrical parts are given starting on **page 651** in the Handbook. These data provide a series of standard types and classes of fits. From the table on **page 658**, establish limits of size and clearance for a 2-inch diameter hole and shaft for a class RC-1 fit (whole H5, shaft g4).

$$\text{Max. hole} = 2 + 0.0005 = 2.0005$$

$$\text{Min. hole} = 2 - 0 = 2$$

$$\text{Max. shaft} = 2 - 0.0004 = 1.9996$$

$$\text{Min. shaft} = 2 - 0.0007 = 1.9993$$

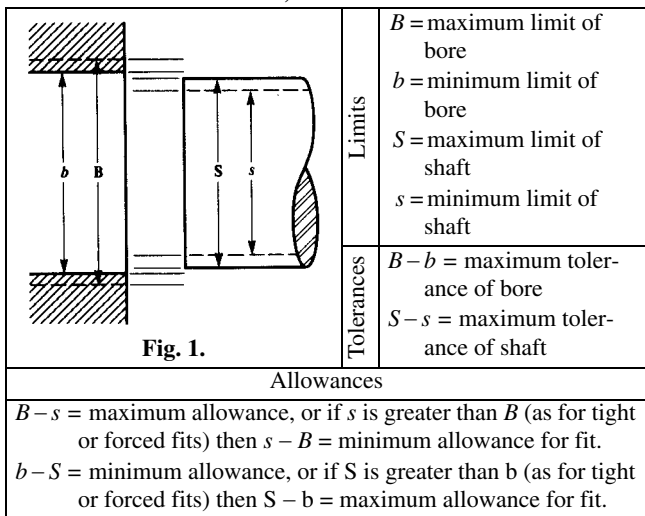
$$\text{Min. allow.} = \text{min. hole} - \text{max. shaft} = 2 - 1.996 = 0.0004$$

$$\begin{aligned} \text{Max. allow.} &= \text{max. hole} - \text{min. shaft} \\ &= 2.0005 - 1.9993 = 0.0012 \end{aligned}$$

*Example 2:* Beginning on Handbook **page 1734**, there are tables of dimensions for the Standard Unified Screw Thread Series—Class 1A, 2A, and 3A and B Fits. Determine the pitch-diameter tolerance of both screw and nut and the minimum and maximum

allowance between screw and nut at the pitch diameter, assuming that the nominal diameter is 1 inch, the pitch is 8 threads per inch, and the fits are Class 2A and 2B for screw and nut, respectively.

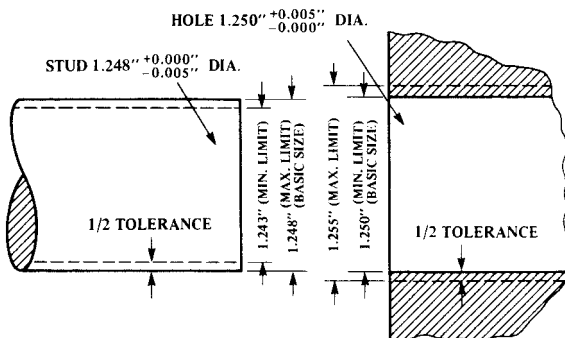
**Diagram Showing Differences Among "Limit," "Tolerance," and "Allowance"**



The maximum pitch diameter or limit of the screw = 0.9168, and the minimum pitch diameter = 0.9100; hence, the tolerance = 0.9168 - 0.9100 = 0.0068 inch. The nut tolerance = 0.9276 - 0.9100 = 0.0176 inch. The maximum allowance for medium fit = maximum pitch diameter of nut - minimum pitch diameter of screw = 0.9276 - 0.9168 = 0.0108 inch. The minimum allowance = minimum pitch diameter of nut - maximum pitch diameter of screw = 0.9188 - 0.9168 = 0.0020.

**Relation of Tolerances to Limiting Dimensions and How Basic Size Is Determined.**—The absolute limits of the various dimensions and surfaces indicate danger points, in as much as parts made beyond these limits are unserviceable. A careful analysis of a mechanism shows that one of these danger points is more sharply

defined than the other. For example, a certain stud must always assemble into a certain hole. If the stud is made beyond its maximum limit, it may be too large to assemble. If it is made beyond its minimum limit, it may be too loose or too weak to function. The absolute maximum limit in this case may cover a range of 0.001 inch, whereas the absolute minimum limit may have a range of at least 0.004 inch. In this case the maximum limit is the more sharply defined.

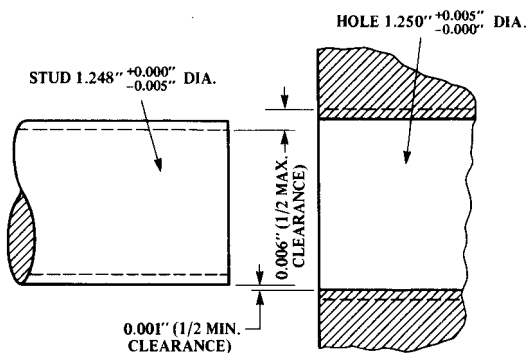


**Fig. 2. Graphic Illustration of the Meaning of the Term Basic Size or Dimension**

The basic size expressed on the component drawing is that limit that defines the more vital of the two danger points, while the tolerance defines the other. In general, the basic dimension of a male part such as a shaft is the maximum limit that requires a minus tolerance. Similarly, the basic dimension of a female part is the minimum limit requiring a plus tolerance, as shown in Fig. 2. There are, however, dimensions that define neither a male nor a female surface, such as, for example, dimensions for the location of holes. In a few such instances, a variation in one direction is less dangerous than a variation in the other. Under these conditions, the basic dimension represents the danger point, and the unilateral tolerance permits a variation only in the less dangerous direction. At other times, the conditions are such that any variation from a fixed point in either direction is equally dangerous. The basic size then represents this fixed point, and tolerances on the drawing are bilateral

and extend equally in both directions. (See Handbook [page 645](#) for explanation of unilateral and bilateral tolerances.)

**When Allowance Provides Clearance Between Mating Parts.**—When one part must fit freely into another part like a shaft in its bearing, the allowance between the shaft and bearing represents a clearance space. It is evident that the amount of clearance vanes widely for different classes of work. The minimum clearance should be as small as will permit the ready assembly and operation of the parts, while the maximum clearance should be as great as the functioning of the mechanism will allow. The difference between the maximum and minimum clearances defines the extent of the tolerances. In general, the difference between the basic sizes of companion parts equals the minimum clearance (see [Fig. 3](#)), and the term “allowance,” if not defined as maximum or minimum, is quite commonly applied to the minimum clearance.



**Fig. 3. Graphic Illustration of the Meaning of the Terms Maximum and Minimum Clearance**

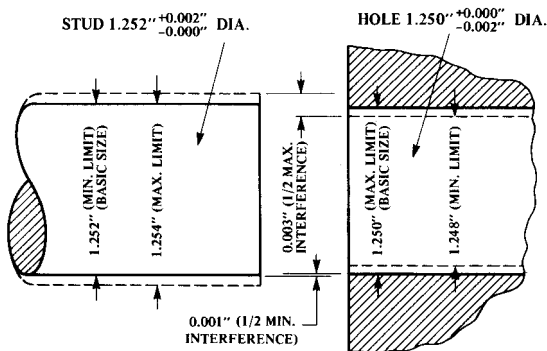
**When “Interference of Metal” Is Result of Allowance.**— If a shaft or pin is larger in diameter than the hole into which it is forced, there is, of course, interference between the two parts. The metal surrounding the hole is expanded and compressed as the shaft or other part is forced into place.

Engine crankpins, car axles, and various other parts are assembled in this way (see paragraph *Allowance for Forced Fits*, Hand-

book [page 647](#)). The force and shrink fits in Table 11 (starting on Handbook [page 663](#)) all represent interference of metal.

If interchangeable parts are to be forced together, the minimum interference establishes the danger point. Thus, for force fits, the basic dimension of the shaft or pin is the minimum limit requiring a plus tolerance, and the basic dimension of the hole is the maximum limit requiring a minus tolerance, (See [Fig. 4](#).)

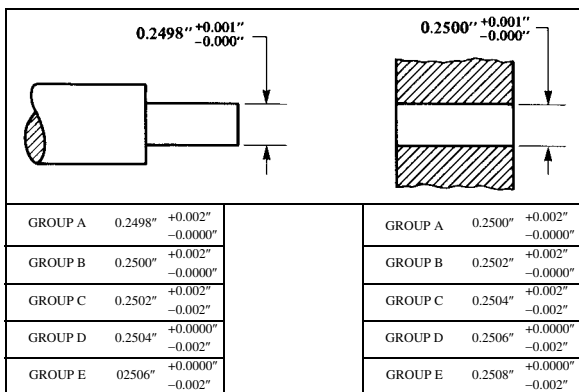
**Obtaining Allowance by Selection of Mating Parts.**—The term “selective assembly” is applied to a method of manufacturing that is similar in many of its details to interchangeable manufacturing. In selective assembly, the mating parts are sorted according to size and assembled or interchanged with little or no further machining nor hand work.



**Fig. 4. Illustration of the Meaning of the Terms Maximum and Minimum Interference**

The chief purpose of manufacturing by selective assembly is the production of large quantities of duplicate parts as economically as possible. As a general rule, the smaller the tolerances, the more exacting and expensive will be the manufacturing processes. However, it is possible to use comparatively large tolerances and then reduce them, in effect, by selective assembly, provided the quantity of parts is large enough to make such selective fitting possible. To illustrate, the table that follows shows a plug or stud that has a plus tolerance of 0.001 inch and a hole that also has a plus tolerance of 0.001 inch. Assume that this tolerance of 0.001 inch repre-

sents the normal size variation on each part when manufactured efficiently. With this tolerance, a minimum plug in a maximum hole would have a clearance  $0.2510 - 0.2498 = 0.0012$  inch, and a maximum plug in a minimum hole would have a “metal interference” of  $0.2508 - 0.2500 = 0.0008$  inch. Suppose, however, that the clearance required for these parts must range from zero to 0.0004 inch. This reduction can be obtained by dividing both plugs and holes into five groups. (See below.) Any studs in Group A, for example, will assemble in any hole in Group A, but the studs in one group will not assemble properly in the holes in another group. When the largest stud in Group A is assembled in the smallest hole in Group A, the clearance equals zero. When the smallest stud in Group A is assembled in the largest hole in Group A, the clearance equals 0.0004 inch. Thus, in selective assembly manufacturing, there is a double set of limits, the first being the manufacturing limits and the second the assembling limits. Often, two separate drawings are made of a part that is to be graded before **Fig. 3** assembly. One shows the manufacturing tolerances only, so as not to confuse the operator, and the other gives the proper grading information.



*Example 3:* Data for force and shrink fits are given in the table starting on **page 663** in the Handbook. Establish the limits of size and interference of the hole and shaft for a Class FN-1 fit of 2-inch diameter.

$$\text{Max. hole} = 2 + 0.0007 = 2.0007; \text{ min. shaft} = 2 - 0 = 2$$

$$\begin{aligned} \text{Max. shaft} &= 2 + 0.0018 = 2.0018; \text{ min. shaft} = 2 + 0.0013 \\ &= 2.0013 \end{aligned}$$

In the second column of the table, the minimum and maximum interference are given as 0.0006 and 0.0018 inch, respectively, for a FN-1 fit of 2-inch diameter. For a “selected” fit, shafts are selected that are 0.0012 inch larger than the mating holes; that is, for any mating pair, the shaft is larger than the hole by an amount midway between the minimum (0.0006-inch) and maximum (0.0018 inch) interference.

**Dimensioning Drawings to Ensure Obtaining Required Tolerances.**—In dimensioning the drawings of parts requiring tolerances, there are certain fundamental rules that should be applied.

*Rule 1:* In interchangeable manufacturing there is only one dimension (or group of dimensions) in the same straight line that can be controlled within fixed tolerances. This dimension is the distance between the cutting surface of the tool and the locating or registering surface of the part being machined. Therefore, it is incorrect to locate any point or surface with tolerances from more than one point in the same straight line.

*Rule 2:* Dimensions should be given between those points that it is essential to hold in a specific relation to each other. Most dimensions, however, are relatively unimportant in this respect. It is good practice to establish common location points in each plane and to give, as far as possible, all such dimensions from these points.

*Rule 3:* The basic dimensions given on component drawings for interchangeable parts should be, except for force fits and other unusual conditions, the “maximum metal” size (maximum shaft or plug and minimum hole). The direct comparison of the basic sizes should check the danger zone, which is the minimum clearance condition in most instances. It is evident that these sizes are the most important ones, as they control the interchangeability, and they should be the first determined. Once established, they should remain fixed if the mechanism functions properly, and the design is unchanged. The direction of the tolerances, then, would be such as to recede from the danger zone. In most instances, this direc-

tionality means that the direction of the tolerances is such as will increase the clearance. For force fits, the basic dimensions determine the minimum interference, and the tolerances limit the maximum interference.

*Rule 4:* Dimensions must not be duplicated between the same points. The duplication of dimensions causes much needless trouble, due to changes being made in one place and not in the others. It is easier to search a drawing to find a dimension than it is to have them duplicated and more readily found but inconsistent.

*Rule 5:* As far as possible, the dimensions on comparison parts should be given from the same relative locations. Such a procedure assists in detecting interference's and other improper conditions.

In attempting to work in accordance with general laws or principles, one other elementary rule should always be kept in mind. Special requirements need special consideration. The following detailed examples are given to illustrate the application of the five rules and to indicate results of their violation.

**Violations of Rules for Dimensioning.**— **Fig. 5** shows a very common method of dimensioning a part such as the stud shown, but one that is bad practice as it violates the first and second rules. The dimensions given for the diameters are correct, so they are eliminated from the discussion. The dimensions given for the various lengths are wrong: First, because they give no indication as to the essential lengths; second, because of several possible sequences of operations, some of which would not maintain the specified conditions.

**Fig. 6** shows one possible sequence of operations indicated alphabetically. If we first finish the dimension *a* and then finish *b*, the dimension *c* will be within the specified limits. However, the dimension *c* is then superfluous. **Fig. 7** gives another possible sequence of operations. If we first establish *a*, and then *b*, the dimension *c* may vary 0.030 instead of 0.010 inch as is specified in **Fig. 5**. **Fig. 8** gives a third possible sequence of operations. If we first finish the overall length *a*, and then the length of the body *b*, the stem *c* may vary 0.030 inch instead of 0.010 inch as specified in **Fig. 5**.



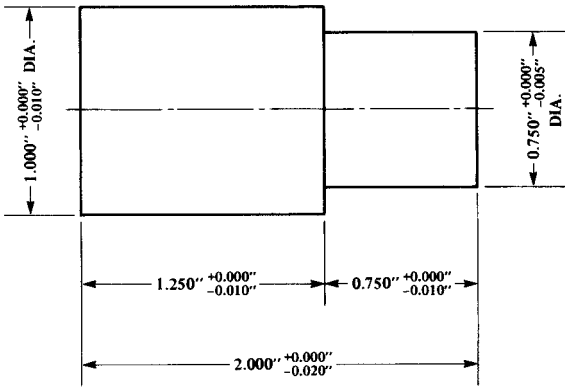


Fig. 5. Common but Incorrect Method of Dimensioning

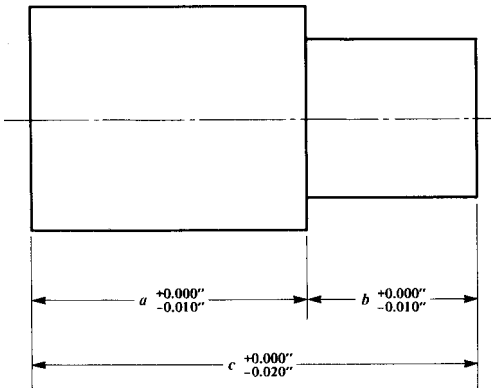


Fig. 6. One Interpretation of Dimensioning in Fig. 5

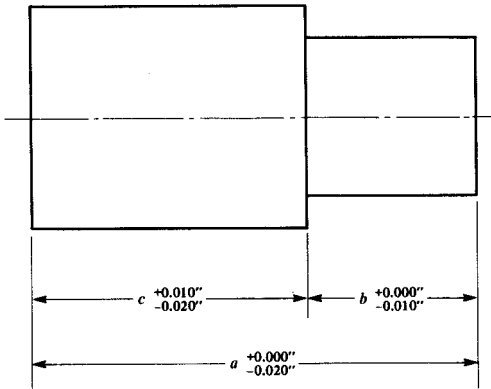


Fig. 7. Another Interpretation of Dimensioning in Fig. 5

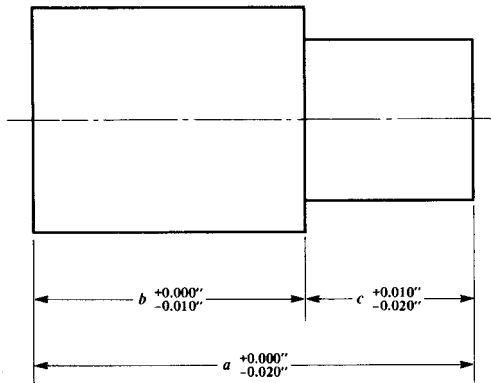
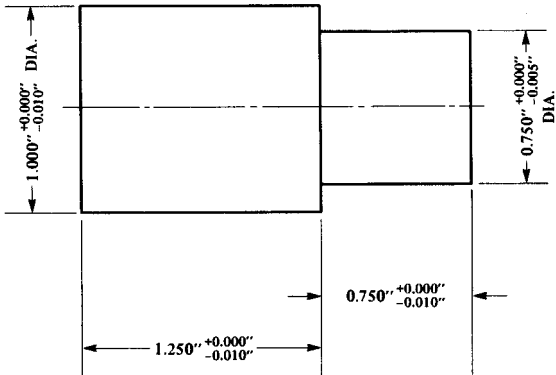
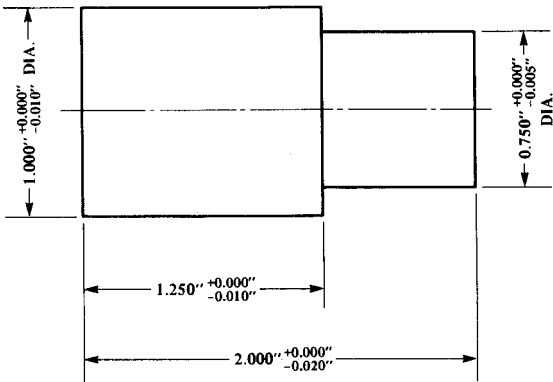


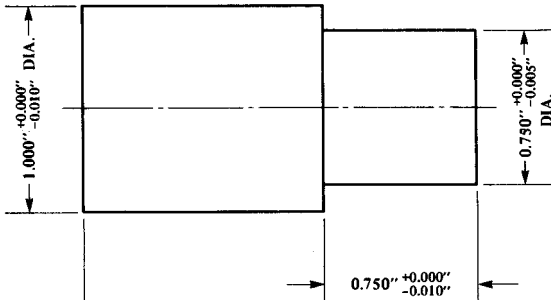
Fig. 8. A Third Interpretation of Dimensioning in Fig. 5



**Fig. 9. Correct Dimensioning if Length of Body and Length of Stem Are Most Important**



**Fig. 10. Correct Dimensioning if Length of Body and Overall Length Are Most Important**



**Fig. 11. Correct Dimensioning if Overall Length and Length of Stem Are Most Important**

If three different plants were manufacturing this part, each one using a different sequence of operations, it is evident from the foregoing that a different product would be received from each plant. The example given is the simplest one possible. As the parts become more complex, and the number of dimensions increases, the number of different combinations possible and the extent of the variations in size that will develop also increase.

**Fig. 9** shows the correct way to dimension this part if the length of the body and the length of the stem are the essential dimensions. **Fig. 10** is the correct way if the length of the body and the length overall are the most important. **Fig. 11** is correct if the length of the stem and the length overall are the most important. If the part is dimensioned in accordance with **Fig. 9**, **Fig. 10**, or **Fig. 11**, then the product from any number of factories should be alike.

### PRACTICE EXERCISES FOR SECTION 12

(See *Answers to Practice Exercises For Section 12* on page 228)

- 1) What factors influence the allowance for a forced fit?
- 2) What is the general practice in applying tolerances to center distances between holes?
- 3) A 2-inch shaft is to have a tolerance of 0.003 inch on the diameter. Show, by examples, three ways of expressing the shaft dimensions.

4) In what respect does a bilateral tolerance differ from a unilateral tolerance? Give an example that demonstrates this difference.

5) What is the relationship between gagemaker's tolerance and workplace tolerance?

6) Name the different class of fits for screw thread included in the American standards.

7) How does the Unified screw for screw threads differ from the former American standard with regard to clearance between mating parts? With regard toward working tolerance?

8) Under what conditions is one limiting dimension or "limit" also a basic dimension?

9) What do the letter symbols RC, LC, LN, signify with regard American Standards

10) According to table at the bottom of Handbook [page 652](#), broaching will produce work within tolerance grades 5 through 8. What does this mean in terms of thousands of an inch, considering a 1-inch diameter broached hole?

11) Does surface roughness affect the ability to work within the tolerance grades specified in Exercise 10?

## **SECTION 13**

### **USING STANDARDS DATA AND INFORMATION**

(References to Standards appear throughout the HANDBOOK)

Standards are needed in metalworking manufacturing to establish dimensional and physical property limits for parts that are to be interchangeable. Standards make it possible for parts such as nuts, screws, bolts, splines, gears, etc., to be manufactured at different times and places with the assurance that they will meet assembly requirements. Standards are also needed for tools such as twist drills, reamers, milling cutters, etc., so that only a given number of sizes need be made available to cover a given range and to ensure adequate performance. Also, performance standards often are established to make sure that machines and equipment will satisfy their application requirements.

A standard may be established by a company on a limited basis for its own use. An industry may find that a standard is needed, and its member companies working through their trade association come to an agreement as to what requirements should be included. Sometimes, industry standards sponsored by a trade association or an engineering society become acceptable by a wide range of consumers, manufacturers, and government agencies as national standards and are made available through a national agency such as the American National Standards Institute (ANSI). More and more countries are coming to find that standards should be universal and are working to this end through the International Standards Organization (ISO).

In the United States and some other English-speaking countries, there are two systems of measurement in use: the inch system and the metric system. As a result, standards for, say, bolts, nuts, and screws have been developed for both inch and metric dimensions as will be found in Machinery's Handbook. However, an increasing number of multinational corporations and their local suppliers

are finding it prohibitively expensive to operate with two systems of measurements and standards. Thus, in order to use available expertise in one plant location, a machine may be designed in an "inch" nation only to be produced later in a "metric" country or vice versa. This situation generates additional costs in the conversion of drawings, substitution of equivalent standard steel sizes and fasteners, and conversion of testing and material specifications, etc. Because of these problems, more and more standards are being developed in the United States and throughout the world that are based, wherever practicable, upon ISO standards.

In the Handbook, the user will find that a large number of both inch and metric standards data and information are provided. It should be noted that at the head of each table of standards data the source is given in parentheses, such as (ANSI B18.3-1982). ANSI indicates the American National Standards Institute; B18.3 is the identifying number of the standard; and 1982 is the date the standard was published, or revised, and became effective.

Generally, new products are produced to the metric standards; older products and replacement parts for them may require reference to older inch standards, and some products such as inch-unit pipe threads are considered as standard for the near future because of widespread use throughout the world.

**Important Objectives of Standardization.**—The purpose of standardization is to manufacture goods for less direct and indirect costs and to provide finished products that meet the demands of the marketplace. A more detailed description of the objectives could be as follows:

*Lower the production costs when the aim is to:*

- 1) Facilitate and systematize the work of skilled designers;
- 2) Ensure optimum selection of materials, components, and semi-finished products;
- 3) Reduce stocks of materials, semifinished products, and finished products;
- 4) Minimize the number of different products sold; and
- 5) Facilitate and reduce the cost of procurement of purchased goods.

*Meet the demands of the market place, when the objective is to:*

- 1) Conform to regulations imposed by government and trade organizations;
- 2) Stay within safety regulations set forth by governments; and
- 3) Facilitate interchangeability requirements with existing products.

**Standardization Technique.**—The two commonly used basic principles for the preparation of a standard are:

- 1) Analytical standardization – Standard developed from scratch.
- 2) Conservative standardization – Standard based, so far as is possible, on existing practice.

In practice, it appears that a standard cannot be prepared completely by one or the other of the two methods but emerges from a compromise between the two. The goal of the standardization technique, then, should be to utilize the basic material and the rules and the aids available in such a way that a valid and practical compromise solution is reached.

The basic material could consist of such items as former company standards, vendor catalog data, national and international standards, requirements of the company's customers, and competitor's material. Increasingly important are the national and international standards in existence on the subject; they should always play an important part in any conservative standardization work. For example, it would be foolish to create a new metric standard without first considering some existing European metric standards.

**Standards Information in the Handbook.**—Among the many kinds of material and data to be found in the Handbook, the user will note that extensive coverage is given to standards of several types: American National Standards, British Standards, ISO Standards, engineering society standards, trade association standards, and, in certain instances, company product standards. Both inch and metric system standards are given wherever appropriate. Inch dimension standards sometimes are provided only for use during transition to metric standards or to provide information for the manufacture of replacement parts.

In selecting standards to be presented in the Handbook, the editors have chosen those standards most appropriate to the needs of Handbook users. Text, illustrations, formulas, tables of data, and



examples have been arranged in the order best suitable for direct and quick use. As an example of this type of presentation, the section on bevel gearing, Handbook starting on [page 2081](#), begins with text material that provides the basis for understanding information presented in the AGMA standards; the illustrations on Handbook [pages 2086](#) and [2087](#) provide visual definition of essential parts and dimensions of a bevel gear; the formulas on Handbook [page 2075](#) show how to calculate dimensions of milled bevel gears; the tables on Handbook, starting on [page 2089](#) give numbers of formed cutters used to mill teeth in mating bevel gear and pinion sets with shafts at right angles; and finally, the worked-out examples beginning on Handbook [page 2091](#) give a step-by-step procedure for selecting formed cutters for milling bevel gears. Also, where combinations of tables and formulas are given, the formulas have been arranged in the best sequence for computation with the aid of a pocket calculator.

**“Soft” Conversion of Inch to Metric Dimensions.**—The dimensions of certain products, when specified in inches, may be converted to metric dimensions, or vice versa, by multiplying by the appropriate conversion factor so that the parts can be fabricated either to inch or to the equivalent metric dimensions and still be fully interchangeable. Such a conversion is called a “soft” conversion. An example of a “soft” conversion is available on Handbook [page 2298](#), which gives the inch dimensions of standard lockwashers for ball bearings. The footnote to the table indicates that multiplication of the tabulated inch dimensions by 25.4 and rounding the results to two decimal places will provide the equivalent metric dimensions.

**“Hard” Metric or Inch Standard Systems.**—In a “hard” system, those dimensions in the system that have been standardized cannot be converted to another dimensional system that has been standardized independently of the first system. As stated in the footnote on [page 2176](#) of the Handbook, “In a ‘hard’ system the tools of production, such as hobs, do not bear a usable relation to the tools in another system; i.e., a 10 diametral pitch hob calculates to be equal to a 2.54 module hob in the metric module system, a hob that does not exist in the metric standard.”

**Interchangeability of Parts Made to Revised Standards.—**

Where a standard has been revised, there may still remain some degree of interchangeability between older parts and those made to the new standard. As an example, starting on [page 2167](#) of the Handbook, there are two tables showing which of the internal and external involute splines made to older standards will mate with those made to newer standards.

**PRACTICE EXERCISES FOR SECTION 13**

(See [Answers to Practice Exercises For Section 13](#) on page 229)

- 1) What is the breaking strength of a  $6 \times 7$  fiber-core wire rope  $\frac{1}{4}$  inch in diameter if the rope material is mild plow steel?
- 2) What factor of safety should be applied to the rope in Exercise 1?
- 3) How many carbon steel balls of  $\frac{1}{4}$ -inch diameter would weigh 1 lb?
- 4) For a 1-inch diameter of shaft, what size square key is appropriate?
- 5) Find the hole size needed for a  $\frac{5}{32}$ -inch standard cotter pin.
- 6) Find the limits of size for a 0.1250-inch diameter hardened and ground dowel pin.
- 7) For a 3AM1-17 retaining ring (snap ring), what is the maximum allowable speed of rotation?
- 8) Find the hole size required for a type AB steel thread-forming screw of number 6 size in 0.105-inch-thick stainless steel.

## SECTION 14

### STANDARD SCREW AND PIPE THREADS

HANDBOOK Pages **1725 – 1919**

Different screw-thread forms and standards have been originated and adopted at various times, either because they were considered superior to other forms or because of the special requirements of screws used for a certain class of work.

A standard thread conforms to an adopted standard with regard to the form or contour of the thread itself and as to the pitches or numbers of threads per inch for different screw diameters.

The United States Standard formerly used in the United States was replaced by an American Standard having the same thread form as the former standard and a more extensive series of pitches, as well as tolerances and allowances for different classes of fits. This American Standard was revised in 1949 to include a Unified Thread Series, which was established to obtain screw-thread interchangeability among the United Kingdom, Canada, and the United States.

The Standard was revised again in 1959. The Unified threads are now the standard for use in the United States and the former American Standard threads are now used only in certain applications where the changeover in tools, gages, and manufacturing has not been completed. The differences between Unified and the former National Standard threads are explained on **pages 1725 and 1732** in the Handbook.

As may be seen in the table on Handbook **page 1735**, the Unified Series of screw threads consists of three standard series having graded pitches (UNC, UNF, and UNEF) and eight standard series of uniform (constant) pitch. In addition to these standard series. There are places in the table beginning on Handbook **page 1736** where special threads (UNS) are listed. These UNS threads are for use only if standard series threads do not meet requirements.

*Example 1:* The table on Handbook [page 1763](#) shows that the pitch diameter of a 2-inch screw thread is 1.8557 inches. What is meant by the term “pitch diameter” as applied to a screw thread and how is it determined?

According to a definition of “pitch diameter” given in connection with American Standard screw threads, the pitch diameter of a straight (nontapering) screw thread is the diameter of an imaginary cylinder, the surface of which would pass through the threads at such points as to make equal the width of the threads and the width of the spaces cut by the surface of the cylinder.

The basic pitch diameter equals the basic major (outside) diameter minus two times the addendum of the external thread (Handbook [page 1734](#)), so the basic pitch diameter for the 2-inch example, with  $4\frac{1}{2}$  threads per inch, is  $2.00 - 2 \times 0.07217 = 1.8557$  inches.

*Example 2:* The tensile strength of a bolt,  $3\frac{1}{2}$  inches in diameter at a stress of 6000 pounds per square inch may be calculated by means of the formulas on Handbook [page 1510](#). This formula uses the largest diameter of the bolt, avoiding the need to take account of the reduced diameter at the thread root, and gives a tensile strength of 35, 175 pounds for the conditions noted.

If the second formula on [page 1510](#), based on the area of the smallest diameter, is used for the same bolt and stress, and the diameter of the thread root is taken as 3.1 inches, then the tensile strength is calculated as 40,636 pounds. The difference in these formulas is that the first uses a slightly greater factor of safety than the second, taking account of possible variations in thread depth.

*Example 3:* Handbook [page 1899](#) gives formulas for checking the pitch diameter of screw threads by the three-wire method (when effect of lead angle is ignored). Show how these formulas have been derived using the one for the American National Standard Unified thread as an example.

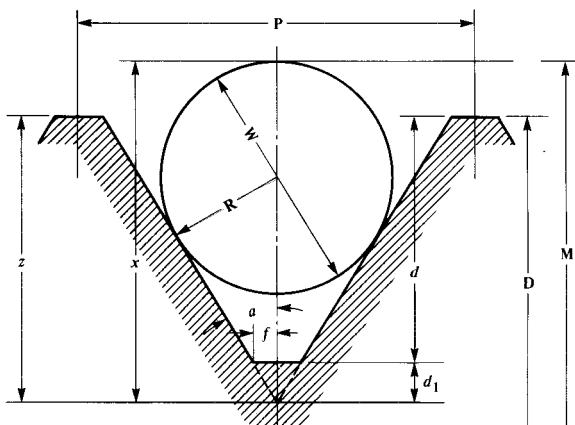
It is evident from the diagram, [Fig. 1](#), that:

$$M = D - 2z + 2x \quad (1)$$

$$x = R + \frac{R}{\sin a} \text{ and } 2x = 2R + \frac{2R}{0.5}; \text{ hence,}$$

$$2x = \frac{(2 \times 0.5 + 2)R}{0.5} = \frac{3R}{0.5} = 6R = 3W$$

$$z = d + d_1 = 0.6495P + f \times \cot a$$



**Fig. 1. Diagram Illustrating the Derivation of Formulas for Three-Wire Measurements of Screw-Thread Pitch Diameters**

$$f = 0.0625P; \text{ therefore,}$$

$$z = 0.6495P + 0.10825P = 0.75775P$$

If, in **Formula (1)**, we substitute the value of  $2z$  or  $2 \times 0.75775P$  and the value of  $2x$ , we have:

$$M = D - 1.5155 \times P + 3W \tag{2}$$

This **Formula (2)** is the one found in previous editions of the Handbook. In the 22nd and subsequent editions of the Handbook use of the outside diameter  $D$  in **Formula (2)** above was eliminated to provide a formula in terms of the pitch diameter  $E$ . Such a formula is useful for finding the wire measurement corresponding to the actual pitch diameter, whether it be correct, undersize, or oversize.

According to the last paragraph of **Example 1**, above,  $E = D - 2 \times \text{thread addendum}$ . On Handbook **page 1734**, the formula for thread addendum given at the top of the last column is  $0.32476P$ . Therefore,  $E = D - 2 \times 0.32476P$ , or, transposing this formula,  $D = E + 2 \times 0.32476P = E + 0.64952P$ . Substituting this value of  $D$  into **Formula (2)** gives:  $M = E + 0.64952P - 1.5155P + 3W = E - 0.8660P + 3W$ , which is the current Handbook formula.

*Example 4:* On Handbook **page 1906**, a formula is given for checking the angle of a screw thread by a three-wire method. How is this formula derived? By referring to the diagram, **Fig. 2**,

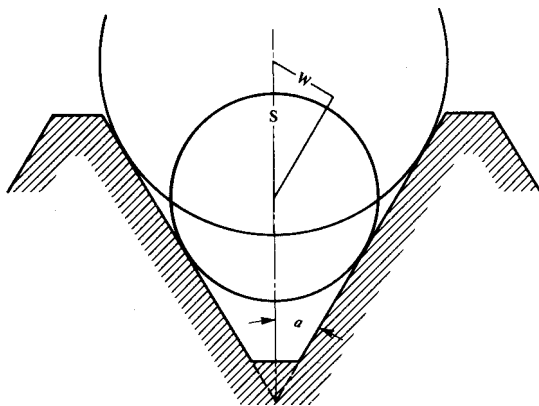
$$\sin a = \frac{W}{S} \quad (1)$$

If  $D$  = diameter of larger wires and  $d$  = diameter of smaller wires,

$$W = \frac{D-d}{2}$$

If  $B$  = difference in measurement over wires, then the difference  $S$  between the centers of the wires is:

$$S = \frac{B - (D - d)}{2}$$



**Fig. 2. Diagram Illustrating the Derivation of Formula for Checking the Thread Angle by the Three-Wire System**

By inserting these expressions for  $W$  and  $S$  in **Formula (1)** and canceling, the formula given in the Handbook is obtained if  $A$  is substituted for  $D - d$ .

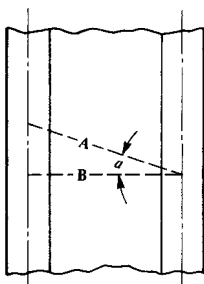
$$\sin a = \frac{A}{B - A}$$

*Example 5:* A vernier gear-tooth caliper (like the one shown on Handbook [page 2052](#)) is to be used for checking the width of an Acme screw by measuring squarely across or perpendicular to the thread. Since standard screw-thread dimensions are in the plane of the axis, how is the width square or normal to the sides of the thread determined? Assume that the width is to be measured at the pitch line and that the number of threads per inch is two.

The table on Handbook [page 1827](#) shows that for two threads per inch, the depth is 0.260 inch; hence, if the measurement is to be at the pitch line, the vertical scale of the caliper is set to  $(0.260 - 0.010) \div 2 = 0.125$  inch. The pitch equals

$$\frac{1}{\text{No. of threads per inch}} = \frac{1}{2} \text{ inch}$$

The width  $A$ , **Fig. 3**, in the plane of the axis equals  $\frac{1}{2}$  the pitch, or  $\frac{1}{4}$  inch. The width  $B$  perpendicular to the sides of the thread = width in axial plane  $\times$  cosine helix angle.



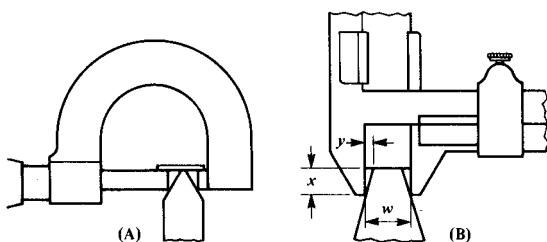
**Fig. 3. Determining the Width Perpendicular to the sides of a Thread at the Pitch Line**

(The helix angle, which equals angle  $a$ , is based upon the pitch diameter and is measured from a plane perpendicular to the axis of the screw thread.) The width  $A$  in the plane of the axis represents

the hypotenuse of a right triangle, and the required width  $B$  equals the side adjacent; hence width  $B = A \times \text{cosine of helix angle}$ . The angle of the thread itself ( $29^\circ$  for an Acme Thread) does not affect the solution.

**Width of Flat End of Unified Screw-Thread and American Standard Acme Screw-Thread Tools.**—The widths of the flat or end of the threading tool for either of these threads may be measured by using a micrometer as illustrated at A, Fig. 4. In measuring the thread tool, a scale is held against the spindle and anvil of the micrometer, and the end of the tool is placed against this scale. The micrometer is then adjusted to the position shown and 0.2887 inch subtracted from the reading for an American Standard screw-thread tool. For American Standard Acme threads, 0.1293 inch is subtracted from the micrometer reading to obtain the width of the tool point. The constants (0.2887 and 0.1293), which are subtracted from the micrometer reading, are only correct when the micrometer spindle has the usual diameter of 0.25 inch.

An ordinary gear-tooth vernier caliper also may be used for testing the width of a thread tool point, as illustrated at B. If the measurement is made at a vertical distance  $x$  of  $\frac{1}{4}$  inch from the points of the caliper jaws, the constants previously given for American Standard caliper reading to obtain the actual width of the cutting end of the tool.



**Fig. 4. Measuring Width of Flat on Threading Tool (A) with a Micrometer; (B) with a Gear-Tooth Vernier**

*Example 6:* Explain how the constants 0.2887 and 0.1293 referred to in a preceding paragraph are derived and deduce a general rule



applicable regardless of the micrometer spindle diameter or vertical dimension  $x$ , **Fig. 4**.

The dimension  $x$  (which also is equivalent to the micrometer spindle diameter) represents one side of a right triangle (the side adjacent), having an angle of  $29 \div 2 = 14$  degrees and 30 minutes, in the case of an Acme thread. The side opposite or  $y =$  side adjacent  $\times$  tangent  $=$  dimension  $x \times \tan 14^\circ 30'$ .

If  $x$  equals 0.25 inch, then side opposite or  $y = 0.25 \times 0.25862 = 0.06465$ ; hence, the caliper reading minus  $2 \times 0.06465 =$  width of the flat end ( $2 \times 0.06465 = 0.1293 =$  constant).

The same result would be obtained by multiplying 0.25862 by  $2x$ ; hence, the following rule: To determine the width of the end of the threading tool, by the general method illustrated in **Fig. 4**, multiply twice the dimension  $x$  (or spindle diameter in the case of the micrometer) by the tangent of one-half the thread tool angle, and subtract this product from the width  $w$  to obtain the width at the end of the tool.

*Example 7:* A gear-tooth vernier caliper is to be used for measuring the width of the flat of an American Standard external screw-thread tool. The vertical scale is set to  $\frac{1}{8}$  inch (corresponding to the dimension  $x$ , **Fig. 4**). How much is subtracted from the reading on the horizontal scale to obtain the width of the flat end of the tool?

$$\frac{1}{8} \times 2 \times \tan 30^\circ = \frac{1}{4} \times 0.57735 = 0.1443 \text{ inch}$$

Hence, the width of the flat equals  $w$ , **Fig. 4**, minus 0.1443. This width should be equal to one-eighth of the pitch of the thread to be cut, since this is the width of flat at the minimum minor diameter of American Standard external screw threads.

### PRACTICE EXERCISES FOR SECTION 14

(See *Answers to Practice Exercises For Section 14* on page 229)

- 1) What form of screw thread is most commonly used (a) in the United States? (b) in Britain?
- 2) What is the meaning of abbreviations 3"–4NC-2?
- 3) What are the advantages of an Acme thread compared to a square thread?
- 4) For what reason would a Stub Acme thread be preferred in some applications?

5) Find the pitch diameters of the following screw threads of American Standard Unified form:  $\frac{1}{4}-28$  (meaning  $\frac{1}{4}$ -inch diameter and 28 threads per inch);  $\frac{3}{4}-10$ ?

6) How much taper is used on a standard pipe thread?

7) Under what conditions are straight, or nontapering, pipe threads used?

8) In cutting a taper thread, what is the proper position for the lathe tool?

9) If a lathe is used for cutting a British Standard pipe thread, in what position is the tool set?

10) A thread tool is to be ground for cutting an Acme thread having 4 threads per inch; what is the correct width of the tool at the end?

11) What are the common shop and toolroom methods of checking the pitch diameters of American Standard screw threads requiring accuracy?

12) In using the formula, Handbook [page 1734](#), for measuring an American Standard screw thread by the three-wire method, why should the constant 0.86603 be multiplied by the pitch before subtracting from measurement  $M$ , even if not enclosed by parentheses?

13) What is the difference between the pitch and the lead ( $a$ ) of a double thread? ( $b$ ) of a triple thread?

14) In using a lathe to cut American Standard Unified threads, what should be the truncations of the tool points and the thread depths for the following pitches: 0.1, 0.125, 0.2, and 0.25 inch?

15) In using the three-wire method of measuring a screw thread, what is the micrometer reading for a  $\frac{3}{4}-12$  special thread of American Standard form if the wires have a diameter of 0.070 inch?

16) Are most nuts made to the United States Standard dimensions?

17) Is there, at the present time, a Manufacturing Standard for bolts and nuts?

18) The American standard for machine screws includes a coarse-thread series and a fine thread series as shown by the tables starting on Handbook [page 1763](#). Which series is commonly used?

19) How is the length (*a*) of a flat head or countersunk type of machine screw measured? (*b*) of a fillister head machine screw?

20) What size tap drill should be used for an American standard machine screw of No. 10 size, 24 threads per inch?

21) What is the diameter of a No. 10 drill?

22) Is a No. 6 drill larger than a No. 16?

23) What is the relation between the letter size drills and the numbered sizes?

24) Why is it common practice to use tap drills that leave about  $\frac{3}{4}$  of the full thread depth after tapping, as shown by the tables starting on **page 1933** in the Handbook?

25) What form of a screw thread is used on (*a*) machine screws? (*b*) cap screws?

26) What standard governs the pitches of cap screw threads?

27) What form of thread is used on the National Standard fire hose couplings? How many standard diameters are there?

28) In what way do hand taps differ from machine screw taps?

29) What are taper taps?

30) The diameter of a  $\frac{3}{4}$  - 10 American Standard Thread is to be checked by the three wire method. What is the largest size wire that can be used?

31) Why is the advance of some threading dies positively controlled by a lead screw instead of relying upon the die to lead itself?

32) What is the included angle of the heads of American Standard (*a*) flat head Machine screws? (*b*) flat head cap screws? (*c*) flat head wood screws?

## SECTION 15

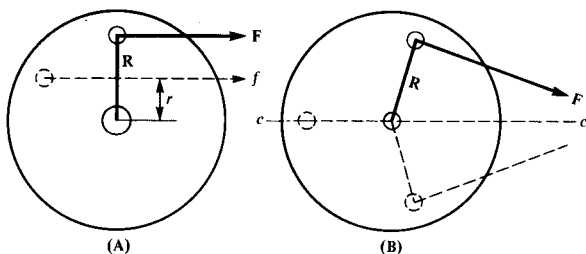
### PROBLEMS IN MECHANICS

HANDBOOK Pages 141 – 163

In the design of machines or other mechanical devices, it is often necessary to deal with the actions of forces and their effects. For example, the problem may be to determine what force is equivalent to two or more forces acting in the same plane but in different directions. Another type of problem is to determine the change in the magnitude of a force resulting from the application of mechanical appliances such as levers, pulleys, and screws used either separately or in combination. It also may be necessary to determine the magnitude of a force in order to proportion machine parts to resist the force safely; or, possibly, to ascertain if the force is great enough to perform a given amount of work. Determining the amount of energy stored in a moving body or its capacity to perform work, and the power developed by mechanical apparatus, or the rate at which work is performed, are additional examples of problems frequently encountered in originating or developing mechanical appliances. The section in Machinery's Handbook on Mechanics, beginning on [page 141](#), deals with fundamental principles and formulas applicable to a wide variety of mechanical problems.

**The Moment of a Force.**—The tendency of a force acting upon a body is, in general, to produce either a motion of translation (that is, to cause every part of the body to move in a straight line) or to produce a motion of rotation. A moment, in mechanics, is the measure of the turning effect of a force that tends to produce rotation. For example, suppose a force acts upon a body that is supported by a pivot. Unless the line of action of the force happens to pass through the pivot, the body will tend to rotate. Its tendency to rotate, moreover, will depend upon two things: (1) the magnitude of the force acting, and (2) the distance of the force from the pivot, *measuring along a line at right angles to the line of action of the*

force. (See Fig. 9 on Handbook page 147 and the accompanying text.)



**Fig. 1. Diagram Showing How the Turning Moment of a Crank Disk Varies from Zero to Maximum**

*Example 1:* A force  $F$  of 300 pounds is applied to a crank disk A (Fig. 1) and in the direction of the arrow. If the radius  $R = 5$  inches, what is the turning moment? Also, determine how much the turning moment is reduced when the crankpin is in the position shown by the dashed lines, assuming that the force is along line  $f$  and that  $r = 2\frac{1}{2}$  inches.

When the crankpin is in the position shown by the solid lines, the maximum turning moment is obtained, and it equals  $F \times R = 300 \times 5 = 1500$  inch-pounds or pound-inches. When the crankpin is in the position shown by the dashed lines, the turning moment is reduced one-half and equals  $f \times r = 300 \times 2\frac{1}{2} = 750$  inch-pounds.

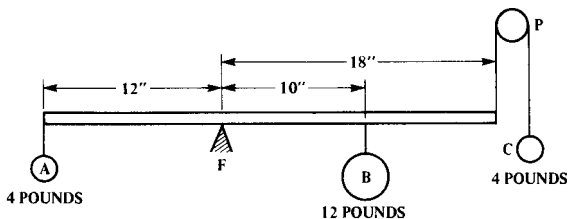
*Note:* Foot-pound is the unit for measurement of work and is in common use in horsepower calculations. However, torque, or turning moment, is also a unit of measurement of work. To differentiate between these two similar terms, which have the same essential meaning, it is convenient to express torque in terms of *pound-feet* (or *pound-inches*). This reversal of word sequence will readily indicate the different meanings of the two terms for units of measurement – the unit of horsepower and the unit of turning moment. A strong reason for expressing the unit of turning moment as *pound-inches* (rather than as *foot-pounds*) is because the dimensions of shafts and other machine parts ordinarily are stated in inches.

*Example 2:* Assume that the force  $F$  (diagram B, **Fig. 1**) is applied to the crank through a rod connecting with a crosshead that slides along center line  $c-c$ . If the crank radius  $R = 5$  inches, What will be the maximum and minimum turning moments?

The maximum turning moment occurs when the radial line  $R$  is perpendicular to the force line  $F$  and equals in inch-pounds,  $F \times 5$  in this example. When the radial line  $R$  is in line with the center line  $c-c$ , the turning moment is 0, because  $F \times 0 = 0$ . This is the "deadcenter" position for steam engines and explains why the crankpins on each side of a locomotive are located 90 degrees apart, or, in such a position that the maximum turning moment, approximately, occurs when the turning moment is zero on the opposite side. With this arrangement, it is always possible to start the locomotive since only one side at a time can be in the dead-center position.

**The Principle of Moments in Mechanics.**—When two or more forces act upon a rigid body and tend to turn it about an axis, then, for equilibrium to exist, the sum of the moments of the forces that tend to turn the body in one direction must be equal to the sum of the moments of those that tend to turn it in the opposite direction about the same axis.

*Example 3:* In **Fig. 2**, a lever 30 inches long is pivoted at the fulcrum  $F$ . At the right, and 10 inches from  $F$ , is a weight,  $B$ , of 12 pounds tending to turn the bar in a right-hand direction about its fulcrum  $F$ . At the left end, 12 inches from  $F$ , the weight  $A$ , of 4 pounds tends to turn the bar in a left-hand direction, while weight  $C$ , at the other end, 18 inches from  $F$ , has a like effect, through the use of the string and pulley  $P$ .



**Fig. 2. Lever in Equilibrium Because the Turning Moment of a Crank Disk Varies from Zero to Maximum**

Taking moments about  $F$ , which is the center of rotation, we have:

$$\text{Moment of } B = 10 \times 12 = 120 \text{ inch-pounds}$$

Oposed to this are the moments of  $A$  and  $C$ :

$$\text{Moment of } A = 4 \times 12 = 48 \text{ inch-pounds}$$

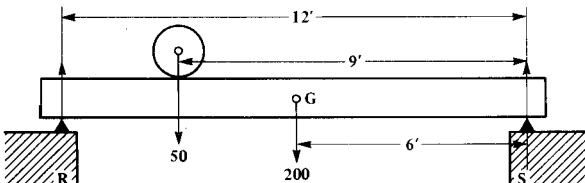
$$\text{Moment of } C = 4 \times 18 = \underline{72 \text{ inch-pounds}}$$

$$\text{Sum of negative numbers} = 120 \text{ inch-pounds}$$

Hence, the moments are equal, and, if we suppose, for simplicity, that the lever is weightless, it will balance or be in equilibrium. Should weight  $A$  be increased, the negative moments would be greater, and the lever would turn to the left, while if  $B$  should be increased or its distance from  $F$  be made greater, the lever would turn to the right. (See Handbook Fig. 9 and the accompanying text on [page 147](#).)

*Example 4:* Another application of the principle of moments is given in [Fig. 3](#). A beam of uniform cross section, weighing 200 pounds, rests upon two supports,  $R$  and  $S$ , that are 12 feet apart. The weight of the beam is considered to be concentrated at its center of gravity  $G$ , at a distance 6 feet from each supports react or push upward, with a force equal to the downward pressure of the beam.

To make this clear, suppose two people take hold of the beam, one at each end, and that the supports are withdrawn. Then, in order to hold the beam in position, the two people must together lift or pull upward an amount equal to the weight of the beam and its load, or 250 pounds. Placing the supports in position again, and resting the beam upon them, does not change the conditions. The weight of the beam acts downward, and the supports react by an equal amount.



**Fig. 3. The Weight on Each Support is Required**

Now, to solve the problem, assume the beam to be pivoted at one support, say, at  $S$ . The forces or weights of 50 pounds and 200 pounds tend to rotate the beam in a left-hand direction about this point, while the reaction of  $R$  in an upward direction tends to give it a right-hand rotation. As the beam is balanced and has no tendency to rotate, it is in equilibrium, and the opposing moments of these forces must balance; hence, taking moments,

$$9 \times 50 = 450 \text{ pound-feet}$$

$$6 \times 200 = \underline{1200 \text{ pound-feet}}$$

$$\text{Sum of negative numbers} = 1650 \text{ pound-feet}$$

By letting  $R$  represent the reaction of support,

$$\text{Moment of } R = R \times 12 = \text{pound-feet}$$

By the principle of moments,  $R \times 12 = 1650$ . That is, if  $R$ , the quantity that we wish to obtain, is multiplied by 12, the result will be 1650; hence, to obtain  $R$ , divide 1650 by 12. Therefore,  $R = 137.5$  pounds, which is also the weight of that end of the beam. As the total load is 250 pounds, the weight at the other end must be  $250 - 137.5 = 112.5$  pounds.

**The Principle of Work in Mechanics.**—Another principle of more importance than the principle of moments, even in the study of machine elements, is the principle of work. According to this principle (neglecting frictional or other losses), the applied force, multiplied by the distance through which it moves, equals the resistance overcome, multiplied by the distance through which it is overcome. The principle of work may also be stated as follows:

$$\text{Work put in} = \text{lost work} + \text{work done by machine}$$

This principle holds absolutely in every case. It applies equally to a simple lever, the most complex mechanism, or to a so-called “perpetual motion” machine. No machine can be made to perform work unless a somewhat greater amount—enough to make up for the losses—is applied by some external agent. In the “perpetual motion” machine no such outside force is supposed to be applied, hence such a machine is impossible, and against all the laws of mechanics.

*Example 5:* Assume that a rope exerts a pull  $F$  of 500 pounds (upper diagram, Handbook [page 162](#)) and that the pulley radius



$R = 10$  inches and the drum radius  $r = 5$  inches. How much weight  $W$  can be lifted (ignoring frictional losses) and upon what mechanical principle is the solution based?

According to one of the formulas accompanying the diagram at the top of Handbook [page 162](#),

$$W = \frac{F \times R}{r} = \frac{500 \times 10}{5} = 1000 \text{ pounds}$$

This formula (and the others for finding the values of  $F$ ,  $R$ , etc.) agrees with the principle of moments, and with the principle of work. The principle of moments will be applied first.

The moment of the force  $F$  about the center of the pulley, which corresponds to the fulcrum of a lever, is  $F$  multiplied by the perpendicular distance  $R$ , it being a principle of geometry that a radius is perpendicular to a line drawn tangent to a circle, at the point of tangency. Also, the opposing moment of  $W$  is  $W \times r$ . Hence, by the principle of moments,

$$F \times R = W \times r$$

Now, for comparison, we will apply the principle of work. Assuming this principle to be true, force  $F$  multiplied by the distance traversed by this force or by a given point on the rim of the large pulley should equal the resistance  $W$  multiplied by the distance that the load is raised. In one revolution, force  $F$  passes through a distance equal to the circumference of the pulley, which is equal to  $2 \times 3.1416 \times R = 6.2832 \times R$ , and the hoisting rope passes through a distance equal to  $2 \times 3.1416 \times r$ . Hence, by the principle of work,

$$6.2832 \times F \times R = 6.2832 \times W \times r$$

The statement simply shows that  $F \times R$  multiplied by 6.2832 equals  $W \times r$  multiplied by the same number, and it is evident therefore, that the equality will not be altered by canceling the 6.2832 and writing:

$$F \times R = W \times r$$

However, this statement is the same as that obtained by applying the principle of moments; hence, we see that the principle of moments and the principle of work are in harmony.

The basis of operation of a train of wheels is a continuation of the principle of work. For example, in the gear train represented by the diagram at the bottom of Handbook [page 162](#), the continued product of the applied force  $F$  and the radii of the driven wheels equals the continued product of the resistance  $W$  and the radii of the drivers. In calculations, the pitch diameters or the numbers of teeth in gear wheels may be used instead of the radii.

**Efficiency of a Machine or Mechanism.**—The efficiency of a machine is the ratio of the power delivered by the machine to the power received by it. For example, the efficiency of an electric motor is the ratio between the power delivered by the motor to the machinery it drives and the power it receives from the generator. Assume, for example, that a motor receives 50 kilowatts from the generator, but that the output of the motor is only 47 kilowatts. Then, the efficiency of the motor is  $47 \div 50 = 94$  per cent. The efficiency of a machine tool is the ratio of the power consumed at the cutting tool to the power delivered by the driving belt. The efficiency of gearing is the ratio between the power obtained from the driven shaft to the power used by the driving shaft. Generally speaking, the efficiency of any machine or mechanism is the ratio of the “output” of power to the “input.” The percentage of power representing the difference between the “input” and “output” has been dissipated through frictional and other mechanical losses.

*Mechanical Efficiency:* If  $E$  represents the energy that a machine transforms into useful work or delivers at the driven end, and  $L$  equals the energy loss through friction or dissipated in other ways, then,

$$\text{Mechanical efficiency} = \frac{E}{E + L}$$

In this equation, the total energy  $F + L$  is assumed to be the amount of energy that is transformed into useful and useless work. The actual total amount of energy, however, may be considerably larger than the amount represented by  $E + L$ . For example, in a steam engine, there are heat losses due to radiation and steam condensation, and considerable heat energy supplied to an internal combustion engine is dissipated either through the cooling water or direct to the atmosphere. In other classes of mechanical and elec-

trical machinery, the total energy is much larger than that represented by the amount transformed into useful and useless work.

*Absolute Efficiency:* If  $E_1$  equals the full amount of energy or the true total, then,

$$\text{Absolute efficiency} = \frac{E}{E_1}$$

It is evident that absolute efficiency of a prime mover, such as a steam or gas engine, will be much lower than the mechanical efficiency. Ordinarily, the term efficiency as applied to engines and other classes of machinery means the mechanical efficiency. The mechanical efficiency of reciprocating steam engines may vary from 85 to 95 per cent, but the thermal efficiency may range from 5 to 25 per cent, the smaller figure representing noncondensing engines of the cheaper class and the higher figure the best types.

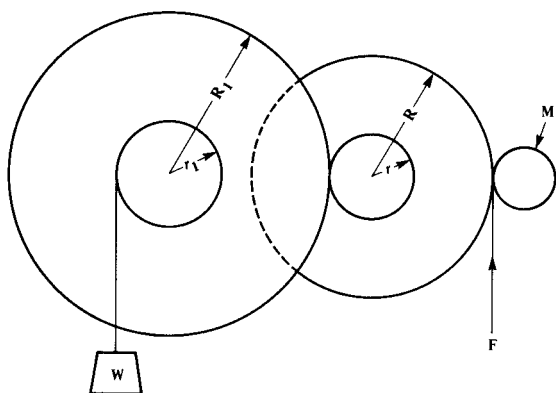
*Example 6:* Assume that a motor driving through a compound train of gearing (see diagram, **Fig. 4**) is to lift a weight  $W$  of 1000 pounds. The pitch radius  $R = 6$  inches;  $R_1 = 8$  inches; pitch radius of pinion  $r = 2$  inches; and radius of winding drum  $r_1 = 2\frac{1}{2}$  inches. What motor horsepower will be required if the frictional loss in the gear train and bearings is assumed to be 10 per cent? The pitch-line velocity of the motor pinion  $M$  is 1200 feet per minute.

The problem is to determine first the tangential force  $F$  required at the pitch line of the motor pinion; then, the equivalent horsepower is easily found. According to the formula at the bottom of Handbook **page 162**, which does not take into account frictional losses,

$$F = \frac{1000 \times 2 \times 2\frac{1}{2}}{6 \times 8} = 104 \text{ pounds}$$

The pitch-line velocity of the motor pinion is 1200 feet per minute and, as the friction loss is assumed to be 10 per cent, the mechanical efficiency equals  $90 \div (90 + 10) = 0.90$  or 90 per cent as commonly written; thus,

$$\text{Horsepower} = \frac{104 \times 1200}{33,000 \times 0.90} = 4\frac{1}{4} \text{ approximately}$$



**Fig. 4. Determining the Power Required for Lifting a Weight by Means of a Motor and a Compound Train of Gearing**

*Example 7:* In designing practice, a motor of horsepower, or larger, might be selected for the drive referred to in [Example 6](#) (depending upon conditions) to provide extra power should it be needed. However, to illustrate the procedure, assume that the gear train is to be modified so that the calculated horsepower will be 4 instead of  $4\frac{1}{4}$ ; conditions otherwise are the same as in [Example 6](#).

$$F = \frac{33,000 \times 4}{1200} = 110 \text{ pounds}$$

Hence, since  $W = 1000$  pounds,

$$1000 = \frac{110 \times 0.90 \times R \times R_1}{r \times r_1}$$

Insert any values for the pitch radii  $R$ ,  $R_1$ , etc., that will balance the equation, so that the right-hand side equals 1000, at least approximately. Several trial solutions may be necessary to obtain a total of about 1000, at the same time, secure properly proportional gears that meet other requirements of the design. Suppose the same radii are used here, except  $R_1$ , which is increased from 8 to  $8\frac{1}{2}$  inches. Then

$$\frac{110 \times 0.90 \times 6 \times 8\frac{1}{2}}{2 \times 2\frac{1}{2}} = 1000 \text{ approximately}$$

This example shows that the increase in the radius of the last driven gear from 8 to  $8\frac{1}{2}$  inches makes it possible to use the 4-horsepower motor. The hoisting speed has been decreased somewhat, and the center distance between the gears has been increased. These changes might or might not be objectionable in actual designing practice, depending upon the particular requirements.

**Force Required to Turn a Screw Used for Elevating or Lowering Loads.**— In determining the force that must be applied at the end of a given lever arm in order to turn a screw (or nut surrounding it), there are two conditions to be considered: (1) when rotation is such that the load *resists* the movement of the screw, as in raising a load with a screw jack; (2) when rotation is such that the load *assists* the movement of the screw, as in lowering a load. The formulas at the bottom of the table on Handbook [page 163](#) apply to both these conditions. When the load resists the screw movement, use the formula “for motion in a direction opposite to  $Q$ .” When the load assists the screw movement, use the formula “for motion in the same direction as  $Q$ .”

If the lead of the thread is large in proportion to the diameter so that the helix angle is large, the force  $F$  may have a negative value, which indicates that the screw will turn due to the load alone, unless resisted by a force that is great enough to prevent rotation of a nonlocking screw.

*Example 8:* A screw is to be used for elevating a load  $Q$  of 6000 pounds. The pitch diameter is 4 inches, the lead is 0.75 inch, and the coefficient of friction  $\mu$  between screw and nut is assumed to be 0.150. What force  $F$  will be required at the end of a lever arm  $R$  of 10 inches? In this example, the load is in the direction opposite to the arrow  $Q$  (see diagram at bottom of the table on Handbook [page 163](#)).

$$F = 6000 \times \frac{0.75 + 6.2832 \times 0.150 \times 2}{6.2832 \times 2 - 0.150 \times 0.75} \times \frac{2}{10}$$

$$= 254 \text{ pounds}$$

*Example 9:* What force  $F$  will be required to lower a load of 6000 pounds using the screw referred to in **Example 8**? In this case, the load assists in turning the screw; hence,

$$F = 6000 \times \frac{6.2832 \times 0.150 \times 2 - 0.75}{6.2832 \times 2 + 0.150 \times 0.75} \times \frac{2}{10} = 107 \text{ pounds}$$

### **Coefficients of Friction for Screws and Their Efficiency.—**

According to experiments Professor Kingsbury made with square-threaded screws, a friction coefficient  $\mu$  of 0.10 is about right for pressures less than 3000 pounds per square inch and velocities above 50 feet per minute, assuming that fair lubrication is maintained. If the pressures vary from 3000 to 10,000 pounds per square inch, a coefficient of 0.15 is recommended for low velocities. The coefficient of friction varies with lubrication and the materials used for the screw and nut. For pressures of 3000 pounds per square inch and by using heavy machinery oil as a lubricant, the coefficients were as follows: Mild steel screw and cast-iron nut, 0.132; mild-steel nut, 0.147; cast-brass nut, 0.127. For pressures of 10,000 pounds per square inch using a mild-steel screw, the coefficients were, for a cast-iron nut, 0.136; for a mild-steel nut, 0.141 for a cast-brass nut, 0.136. For dry screws, the coefficient may be 0.3 to 0.4 or higher.

Frictional resistance is proportional to the normal pressure, and for a thread of angular form, the increase in the coefficient of friction is equivalent practically to  $\mu \sec \beta$ , in which  $\beta$  equals one-half the included thread angle; hence, for a sixty-degree thread, a coefficient of  $1.155\mu$  may be used. The square form of thread has a somewhat higher efficiency than threads with sloping sides, although when the angle of the thread form is comparatively small, as in an Acme thread, there is little increase in frictional losses. Multiple-thread screws are much more efficient than single-thread screws, as the efficiency is affected by the helix angle of the thread.

The efficiency between a screw and nut increases quite rapidly for helix angles up to 10 to 15 degrees (measured from a plane perpendicular to the screw axis). The efficiency remains nearly constant for angles between about 25 and 65 degrees, and the angle of maximum efficiency is between 40 and 50 degrees. A screw will not be self-locking if the efficiency exceeds 50 per cent. For example, the screw of a jack or other lifting or hoisting appliance would turn under the action of the load if the efficiency were over 50 per cent. It is evident that maximum efficiency for power transmission screws often is impractical, as for example, when the smaller helix angles are required to permit moving a given load by the application of a smaller force or turning moment than would be needed for a multiple screw thread.

In determining the efficiency of a screw and a nut, the helix angle of the thread and the coefficient of friction are the important factors. If  $E$  equals the efficiency,  $A$  equals the helix angle, measured from a plane perpendicular to the screw axis, and  $\mu$  equals the coefficient of friction between the screw thread and nut, then the efficiency may be determined by the following formula, which does not take into account any additional friction losses, such as may occur between a thrust collar and its bearing surfaces:

$$E = \frac{\tan A(1 - \mu \tan A)}{\tan A + \mu}$$

This formula would be suitable for a screw having ball-bearing thrust collars. Where collar friction should be taken into account, a fair approximation may be obtained by changing the denominator of the foregoing formula to  $\tan A + 2\mu$ . Otherwise, the formula remains the same.

**Angles and Angular Velocity Expressed in Radians.**—There are three systems generally used to indicate the sizes of angles, which are ordinarily measured by the number of degrees in the arc subtended by the sides of the angle. Thus, if the arc subtended by the sides of the angle equals one-sixth of the circumference, the angle is said to be 60 degrees. Angles are also designated as multiples of a right angle. As an example, the sum of the interior angles of any polygon equals the number of sides less two, times two right angles. Thus the sum of the interior angles of an octagon

equals  $(8 - 2) \times 2 \times 90 = 6 \times 180 = 1080$  degrees. Hence each interior angle equals  $1080 \div 8 = 135$  degrees.

A third method of designating the size of an angle is very helpful in certain problems. This method makes use of radians. A radian is defined as a central angle, the subtended arc of which equals the radius of the arc.

By using the symbols on Handbook [page 88](#),  $v$  may represent the length of an arc as well as the velocity of a point on the periphery of a body. Then, according to the definition of a radian:  $\omega = v/r$ , or the angle in radians equals the length of the arc divided by the radius. Both the length of the arc and the radius must, of course, have the same unit of measurement – both must be in feet or inches or centimeters, etc. By rearranging the preceding equation:

$$v = \omega r \quad \text{and} \quad r = \frac{v}{\omega}$$

These three formulas will solve practically every problem involving radians.

The circumference of a circle equals  $\pi d$  or  $2\pi r$ , which equals  $6.2832r$ , which indicates that a radius is contained in a circumference 6.2832 times; hence there are 6.2832 radians in a circumference. Since a circumference represents 360 degrees, 1 radian equals  $360 \div 6.2832 = 57.2958$  degrees. Since  $57.2958$  degrees = 1 radian,  $1$  degree =  $1$  radian  $\div 57.2958 = 0.01745$  radian.

*Example 10:* 2.5 radians equal how many degrees? One radian = 57.2958 degrees; hence, 2.5 radians =  $57.2958 \times 2.5 = 143.239$  degrees.

*Example 11:*  $22^\circ 31' 12'' =$  how many radians? 12 seconds =  $\frac{12}{60} = \frac{1}{5} = 0.2$  minute;  $31.2' \div 60 = 0.52$  degree. One radian = 57.3 degrees approximately.  $22.52^\circ = 22.52 + 57.3 = 0.393$  radian.

*Example 12:* In the figure on Handbook [page 71](#), let  $l = v = 30$  inches; and radius  $r = 50$  inches; find the central angle  $\omega = v/r = \frac{30}{50} = \frac{3}{5} = 0.6$  radian.

$$57.2958 \times 0.6 = 34^\circ 22.6'$$

*Example 13:*  $\frac{3\pi}{4}$  radians equal how many degrees?  $2\pi$  radians =  $360^\circ$ ;  $\pi$  radians =  $180^\circ$ .  $\frac{3\pi}{4} = \frac{3}{4} \times 180 = 135$  degrees.



*Example 14:* A 20-inch grinding wheel has a surface speed of 6000 feet per minute. What is the angular velocity?

The radius ( $r$ ) =  $\frac{10}{12}$  foot; the velocity ( $n$ ) in feet per second =  $\frac{6000}{60}$ ; hence,

$$\omega = \frac{6000}{60 \times \frac{10}{12}} = 120 \text{ radians per second}$$

*Example 15:* Use the table on Handbook [page 96](#) to solve [Example 11](#).

$$20^\circ = 0.349066 \text{ radian}$$

$$2^\circ = 0.034907 \text{ radian}$$

$$31' = 0.009018 \text{ radian}$$

$$12'' = 0.000058 \text{ radian}$$

---


$$22^\circ 31' 12'' = 0.393049 \text{ radian}$$

*Example 16:* 7.23 radians equals how many degrees? On Handbook [page 97](#), find:

$$7.0 \text{ radians} = 401^\circ 4' 14''$$

$$0.2 \text{ radian} = 11^\circ 27' 33''$$

$$0.03 \text{ radian} = 1^\circ 43' 8''$$

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$$7.23 \text{ radians} = 414^\circ 14' 55''$$

### PRACTICE EXERCISES FOR SECTION 15

(See [Answers to Practice Exercises For Section 15](#) on page 231)

- 1) In what respect does a foot-pound differ from a pound?
- 2) If a 100-pound weight is dropped, how much energy will it be capable of exerting after falling 10 feet?
- 3) Can the force of a hammer blow be expressed in pounds?
- 4) If a 2-pound hammer is moving 30 feet per second, what is its kinetic energy?
- 5) If the hammer referred to in Exercise 4 drives a nail into a  $\frac{1}{4}$ -inch board, what is the average force of the blow?
- 6) What relationship is there between the muzzle velocity of a projectile fired upward and the velocity with which the projectile strikes the ground?
- 7) What is the difference between the composition of forces and the resolution of forces?

8) If four equal forces act along lines 90 degrees apart through a given point, what is the shape of the corresponding polygon of forces?

9) Skids are to be employed for transferring boxed machinery from one floor to the floor above. If these skids are inclined at an angle of 35 degrees, what force in pounds, applied parallel to the skids, will be required to slide a boxed machine weighing 2500 pounds up the incline, assuming that the coefficient of friction is 0.20?

10) Refer to Exercise 9. If the force or pull were applied in a horizontal direction instead of in line with the skids, what increase, if any, would be required?

11) Will the boxed machine referred to in Exercise 9 slide down the skids by gravity?

12) At what angle will the skids require to be before the boxed machine referred to in Exercise 9 begins to slide by gravity?

13) What name is applied to the angle that marks the dividing line between sliding and nonsliding when a body is placed on an inclined plane?

14) How is the "angle of repose" determined?

15) What figure or value is commonly used in engineering calculations for acceleration due to gravity?

16) Is the value commonly used for acceleration due to gravity strictly accurate for any locality?

17) A flywheel 3 feet in diameter has a rim speed of 1200 feet per minute, and another flywheel 6 feet in diameter has the same rim speed. Will the rim stress or the force tending to burst the larger flywheel be greater than the force in the rim of the smaller flywheel?

18) What factors of safety are commonly used in designing flywheels?

19) Does the stress in the rim of a flywheel increase in proportion to the rim velocity?

20) What is generally considered the maximum safe speed for the rim of a solid or one-piece cast-iron flywheel?

21) Why is a well-constructed wood flywheel better adapted to higher speeds than one made of cast iron?

- 22) What is the meaning of the term “critical speed” as applied to a rotating body?
- 23) How is angular velocity generally expressed?
- 24) What is a radian, and how is its angle indicated?
- 25) How many degrees are there in 2.82 radians?
- 26) How many degrees are in the following radians:  $\frac{\pi}{3}$ ;  $\frac{2\pi}{5}$ ;
- 27) Reduce to radians:  $63^\circ$ ;  $45^\circ 32'$ ;  $6^\circ 37' 46''$ ;  $22^\circ 22' 22''$ .
- 28) Find the angular velocity in radians per second of the following: 157 rpm; 275 rpm; 324 rpm.
- 29) Why do the values in the *l* column starting on Handbook [page 71](#) equal those in the radian column on [page 96](#)?
- 30) If the length of the arc of a sector is  $4\frac{7}{8}$  inches, and the radius is  $6\frac{7}{8}$  inches, find the central angle.
- 31) A 12-inch grinding wheel has a surface speed of a mile a minute. Find its angular velocity and its revolutions per minute.
- 32) The radius of a circle is  $1\frac{1}{2}$  inches, and the central angle is 60 degrees. Find the length of the arc.
- 33) If an angle of  $34^\circ 12'$  subtends an arc of 16.25 inches, find the radius of the arc.

## SECTION 16

### STRENGTH OF MATERIALS

HANDBOOK Pages 203 – 225

The Strength of Materials section of Machinery's Handbook contains fundamental formulas and data for use in proportioning parts that are common to almost every type of machine or mechanical structure. In designing machine parts, factors other than strength often are of vital importance. For example, some parts are made much larger than required for strength alone to resist extreme vibrations, deflection, or wear; consequently, many machine parts cannot be designed merely by mathematical or strength calculations, and their proportions should, if possible, be based upon experience or upon similar designs that have proved successful. It is evident that no engineering handbook can take into account the endless variety of requirements relating to all types of mechanical apparatus, and it is necessary for the designer to determine these local requirements for each, but, even when the strength factor is secondary due to some other requirement, the strength, especially of the more important parts, should be calculated, in many instances, merely to prove that it will be sufficient.

In designing for strength, the part is so proportioned that the maximum working stress likely to be encountered will not exceed the strength of the material by a suitable margin. The design is accomplished by the use of a factor of safety. The relationship between the working stress  $s_w$ , the strength of the material,  $S_m$ , and the factor of safety,  $f_s$  is given by Equation (1) on [page 208](#) of the Handbook:

$$s_w = \frac{S_m}{f_s} \quad (a)$$

The value selected for the strength of the material,  $S_m$  depends on the type of material, whether failure is expected to occur

because of tensile, compressive, or shear stress, and on whether the stresses are constant, fluctuating, or are abruptly applied as with shock loading. In general, the value of  $S_m$  is based on yield strength for ductile materials, ultimate strength for brittle materials, and fatigue strength for parts subject to cyclic stresses. Moreover, the value for  $S_m$  must be for the temperature at which the part operates. Values of  $S_m$  for common materials at 68°F can be obtained from the tables in Machinery's Handbook from [page 474](#) and [554](#). Factors from the table given on Handbook [page 421](#), *Influence of Temperature on the Strength of Metals*, can be used to convert strength values at 68°F to values applicable at elevated temperatures. For heat-treated carbon and alloy steel parts, see data starting on Handbook [page 468](#).

The factor of safety depends on the relative importance of reliability, weight, and cost. General recommendations are given in the Handbook on [page 208](#).

Working stress is dependent on the shape of the part, hence on a stress concentration factor, and on a nominal stress associated with the way in which the part is loaded. Equations and data for calculating nominal stresses, stress concentration factors, and working stresses are given starting on Handbook [page 208](#).

*Example 1:* Determine the allowable working stress for a part that is to be made from SAE 1112 free-cutting steel; the part is loaded in such a way that failure is expected to occur in tension when the yield strength has been exceeded. A factor of safety of 3 is to be used.

From the table, *Strength Data for Iron and Steel*, on [page 474](#) of the Handbook, a value of 30,000 psi is selected for the strength of the material,  $S_m$ . Working stress  $S_w$  is calculated from [Equation \(a\)](#) as follows:

$$s_w = \frac{30,000}{3} = 10,000 \text{ psi}$$

**Finding Diameter of Bar to Resist Safely Under a Given Load.**—Assume that a direct tension load,  $F$ , is applied to a bar such that the force acts along the longitudinal axis of the bar. From Handbook [page 213](#), the following equation is given for calculating the nominal stress:

$$\sigma = \frac{F}{A} \quad (\text{b})$$

where  $A$  is the cross-sectional area of the bar. Equation (2) on Handbook [page 208](#) related the nominal stress to the stress concentration factor,  $K$ , and working stress,  $S_w$ :

$$s_w = K\sigma \quad (\text{c})$$

Combining [Equations \(a\)](#), [\(b\)](#), and [\(c\)](#) results in the following:

$$\frac{S_m}{Kf_s} = \frac{F}{A} \quad (\text{d})$$

*Example 2:* A structural steel bar supports in tension a load of 40,000 pounds. The load is gradually applied and, then, after having reached its maximum value, is gradually removed. Find the diameter of round bar required.

According to the table on Handbook [page 474](#), the yield strength of structural steel is 33,000 psi. Suppose that a factor of safety of 3 and a stress concentration factor of 1.1 are used. Then, inserting known values in [Equation \(d\)](#):

$$\frac{33,000}{1.1 \times 3} = \frac{40,000}{A}; A = \frac{40,000 \times 3.3}{33,000}; A = 4 \text{ square inches}$$

Hence, the cross-section of the bar must be about 4 square inches. As the bar is circular in section, the diameter must then be about  $2\frac{1}{4}$  inches.

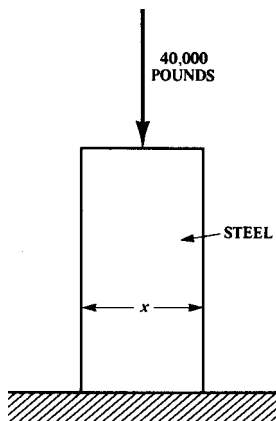
**Diameter of Bar to Resist Compression.**—If a short bar is subjected to compression in such a way that the line of application of the load coincides with the longitudinal axis of the bar, the formula for nominal stress is the same as for direct tension loading. [Equation \(b\)](#) and hence [Equation \(d\)](#) also may be applied to direct compression loading.

*Example 3:* A short structural steel bar supports in compression a load of 40,000 pounds. (See Fig. 1.) The load is steady. Find the diameter of the bar required.

From [page 474](#) in the Handbook, the yield strength of structural steel is 33,000 psi. If a stress concentration factor of 1.1 and a fac-

tor of safety of 2.5 are used, then, substituting values into **Equation (d)**:

$$\frac{33,000}{1.1 \times 2.5} = \frac{40,000}{A}; A = 3.33 \text{ square inches}$$



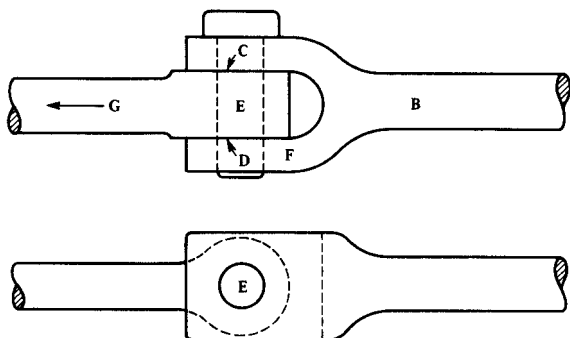
**Fig. 1. Calculating Diameter  $x$  to Support a Given Load Safely**

The diameter of a bar, the cross-section of which is 3.33 square inches, is about  $2\frac{1}{16}$  inches.

According to a general rule, the simple formulas that apply to compression should be used only if the length of the member being compressed is not greater than 6 times the least cross-sectional dimension. For example, these formulas should be applied to round bars only when the length of the bar is less than 6 times the diameter. If the bar is rectangular, the formulas should be applied only to bars having a length less than 6 times the shortest side of the rectangle. When bars are longer than this, a compressive stress causes a sidewise bending action, and an even distribution of the compression stresses over the total area of the cross-section should no longer be depended upon. Special formulas for long bars or columns will be found on Handbook [page 287](#); see also text beginning on [page 285](#), *Strength of Columns or Struts*.

**Diameter of Pin to Resist Shearing Stress.**—The pin  $E$  shown in the illustration, [Fig. 2](#), is subjected to shear. Parts  $G$  and  $B$  are held

together by the pin and tend to shear it off at *C* and *D*. The areas resisting the shearing action are equal to the pin at these points.



**Fig. 2. Finding the Diameter of Connecting-Rod Pin to Resist a Known Load *G***

From the *Table of Simple Stresses* on [page 213](#) of the Handbook, the equation for direct shear is:

$$\tau = \frac{F}{A} \quad (\text{e})$$

$\tau$  is a simple stress related to the working stress,  $s_w$ , by Equation (3) on Handbook [page 208](#):

$$s_w = K\tau \quad (\text{f})$$

where  $K$  is a stress concentration factor. Combining [Equation \(a\)](#), [\(e\)](#), and [\(f\)](#) gives [Equation \(d\)](#) on page 140, where  $S_m$  is, of course, the shearing strength of the material.

If a pin is subjected to shear as in [Fig. 2](#), so that two surfaces, as at *C* and *D*, must fail by shearing before breakage occurs, the areas of both surfaces must be taken into consideration when calculating the strength. The pin is then said to be in *double shear*. If the lower part *F* of connecting rod *B* were removed, so that member *G* were connected with *B* by a pin subjected to shear at *C* only, the pin would be said to be in *single shear*.

*Example 4:* Assume that in [Fig. 2](#) the load at *G* pulling on the connecting rod is 20,000 pounds. The material of the pin is SAE



1025 steel. The load is applied in such a manner that shocks are liable to occur. Find the required dimensions for the pin.

Since the pins are subjected to shock loading, the nominal stress resulting from the application of the 20,000-pound load must be assumed to be twice as great (see Handbook starting on [page 282](#)) as it would be if the load were gradually applied or steady. From Handbook [page 474](#), the ultimate strength in shear for SAE 1025 steel is 75 per cent of 60,000 or 45,000 psi. A factor of safety of 3 and a stress concentration factor of 1.8 are to be used. By substituting values into [Equation \(d\)](#):

$$\frac{45,000}{1.8 \times 3} = \frac{2 \times 20,000}{A}; \quad A = \frac{10.8 \times 20,000}{45,000}$$

$$= 4.8 \text{ sq. in.}$$

As the pin is in double shear, that is, as there are two surfaces *C* and *D* over which the shearing stress is distributed, each surface must have an area of one-half the total shearing area *A*. Then, the cross-sectional area of the pin will be 2.4 square inches, and the diameter of the pin, to give a cross-sectional area of 2.4 square inches, must be  $1\frac{3}{4}$  inches.

**Beams, and Stresses to Which They Are Subjected.**—Parts of machines and structures subjected to bending are known mechanically as *beams*. Hence, in this sense, a lever fixed at one end and subjected to a force at its other end, a rod supported at both ends and subjected to a load at its center, or the overhanging arm of a jib crane would all be known as beams.

The stresses in a beam are principally tension and compression stresses. If a beam is supported at the ends, and a load rests upon the upper side, the lower fibers will be stretched by the bending action and will be subjected to a tensile stress, while the upper fibers will be compressed and be subjected to a compressive stress. There will be a slight lengthening of the fibers in the lower part of the beam, while those on the upper side will be somewhat shorter, depending upon the amount of deflection. If we assume that the beam is either round or square in cross-section, there will be a layer or surface through its center line, which will be neither in compression nor in tension.

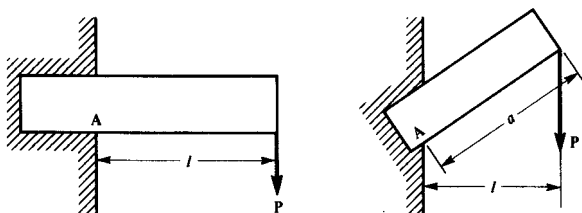
This surface is known as the neutral surface. The stresses of the individual layers or fibers of the beam will be proportional to their distances from the neutral surface, the stresses being greater the farther away from the neutral surface the fiber is located. Hence, there is no stress on the fibers in the neutral surface, but there is a maximum tension on the fibers at the extreme lower side and a maximum compression on the fibers at the extreme upper side of the beam. In calculating the strength of beams, it is, therefore, only necessary to determine that the fibers of the beam that are at the greatest distance from the neutral surface are not stressed beyond the safe working stress of the material. If this condition exists, all the other parts of the section of the beam are not stressed beyond the safe working stress of the material.

In addition to the tension and compression stresses, a loaded beam is also subjected to a stress that tends to shear it. This shearing stress depends upon the magnitude and kind of load. In most instances, the shearing action can be ignored for metal beams, especially if the beams are long and the loads far from the supports. If the beams are very short and the load quite close to a support, then the shearing stress may become equal to or greater than the tension or compression stresses in the beam and the beam should then be calculated for shear.

**Beam Formulas.**— The bending action of a load upon a beam is called the *bending moment*. For example, in **Fig. 3** the load  $P$  acting downward on the free end of the cantilever beam has a moment or bending action about the support at  $A$  equal to the load multiplied by its distance from the support. The bending moment is commonly expressed in inch-pounds, the load being expressed in pounds and the lever arm or distance from the support in inches. The length of the lever arm should always be measured in a direction at right angles to the direction of the load. Thus, in **Fig. 4**, the bending moment is not  $P \times a$ , but is  $P \times l$ , because  $l$  is measured in a direction at right angles to the direction of the load  $P$ .

The property of a beam to resist the bending action or the bending moment is called the *moment of resistance* of the beam. It is evident that the bending moment must be equal to the moment of resistance. The moment of resistance, in turn, is equal to the stress in the fiber farthest away from the neutral plane multiplied by the

section modulus. The *section modulus* is a factor that depends upon the shape and size of the cross-section of a beam and is given for different cross-sections in all engineering handbooks. (See table, *Moments of Inertia, Section Moduli, and Radii of Gyration* starting on Handbook [page 238](#).) The section modulus, in turn, equals the moment of inertia of the cross-section, divided by the distance from the neutral surface to the most extreme fiber. The moment of inertia formulas for various cross-sections also will be found in the table just mentioned.



**Fig. 3. Diagrams Illustrating Principle of Bending Moments**

The following formula on Handbook [page 213](#) may be given as the fundamental formula for bending of beams:

$$\sigma = \pm \frac{M}{Z} = \pm \frac{My}{I} \quad (g)$$

The moment of inertia  $I$  is a property of the cross-section that determines its relative strength. In calculations of strength of materials, a handbook is necessary because of the tabulated formulas and data relating to section moduli and moments of inertia, areas of cross-sections, etc., to be found therein.

There are many different ways in which a beam can be supported and loaded, and the bending moment caused by a given load varies greatly according to whether the beam is supported at one end only or at both ends, also whether it is freely supported at the ends or is held firmly. The load may be equally distributed over the full length of the beam or may be applied at one point either in the center or near to one or the other of the supports. The point where stress is maximum is generally called the critical point. The stress at the critical point equals bending moment divided by section modulus.

Formulas for determining the stresses at the critical points will be found in the table of beam formulas, starting on Handbook page 261.

*Example 5:* A rectangular steel bar 2 inches thick and firmly built into a wall, as shown in Fig. 4, is to support 3000 pounds at its outer end 36 inches from the wall. What would be the necessary depth  $h$  of the beam to support this weight safely?

The bending moment equals the load times the distance from the point of support, or  $3000 \times 36 = 108,000$  inch-pounds.

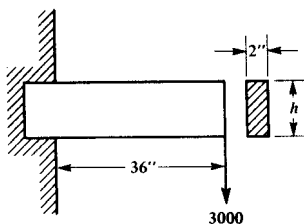
By combining Equation (a), (c), and (g), the following equation is obtained:

$$\frac{S_m}{Kf_s} = \frac{M}{Z} \quad (h)$$

If the beam is made from structural steel, the value for  $S_m$ , based on yield strength, from page 474 in the Handbook, is 33,000 psi. By using a stress concentration factor of 1.1 and a factor of safety of 2.5, values may be inserted into the above equation:

$$\frac{33,000}{1.1 \times 2.5} = \frac{108,000}{Z}; \quad Z = \frac{2.75 \times 108,000}{33,000}; \quad Z = 9 \text{ inches}^3$$

The section modulus for a rectangle equals  $bd^2/6$ , in which  $b$  is the length of the shorter side and  $d$  of the longer side of the rectangle (see Handbook page 239), hence,  $Z = bd^2/6$ .



**Fig. 4. Determining the Depth  $h$  of a Beam to Support a Known Weight**

But  $Z = 9$  and  $b = 2$ . Inserting these values into the formula, we have:

$$9 = \frac{2d^2}{6}$$

from which  $d^2 = 27$ , and  $d = 5.2$  inches. This value  $d$  corresponds to dimension  $h$  in **Fig. 4**. Hence, the required depth of the beam to support a load of 3000 pounds at the outer end with a factor of safety of 3 would be 5.2 inches.

In calculating beams having either rectangular or circular cross-sections, the formulas on Handbook **page 273** are convenient to use. A beam loaded as shown by **Fig. 4** is similar to the first diagram on Handbook **page 273**. If the formula on this page in the Handbook for determining height  $h$  is applied to **Example 5, Fig. 4**, then,

$$h = \sqrt{\frac{6lW}{bf}} = \sqrt{\frac{6 \times 36 \times 3000}{2 \times 12,000}} = 5.2 \text{ inches}$$

In the above calculation the stress value  $f$  is equivalent to  $S_m/Kf_s$ .

*Example 6:* A steel I-beam is to be used as a crane trolley track. This I-beam is to be supported at the ends, and the unsupported span is 20 feet long. The maximum load is 6000 pounds, and the nominal stress is not to exceed 10,000 pounds per square inch. Determine the size of the standard I-beam; also determine the maximum deflection when the load is at the center of the beam.

The foregoing conditions are represented by Case 2, Handbook **page 261**. A formula for the stress at the critical point is  $Wl/4Z$ . As explained on Handbook **page 260**, all dimensions are in inches, and the minus sign preceding a formula merely denotes compression of the upper fibers and tension in the lower fibers.

By inserting the known values in the formula:

$$10,000 = \frac{6000 \times 240}{4Z}; \text{ hence}$$

$$Z = \frac{6000 \times 240}{10,000 \times 4} = 36$$

The table of standard I-beams on Handbook **page 2513** shows that a 12-inch I-beam, which weighs 31.8 pounds per foot, has a section modulus of 36.4.

The formula for maximum deflection (see Handbook starting on [page 261](#), Case 2) is  $Wl^3/48EI$ . According to the table on Handbook [page 474](#), the modulus of elasticity ( $E$ ) of structural steel is 29,000,000.

As  $Z$  = moment of inertia  $I \div$  distance from neutral axis to extreme fiber (see Handbook [page 260](#)), then for a 12-inch I-beam  $I = 6Z = 216$ ; hence,

$$\text{Maximum deflection} = \frac{6000 \times (240)^3}{48 \times 29,000,000 \times 216} = 0.27 \text{ inch}$$

*Example 7:* All conditions are the same as in [Example 6](#), except that the maximum deflection at the “critical point,” or center of the I-beam, must not exceed  $\frac{1}{8}$  inch. What size I-beam is required?

To meet the requirement regarding deflection,

$$\frac{1}{8} = \frac{Wl^3}{48EI}; \text{ therefore,}$$

$$I = \frac{8Wl^3}{48E} = \frac{8 \times 6000 \times (240)^3}{48 \times 29,000,000} = 476$$

If  $x$  = distance from neutral axis to most remote fiber ( $\frac{1}{2}$  beam depth in this case), then  $Z = I/x$ , and the table on Handbook [page 2513](#) shows that a 15-inch, 50-pound I-beam should be used because it has a section modulus of 64.8 and  $476/7.5 = 63.5$  nearly.

If 476 were divided by 6 ( $\frac{1}{2}$  depth of a 12-inch I-beam), the result would be much higher than the section modulus of any standard 12-inch I-beam ( $476 \div 6 = 79.3$ ); moreover,  $576 \div 9 = 64$ , which shows that an 18-inch I-beam is larger than is necessary because the lightest beam of this size has a section modulus of 81.9.

*Example 8:* If the speed of a motor is 1200 revolutions per minute and if its driving pinion has a pitch diameter of 3 inches, determine the torsional moment to which the pinion shaft is subjected, assuming that 10 horsepower is being transmitted.

If  $W$  = tangential load in pounds,  $H$  = the number of horsepower, and  $V$  = pitch-line velocity in feet per minute,

$$\begin{aligned}
 W &= \frac{33,000 \times H}{V} \\
 &= \frac{33,000 \times 10}{943} = 350 \text{ pounds}
 \end{aligned}$$

The torsional moment =  $W \times$  pitch radius of pinion =  $350 \times 1.5 = 525$  pound-inches (or inch-pounds).

*Example 9:* If the pinion referred to in **Example 8** drives a gear having a pitch diameter of 12 inches, to what torsional or turning moment is the gear shaft subjected?

The torque or torsional moment in any case = pitch radius of gear  $\times$  tangential load. The latter is the same for both gear and pinion; hence, torsional moment of gear =  $350 \times 6 = 2100$  inch-pounds.

The torsional moment or the turning effect of a force that tends to produce rotation depends upon (1) the magnitude of the force acting, and (2) the distance of the force from the axis of rotation, measuring along a line at right angles to the line of action of the force.

### PRACTICE EXERCISES FOR SECTION 16

(See *Answers to Practice Exercises For Section 16* on page 233)

- 1) What is a "factor of safety," and why are different factors used in machine design?
- 2) If the ultimate strength of a steel rod is 60,000 pounds per square inch, and the factor of safety is 5, what is the equivalent working stress?
- 3) If a steel bar must withstand a maximum pull of 9000 pounds and if the maximum nominal stress must not exceed 12,000 pounds per square inch, what diameter bar is required?
- 4) Is a steel rod stronger when at ordinary room temperature or when heated to 500°F?
- 5) What is the meaning of the term "elastic limit"?
- 6) Approximately what percentages of copper and zinc in brass result in the greatest tensile strength?
- 7) If four 10-foot-long pipes are to be used to support a water tank installation weighing 100,000 pounds, what diameter standard weight pipe is required?

## SECTION 17

### DESIGN OF SHAFTS AND KEYS FOR POWER TRANSMISSION

HANDBOOK Pages 299 – 307 and Pages 2363 – 2387

This section is a review of the general procedure in designing shafts to resist both torsional and combined torsional and bending stresses. The diameter of a shaft through which power is transmitted depends, for a given shaft material, upon the amount and kind of stress or stresses to which the shaft is subjected. To illustrate the general procedure, we shall assume first that the shaft is subjected only to a uniform torsional or twisting stress and that there is no additional bending stress that needs to be considered in determining the diameter.

*Example 1:* A lineshaft carrying pulleys located close to the bearings is to transmit 50 horsepower at 1200 revolutions per minute. If the load is applied gradually and is steady, what diameter steel shaft is required, assuming that the pulleys are fastened to the shaft by means of keys and that the bending stresses caused by the pull of the belts are negligible?

According to the former American Standard Association's Code for the Design of Transmission Shafting, the diameter of shaft required to meet the stated conditions can be determined by using the following formula (Formula (16b), Handbook page 304).

$$D = B \times \sqrt[3]{\frac{321,000 K_t P}{S_s N}}$$

In this formula,  $D$  = required shaft diameter in inches;  $B$  = a factor, which for solid shafts is taken as 1;  $K_t$  = combined shock and fatigue factor;  $P$  = maximum horsepower transmitted by shaft;  $S_s$  = maximum allowable torsional shearing stress in pounds per square inch; and  $N$  = shaft speed in revolutions per minute.



From Table 1 on Handbook [page 305](#),  $K_t = 1.0$  for gradually applied and steady loads, and from Table 2 the recommended maximum allowable working stress for “Commercial Steel” shafting with keyways subjected to pure torsion loads is 6000 pounds per square inch. By substituting in the formula,

$$D = 1 \times 3 \sqrt[3]{\frac{321,000 \times 1.0 \times 50}{6000 \times 1200}} = 1.306 \text{ inches}$$

The nearest standard size transmission shafting from the table on Handbook [page 303](#) is  $1\frac{7}{16}$  inches.

*Example 2:* If, in [Example 1](#), the shaft diameter had been determined by using Formula (5b), Handbook [page 299](#), what would the result have been and why?

$$D = 3 \sqrt[3]{\frac{53.5P}{N}} = 3 \sqrt[3]{\frac{53.5 \times 50}{1200}} = 1.306 \text{ inches}$$

This formula gives the same shaft diameter as was previously determined because it is simplified form of the first formula used and contains the same values of  $K_t$  and  $S_s$ , but combined as the single constant 53.5. For lineshafts carrying pulleys under conditions ordinarily encountered, this simplified formula is usually quite satisfactory; but, where conditions of shock loading are known to exist, it is safer to use Formula (16b), Handbook [page 304](#), which takes such conditions into account.

**Shafts Subjected to Combined Stresses.**—The preceding formulas are based on the assumption that the shaft is subjected to torsional stresses only. However, many shafts must withstand stresses that result from combinations of torsion, bending, and shock loading. In such conditions it is necessary to use formulas that take such stresses into account.

*Example 3:* Suppose that, after the lineshaft in [Example 1](#) was installed, it became necessary to relocate a machine that was being driven by one of the pulleys on the shaft. Because of the new machine location, it was necessary to move the pulley on the lineshaft farther away from the nearest bearing, and, as a result, a bending moment of 2000 inch-pounds was introduced. Is the  $1\frac{7}{16}$ -

inch diameter shaft sufficient to take this additional stress, or will it be necessary to relocate the bearing to provide better support?

Since there are now both bending and torsional loads acting on the shaft, Formula (18b), Handbook [page 304](#) should be used to compute the required shaft diameter. This diameter is then compared with the  $1\frac{7}{16}$  inch diameter previously determined.

$$D = B \times 3 \sqrt[3]{\frac{5.1}{p_t} \sqrt{(K_m M)^2 + \left(\frac{63,000 K_t P}{N}\right)^2}}$$

In this formula  $B$ ,  $K_t$ ,  $P$ , and  $N$  are quantities previously defined and  $p_t$  = maximum allowable shearing stress under combined loading conditions in pounds per square inch;  $K_m$  = combined shock and fatigue factor; and  $M$  = maximum bending moment in inch-pounds.

From Table 1 on Handbook [page 305](#),  $K_m = 1.5$  for gradually applied and steady loads and from Table 2,  $p_t = 6000$  pounds per square inch. By substituting in the formula,

$$\begin{aligned} D &= 1 \times 3 \sqrt[3]{\frac{5.1}{6000} \sqrt{(1.5 \times 2000)^2 + \left(\frac{63,000 \times 1 \times 50}{1200}\right)^2}} \\ &= 3 \sqrt[3]{\frac{5.1}{6000} \sqrt{9000000 + 6,890,625}} = 3 \sqrt[3]{\frac{5.1}{6000} \times 3986} \\ &= \sqrt[3]{3.388} = 1.502 \text{ inches or about } 1\frac{1}{2} \text{ inches} \end{aligned}$$

This diameter is larger than the  $1\frac{7}{16}$ -inch diameter used for the shaft in [Example 1](#), so it will be necessary to relocate the bearing closer to the pulley, thus reducing the bending moment. The  $1\frac{7}{16}$ -inch diameter shaft will then be able to operate within the allowable working stress for which it was originally designed.

**Design of Shafts to Resist Torsional Deflection.**—Shafts must often be proportioned not only to provide the strength required to transmit a given torque, but also to prevent torsional deflection (twisting) through a greater angle than has been found satisfactory for a given type of service. This requirement is particularly true for machine shafts and machine-tool spindles.

For ordinary service, it is customary that the angle of twist of machine shafts be limited to  $\frac{1}{10}$  degree per foot of shaft length, and for machine shafts subject to load reversals,  $\frac{1}{20}$  degree per foot of shaft length. As explained in the Handbook, the usual design procedure for shafting that is to have a specified maximum angular deflection is to compute the diameter of shaft required based on both deflection and strength considerations and then to choose the larger of the two diameters thus determined.

*Example 4:* A 6-foot-long feed shaft is to transmit a torque of 200 inch-pounds. If there are no bending stresses, and the shaft is to be limited to a torsional deflection of  $\frac{1}{20}$  degree per foot of length, what diameter shaft should be used? The shaft is to be made of cold drawn steel and is to be designed for a maximum working stress of 6000 pounds per square inch in torsion.

The diameter of shaft required for a maximum angular deflection  $\alpha$  is given by Formula (13), Handbook [page 301](#).

$$D = 4.9 \sqrt[4]{\frac{Tl}{G\alpha}}$$

In this formula  $T$  = applied torque in inch-pounds;  $l$  = length of shaft in inches;  $G$  = torsional modulus of elasticity, which, for steel, is 11,500,000 pounds per square inch; and  $\alpha$  = angular deflection of shaft in degrees.

In the problem at hand,  $T = 200$  inch-pounds;  $l = 6 \times 12 = 72$  inches; and  $\alpha = 6 \times 1/20 = 0.3$  degree.

$$\begin{aligned} D &= 4.9 \sqrt[4]{\frac{200 \times 72}{11,500,000 \times 0.3}} = 4.9 \sqrt[4]{0.0041739} \\ &= 4.9 \times 0.254 = 1.24 \text{ inches} \end{aligned}$$

The diameter of the shaft based on strength considerations is obtained by using Formula (3a), Handbook [page 299](#).

$$D = \sqrt[3]{\frac{5.1T}{S_s}} = \sqrt[3]{\frac{5.1 \times 200}{6000}} = \sqrt[3]{0.17} = 0.55 \text{ inch}$$

From the above calculations, the diameter based on torsional deflection considerations is the larger of the two values obtained, so the nearest standard diameter,  $1\frac{1}{4}$  inches, should be used.

**Selection of Key Size Based on Shaft Size.**—Keys are generally proportioned in relation to shaft diameter instead of in relation to torsional load to be transmitted because of practical reasons such as standardization of keys and shafts. Standard sizes are listed in the table, *Key Size Versus Shaft Diameter ANSI B17.1-1967 (R1998)* on Handbook [page 2363](#). Dimensions of both square and rectangular keys are given, but for shaft diameters up to and including  $6\frac{1}{2}$  inches, square keys are preferred. For larger shafts, rectangular keys are commonly used.

Two rules that base key length on shaft size are: (1)  $L = 1.5D$  and (2)  $L = 0.3D^2 \div T$ , where  $L$  = length of key,  $D$  = diameter of shaft, and  $T$  = key thickness.

If the keyset is to have fillets, and the key is to be chamfered, suggested dimensions for these modifications are given on Handbook [page 2368](#). If a set screw is to be used over the key, suggested sizes are given in the table on Handbook [page 2368](#).

*Example 5:* If the maximum torque output of a 2-inch diameter shaft is to be transmitted to a keyed pulley, what should be the proportions of the key?

According to the table on Handbook [page 2363](#), a  $\frac{1}{2}$ -inch square key would be preferred. If a rectangular key were selected, its dimensions would be  $\frac{1}{2}$  inch by  $\frac{3}{8}$  inch. According to rule 1 above, its length would be 3 inches.

The key and shaft may be proportioned so as to provide a clearance or an interference fit. The table on Handbook [page 2367](#) gives tolerances for widths and depths of keys and caskets to provide Class 1 (clearance) and Class 2 (interference) fits. An additional Class 3 (interference) fit, which has not been standardized, is mentioned on Handbook [page 2363](#) together with suggested tolerances.

**Keys Proportioned According to Transmitted Torque.**—As previously stated, if key sizes are based on shaft diameter, the dimensions of the key sometimes will be excessive, usually when a gear or pulley transmits only a portion of the total torque capacity of the shaft to which it is keyed. If excessively large keys are to be avoided, it may be advantageous to base the determination on the torque to be transmitted rather than on the shaft diameter and to

use the dimensions thus determined as a guide in selecting a standard size key.

A key proportioned to transmit a specified torque may fail in service either by shearing or by crushing, depending on the proportions of the key and the manner in which it is fitted to the shaft and hub. The best proportions for a key are those that make it equally resistant to failure by shearing and by crushing. The safe torque in inch-pounds that a key will transmit, based on the allowable shearing stress of the key material, may be found from the formula:

$$T_s = L \times W \times \frac{D}{2} \times S_s \quad (1)$$

The safe torque based on the allowable compressive stress of the key material is found from the formula:

$$T_c = L \times \frac{H}{2} \times \frac{D}{2} \times S_c \quad (2)$$

(For Woodruff keys the amount that the key projects above the shaft is substituted for  $H/2$ .)

In these formulas,  $T_s$  = safe torque in shear;  $T_c$  = safe torque in compression;  $S_s$  = allowable shearing stress;  $S_c$  = allowable compressive stress;  $L$  = key length in inches;  $W$  = key width in inches;  $H$  = key thickness in inches; and  $D$  = shaft diameter in inches.

To satisfy the condition that the key be equally resistant to shearing and crushing,  $T_s$  should equal  $T_c$ . Thus, by equating Formulas (1) and (2), it is found that the width of the keyway in terms of the height of the keyway is:

$$W = \frac{HS_c}{2S_s} \quad (3)$$

For the type of steel commonly used in making keys, the allowable compressive stress  $S_c$  may be taken as twice the allowable shearing stress  $S_s$ , of the material if the key is properly fitted on all four sides. By substituting  $S_c = 2S_s$  in Formula (3) it will be found that  $W = H$ , so that for equal strength in compression and shear a square key should be used.

If a rectangular key is used, and the thickness  $H$  is less than the width  $W$ , then the key will be weaker in compression than in shear

so that it is sufficient to check the torque capacity of the key using **Formula (2)**.

*Example 6:* A 3-inch shaft is to deliver 100 horsepower at 200 revolutions per minute through a gear keyed to the shaft. If the hub of the gear is 4 inches long, what size key, equally strong in shear and compression, should be used? The allowable compressive stress in the shaft is not to exceed 16,000 pounds per square inch and the key material has an allowable compressive stress of 20,000 pounds per square inch and an allowable shearing stress of 15,000 pounds per square inch.

The first step is to decide on the length of the key. Since the hub of the gear is 4 inches long, a key of the same length may be used. The next step is to determine the torque that the key will have to transmit. By using Formula (2), Handbook **page 299**,

$$T = \frac{63,000P}{N} = \frac{63,000 \times 100}{200} = 31,500 \text{ inch-pounds}$$

To determine the width of the key, based on the allowable shearing stress of the key material, **Equation (1)** above is used.

$$T_s = L \times W \times \frac{D}{2} \times S_s$$

$$31,500 = 4 \times W \times \frac{D}{2} \times 15,000$$

or

$$W = \frac{31,500 \times 2}{15,000 \times 4 \times 3} = 0.350, \text{ say, } \frac{3}{8} \text{ inch}$$

In using **Equation (2)** to determine the thickness of the key, however, it should be noted that, if the shaft material has a different allowable compressive stress than the key material, then the lower of the two values should be used. The shaft material then has the lower allowable compressive stress, and the keyway in the shaft would fail by crushing before the key would fail. Therefore,

$$T_c = L \times \frac{H}{2} \times \frac{D}{2} \times S_c$$

$$31,250 = 4 \times \frac{H}{2} \times \frac{3}{2} \times 16,000$$

or

$$H = \frac{31,250 \times 2 \times 2}{16,000 \times 4 \times 3} = 0.656 = 21/32 \text{ inch}$$

Therefore, the dimensions of the key for equal resistance to failure by shearing and crushing are  $\frac{3}{8}$  inch wide,  $\frac{21}{32}$  inch thick, and 4 inches long. If, for some reason, it is desirable to use a key shorter than 4 inches, say, 2 inches, then it will be necessary to increase both the width and thickness by a factor of  $4 \div 2$  if equal resistance to shearing and crushing is to be maintained. Thus the width would be  $\frac{3}{8} \times \frac{4}{2} = \frac{3}{4}$  inch, and the thickness would be  $\frac{21}{32} \times \frac{4}{2} = 1\frac{5}{16}$  inch for a 2-inch-long key.

**Set-Screws Used to Transmit Torque.**—For certain applications it is common practice to use set-screws to transmit torque because they are relatively inexpensive to install and permit axial adjustment of the member mounted on the shaft. However, set-screws depend primarily on friction and the shearing force at the point of the screw, so they are not especially well-suited for high torques or where sudden load changes take place.

One rule for determining the proper size of a set-screw states that the diameter of the screw should equal  $\frac{5}{16}$  inch plus one-eighth the shaft diameter. The holding power of set-screws selected by this rule can be checked using the formula on [page 1637](#) of the Handbook.

### PRACTICE EXERCISES FOR SECTION 17

(See *Answers to Practice Exercises For Section 17* on page 233)

- 1) What is the polar section modulus of a shaft 2 inches in diameter?
- 2) If a 3-inch shaft is subjected to a torsional or twisting moment of 32,800 pound-inches, what is the equivalent torsional or shearing stress?

3) Is the shaft referred to in Exercise 2 subjected to an excessive torsional stress?

4) If a 10-horsepower motor operating at its rated capacity connects by a belt with a 16-inch pulley on the driving shaft of a machine, what is the load tangential to the pulley rim and the resulting twisting moment on the shaft, assuming that the rim speed of the driven pulley is 600 feet per minute?

5) How is the maximum distance between bearings for steel line-shafting determined?

6) What are "gib-head" keys, and why are they used on some classes of work?

7) What is the distinctive feature of Woodruff keys?

8) What are the advantages of Woodruff keys?

9) If a  $\frac{3}{8}$ -inch wide keyseat is to be milled into a  $1\frac{1}{2}$ -inch diameter shaft and if the keyseat depth is  $\frac{3}{16}$  inch (as measured at one side), what is the depth from the top surface of the shaft or the amount to sink the cutter after it grazes the top of the shaft?



## SECTION 18

### SPLINES

HANDBOOK Pages **2156** – **2188**

This section of the Handbook shows how to calculate the dimensions of involute splines and how to provide specifications for manufacturing drawings. Many types of mechanical connections between shafts and hubs are available for both fixed and sliding applications. Among these connections are the ordinary key and keyway (Handbook **page 2363** to **2388**), multiple keys and keyways, three- and four-lobed polygon shaft and hub connections, and involute splines of both inch dimension and metric module sizes.

The major advantages of involute splines are that they may be manufactured on the same equipment used to manufacture gears, they may be used for fixed and interference fit connections as well as for sliding connections, and they are stronger than most other connections with the exception of polygon-shaped members.

The section in the Handbook on involute splines, **page 2156** to **2175**, provides tables, data, formulas, and diagrams for American Standard splines made to both inch and metric module systems. Both systems share common definitions of terms, although the symbols used to identify dimensions and angles may differ, as shown on Handbook **page 2177**. The two systems do not provide for interchangeability of parts; the new metric module standard is the American National Standards Institute version of the International Standards Organization involute spline standard, which is based upon metric, not inch, dimensions.

*Example 1:* A metric module involute spline pair is required to meet the following specification: pressure angle  $\alpha_D = 30^\circ$ ; module  $m = 5$ ; number of teeth  $Z = 32$ ; fit class = H/h; tolerance class 5 for both the internal and external splines; flat root design for both members; length of engagement of the splines is 100 mm.

Table 13 beginning on Handbook [page 2179](#) provides all the formulas necessary to calculate the dimensions of these splines. Pitch diameter:

$$D = mZ = 5 \times 32 = 160 \text{ mm} \quad (1)$$

Base diameter:

$$\begin{aligned} DB &= mZ \cos \alpha_D = 160 \times \cos \alpha_D = 160 \times \cos 30^\circ \\ &= 160 \times 0.86603 = 138.5641 \text{ mm} \end{aligned} \quad (2)$$

Circular pitch:

$$p = \pi m = 3.1416 \times 5 = 15.708 \quad (3)$$

Base pitch:

$$p_b = \pi m \cos \alpha_D = \pi \times 5 \times 0.86603 = 13.60350 \quad (4)$$

Tooth thickness modification:

$$es = 0 \quad (5)$$

in accordance with the footnote to Table 14, Handbook [page 2180](#), and the Fit Classes paragraph on [page 2177](#) that refers to H/h fits.

Minimum major diameter, internal spline,

$$DEI \text{ min} = m(Z + 1.8) = 5 \times (32 + 1.8) = 169.000 \quad (6)$$

Maximum major diameter, internal spline,

$$\begin{aligned} DEI \text{ max} &= DEI \text{ min} + (T + \lambda) / (\tan \alpha_D) \\ &= 169.000 + 0.248 / \tan 30^\circ \\ &= 169.4295 \text{ mm} \end{aligned} \quad (7)$$

In this last calculation, the value of  $(T + \lambda) = 0.248$  for class 7 was calculated using the formula in Table 15, Handbook [page 2180](#), as follows:

$$\begin{aligned} i^* &= 0.001(0.45 \sqrt[3]{D} + 0.001D) \\ &= 0.001(0.45 \sqrt[3]{160} + 0.001 \times 160) \\ &= 0.00260 \end{aligned} \quad (8a)$$

$$\begin{aligned} i^{**} &= 0.001(0.45 \sqrt[3]{7.85398} + 0.001 \times 7.85398) \\ &= 0.00090 \end{aligned} \quad (8b)$$

In this calculation, 7.85398 is the value of  $S_{bsc}$  calculated from the formula  $S_{bsc} = 0.5\pi m$  given in the table starting on Handbook [page 2179](#).

$$\begin{aligned}(T + \lambda) &= 40i^* + 160i^* \\ &= 40 \times 0.00260 + 160 \times 0.00090 \\ &= 0.248 \text{ mm}\end{aligned}\tag{8c}$$

Form diameter, internal spline,

$$\begin{aligned}DFI &= m(Z + 1) + 2c_F \\ &= 5(32 + 1) + 2 \times 0.1m \\ &= 5(32 + 1) + 2 \times 0.1 \times 5 \\ &= 166 \text{ mm}\end{aligned}\tag{9}$$

In the above calculation the value of  $c_F = 0.1m$  is taken from the diagram on Handbook [page 2181](#), and the corresponding formula for form clearance on Handbook [page 2179](#). Minimum minor diameter, internal spline,

$$\begin{aligned}DII \text{ min} &= DFE + 2c_F \\ &= 154.3502 + 2 \times 0.1 \times 5 \\ &= 155.3502 \text{ mm}\end{aligned}\tag{10}$$

The  $DFE$  value of 154.3502 used in this calculation was calculated from the formula on Handbook [page 2179](#) as follows:  $DB = 138.564$  from step (2);  $D = 160$  from step (1);  $h_s = 0.6m = 3.0$  from the last formula in the table starting on Handbook [page 2179](#);  $es = 0$  from step (5);  $\sin 30^\circ = 0.50000$ ;  $\tan 30^\circ = 0.57735$ . Therefore,

$$\begin{aligned}DFE &= 2 \times \sqrt{(0.5 \times 138.564)^2 + \left[ 0.5 \times 160 \times 0.50000 \right. \\ &\quad \left. - \frac{0.6 \times 5 + \left( \frac{0.5 \times 0}{0.57735} \right)}{0.50000} \right]^2} \\ &= 154.3502\end{aligned}\tag{11}$$

Maximum minor diameter, internal spline,

$$\begin{aligned} D_{II} \max &= D_{II} \min + (0.2m^{0.667} - 0.1m^{-0.5}) \\ &= 155.3502 + 0.58 \\ &= 155.9302 \text{ mm} \end{aligned} \quad (12)$$

The value 0.58 used in this calculation comes from the footnote c to the table on Handbook [page 2179](#). Circular space width, basic,

$$E_{b_{sc}} = 0.5\pi m = 0.5 \times 3.1416 \times 5 = 7.854 \text{ mm} \quad (13)$$

Circular space width, minimum effective,

$$EV \min = E_{b_{sc}} = 7.854 \text{ mm} \quad (14)$$

Circular space width, maximum actual,

$$\begin{aligned} E \max &= EV \min + (T + \lambda) \\ &= 7.854 + 0.0992 \quad \text{from step (16c)} \\ &= 7.9532 \text{ mm} \end{aligned} \quad (15)$$

The value of  $(T + \lambda)$  calculated in step (16c) is based upon class 5 fit stated at the beginning of the example. The value calculated in step (8c), on the other hand, is based upon class 7 fit as required by the formula in step (7). For class 5 fit, using the formula given in Table 15, Handbook [page 2180](#):

$$i^* = 0.00260 \quad \text{from step (8a)} \quad (16a)$$

$$i^{**} = 0.00090 \quad \text{from step (8b)} \quad (16b)$$

$$\begin{aligned} (T + \lambda) &= 16i^* + 64i^{**} = 16 \times 0.00260 + 64 \times 0.00090 \\ &= 0.0992 \text{ mm} \end{aligned} \quad (16c)$$

Circular space width, minimum actual,

$$E \min = EV \min + \lambda = 7.854 + 0.045 = 7.899 \text{ mm} \quad (17)$$

The value of  $\lambda$  used in this formula was calculated from the formulas for class 5 fit in the Table 16 and the formula in the text on Handbook [page 2181](#) as follows:

## SPLINES

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$$F_p = 0.001(3.55\sqrt{5 \times 32 \times 3.1416/2} + 9) = 0.065 \text{ mm} \quad (18a)$$

$$f_f = 0.001[2.5 \times 5(1 + 0.0125 \times 32) + 16] = 0.034 \text{ mm} \quad (18b)$$

$$F_\beta = 0.001(1 \times \sqrt{100} \times 5) = 0.015 \text{ mm} \quad (18c)$$

$$\lambda = 0.6\sqrt{(0.065)^2 + (0.034)^2 + (0.015)^2} = 0.045 \text{ mm} \quad (18d)$$

Circular space width, maximum effective,

$$\begin{aligned} EV \text{ max} &= E \text{ max} - \lambda \\ &= 7.9532 \text{ from step (15)} - 0.045 \text{ from step (18d)} \quad (19) \\ &= 7.9082 \text{ mm} \end{aligned}$$

Maximum major diameter, external spline,

$$\begin{aligned} DEE \text{ max} &= m(Z + 1) - es/\tan\alpha_D = 5(32 + 1) - 0 \\ &= 165 \text{ mm} \end{aligned} \quad (20)$$

The value 0 in this last calculation is from Table 17, Handbook [page 2181](#), for h class fit.

Minimum major diameter, external spline, is calculated using the results of step (20) and footnote c on Handbook [page 2180](#),

$$\begin{aligned} DEE \text{ min} &= DEE \text{ max} - (0.2m^{0.667} - 0.01m^{-0.5}) \quad (21) \\ &= 165 - 0.58 = 164.42 \text{ mm} \end{aligned}$$

Maximum minor diameter, external spline,

$$\begin{aligned} DIE \text{ max} &= m(Z - 1.8) - es/\tan\alpha_D \\ &= 5(32 - 1.8) - 0 \quad (22) \\ &= 151 \text{ mm} \end{aligned}$$

The value 0 in this calculation is from Table 17, Handbook [page 2181](#), for h class fit.

Minimum minor diameter, external spline, is calculated using the results of steps (22) and (7),

$$\begin{aligned}
 DIE \text{ min} &= DIE \text{ max} - (T + \lambda) / \tan \alpha_D \\
 &= 151 - 0.248 / \tan 30^\circ \\
 &= 151 - 0.4295 \\
 &= 150.570 \text{ mm}
 \end{aligned}
 \tag{23}$$

Circular tooth thickness, basic, has been taken from the step **(13)**

$$S_{bsc} = 7.854 \text{ mm} \tag{24}$$

Circular tooth thickness, maximum effective, is calculated using the results of steps **(13)** and step **(5)**,

$$\begin{aligned}
 SV \text{ max} &= S_{bsc} - es \\
 &= 7.854 - 0 \\
 &= 7.854 \text{ mm}
 \end{aligned}
 \tag{25}$$

Circular tooth thickness, minimum actual, is calculated using the results of steps **(25)** and **(16c)**,

$$S \text{ min} = SV \text{ max} - (T + \lambda) = 7.854 - 0.0992 = 7.7548 \text{ mm} \tag{26}$$

Circular tooth thickness, maximum actual, is calculated using the results of steps **(25)** and **(18d)**,

$$\begin{aligned}
 S \text{ max} &= SV \text{ max} - \lambda \\
 &= 7.854 - 0.045 \\
 &= 7.809 \text{ mm}
 \end{aligned}
 \tag{27}$$

Circular tooth thickness, minimum effective, is calculated using the results of steps **(26)** and **(18d)**,

$$\begin{aligned}
 SV \text{ min} &= S \text{ min} + \lambda \\
 &= 7.754 + 0.045 \\
 &= 7.799 \text{ mm}
 \end{aligned}
 \tag{28}$$

*Example 2:* As explained on Handbook **page 2174**, spline gages are used for routine inspection of production parts. However, as part of an analytical procedure to evaluate effective space width or effective tooth thickness, measurements with pins are often used. Measurements with pins are also used for checking the actual space width and tooth thickness of splines during the machining process. Such measurements help in making the necessary size

adjustments both during the setup process and as manufacturing proceeds. For the splines calculated in **Example 1**, what are the pin measurements for the tooth thickness and space width?

The maximum space width for the internal spline is 7.953 mm from step (15) in **Example 1**. The minimum tooth thickness for the external spline is 7.755 mm from step (26).

Handbook **page 2175** gives a method for calculating pin measurements for splines. This procedure was developed for inch-dimension splines. However, it may be used for metric module splines simply by replacing  $P$  wherever it appears in a formula by  $1/m$ ; and by using millimeters instead of inches as dimensional units throughout.

For two-pin measurement *between* pins for the *internal* spline, steps 1, 2, and 3 on Handbook **page 2175** are used as follows:

$$\begin{aligned} \text{inv } \phi_i &= 7.953/160 + \text{inv } 30^\circ - 8.64/138.564 \\ &= 0.049706 + 0.053751 - 0.062354 = 0.041103 \end{aligned} \quad (1)$$

The numbers used in this calculation are taken from the results in **Example 1** except for the involute of  $30^\circ$ , which is from the table on **page 105** of the Handbook, and 8.64 is the diameter of the wire as calculated from the formula on Handbook **page 2175**,  $1.7280/P$  in which  $1/m$  has been substituted for  $P$  to give  $1.7280m = 1.7280 \times 5 = 8.64$ . Note that the symbols on **page 2175** are not the same as those used in **Example 1**. This is because the metric standard for involute splines uses different symbols for the same dimensions. The table on **page 2177** of the Handbook shows how these different symbols compare.

The value of  $\text{inv } \phi_i = 0.041103$  is used to enter the table on Handbook **page 105** to find, by interpolation,

$$\phi_i = 27^\circ 36' 20'' \quad (2)$$

From a calculator find

$$\sec 27^\circ 36' 20'' = 1.1285 \quad (3)$$

Calculate the measurement between wires:

$$\begin{aligned} M_i &= D_b \sec \phi_i - d_i = 138.564 \times 1.1285 - 8.64 \\ &= 147.729 \text{ mm} \end{aligned} \quad (4)$$

For two-pin measurement *over* the teeth of *external* splines, steps 1, 2, and 3 on Handbook [page 2175](#) are used as follows:

$$\begin{aligned} \text{inv } \phi_e &= 7.755/160 + 0.053751 + 9.6/138.564 - 3.1416/32 \\ &= 0.073327 \end{aligned} \quad (5)$$

Therefore, from Handbook [page 106](#),  $\phi_e = 32^\circ 59'$  and, from a calculator,  $\sec 32^\circ 59' = 1.1921$ . From the formula in step 3 on Handbook [page 2175](#):

$$M_e = 138.564 \times 1.1921 + 9.6 = 174.782 \text{ mm} \quad (6)$$

The pin diameter 9.6 in this calculation was calculated from the formula in step 3 on Handbook [page 2175](#) by substituting  $1/m$  for  $P$  in the formula  $d_e = 1.9200/P = 1.9200m$ .

**Specifying Spline Data on Drawings.**—As stated on Handbook [page 2169](#), if the data specified on a spline drawing are suitably arranged and presented in a consistent manner, it is usually not necessary to provide a graphic illustration of the spline teeth. Table 6 on Handbook [page 2168](#) illustrates a flat root spline similar to the one in [Example 1](#) except that it is an inch-dimension spline. The method of presenting drawing data for metric module splines differs somewhat from that shown on [page 2168](#) in that the number of decimal places used for metric spline data is sometimes less than that for the corresponding inch-dimension system.

*Example 3:* How much of the data calculated or given in [Example 1](#) and [2](#) should be presented on the spline drawing?

For the internal spline the data required to manufacture the spline should be presented as follows, including the number of decimal places shown:

#### Internal Involute Spline Data

| Flat Root Side Fit | Tolerance class 5H |
|--------------------|--------------------|
| Number of Teeth    | 32                 |
| Module             | 5                  |
| Pressure Angle     | 30 deg             |
| Base Diameter      | 138.5641 REF       |



**Internal Involute Spline Data (Continued)**

|                                     |               |
|-------------------------------------|---------------|
| Pitch Diameter                      | 160.0000 REF  |
| Major Diameter                      | 169.42 Max    |
| Form Diameter                       | 166.00        |
| Minor Diameter                      | 155.35/155.93 |
| <i>Circular Space Width:</i>        |               |
| Max Actual                          | 7.953         |
| Mm Effective                        | 7.854         |
| <i>Max Measurement Between Pins</i> | 147.729 REF   |
| Pin Diameter                        | 8.640         |

For the external spline:

**External Involute Spline Data**

| Flat Root Side Fit               | Tolerance Class 5h |
|----------------------------------|--------------------|
| Number of Teeth                  | 32                 |
| Module                           | 5                  |
| Pressure Angle                   | 30 deg             |
| Base Diameter                    | 138.5641 REF       |
| Pitch Diameter                   | 160.0000 REF       |
| Major Diameter                   | 164.42/165.00      |
| Form Diameter                    | 154.35             |
| Minor Diameter                   | 150.57 MIN         |
| <i>Circular Tooth Thickness:</i> |                    |
| Mm Actual                        | 7.854              |
| Max Effective                    | 7.809              |
| <i>Mm Measurement Over Pins:</i> | 74.782 REF         |
| Pin Diameter                     | 9.6                |

### PRACTICE EXERCISES FOR SECTION 18

(See *Answers to Practice Exercises For Section 18* on page 234)

- 1) What is the difference between a “soft” conversion of a standard and a “hard” system?
- 2) The standard for metric module splines does not include a major diameter fit. What standard does provide for a major diameter fit?
- 3) What is an involute serration and is it still called this in American standards?
- 4) What are some of the advantages of involute splines?
- 5) What is the meaning of the term “effective tooth thickness”?
- 6) What advantage is there in using an odd number of spline teeth?
- 7) If a spline connection is misaligned, fretting can occur at certain combinations of torque, speed, and misalignment angle. Is there any method for diminishing such damage?
- 8) For a given design of spline is there a method for estimating the torque capacity based upon wear? Based on shearing stress?
- 9) What does REF following a dimension of a spline mean?
- 10) Why are fillet root splines sometimes preferred over flat root splines?

## SECTION 19

### PROBLEMS IN DESIGNING AND CUTTING GEARS

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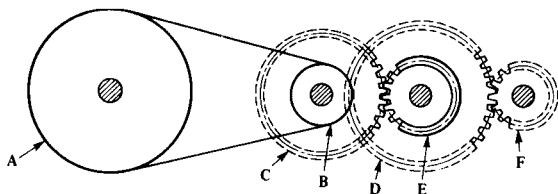
In the design of gearing, there may be three distinct types of problems. These are: (1) determining the relative sizes of two or more gears to obtain a given speed or series of speeds; (2) determining the pitch of the gear teeth so that they will be strong enough to transmit a given amount of power; and (3) calculating the dimensions of a gear of a given pitch, such as the outside diameter, the depth of the teeth, and other dimensions needed in cutting the gear.

When the term “diameter” is applied to a spur gear, the pitch diameter is generally referred to and not the outside diameter. In calculating the speeds of gearing, the pitch diameters are used and not the outside diameters, because when gears are in mesh, the imaginary pitch circles roll in contact with each other.

**Calculating Gear Speeds.**—The simple rules for calculating the speeds of pulleys beginning on Handbook **page 2388** may be applied to gearing, provided either the pitch diameters of the gears or the numbers of teeth are substituted for the pulley diameters. Information on gear speeds, especially as applied to compound trains of gearing, also will be found in the section dealing with lathe change gears beginning on Handbook **page 1946**. When gear trains must be designed to secure unusual or fractional gear ratios, the directions beginning on Handbook **page 1947** will be found very useful. A practical application of these methods is shown by examples beginning on Handbook **page 1951**.

Planetary or epicyclic gearing is an increasingly important class of power transmission in various industries because of compactness, efficiency, and versatility. The rules for calculating rotational speeds and ratios are different from those for other types of gear-

ing. Formulas for the most commonly used types of planetary gears are provided on Handbook pages 2116 to 2119.



**Fig. 1. Combination Pulley and Compound Gear Drive**

*Example 1:* The following example illustrates the method of calculating the speed of a driven shaft in a combination belt and gear drive when the diameters of the pulleys and the pitch diameters of the gears are known, and the number of revolutions per minute of the driving shaft is given. If driving pulley *A*, Fig. 1, is 16 inches in diameter, and driven pulley *B*, 6 inches in diameter, and the pitch diameter of driving gear *C* is 12 inches, driving gear *D* is 14 inches, driven gear *E*, 7 inches, driven gear *F*, 6 inches, and driving pulley *A* makes 60 revolutions per minute, determine the number of revolutions per minute of *F*.

$$\frac{16 \times 12 \times 14}{6 \times 7 \times 6} \times 60 = 640 \text{ revolutions per minute}$$

The calculations required in solving problems of this kind can be simplified if the gears are considered as pulleys having diameters equal to their pitch diameters. When this is done, the rules that apply to compound belt drives can be used in determining the speed or size of the gears or pulleys.

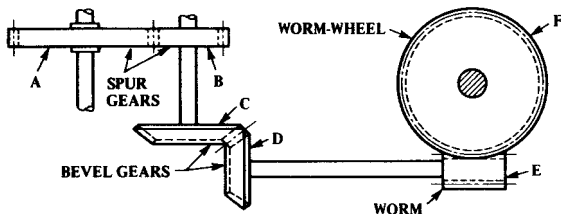
Substituting the numbers of teeth in each gear for the pitch diameter gives the same result as when the pitch diameters are used.

*Example 2:* If driving spur gear *A* (Fig. 2) makes 336 revolutions per minute and has 42 teeth, driven spur gear *B*, 21 teeth, driving bevel gear *C*, 33 teeth, driven bevel gear *D*, 24 teeth, driving worm *E*, one thread, and driven worm-wheel *F*, 42 teeth, determine the number of revolutions per minute of *F*.

When a combination of spur, bevel, and wormgearing is employed to transmit motion and power from one shaft to another,

the speed of the driven shaft can be found by the following method: Consider the worm as a gear having one tooth if it is single-threaded and as a gear having two teeth if double-threaded, etc. The speed of the driving shaft can then be found by applying the rules for ordinary compound spur gearing. In this example,

$$\frac{42 \times 33 \times 1}{21 \times 24 \times 42} \times 336 = 22 \text{ revolutions per minute}$$



**Fig. 2. Combination of Spur, Bevel, and Worm Gearing**

If the pitch diameters of the gears are used instead of the number of teeth in making calculations, the worm should be considered as a gear having a pitch diameter of 1 inch if single-threaded, and 2 inches if a double-threaded worm, etc.

*Example 3:* If a worm is triple-threaded and makes 180 revolutions per minute, and the worm-wheel is required to make 5 revolutions per minute, determine the number of teeth in the worm-wheel.

*Rule:* Multiply the number of threads in the worm by its number of revolutions per minute, and divide the product by the number of revolutions per minute of the worm-wheel. By applying this rule,

$$\frac{3 \times 180}{5} = 108 \text{ teeth}$$

*Example 4:* A 6-inch grinding machine with a spindle speed of 1773 revolutions per minute, for a recommended peripheral speed of 6500 feet per minute (as figured for a full-size 14-inch wheel for this size of machine), has two steps on the spindle pulley; the large step is 5.5 inches in diameter and the small step, 4 inches. What should be the minimum diameter of the wheel before the belt is shifted to the smaller step in order to select a peripheral wheel speed of 6500 feet per minute?

As the spindle makes 1773 revolutions per minute when the belt is on the large pulley, its speed with the belt on the smaller pulley may be determined as follows:  $5.5:4 = x:1773$ , or  $(5.5 \times 1773)/4 = 2438$  revolutions per minute, approximately. To obtain the same peripheral speed as when the belt is on the large pulley, the diameters of the grinding wheel should be  $14:x = 2438:1773$ , or  $(14 \times 1773)/2438 = 10.18$  inches. Therefore, when the grinding wheel has been worn down to a diameter of 10.18 inches, or approximately  $10\frac{3}{16}$  inches, the spindle belt should be shifted to the smaller step of the spindle pulley to obtain a peripheral speed of 6500 feet per minute. The method used in this example may be reduced to a formula for use with any make of grinding machine having a two-step spindle pulley.

Let

$D$  = diameter of wheel, full size

$D_1$  = diameter of wheel, reduced size

$d$  = diameter of large pulley step

$d_1$  = diameter of small pulley step

$V$  = spindle rpm, using large pulley step

$v$  = spindle rpm, using small pulley step

Then,

$$v = \frac{dV}{d_1}; \quad D_1 = \frac{DV}{v}$$

*Example 5:* Planetary gear sets are widely used in power transmission because of their compactness and relatively high efficiency when properly designed. The simple planetary configuration shown in Fig. 10 on Handbook page 2117 is typical of high-efficiency designs. If  $A = 20$  and  $C = 40$ , what is the rotation of the driver  $D$  per revolution of the follower?

Using the formula given on Handbook page 2117,

$$D = 1 + \frac{C}{A} = 1 + \frac{40}{20} = 3$$

*Example 6:* If, in Example 5, the diameter of the fixed gear is doubled to  $C = 80$ , what effect does that produce in the rotation of the drive  $D$ ?

$$D = 1 + \frac{80}{20} = 5$$

Note that doubling the size of the fixed gear  $C$  does not double the ratio or the driver speed of the gear set because the overall ratio is always plus the ratio of  $C$  to  $A$ .

*Example 7:* The compound type of planetary gear shown in Fig. 13 on Handbook page 2116 can provide high revolution ratios, although the efficiency decreases as the ratio increases. What is the rotation of the follower  $F$  when  $B = 61$ ,  $C = 60$ ,  $x = 19$ , and  $y = 20$ ?

$$F = 1 - \left( \frac{C \times x}{y \times B} \right) = 1 - \left( \frac{60 \times 19}{20 \times 61} \right) = 1 - \frac{57}{61} = 0.06557$$

*Example 8:* In Example 7, what is the rotation of the driver per revolution of the follower?

$$\text{Driver} = \frac{1}{\text{follower}} = \frac{1}{0.06557} = 15.25$$

Note that in compound planetary gear drives the sum of meshing tooth pairs must be equal for proper meshing. Thus,  $C + y = x + B$ .

**Diametral Pitch of a Gear.**— The diametral pitch represents the number of gear teeth for each inch of pitch diameter and, therefore, equals the number of teeth divided by the pitch diameter. The term diametral pitch as applied to bevel gears has the same meaning as with spur gears. This method of basing the pitch on the relation between the number of teeth and the pitch diameter is used almost exclusively in connection with cut gearing and to some extent for cast gearing. The circular pitch or the distance between the centers of adjacent teeth measured along the pitch circle is used for cast gearing but very little for cut gearing except very large sizes. If 3.1416 is divided by the diametral pitch, the quotient equals the circular pitch, or, if the circular pitch is known, the diametral pitch may be found by dividing 3.1416 by the circular pitch. The pitch of the gear teeth may depend primarily upon the strength required to transmit a given amount of power.

**Power Transmitting Capacity of Bevel Gears.**—The design of bevel gears to meet a set of operating conditions is best accomplished in four steps: (1) determine the design load upon which the

bevel gear sizes will be based; (2) using design literature and charts available from gear manufacturers and distributors, select approximate gear and pinion sizes to satisfy the load requirements; (3) determine the maximum safe tooth load, based on gear geometry and material, using manufacturer's and/or AGMA formulas; and (4) determine the safe horsepower capacity of the gears, based on safe tooth load and tooth surface durability. The horsepower capacity of the gears should meet or exceed the design load requirements. To check the capacity of an existing bevel gear drive, only steps (3) and (4) are necessary.

**Dimensions and Angles Required in Producing Gears.**—Many of the rules and formulas given in the gear section of the Handbook beginning on [page 2029](#) are used in determining tooth dimensions, gear blank sizes, also angles in bevel, helical, and wormgearing. These dimensions or angles are required on the working drawings used in connection with machining operations, such as turning gear blanks and cutting the teeth.

*Example 9:* If a spur gear is to have 40 teeth of 8 diametral pitch, to what diameter should the blank be turned? By applying Formula (7a), Handbook [page 2035](#),  $(40 + 2)/8 = 5.25$  inches. Therefore, the outside diameter of this gear or the diameter to which the blank would be turned is  $5\frac{1}{4}$  inches.

For internal spur gears, the inside diameter to which the gear blank would be bored may be obtained by subtracting 2 from the number of teeth and dividing the remainder by the diametral pitch.

*Example 10:* A sample spur gear has 22 teeth, and the outside diameter, or diameter measured across the tops of the teeth, is 6 inches. Determine the diametral pitch. According to Formula (7a), Handbook [page 2035](#),

$$D_o = \frac{N + 2}{P}$$

Hence,

$$P = \frac{N + 2}{D_o} = \frac{22 + 2}{6} = 4 \text{ diametral pitch}$$



The table, Handbook [page 2035](#), also shows that when the sample gear has American Standard Stub teeth, Formula (8a) should be used to determine the outside diameter, or diametral pitch.

*Example 11:* A 25-degree involute full-depth spur gear is to be produced by hobbing. How is the hob tip radius found?

As shown on Handbook [page 2061](#), the maximum hob tip radius,  $r_c$  (max), is found by the formula:

$$r_c \text{ (max)} = \frac{0.785398 \cos \phi - b \sin \phi}{1 - \sin \phi}$$

where  $\phi$  is the pressure angle, here,  $25^\circ$ , and  $b$  is the dedendum constant, which is 1.250 according to Table 2 on Handbook [page 2035](#). Thus,

$$\begin{aligned} r_c \text{ (max)} &= \frac{0.785398 \times 0.90631 - 1.25 \times 0.42262}{1 - 0.42262} \\ &= 0.3179 \text{ inch for a 1 diametral pitch gear} \end{aligned}$$

*Example 12:* If a 20-degree involute full-depth pinion having 24 teeth of 6 diametral pitch is to mesh with a rack, determine the whole depth of the rack teeth and the linear pitch of the teeth.

The teeth of a rack are of the same proportions as the teeth of a spur gear or pinion that is intended to mesh with the rack; hence the pitch of the rack teeth is equal to the circular pitch of the pinion and is found by dividing 3.1416 by the diametral pitch.

The pitch =  $3.1416 \div 6 = 0.5236$  inch = linear pitch of a rack to mesh with a pinion of 6 diametral pitch. This dimension (0.5236) represents the distance that the cutter would be indexed when milling rack teeth or the distance that the planer tool would be moved for cutting successive teeth if a planer were used. The whole depth of a full-depth rack tooth of 20-degree pressure angle equals 2.157 divided by the diametral pitch of the meshing gear, or the whole depth equals the circular pitch multiplied by 0.6866. Here, the circular pitch is 0.5236, and the whole depth equals  $0.5236 \times 0.6866 = 0.3595$  inch.

*Example 13:* If the teeth of a spur gear are to be cut to a certain diametral pitch, is it possible to obtain any diameter that may be desired? Thus, if the diametral pitch is 4, is it possible to make the pitch diameter  $5\frac{1}{8}$  inches?

The diametral pitch system is so arranged as to provide a series of tooth sizes, just as the pitches of screw threads are standardized. In as much as there must be a whole number of teeth in each gear, it is apparent that gears of a given pitch vary in diameter according to the number of teeth. Suppose, for example, that a series of gears are of 4 diametral pitch. Then the pitch diameter of a gear having, say, 20 teeth will be 5 inches; 21 teeth,  $5\frac{1}{4}$  inches; 22 teeth,  $5\frac{1}{2}$  inches, and so on. It will be seen that the increase in diameter for each additional tooth is equal to  $\frac{1}{4}$  inch for 4 diametral pitch. Similarly, for 2 diametral pitch, the variations for successive numbers of teeth would equal  $\frac{1}{2}$  inch, and for 10 diametral pitch the variations would equal  $\frac{1}{10}$  inch, etc.

The center-to-center distance between two gears is equal to one-half the total number of teeth in the gears divided by the diametral pitch. It may be desirable at times to have a center distance that cannot be obtained exactly by any combination of gearing of given diametral pitch, but this condition is unusual, and, ordinarily, the designer of a machine can alter the center distance whatever slight amount may be required for gearing of the desired ratio and pitch. By using a standard system of pitches, all calculations are simplified, and it is also possible to obtain the benefits of standardization in the manufacturing of gears and gear-cutters.

#### **Proportioning Spur Gears When Center Distance Is Fixed.—**

If the center-to-center distance between two shafts is fixed, and it is desired to use gears of a certain pitch, the number of teeth in each gear for a given speed may be determined as follows: Since the gears must be of a certain pitch, the total number of teeth available should be determined and then the number of teeth in the driving and the driven gears. The total number of teeth equals twice the product of the center distance multiplied by the diametral pitch. If the center distance is 6 inches, and the diametral pitch 10, the total number of teeth equals  $6 \times 2 \times 10 = 120$  teeth. The next step is to find the number of teeth in the driving and the driven gears for a given rate of speed.

*Rule:* Divide the speed of the driving gear in revolutions per minute by the speed of the driven gear and add one to the quotient. Next divide the total number of teeth in both gears by the sum pre-

viously obtained, and the quotient will equal the number of teeth required in the driving gear. This number subtracted from the total number of teeth will equal the number of teeth required in the driven gear.

*Example 14:* If the center-to-center distance is 6 inches, and the diametral pitch is 10, the total number of teeth available will be 120. If the speeds of the driving and the driven gears are to be 100 and 60 revolutions per minute, respectively, find the number of teeth for each gear.

$$100/60 = 1\frac{2}{3} \text{ and } 1\frac{2}{3} + 1 = 2\frac{2}{3}$$

$$120 \div 2\frac{2}{3} = 120/1 \times \frac{3}{8} = 45 = \text{number of teeth in driving gear}$$

The number of teeth in the driven gear equals  $120 - 45 = 75$  teeth.

When the center distance and the velocity ratios are fixed by some essential construction of a machine, it is often impossible to use standard diametral pitch gear teeth. If cast gears are to be used, it does not matter so much, as a pattern maker can lay out the teeth according to the pitch desired, but if cut gears are required, an effort should be made to alter the center distance so that standard diametral pitch cutters can be used since these are usually carried in stock.

**Dimensions in Generated Bevel gears.**—*Example 15:* Find all the dimensions and angles necessary to manufacture a pair of straight bevel gears if the number of teeth in the pinion is 16, the number of teeth in the mating gear is 49, the diametral pitch is 5, and the face width is 1.5 inches. The gears are to have a 20-degree pressure angle, a 90 degree shaft angle, and must be in accordance with the Gleason System.

On [page 178](#) of this guide, [Table 1](#) gives formulas for Gleason System 20-degree pressure angle straight bevel gears with 90-degree shaft angle. These formulas are given in the same order as is normally used in computation. Computations of the gear dimensions should be arranged as shown in the table on the following pages to establish a consistent procedure when calculations for bevel gears are required frequently.

Given:

- Number of pinion teeth,  $n$  = 16 (1)
- Number of gear teeth,  $N$  = 49 (2)
- Diametral pitch,  $P$  = 5 (3)
- Face width,  $F$  = 1.5 (4)
- Pressure angle,  $\phi = 20^\circ$  =  $20^\circ$  (5)
- Shaft angle,  $\Sigma = 90^\circ$  =  $90^\circ$  (6)

**Table 1. Formulas for Gleason System 20-Degree Straight Bevel Gears—90-Degree Shaft Angle**

|     |                       | To Find                                |  |
|-----|-----------------------|--|--|
| No. | Item                  | Formula                                |  |
|     |                       | Pinion                                 | Gear   |
| 7   | Working Depth         | $h_k = \frac{2.000}{P}$                | Same as pinion   |
| 8   | Whole Depth           | $h_t = \frac{2.188}{P} + 0.002$        | Same as pinion   |
| 9   | Pitch Diameter        | $d = \frac{n}{P}$                      | $D = \frac{N}{P}$  |
| 10  | Pitch Angle           | $\gamma = \tan^{-1} \frac{n}{N}$       | $\Gamma = 90^\circ - \gamma$   |
| 11  | Cone Distance         | $A_O = \frac{D}{2 \sin \Gamma}$        | Same as pinion   |
| 12  | Circular Pitch        | $p = \frac{3.1416}{P}$                 | Same as pinion   |
| 13  | Addendum              | $a_p = h_t - a_G$                      | $a_G = \frac{0.540}{P} + \frac{0.460}{P \left(\frac{N}{n}\right)^2}$ |
| 14  | Dedendum <sup>a</sup> | $b_p = \frac{2.188}{P} - a_p$          | $b_G = \frac{2.188}{P} - a_G$  |
| 15  | Clearance             | $c = h_t - h_k$                        | Same as pinion   |
| 16  | Dedendum Angle        | $\delta_p = \tan^{-1} \frac{b_p}{A_O}$ | $\delta_G = \tan^{-1} \frac{b_G}{A_O}$                               |
| 17  | Face Angle of Blank   | $\gamma_O = \gamma + \delta_G$         | $\Gamma_O = \Gamma + \delta_p$                                       |
| 18  | Root Angle            | $\gamma_r = \gamma - \delta_p$         | $\Gamma_R = \Gamma - \delta_G$                                       |
| 19  | Outside Diameter      | $d_O = d + 2a_p \cos \gamma$           | $D_O = D + 2a_G \cos \Gamma$   |

**Table 1. (Continued) Formulas for Gleason System 20-Degree Straight Bevel Gears—90-Degree Shaft Angle**

|     |                     | To Find   |   |
|-----|---------------------|---|---|
| No. | Item                | Formula   |   |
|     |                     | Pinion  | Gear  |
| 20  | Pitch Apex to Crown | $x_O = \frac{D}{2} - a_p \sin \gamma$                                 | $X_O = \frac{d}{2} - a_G \sin \Gamma$   |
| 21  | Circular Thickness  | $t = p - T$   | $T = \frac{p}{2} - (a_p - a_G) \tan \phi - \frac{K}{P}$<br>$K = (\text{Chart 1})$ |
| 22  | Backlash            | $B = (\text{See table on Handbook page 2068})$                        |   |
| 23  | Chordal Thickness   | $t_c = t - \frac{t^3}{6d^2} - \frac{B}{2}$                            | $T_c = T - \frac{T^3}{6D^2} - \frac{B}{2}$  |
| 24  | Chordal Addendum    | $a_{cp} = a_p + \frac{t^2 \cos \gamma}{4d}$                           | $a_{cG} = a_G + \frac{T^2 \cos \Gamma}{4D}$                                       |
| 25  | Tooth Angle         | $\frac{3438}{A_O} \left( \frac{t}{2} + b_p \tan \phi \right)$ minutes | $\frac{3438}{A_O} \left( \frac{T}{2} + b_G \tan \phi \right)$ minutes             |
| 26  | Limit Point Width   | $\frac{A_O - F}{A_O} (T - 2b_p \tan \phi) - 0.0015$                   | $\frac{A_O - F}{A_O} (t - 2b_G \tan \phi) - 0.0015$                               |

<sup>a</sup>The actual dedendum will be 0.002-inch greater than calculated due to tool advance. All linear dimensions are in inches.

The tooth angle (Item 25, **Table 1**) is a machine setting and is only computed if a Gleason two-tool type straight bevel gear generator is to be used. Calculations continue on **page 180**.

**Dimensions of Milled Bevel Gears.**—As explained on Handbook **page 2085**, the tooth proportions of milled bevel gears differ in some respects from those of generated bevel gears. To take these differences into account, a separate table of formulas is given on Handbook **page 2087** for use in calculating dimensions of milled bevel gears.

*Example 16:* Compute the dimensions and angles of a pair of mating bevel gears that are to be cut on a milling machine using rotary formed milling cutters if the data given are as follows:

**Table 2. Calculations of Dimensions for Example 15**

|      | Dimension           | Pinion  | Gear   |
|------|---------------------|---|--|
| (7)  | Working depth       | $2.000/5 = 0.400$   | Same as Pinion   |
| (8)  | Whole depth         | $2.188/5 + 0.002 = 0.440$   | Same as Pinion   |
| (9)  | Pitch diameter      | $1\frac{6}{5} = 3.2000$   | $4\frac{9}{5} = 9.8000$  |
| (10) | Pitch angle         | $\tan^{-1}(1\frac{6}{40}) = 18^\circ 5'$                                    | $90^\circ - 18^\circ 5' = 71^\circ 55'$  |
| (11) | Cone distance       | $9.8000/(2 \times \sin 71^\circ 55') = 5.1546$                              | Same as pinion   |
| (12) | Circular pitch      | $3.1416 / 5 = 0.6283$   | Same as pinion   |
| (13) | Addendum            | $0.400 - 0.118 = 0.282$   | $0.540/5 + 0.460/(5(49/16)^2) = 0.118$   |
| (14) | Dedendum            | $2.188/5 - 0.282 = 0.1554$  | $2.188/5 - 0.118 = 0.3196$   |
| (15) | Clearance           | $0.440 - 0.400 = 0.040$   | Same as pinion   |
| (16) | Dedendum angle      | $\tan^{-1}(0.1536/5.1546) = 1^\circ 42'$                                    | $\tan^{-1}(0.3214/5.1546) = 3^\circ 34'$   |
| (17) | Face angle of blank | $18^\circ 5' + 3^\circ 34' = 21^\circ 39'$                                  | $71^\circ 55' + 1^\circ 42' = 73^\circ 37'$                                      |
| (18) | Root angle          | $18^\circ 5' - 1^\circ 42' = 16^\circ 23'$                                  | $71^\circ 55' - 3^\circ 34' = 68^\circ 21'$                                      |
| (19) | Outside diameter    | $3.2000 + 2 \times 0.282 \cos 18^\circ 5' = 3.735$                          | $9.8000 + 2 \times 0.118 \cos 71^\circ 55' = 9.875$                              |
| (20) | Pitch apex to crown | $9.8000/2 - 0.284 \sin 18^\circ 5' = 4.812$                                 | $3.2000/2 - 0.118 \sin 71^\circ 55' = 1.488$                                     |
| (21) | Circular thickness  | $0.6283 - 0.2467 = 0.3816$  | $0.6283/2 - (0.284 - 0.118) \tan 20^\circ - (0.038(\text{chart } 1))/5 = 0.2467$ |
| (22) | Backlash            | 0.006   | 0.006  |
| (23) | Chordal thickness   | $0.3816 - \frac{(0.3816)^3}{6 \times (3.2000)^2} - \frac{0.006}{2} = 0.378$ | $0.2467 - \frac{(0.2467)^3}{6 \times (9.8000)^2} - \frac{0.006}{2} = 0.244$      |
| (24) | Chordal addendum    | $0.282 + \frac{0.3816^2 \cos 18^\circ 5'}{4 \times 3.2000} = 0.293$         | $0.118 + \frac{0.2467^2 \cos 71^\circ 55'}{4 \times 9.8000} = 0.118$             |

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|                        |                         |
|------------------------|-------------------------|
| Number of pinion teeth | = 15                    |
| Number of gear teeth   | = 60                    |
| Diametral pitch        | = 3                     |
| Face width             | = 1.5                   |
| Pressure angle         | = $14\frac{1}{2}^\circ$ |
| Shaft angle            | = $90^\circ$            |

By using the formulas on Handbook [page 2087](#),

$$\tan \alpha_p = 15 \div 60 = 0.25 = \tan 14^\circ 2.2', \text{ say, } 14^\circ 2'$$

$$\alpha_G = 90^\circ - 14^\circ 2' = 75^\circ 57.8', \text{ say, } 75^\circ 58'$$

$$D_p = 15 \div 3 = 5.0000 \text{ inches}$$

$$D_G = 60 \div 3 = 20.0000 \text{ inches}$$

$$S = 1 \div 3 = 0.3333 \text{ inch}$$

$$S + A = 1.157 \div 3 = 0.3857 \text{ inch}$$

$$W = 2.157 \div 3 = 0.7190 \text{ inch}$$

$$T = 1.571 \div 3 = 0.5236 \text{ inch}$$

$$C = \frac{5.000}{2 \times 0.24249} = 10.308 \text{ inches}$$

(In determining  $C$ , the sine of unrounded value of  $\alpha_p$ ,  $14^\circ 2.2'$ , is used.)

$$F = 8 \div 3 = 2\frac{2}{3}, \text{ say, } 2\frac{5}{8} \text{ inches}$$

$$s = 0.3333 \times \frac{10.308 - 2\frac{5}{8}}{10.308} = 0.2484 \text{ inch}$$

$$t = 0.5236 \times \frac{10.308 - 2\frac{5}{8}}{10.308} = 0.3903 \text{ inch}$$

$$\tan \theta = 0.3333 \div 10.308 = \tan 1^\circ 51'$$

$$\tan \phi = 0.3857 \div 10.308 = \tan 2^\circ 9'$$

$$\gamma_P = 14^\circ 2' + 1^\circ 51' = 15^\circ 53'$$

$$\gamma_G = 75^\circ 58' + 1^\circ 51' = 77^\circ 49'$$

$$\delta_P = 90^\circ - 15^\circ 53' = 74^\circ 7'$$

$$\delta_G = 90^\circ - 77^\circ 49' = 12^\circ 11'$$

$$\xi_P = 14^\circ 2' + 2^\circ 9' = 11^\circ 53'$$

$$\xi_G = 75^\circ 58' + 2^\circ 9' = 73^\circ 49'$$

$$K_P = 0.3333 \times 0.97015 = 0.3234 \text{ inch}$$

$$K_G = 0.3333 \times 0.24249 = 0.0808 \text{ inch}$$

$$O_P = 5.000 + 2 \times 0.3234 = 5.6468 \text{ inches}$$

$$O_G = 20.000 + 2 \times 0.0808 = 20.1616 \text{ inches}$$

$$J_P = \frac{5.6468}{2} \times 3.5144 = 9.9226 \text{ inches}$$

$$J_G = \frac{20.1616}{2} \times 0.21590 = 2.1764 \text{ inches}$$

$$j_p = 9.9226 \times \frac{10.3097 - 2\frac{5}{8}}{10.3097} = 7.3961 \text{ inches}$$

$$j_g = 2.1764 \times \frac{10.3097 - 2\frac{5}{8}}{10.3097} = 1.6222 \text{ inches}$$

$$N'_P = \frac{15}{0.97015} = 15.4, \text{ say, } 15 \text{ teeth}$$

$$N'_G = \frac{60}{0.24249} = 247 \text{ teeth}$$

If these gears are to have uniform clearance at the bottom of the teeth, in accordance with the recommendation given in the last paragraph on Handbook [page 2085](#), then the cutting angles  $\zeta_P$  and  $\zeta_G$  should be determined by subtracting the addendum angle from the pitch cone angles. Thus,

$$\zeta_P = 14^\circ 2' - 1^\circ 51' = 12^\circ 11'$$

$$\zeta_G = 75^\circ 58' - 1^\circ 51' = 74^\circ 7'$$

**Selection of Formed Cutters for Bevel Gears.**—*Example 17:* In [Example 16](#), the numbers of teeth for which to select the cutters were calculated as 15 and 247 for the pinion and gear, respectively. Therefore, as explained on [page 2091](#) of the Handbook, the cutters selected from the table on [page 2054](#) are the No. 7. and the No. 1 cutters. As further noted on [page 2091](#), bevel gear milling cutters may be selected directly from the table beginning on [page 2089](#), when the shaft angle is 90 degrees, instead of using the computed value of  $N'$  to enter the table on [page 2054](#). Thus, for a 15-tooth pinion and a 60-tooth gear, the table on [page 2089](#) shows that the numbers of the cutters to use are 1 and 7 for gear and pinion, respectively.



**Pitch of Hob for Helical Gears.**—*Example 18:* A helical gear that is to be used for connecting shafts has 83 teeth, a helix angle of 7 degrees, and a pitch diameter of 47.78 inches. Determine the pitch of hob to use in cutting this gear.

As explained on Handbook [page 2100](#), the normal diametral pitch and the pitch of the hob are determined as follows: the transverse diametral pitch equals  $83 \div 47.78 = 1.737$ . The cosine of the helix angle of the gear (7 degrees) is 0.99255; hence the normal diametral pitch equals  $1.737 \div 0.99255 = 1.75$ ; therefore, a hob of  $1\frac{3}{4}$  diametral pitch should be used. This hob is the same as would be used for spur gears of  $1\frac{3}{4}$  diametral pitch, and it will cut any spur or helical gear of that pitch regardless of the number of teeth, provided  $1\frac{3}{4}$  is the diametral pitch of the spur gear and the normal diametral pitch of the helical gear.

**Determining Contact Ratio.**—As pointed out on Handbook [page 2060](#), if a smooth transfer of load is to be obtained from one pair of teeth to the next pair of teeth as two mating gears rotate under load, the contact ratio must be well over 1.0. Usually, this ratio should be 1.4 or more, although in extreme cases it may be as low as 1.15.

*Example 19:* Find the contact ratio for a pair of 18-diametral pitch, 20-degree pressure gears, one having 36 teeth and the other 90 teeth. From Formula (1) given on Handbook [page 2059](#):

$$\cos A = \frac{90 \times \cos 20^\circ}{5.111 \times 18} = \frac{90 \times 0.93969}{91.9998} = 0.91926 \quad \text{and}$$

$$A = 23^\circ 11'$$

From Formula (4) given on Handbook [page 2059](#):

$$\cos a = \frac{36 \times \cos 20^\circ}{2.111 \times 18} = \frac{36 \times 0.93969}{37.9998} = 0.89024 \quad \text{and}$$

$$a = 27^\circ 6'$$

From Formula (5) given on Handbook [page 2059](#):

$$\begin{aligned} \tan B &= \tan 20^\circ - \frac{36}{90}(\tan 27^\circ 6' - \tan 20^\circ) \\ &= 0.36397 - \frac{36}{90}(0.51172 - 0.36397) = 0.30487 \end{aligned}$$

From Formula (7a) given on Handbook [page 2059](#), the contact ratio  $m_f$  is found:

$$\begin{aligned} m_f &= \frac{90}{6.28318}(0.42826 - 0.30487) \\ &= 1.77 \end{aligned}$$

which is satisfactory.

**Dimensions Required When Using Enlarged Fine-Pitch Pinions.**—On Handbook [pages 2055 to 2058](#), there are tables of dimensions for enlarged fine-pitch pinions. These tables show how much the dimensions of enlarged pinions must differ from standard when the number of teeth is small, and undercutting of the teeth is to be avoided.

*Example 20:* If a 10- and a 31-tooth mating pinion and gear of 20 diametral pitch and  $14\frac{1}{2}^\circ$  pressure angle have both been enlarged to avoid undercutting of the teeth, what increase over the standard center distance is required?

$$\text{Standard center distance} = \frac{n + N}{2P} = \frac{10 + 31}{2 \times 20} = 1.0250 \text{ inches}$$

The amount by which the center distance must be increased over standard can be obtained by taking the sum of the amounts shown in the eighth column of Table 9b on Handbook [page 2055](#) and dividing this sum by the diametral pitch. Thus, the increase over the standard center distance is  $(0.6866 + 0.0283)/20 = 0.0357$  inch.

*Example 21:* At what center distance would the gears in [Example 20](#) have to be meshed if there were to be no backlash?

Obtaining the two thicknesses of both gears at the standard pitch diameters from Table 9b on Handbook [page 2055](#), dividing them by 20, and using the formulas on Handbook [page 2059](#):

$$\text{inv } \phi_1 = \text{inv } 14\frac{1}{2}^\circ + \frac{20(0.09630 + 0.07927) - 3.1416}{10 + 31}$$

The involute of  $14\frac{1}{2}^\circ$  is found on Handbook [page 104](#) to be 0.0055448. Therefore,

$$\text{inv } \phi_1 = 0.0055448 + 0.0090195 = 0.0145643$$

By referring to the table on Handbook [page 104](#):

$$\phi_1 = 19^\circ 51' 6''$$

$$C = \frac{10 + 31}{2 \times 20} = 1.025 \text{ inch}$$

$$C_1 = \frac{\cos 14\frac{1}{2}^\circ}{\cos 19^\circ 51' 6''} \times 1.025 = \frac{0.96815}{0.94057} \times 1.025 = 1.0551 \text{ inch}$$

### End Thrust of Helical Gears Applied to Parallel Shafts.—

*Example 22:* The diagrams on Handbook [pages 2101](#) to [2102](#) show the application of helical or spiral gears to parallel shaft drives. If a force of 7 horsepower is to be transmitted at a pitch-line velocity of 200 feet per minute, determine the end thrust in pounds, assuming that the helix angle of the gear is 15 degrees.

To determine the end thrust of helical gearing as applied to parallel shafts, first calculate the tangential load on the gear teeth.

$$\text{Tangential load} = \frac{33,000 \times 7}{200} = 1155 \text{ pounds}$$

(This formula is derived from the formulas for power given on Handbook [page 178](#).)

The axial or end thrust may now be determined approximately by multiplying the tangential load by the tangent of the tooth angle. Thus, in this instance, the thrust = 1155  $\times$  tan 15 degrees = about 310 pounds. (Note that this formula agrees with the one on Handbook [page 161](#) for determining force P parallel to base of inclined plane.) The end thrust obtained by this calculation will be somewhat greater than the actual end thrust, because frictional losses in the shaft bearings, etc., have not been taken into account, although a test on a helical gear set, with a motor drive, showed that the actual thrust of the 7½-degree helical gears tested was not much below the values calculated as just explained.

According to most textbooks, the maximum angle for single helical gears should be about 20 degrees, although one prominent manufacturer mentions that the maximum angle for industrial drives ordinarily does not exceed 10 degrees, and this will give quiet running without excessive end thrust. On some of the heavier single helical gearing used for street railway transmissions, etc., an angle of 7 degrees is employed.

**Dimensions of Wormgear Blank and the Gashing Angle.—**

*Example 23:* A wormgear having 45 teeth is to be driven by a double threaded worm having an outside diameter of  $2\frac{1}{2}$  inches and a lead of 1 inch, the linear pitch being  $\frac{1}{2}$  inch. The throat diameter and throat radius of the wormgear are required as well as the angle for gashing the blank.

The throat diameter  $D_t$  equals the pitch diameter  $D$  plus twice the addendum  $A$ ; thus,  $D_t = D + 2A$ . The addendum of the worm thread equals the linear pitch multiplied by 0.3183, and here,  $0.5 \times 0.3183 = 0.1591$  inch. The pitch diameter of the wormgear =  $45 \times 0.5 \div 3.1416 = 7.162$  inches; hence, the throat diameter equals  $7.162 + 2 \times 0.1591 = 7.48$  inches.

The radius of the wormgear throat is found by subtracting twice the addendum of the worm thread from  $\frac{1}{2}$  the outside diameter of the worm. The addendum of the worm thread equals 0.1591 inch, and the radius of the throat, therefore, equals  $(2.5 \div 2) - 2 \times 0.1591 = 0.931$  inch.

When a wormgear is hobbled in a milling machine, gashes are milled before the hobbing operation. The table must be swiveled around while gashing, the amount depending upon the relation between the lead of the worm thread and the pitch circumference. The first step is to find the circumference of the pitch circle of the worm. The pitch diameter equals the outside diameter minus twice the addendum of the worm thread; hence, the pitch diameter equals  $2.5 - 2 \times 0.1591 = 2.18$  inches, and the pitch circumference equals  $2.18 \times 3.1416 = 6.848$  inches.

Next, divide the lead of the worm thread by the pitch circumference to obtain the tangent of the desired angle, and then refer to a table of tangents or a calculator to determine what this angle is. For this example, it is  $1 \div 6.848 = 0.1460$ , which is the tangent of  $8\frac{1}{3}$  degrees from its normal position.

**Change Gear Ratio for Diametral-Pitch Worms.—**

*Example 24:* In cutting worms to a given diametral pitch, the ratio of the change gears is  $22 \times$  threads per inch /  $7 \times$  diametral pitch.

The reason why the constants 22 and 7 are used in determining the ratio of change-gears for cutting worm threads is because  $\frac{22}{7}$

equals, very nearly, 3. 1416, which is the circular pitch equivalent to diametral pitch.

Assume that the diametral pitch of the wormgear is 5, and the lathe screw constant is 4. (See Handbook page 1836 for the meaning of "lathe screw constant.") Then,  $(4 \times 22)/(5 \times 7) = 88/35$ . If this simple combination of gearing were used, the gear on the stud would have 88 teeth and the gear on the lead screw, 35 teeth. Of course, any other combination of gearing having this same ratio could be used, as, for example, the following compound train of gearing:  $(24 \times 66)/(30 \times 21)$ .

If the lathe screw constant is 4, as previously assumed, then the number of threads per inch obtained with gearing having a ratio of  $88/35 = (4 \times 35)/88 = 1.5909$ ; hence, the pitch of the worm thread equals  $1 \div 1.5909 = 0.6284$  inch, which is the circular pitch equivalent to 5 diametral pitch, correct to within 0.0001 inch.

**Bearing Loads Produced by Bevel Gears.**—In applications where bevel gears are used, not only must the gears be proportioned with regard to the power to be transmitted, but also the bearings supporting the gear shafts must be of adequate size and design to sustain the radial and thrust loads that will be imposed on them. Assuming that suitable gear and pinion proportions have been selected, the next step is to compute the loads needed to determine whether or not adequate bearings can be provided. To find the loads on the bearings, first, use the formulas on the following pages to compute the tangential, axial, and separating components of the load on the tooth surfaces. Second, use the principle of moments, together with the components determined in the first step, to find the radial loads on the bearings. To illustrate the procedure, the following example will be used.

*Example 25:* A 16-tooth left-hand spiral pinion rotating clockwise at 1800 rpm transmits 71 horsepower to a 49-tooth mating gear. If the pressure angle is 20 degrees, the spiral angle is 35 degrees, the face width is 1.5 inches, and the diametral pitch is 5 what are the radial and thrust loads that govern the selection of bearings?

In **Fig. 3**, the locations of the bearings for the gear shafts are shown. It should be noted that distances  $K$ ,  $L$ ,  $M$ , and  $N$  are measured from the center line of the bearings and from the midfaces of the gears at their mean pitch diameters. In this example, it will be

assumed that these distances are given and are as follows:  $K = 2.5$  inches;  $N = 3.5$  inches;  $L = 1.5$  inches; and  $M = 5.0$  inches.

Also given:

- Number of pinion teeth,  $n$  = 16 (1)
- Number of gear teeth,  $N$  = 49 (2)
- Diametral pitch,  $P$  = 5 (3)
- Face width,  $F$  = 1.5 (4)
- Pressure angle,  $\phi = 20^\circ$  =  $20^\circ$  (5)
- Shaft angle,  $\Sigma = 90^\circ$  =  $90^\circ$  (6)

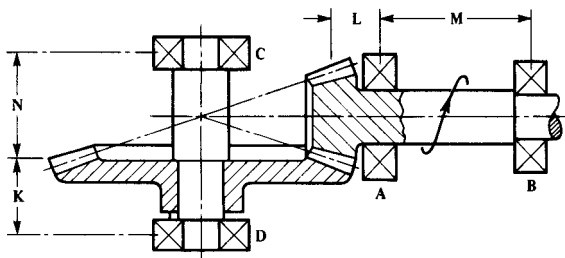
**Table 3. Formulas for Gleason System 20-Degree Pressure Angle, Spiral Bevel Gears—90-Degree Shaft Angle**

| No | Item                | Formula                                |  |
|----|---------------------|--|--|
|    |                     | Pinion                                 | Gear   |
| 7  | Working Depth       | $h_k = \frac{1.700}{P}$                | Same as pinion   |
| 8  | Whole Depth         | $h_t = \frac{2.188}{P}$                | Same as pinion   |
| 9  | Pitch Diameter      | $d = \frac{n}{P}$                      | $D = \frac{N}{P}$  |
| 10 | Pitch Angle         | $\gamma = \tan^{-1} \frac{n}{N}$       | $\Gamma = 90^\circ - \gamma$   |
| 11 | Cone Distance       | $A_O = \frac{D}{2 \sin \Gamma}$        | Same as pinion   |
| 12 | Circular Pitch      | $p = \frac{3.1416}{P}$                 | Same as pinion   |
| 13 | Addendum            | $a_p = h_k - a_G$                      | $a_G = \frac{0.540}{P} + \frac{0.390}{P \left(\frac{N}{n}\right)^2}$ |
| 14 | Dedendum            | $b_p = h_t - a_p$                      | $b_G = h_t - a_G$  |
| 15 | Clearance           | $c = h_t - h_k$                        | Same as pinion   |
| 16 | Dedendum Angle      | $\delta_P = \tan^{-1} \frac{b_p}{A_O}$ | $\delta_G = \tan^{-1} \frac{b_G}{A_O}$                               |
| 17 | Face Angle of Blank | $\gamma_O = \gamma + \delta_G$         | $\Gamma_O = \Gamma + \delta_p$                                       |

**Table 3. (Continued) Formulas for Gleason System 20-Degree Pressure Angle, Spiral Bevel Gears—90-Degree Shaft Angle**

| No | Item                  | Formula  |  |
|----|-----------------------|--|--|
|    |                       | Pinion   | Gear   |
| 18 | Root Angle            | $\gamma_R = \gamma - \delta_p$                         | $\Gamma_R = \Gamma - \delta_G$   |
| 19 | Outside Diameter      | $d_O = d + 2a_p \cos \gamma$                           | $D_O = D + 2a_G \cos \Gamma$   |
| 20 | Pitch Apex to Crown   | $x_O = \frac{D}{2} - a_p \sin \gamma$                  | $X_O = \frac{d}{2} - a_G \sin \Gamma$                                      |
| 21 | Circular Thickness    | $t = p - T$  | $T = \frac{(1.5708 - K)}{P}$<br>$-\frac{\tan \phi}{\cos \psi} (a_p - a_G)$ |
| 22 | Backlash <sup>a</sup> | B = (See table on Handbook <a href="#">page 2067</a> ) |  |

<sup>a</sup> When the gear is cut spread-blade, all the backlash is taken from the pinion thickness. When both members are cut single-side, each thickness is reduced by half of the backlash. All linear dimensions are in inches.


**Fig. 3. Diagram Showing Location of Bearings for Bevel Gear Drive in Example 25**

Other quantities that will be required in the solution of this example are the pitch diameter, pitch angle, and mean pitch diameter of both the gear and pinion. These are computed using formulas given in [Table 3](#) on the previous page as follows:

By using Formula 9 in [Table 3](#),

Pitch dia. of pinion  $d = 3.2$  inches

Pitch dia. of gear  $D = 9.8$  inches

By using Formula 10 in [Table 3](#),

Pitch angle of pinion  $\gamma = 18^\circ 5'$

Pitch angle of gear  $\Gamma = 71^\circ 55'$

By using the formula given below,

Mean pitch diameter of pinion

$$\begin{aligned} d_m &= d - F \sin \gamma \\ &= 3.2 - 1.5 \times 0.31040 \\ &= 2.734 \text{ inches} \end{aligned}$$

Mean pitch diameter of gear

$$\begin{aligned} D_m &= D - F \sin \Gamma \\ &= 9.8 - 1.5 \times 0.95061 \\ &= 8.374 \text{ inches} \end{aligned}$$

The first step in determining the bearing loads is to compute the tangential  $W_t$ , axial  $W_x$ , and separating  $W_s$ , components of the tooth load, using the formulas that follow.

$$W_t = \frac{126,050P}{nd_m} = \frac{126,050 \times 71}{1800 \times 2.734} = 1819 \text{ pounds}$$

$$\begin{aligned} W_x(\text{pinion}) &= \frac{W_t}{\cos \psi} (\tan \phi \sin \gamma_d + \sin \psi \cos \gamma_d) \\ &= \frac{1819}{0.81915} (0.36397 \times 0.31040 + 0.57358 \times 0.95061) \\ &= 1462 \text{ pounds} \end{aligned}$$

$$\begin{aligned} W_x(\text{gear}) &= \frac{W_t}{\cos \psi} (\tan \phi \sin \gamma_D - \sin \psi \cos \gamma_D) \\ &= \frac{1819}{0.81915} (0.36397 \times 0.95061 - 0.57358 \times 0.31040) \\ &= 373 \text{ pounds} \end{aligned}$$

$$\begin{aligned} W_s(\text{pinion}) &= \frac{W_t}{\cos \psi} (\tan \phi \cos \gamma_d - \sin \psi \cos \gamma_d) \\ &= \frac{1819}{0.81915} (0.36397 \times 0.95061 - 0.57358 \times 0.31040) \\ &= 373 \text{ pounds} \end{aligned}$$



$$\begin{aligned}
 W_s (\text{gear}) &= \frac{W_t}{\cos \psi} (\tan \phi \cos \gamma_D + \sin \psi \cos \gamma_D) \\
 &= \frac{1819}{0.81915} (0.36397 \times 0.31040 + 0.57358 \times 0.95061) \\
 &= 1462 \text{ pounds}
 \end{aligned}$$

The axial thrust load on the bearings is equal to the axial component of the tooth load  $W_x$ . Since thrust loads are always taken up at only one mounting point, either bearing  $A$  or bearing  $B$  must be a bearing capable of taking a thrust of 1462 pounds, and either bearing  $C$  or bearing  $D$  must be capable of taking a thrust of 373 pounds.

The next step is to determine the magnitudes of the radial loads on the bearings  $A$ ,  $B$ ,  $C$ , and  $D$ . For an overhung mounted gear, or pinion, it can be shown, using the principle of moments, that the radial load on bearing  $A$  is:

$$R_A = \frac{1}{M} \sqrt{[W_t(L+M)]^2 + [W_s(L+M) - W_x r]^2} \quad (1)$$

And the radial load on bearing  $B$  is:

$$R_B = \frac{1}{M} \sqrt{(W_t L)^2 + (W_s L - W_x r)^2} \quad (2)$$

For a *straddle mounted gear* or pinion the radial load on bearing  $C$  is:

$$R_C = \frac{1}{N+K} \sqrt{(W_t K)^2 + (W_s K - W_x r)^2} \quad (3)$$

And the radial load on bearing  $D$  is:

$$R_D = \frac{1}{N+K} \sqrt{(W_t N)^2 + (W_s N + W_x r)^2} \quad (4)$$

In these formulas,  $r$  is the mean pitch radius of the gear or pinion.

These formulas will now be applied to the gear and pinion bearings in the example. An overhung mounting is used for the pinion, so **Formula (1)** and **(2)** are used to determine the radial loads on the pinion bearings:

$$R_A = \frac{1}{5} \sqrt{[1819(1.5 + 5)]^2 + [373(1.5 + 5) - 1462 \times 1.367]^2}$$

$$= 2365 \text{ pounds}$$

$$R_B = \frac{1}{5} \sqrt{(1819 \times 1.5)^2 + [373 \times 1.5 - 1462 \times 1.367]^2}$$

$$= 618 \text{ pounds}$$

Because of the straddle mounting used for the gear, **Formula (3)** to **(4)** are used to determine the radial loads on the gear bearings:

$$R_C = \frac{1}{3.5 + 2.5} \sqrt{(1819 \times 2.5)^2 + (1462 \times 2.5 - 373 \times 4.187)^2}$$

$$= 833 \text{ pounds}$$

$$R_D = \frac{1}{3.5 + 2.5} \sqrt{(1819 \times 3.5)^2 + (1462 \times 3.5 + 373 \times 4.187)^2}$$

$$= 1533 \text{ pounds}$$

These radial loads, and the thrust loads previously computed, are then used to select suitable bearings from manufacturers' catalogs.

It should be noted, in applying **Formula (1)** to **(4)**, that if both gear and pinion had overhung mountings, then **Formulas (1)** and **(2)** would have been used for both; if both gear and pinion had straddle mountings, then **Formulas (3)** and **(4)** would have been used for both. In any arrangement, the dimensions and loads for the corresponding member must be used. Also, in applying the formulas, the computed values of  $W_x$  and  $W_s$ , if they are negative, must be used in accordance with the rules applicable to negative numbers.

**Gear Strength Calculations.**—Methods of calculating the strength and power capacity for gears used in all types of applications are provided in American Gear Manufacturers Association (AGMA) standards. These standards are revised as needed by improvements in gear materials, calculation methods, and increased field experience with typical designs and application factors.

AGMA Standard 2001-B88, *Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth*, is a revision of, and supersedes, AGMA 218.01.

The AGMA Standard presents general formulas for rating the pitting resistance and the bending strength of spur and helical involute gear teeth. It is intended to establish a common base for rating various types of gears for differing applications and to encourage the maximum practical degree of uniformity and consistency between rating practices in the gear industry. The Standard provides the basis from which more detailed AGMA Application Standards are developed and is a means for calculation of approximate ratings in the absence of such Standards. Where applicable AGMA standards exist, they should be used in preference to this Standard. Where no application standard exists, numerical values may be estimated for the factors used in the general equations presented in the Standard. The values of these factors may vary significantly, depending on the application, system effects, gear accuracy, manufacturing practice, and definition of what constitutes gear failure.

Information on geometry factors used in pitting resistance independent strength calculations for AGMA 908-B89, *Geometry Factors for Determining the Pitting Resistance and Bending Strength of Spur, Helical, and Herringbone Gear Teeth*, is used in conjunction with AGMA 2001-B88 formulas.

### PRACTICE EXERCISES FOR SECTION 19

(See *Answers to Practice Exercises For Section 19* on page 235)

- 1) A spur gear of 6 diametral pitch has an outside diameter of 3.3333 inches. How many teeth has it? What is the pitch diameter? What is the tooth thickness measured along the pitch circle?
- 2) A gear of 6 diametral pitch has 14 teeth. Find the outside diameter, the pitch diameter, and the addendum.
- 3) When is the 25-degree tooth form standard preferred?
- 4) What dimension does a gear-tooth vernier caliper measure?
- 5) What are the principal 20-degree pressure angle tooth dimensions for the following diametral pitches: 4; 6; 8; 18?

- 6) Give the important  $14\frac{1}{2}$  degree pressure angle tooth dimensions for the following circular pitches:  $\frac{1}{2}$  inch;  $\frac{3}{4}$  inch;  $\frac{9}{16}$  inch.
- 7) What two principal factors are taken into consideration in determining the power transmitting capacity of spur gears?
- 8) The table on Handbook [page 2054](#) shows that a No. 8 formed cutter (involute system) would be used for milling either a 12- or 13-tooth pinion, whereas a No. 7 would be used for tooth numbers from 14 to 16, inclusive. If the pitch is not changed, why is it necessary to use different cutter numbers?
- 9) Are hobs made in series or numbers for each pitch similar to formed cutters?
- 10) If the teeth of a gear have a  $\frac{9}{8}$  pitch, what name is applied to the tooth form?
- 11) A stub-tooth gear has  $\frac{8}{10}$  pitch. What do the figures 8 and 10 indicate?
- 12) What is the module of a gear?
- 13) Explain the use of the table of chordal thicknesses on Handbook [page 2047](#).
- 14) Give the dimensions of a 20-degree stub tooth of 12 pitch.
- 15) What are the recommended diametral pitches for fine-pitch standard gears?
- 16) What tooth numbers could be used in pairs of gears having the following ratios: 0.2642; 0.9615?
- 17) What amount of backlash is provided for general-purpose gearing, and how is the excess depth of cut to obtain it calculated?
- 18) What diametral pitches correspond to the following modules: 2.75; 4; 8?
- 19) Can bevel gears be cut by formed milling cutters?
- 20) Can the formed cutters used for cutting spur gears also be used for bevel gears?
- 21) What is the pitch angle of a bevel gear?
- 22) When is the term "miter" applied to bevel gears?

23) What is the difference between the terms “whole depth” and “working depth” as applied to gear teeth?

24) Why do perceived gears have a greater dedendum than gears that are finish-hobbled?

25) Are gear teeth of 8 diametral pitch larger or smaller than teeth of 4 diametral pitch, and how do these two pitches compare in regard to tooth depth and thickness?

26) Where is the pitch diameter of a bevel gear measured?

27) What is the relation between the circular pitch of a wormgear and the linear pitch of the mating worm?

28) In what respect does the helix angle of a worm differ from the helix angle of a helical or spiral gear?

29) How do the terms “pitch” and “lead,” as applied to a worm, compare with the same terms as applied to screw threads?

30) Why is the outside diameter of a hob for cutting a wormgear somewhat larger than the outside diameter of the worm?

31) Why are triple, quadruple, or other multiple-threaded worms used when an efficient transmission is required?

32) In designing worm drives having multi threaded worms, it is common practice to select a number of wormgear teeth that is not an exact multiple of the number of worm threads. Why is this done? When should this practice be avoided?

33) Explain the following terms used in connection with helical or spiral gears: transverse diametral pitch; normal diametral pitch. What is the relation between these terms?

34) Are helical gear calculations based upon diametral pitch or circular pitch?

35) Can helical gears be cut with the formed cutters used for spur gears?

36) In spiral gearing, the tangent of the tooth or helix angle = the circumference  $\div$  lead. Is this circumference calculated from the outside diameter, the pitch diameter, or the root diameter?

37) What advantages are claimed for gearing of the herringbone type?

## SECTION 20

### CUTTING SPEEDS, FEEDS, AND MACHINING POWER

HANDBOOK Pages **1009** – **1091**

Metal cutting operations such as turning and drilling may not be as productive as they could be unless the material removal rate is at or near the maximum permitted by the available power of the machine. It is not always possible to use the machine's full power owing to limitations imposed by a combination of part configuration, part material, tool material, surface finish and tolerance requirements, coolant employed, and tool life. However, even with such restrictions, it is practical to find a combination of depth of cut, feed rate, and cutting speed to achieve the best production rate for the job at hand.

The information on Handbook **pages 1009** to **1091** is useful in determining how to get the most out of machining operations. The tabular data are based on actual shop experience and extensive testing in machining laboratories. A list of machining data tables is given on Handbook **page 1022**, and these tables are referred to in the following.

Most materials can be machined over a wide range of speeds; however, there is usually a narrower spread of speeds within which the most economical results are obtained. This narrower spread is determined by the economical tool life for the job at hand as, for example, when a shorter tool life is tolerable the speed can be increased. On the other hand, if tool life is too short, causing excessive down time, then speed can be reduced to lengthen tool life.

To select the best cutting conditions for machining a part the following procedure may be followed:

- 1) Select the maximum depth of cut consistent with the job.
- 2) Select the maximum feed rate that can be used consistent with such job requirements as surface finish and the rigidity of the cut-

ting tool, workpiece, and the machine tool. Use Table 15a to assist in feed selection for milling. When possible, use the combined feed/ speed portions of the tables to select two pairs of feed and speed data and determine the spindle speed as illustrated by **Example 1**.

3) If the combined feed/speed data are not used, select the cutting speed and determine the spindle speed (for turning use Table 5a also). This order of selection is based on the laws governing tool life; i.e., the life of a cutting tool is affected most by the cutting speed, then by the feed, and least by the depth of cut.

By using the same order of selection, when very heavy cuts are to be taken, the cutting speed that will utilize the maximum power available on the machine tool can be estimated by using a rearrangement of the machining power formulas on Handbook **pages 1084 to 1088**. These formulas are used together with those on Handbook **pages 1016 and 1040** which are used when taking ordinary cuts, as well as heavy cuts. Often, the available power on the machine will limit the size of the cut that can be taken. The maximum depth of cut and feed should then be used and the cutting speed adjusted to utilize the maximum available power. When the cutting speed determined in this manner is equal to or less than recommended, the maximum production and the best possible tool life will be achieved. When the estimated cutting speed is greater than recommended, the depth of cut or feed may be increased, but the cutting speed should not be increased beyond the value that will provide a reasonable tool life.

*Example 1:* An ASTM Class 25 (160–180 Bhn) grey-iron casting is to be turned on a geared head lathe using a cemented carbide cutting tool. The heaviest cut will be 0.250 inch (6.35 mm) deep, taken on an 8-inch (203.2-mm) diameter of the casting; a feed rate of 0.020 in/rev (0.51 mm/rev) is selected for this cut. Calculate the spindle speed of the lathe, and estimate the power required to take this cut.

Locate the selected work material in Table 4a, and select the feed/speed pairs that correspond to the chosen cutter material. For an uncoated carbide tool, the given feed/speed pairs are: optimum 28/240, and average 13/365.

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Factors to correct for feed and depth of cut are found in Table 5a. First, determine the ratios of  $\frac{\text{chosen feed}}{\text{optimum feed}} = \frac{20}{28} = 0.71$  and  $V_{\text{avg}}/V_{\text{opt}} = \frac{365}{240} = 1.52$ , then, by estimation or interpolation, determine  $F_f$  and  $F_d$ , and calculate  $V$  and  $N$  as follows:

$$F_f = 1.22; F_d = 0.86$$

$$V = V_{\text{opt}} \times F_f \times F_d = 240 \times 1.22 \times 0.86 = 252 \text{ ft/min}$$

$$N = \frac{12V}{\pi D} = \frac{12 \times 252}{\pi \times 8} = 120 \text{ rpm}$$

Next, estimate the power requirements using:  $K_p = 0.52$  (Table 3a),  $C = 0.90$  (Table ),  $Q = 12Vfd$  (Table 7),  $W = 1.30$  (Table ), and  $E = 0.80$  (Table 6).

$$Q = 12Vfd = 12 \times 252 \times 0.020 \times 0.250 = 15.12 \text{ in}^3/\text{min}$$

$$P_m = \frac{K_p C Q W}{E} = \frac{0.52 \times 0.90 \times 15.12 \times 1.30}{0.80} = 11.5 \text{ hp}$$

The equivalent results, expressed in the metric system, can be obtained by converting the cutting speed  $V$ , the metal removal rate  $Q$ , and the power at the motor  $P_m$  into metric units using factors found starting on [page 2549](#) of the Handbook, as illustrated in the following.

$$V = 252 \text{ ft/min} = 252 \times 0.3 = 76 \text{ m/min}$$

$$Q = 15.12 \text{ in}^3/\text{min} = 15.12 \times 16.4 \div 60 = 4.13 \text{ cm}^3/\text{s}$$

$$P_m = 11.5 \text{ hp} = 11.5 \times 0.745 = 8.6 \text{ kw}$$

Alternatively, if metric units are used throughout the problem,  $F_f$  and  $F_d$  are determined in the same manner as above. However, if  $V$  is in meters per minute, and  $D$  and  $d$  are in millimeters, then  $N = 1000V/\pi D$ , and  $Q = Vfd/60$ .

*Example 2:* If the lathe in [Example 1](#) has only a 10-hp motor, estimate the cutting speed and spindle speed that will utilize the maximum available power. Use inch units only.



$$Q_{max} = \frac{P_m E}{K_p C W} = \frac{10 \times 0.80}{0.52 \times 0.90 \times 1.30} \quad \left( P_m = \frac{K_p C Q W}{E} \right)$$

$$= 13.15 \text{ ( in}^3\text{/ min)}$$

$$V = \frac{Q_{max}}{12fd} = \frac{13.15}{12 \times 0.020 \times 0.250} \quad (Q = 12Vfd)$$

$$= 219 \text{ fpm}$$

$$N = \frac{12V}{\pi D} = \frac{12 \times 219}{\pi \times 8} = 105 \text{ rpm}$$

*Example 3:* A slab milling operation is to be performed on 120–140 HB AISI 1020 steel using a 3-inch diameter high-speed-steel plain milling cutter having 8 teeth. The width of this cut is 2 inches; the depth is 0.250 inch, and the feed rate is 0.004 in/tooth. Estimate the power at the motor required to take this cut.

$$V = 110 \text{ fpm (Table 11, page 1045)} \quad Q = f_m w d \text{ (Table 7)}$$

$$K_p = 0.69 \text{ (Table 3b, page 1086)} \quad W = 1.10 \text{ (Table 5)}$$

$$C = 1.25 \text{ (Table 4)} \quad E = 0.80 \text{ (Table 6)}$$

$$N = \frac{12V}{\pi D} = \frac{12 \times 110}{\pi \times 3} = 140 \text{ rpm}$$

$$f_m = f_t n_t N = 0.004 \times 8 \times 140 = 4.5 \text{ in/min}$$

$$P_m = \frac{K_p C Q W}{E} = \frac{0.69 \times 1.25 \times 2.25 \times 1.10}{0.80} = 2.67 \text{ hp}$$

*Example 4:* A 16-inch diameter cemented carbide face milling cutter having 18 teeth is to be used to take a 14-inch wide and 0.125-inch deep cut on an H12 tool steel die block having a hardness of 250–275 HB. The feed used will be 0.008 in/tooth, and the milling machine has a 20-hp motor. Estimate the cutting speed and the spindle speed to be used that will utilize the maximum horsepower available on the machine.

$$K_p = 0.98 \text{ fpm (Table 3a)} \quad W = 1.25 \text{ (Table 5)}$$

$$C = 1.08 \text{ (Table 4, page 1087)} \quad E = 0.80 \text{ (Table 6)}$$

$$Q = f_m w d \text{ (Table 7)}$$

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$$Q_{max} = \frac{P_m E}{K_p C W} = \frac{20 \times 0.80}{0.98 \times 1.08 \times 1.25} \quad \left( P_m = \frac{K_p C Q W}{E} \right)$$

$$= 12.1 \text{ (in}^3 / \text{min)}$$

$$f_m = \frac{Q_{max}}{w d} = \frac{12}{14 \times 0.125} \quad (Q = f_m w d)$$

$$= 6.9 \text{ in/min; use 7 in/min}$$

$$N = \frac{f_m}{f_t n_t} = \frac{7}{0.008 \times 18} \quad (f_m = f_t n_t N)$$

$$= 48.6 \text{ rpm; use 50 rpm}$$

$$V = \frac{\pi D N}{12} = \frac{\pi \times 16 \times 50}{12} = 209 \text{ fpm}$$

Formulas for estimating the thrust, torque, and power for drilling are given on Handbook [page 1090](#). Thrust is the force required to push or feed the drill when drilling. This force can be very large. It is sometimes helpful to know the magnitude of this force and the torque exerted by the drill when designing drill jigs or work-holding fixtures; it is essential to have this information as well as the power required to drill when designing machine tools on which drilling operations are to be performed. In the ordinary shop, it is often helpful to be able to estimate the power required to drill larger holes in order to determine if the operation is within the capacity of the machine to be used.

*Example 5:* Estimate the thrust, torque, and power at the motor required to drill a  $\frac{3}{4}$ -inch diameter hole in a part made from AISI 1117 steel, using a conventional twist drill and a feed rate of 0.008 in/rev.

|   |   |
|---|---|
| $K_d = 12,000$ ( <a href="#">Table 8, page 1090</a> ) | $B = 1.355$ (Table 9)   |
|   | $J = 0.030$ (Table 9)   |
| $F_f = 0.021$ (Table 10)                              | $E = 0.80$ (Table 6)  |
| $F_T = 0.794$ (Table 11)                              | $W = 1.30$ (Table 5)  |
| $F_M = 0.596$ (Table 11)                              | $V = 101 \text{ fpm}$ ( <a href="#">Table 17, page 1061</a> ) |
| $A = 1.085$ (Table 9)                                 |   |

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$$T = 2K_d F_f F_T B W + K_d d^2 J W$$

$$= 2 \times 12,000 \times 0.021 \times 0.794 \times 1.355 \times 1.30 + 12,000 \times 0.75^2 \times 0.030 \times 1.30$$

$$= 968 \text{ lb}$$

$$M = K_d F_f F_M A W$$

$$= 12,000 \times 0.021 \times 0.596 \times 1.085 \times 1.30$$

$$= 212 \text{ in-lb}$$

$$N = \frac{12V}{\pi D} = \frac{12 \times 101}{\pi \times 0.750} = 514 \text{ rpm}$$

$$P_c = \frac{MN}{63,025} = \frac{212 \times 514}{63,025} = 1.73 \text{ hp}$$

$$P_m = \frac{P_c}{E} = \frac{1.73}{0.80} = 2.16 \text{ hp}$$

**PRACTICE EXERCISES FOR SECTION 20**

(See *Answers to Practice Exercises For Section 20* on page 237)

1) Calculate the spindle speeds for turning 1/2 inch and 4-inch bars made from the following steels, using a high-speed steel cutting tool and the cutting conditions given as follows:

| Steel Designation     | Feed, in/rev | Depth of Cut, inch |
|-----------------------|--------------|--------------------|
| AISI 1108, Cold Drawn | 0.012        | 0.062              |
| 12L13, 150 — 200 HB   | 0.008        | 0.250              |
| 1040, Hot Rolled      | 0.015        | 0.100              |
| 1040, 375 — 425 HB    | 0.015        | 0.100              |
| 41L40, 200 — 250 HB   | 0.015        | 0.100              |
| 4140, Hot Rolled      | 0.015        | 0.100              |
| O2, Tool Steel        | 0.012        | 0.125              |
| M2, Tool Steel        | 0.010        | 0.200              |

2) Calculate the spindle speeds for turning 6-inch diameter sections of the following materials, using a cemented carbide cutting tool and the cutting conditions given below:

| Material                        | Feed, in/rev | Depth of Cut, inch |
|---------------------------------|--------------|--------------------|
| AISI 1330, 200 HB               | 0.030        | 0.150              |
| 201 Stainless Steel, Cold Drawn | 0.012        | 0.100              |
| ASTM Class 50 Gray Cast Iron    | 0.016        | 0.125              |
| 6A1-4V Titanium Alloy           | 0.018        | 0.188              |
| Waspaloy                        | 0.020        | 0.062              |

3) A 200 HB AISI 1030 forged steel shaft is being turned at a constant spindle speed of 400 rpm, using a cemented carbide cutting tool. The as-forged diameters of the shaft are 1½, 3, and 4 inches. Calculate the cutting speeds (fpm) at these diameters, and check to see if they are within the recommended cutting speed.

4) A 75-mm diameter bar of cold drawn wrought aluminum is to be turned with a high-speed steel cutting tool, using a cutting speed of 180 in/mm. Calculate the spindle speed that should be used.

5) Calculate the spindle speed required to mill a 745 nickel silver part using a ½ inch end milling cutter.

6) An AISI 4118 part having a hardness of 200 HB is to be machined on a milling machine. Calculate the spindle speeds for each of the operations below and the milling machine table feed rates for Operations a) and b).

a) Face mill top surface, using an 8-inch diameter cemented carbide face milling cutter having two teeth. (Use  $f_t = 0.008$  in/tooth.)

b) Mill ¼ inch deep slot, using a ¾ inch diameter two-fluted high-speed steel end milling cutter.

c) Drill a 23/64 inch hole.

d) Ream the hole 3/8 inch, using HSS reamer.

7) A 3-inch diameter high-speed steel end milling cutter having 12 teeth is used to mill a piece of D2 high carbon, high chromium cold work tool steel having a hardness of 220 HB. The spindle speed used is 75 rpm, and the milling machine table feed rate is 10 in/mm. Check the cutting conditions with respect to the recommended values, and make recommendations for improvements, if possible.

8) A 100–150 HB low carbon steel casting is to be machined with a 12-inch diameter cemented carbide face milling cutter having 14 teeth, using a spindle speed of 60 rpm and a table feed rate of 5 in/mm. Check these cutting conditions and recommend improvements, if possible.

9) Estimate the cutting speed and the power at the cutter and at the motor required to turn 210 HB AISI 1040 steel in a geared head lathe, using an uncoated carbide tool, a depth of cut of 0.125 in., a feed of 0.015 in/rev, and efficiency  $E$  of 0.80.

10) A 165 HB A286 high temperature alloy, or superalloy, is to be turned on a 3-hp geared head lathe using a cemented carbide cutting tool. The depth of cut selected is 0.100 inch, and the feed is 0.020 in/rev. Estimate the cutting speed that will utilize the maximum power available on the lathe.

11) An AISI 8642 steel having a hardness of 210 HB is to be milled with a 6-inch diameter cemented carbide face milling cutter having 8 teeth on a 10 hp milling machine. The depth of cut is to be 0.200 inch, the width is 4 inches, and the feed is to be 0.010 in/tooth. Estimate the cutting speed that will utilize the maximum power available on the machine.

12) Estimate the thrust, torque, and power at the motor required to drill 200 HB steel using the following drill sizes, feeds, and spindle speeds.

| Drill Size | Feed          | Spindle Speed |
|------------|---------------|---------------|
| ¼ in.      | 0.0005 in/rev | 1500 rpm      |
| ½ in.      | 0.002 in/rev  | 750 rpm       |
| 1 in.      | 0.008 in/rev  | 375 rpm       |
| 19 mm      | 0.15 mm/rev   | 500 rpm       |

13) Estimate the thrust, torque, and power at the motor for the 1-inch drill in Exercise 12 if the drill is ground to have a split point.

14) Describe the general characteristics of high speed steels that make them suitable for use as cutting tool materials.

15) What guidelines should be followed in selecting a grade of cemented carbide?

16) How does the cutting speed, feed, and depth of cut influence tool life?

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17) List the steps for selecting the cutting conditions in their correct order and explain why.

18) What are the advantages of coated carbides, and how should they be used?

19) Name the factors that must be considered when selecting a cutting speed for tapping.

20) Why is it important to calculate the table feed rate for milling?

21) Name the factors that affect the basic feed rate for milling.

22) When should the power required to take a cut be estimated? Why?

23) Name the factors that affect the power constant,  $K_p$ . This constant is unaffected by what?

24) Why is it necessary to have a separate method for estimating the drilling thrust, torque, and power?

## **SECTION 21**

### **NUMERICAL CONTROL**

HANDBOOK Pages **1254** – **1314**

Numerical control (NC) is defined by the Electronic Industries Association as “a system in which actions are controlled by the direct insertion of numerical data at some point. The system must automatically interpret at least some portion of these data.” Applied to machine tools, NC is used to tell the unit what to do in such explicit detail that it can produce a component part or parts in a completely automatic cycle without intervention from the operator. This cycle may extend from loading of a raw casting or other workpiece through unloading of a finished component ready for assembly and can be repeated precisely, as often as required. An important aspect of NC is that machines so equipped can often be set up to process even single components economically.

Apart from systems that are designed to load, locate, and clamp the part to be machined, and to select the tool and the spindle speed to be used, for instance, NC installations use programs designed to control movements of the cutting edge of the tool relative to the work (or the work relative to the tool). These machining control instructions, called part programs, may be put together by a machine operator with a push-button panel on the machine if the part is simple, or they may be written in an engineering office, often with the aid of a computer. Some part programs may provide for simply moving the tool or workpiece from one position, at which a fixed machining cycle (known as a subroutine or subprogram) is to be performed, to other positions where the same cycle is to be repeated and triggering the subroutine at each position. Such a program is called point-to-point positioning. There are subroutines for drilling, reaming, counterboring, and tapping, for which tools will be inserted into, clamped, and removed from the spindle automatically.

Other, more complex, programs may be written to cause the workpiece to move past the cutting tool in a series of curves, to generate contoured surfaces on the work. Such a program is called continuous-path or contouring program. In the associated machining operation, the movement of the table carrying the workpiece along (usually) two axis, and (sometimes) of the spindle head holding the cutter along one axis, is coordinated by electronic signals in a binary digital code that are converted to DC or AC power and fed continuously to controllers connected to the units powering the slides. Measuring equipment attached to each lead screw or slide provides continuous feedback information of the slide position to the control system for comparison with the command program.

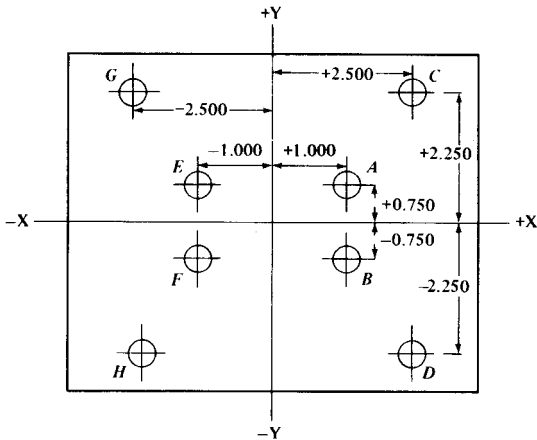
Information in the Handbook, [pages 1254 to 1314](#), is arranged by subject matter for ease of reference and, because of the complexity of the subject, depends to some extent on definitions to explain the various aspects. Much attention is paid to the use of the Automatic Programmed Tool (APT) language in part programming, and examples of typical computational and geometric programs are discussed. For instance, the APT language can be used to specify the four arithmetical operations and the exponential and trigonometric computations used in many algebraic formulas. The APT language visualizes the part program as if it were designed to move the tool past a stationary workpiece, but the formulas for generation of the required shapes most often are translated by the control system into movements of the slides to carry the workpiece past the cutting tool.

**Point-to-Point Programming.**—As an example of the use of NC for point-to-point part programs, consider the rectangular plate shown in [Fig. 1](#), in which it is required to machine eight holes as shown. Dimensions for the positions of the holes are here provided in terms of their distances from *X* and *Y* axes, which are conveniently located at a central point on the part. This positioning information is easily transferred to the punched paper tape or other means used to feed it to the machine. Instructions for the tooling to be loaded into the spindle for the work to be performed are also included in the part program, in accordance with the special codes, many of which are listed in the Handbook. The hole location infor-



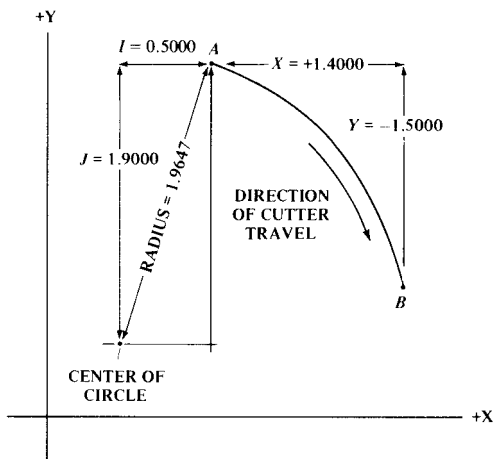
mation in the table following **Fig. 1** is entered in a part programming manuscript, together with coded details such as spindle speed and feed rates, and is subsequently saved in a form that will be read by the NC machine when the machining work is started.

**Continuous-Path Programming.**— Surfaces at angles to the axes and curved surfaces are produced by continuous-path, or contouring, programs. These programs coordinate two or more machine motions simultaneously and precisely, so that the movement of the workpiece relative to the cutting tool generates the required curved shape. Angular shapes are generated by straight-line or linear interpolation programs that coordinate movements of two slides to produce the required angle. Circular arcs can be generated by means of a circular interpolation program that controls the slide movements automatically to produce the curved outline. Arcs that are not circular generally must be broken down into a sequence of straight-line segments. Surfaces generated by this method can be held within tolerance by using a large number of segments closely spaced together.



**Fig. 1. Alternative Methods of Dimensioning for the Positions of Eight Holes to Be Machined in a Rectangular Plate**

| Point | Dimensions on Axes |         | Point | Dimensions on Axes |         |
|-------|--------------------|---------|-------|--------------------|---------|
|       | X                  | Y       |       | X                  | Y       |
| A     | + 1.000            | + 0.750 | E     | - 1.000            | + 0.750 |
| B     | + 1.000            | - 0.750 | F     | - 1.000            | - 0.750 |
| C     | + 2.500            | + 2.250 | G     | - 2.500            | + 2.250 |
| D     | + 2.500            | - 2.250 | H     | - 2.500            | - 2.250 |



**Fig. 2. Curved Path of Cutter Produced by a Circular Interpolation**

For example, in programming the movement of a cutter, relative to the workpiece, along the curved line shown in the diagram, **Fig. 2**, it is first necessary to indicate that the cutter is to move in a clockwise and circular path by inserting code  $GO_2$  into the program. Next, the movements along the X and Y axes, which define the component lengths of the arc, are inserted. In **Fig. 2**, the X movement is +1.4000 inches and the Y movement is -1.5000 inches. The I dimension of 0.5000 inch parallel to the X axis is the horizontal distance of point A from the arc center and is next included in the program. The vertical distance J of 1.9000 inches from the arc center to the circle is next entered, and the feed rate also must be entered.

Fig. 3 and 4 are included as the basis for practice exercises only.

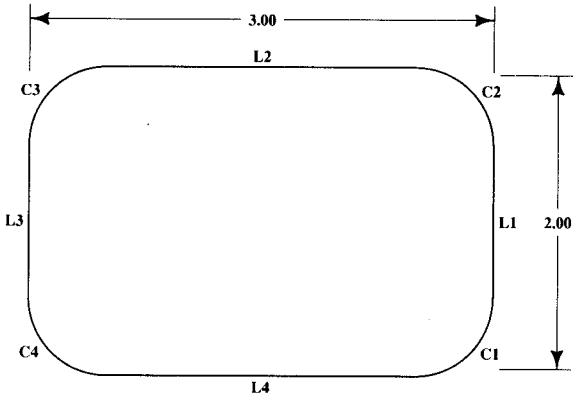


Fig. 3. Dimensions of a pocket to Be Milled under Numerical Control

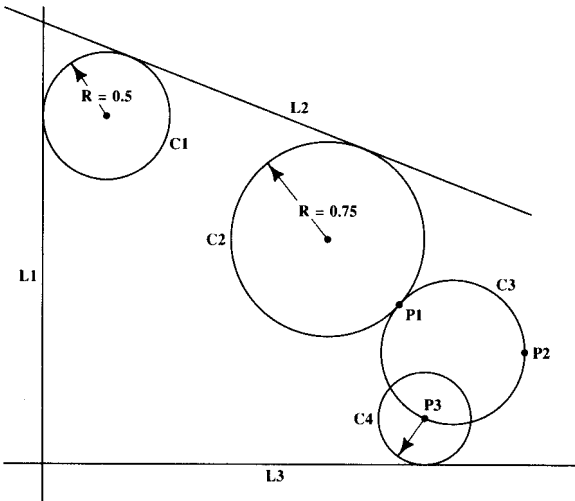


Fig. 4. Circles for Which APT Statements Are Required

**PRACTICE EXERCISES FOR SECTION 21**

(See *Answers to Practice Exercises For Section 21* on page 239)

1) List five or more machine tools on which point-to-point programming is used.

2) List five or more applications of continuous-path, or contouring, programs.

3) Give some reasons why NC machines are being used increasingly.

4) Which of the following applications of NC is the most used?

(a) Grinding, (b) turning, (c) broaching.

5) A \_\_\_ is a rotary device used to feed signals to the control system to close the servo loop of an NC installation.

6) CNC systems are far superior to their hardwire predecessors. Name several advantages of CNC systems.

7) What purpose is served by the feedbacks in an NC servo system?

8) If a stepping motor connected directly to a lead screw rotates 1.8 degrees per pulse, how far would a 5-pitch lead screw move a slide if the motor received 254 pulses?

9) With a CNC system, the *F* or feedrate word is most commonly described as (a) Ratio of rpm feed divided by the distance moved. (b) Directly in rpm.

10) The word that identifies a block is called a \_\_\_\_ \_\_\_\_.

11) The word address letter for the velocity of a slide on an NC machine is \_\_\_\_.

12) What is the difference between cutter offset and cutter compensation?

13) Circular interpolation reduces the number of straight-line segments required to be calculated when a machine is moving about a circular arc. (True, False.)

14) With most control systems, how many blocks would be needed to move around a complete circle (360 degrees) when circular interpolation is used?

15) In the first column below are shown the various subroutines or canned cycles. In the second column are some preparatory codes. Match the functions with the codes.

- |  |        |
|--|--------|
| a. Drill plus dwell  | 1. G89 |
| b. Deep hole drill   | 2. G81 |
| c. Boring, spindle rotating on withdrawal at feedrate            | 3. G85 |
| d. Drill   | 4. G84 |
| e. Tapping   | 5. G82 |
| f. Boring, spindle rotating on withdrawal at feedrate plus dwell | 6. G83 |

16) A parametric subroutine is used exclusively for describing the path around the outside of a part. (True, False.)

17) Computer-aided part programming refers to the assistance offered by the computer within the CNC system. (True, False.)

18) The media used for transmitting data and instructions to an NC system is (a) floppy disc, (b) magnetic tape, (c) punched tape.

19) Name the three surfaces involved in an APT move.

20) Two of the three surfaces in APT appear as lines when viewed from directly above. What are these surfaces?

21) What is a G word?

22) What is an APT startup statement?

23) Explain the rule that describes the orientation and directions of the motions of slides and spindles on a machine tool.

24) Write APT statements for the lines L1, L2, L3, and L4 for the pocket shown in **Fig. 3**. Assume that C1, C2, C3, and C4 are defined.

25) Write APT statements for the circles C1 through C4, shown in **Fig. 4**. Assume that L1, L2, L3, P1, P2, and P3 are defined.

26) Write computation statements for the following mathematical terms:

$$\frac{1 + 25}{42}; 6 \times 8 + 8 \div 2 - 52; 6 \times \frac{8 \times 8}{2 - 52}$$

$$\frac{4^2 + \sqrt{(12 + 8)^3}}{2 \times 6.8 \div 2(1 + 3)^4}; \sin 30 \text{ degrees}; \arctan 0.486$$

27) Of the five APT sections in a computer, which is responsible for developing the G and M words for a particular machine tool?

## SECTION 22

### GENERAL REVIEW QUESTIONS

(See *Answers to General Review Questions* on page 242)

- 1) If a regular polygon of 20 sides is to have an area of 100 square inches what formula may be used to calculate the length of one side of the polygon?
- 2) What does the number of a Jarno taper indicate?
- 3) What is the general rule for determining the direction in which to apply tolerances?
- 4) Why is 1 horsepower equivalent to 33,000 foot-pounds of work per minute? Why not 30,000 or some other number?
- 5) What is the chief element in the composition of babbitt metals?
- 6) If the pitch of a stub-tooth gear is  $\frac{8}{10}$ , what is the tooth depth?
- 7) What does the figure 8 mean if the pitch of a stub-tooth gear is  $\frac{8}{10}$ ?
- 8) Explain how to determine the diametral pitch of a spur gear from a sample gear.
- 9) If a sample gear is cut to circular pitch, how can this pitch be determined?
- 10) What gage is used for seamless tubing, and does it apply to all metals?
- 11) How does the strength of iron wire rope compare with steel rope?
- 12) Is the friction between two bearing surfaces proportional to the pressure?
- 13) If the surfaces are well lubricated, upon what does frictional resistance depend?
- 14) What is the general rule for subtracting a negative number from a positive number? For example,  $8 - (-4) = ?$
- 15) Is 1 meter longer than 1 yard?

16) On Handbook **page 2578**, two of the equivalents of horse-power-hour are: 1,980,000 foot-pounds and 2.64 pounds of water evaporated at 212°F. How is this relationship between work and heat established?

17) Are “extra strong” and “double extra strong” wrought or steel pipe larger in diameter than standard weight pipe?

18) In the design of plain bearings, what is the general relationship between surface finish and hardness of journal?

19) Are the nominal sizes of wrought or steel pipe ever designated by giving the outside diameter?

20) What are the advantages of plastics pipe?

21) Will charcoal ignite at a lower temperature than dry pine?

22) What general classes of steel are referred to as “stainless”?

23) What are free cutting steels?

24) Does the nominal length of a file include the tang? For example, is a 12-inch file 12 inches long over all?

25) Is steel heavier (denser) than cast iron?

26) What is meant by specific heat?

27) What is the specific gravity (a) of solid bodies, (b) of liquids, (c) of gases?

28) A system of four-digit designations for wrought aluminum and aluminum alloys was adopted by The Aluminum Association in 1954. What do the various digits signify?

29) What alloys are known as “red brass,” and how do they compare with “yellow brass”?

30) What is the difference between adiabatic expansion or compression and isothermal expansion or compression?

31) Are the sizes of all small twist drills designated by numbers?

32) Why are steel tools frequently heated in molten baths to harden them?

33) In hardening tool steel, what is the best temperature for refining the grain of the steel?

34) In cutting a screw thread on a tap assume that the pitch is to be increased from 0.125 inch to 0.1255 inch to compensate for shrinkage in hardening. How can this be done?

35) What is the general rule for reading a vernier scale (a) for linear measurements; (b) for angular measurements?

36) The end of a shaft is to be turned to a taper of  $\frac{3}{8}$  inch per foot for a length of inches without leaving a shoulder at the end of the cut. How is the diameter of the small end determined?

37) Is there a simple way of converting the function of  $90^\circ$  plus an angle to the function of the angle itself?

38) What decimal part of a degree is 53 minutes?

39) If  $10x - 5 = 3x + 16$ , what is the value of  $x$ ?

40) Approximately what angle is required for a cone clutch to prevent either slipping or excessive wedging action?

41) What is the coefficient of friction?

42) Is Stub's steel wire gage used for the same purpose as Stub's iron wire gage?

43) Why are some ratchet mechanisms equipped with two pawls of different lengths?

44) How does the modulus of elasticity affect the application of flat belts?

45) What is the effect of centrifugal force on flat and V-belts?

46) Is the ultimate strength of a crane or hoisting chain equal to twice the ultimate strength of the bar or rod used for making the links?

47) How would you determine the size of chain required for lifting a given weight?

48) If a shaft  $3\frac{1}{2}$  inches in diameter is to be turned at a cutting speed of 90 feet per minute, what number of revolutions per minute will be required?

49) In lapping by the "wet method," what kind of lubricant is preferable (a) with a steel lap, (b) with a cast-iron lap?

50) What is the meaning of the terms right-hand and left-hand as applied to helical or spiral gears, and how is the "hand" of the gear determined?

51) Are mating helical or spiral gears always made to the same hand?

52) How would you determine the total weight of 100 feet of  $1\frac{1}{2}$  inch standard weight pipe?

53) What is the difference between casehardening and packhardening?



- 54) What is the nitriding process of heat-treating steel?
- 55) What is the difference between single-cut and double-cut files?
- 56) For general purposes, what is the usual height of work benches?
- 57) What do the terms "major diameter" and "minor diameter" mean as applied to screw threads in connection with the American Standard?
- 58) Is the present SAE Standard for screw threads the same as the Unified and American Standard?
- 59) Does the machinability of steel depend only upon its hardness?
- 60) Is there any direct relationship between the hardness of steel and its strength?
- 61) What is the millimeter equivalent of  $\frac{33}{64}$ ths of an inch?
- 62) How is the involute function of an angle calculated?
- 63) What is the recommended cutting speed in feet per minute for turning normalized AISI 4320 alloy steel with a Bhn hardness of 250, when using an uncoated, tough carbide tool?
- 64) The diametral pitch of a spur gear equals the number of teeth divided by pitch diameter. Is the diametral pitch of the cutter or hob for a helical or spiral gear determined in the same way?
- 65) Why are casehardening steels preferred for some gears and what special heat treatment is recommended?
- 66) Are the symbols for dimensions and angles used in spline calculations the same for both inch-dimension and metric module involute splines?
- 67) What kind of bearing surface and tool insert rake are provided by an indexable insert tool holder?
- 68) Is it necessary in making ordinary working drawings of gears to lay out the tooth curves? Why?
- 69) In milling plate cams on a milling machine, how is the cam rise varied other than by changing the gears between the dividing head and feed screw?
- 70) How is the angle of the dividing head spindle determined for milling plate cams?

71) How is the center-to-center distance between two gears determined if the number of teeth and diametral pitch are known?

72) How is the center-to-center distance determined for internal gears?

73) In the failure of riveted joints, rivets may fail through one or two cross-sections or by crushing. How may plates fail?

74) What gage is used in Britain to designate wire sizes?

75) What is a transmission dynamometer?

76) What is the advantage of a dynamometer for measuring power?

77) If a beam supported at each end is uniformly loaded throughout its length, will its load capacity exceed that of a similar beam loaded at the center only?

78) Is there any relationship between Brinell hardness and tensile strength of steel?

79) Is the outside diameter of a 2-inch pipe about 2 inches?

80) The hub of a lever 10 inches long is secured to a 1-inch shaft by a taper pin. If the maximum pull at the end of the lever equals 60 pounds, what pin diameter is required? (Give mean diameter or diameter at center.)

81) What are the two laws that form the basis of all formulas relating to the solution of triangles?

82) What are the sine and the cosine of the angle 45 degrees?

83) How is the pressure of water in pounds per square inch determined for any depth?

84) When calculating the basic load rating for a unit consisting of two bearings mounted in tandem, is the rated load of the combination equal to 2 times the capacity of a single bearing?

85) If a machine producing 50 parts per day is replaced by a machine that produces 100 parts per day, what is the percentage of increase?

86) If production is decreased from 100 to 50, what is the percentage of reduction?

87) What kind of steel is used ordinarily for springs in the automotive industry?

88) What is the heat-treating process known as "normalizing"?

89) What important standards apply to electric motors?

90) Is there an American standard for section linings to represent different materials on drawings?

91) Is the taper per foot of the Morse standard uniform for all numbers or sizes?

92) Is there more than one way to remove a tap that has broken in the hole during tapping?

93) The center-to-center distance between two bearings for gears is to be 10 inches, with a tolerance of 0.005 inch. Should this tolerance be (a) unilateral and plus, (b) unilateral and minus, (c) bilateral?

94) How are the available pitch diameter tolerances for Acme screw threads obtained?

95) On Handbook [page 1331](#), there is a rule for determining the pressure required for punching circular holes into steel sheets or plates. Why is the product of the hole diameter and stock thickness multiplied by 80 to obtain the approximate pressure in tons?

96) What gage is used in the United States for cold-rolled sheet steel?

97) What gage is used for brass wire and is the same gage used for brass sheets?

98) Is the term "babbitt metal" applied to a single composition?

99) What are the chief elements in high-grade babbitt metal?

100) How many bars of stock 20 feet long will be needed to make 20,000 dowel-pins 2 inches long if the tool for cutting them off is 0.100 inch wide?

101) What is the melting point and density of cast iron; steel; lead; copper; nickel?

102) What lubricant is recommended for machining aluminum?

103) What relief angles are recommended for cutting copper, brass, bronze, and aluminum?

104) Why is stock annealed between drawing operations in producing parts in drawing dies?

105) When is it advisable to mill screw threads?

106) How does a fluted chucking reamer differ from a rose chucking reamer?

107) What kind of material is commonly used for gage blocks?

108) What grade of gage blocks is used as shop standards?

- 109) What is the “lead” of a milling machine?
- 110) The table on Handbook **page 1972** shows that a lead of 9.625 inches will be obtained if the numbers of teeth in the *driven* gears are 44 and 28 and the numbers of teeth on the *driving* gears 32 and 40. Prove that this lead of 9.625 inches is correct.
- 111) Use the prime number and factor table beginning on Handbook **page 20** to reduce the following fractions to their lowest terms:  $\frac{210}{462}$ ;  $\frac{2765}{6405}$ ;  $\frac{741}{1131}$ .
- 112) If a bevel gear and a spur gear each have 30 teeth of 4 diametral pitch, how do the tooth sizes compare?
- 113) For what types of work are the following machinists’ files used: (a) flat files? (b) half round files? (c) hand files? (d) knife files? (e) general-purpose files? (f) pillar files?
- 114) Referring to the illustration on Handbook **page 713**, what is the dimension  $x$  over the rods used for measuring the dovetail slide if  $a$  is 4 inches, angle  $\alpha$  is 60 degrees, and the diameter of the rods used is  $\frac{5}{8}$  inch?
- 115) Determine the diameter of the bar or rod for making the links of a single chain required to lift safely a load of 6 tons.
- 116) Why will a helical gear have a greater tendency to slip on an arbor while the teeth are being milled than when milling a straight tooth gear?
- 117) What is meant by “trepanning”?
- 118) When is a removable or “slip” bushing used in a jig?
- 119) What are the relative ratings and properties of an H43 molybdenum high-speed tool steel?
- 120) What systematic procedure may be used in designing a roller chain drive to meet certain requirements as to horsepower, center distance, etc.?
- 121) In the solution of oblique triangles having two sides and the angle opposite one of the sides known, it is possible to have no solution or more than one solution. Under what condition will there be no solution?
- 122) What gear steels would you use (1) for casehardened gears? (2) for fully hardened gears? (3) for gears that are to be machined after heat treatment?

123) Is it practicable to tap holes and obtain (1) Class 2B fits? (2) Class 3B fits?

124) What is the maximum safe operating speed of an organic bonded Type grinding wheel when used in a bench grinder?

125) What is the recommended type of diamond wheel and abrasive specification for internal grinding?

126) Is there a standard direction of rotation for all types of nonreversing electric motors?

127) Antifriction bearings are normally grease-lubricated. Is oil ever used? If so, when?

128) In the example on Handbook [page 1945](#), the side relief angle at the leading edge of the single-point Acme thread cutting tool was calculated to be  $19.27^\circ$ , or  $19^\circ 16'$ , which provides an effective relief angle ( $a_e$ ) between the flank of the tool and the side of the thread of  $10^\circ$  at the minor diameter. What is the effective relief angle of this tool at the pitch diameter ( $E$ ) and at the major diameter ( $D$ )? The pitch diameter of the thread is 0.900 inch, the major diameter is 1.000 inch, and the lead of the thread is 0.400 inch.

129) Helical flute milling cutters having eccentric relief are known to provide better support of the cutting edge than cutters ground with straight or concave relief. For a 1-inch diameter milling cutter having a 35-degree helix angle, what is the measured indicator drop according to the methods described beginning on Handbook page 800 if the radial relief angle is to be  $7^\circ$ ?

130) On Handbook [page 2265](#), Table 6 shows that TFE fabric bearings have a load capacity of 60,000 pounds per square inch. Also shown in the table is a PV limit of 25,000 for this material. At what maximum surface speed in feet per minute can this material operate when the load is 60,000 psi?

131) Is there a standard for shaft diameter and housing bore tolerance limits that applies to rolling element bearings?

132) In designing an aluminum bronze plain bearing, what hardness should the steel journal have?

133) Steel balls are usually sold by the pound. How many pounds will provide 100 balls of  $\frac{13}{32}$ -inch diameter carbon steel?

GENERAL REVIEW QUESTIONS

134) If a 3AM1–18 steel retaining ring were used on a rotating shaft, what is the maximum allowable speed of rotation?

135) What procedure applies to 3-wire measurements of Acme threads when the lead angle is greater than 5 degrees?

136) Twelve 1½-inch diameter rods are to be packed in a tube. What is the minimum inside diameter of the tube?

## SECTION 23

### ANSWERS TO PRACTICE EXERCISES

All references are to Handbook page numbers

#### Answers to Practice Exercises For Section 1

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 1                  | 78.54 mm <sup>2</sup> ; 31.416 mm   |
| 2                  | 4.995 or 5, approx.   |
| 3                  | 3141.6 mm <sup>2</sup>  |
| 4                  | 127.3 psi   |
| 5                  | 1.27  |
| 6                  | 1.5708  |
| 7                  | 8 hours, 50 minutes   |
| 8                  | 2450.448 pounds   |
| 9                  | 2 $\frac{1}{16}$ inches   |
| 10                 | 7 degrees, 10 minutes   |
| 11                 | Yes. The $x$ , $y$ coordinates given in the tables of Jig Boring coordinates, Handbook <b>pages 993 to 1002</b> , may be used |

#### Answers to Practice Exercises For Section 2

| Number of Question | Answers<br>(Or where information is given in Handbook) |
|--------------------|--|
| 1                  | Handbook <b>page 989</b>                               |
| 2                  | (a) 0.043 inch, (b) 0.055 inch, (c) 0.102 inch         |
| 3                  | 0.336 inch   |
| 4                  | 2.796 inches   |
| 5                  | 4.743 inches   |
| 6                  | 4.221 feet   |
| 7                  | Handbook <b>page 63</b> and <b>71</b>                  |
| 8                  | 740 gallons, approximately                             |

**Answers to Practice Exercises For Section 2** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook) |
|--------------------|--|
| 9                  | Formula on Handbook <b>page 78</b>                     |
| 10                 | Formula on Handbook <b>page 78</b>                     |
| 11                 | Formulas on Handbook <b>page 78</b>                    |

**Answers to Practice Exercises For Section 3**

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 1                  | (a) 104 horsepower;<br>(b) if reciprocal is used, $H = 0.33 D^2 SN$  |
| 2                  | 65 inches  |
| 3                  | 5.74 inches  |
| 4                  | Side $s = 5.77$ inches; diagonal $d = 8.165$ inches, and volume = 192.1 cubic inches   |
| 5                  | 91.0408 square inches  |
| 6                  | 4.1888 and 0.5236  |
| 7                  | 59.217 cubic inches  |
| 8                  | Handbook <b>page 2542</b>  |
| 9                  | $a = \frac{2A}{h} - b$   |
| 10                 | $r = \sqrt{R^2 - \frac{s^2}{4}}$   |
| 11                 | $a = \sqrt{\frac{(P/\pi)^2}{2} - b^2}$   |
| 12                 | $\sin A = \sqrt{1 - \cos^2 A}$   |
| 13                 | $a = \frac{b \times \sin A}{\sin B}; b = \frac{a \times \sin B}{\sin A}$<br>$\sin A = \frac{a \times \sin B}{b}$<br>$\sin B = \frac{b \times \sin A}{a}$ |



**Answers to Practice Exercises For Section 4**

| Number of Question | Answers<br>(Or where information is given in Handbook) |
|--------------------|--|
| 2                  | 4; 35; 72  |
| 5                  | \$5,954.45; \$6,131.81                                 |

**Answers to Practice Exercises For Section 5**

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 1                  | Handbook <b>page 112</b>   |
| 2                  | Table beginning on Handbook <b>page 115</b>  |
| 3                  | 2; 2; 1; $\bar{3}$ ; 3; 1  |
| 4                  | As location of decimal point is indicated by characteristic, which is not given, the number might be 7082, 708.20, 70.82, 7.082, 0.7082, 0.07082, etc.; 7675, 767.5, etc.; 1689, 168.9, etc. |
| 5                  | (a) 70.82; 76.75; 16.89; (b) 708.2; 767.5, 168.9; 7.082, 7.675, 1.689; 7082, 7675, 1689  |
| 6                  | 2.88389; 1.94052; $\bar{3}$ .94151   |
| 7                  | 792.4; 17.49; 1.514; 486.5   |
| 8                  | 4.87614; 1.62363   |
| 9                  | 67.603; 4.7547   |
| 10                 | 146.17; 36.8   |
| 11                 | 9.88; 5.422; 5.208   |
| 12                 | 0.2783   |
| 13                 | 0.0000001432   |
| 14                 | 237.6  |
| 15                 | 187.08   |
| 16                 | 14.403 square inches   |
| 17                 | 2.203 or, say, $2\frac{1}{4}$ inches   |
| 18                 | 107 horsepower   |
| 19                 | No   |
| 20                 | Yes, See <b>page 1950</b>  |

**Answers to Practice Exercises For Section 6**

| Number of Question | Answers<br>(Or where information is given in Handbook) |
|--------------------|--|
| 1                  | 8001.3 cubic inches                                    |
| 2                  | 83.905 square inches                                   |
| 3                  | 69.395 cubic inches                                    |
| 4                  | 1.299 inches   |
| 5                  | 22.516 cubic inches                                    |
| 6                  | 8 inches   |
| 7                  | 0.0276 cubic inch                                      |
| 8                  | 4.2358 inches  |
| 9                  | 1.9635 cubic inches                                    |
| 10                 | 410.5024 cubic inches                                  |
| 11                 | 26.4501 square inches                                  |
| 12                 | Radius; 1.4142 inches; area, 0.43 square inch          |
| 13                 | Area, 19.869 square feet; volume, 10.2102 cubic feet   |
| 14                 | Area, 240 square feet; volume, 277.12 cubic feet       |
| 15                 | 11.3137 inches   |
| 16                 | 41.03 gallons  |
| 17                 | 17.872 square gallons                                  |
| 18                 | 1.032 inches   |
| 19                 | 40 cubic inches  |
| 20                 | Table Handbook <b>page 74</b>                          |
| 21                 | Table Handbook <b>page 74</b>                          |
| 22                 | 5.0801 inches  |
| 23                 | 4 inches; 5226 inches                                  |

**Answers to Practice Exercises For Section 7**

| Number of Question | Answers<br>(Or where information is given in Handbook) |
|--------------------|--|
| 1                  | Handbook <b>page 49</b>                                |
| 2                  | Handbook <b>page 49</b>                                |
| 3                  | Handbook <b>page 49</b>                                |
| 4                  | Handbook <b>page 49</b>                                |
| 5                  | Handbook <b>page 50</b>                                |
| 6                  | Handbook <b>page 50</b>                                |
| 7                  | Handbook <b>page 50</b>                                |

**Answers to Practice Exercises For Section 7** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook) |
|--------------------|--|
| 8                  | Handbook <b>page 50</b>                                |
| 9                  | Handbook <b>page 51</b>                                |
| 10                 | Handbook <b>page 51</b>                                |
| 11                 | Handbook <b>page 51</b>                                |
| 12                 | Handbook <b>page 51</b>                                |
| 13                 | Handbook <b>page 52</b>                                |
| 14                 | Handbook <b>page 51</b>                                |
| 15                 | Handbook <b>page 51</b>                                |
| 16                 | Handbook <b>page 51</b>                                |
| 17                 | Handbook <b>page 51</b>                                |
| 18                 | Handbook <b>page 51</b>                                |
| 19                 | Handbook <b>page 51</b>                                |
| 20                 | Handbook <b>page 52</b>                                |
| 21                 | Handbook <b>page 52</b>                                |
| 22                 | Handbook <b>page 52</b>                                |
| 23                 | Handbook <b>page 53</b>                                |
| 23                 | Handbook <b>page 53</b>                                |
| 24                 | Handbook <b>page 53</b>                                |
| 25                 | Handbook <b>page 53</b>                                |
| 26                 | Handbook <b>page 53</b>                                |

**Answers to Practice Exercises For Section 8**

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 1                  | See Handbook <b>pages 91 – 96</b>  |
| 2                  | In any right-angle triangle having an acute angle of 30 degrees, the side opposite that angle equals $0.5 \times$ hypotenuse                               |
| 3                  | Sine = 0.31634; tangent = 0.51549;<br>cosine = 0.83942   |
| 4                  | Angles equivalent to tangents are $27^{\circ}29'24''$ and $7^{\circ}25'16''$ ; angles equivalents to cosines are $86^{\circ}5'8''$ and $48^{\circ}26'52''$ |

**Answers to Practice Exercises For Section 8** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 5                  | Rule 1: Side opposite = hypotenuse $\times$ sine;<br>Rule 2: Side opposite = side adjacent $\times$ tangent     |
| 6                  | Rule 1: Side adjacent = hypotenuse $\times$ cosine;<br>Rule 2: Side adjacent = side opposite $\times$ cotangent |
| 7                  | Handbook <b>page 91</b>   |
| 8                  | Handbook <b>page 89</b>   |
| 9                  | After dividing the isosceles triangle into two right angle triangles  |
| 10                 | Page <b>91</b>  |

**Answers to Practice Exercises For Section 9**

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 1                  | 2 degrees, 58 minutes   |
| 2                  | 1 degree, 47 minutes  |
| 3                  | 2.296 inches, as shown by the table on Handbook <b>page 992</b>   |
| 4                  | $360^\circ/N - 2a =$ angle intercepted by width $W$ . The sine of $\frac{1}{2}$ this angle; $\frac{1}{2}B = \frac{1}{2}W$ hence, this sine $\times B = W$ |
| 5                  | 3.1247 inches   |
| 6                  | 3.5085 inches   |
| 7                  | 1.7677 inches   |
| 8                  | 75 feet approximately   |
| 9                  | $a = 1.0316$ inches; $b = 3.5540$ inches; $c = 2.2845$ inches; $d = 2.7225$ inches  |
| 10                 | $a = 18^\circ 22'$ . For solution of similar problem, see <b>Example 4</b> of Section 8   |

**Answers to Practice Exercises For Section 9** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 11                 | $A = 5.8758''$ ; $B = 6.0352''$ ; $C = 6.2851''$ ;<br>$D = 6.4378''$ ; $E = 6.1549''$ ; $F = 5.8127''$ .<br>apply formula on Handbook <a href="#">page 94</a> |
| 12                 | $2^{\circ}37'33''$ ; $5^{\circ}15'6''$  |
| 13                 | 5.2805 inches   |
| 14                 | 10 degrees, 23 minutes  |

**Answers to Practice Exercises For Section 10**

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 1                  | $84^{\circ}$ ; $63^{\circ}31'$ ; $32^{\circ}29'$   |
| 2                  | $B = 29^{\circ}$ ; $b = 3.222$ feet; $c = 6.355$ feet;<br>area = 10.013 square feet  |
| 3                  | $C = 22^{\circ}$ ; $b = 2.33$ inches; $c = 1.358$ inches;<br>area = 1.396 square inches  |
| 4                  | $A = 120^{\circ}10'$ ; $a = 0.445$ foot; $c = 0.211$ foot;<br>area = 0.027 square feet   |
| 5                  | The area of a triangle equals one-half the product of two of its sides multiplied by the sine of the angle between them. The area of a triangle may also be found by taking one-half of the product of the base and the altitude |

**Answers to Practice Exercises For Section 11**

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 1                  | Handbook <a href="#">page 927</a> for Morse<br>Handbook <a href="#">page 937</a> for Jarno<br>Handbook <a href="#">page 937</a> for milling machine<br>Handbook <a href="#">page 1677</a> for taper pins |
| 2                  | 2.205 inches; 12.694 inches  |

**Answers to Practice Exercises For Section 11** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook) |
|--------------------|--|
| 3                  | 4.815 inches. Handbook <b>page 696</b>                 |
| 4                  | 1.289 inches. Handbook <b>page 696</b>                 |
| 5                  | 3.110 inches. Handbook <b>page 697</b>                 |
| 6                  | 0.0187 inch  |
| 7                  | 0.2796 inch  |
| 8                  | 1.000 inch   |
| 9                  | 26 degrees, 7 minutes                                  |

**Answers to Practice Exercises For Section 12**

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 1                  | Handbook <b>pages 647, 649</b>  |
| 2                  | Handbook <b>page 646</b>  |
| 3                  | Handbook <b>page 646</b>  |
| 4                  | Handbook <b>page 645</b>  |
| 5                  | Handbook <b>page 678</b>  |
| 6                  | Handbook <b>page 1736</b>   |
| 7                  | Handbook <b>pages 1725, 1736</b>  |
| 8                  | When the tolerance is unilateral  |
| 9                  | See Handbook <b>page 646</b>  |
| 10                 | It means that a tolerance of 0.0004 to 0.0012 inch could normally be worked to. See table on Handbook <b>page 652</b> |
| 11                 | Yes. See Handbook <b>page 729</b>   |

**Answers to Practice Exercises For Section 13**

| Number of Question | Answers<br>(Or where information is given in Handbook) |
|--------------------|--|
| 1                  | 4000 pounds. Handbook <b>page 372</b>                  |
| 2                  | Handbook <b>page 377</b>                               |
| 3                  | 430 balls. Handbook <b>page 2330</b>                   |
| 4                  | $\frac{1}{4}$ inch. Handbook <b>page 2363</b>          |
| 5                  | 0.172 inch. Handbook <b>page 1720</b>                  |
| 6                  | 0.1251 to 0.1252. Handbook <b>page 1670</b>            |
| 7                  | 24,000 rpm. Handbook <b>page 1688</b>                  |
| 8                  | 0.128 inch. Handbook <b>page 1649</b>                  |

**Answers to Practice Exercises For Section 14**

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 1                  | Both countries have used the Unified Standard, but Britain is changing to the ISO Metric. See Handbook <b>page 1725</b> and <b>page 1814</b>   |
| 2                  | The symbol is used to specify an American Standard screw thread 3 inches in diameter, 4 threads per inch or the coarse series, and Class 2 fit |
| 3                  | An Acme thread is stronger, easier to cut with a die, and more readily engaged by a split nut used with a lead screw                           |
| 4                  | The Stub Acme form of thread is preferred for those applications where a coarse thread of shallow depth is required                            |
| 5                  | See tables, Handbook <b>pages 1763, 1764</b>   |
| 6                  | $\frac{3}{4}$ inch per foot measured on the diameter—American and British standards  |
| 7                  | Handbook <b>page 1834</b>  |

**Answers to Practice Exercises For Section 14** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 8                  | Center line of tool is set square to axis of screw thread  |
| 9                  | Present practice is to set center line of tool square to axis of pipe  |
| 10                 | See formulas for $F_m$ and $F_{rs}$ , Handbook <b>page 1834</b>  |
| 11                 | By three-wire method or by use of special micrometers. See Handbook <b>pages 1893 to 1914</b>  |
| 12                 | Two quantities connected by a multiplication sign are the same as if enclosed by parentheses. See instructions about order of operations, Handbook <b>page 5</b> |
| 13                 | (a) Lead of double thread equals twice the pitch;<br>(b) lead of triple thread equals three times the pitch. See Handbook <b>page 1893</b>                       |
| 14                 | See Handbook <b>page 1734</b>  |
| 15                 | 0.8337 inch. See <b>page 1901</b>  |
| 16                 | No. Bulk of production is made to American Standard dimensions given in Handbook   |
| 17                 | This standard has been superseded by the American Standard   |
| 18                 | Most Machine screws (about 80% of the production) have the coarse series of pitches  |
| 19                 | (a) Length includes head; (b) Length does not include head   |
| 20                 | No. 25. See table, Handbook <b>page 1934</b>   |
| 21                 | 0.1935 inch. See table, Handbook <b>page 856</b>   |
| 22                 | Yes. The diameters decrease as the numbers increase  |
| 23                 | The numbered sizes range in diameter from 0.0059 to 0.228 inch, and the letter sizes from 0.234 to 0.413 inch. See Handbook <b>pages 854 to 864</b>              |



**Answers to Practice Exercises For Section 14** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 24                 | A thread of $\frac{3}{4}$ standard depth has sufficient strength, and tap breakage is reduced                          |
| 25                 | (a) and (b) the American Standard Unified form   |
| 26                 | Cap-screws are made in the same pitches as the Coarse-, Fine-, and 8- thread series of the American standard, class 2A |
| 27                 | For thread form, see Handbook <b>page 1872</b> . There are seven standard diameters as shown on <b>page 1873</b> .     |
| 28                 | Handbook <b>page 892</b>   |
| 29                 | Handbook <b>page 892</b>   |
| 30                 | $0.90 \times$ pitch. See Handbook <b>pages 1896</b>  |
| 31                 | To reduce errors in the finished thread  |
| 32                 | Included angle is $82^\circ$ for each  |

**Answers to Practice Exercises For Section 15**

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 1                  | A foot-pound in mechanics is a unit of work and is the work equivalent to raising 1 pound 1 foot high   |
| 2                  | 1000 foot-pounds  |
| 3                  | Only as an average value. See Handbook <b>page 175</b>  |
| 4                  | 28 foot-pounds. See Handbook <b>pages 173 and 175</b>   |
| 5                  | 1346 pounds   |
| 6                  | Neglecting air resistance, the muzzle velocity is the same as the velocity with which the projectile strikes the ground. See Handbook <b>page 167</b> |
| 7                  | See Handbook <b>page 148</b>  |

**Answers to Practice Exercises For Section 15** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 8                  | Square  |
| 9                  | 1843 pounds approximately   |
| 10                 | The pull will have been increased from 1843 pounds to about 2617 pounds. See Handbook <b>page 161</b>   |
| 11                 | Yes   |
| 12                 | About 11 degrees  |
| 13                 | The angle of repose   |
| 14                 | The coefficient of friction equals the tangent of the angle of repose   |
| 15                 | 32.16 feet per second <sup>2</sup>  |
| 16                 | No. 32.16 feet per second <sup>2</sup> is the value at sea level at a latitude of about 40 degrees, but this figure is commonly used. See Hand book <b>page 142</b> |
| 17                 | No. The rim stress is independent of the diameter and depends upon the velocity. See Handbook <b>page 188</b>   |
| 18                 | 10 to 13. See Handbook <b>page 190</b>  |
| 19                 | No. The increase in stress is proportional to the square of the rim velocity  |
| 20                 | 110 feet per second or approximately 1.25 miles per minute  |
| 21                 | Because the strength of wood is greater in proportion to its weight than cast iron  |
| 22                 | See Handbook <b>page 195</b>  |
| 23                 | In radians per second   |
| 24                 | A radian equals the angle subtended by the arc of circle; this angle is 57.3 degrees nearly   |
| 25                 | Handbook <b>page 97</b>   |
| 26                 | 60 degrees; 72 degrees; 360 degrees   |
| 27                 | Handbook <b>page 97</b>   |

**Answers to Practice Exercises For Section 15** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 28                 | Handbook <b>page 195</b> (see Guide <b>page 135</b> for example illustrating method of using tables) |
| 29                 | Length of arc = radians $\times$ radius. As radius = 1 in the table segments, $l$ = radians          |
| 30                 | 40 degrees, 37.5 minutes   |
| 31                 | 176 radians per second;<br>1680.7 revolutions per minute   |
| 32                 | 1.5705 inches  |
| 33                 | 27.225 inches  |

**Answers to Practice Exercises For Section 16**

| Number of Question | Answers<br>(Or where information is given in Handbook) |
|--------------------|--|
| 1                  | Handbook <b>page 208</b>                               |
| 2                  | 12,000 pounds  |
| 3                  | 1 inch   |
| 4                  | Handbook <b>page 554</b>                               |
| 5                  | Handbook <b>page 203</b>                               |
| 6                  | Handbook <b>page 554</b>                               |
| 7                  | 3-inch diameter. See Handbook <b>page 290</b>          |

**Answers to Practice Exercises For Section 17**

| Number of Question | Answers<br>(Or where information is given in Handbook)                |
|--------------------|---|
| 1                  | 1.568 (See formula on Handbook <b>page 249</b> )                      |
| 2                  | 6200 pounds per square inch approximately                             |
| 3                  | It depends upon the class of service.<br>See Handbook <b>page 303</b> |
| 4                  | Tangential load = 550 pounds;<br>twisting moment = 4400 inch-pounds   |
| 5                  | See formulas on Handbook <b>page 302</b>                              |

**Answers to Practice Exercises For Section 17** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 6                  | The head is useful for withdrawing the key, especially when it is not possible to drive against the inner end. See Handbook <a href="#">page 2366</a> |
| 7                  | Key is segment-shaped and fits into circular key-seat. See Handbook <a href="#">pages 2369, 2370</a>  |
| 8                  | These keys are inexpensive to make from round bar stock, and keyseats are easily formed by milling  |
| 9                  | 0.211 inch. See table, Handbook <a href="#">page 2375</a>   |

**Answers to Practice Exercises For Section 18**

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 1                  | See text and footnote on Handbook <a href="#">page 2156</a>  |
| 2                  | American Standard B92.1, Handbook <a href="#">pages 2156</a> and <a href="#">2162</a>  |
| 3                  | See text, Handbook <a href="#">page 2156</a>   |
| 4                  | See text, Handbook <a href="#">page 2156</a>   |
| 5                  | See definitions, Handbook <a href="#">page 2158</a>  |
| 6                  | None. See text, Handbook <a href="#">page 2162</a>   |
| 7                  | Yes, a crowned spline permits small amount of misalignment. See Handbook <a href="#">page 2174</a> .   |
| 8                  | The torque capacity of splines may be calculated using the formulas and charts on Handbook <a href="#">page 2170</a> to <a href="#">2174</a> |
| 9                  | Handbook <a href="#">page 2169</a>   |
| 10                 | The fillet radius permits heavier loading and effects greater fatigue resistance than flat roots through absence of stress raisers           |

**Answers to Practice Exercises For Section 19**

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 1                  | 18 teeth; 3 inches; 0.2618 inch   |
| 2                  | 2.666 inches; 2.333 inches; 0.166 inches  |
| 3                  | Handbook <b>page 2039</b> and <b>page 2040</b>  |
| 4                  | Chordal thickness at intersections of pitch circle with sides of tooth  |
| 5                  | Table, Handbook <b>page 2038</b>  |
| 6                  | Calculate using table, Handbook <b>page 2040</b>  |
| 7                  | Surface durability stress and tooth fillet tensile stress are the two principle factors to be found in determining the power transmitting capacity of spur gears. |
| 8                  | Because the tooth shape varies as the number of teeth is changed  |
| 9                  | No; one hob may be used for all tooth numbers, and the same applies to any generating process   |
| 10                 | Stub  |
| 11                 | Handbook (see <i>Fellows Stub Tooth</i> on <b>page 2041</b> )   |
| 12                 | Handbook <b>page 2121</b>   |
| 13                 | Handbook <b>page 2051</b>   |
| 14                 | Handbook <b>page 2041</b>   |
| 15                 | See table on Handbook <b>page 2040</b>  |
| 16                 | Handbook <b>page 1950</b>   |
| 17                 | Handbook <b>pages 2067 to 2072</b>  |
| 18                 | Handbook <b>page 2122</b>   |
| 19                 | Yes, but accurate tooth form is obtained only by a generating process   |
| 20                 | See paragraph on Handbook <b>page 2091</b>  |
| 21                 | Handbook <b>page 2085</b>   |
| 22                 | When the numbers of teeth in both the pinion and the gear are the same, the pitch angle being 45 degrees for each   |

**Answers to Practice Exercises For Section 19** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 23                 | The whole depth minus the clearance between the bottom of a tooth space and the end of a mating tooth = the working depth                     |
| 24                 | See Handbook <b>page 2045</b>   |
| 25                 | See Handbook <b>pages 2033</b> and <b>2035</b>  |
| 26                 | See diagram, Handbook <b>page 2085</b>  |
| 27                 | Circular pitch of gear equals linear pitch of worm  |
| 28                 | Helix angle or lead angle of worm is measured from a plane perpendicular to the axis; helix angle of a helical gear is measured from the axis |
| 29                 | These terms each have the same meaning  |
| 30                 | To provide a grinding allowance and to increase hob life over repeated sharpening   |
| 31                 | See explanation beginning on Handbook <b>page 2098</b>  |
| 32                 | Handbook <b>page 2098</b>   |
| 33                 | Handbook <b>page 2100</b>   |
| 34                 | Normal diameter pitch is commonly used  |
| 35                 | Yes (See Handbook <b>page 2100</b> ), but the hobbing process is generally applied  |
| 36                 | Pitch diameter  |
| 37                 | Handbook <b>page 2114</b>   |

**Answers to Practice Exercises For Section 20**

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 1                  | AISI 1108 CD $\frac{1}{2}$ in. dia. = 1008 rpm<br>12L13, 150–200 HB : = 1192 rpm<br>1040, HR : = 611 rpm<br>1040, 375–425 HB : = 214 rpm<br>41L40, 200–250 HB : = 718 rpm<br>4140, HR : = 611 rpm<br>O2, Tool Stee : = 535 rpm<br>M2, Tool Steel : = 497 rpm<br>AISI 1108 CD : 4 in.dia. = 126 rpm<br>12L13, 150–200 HB : = 149 rpm<br>1040, HR : = 576 rpm<br>1040, 375–425 HB : = 27 rpm<br>41L40, 200–250 HB : = 90 rpm<br>4140, HR : = 76 rpm<br>O2, Tool Steel : = 67 rpm<br>M2, Tool Steel : = 62 rpm |
| 2                  | AISI 1330, 200 HB : 153 rpm<br>201 Stainless Steel, CD : 345 rpm<br>ASTM Class 50 Gray Cast Iron : 145 rpm<br>6A1 – 4V Titanium Alloy : 52 rpm<br>Waspaloy : 20 rpm<br>(V = 60 fpm)   |
| 3                  | 1½-in. Dia.: 157 fpm—OK<br>3-in. Dia. : 314 fpm—OK<br>4-in. Dia. : 419 fpm—Too Fast   |
| 4                  | 764 rpm   |
| 5                  | 840 rpm (V = 110 fpm)   |
| 6                  | Operation:<br>1: $N = 167$ rpm; $f_m = 13$ in./min.<br>2: $N = 127$ rpm; $f_m = 2.0$ in./min.<br>3: $N = 744$ rpm<br>4: $N = 458$ rpm   |

**Answers to Practice Exercises For Section 20** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 7                  | Existing operation:<br>$V = 59$ fpm (Too Fast)<br>$f_t = 0.011$ in./tooth (Too Severe)<br>Change to:<br>$V = 40$ fpm $N = 50$ rpm<br>$f_t = 0.006$ in./tooth; $f_m = 3.6$ in./min  |
| 8                  | Existing operation:<br>$V = 188$ fpm (Too slow)<br>$f_t = 0.006$ in./tooth (Too Slow)<br>Change to:<br>$V = 375$ fpm $N = 120$ rpm<br>$f_t = 0.012$ in./tooth; $f_m = 520$ in./min   |
| 9                  | $V = 414$ fpm, $P_c = 9.0$ hp, $P_m = 11.24$ hp  |
| 10                 | $V = 104$ fpm  |
| 11                 | $V = 205$ fpm<br>$(Q_{max} = 8.55$ in <sup>3</sup> /min.;<br>$f_m = 10.5$ in./min;<br>$N = 131$ rpm)   |
| 12                 | $\frac{1}{4}$ in.: $T = 123$ lb; $M = 6.38$ in-lb;<br>$P_m = 0.19$ hp<br>$\frac{1}{2}$ in.: $T = 574$ lb; $M = 68$ in-lb;<br>$P_m = 1.0$ hp<br>$1$ in.: $T = 2712$ lb; $M = 711$ in-lb;<br>$P_m = 5.3$ hp<br>$19$ mm.: $T = 7244$ N; $M = 37.12$ N-m;<br>$P_m = 2.43$ kw |
| 13                 | $T = 1473$ lb; $M = 655$ in-lb; $P_m = 4.9$ hp   |
| 14                 | Handbook <b>page 1009</b>  |
| 15                 | Handbook <b>page 1010</b>  |
| 16                 | Handbook <b>page 1013</b>  |
| 17                 | Handbook <b>page 1014</b>  |
| 18                 | Handbook <b>page 776</b> and <b>1011</b>   |



**Answers to Practice Exercises For Section 20** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook) |
|--------------------|--|
| 19                 | Handbook <b>pages 1072</b> and <b>1074</b>             |
| 20                 | Handbook <b>pages 1040</b> and <b>1043</b>             |
| 21                 | Handbook <b>page 1040</b>                              |
| 22                 | Handbook <b>page 1084</b>                              |
| 23                 | Handbook <b>pages 1084</b> , and <b>1085</b>           |
| 24                 | Handbook <b>page 1090</b>                              |

**Answers to Practice Exercises For Section 21**

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 1                  | Drill press, Jig-borer, turret punch press, spot welder, riveting machine, shear, inspection machine  |
| 2                  | Contour milling machine, lathe, grinder, vertical mill, flame cutting machine   |
| 3                  | NC machines are more productive, more accurate, and produce less scrap, see Handbook <b>page 1254</b>   |
| 4                  | (b)   |
| 5                  | Resolver. See Handbook <b>page 1262</b>   |
| 6                  | CNC systems are less costly, more reliable, and have greater capability than hardware. See Handbook <b>page 1254</b>  |
| 7                  | They provide data of slide position and velocity. See Handbook <b>page 1262</b>   |
| 8                  | At 1.8 degrees per pulse, 200 pulse would be needed to turn the lead screw 360 degrees, or one revolution. With a 5-pitch screw, the linear movement of the slide would be 0.200 inch, or 0.001 inch per pulse. With 254 pulses, the slide would move 0.254 inch. |
| 9                  | (b). See Handbook <b>page 1280</b>  |
| 10                 | Sequence number. See Handbook <b>page 1274</b>  |
| 11                 | F. See Handbook <b>page 1278</b>  |

**Answers to Practice Exercises For Section 21** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 12                 | Cutter offset is an adjustment parallel to one of the axes. (See Handbook <a href="#">page 1280</a> .) Cutter compensation is an adjustment that is normal to the part, whether or not the adjustment is parallel to an axis. See Handbook <a href="#">page 1282</a> |
| 13                 | False. Circular interpolation eliminates the need for approximating straight lines. See Handbook <a href="#">page 1282</a>   |
| 14                 | One. See Handbook <a href="#">page 1282</a>  |
| 15                 | a-5, b-6, c-3, d-2, e-4, f-1.<br>See Handbook <a href="#">pages 1287 – 1291</a>  |
| 16                 | False. See Handbook <a href="#">page 1286</a>  |
| 17                 | False. See Handbook <a href="#">page 1287</a>  |
| 18                 | All three. See Handbook <a href="#">page 1254</a>  |
| 19                 | Drive, part, and check surfaces.<br>See Handbook <a href="#">pages 1299 – 1304</a>   |
| 20                 | Drive, part, and check surfaces.<br>See Handbook <a href="#">page 1299</a>   |
| 21                 | A G word is a preparatory code word consisting of the three address G, and two digits, that is used to tell the control system to accept the remainder of the block in the required way. See Handbook <a href="#">pages 1274 – 1278</a>                              |
| 22                 | A startup statement consists of code instructions that will move the workplace into contact with one or more of the three guiding surfaces (drive, part, and check). See Handbook <a href="#">pages 1292 – 1307</a>  |

**Answers to Practice Exercises For Section 21** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 23                 | The "right hand rule" says that if a right hand is laid palm up on the table of a vertical milling machine, the thumb will point in the positive X direction, the forefinger in the positive Y direction, and the erect middle finger in the positive Z direction. See Handbook <a href="#">page 1264</a>   |
| 24                 | <p><math>L_1 = \text{LINE/ RIGHT, TANTO, } C_1,</math><br/> <math>\text{RIGHT, TANTO, } C_2</math></p> <p><i>or</i></p> <p><math>L_1 = \text{LINE/ LEFT, TANTO, } C_2,</math><br/> <math>\text{LEFT, TANTO, } C_1</math></p> <p><math>L_2 = \text{LINE/ RIGHT, TANTO, } C_2,</math><br/> <math>\text{RIGHT, TANTO, } C_3</math></p> <p><i>or</i></p> <p><math>L_2 = \text{LINE/ LEFT, TANTO, } C_3,</math><br/> <math>\text{LEFT, TANTO, } C_2</math></p> <p><math>L_3 = \text{LINE/ RIGHT, TANTO, } C_3,</math><br/> <math>\text{RIGHT, TANTO, } C_4</math></p> <p><i>or</i></p> <p><math>L_3 = \text{LINE/ LEFT, TANTO, } C_4,</math><br/> <math>\text{LEFT, TANTO, } C_3</math></p> <p><math>L_4 = \text{LINE/ RIGHT, TANTO, } C_4,</math><br/> <math>\text{RIGHT, TANTO, } C_1</math></p> <p><i>or</i></p> <p><math>L_4 = \text{LINE/ LEFT, TANTO, } C_1,</math><br/> <math>\text{LEFT, TANTO, } C_4</math></p> <p>See Handbook <a href="#">page 1296</a></p> |

**Answers to Practice Exercises For Section 21** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 25                 | $C_1 = \text{CIRCLE}/\text{XLARGE}, L_1, \text{YSMALL},$<br>$L_2, \text{RADIUS},$<br>$C_2 = \text{CIRCLE}/\text{TANTO}, L_2, \text{XSMALL},$<br>$P_1, \text{RADIUS}, .75$<br>$C_3 = \text{CIRCLE}/P_1, P_2, P_3$<br>$C_4 = \text{CIRCLE}/\text{CENTER}, P_3, \text{TANTO}, l_3$<br>See Handbook <b>pages 1298, 1301</b> |
| 26                 | $(1+25)/42$<br>$6*8 + 8/2-52$<br>$6*(8+8)/(2- 52)$<br>$(4**2 +\text{SQRTF}((12+8)**3))/(2*6.8/(1+3)**4)$<br>$\text{SINF}(30)$<br>$\text{ATANF}(.486)$<br>See Handbook <b>page 1294</b>  |
| 27                 | Postprocessor. See Handbook <b>page 1294</b>  |

**Answers to General Review Questions**

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 1                  | Handbook <b>page 69</b> gives the formula for length of side $S$ in terms of the given area $A$  |
| 2                  | The diameter of each end and the length of the taper; see explanation on Handbook <b>page 926</b> , also table, <b>page 937</b>  |
| 3                  | Tolerance is applied in whatever direction is likely to be the least harmful; see <b>page 647</b>  |
| 4                  | It is said that James Watt found, by experiment, that an average carthorse can develop 22,000 foot-pounds per minute, and added 50 percent to ensure good measure to purchasers of his engines ( $22,000 \times 1.50 = 33,000$ ) |
| 5                  | Tin in the high grades, and lead in the lower grades   |
| 6                  | Same depth as ordinary gear of 10 diametral pitch  |

**Answers to General Review Questions** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 7                  | The tooth thickness and the number of teeth are the same as an ordinary gear of 8 diametral pitch   |
| 8                  | Add 2 to the number of teeth and divide by the outside diameter   |
| 9                  | Multiply the outside diameter by 3.1416 and divide the product by the number of teeth plus 2  |
| 10                 | Birmingham or Stub's iron wire gage is used for seamless steel, brass, copper, and aluminium tubing   |
| 11                 | Iron wire rope has the least strength of all wire rope materials. See Handbook <a href="#">page 369</a>   |
| 12                 | If surfaces are well lubricated, the friction is almost independent of the pressure, but if the surfaces are unlubricated, the friction is directly proportional to the normal pressure except for the higher pressures   |
| 13                 | It depends very largely upon temperature. See Handbook section, <i>Lubricated Surfaces</i> on <a href="#">page 157</a>  |
| 14                 | $8 - (-4) = 12$ . See rules for positive and negative numbers, Handbook <a href="#">page 4</a>  |
| 15                 | Yes. One meter equals 3.2808 feet; see other equivalents on Handbook <a href="#">page 2549</a>  |
| 16                 | Experiments have shown that there is a definite relationship between heat and work and that 1 British thermal unit equals 778 foot-pounds. To change 1 pound of water at 212°F into steam at that temperature requires about 966 British thermal units, or $966 \times 788 =$ about 751,600 foot-pounds; hence, the number of pounds of water evaporated 212°F, equivalent to 1 horsepower-hour = $1,980,000 \div 751,600 = 2.64$ pounds of water as given in Handbook, <a href="#">page 2578</a> |

**Answers to General Review Questions** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 17                 | No. The thickness of the pipe is increased by reducing the inside diameter; compare thickness in the table on Handbook <a href="#">page 2527</a>  |
| 18                 | As a general rule, smoother finishes are required for harder materials, for high loads, and for high speeds. See Handbook <a href="#">page 2225</a>   |
| 19                 | Yes. The so-called "O.D. pipe" begins, usually, with the $\frac{1}{4}$ -inch size   |
| 20                 | It is light in weight and resists deterioration from corrosive or caustic fluids. See Handbook <a href="#">page 2532</a>  |
| 21                 | Yes. About 140 degrees lower. See Handbook <a href="#">page 403</a>   |
| 22                 | Low-carbon alloy steels of high-chromium content. See Handbook <a href="#">page 439</a>   |
| 23                 | Low-carbon steels containing 0.20% sulfur or less and usually from 0.90 to 1.20% manganese. See Handbook <a href="#">page 454</a>   |
| 24                 | No. The nominal length of a file indicates the distance from the point to the "heel" and does not include the tang  |
| 25                 | Yes. See table, Handbook <a href="#">page 407</a>   |
| 26                 | Specific heat is a ratio of the amount of heat required to raise the temperature of a certain weight of substance 1°F to the amount of heat required to raise the temperature of an equivalent of water 1°F. See Handbook <a href="#">page 399</a>      |
| 27                 | (a) and (b) A number indicating how a given volume of the material or liquid compares in weight with an equal volume of water. (c) A number indicating a comparison in weight with an equal volume of air. See Handbook <a href="#">pages 407 – 408</a> |
| 28                 | The first digit identifies the alloy type; the second, the impurity control; etc. See Handbook <a href="#">page 575</a>   |

**Answers to General Review Questions** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 29                 | Red brass contains 84 to 86% copper, about 5% tin, 5% lead, and 5% zinc whereas yellow brass contains 62 to 67% copper, about 30% zinc, 1.5 to 3.5% lead and not even 1% tin. See UNS Designations on Handbook <b>pages 556, 571</b>   |
| 30                 | See Handbook <b>pages 430 and 433</b>  |
| 31                 | No. Twenty-six sizes ranging from 0.234 to 0.413 inch are indicated by capital letters of the alphabet (see table, Handbook <b>page 856–864</b> ). Fractional sizes are also listed in manufacturers' catalogues beginning either at $\frac{1}{32}$ inch, $\frac{1}{16}$ inch, or $\frac{1}{8}$ inch, the smallest size varying with different firms |
| 32                 | To ensure uniform heating at a given temperature and protect the steel against oxidation. See Handbook <b>page 516</b>   |
| 33                 | Hardening temperature vary for different steels; see critical tempratures and how they are determined, Handbook <b>pages 515 and 516</b>   |
| 34                 | Set the taper attachment to an angle the cosine of which equals $0.125 \div 0.1255$ . See Handbook <b>page 1964</b>  |
| 35                 | See Handbook <b>page 692</b>   |
| 36                 | Divide $\frac{3}{4}$ by 12; multiply the taper per inch found by 5 and subtract the result from the large diameter. See rules for figuring tapers, Handbook <b>page 713</b>  |
| 37                 | Yes. See "Useful Relationships Among Angles," Handbook <b>page 99</b>  |
| 38                 | 0.8833. See Handbook <b>page 97</b>  |
| 39                 | $x = 3$  |
| 40                 | About $12\frac{1}{2}$ degrees. See Handbook <b>page 2351</b>   |

**Answers to General Review Questions** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 41                 | Ratio between resistance to the motion of a body due to friction, and the perpendicular pressure between the sliding and fixed surfaces. See formula, Handbook <a href="#">page 157</a>  |
| 42                 | No. Stub's steel wire gage applies to tool steel rod and wire, and the most important applications of Stub's iron wire gage (also known as Birmingham) are to seamless tubing, steel strips, and telephone and telegraph wire      |
| 43                 | If the difference between the length of the pawls equals one-half of the pitch of the ratchet wheel teeth, the practical effect is that of reducing the pitch of one-half. See ratchet gearing, Handbook <a href="#">page 2099</a> |
| 44                 | The high modulus of elasticity eliminates the need for periodic retensioning that is normally required with V-belts. See Handbook <a href="#">page 2388</a>  |
| 45                 | Increasing centrifugal force has less effect on flat belts because of the low center of gravity. See Handbook <a href="#">page 2388</a>  |
| 46                 | The ultimate strength is less due to bending action. See formula, Handbook <a href="#">page 386</a> , and also Handbook table, <i>Close-link Hoisting, Sling and Crane Chain</i> on <a href="#">page 390</a>                       |
| 47                 | Refer to Handbook <a href="#">page 388</a>   |
| 48                 | Multiply 90 by 12 and divide the circumference of the shaft to obtain rpm. See cutting speed calculations, Handbook <a href="#">pages 1016– 1018</a>   |
| 49                 | (a) Lard oil; (b) gasoline   |
| 50                 | If the teeth advance around the gear to the right, as viewed from one end, the gear is right handed; and, if they advance to the left, it is a left hand gear. See illustrations, Handbook <a href="#">page 2099</a>               |



**Answers to General Review Questions** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 51                 | No. They may be opposite hand depending upon the helix angle. See Handbook <b>pages 2099</b> and <b>2100</b>   |
| 52                 | Multiply the total length by the weight per foot for plain end and coupled pipe, given in the table, Handbook <b>page 2527</b>   |
| 53                 | The processes are similar but the term “packhardening” usually is applied to the casehardening of tool steel. See Handbook <b>page 526</b> and <b>page 516</b>                         |
| 54                 | A gas process of surface hardening. See Handbook <b>page 526</b>   |
| 55                 | See definitions for these terms given on Handbook <b>page 962</b>  |
| 56                 | About 34 inches, but the height may vary from 32 to 36 inches for heavy and light assembling, respectively   |
| 57                 | Major diameter is the same as outside diameter, and the minor diameter is the same as root diameter. See definitions, on Handbook <b>page 1729</b>                                     |
| 58                 | The SAE Standards conforms, in general, with the Unified and American Standard Screw Thread Series as revised in 1959 and may, therefore, be considered to be the same for all purpose |
| 59                 | See informations on work materials, Handbook <b>page 1009</b>  |
| 60                 | Yes. See Handbook <b>page 513</b> and <b>page 552</b>  |
| 61                 | 13.097 millimeters. See the table on Handbook <b>page 2552</b> , which gives millimeter equivalents of inch fractions, inches, and feet  |

**Answers to General Review Questions** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 62                 | The involute of an angle is obtained by subtracting the involute of the angle from the secant of that angle. See Handbook <b>page 103</b> . The involute functions of angles are found in the tables beginning on handbook <b>page 104</b>   |
| 63                 | According to the table on Handbook page 990, the recommended cutting speed is 200 feet per minute at 0.017 in./rev. This speed is for average conditions and is intended as a starting point, so it is important to know the factors that affect the cutting speed as covered in the "How to Use the Feeds and Speeds Tables" section on Handbook <b>page 1027</b> |
| 64                 | No. First determine the diametral pitch the same as for a spur gear; then divide this "real diametral pitch" by the cosine of "real diametral pitch" by the cosine of the helix angle to obtain the "normal diametral pitch." which is the pitch of the cutter. See Handbook <b>page 2100</b>  |
| 65                 | Casehardening steels can have hard, fine grained surfaces and a soft, ductile core giving good strength combined with wear resistance. See Handbook <b>page 2144</b>   |
| 66                 | Not in every instance. See Handbook <b>page 2176</b>   |
| 67                 | A cemented carbide seat provides a flat bearing surface and a positive-, negative-, or neutral-rake orientation to the tool insert. See Handbook <b>page 758</b>   |
| 68                 | No. The size of the gear blank, the pitch of the teeth, and depth of cut are sufficient for the operator in the shop. The tooth curvature is the result of the gear-cutting process. Tooth curves on the working drawing are of no practical value   |

**Answers to General Review Questions** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 69                 | By changing the inclination of the dividing head spindle. See Handbook <a href="#">page 2212</a>   |
| 70                 | See formula and example on Handbook <a href="#">page 2212</a>  |
| 71                 | Divide the total number of teeth in both gears by twice the diametral pitch to obtain the theoretical center-to-center distance. (See formula in the table of Formulas for Dimensions of Standard Spur Gears, Handbook <a href="#">page 2035</a> ) |
| 72                 | Subtract number of teeth on pinion from number of teeth on gear and divide the remainder by two times the diametral pitch (See Rule at bottom of Handbook <a href="#">page 2075</a> )  |
| 73                 | See Handbook <a href="#">page 1479</a>   |
| 74                 | The Standard Wire Gage (S.W.G), also known as the Imperial Wire Gage and as the English Legal Standard, is used in Britain for all wires   |
| 75                 | A simple type of apparatus for measuring power   |
| 76                 | With a dynamometer, the actual amount of power delivered may be determined; that is, the power input minus losses. See Handbook <a href="#">page 2360</a>  |
| 77                 | The uniformly loaded beam has double the load capacity of a beam loaded at the center only. See formulas, Handbook <a href="#">page 261</a>  |
| 78                 | Refer to Handbook <a href="#">page 514</a> for graph of SAE-determined relationships.  |
| 79                 | No. The nominal size of steel pipe, except for sizes above 12 inches, is approximately equal to the inside diameter. See tables, Handbook <a href="#">pages 2527</a> and <a href="#">2529</a>  |
| 80                 | 0.357 inch. See formula, Handbook <a href="#">page 224</a>   |
| 81                 | The laws of sines and cosines are stated on Handbook <a href="#">page 89</a>   |
| 82                 | Both the sine and cosines of 45 degrees are 0.70711  |

**Answers to General Review Questions** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 83                 | Multiply depth in feet by 0.4335  |
| 84                 | No. See Handbook <a href="#">page 2314</a>  |
| 85                 | 100%  |
| 86                 | 50%   |
| 87                 | Various steels are used, depending on kind of spring. See Handbook <a href="#">page 450</a>   |
| 88                 | Normalizing is a special annealing process. The steel is heated above the critical range and allowed to cool in still air at ordinary temperature, Handbook <a href="#">page 526</a> . Normalizing temperatures for steels are given on Handbook pages <a href="#">page 532 – 533</a> |
| 89                 | The standard mounting dimensions, frame sizes, horsepower, and speed ratings. See section beginning on Handbook <a href="#">page 2465</a>   |
| 90                 | Yes. The American standard drafting room practice includes section lining, etc. See Handbook <a href="#">page 632</a>   |
| 91                 | No. There are different tapers per foot, ranging from 0.5986 to 0.6315 inch. See table, Handbook <a href="#">page 927</a>   |
| 92                 | Yes. See Handbook <a href="#">page 1941</a>   |
| 93                 | Unilateral and plus. See Handbook <a href="#">page 646</a>  |
| 94                 | See table, Handbook <a href="#">page 1832</a>   |
| 95                 | If $D$ = diameter of hole in inches; $T$ = stock thickness in inches; shearing strength of steel = 51,000 pounds per square inch, then tonnage for punching = $51,000D\pi T/2000 = 80DT$  |
| 96                 | See Handbook <a href="#">pages 2522 to 2523</a>   |
| 97                 | The Brown & Sharpe or American wire gage is used for each. See Handbook <a href="#">pages 2519 to 2523</a>  |

**Answers to General Review Questions** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 98                 | No, this name is applied to several compositions that vary widely  |
| 99                 | Antimony and copper  |
| 100                | 177 nearly. See table on Handbook <a href="#">page 1137</a>  |
| 101                | See Handbook pages <a href="#">page 398</a> , <a href="#">403</a> , to <a href="#">407</a>   |
| 102                | See Handbook <a href="#">page 1147</a>   |
| 103                | See Handbook <a href="#">page 1148</a>   |
| 104                | See Handbook <a href="#">page 1330</a>   |
| 105                | See Handbook <a href="#">page 1964</a>   |
| 106                | See Handbook <a href="#">page 833</a>  |
| 107                | Steel, chromium-plated steel, chromium carbide, tungsten carbide, and other materials.<br>See Handbook <a href="#">page 743</a>  |
| 108                | See text on Handbook <a href="#">page 743</a>  |
| 109                | The lead of a milling machine equals lead of helix or spiral milled when gears of equal size are placed on feed screw and wormgear stud; see rule for finding lead on Handbook <a href="#">page 1981</a> |
| 110                | Multiply product of driven gears by lead of machine and divide by product of driving gears.<br>If lead of machine is 10, divide 10 times product of driven gears by product of drivers                   |
| 111                | $\frac{5}{11}$ ; $\frac{79}{183}$ ; $\frac{19}{29}$  |
| 112                | The whole depth and tooth thickness at the large ends of the bevel gear teeth are the same as the whole depth and thickness of spur gear teeth of the same pitch   |
| 113                | See Text on Handbook <a href="#">page 963</a>  |

**Answers to General Review Questions** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)   |
|--------------------|--|
| 114                | 5.7075 inches  |
| 115                | <p>Use the formula (Handbook <b>page 386</b>) for finding the breaking load, which in this case is taken as three times the actual load. Transposing,</p> $D = \sqrt{\frac{6 \times 2000 \times 3}{54,000}} = 0.816, \text{ say,}$ <p><math>\frac{7}{8}</math> inch diameter</p> |
| 116                | Because the direction of the cutter thrust tends to cause the gear to rotate upon the arbor. See Handbook <i>Milling the Helical Teeth</i> on <b>page 2109</b>   |
| 117                | Trepanning describes use of a fly-cutter or circular toothed cutter to cut a groove to the full depth of a plate, producing a hole of the required size. See Handbook <b>page 1081</b>   |
| 118                | Chiefly when a hole is to be tapped or reamed after drilling. See Handbook <b>page 976</b>   |
| 119                | See table on Handbook <b>page 492</b>  |
| 120                | See Handbook <b>page 2464</b>  |
| 121                | See Handbook <b>page 95</b>  |
| 122                | See Handbook <b>page 2144</b> and <b>2145</b>  |
| 123                | See Handbook <b>page 915</b>   |
| 124                | See table Handbook <b>page 1210</b>  |
| 125                | See table Handbook <b>page 1194</b>  |
| 126                | Motor rotation has been standardized by the National Electrical Manufacturers Association. See Handbook <b>page 2467</b>   |

**Answers to General Review Questions** (Continued)

| Number of Question | Answers<br>(Or where information is given in Handbook)  |
|--------------------|---|
| 127                | Yes. See last paragraph on Handbook <b>page 2340</b>  |
| 128                | <p>To solve this problem, the helix angle <math>\phi</math> of the thread at the pitch and major diameters must be found, which is accomplished by substituting these diameters (<math>E</math> and <math>D</math>) for the minor diameters (<math>K</math>) in the formula for <math>\phi</math>. Thus, at the pitch diameter:</p> $\tan \phi = \frac{\text{lead of thread}}{\pi E} = \frac{0.400}{\pi \times 0.900}$ $\phi = 8.052^\circ = 8^\circ 3'$ $a = a_e + \phi$ $a_e = a - \phi = 19^\circ 16' - 8^\circ 3' = 11^\circ 13'$ <p>At the major diameter:</p> $\tan \phi = \frac{\text{lead of thread}}{\pi D} = \frac{0.400}{\pi \times 1.000}$ $\phi = 7.256^\circ = 7^\circ 15'$ $a_e = a - \phi = 19^\circ 16' - 7^\circ 15' = 12^\circ 1'$ |
| 129                | 0.0037 inch   |
| 130                | $\frac{5}{12}$ foot (5 inches) per minute obtained by dividing 25,000 by 60,000. Note that this speed is considerably less than maximum surface speed at any load to prevent excess heat and wear   |
| 131                | Yes. See Table 14, Handbook <b>page 2287</b> , and following tables   |
| 132                | 550 to 600 Bhn (Brinell hardness number)<br>(See Handbook <b>page 2225</b> )  |
| 133                | 1 pound (See Table 6, Handbook <b>page 2330</b> )   |
| 134                | 23,000 rpm. See Handbook <b>page 1688</b>   |
| 135                | See Handbook <b>page 1905</b>   |
| 136                | See footnote, Table 2, Handbook <b>page 82</b>  |

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